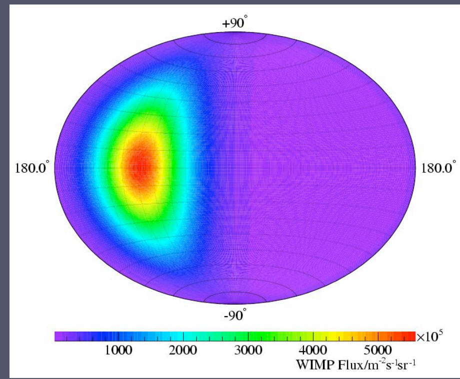
Direction-sensitive Direct Search Review



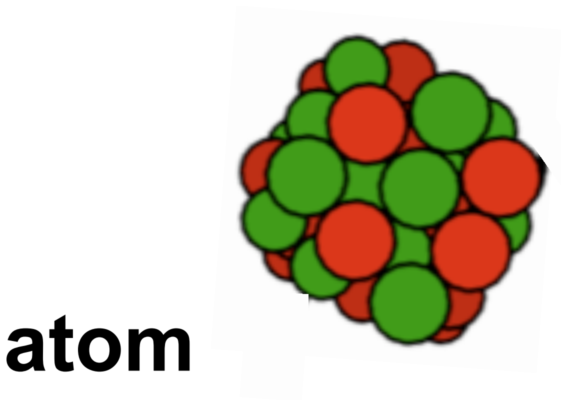
Neil Spooner, University of Sheffield

- Directional Detector Motivation and Basics
- Gas TPCs and DRIFT
- Alternative technologies

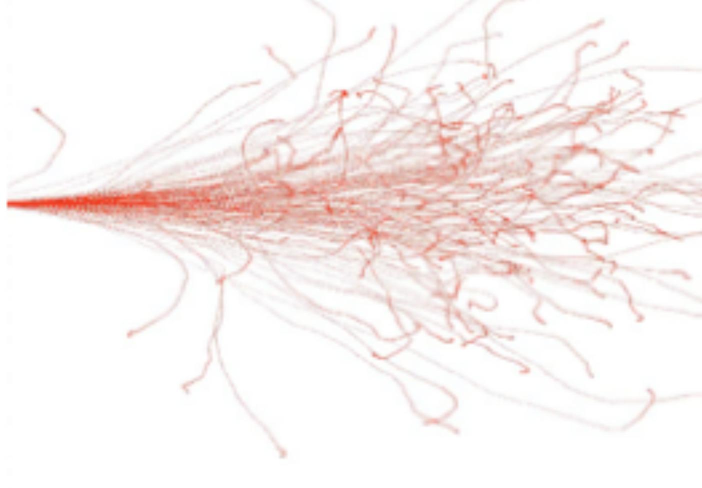
Special thanks to Dinesh Loomba and DRIFT collaborators

Collaboration....!

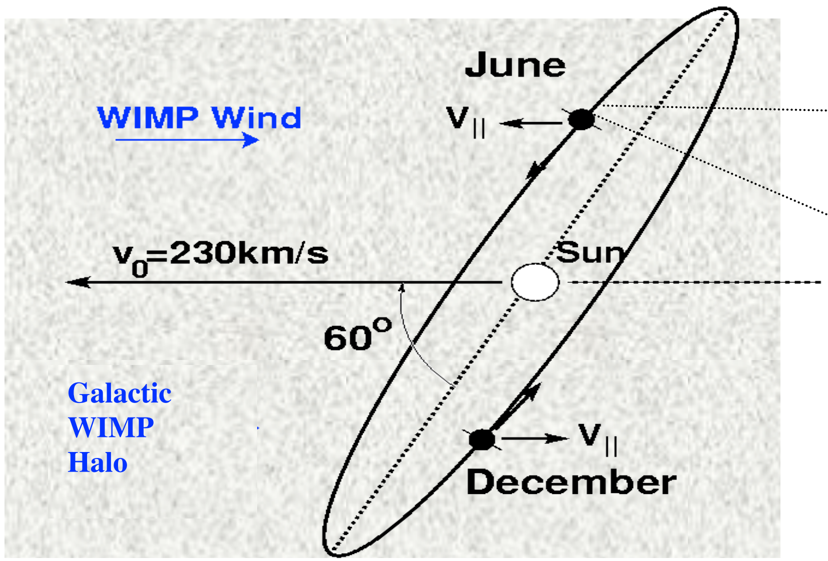
What a WIMP does

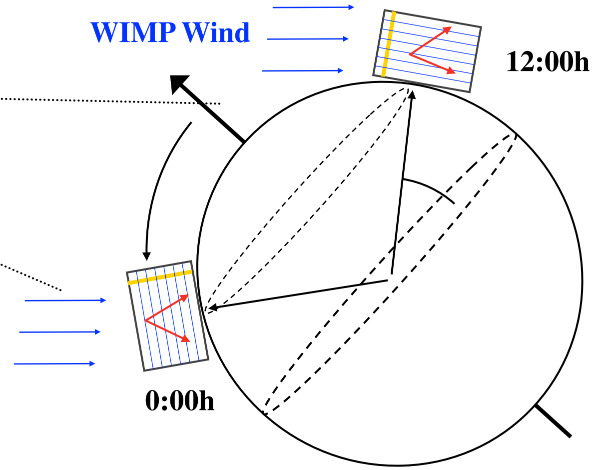


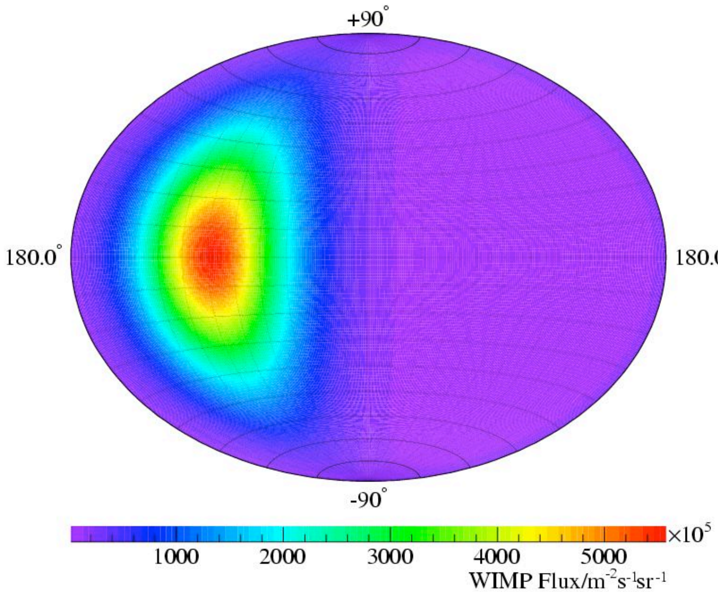
SRIM simulation - 100 keV F recoil
in 75 Torr CF_4 (D3 collaboration)



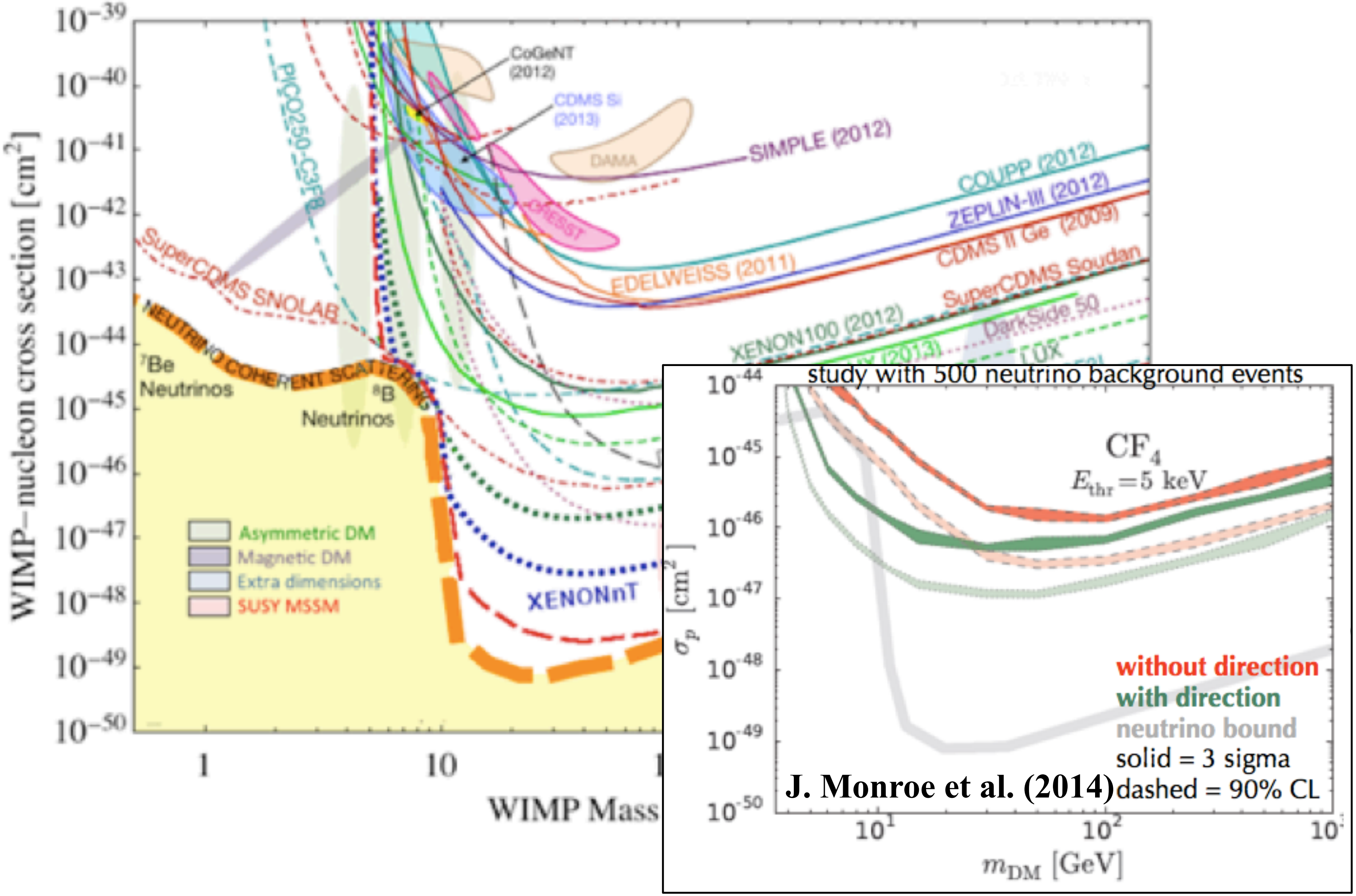
What a WIMP does





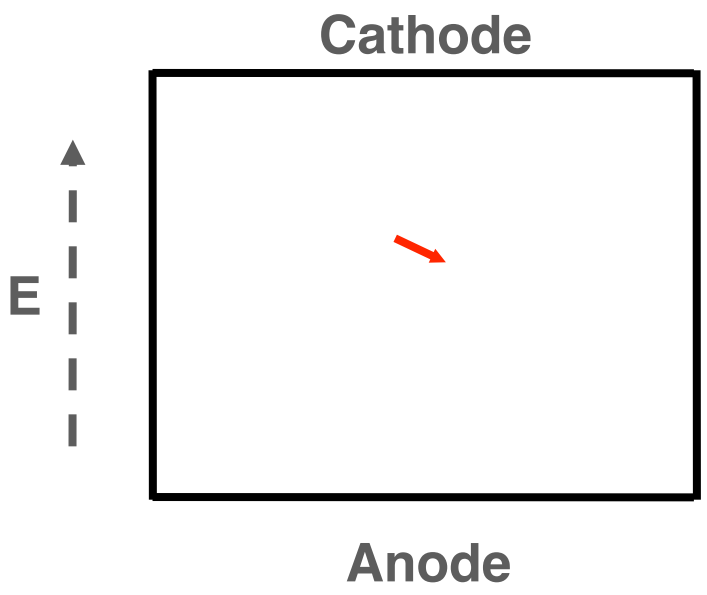


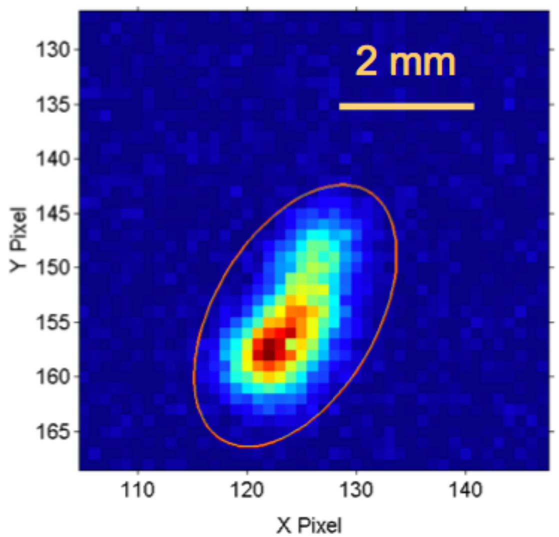
Particle ID, even neutrinos



Directional Basics

Most experiments use low pressure gas-based TPCs:





- total ionisation
- particle range
- dE/dX topology
- track orientation (axial)
- track sense (vector)

Results from UNM (Dinesh Loomba)

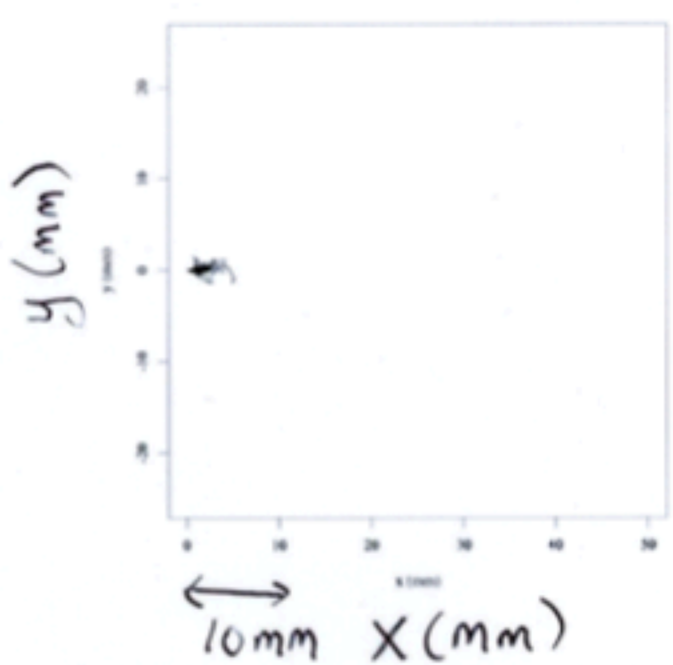
Far more information on events than possible with conventional DM technologies:

But the challenge is detecting ~mm tracks in cubic meter volumes

Background Rejection

Each produces ~500 electron-ion pairs in 40 Torr Ar

40 KeV Ar recoils

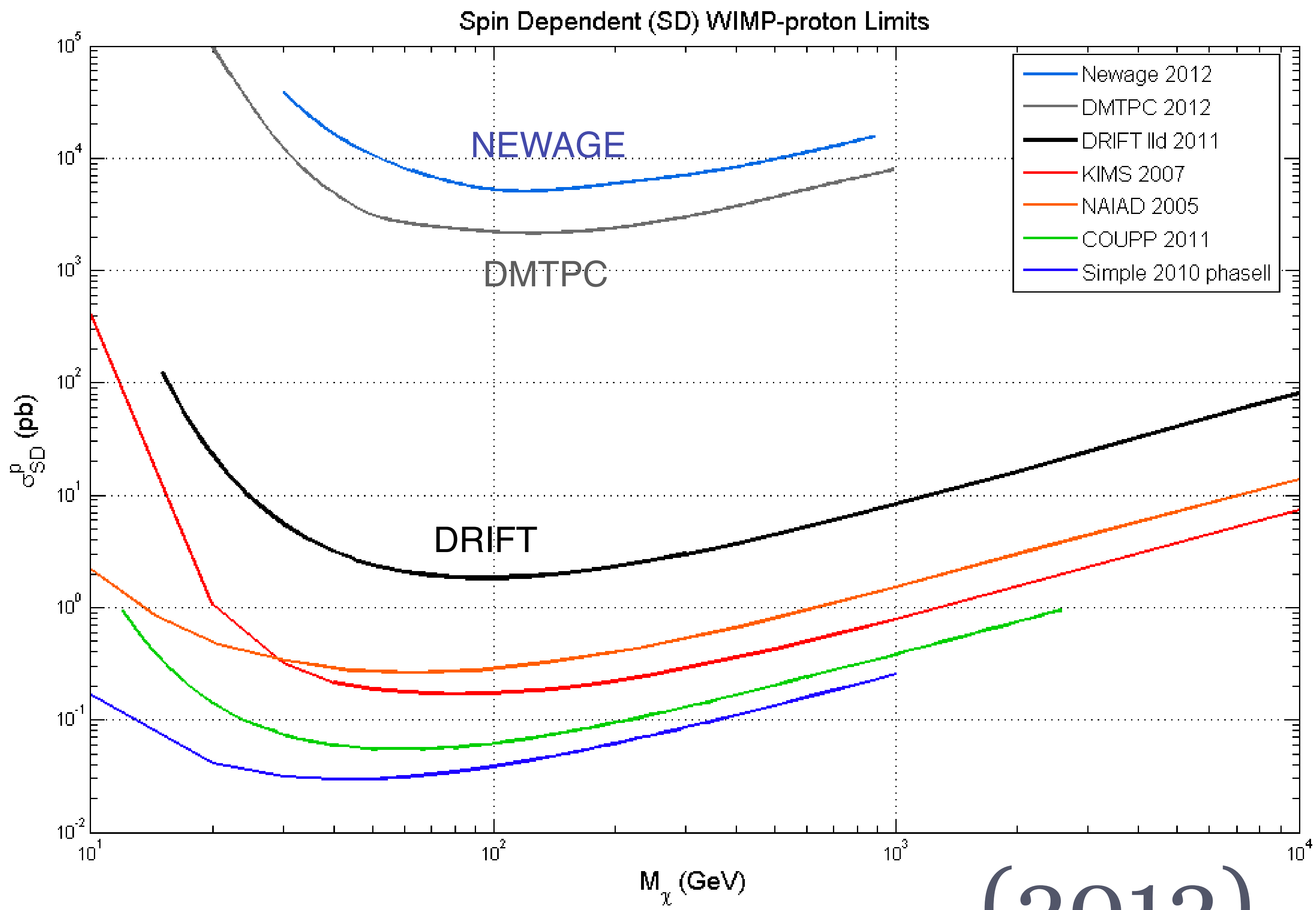


13 KeV electrons

Simulations from SRIM97, EGS4/Presta

thanks to Dinesh Loomba

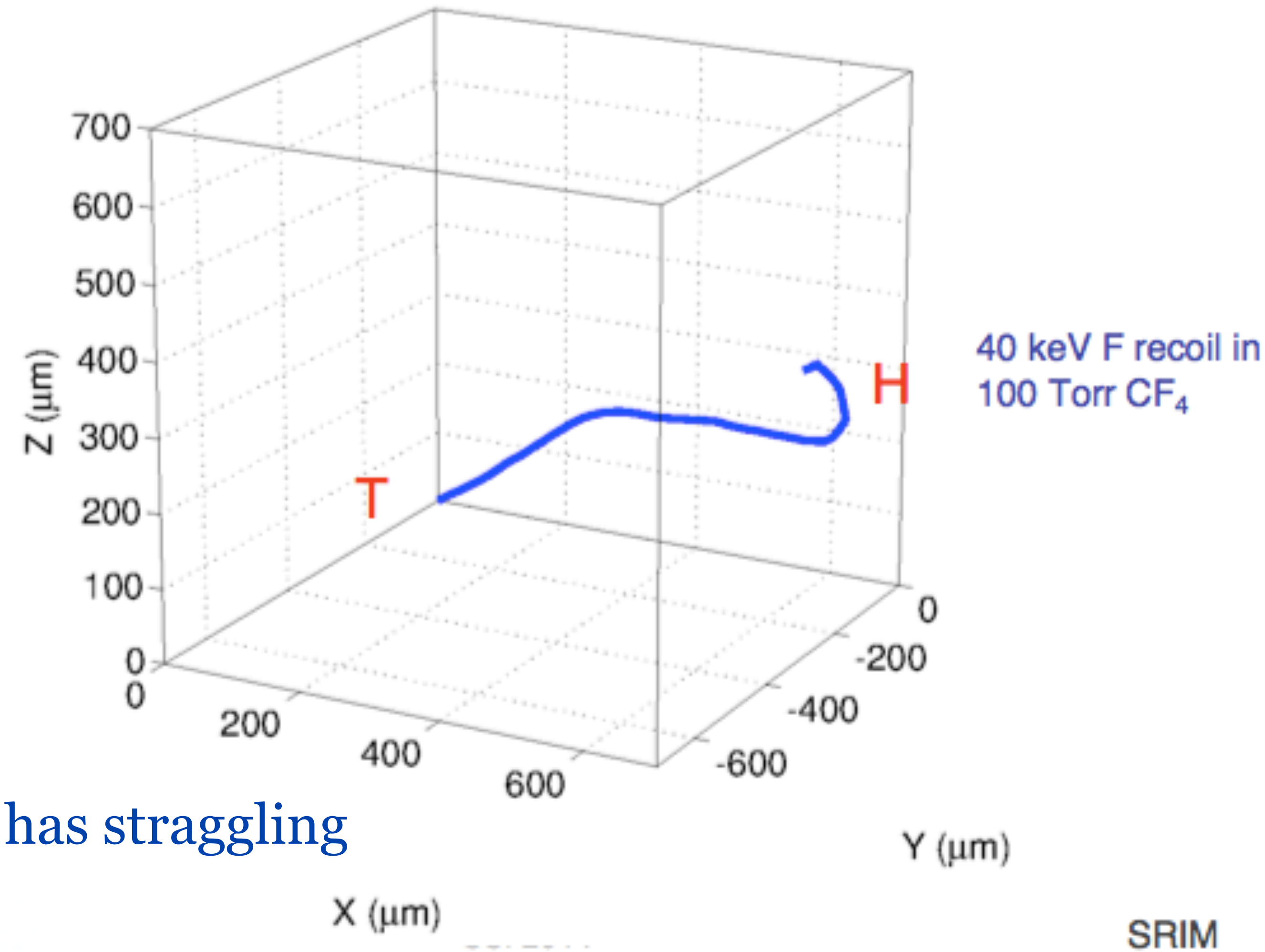
Limits even with small mass



(2012)

Directionality and Tracking

From concept to reality

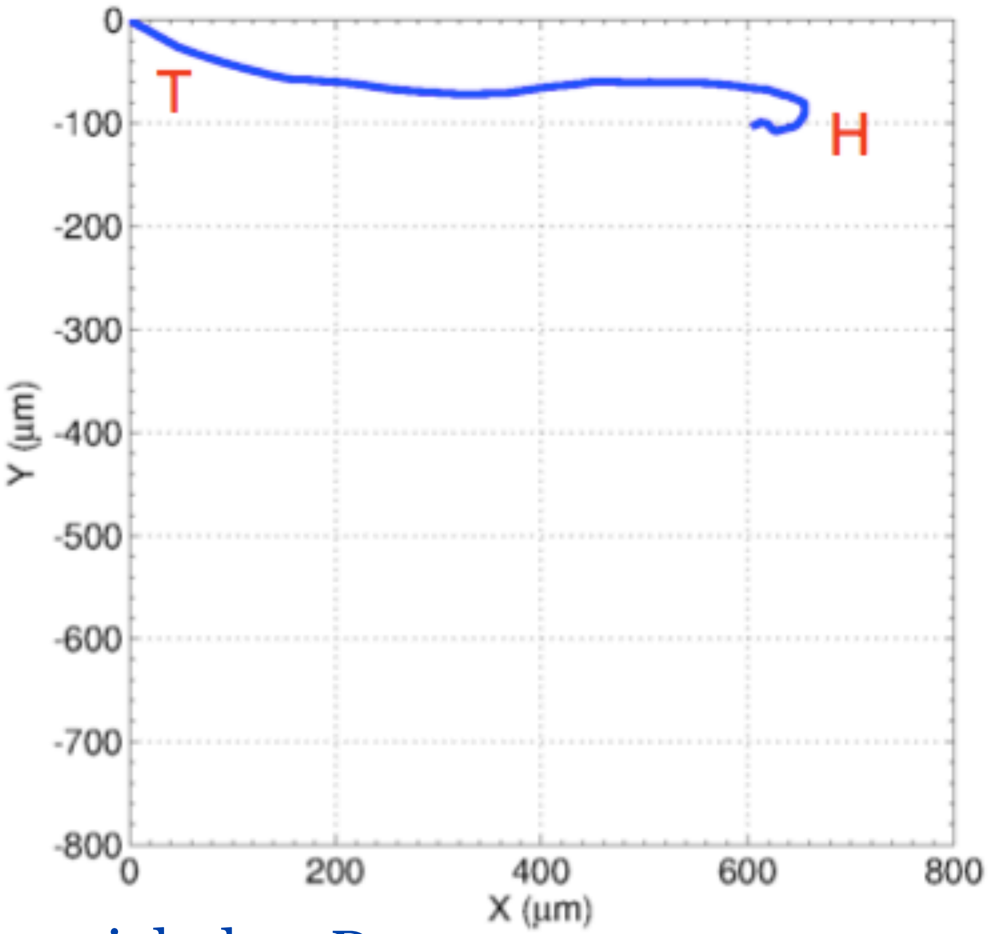


A real track has straggling

thanks to Dinesh Loomba

Directionality and Tracking

Projection (2D or 3D):



A real readout might be 2D

Optimising Directionality

How many WIMPs are needed to get a directional (non-isotropic) signal?

A. Green et al., AstroP 27 (2007) 142

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 unrealisti

} assuming perfect angular resolution

A conclusion - head-tail discrimination ("vector") may be more important than 3D reconstruction (however, 3D may be important for background rejection).

Only about 10 WIMP events may be needed to see directionality

Optimising Directionality

Directional sensitivity vs. energy threshold

A. Green et al.

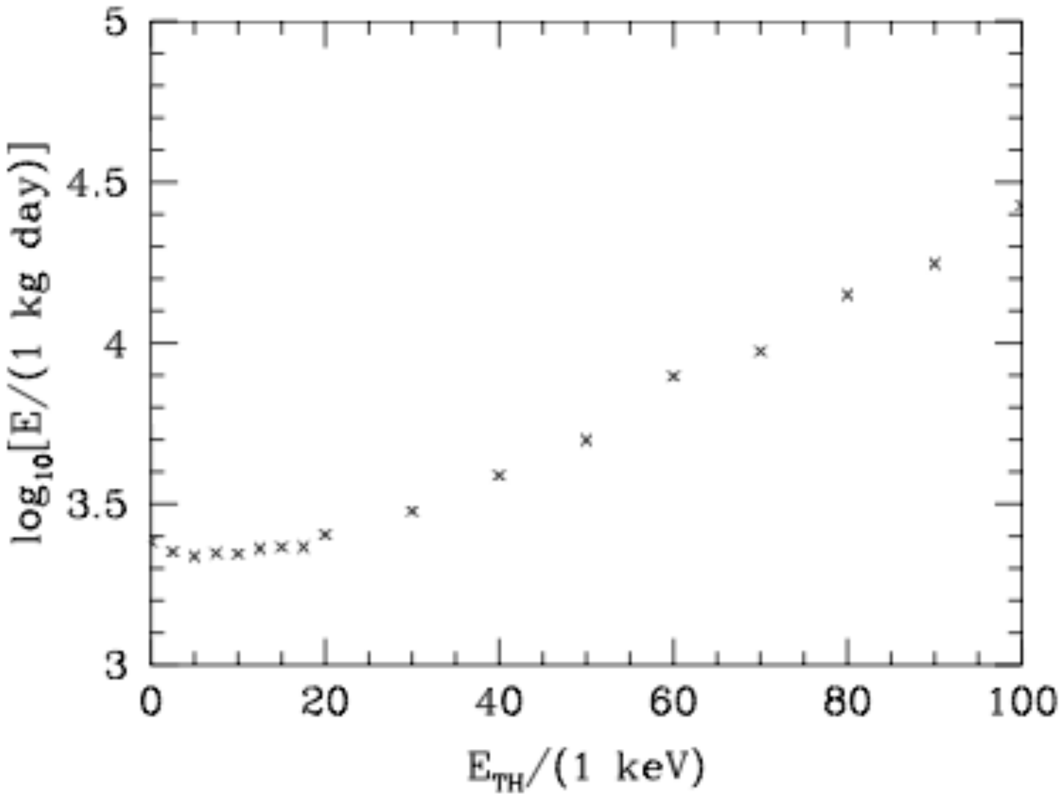
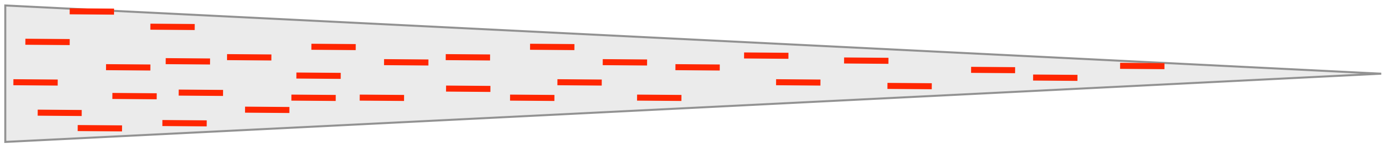


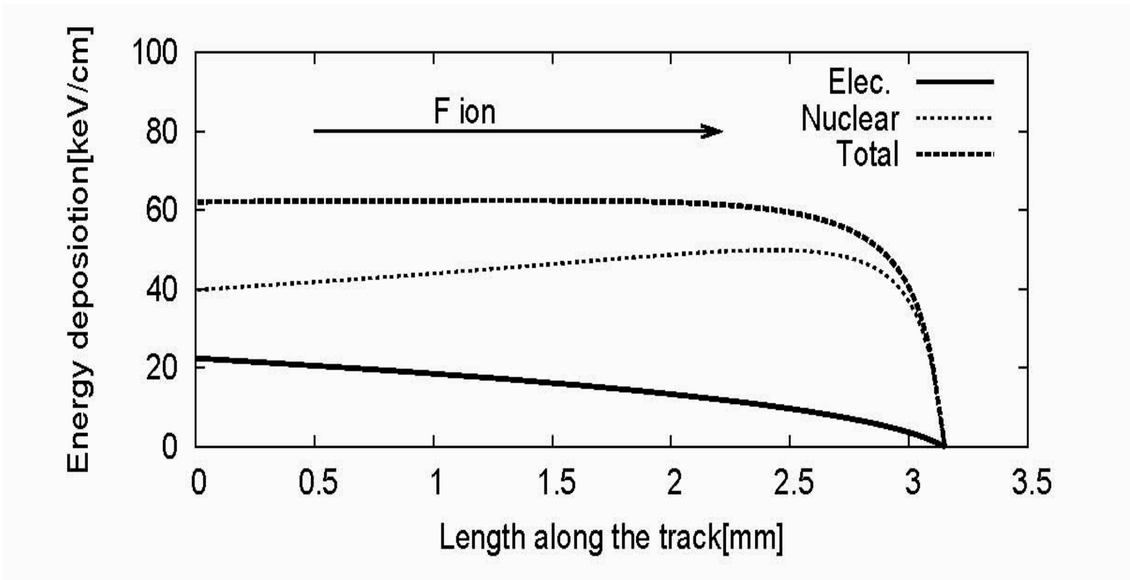
Fig. 4. The exposure required to reject isotropy (and detect a WIMP signal) at 95% confidence in 95% of experiments as a function of energy threshold, for WIMP-proton elastic scattering cross-section $\sigma_0 = 10^{-7}$ pb, assuming a local WIMP density of $\rho = 0.3\ \mathrm{GeV\,cm^{-3}}$.

A conclusion - low energy threshold may not be important for directionality (however, it may be important for background rejection).

Head - Tail

Zoom in on the recoil:

Tail  **Head**



Importance:

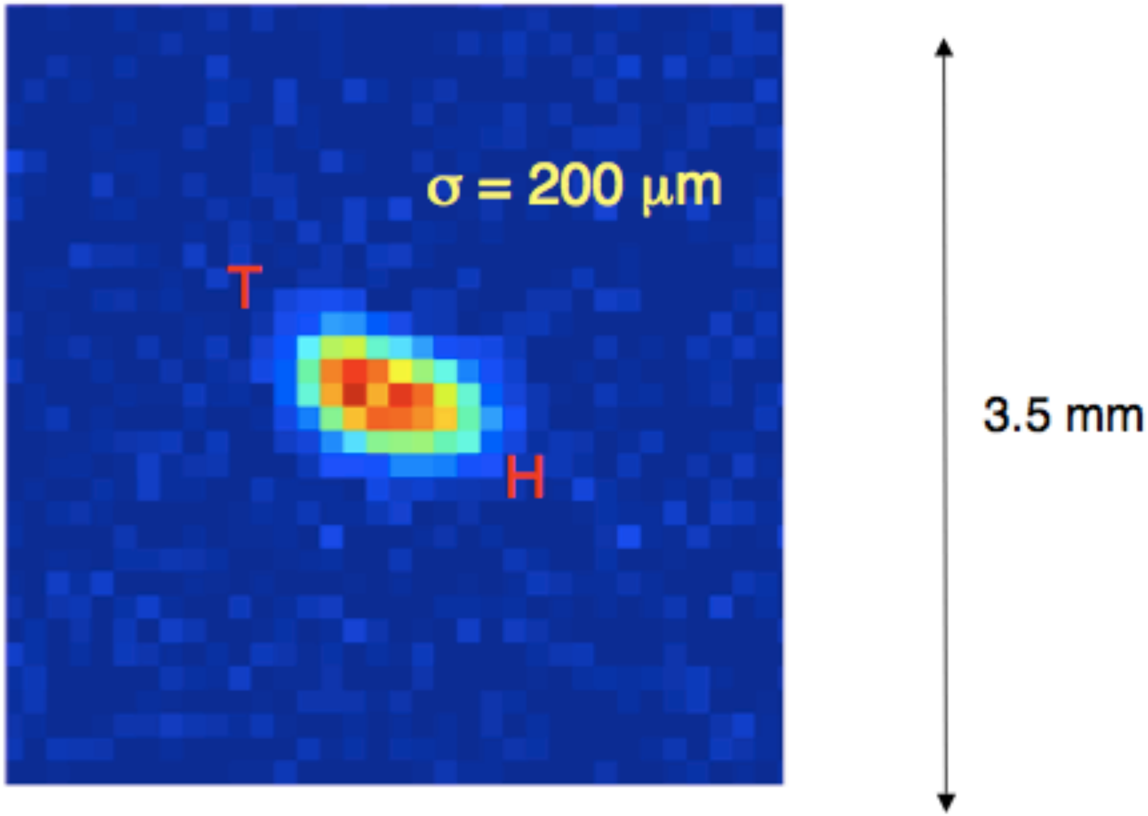
with H/T need ~10’s of events to rule out isotropy, w/o H/T need ~100’s

From Tanimori, et al Phys.Lett. B578 (2004)
Hitachi’s work

How close to 10 events can we get?

Diffusion

A real track will suffer diffusion

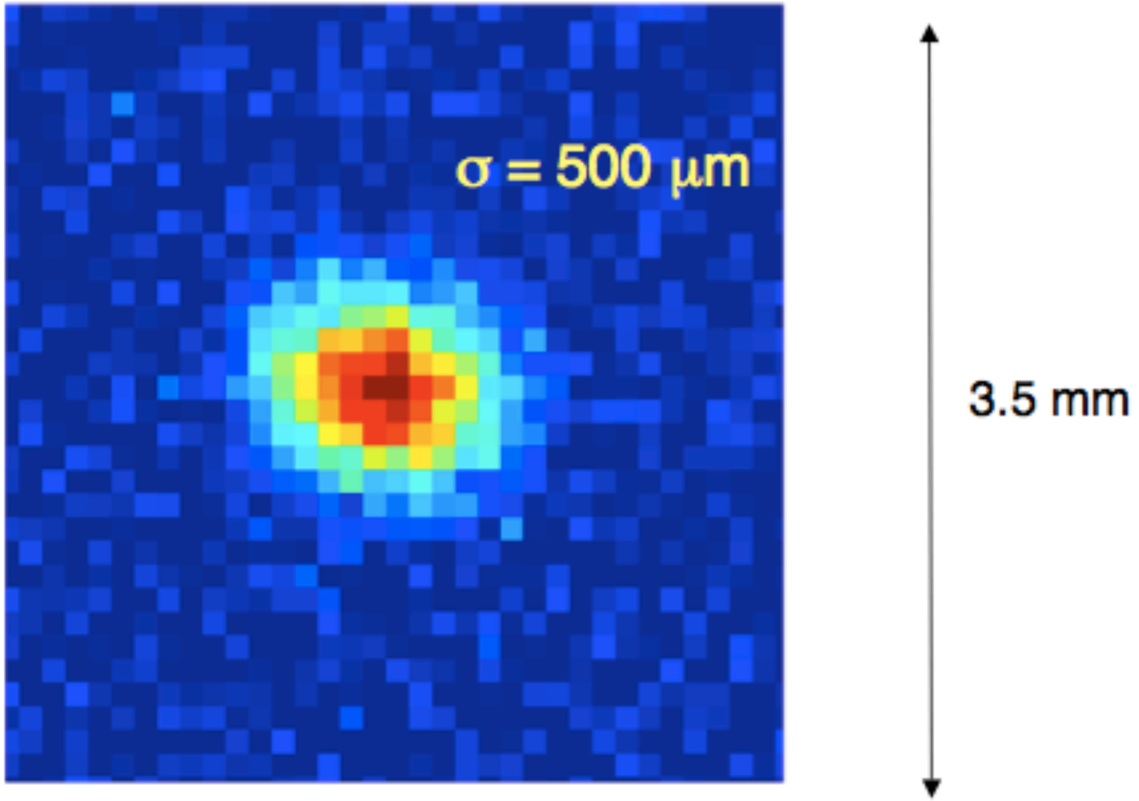


100 μm pixel readout

thanks to Dinesh Loomba

Diffusion

A real track will suffer diffusion

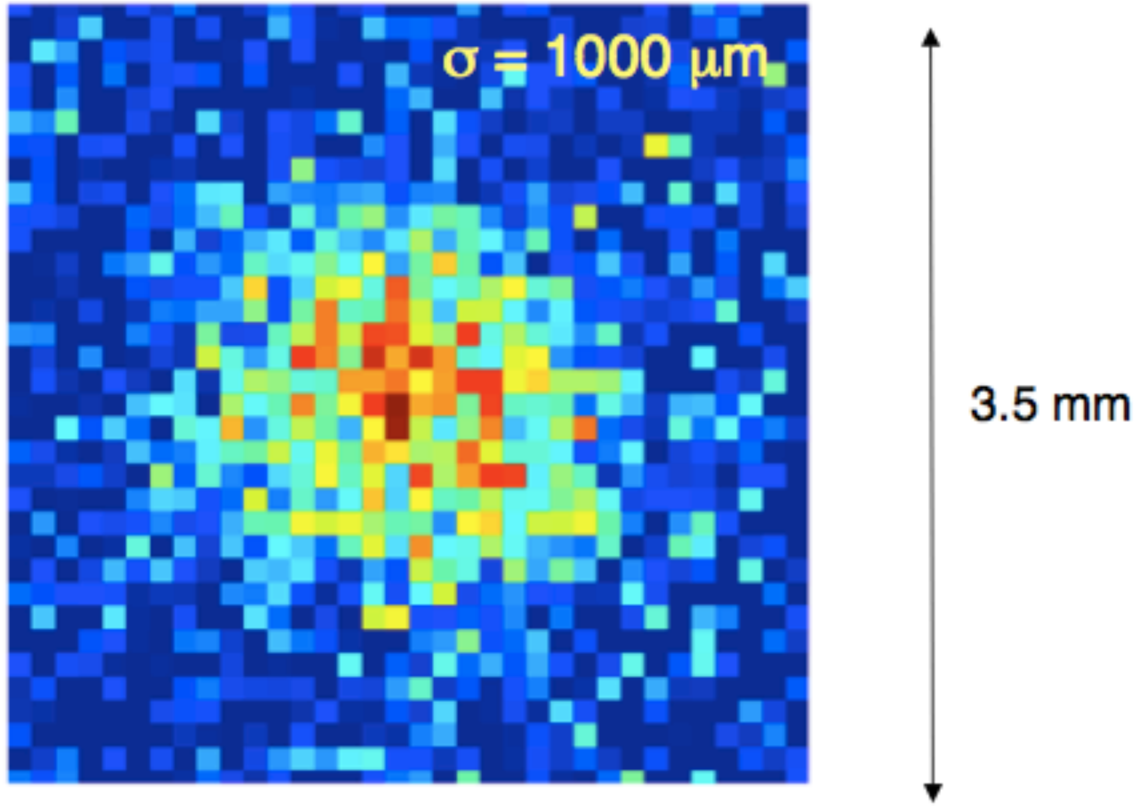


100 μm pixel readout

thanks to Dinesh Loomba

Diffusion

A real track will suffer diffusion



100 μm pixel readout

So diffusion must be kept low

thanks to Dinesh Loomba

Discovery Strategy

These issues lead to a complex optimisation and choice of detector parameters and detector design depending on technology and strategy:

- Full track imaging or asymmetry signal only?
- 1D, 2D or 3D tracking?
- Track sense and head-tail discrimination or not?
- Low energy threshold or not? Low mass WIMP or not?
- Background rejection power
- SI and SD sensitivity, or both
- Scale-up to multi-tonne or not

(1) Search phase (detection of nonzero recoil signal)
(2) Detection of anisotropy
(3) Study of properties of anisotropy

GAS

DRIFT-UNM optical TPC R&D
DM-TPC
MIMAC
NEWAGE
D3

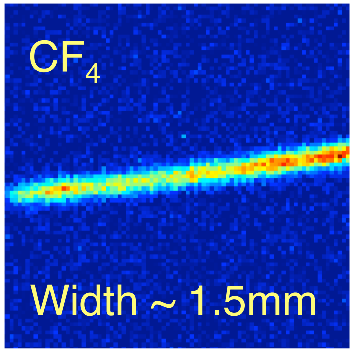
Gas: A Flexible Technology

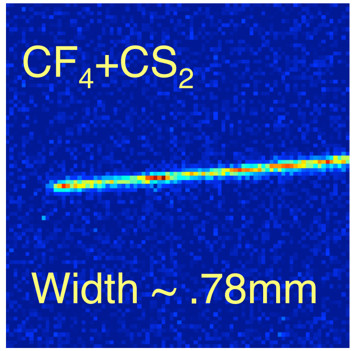
- Flexibility in choice of target A: light targets (He, C, O) for low mass WIMPs, F for spin-dependent, etc.

- Negative ion drift: target +CS_2 mixtures enable drift with thermal diffusion (Martoff).

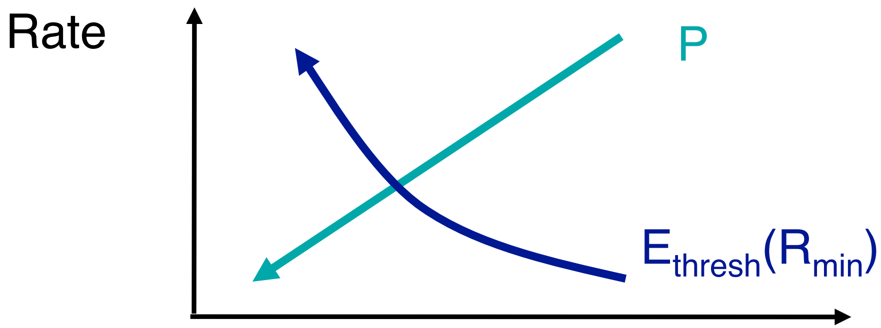
vs

Shorter drift distance





- Pressure is tunable: given a minimum resolvable track-size, R_{min},one can vary the directionality E_{th} by lowering pressure:



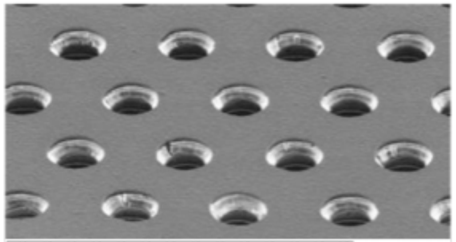
UNM R&D (DRIFT)

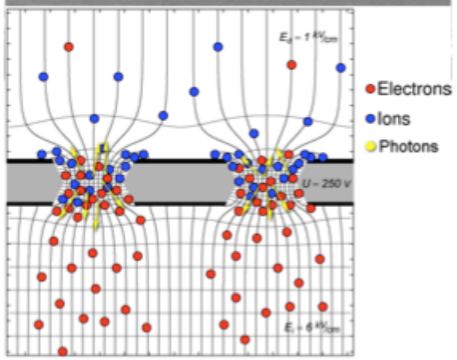
How close to 10 events can we get?:

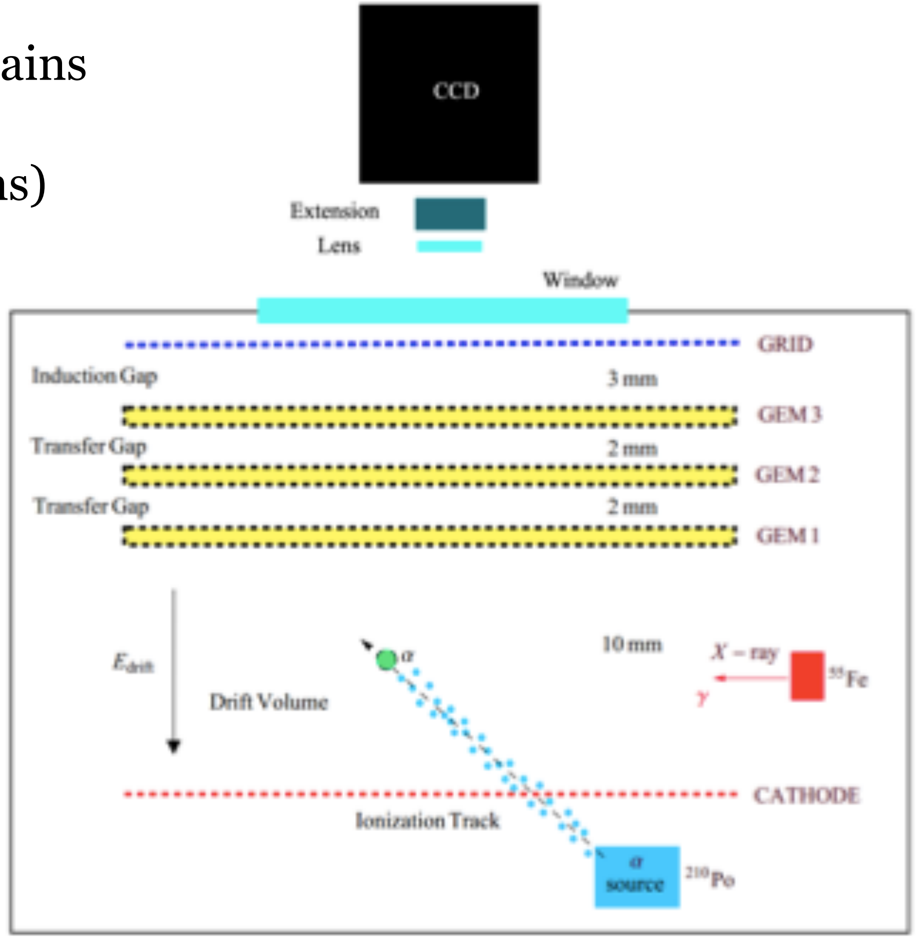
Dinesh Loomba
UNM
University of New Mexico

Concept: 100 Torr CF_4 (and CS_2 later) with ThGEM and CCD optical readout

- 2D readout with ~160 µm pixels
- 3 CERN GEMs - high signal-to-noise, gas gains achieved ~100,000
- back-illuminated CCD (QE ~ 93%, 10 e- rms)
- Low diffusion, σ ~ 0.4mm







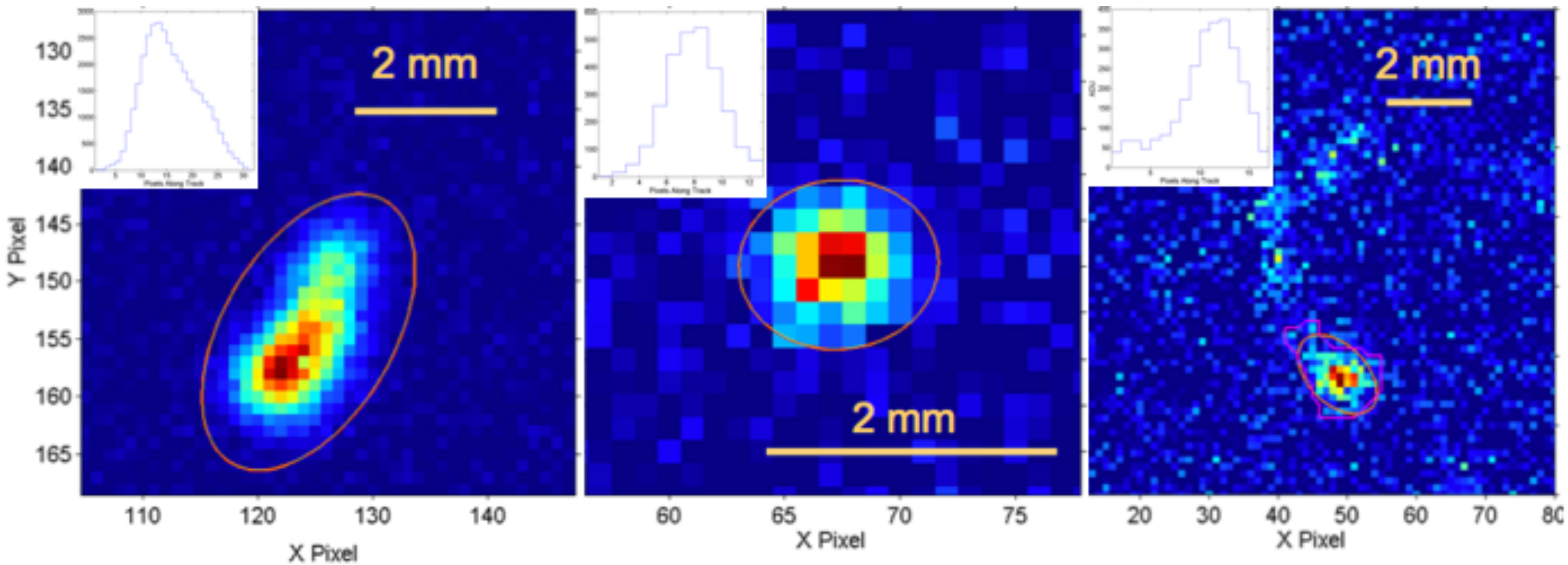
UNM R&D

Powerful background reduction with the GEM and CS_2/CF_4:

178 keV F recoil

F recoil axial skewness seen even at ~ 20 keV_{rec}

electron recoil ($9.7\ keV_{ee}$)

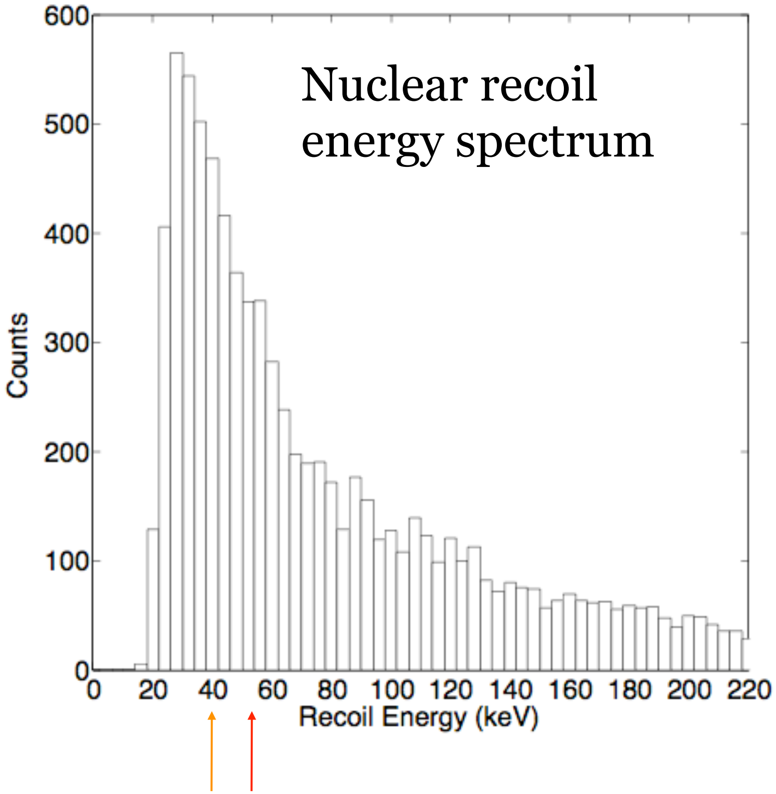


- Results reveal how low energy electron tracks look "blobby" so good S/N is essential in CCD technique to separate from low energy recoils.

UNM R&D

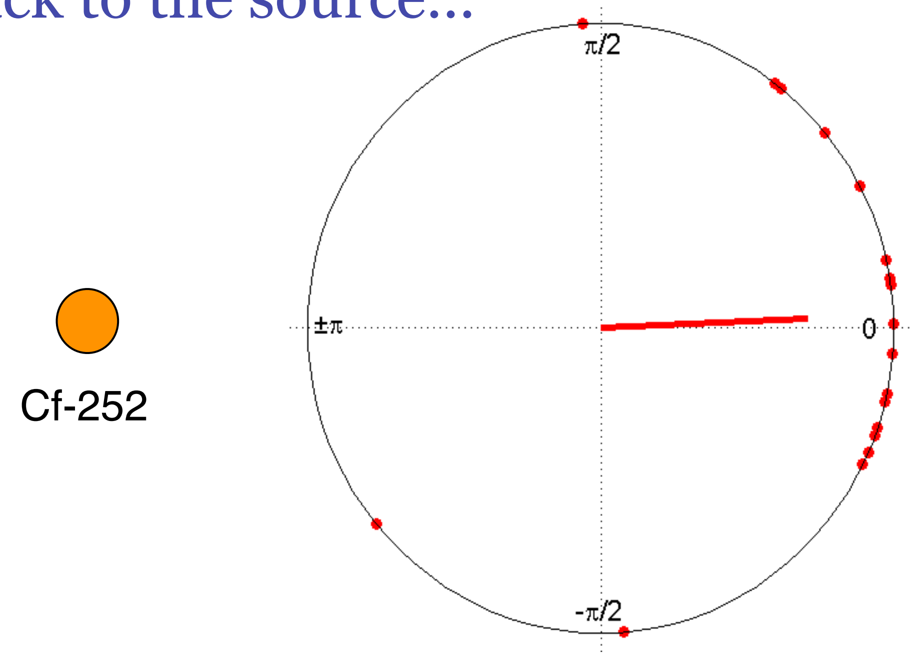
Cf-252 neutrons show powerful head-tail and directional discrimination:

Axial directional threshold: ~40 keV_{recoil}
Vector (head-tail) directional threshold: ~55 keV_{recoil}



Directionality threshold: axial, vector

~18 events needed to point back to the source...



...after quality cuts on ~40 events randomly chosen from dataset with vector directionality

Kentaro Muichi et al.

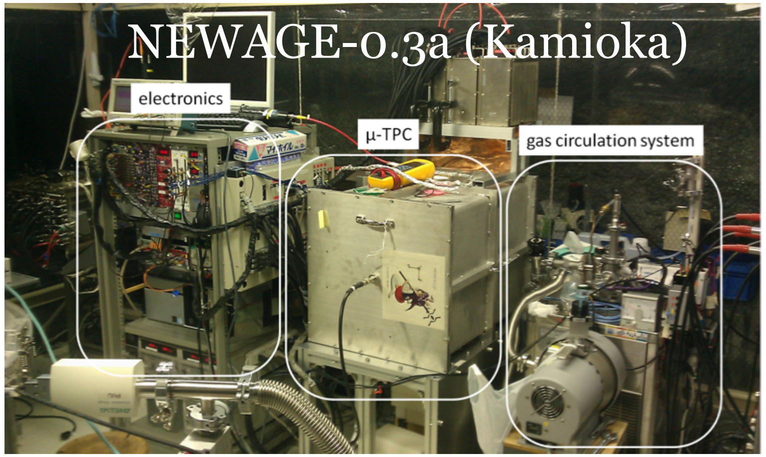
NEWAGE

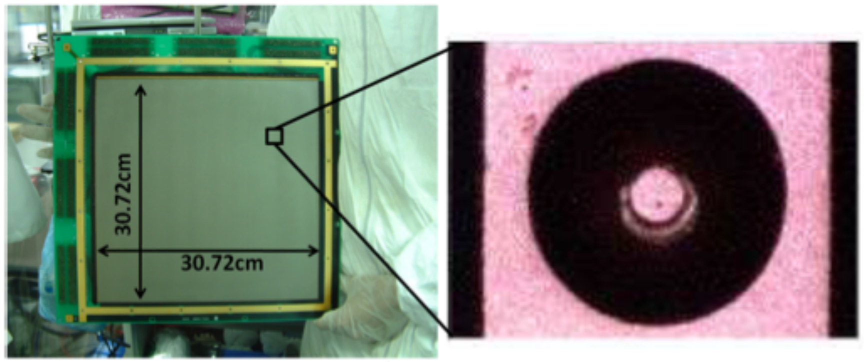
T.Tanimori[1], K.Miuchi[2], K.Kubo[1], T.Mizumoto[1], J.Parker[1], A.Takada[3], H.Nishimura[1], T.Sawano[1], Y.Matsuoka[1], S.Komura[1], Y.Yamaguchi[2], S.Nakaura[2]

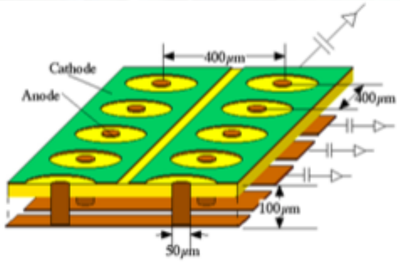
(1) Kyoto university department of physics
(2) Kobe university department of physics
(3) Kyoto university RISH

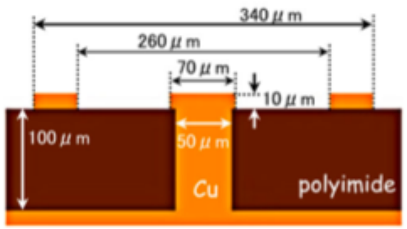
Concept: low pressure CF_4 with charge readout via micro-PIC TPC

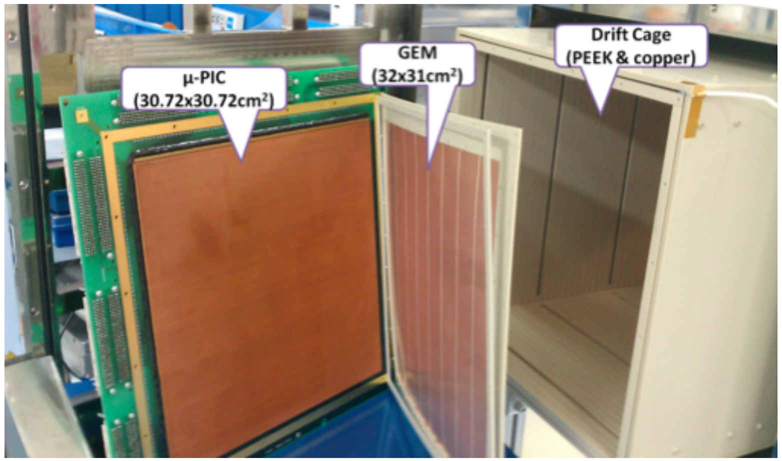
- Three detectors: NEWAGE-0.3a (Kamioka); NEWAGE-0.3b, NEWAGE-0.1 (HT R&D)
- Micro patterned gaseous detectors (MPGDs) 768 × 768 pixels (400 μm) a micro pixel chamber (μ-PIC) which is a two-dimensional fine-pitch imaging device plus a gas electron multiplier (GEM)
- 30 × 30 × 41 cm^3 of detection volume.
- CF4 gas at 0.2 atm
- A gas circulation system with cooled charcoal











MIMAC

Daniel Santos et al.

LPSC (Grenoble) : J. Lamblin, F. Mayet , D. Santos
J. Billard (Ph.D) (left in July 2012), Q. Riffard (Ph.D) (started in October 2012)

Technical Coordination : O. Guillaudin
- Electronics : G. Bosson, O.Bourrion, J-P. Richer
- Gas detector : O. Guillaudin, A. Pellisier
- Data Acquisition: O. Bourrion
- Mechanical Structure : Ch. Fourel, S. Roudier, M. Marton
- Ion source (quenching) : J-F. Muraz, J. Médard (CDD-1year)

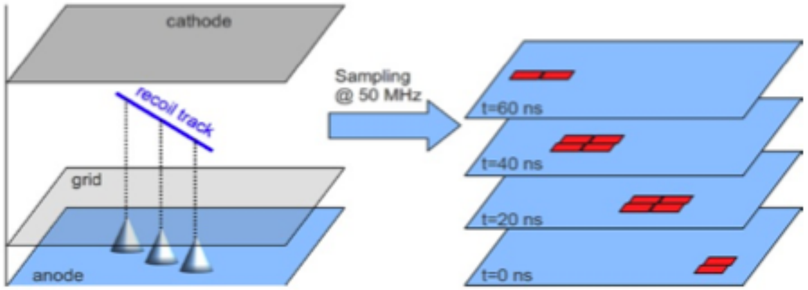
CCPM (Marseille): J. Busto, Ch. Tao, D. Fouchez, J. Brunner (Radon filtering)

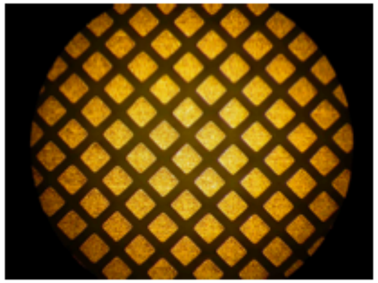
Neutron facility (AMANDE) :
IRSN (Cadarache): L. Lebreton, D. Maire (Ph. D.)

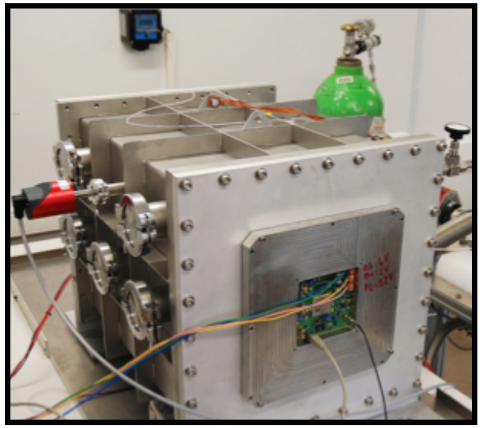
Concept: low pressure CF_4, CHF_3 and H with charge readout via Micromegas + pixel technology

- X and Y coordinates are measured on the pixelated anode
- Z direction by anode sampling at 50 MHz, use of CF4 + 30% CHF3 to slow the events
- The anode is read every 20 ns. The 3D track is reconstructed, from the consecutive number of images defining the event

Bi-chamber module 2 x (10.8x10.8x25 cm^3)

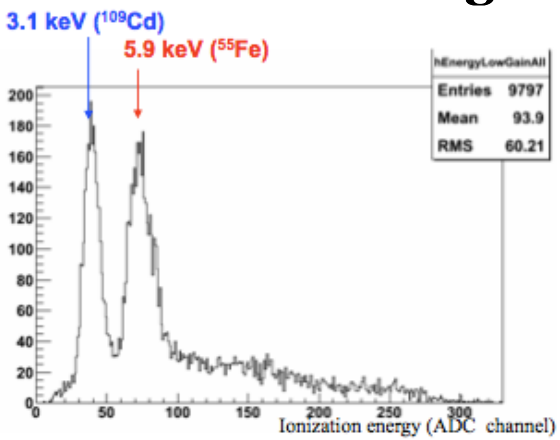




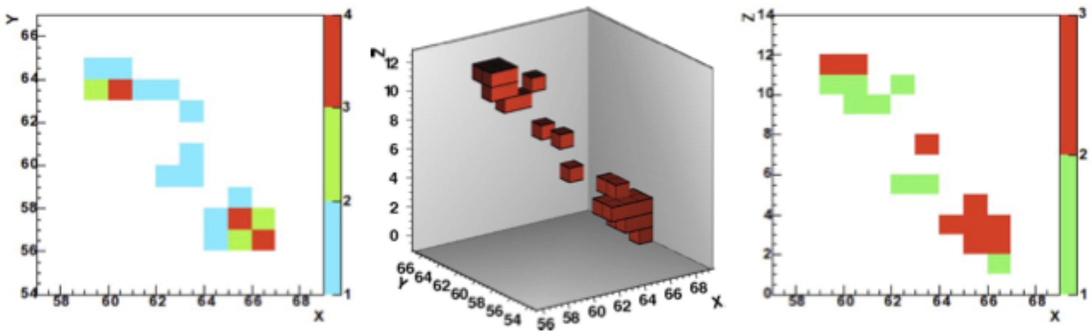


Pixel micromegas from IRFU (Saclay) - 200 µm

Performance underground at Modane:



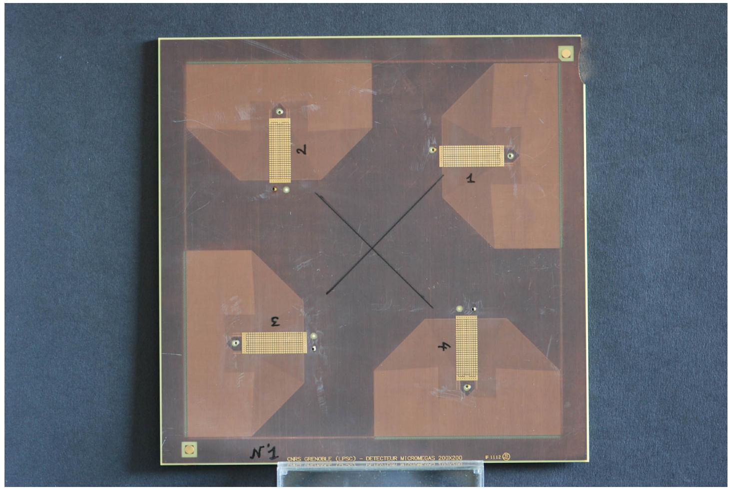
A 5.9 keV electron track in 350 mbar 95% 4He + C4H10



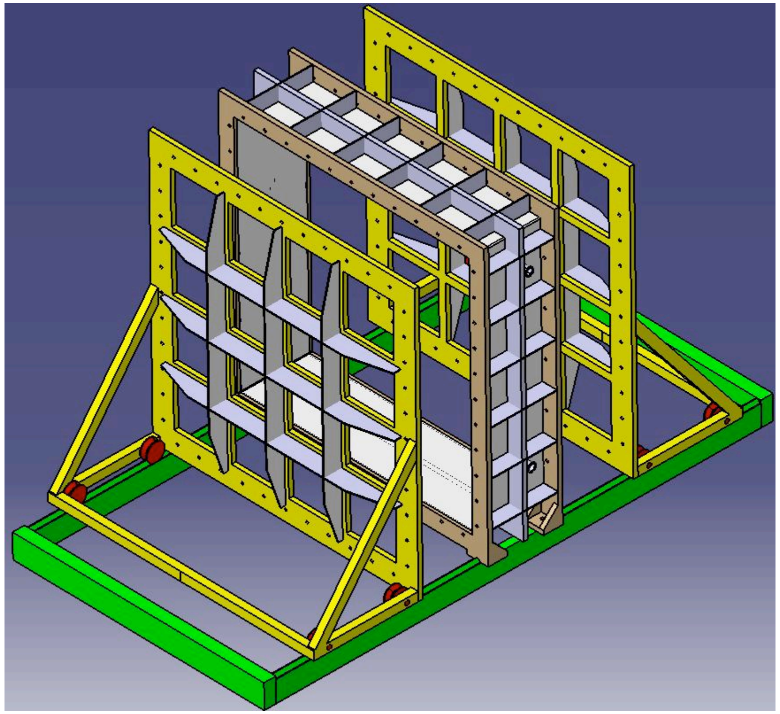
MIMAC

Future: MIMAC – 1m³ = 16 bi-chamber modules (2 x 35 x 35 x 25.5 cm³)

i) New technology anode 35cmx35cm
ii) Stretched thin grid at 500um.
iii) New electronic board
iv) Only one big chamber



New 20cm x 20cm pixel anode (1024 channels)



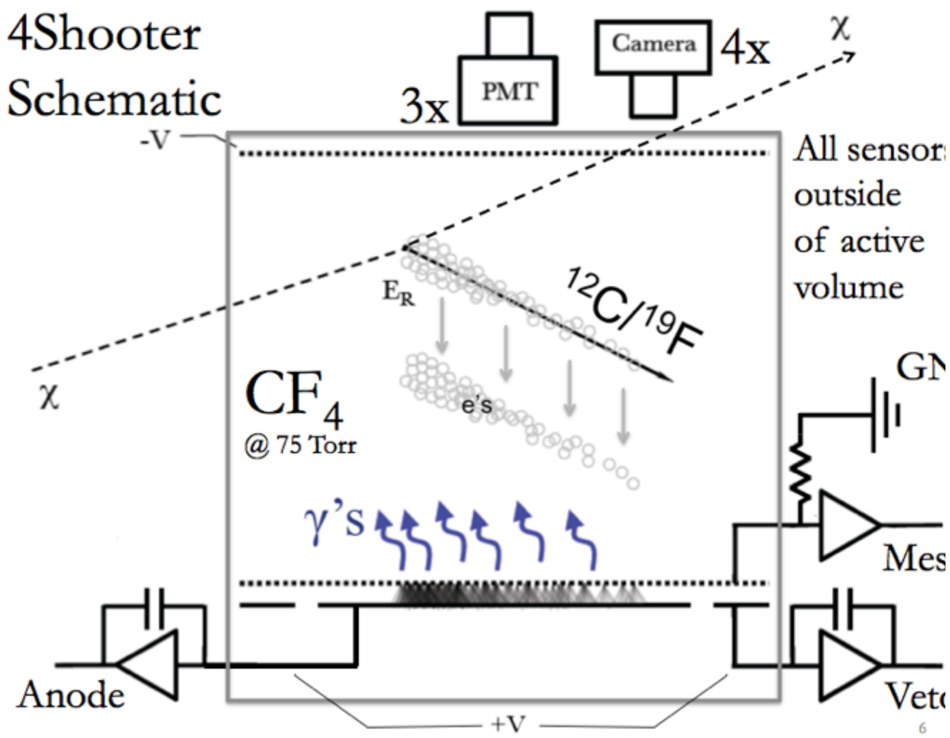
Challenges for MIMAC?:

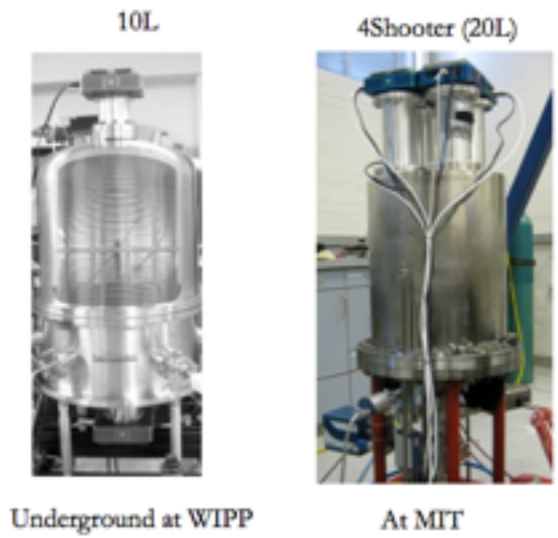
- Use of CF_4 requires addition of CHF_3 to slow the gas down to allow z-determination
- No Z fiducialisation
- Can pixilated daq be scaled-up and reasonable cost
- background issues?

DM-TPC

DMTPC Collaboration
Brandeis University
A. Dushkin, H. Wellenstein*
Bryn Mawr/Wellesley
T. Ananna, E. Barbosa de Souza, J. Battat*, **V. Gregoric, K. Recine,**, *L. Schaefer*
University of Hawaii
I. Jaegle, **S. Ross**, S. Vahsen*
MIT
H. Choi, **C. Deaconu**, P. Fisher*, **S. Henderson, W. Koch, J. Lopez**, H. Tomita
Royal Holloway (UK)
ıpa, J. Monroe*

Concept: low pressure CF_4 with charge mesh and CCD



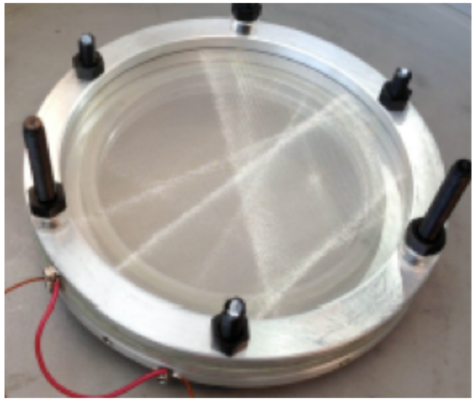


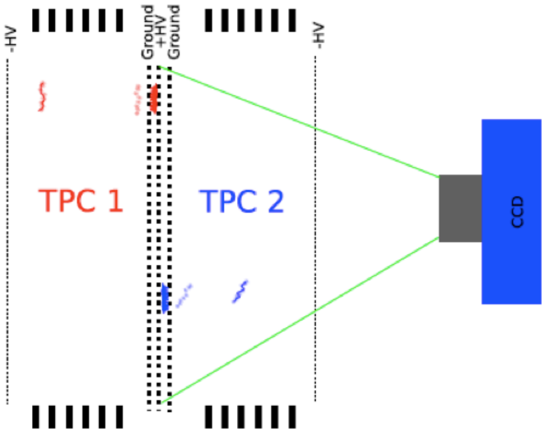
- Avalanche in mesh produces amplification and scintillation
- Primary ionisation encodes track direction via dE/dx profile
- Light and charge readout required for tracking backgrounds
- Light used to reject wrong Range vs. E; charge to reject e^-. CCD artefacts
- No ΔZ from light (for 3D) - R&D to use charge signal for 3D
- No absolute Z or Z fiducialisation

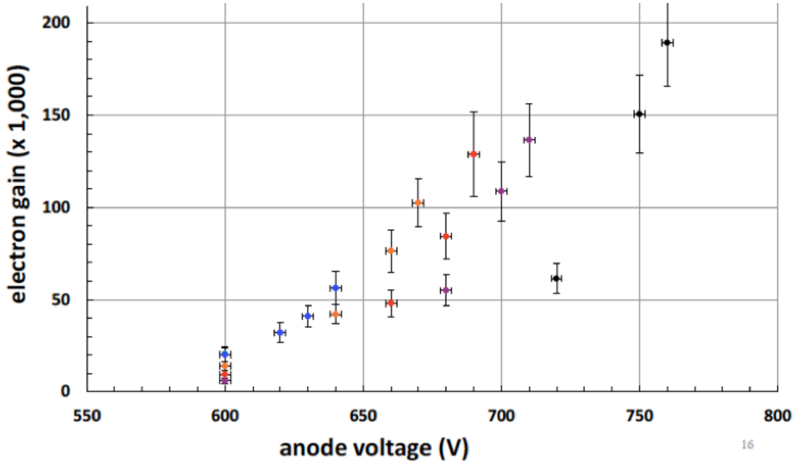
arXiv:1301.5685v2 (2013)

DM-TPC

DMTPCino: 1m³ Detector







- Prototype for very large detector: build many 1 m³ modules because of diffusion limit.

- Design based on 4-shooter 20L prototype:

Challenges for DM-TPC?:

- Fast CF_4 makes makes ΔZ hard to do
- No Z fiducialisation
- Can CCD technology be scaled-up?
- CCD noise: residual bulk images (e.g. from sparks), (2) intermittent hot pixels, (3) noise

(i) new mesh with high gain
(ii) multi-camera readout imaging 2 drift regions
(ii) low-background materials
(iii) triggering with charge/PMTs

DRIFT

DRIFT IIa, b, c, d, e, DRIFT III

Directional Recoil Identification From Tracks (DRIFT)

Sheffield University
Neil Spooner – PI
Matt Robinson
Dan Walker
Stephen Sadler
Sam Tefler
Andrew Scarff
Anthony Ezeribe
Leonid Yuriev
Trevor Gamble

Occidental College
Dan Snowden-Ifft - PI
Jean-Luc Gauvreau
Chuck Oravec
Alex Lumnah
Chongmo Tang

Colorado State University
John Harton – PI
Jeff Brack
Dave Warner
Alexei Dorofeev
Fred Shuckman II
Ryan Held

University of New Mexico
Dinesh Loomba - PI
Michael Gold – PI
John Matthews - PI
Eric Lee
Eric Miller
Nguyen Phan
Randy Lafler

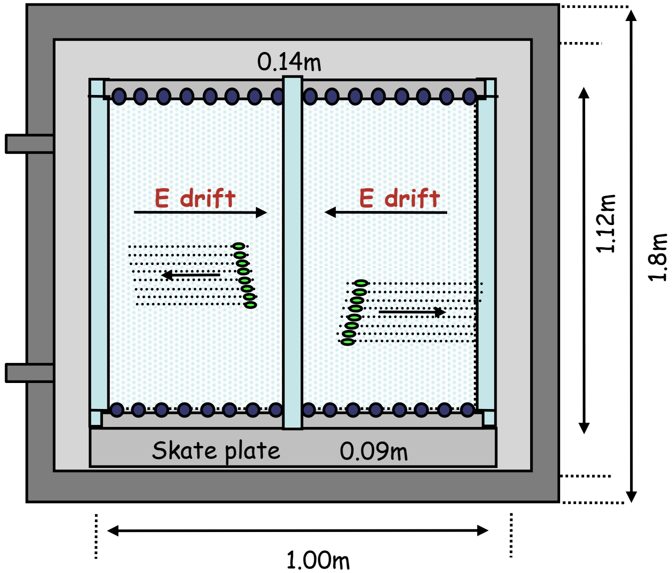
The University of Edinburgh
Alex Murphy – PI

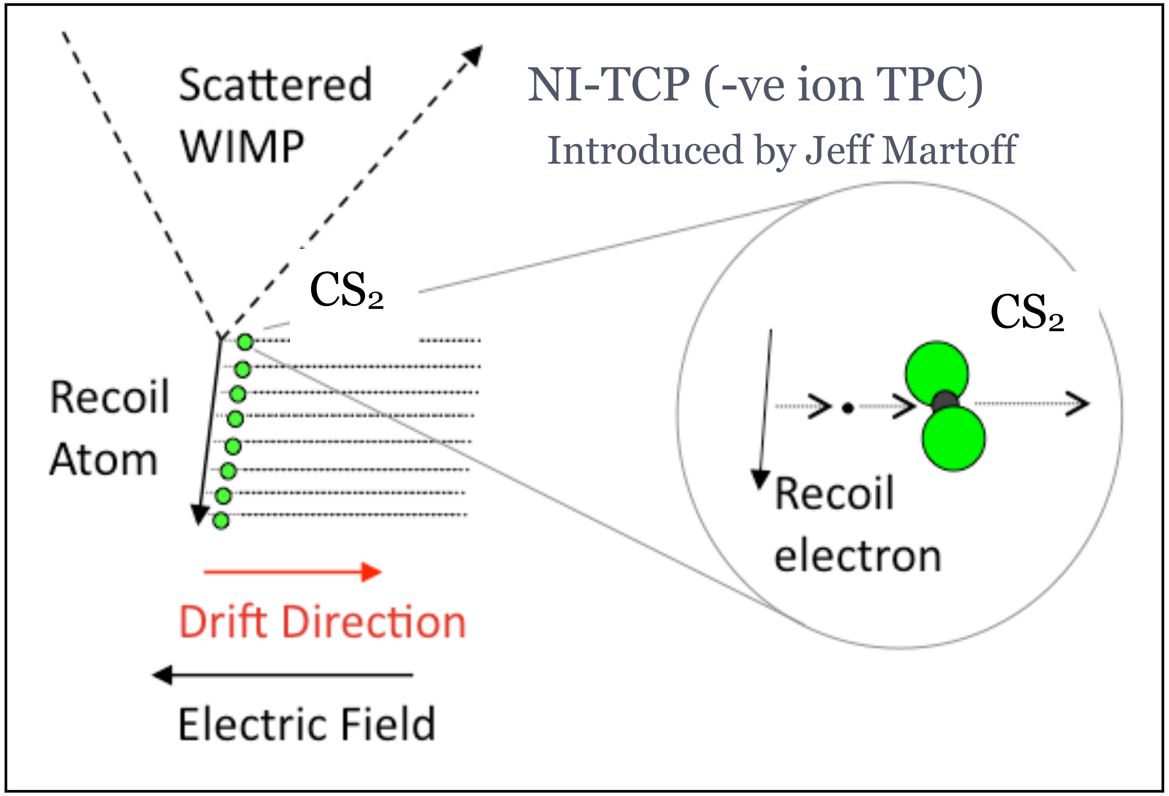
Wellesley College
James Battat – PI
NEW!

University of Hawaii
Sven Vahsen – PI
NEW!

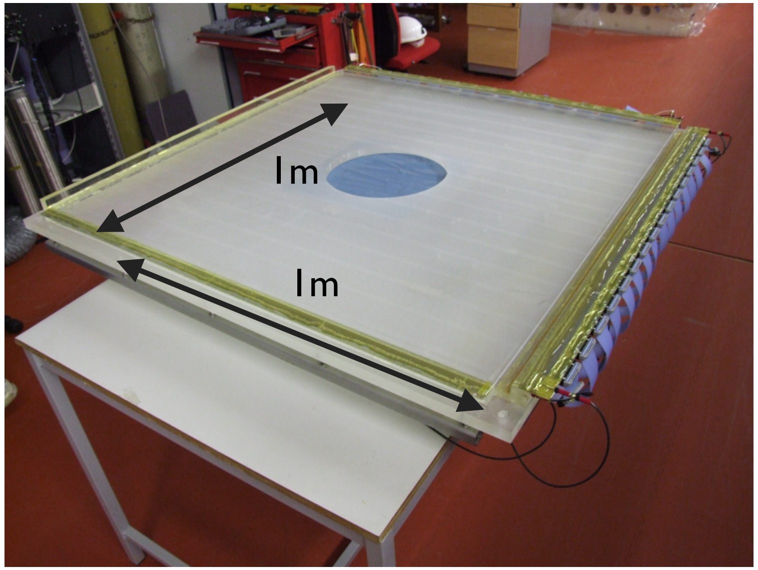
Boulby Mine
Sean Paling – PI
Emma Meehan
Louise Yeoman

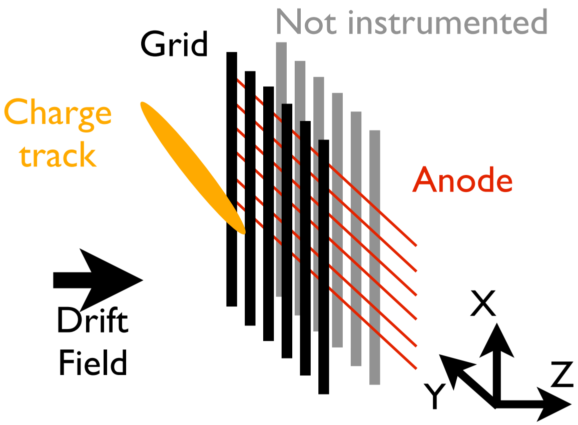
Concept: -ve ion CS_2 + CF_4 TPC, MWPC readout, m^3 volume, 40 Torr

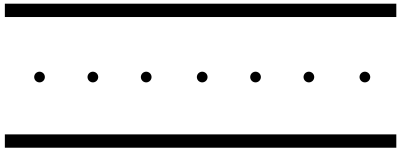


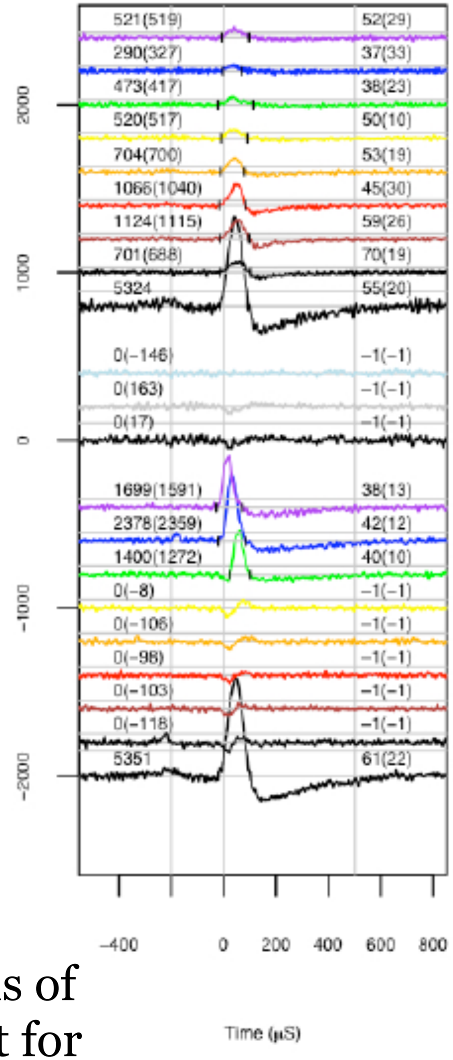


DRIFT-II Readout









ΔX: Number of anode wires crossed
ΔY: Progression across grid wires
ΔZ: Drift time between start and end of track

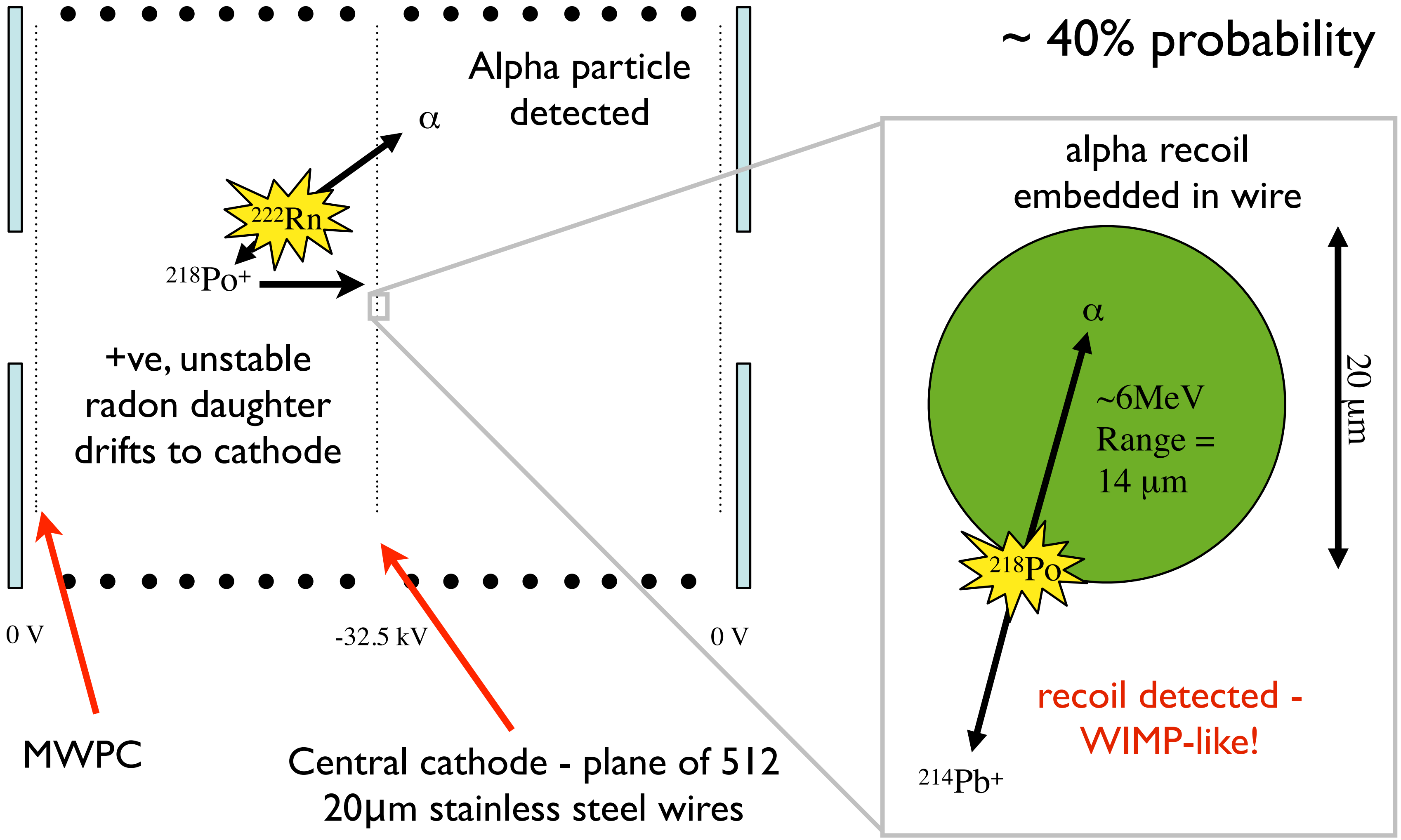
- Anode plane of 512 20μm wires with 2mm pitch
- 2 cathode planes of 512 100μm wires perpendicular to anode plane, 2mm pitch - one of which is read out

Multiplexed to 18 channels of digitised waveform output for 1m² readout plane

<u>Simple, cheap & scalable</u>

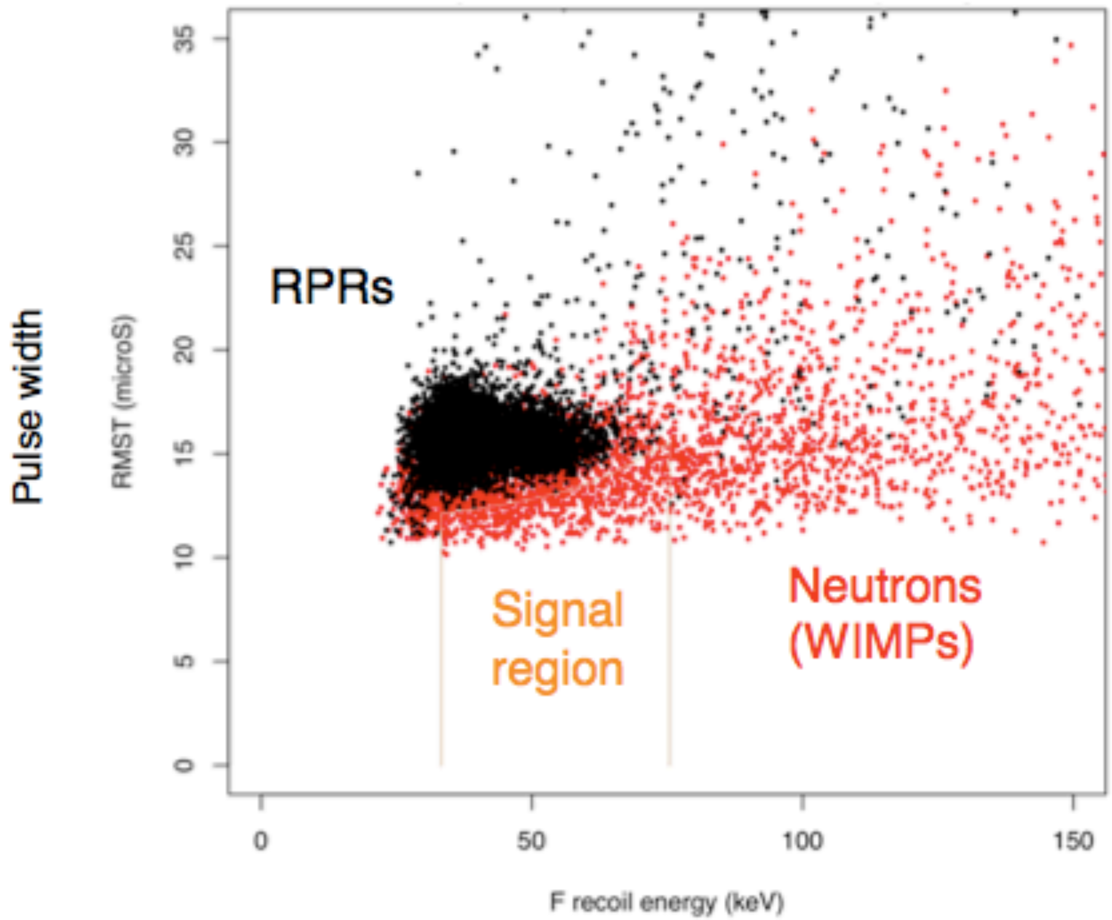
DRIFT-II Backgrounds

- Gamma/electron rejection is >10^5 and is not an issue at our E threshold
- The main background is from Radon Recoil Progenies (RPRs)



RPR Discrimination

- DRIFT-IIa runs revealed ~600 RPR events per day!
- But RPRs have large pulse widths as expected from maximally diffused tracks drifting from cathode. So, RPRs can be reduced in analysis



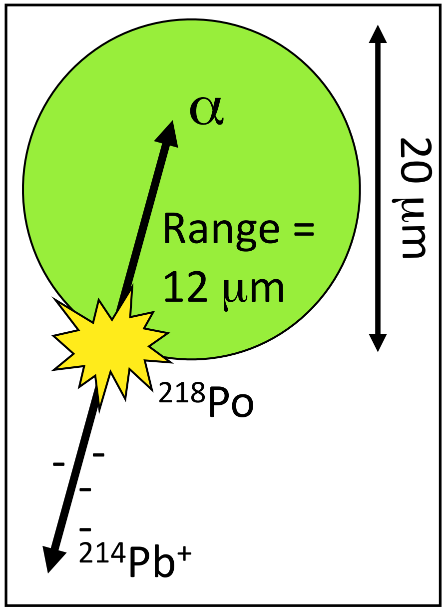
DRIFT-II RPR Reduction

DRIFT IId upgrade to thin Cathode

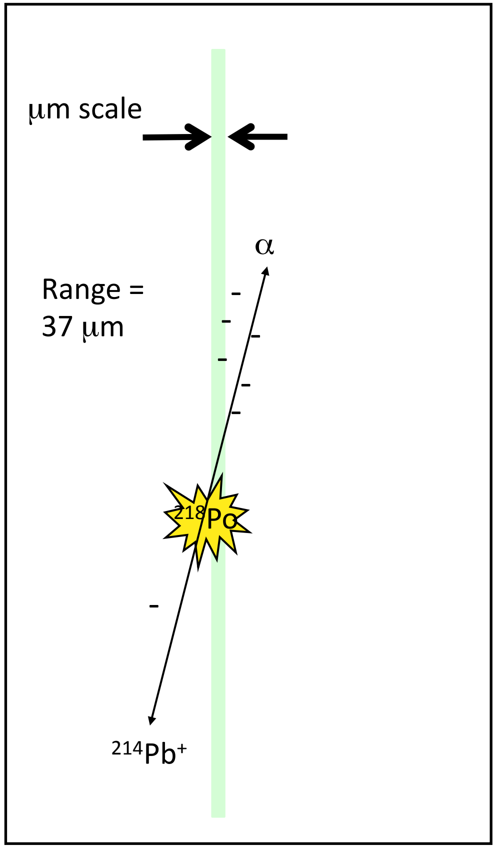
Wire Cathode → Thin Cathode → Thin Texturised Cathode

~600 RPRs/day | ~130 RPRs/day (with nitric etch) | ~1 RPRs/day

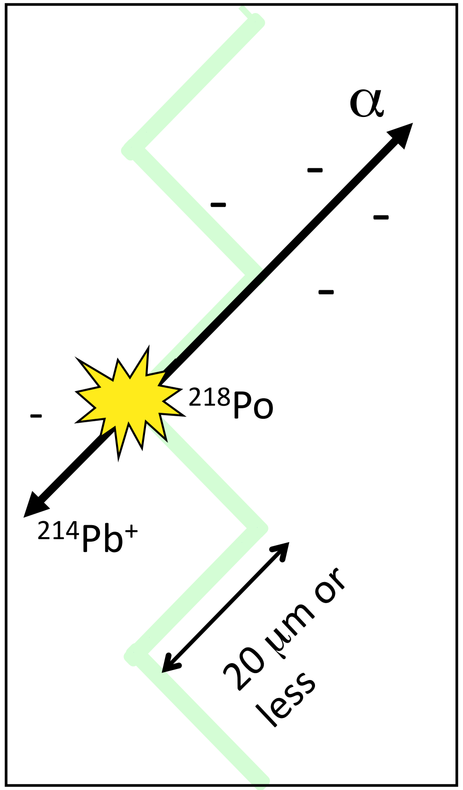
Wire Cathode



Thin Film



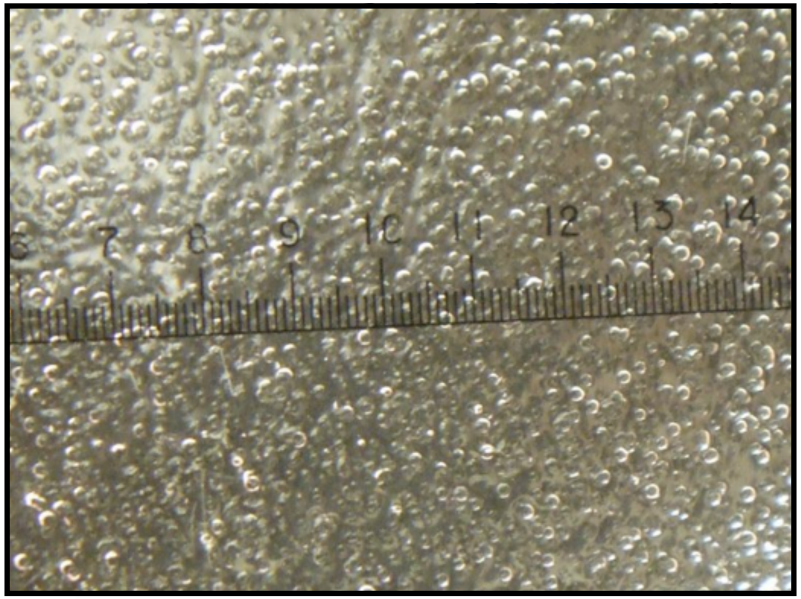
Texturised Cathode



DRIFT-IId

Use of multi-panel 0.9μm thick DRIFT cathode

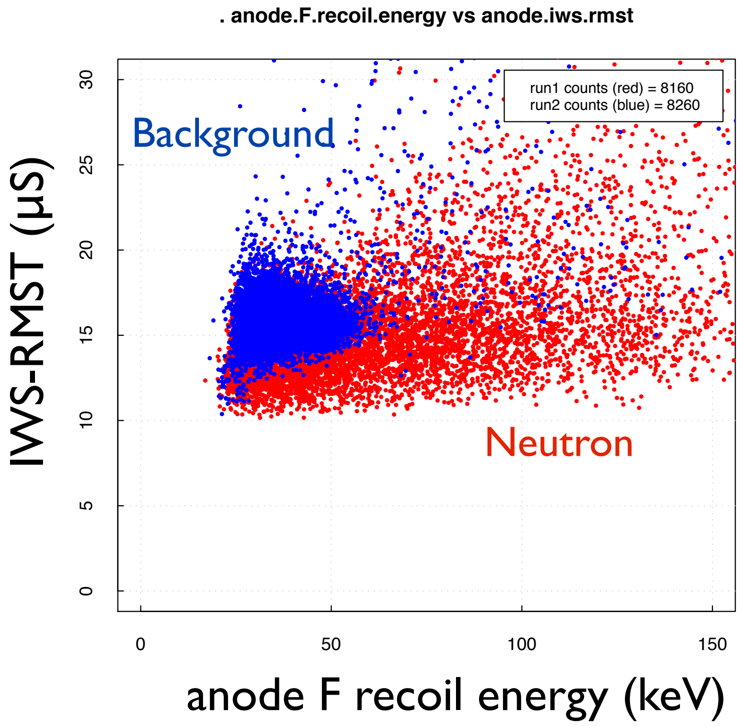
cathode tested at full voltage (32.5kV)



DRIFT-II RPR Reduction

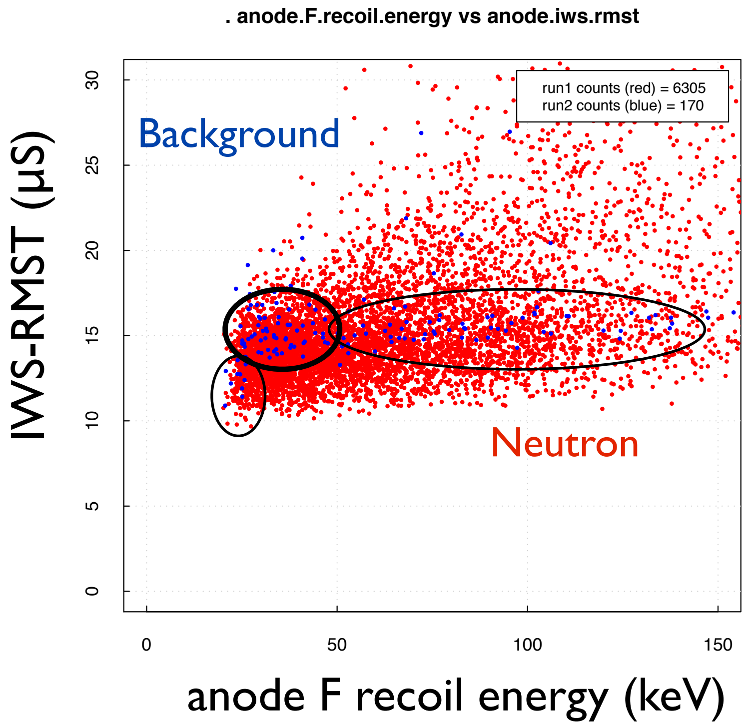
20 μm wire cathode

Background events
174 events/day



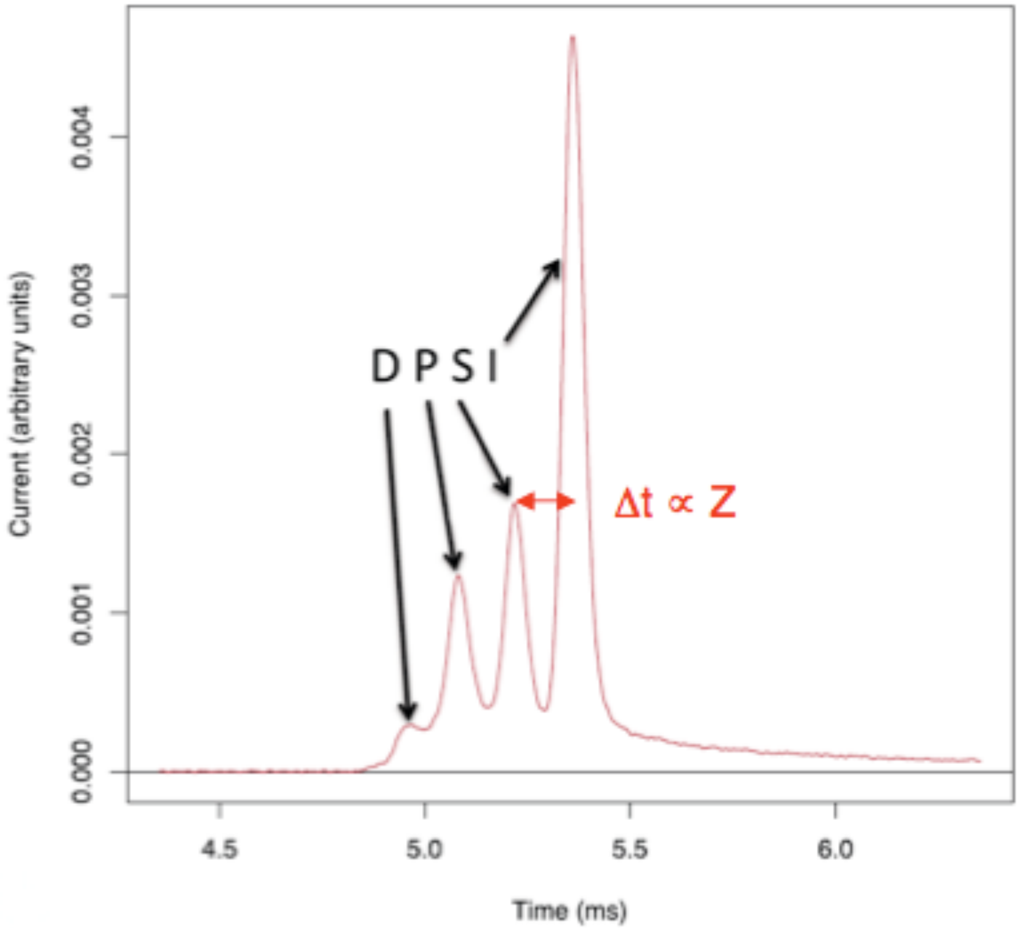
0.9 μm film cathode

Background events
14.7 events/day



DRIFT - Full Z Fiducialization

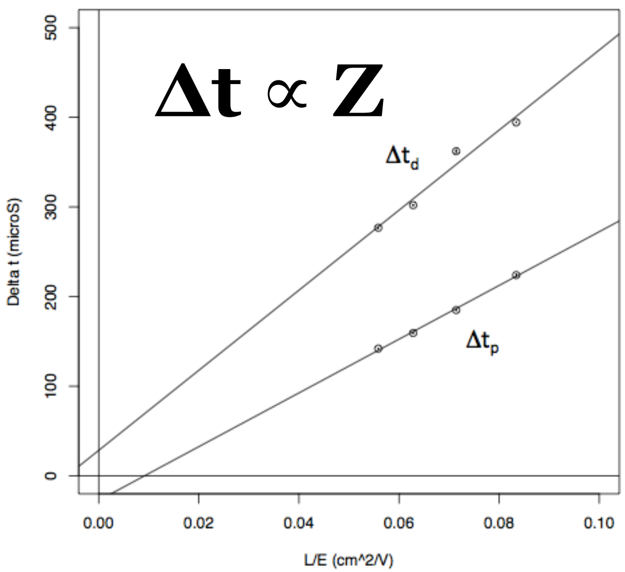
Discovery of “minority peaks” in $CS_2 + O_2$ mixtures:



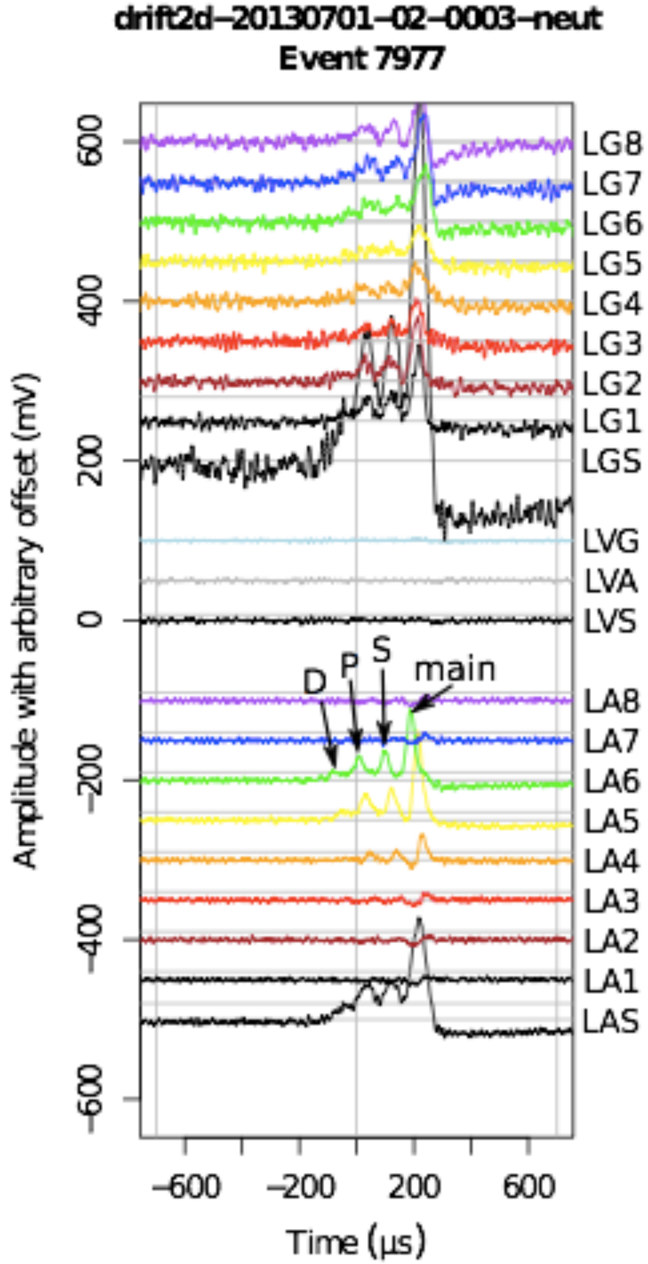
D.P.S-I, Rev. Sci. Instrum. (2014)

DRIFT - Full Z Fiducialization

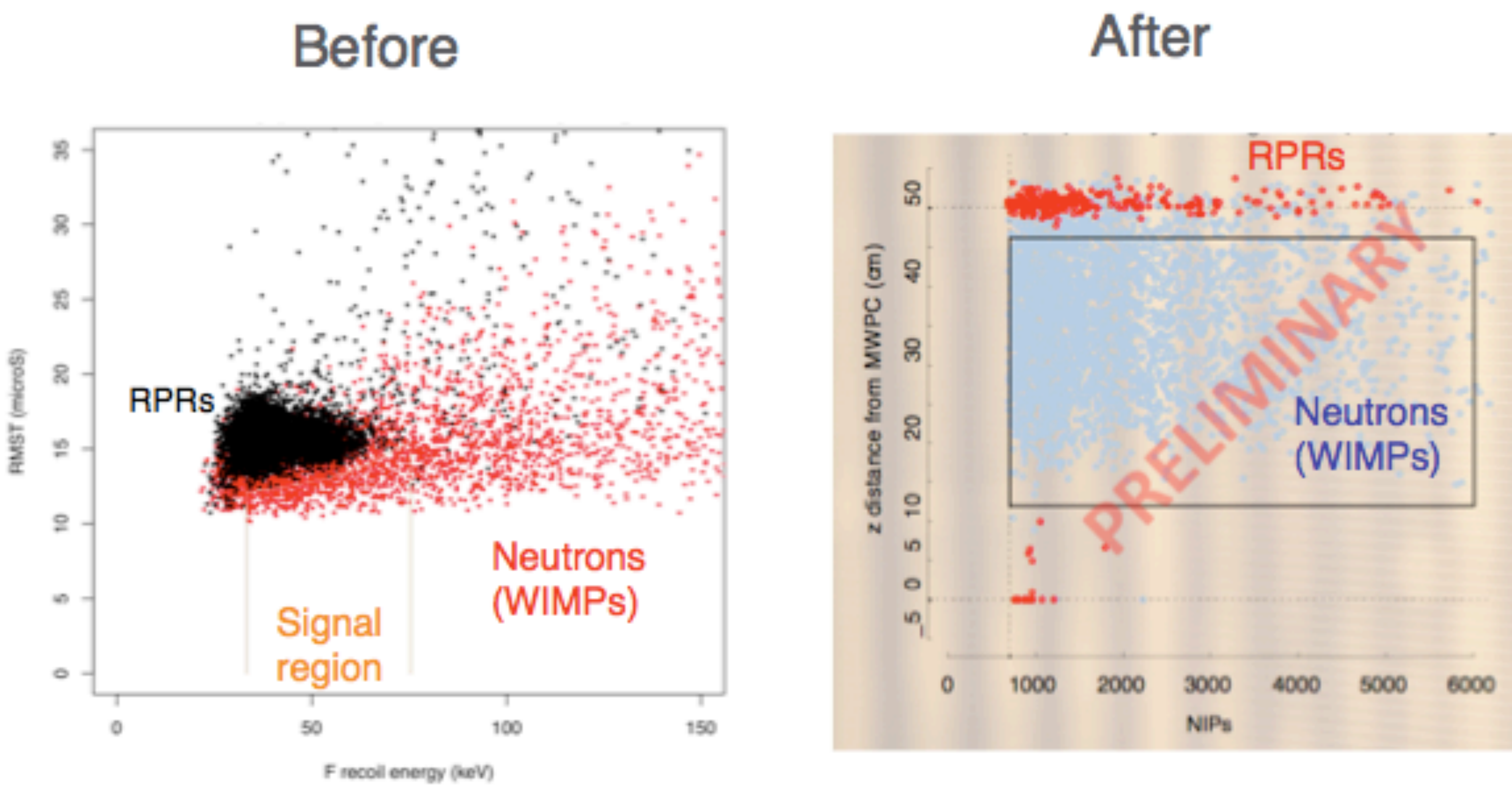
- **1% oxygen** added to 30:10 Torr CS_2: CF_4 mixture
- Appearance of "minority carrier" peaks **earlier** than the "majority" peak, carrying ~1/2 of the total charge (see Snowden-Ifft Rev. Sci. Instr. 85 (2014))
- Timing between main peak and minority peaks gives **absolute Z information** on events
- This allows rejection of RPRs that originate near the cathode at z = 50 cm or MWPC planes at z = 0 cm



$$z = (t_m - t_p)\frac{v^m_{drift} v^p_{drift}}{v^m_{drift} - v^p_{drift}}$$



DRIFT - Full Z Fiducialization



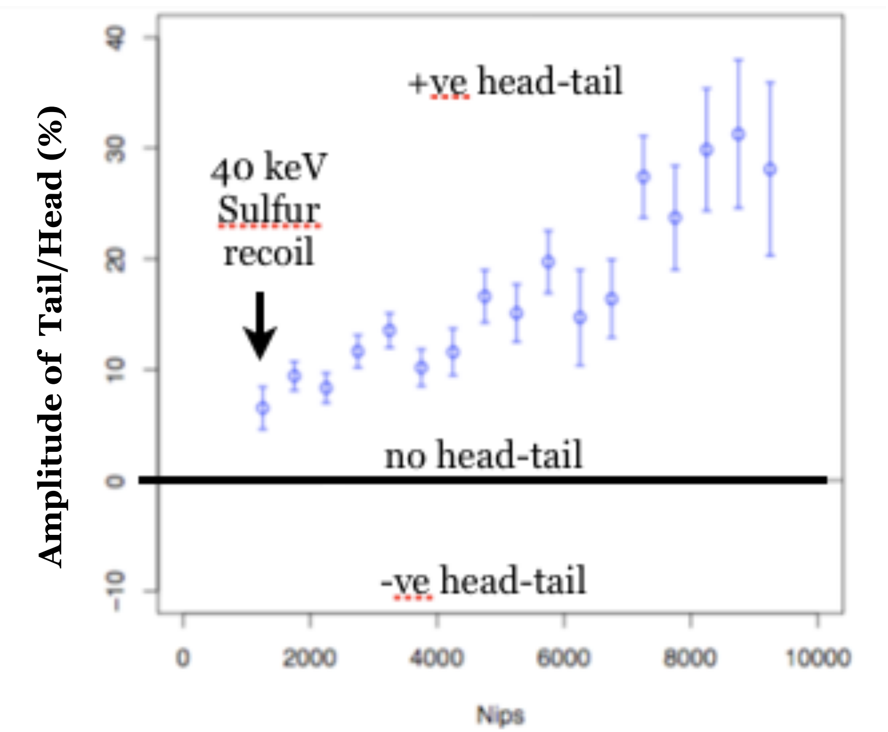
Both are from ~50 day dark matter runs at Boulby

An expanded region with zero background....

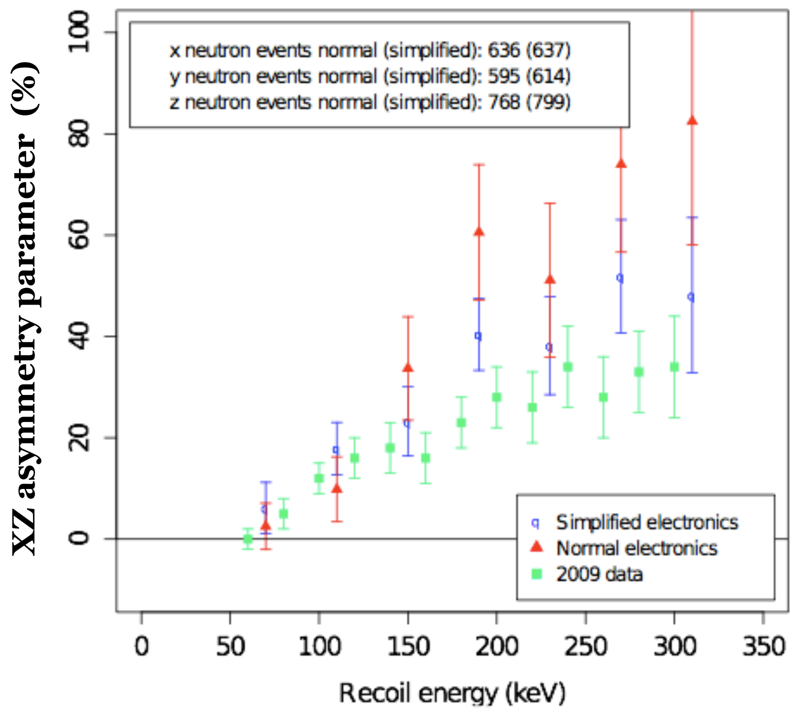
DRIFT-II Direction Sensitivity

S. Burgos et al., Astropart. Phys. 31 (2009) 261-266
S. Burgos et al., NIM A600 (2009) 417-423

Head-Tail discrimination



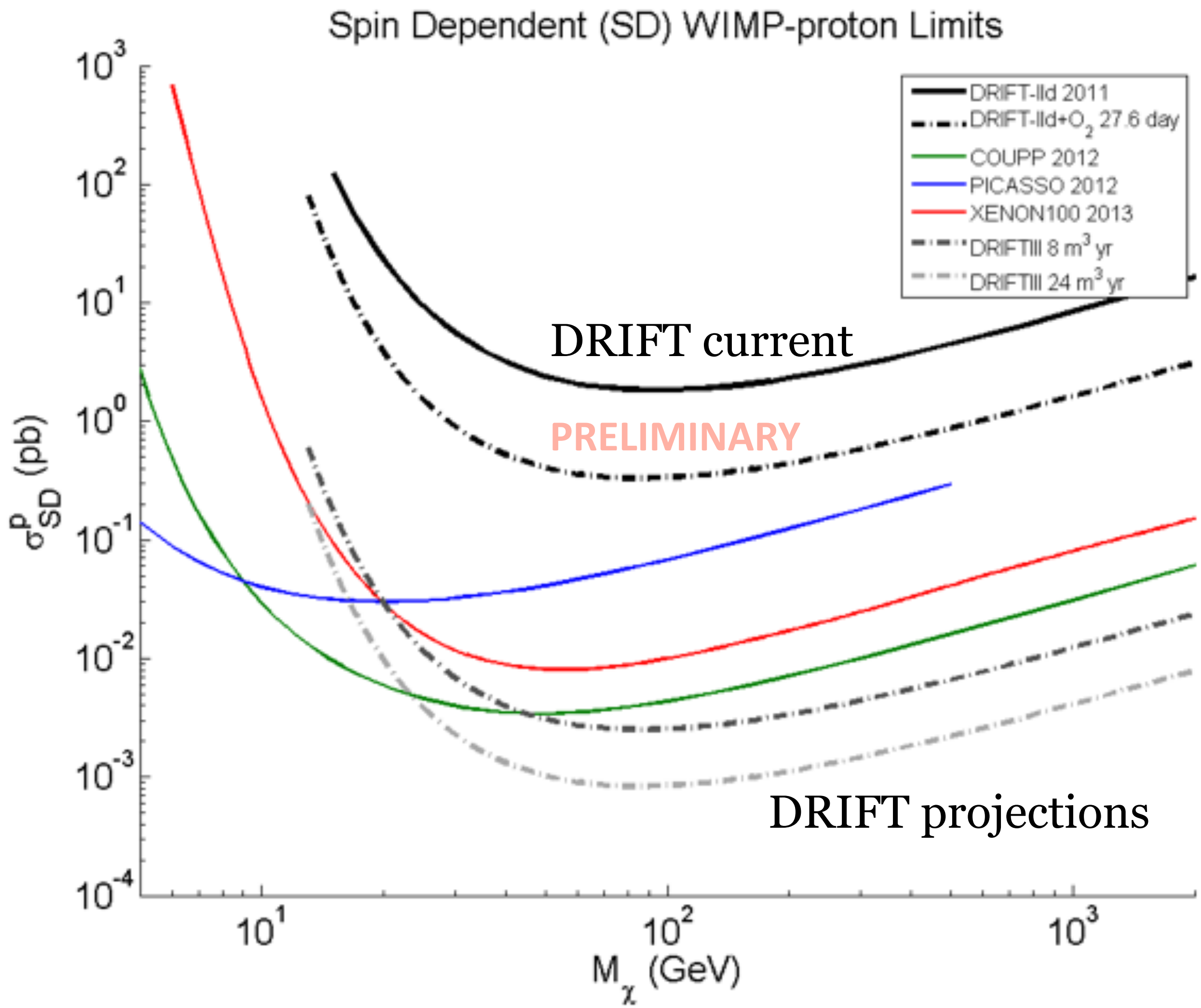
Axial directional discrimination



DRIFT's directional signature is based on measuring the recoil's range in 2D (Δx, Δz) and its head-tail in 1D (z). This enables DRIFT to detect WIMPs with a few 100 events at the 90% C.L.

DRIFT was first to show HT discrimination (in 1 m^3 at low energy)!

DRIFT II Status and prospects

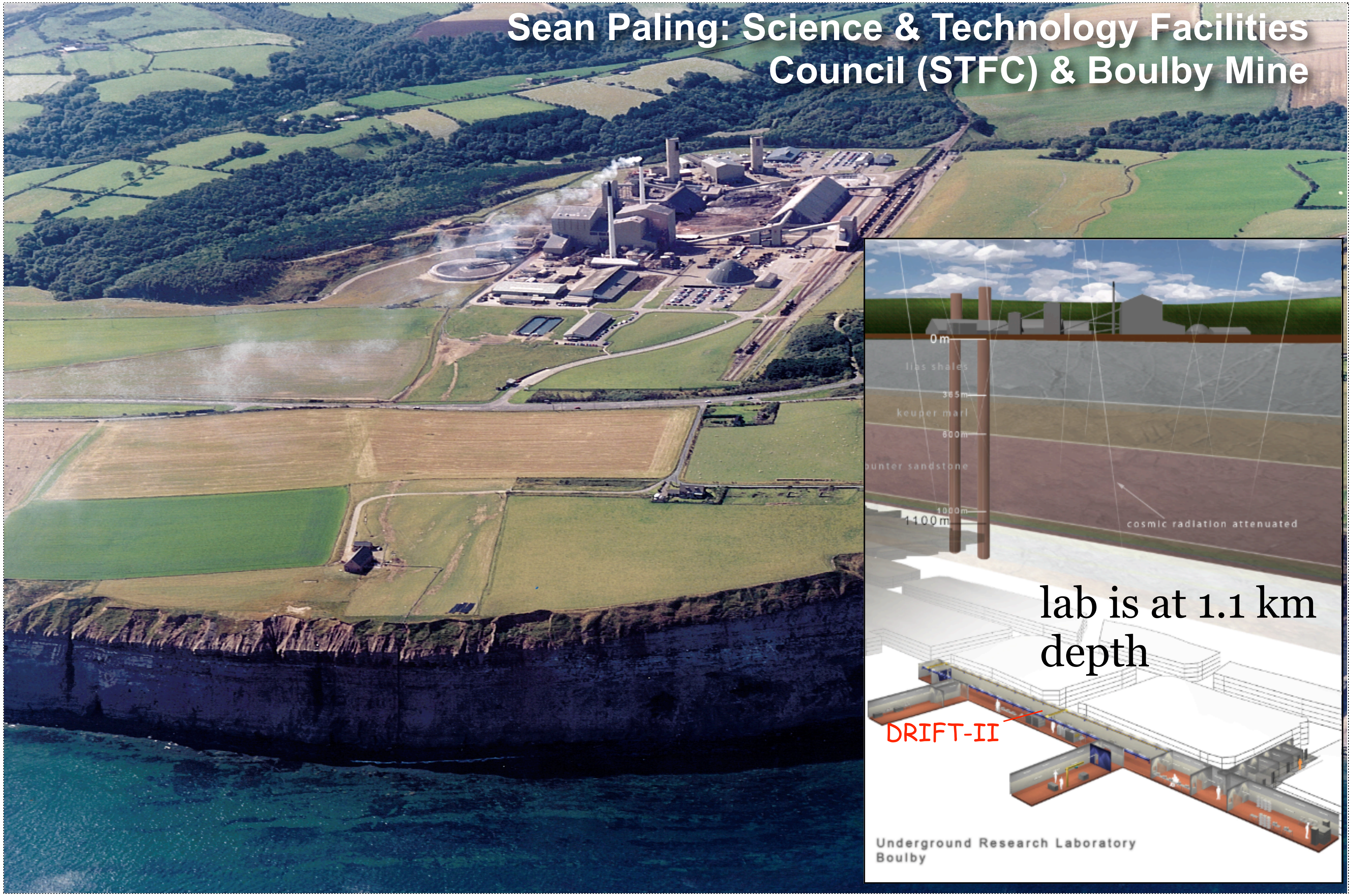


- Apology - not all latest results included yet

DRIFT-IId is currently volume limited

Scale-up looks feasible

Boulby Underground Laboratory, UK



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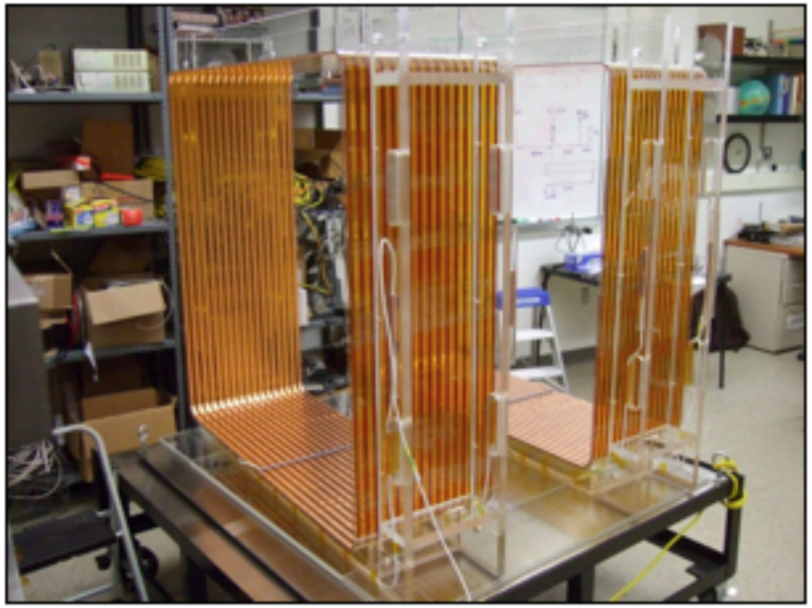
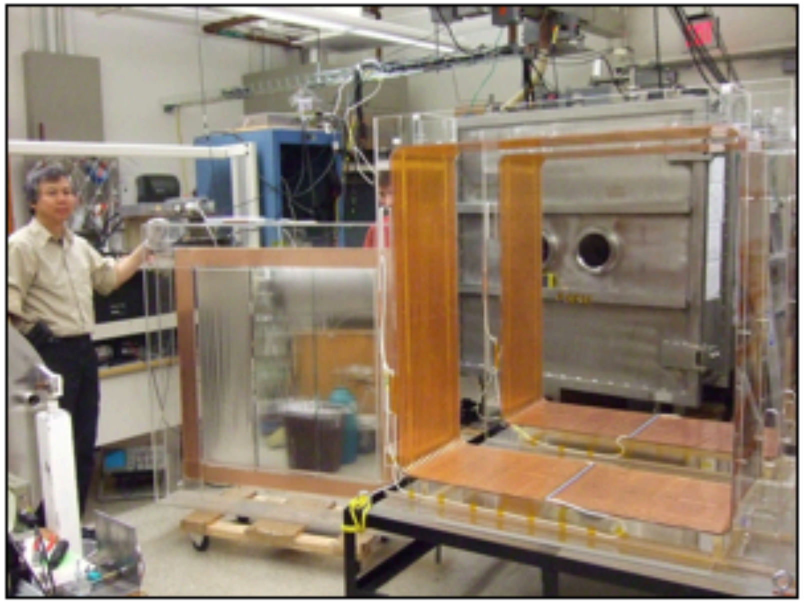
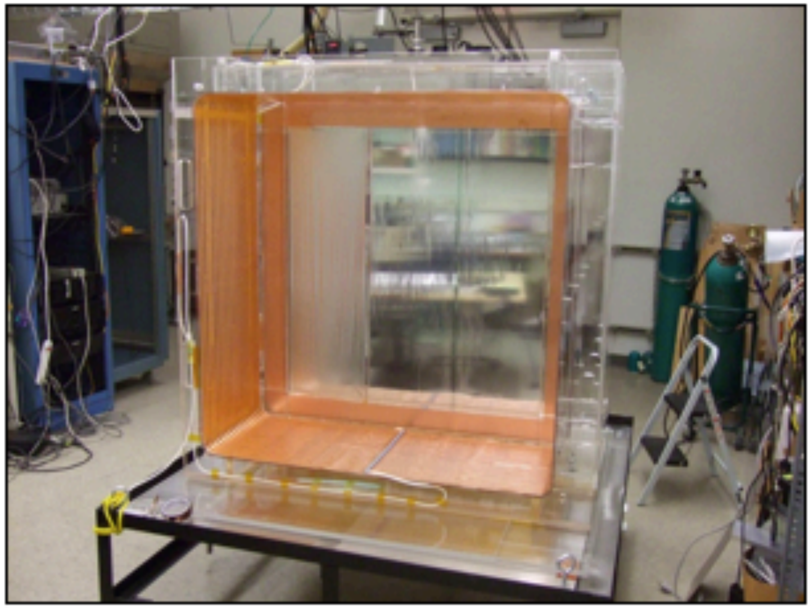
Due for completion in 2014

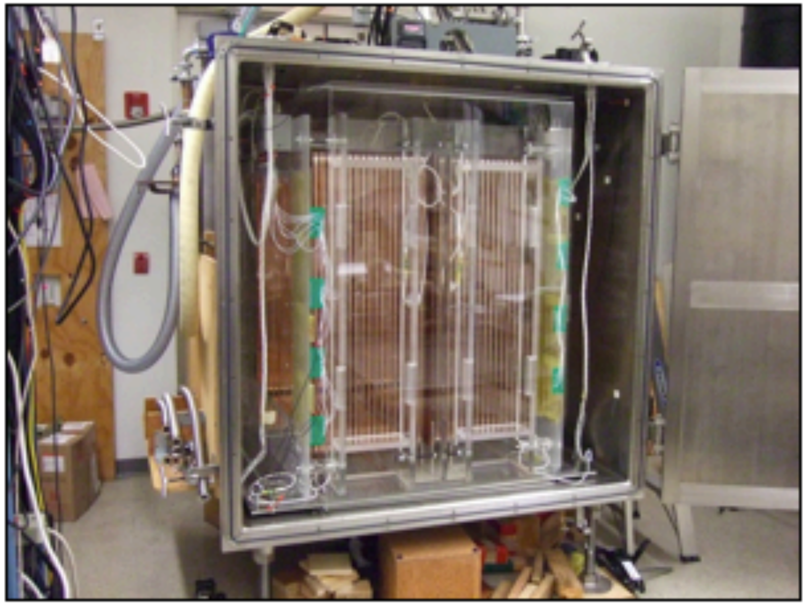
DRIFT-IIe

Study directionality, lower background, robustness

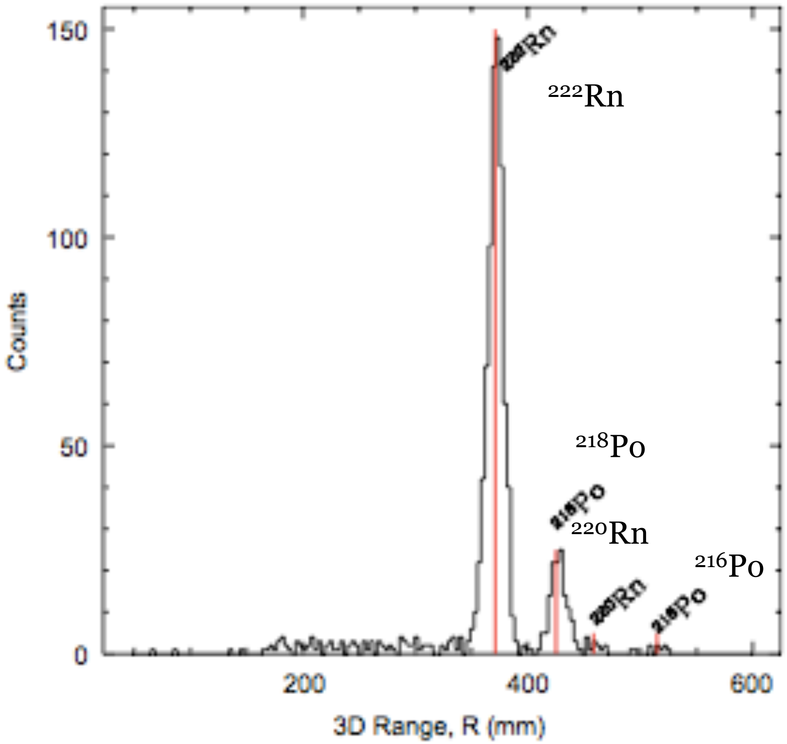








Aside: A powerful tool for Rn Assay

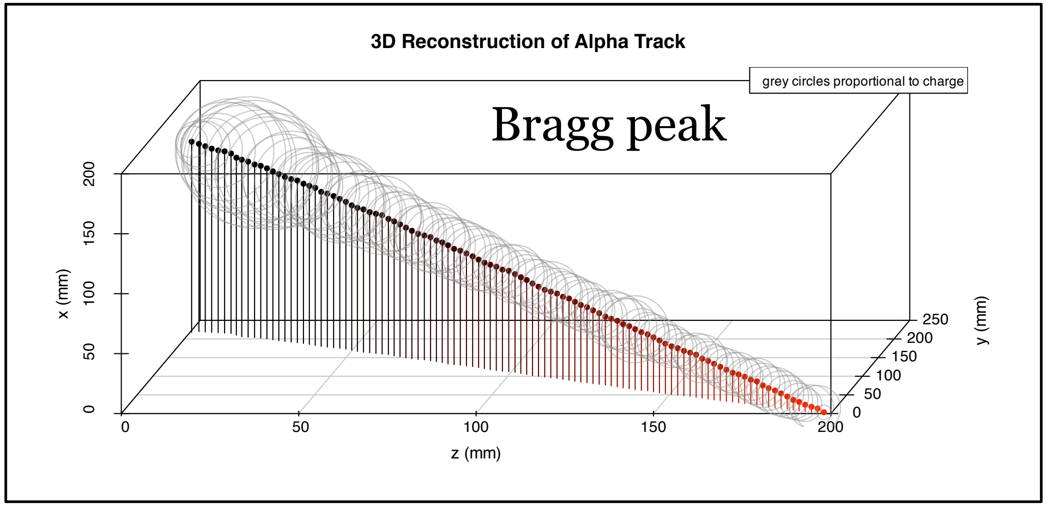


DRIFT is very good at identifying classes of alpha particle and nuclear recoils.

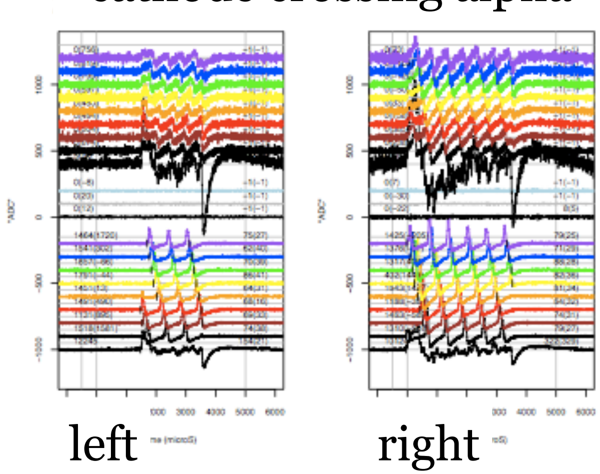
An excellent tool for assay of materials:

Sensitivity to surface alphas on contaminated material (e.g. ^{210}Pb):
0.1-0.01 mBq/m²

Sensitivity to ^{222}Rn emanation:
1-2 μBq/m²



cathode crossing alpha



SOLID?

Between detectors without directionality and gas TPCs with directional sensitivity, a difference of at least three orders of magnitude in active mass exists; how can this gap be confronted?

Can we find a directional technology with higher density?

It would be nice! But a long history of looking has not so far produced much

Stilbene
Rotons in Lq He
Phonon focussing
Multilayers....

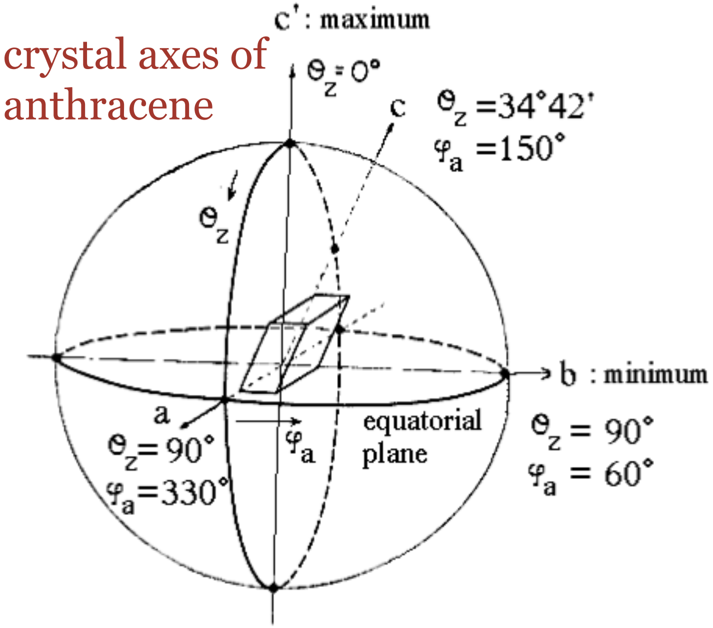
It is hard...but recent work is progressing...

Anisotropic Scintillators
Nuclear Emulsions
High pressure Xe, LAr
DNA strands
Carbon nanotubes

Anisotropic Scintillators

Concept (1): Anisotropic organic scintillator, anthracene or stilbene where light response p, α, recoil nuclei, ⋯ depends on direction with respect to the crystal axes:

crystal axes of anthracene



- Groups in UK, Italy and Japan

  Y. Shimizu et al., Nucl. Instr. and Meth. A 496, 347 (2003)

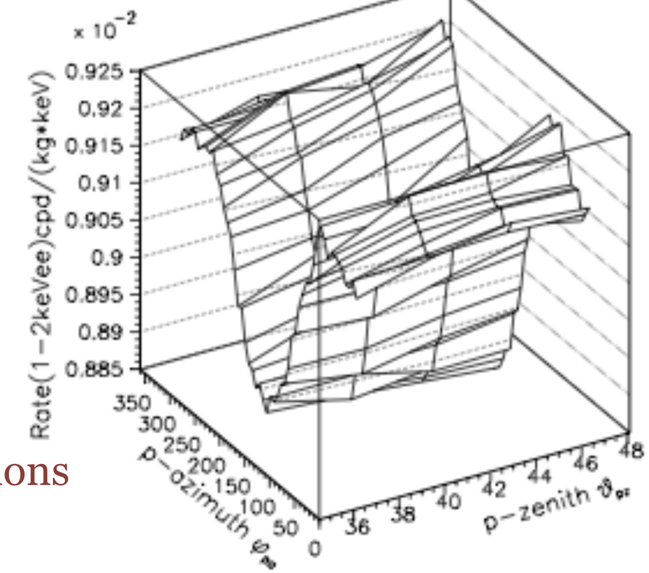
  N.J.C. Spooner et al., IDM (World Scientific 1997), p. 481

  R. Bernabei et al. Eur. Phys. J. C 28, 203–209 (2003)

- Effect arises from preferred directions of the exciton propagation in the crystal lattice
- e.g. in Anthracene 6.56 MeV alpha impinging along b-axis (a-axis) gives 66% (80%) of the light for direction along the c′-axis

Effectively the quench factor has an angular dependence:

$$q_n(\Omega_{\mathrm{out}}) = q_{n,x}\sin\gamma\cos\phi + q_{n,y}\sin\gamma\sin\phi + q_{n,z}\cos\gamma,$$

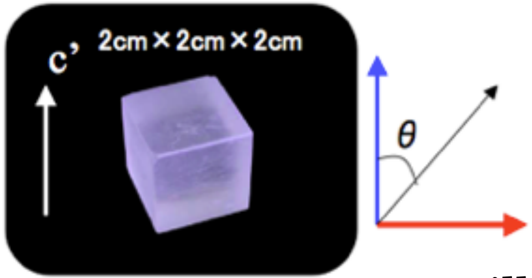


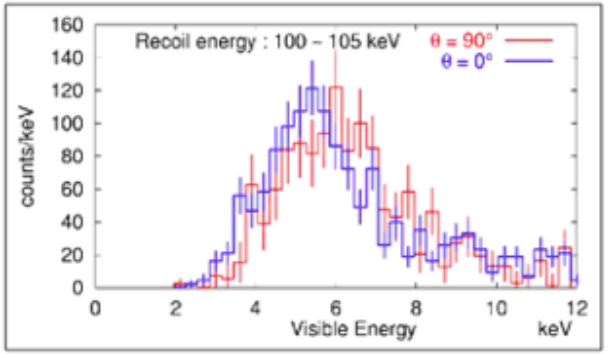
Expected rate at 1–2 keV vs. detector possible velocity directions for 50 GeV WIMP at WIMP–proton cross section $3 \cdot 10^{-6}$ pb

Anisotropic Scintillators

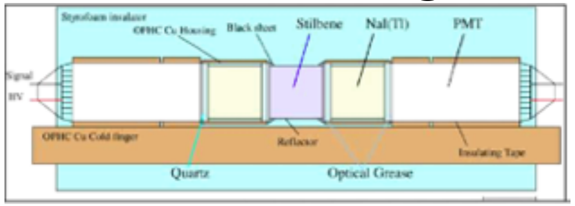
Example work (2003): **Hiroyuki Sekiya (Kyoto University) M.Minowa, Y.Shimizu, Y.Inoue, W.Suganuma (University of Tokyo)**

Respons to ~100 keV carbon recoils:





116g stilbene crystal + 2 R8778 PMTs

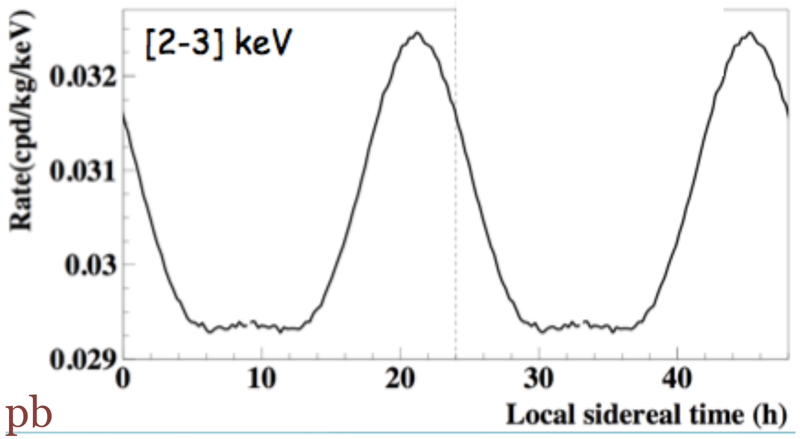


Challenges for directional organics:

- Only carbon is the target (SI)
- Anisotropy is likely <20%
- Low quench factors
- No head-tail
- High backgrounds?
- Small crystals

Alternative example (2013) - $ZnWO_4$: F. Cappella et al., Eur. Phys. J. C 73 (2013) 2276

Both the light output and the pulse shape of ZnWO4 detectors depend on the direction of the impinging particles with respect to the crystal axes - this can provide two independent ways to exploit the directionality approach

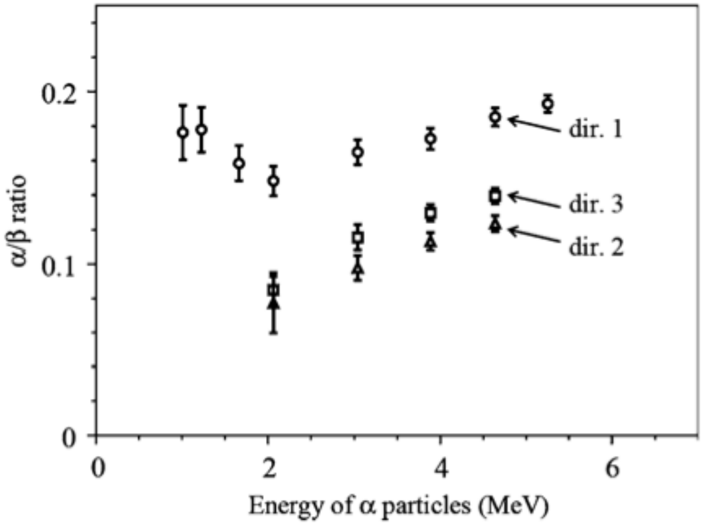


Expected for 10 GeV WIMP–p cross section $3 \cdot 10^{-5}$ pb

ADAMO

Concept: $ZnWO_4$

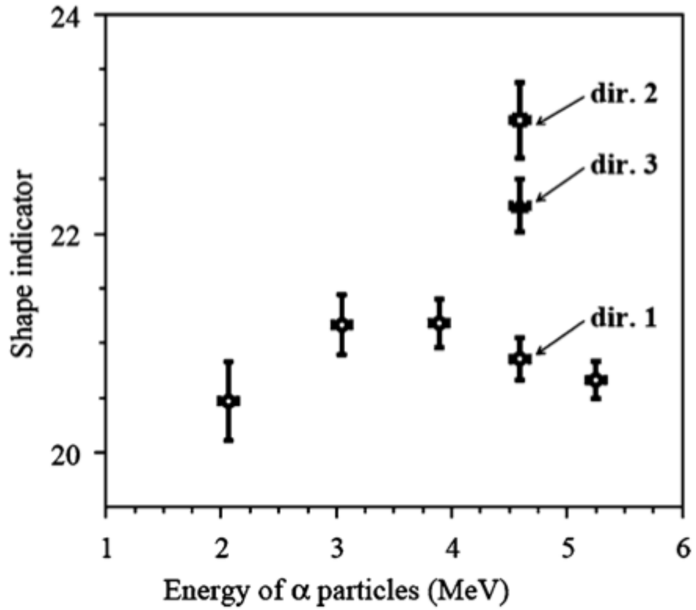
DAMA group - F. Cappella et al., Eur. Phys. J. C 73 (2013) 2276



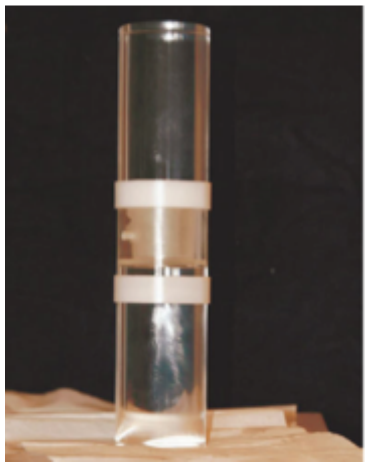
Dependence of α/β ratio on energy of α particles in ZnWO4 - directions perpendicular to (010), (001) and (100) crystal planes (directions 1, 2 and 3, respectively).

Ion	Quenching factor		
	dir. 1	dir. 2	dir. 3
O	0.235	0.159	0.176
Zn	0.084	0.054	0.060
W	0.058	0.037	0.041

QF for O, Zn and W ions with energy 5 keV for different directions in ZnWO4.



Dependence of pulse shape on energy and direction of α particles relatively to (010), (001) and (100) crystal planes.



Prototype now under study

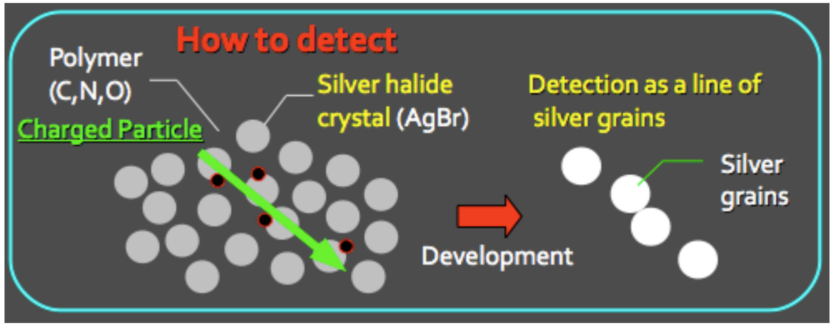
Issues for $ZnWO_4$:

- Check low energy response
- Backgrounds
- No head-tail

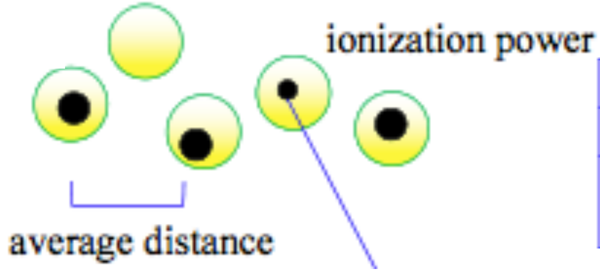
Nuclear Emulsion

Nagoya University, OPERA…

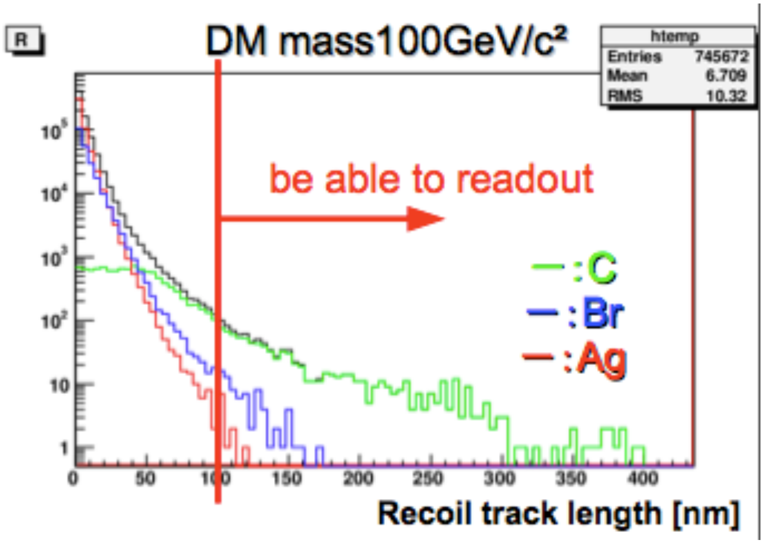
Concept (1): Use of emulsion film to give 3D tracking - solid detector (3g/cc), high spatial resolution, low cost, target Ag(46%), Br(34%), C(N,O) (19%)



- Track produces line of silver grains

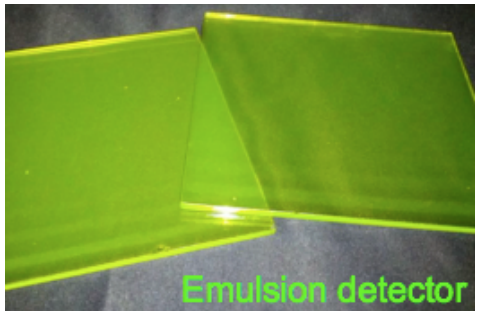


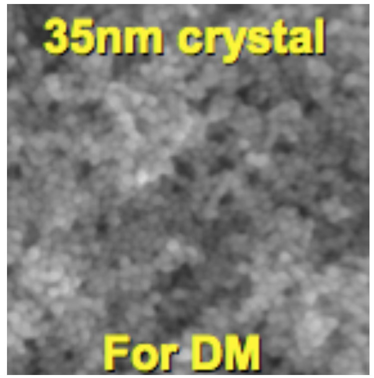
crystal size	45nm
crystal distance	85nm
crystal sensitivity for alpha-ray	>20% (not sensitized)



- Challenge is to get: (i) small grains <40nm (OPERA had 200 nm), (ii) closely packed, and (iii) sensitive to low ionisation

- Typical recoils are order 100nm - Ag, Br likely produce tracks too short so need to use C, N, O target





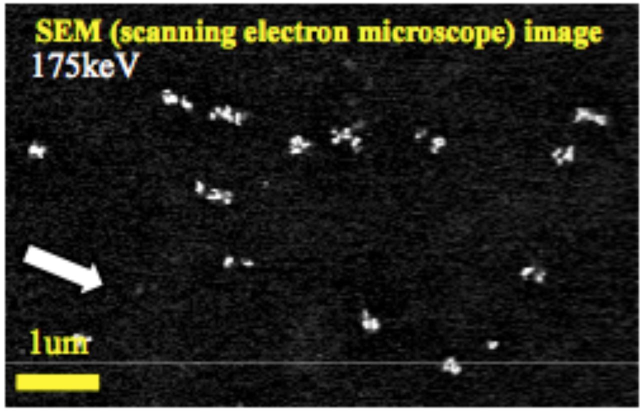
- Progress made to produce stable very fine crystals by using the PVA techniques

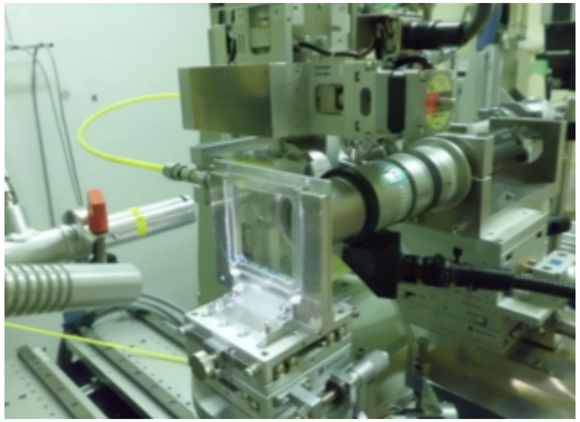
Nuclear Emulsion

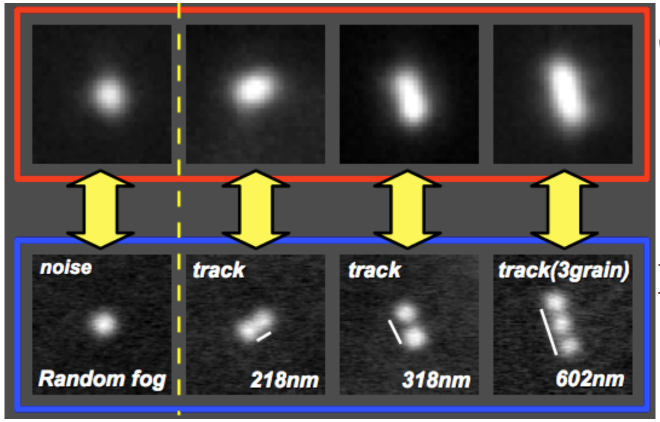
- Progress with carbon recoil tests

  track detection efficiency 175 keV (520nm expected): 80% 80 keV (250nm expected) : 50% crystal separation is shorter than carbon tracks

- Scanning process being developed combining optical and x-ray techniques







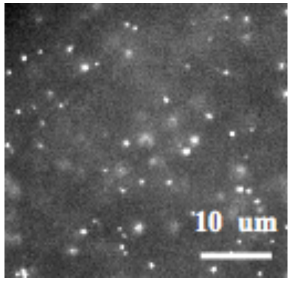
optical

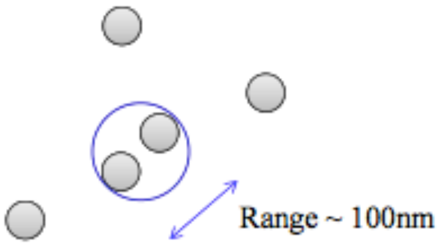
X-ray

Challenges for directional organics:

- What range threshold can be achieved (100nm)?
- Efficiency of grain production by recoils
- No head-tail?
- Not real time - target rotation?
- Can background grains be reduced?

e.g. unexpected silver grains are generated at random, if too close, they become noise tracks

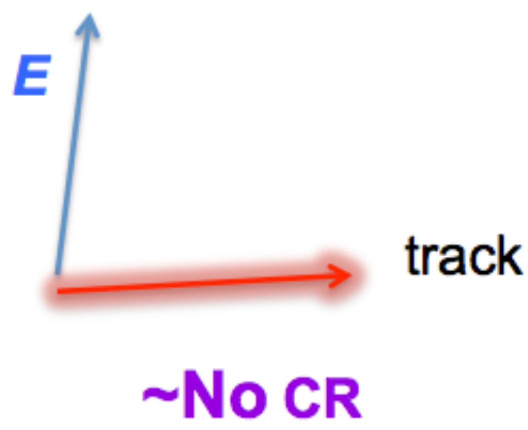




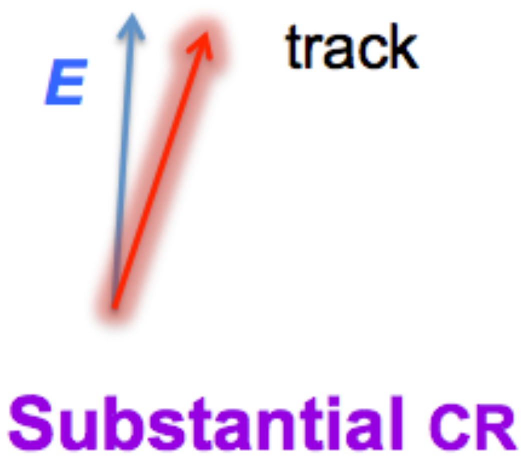
High-Pressure Xenon

D. Nygren et al.

Concept: Idea to use *columnar recombination* (CR) based on atomic/molecular processes in xenon-TMA. CR may be sensitive to the angle between nuclear recoil direction and drift field E in a gaseous TPC.



A large angle between track and field leads electrons transversely away from the ion column. Recombination signal is small relative to the ionisation signal.

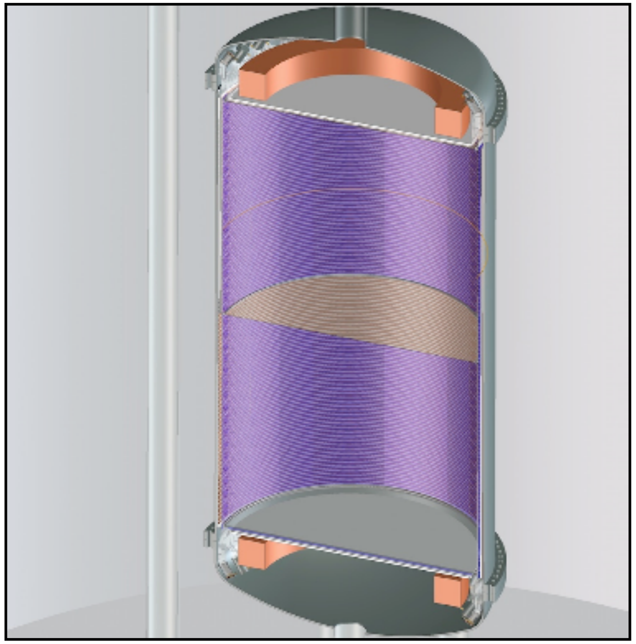


A small angle implies a higher level of recombination as the electrons drift more or less parallel to the ions, encountering many; a recombination signal is relatively large in comparison to the surviving ionization signal.

High-Pressure Xenon

Conceptual design: scheme in which all information is collected in the form of optical signals using high-pressure xenon gas electroluminescent (EL) TPC

Journal of Physics: Conference Series **460** (2013) 012006



- 10 bars Xe gas TPC with penning additive
- Two drift regions of 2.5m
- WLS 4π for light collection

Directionality is via the ratio of recombination signal "**R**" (UV scintillation) to the surviving ionisation signal "**I**". The challenge is to maximise the detection efficiency of the **R** signal in a detector of interesting scale.

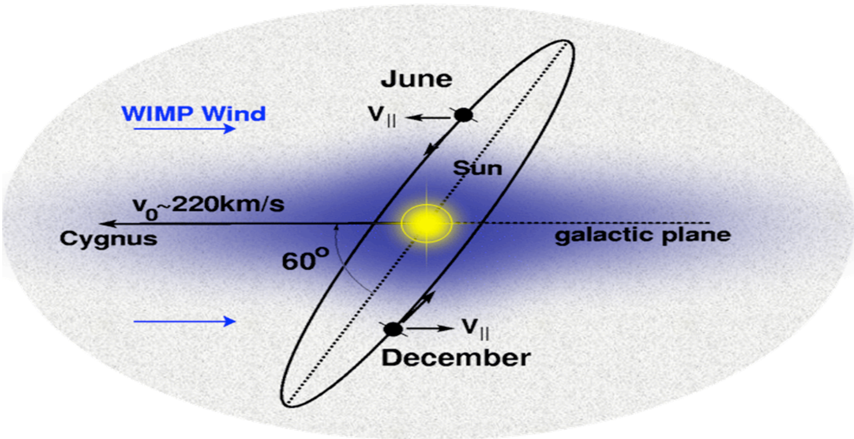
Although unknown at present, a head-tail effect may appear as a difference in **R/I** between the upper and lower halves of the TPC.

Challenges for HPXe:

- No demonstration yet
- The density for optimal Onsager radius may not be matched for directionality
- Optical detection efficiency - does TMA additive work sufficiently, what fraction?
- What electric field is required at given xenon density - is it reasonable?
- No head-tail sensitivity?
- Simulation so far do not show CR exists at the recoil energy

Conclusions

There is a simple, strong, SIGNATURE for WIMP dark matter - that nuclear recoils produced move opposite to our motion in galactic coordinates towards Cygnus. No terrestrial background can mimic this signal.



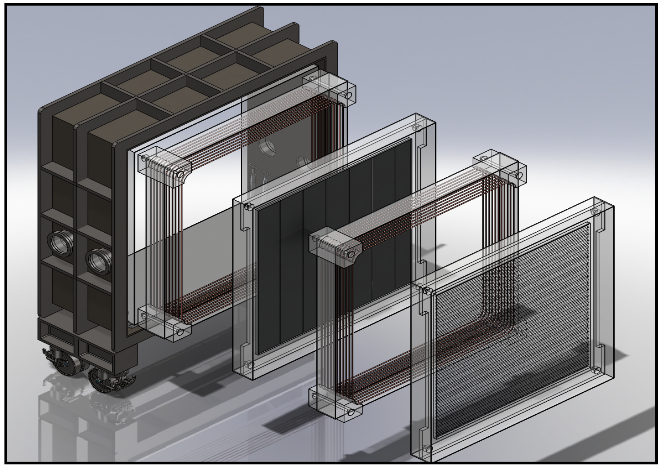
advert:

Workshop on Directional Detection of WIMPs

Backup

DRIFT III Scale-up

- Two modules composed of 8 m^3 footprint ~6 m by 3 m.
- Modular design to allow approach to ton-scale
- 4 kg target - 24 m^3
- 250 of 4 kg modules gives 1 ton would fit into a standard DUSEL module or 500m tunnel at Boulby



- Preference for CH-based material