Directional Detection Methods

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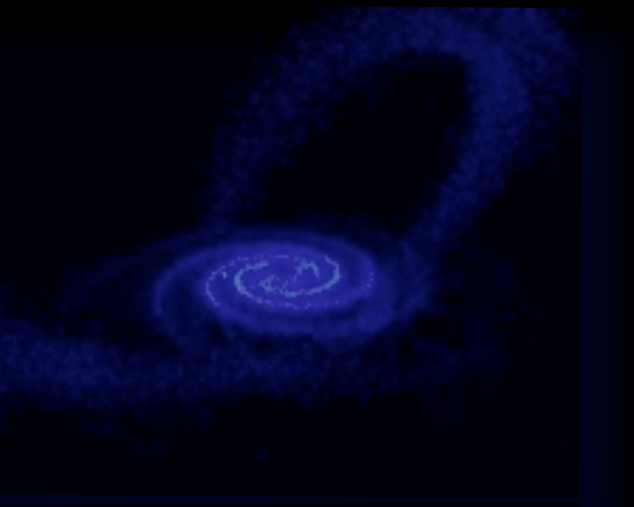
Royal Holloway University of London

Dark Matter Silver Jubilee
Pacific Northwest National Laboratory
June 20, 2012



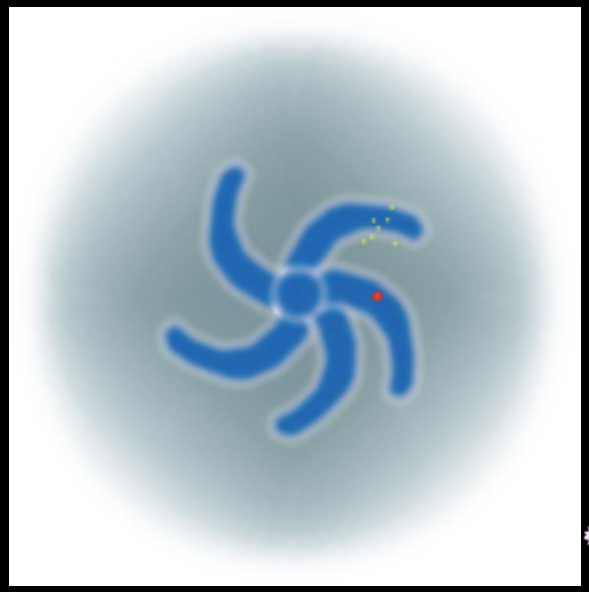
Outline

Motivation

Directional Dark Matter Detection

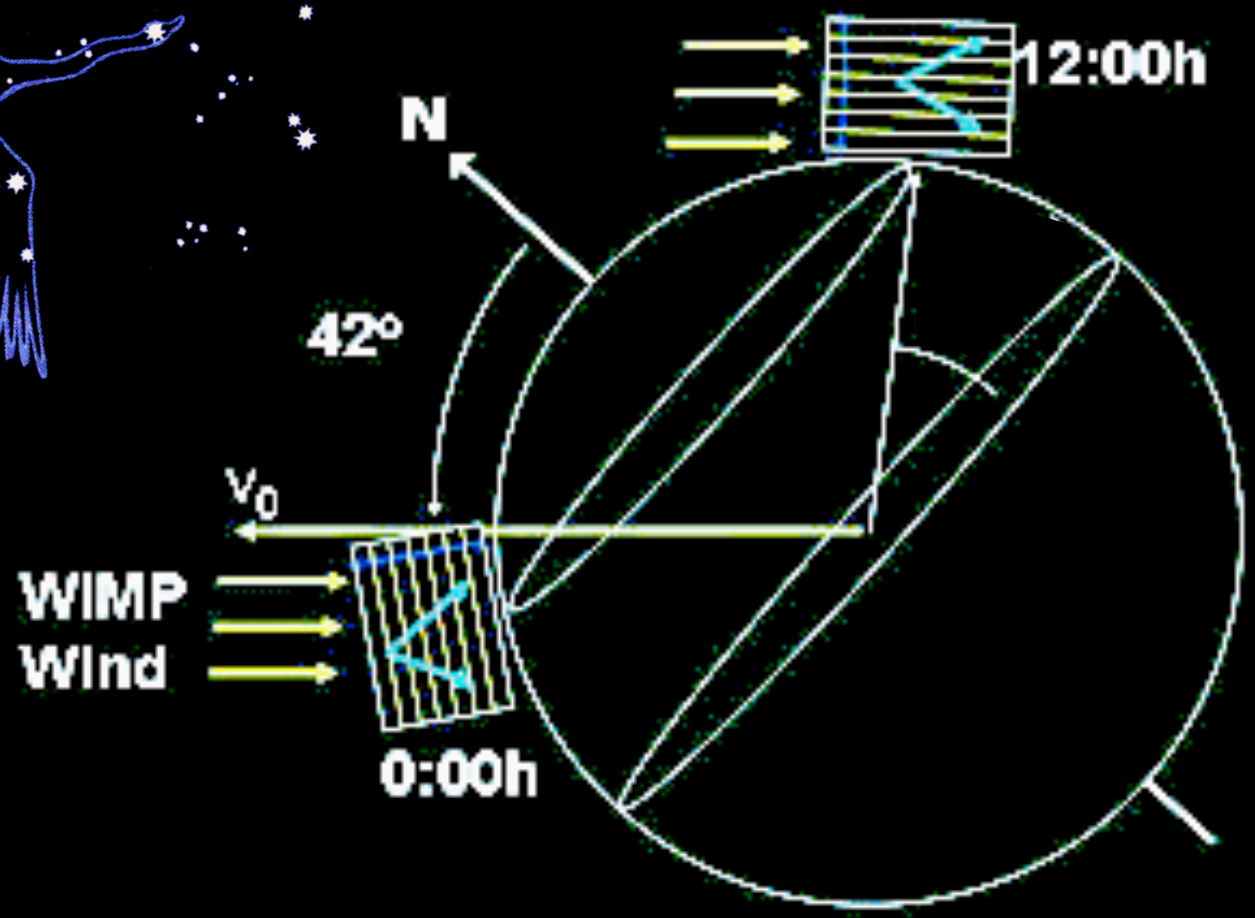
Recent Progress from Directional Detectors

directional detection: search for a dark matter source



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

The Dark Matter Wind apparently "blows" from Cygnus



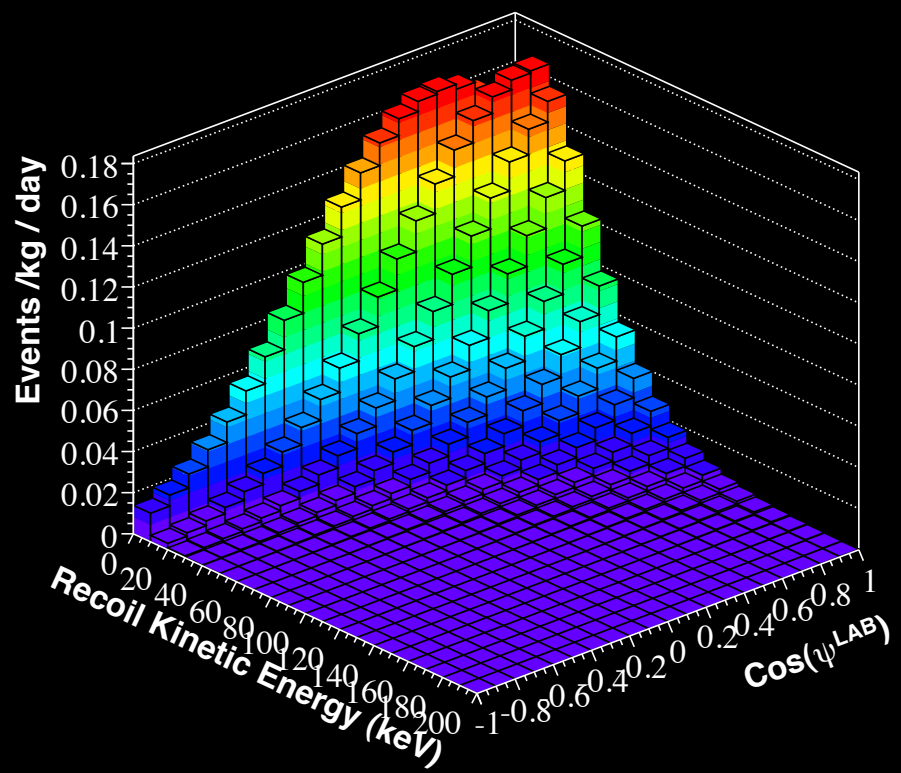
Daily direction modulation: asymmetry ~ 20-100% in forward-backward event rate.

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

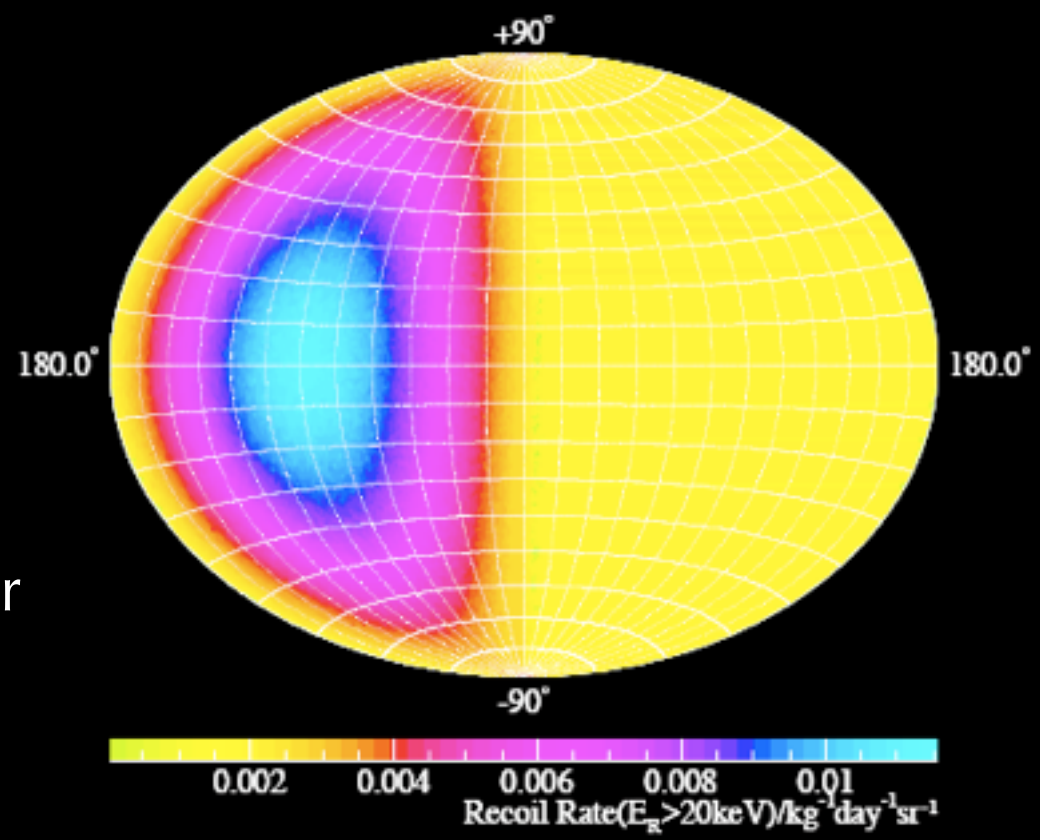
Unambiguous proof:
Correlation of WIMP-induced nuclear recoil signal with galactic motion

Directional Detection Goal

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

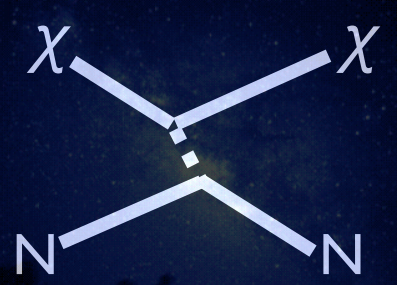


A. M. Green, B. Morgan, astro-ph/0609115

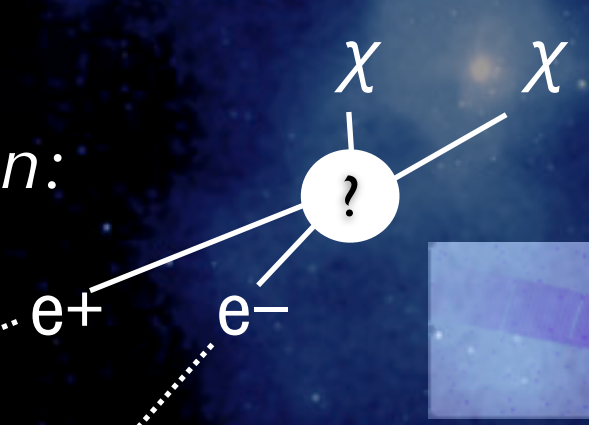


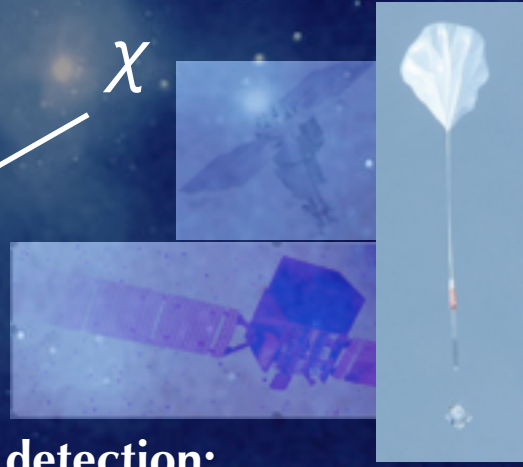
simulated reconstructed dark matter sky map: search for anisotropy

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

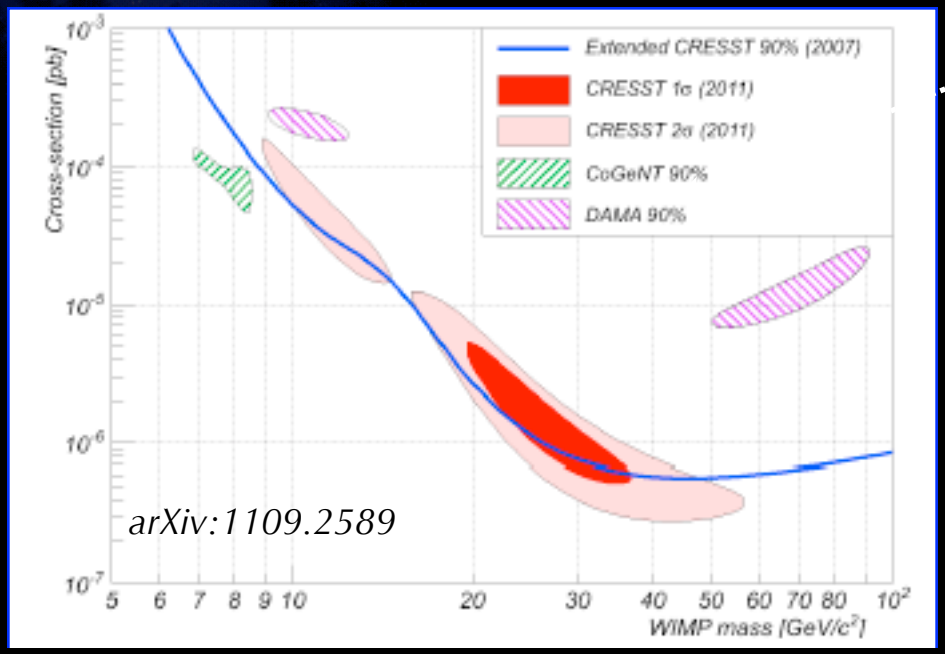


Motivation for Directional Detection:



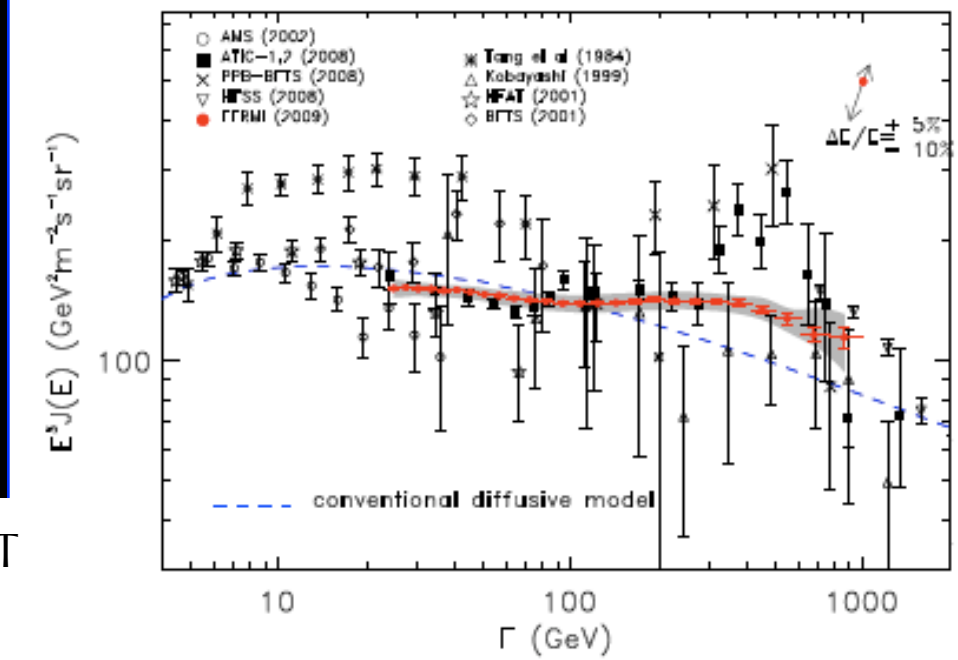


direct detection:

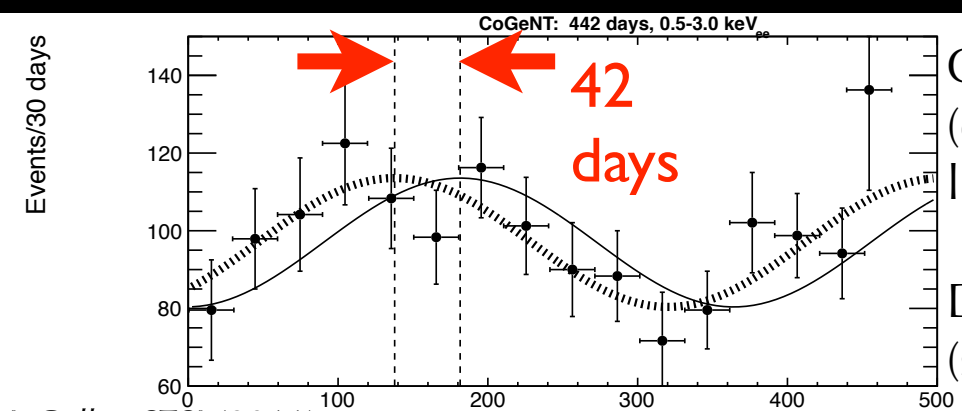


indirect detection:

arXiv:0905.0025



modulation searches:



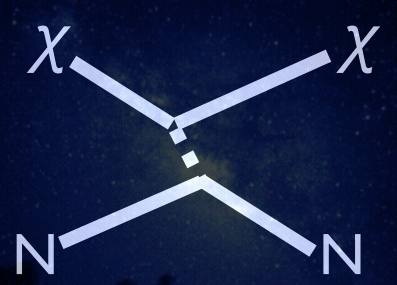
CoGeNT (dashed line)

DAMA (solid line)

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

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

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



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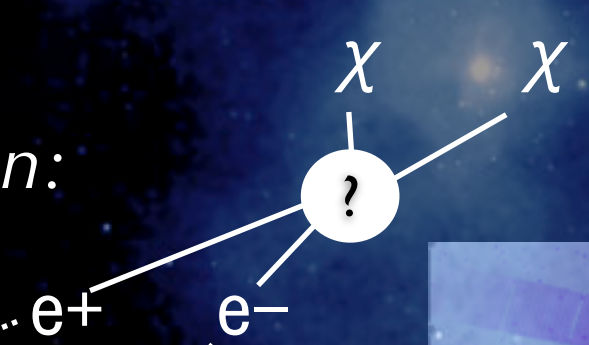
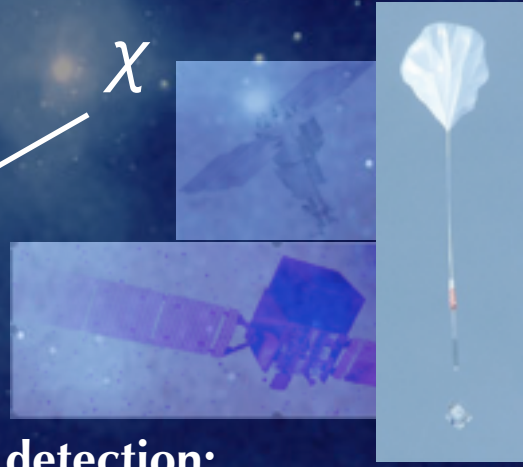
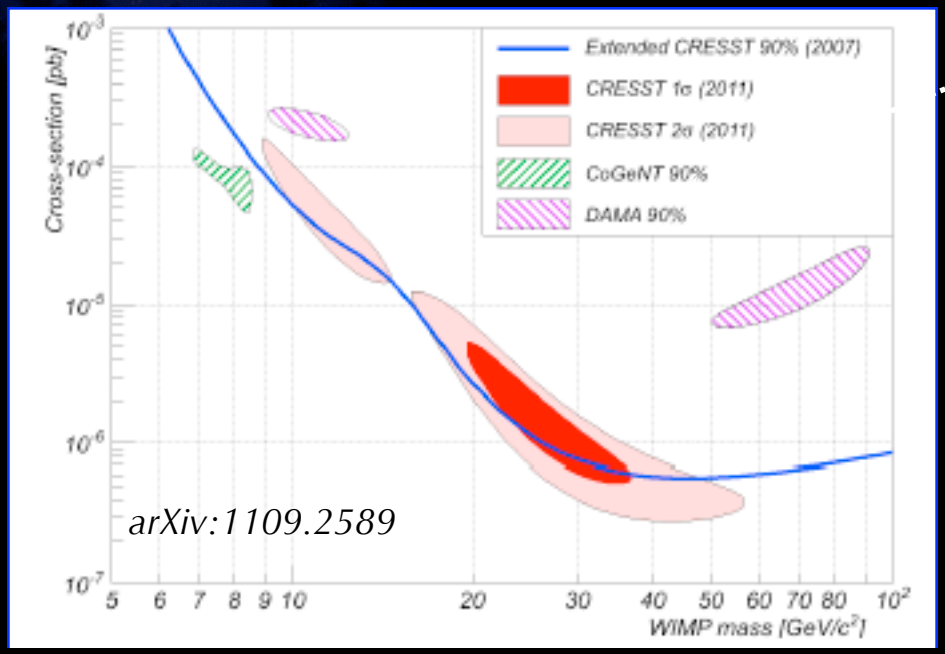




direct detection:



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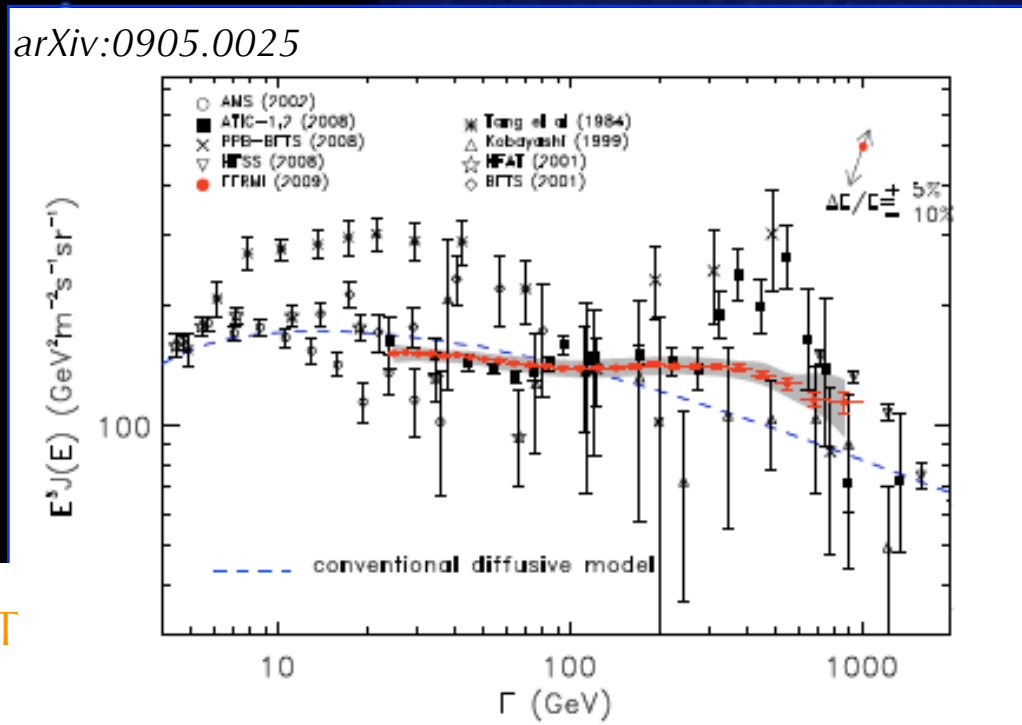

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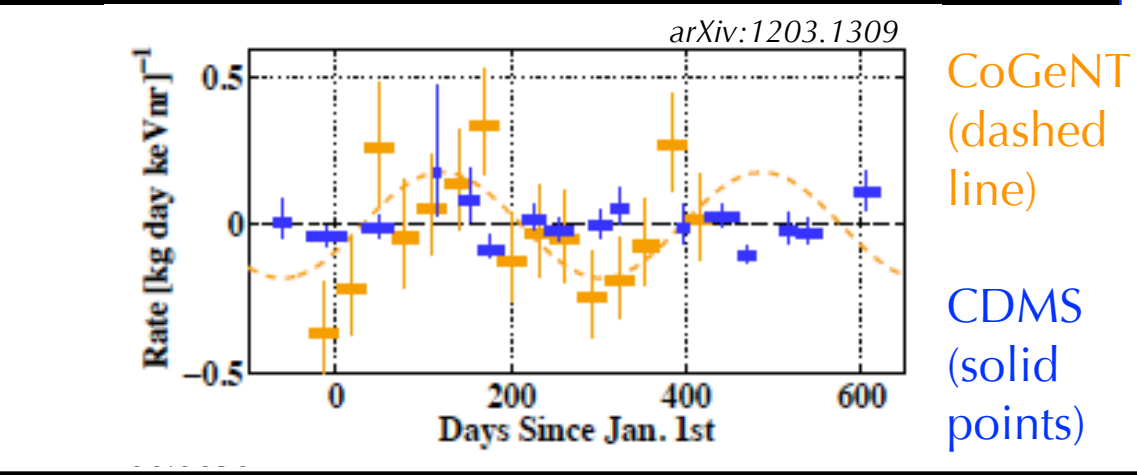

CoGeNT (dashed line)

CDMS (solid points)

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

Outline

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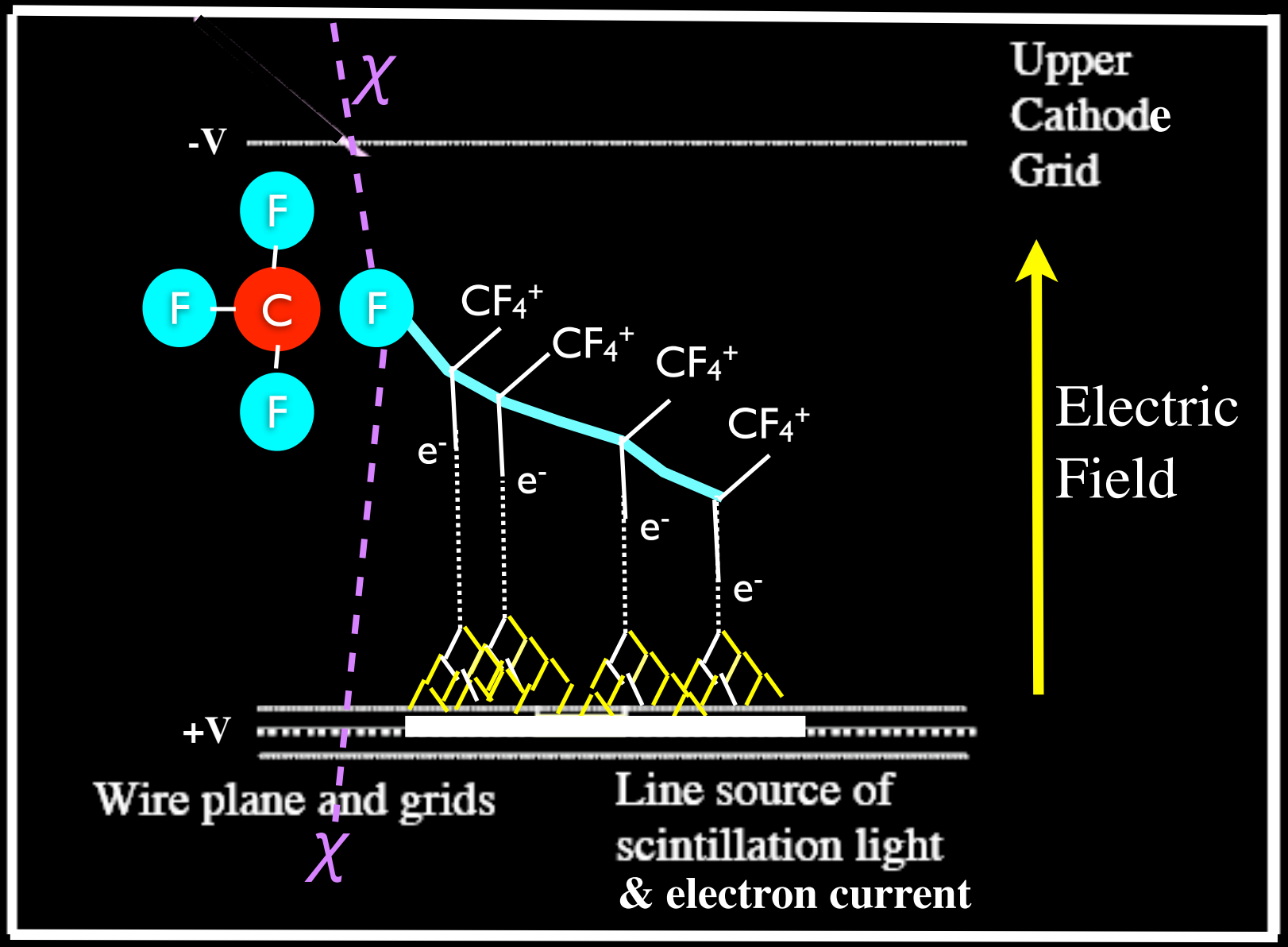
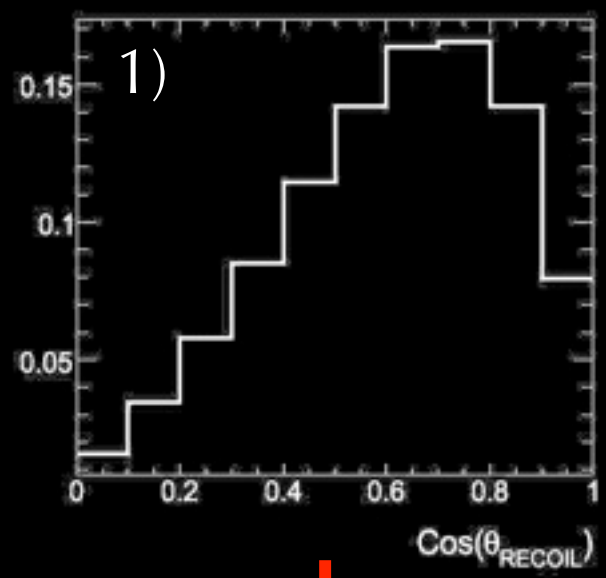
Recent Progress from Directional Detectors

Detector Concept



Signals in Directional Detectors



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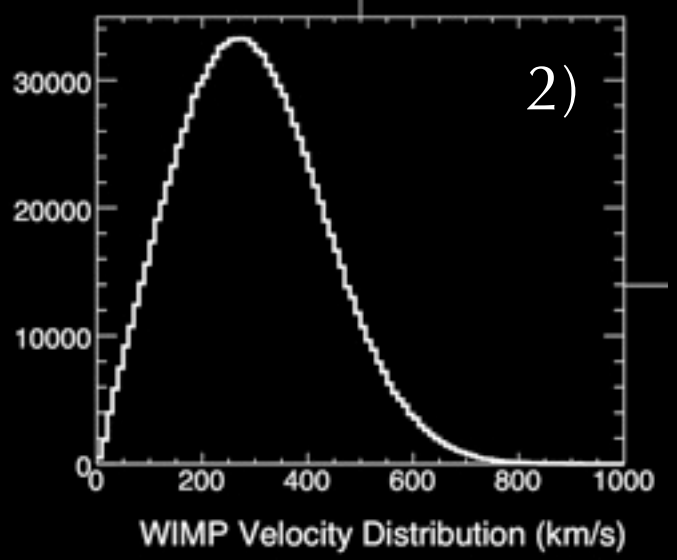

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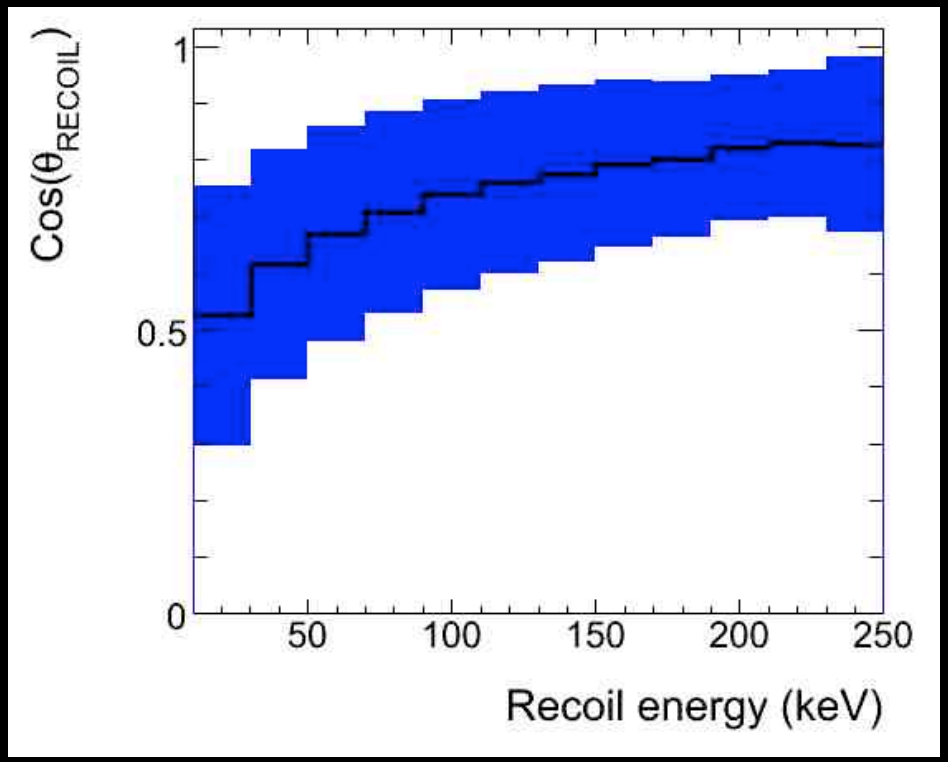
distribution of signal events determined by:

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



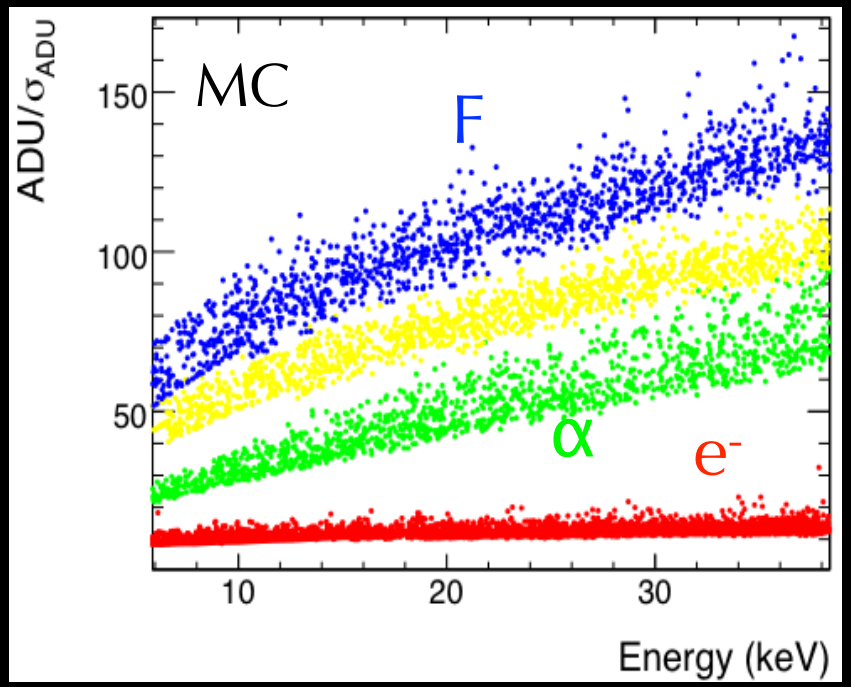
need ~50 keV threshold for directional detectors (for 100 GeV WIMPs), 35º resolution

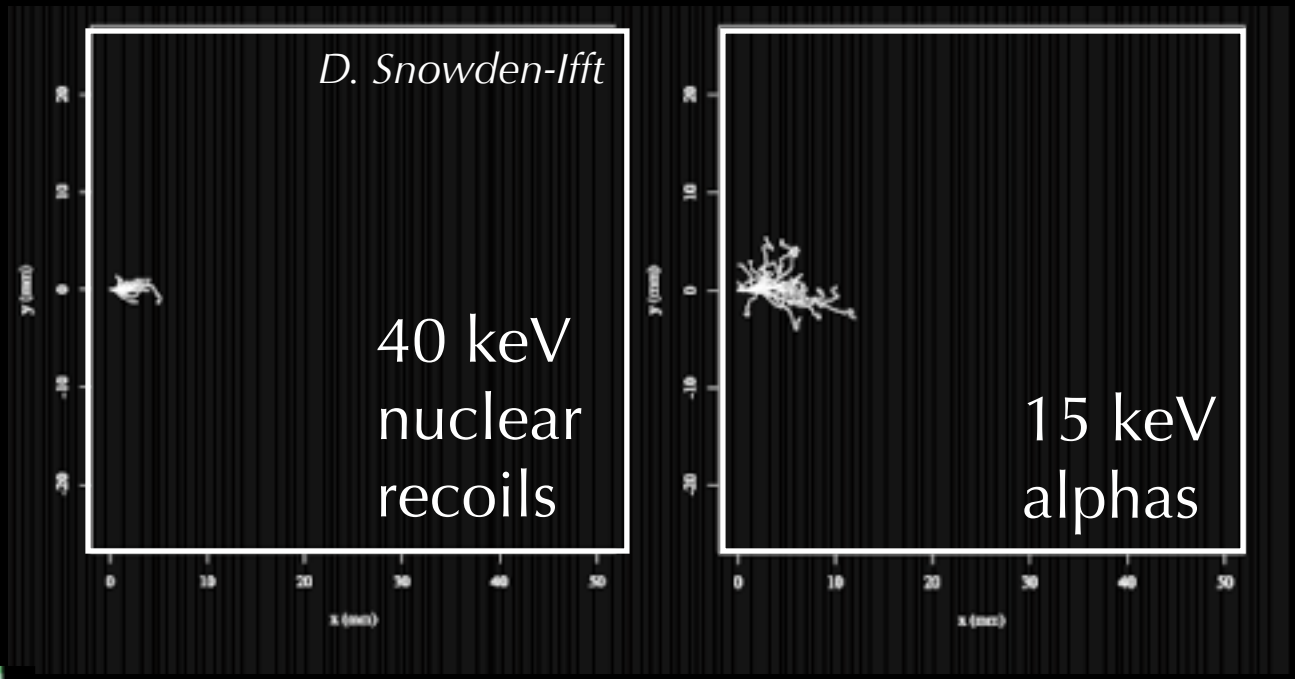
Backgrounds in Directional Detectors

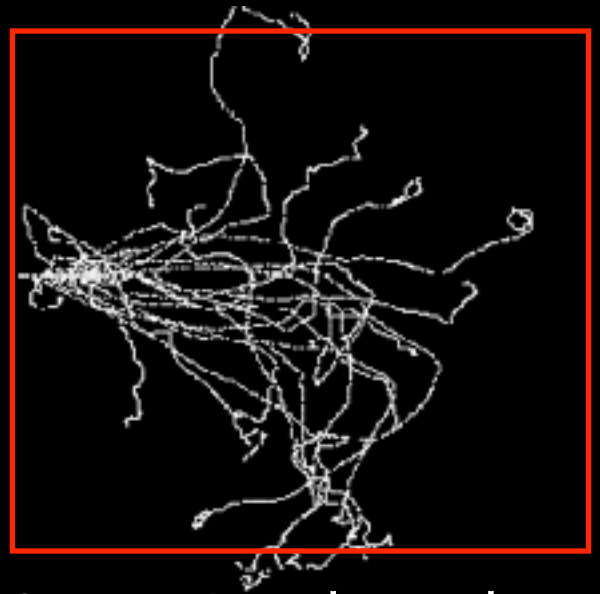
Three strategies:

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

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







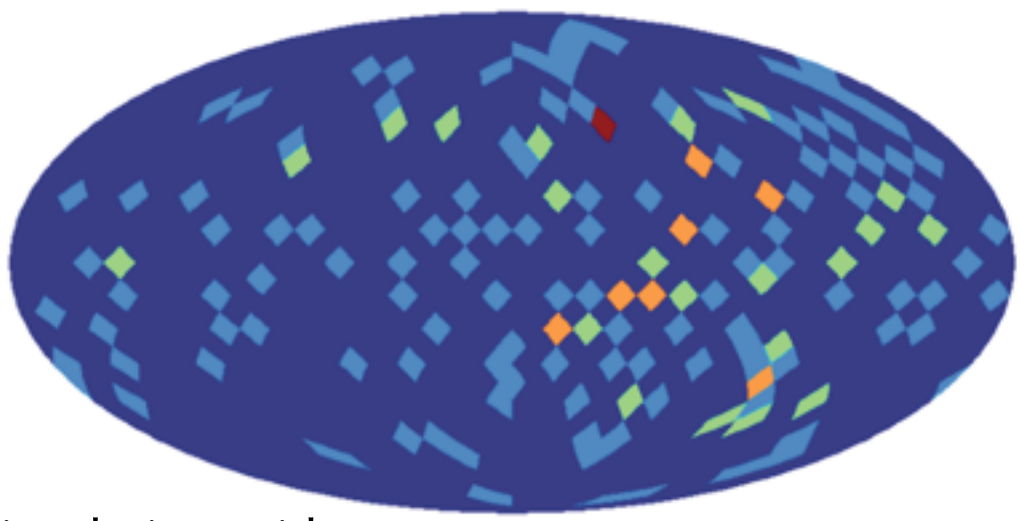
13 keV electrons

Optimization

how many events to detect the dark matter wind?

<u>Detector Properties:</u>
detector resolution
energy threshold
background
reconstruction
(2D vs. 3D)
vector ↗ or axial ↔
reconstruction

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



simulation with
100 signal, 100 background

Billard et al. 2010

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

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

do not need "zero background" for directional detectors

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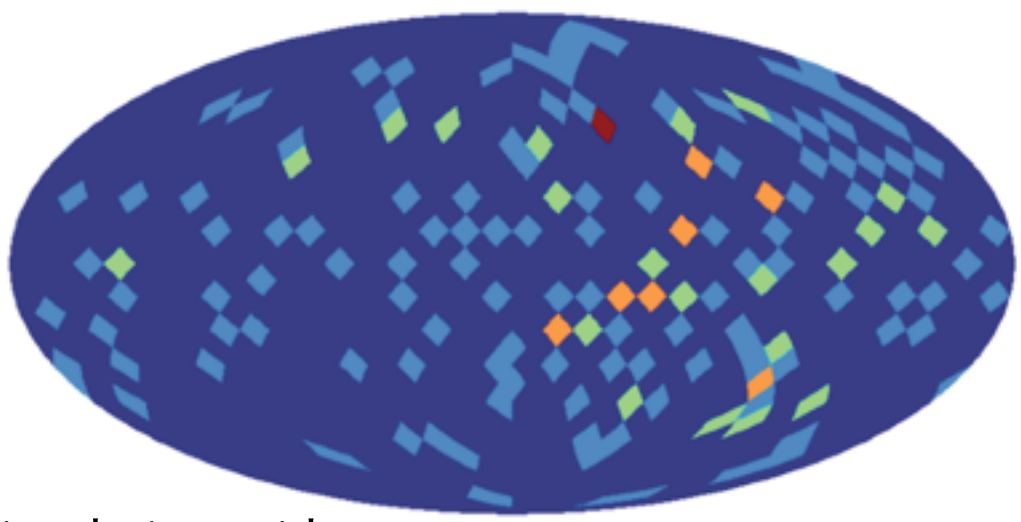

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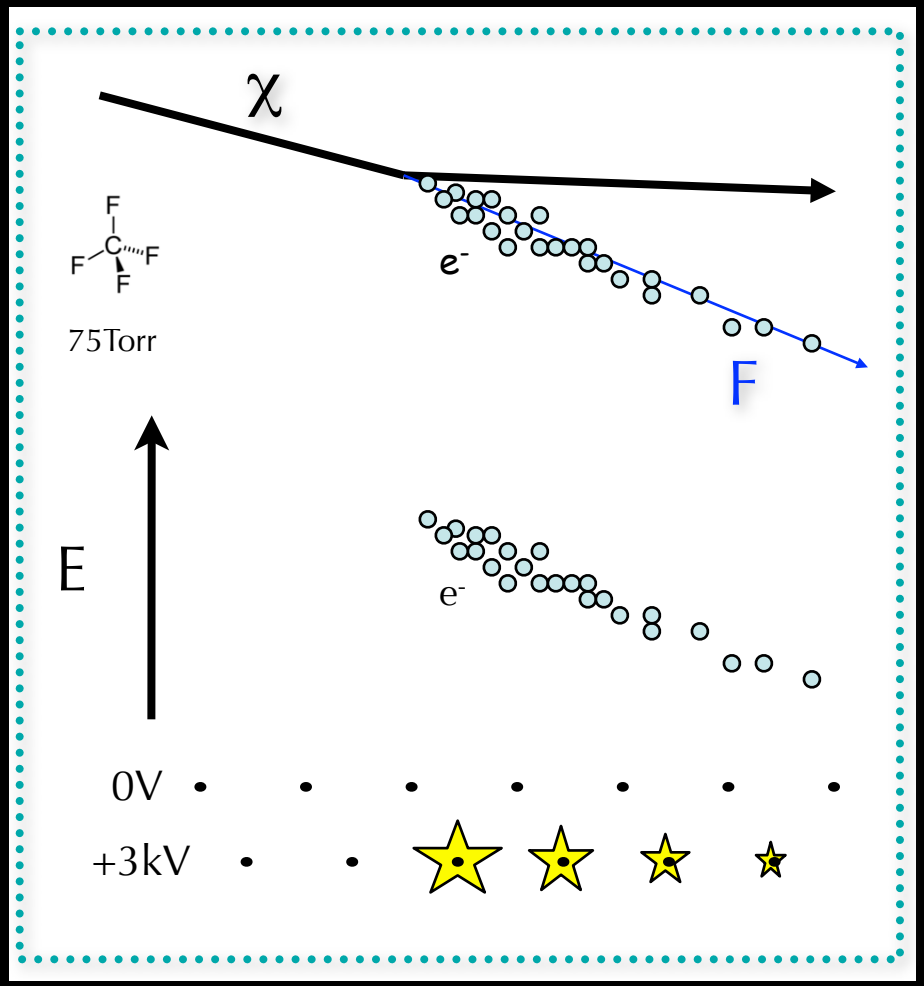
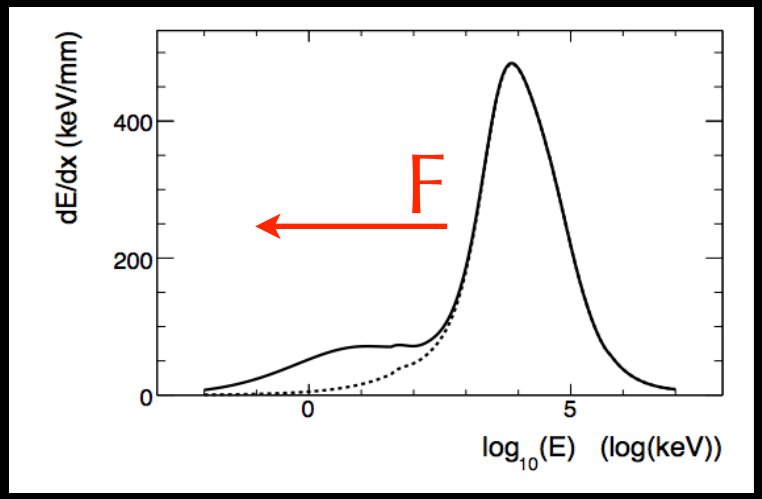
Head-Tail Detection



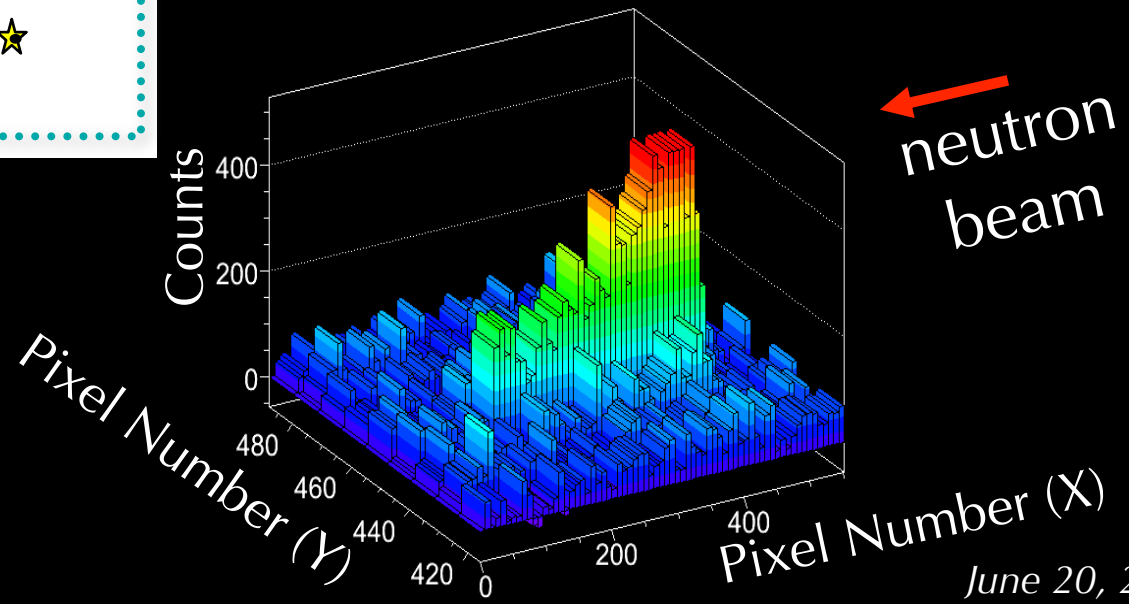
D. Dujmic, JM, et al., NIMA 584:337 (2008)

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

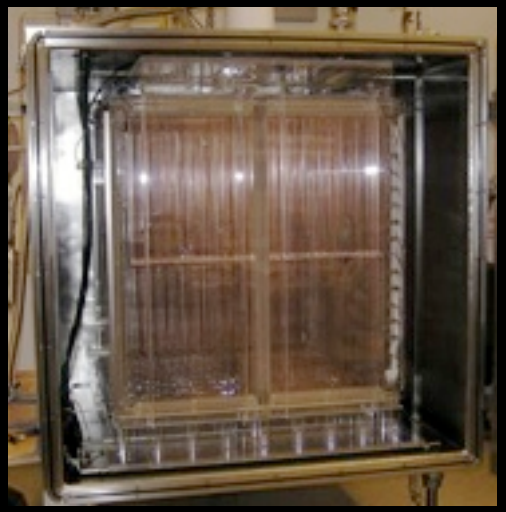


2. drifting electrons preserve dE/dx profile if diffusion is small

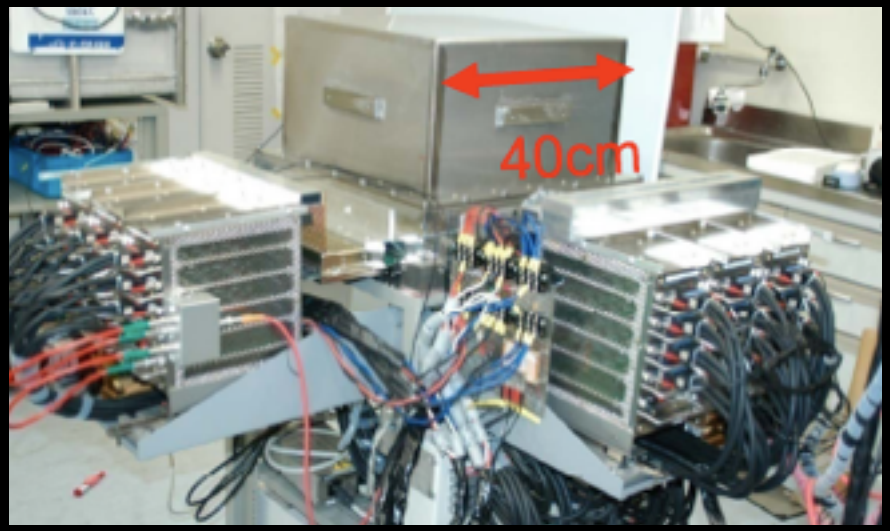
3. multiplication in amplification region produces e- + scintillation



Directionality Around the World

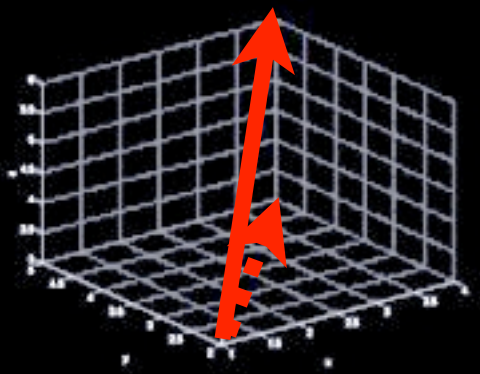


DRIFT: in Boulby (UK),
first directional experiment!
S. Burgos et al., Astropart. Phys. 28, 409 (2007)



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

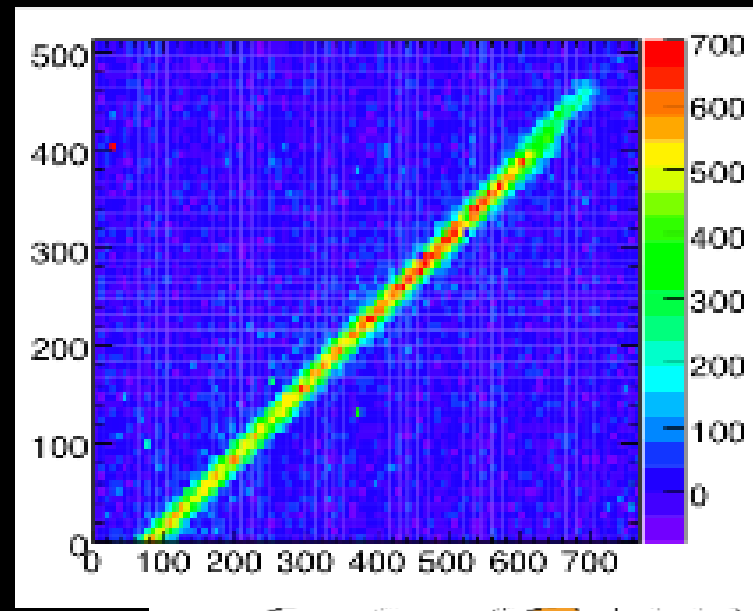
DMTPC: in WIPP (US),
optical and charge readout
D. Dujmic, JM, et al.,
NIM A 584:337 (2008)



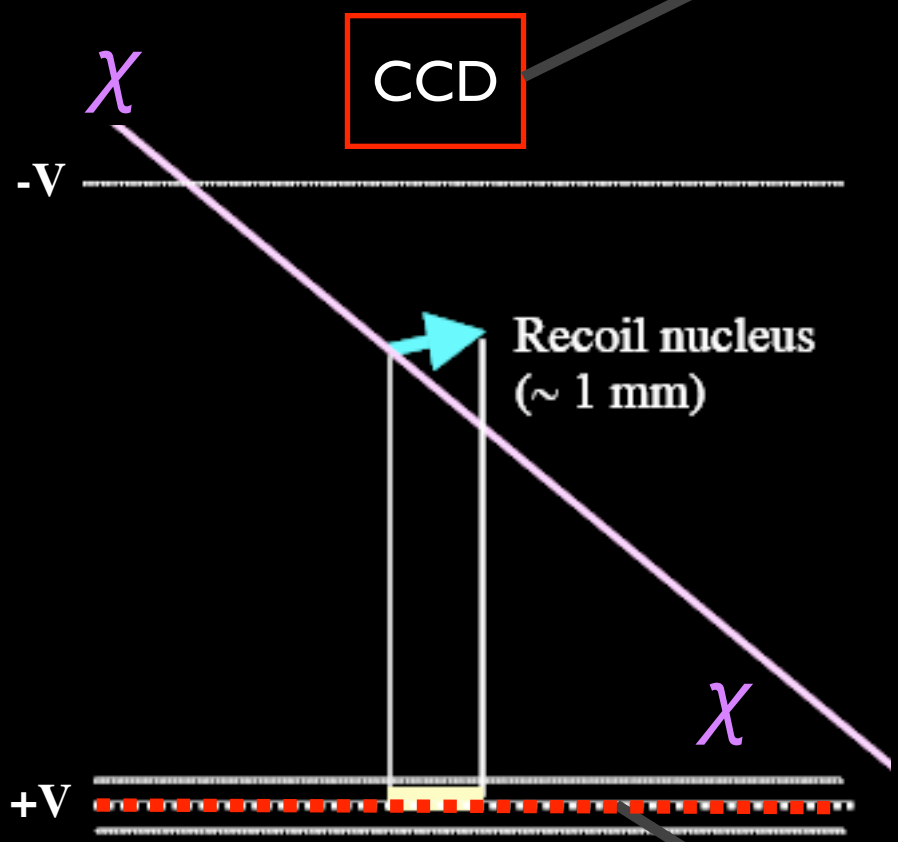
MiMAC-He3: ILL, planned for
Modane (France), A-dependence
D. Santos, et al., J. Phys. Conf. 65, 021012 (2007)

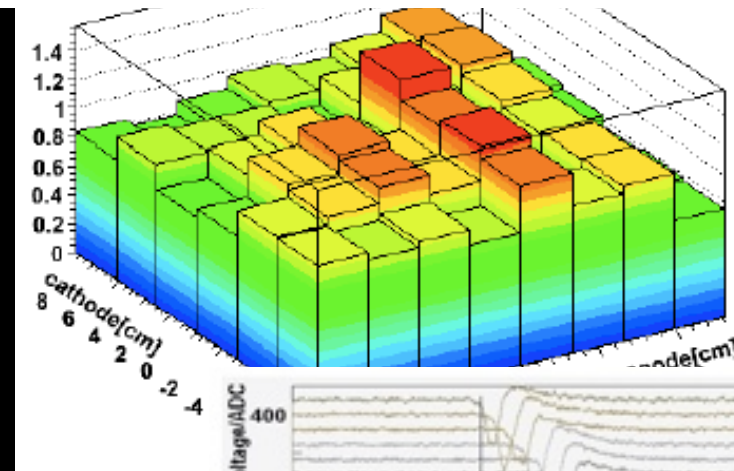
R&D: emulsion detectors, charge focussing, pixel chip readout, scintillating crystals...

Photon Signal

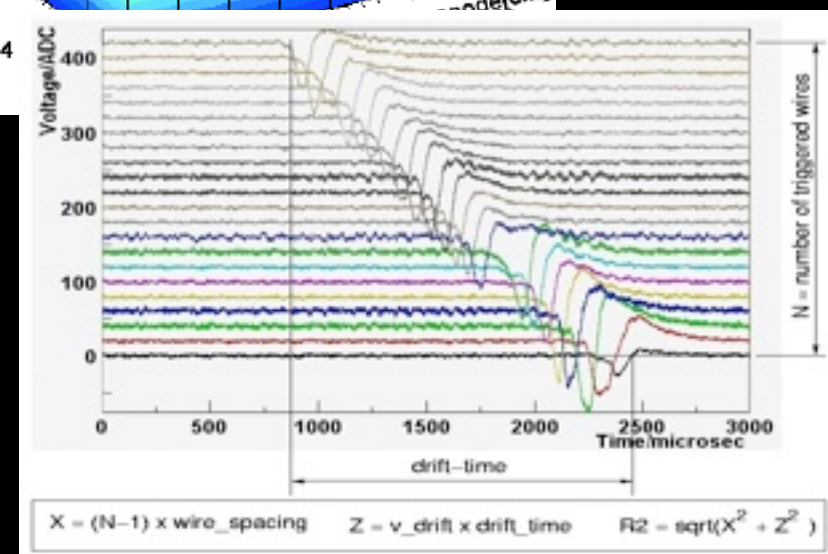


Optical Readout (DMTPC)





Charge Readout (NEWAGE, MIMAC)



Electron/Ion Signal

Directional Detection Whitepaper: arXiv:0911.0323

MWPC Readout (DRIFT)

Outline

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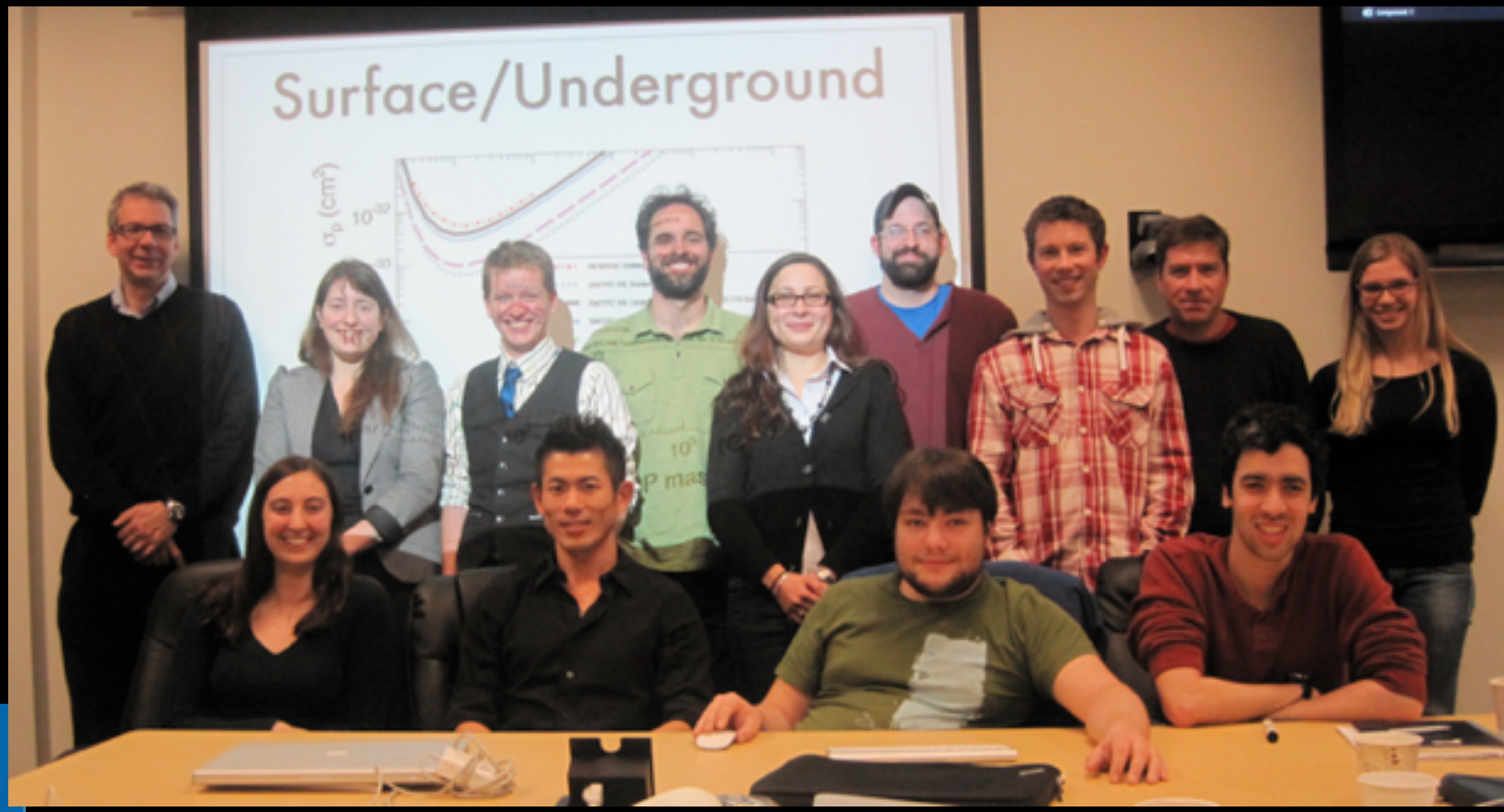
Directional Dark Matter Detection

Recent Progress from Directional Detectors

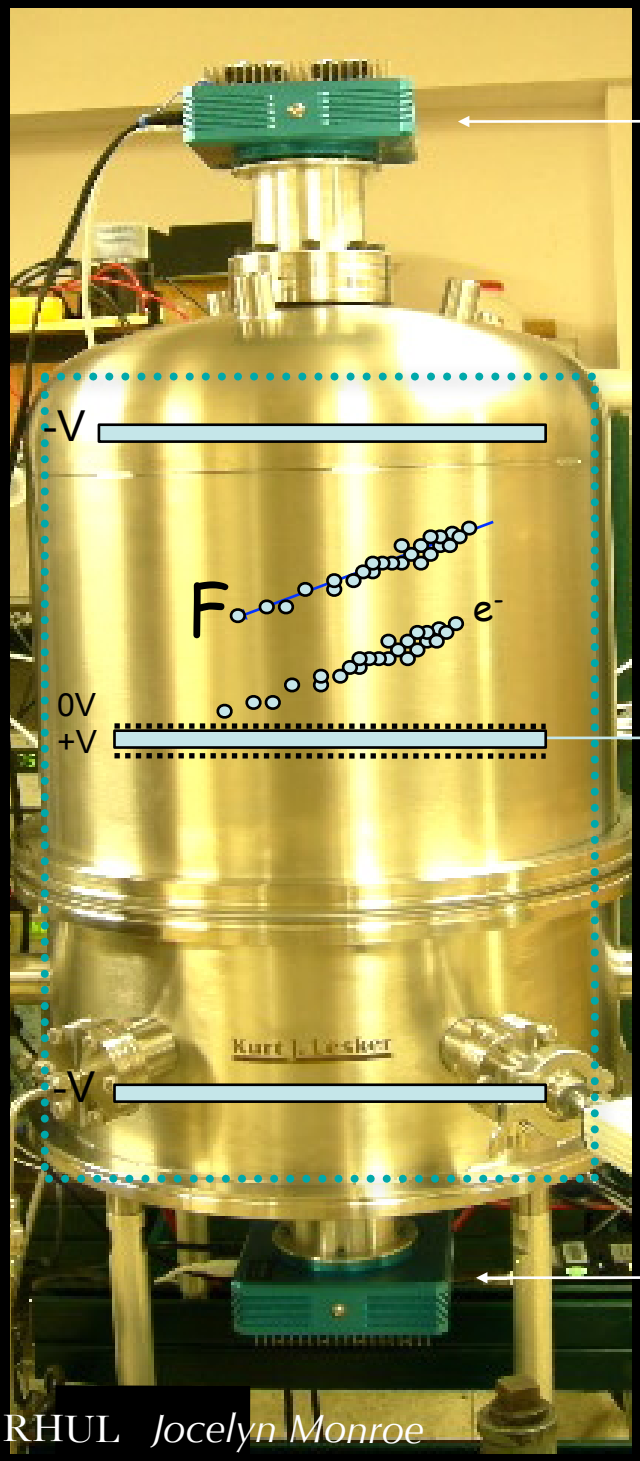
DMTPC Collaboration



Boston University: S. Ahlen*, A. Inglis, H. Tomita
Brandeis University: A. Dushkin, *H. Ouyang*, G. Sciolla, H. Wellenstein*
Bryn Mawr: J. B. R. Battat*, ***K. Recine***
MIT: ***C. Deaconu***, D. Dujmic, P. Fisher*, ***S. Henderson, A. Kaboth, J. Lopez***
University of Hawai'i at Manoa: I. Jaegle, S. Vahsen*
Royal Holloway University of London: *P. Giampa*, ***R. Eggleston,*** J. Monroe**, *G. Muraru*

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

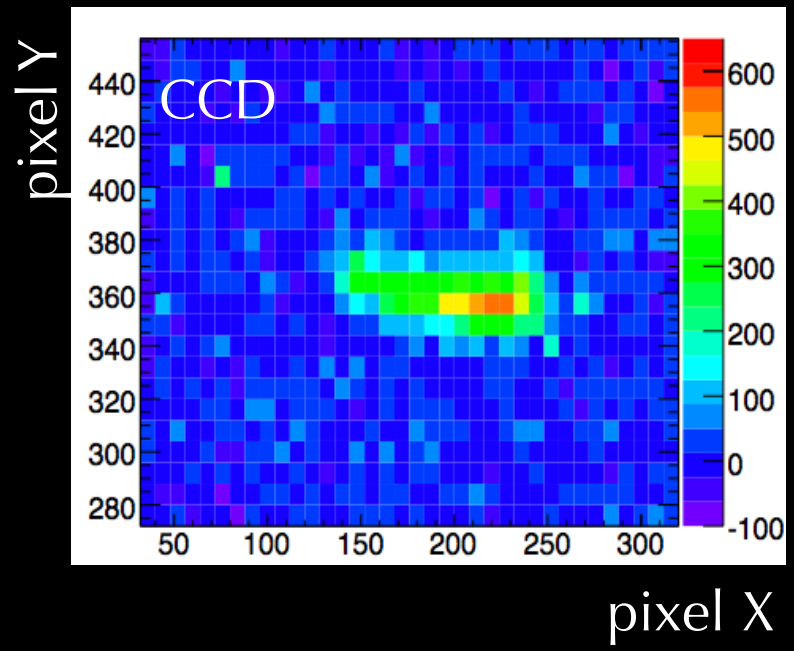
DMTPC Detector Design

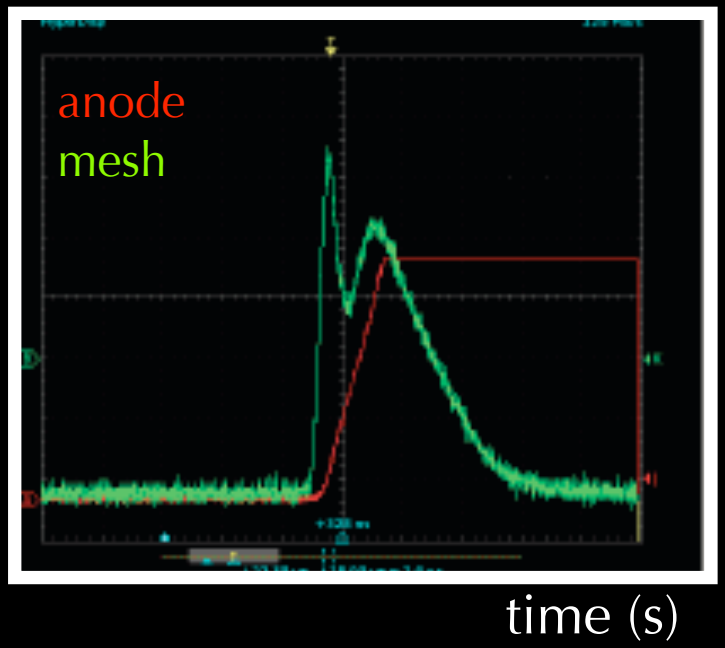


Light readout

Charge readout

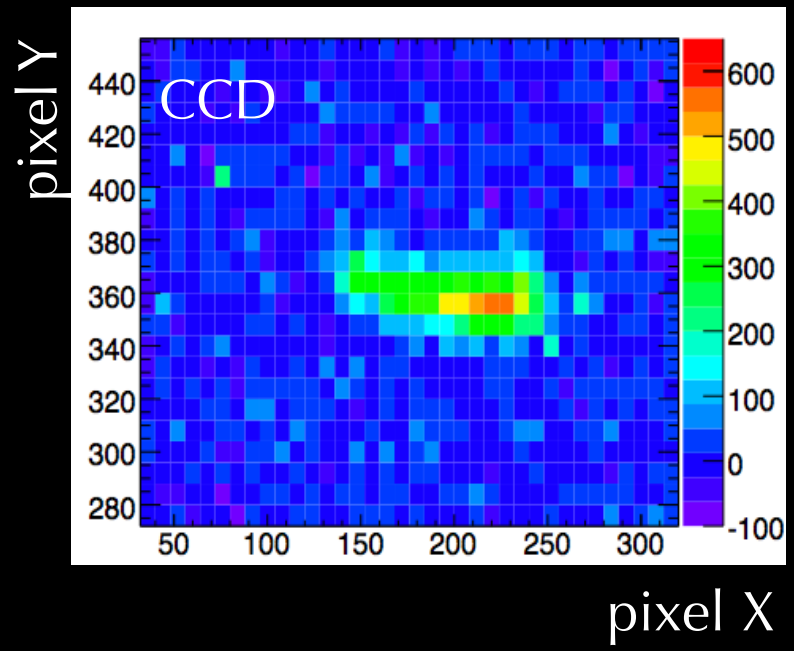
Light readout

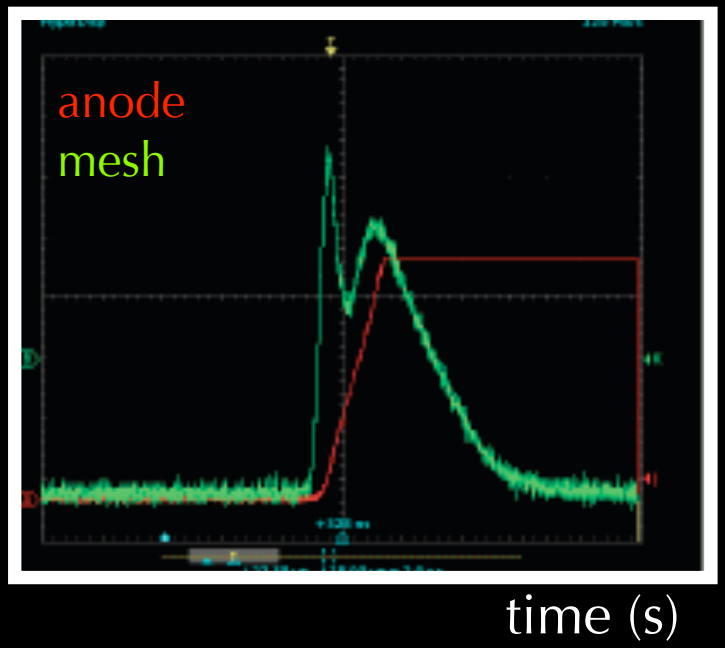




goal: charge and light= background rejection, 2->3D

DMTPC Detector Design





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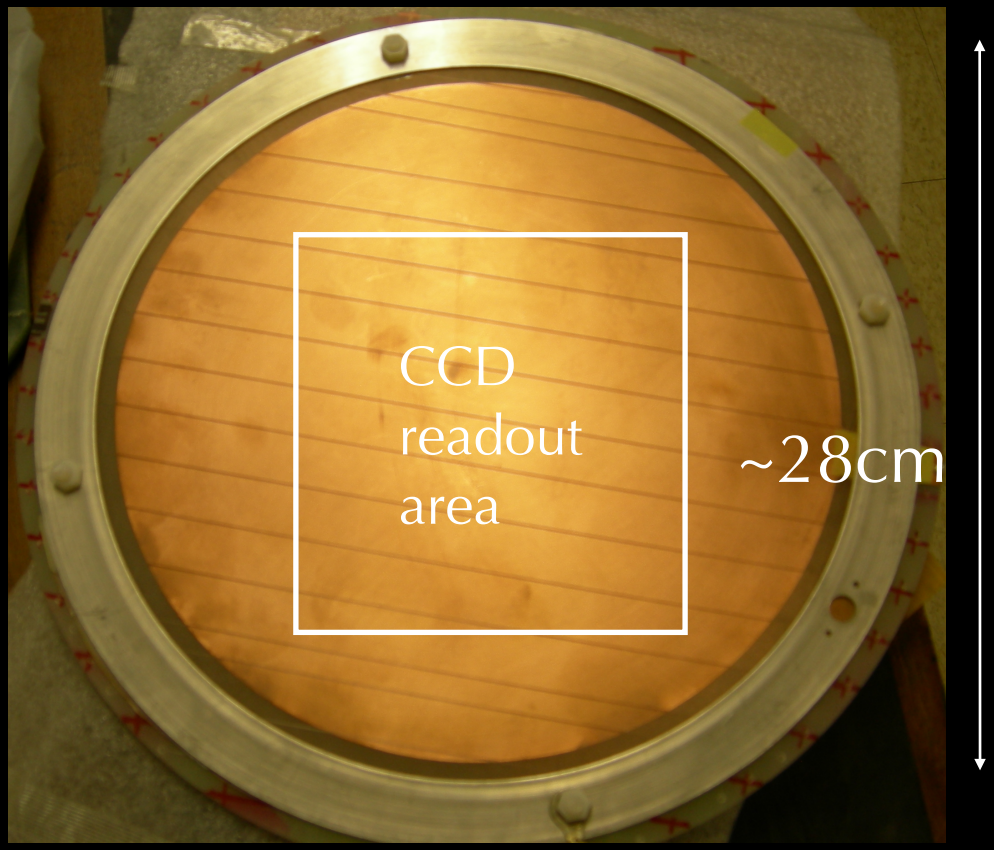
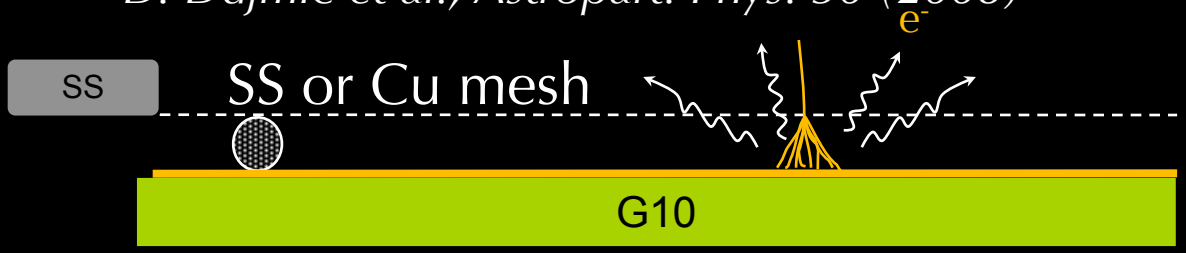
Amplification Plane

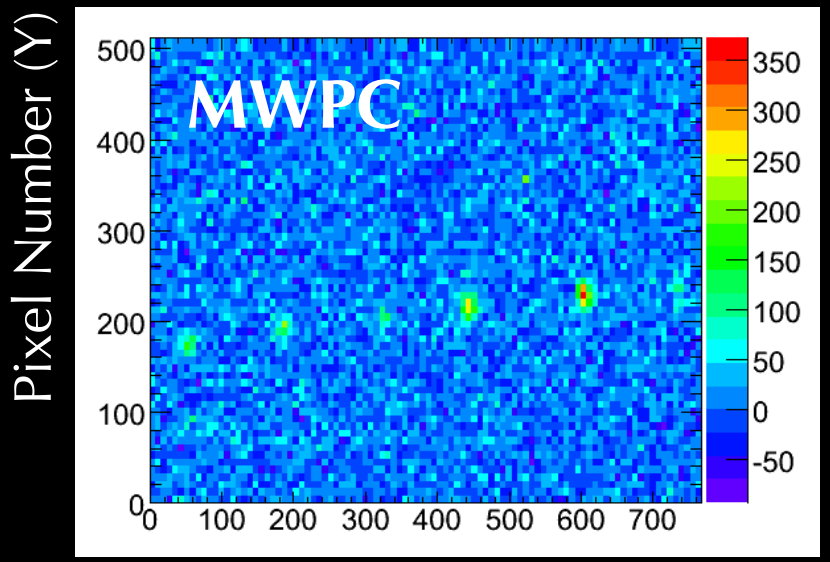
Copper Mesh, 256 um pitch

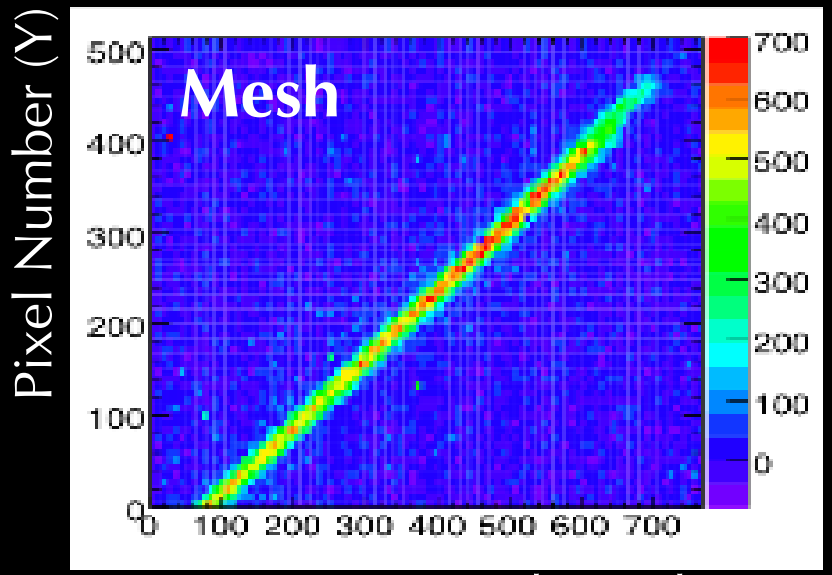


D. Dujmic et al., Astropart. Phys. 30 (2008)



Resistive separators, dia=0.5mm, every 2.5cm



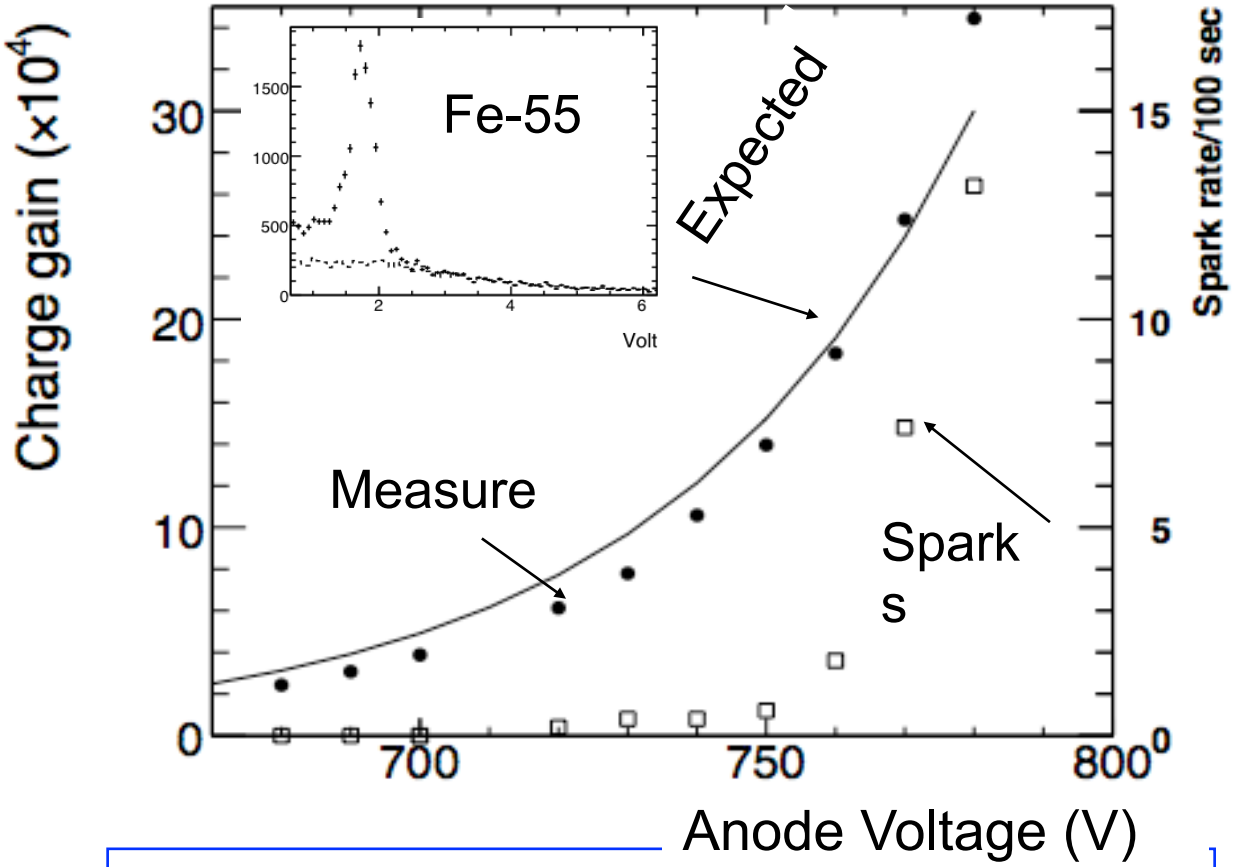


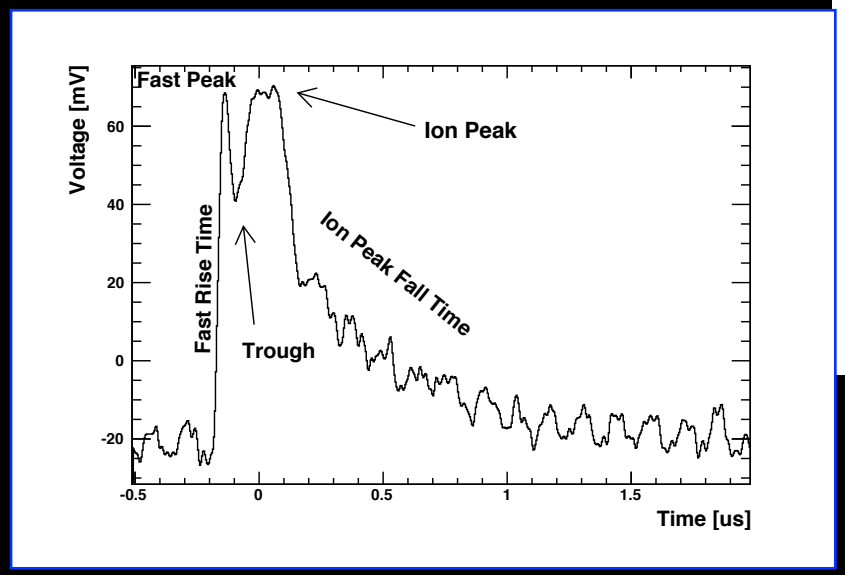
20x smaller pitch,
higher gain, 1->2D

Charge Readout

Anode readout for energy measurement, veto ring

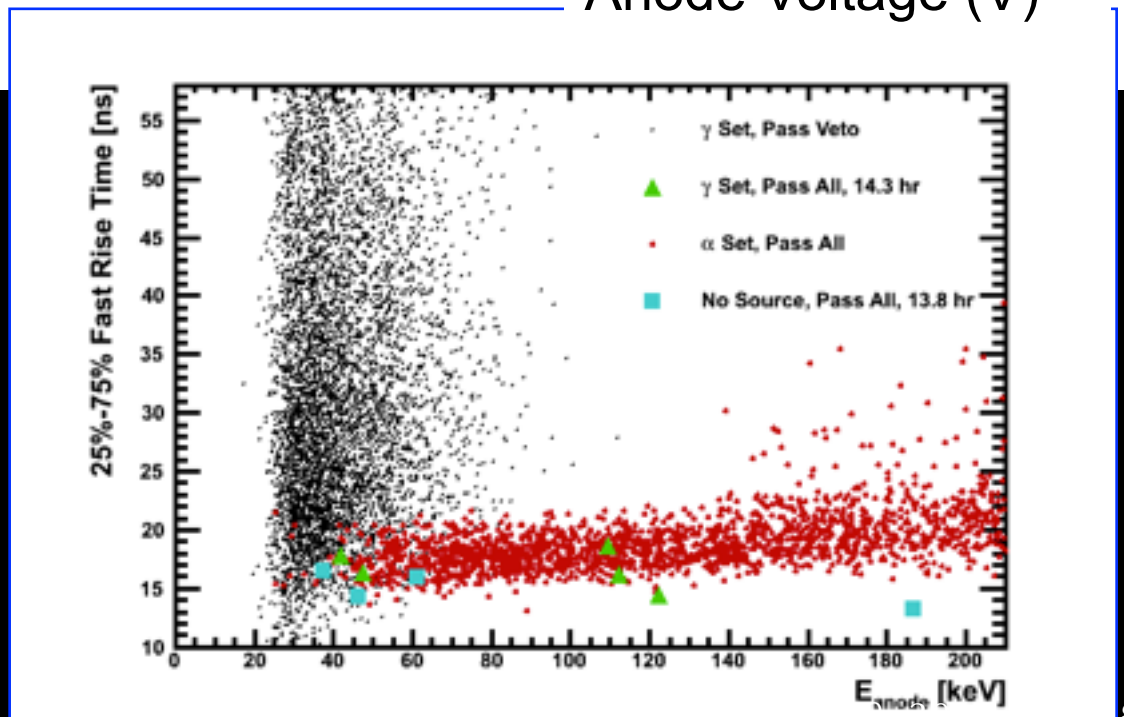
- Multiplication calibrated with Fe-55: 10^4 - 10^5
- W = 33.8 +/- 0.4 eV *(I. Wolfe thesis)*





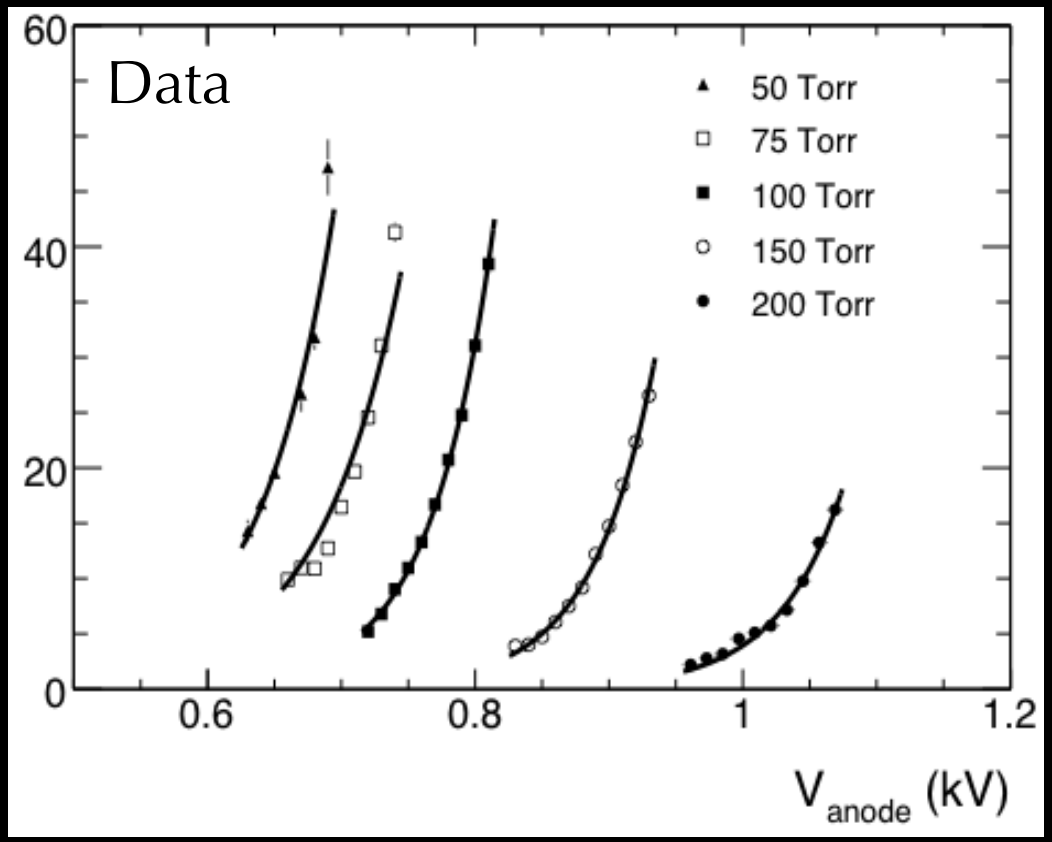
Mesh signal readout with fast amplifier to measure Δz

- gamma rejection: <5.6x10^{-6} (90% CL)
- *J. Lopez et al., arXiv:1109.3501*



Optical Readout

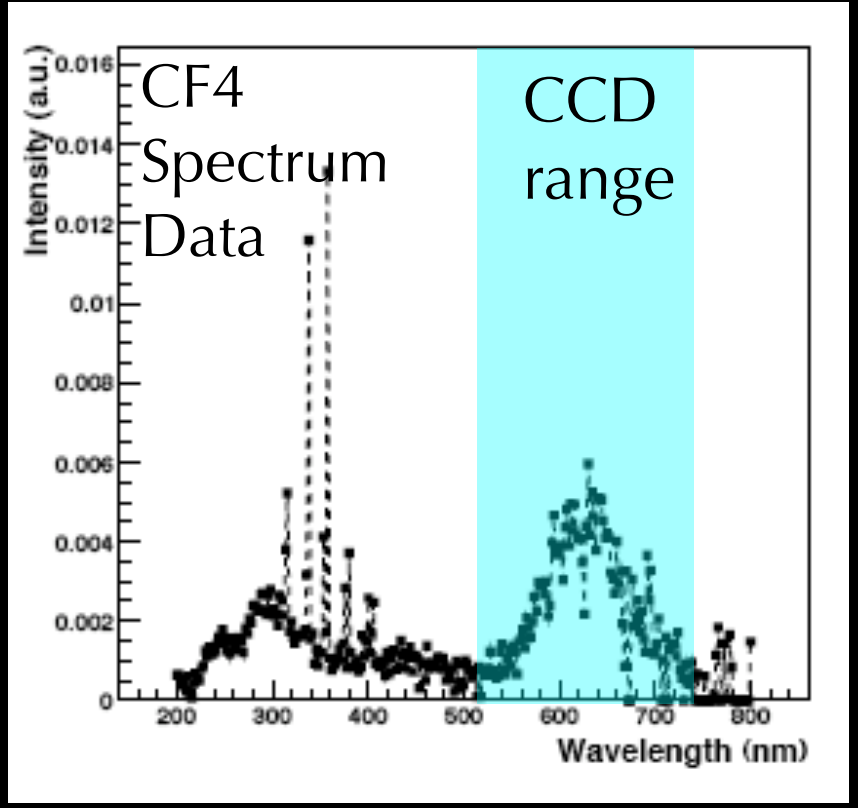
System gain:

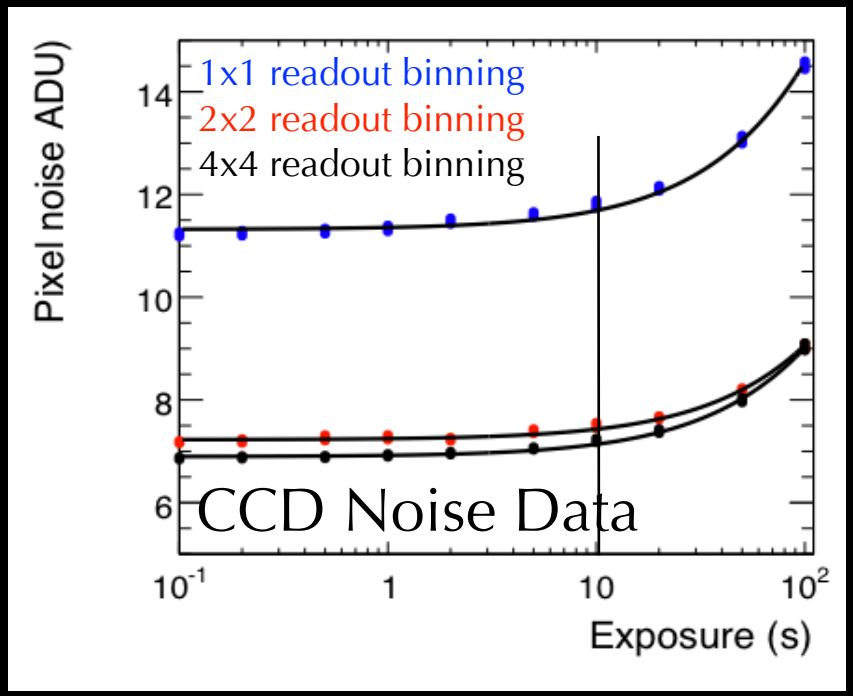


Increasing gain + track length with lower pressure, but decreasing mass!

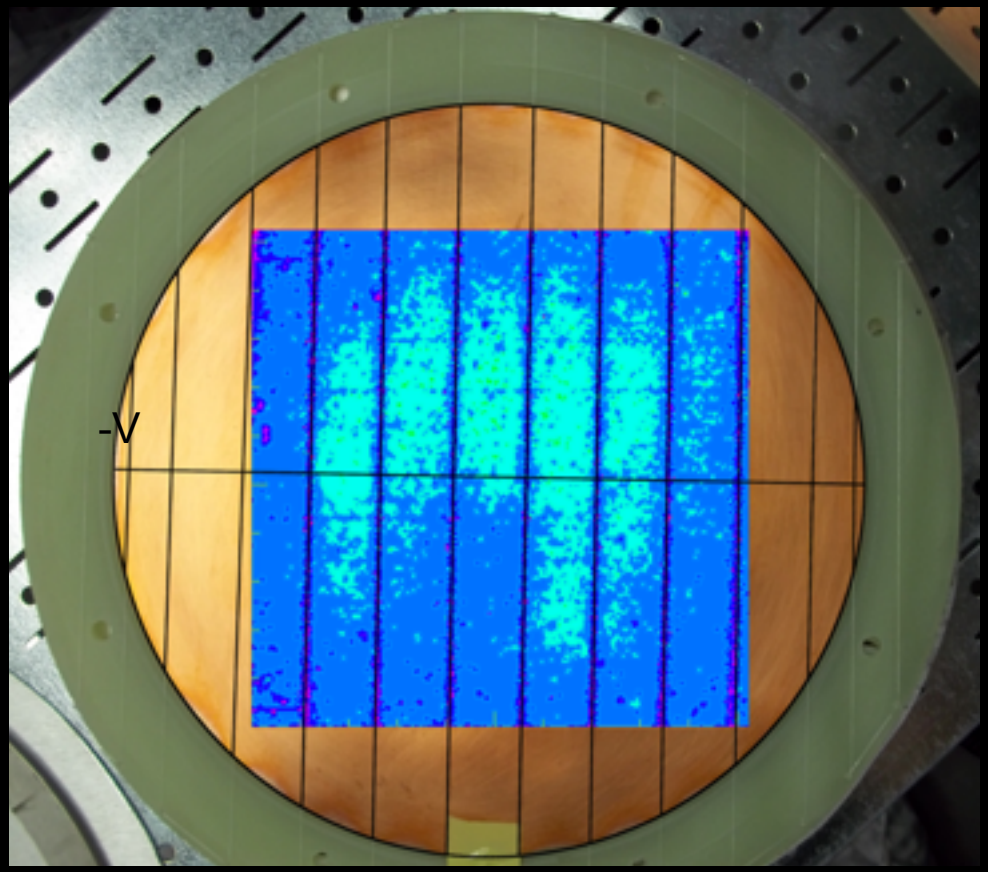
CF4 scintillation: $\gamma/e^- = 0.38 +/- 0.04$

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





Track Length and Energy Calibration

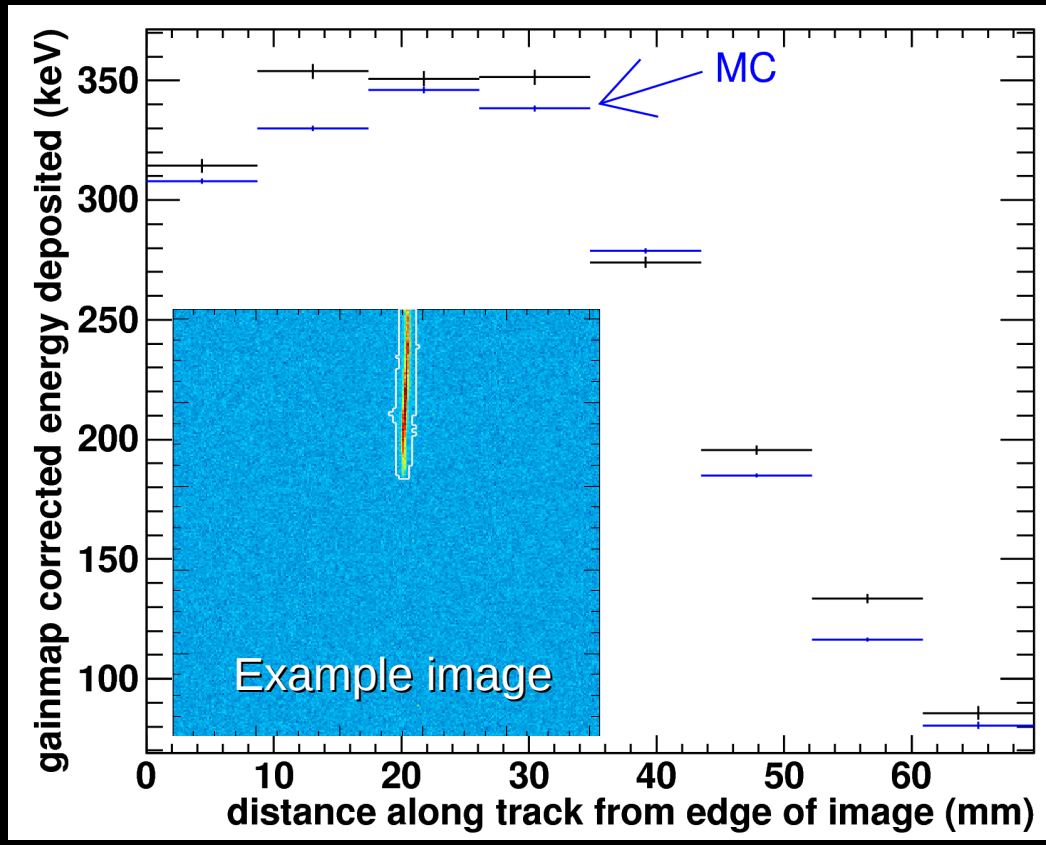


illuminate TPC with Co-57 (122,137 keV) and Cs-137 (662 keV) for length calibration

measure optical plate scale, by comparing spacer positions in gamma data with photo ~ 150 um/pixel, and gain uniformity

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

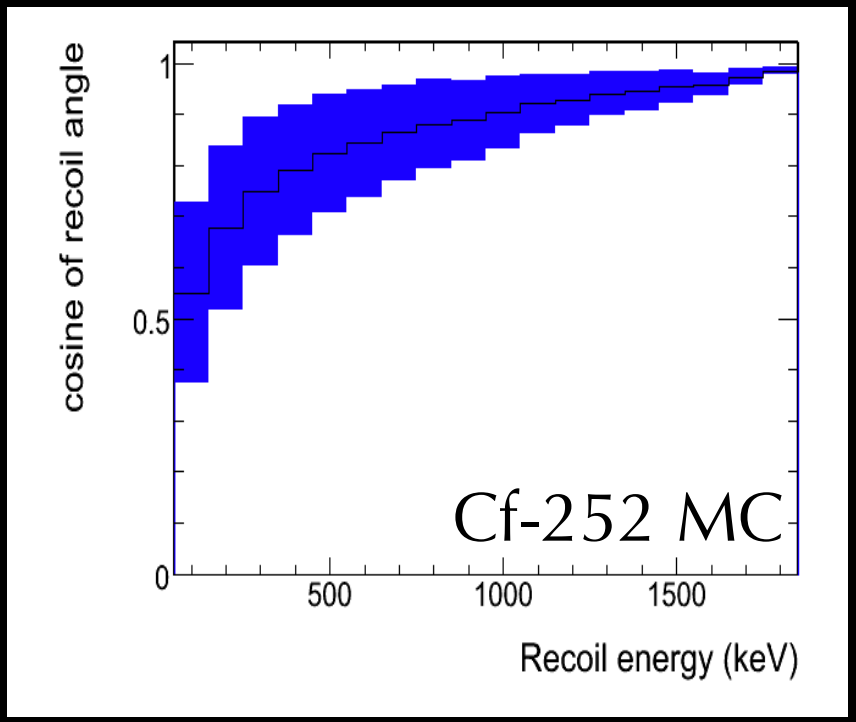


"WIMP" Calibration

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

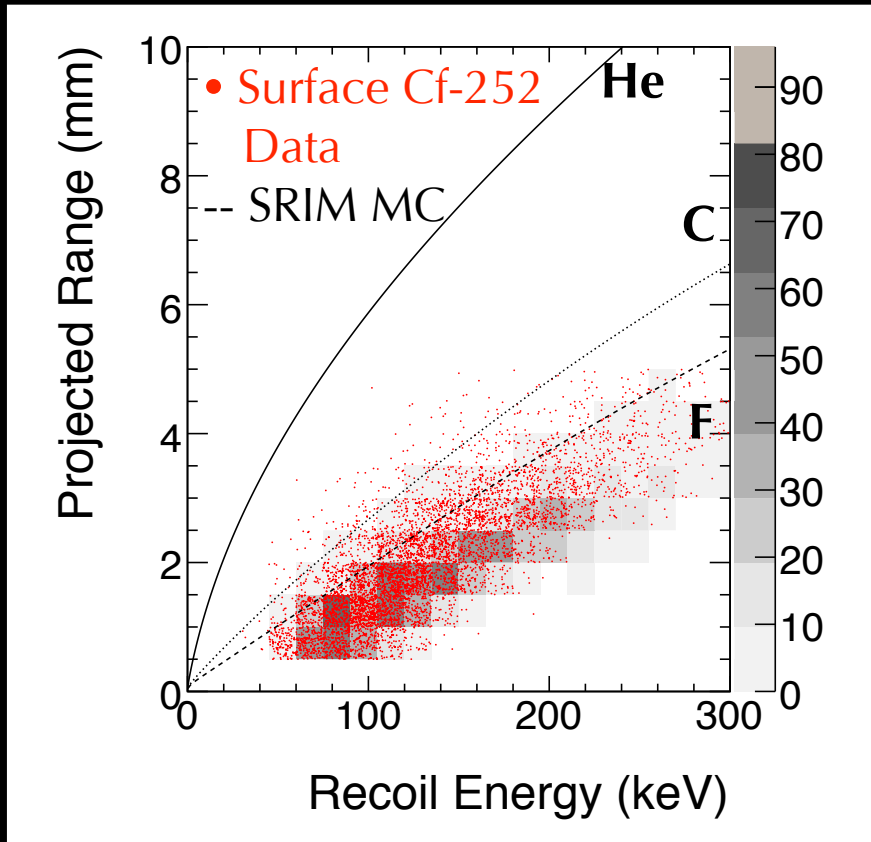
Energy and recoil angle distributions similar to dark matter induced recoils

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



minimum recoil energy detected: ~50 keVr

(Hitachi quenching model)

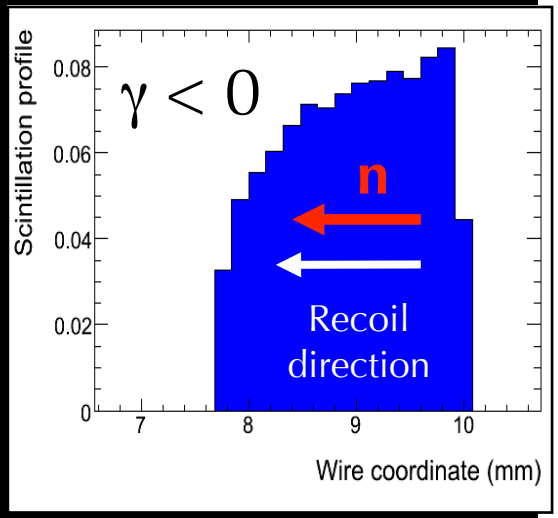


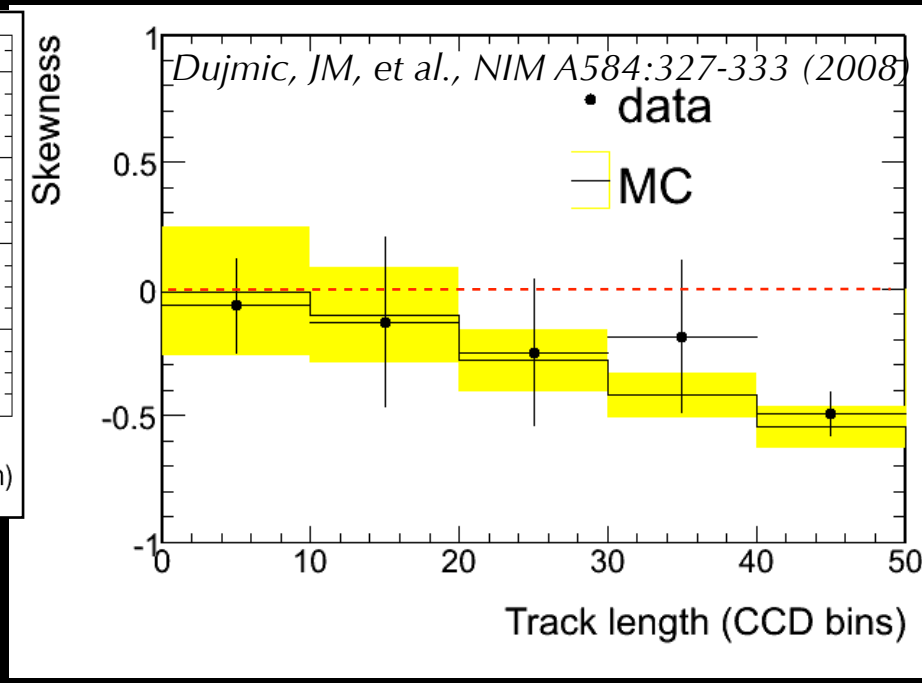
10^4 rejection of backgrounds from range vs. energy in directional detectors

S. Ahlen, JM, et al., PLB 695 (2011)

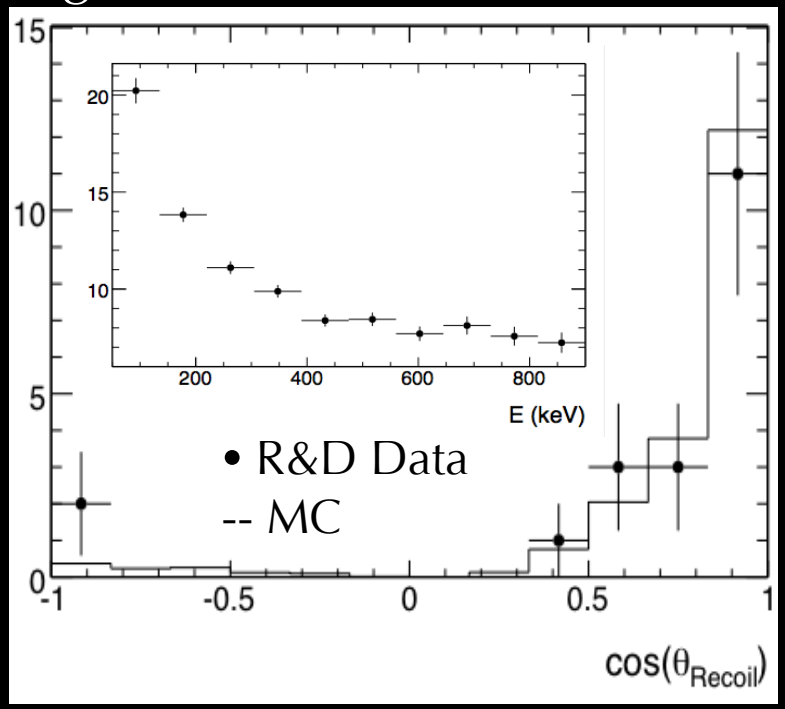
Directionality

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

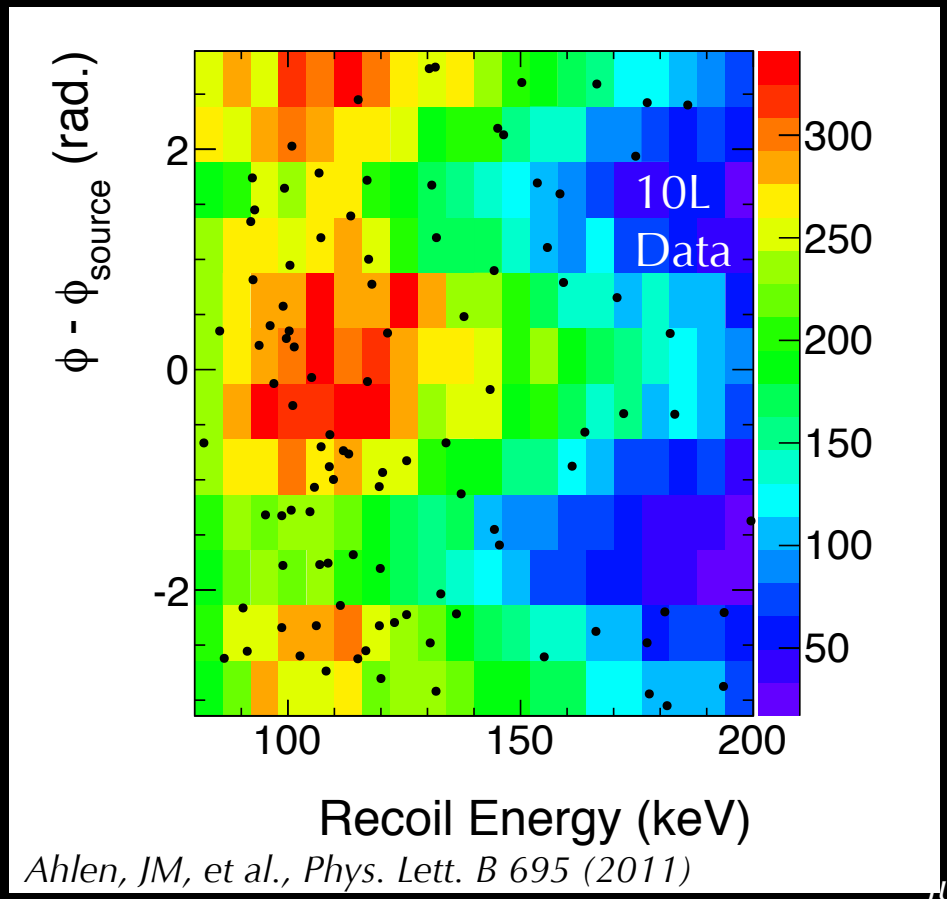




Signed cosine (E>200 keVr), 5 cm drift



diffusion has a big impact!



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

1D "sky map" for ^{252}Cf, and "WIMP " data

80-200 keVr, 20 cm drift

MC: 40° resolution at 80 keVr

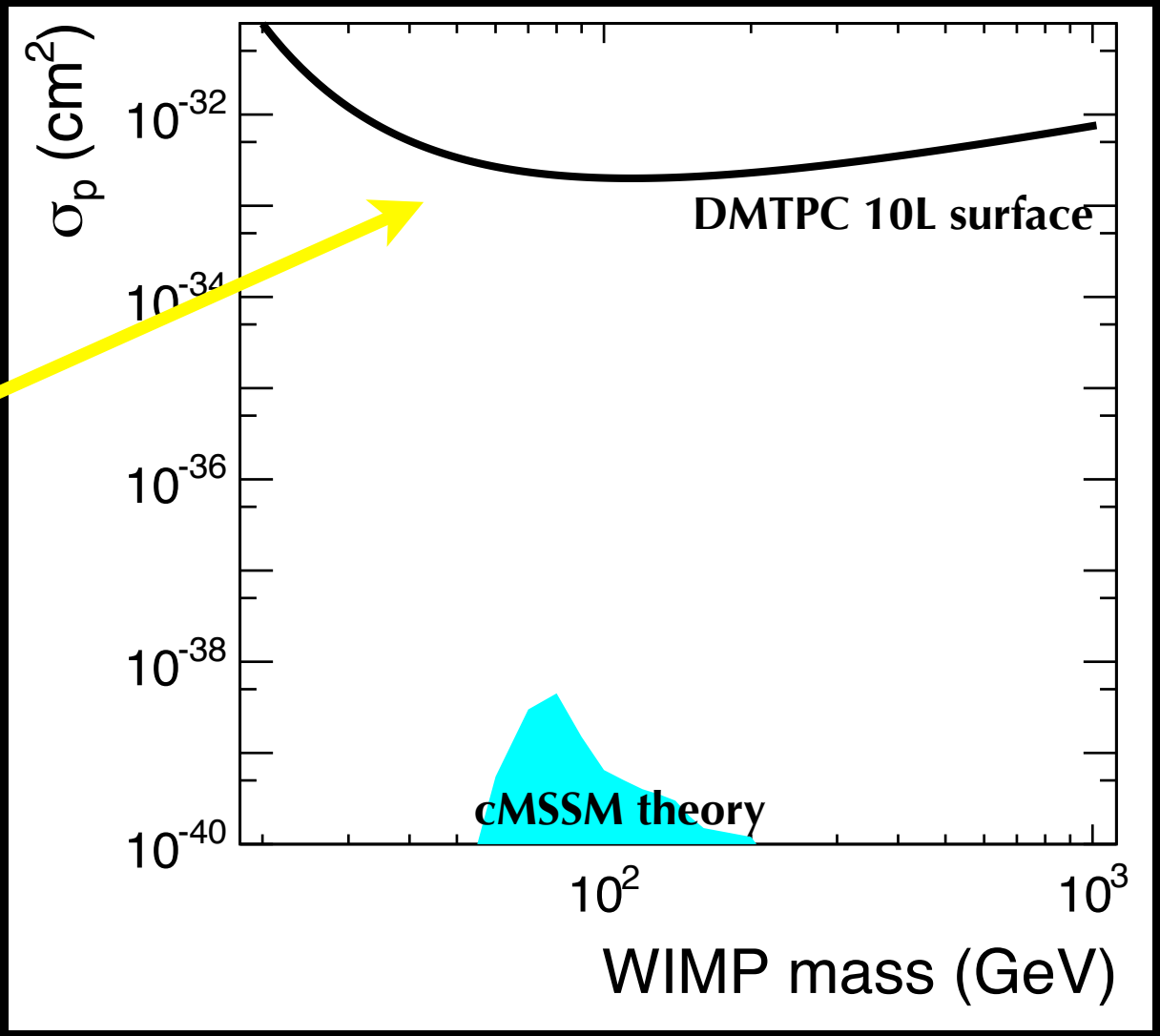
DMTPC Surface Run Result

observed 105 events in 80-200 keVr, expected 74 from surface neutrons

DMTPC limit at the surface, 38 gm-day exposure

at 80 keVr threshold, ~15 events/keV/kg/day

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



Theory region:
Rozkowski et al JHEP 07 (2007) 075
Ellis et al PRD63 (2001) 065016

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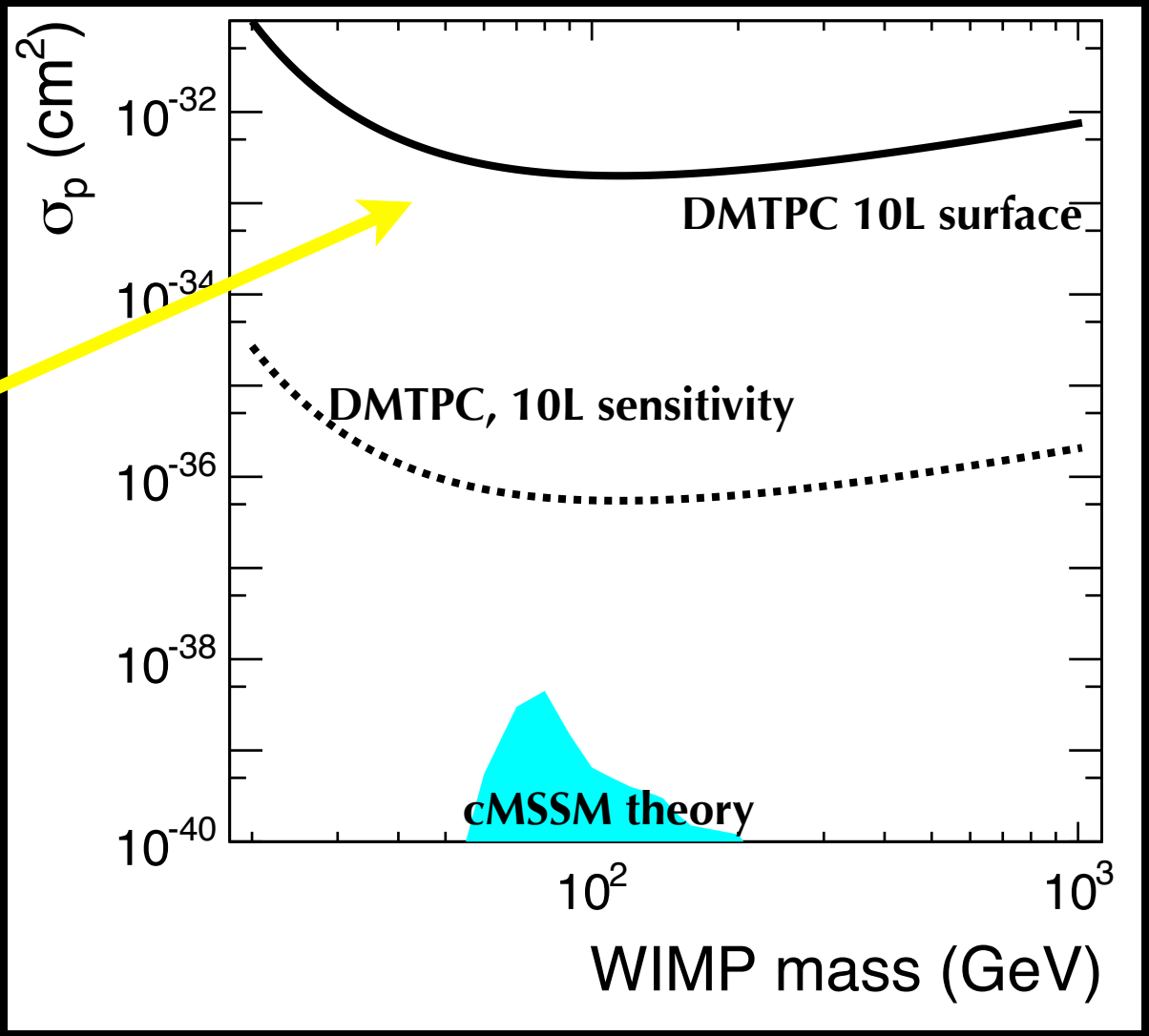

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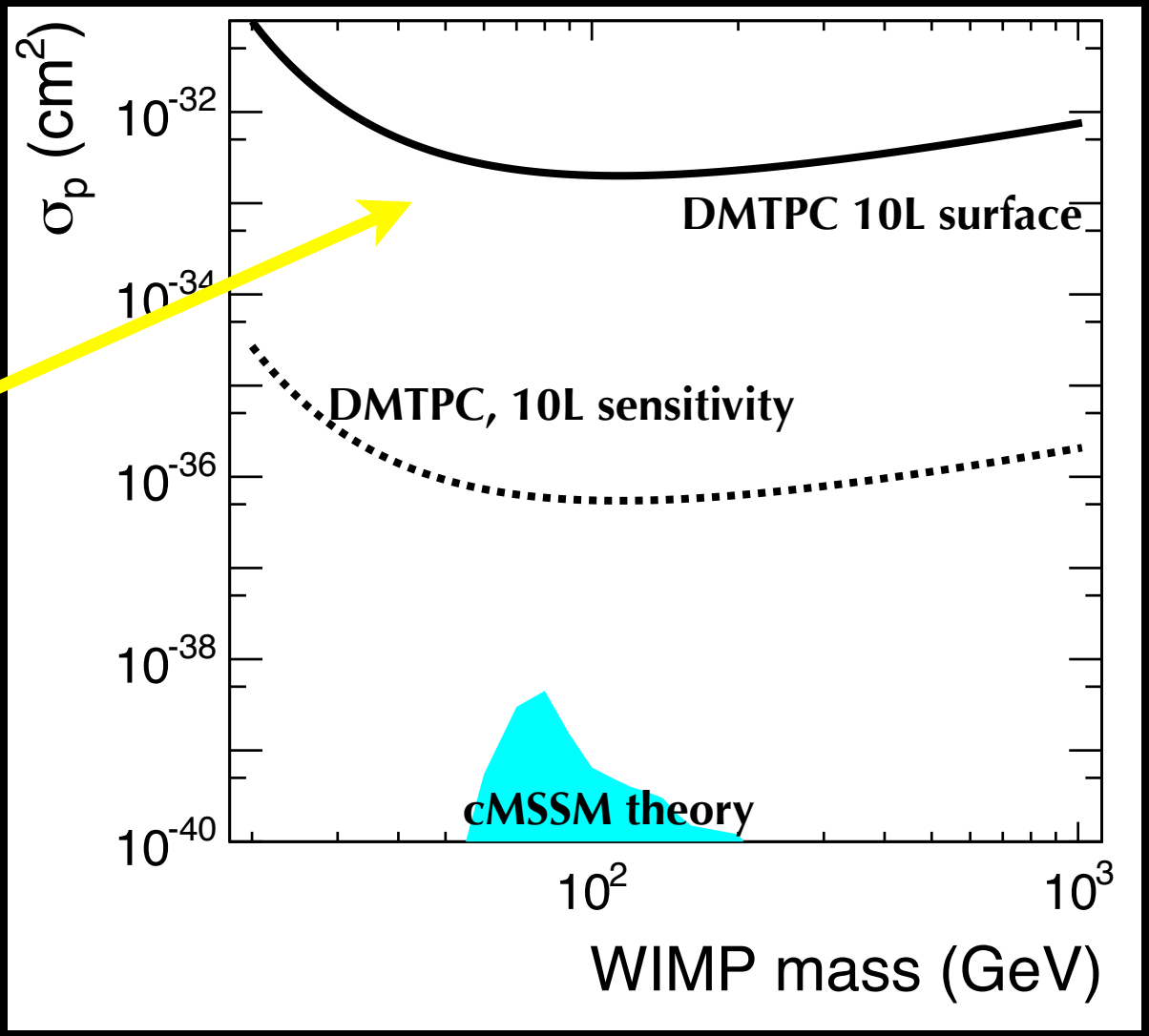
S. Ahlen, JM, et al., Phys. Lett. B 695 (2011)

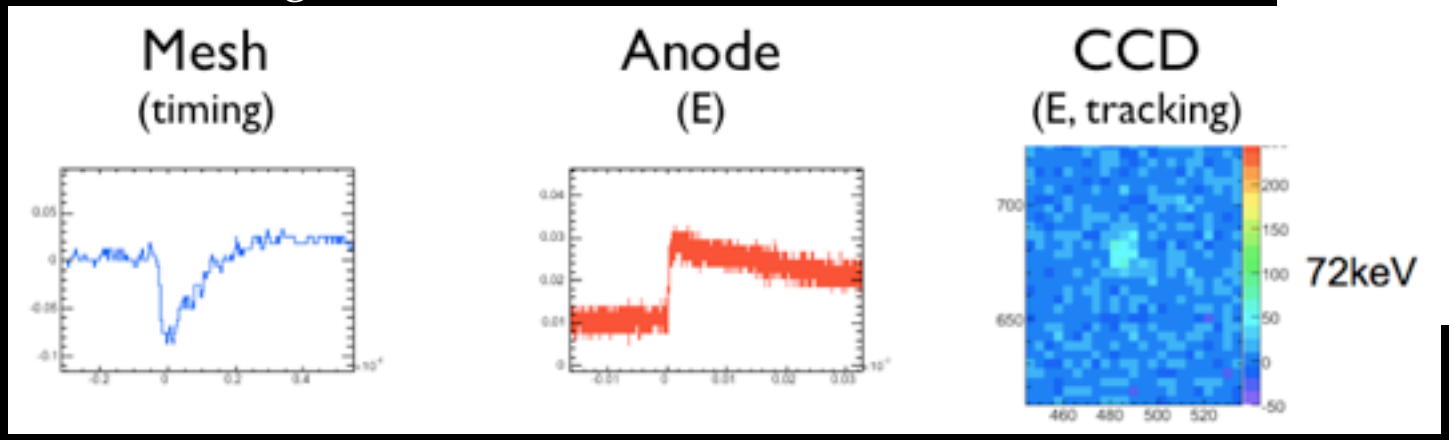


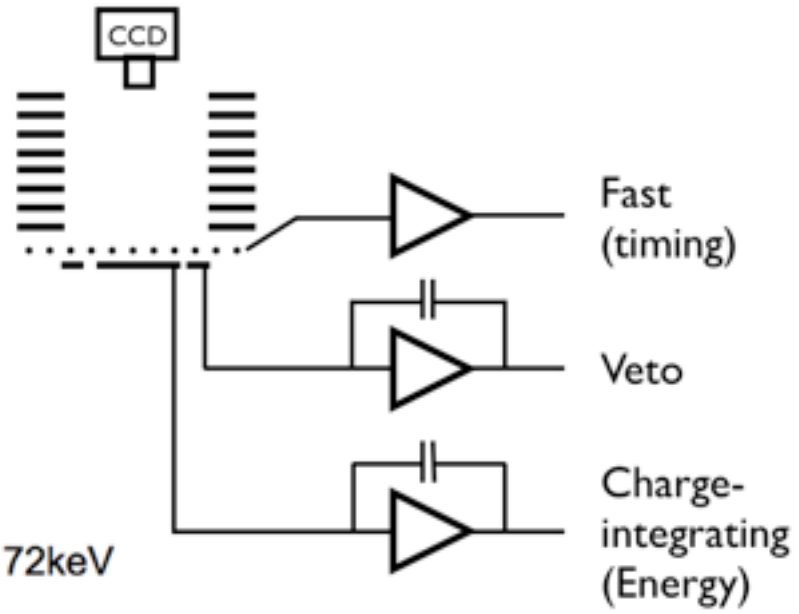
Next steps for DMTPC: low-background detector R&D, 2150′ underground at WIPP, DMTPCino at WIPP (1m^3)

Theory region:
Rozkowski et al JHEP 07 (2007) 075
Ellis et al PRD63 (2001) 065016

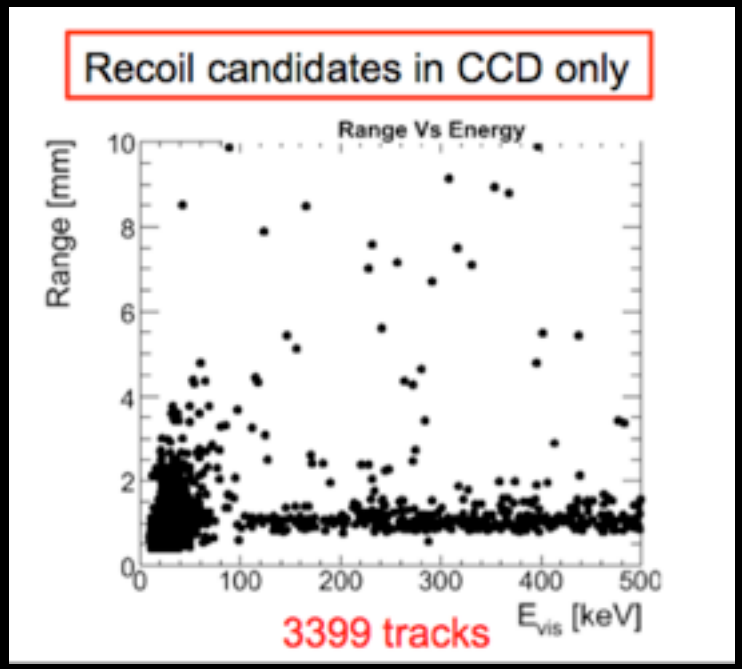
DMTPC R&D: Redundant Readout

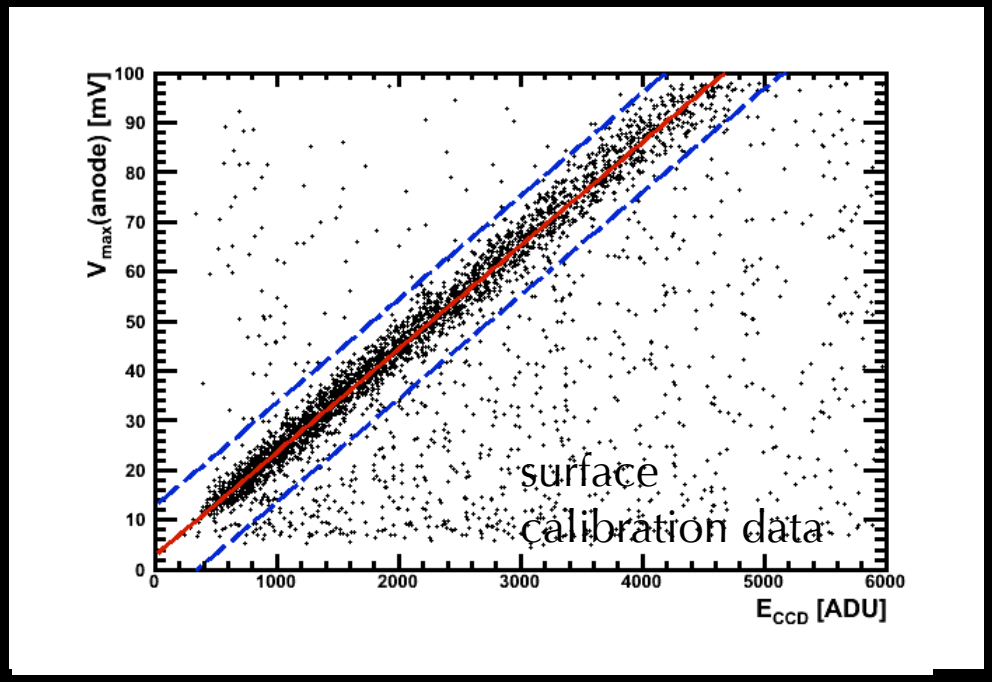
(i) fiducialization, (ii) background rejection, and (iii) tracking in z (2D-> 3D)





(i) require no signal in veto ring of anode, *(ii)* require CCD & anode energy match





J. Lopez, JM, et al., arXiv:1109.3501

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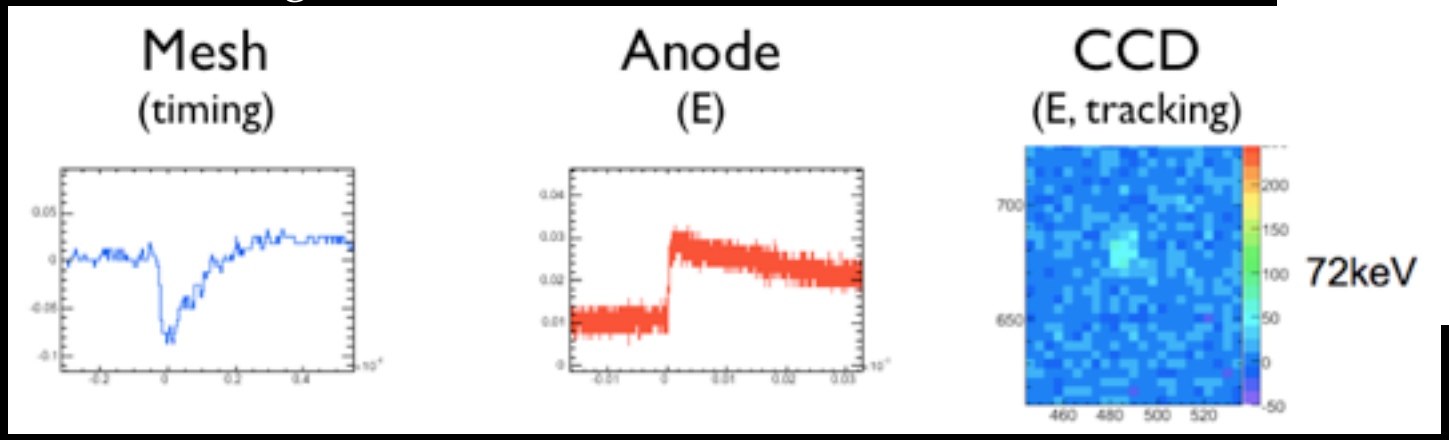

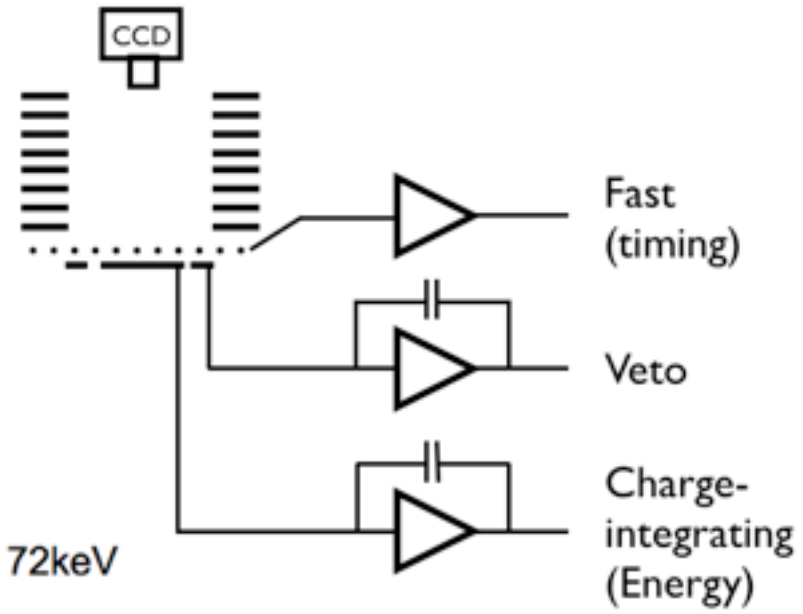

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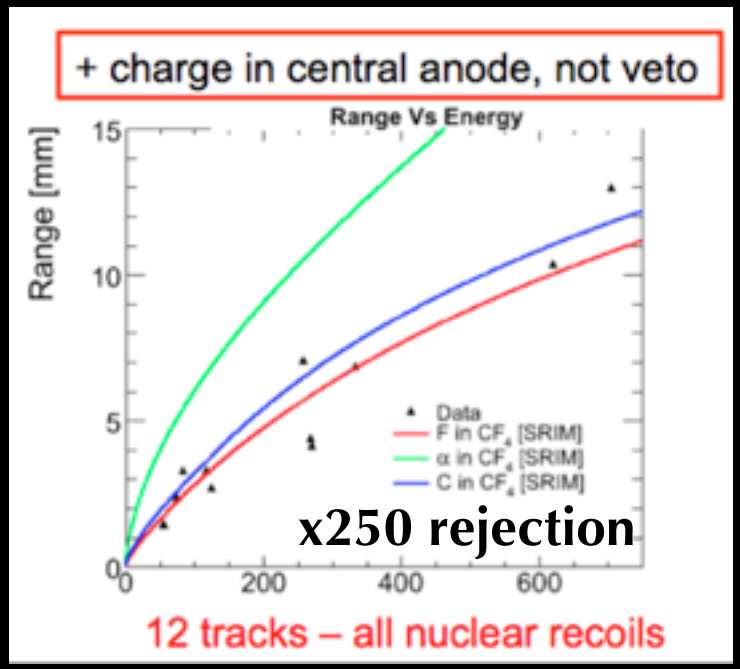

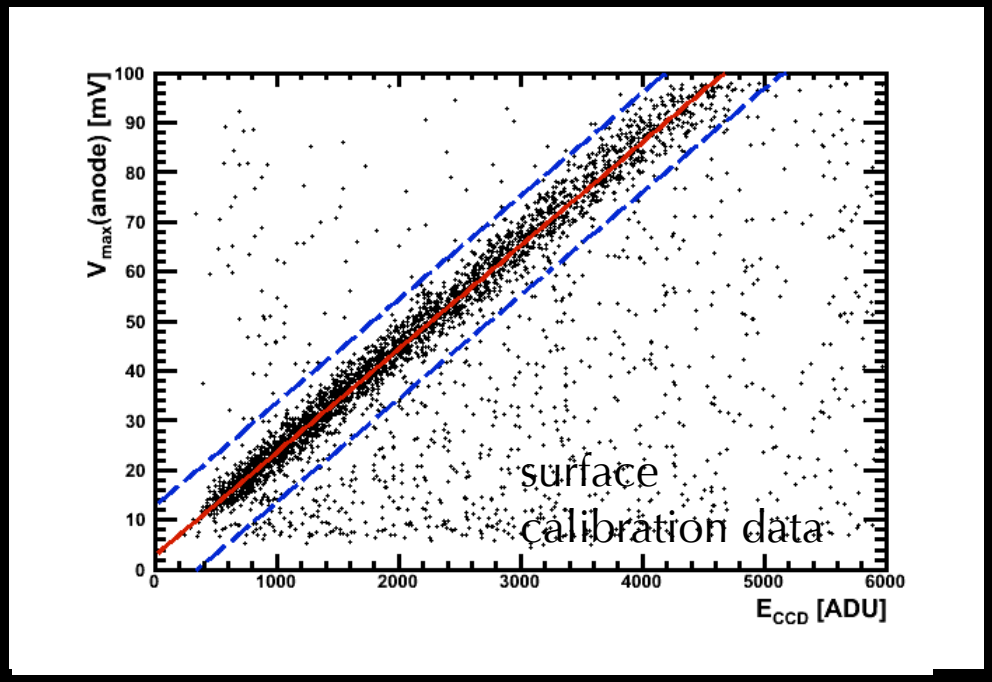

J. Lopez, JM, et al., arXiv:1109.3501

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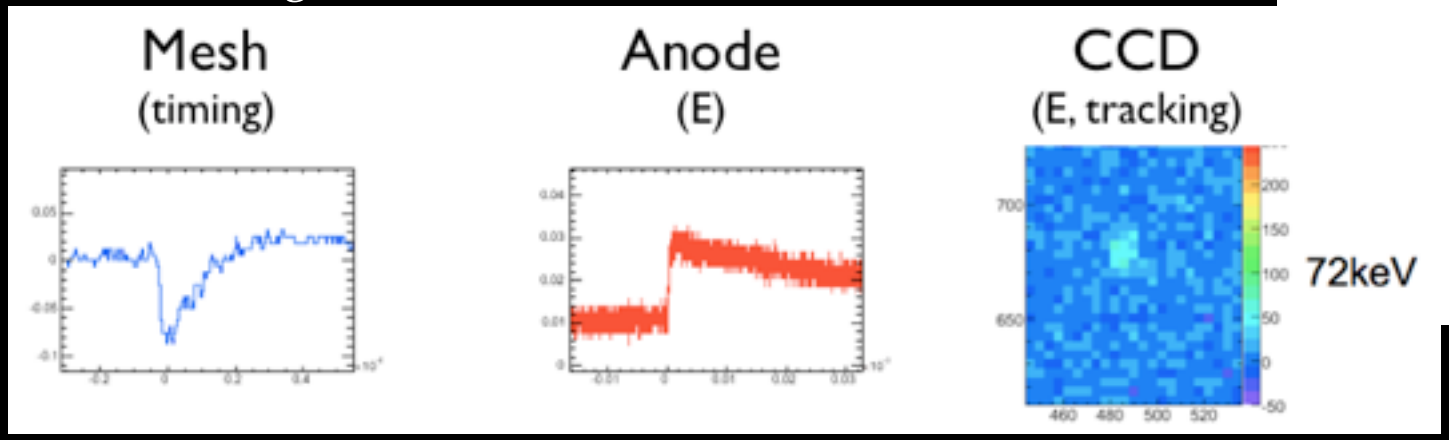

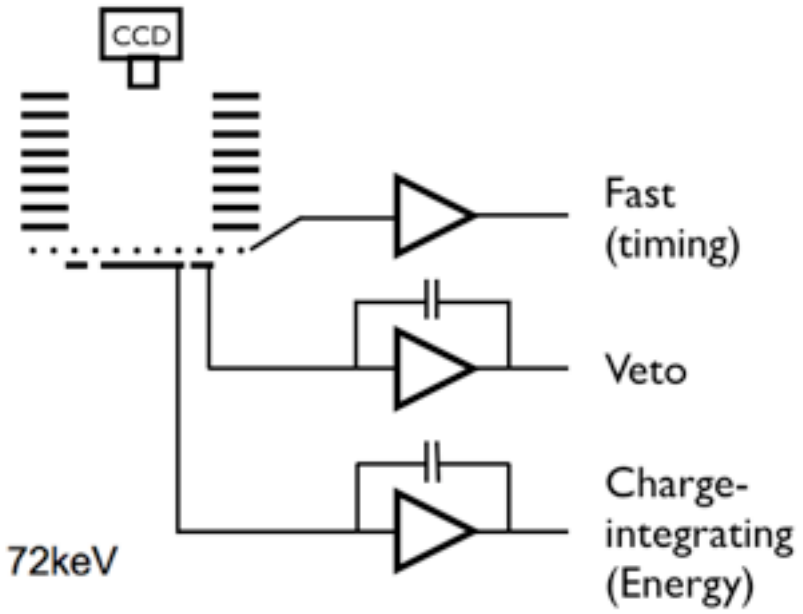

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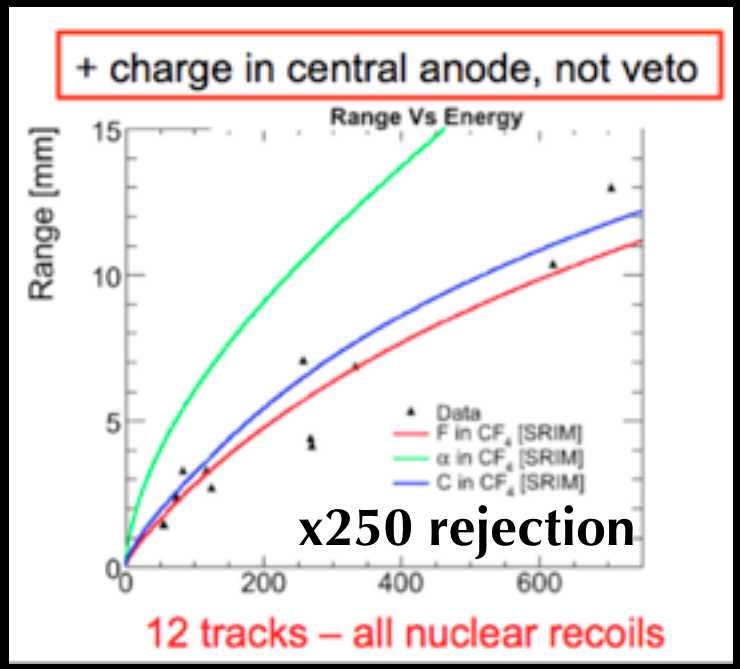
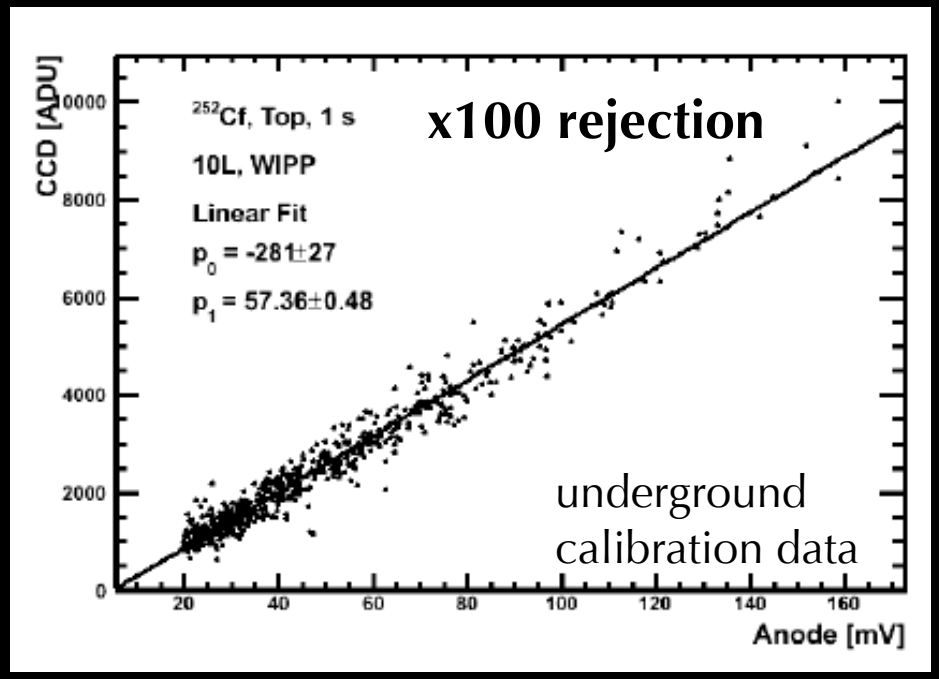


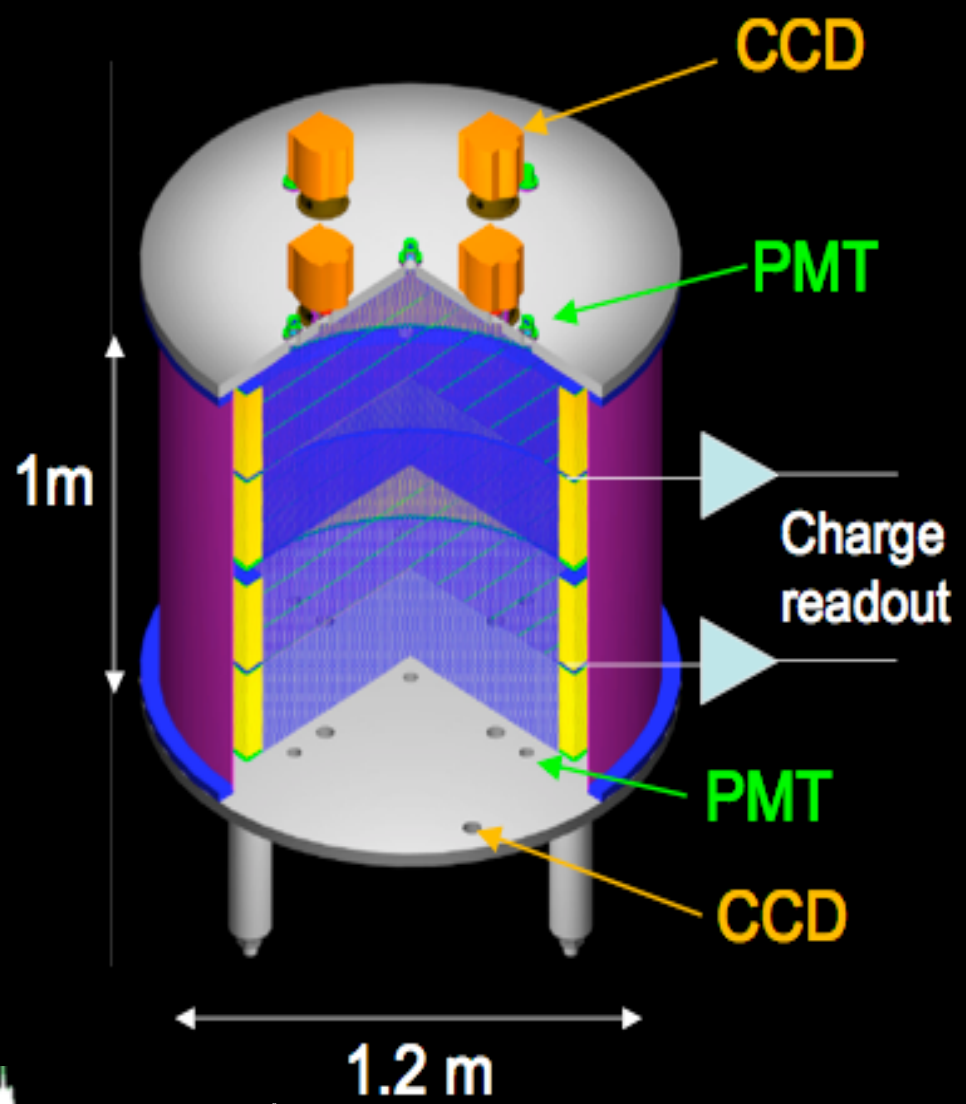


J. Lopez, JM, et al., arXiv:1109.3501

DMTPCino: 1m^3 Detector at WIPP

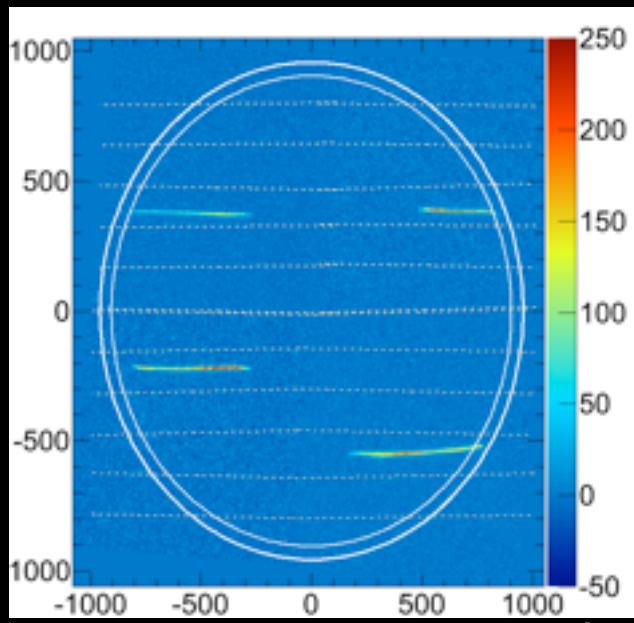
prototype for O(10 kg) fiducial mass detector, with 1 m^3 (0.25 kg) instrumented now

For a very large detector, build many 1m^3 modules because of diffusion limit.



4-shooter 20L detector tests design:

(i) multi-camera readout
(ii) triggering with charge & PMTs
(iii) directionality with charge
(iv) low-background materials



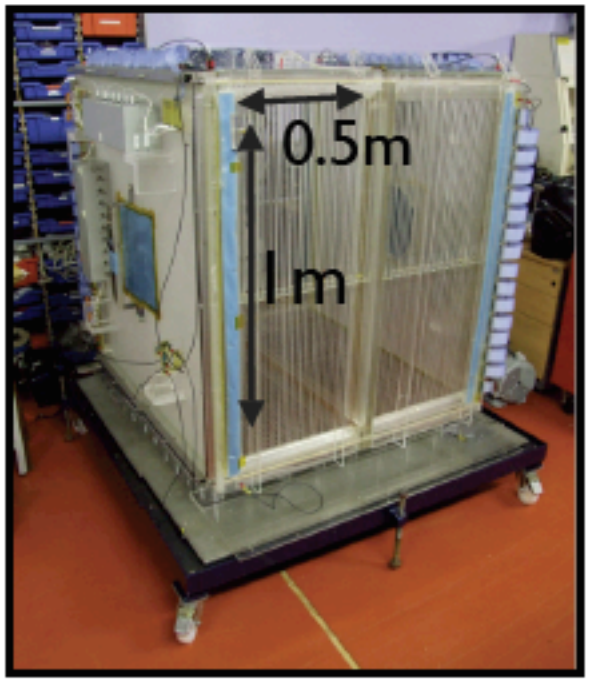
pixel x

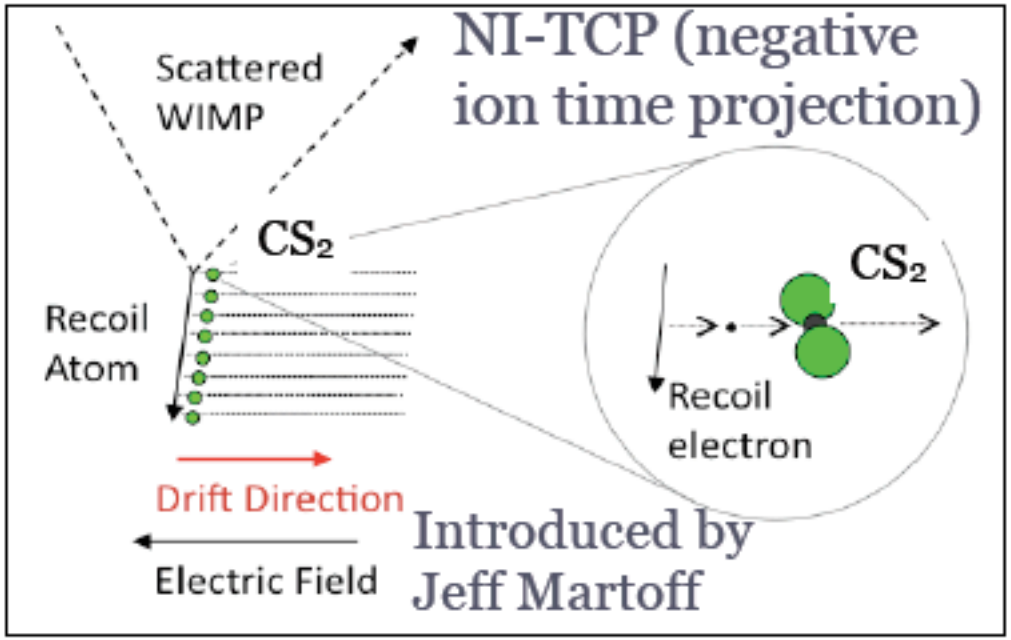
DMTPCino design underway, infrastructure ready, detector construction 2012.

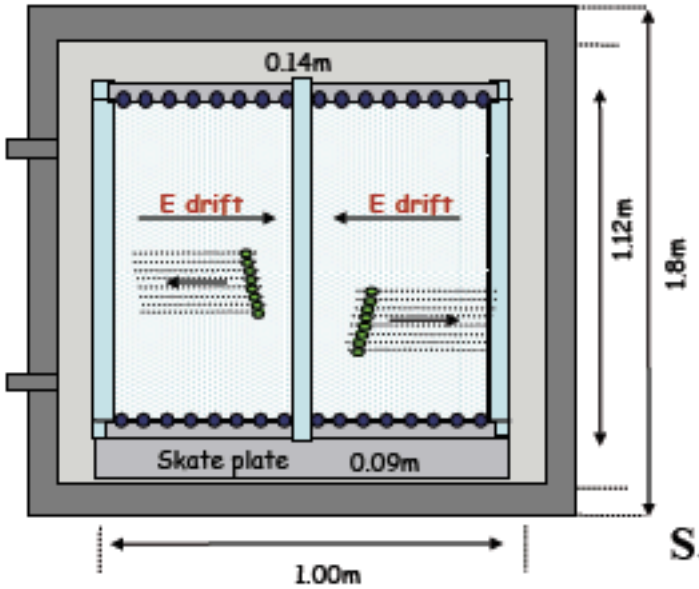
DRIFT Experiment

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

DRIFT II Concept







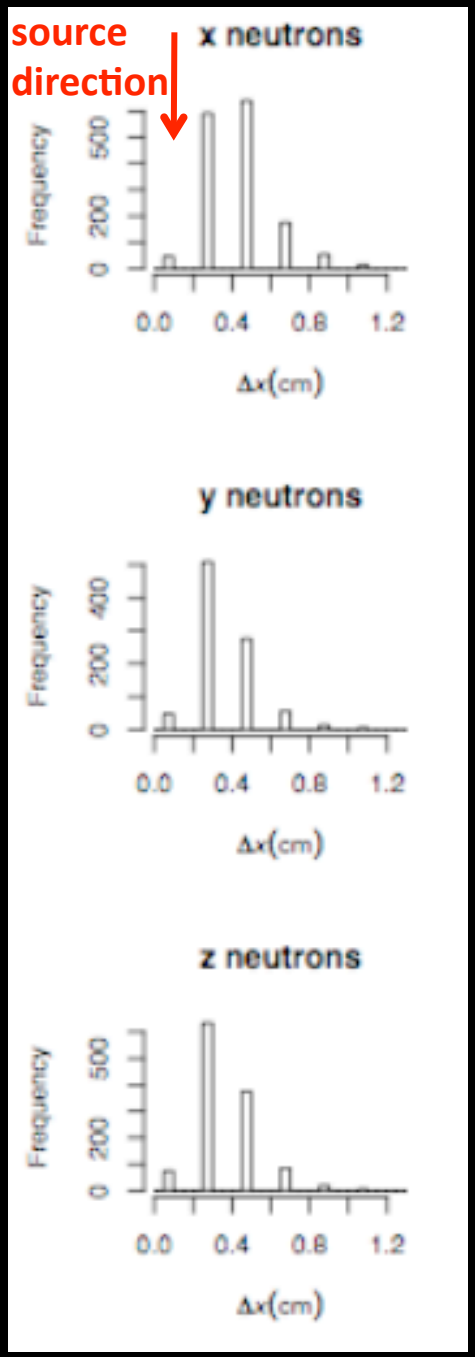
- 1 m³ active volume - back to back MWPCs
- Gas fill 40 Torr CS_2 => 167 g of target gas
- 2 mm pitch anode wires left and right
- Grid wires read out for Δy measurement
- Veto regions around outside
- Central cathode made from 20 μm diameter wires at 2 mm pitch
- Drift field 624 V/cm
- Modular design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

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

(N. Spooner, Cygnus'11)

DRIFT Directionality

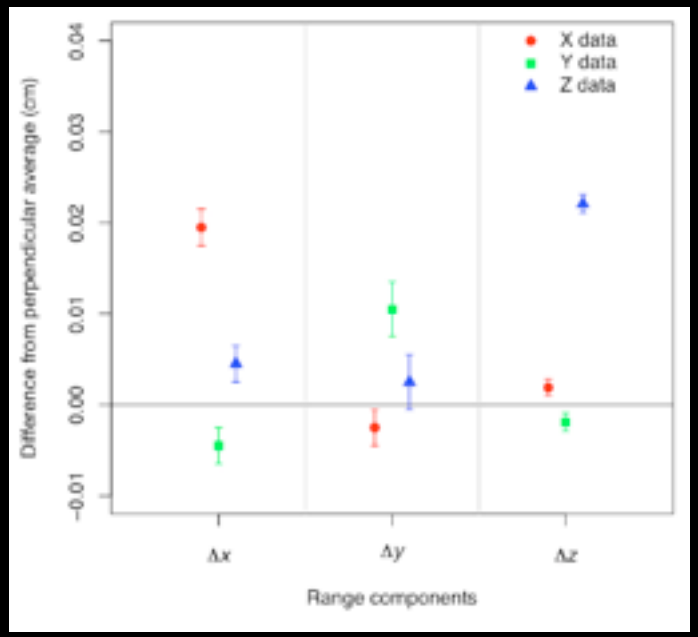
S. Burgos et al., NIMA 600:417-423,2009



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



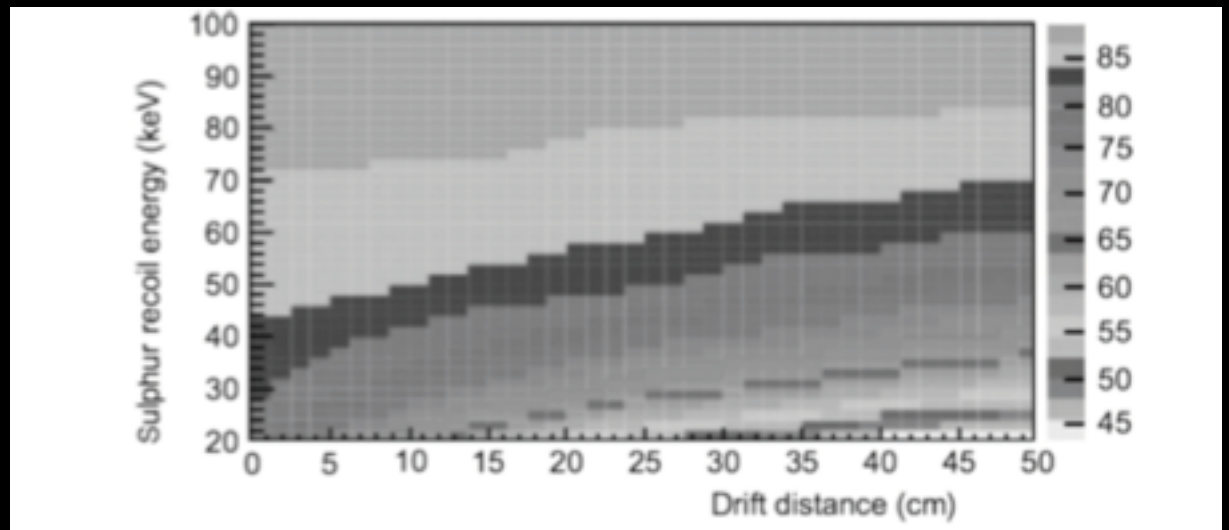
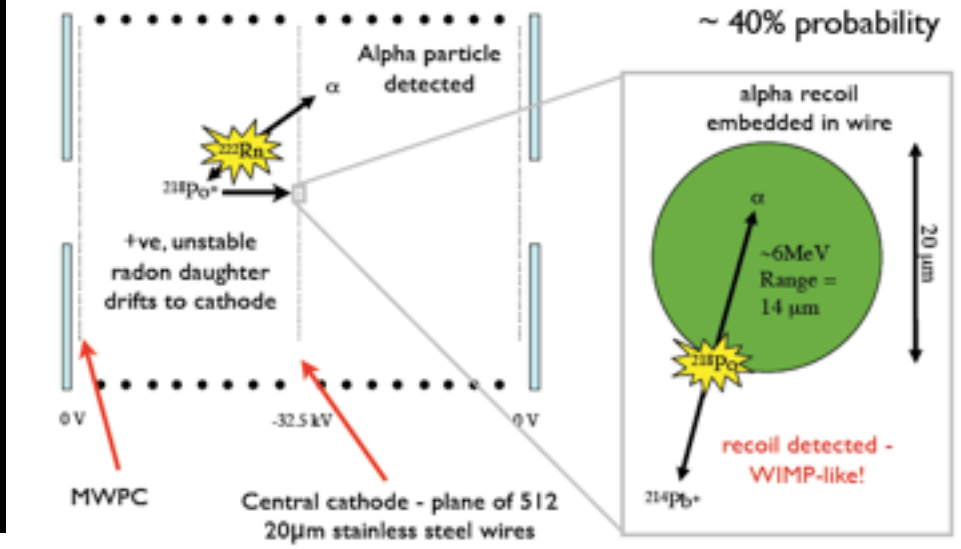


Fig. 10. Simulated angular reconstruction accuracy for DRIFT-II. Shading denotes the probability that the recoil direction is reconstructed within 30 degrees of the known initial direction.

DRIFT R&D: Backgrounds

30 Torr CS2, 10 Torr CF4 = 139 gm target

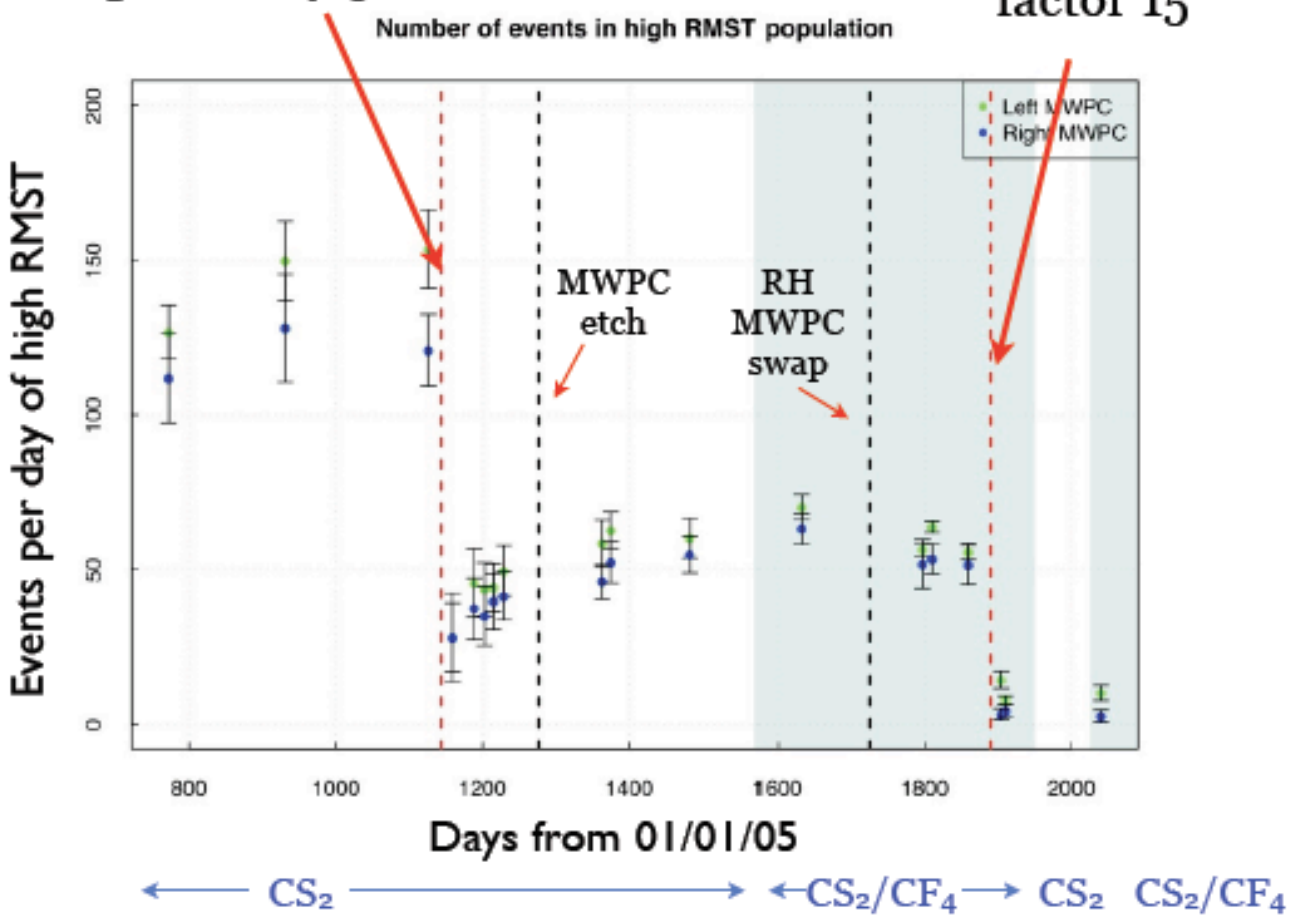
130 events/day nuclear recoil candidates
estimate: at threshold ~25 keVr, ~5 events/keV/kg/day



(N. Spooner, Cygnus'11)

nitric acid etch of cathode reduced background by 5

thin film cathode reduces by further factor 15



ID radon backgrounds with pulse width

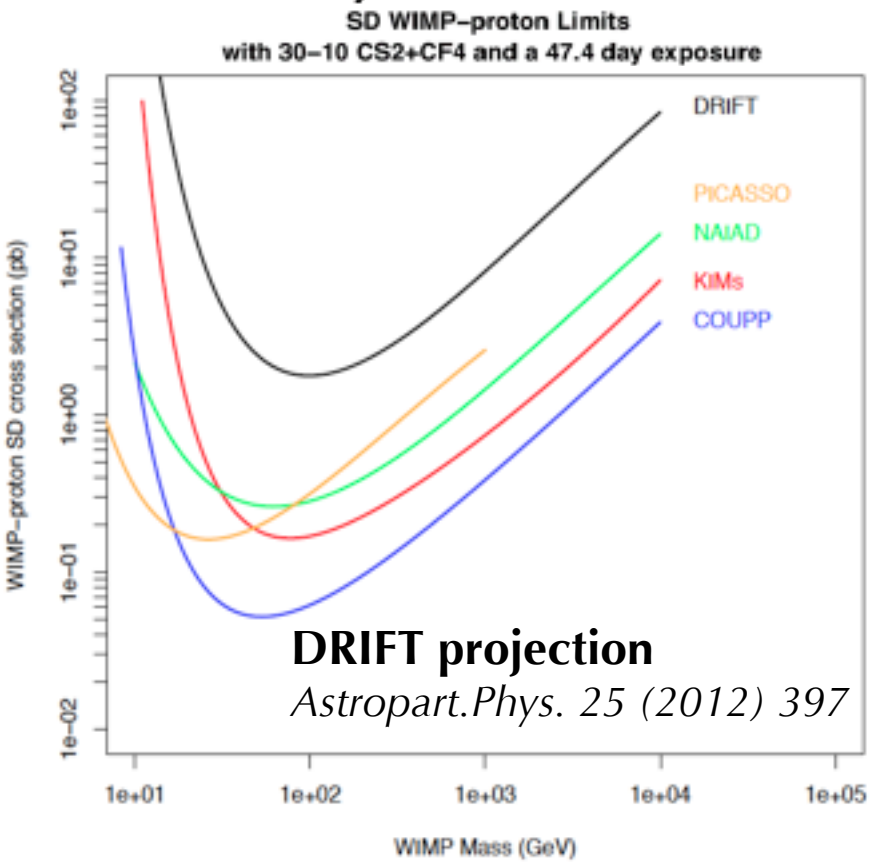
shown x100 reduction of background, project x40 further with cathode R&D

DRIFT Results

(N. Spooner, Cygnus'11)

SD Limit from 47.2 days

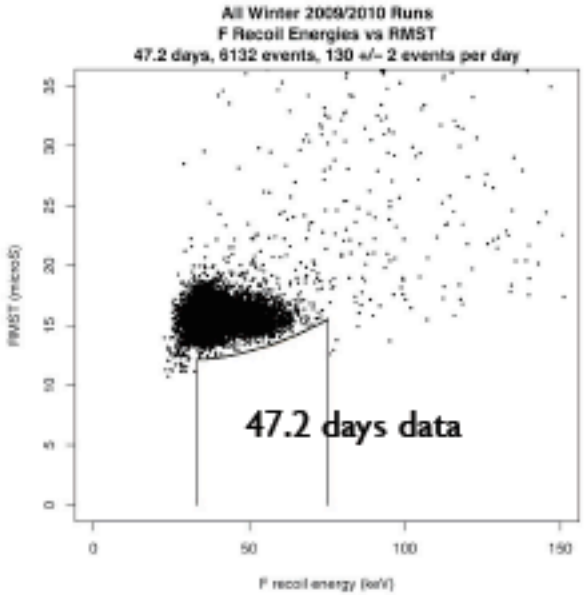
- 30 Torr -10 Torr CS2-CF4, 47.2 days background data = 1.5kg-days (^{19}F)
- MC simulation calibrated by neutron data
- No compromise on directional sensitivity
- Signal region chosen for zero events (unblind analysis)
- Further 53 days data on disk for a full blind analysis

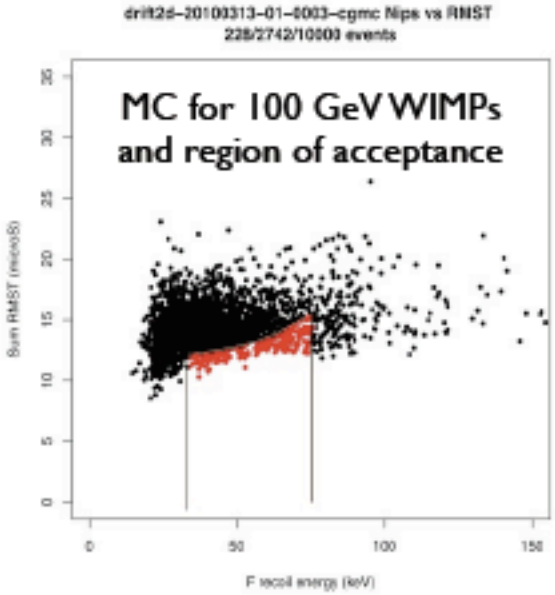


DRIFT projection
Astropart.Phys. 25 (2012) 397

Min. SD limits, directional detectors:
DRIFT: 1.8 pb
NEWAGE: 5400 pb
DM-TPC: 2400 pb

DRIFT: 1.5 kg-days
COUPP: 28 kg-days
NAIAD: 12,500 kg-days
KIMS: 3,400 kg-days



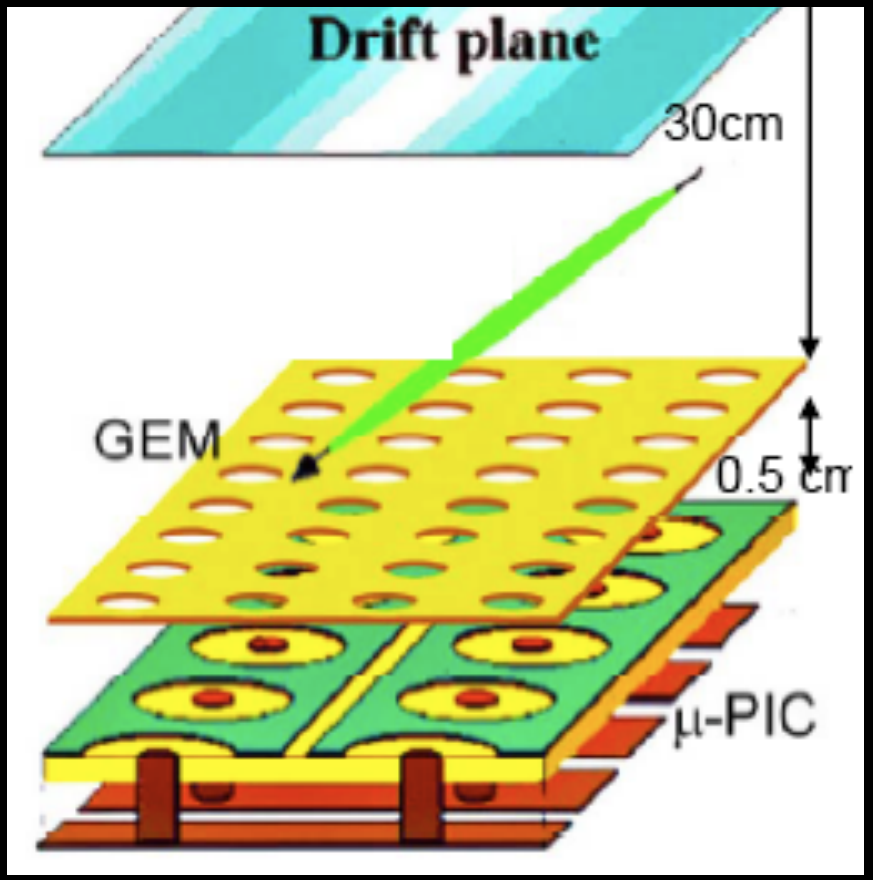


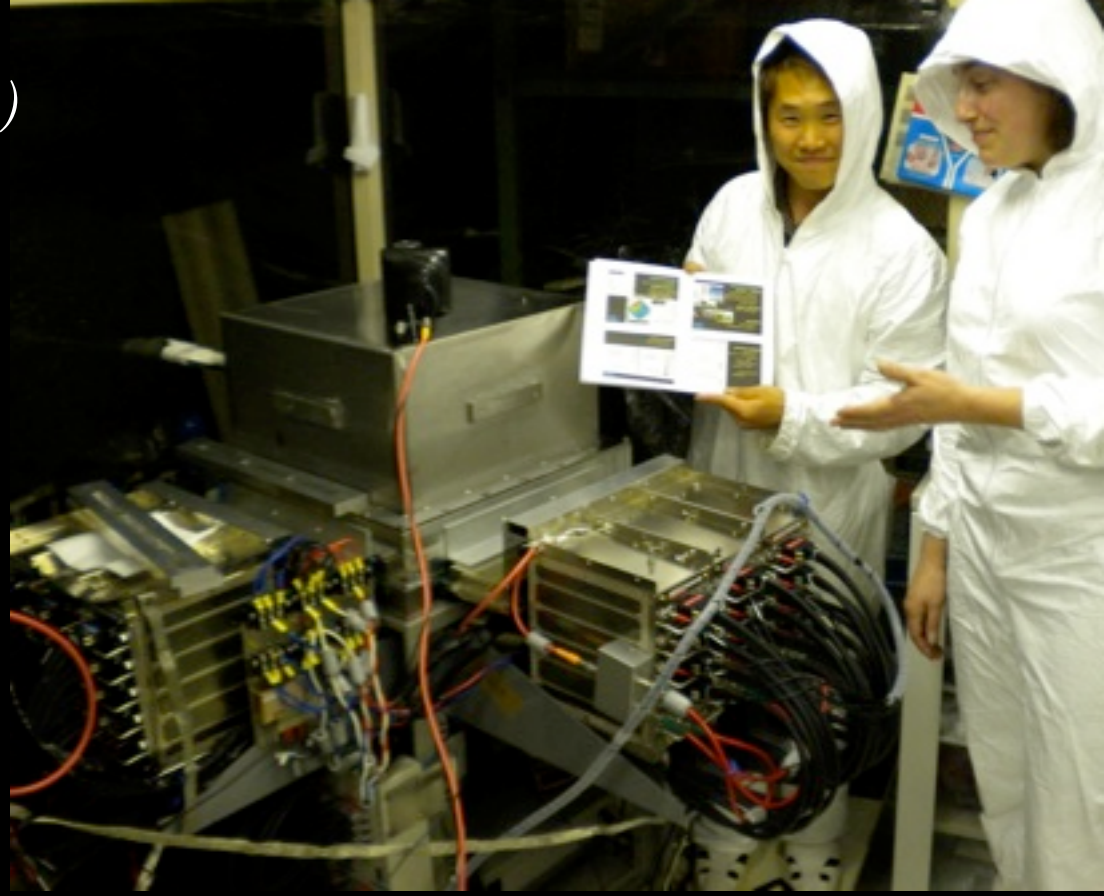
Next: R&D towards 24 m^3 DIII, funded to expand DII to multiple units, z-fiducialization

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

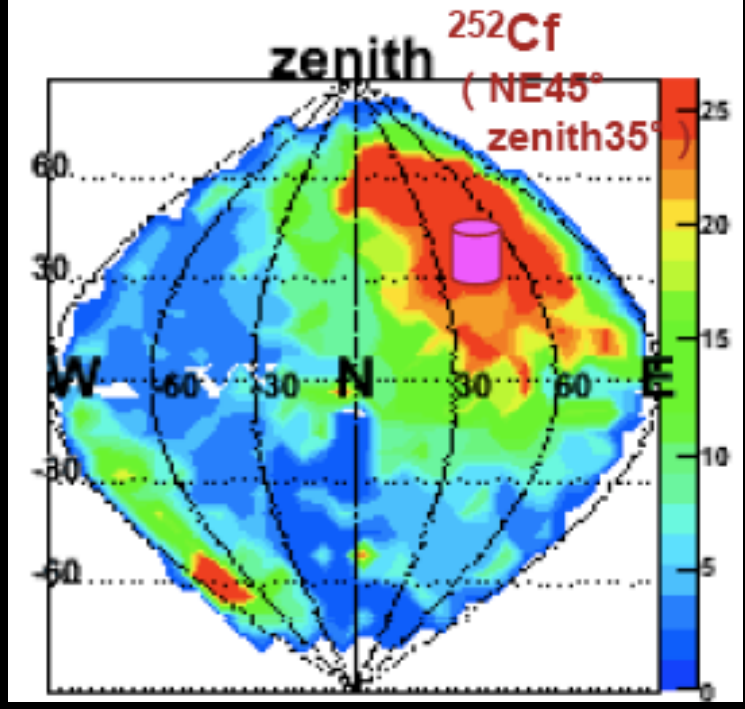
axial 3D track reconstruction with ^{252}Cf source
QPIX upgrade planned for head-tail

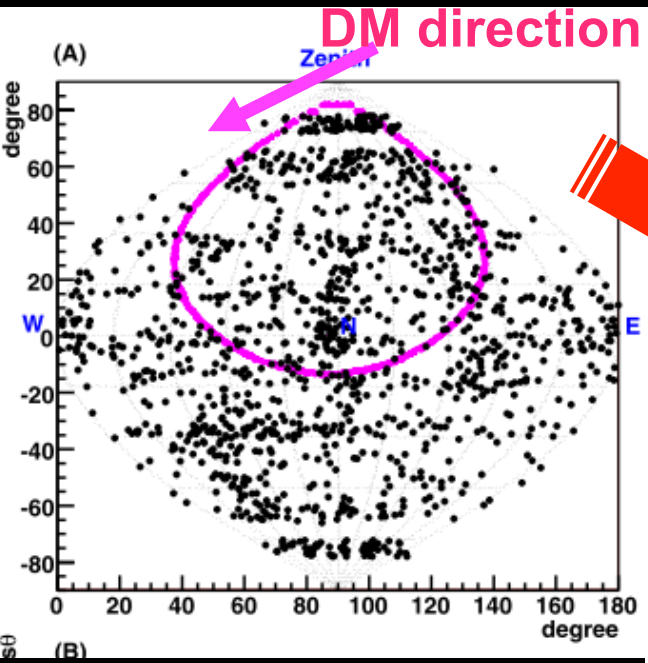
e- rejection: < 1E-5 *K. Miuchi et al, PLB654 (2007) 58*

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

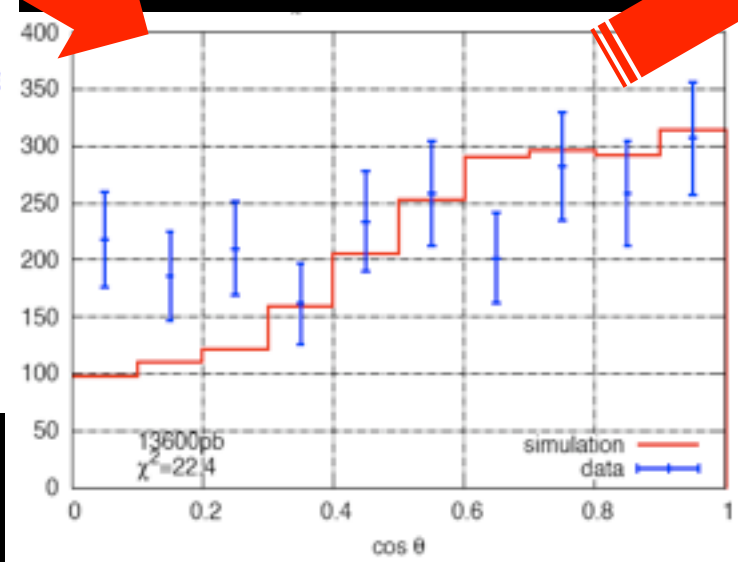
$\Delta\chi^2$ between WIMP and null hypothesis in cos(θ),
observe 1244 events, consistent with background

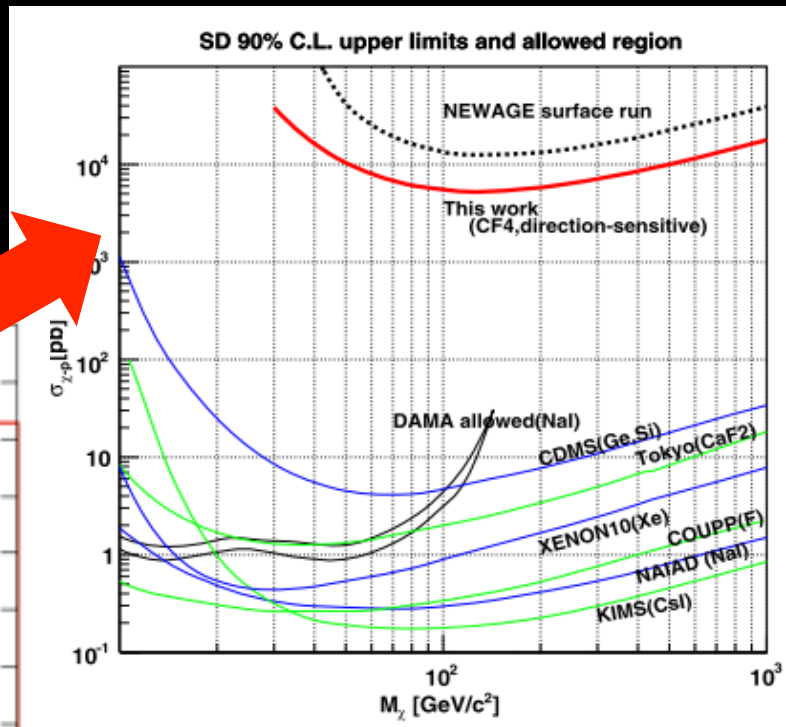
at 100 keVee threshold ~50 events/keV/kg/day





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





NEWAGE

Recent progress in R&D:

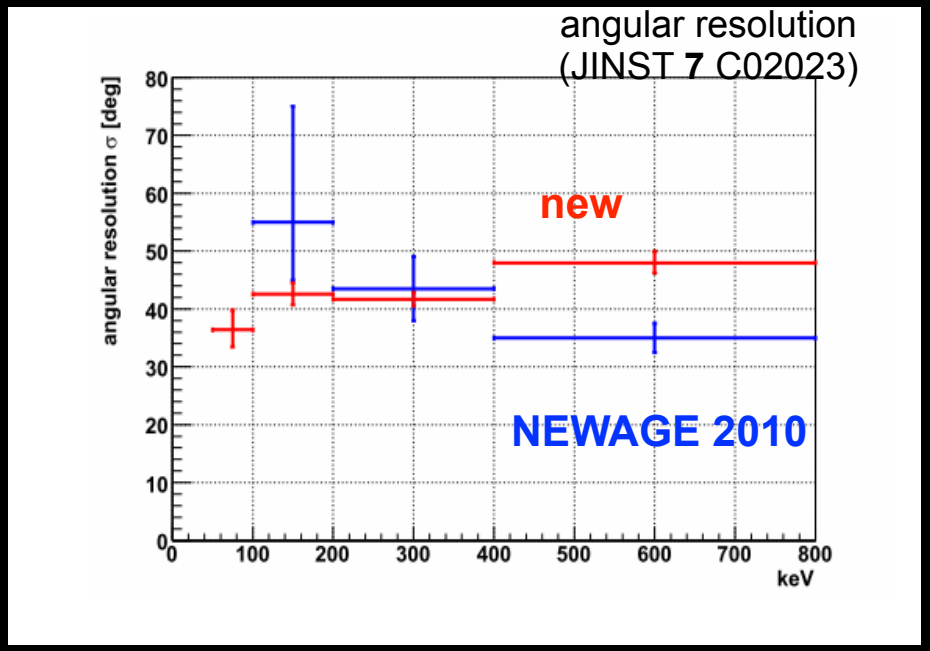
Energy threshold reduction:100 -> 50 keVee
- 152 -> 76 torr CF_4 target
- nuclear recoil efficiency: 60% at 50 keVee
- angular resolution: 40º (50-100 keVee)
- *K. Miuchi et al., JINST 7 C02023*

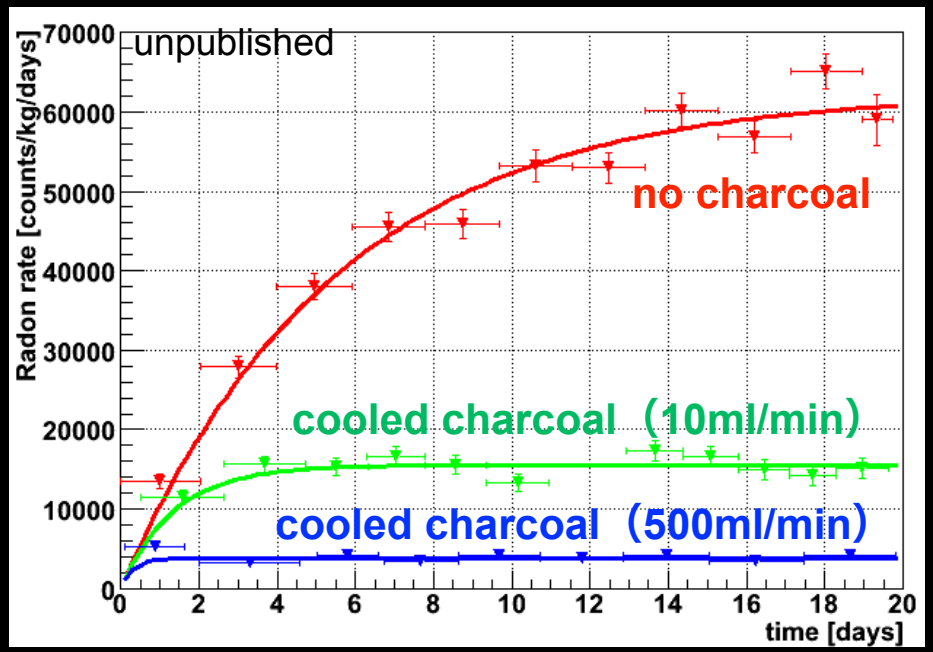
Rn background reduction by 10x
- Gas circulation system with cooled charcoal

KISEKI NAKAMURA
WON "CHARPAK AWARD" in MPGD2012

CERN COURIER March 2012

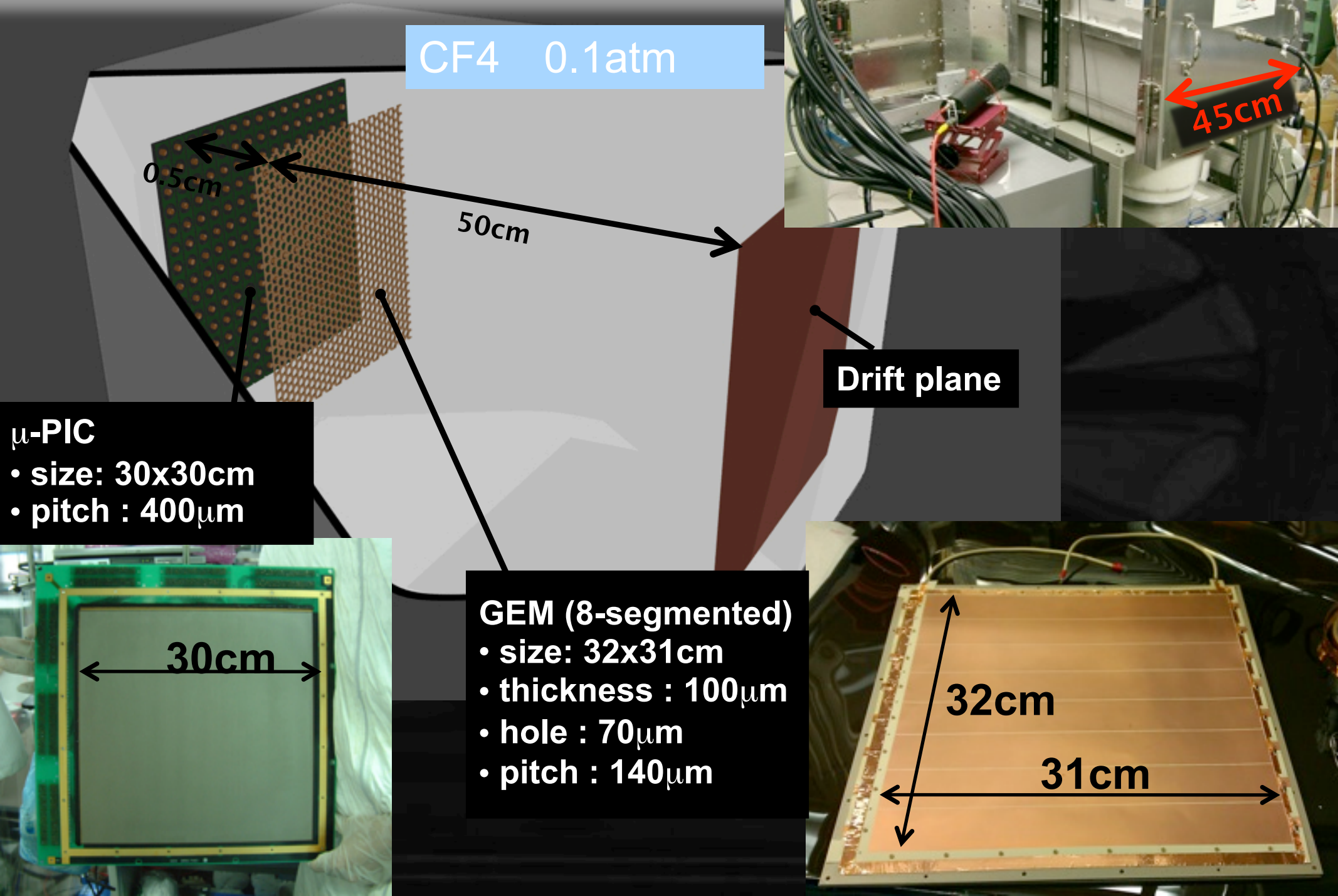
Fabio Sauli, left, presented the young scientist "Charpak Award" to Kiseki Nakamura of Kyoto University, centre, and Sverre Dørheim of Technische Universität München. (Image credit: Tadaaki Isobe/RIKEN.)





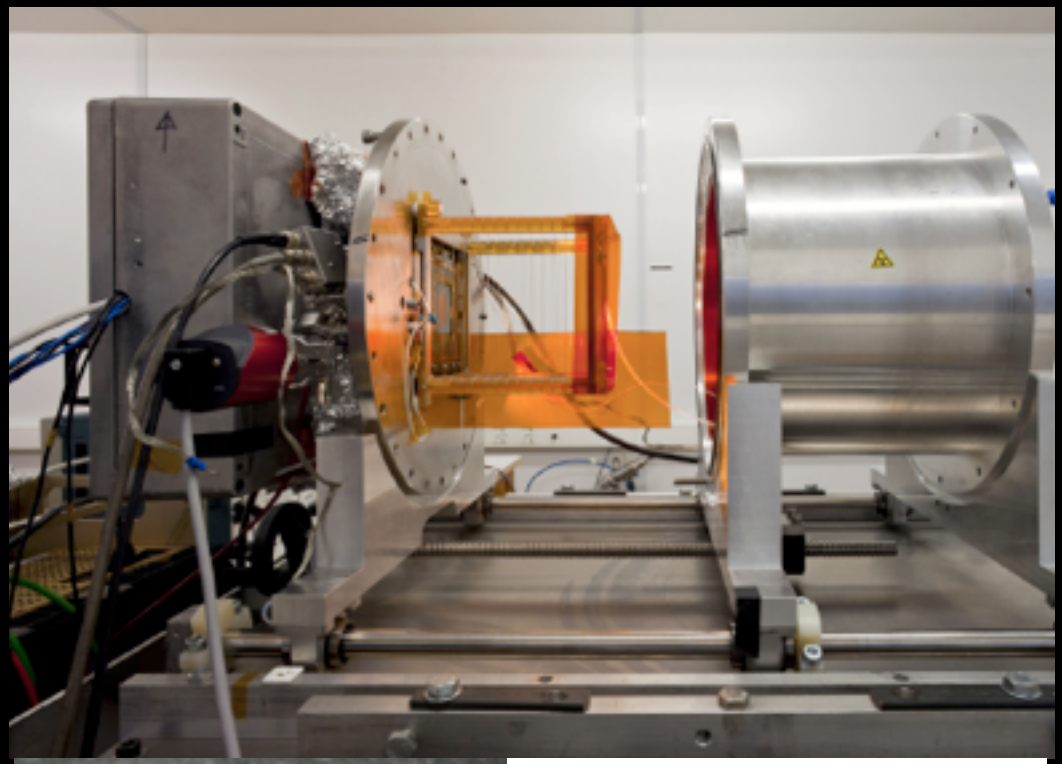
Detector(NEWAGE-0.3b)

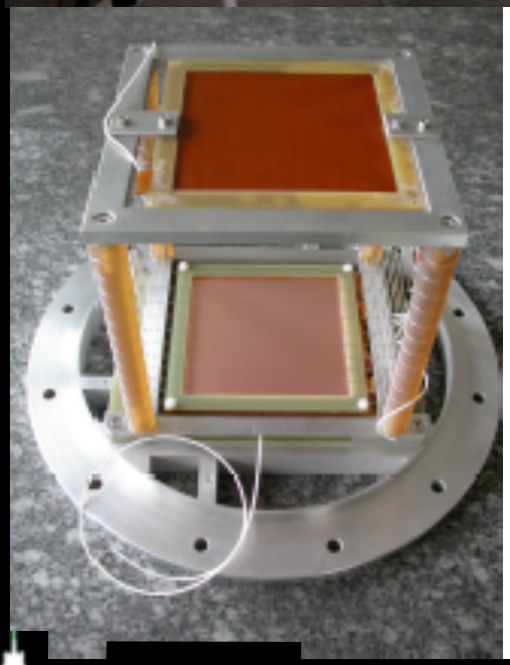
CF4 0.1atm

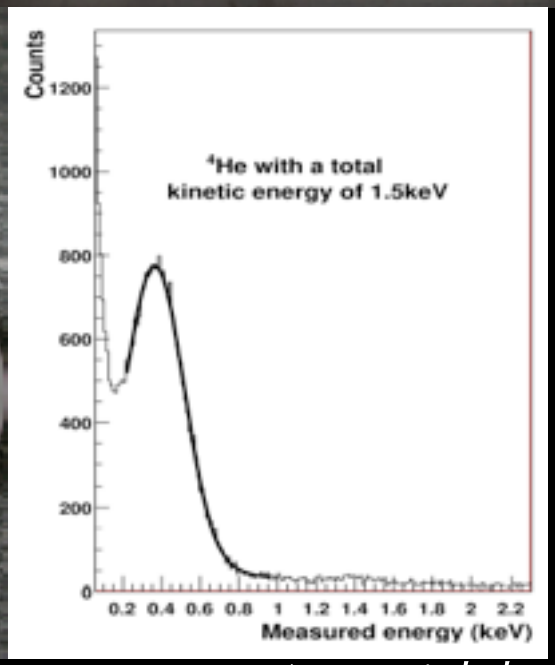


MiMAC Experiment

(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

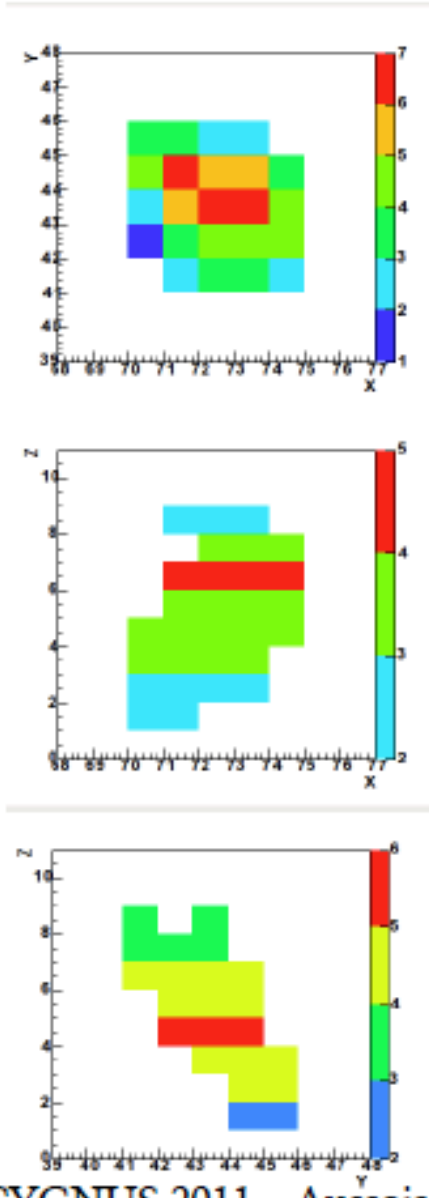
AIP Conf.Proc. 1412 (2011) 192-199

(material thanks to D. Santos)

MiMAC Directionality

(D. Santos, Cygnus'11)

Trak in 3D : ^{19}F in 70 % CF_4 + 30% CHF_3 !!!



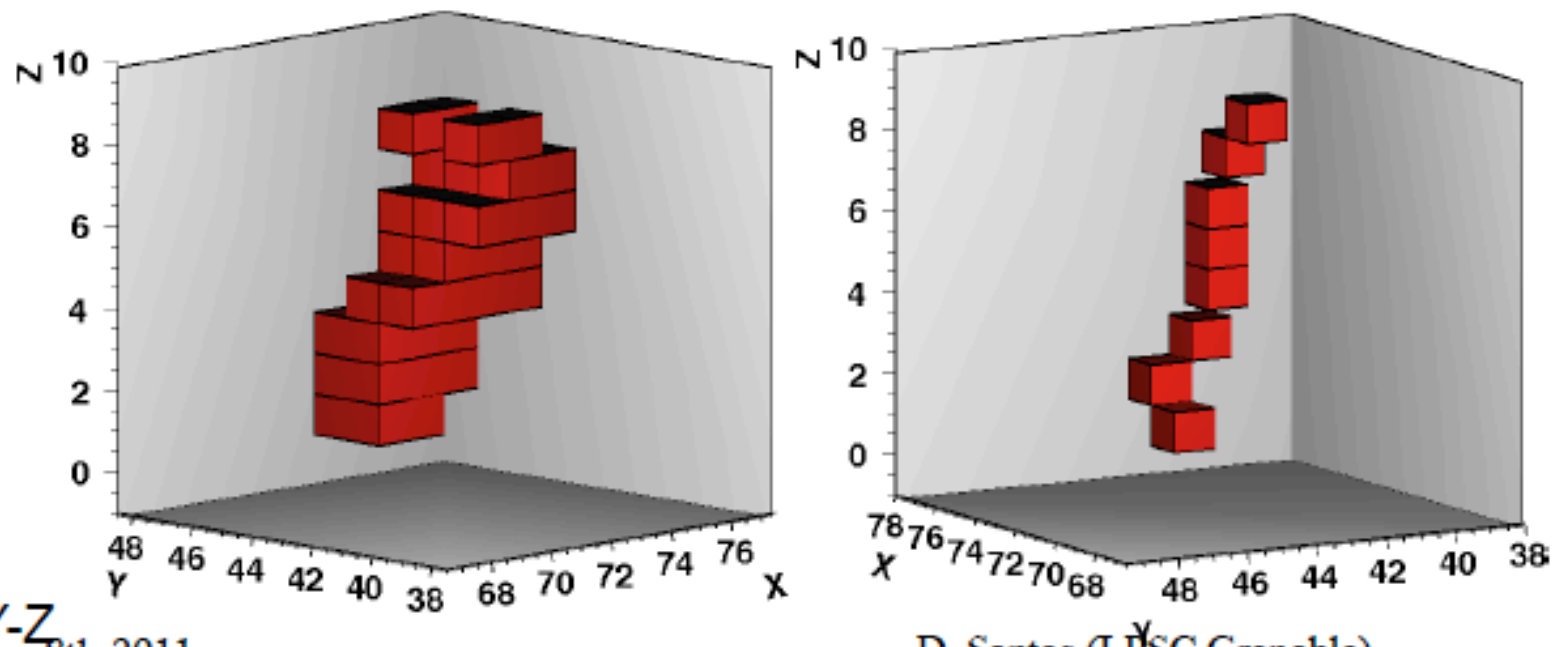
70 % CF_4 + 30% CHF_3

55 mbar,
170 V/cm

example event from calibration with Amande neutron source at Cadarache

~40 keV (ionization), ~3 mm

MC: 55° angular resolution at 20 keVr.



CYGNUS 2011 – Aussois June 8th,2011

D. Santos (LPSC Grenoble)

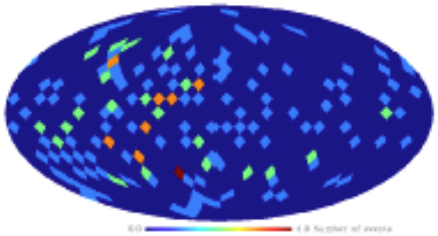
MiMAC Sensitivity

(D. Santos, Cygnus'11)

MIMAC : Dark Matter discovery/exclusion

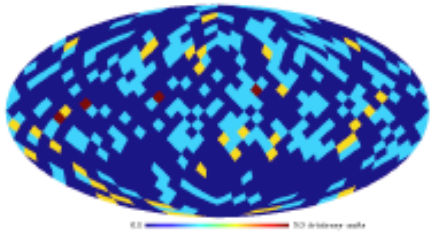
J. Billard *et al.*, PLB 2010
J. Billard *et al.*, PRD 2010

- ***discovery (5σ)***
  Up to 10^{-4} pb

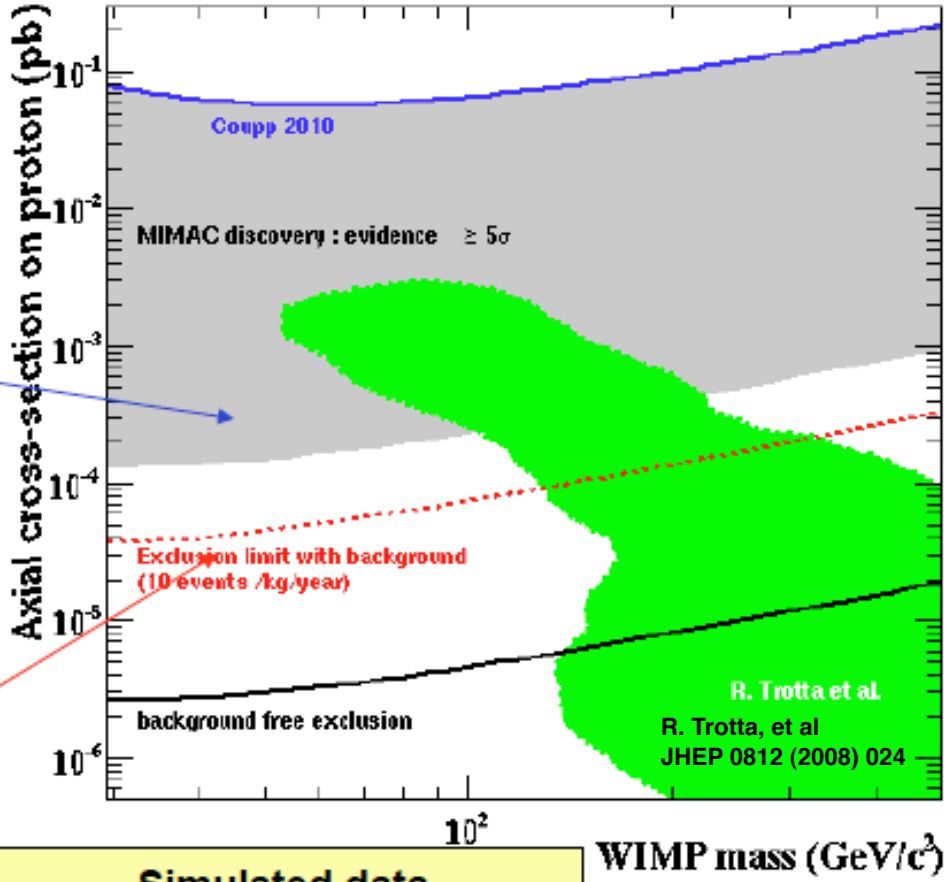


100 WIMP, 100 bkg

- **exclusion**
  Up to 10^{-6} pb



0 WIMP, 300 bkg



Simulated data
- 30 kg.year CF_4
- Recoil energy [5, 50] keV
- Angular resolution : 15°

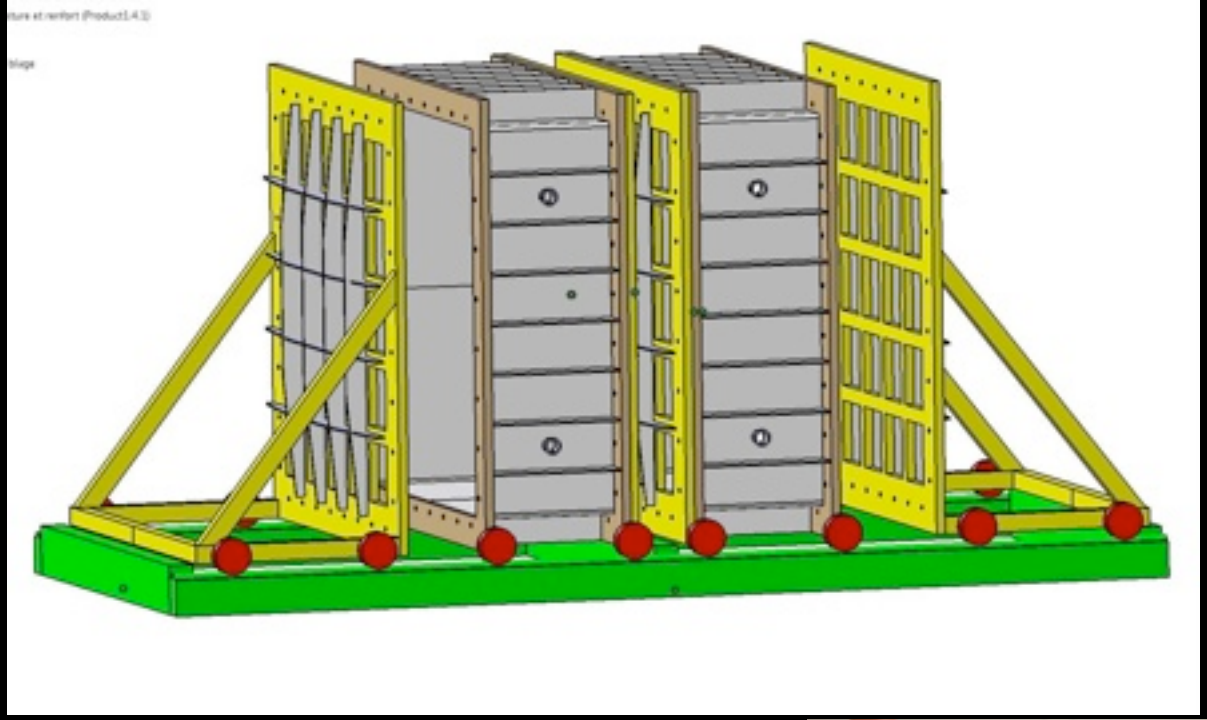
49

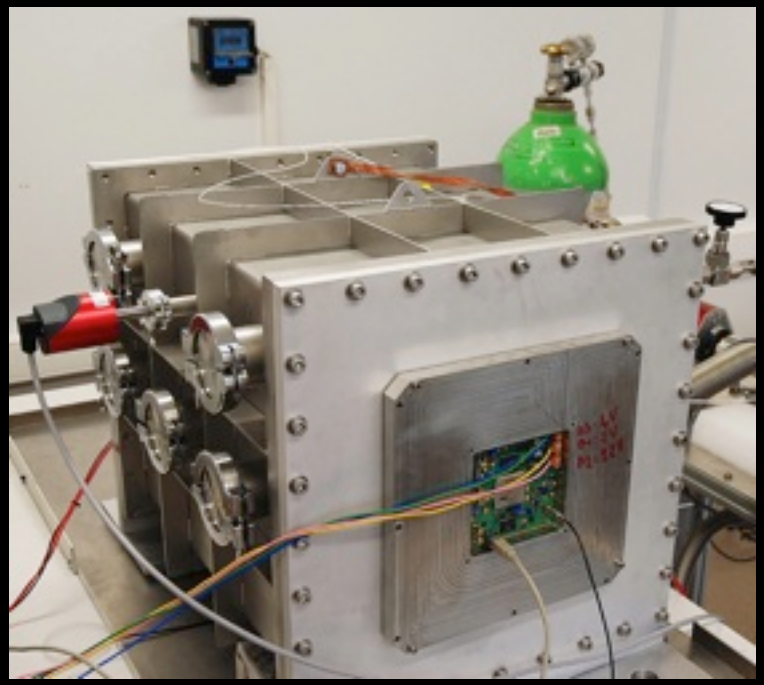
Next steps: install prototype detector underground in Modane, measure background rates and resolutions (MC: 55° at 20 keVr).

MiMAC Future

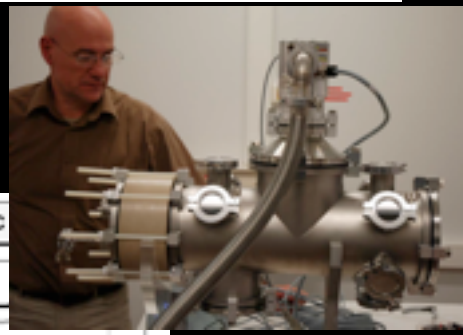
1m^3 detector design:
- 50 modules of 5L:
  - 2 x (10 x 10 x 25 cm^3)
- multiple targets (H, He, F) at ~40 torr pressure

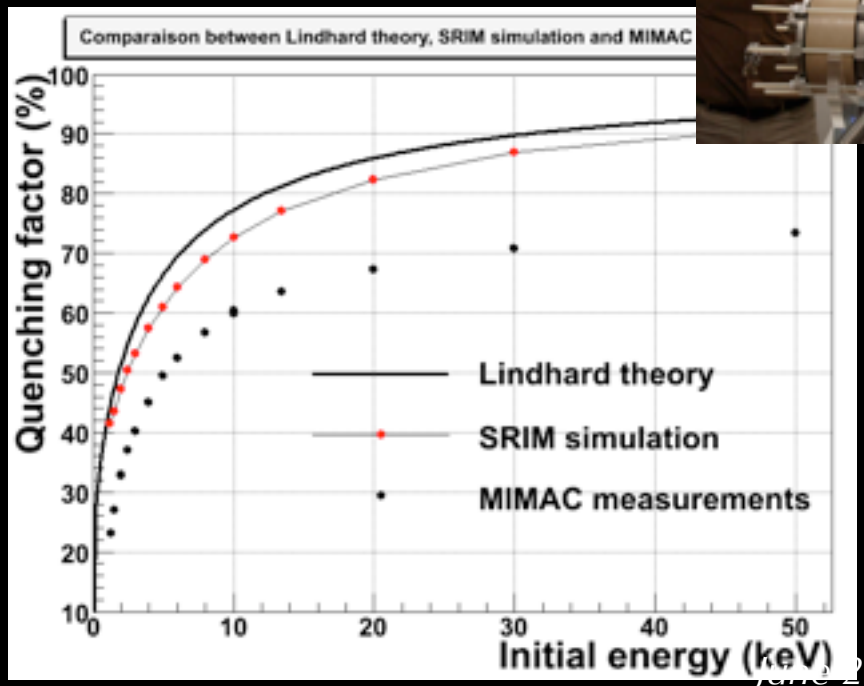
5L prototype tested at ILL, install in Modane June 20012





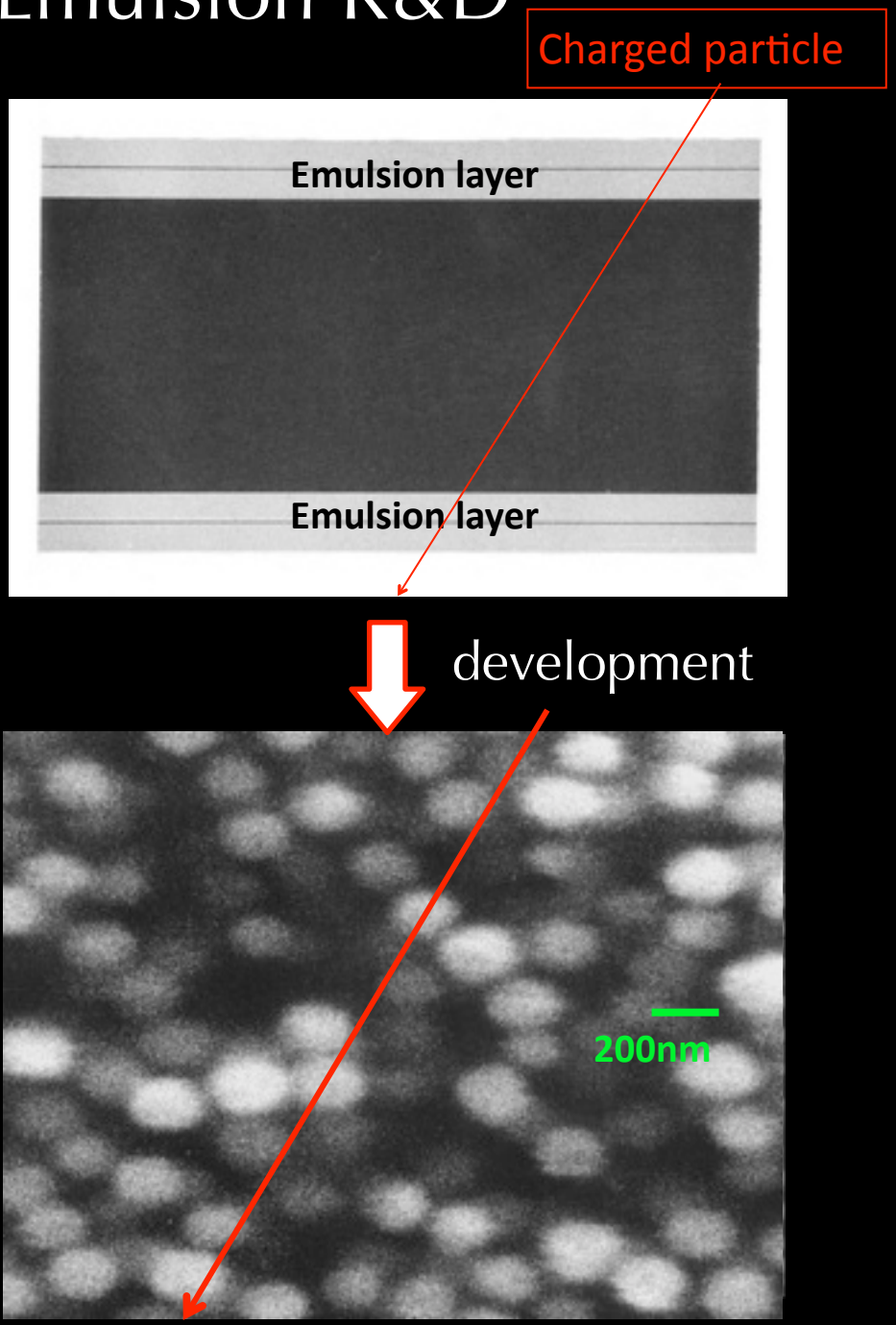
quenching measurements with dedicated ion source





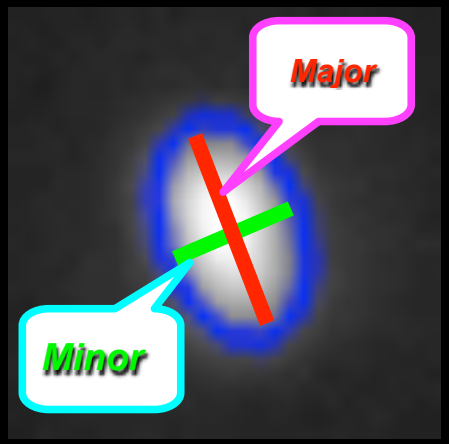
Emulsion R&D

(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

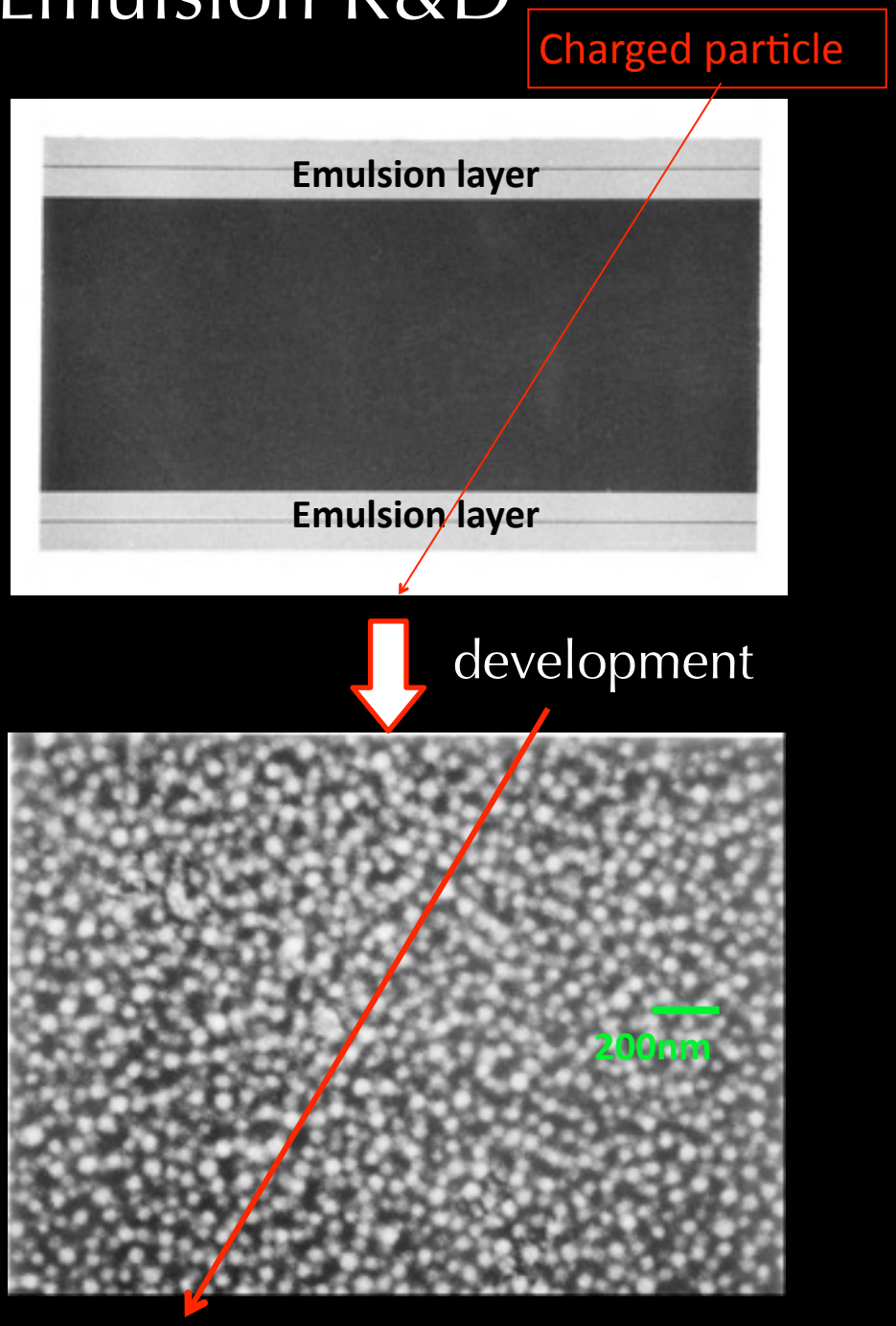
- 30° resolution with optical readout, efficiency >50% above 150 nm tracks

Underground R&D at LNGS, 2012

(material thanks to T. Naka)

Emulsion R&D

(Nagoya, Fuji, + Napoli, Padova)



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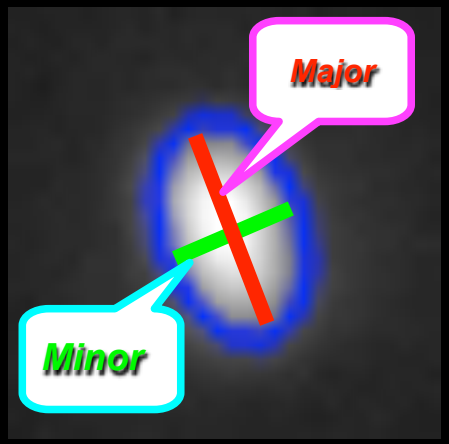

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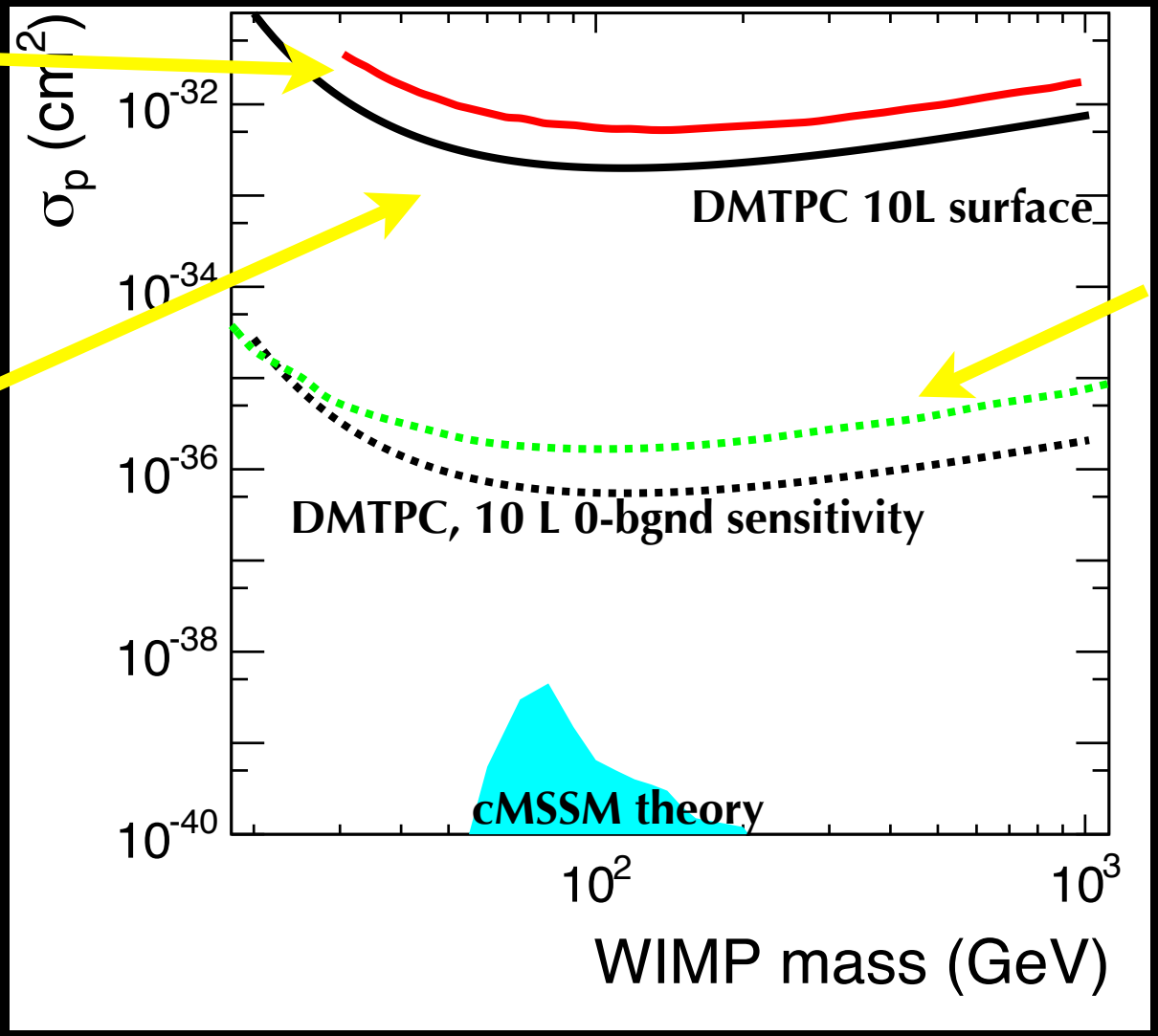
Spin-Dependent Cross Section Results

NEWAGE limit (Kamioka)

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

DMTPC limit (surface, 38 gm-day)

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



directional searches

DRIFT 0-bgnd sensitivity, *Astropart.Phys. 25 (2012) 397*

Theory region:
Rozkowski et al JHEP 07 (2007) 075
Ellis et al PRD63 (2001) 065016

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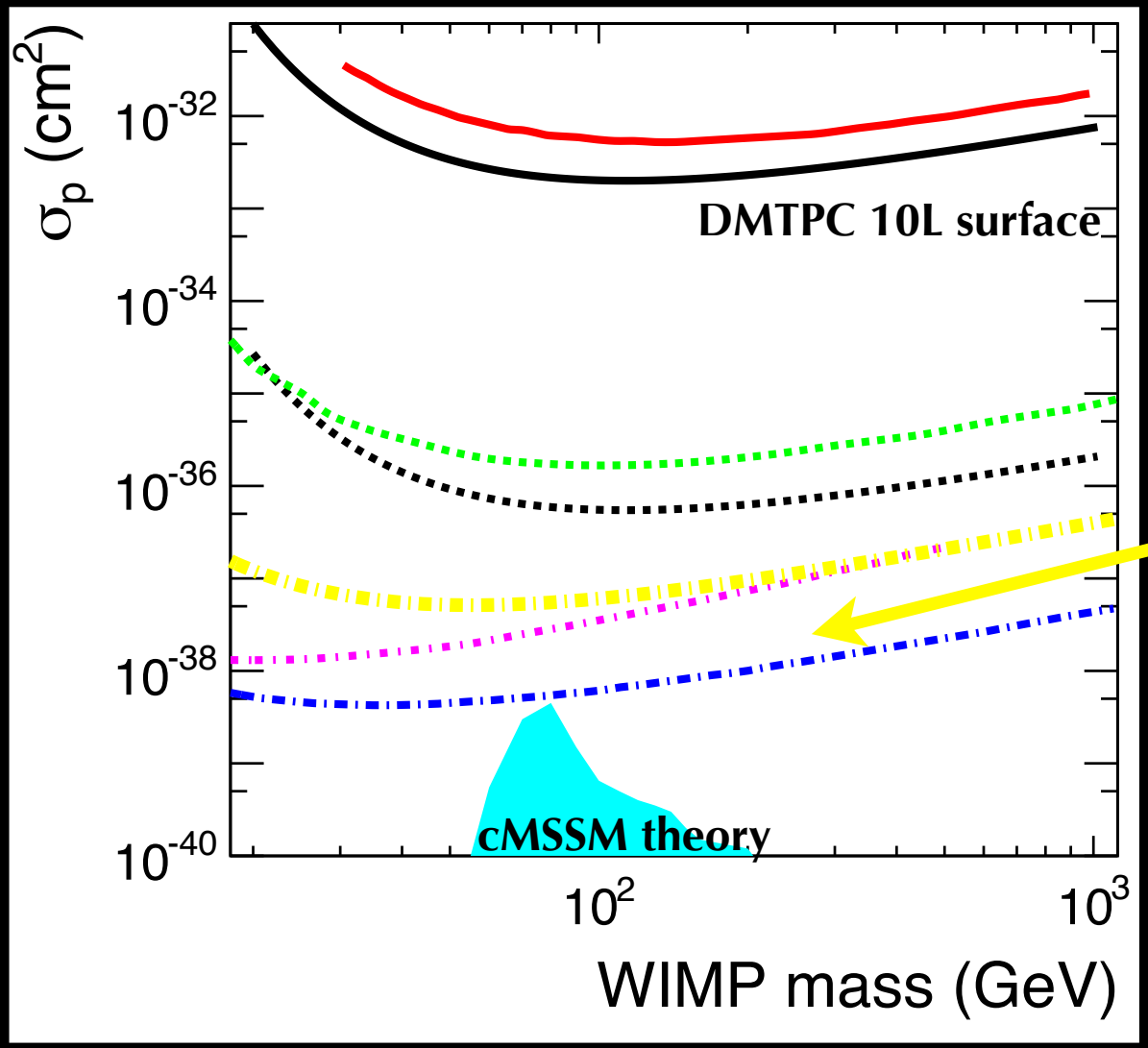

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1D results

COUPP *PRL.106, 021303 (2011)*

SIMPLE *arXiv:1106.3014*

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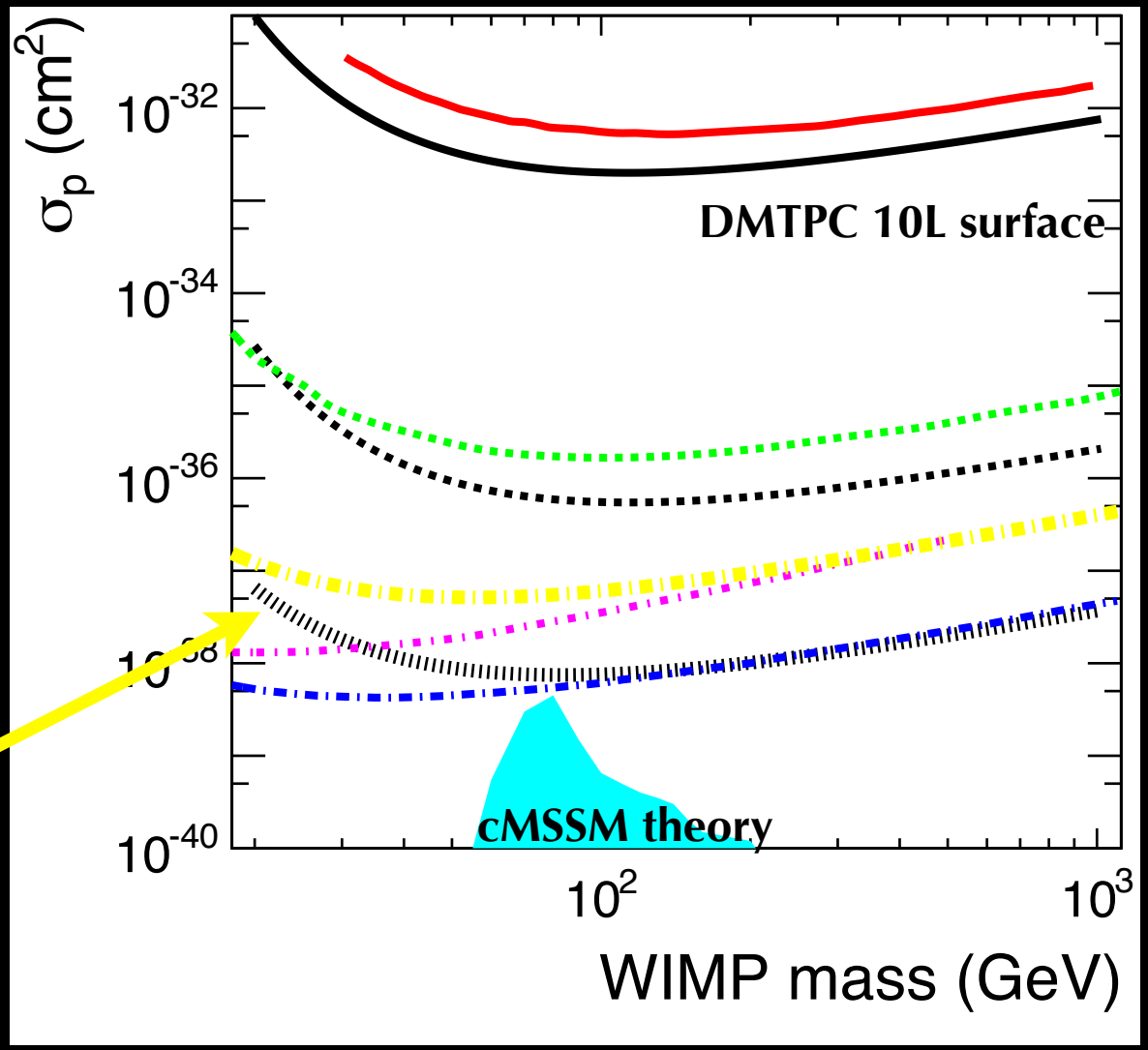
S. Ahlen et al., Phys. Lett. B 695 (2011)

1m^3 projected sensitivity, 80 keVr threshold, 0-bgnd **(DMTPCino** at WIPP)



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1D results

COUPP *PRL.106, 021303 (2011)*

SIMPLE *arXiv:1106.3014*

PICASSO *arXiv:1202.1240*

Next steps for directional searches:

lower backgrounds, modest improvement in angular resolution, scale up...

Theory region:
Rozkowski et al JHEP 07 (2007) 075
Ellis et al PRD63 (2001) 065016

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

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

- Recoil DIrection Test: *A. M. Green & B. Morgan, PRD 2010; Borzognia, Gelmini, Gondolo arXiv:1205.2333*
- 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*

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

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

Backgrounds make directional detection very attractive. Large low-energy, low-background tracking detectors have potential for *confirmation* of the astrophysical origin of a candidate direct detection dark matter signal.

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 DRIFT, NEWAGE, DMTPC, MiMAC, emulsions, ++ ... lots of new ideas.

Dark matter telescope:
transition from discovery to observatory.