Dark Matter Time Modulations and Directional Signatures

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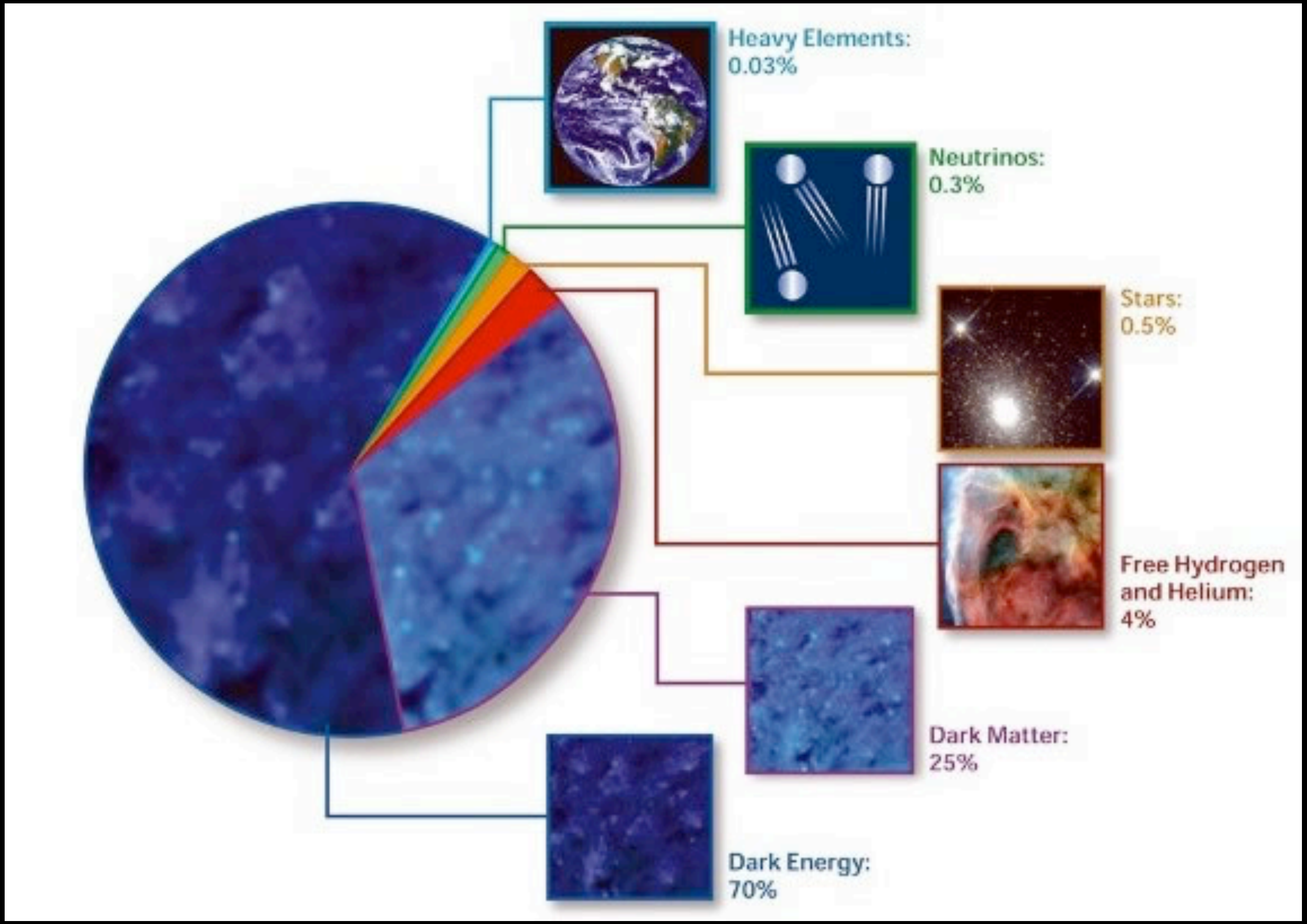
Gran Sasso Summer Institute 2014
September 24, 2014

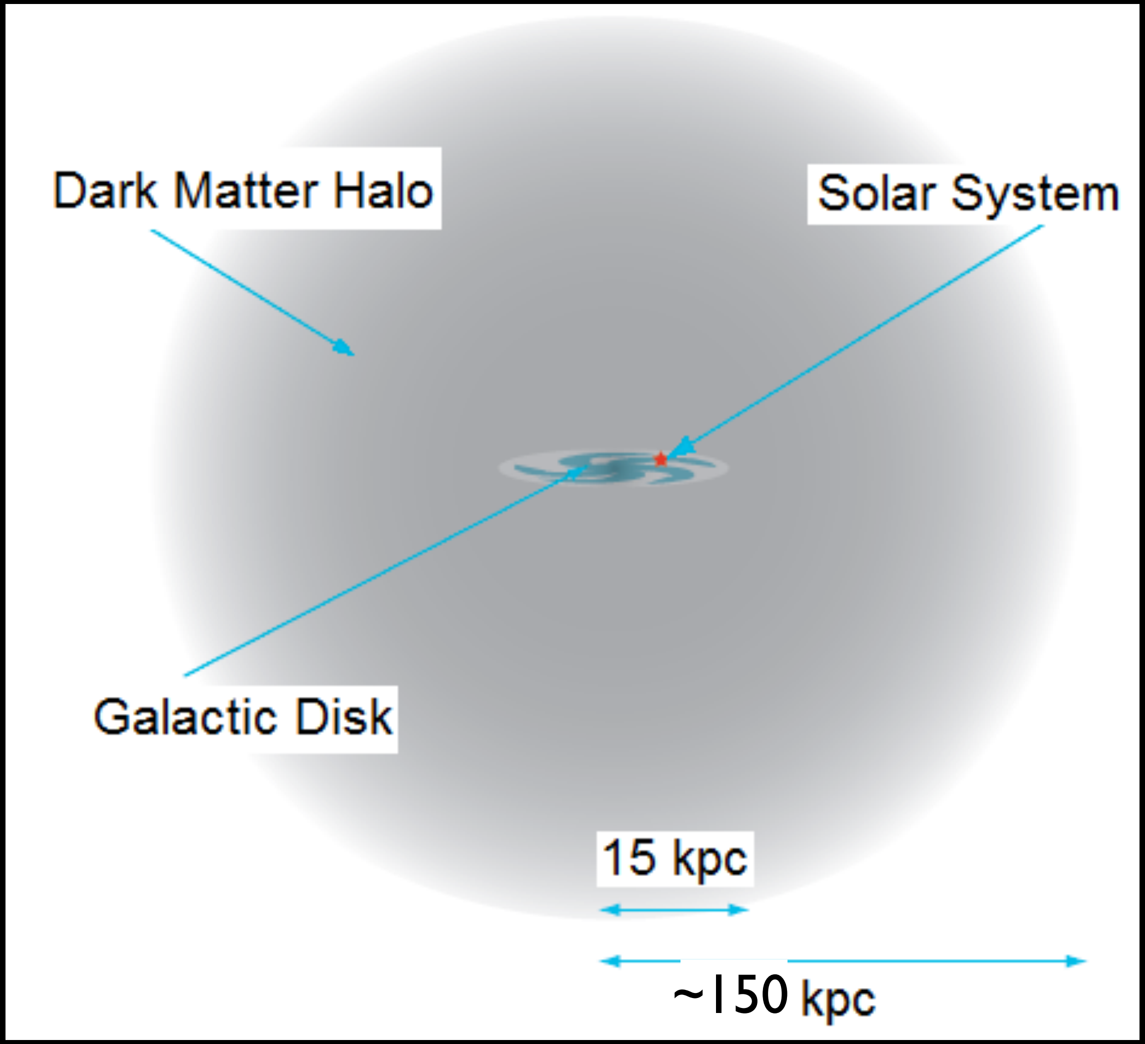
Outline

1. **Introduction and Context**
2. Modulating Signals
3. Directional Detection Experimental Considerations
4. Recent Progress from Directional Detectors
5. Physics Reach with Directional Data

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



What do we know about Dark Matter?



optically dark

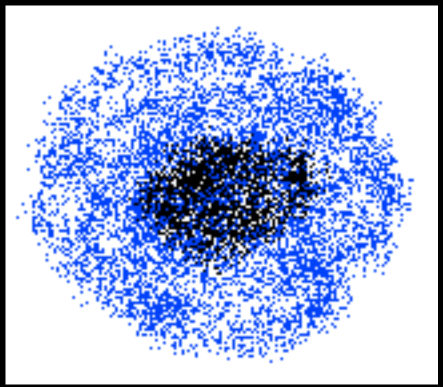
density ~ 0.3 GeV/cm^3

dark matter particle mass: ~unknown

interactions: very weak, ~collision-less

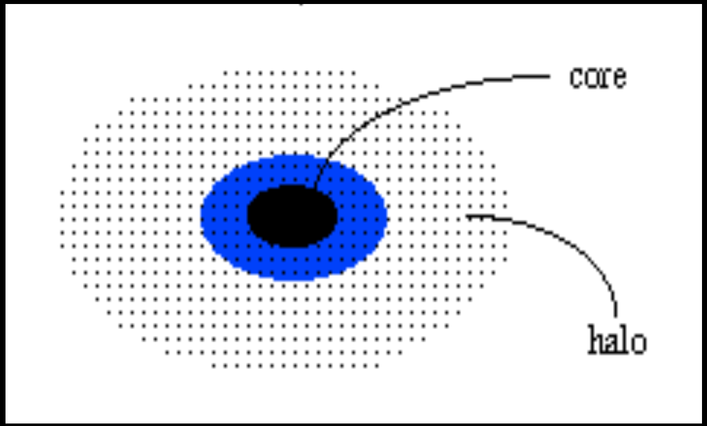
(J. Schombert)

Galaxy Formation

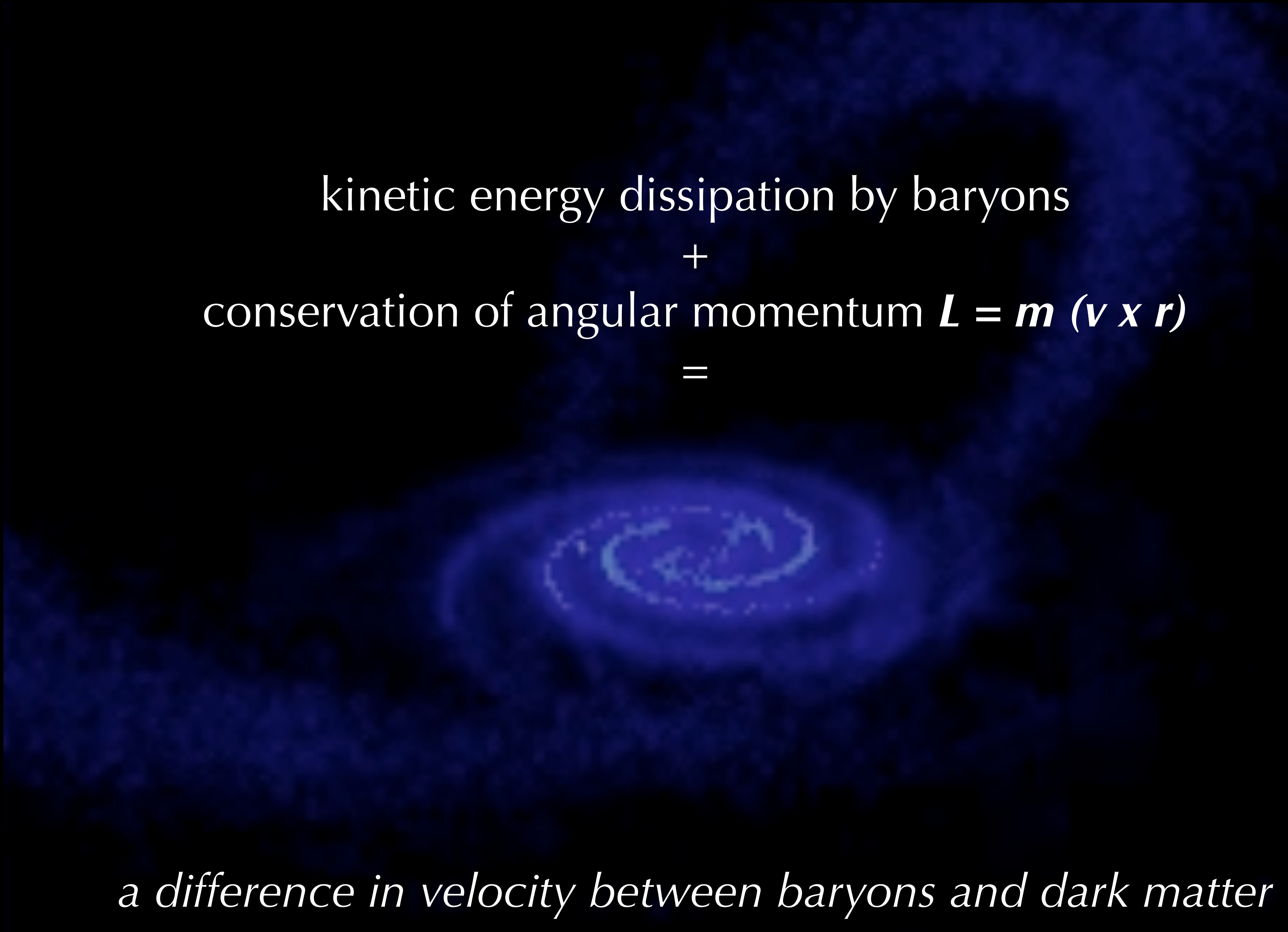


a lump of dark matter and gas collapses under its own gravity to form a protogalaxy

gravity separates out the protogalaxy into a core and halo. The baryons that make up the gas can interact to lose energy and fall to the core.



The dark matter, which only weakly interacts, remains in the halo.



kinetic energy dissipation by baryons

+

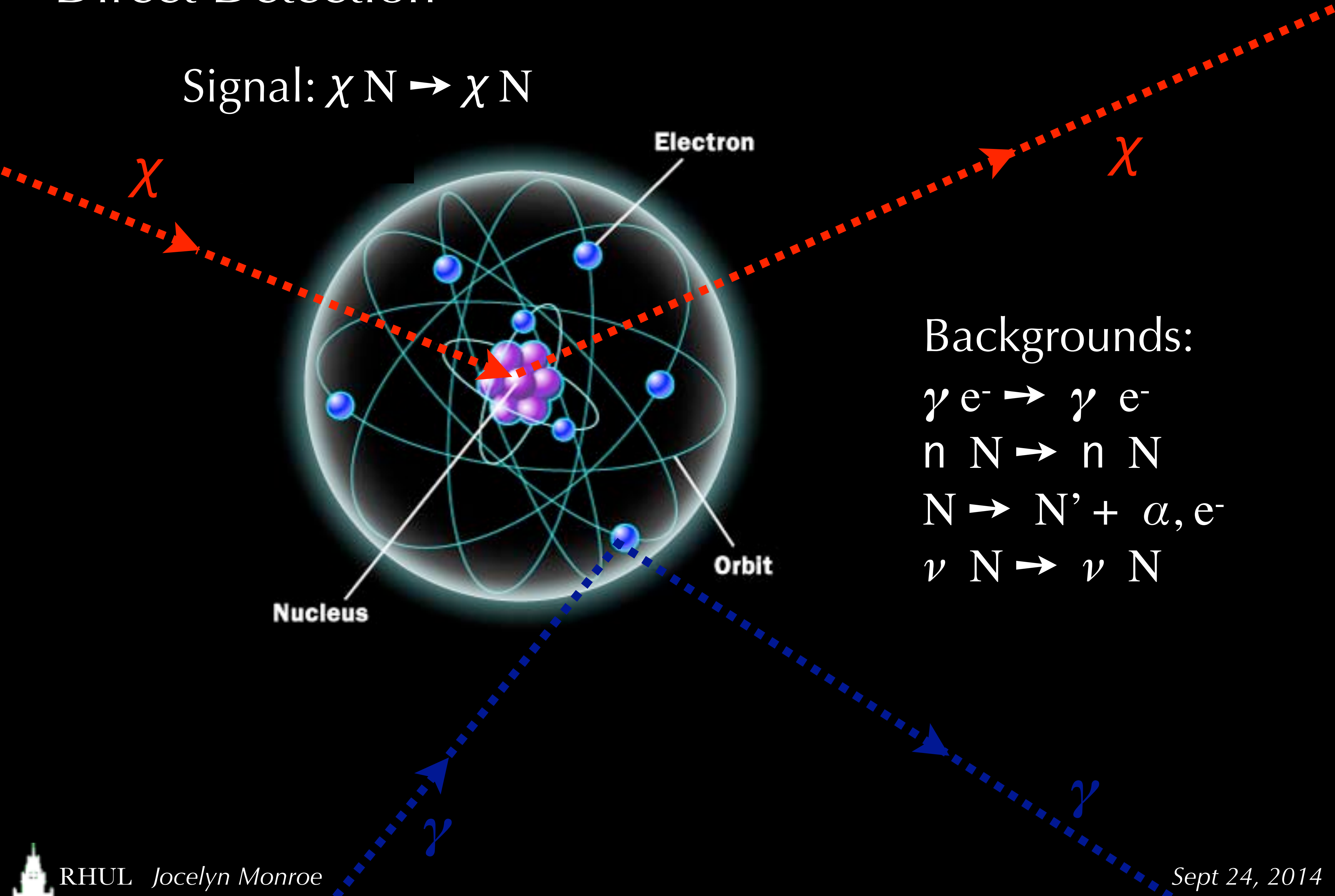
conservation of angular momentum ***L = m (v x r)***

=

a difference in velocity between baryons and dark matter

Direct Detection

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



Backgrounds:

$\gamma e^- \rightarrow \gamma e^-$

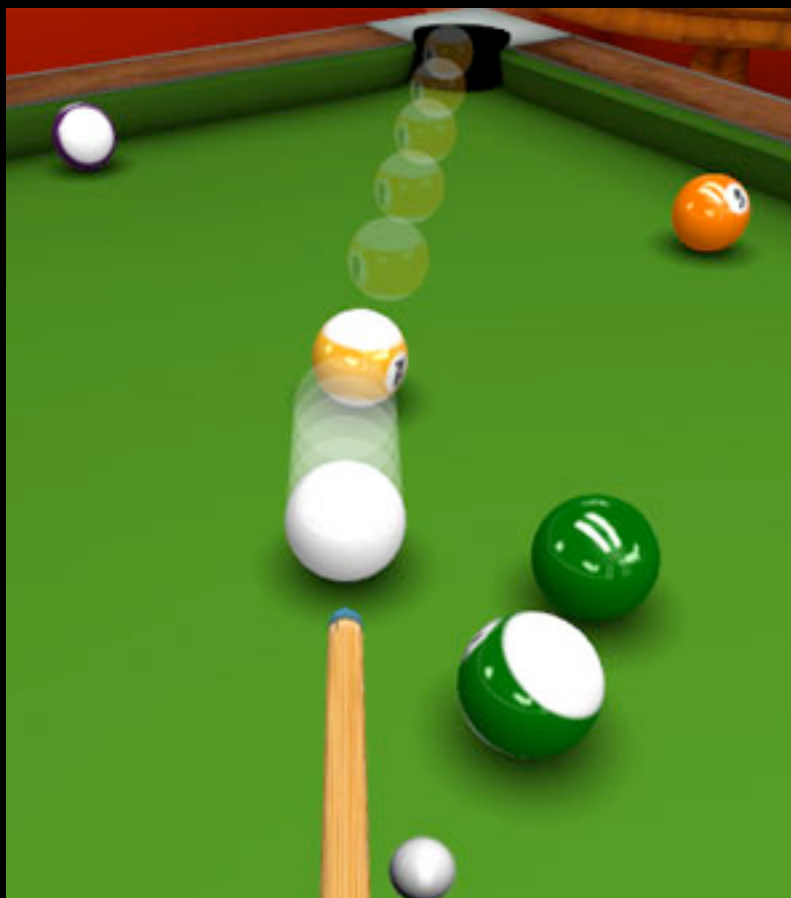
$n N \rightarrow n N$

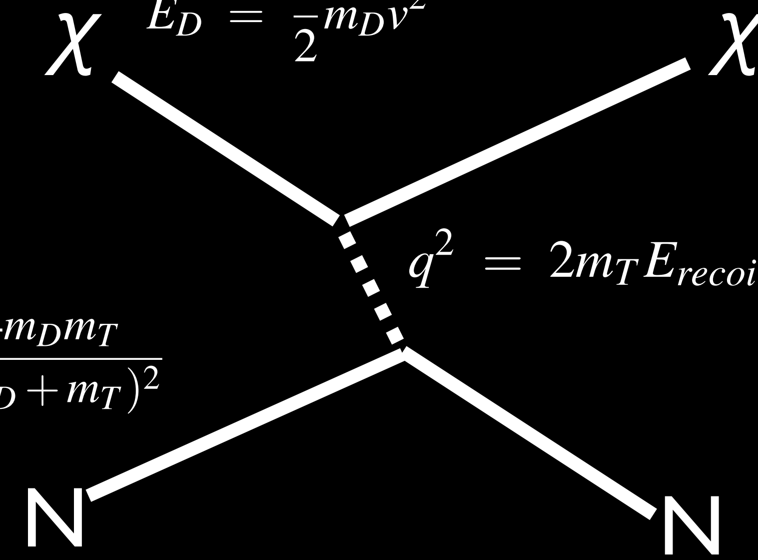
$N \rightarrow N' + \alpha, e^-$

$\nu N \rightarrow \nu N$

WIMP Scattering

kinematics: *v/c ~ 8E-4!*





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

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

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

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

<u>Spin Independent:</u>

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

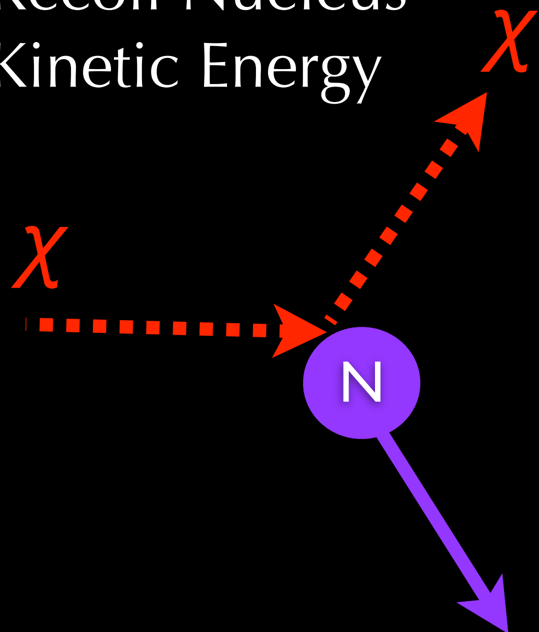
D. Z. Freedman, PRD 9, 1389 (1974)

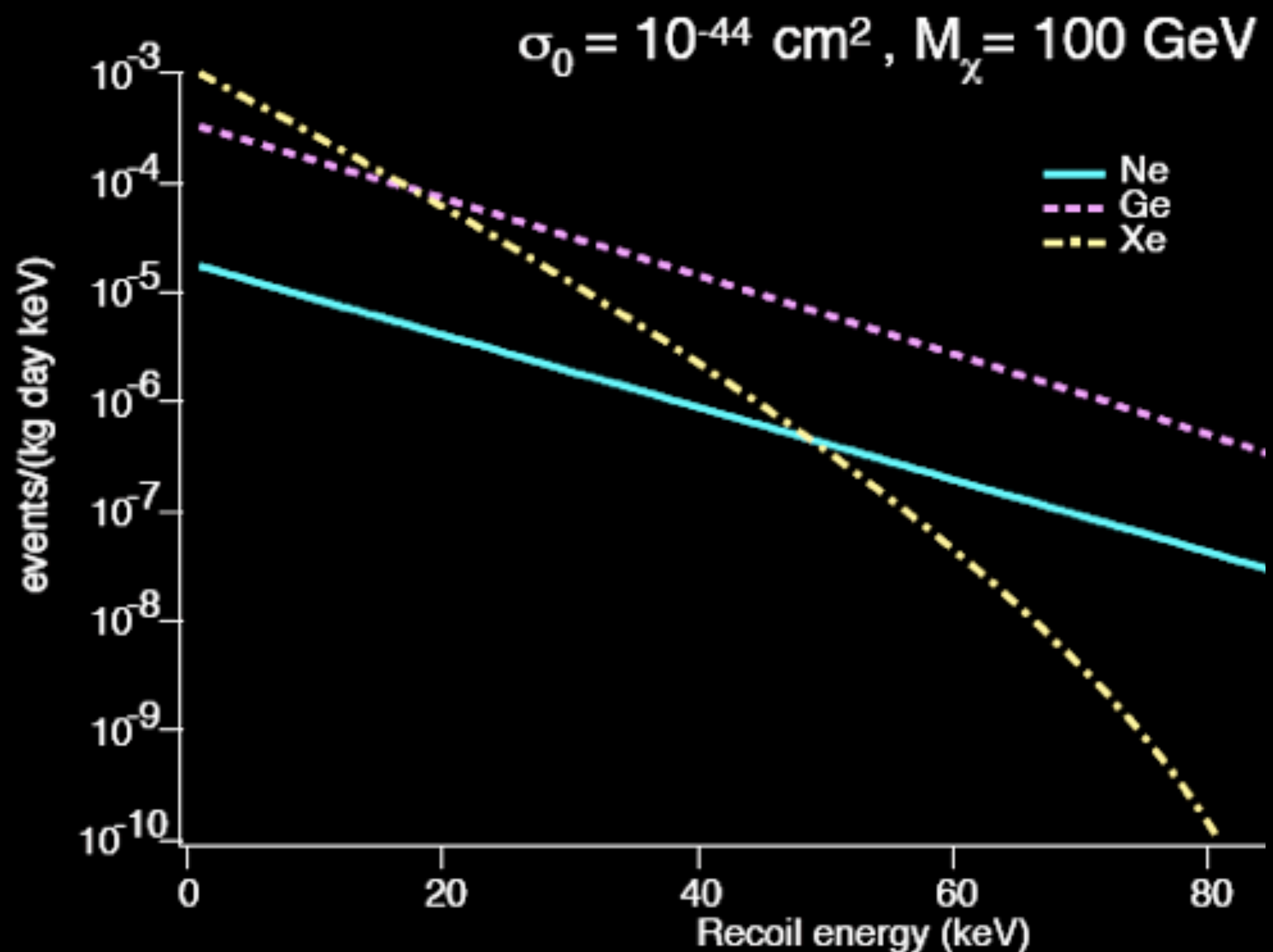
<u>Spin Dependent:</u>

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

Measurement

Recoil Nucleus Kinetic Energy



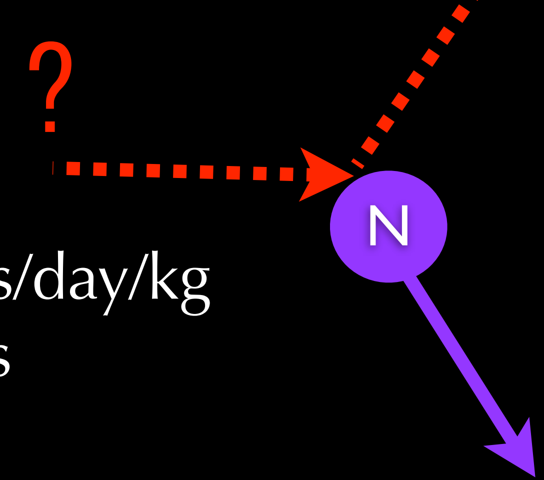


Scattering rate — Sun's velocity around the galaxy — WIMP velocity distribution

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

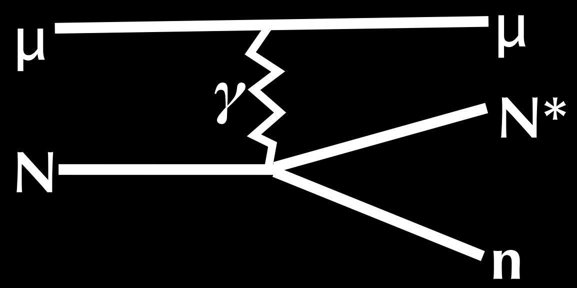
WIMP energy density, 0.3 GeV/cm³ — Form factor

Reducible Backgrounds

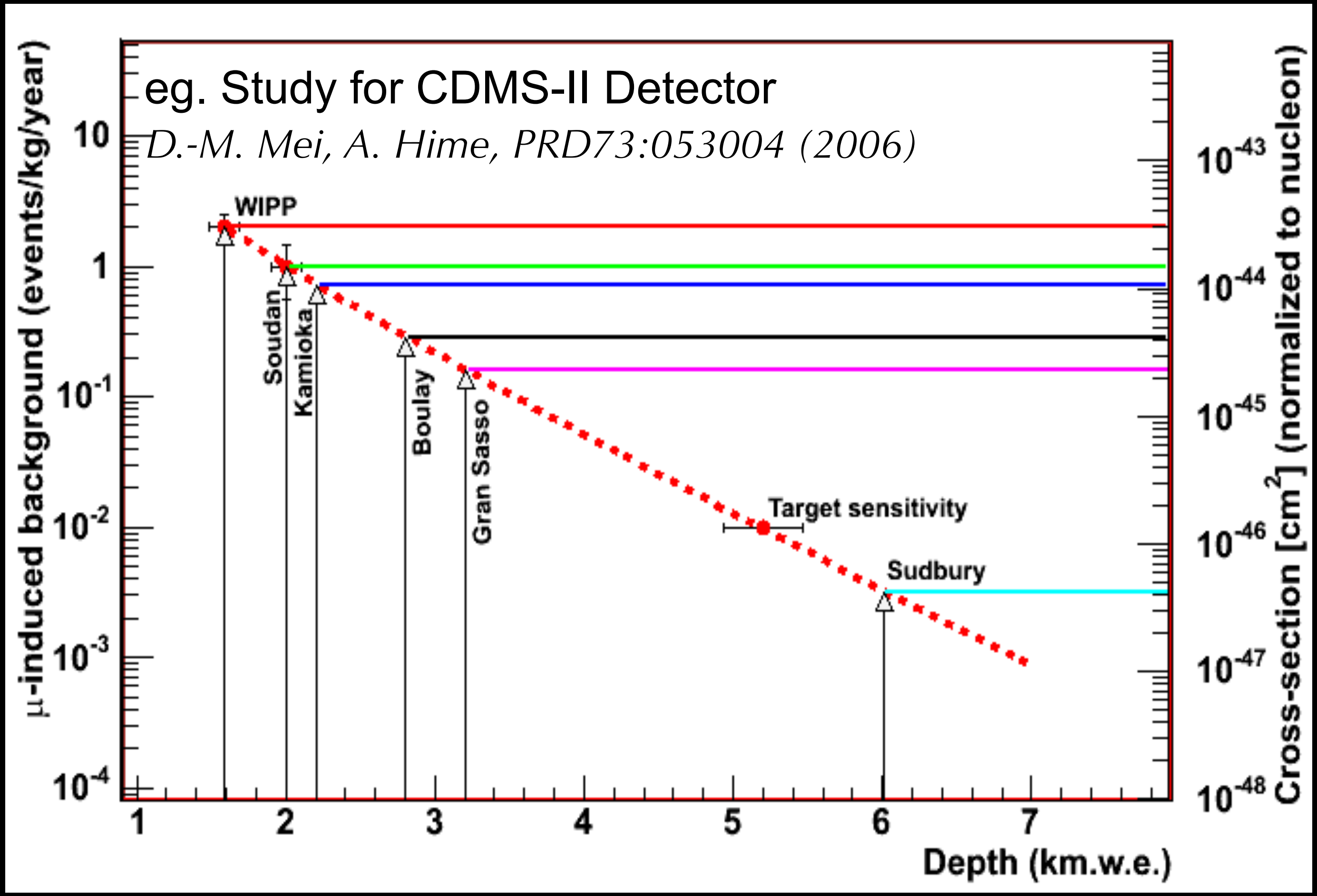


Gamma ray interactions:
rate ~ N_e x (gamma flux), typically 10 million events/day/kg
mis-identified electrons mimic nuclear recoil signals

Neutrons:
(alpha,n), U, Th fission, cosmogenic spallation

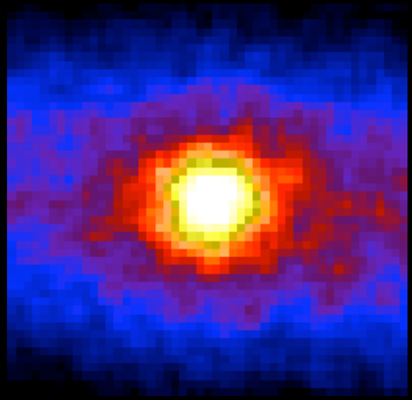


nuclear recoil final state



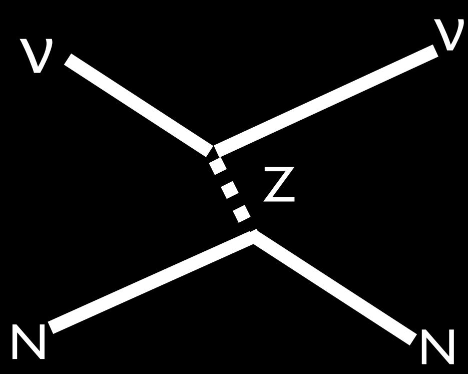
Contamination:
^{238}U and ^{232}Th decays, recoiling progeny and mis-identified alphas mimic nuclear recoils

Irreducible Backgrounds

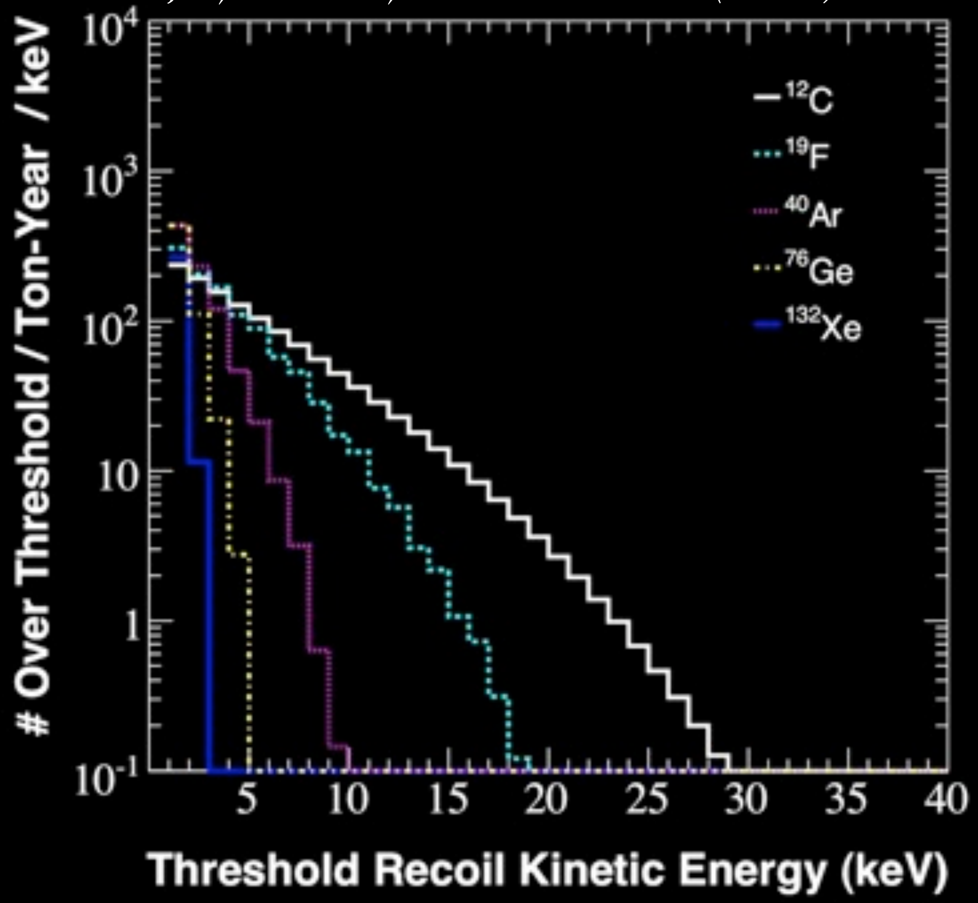


impossible to shield a detector from coherent neutrino scattering:

Φ(solar B^8) = 5.86×10^6 cm^{-2} s^{-1}



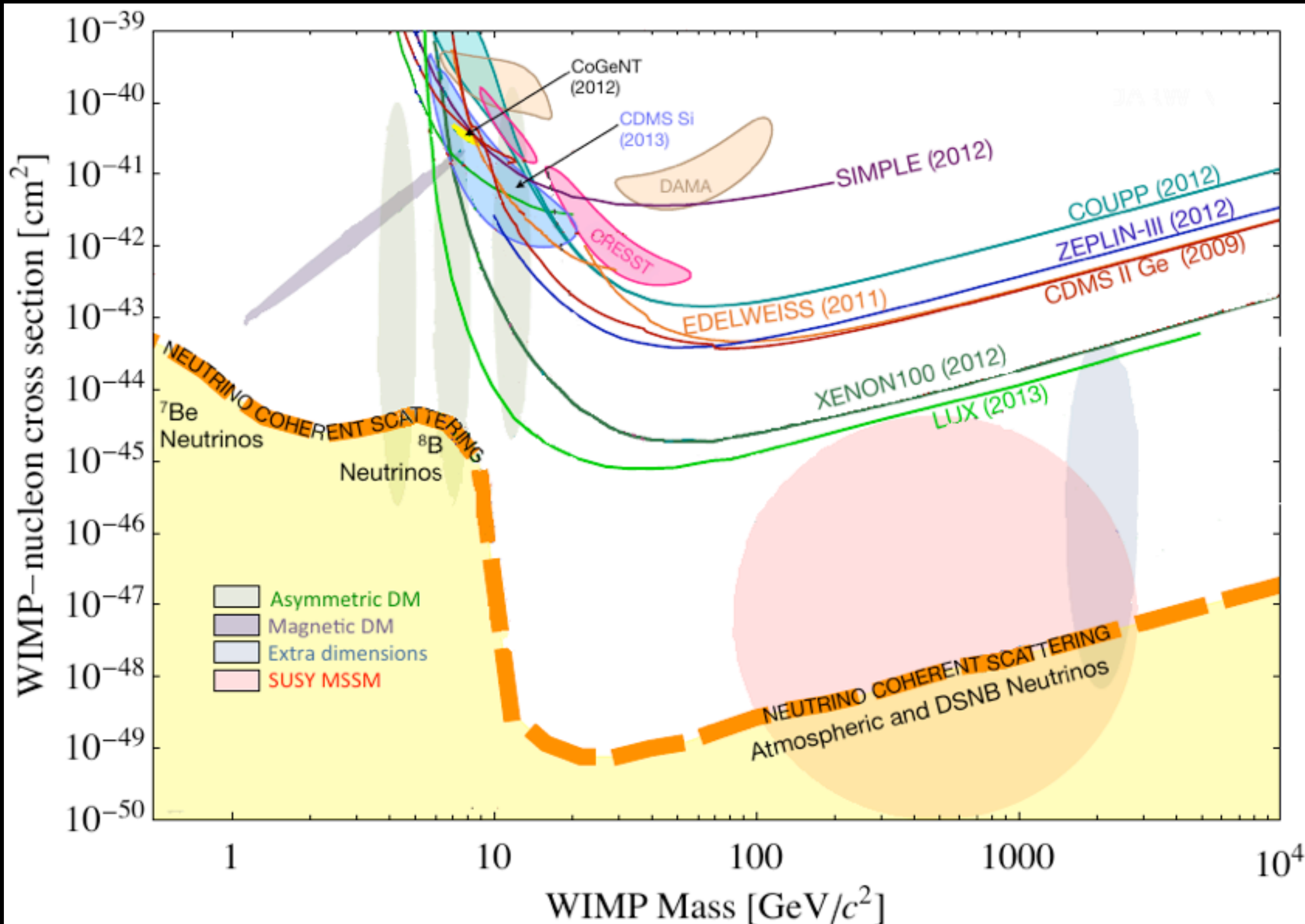
JM, P. Fisher, PRD76:033007 (2007)



nuclear recoil final state
1 event/ton-year = ~10^{-46} cm^2 limit
in zero-background paradigm

unless you measure
the direction!

The Low-Background Frontier



1 event/ kg/day

1 event/ 100kg/day

1 event/ 100 kg/ 100 days

so far: ~3 years / order of magnitude

A Long Way to Go...

10^{-24} cm^2: σ(neutron-A elastic scattering)

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

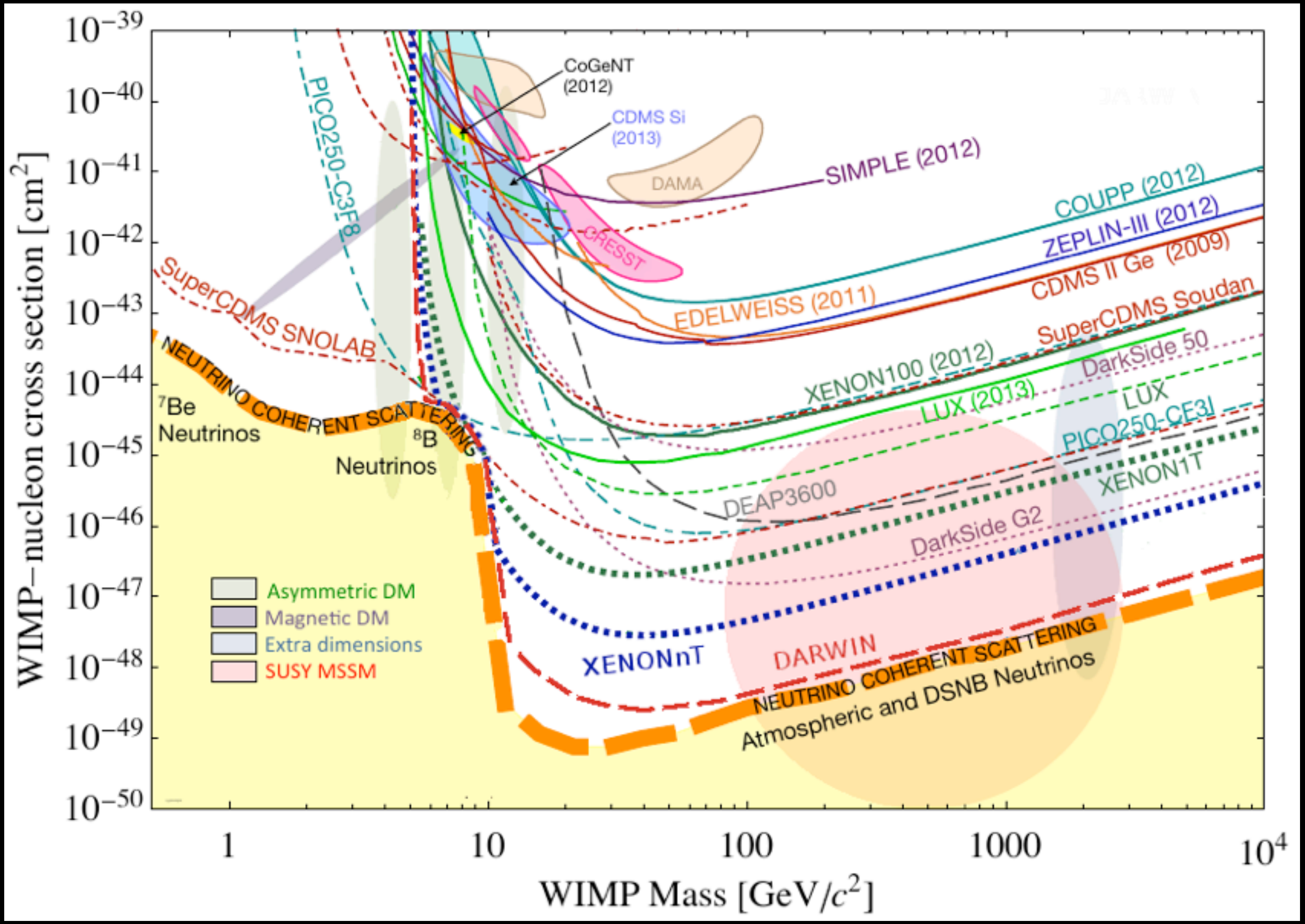
10^{-43} cm^2: σ(ν NC Elastic) for geo-ν

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

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

Not to Scale

The Low-Background Frontier: Next Decade



1 event/ kg/day

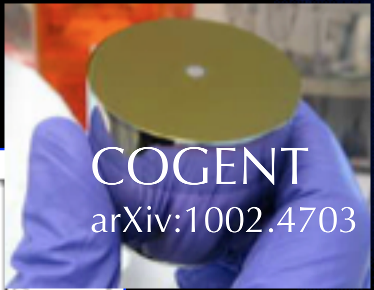
1 event/ 100kg/day

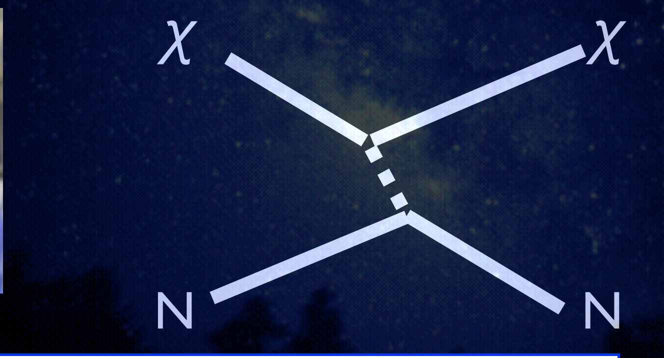
1 event/ 100 kg/ 100 days

Neutrino bound approaches…….

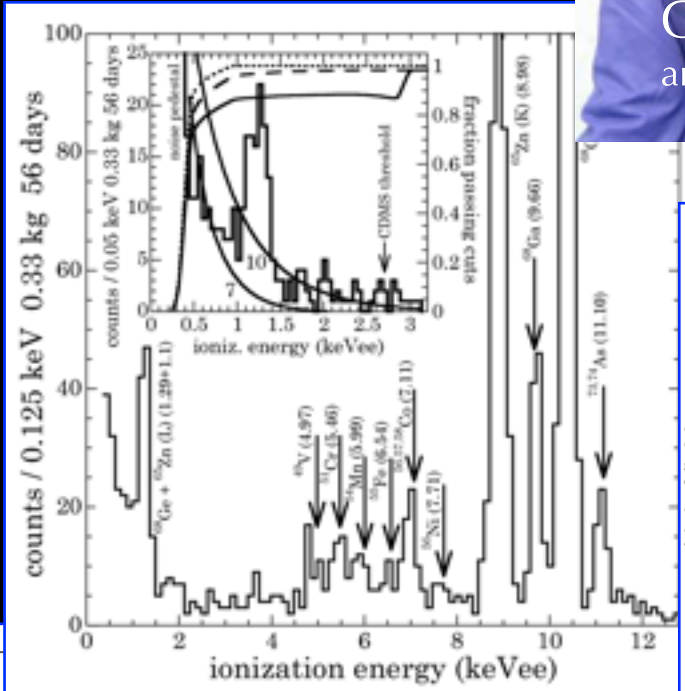
Billard, Strigari, Figueroa-Feliciano, Phys.Rev. D89, 023524 (2014)

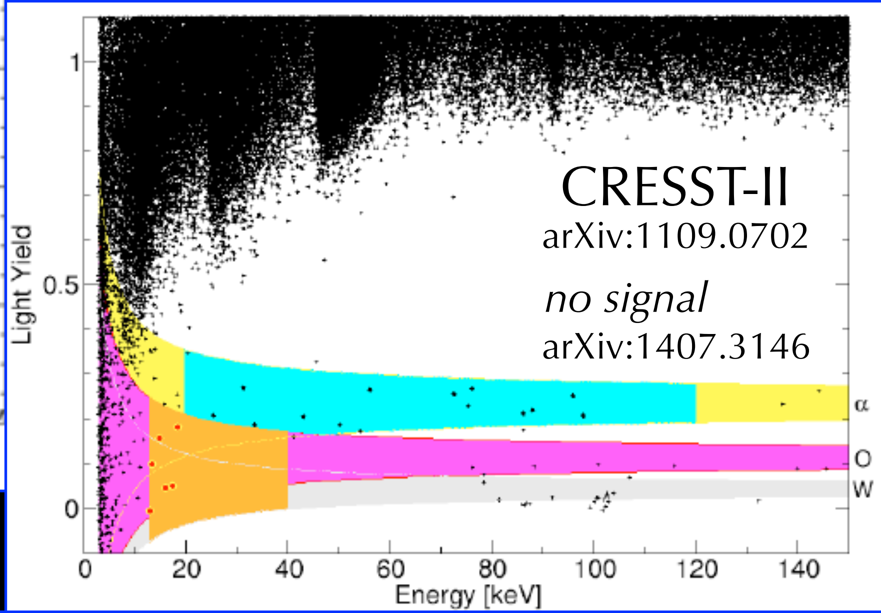
(Historical) Dark Matter Signals

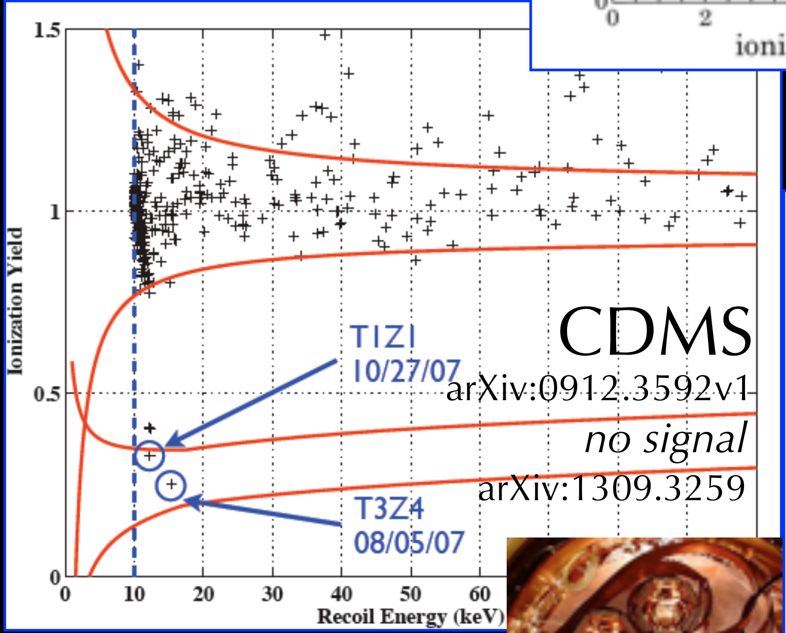


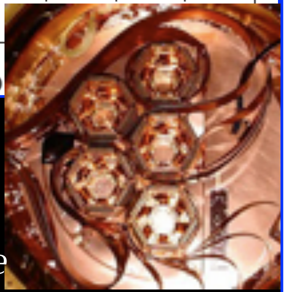


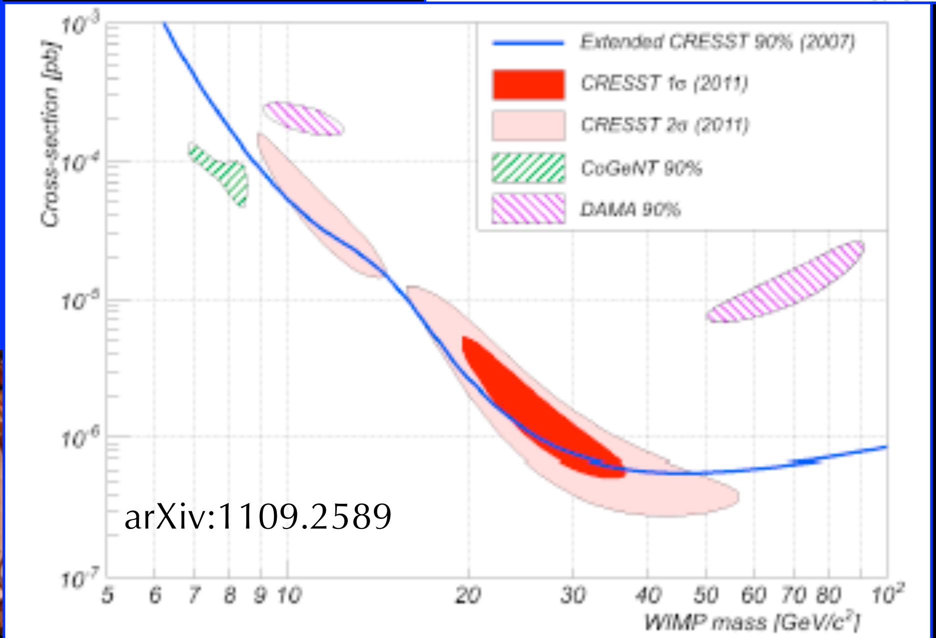
DAMA/Libra





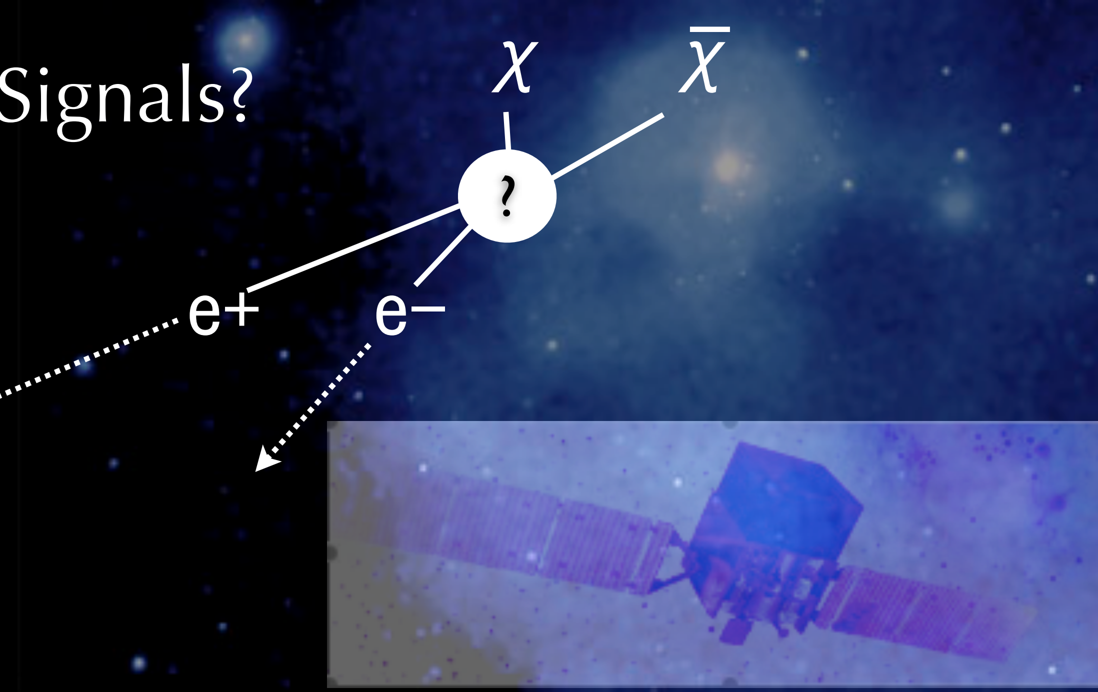


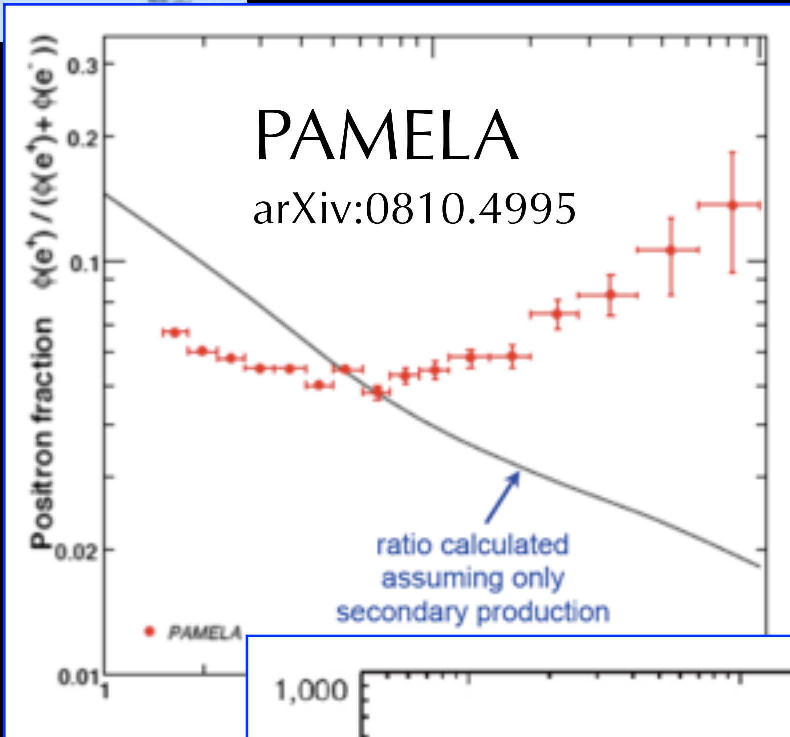


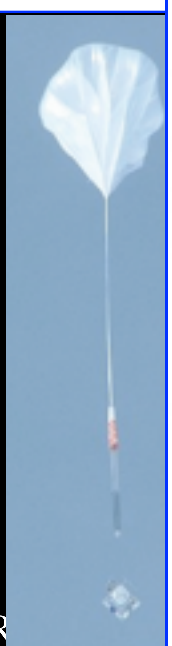


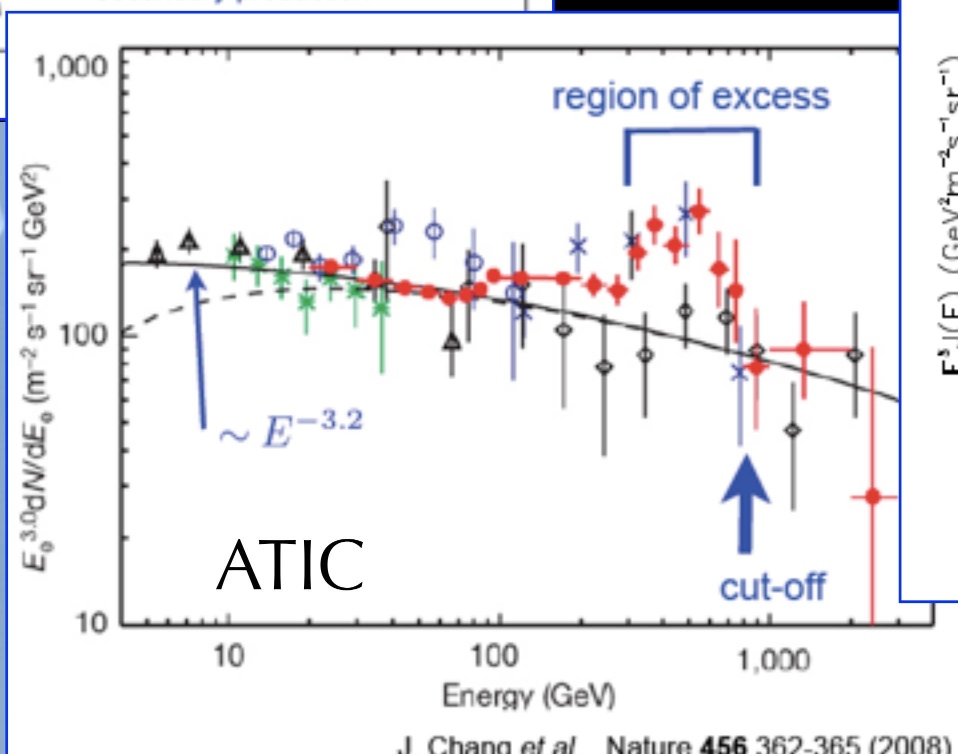
dark matter?
backgrounds?

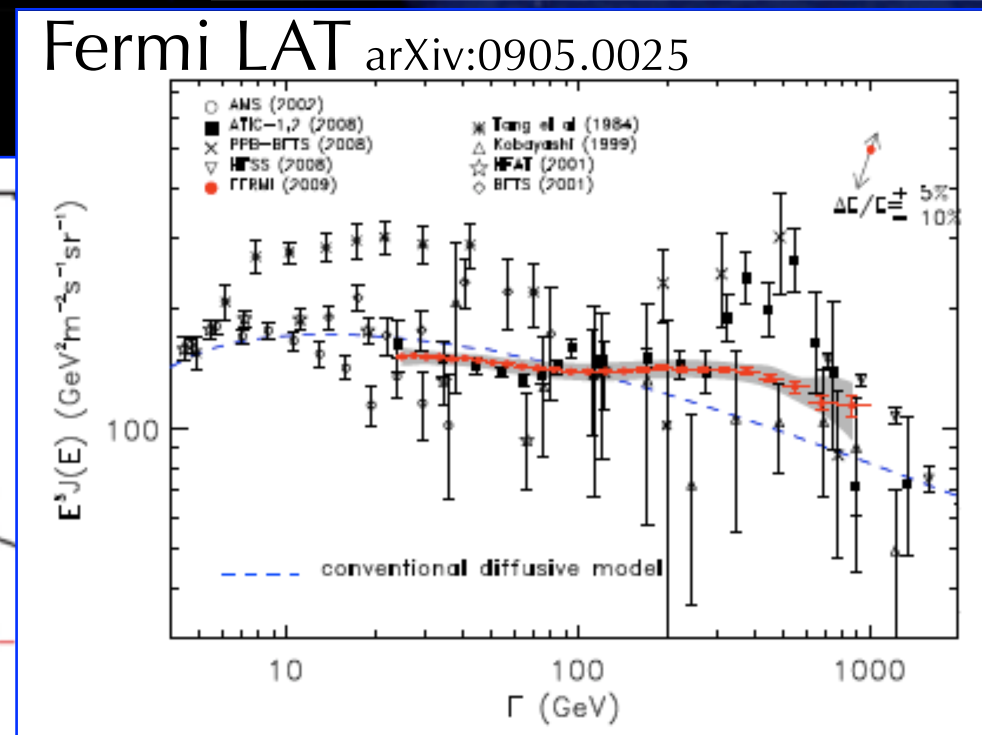
Indirect Dark Matter Signals?



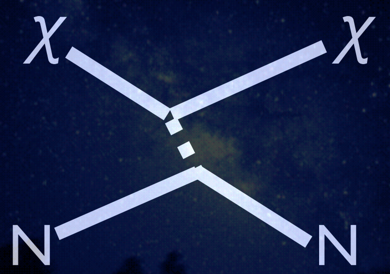


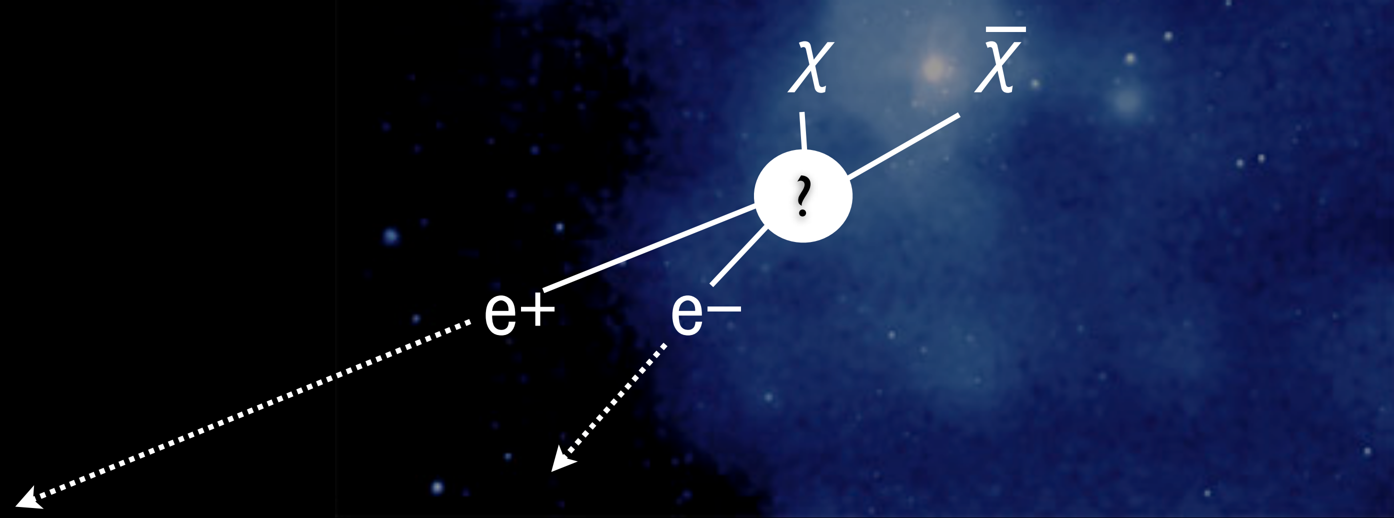






dark matter? local astrophysics?





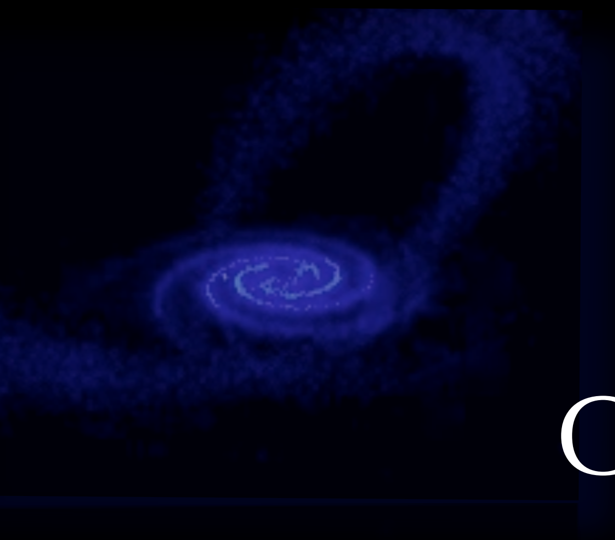
Motivation for Modulation Searches in Dark Matter Detection:

The current experimental situation is ~inconclusive.

Recent anomalies...

- local astrophysics?
- new backgrounds?
- dark matter?

Modulation tests the astrophysical origin of a candidate dark matter signal.



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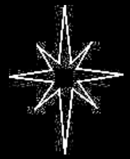
5. Physics Reach with Directional Data

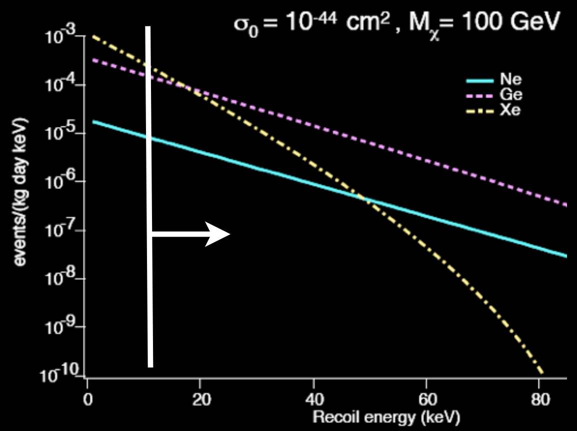
The Dark Matter Wind: Annual Modulation

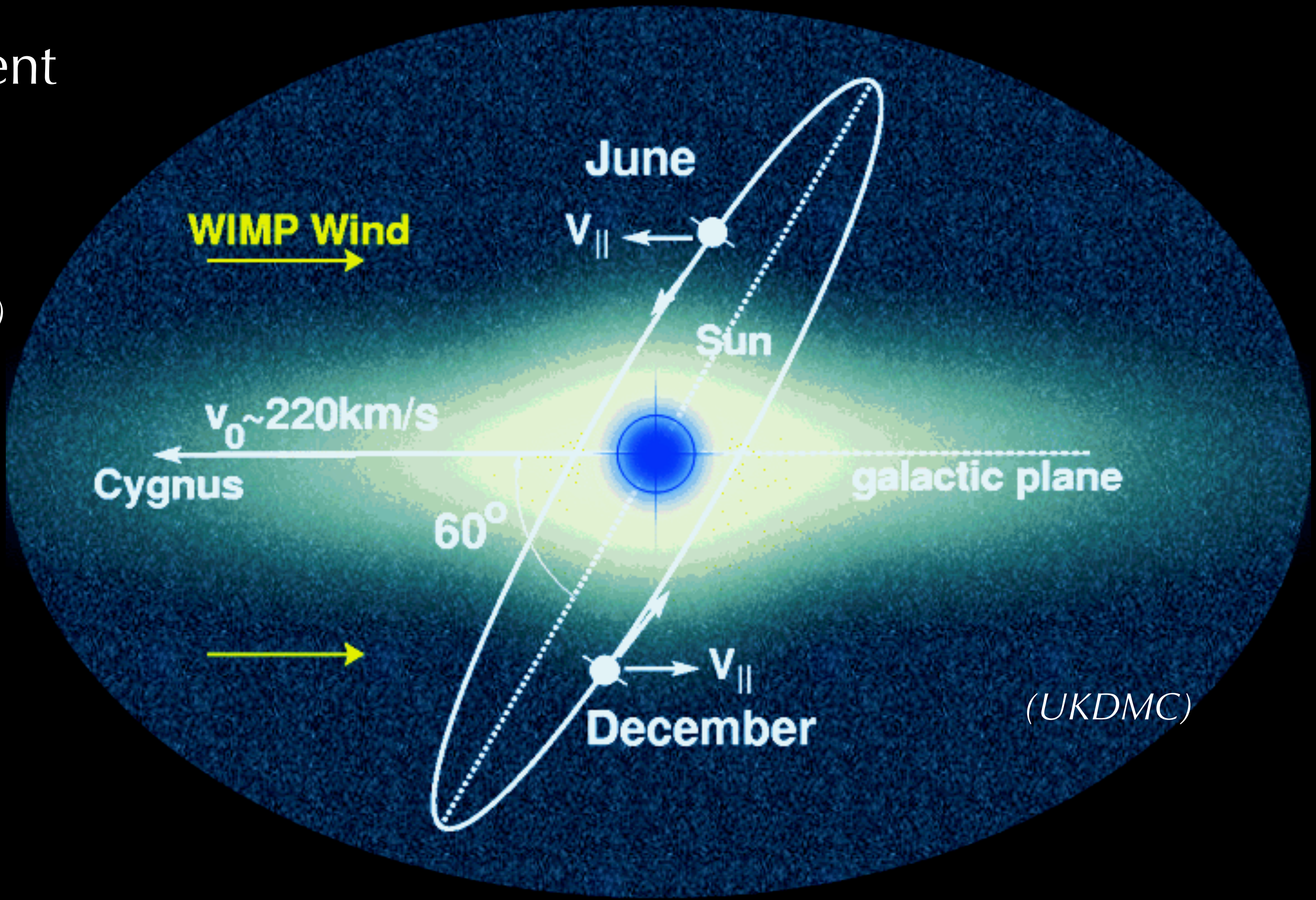
June-December event rate asymmetry ~2-10%

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



Cygnus





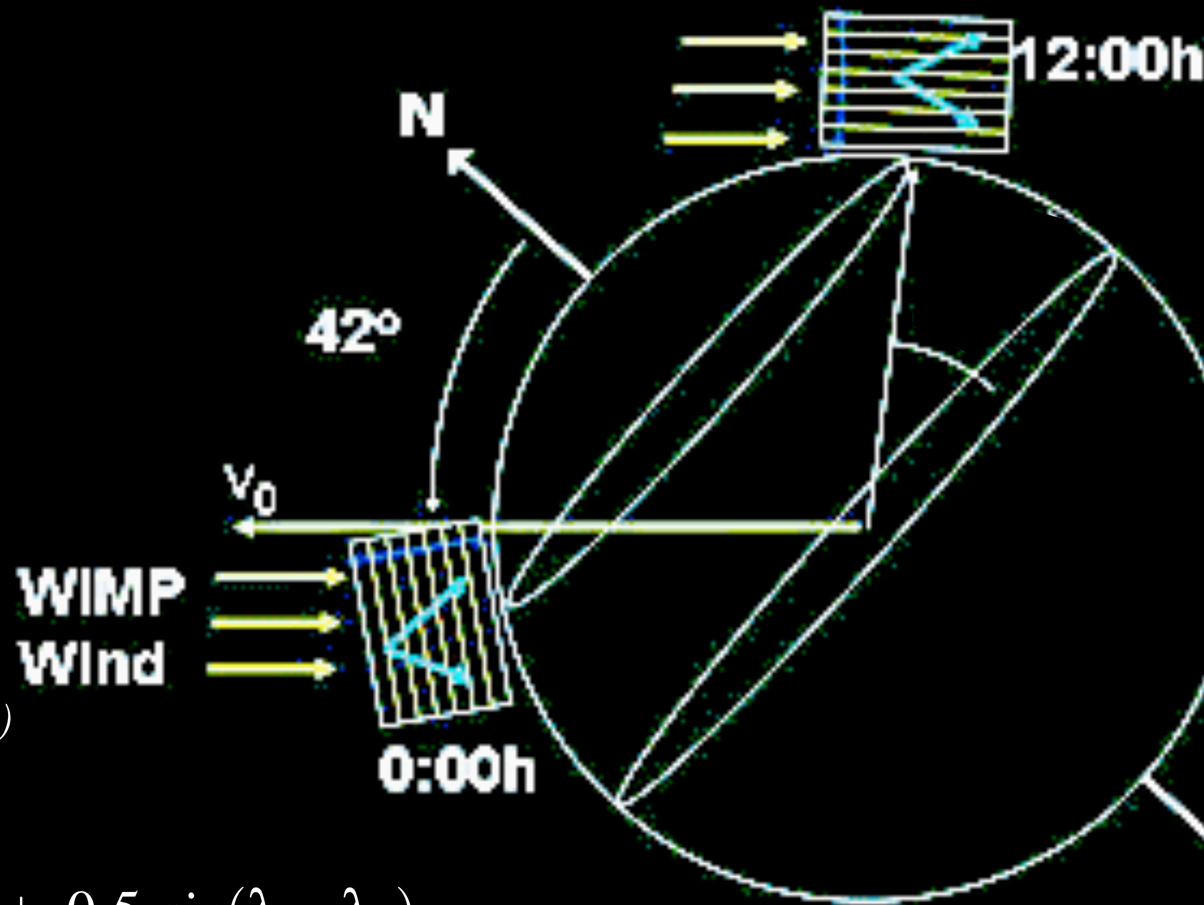
(UKDMC)

$$v_E(t)\ [km/s] = 232 + 15\cos\left(2\pi\frac{t-152.5}{365.25}\right)$$

t = days since Jan. 1

The Dark Matter Wind: Sidereal Modulation

Cygnus



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

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

$$u_E(\lambda)\ [km/s] = 29.8 + 0.5\ sin(\lambda - \lambda_0)$$

$\lambda_0 = 13^o \pm 1^o$ longitude of earth's orbit minor axis

$\lambda = L + 1.9^o sin\ g + 0.02^o\ sin\ 2g; \quad L = 280.5^o + 0.99^o\ n; \quad g = 357.5^o + 0.99^o\ n$

n = fractional day number relative to Dec 31, 1999

Event Rate Prediction in Direct Detection Searches

1. Rate = Flux x Cross Section x Number of Targets
2. flux = number density of WIMPs x relative velocity of WIMP and target
3. include WIMP velocity distribution in the flux (Maxwell-Boltzmann)

$$dn = \frac{n_0}{k} f(\vec{v},\vec{v}_E)\, d^3\vec{v}; \qquad n_0 = \frac{\rho_D}{m_D}; \qquad k = \int f(\vec{v},\vec{v}_E)\, d^3\vec{v}$$

-relative velocity of WIMPs w.r.t. detector targets *modulates*

[mostly annual]

-integrate over the WIMP velocity distribution to find total flux,

with appropriate limits (v_{EARTH}, v_{ESCAPE})

4. include recoil energy dependence on scattering angle (elastic)

$$E_R = E_0\, r \,\frac{(1 - cos\theta)}{2}; \qquad r = \frac{4\, m_D\, m_{target}}{(m_D + m_{target})^2}$$

5. relative angle of incidence of WIMPs w.r.t. detector axis *modulates*
[mostly sidereal]

Coordinate System

(D. Akerib)

collision kinematics

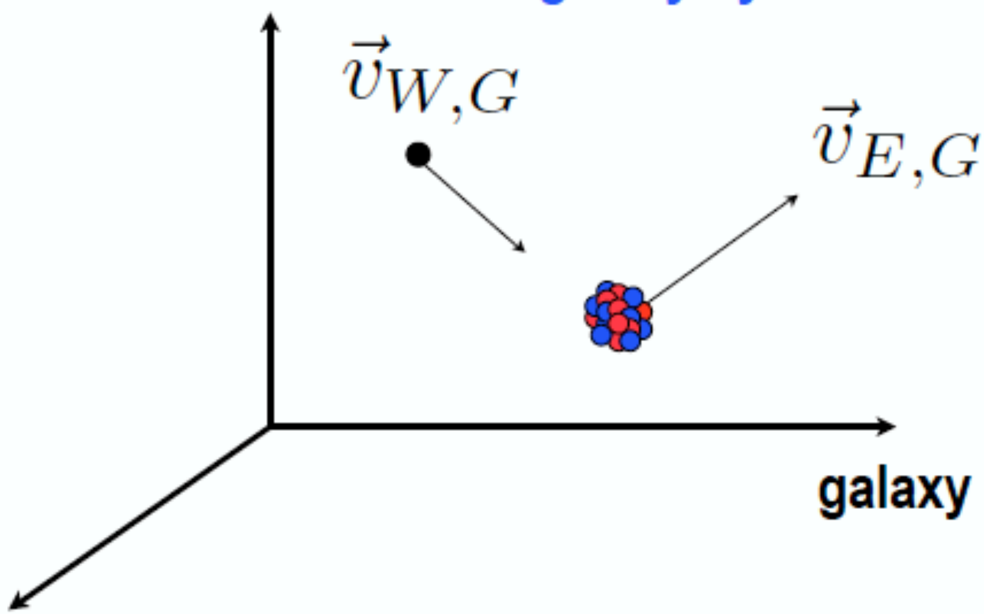
$$\vec{v} \quad = \quad \vec{v}_{W,E} \quad = \quad \text{WIMP velocity in the target/Earth frame}$$

$$\vec{v}_{E,G} \quad = \quad \text{Earth velocity in the Galaxy frame}$$

$$\vec{v}_{W,G} \quad = \quad \text{WIMP velocity in the Galaxy frame}$$

galaxy dynamics

$$\begin{aligned} \vec{v}_{W,G} &= \vec{v}_{W,E} + \vec{v}_{E,G} \\ &= \vec{v} \quad + \vec{v}_{E} \end{aligned}$$



$$f(\vec{v}, \vec{v}_E) = e^{-(\vec{v}+\vec{v}_E)^2/v_0^2}$$

Maxwellian velocity distribution

Setting a Limit in Direct Detection Searches

1. Predict the dark matter interaction rate:

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

E_R = nuclear recoil kinetic energy,
E_0 = DM particle kinetic energy =
c1, c2 = constants
r = f(m_D,m_{target})

2. Experiments measure:

$$R_0 = \frac{2}{\sqrt{\pi}}\left[\left(\frac{\rho_D}{m_D} v_0\right) \times \sigma_0 \times \left(\frac{N_A}{A}\right)\right]$$ *rate of events per unit mass*

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

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

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

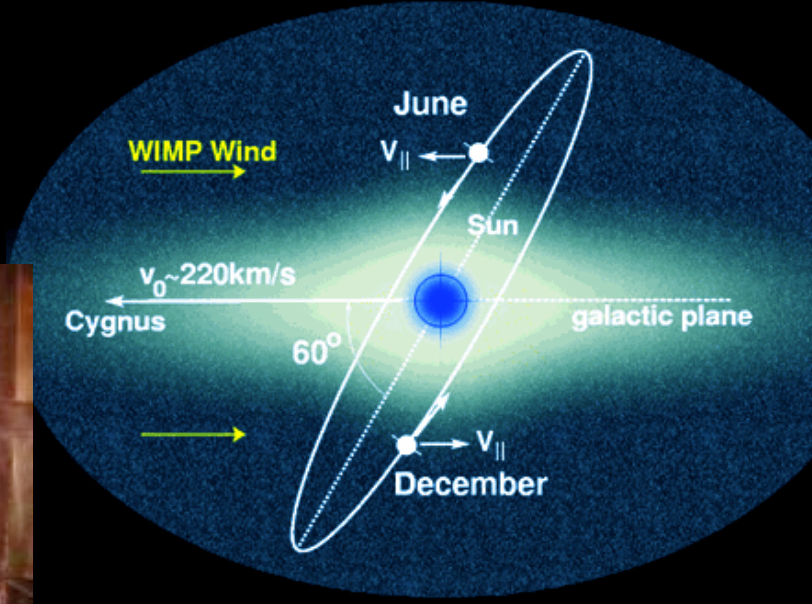
$$\sigma_{W-N} = \left(\frac{\mu_1}{\mu_A}\right)^2 \left(\frac{1}{A}\right)^2 \sigma_A$$

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

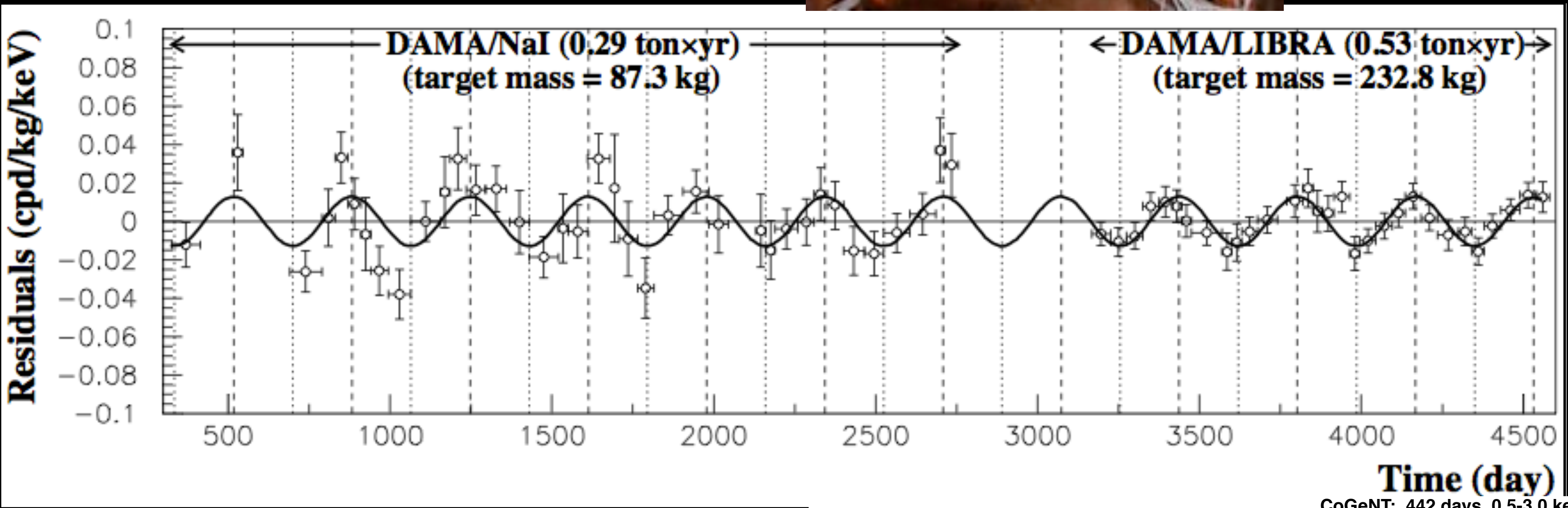
Annual Modulation Searches

June-December event rate asymmetry ~2-10%

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



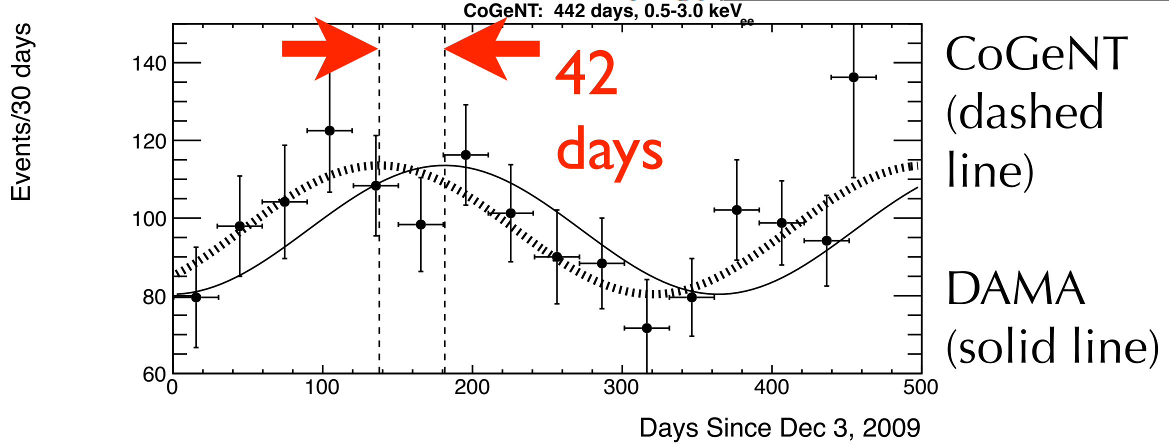
Eur. Phys. J. C56:333-355 (2008)



DAMA/Libra positive result, >8σ, *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)

Annual Modulation Searches

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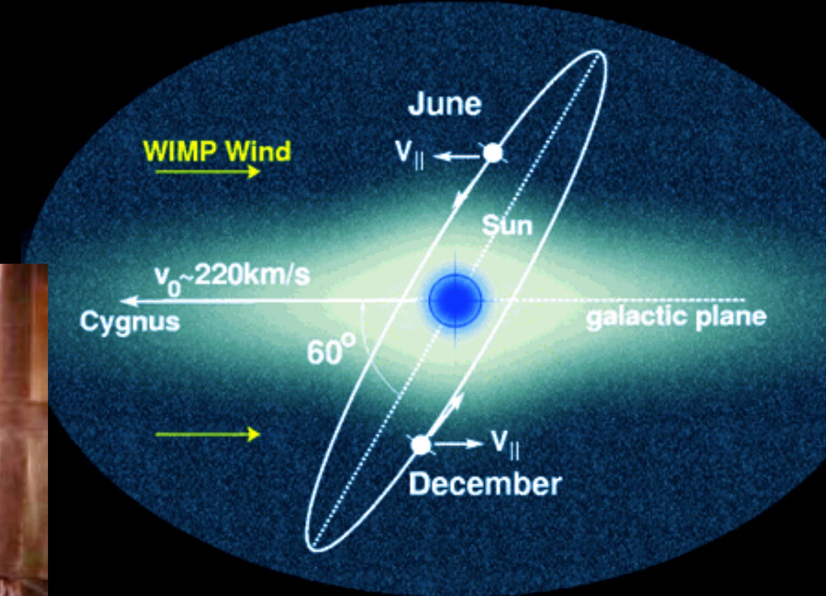

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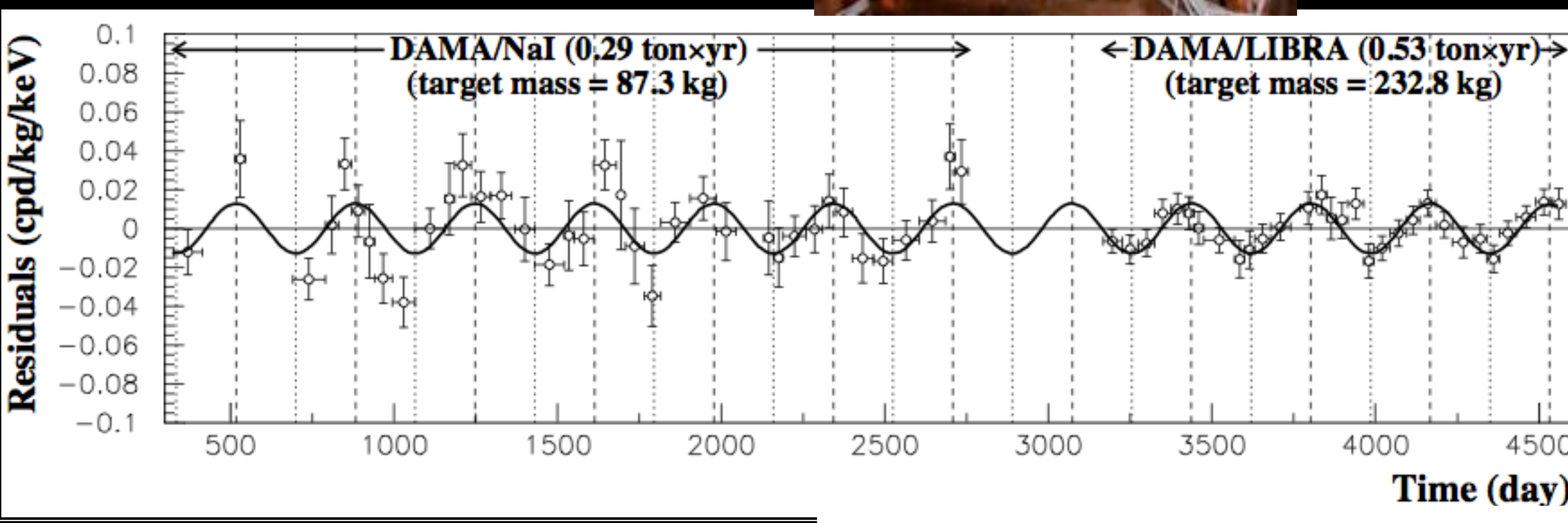
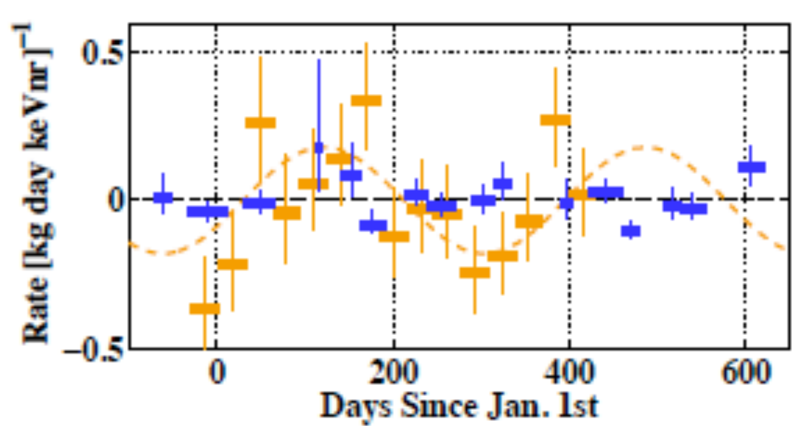


DAMA/Libra positive result, >8σ, *inconsistent with many expts*

CDMS modulation search *not consistent with CoGeNT or DAMA/Libra (98.3% CL)*

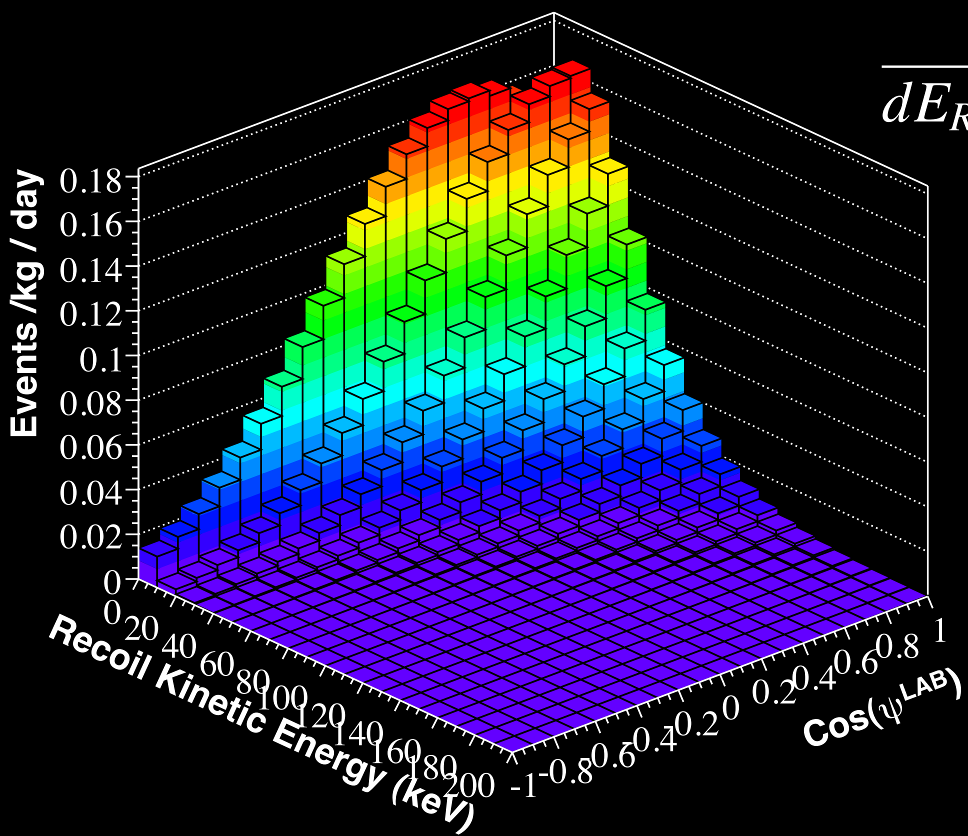
arXiv:1203.1309



CoGeNT (dashed line)

CDMS (solid points)

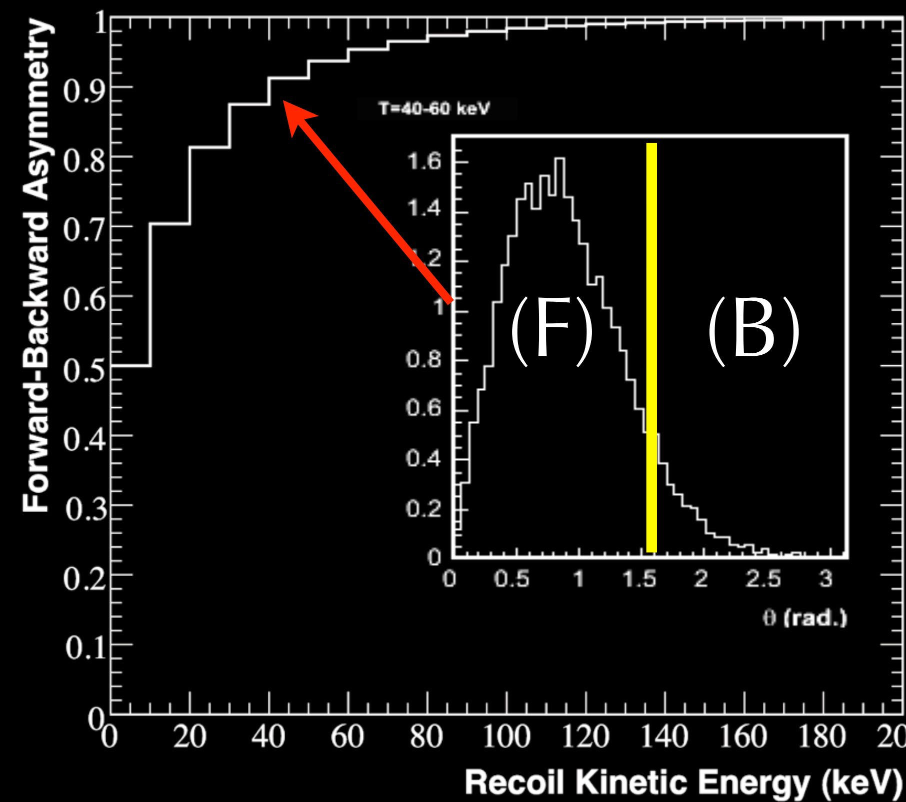
Sidereal Modulation Searches: Directional Detection



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

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

$$\psi = lab\ recoil\ angle$$



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

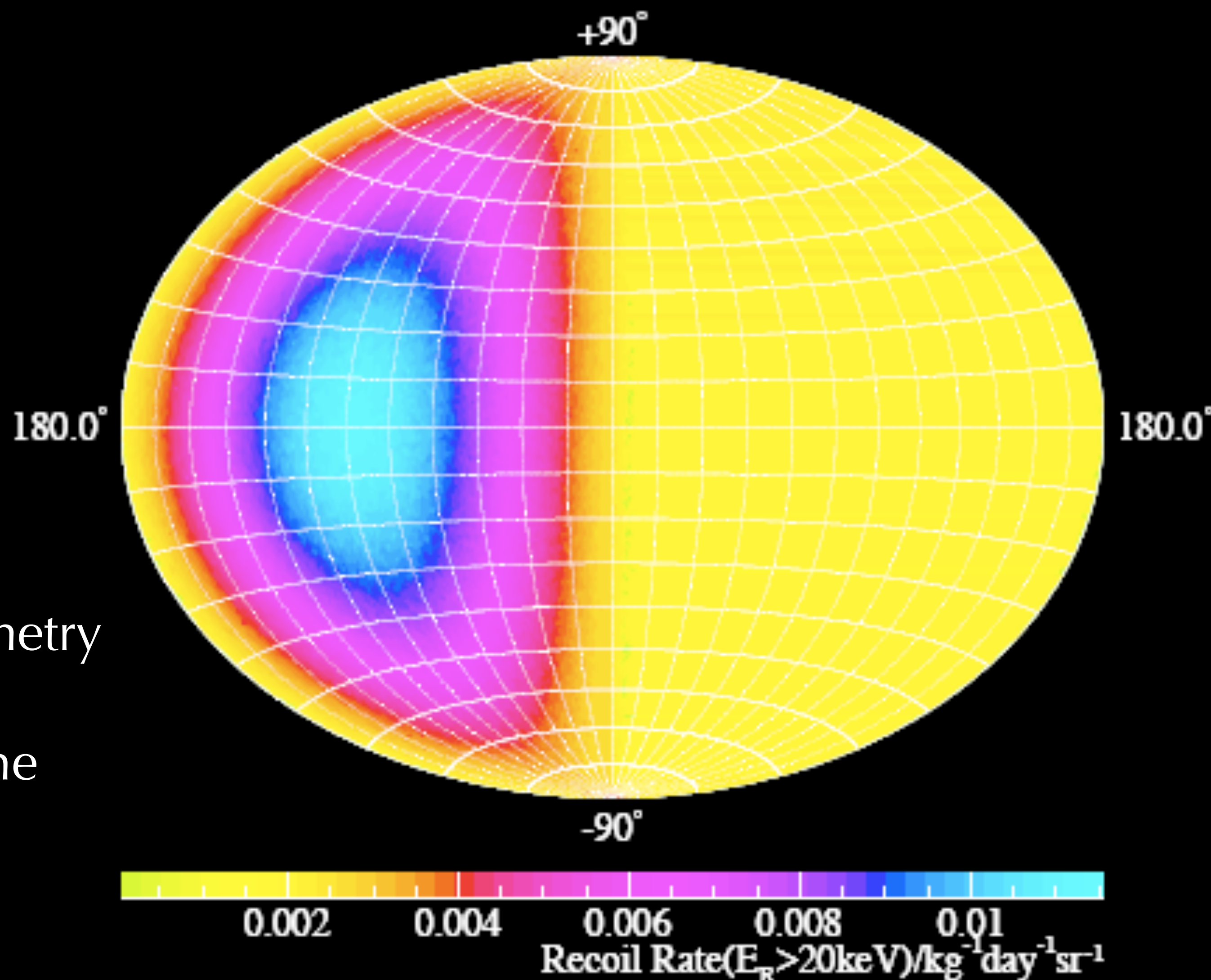
Asymmetry increases with recoil kinetic energy.

Sidereal Modulation Searches: Directional Detection

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

simulated reconstructed dark matter sky map: search for anisotropy

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



Signal characteristics:
(i) forward-backward asymmetry in the galactic frame,
(ii) sidereal modulation in the laboratory frame

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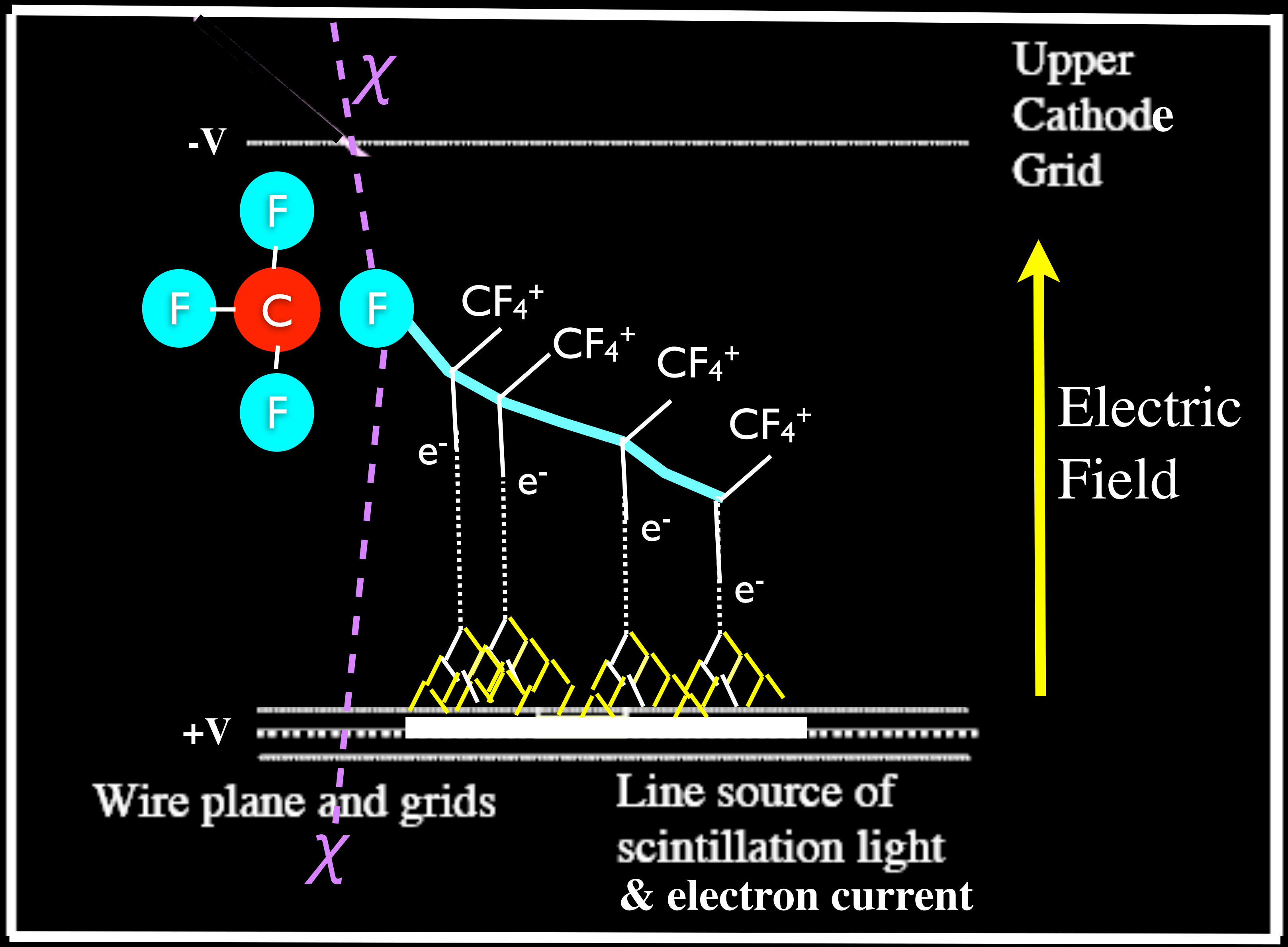
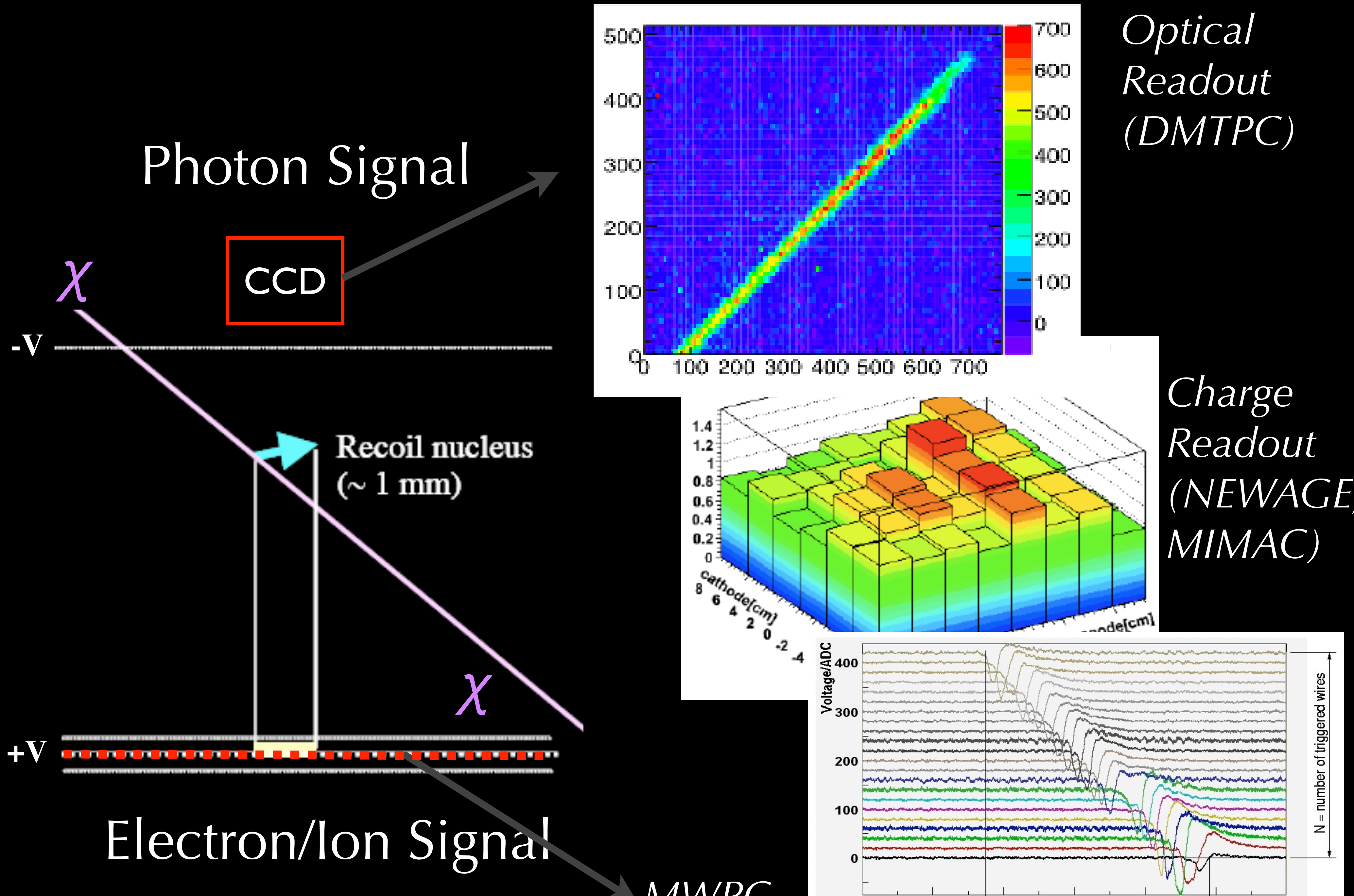
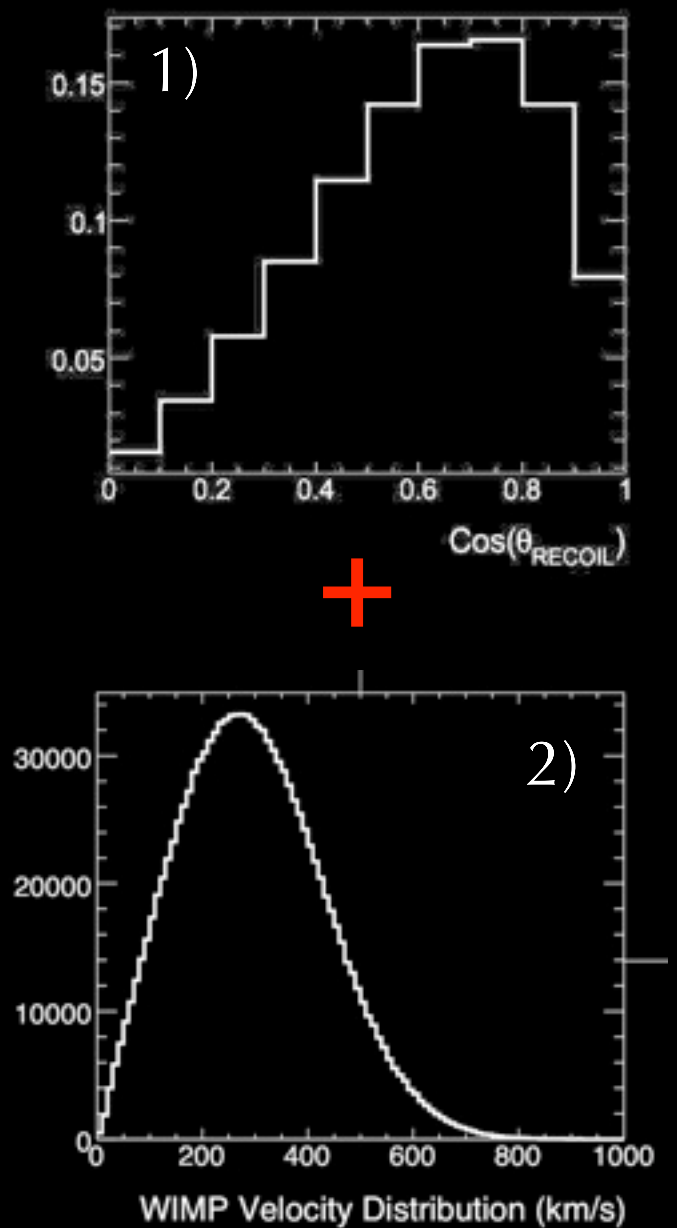
Detector Concept





Directional Detection
Whitepaper: arXiv:0911.0323

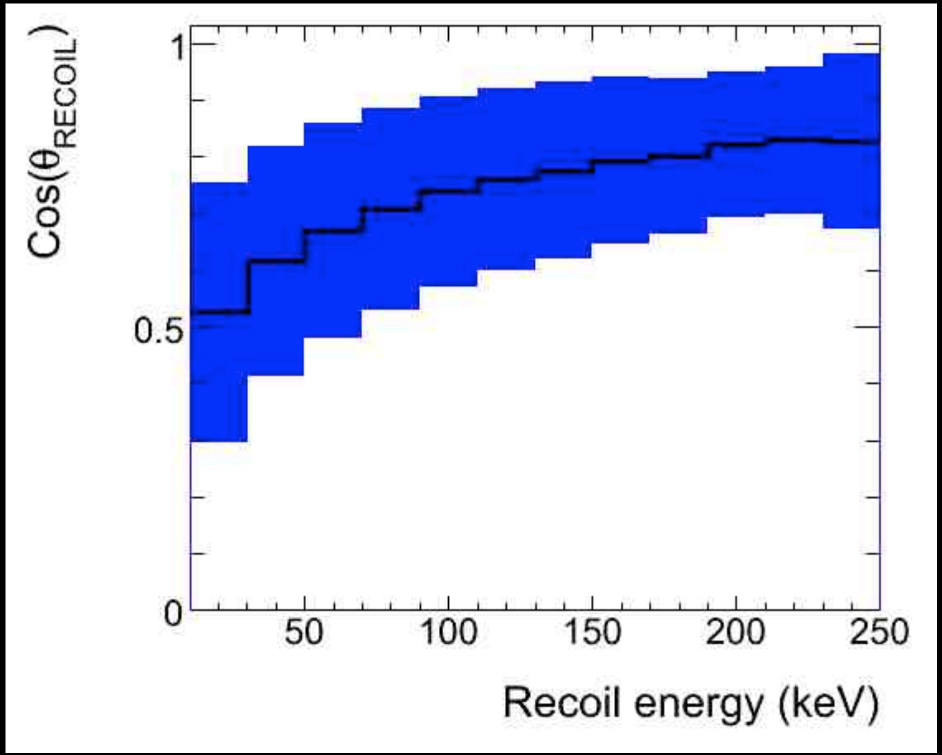
Signals in Directional Detectors



distribution of signal events determined by:

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

=



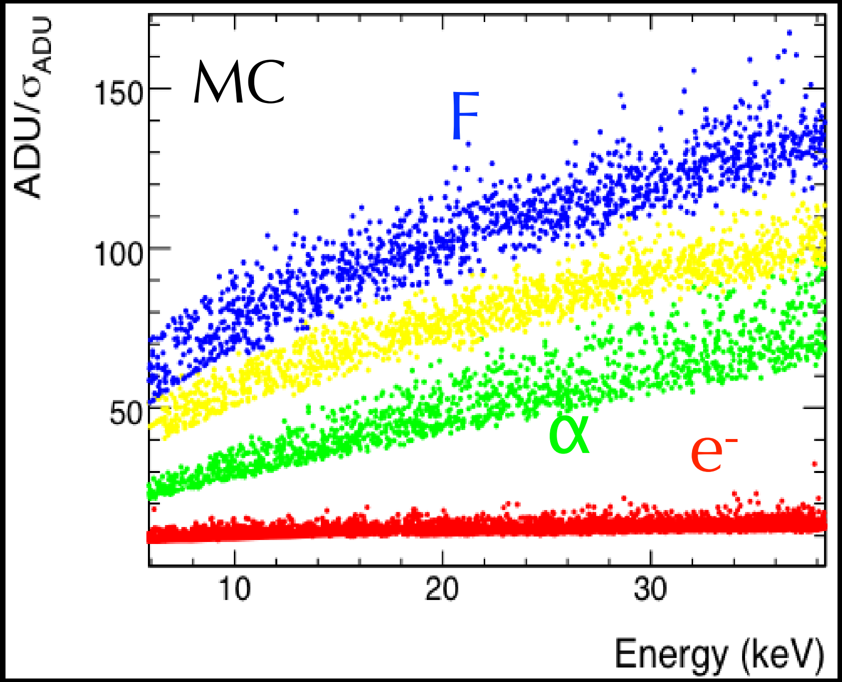
need ~50 keV threshold for directional detectors (for 100 GeV WIMPs), 35º resolution

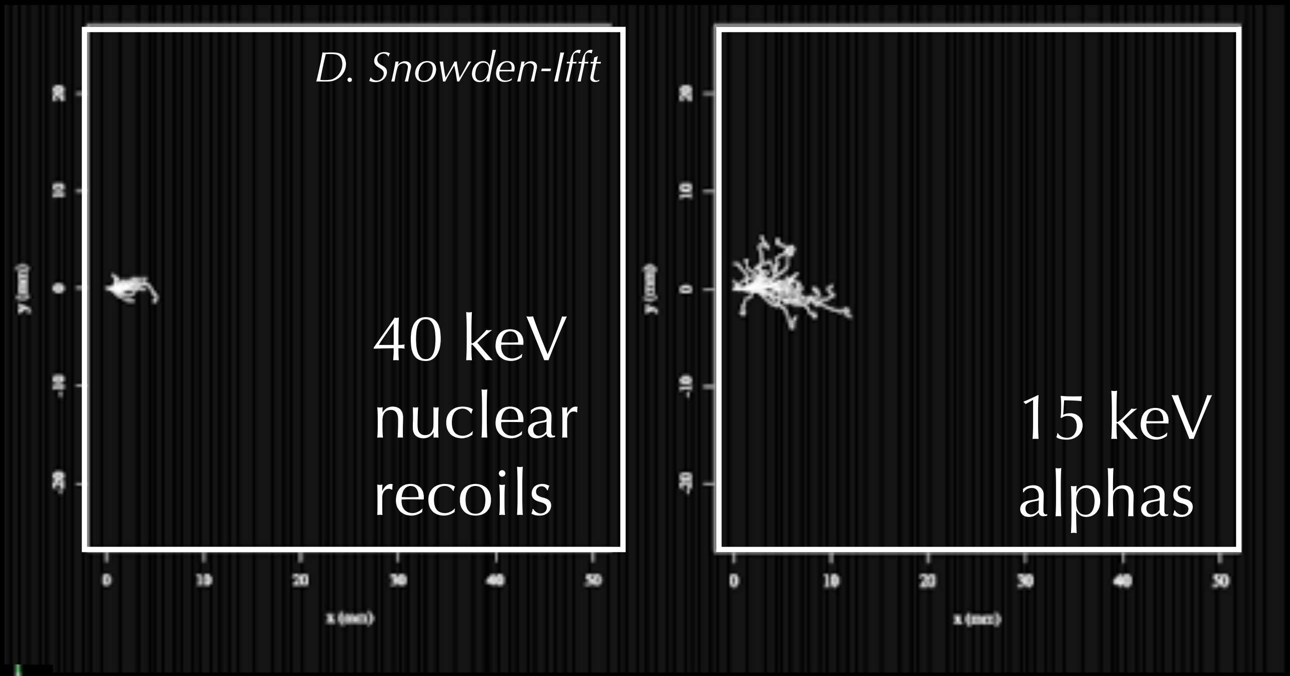
Backgrounds in Directional Detectors

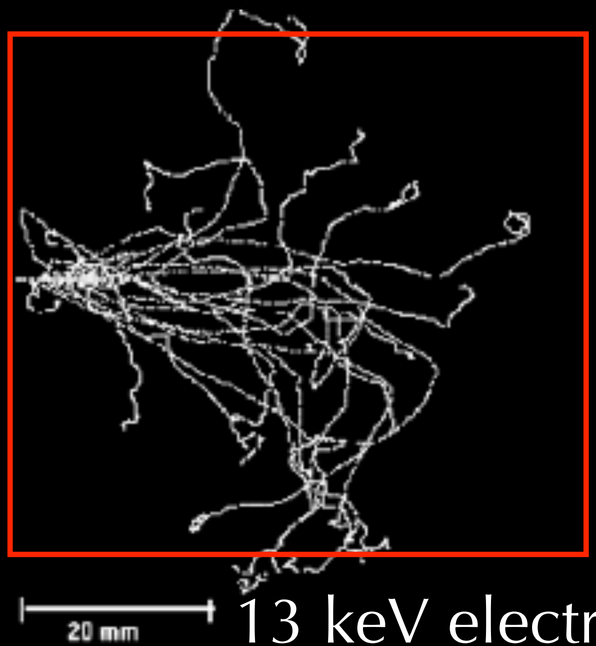
Three strategies:

1. range vs. energy
2. tracking (10^6 electron rejection)
3. angular distribution
   (important for ν-N coherent scattering!)

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

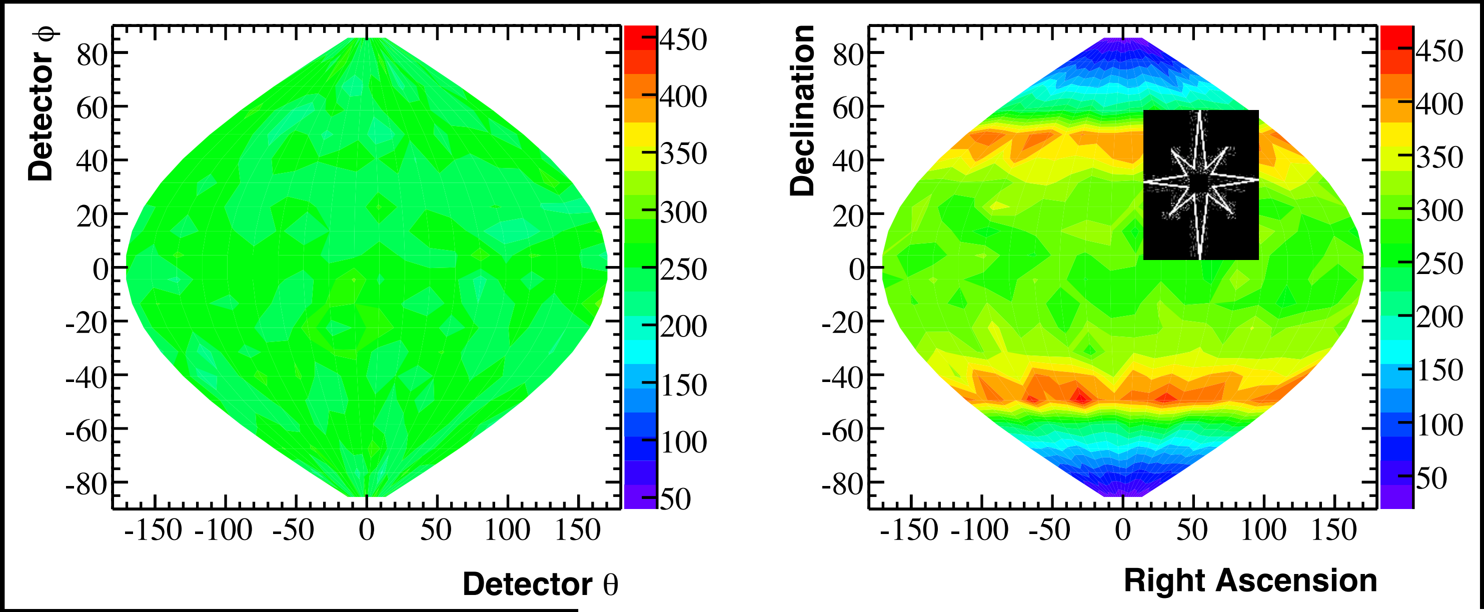






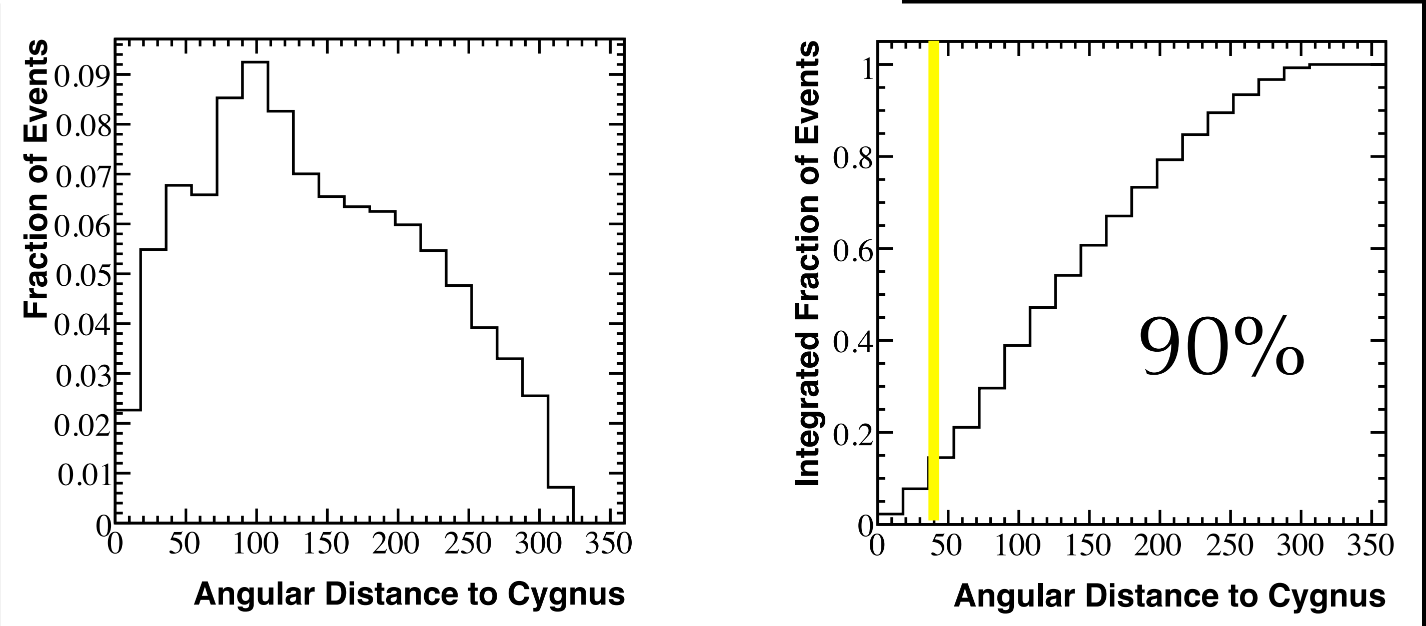
13 keV electrons

What Happens to Isotropic Backgrounds?



not isotropic in celestial coordinates

small fraction of locally isotropic events are near Cygnus



Optimization

how many events to detect the dark matter wind?

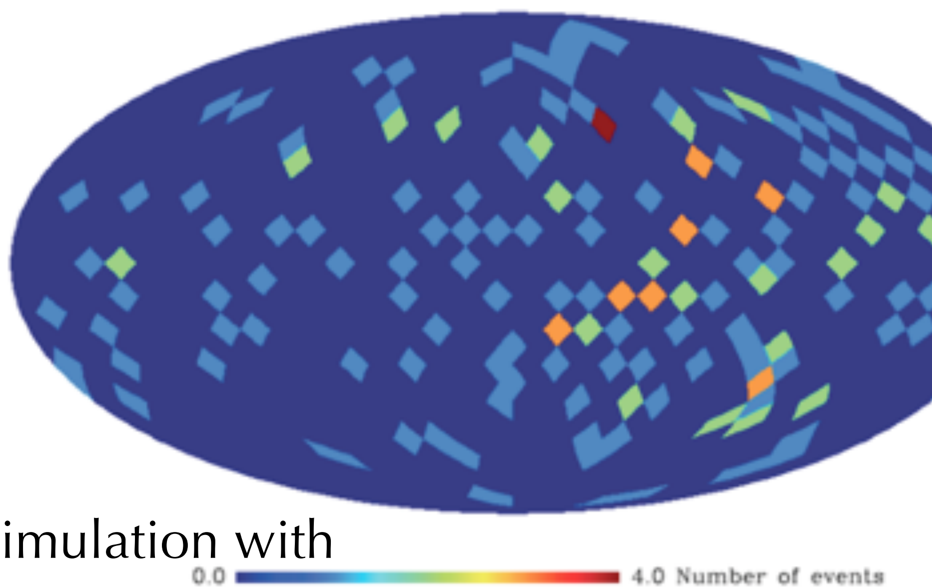
Detector Properties:

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

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

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

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



simulation with
100 signal, 100 background

Billard et al. 2010

do not need "zero background" for directional detectors

Sept 24, 2014

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
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No background, 3-d vector read-out, $E_T = 20$ keV	5
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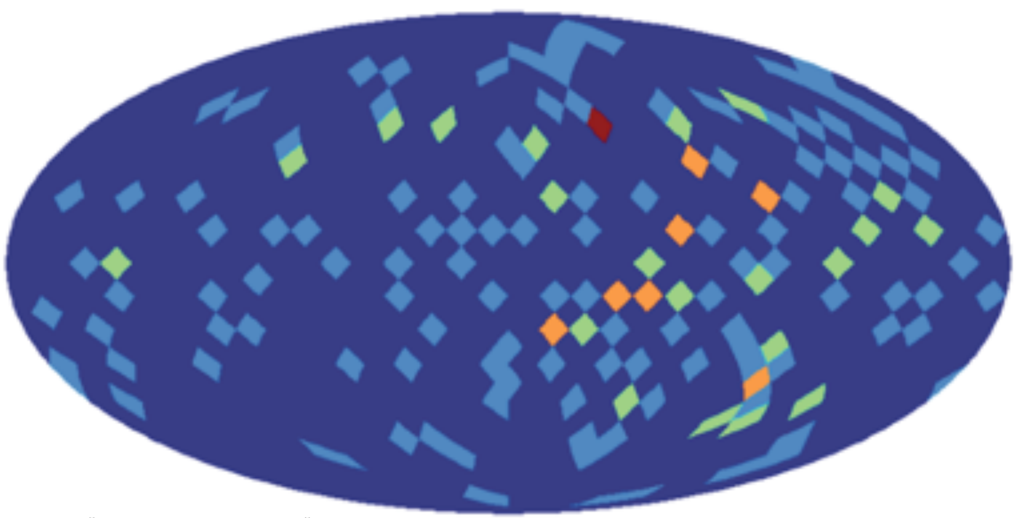


0.0 4.0 Number of events

simulation with
100 signal, 100 background

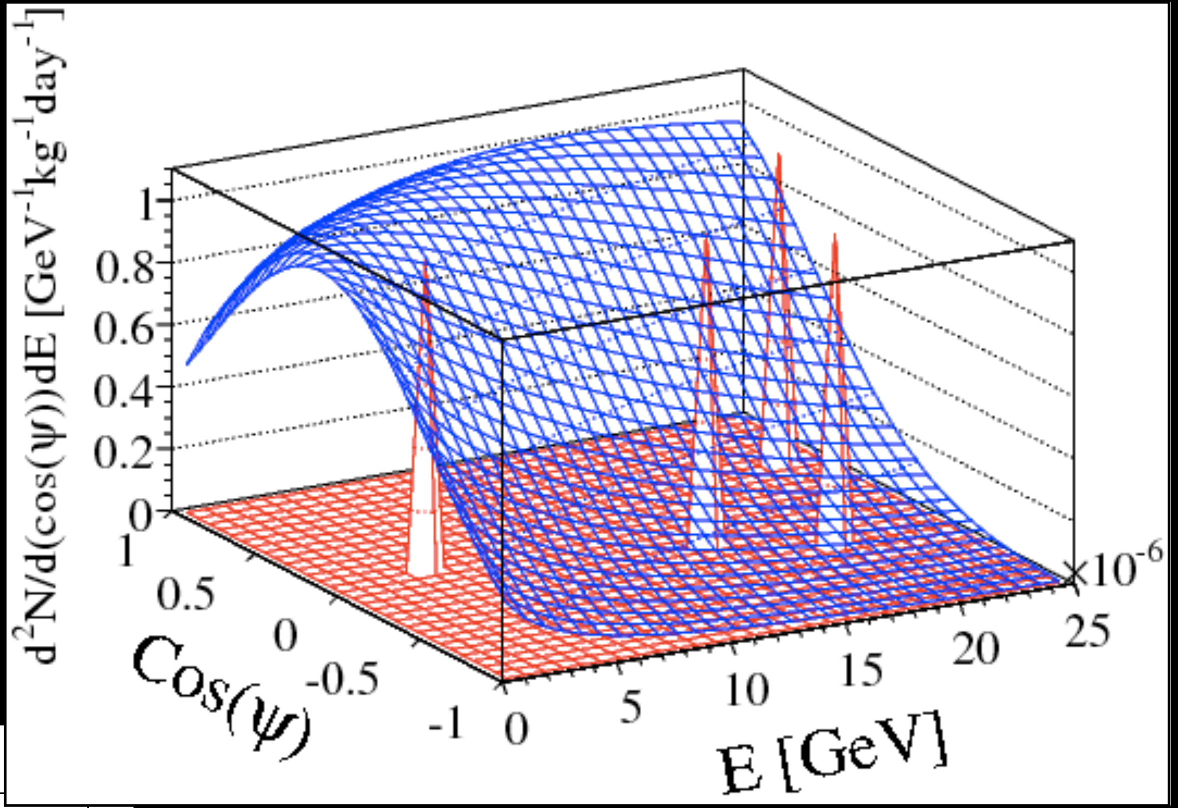
Billard et al. 2010

do not need "zero background" for directional detectors

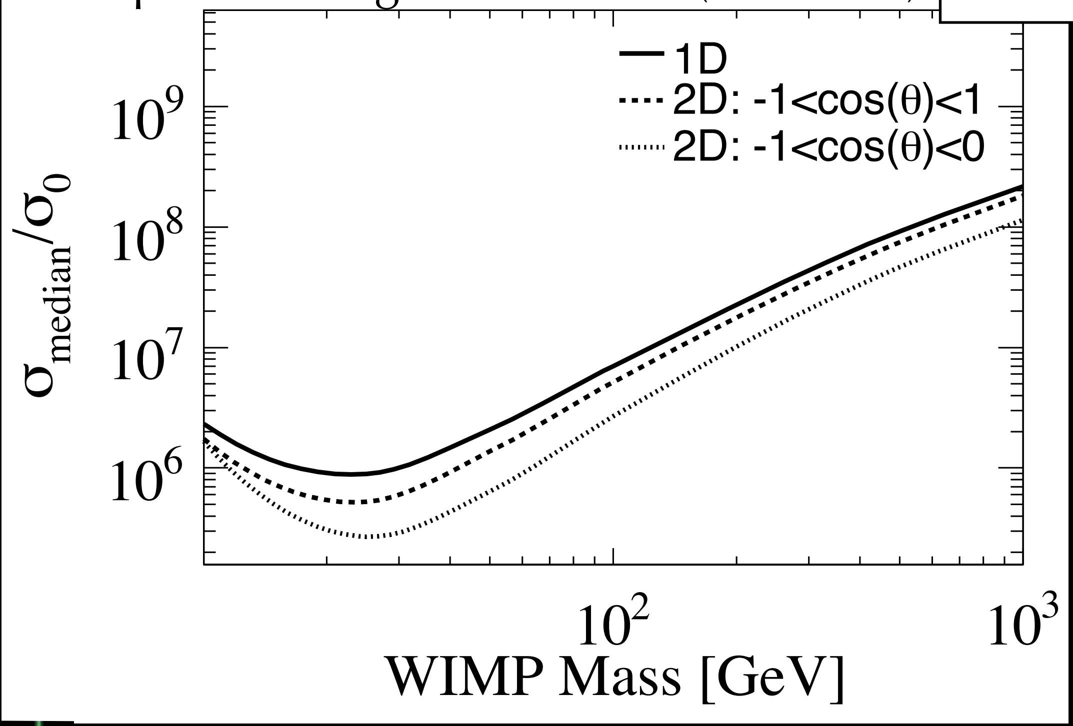
Sensitivity Example

in the presence of backgrounds

need to *measure* the neutron background energy, angle distributions (both ~unknown)



example: 7 background events (Xenon10)



maximum patch method (based on Yellin gap)

S. Henderson, JM, P. Fisher, Phys. Rev. D 78:015020 (2008)

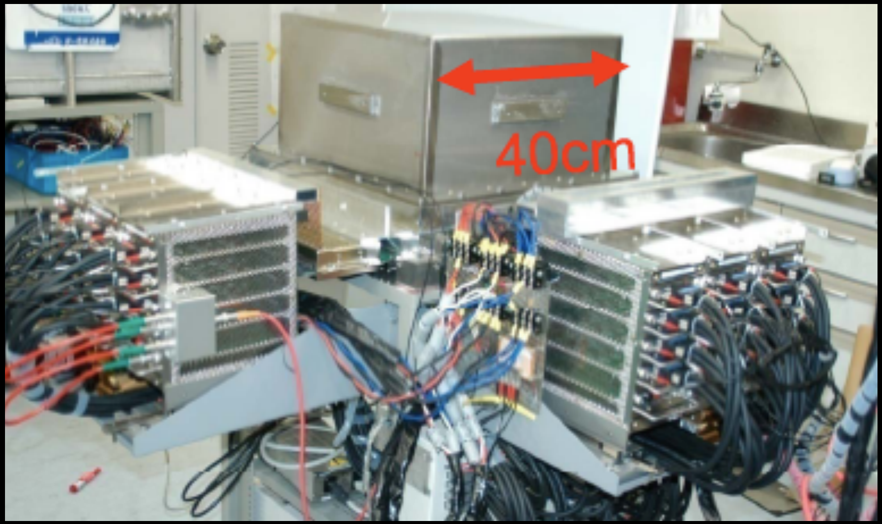
result:
with backgrounds, 2D dark matter detection sensitivity up to ~10x 1D sensitivity, but, depends strongly on distribution!

Outline

1. Introduction and Context
2. Modulating Signals
3. Directional Detection Experimental Considerations
4. **Recent Progress from Directional Detectors**
5. Physics Reach with Directional Data

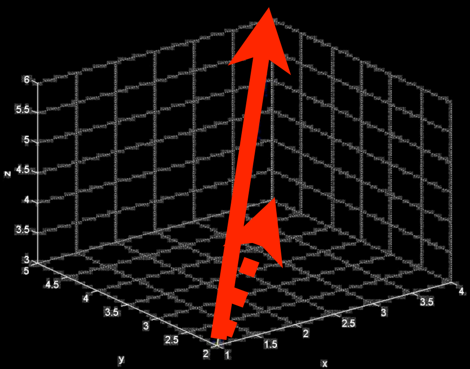
Directionality Around the World

DRIFT: in Boulby (UK),
first directional experiment!
S. Burgos et al., Astropart. Phys. 28, 409 (2007)



NEWAGE: in Kamioka (Japan),
first directional dark matter limit!
K. Miuchi, et al., Phys.Lett.B654:58-64 (2007)

DMTPC: in WIPP (US),
optical and charge readout
D. Dujmic, JM, et al.,
NIM A 584:337 (2008)

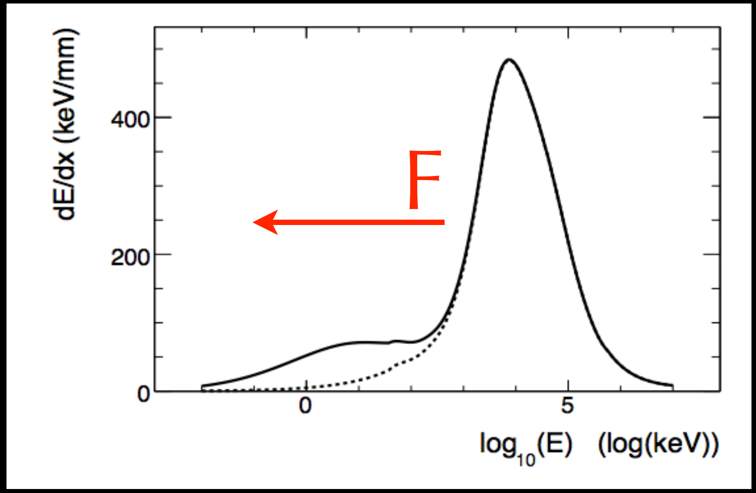


MiMAC-He3: ILL, planned for
Modane (France), A-dependence
D. Santos, et al., J. Phys. Conf. 65, 021012 (2007)

R&D: emulsion detectors, charge focussing, pixel chip readout, scintillating crystal...

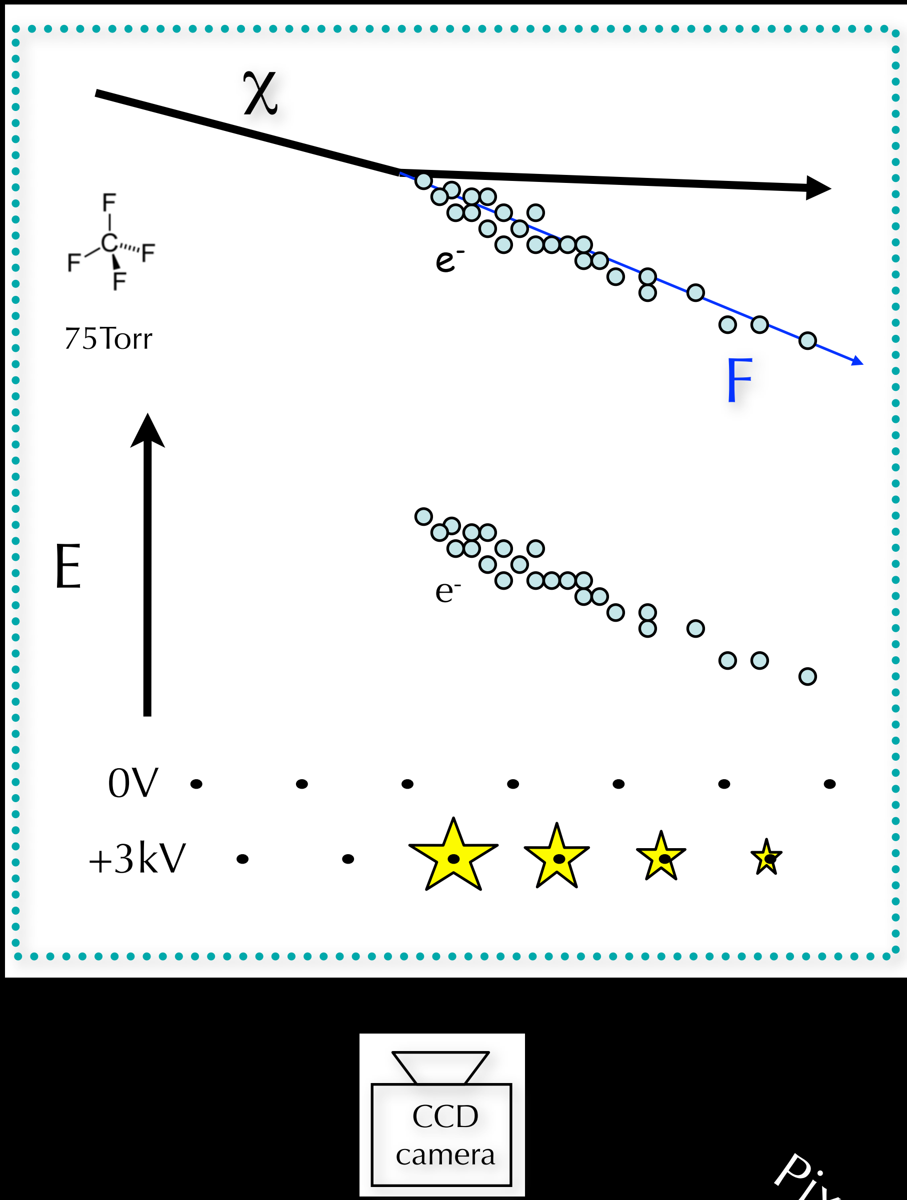
Detailed Example: DMTPC

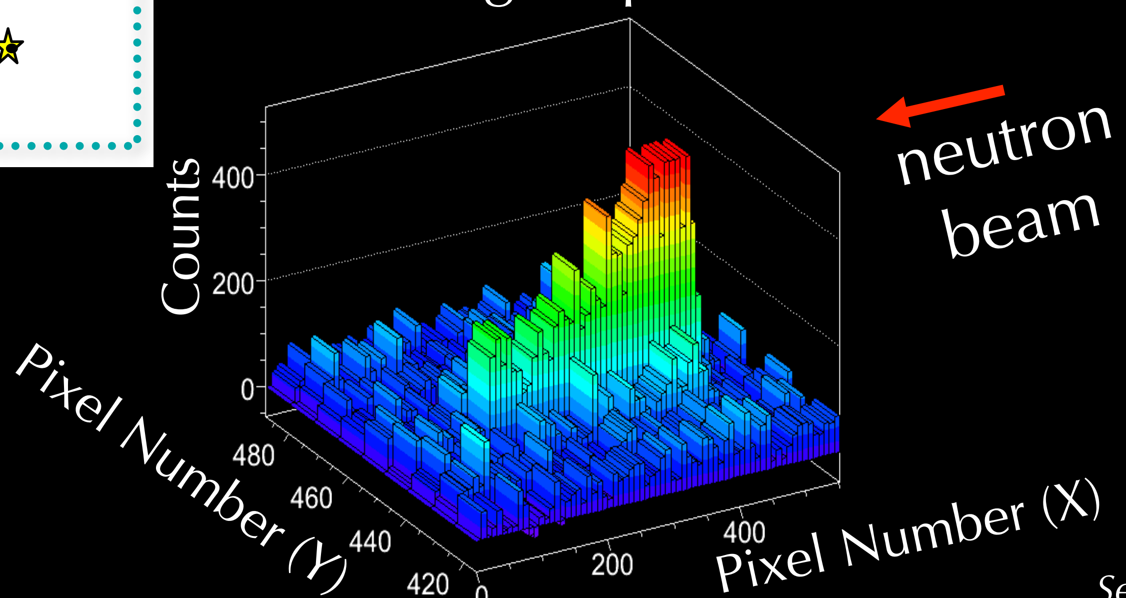
1. primary ionization encodes track direction via dE/dx profile



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

3. multiplication in amplification region produces e- + scintillation

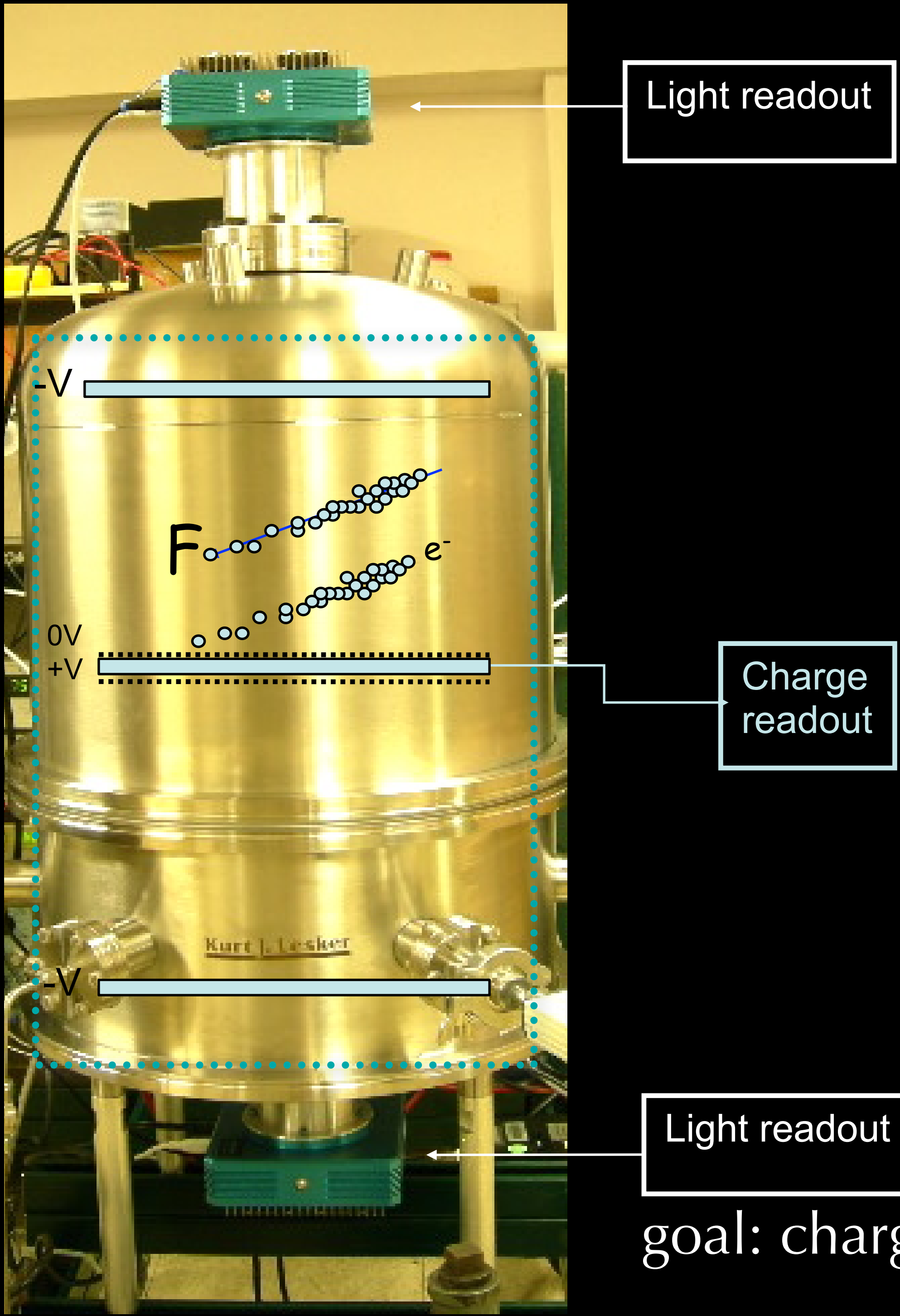


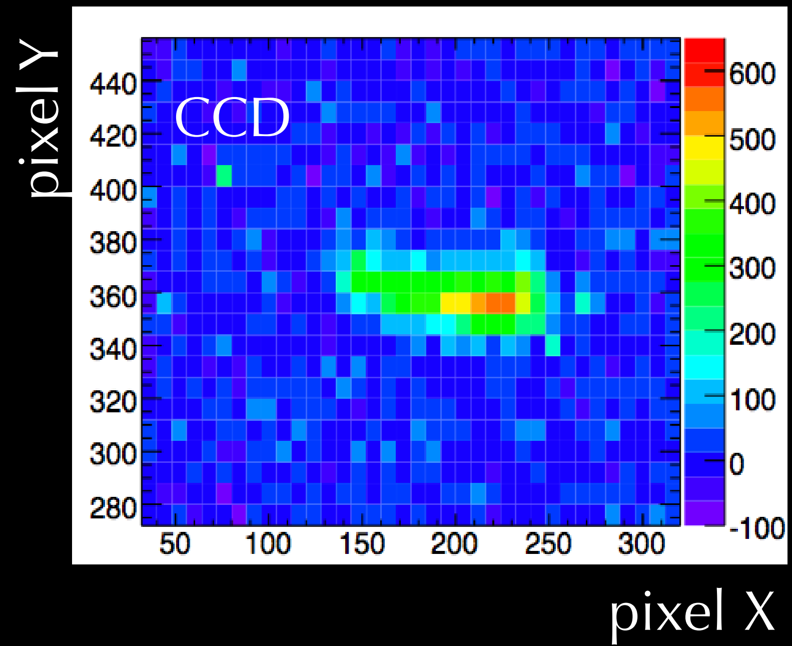


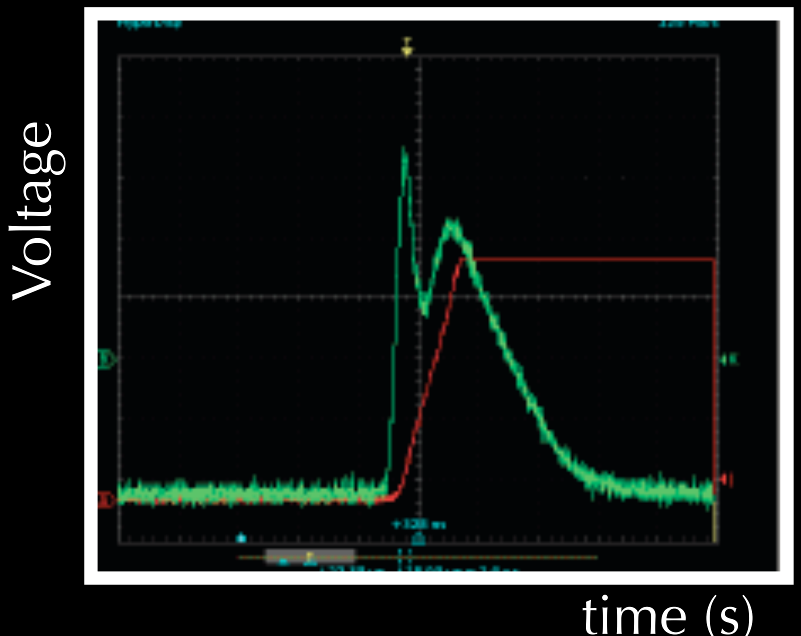
D. Dujmic, JM, et al.,
NIMA 584:337 (2008)

TPC Readout

(Royal Holloway, MIT, Boston University, Bryn Mawr)



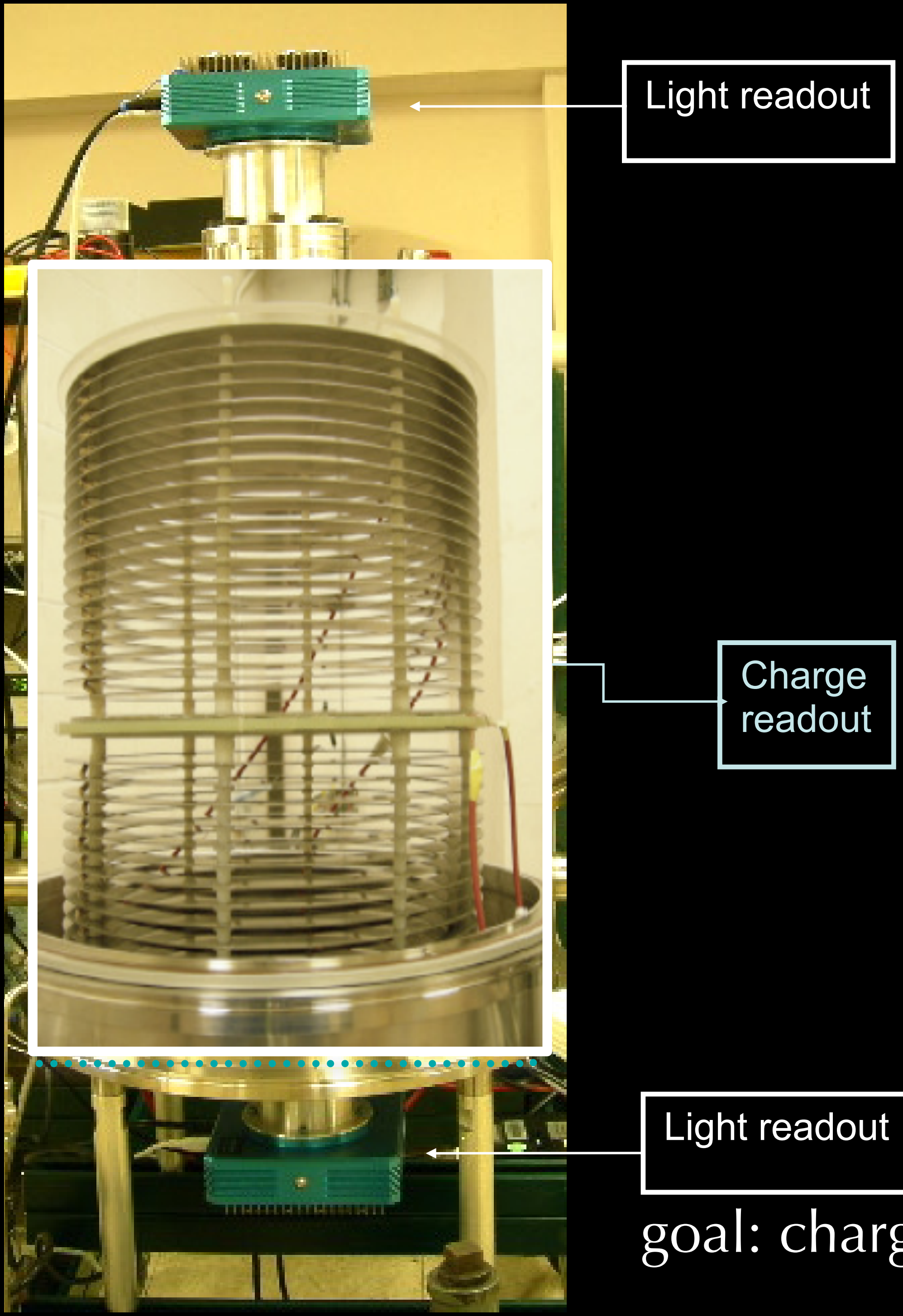


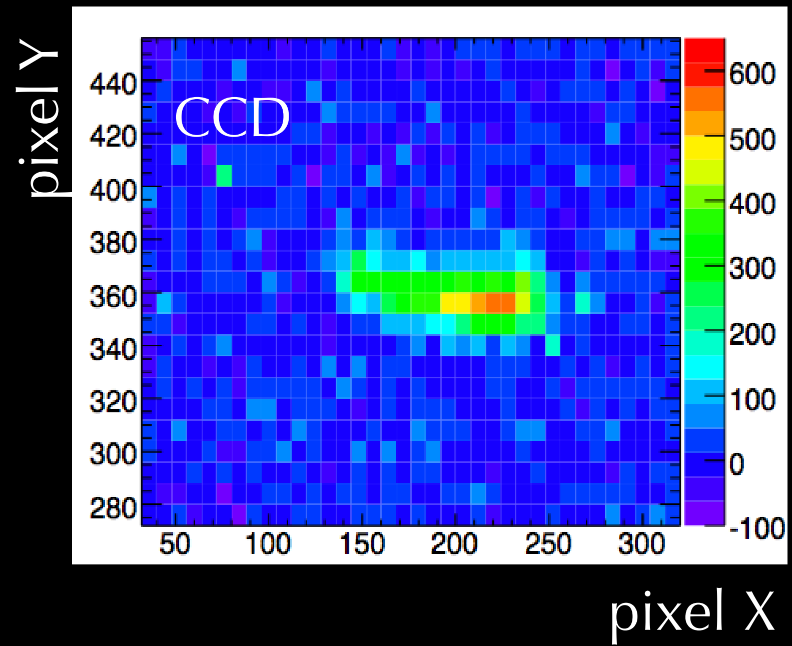


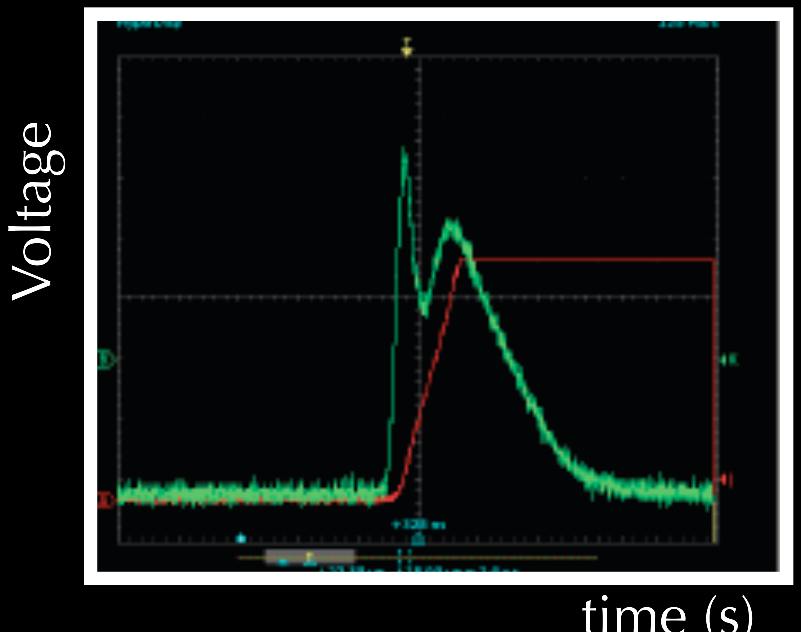
goal: charge and light= 2->3D, background ID

TPC Readout

(Royal Holloway, MIT, Boston University, Bryn Mawr)







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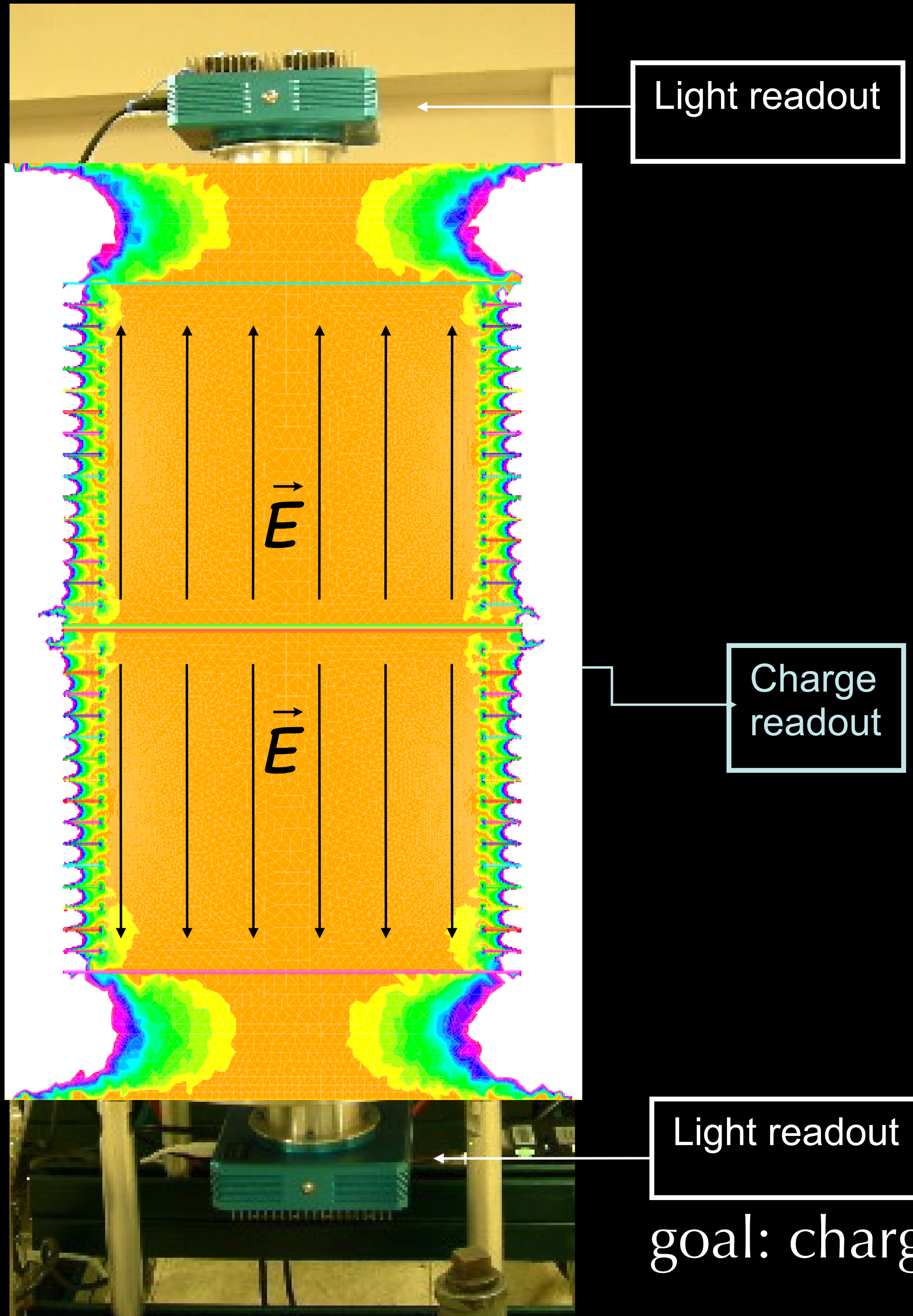
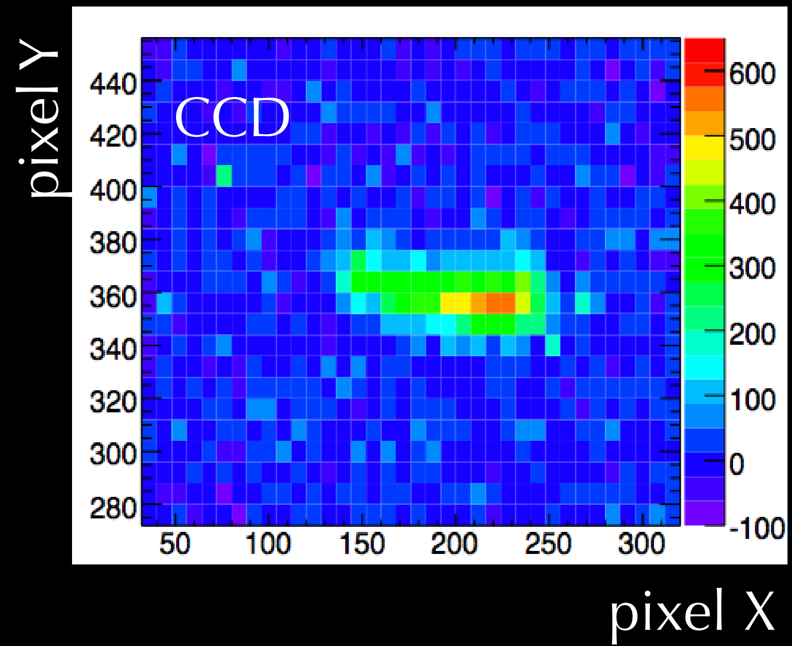
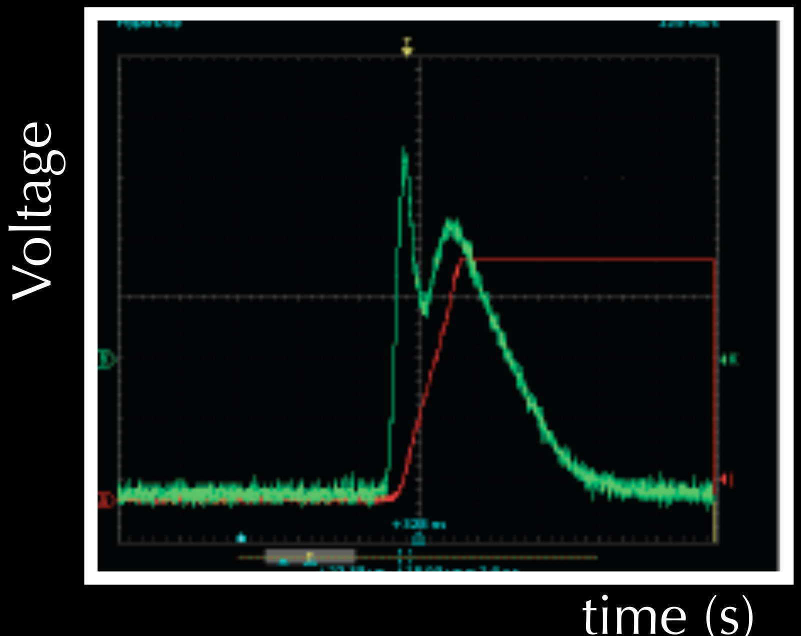
(Royal Holloway, MIT, Boston University, Bryn Mawr)







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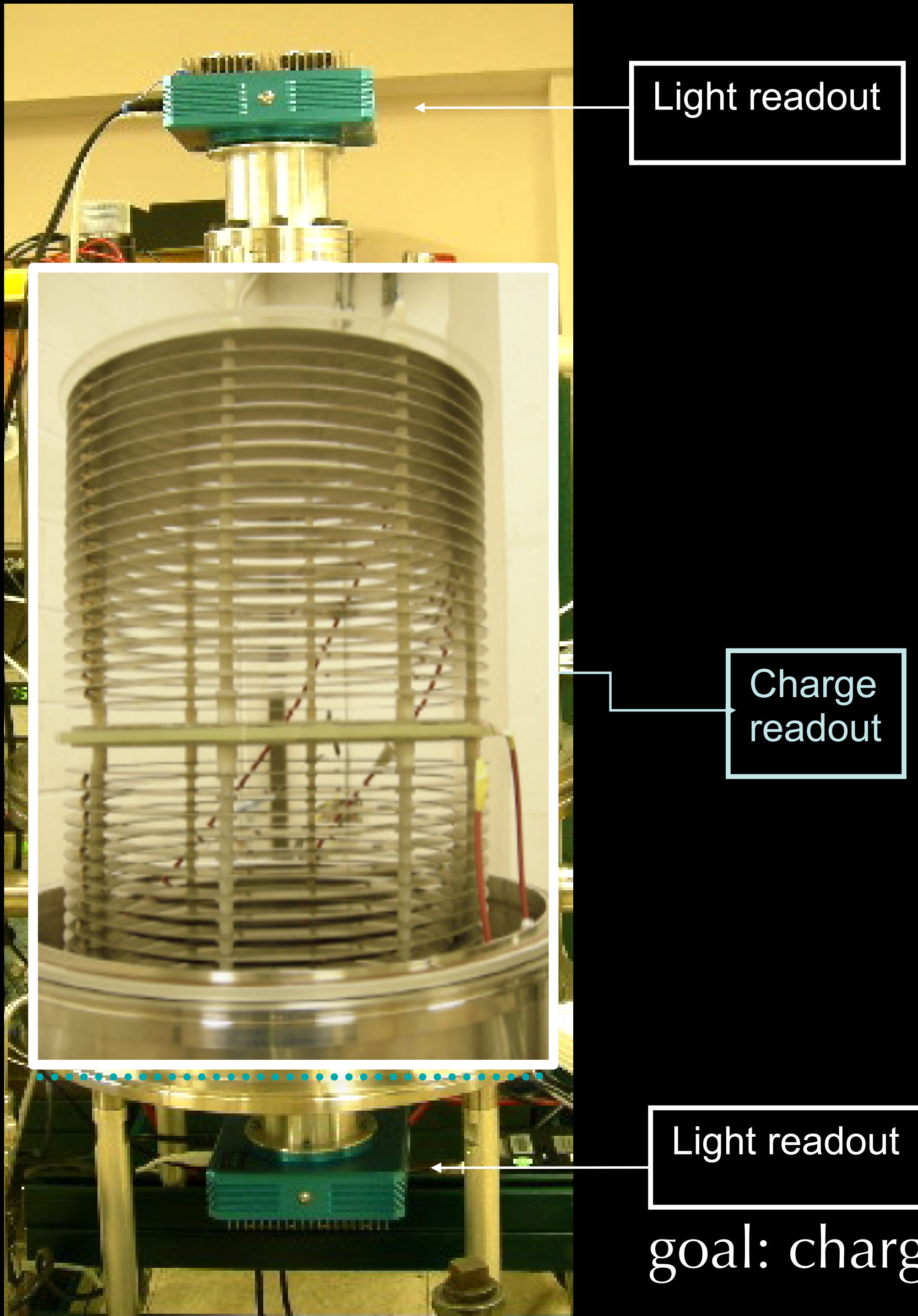
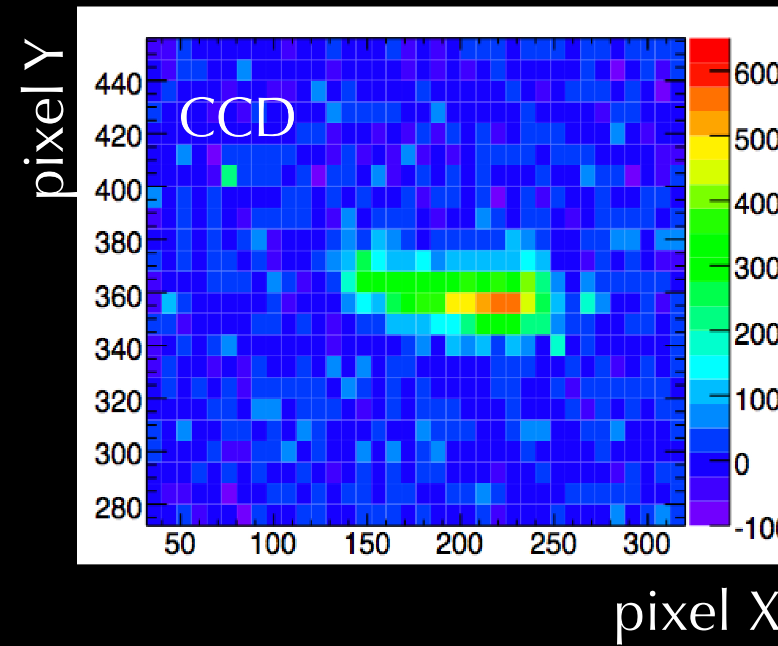
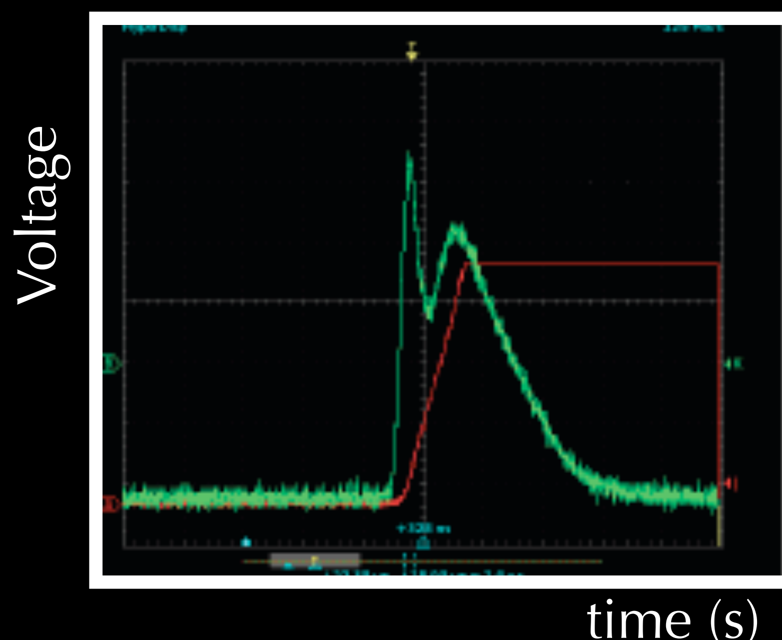


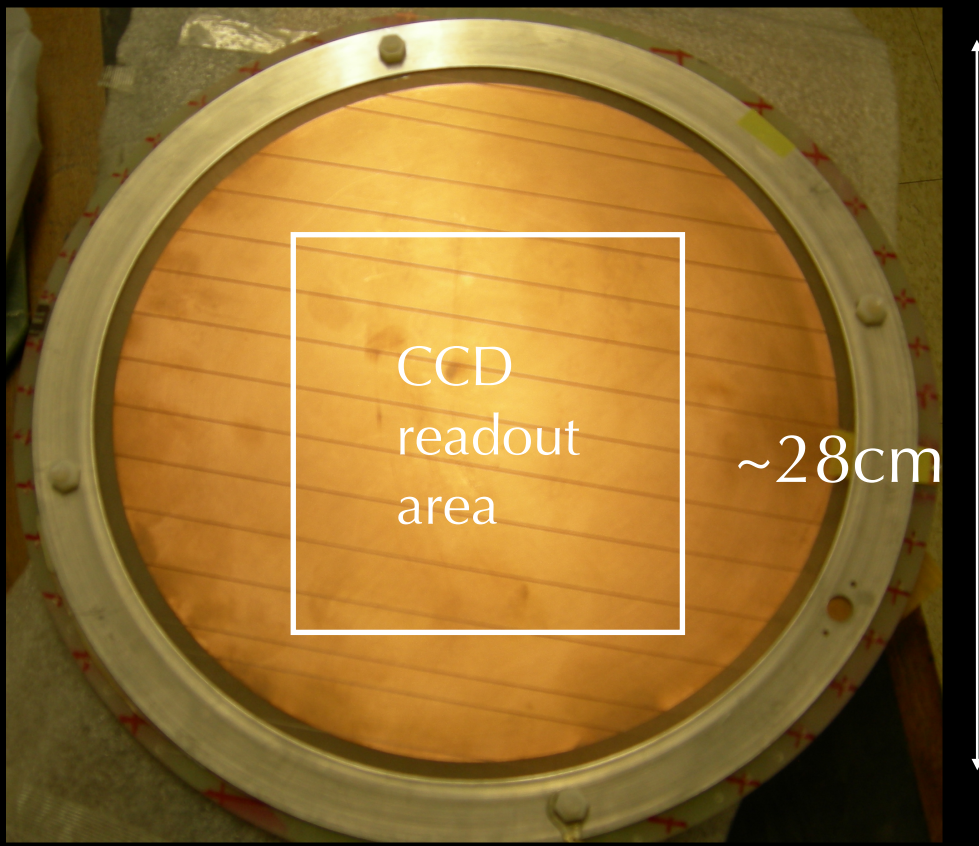




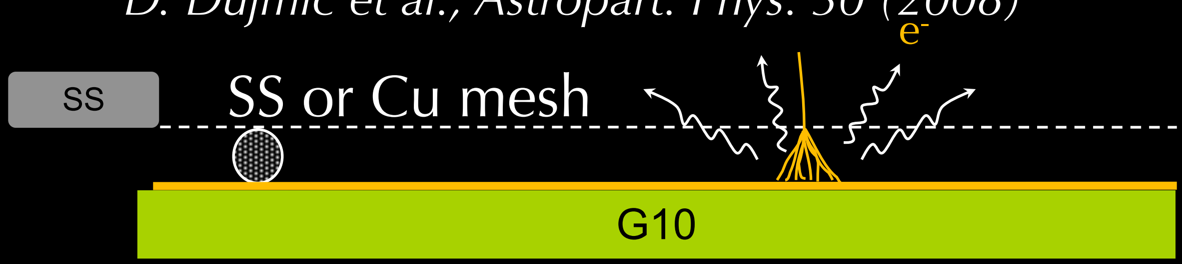
goal: charge and light= 2->3D, background ID

Amplification Plane

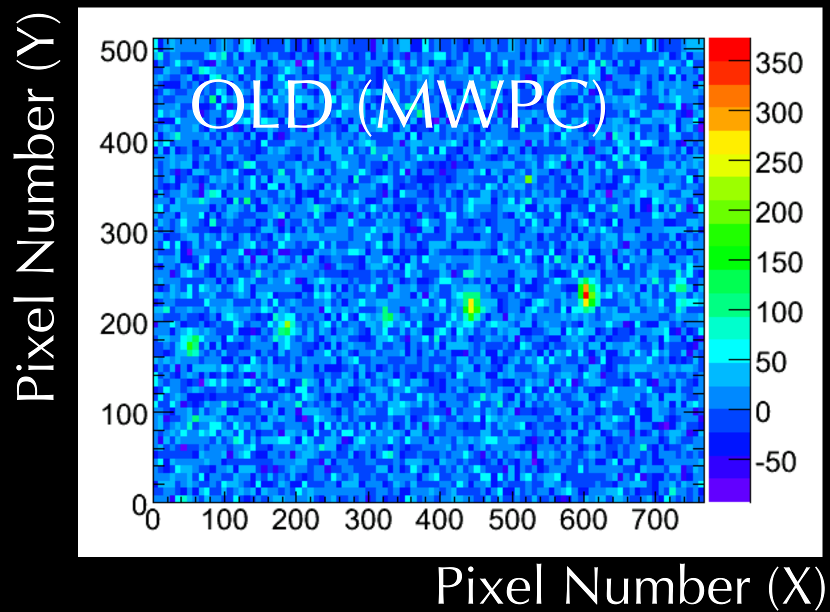
Copper Mesh, 256 um pitch

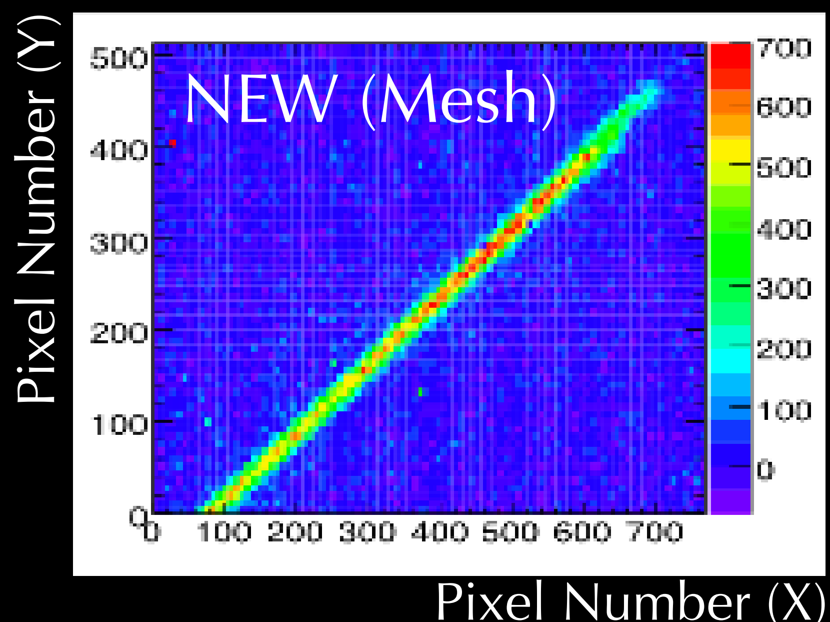


D. Dujmic et al., Astropart. Phys. 30 (2008)



Resistive separators, dia=0.5mm, every 2.5cm

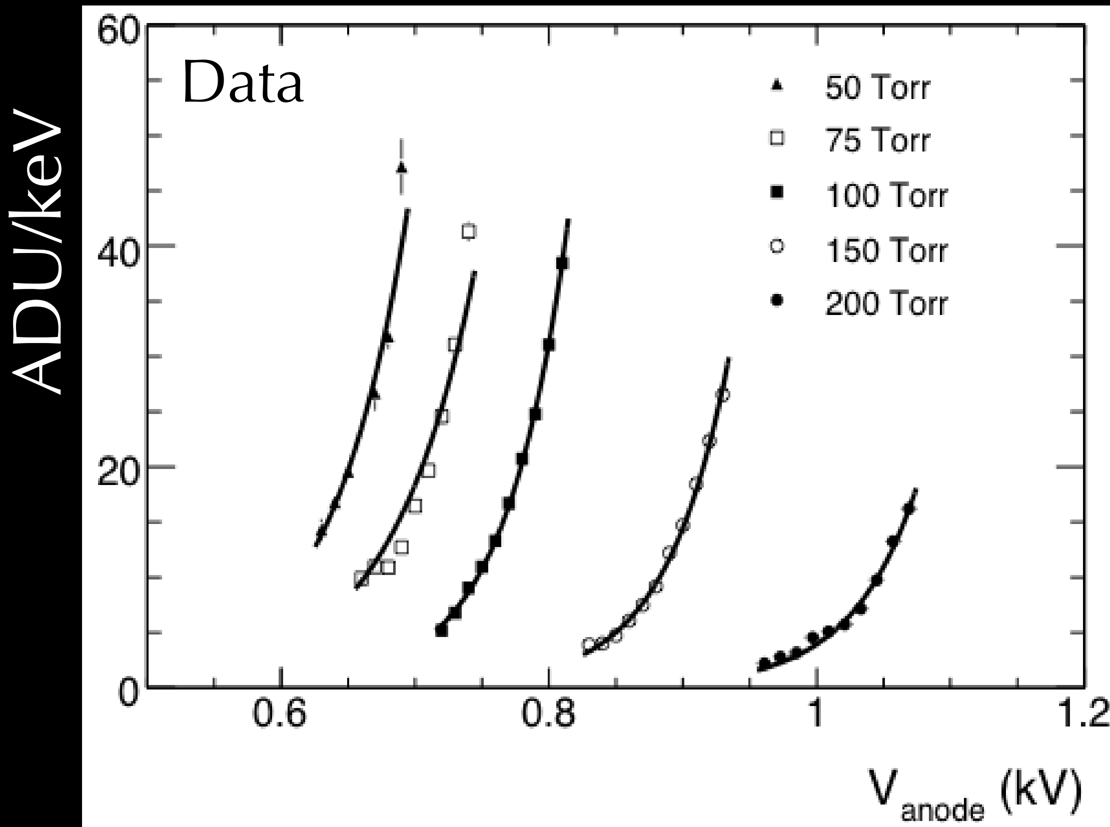


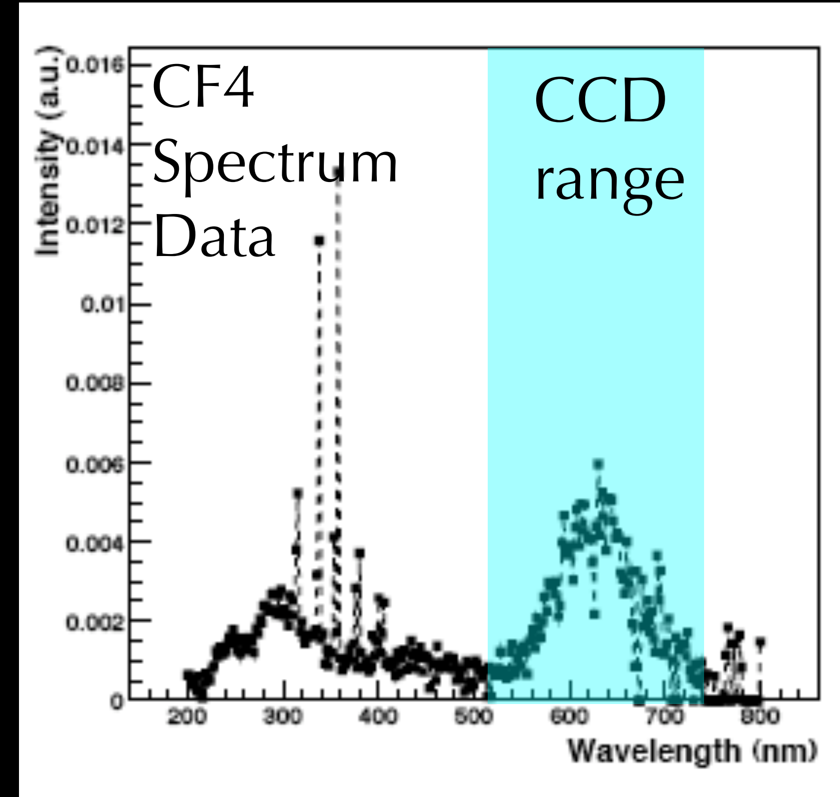


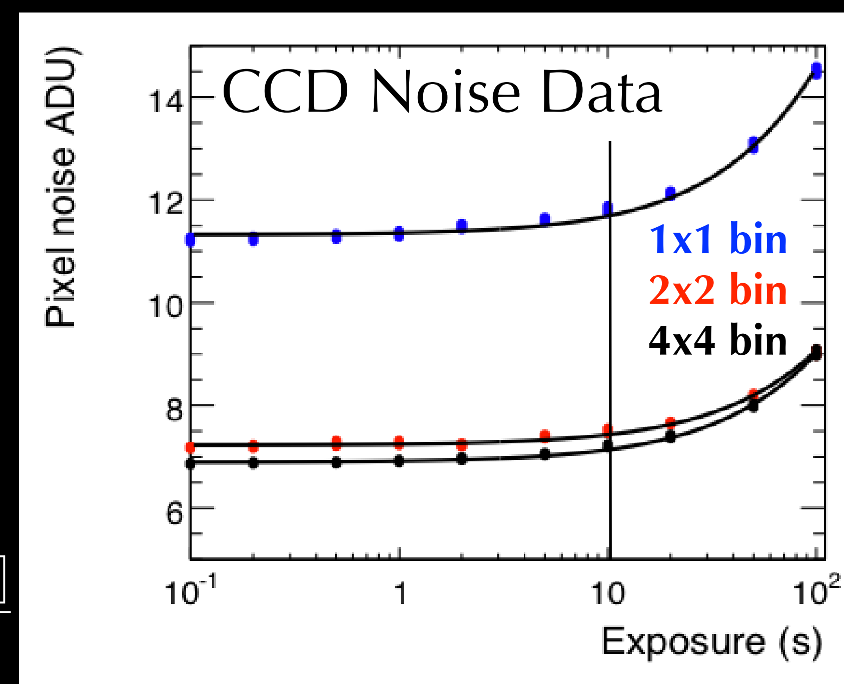
20x smaller pitch,
13x higher gain, 1->2D

CCD Readout

Total light output:







CF4 scintillation: **γ**/*e⁻ = 0.38 +/- 0.04*

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

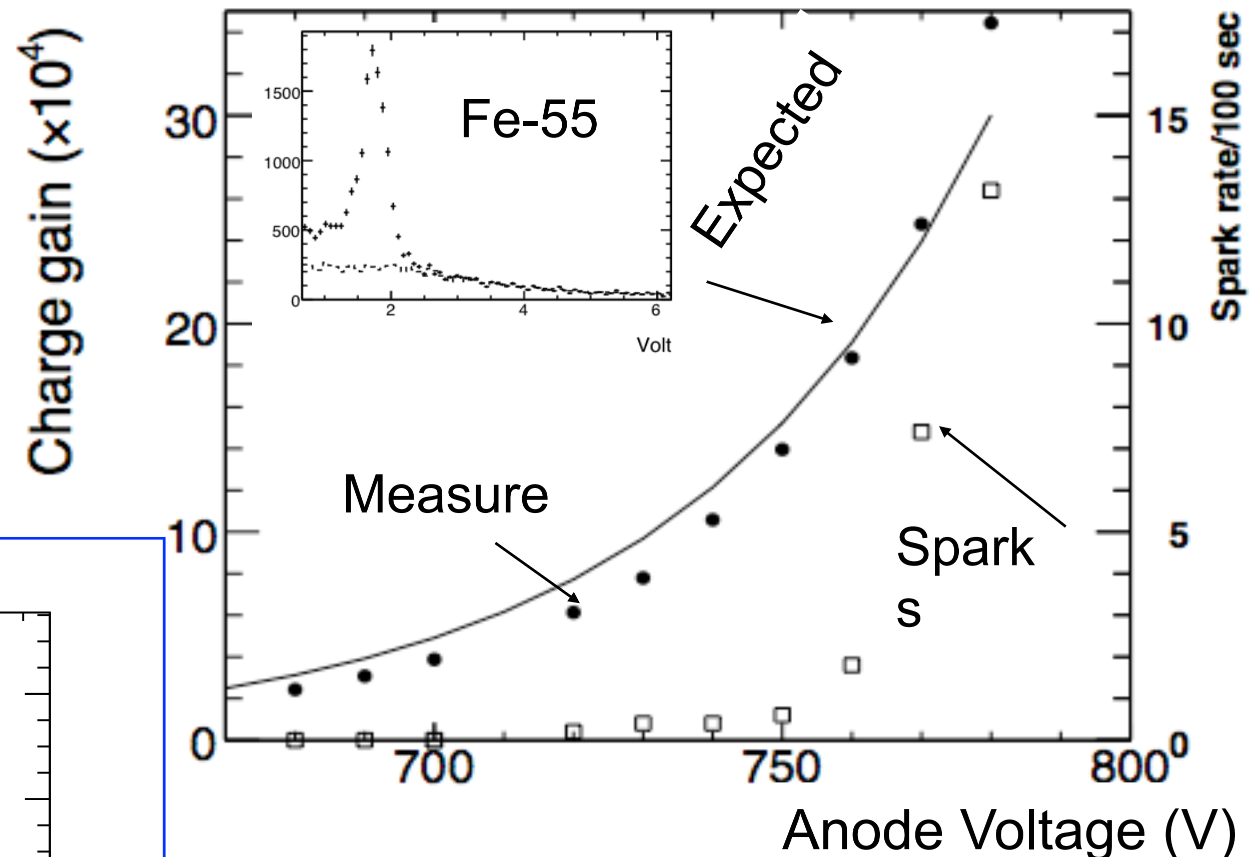
Key: S:N per pixel, @50 keVr S:N~10-20

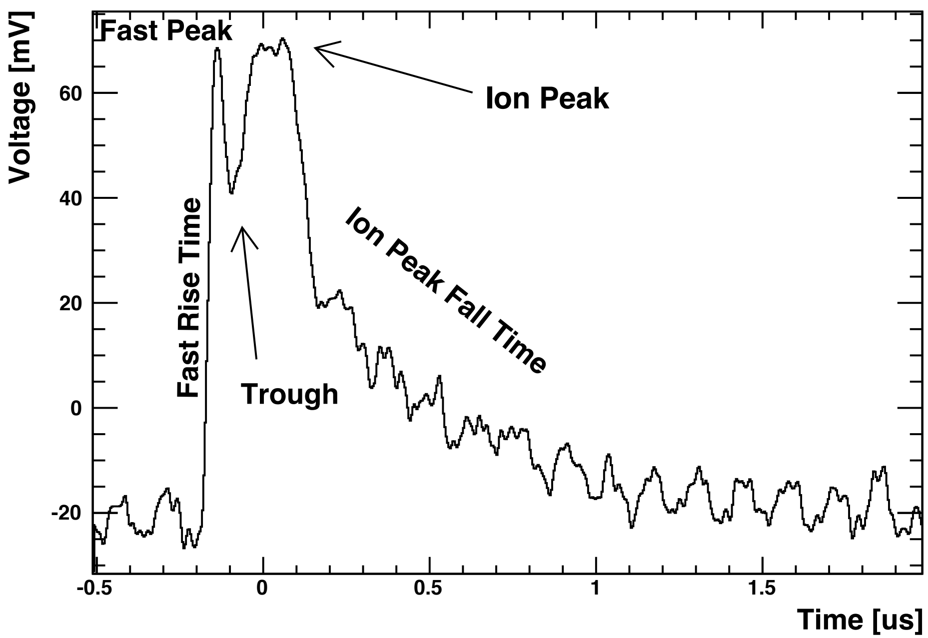
$$\left(\frac{signal}{noise}\right)/pixel \simeq \frac{[(ADU/keV)\times E_r \times q(E_r)]/[Range/pixel\ size]}{\sqrt{N_{shot}^2+N_{read}^2+N_{dark}^2}}$$

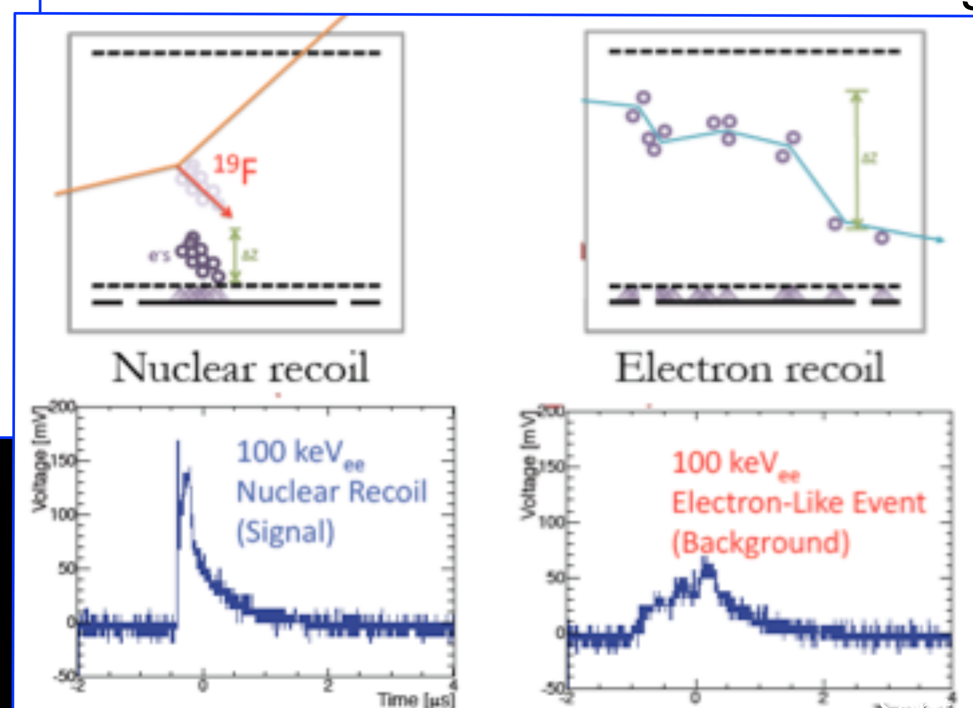
Charge Readout

Multiplication calibrated with Fe-55, anode signal amplitude

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

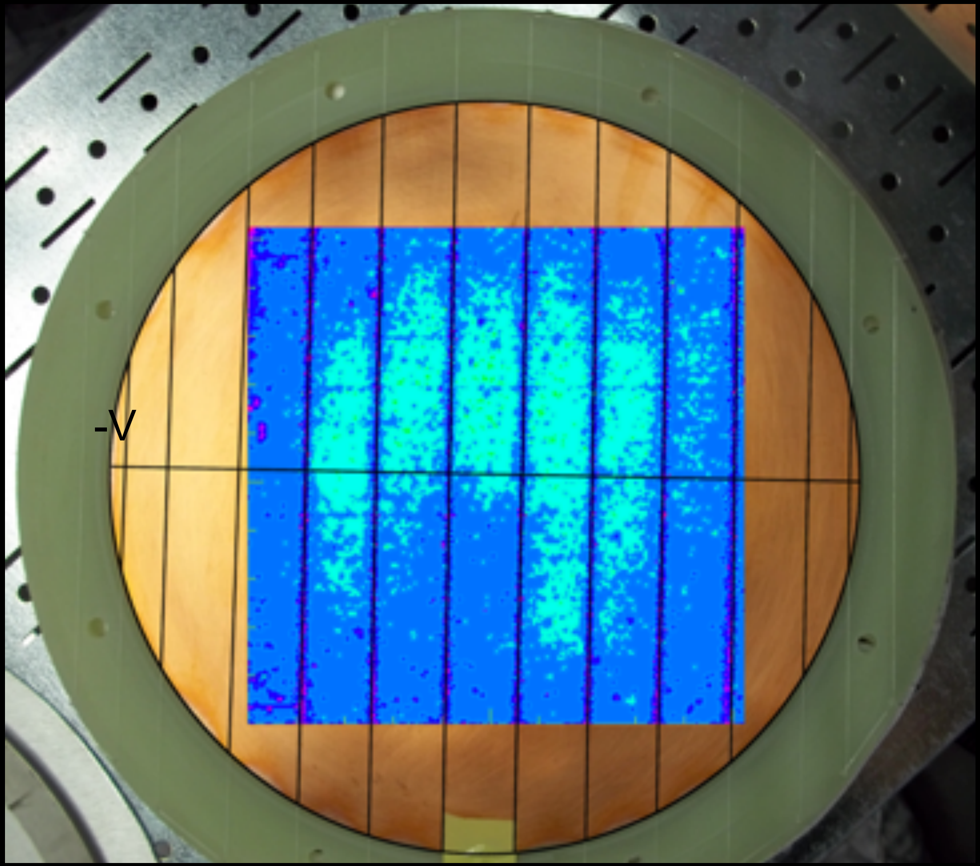






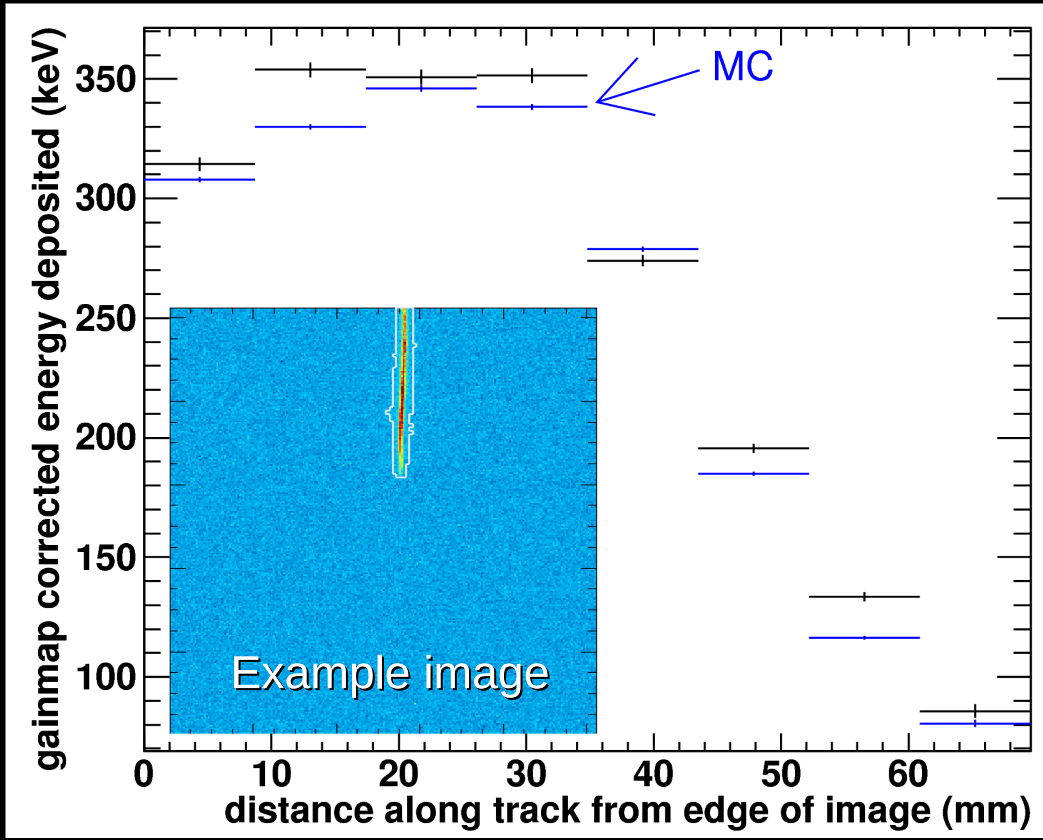
Mesh signal readout with ns-risetime amplifier, to measure Δz and for PID

CCD Length and Energy Calibration



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

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



α sources for energy calibration (4.4 MeV)

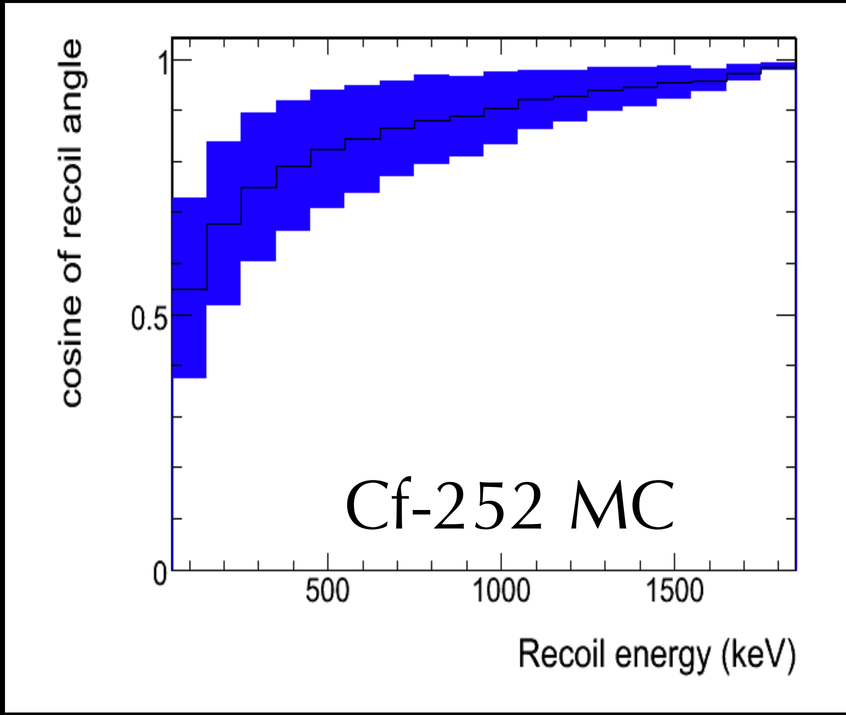
measure gain (ADU/keVee) by comparing α energy measured in external solid state detector with energy in CCD, at track end: typical gain ~ 20-40 ADU/keV

“WIMP” Calibration

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

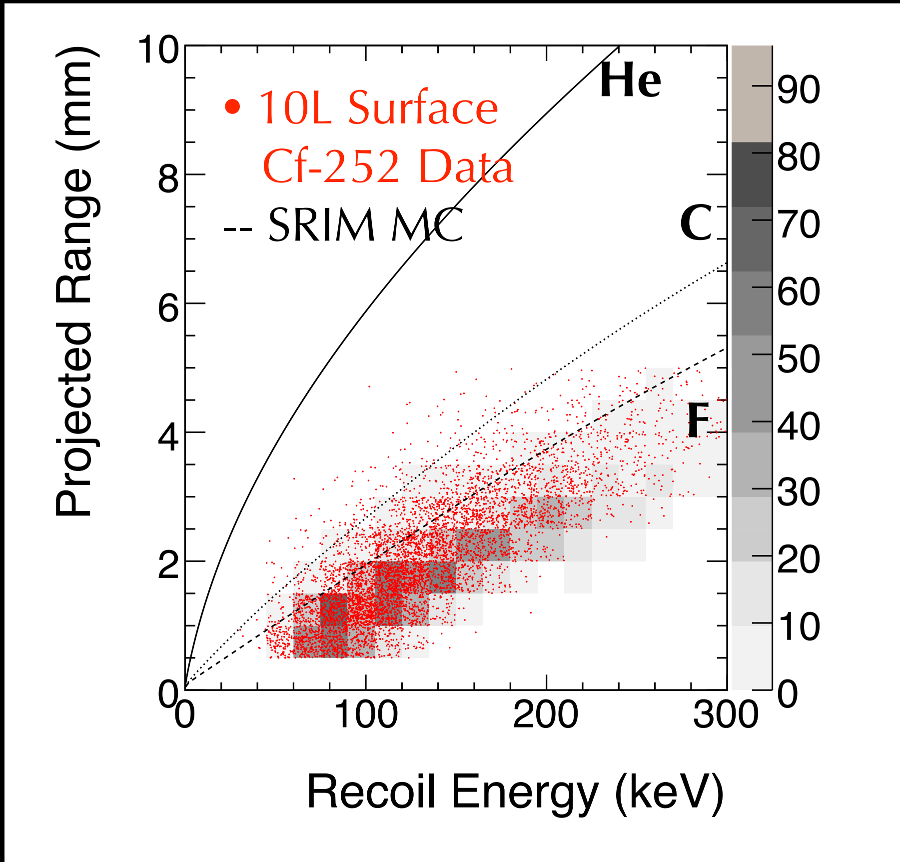
Cf-252 (~mCi) and d-t sources at surface, AmBe (8.9 uCi) source underground

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



minimum recoil energy detected: 30-50 keV

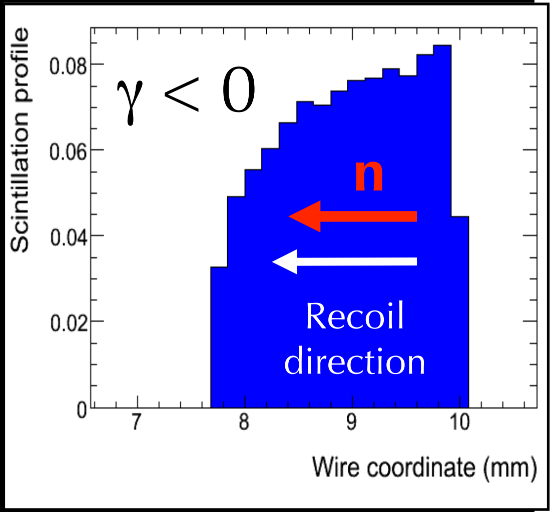
(Hitachi quenching model)

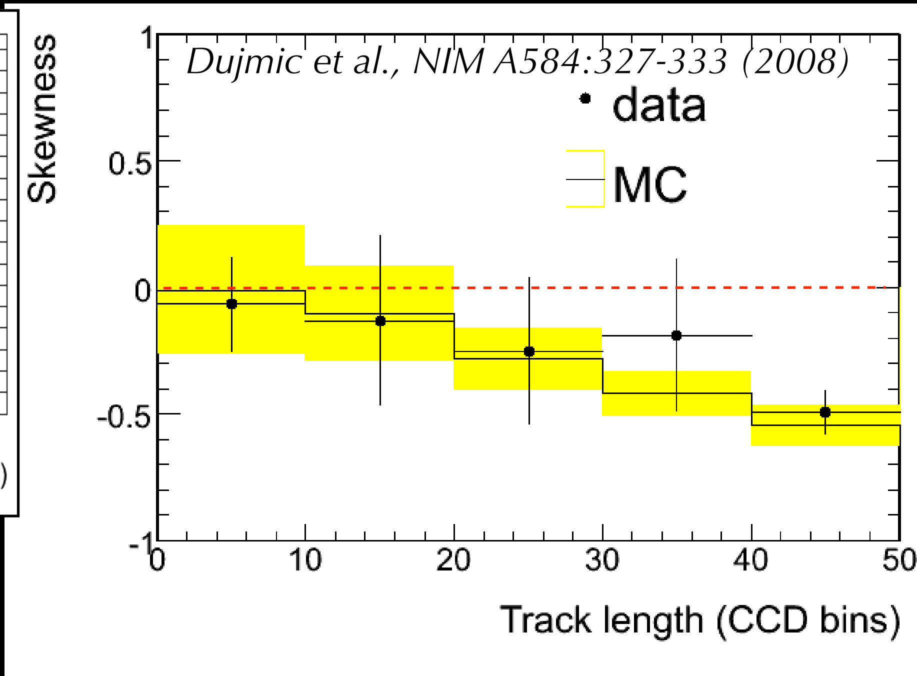


Energy and recoil angle distributions similar to dark matter induced recoils

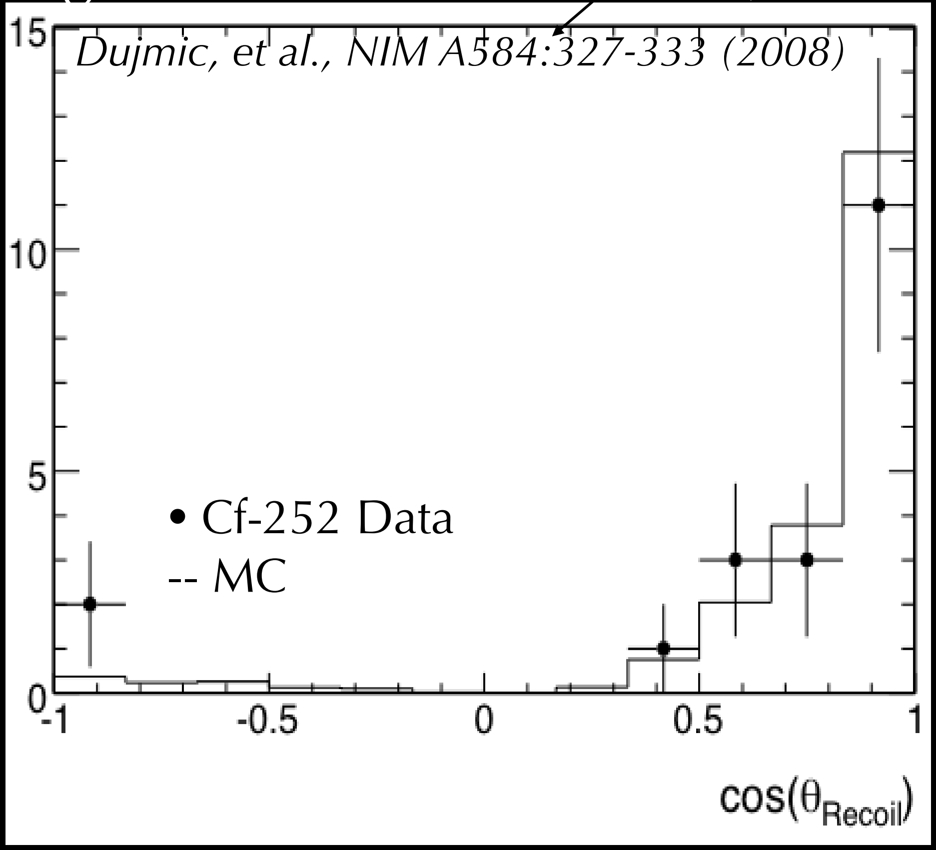
Directionality I

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

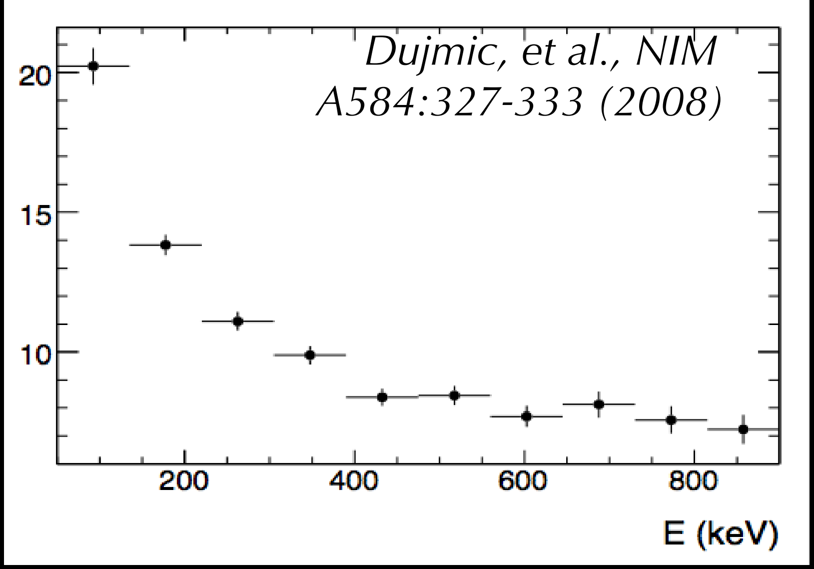




Signed cosine (E>200 keV), 5 cm drift



Angular resolution, 5 cm drift



challenge to scaling up: diffusion!

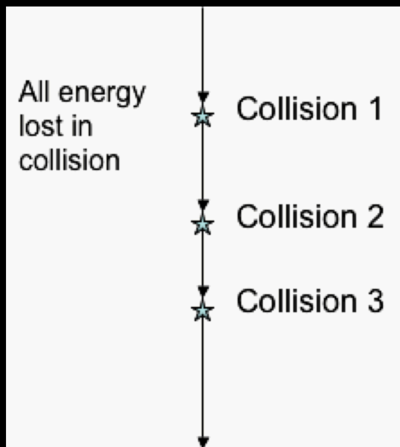
$\sigma^2 = (D/\mu)\ 2\ z_{DRIFT} / E$

(T. Caldwell thesis)

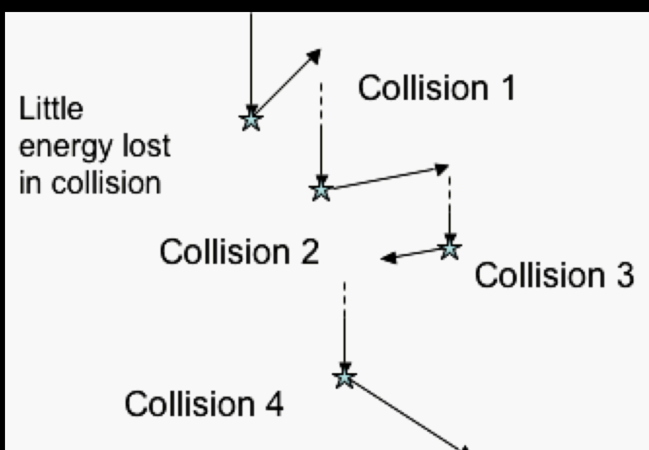
CF_4 Electron Diffusion

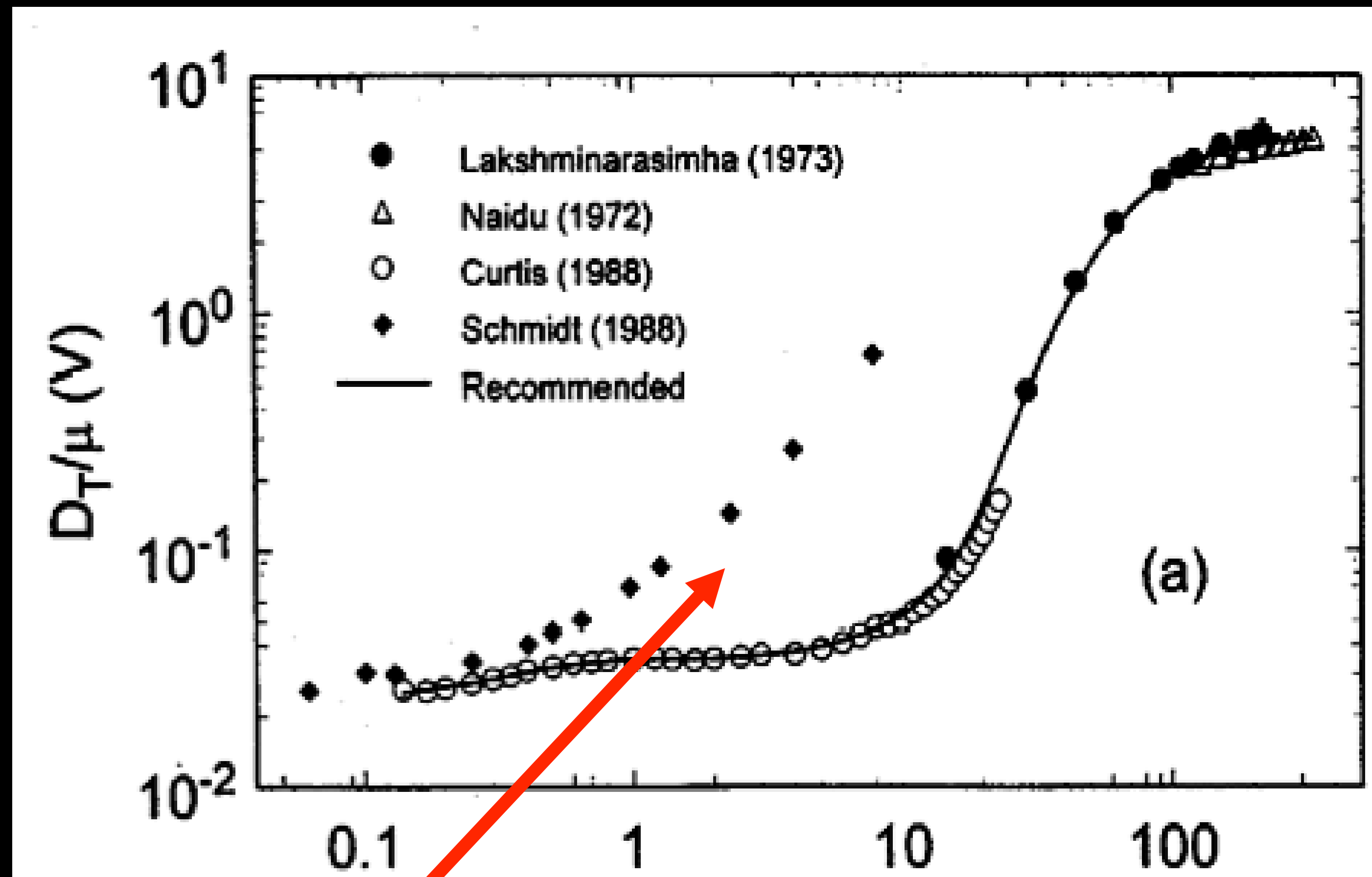
Large impact on spatial resolution:

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



or?





E/N [Td]

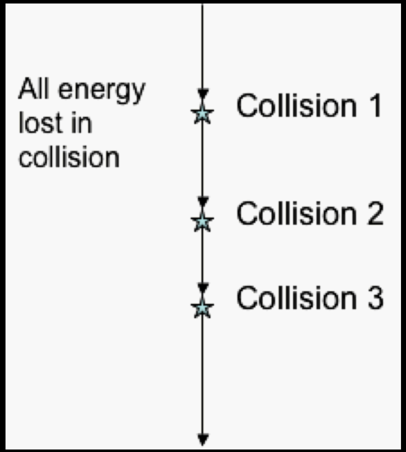
>10x discrepancy in measurements in our range-of-interest

(T. Caldwell thesis)

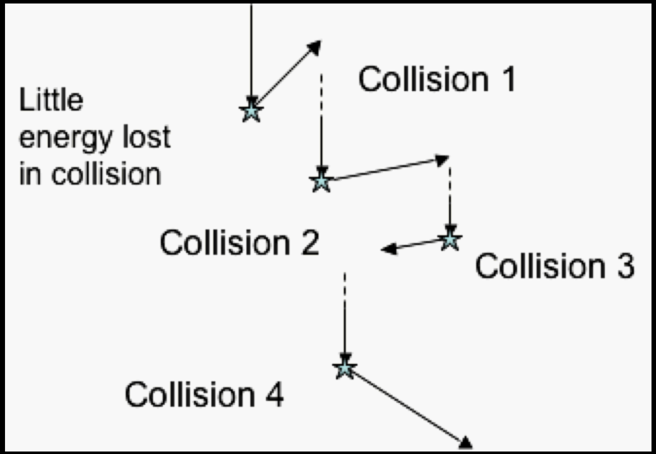
CF_4 Electron Diffusion

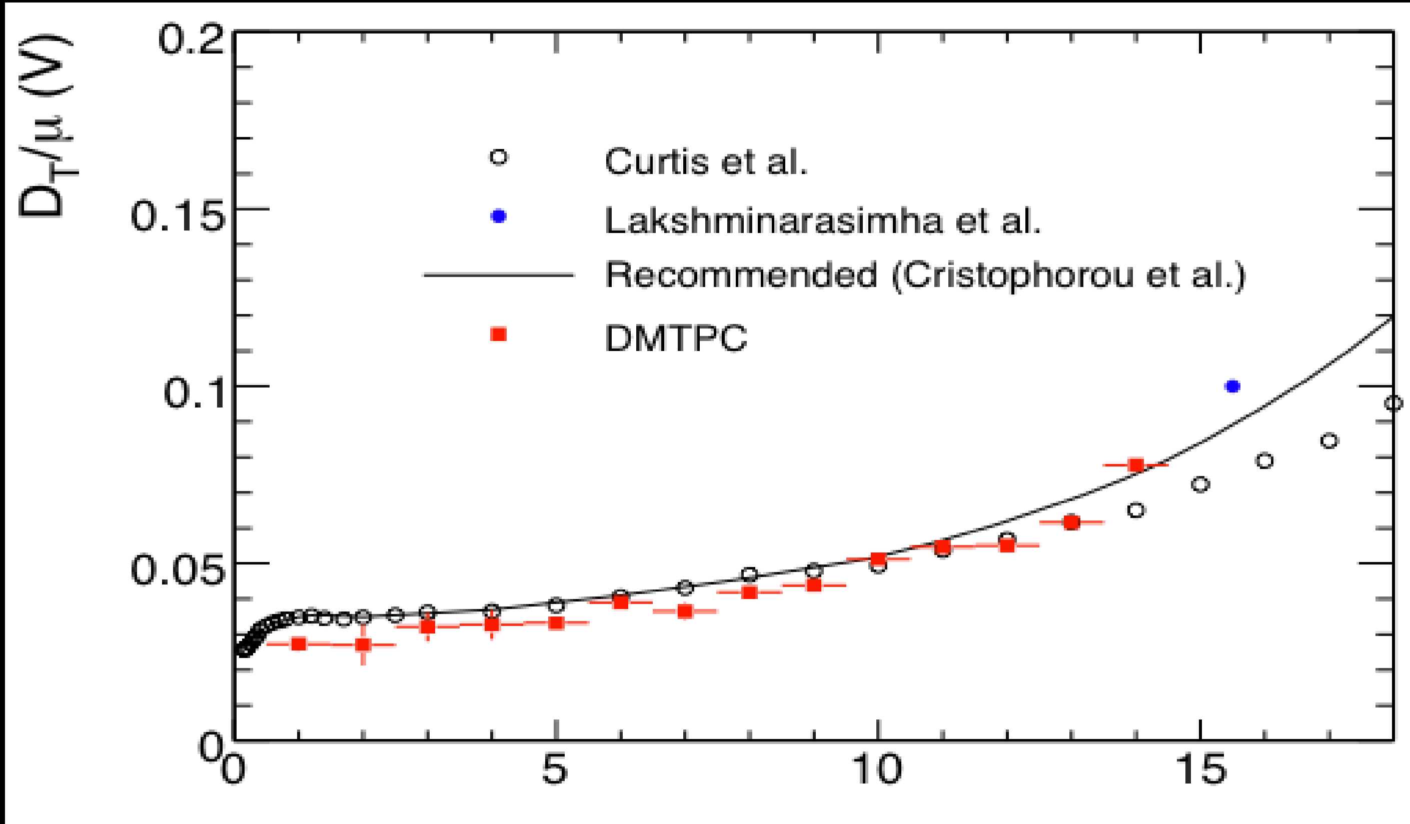
Large impact on spatial resolution:

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



or?





T. Caldwell, et al., arXiv:0905.2549

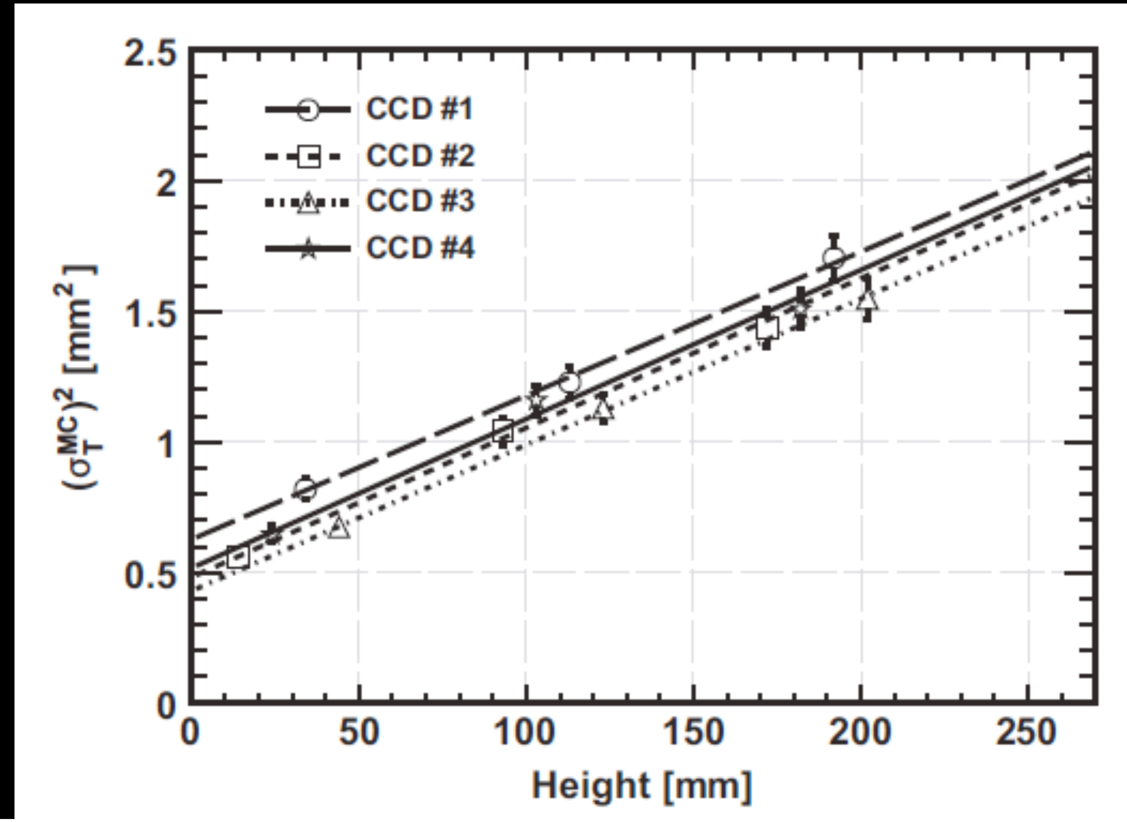
E/N [Td]

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

Diffusion Measurement

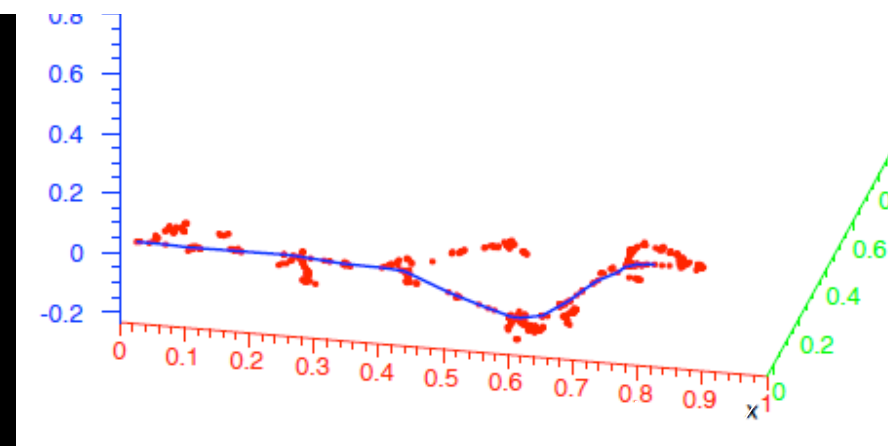
Measure track width from alpha source at known heights in detector,

- 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



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

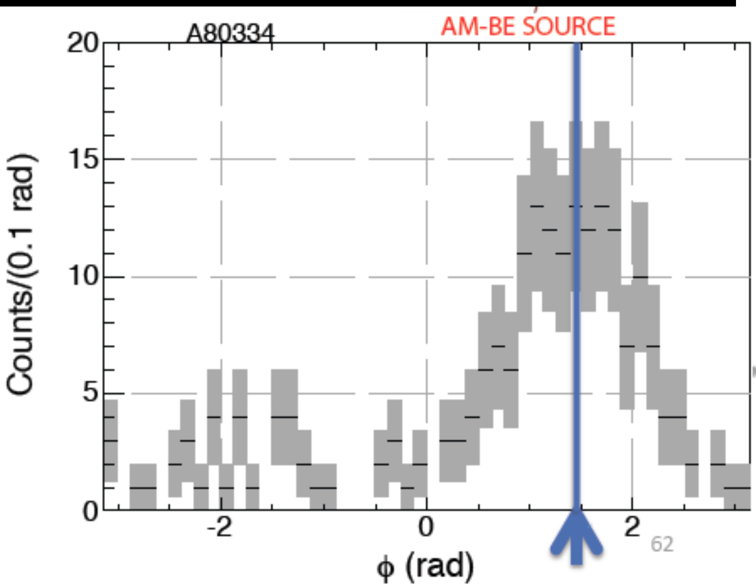
- find constant term dominates until z~20cm, and z=25 cm for σ^2_T<1mm
  J. Battat et al., NIMA 755 (2014)



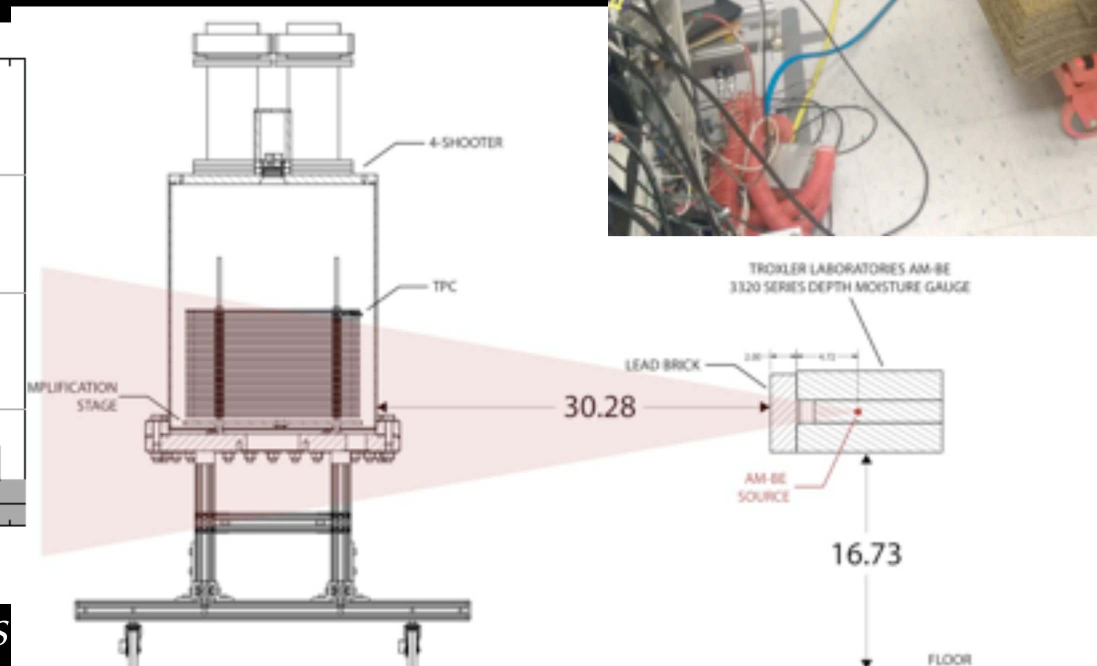
- from simulation, constant term mainly comes from straggling of the primary ion

Direction Calibration

Need a source of known energy and angle



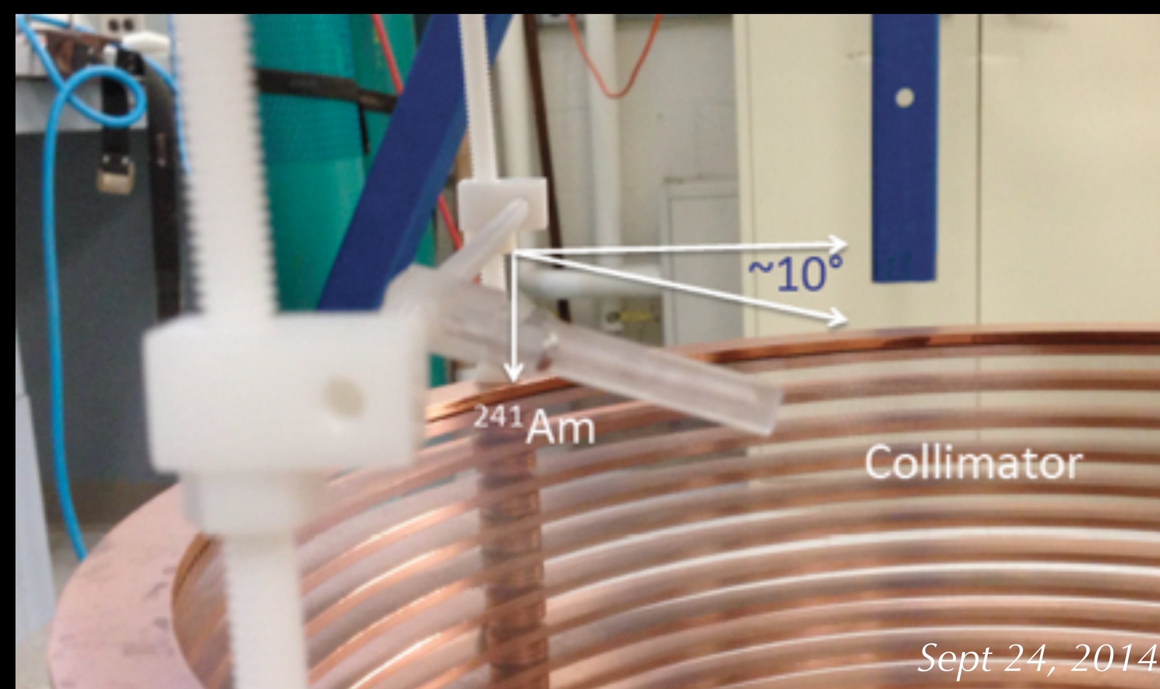
S. Henderson, PhD thesis



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

Angled alpha calibration:

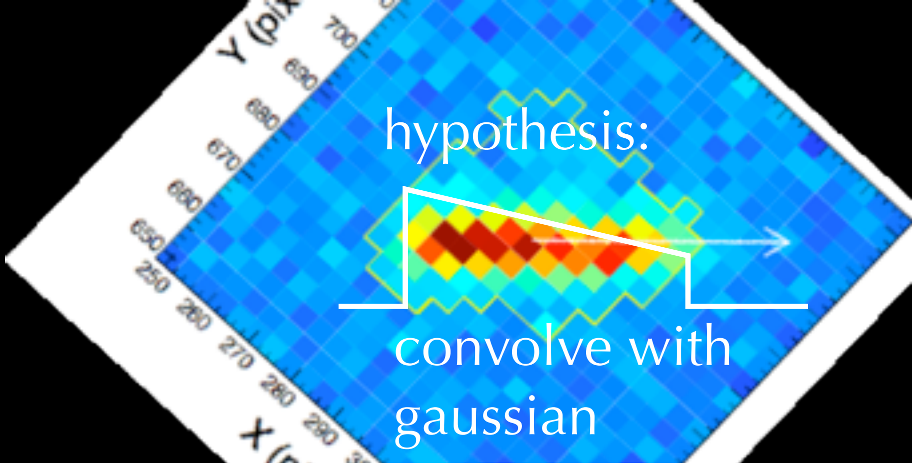
- only track ends in active region, can tune energy ~100 keVee
- tune angle by rotating collimator

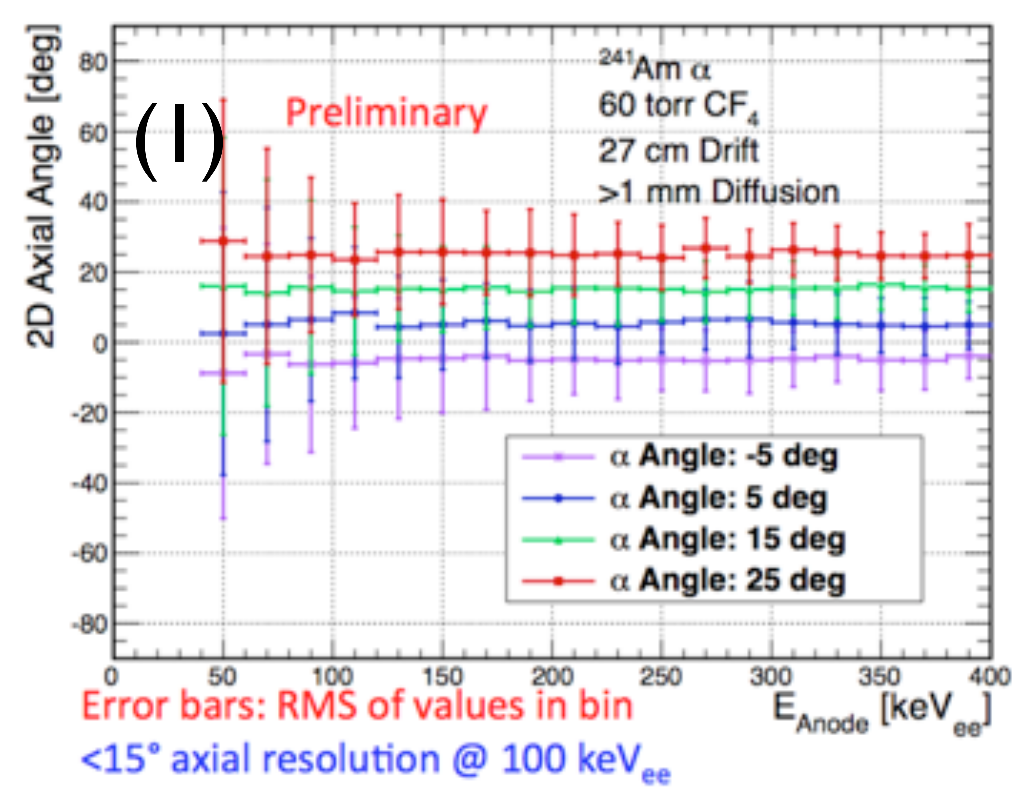


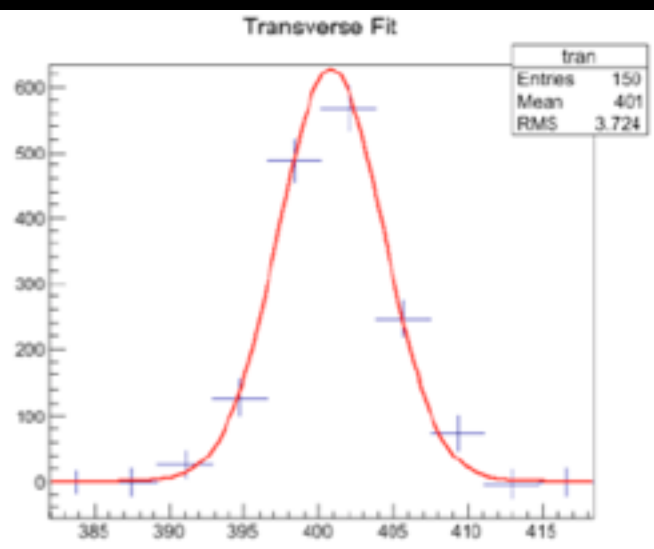
Track Reconstruction

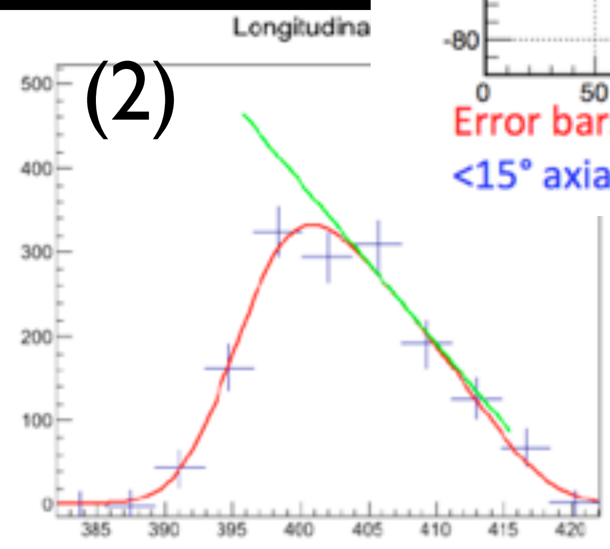
Measure energy from track intensity integral

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







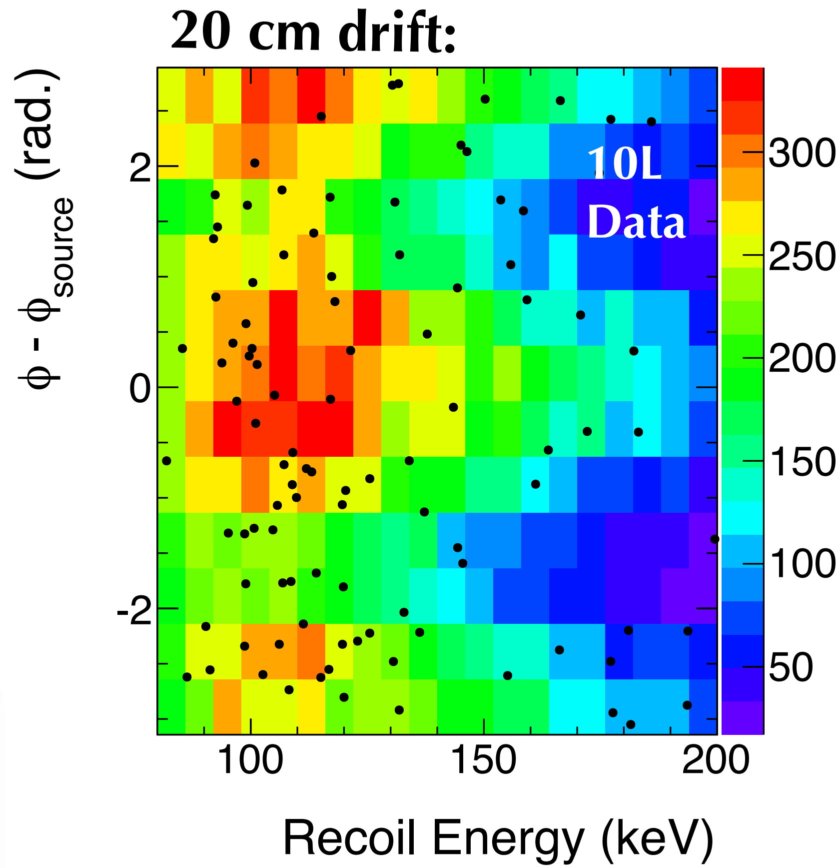


S. Henderson, PhD thesis

Directionality II

diffusion has a big impact!

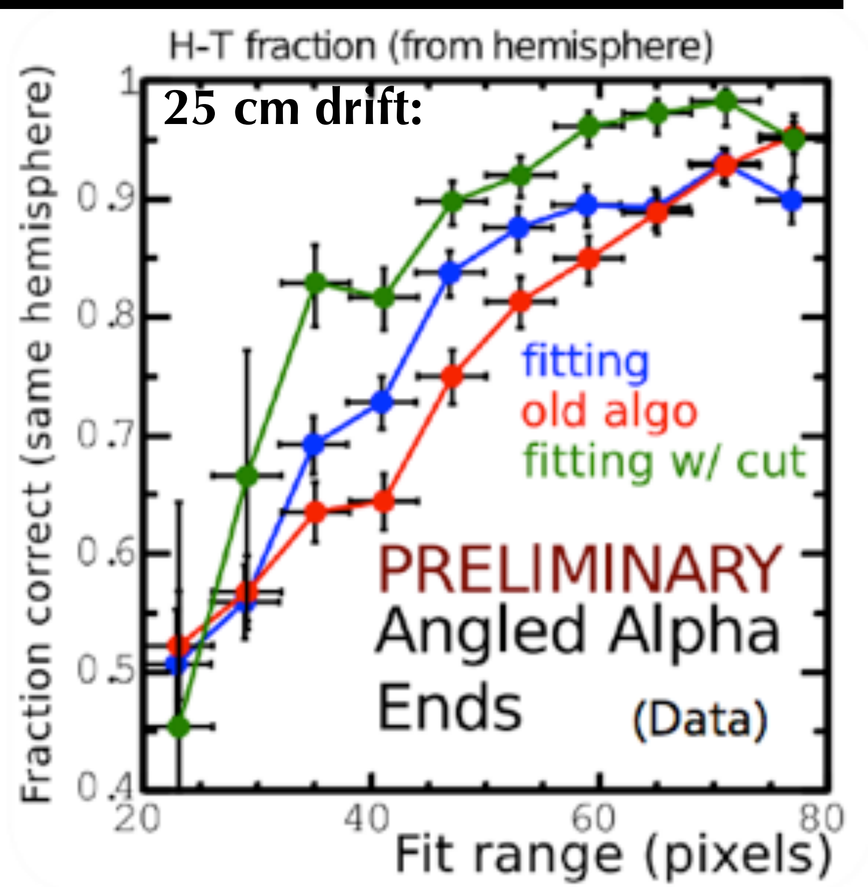
- measure with 20, 25 cm drift
- find direction reconstruction depends most on track length, range/width>3 for head-tail ID,
- lower pressure = lower $E_{threshold}$



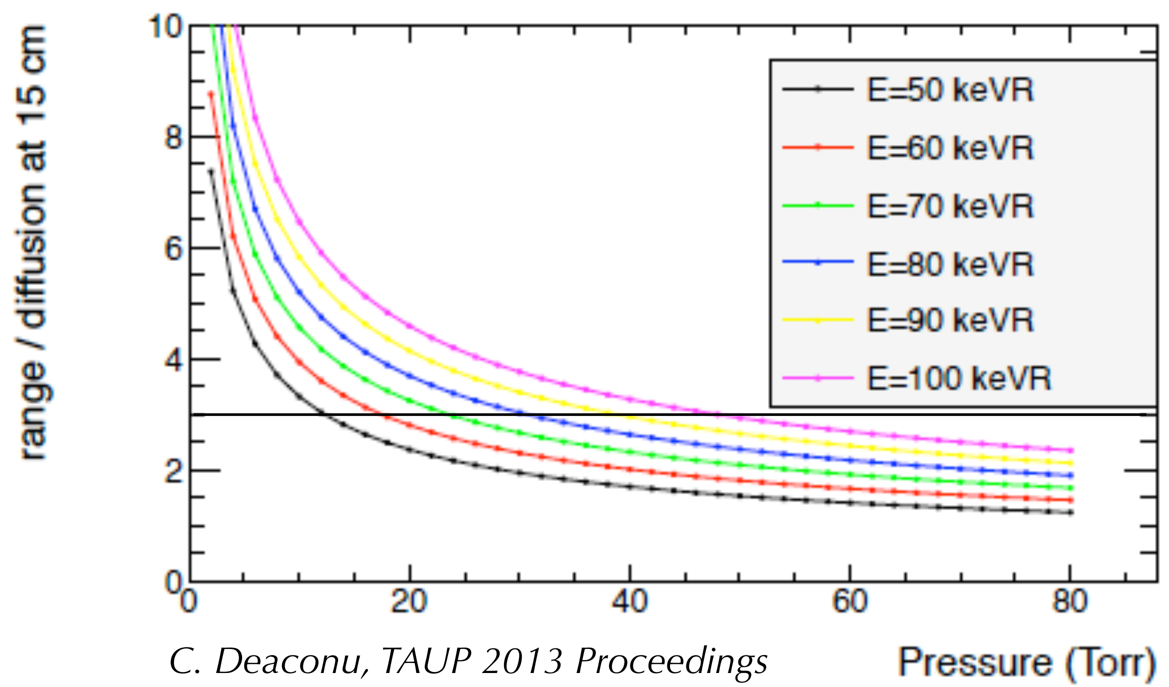
1D "sky map" for ^{252}Cf, and "WIMP " data (80-200 keV)

MC: 40º resolution at 80 keVr

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



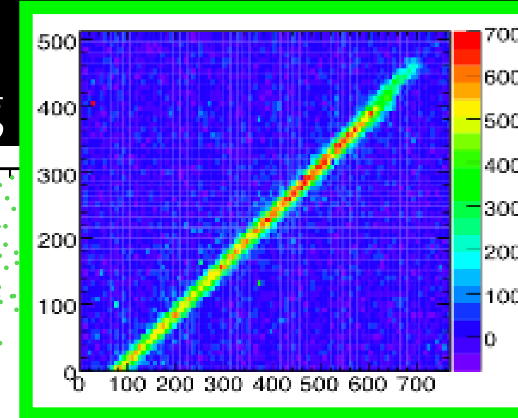
Energy range equivalent ~50-200 keV

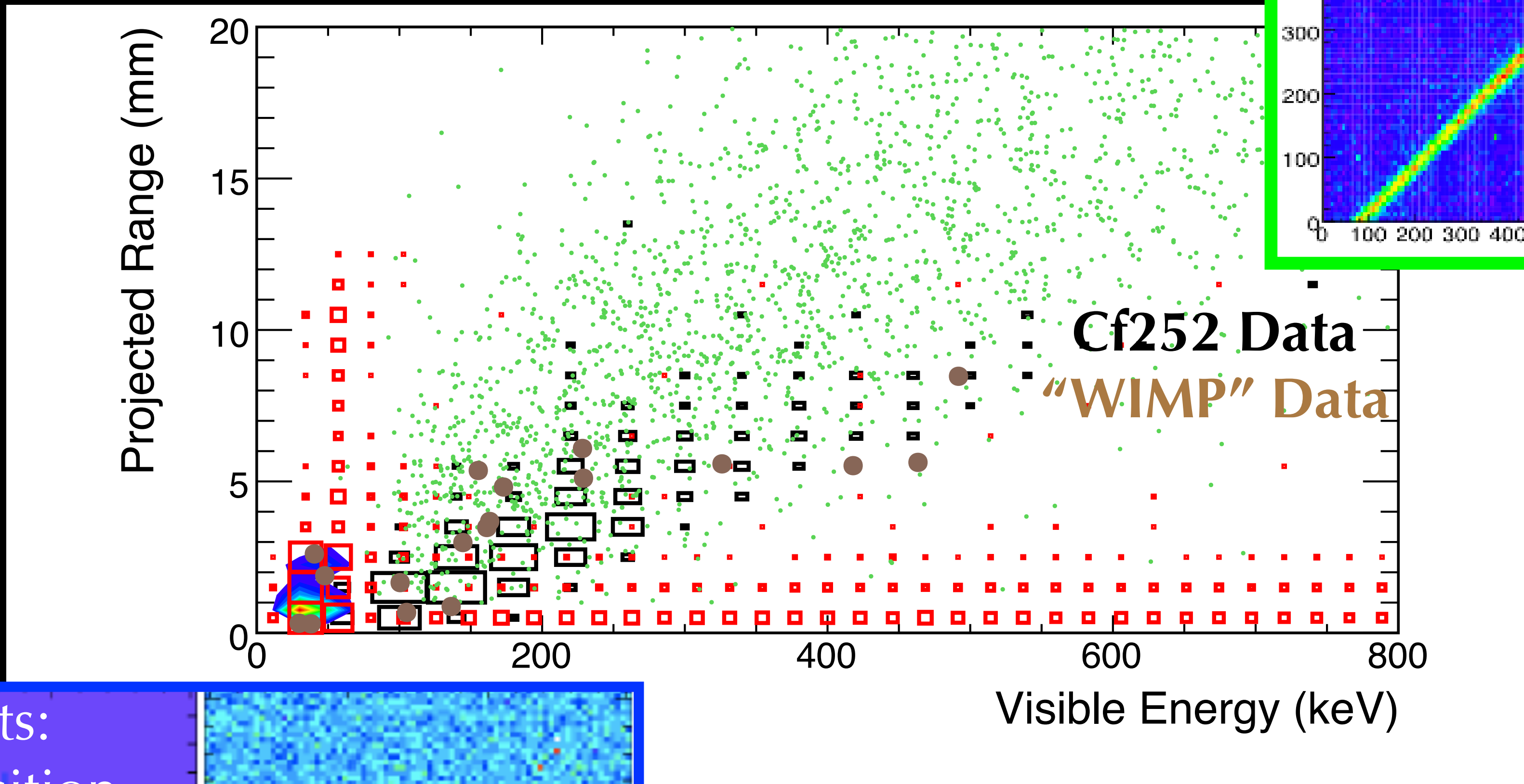


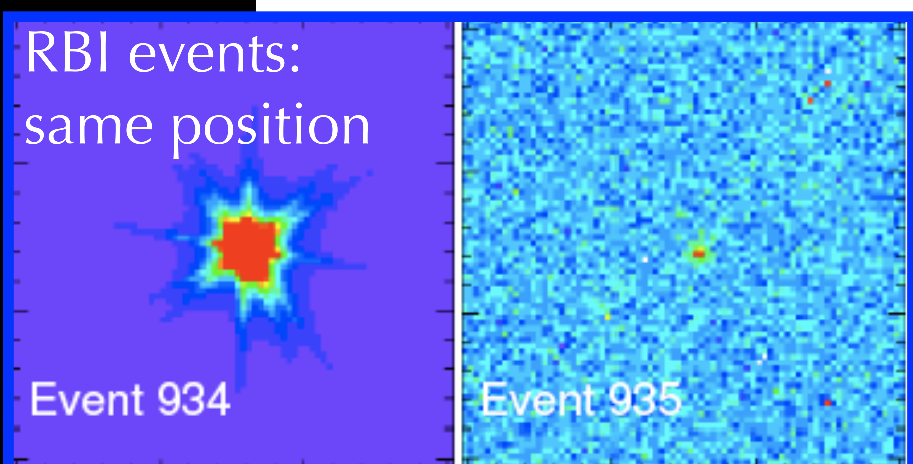
C. Deaconu, TAUP 2013 Proceedings

Background Rejection I

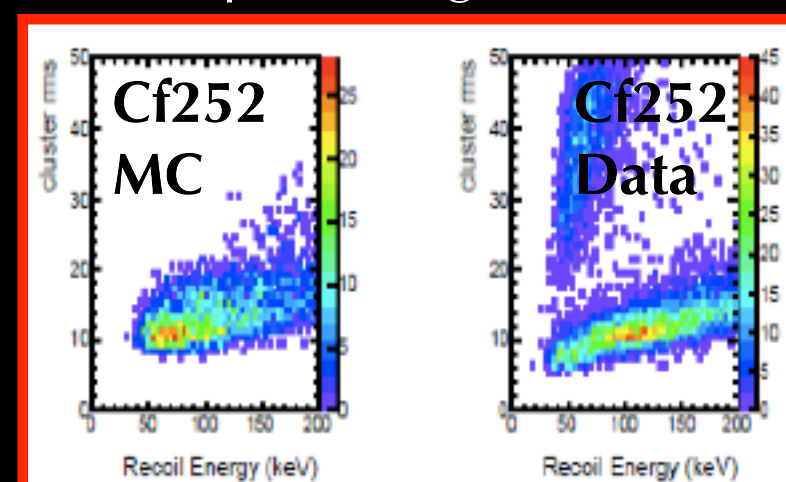
Alphas:
edge crossing







“Worms”: one hot pixel, large cluster rms

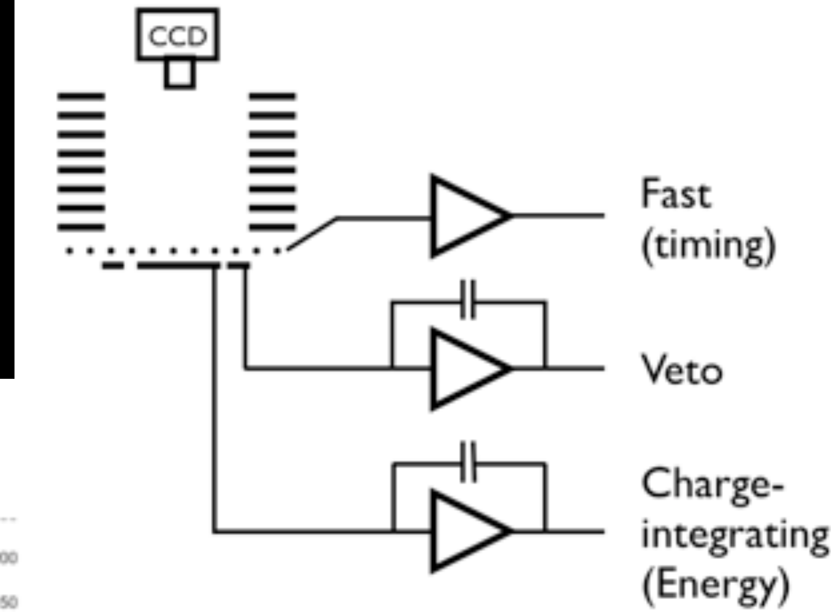


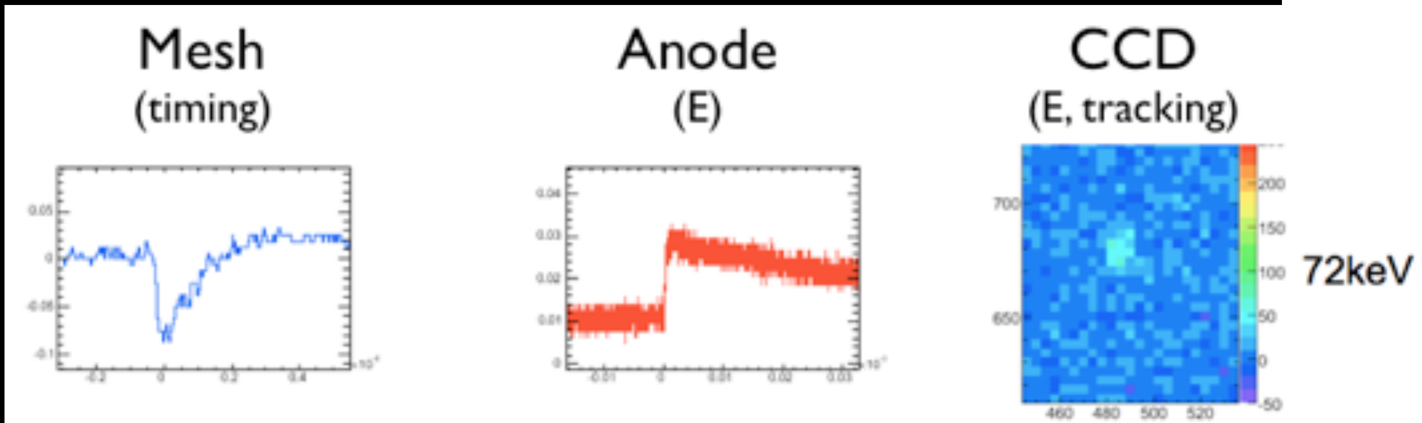
$>10^4$ rejection of backgrounds from R vs. E

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

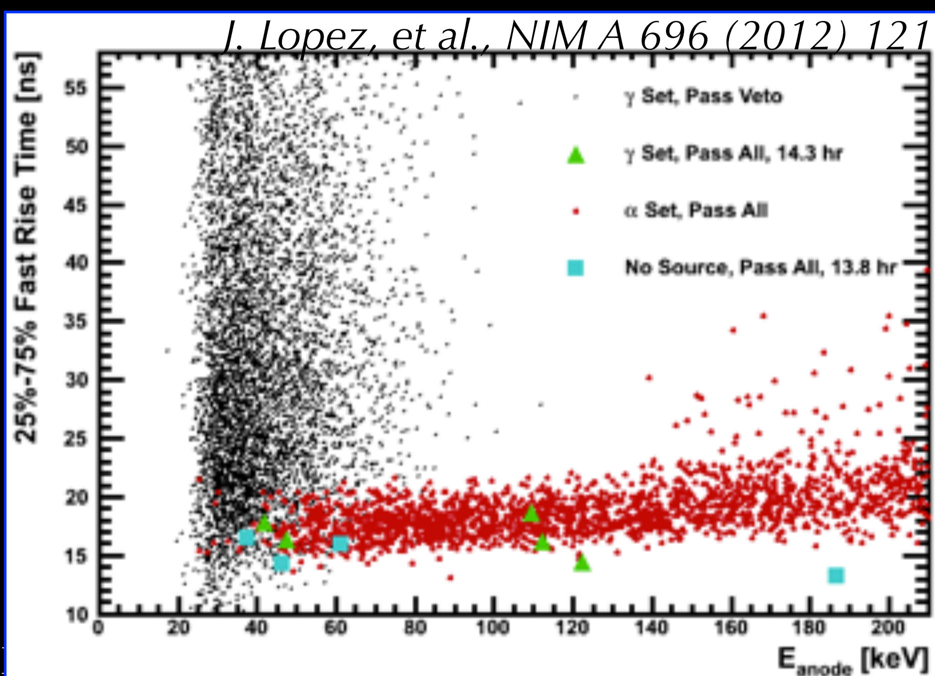
Background Rejection II

requiring coincidence of optical AND charge readout to reject gammas, CCD artifacts

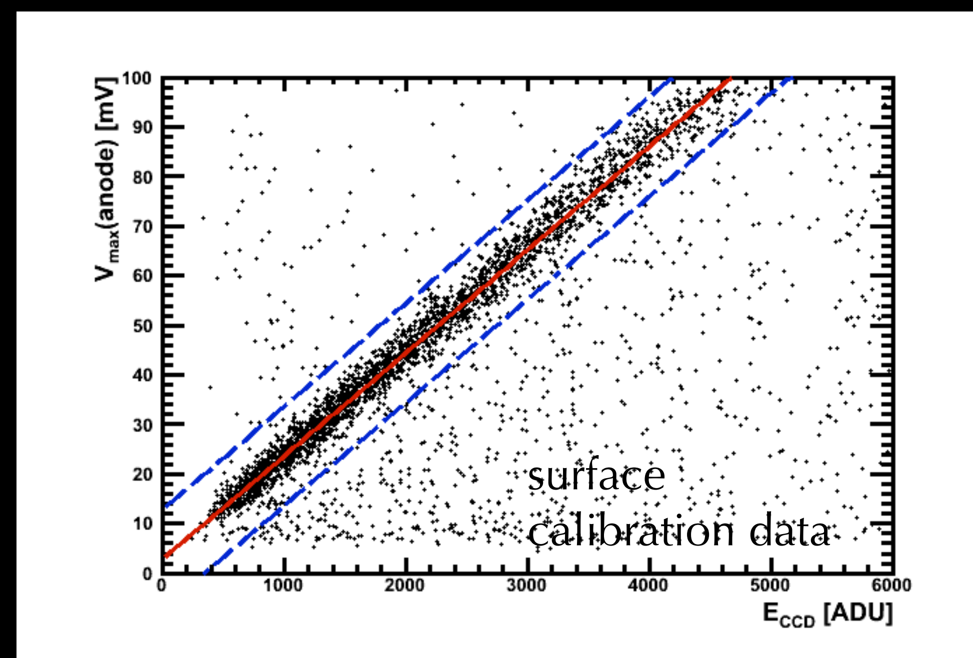




>1.1E-5 (90% CL) γ rejection from rise time vs. E:



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



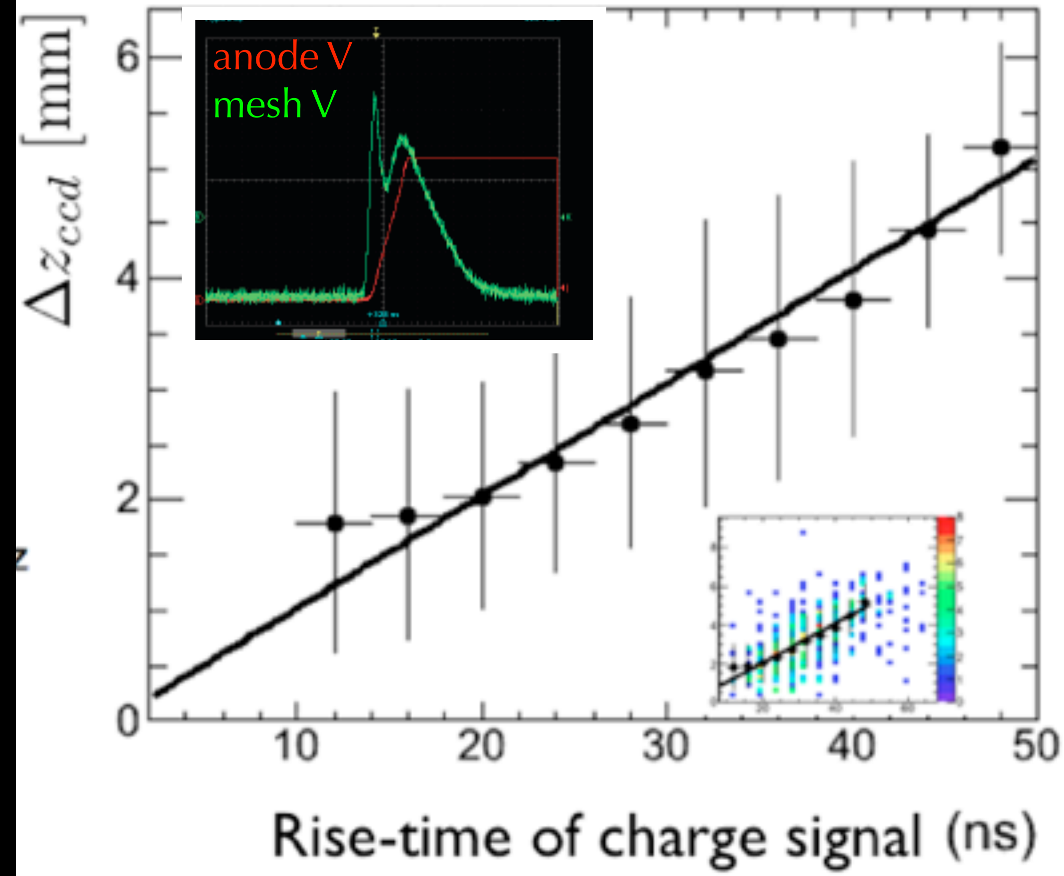
3D R&D

tracking in z (drift direction):

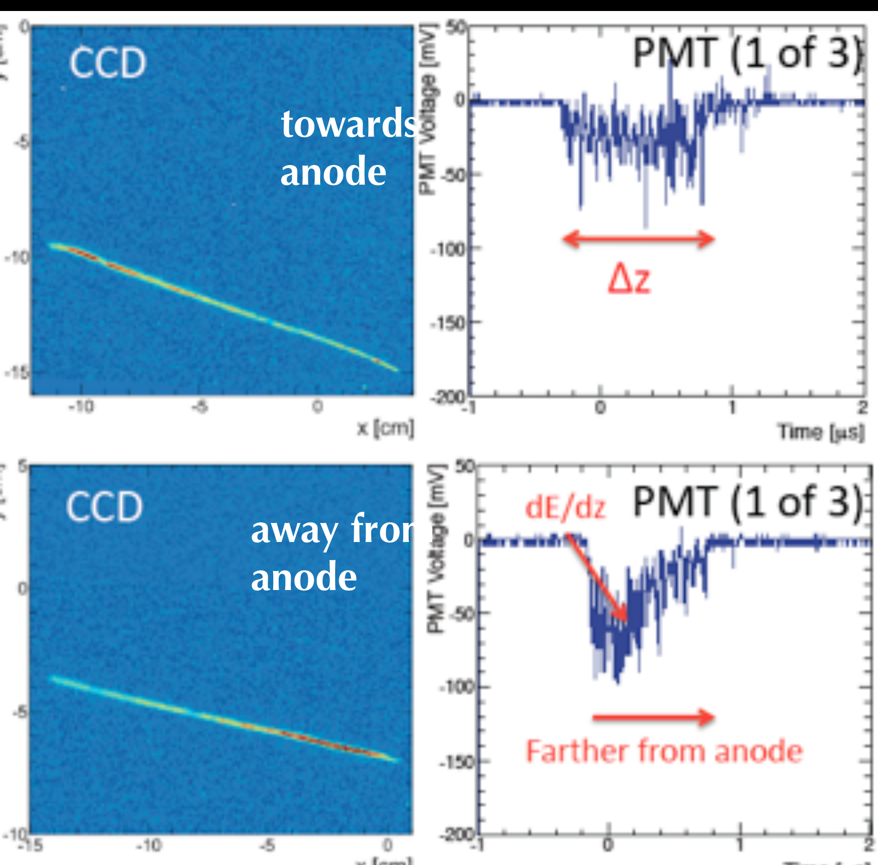
- angled alpha calibration source produces tracks of known Δz

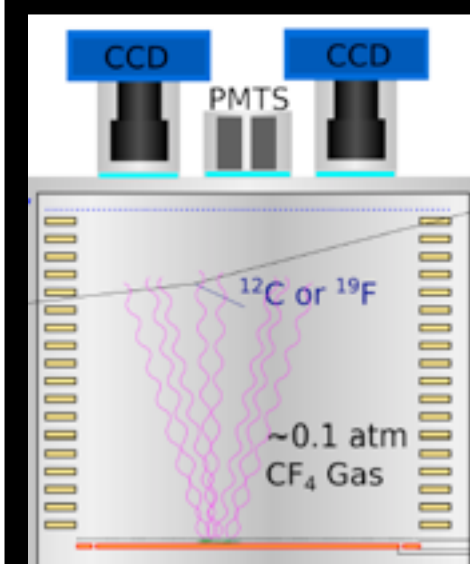
charge:

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



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





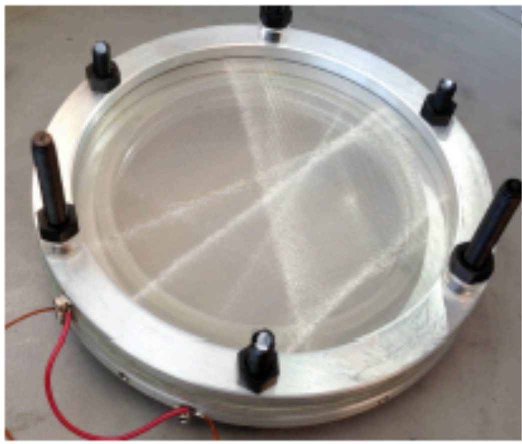
light:

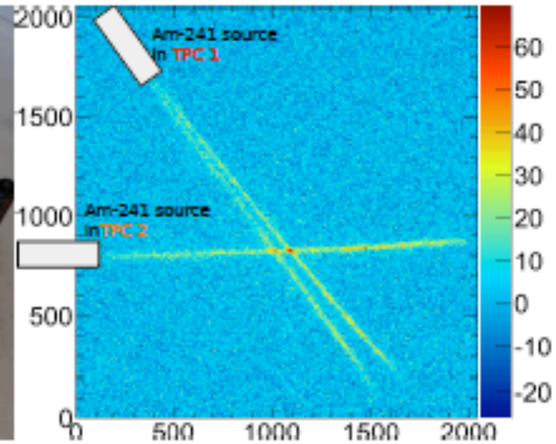
- measure PMT signal pulse width
- pulse width varies with Δz, shape varies with +/-Δz

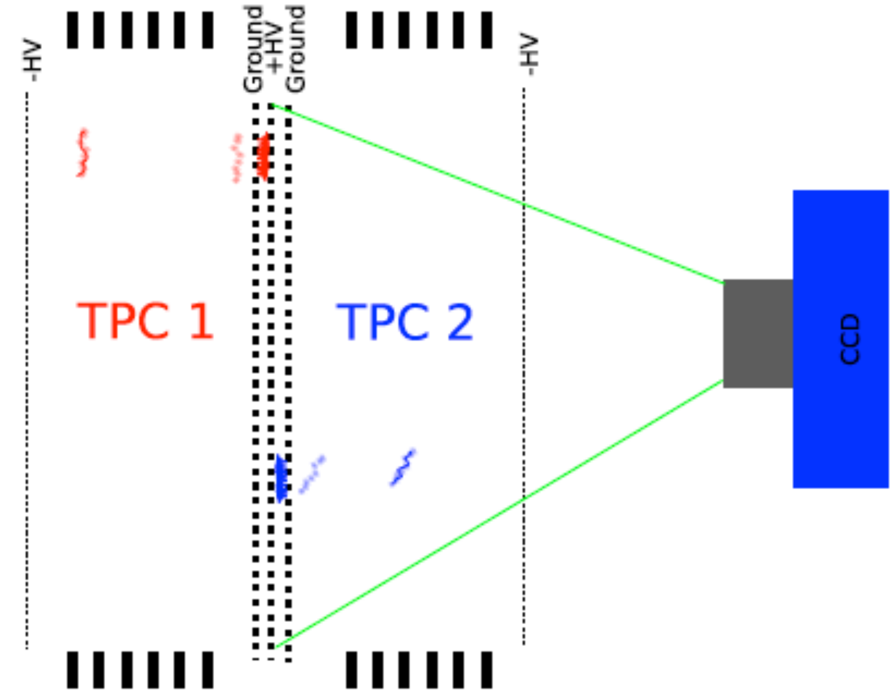
R&D on cathode readout for absolute z measurement

TPC R&D

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

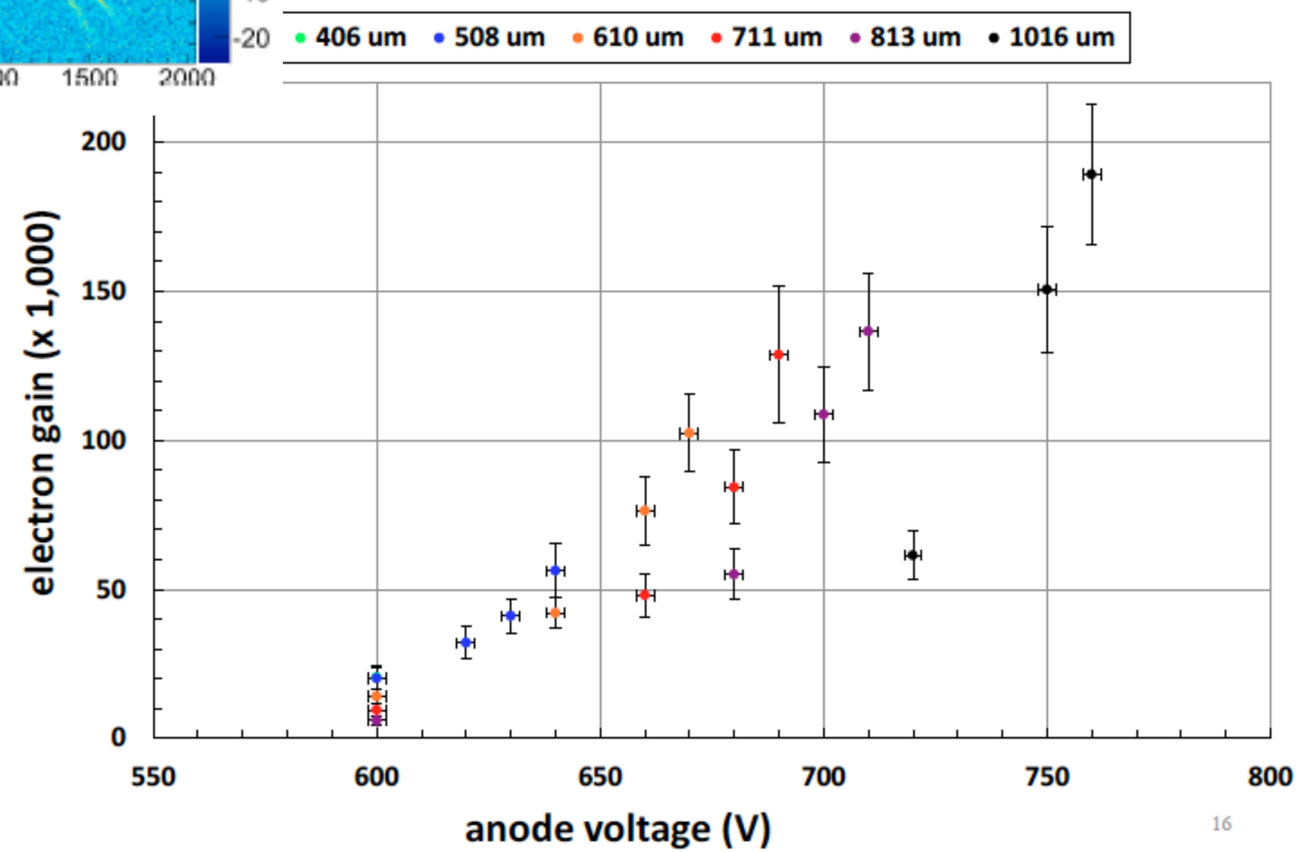






demonstrated high gain in small prototypes, 50-200k

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



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

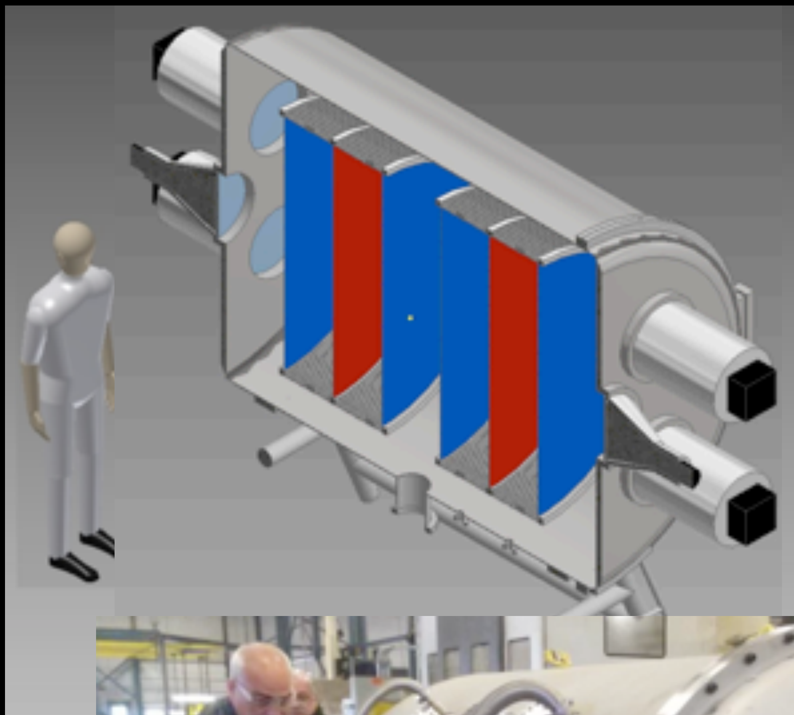
•10x gain with 2x gap size

price: 25% amplification region diffusion tails increase

H. Tomita, PhD thesis

DMTPCino: 1m^3 Detector Module

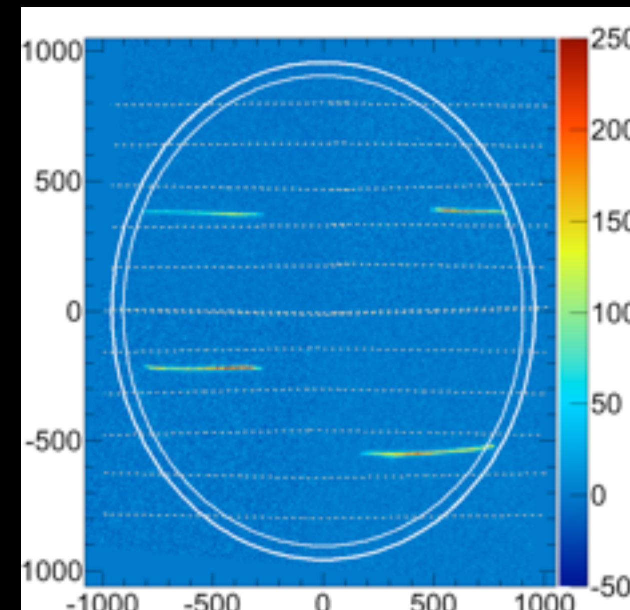
prototype for very large detector: build many 1m^3 modules, because of diffusion limit.



amplification regions

cathode planes

goal: achieve similar S:N per pixel, for 35^o resolution at 50 keVr in 1m^3 module, ideally: 1 camera+lens/side



pixel x

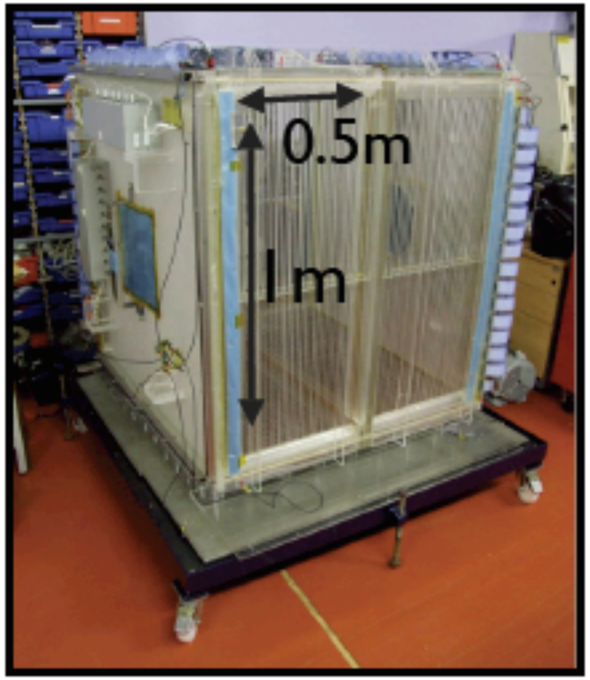
4-shooter 20L prototype has demonstrated
- (i) multi-camera readout
- (ii) low-background materials
- (iii) event discrimination with charge

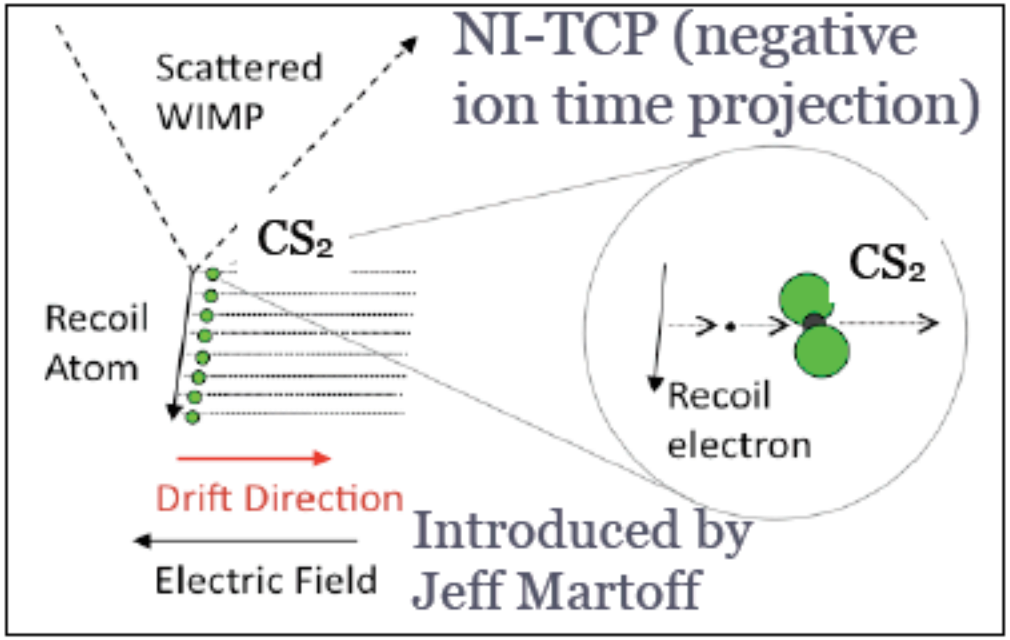
DMTPCino under construction now

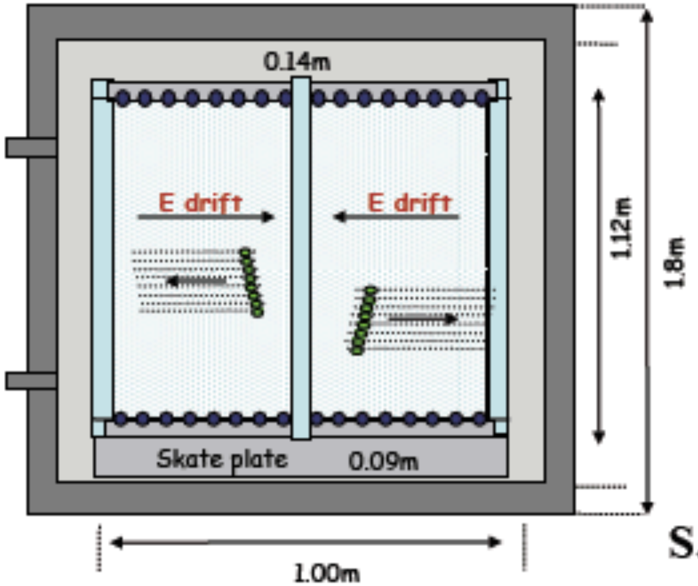
DRIFT Experiment

(Sheffield, Edinburgh, STFC, Occidental, UNM, CSU)

DRIFT II Concept







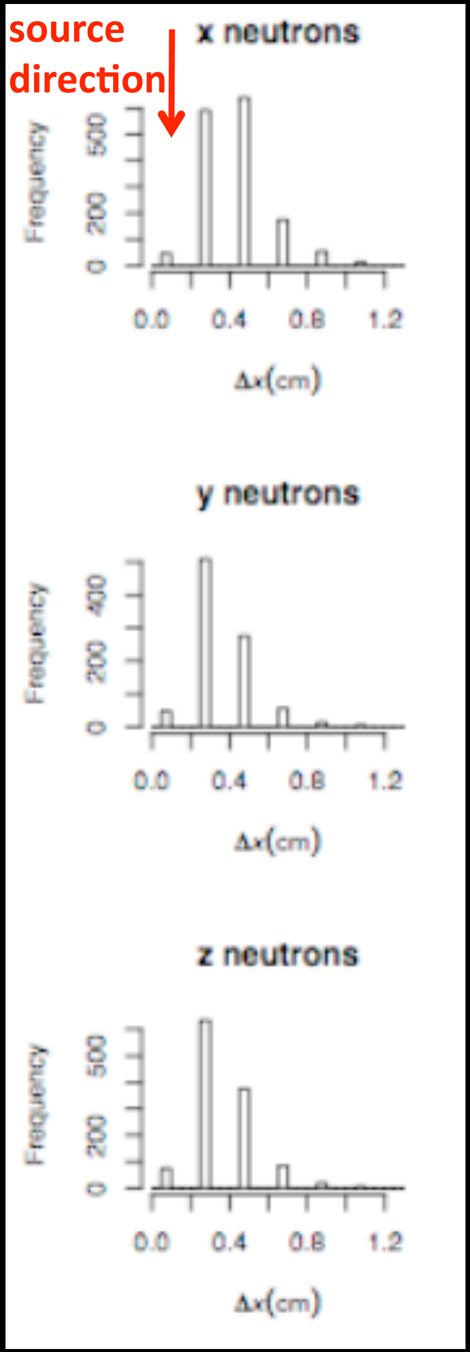
- 1 m³ active volume - back to back MWPCs
- Gas fill 40 Torr CS_2 => 167 g of target gas
- 2 mm pitch anode wires left and right
- Grid wires read out for Δy measurement
- Veto regions around outside
- Central cathode made from 20 μm diameter wires at 2 mm pitch
- Drift field 624 V/cm
- Modular design for modest scale-up

S. Burgos et al., Nucl. Instr. Meth. A 584, 114 (2008)

(N. Spooner, Cygnus'13)

DRIFT Directionality

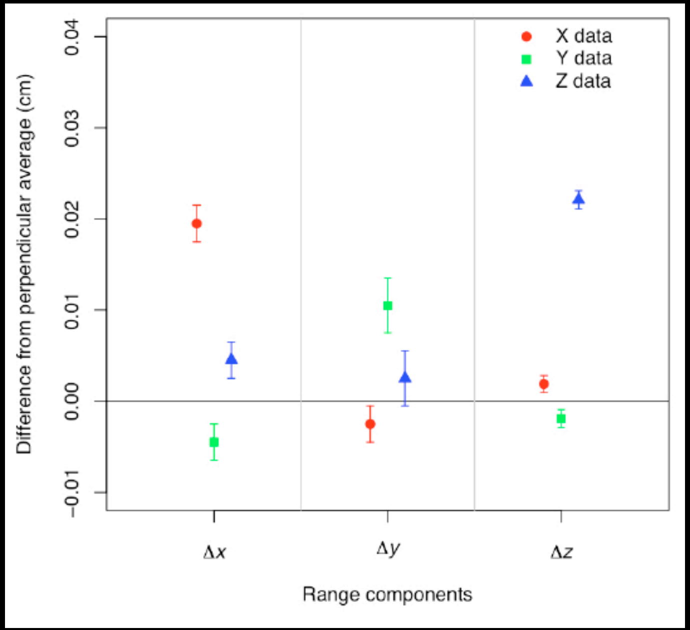
S. Burgos et al., NIMA 600:417-423,2009



direction reconstruction sensitivity measured with Cf-252, oriented along x, y, z axes, compare track lengths Δx, Δy, Δz

measured mean S(C) track lengths of recoils with E > 236 (155) keVr:
- 10-20% increase in mean track length along source direction

simulated angular resolution:
- probability to reconstruct recoil within 30° of true direction is 45-85% above 47 (30) keVr



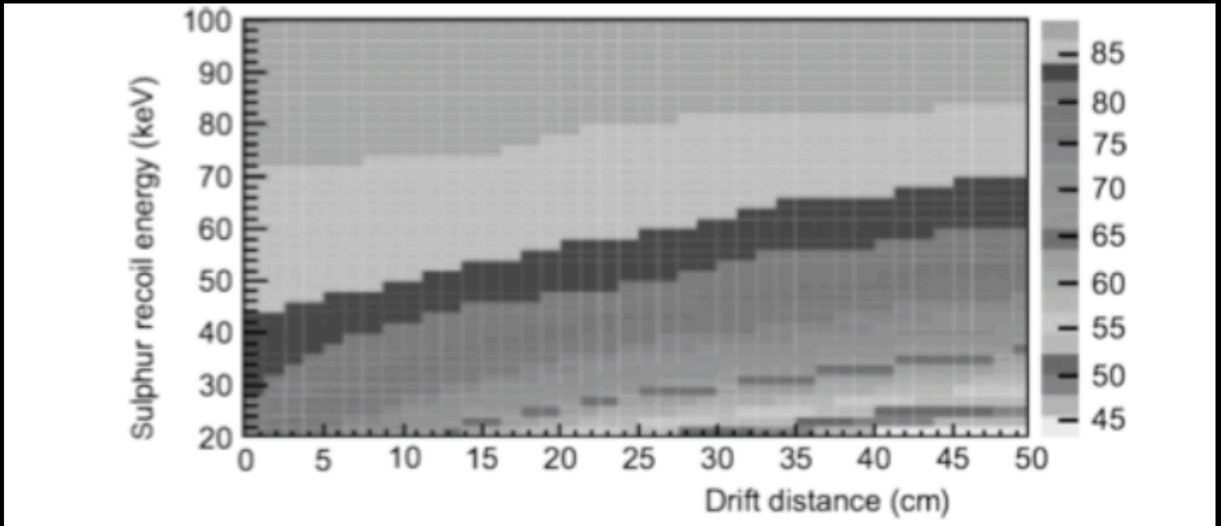
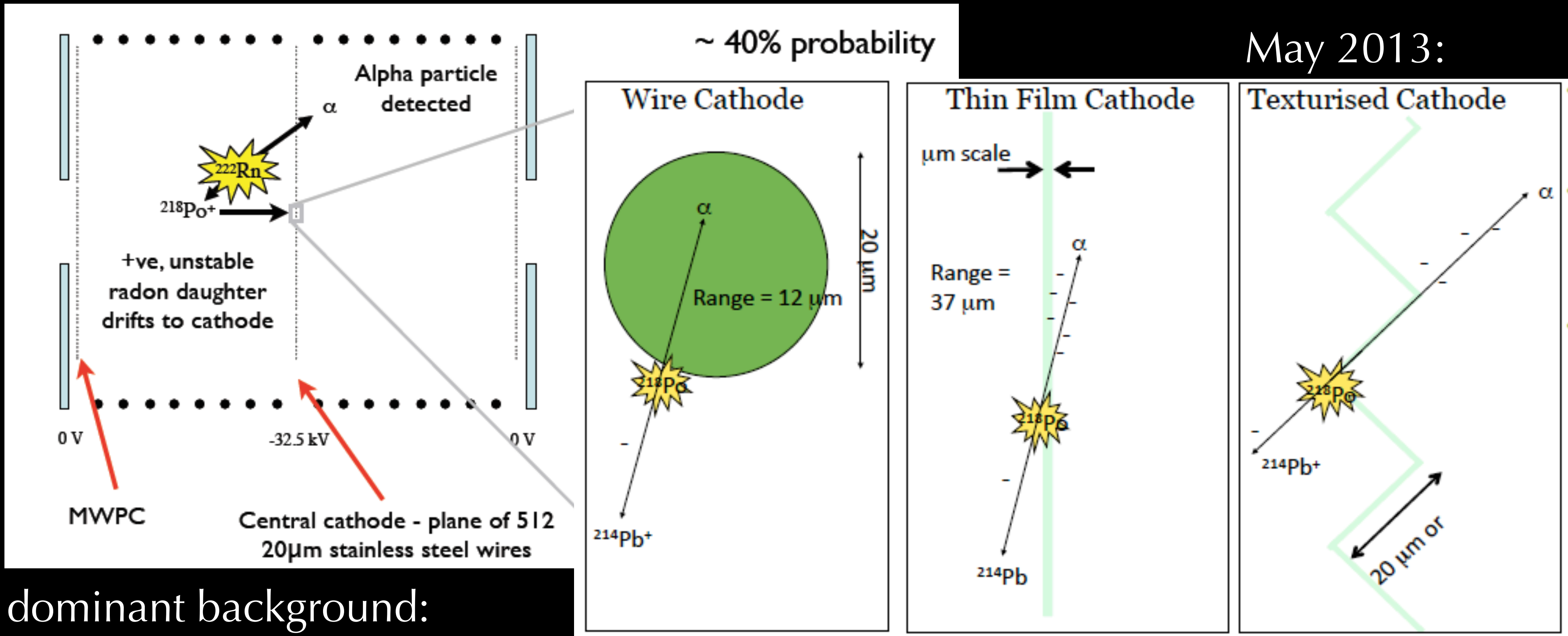


Fig. 10. Simulated angular reconstruction accuracy for DRIFT-II. Shading denotes the probability that the recoil direction is reconstructed within 30 degrees of the known initial direction.

DRIFT R&D: Reducing Backgrounds

(N. Spooner, Cygnus'13)

May 2013:



dominant background:
Radon-progeny recoils, ID with high pulse width from long drift to MWPC plane

Mitigation strategy: 1) reduce probability of missing the alpha

Wire Cathode ⟶ Thin Cathode ⟶ Thin Texturised Cathode

~500 RPRs/day | ~100 RPRs/day nitric etch | ~2 RPRs/day | ~0.01? RPRs/day

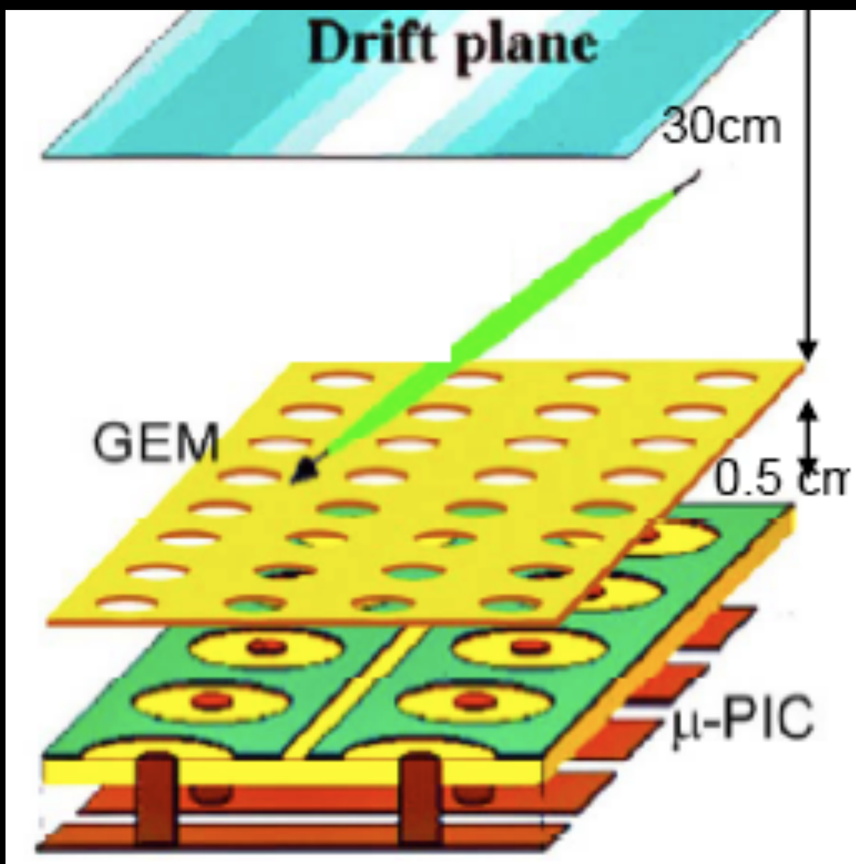
2) fiducialize: cut tracks originating from cathode, using minority carrier velocity difference.

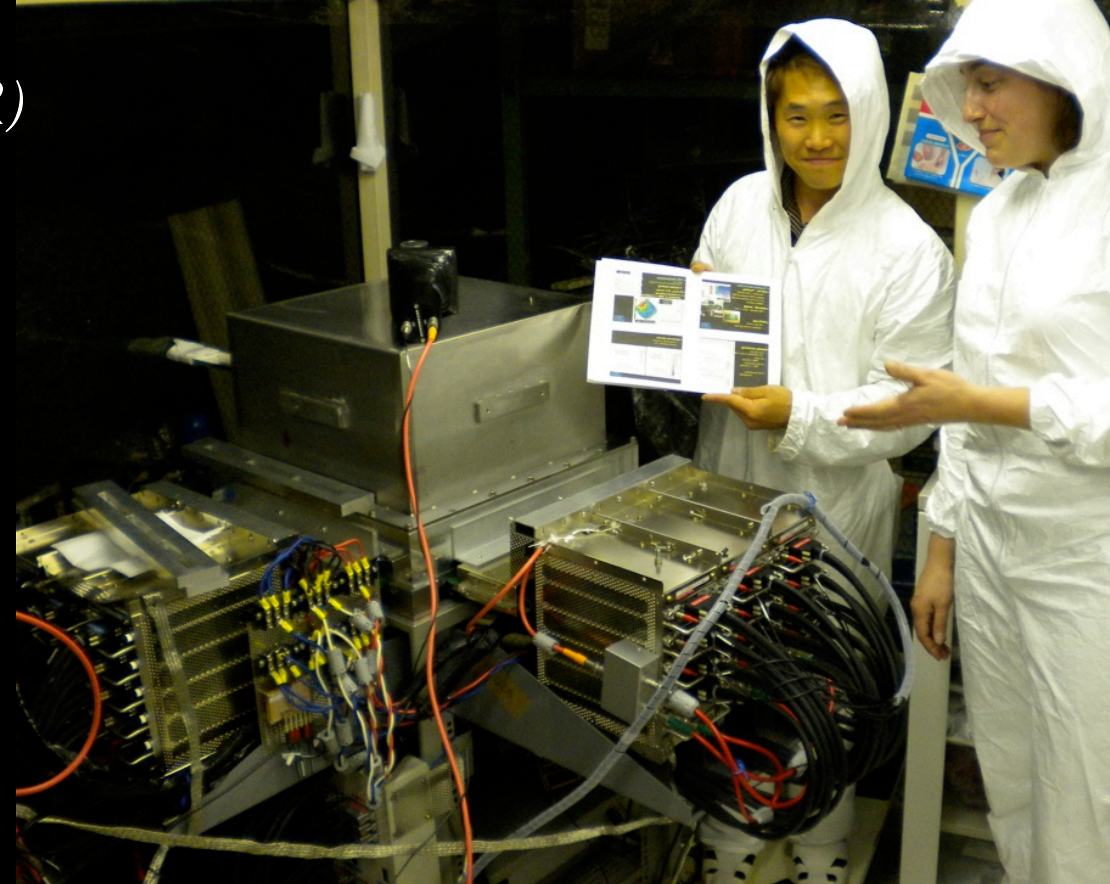
Projection: increase WIMP fiducial volume from 5 to 90% of detector volume.

NEWAGE *(Kobe, Kyoto, ICRR)*

CF_4 gas-filled TPC with e^- drift, GEM amplification

operating in Kamioka (Japan)





μ−pattern gas detector ($23x28x31cm^3$),
768 anode + 768 cathode channels,
analog sum for energy measurement
400 um "pixels", 100 MHz sampling
fiducial mass: 152 torr CF_4 = 11.5 gm

K. Miuchi et al., PLB 578 (204) 241

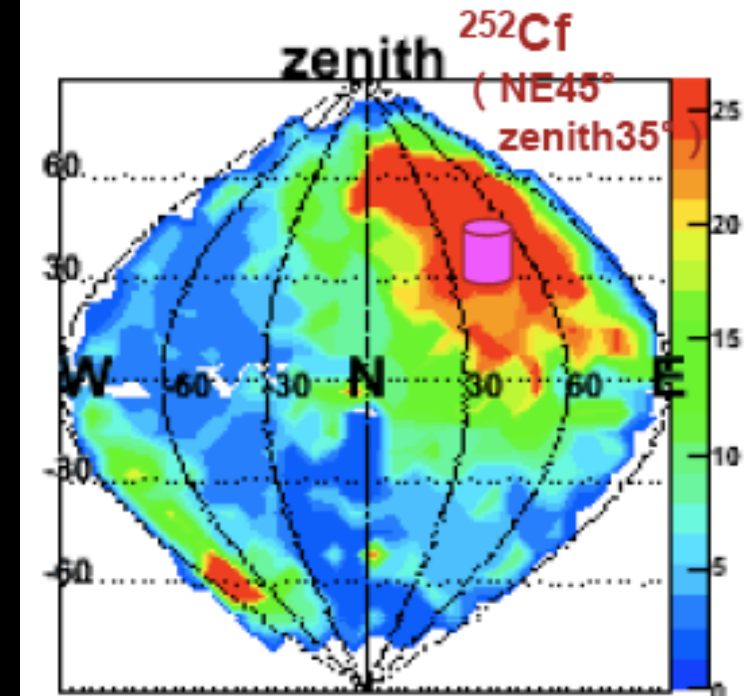
NEWAGE

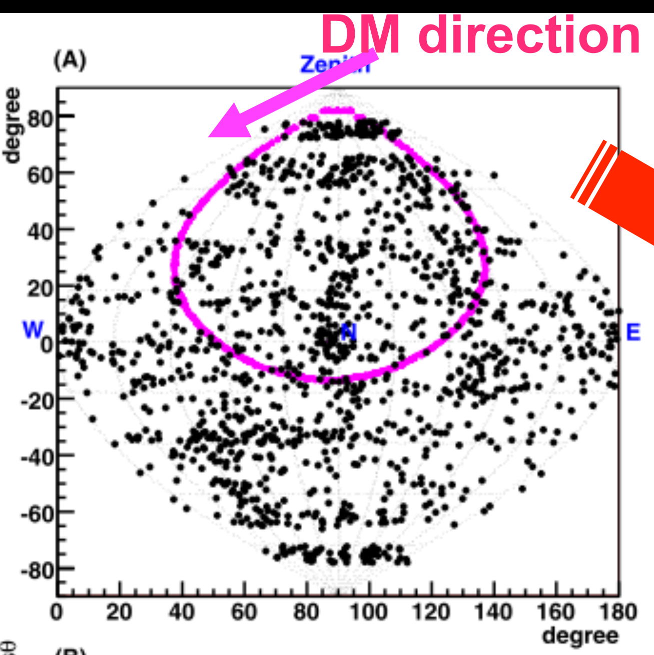
axial 3D track reconstruction with ^{252}Cf source
QPIX upgrade planned for head-tail

e- rejection: < 1E-5 *K. Miuchi et al, PLB654 (2007) 58*

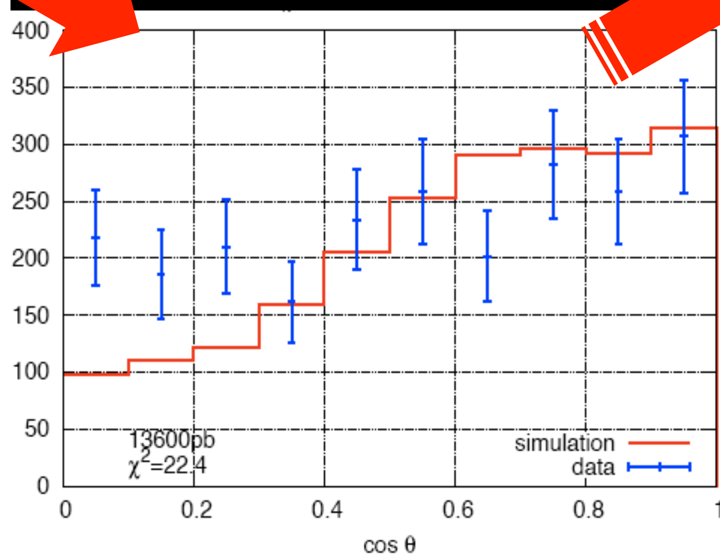
first directional limit! *K. Miuchi et al, PLB686 (2010) 11*

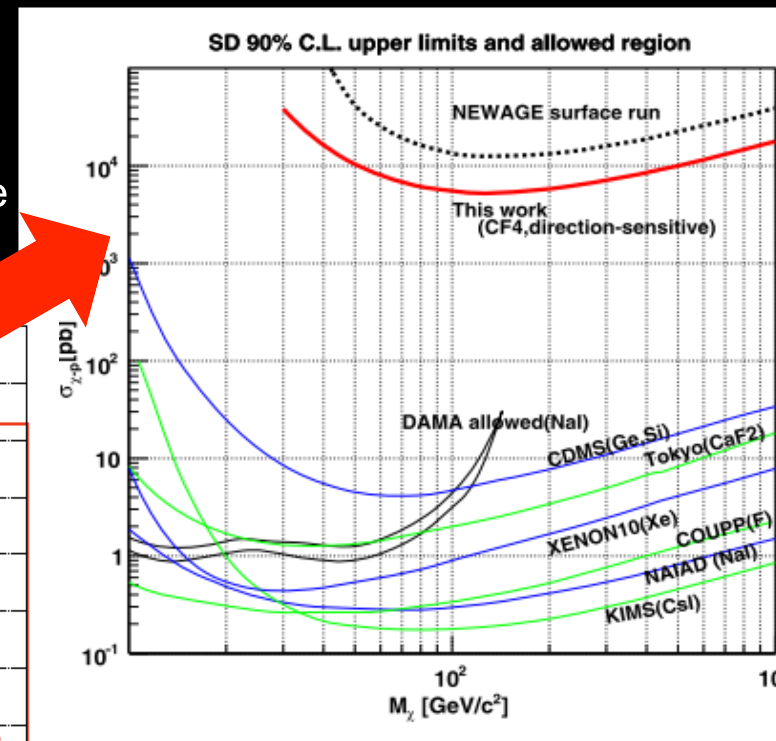
- $\Delta\chi^2$ between WIMP and null hypothesis in cos(θ), observe 1244 events, consistent with background
- at 100 keVee threshold ~50 events/keV/kg/day





North sky in C and F nuclei
(100-400keVee)
55° angular resolution at 100 keVee
0.524 kg-day exposure





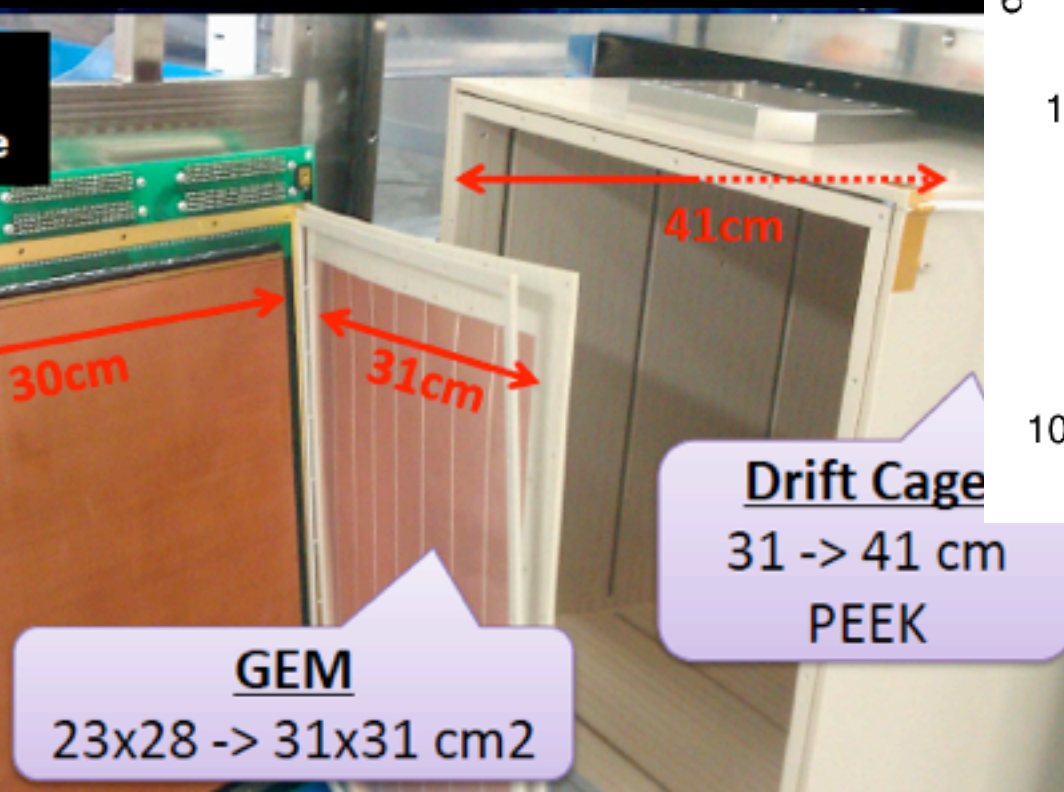
NEWAGE

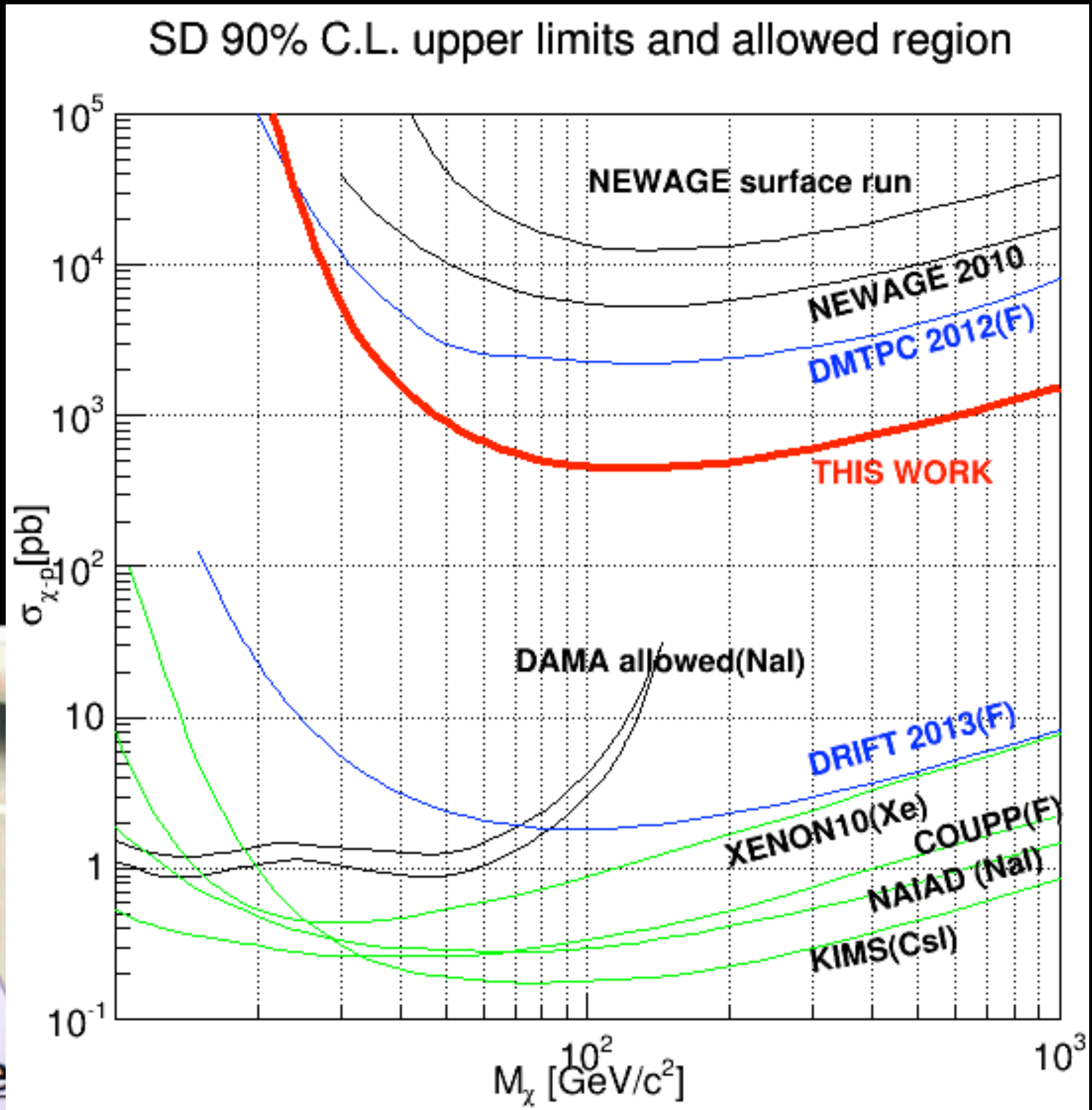
(T. Nakamura, Cygnus'13)

Recent progress in R&D:
$E_{threshold}$:100 -> 50 keVee

Rn background reduction by 10x
Gas system with cooled charcoal

measured angular resolution:
40º (50-100 keVee)
K. Miuchi et al., JINST 7 C02023

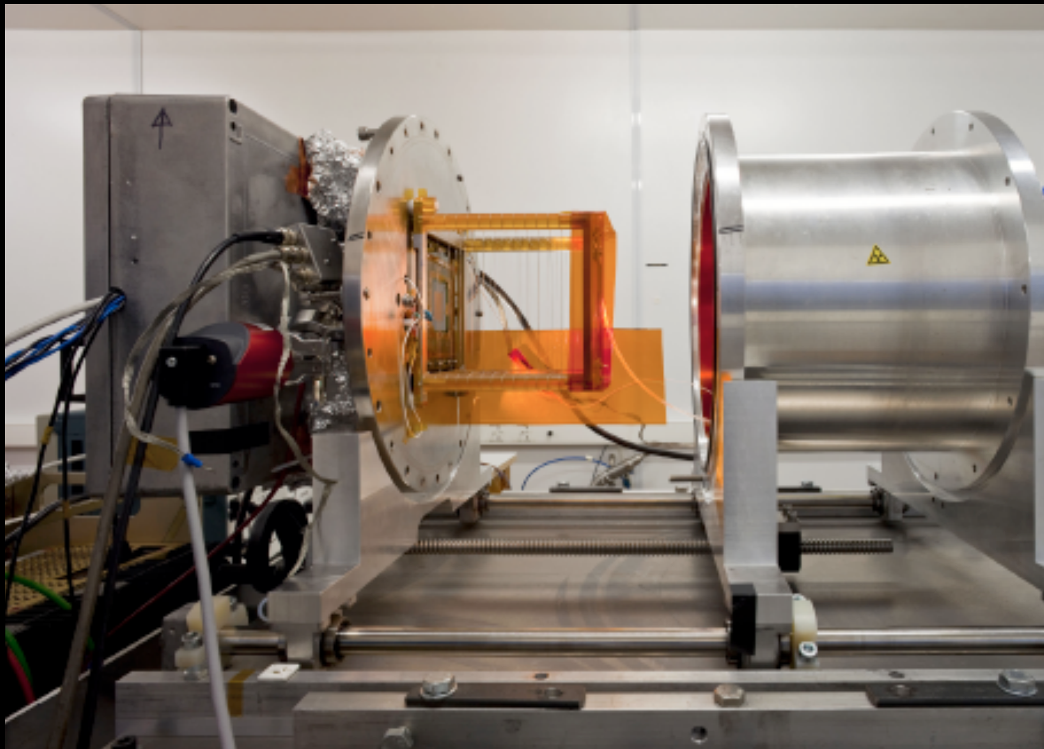




deploying new detector with 2x volume, radiopure materials

MiMAC Experiment

(LPSC-Grenoble, CEA-Saclay, IRSN, CCPM)

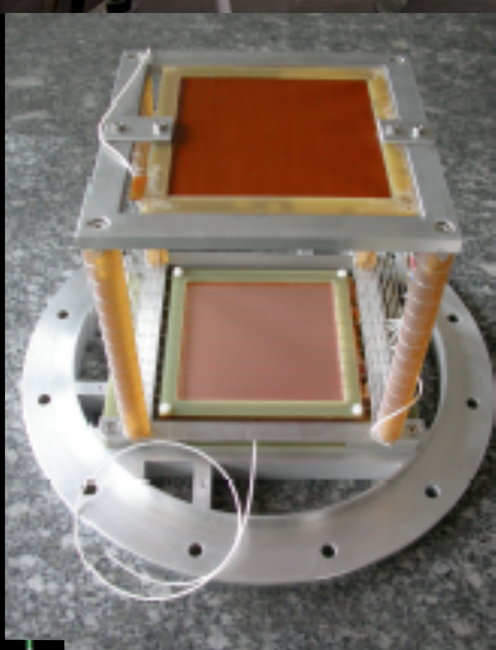


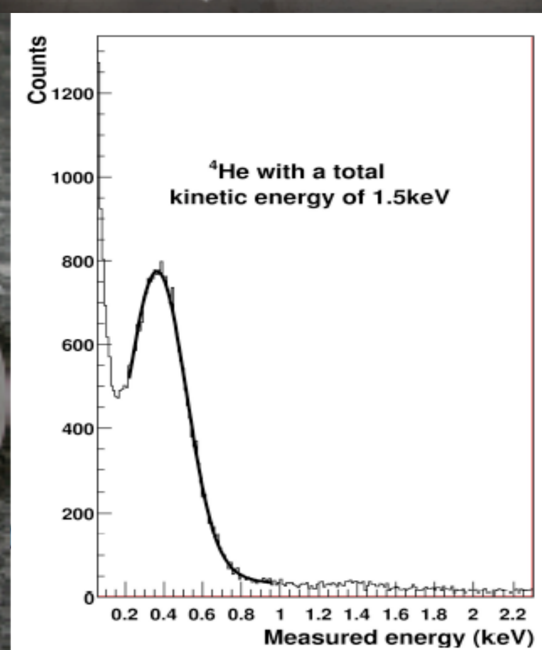
Detector design:
- micromegas TPC, 400 um pixels
- read out Q/pixel at 50 MHz
- analog sum energy measurement

Physics goals:
- 3D tracking with head-tail
- spin-dependent dark matter
  search with multiple targets,
  in a matrix of chambers
  (CF_4, ^3He, ^1H)
- very low energy threshold (~keV),
  operate at low pressure

Prototype calibrated at Cadarache
- 10 cm x 10 cm x 18 cm
- fiducial mass: 5 gm

AIP Conf.Proc. 1412 (2011) 192-199

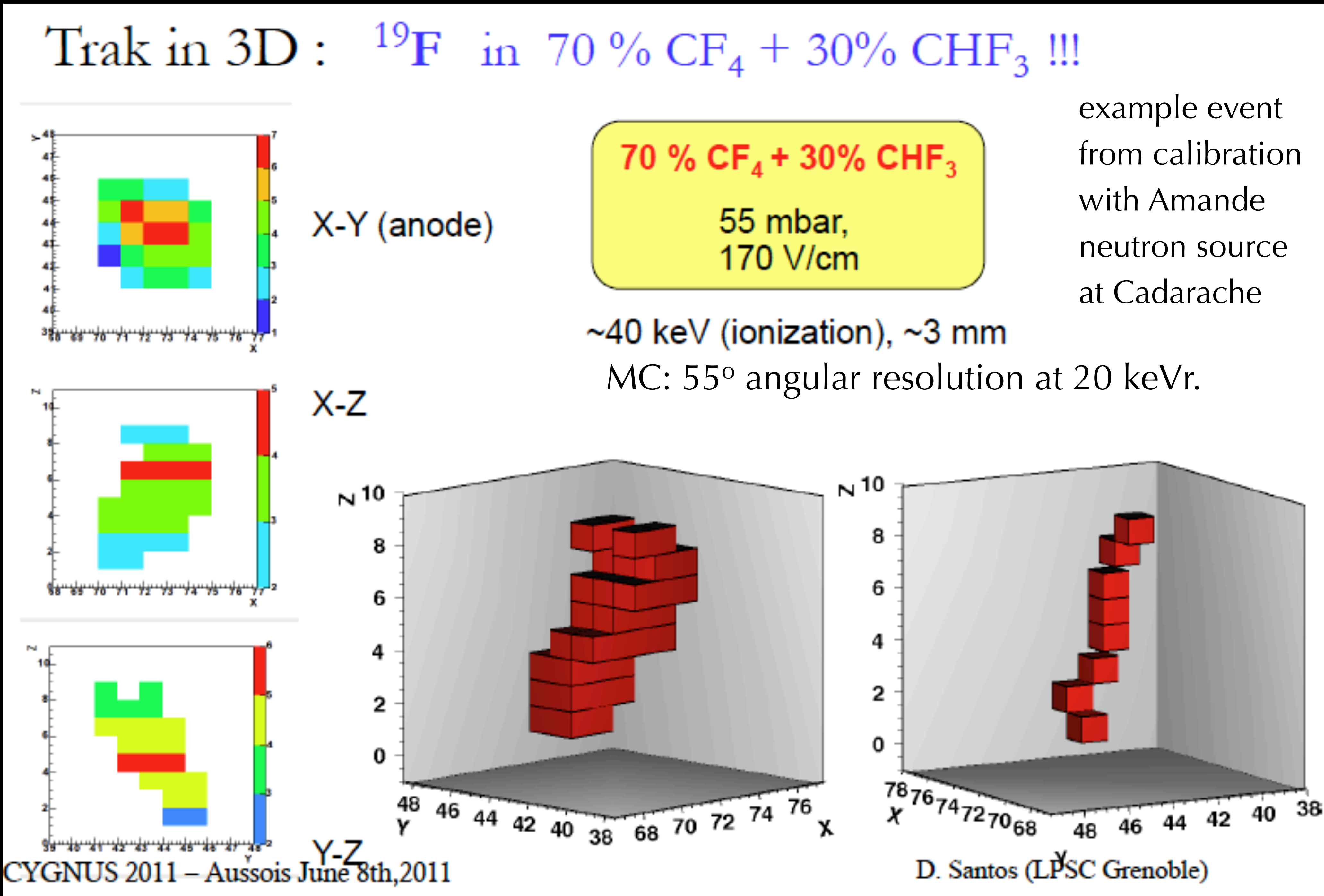




(material thanks to D. Santos)

MiMAC Directionality

(D. Santos, Cygnus'11)



MiMAC Sensitivity

(F. Mayet, Cygnus'13)

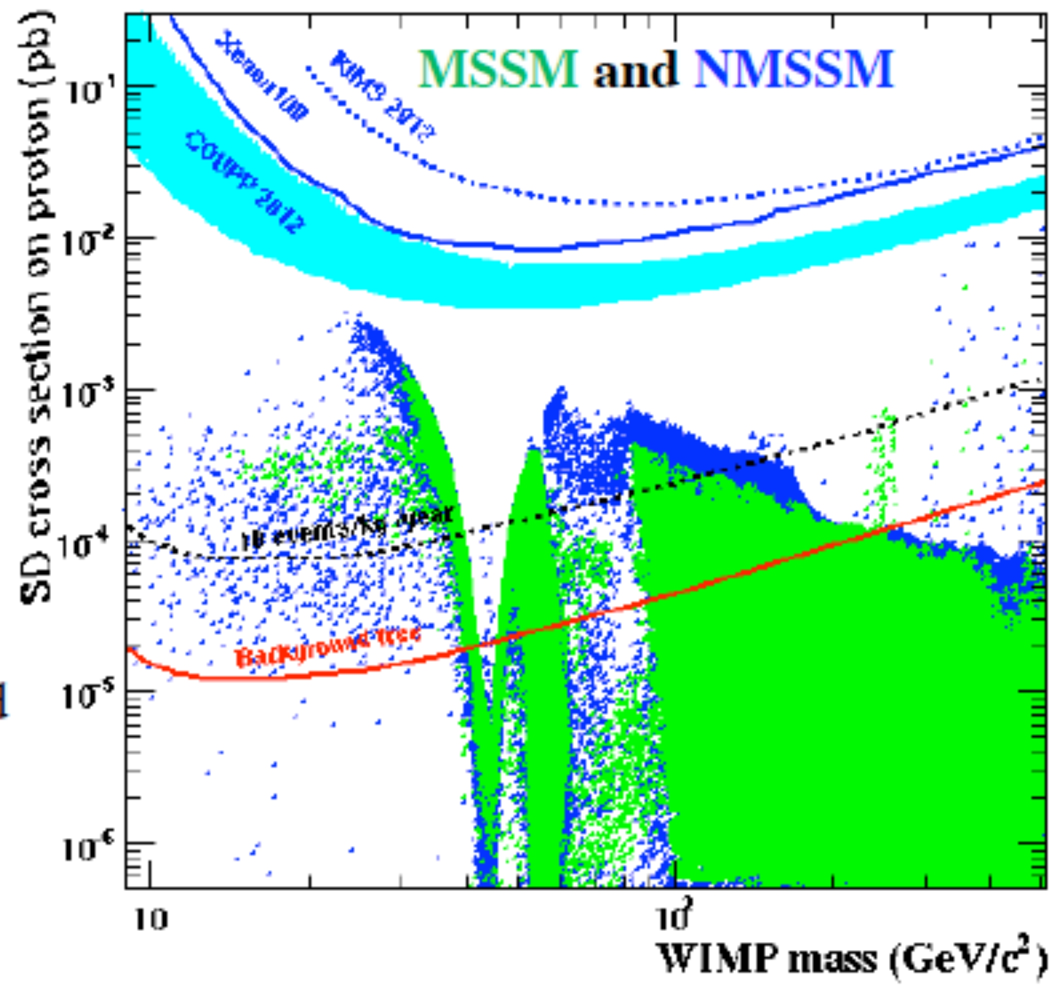
Discovery

J. Billard *et al.*, PLB 2010, PRD 2012

D. Albornoz-Vasquez *et al.*, PRD 2012

Estimation of the discovery potential considering astrophysical uncertainties
=> *Profile likelihood method*

detector characteristics
-10 kg CF_4
- DAQ : 3 years
- Recoil energy range [5, 50] keV



Discovery at 3σ — With BKG (300) / Without BKG

→ Even with a large number of background events, discovery is still possible

→ Only low number of WIMP events are required at low masses

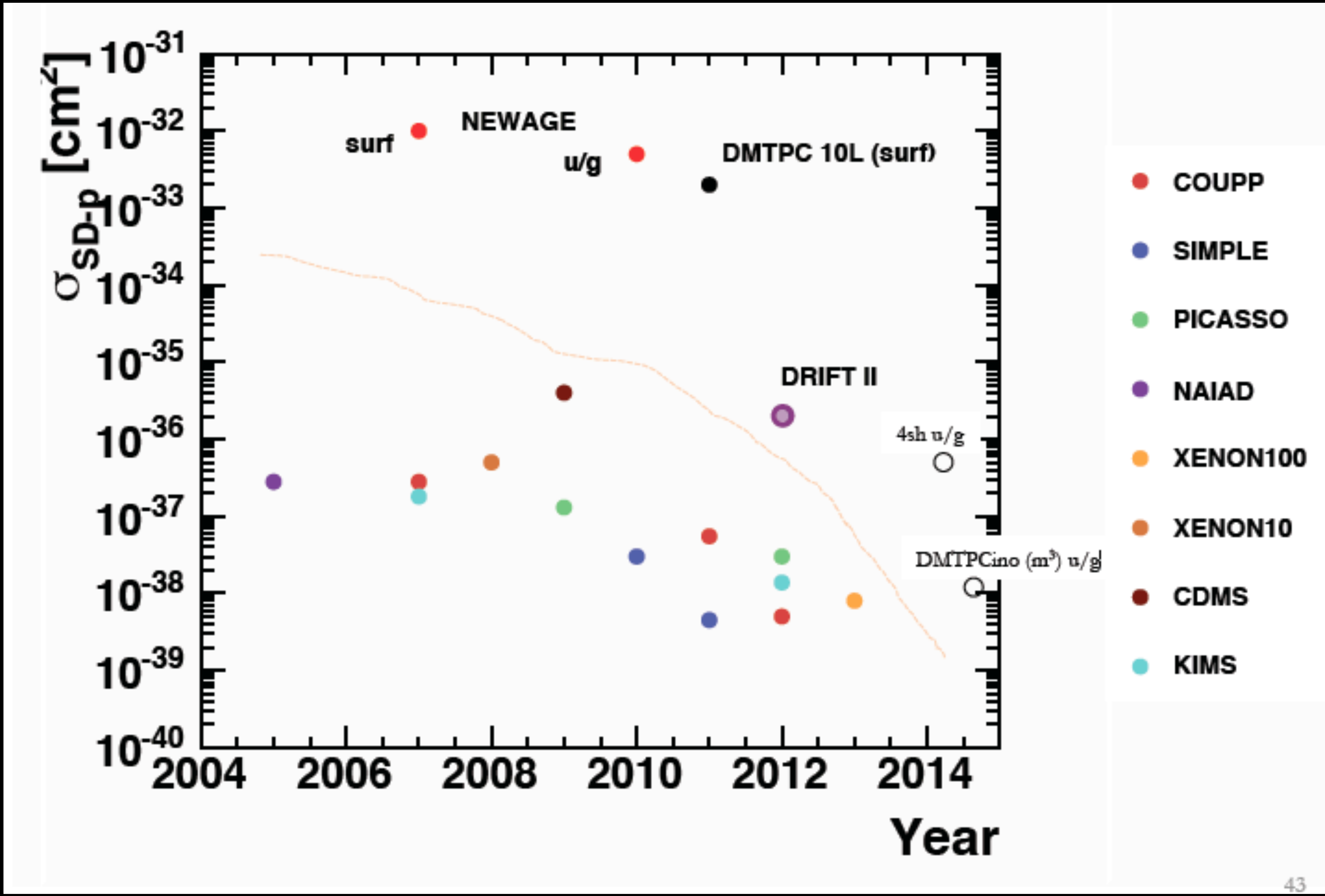
→ *A discovery (>3σ @90%CL) with BKG* is possible down to *10^{-3}-10^{-4} pb*

Outline

1. Introduction and Context
2. Modulating Signals
3. Directional Detection Experimental Considerations
4. Recent Progress from Directional Detectors
5. **Physics Reach with Directional Data**

Directional Detection Cross Section Results

(J. Battat)

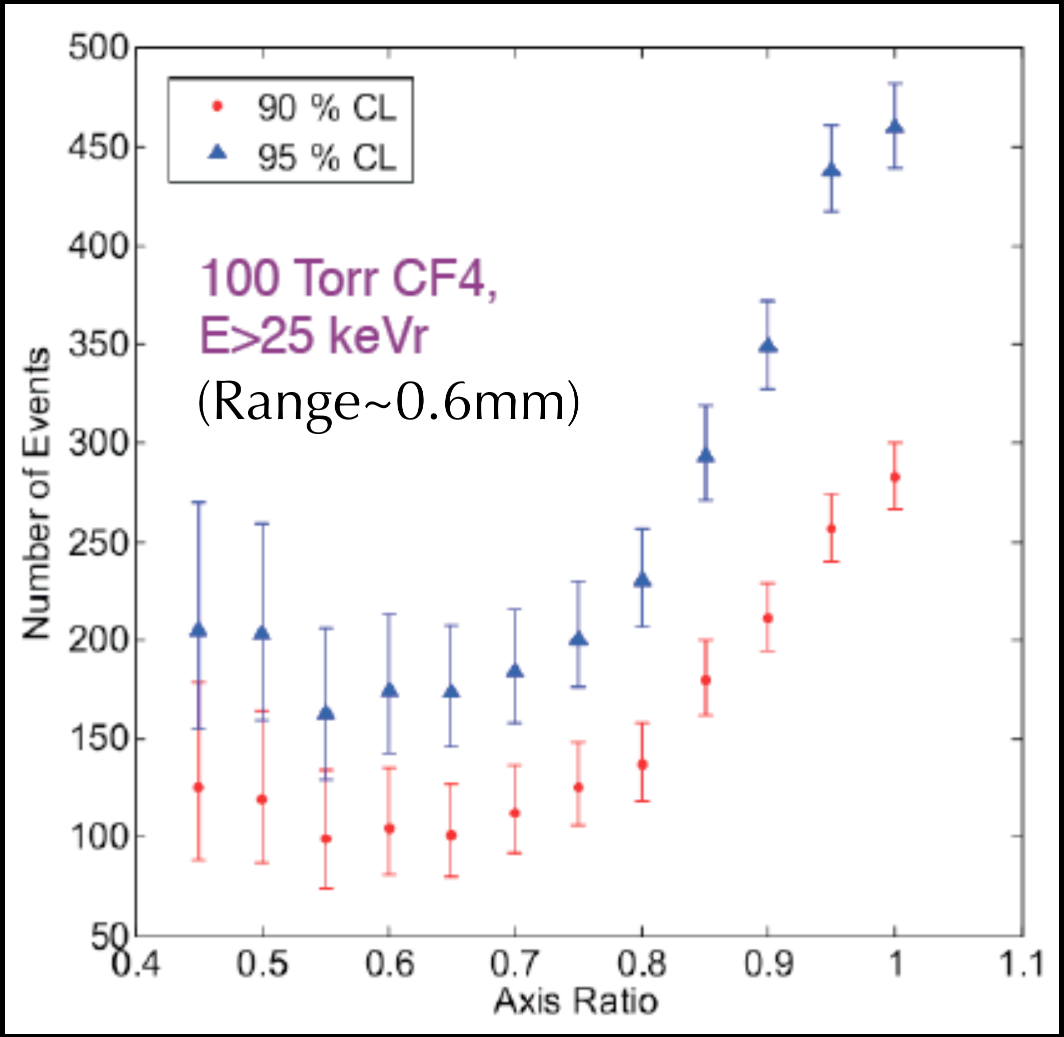


Starting to catch up with non-directional searches....

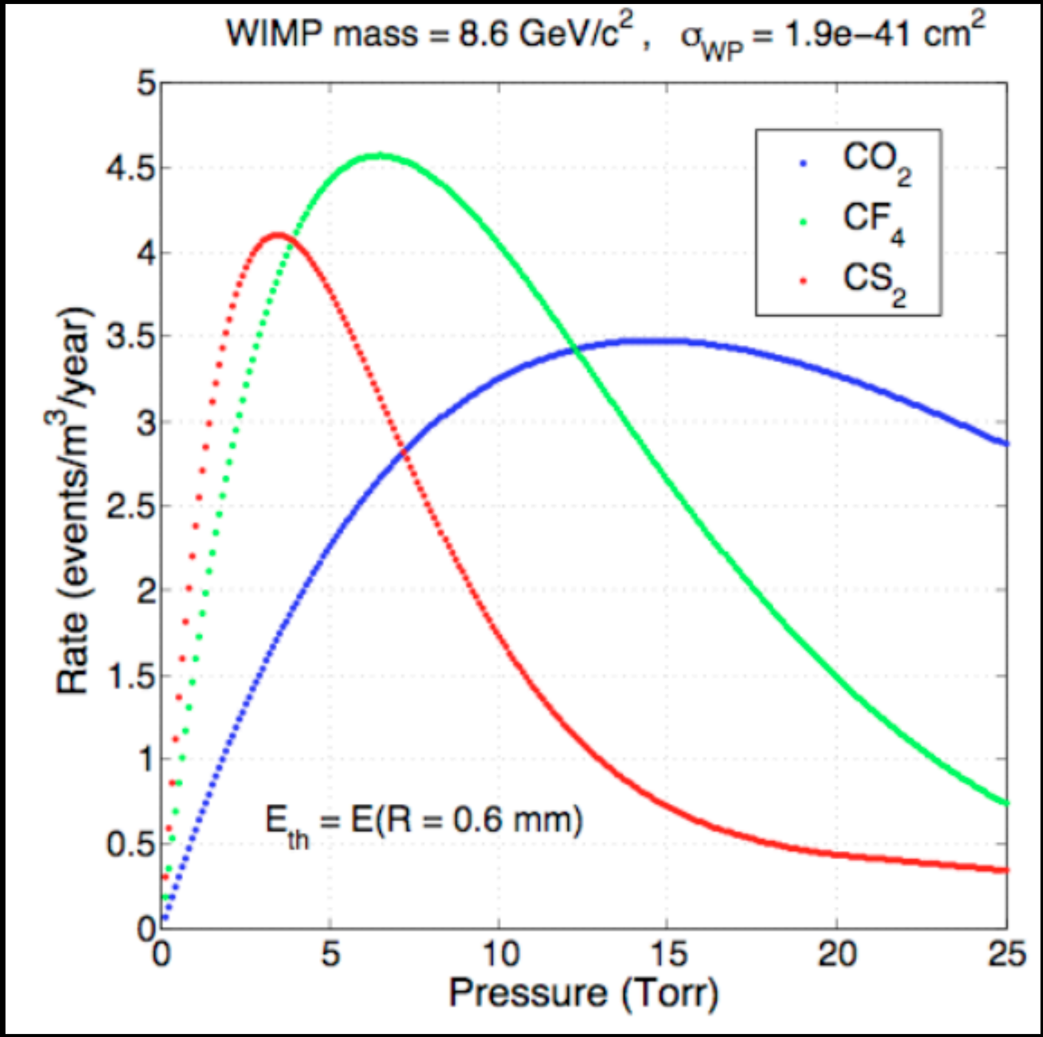
Directionality and Low Mass Dark Matter

(D. Loomba, Cygnus'13)

1) Number of events to reject isotropy as a function of track 'ellipticity:'

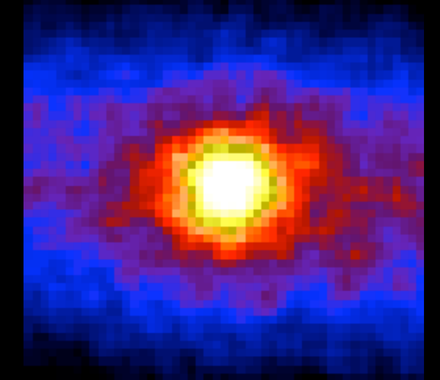


2) Require $E_{threshold}$ for R>=0.6mm, find gas pressure to maximize rate

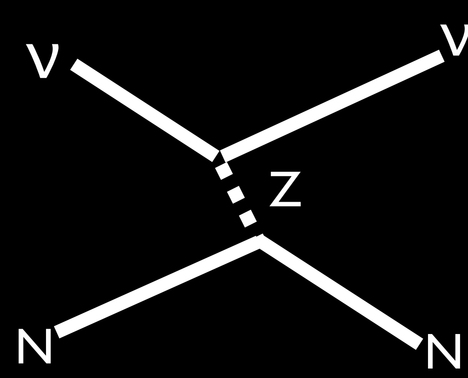


Bottom line: directional detection of low-mass dark matter possible with low gas pressures and low energy thresholds (need large volume, high S:N)

Directionality and the Neutrino Bound



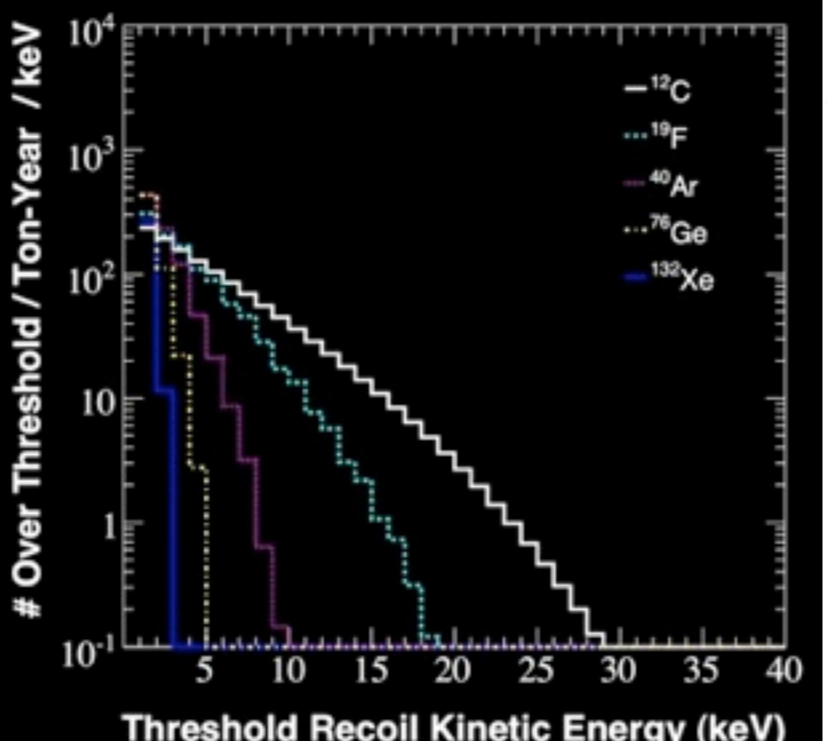
impossible to shield a detector from coherent neutrino scattering!

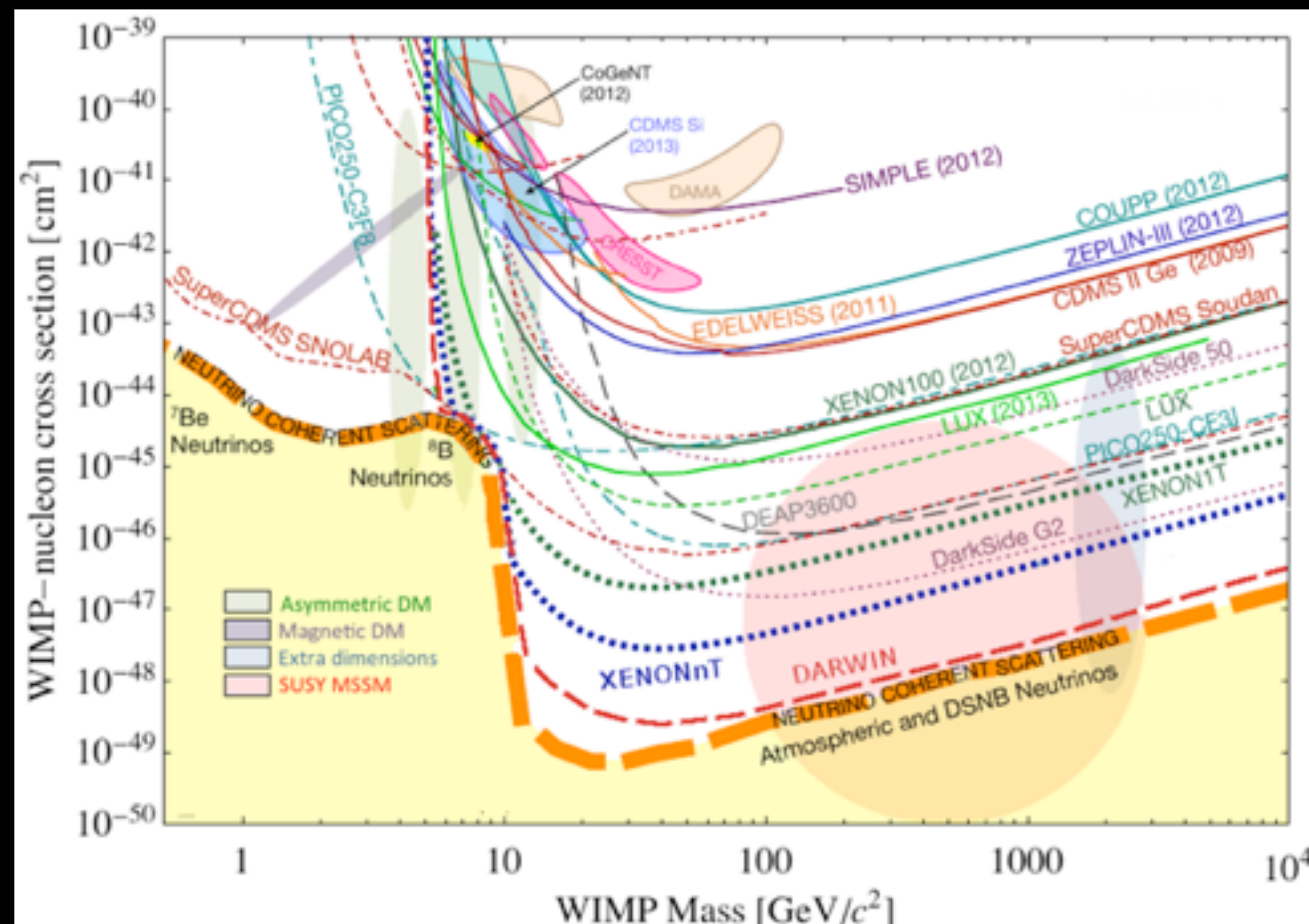


nuclear recoil final state

1 event/ton-year = 10^{-46}-10^{-48} cm^2 limit

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



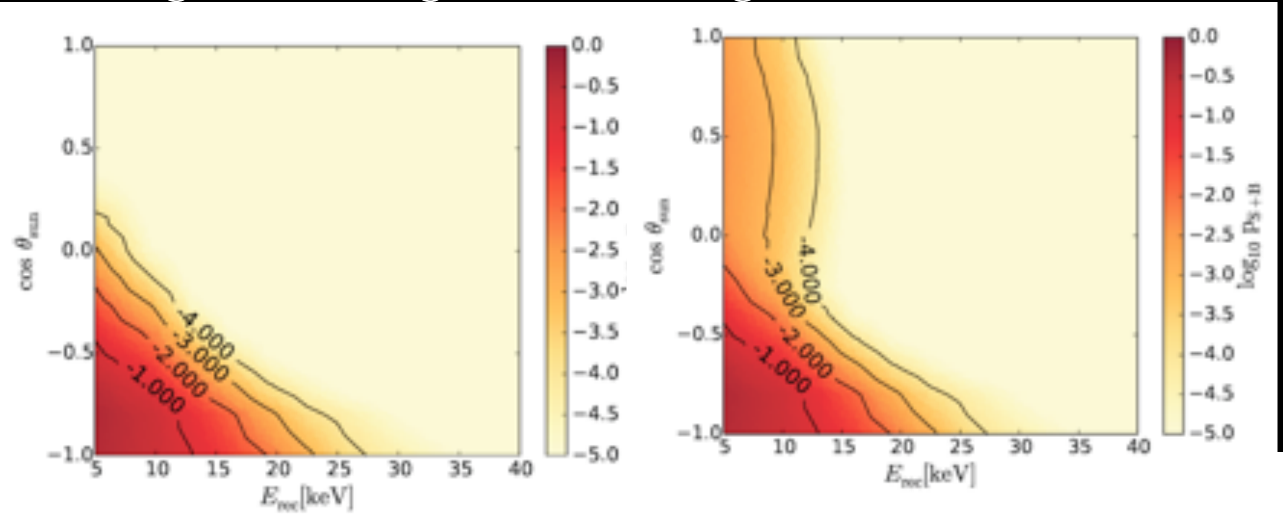


irreducible background, unless you measure the direction!

Beyond the Neutrino Bound

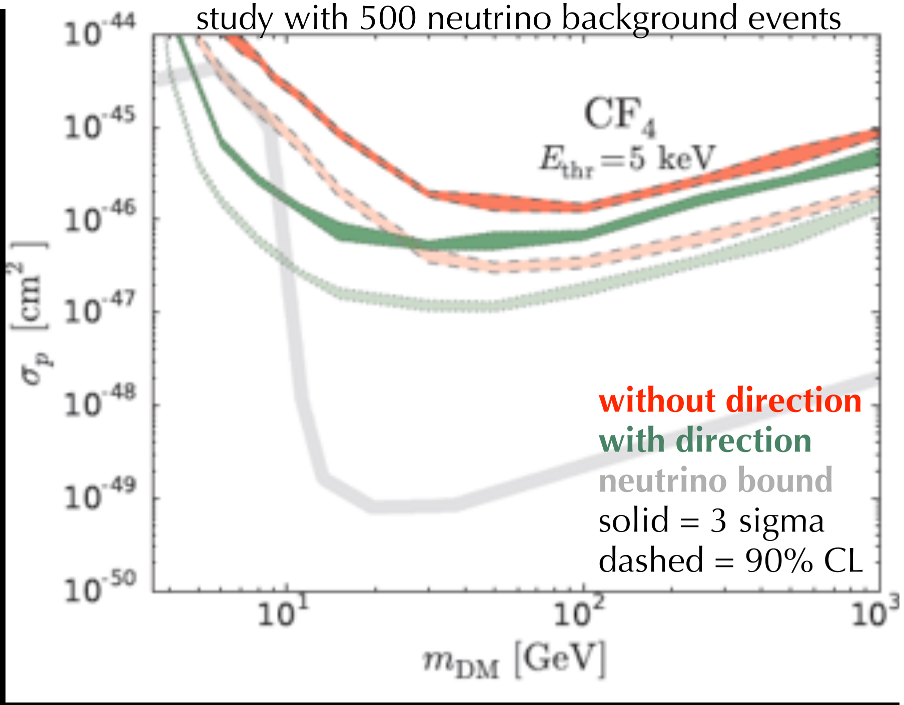
Grothaus, Fairbairn, JM
arXiv:1406.5047

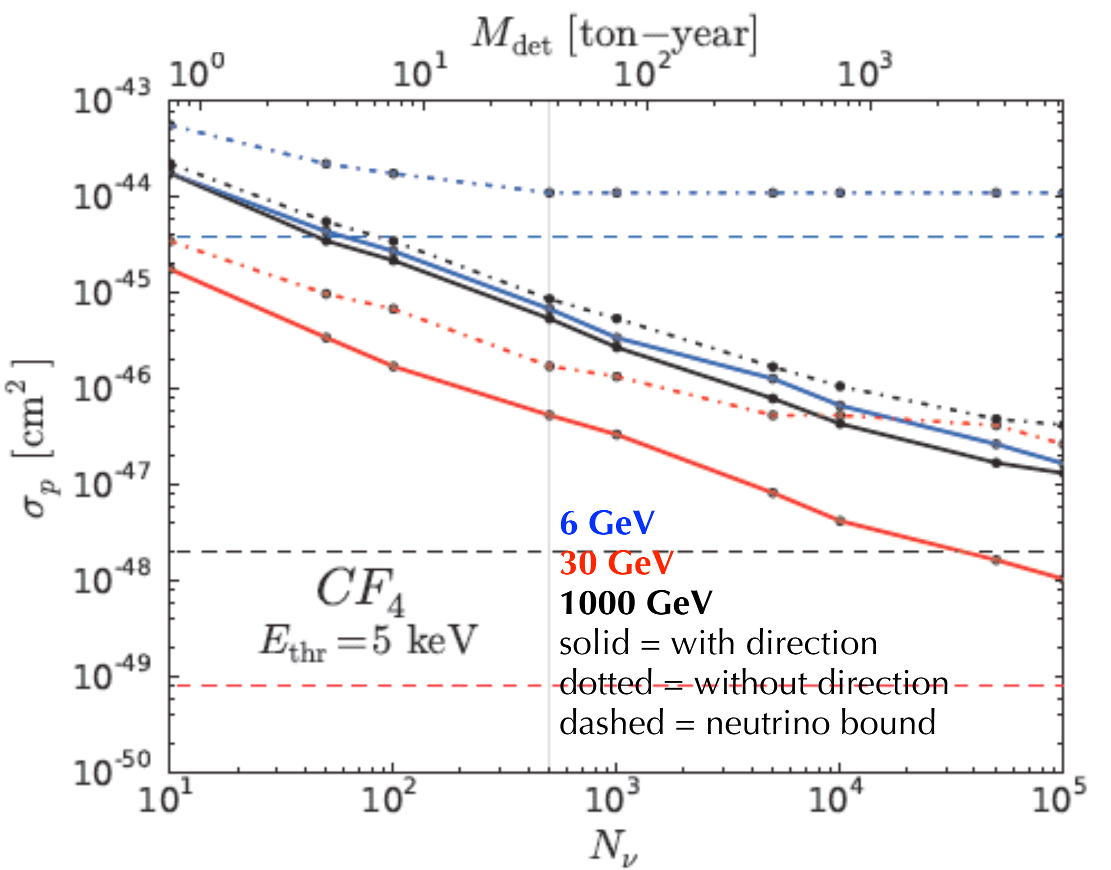
PDFs in (energy, angle, time) of event for coherent solar nu background vs. background+signal show significant differences, including 35° resolution:



statistical test (CLs) shows

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





Directionality and Dark Matter Astrophysics

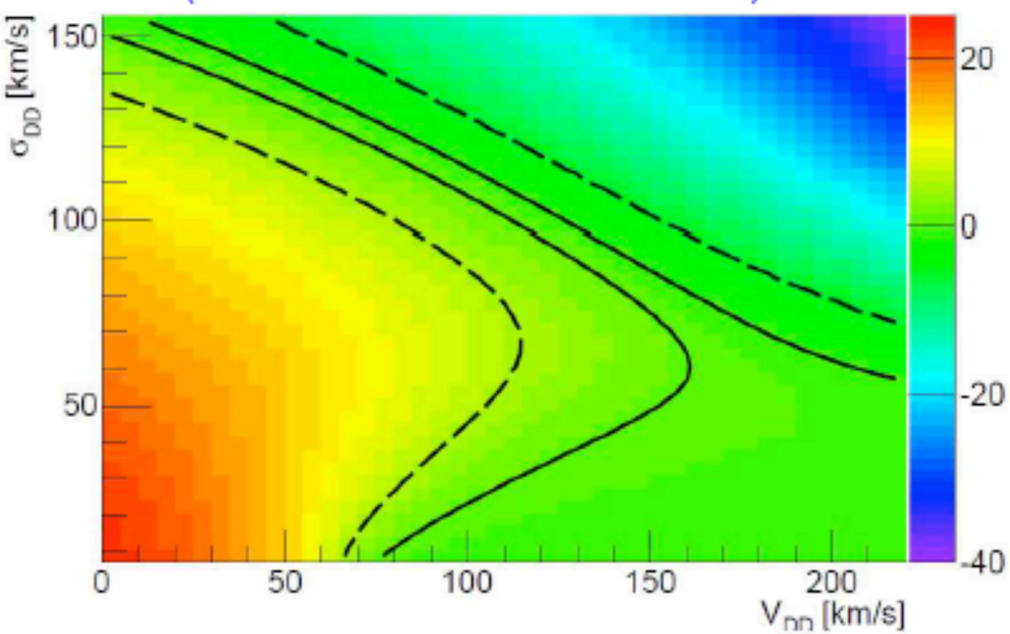
Discovery : beyond the standard halo

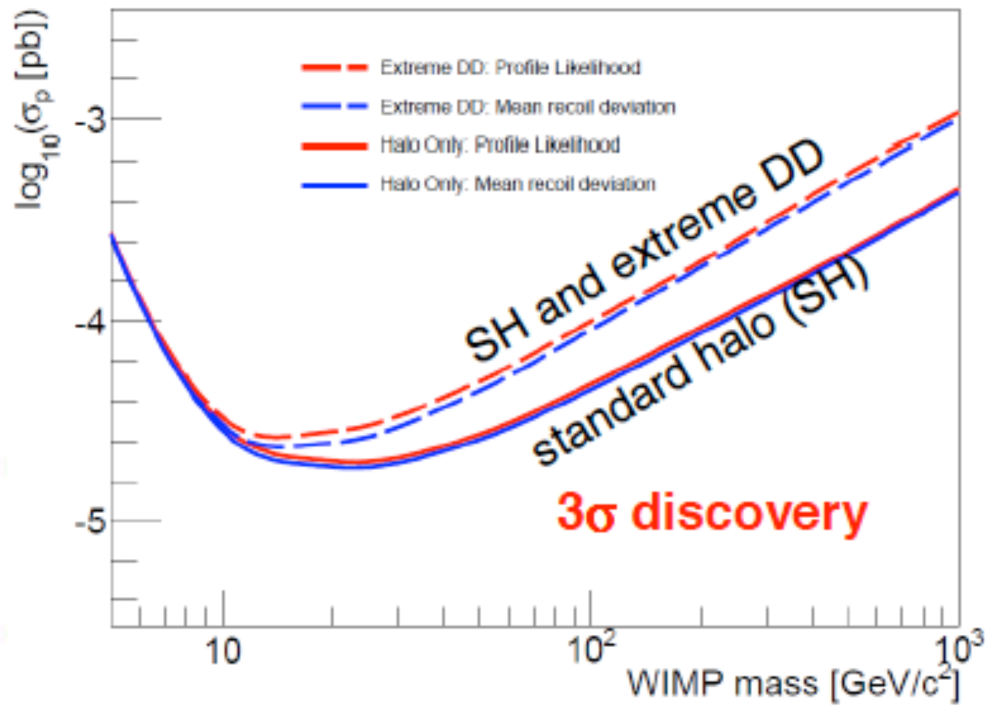
J. Billard *et al.*, PLB 2013

N-body simulations favor a co-rotating Dark Disk (10%-50% of local DM density)

→for a nul lag velocity, Dark Disk Wimps have an isotropic velocity distribution

Relative Asymmetry
(in the mean recoil deviation)





→only extreme Dark Disk parameters may affect the directional signal

→not a threat for directional detection

What to do with Directional Data?

1. Exclusion

- Maximum Patch Method, *S. Henderson, JM and P. Fisher, PRD 2008*
- Directional Likelihood Method, *J. Billard, F. Mayet and D. Santos, PRD 2010*

bottom line: 2 variables (angle + energy) can be better or worse than 1 (energy)

2. Hypothesis Test: is a candidate signal compatible with background?

- *C. J. Copi & L. M. Krauss, PLB 1999; C. J. Copi & L. M. Krauss, PRD 2001; B. Morgan & A. M. Green, PRD 2005; B. Morgan, A. M. Green and N. J. C. Spooner, PRD 2005; A. M. Green & B. Morgan, PRD 2008; O. Host & S. H. Hansen, JCAP 2007; J. D. Vergados & A. Faessler, PRD 2007; M. S. Alenazi & P. Gondolo, PRD 2008*

bottom line: require few 10s of events to reject isotropy

3. Discovery: search for a signal from the direction of Cygnus

- Median Recoil DIrection Test: *A. M. Green & B. Morgan, PRD 2010*
- Blind Likelihood Test: *J. Billard et al., PLB 2010*

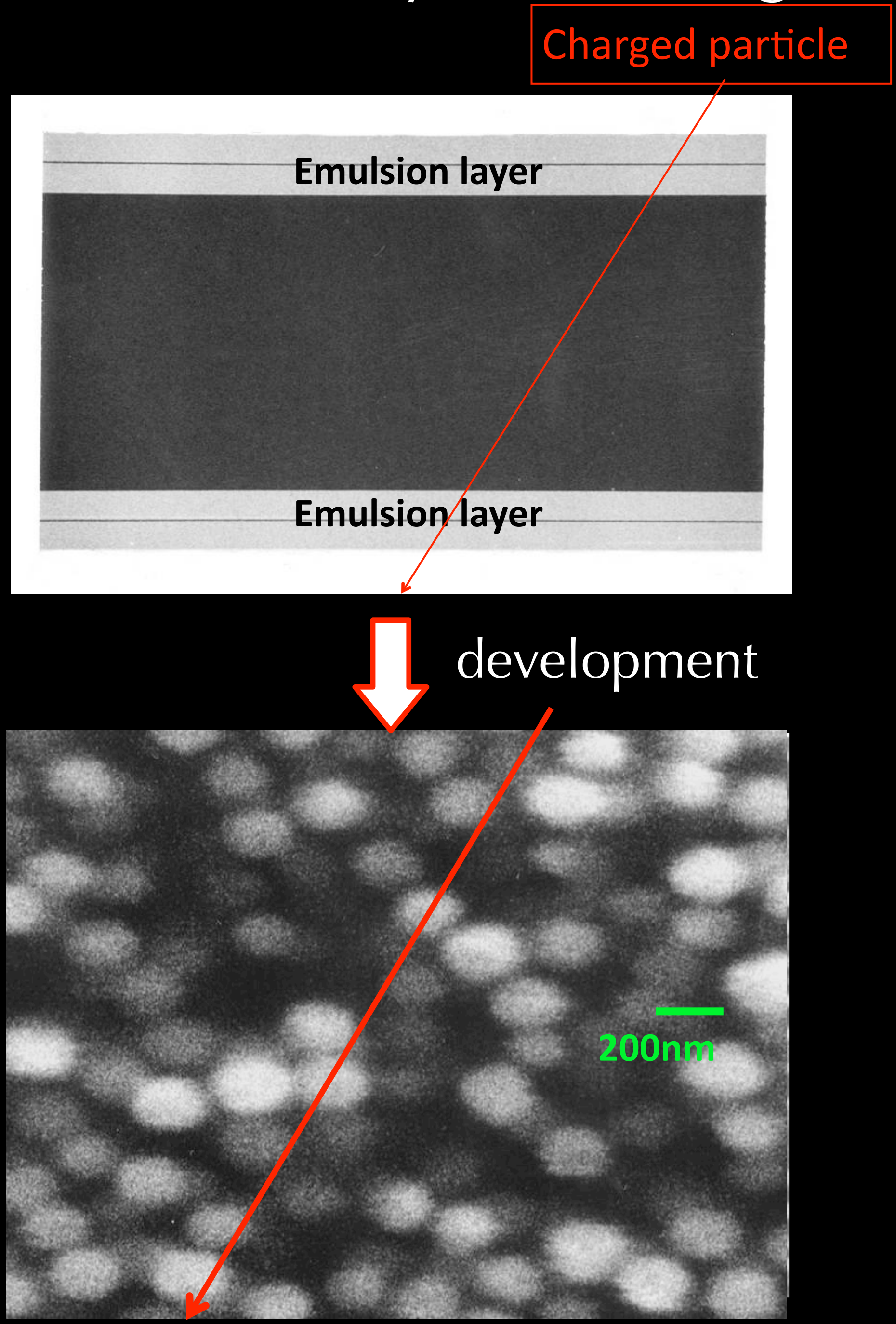
bottom line: high significance discovery with relatively small exposure (~10 kg-yr)

4. Study Dark Matter Properties: halo, mass, cross section

- *Lee and Peter, arXiv:1202.5035; Borzognia, Gelmini, Gondolo, arXiv:1111.6361; Billard, Mayet and Santos, PRD 2011; Copi et al., PRD 2007; Green and Morgan, Astropart. Phys. 2007; ...*
- Dark Matter Model Discrimination: *D. Finkbeiner, T. Lin, N. Weiner, PRD80 (2009)*
- Community White Paper: *S. Ahlen et al., Int.J.Mod.Phys.A25:1-51,2010*
- And beat the neutrino background limit! *M. Fairbairn et al. IOP2014, in preparation*

bottom line: need large numbers of events O(1000+) to measure halo parameters

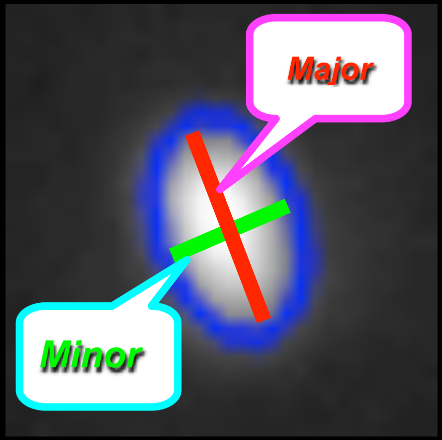
Directionality with Large Target Mass: Emulsion R&D



(Nagoya, Fuji, + Napoli, Padova)

dark matter detector design:

- 10-100 keV recoils travel <400 nm
- Fuji developed new emulsion with finer AgBr (35 nm crystals)
- chemical expansion of emulsion by 2x before microscope readout scan



analysis:

1. major axis: track length

2. minor axis: grain size

3. cut on ellipticity

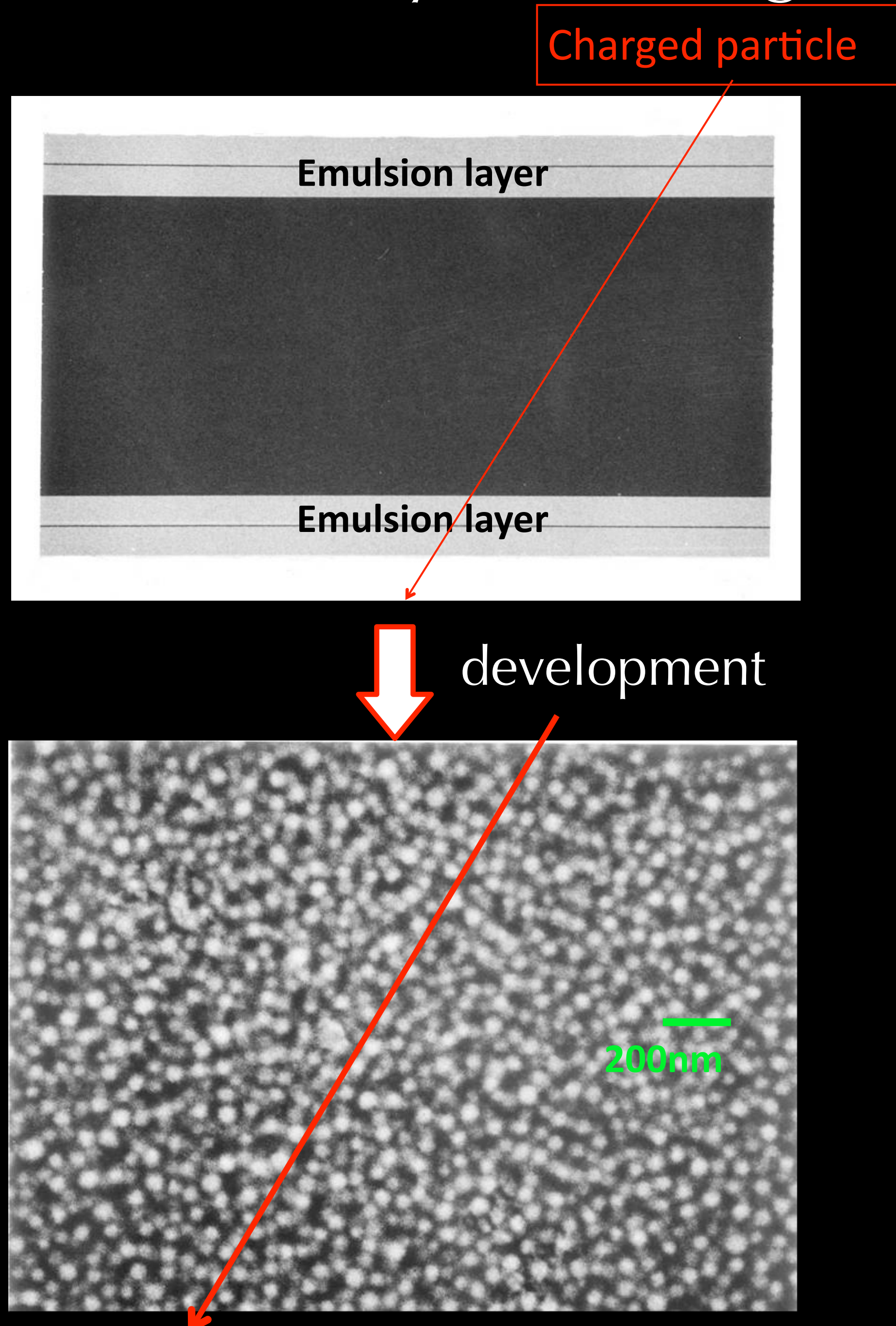
Calibration with ion source, d-t neutrons

- 30º resolution with optical readout,
- efficiency >50% above 150 nm tracks

Underground R&D at LNGS

(material thanks to T. Naka)

Directionality with Large Target Mass: Emulsion R&D



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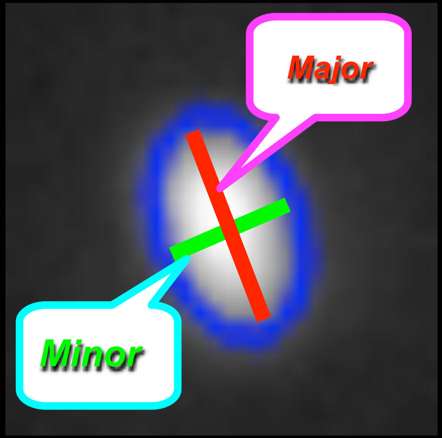

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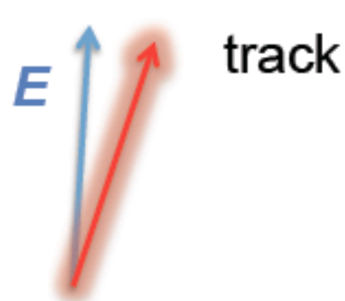
Directionality with Large Target Mass: No Tracking

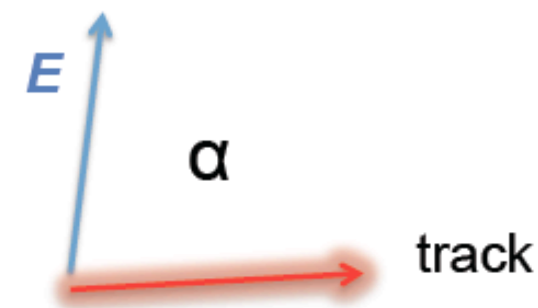
Ratio of recombination to ionization yield in gas target is sensitive to track direction relative to TPC drift field.

- Columnar Recombination (CR) occurs when:
  - A drift electric field ***E*** exists;
  - Tracks are highly ionizing;
  - Tracks display an approximately linear character;
  - The angle α between ***E*** and track is small:
  - **Recombination** ≈ dot-product of vectors E and "track"



Substantial CR

(D. Nygren, Cygnus'13)



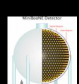
~No CR

Photons from R vs. I separated in arrival time at TPC readout plane.
Measure event energy vs. time of day (direction to cygnus), in HPXe TPC.
No tracking needed for directional dark matter detection!

Directional Detection Future

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

MiniBooNE:
6 x 6 x 6 m^3



Directional Detection Observatory
16 x 16 x 16 m^3

1 ton of CF_4 @50Torr

MINOS:
15 x 13 x 30 m^3

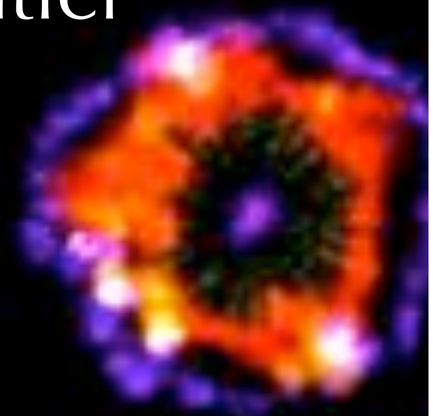
SNO:
21 x 21 x 34 m^3

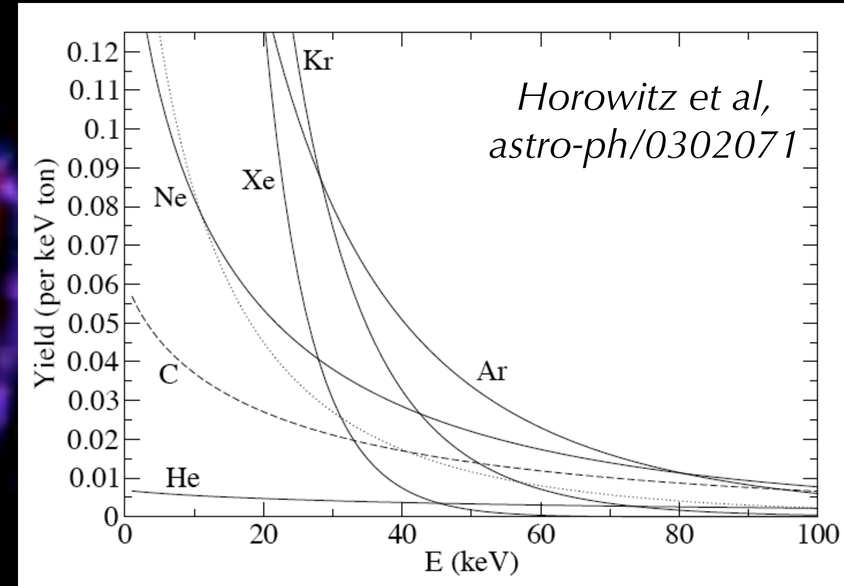
SuperK:
40 x 40 x 40 m^3

detector size for 10^{-44} cm^2 SI sensitivity at 50 Torr pressure

Low Background Frontier

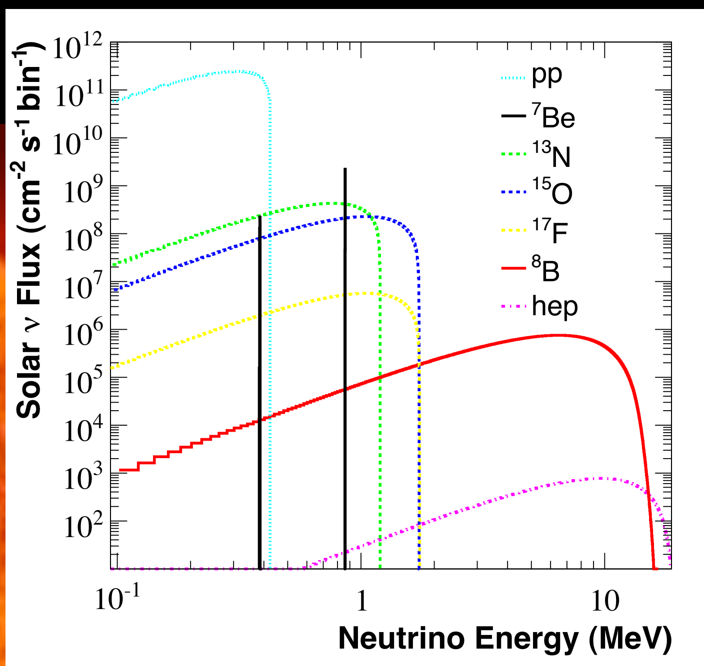
tonne scale, keV threshold, low background detectors have potential for first observations of...





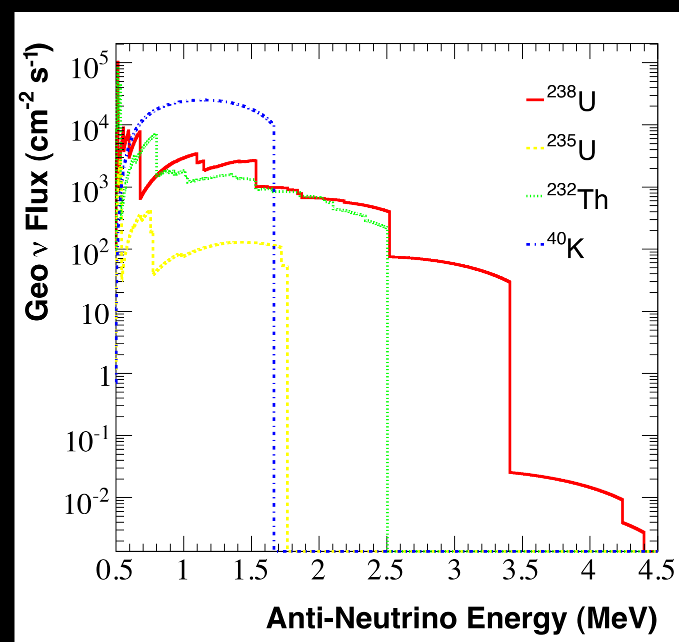
Supernova neutrinos in NC, flux and spectrum

P. Giampa, in preparation

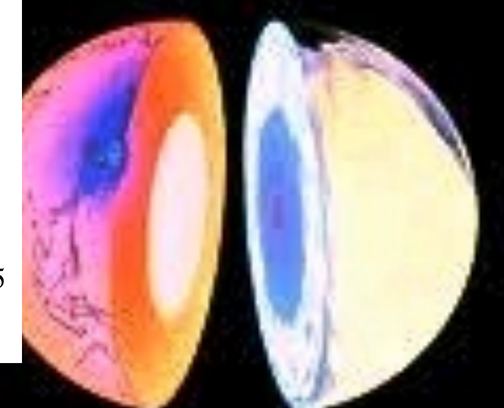


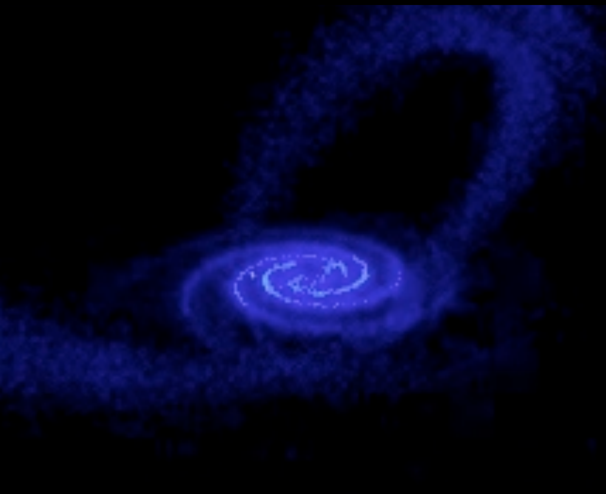
neutrino-nucleus coherent elastic scattering of solar neutrinos *JM, P. Fisher, PRD76:033007*

with direction measurement: 40K geo-neutrinos, CNO solar neutrinos



JM, Nucl.Phys.Proc.Suppl. 229-232 (2012) 570





Modulation searches can establish the astrophysical origin of candidate dark matter-induced recoil signals.

Backgrounds make directional detection very attractive!

Big challenges: direction reconstruction at low energy, scaling to large target mass, nuclear recoil backgrounds.

There has been great progress in last 5 years from DMTPC, NEWAGE, DRIFT, MiMAC, emulsions...
Cygnus'15 (June 2-4, 2015, L.A.)

Directional detector physics reach from particle physics to dark matter telescope.

Backup Slides

CF_4 Electron Attenuation

(D. Dujmic, T. Caldwell)

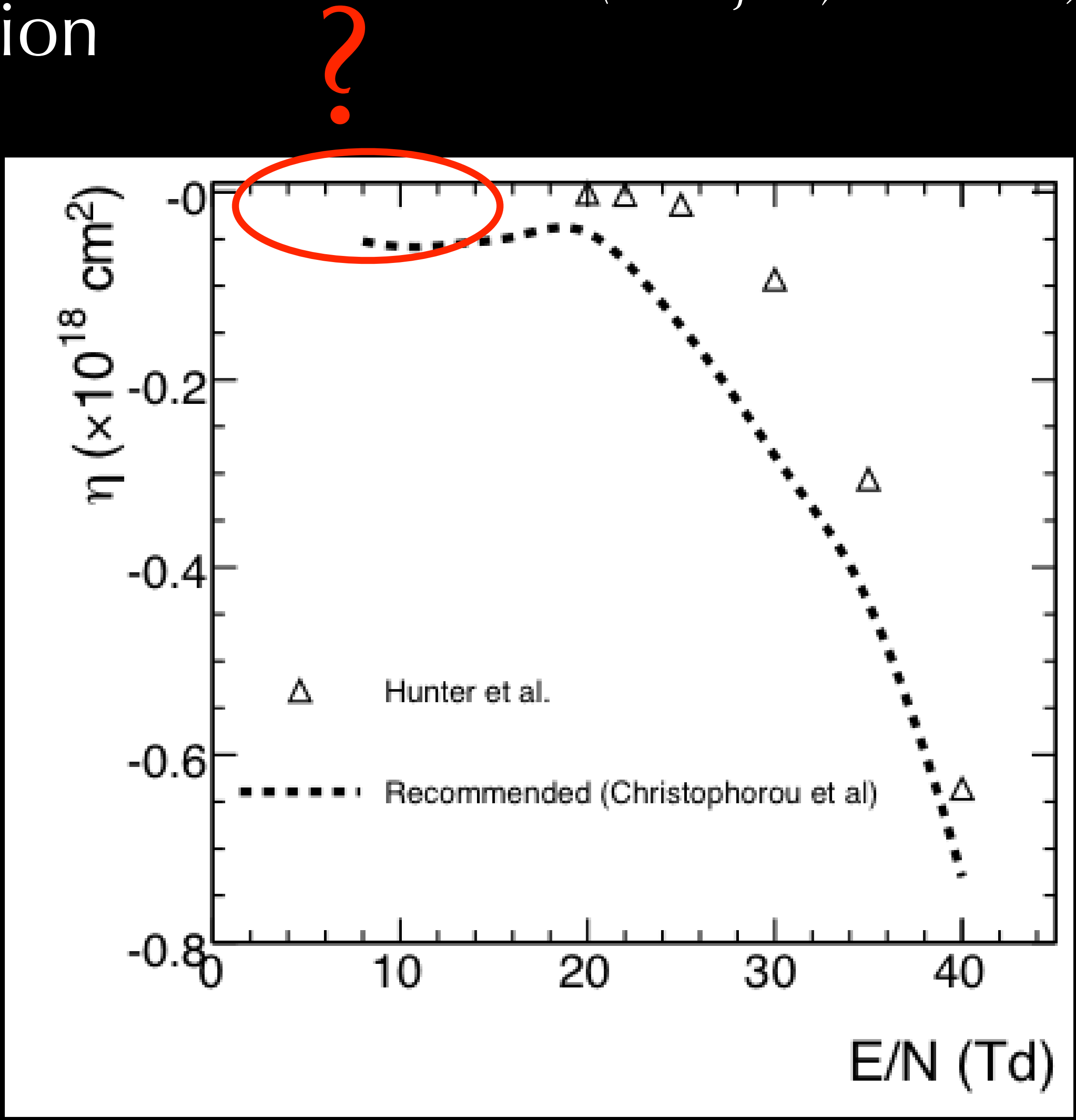
Attachment to CF_4:

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?

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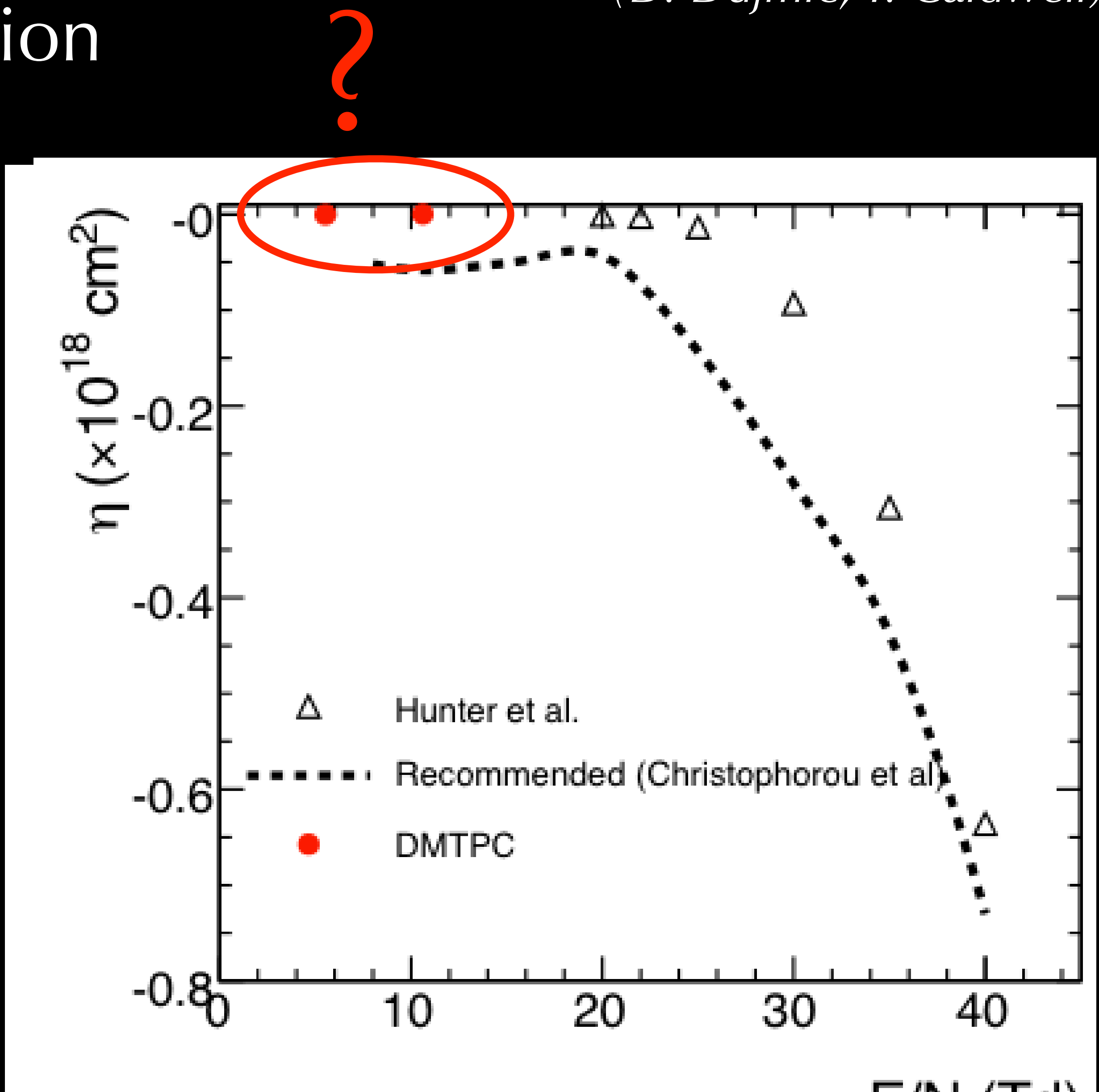


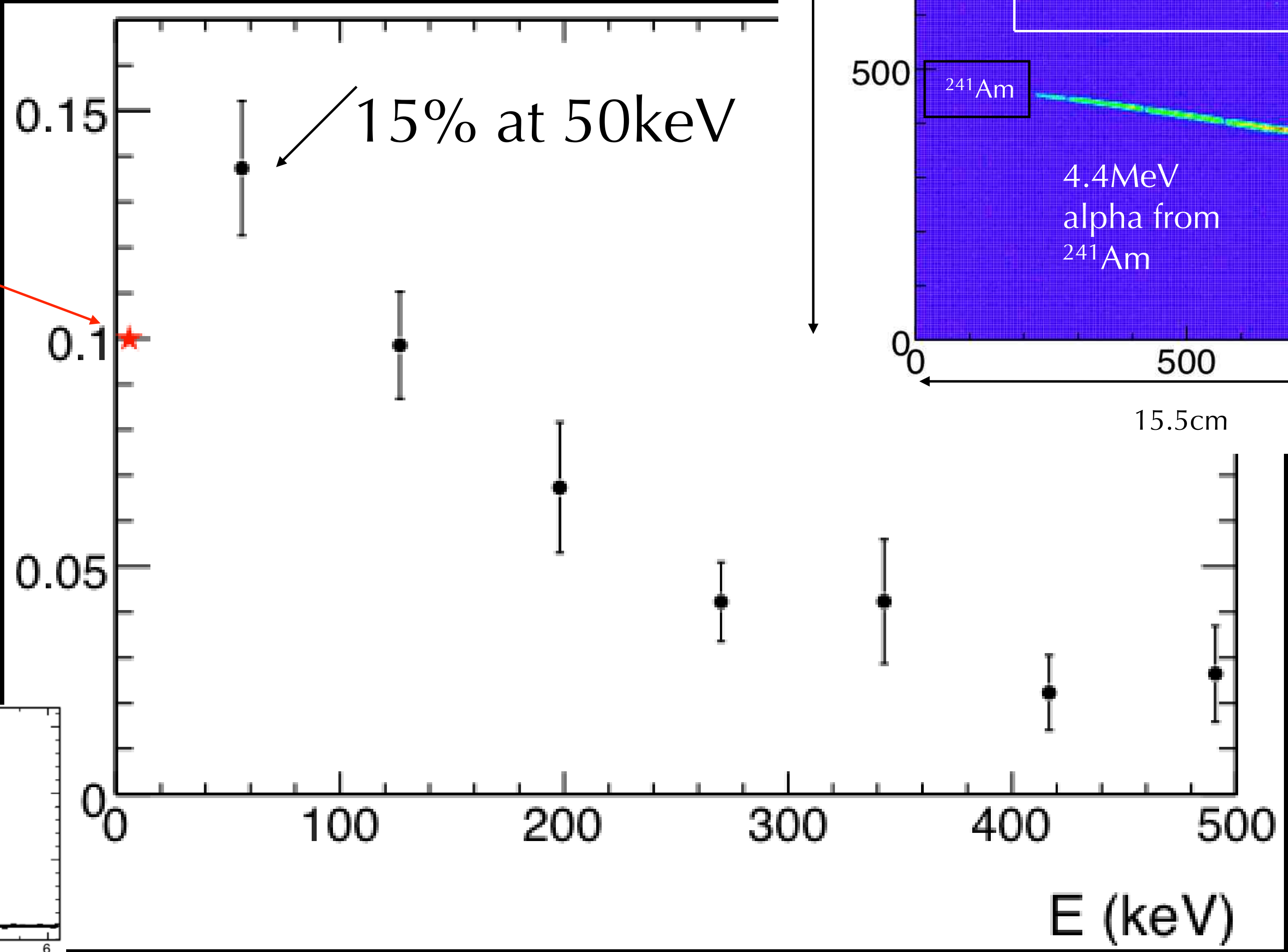
T. Caldwell, et al., arXiv:0905.2549

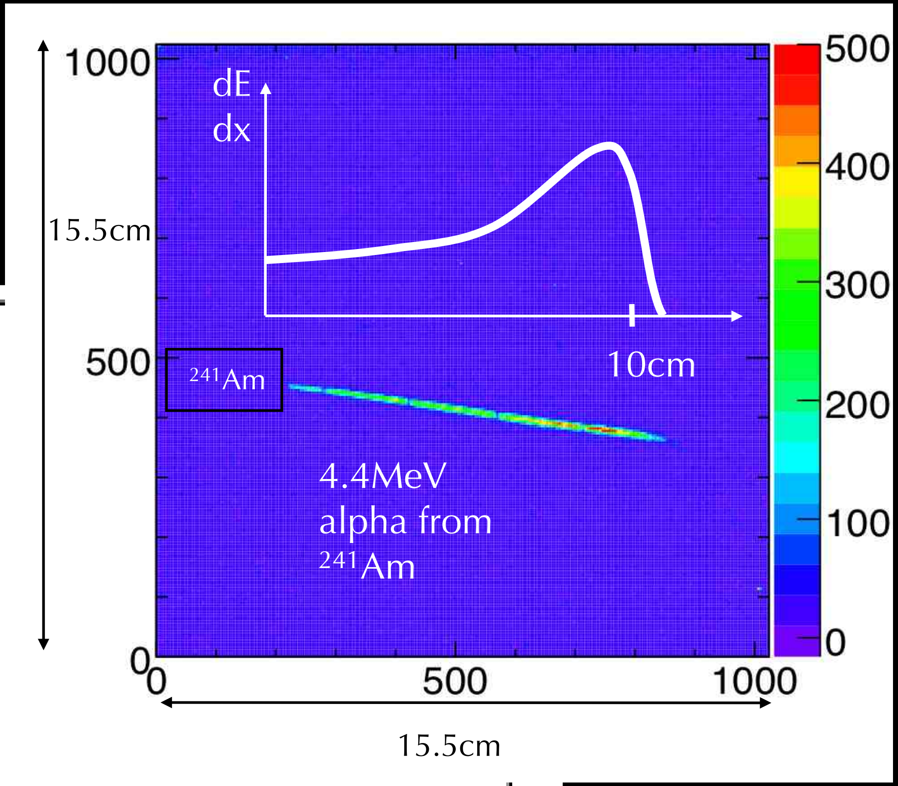
DMTPC measures ~0 charge loss over 20 cm drift length.

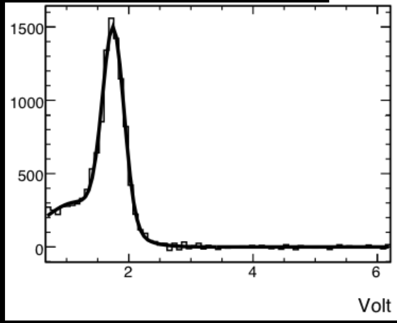
Energy Resolution

σ_E/E from CCD Readout:

~10% at 5.9keV for charge readout







Expected fluctuation (avalanche + primary) ~ 10%

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