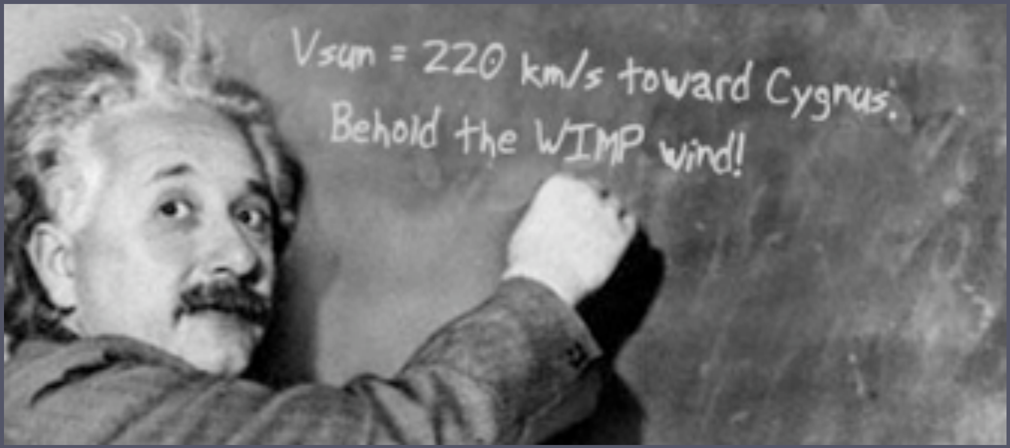


Directional Dark Matter Searches and Future

- Overview and CYGNUS
  - DM-TPC, NEWAGE, MIMAC
- progress with DRIFT
- DRIFT future
- Scale-up?

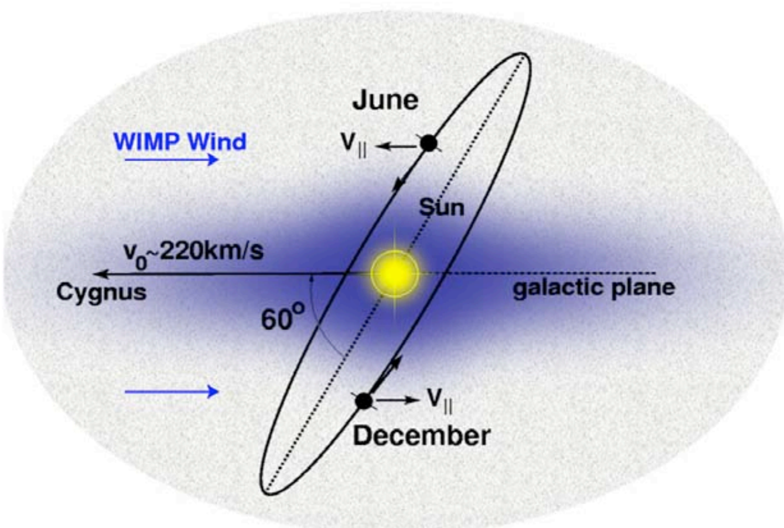
Neil Spooner

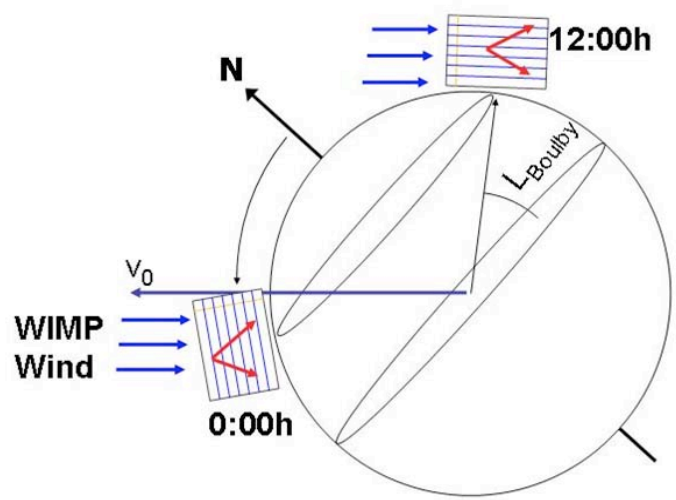
The University Of Sheffield.

Dark Matter Signals

and directionality

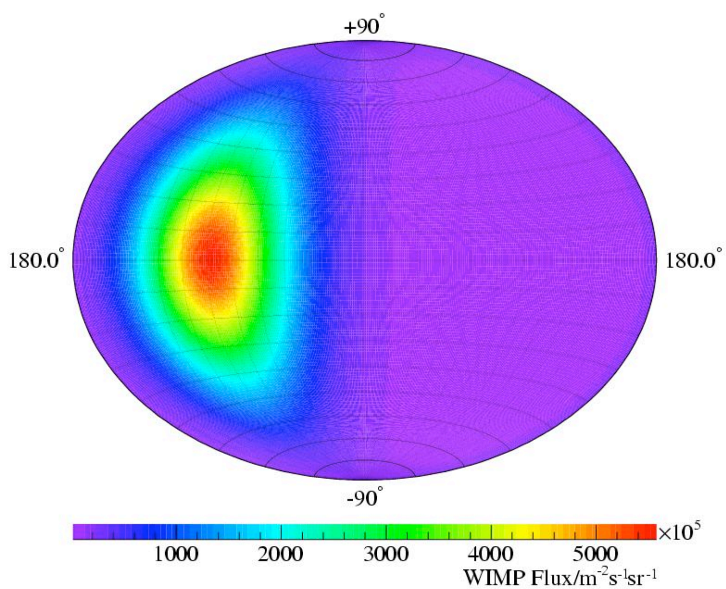
- Motion of the Earth through a static WIMP 'halo' -> Earth is subject to a 'wind' of WIMPs
- of average speed ~220kms^{-1} coming roughly from the direction of the constellation Cygnus.
- The Earths rotation relative to the WIMP wind -> Direction changes by ~90° every 12 hours



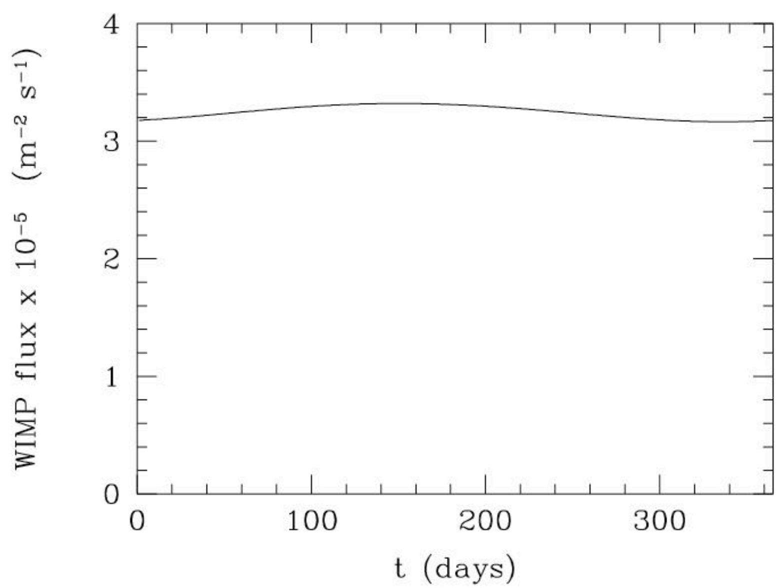


Directional Dependence vs. Annual Modulation

Directional signal



Annual modulation signal



Hard for a background to mimic the directional signal.

(anisotropic backgrounds in lab are isotropic in Galactic rest-frame)

A WIMP directional signal could ***(in principle)*** be detected with of

order 10 events

[Copi, Heo & Krauss; Copi & Krauss; Lehner & Spooner et al.]

Towards WIMP Astronomy

How Many WIMPs Needed?

Dependence of number of events to reject isotropy (*and detect a WIMP signal*) at 90 (95)% c.l. in 90 (95)% of experiments, N_{90} (N_{95}), on detector capabilities:

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

} upgraded and unrealistic

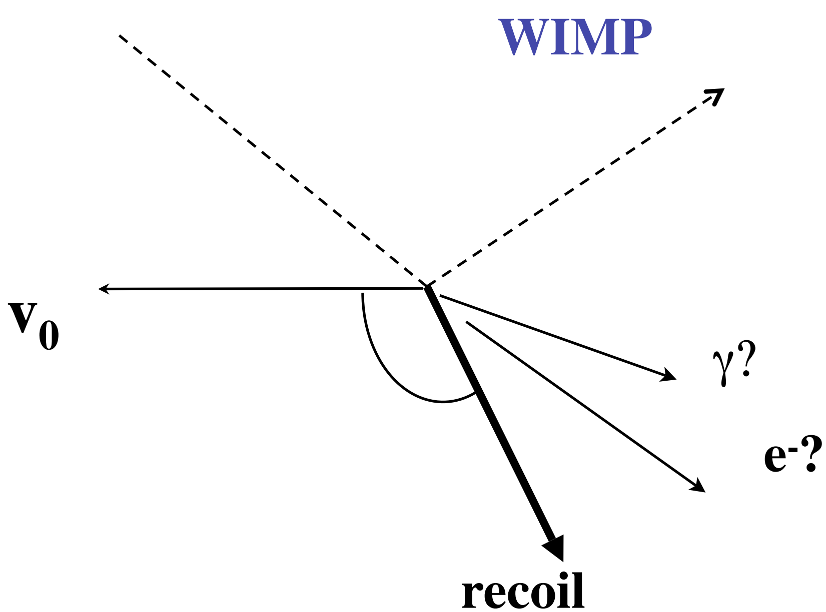
Green & Morgan 'PRD '08, arXiv:0711.2234
Green & Morgan, Astropart. Phys '07, astro-ph/0609115
Morgan & Green, PRD '06 ,astro-ph/0508134
Morgan, Green & Spooner, PRD '05, astro-ph/0408047

} assuming optimal position sensitivity

baseline configuration: 3-d vector read-out,
20 keV threshold,
zero background,
recoil reconstruction uncertainty taken into account

Advantages of Directionality

- 3D recoil direction, and sense (head-tail), full particle ID
- A definitive signal, linked to the galaxy, can not be mimicked
- Event by event background rejection, gamma, electron, recoil tracking in space and time (>10^6 gamma rejection)
- Low threshold, <5 keV nuclear recoil feasible
- Many targets possible, C, S, F, Xe… (SD)
- Room temperature operation, relatively known technology



- Potential for other physics e.g. KK axions

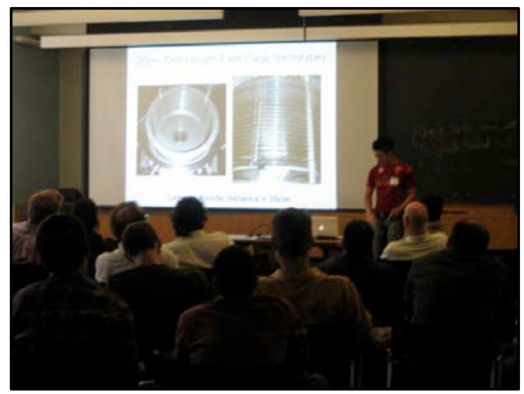
B. Morgan, N.J.C. Spooner and K. Zioutous, Astropart. Phys. 23 (2005) 287

CYGNUS Cooperation links most groups interested in directional detection

- Interest in directional detection rapidly increasing
- DRIFT (US-UK), MIMAC (France), (CAST), NEWAGE (Japan), DMTPC (US), Emulsions (Japan)
- Theory groups....

CYGNUS2007 meeting
22-24 July 2007, Boulby, UK

CYGNUS2009
11-13 June 2009, Boston, USA



CYGNUS2011, June 8-10, Aussois, France

Cooperation on joint document towards scale-up

White Paper

International Journal of Modern Physics A
Vol. 25, No. 1 (2010) 1–51

World Scientific
www.worldscientific.com

International Journal of Modern Physics A
Vol. 25, No. 1 (2010) 1–51

THE CASE FOR A DIRECTIONAL DARK MATTER DETECTOR AND THE STATUS OF CURRENT EXPERIMENTAL EFFORTS

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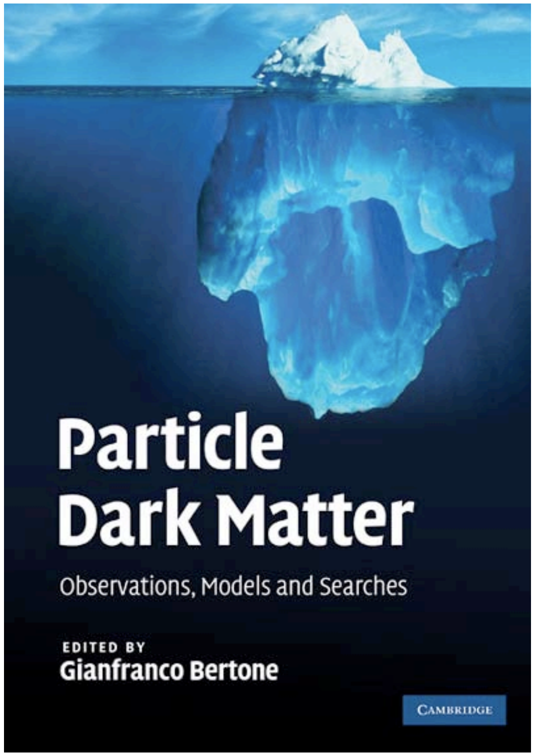
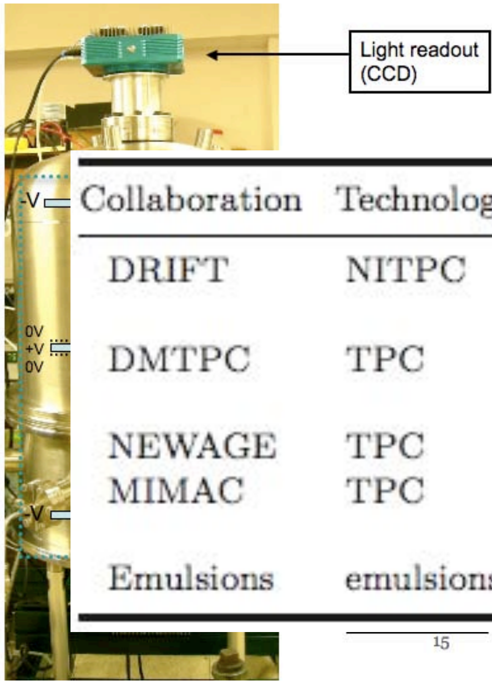
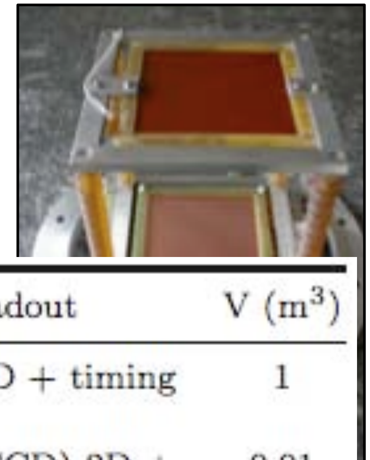


22 Directional detectors *N. Spooner* 437
22.1 Direct dark matter detection technologies and directionality 437
22.2 The directional signature and statistics 438
22.3 Directional detector concepts 440
22.4 Gas detector physics – diffusion and straggling 442
22.5 TPC gamma background rejection and energy threshold 447
22.6 TPC neutron background rejection, solar neutrinos and radon 450
22.7 Electronic noise and other background 452
22.8 WIMP detection and directional sensitivity in practice 452
22.9 Head–tail recoil discrimination, theory and experiment 456
22.10 Experimental status and readout technology 457
22.11 Scale-up and a future WIMP telescope 463

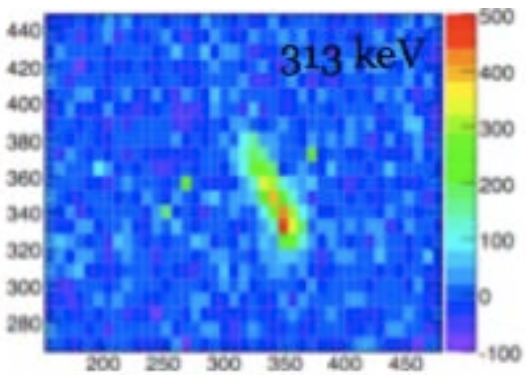
Latest, e.g.:

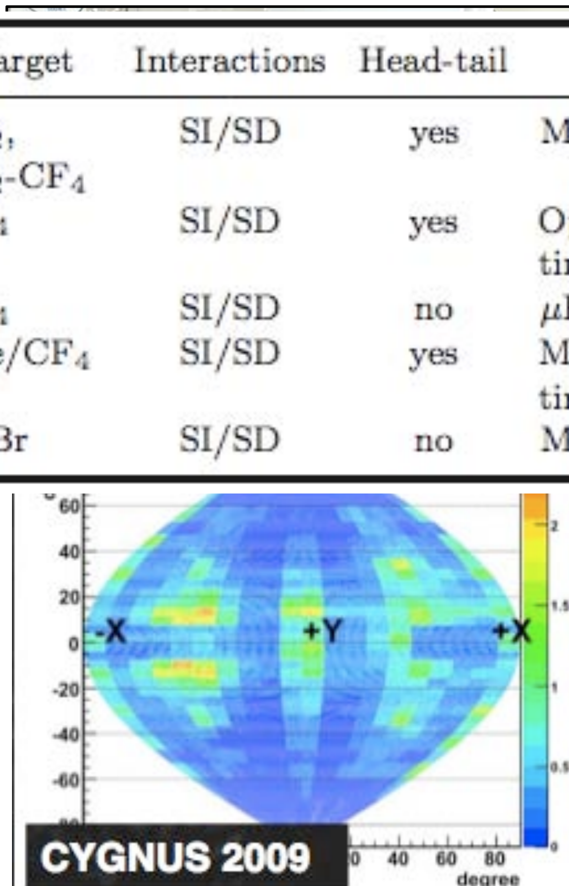


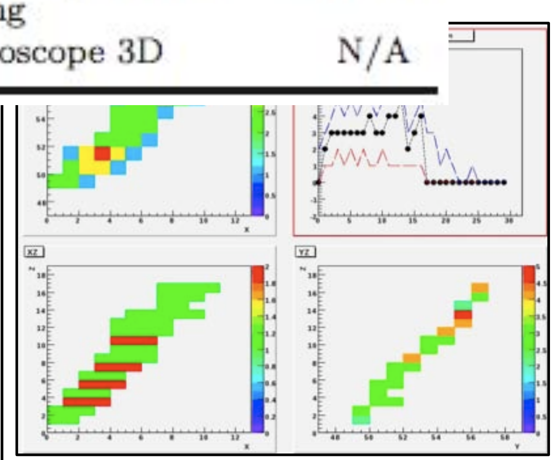
NEWAGE (Japan)



Collaboration	Technology	Target	Interactions	Head-tail	Readout	V (m^3)
DRIFT	NITPC	CS_2, CS_2-CF_4	SI/SD	yes	MWPC 2D + timing	1
DMTPC	TPC	CF_4	SI/SD	yes	Optical (CCD) 2D + timing	0.01
NEWAGE	TPC	CF_4	SI/SD	no	μPIC 2D + timing	0.03
MIMAC	TPC	$^3He/CF_4$	SI/SD	yes	Micromegas 2D + timing	0.00013
Emulsions	emulsions	AgBr	SI/SD	no	Microscope 3D	N/A







5.9 keV electron track

DM-TPC 10-Litre

MIT, U Boston, U Brandeis - US

Low-pressure CF_4 TPC

- 50-75 torr: 40 keV F recoil ~2mm

Optical readout (CCD)

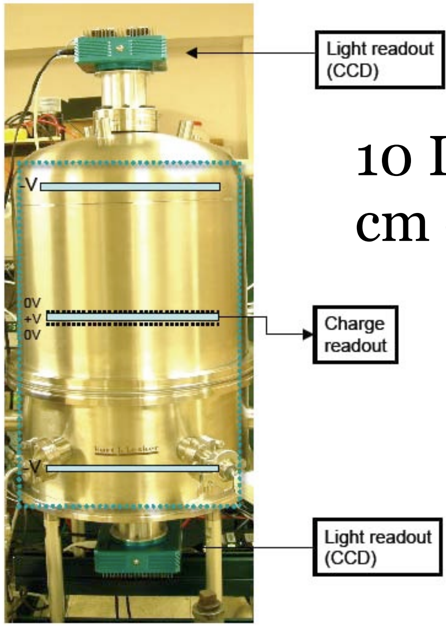
- Image scintillation photons produced in amplification region
- 2D, low-cost, proven technology

Amplification region

- Wire planes → mesh detector
- Woven mesh 25μm, 250μm pitch

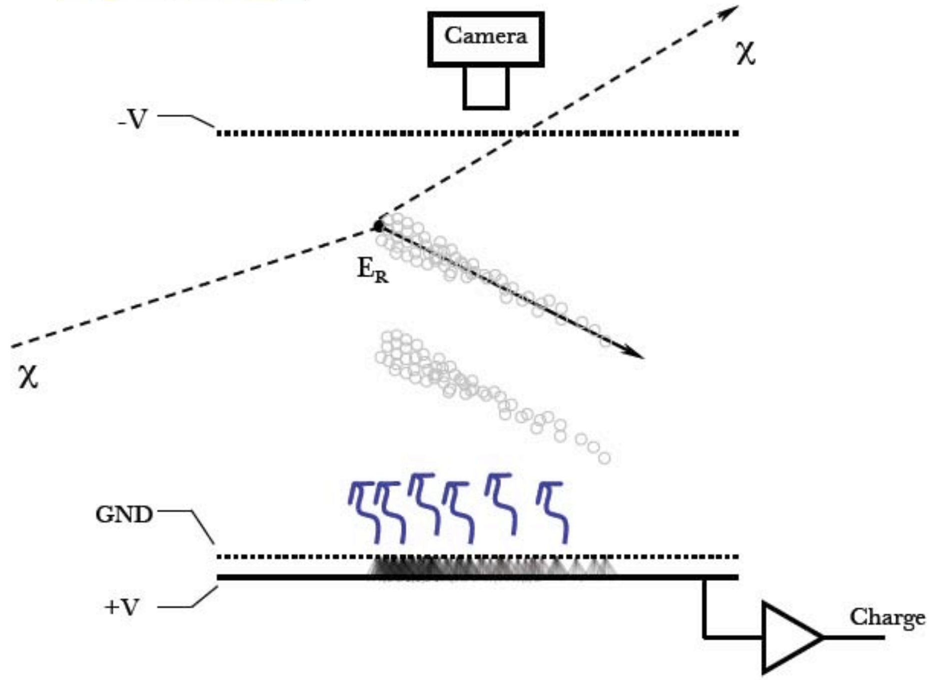
CF_4 is ideal gas

- F: spin-dependent interactions
- Good scintillation efficiency
- Low transverse diffusion
- Non flammable, non toxic



10 L fiducial volume 20 cm drift 3.3 g at 75 torr

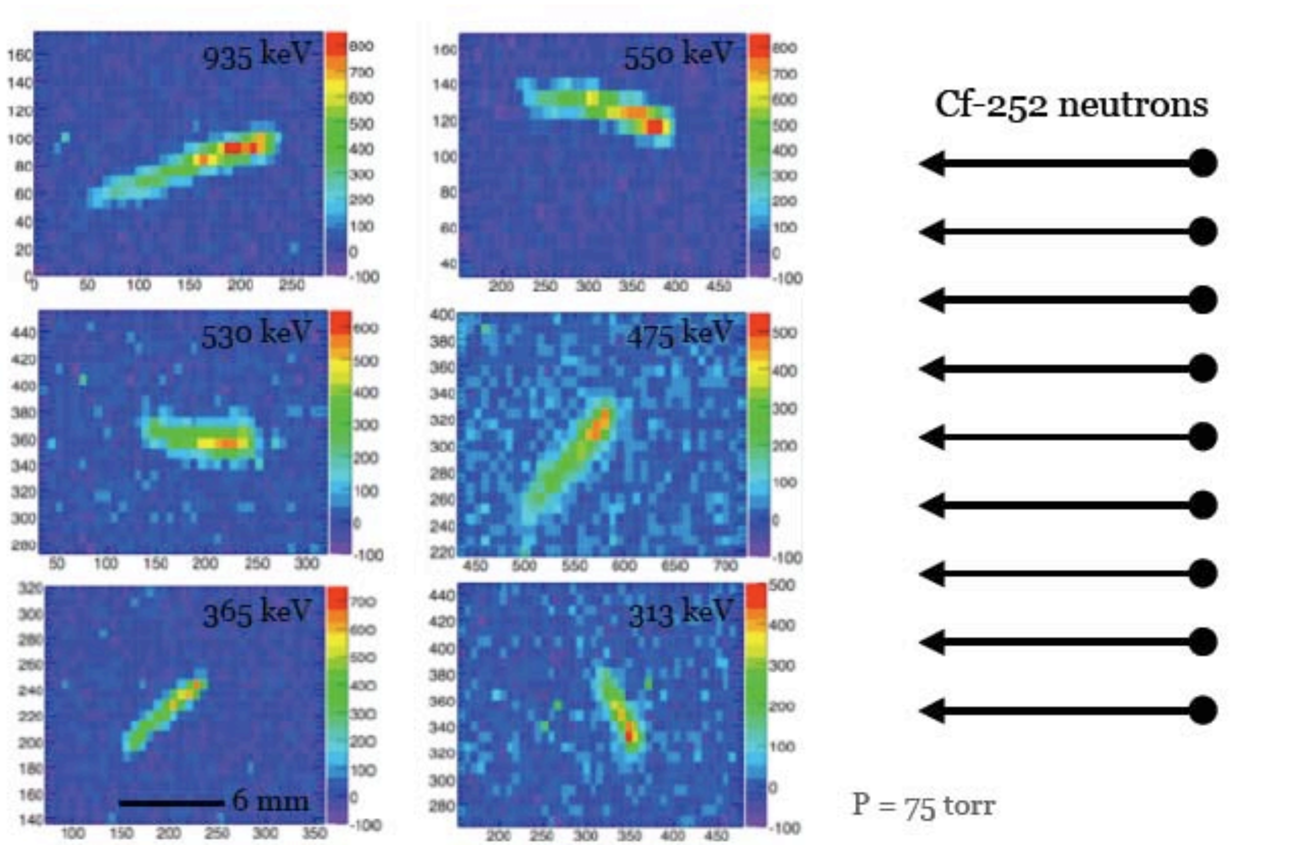
Charge and scintillation readout



DM-TPC head-tail

^{252}Cf run with mesh detector @ 75 torr
Mesh-based detector: 2D projection of recoil

Stable data-taking at 75 torr
"Head-tail" effect down ~ 100 keV
Good data-MC agreement



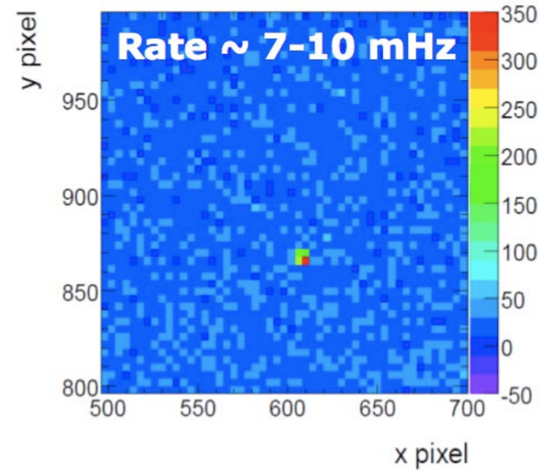
100 pixels = 6 mm

Dujmic et al. Astropart. Phys. 30 (2008) arXiv:0804.4827

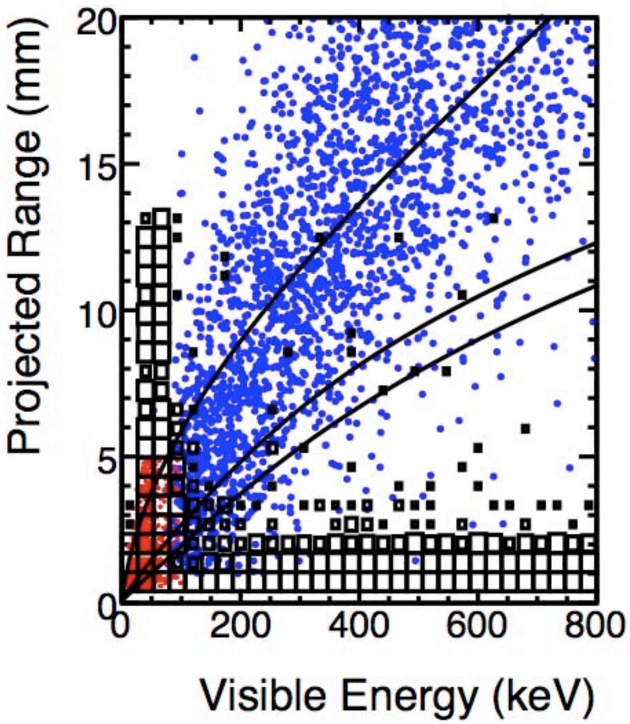
Astropart. Phys. 30 (2008) 58-64

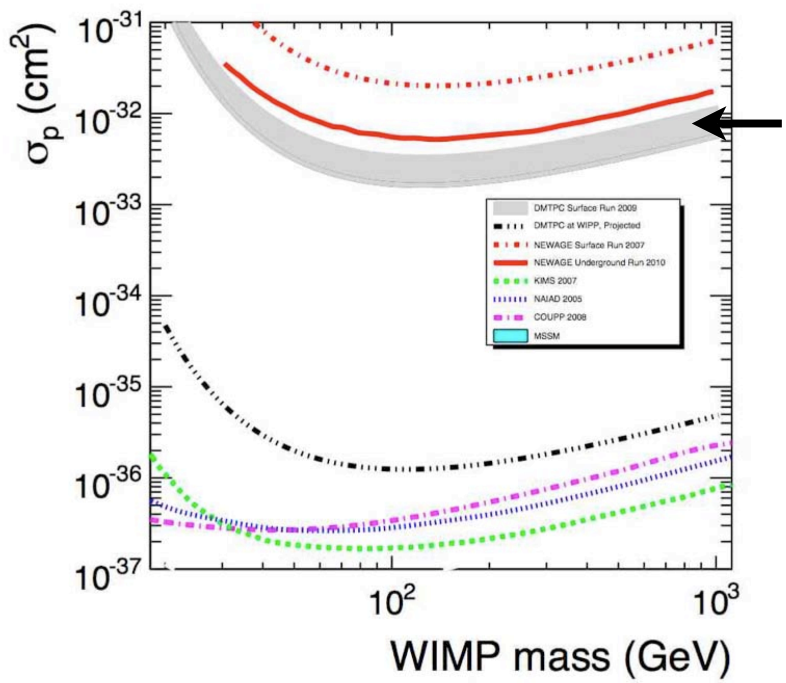
DM-TPC Surface run

- Surface run of 10 litre
- F SD WIMP-p limit ~2400pb
- CCD-specific backgrounds "worms"



Surface run data passing all cuts except:
alpha
worm
burn-in



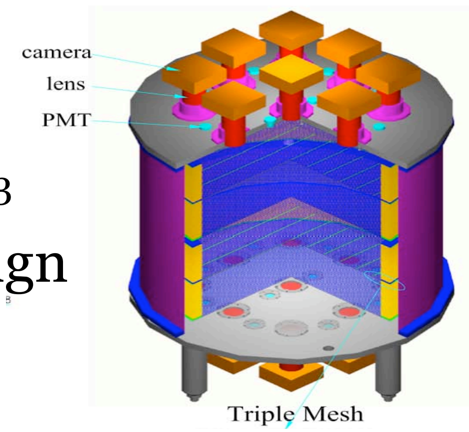


DM2010

DM-TPC Future

- Going underground to WIPP
- 2x larger detector under-construction
- Cubic meter design underway

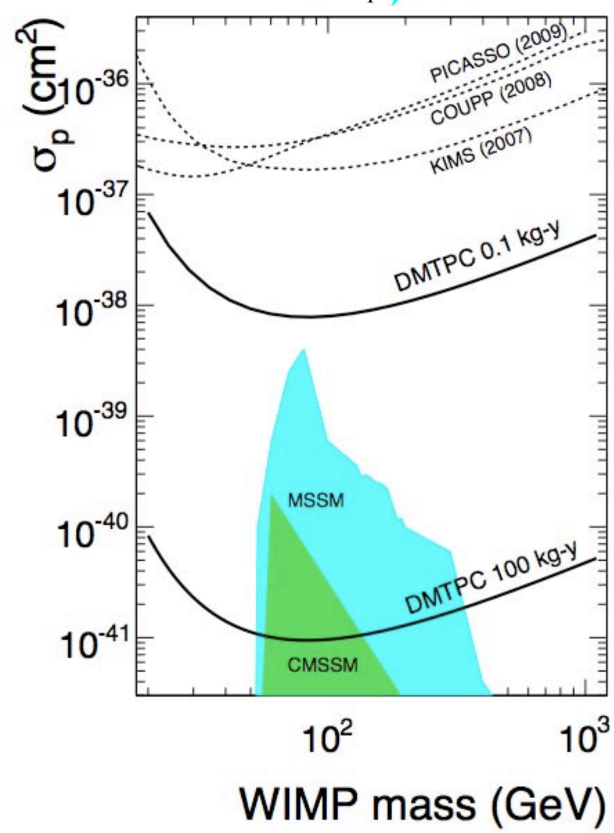
1 m^3 design

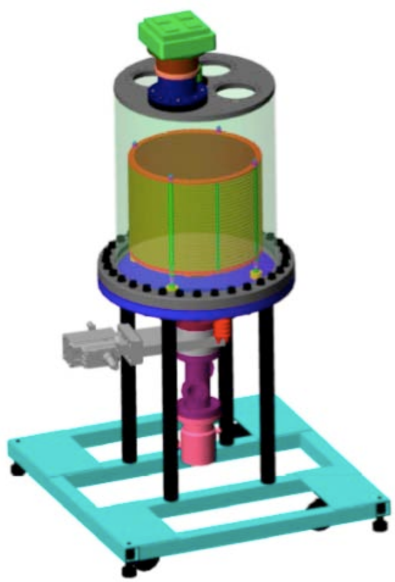


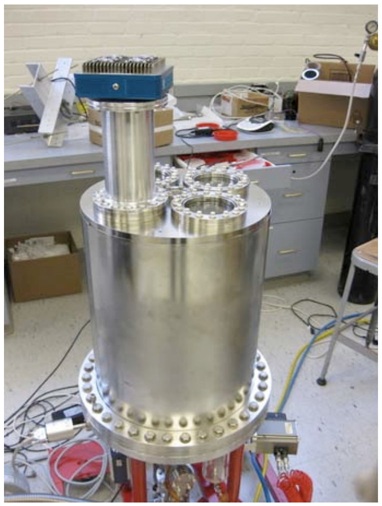
Attention to radiopurity, material selection, high-purity copper, non-thoriated welds

Higher vacuum, more stable gain

PMT signal 3D track recon worm veto



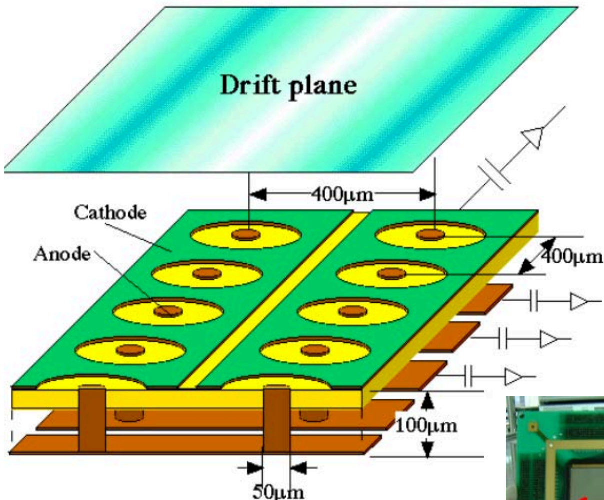


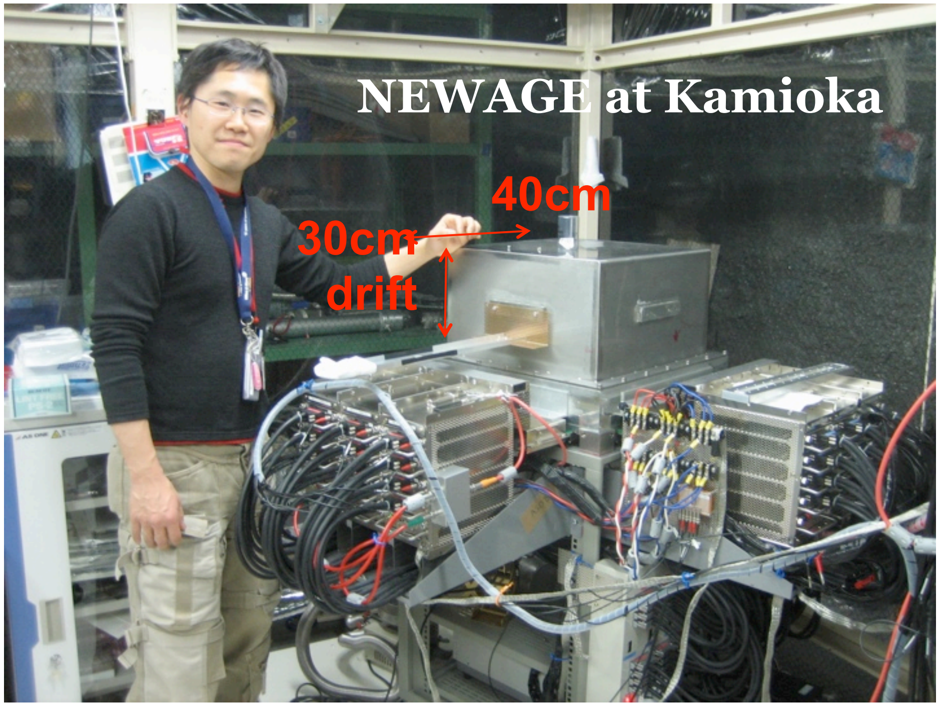


NEWAGE Concept

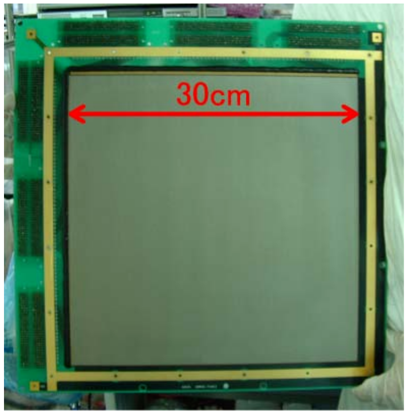
Kyoto University – Japan

CF_4 filled 3D imaging gaseous TPC detector using micro-pattern pixellated readout ('μ-PIC')





Key device: Kyoto designed μ-PIC readout – 400μm resolution



CF_4 gas @ 0.2 bar (aiming for 0.05 bar soon)

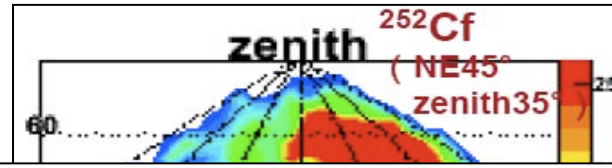
Now running in Kamioka

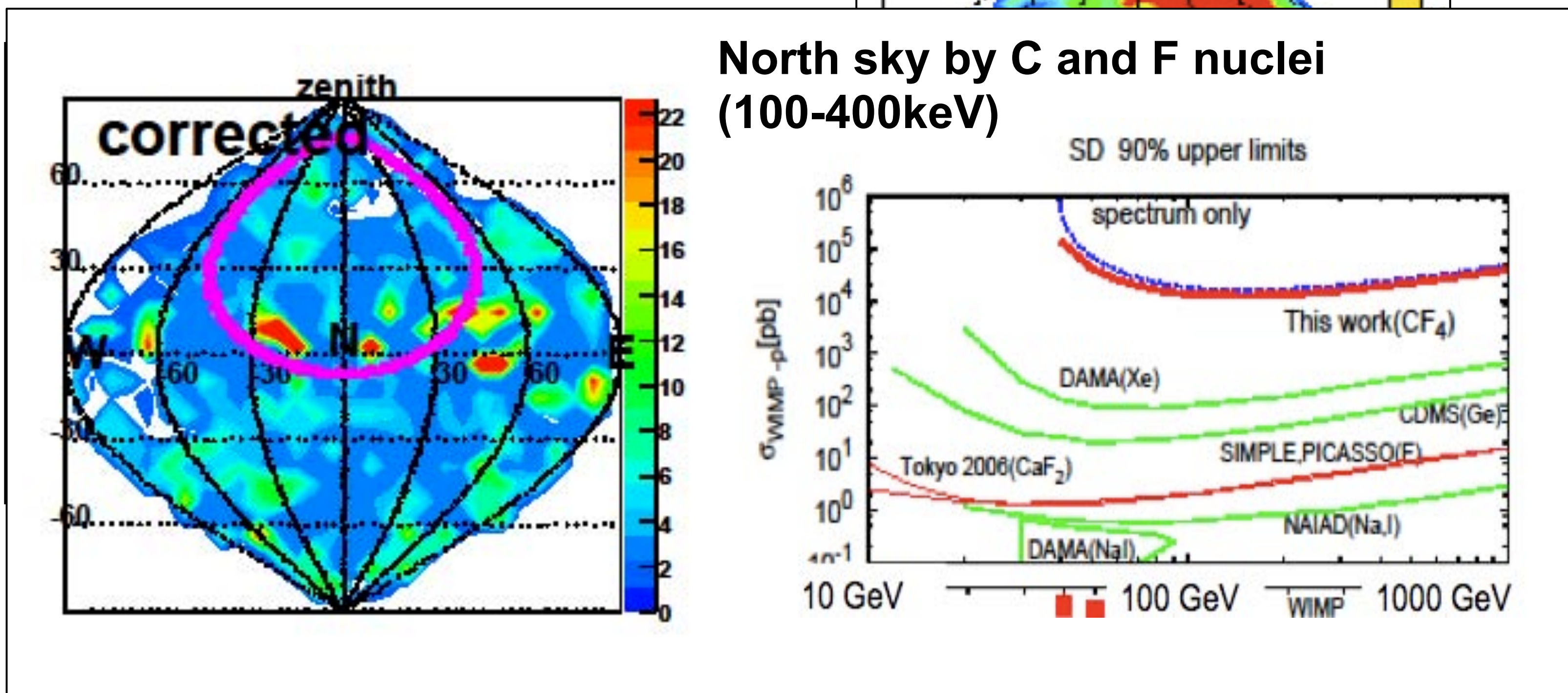
Aiming for 1m³ detector operating @ kamioka by 2013

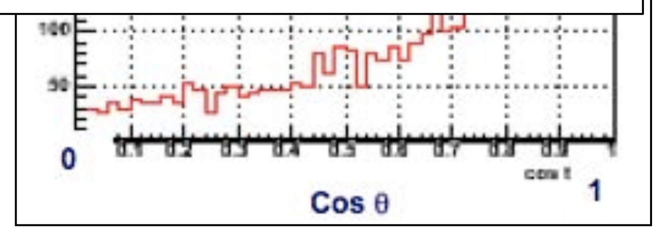
PLB 654 (2007) 58 (Miuchi *et.al.*)
Preprints: physics/0701085

NEWAGE Result status

Directional sensitivity confirmed for 'low energy' recoils (>200keV) from ^{252}Cf neutrons.





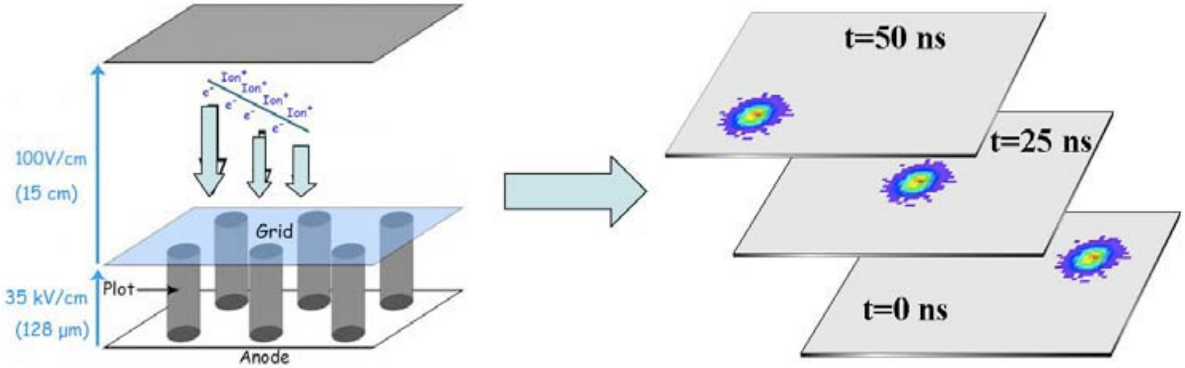


Also a 10^4 σ_{WIMP-p} SD limit based on isotropy of no-source recoil tracks >100-400keV

(PLB 654 (2007) 58)

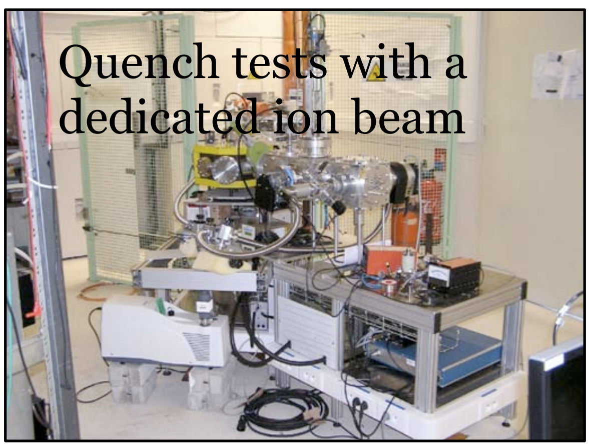
MIMAC Concept **Grenoble, Saclay - France**

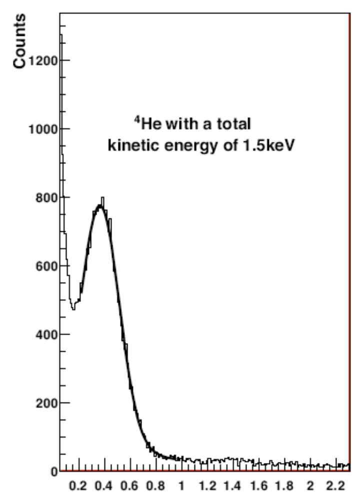
Matrix of micromegas µTPC filled with ^3He, CF_4, CH_4 or/and C_4H_{10}. A 10 kg 3He dark matter detector, or the equivalent mass of CF_4, with a 1 keV threshold (MIMAC) would be sensitive to SUSY models

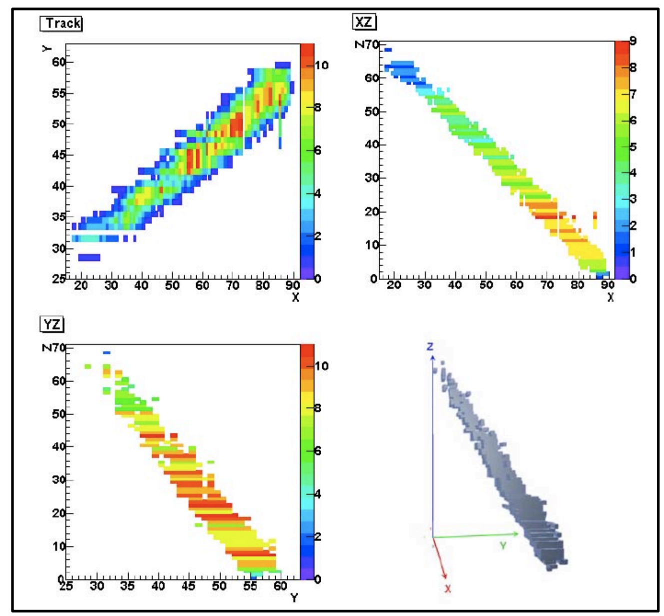


The x–y, y–z and x–z projections of a 5.5 MeV alpha track

Developed a specific chip giving access to a 3D track reconstruction with a 300 µm spatial resolution







DRIFT
Dark Matter Search

PI - D.P. Snowden-Ifft

PIs – D. Loomba and M. Gold

UNM

PIs - N.J.C. Spooner and E. Daw

The University Of Sheffield.

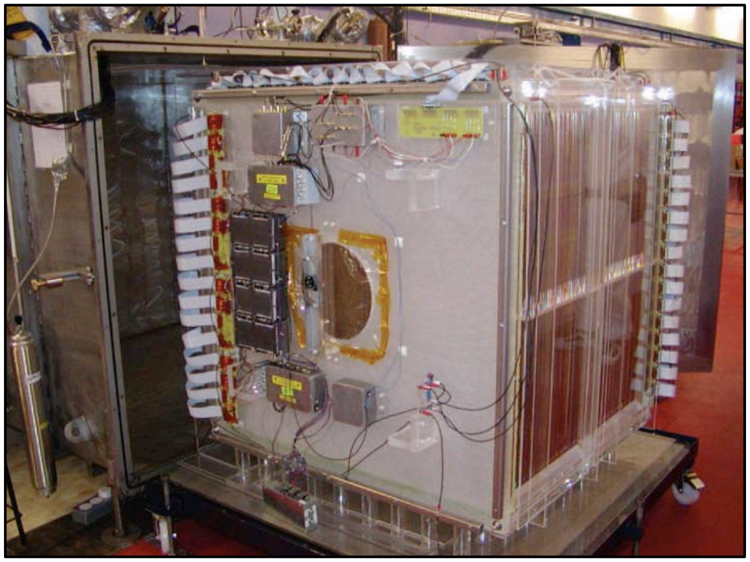
PI - A.S. Murphy

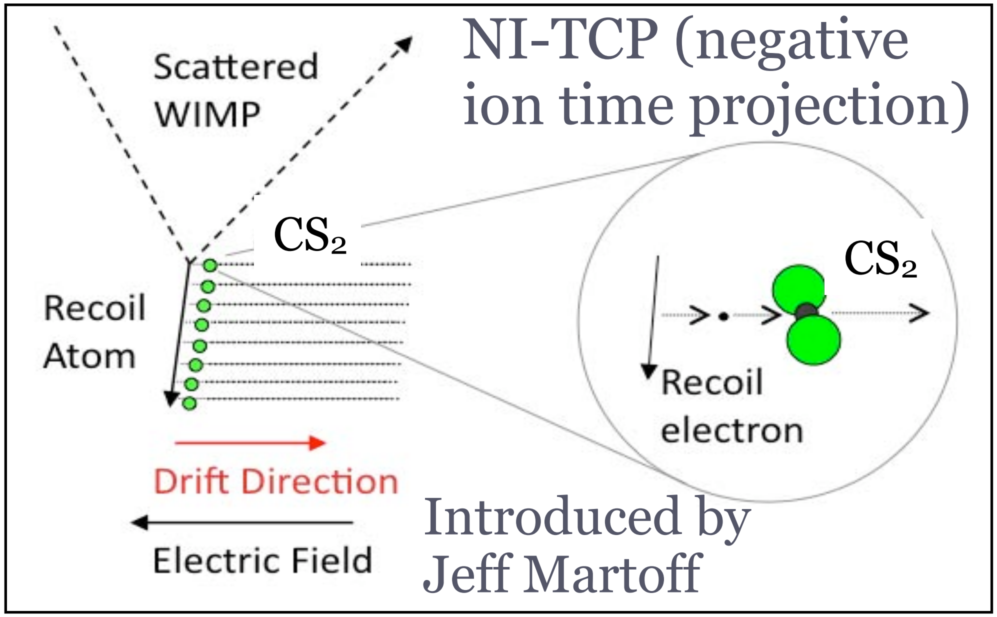
(Directional Recoil Identification From Tracks)

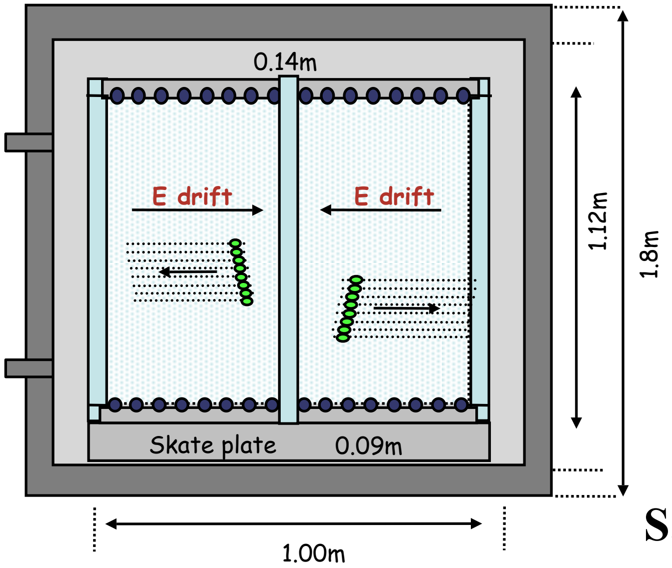
Progress with DRIFT

- Overview
- New SD limits
- Fiducialisation and 24m^3 DRIFT-III

DRIFT IIa-d



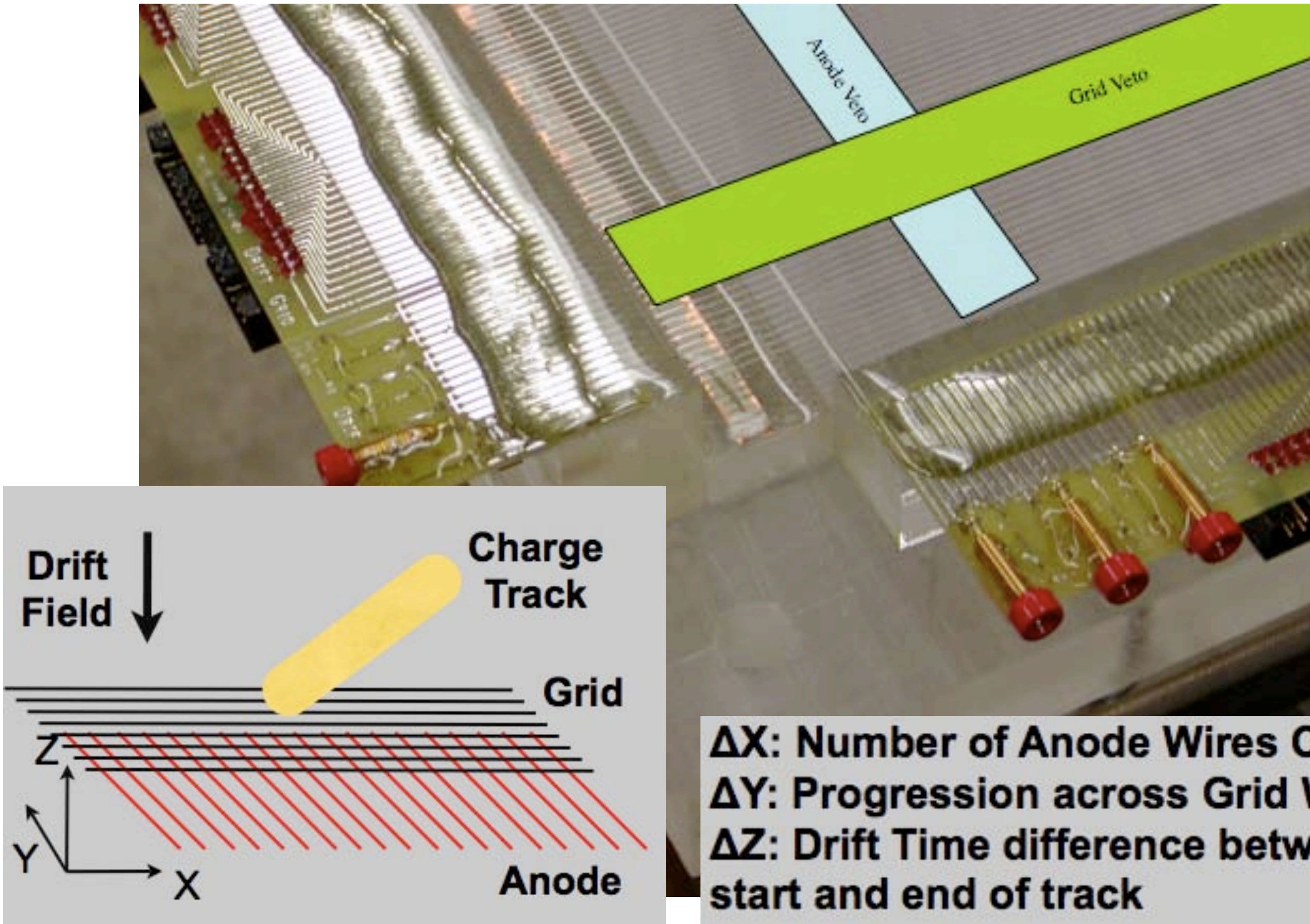




- 1 m³ active volume - back to back MWPCs
- Gas fill 40 Torr CS_2 => 167 g of target gas
- 2 mm pitch anode wires left and right
- Grid wires read out for Δy measurement
- Veto regions around outside
- Central cathode made from 20 μm diameter wires at 2 mm pitch
- Drift field 624 V/cm
- Modular design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

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

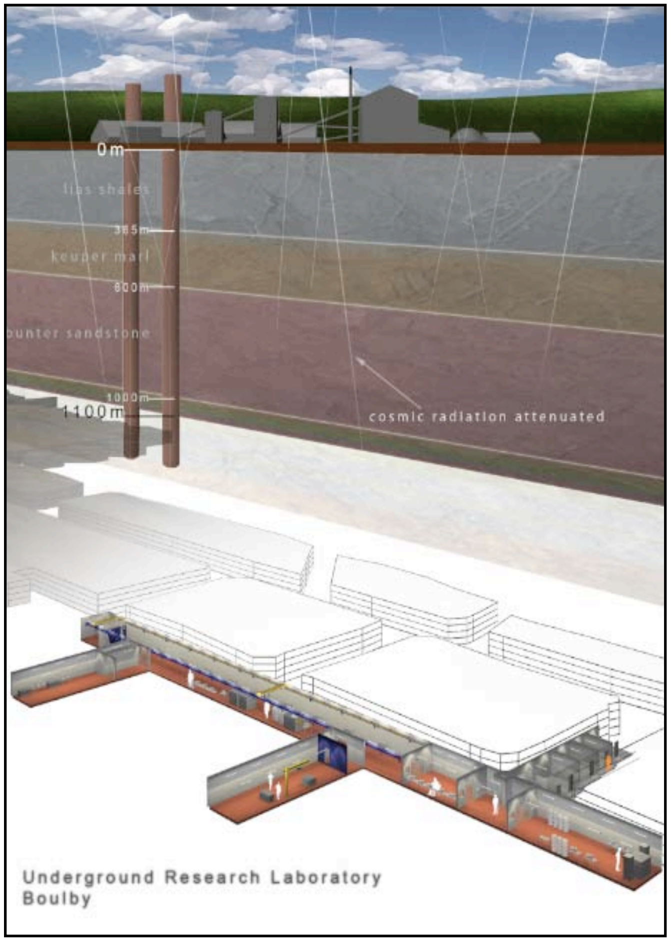
MWPC Concept in DRIFT



ΔX: Number of Anode Wires Crossed
ΔY: Progression across Grid Wires
ΔZ: Drift Time difference between start and end of track

Boulby Mine (UK)

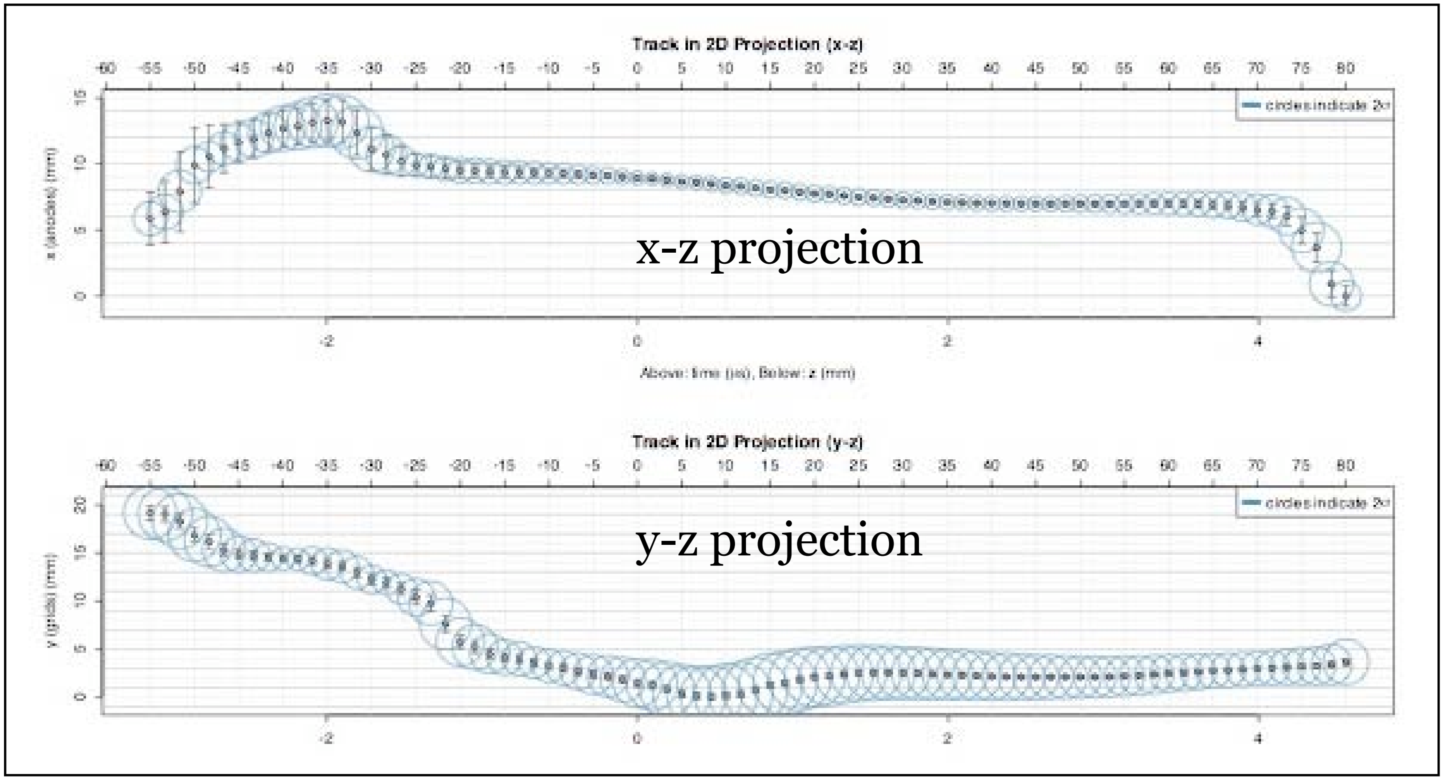
- Current site (1.1 km deep) hosts dark matter experiments in salt rock
- But new excavation underway to deeper levels, hard dolomite rock
- Suitable for a large TPC!



(1) 3D Track Reconstruction Results

D. Muna Thesis, University of Sheffield (2008)

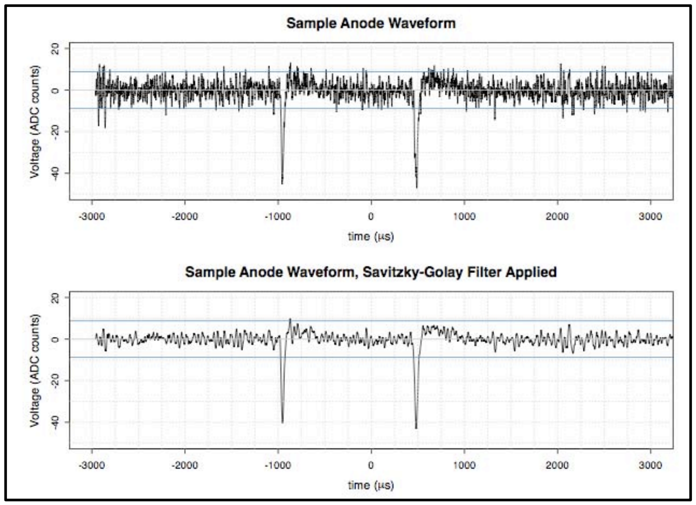
Example 3D reconstruction (x-z and y-z projections) of a ~100 keV S recoil in DRIFT IIb (size of circles is indicative of the size of charge deposited).

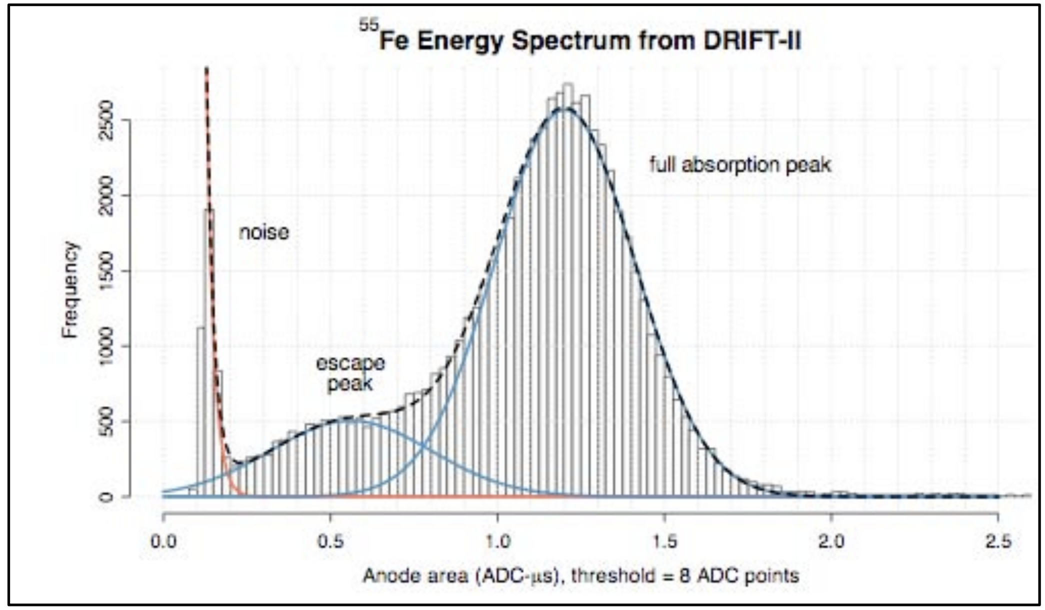


(2) Low Energy Results

S. Burgos et al., Astroparticle Physics 31 (2009) 261

use of Savitzky-Golay digital filter





^{55}Fe track reconstruction and digital polynomial smoothing - data fit to exponential decay(noise) plus Gaussians

Energy thresholds -->

Source of Track	Thres. Energy (keV)
Electron	1.23
Alpha	1.23
Carbon nuclear recoil	2.15
Sulphur nuclear recoil	3.46

Note these are not the trigger thresholds yet

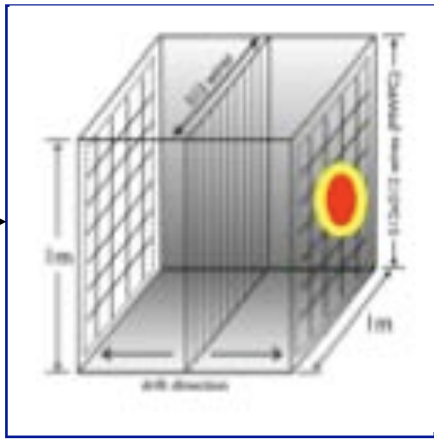
(3) Head-Tail Results

<u>Experiment</u>: S. Burgos et al., Astroparticle Physics 31 (2009) 261

<u>Theory</u>: P. Majewski, D. Muna, D.P. Snowden-Ifft, N.J.C. Spooner (2009) arXiv:0902.4430

Cf-252

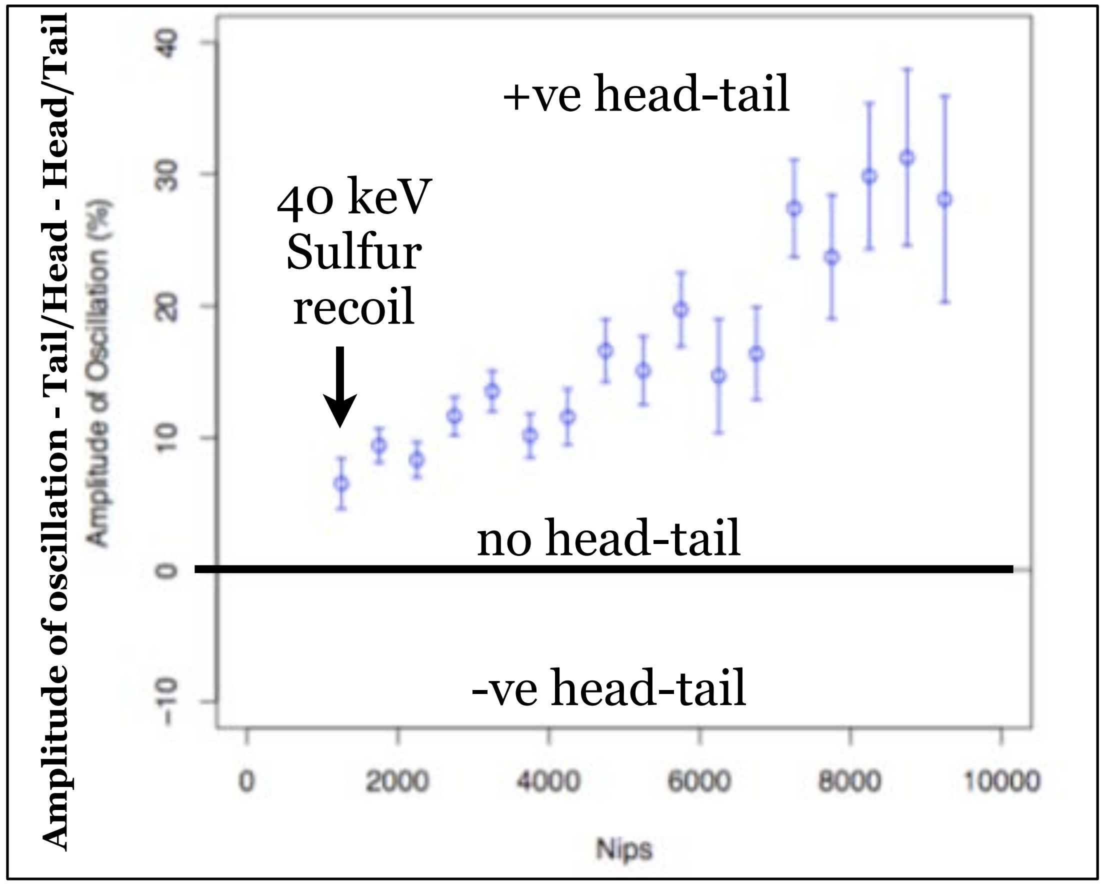
+z



Cf-252

-z

Directed neutron runs (DRIFT IIc): +z, -z,+x, -y



Note: extrapolation indicates head-tail discrimination continues below current threshold

Clear head-tail discrimination (in 1 m^3 at low energy)!

Theory Conclusion:

- expect head-tail
- expect more ionization at start (near interaction)
- depends on W

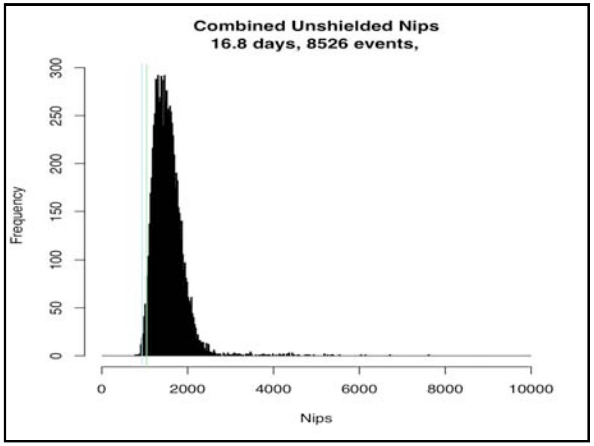
(4) Radon Progeny Recoil (RPR) Results

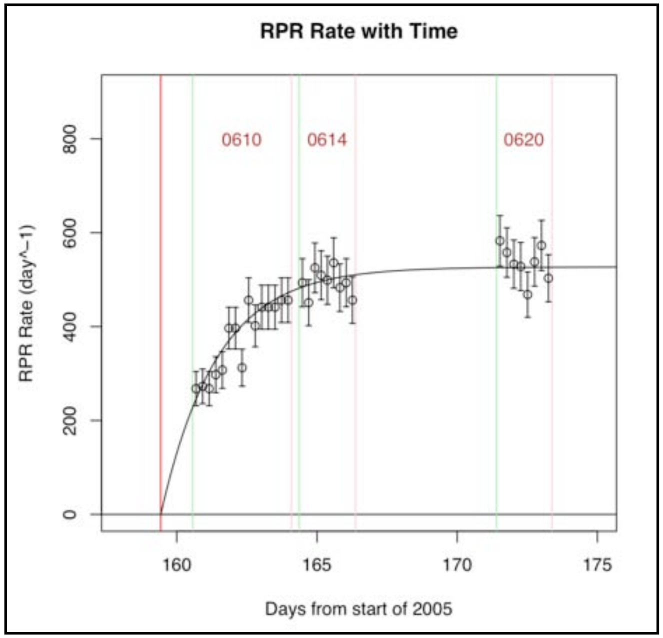
S. Burgos et al., Astropart. Phys. 28 (2007) 409

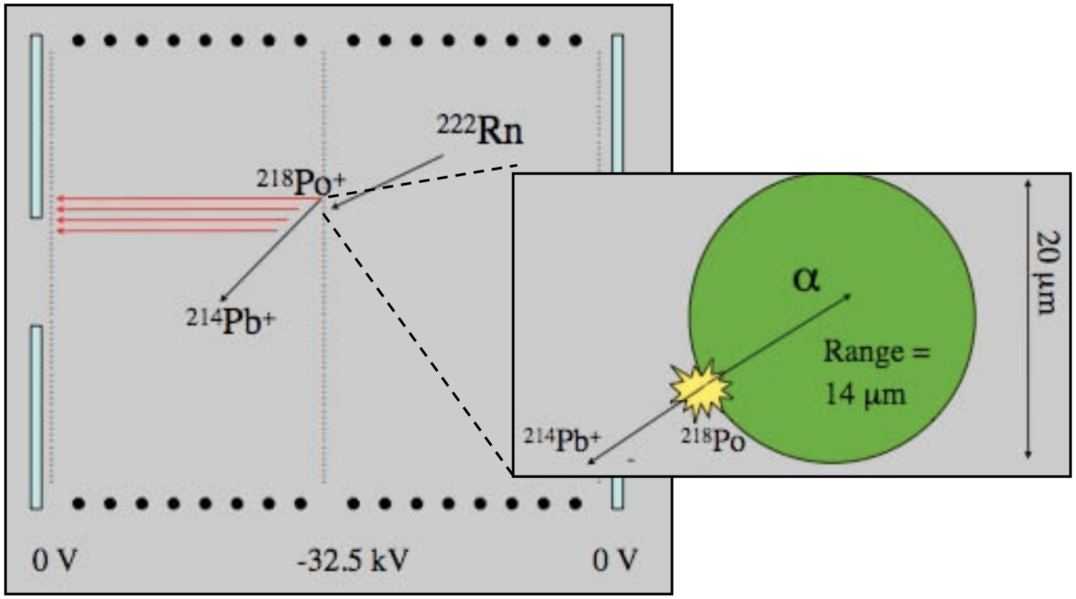
First low background runs of DRIFT-II see a recoil-like background ~200-600 / day (50-250 keV).

Increase with time consistent with Rn emanation.

Hypothesis: Recoil of radon progeny on central cathode - with alpha absorbed in wire.







RPR Reduction

Steps taken to reduce RPRs

(1) Reduce radon producing contaminants from vessel:

Sample (Emanating into vacuum)	Fill gas	Emanation time (days)	Humidity (%)	Raw result (Bq/m^3)	Adjusted result (Rn atoms.s^{-1})
RG58 coax cables (72m)	Dry N2	12.5	24	9.4 +/- 0.7	0.36 +/- 0.03
Electronics boxes	Dry N2	12	37	1.5 +/- 0.3	0.05 +/- 0.02
Ribbon cables	Dry N2	6.5	23	10.1 +/- 0.7	0.50 +/- 0.04
Electronics & PCBs	Dry N2	10	37	0.3 +/- 0.2	<0.02 *
Single core & thin coax cables	Dry N2	7	19	1.3 +/- 0.3	0.04 +/- 0.02
Field cage parts	Dry N2	7	33.3	0.6 +/- 0.2	<0.03 *
				Total	0.95 +/- 0.5

S. Paling et al. (Sheffield)

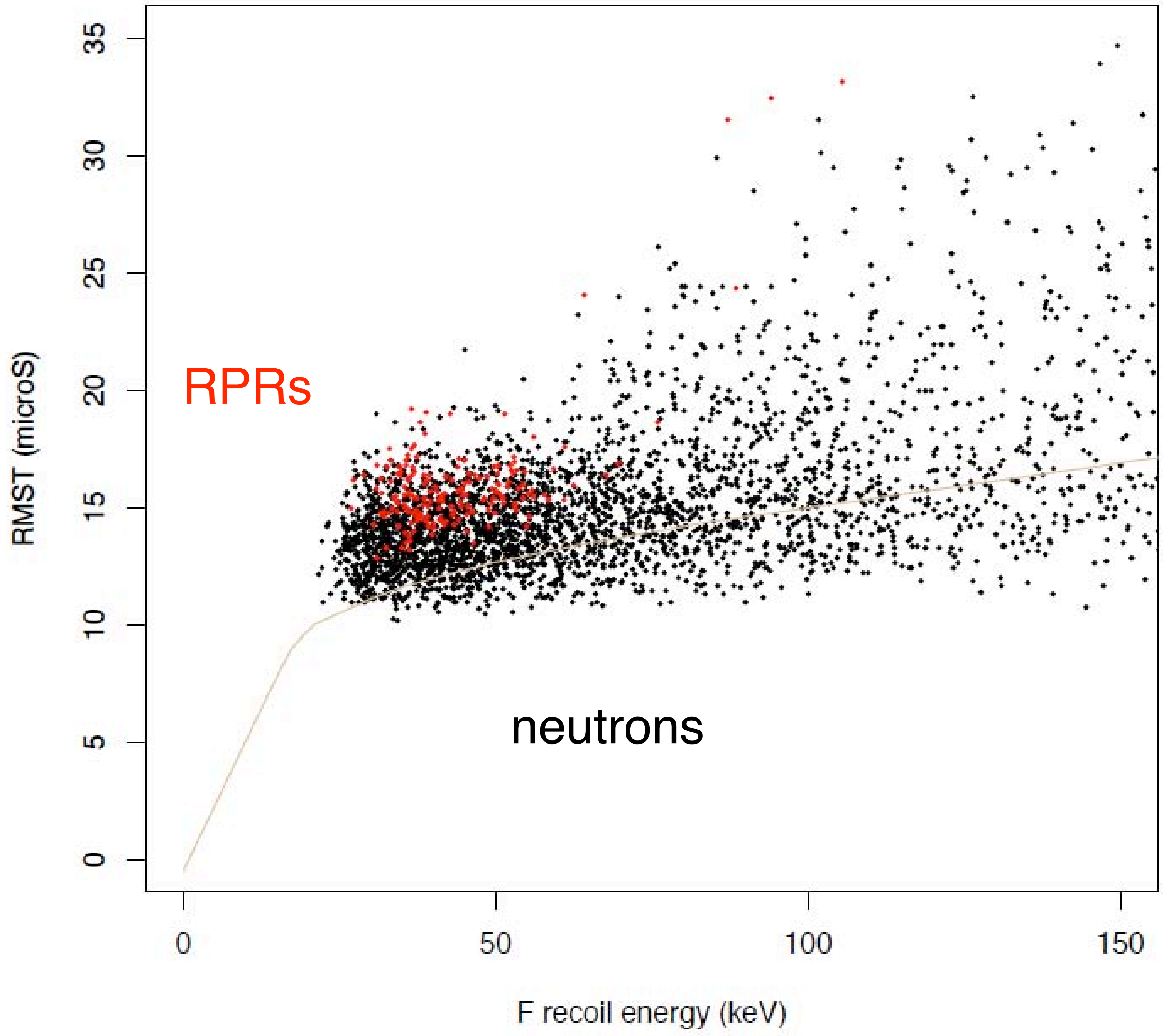
(2) RPRs still produced from Pb isotopes plated out on cathode. Clean cathode with nitric acid

Together, these reduced the RPRs by 96% relative to D-IIa rate

D. Snowden-Ifft, Oxy, J. Turk, UNM
(PhD thesis 2008)

RPR Reduction

(3) RPRs have large pulse-widths as expected from maximally diffused tracks drifting from cathode. So, residual RPRs may be removed in analysis:



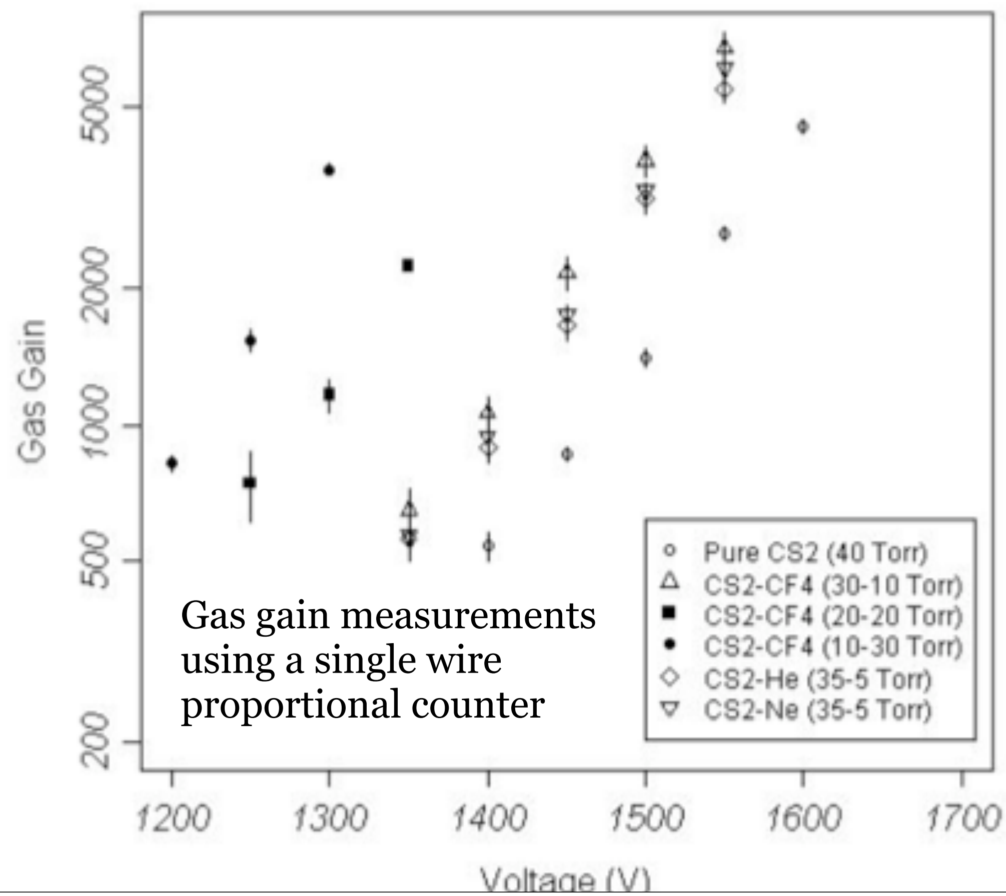
(5) CS_2-CF_4 Measurement Results

Measurements of Gain, W-value, Mobility, stability…

(Pushkin, Snowden-Ifft, Oxy 2009)

e.g. Gain Tests

From the known gain of the amplifier chain and the size of events gives us the gain for a single electron



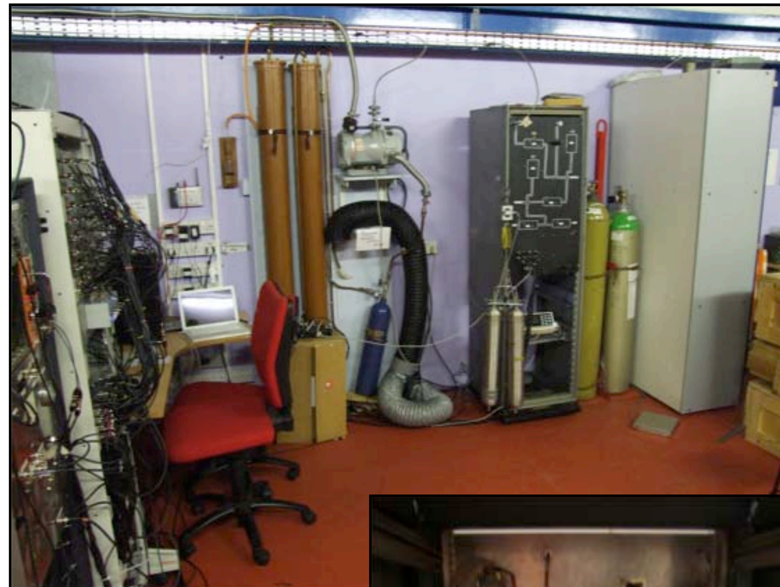
- All mixtures total 40 Torr
  - Gas gain increases for added CF_4
  - Stability decreases
  - High gas gains even with 75% CF_4
  - Best stability with 50:50 mix or lower CF4
- Need to run at lower voltages for stability of high voltage systems – lose MWPC gain
- Loss in MWPC gain is compensated for by improved gas gain.

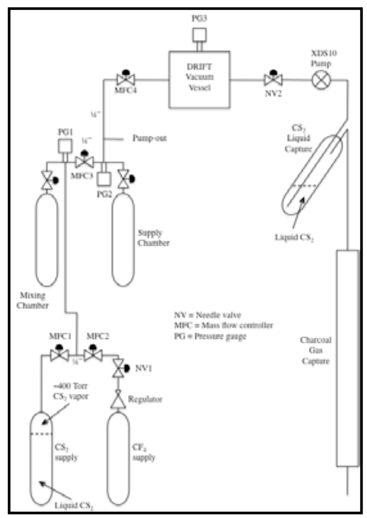
CS_2-CF_4 Mixing Installed at Boulby

(M. Pipe et al., Sheffield)

- Built a fully automated gas mixing system to supply a <u>continuous flow</u> of pre-mixed CS_2-CF_4 gas mixture to the vacuum vessel
- Designed by Oxy-Sheffield
- System of mass flow controllers and capacitance manometers to accurately control and monitor gas
- Fully automated and integrated into the current DRIFT slow control

- Installed at Boulby in May 2009
- Installed and working in 2 days
- Now taking CF_4 data



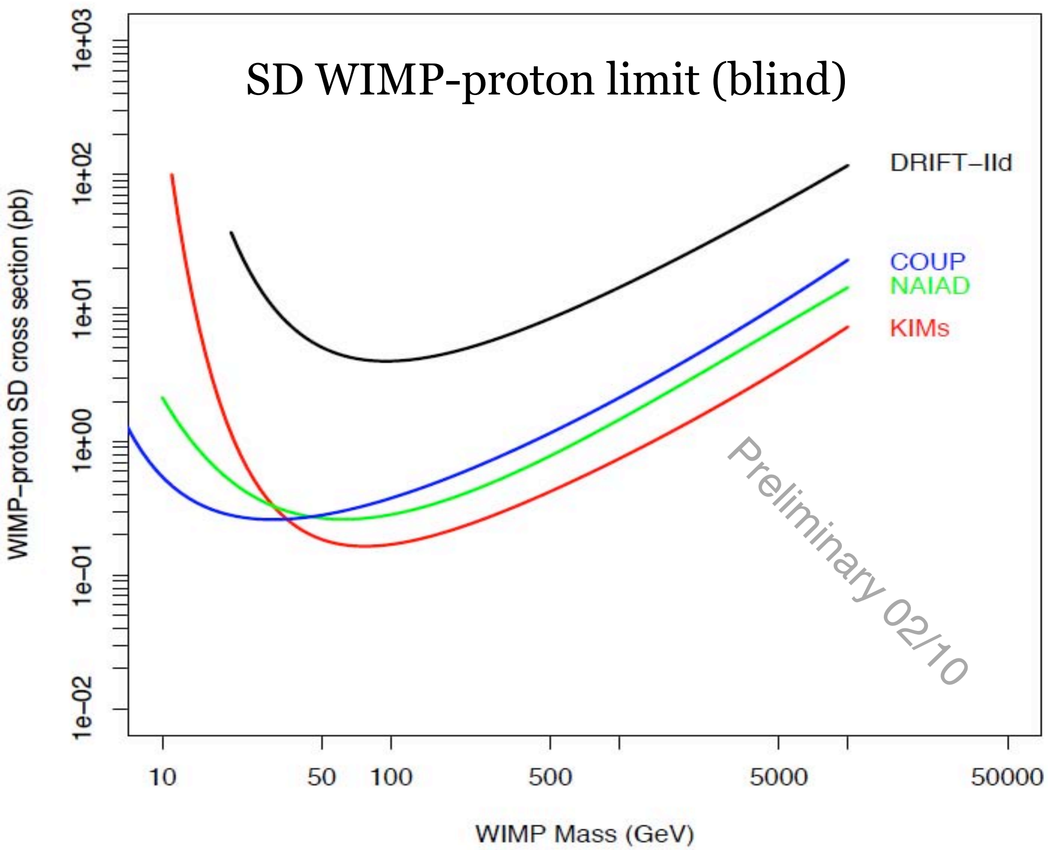


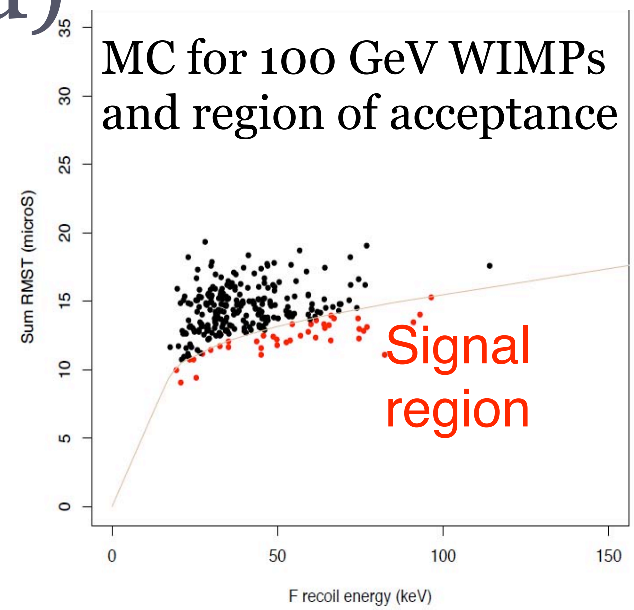
SD Limit 14.8 days (blind)

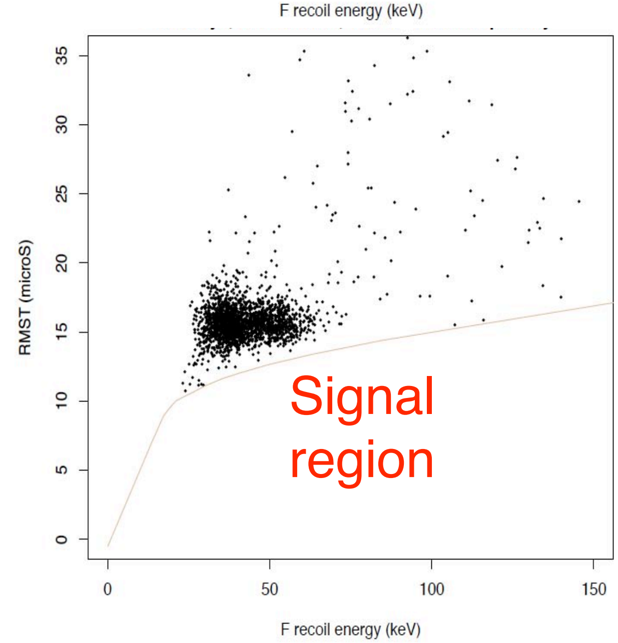
- Signal region chosen for zero expected events
- MC and Neutron calibration
- Blind analysis

30-10 CS_2-CF_4 2009/2010 Shielded WIMP runs

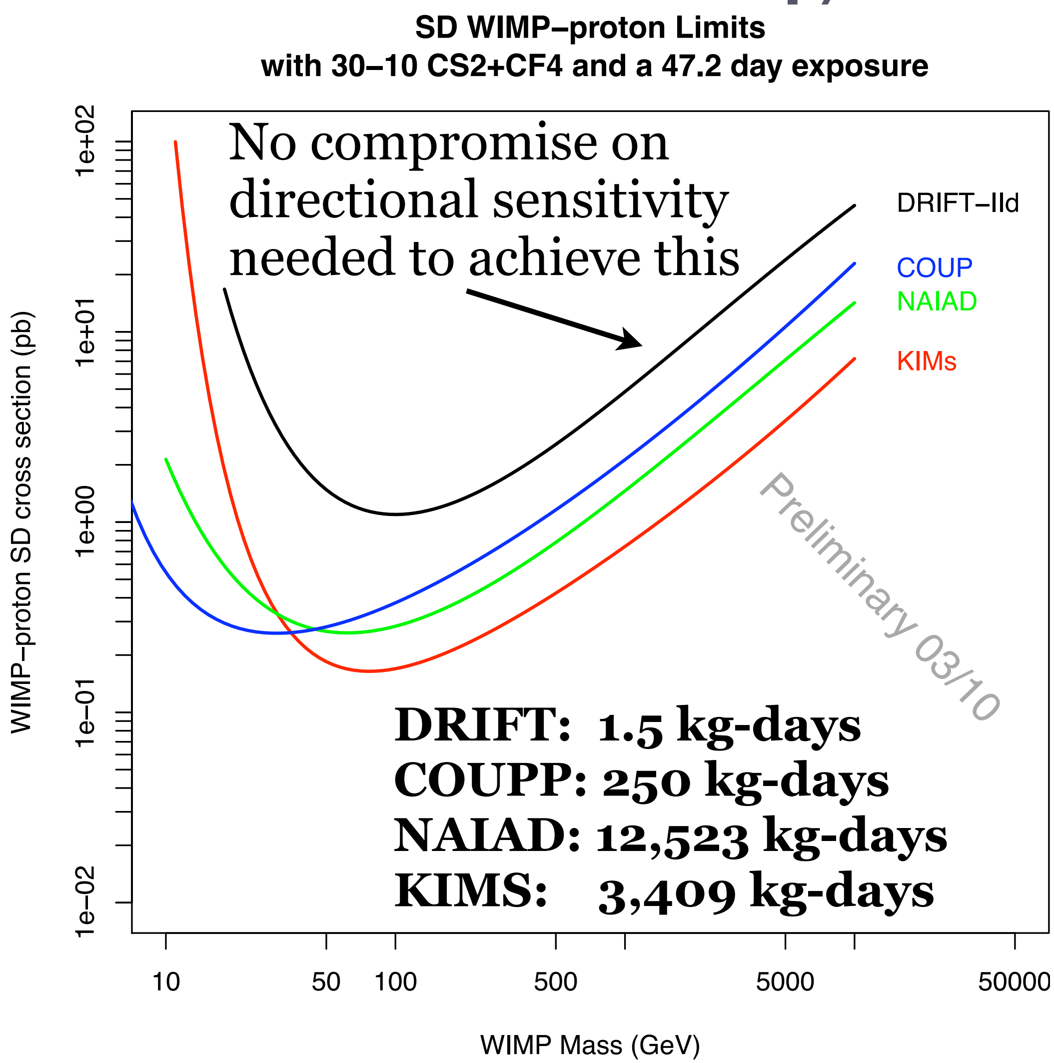
14.8 days, 2050 events, 138 +/− 3 events per





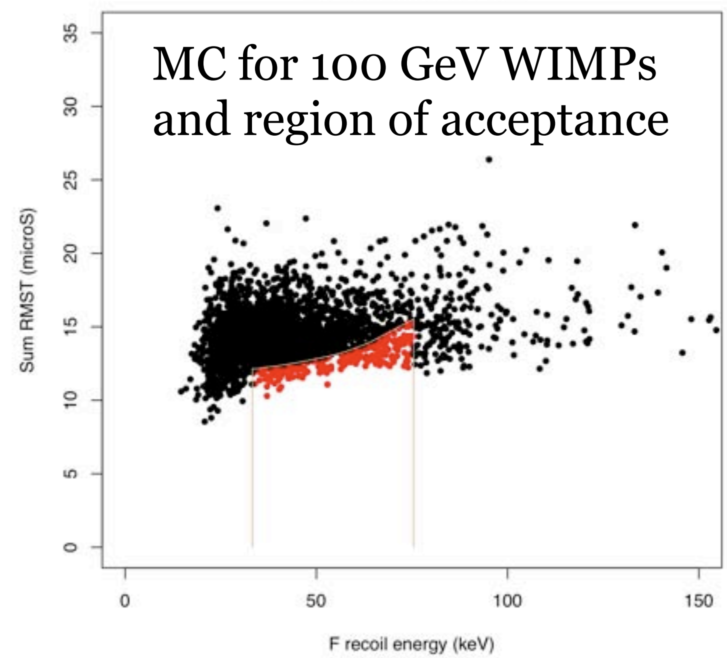


Latest SD Limit 47.2 days (unblind)



DRIFT: 1.5 kg-days (CF4)
<u>with full directional sensitivity</u>
25keV F threshold

DRIFT: 1.2 pb minimum
c.f.
NEWAGE: 5400 pb
DM-TPC: 2400 pb



0 events detected resulting in an upper limit of 2.44 (double-sided) by Feldman and Cousins. Gas mass = 0.134 kg Fraction of fluorine by mass = 0.241Run time = 47.2 days

DRIFT What Next

(1) Main thrust is RPR elimination:
- (a) reduction of intrinsic radon/RPR contamination
- (b) improved PSD/position analysis and cuts
- (c) introduction of alpha-transparent cathode
- (d) full z-fiducialisation via +ve ion

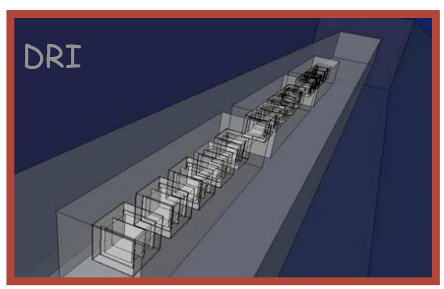
(2) Upgrade/streamlined electronics and gas system

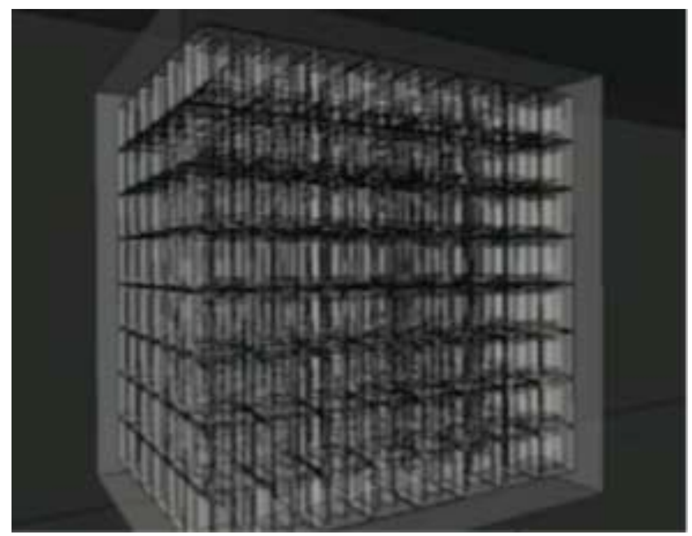
(3) DRIFT III scale-up design

24 m^3

in 4 m^3 segments

(4) 1 tonne directional target:

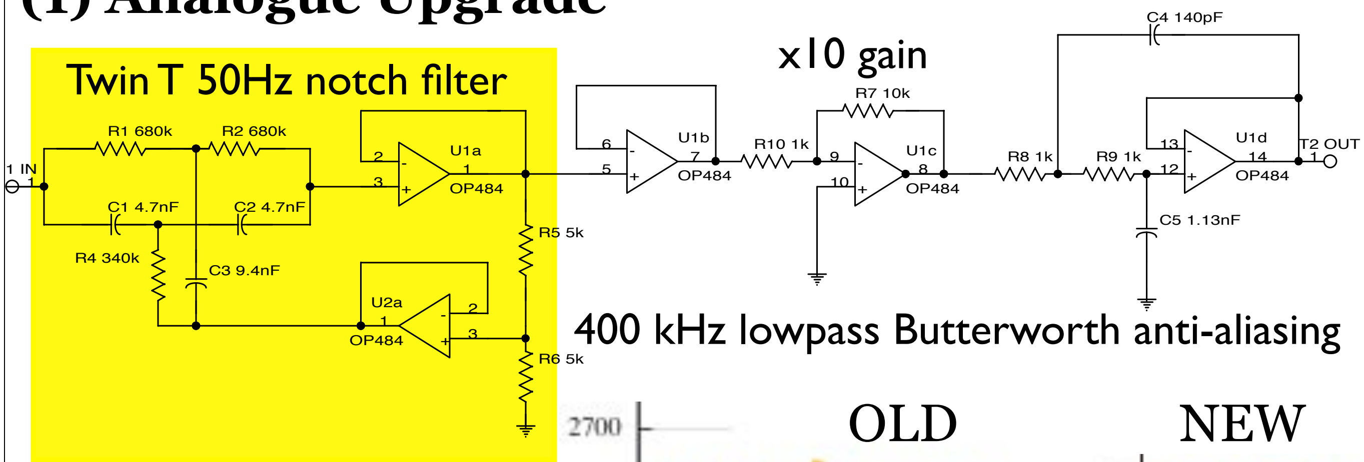


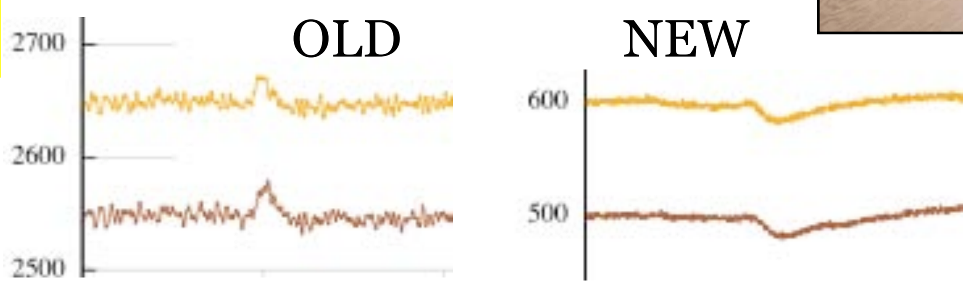


Electronics Upgrade (E. Daw, M. Robinson, Sheffield)

Aim: lower noise, better PSD for track reconstruction, simplification to allow multiple module operation, integrated slow control and safety

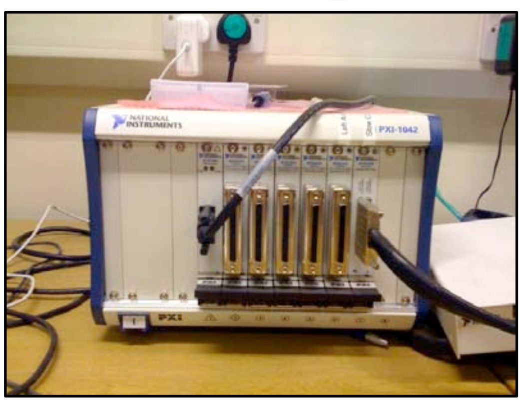
(1) Analogue Upgrade





Neutron event

(2) Digital Upgrade



14 bit, better pulse shape accuracy, lower dead-time for calibration, reduced cabling and noise, integrated slow control, improved web interface

Thin Cathode

(Eric Lee, UNM 2009)

Alpha transparencies for different cathode materials and thicknesses

	Cathode Type	Fraction Lost (%) Po 214 (7.69 MeV)	Fraction Lost (%) Po 218 (6 MeV)
Current: →	20 micron steel wire	37	41
	20 micron quartz fiber	8.6	14
	8.2 micron quartz fiber	3.4	5.1
	6.5 micron quartz fiber	2.6	4.1
	10 micron mylar sheet	9.1	13
	2 micron mylar sheet	1.8 (1.6)	2.7 (2.5)
	1.5 micron mylar sheet	1.4	2.0
Factor ~40 reduction in RPRs expected →	0.9 micron mylar sheet	0.8	1.2

With 0.9 micron thick cathode the projected RPR rates would drop from current rate of 138/day to between 0.5/day to 3.5/day

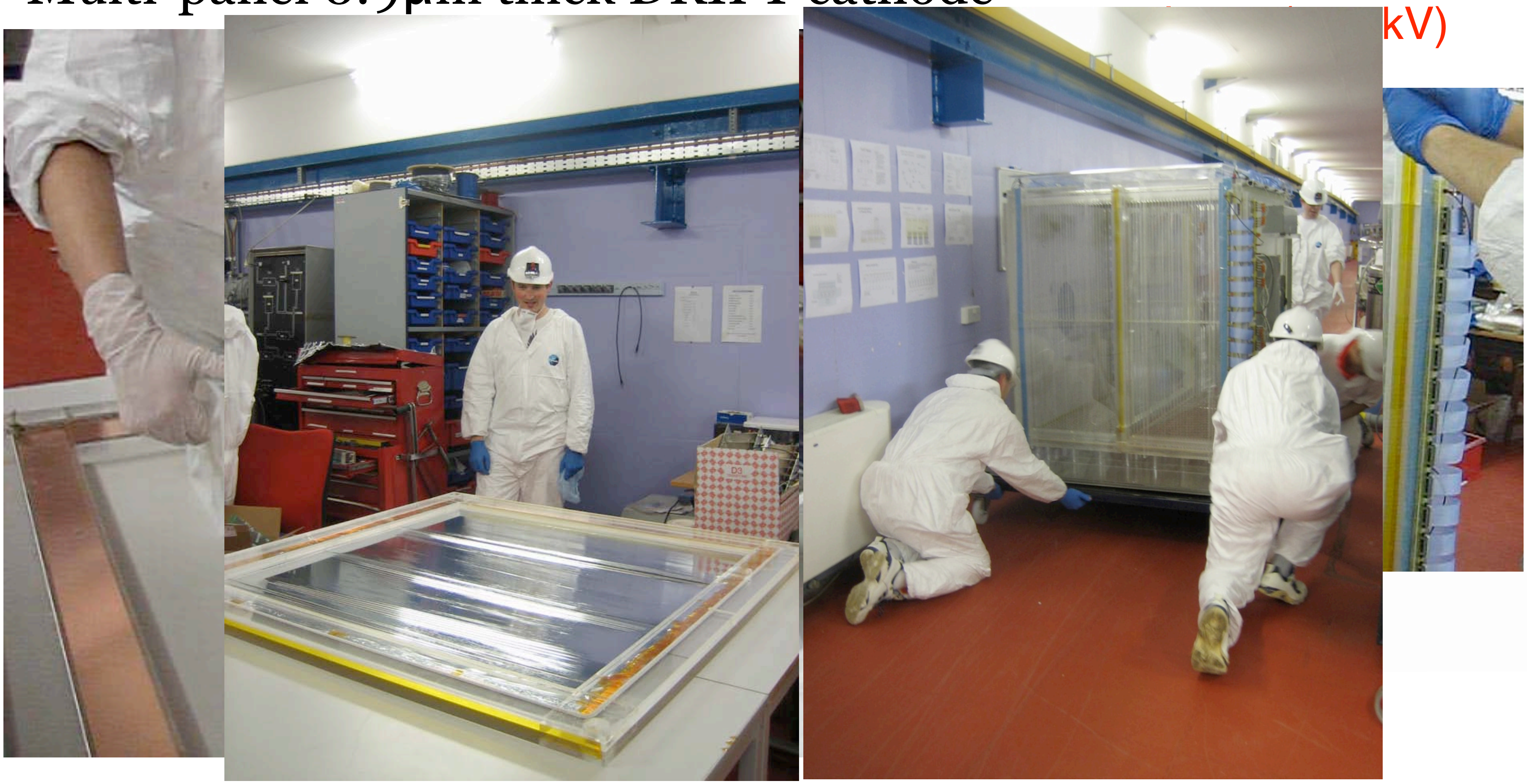
Thin Cathode

Installation at Boulby last week

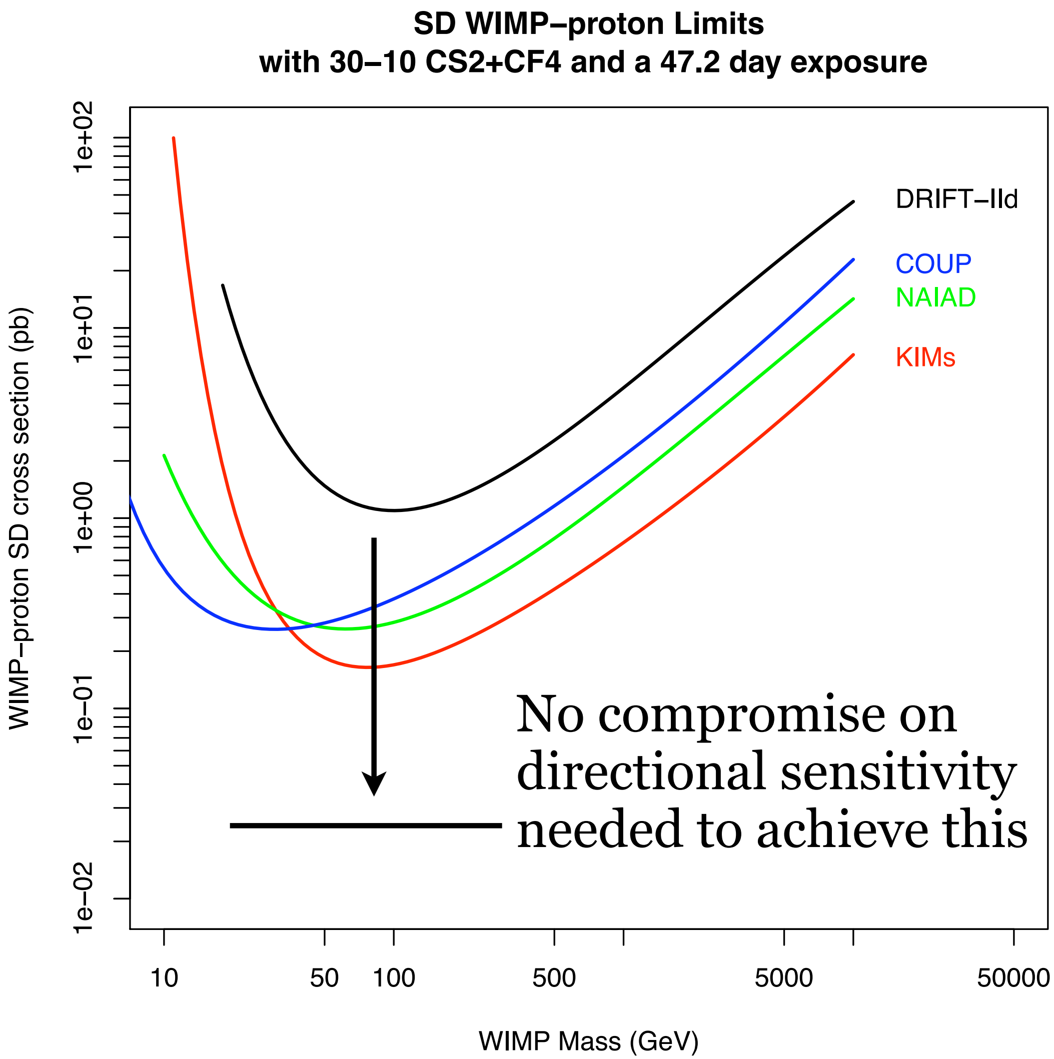
cathode tested at full

kV)

Multi-panel 0.9μm thick DRIFT cathode



Thin Cathode Limit Prediction



x40-50 reduction in background (RPR) expected

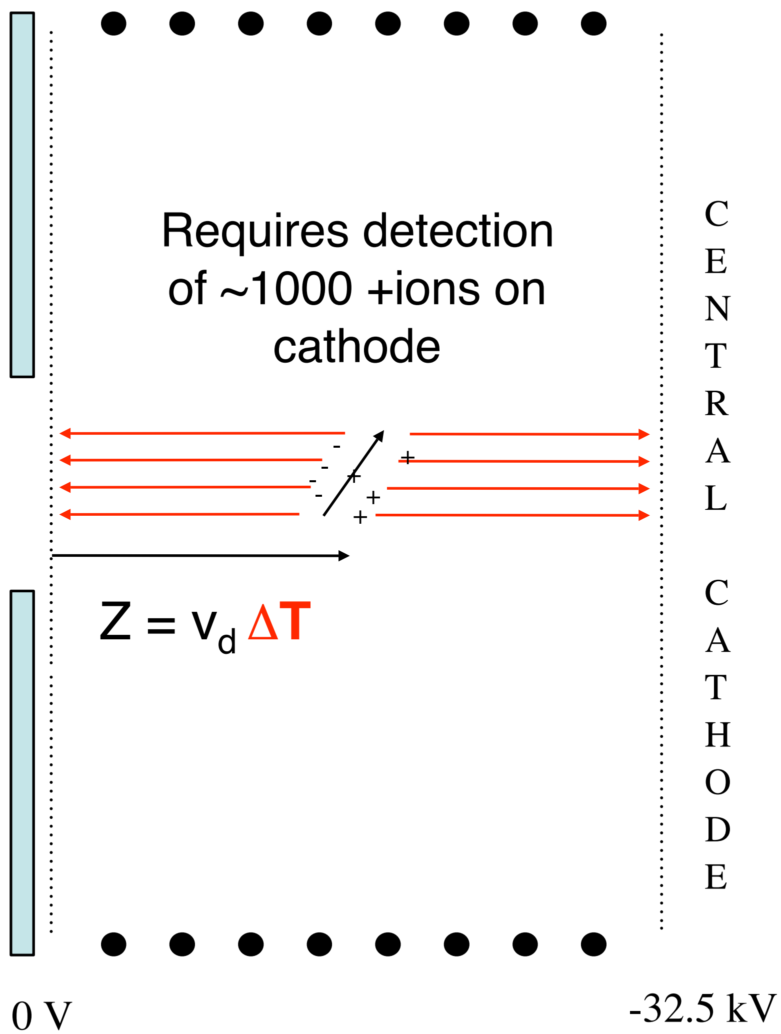
i.e. ~ 0.02 pb assuming remaining RPRs distributed the same

This would take 2000 days live time

DRIFT II is now volume limited…. not background limited

Z-fiducialisation

Z-fiducialisation by measuring ΔT:



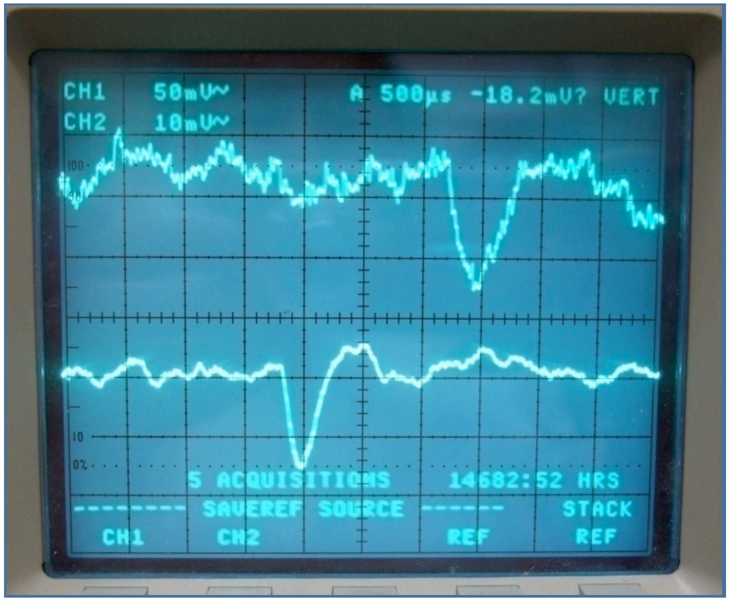
Eric Lee, UNM (2009)

Z-fiducialisation test

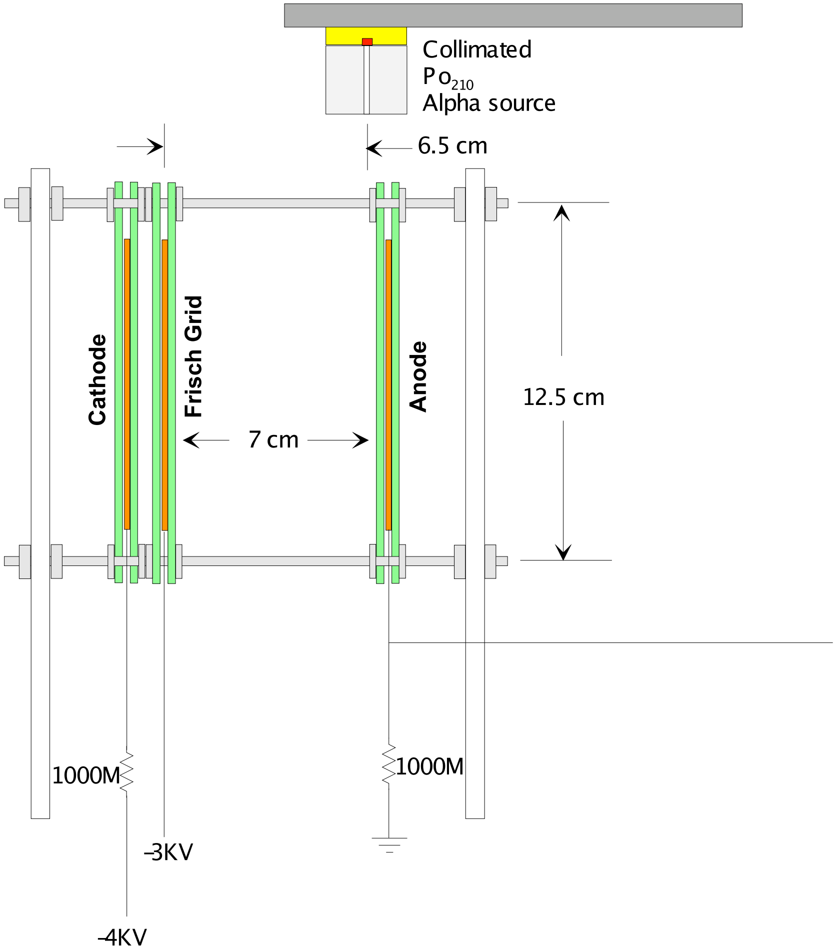
CS_2 – 40 Torr

Cathode

Anode



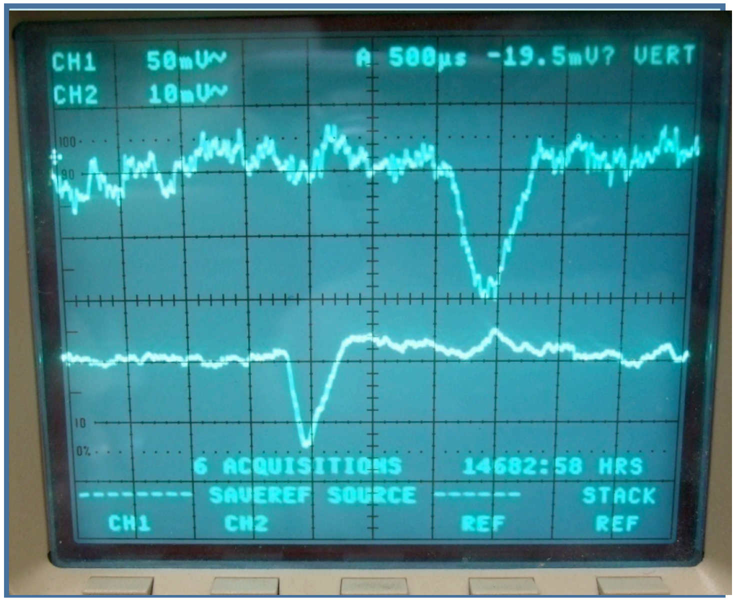
Expected delay = 1.5 milliseconds



Z-fiducialisation test

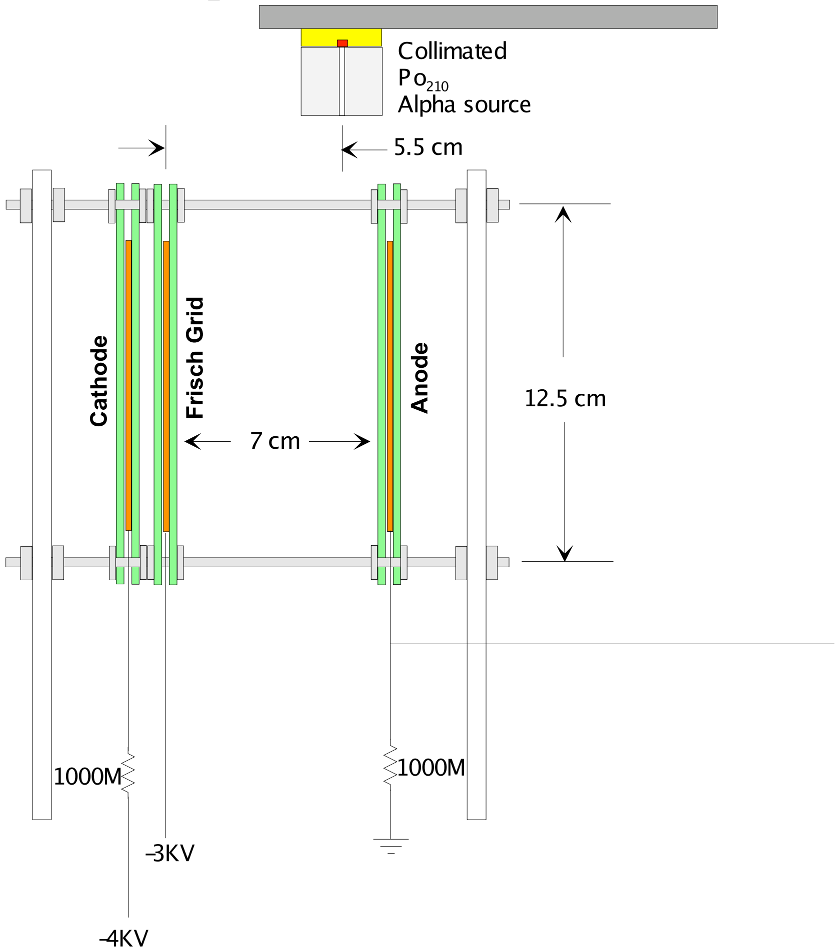
Cathode

Anode



Expected delay = 1.3 milliseconds

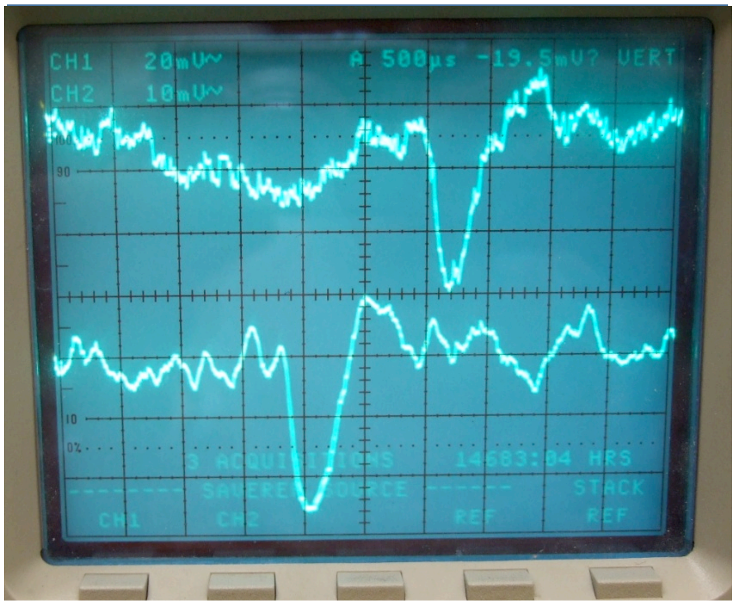
CS_2 – 40 Torr



Z-fiducialisation test

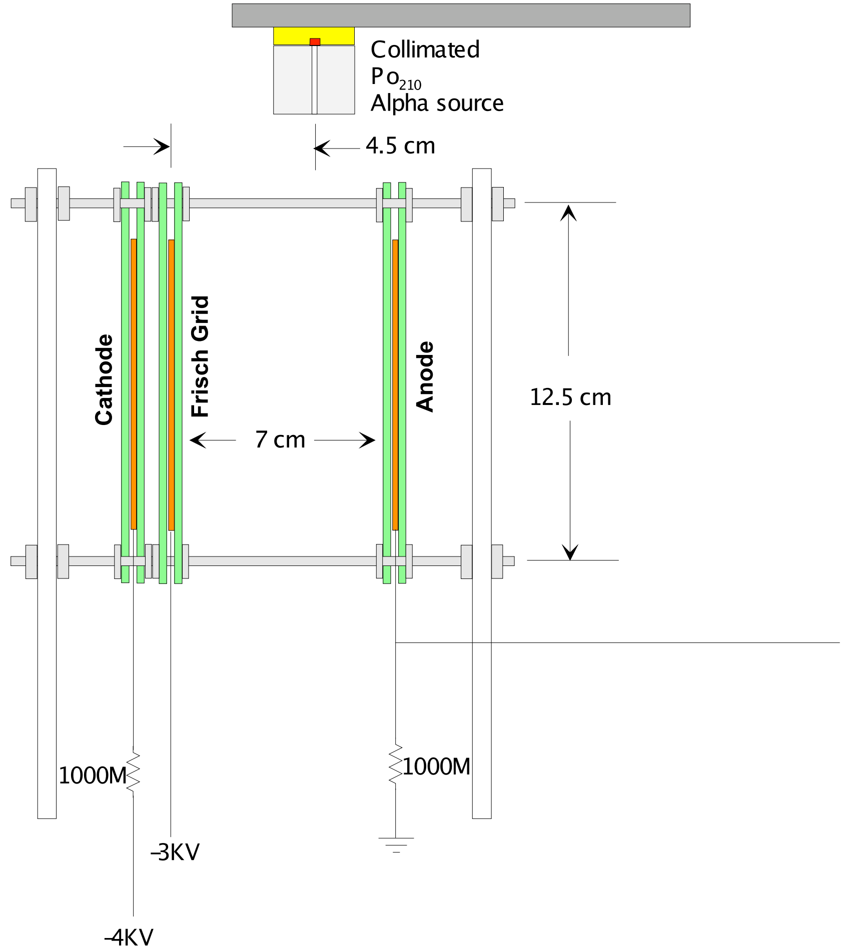
Cathode

Anode



Expected delay = 1.1 milliseconds

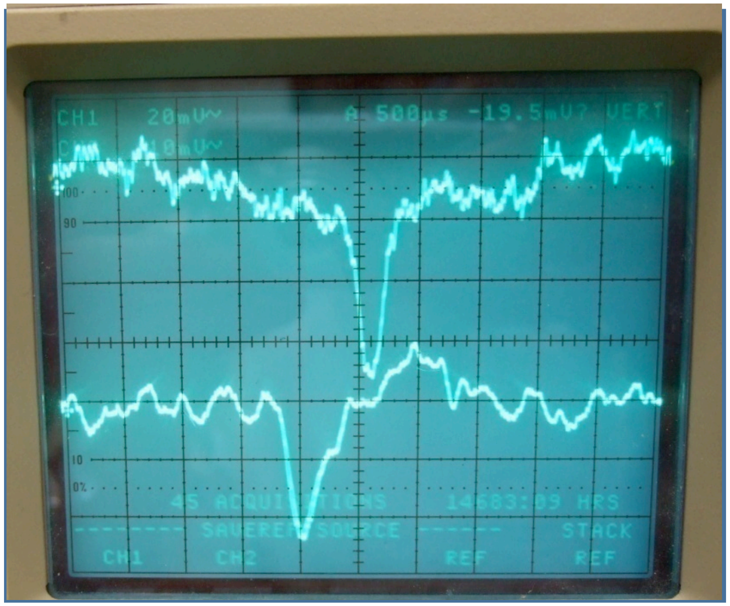
CS_2 – 40 Torr



Z-fiducialisation test

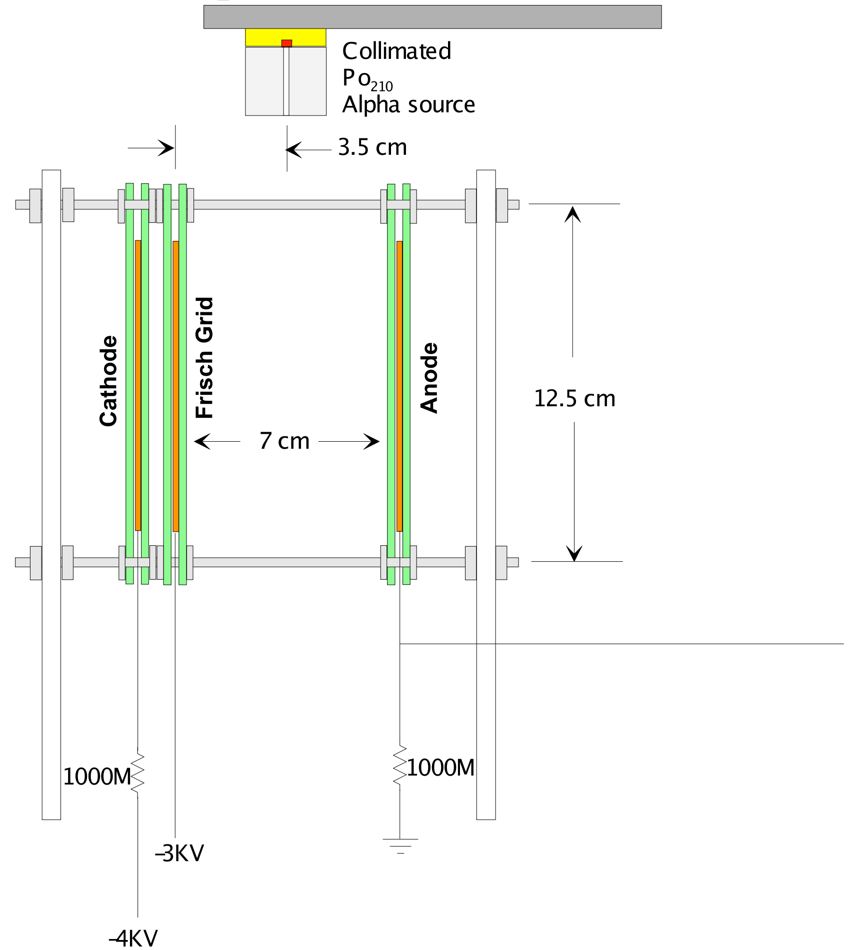
Cathode

Anode



Expected delay = 0.8 milliseconds

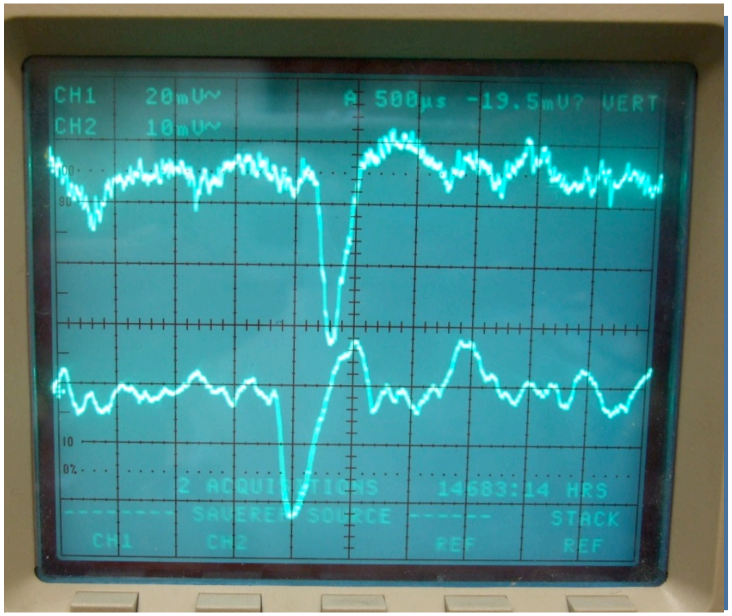
CS_2 – 40 Torr



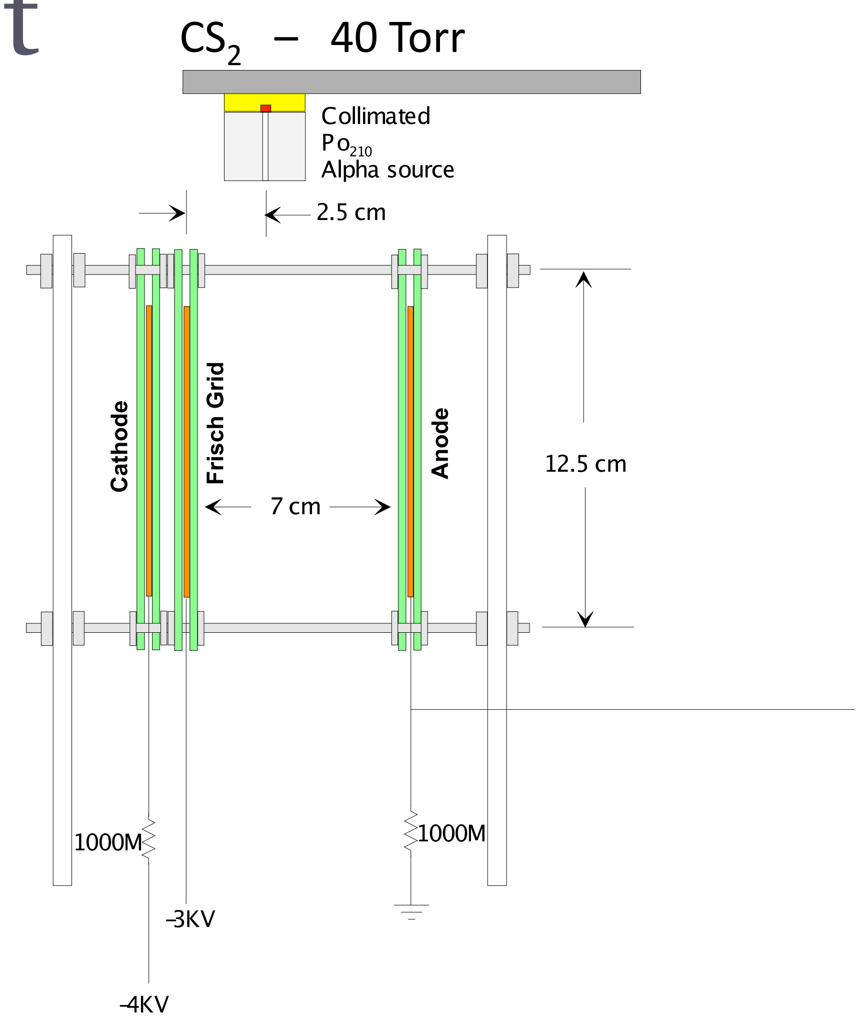
Z-fiducialisation test

Cathode

Anode



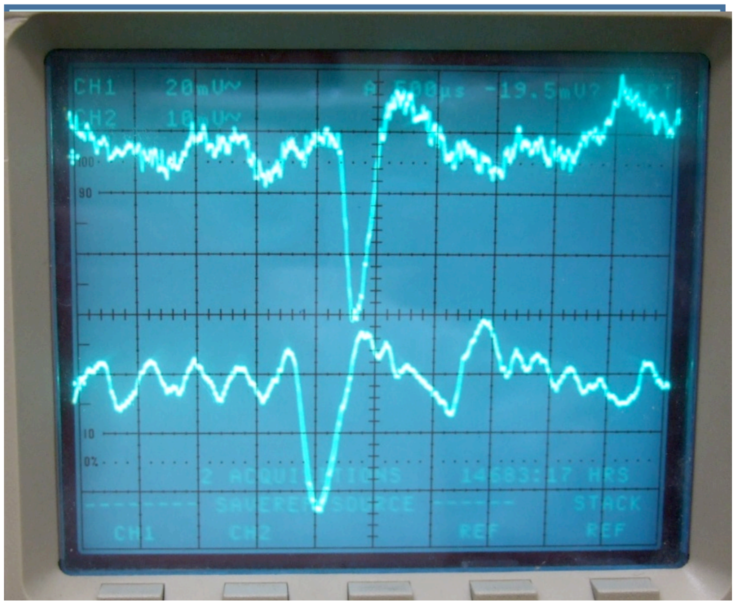
Expected delay = 0.6 milliseconds



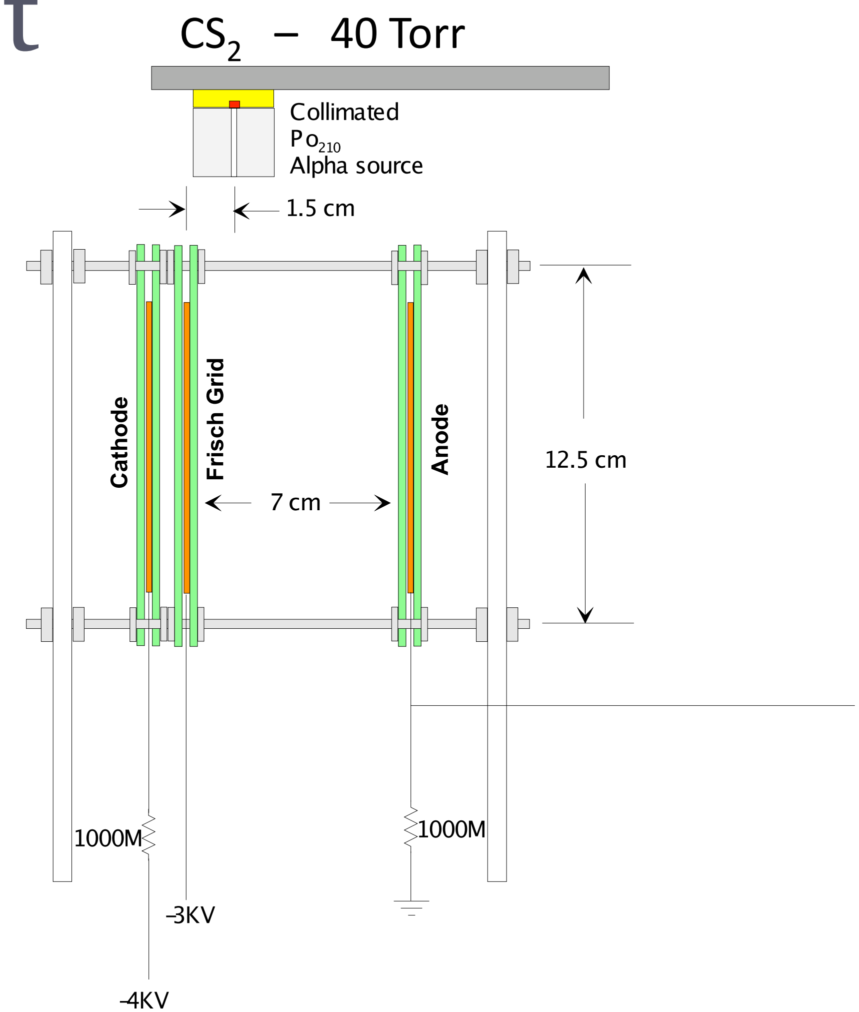
Z-fiducialisation test

Cathode

Anode



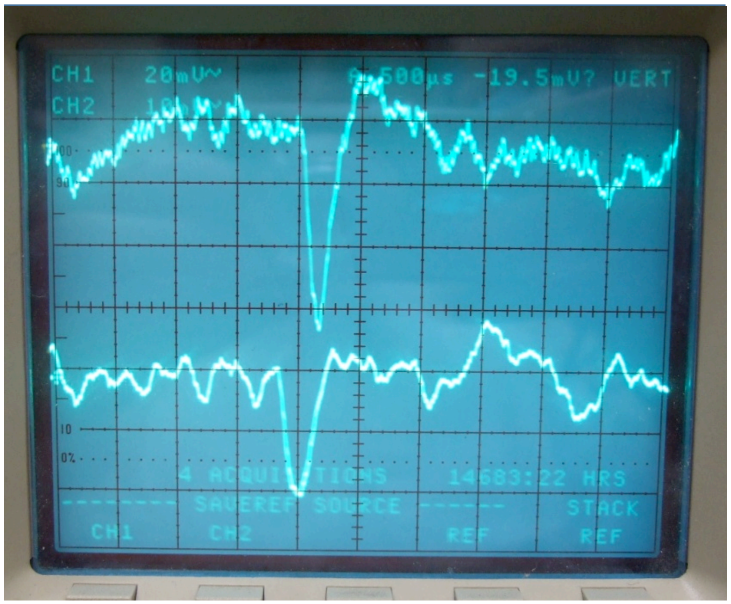
Expected delay = 0.4 milliseconds



Z-fiducialisation test

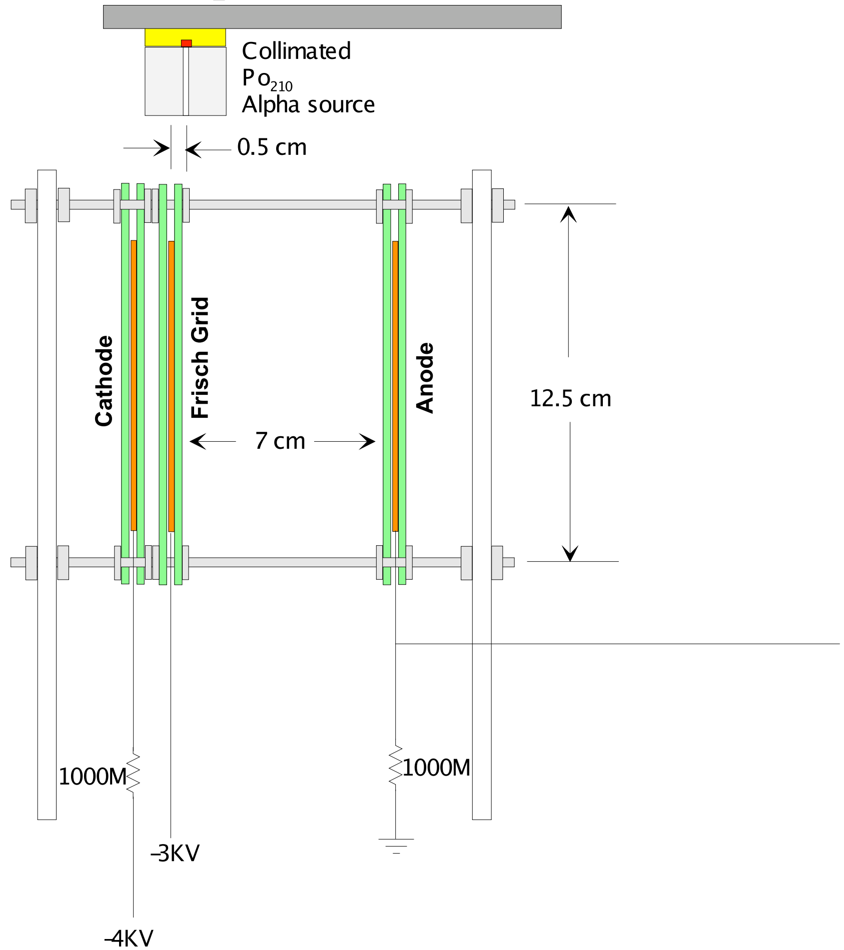
Cathode

Anode



Expected delay = 0.1 milliseconds

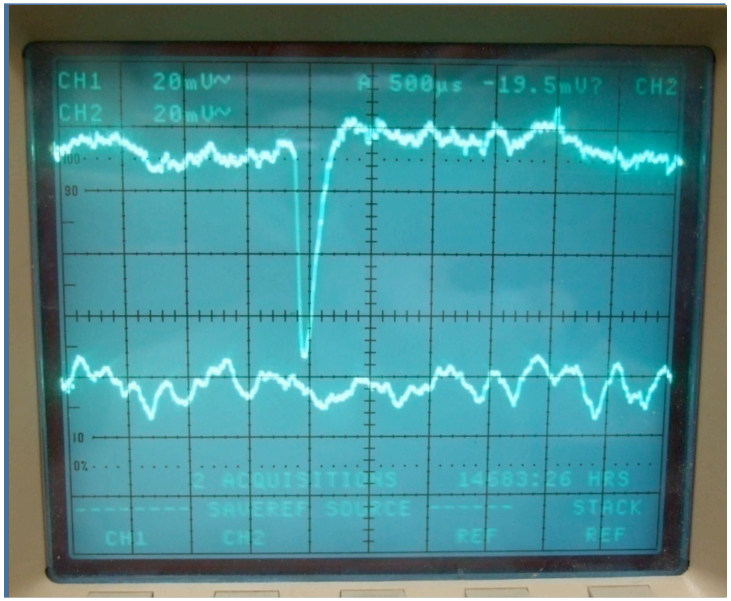
CS_2 – 40 Torr



Z-fiducialisation test

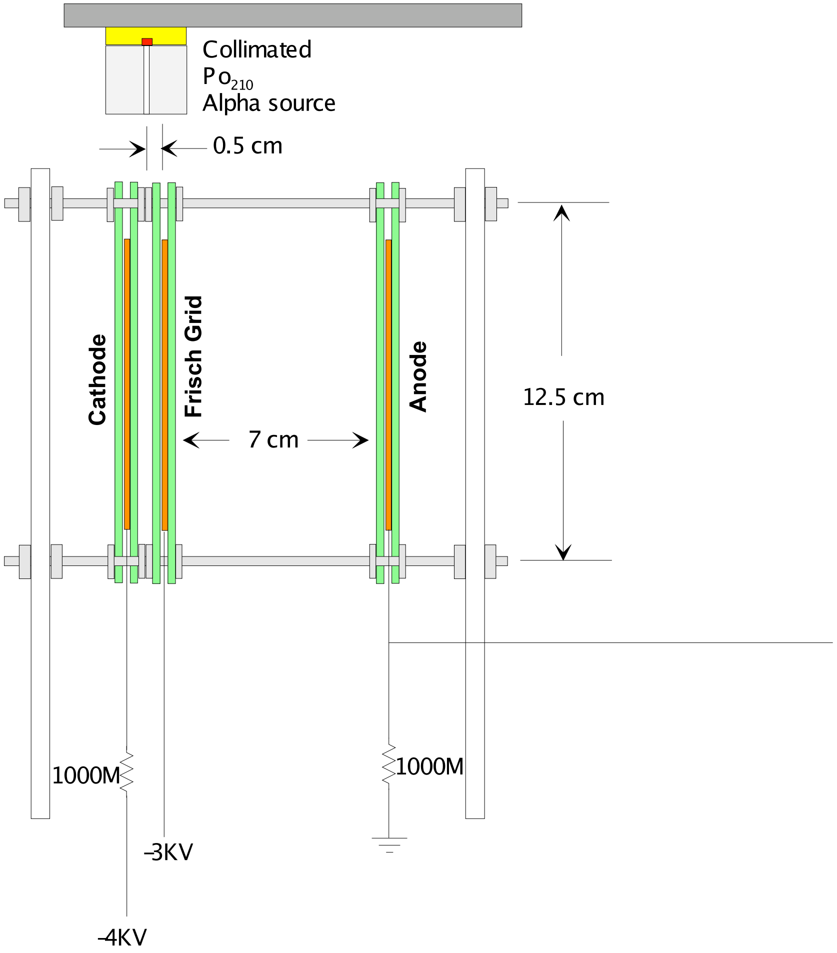
Cathode

Anode



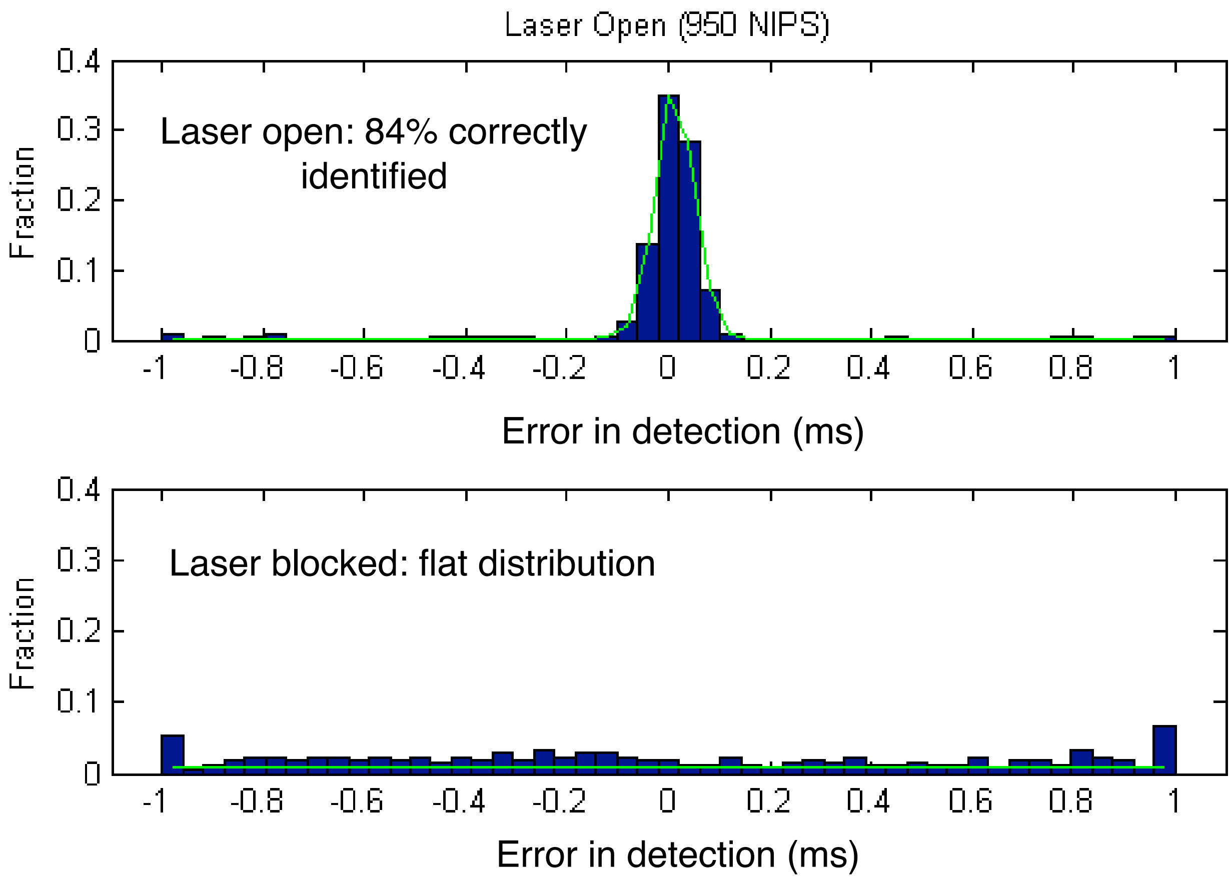
Expected delay = 0.0 milliseconds

CS_2 – 40 Torr



Z-fiducialisation test

Results from cathode readout scheme:
detection of ~950 +ions produced with an N_2 laser



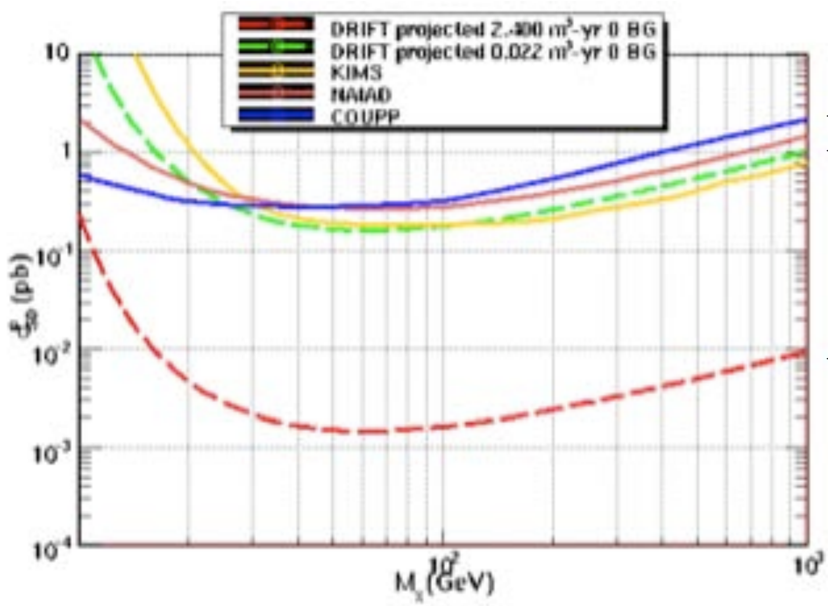
Eric Lee, Eric Miller (UNM)

Detection of ~500 +ions at 54% has now been achieved

SD Sensitivity of DRIFT IId

- Plan is to run for 2.4 m^3-years of exposure (started)
- Simulations are in progress – understand the expected behavior in the mixed gas

Expected WIMP-proton spin dependent sensitivity



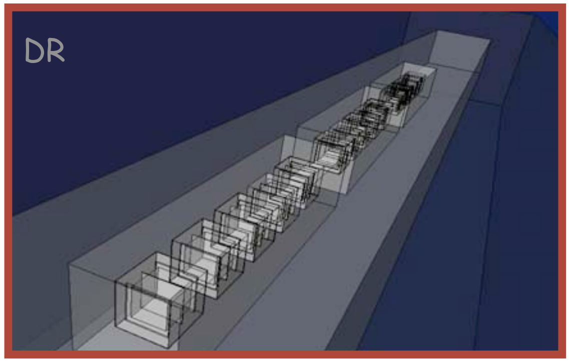
current limits

DRIFT IId - 10 day run, zero background prediction

DRIFT IId - 2.4 m^3-years, zero background prediction **with directional capability**

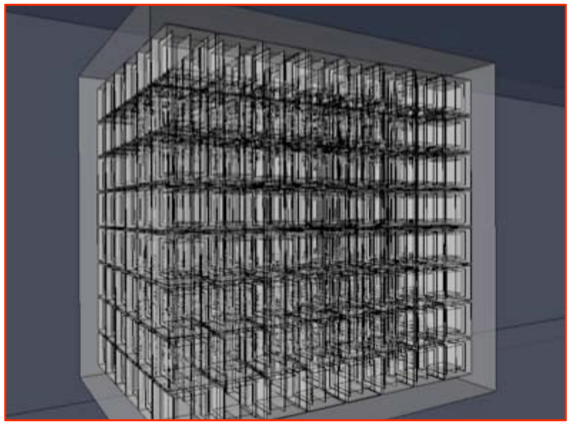
Scale-up Speculation (ultimate for SI)

1 Tonne



- A 1 Tonne target (10keV Thresh, 0 bg) would give 10^{-10}pb (raw) & >10^{-9}pb (halo) SI sensitivity.
- Vol = 2,500–10,000m^3 (160-40 Torr).
- 1/30th-1/120th volume of LNGS
- 4/3^{rds} – 1/3rd the size of MINOS

Bigger



SuperK size cavern device:

- 10 tonnes (40 Torr)
- 50 tonnes max

Ultimate - on scale of proton decay caverns:

- 400 - 2000 tonne directional target mass

Excavation not a cost driver: €20-50/m^3, €250K/tonne target

Cost extrapolation from DRIFT IId: €50K/m^3

⇒ ~€40M/tonne (with scale factors)???

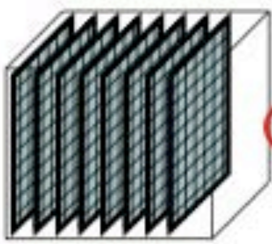
The Ultimate Dream Detector?
halo sensitivity at 10^{-12}pb

Basic numbers for worst case cross section

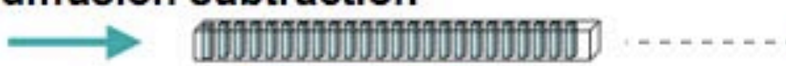
Exposure, Mass 1000 ton.yr (galactic confirmation), 10,000 ton.yr (halo confirmation)

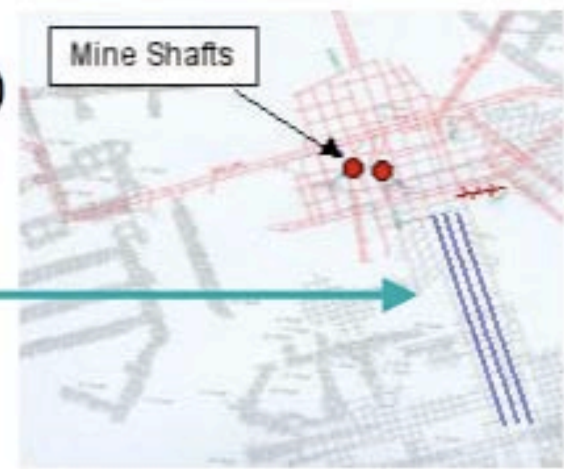
Depth >4000 mwe (ignores statistical discrimination of neutrons via isotropy)

(if) Gas technology go for 1 atm. (easier vessel?)



50 μm track μmgas readout (interpolation)
3 kg/m^3 target
1cm readout plane spacing (2d/3d)
diffusion subtraction





Caverns 3 caverns of 2km x 10m x 5m

Low background components ok: Lucite, Cu, Kapton

Conclusions

- BIG PROGRESS in the last year
  - Event by event discrimination - FIRST COMPETATIVE SD LIMITS
  - Directional signals possible at 1 m^3 scale
  - Head-tail (sense) exists and is understood at 1 m^3 scale
  - Low recoil thresholds feasible (e.g. 2 keV S-recoil) at 1 m^3 scale
  - Negative ion (low diffusion) operation with other targets demonstrated, in particular Fluorine (CS_2-CF_4)
  - Solution to Z-fiducialisation and RPR reduction
- More international activity
  - DM-TPC
  - NEWAGE
  - MIMAC, CAST

CYGNUS cooperation and conference series on directional dark matter successful and expanding

- Large scale-up design studies underway
  - e.g. 24m^3 DRIFT III module