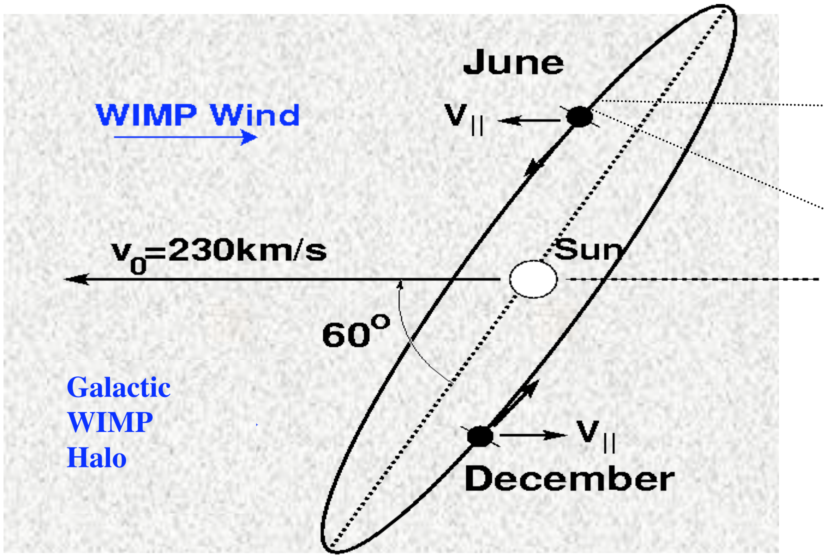
A Review of the Directional Signature for Dark Matter Searches

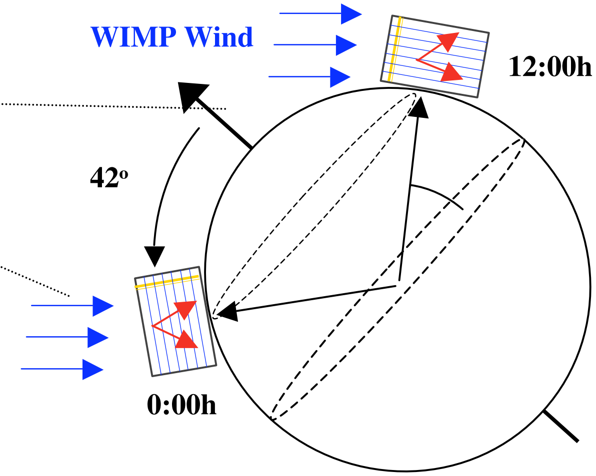
Dinesh Loomba

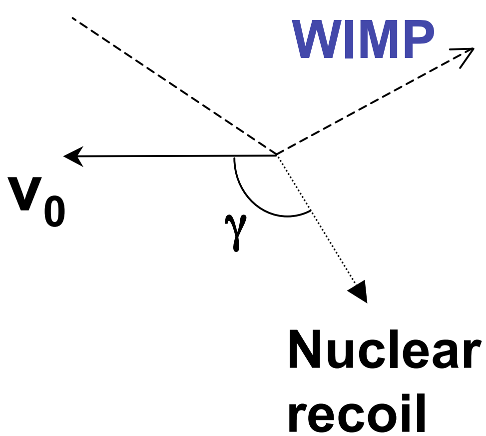
TeVPA/IDM, Amsterdam

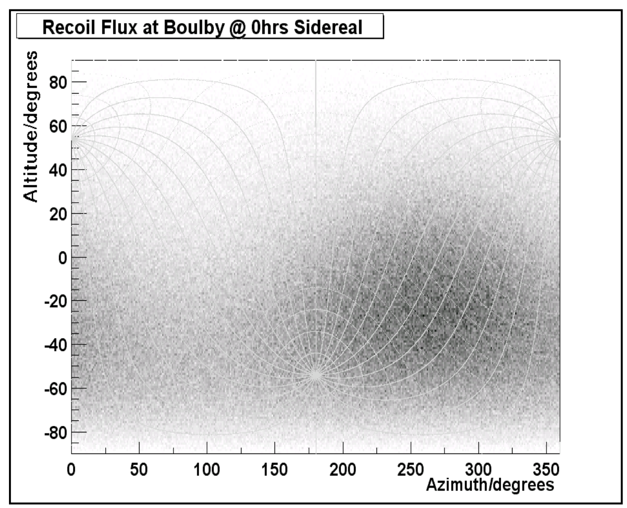
June 22 2014

The WIMP directionality signature









Theoretical Studies

Motion of the Earth and the detection of weakly interacting massive particles

David N. Spergel*
Institute for Advanced Study, Princeton, New Jersey 08540
(Received 21 September 1987)

If the galactic halo is composed of weakly interacting massive particles (WIMP's), then cryogenic experiments may be capable of detecting the recoil of nuclei struck by the WIMP's. Earth's motion relative to the galactic halo produces a seasonal modulation in the expected event rate. The direction of nuclear recoil has a strong angular dependence that also can be used to confirm the detection of WIMP's. I calculate the angular dependence and the amplitude of the seasonal modulation for an isothermal halo model.

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

- Sidereal modulation is about an order of magnitude larger than annual modulation

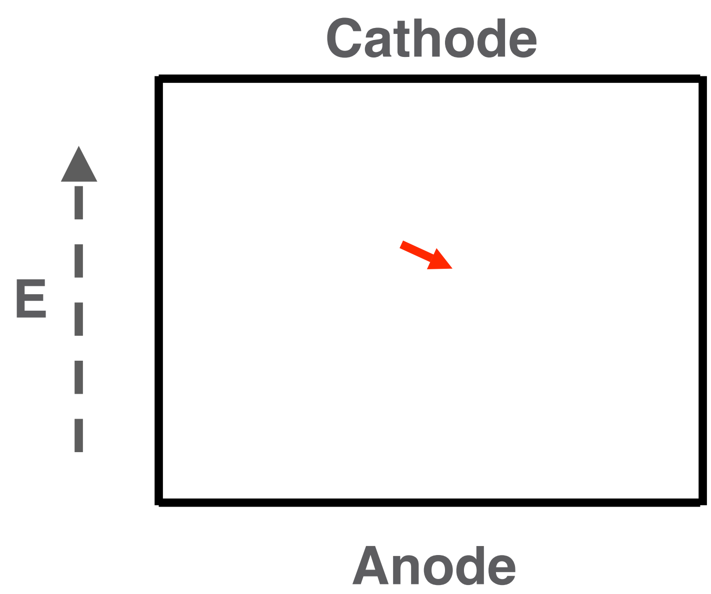
- Huge body of literature on directionality (non-standard halo models, real detector responses, various statistical tests, presence of backgrounds, etc, etc)

The result of this work is that of order 10's - 100's of events are needed to confirm a DM signal

(Lewin, Smith, Krauss, Copi, Green, Morgan, Gondolo, Billard, and many others)

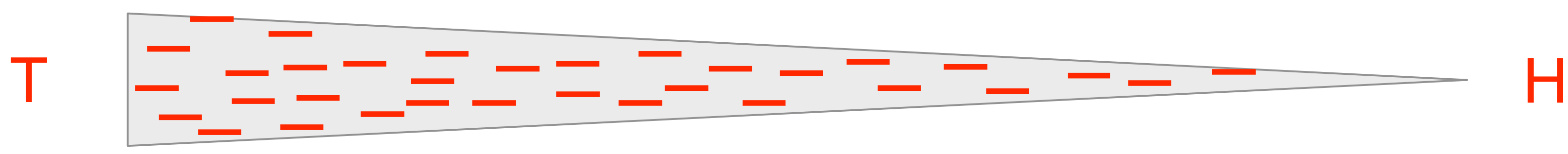
The Experimental Challenges to Measuring Recoil Tracks

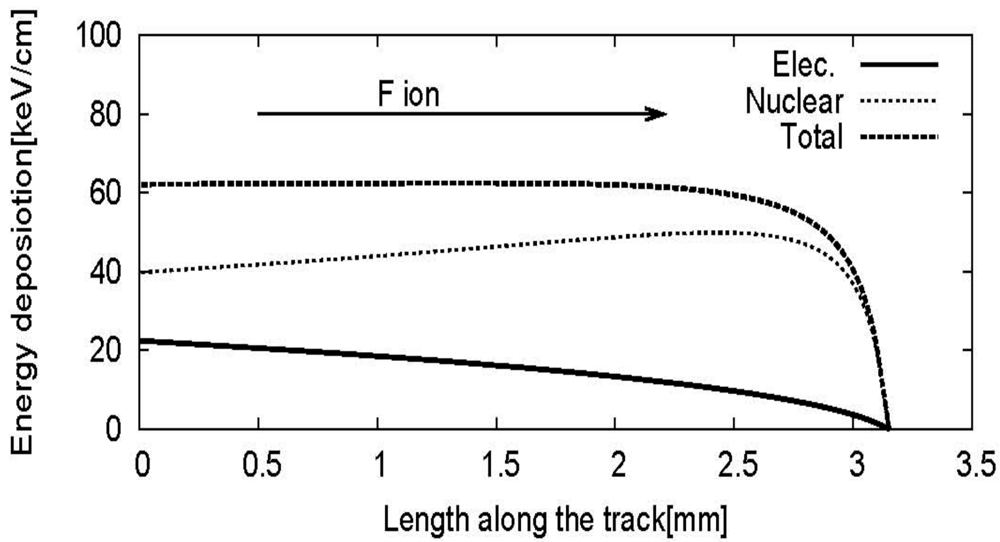
Most experiments use low pressure gas-based TPCs:



The challenge:
detecting ~mm tracks
in cubic meter volumes

Zoom in on the recoil:



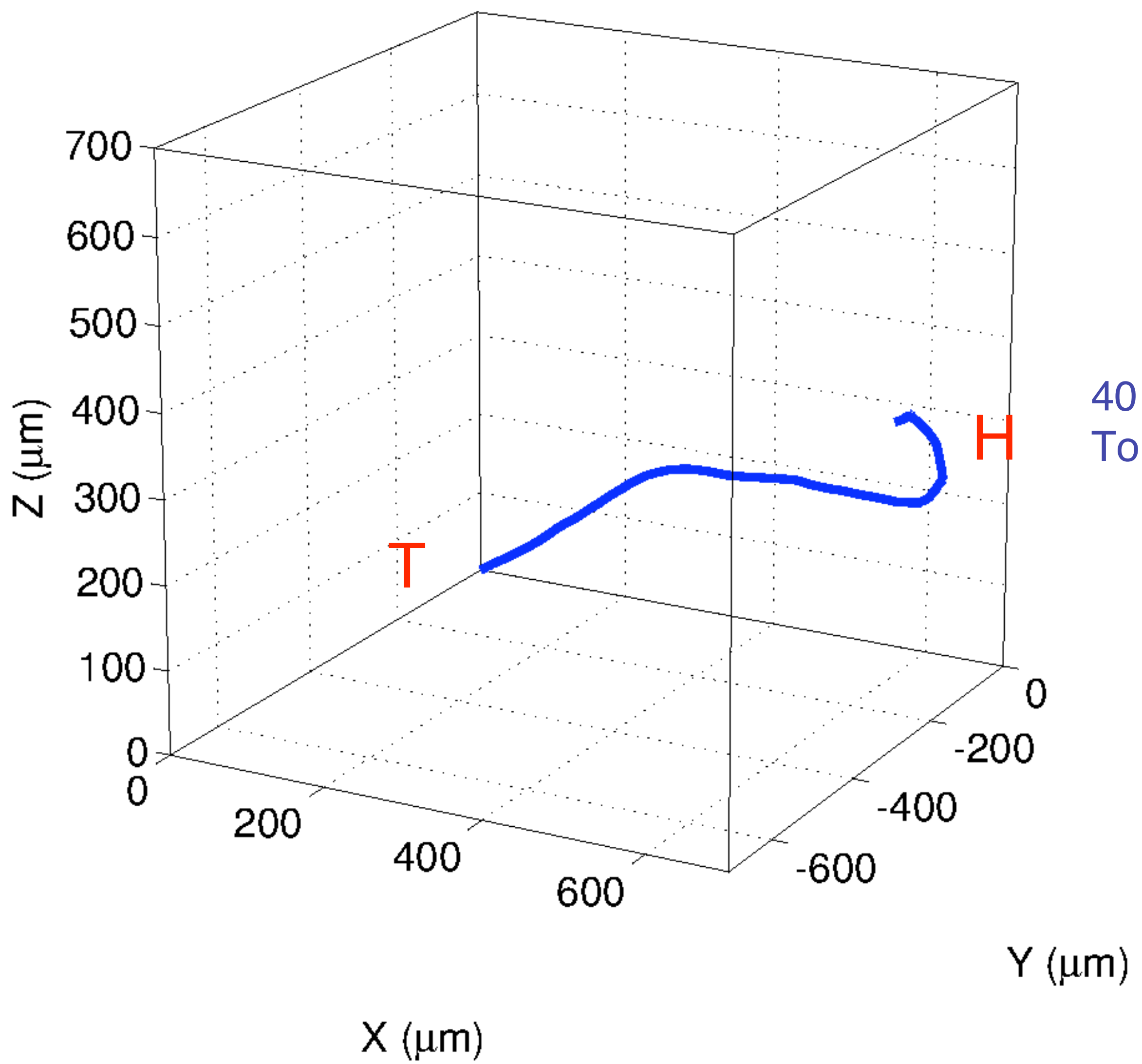


Importance:

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

A real recoil has straggling:

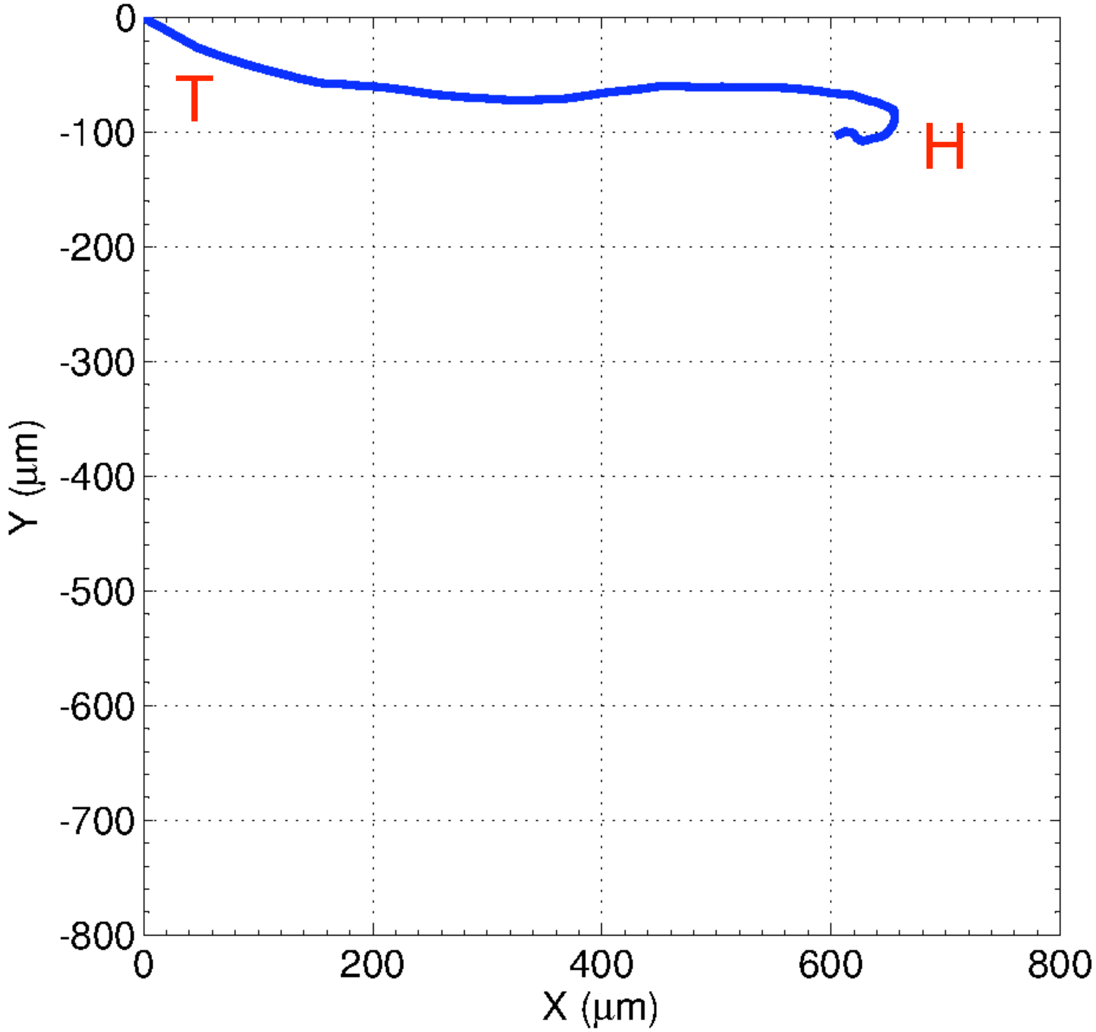


40 keV F in 100 Torr CF_4

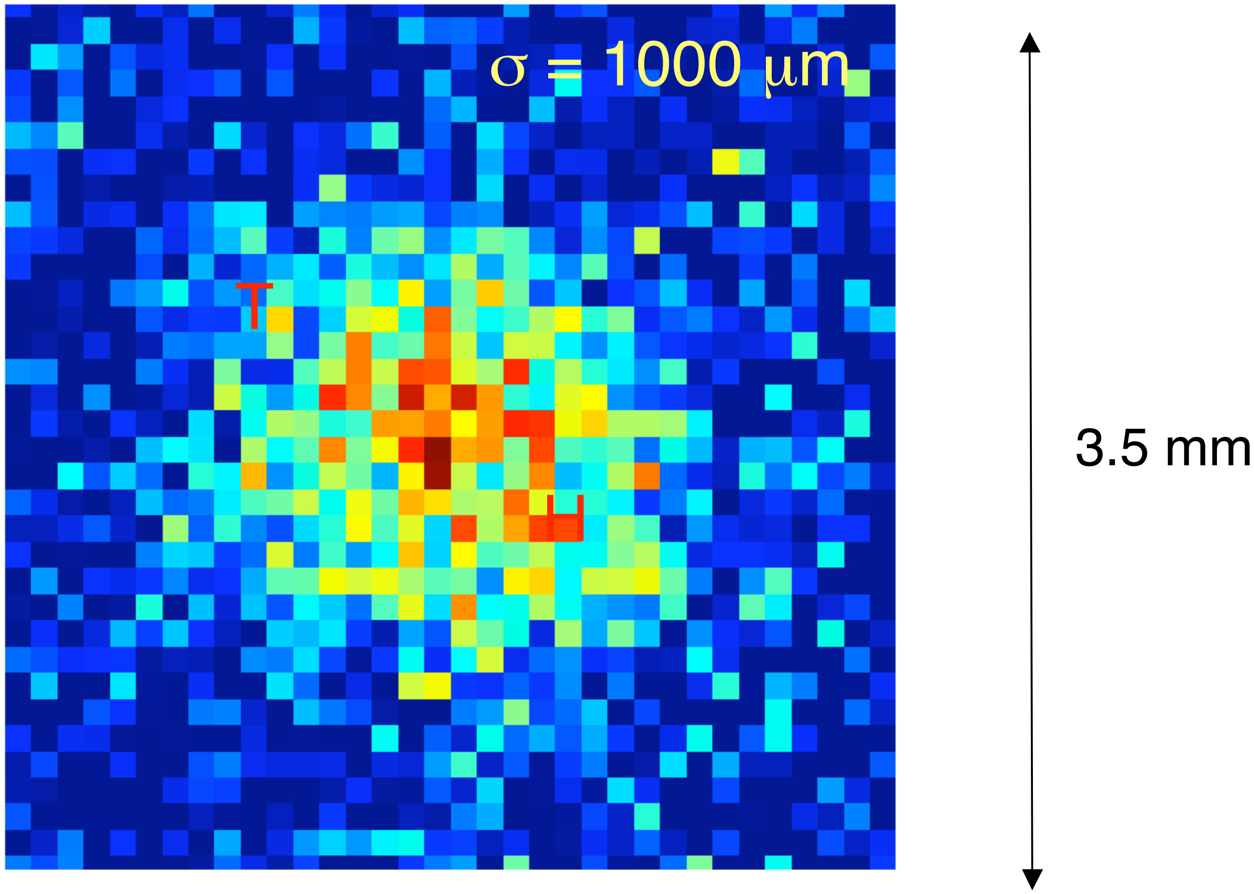
Dinesh Loomb

SRIM

Projection (2D or 3D):



Diffusion: you need to keep it low!!



100 μm pixel readout

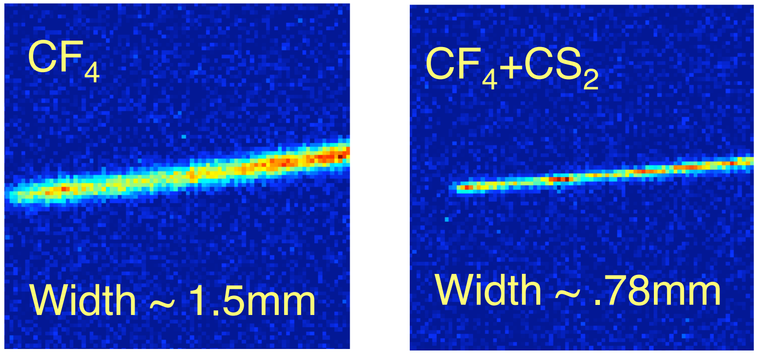
Flexible technology

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

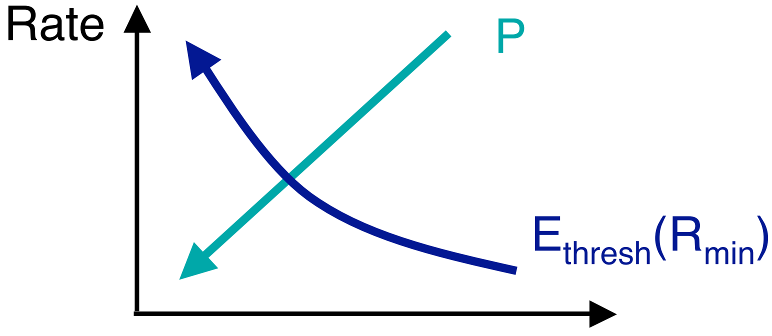
• Negative ion drift: target $+CS_2$ mixtures enable drift with thermal diffusion (Martoff).

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:

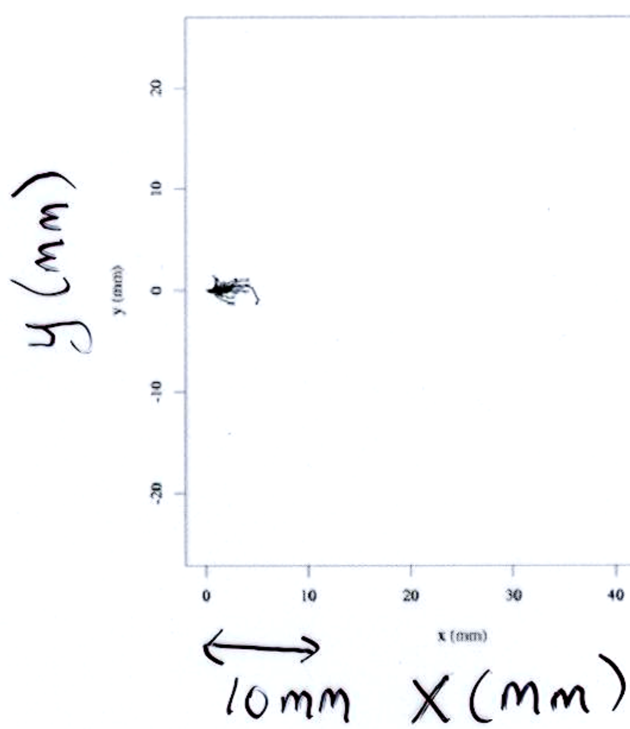


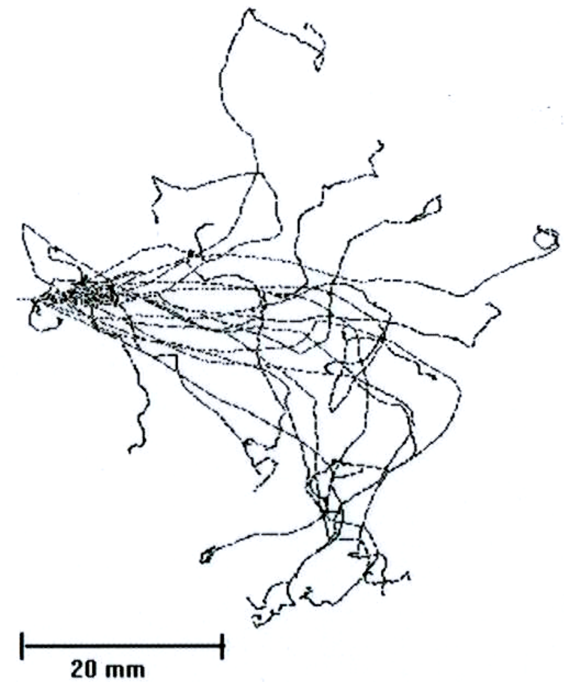
Background discrimination

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

40 KeV Ar recoils

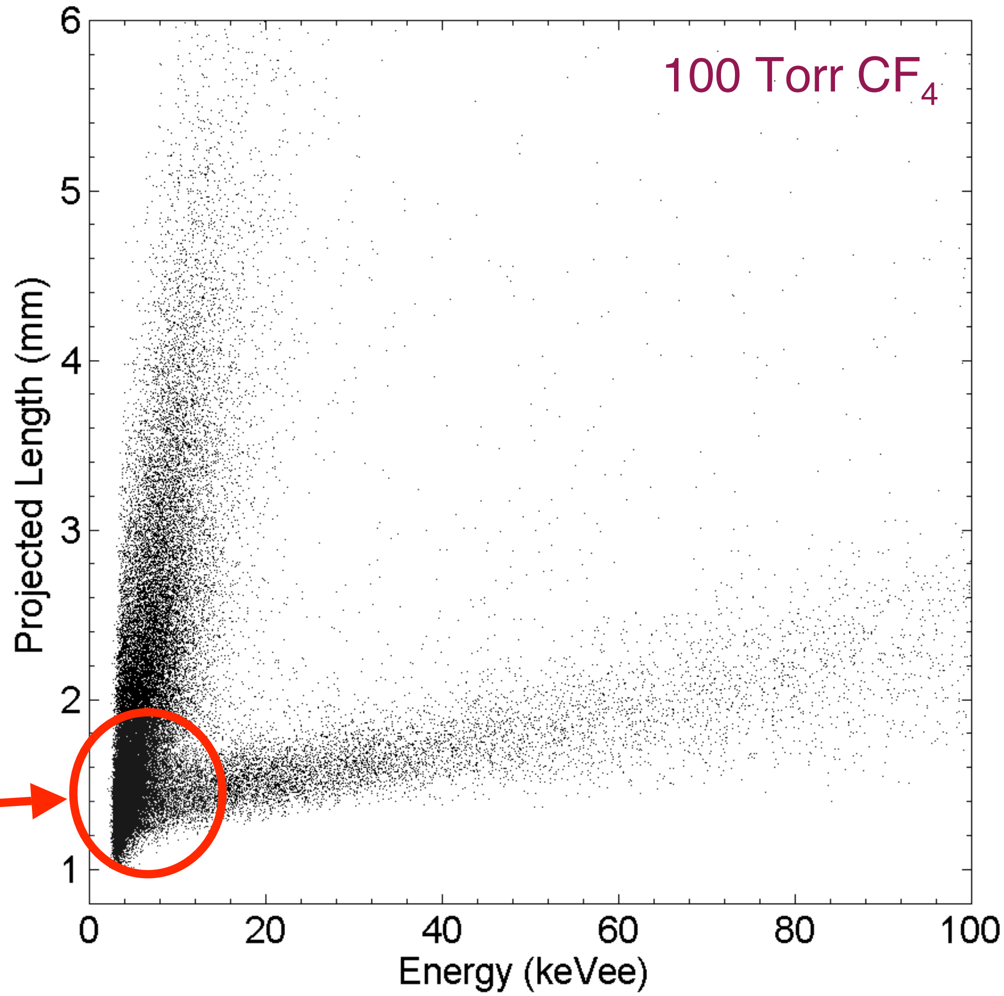
13 KeV electrons





Simulations from SRIM97, EGS4/Presta

Range vs Energy

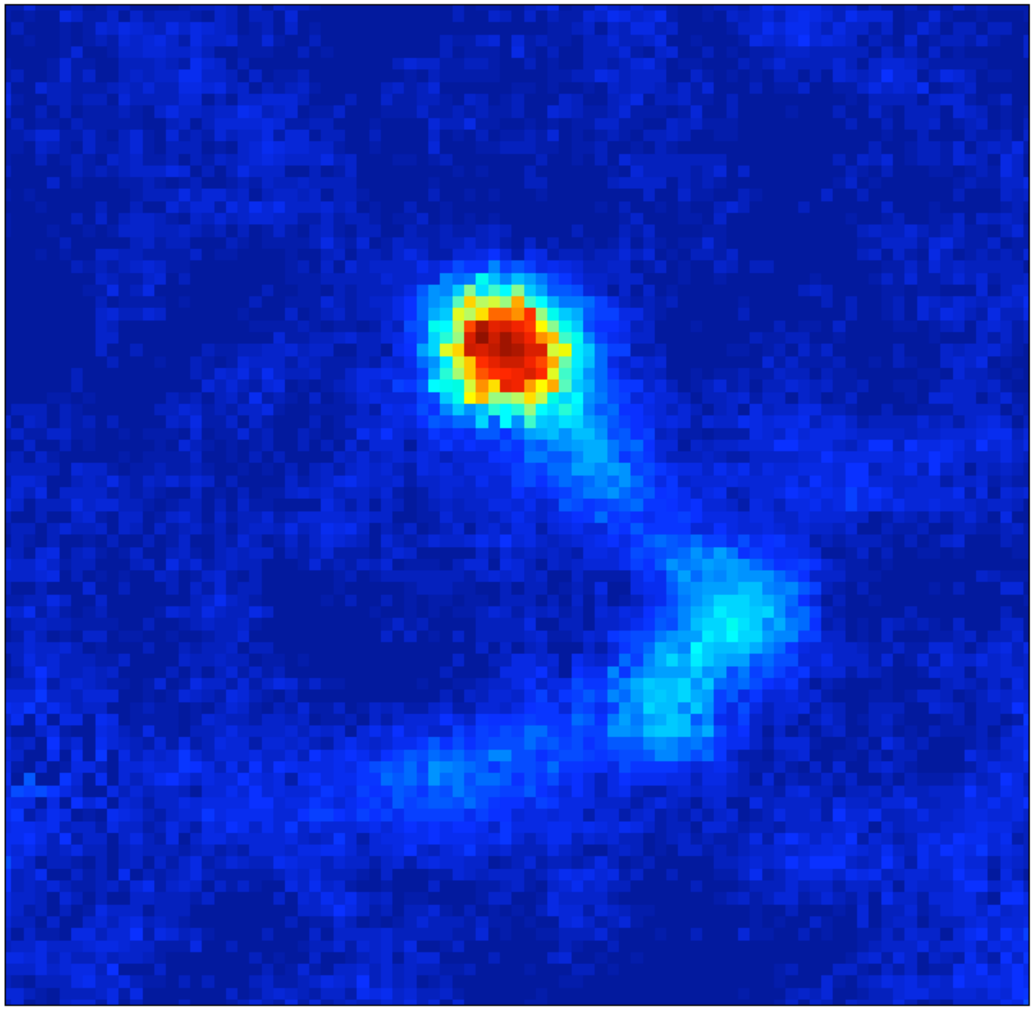


Low dE/dx:
γ's

High dE/dx:
nuc. recoils

Can we do better?

Gamma backgrounds have small dE/dx, large fluctuations:
high signal-to-noise is important



And 3D
should help

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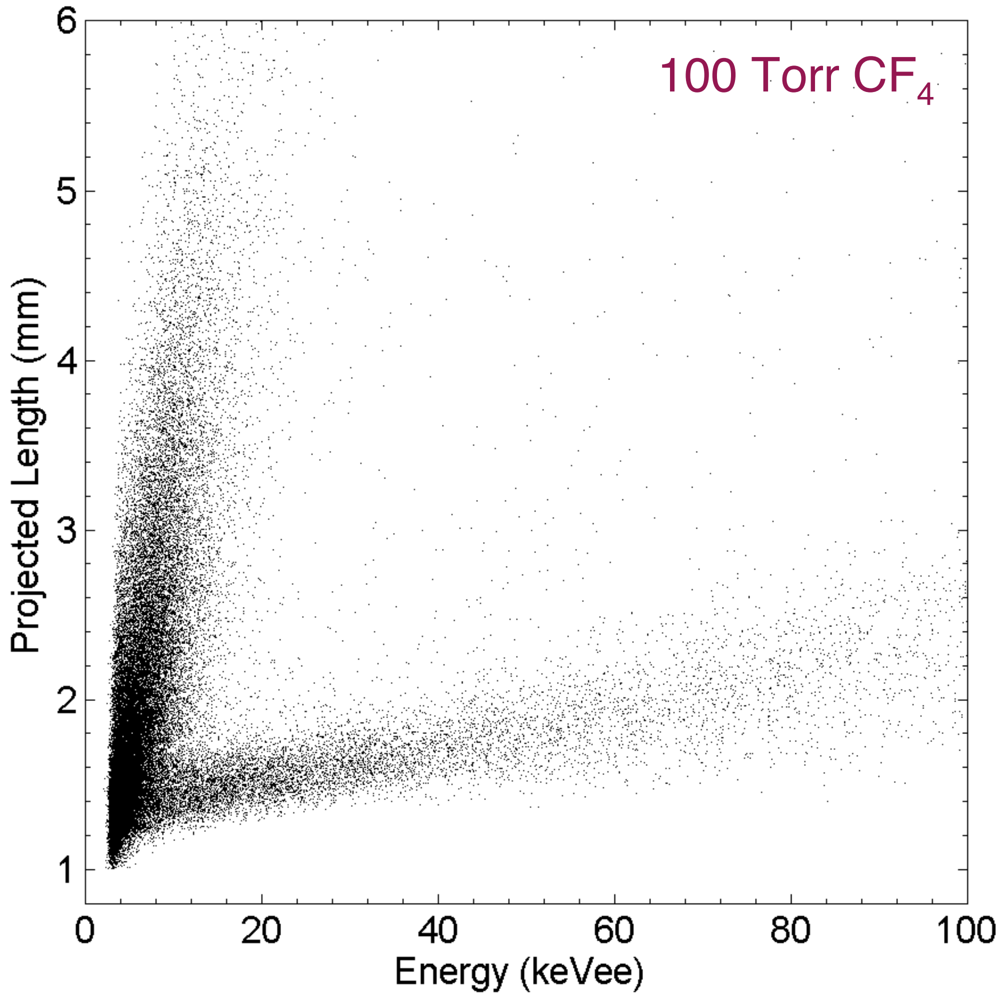
An example: discrimination and directionality from an optimized detector

- 100 Torr CF_4
- High resolution 2D readout with ~160 μm pixels
- High signal-to-noise, gas gains ~100,000
- Low diffusion, σ~0.4mm

Range vs Energy from Cf-252

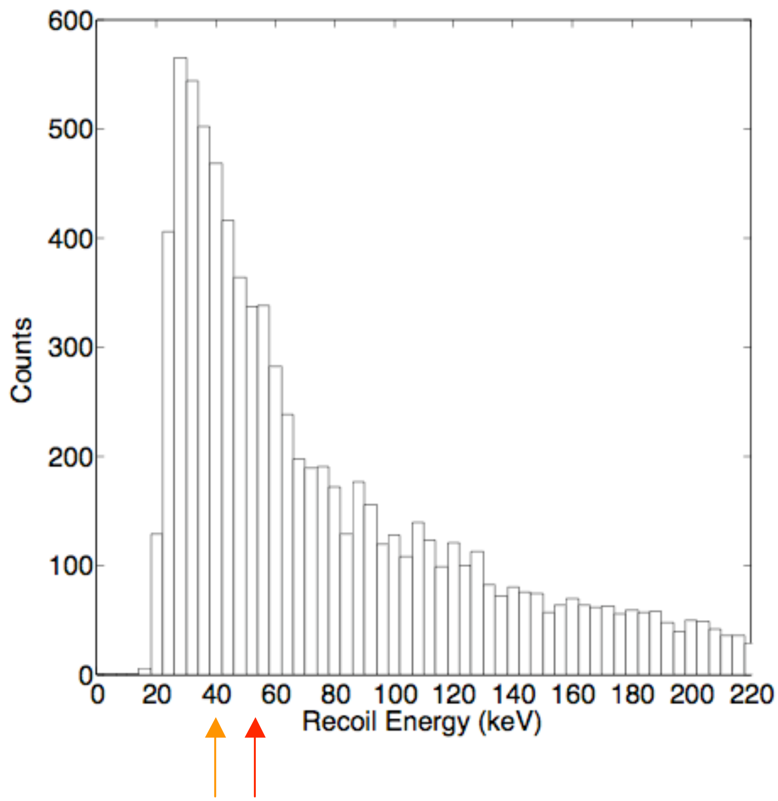
Low dE/dx:
γ's



High dE/dx:
nuc. recoils

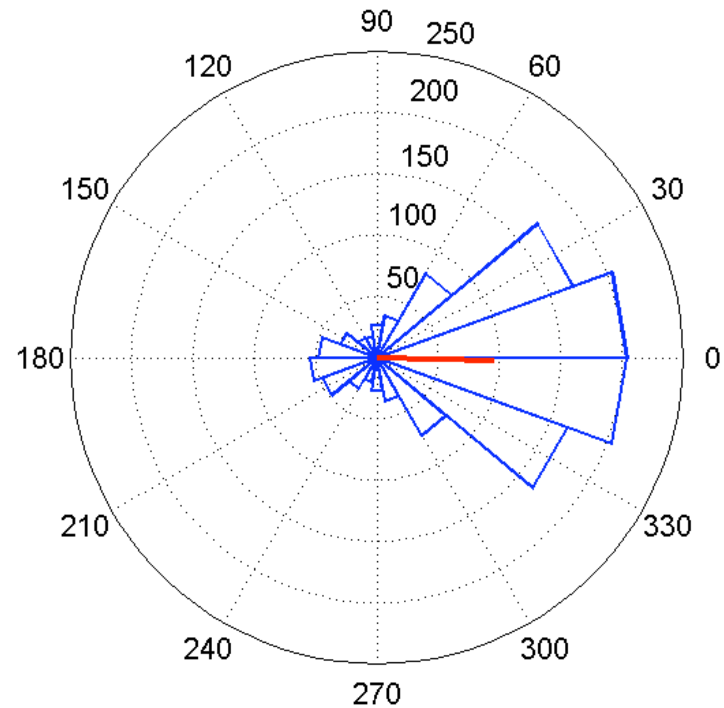
Results from Cf-252 exposure:

Nuclear recoil energy spectrum

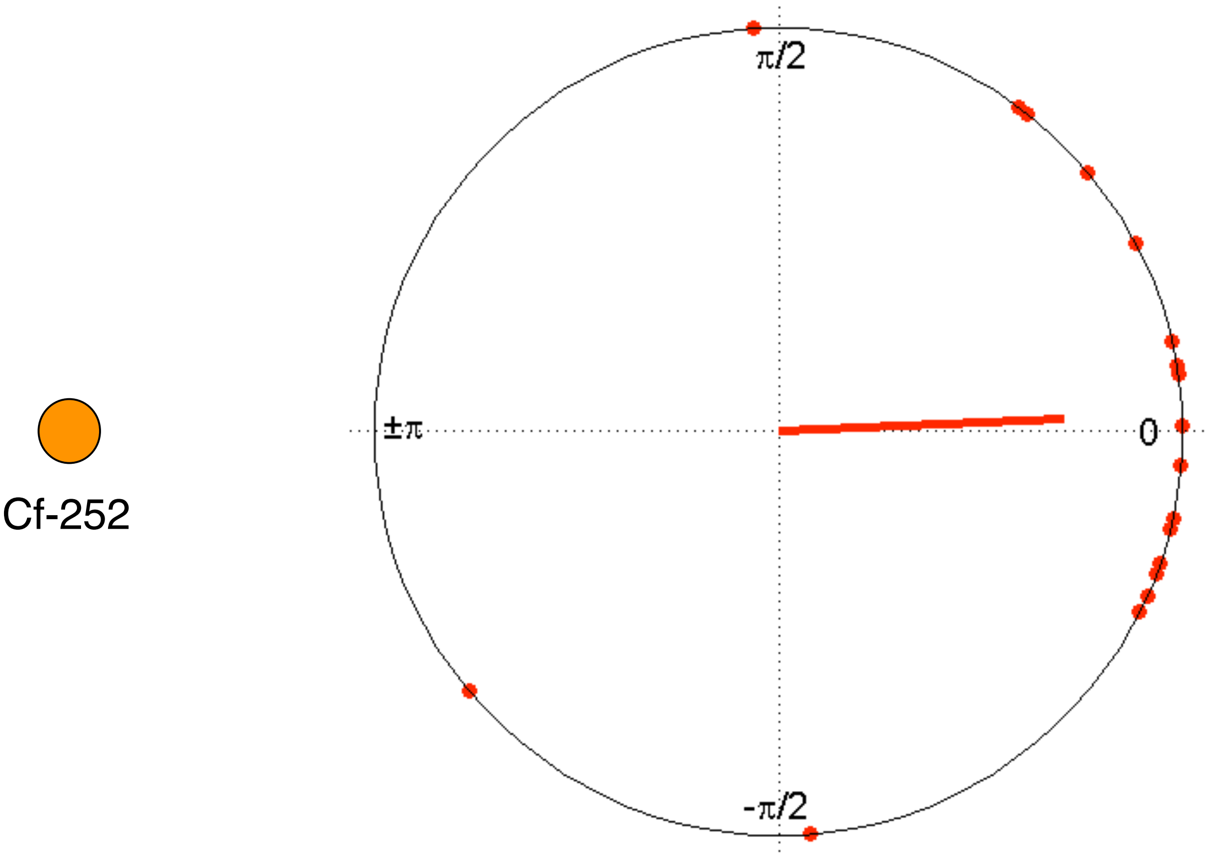


Directionality threshold: axial, vector

2D circular histogram of vector recoil directions, after cuts



~18 events needed to point back to the source…



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

Comments:

- **40** events needed, from which ~18 with high track quality are selected
- These ~18 sit in the high energy tail of the spectrum
- About 1/4 - 1/3 of the recoils in the dataset are produced by scattered neutrons. So, these results are conservative

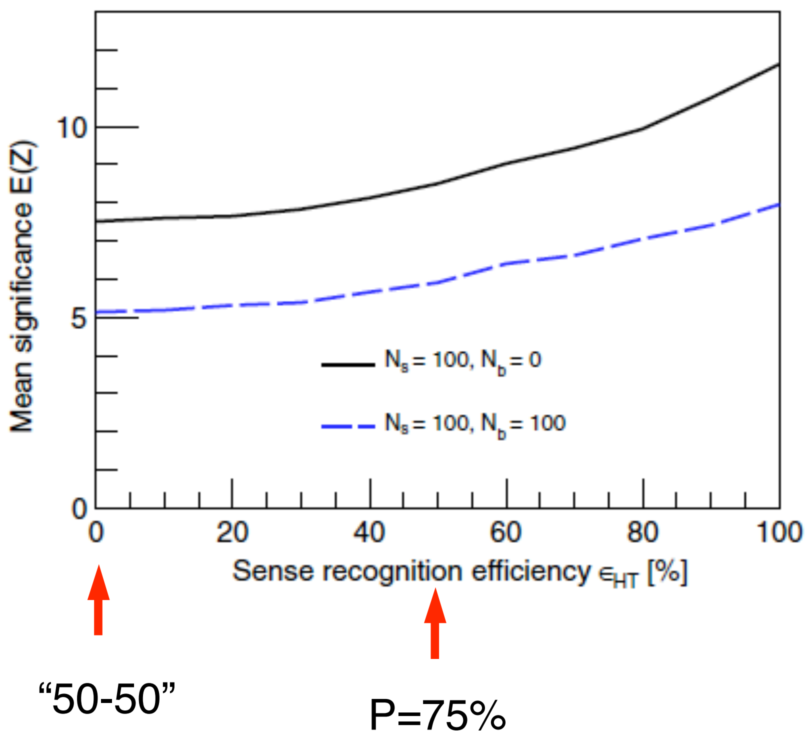
Using Cf-252 results to simulate directionality for 100 GeV WIMP ~**54** events needed to locate source (90% CL)

Pretty good…BUT why ~50 events and not ~10, as expected from **vector** directionality??

Quality of head-tail:

Green, Morgan (PRD 77, 2008), and Billard et al (PRD 85, 2012) point out importance of a high probability of getting head-tail correct:

"The linearly increasing sense determination probability with $P(E_{th}) = 0.75$ (0.50) … requires ~3 times (10 times) more events than the constant P = 1."



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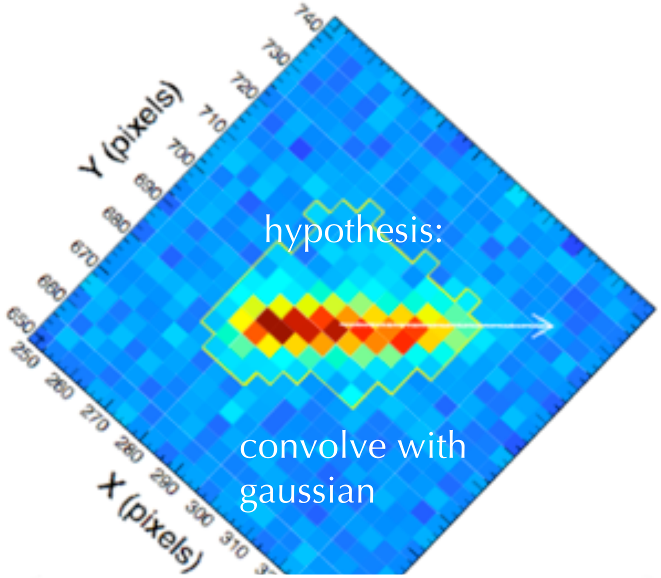
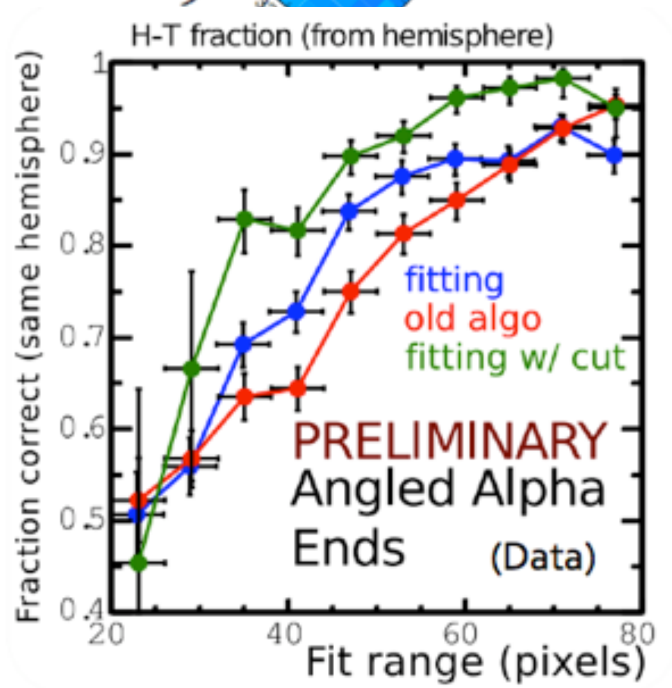




Energy range equivalent ~50-200 keV

Comments:

• 3D should help and nature provides a population of less straggled events.

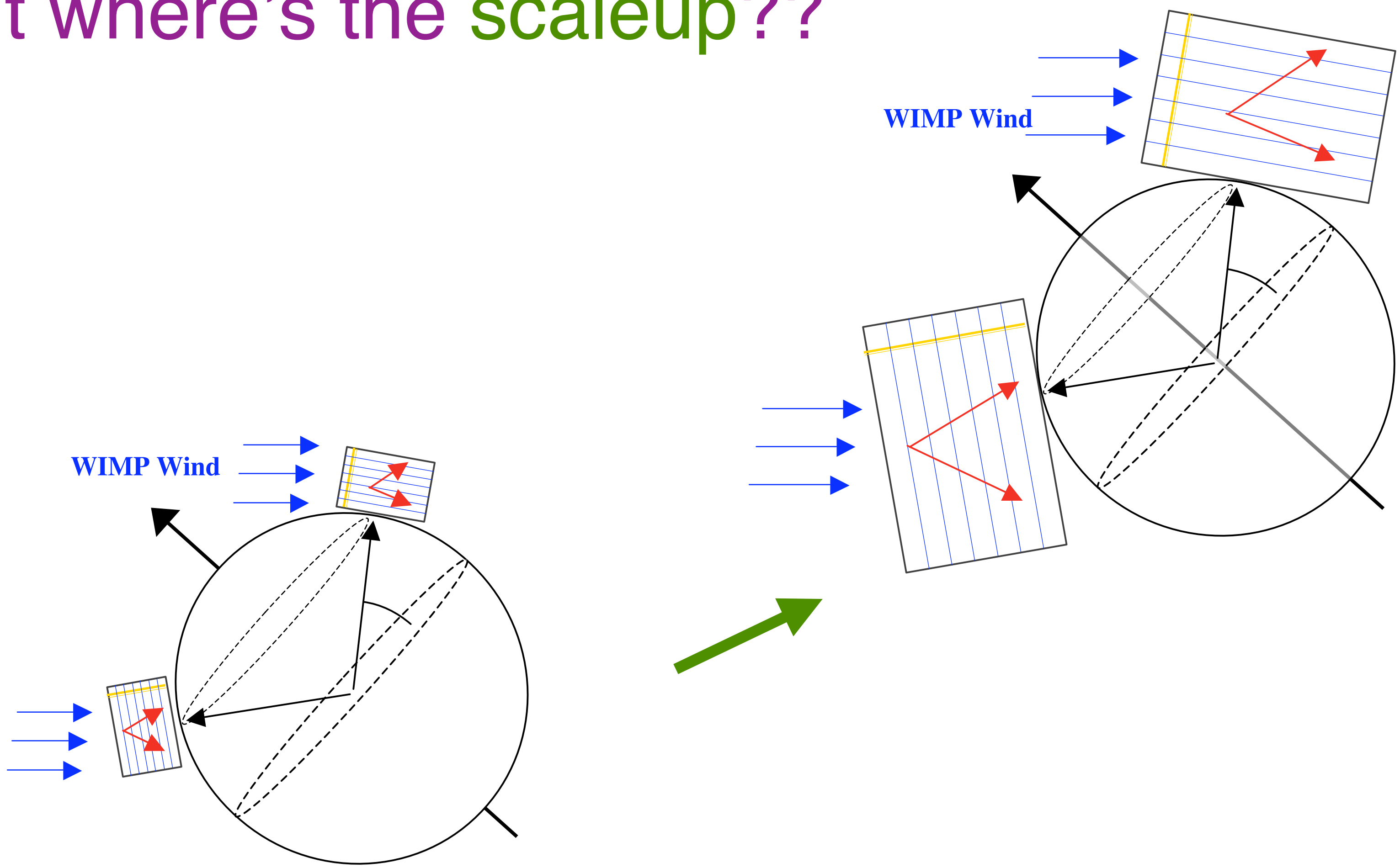
• Maybe its better to pick a higher directionality threshold, e.g., one where P>0.7? If minimizing the directional exposure is the goal, this data says: NO, its better to pick the lowest possible threshold where there's directionality. Consistent with Green, Billard.

• Gas-based TPCs have a unique knob, P, plus the ability to vary target A. So one can lower the directionality threshold, e,g, for a low mass WIMP search. (See Nguyen Phan's talk).

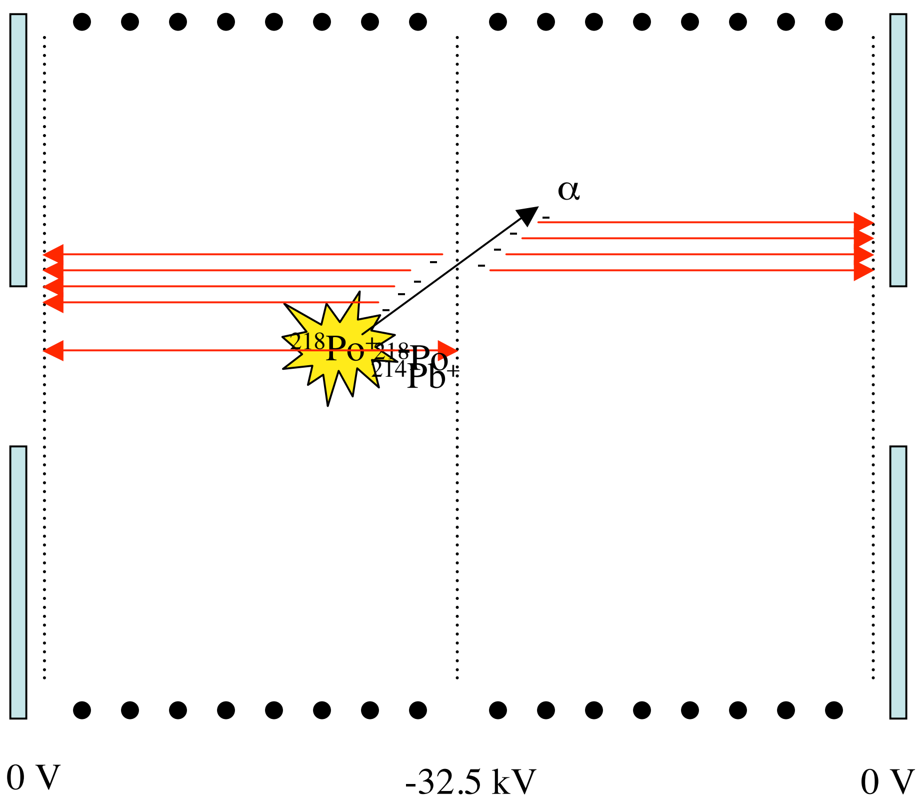
• Better sense-sensing algorithms. From *C. Deaconu, TAUP 2013 Proceedings* - See Jocelyn Monroe's talk)

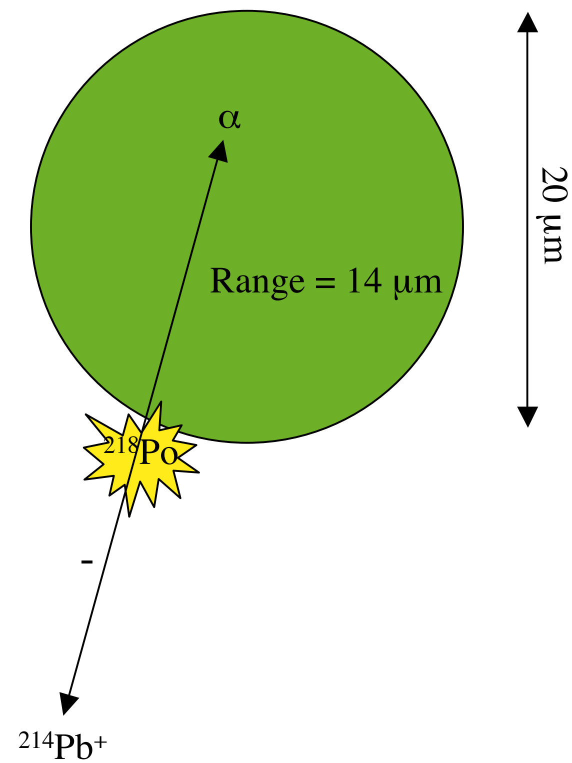
2014

Good directionality and discrimination.. but where's the scaleup??

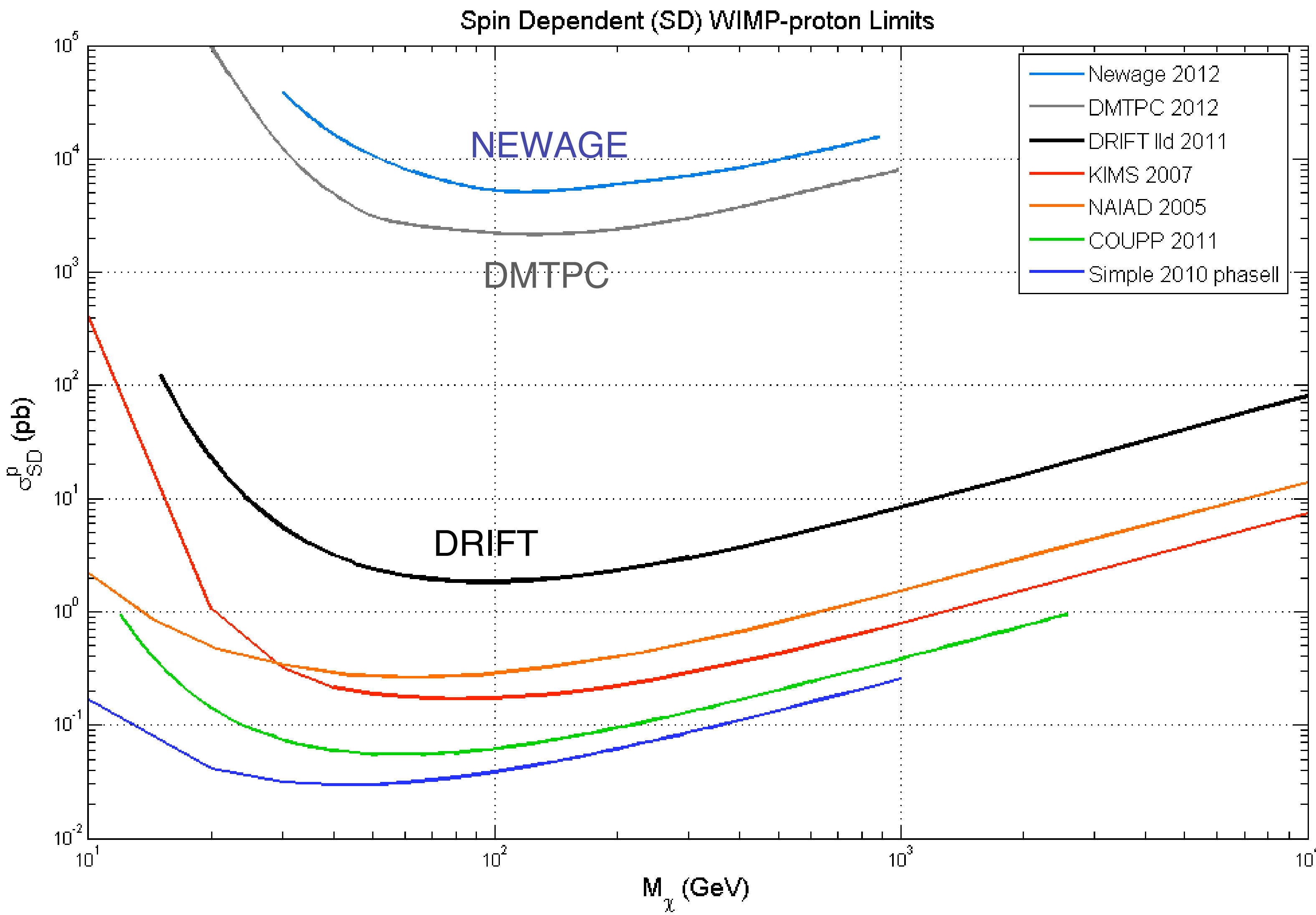


A detour: Radon Progeny Recoils (RPRs)



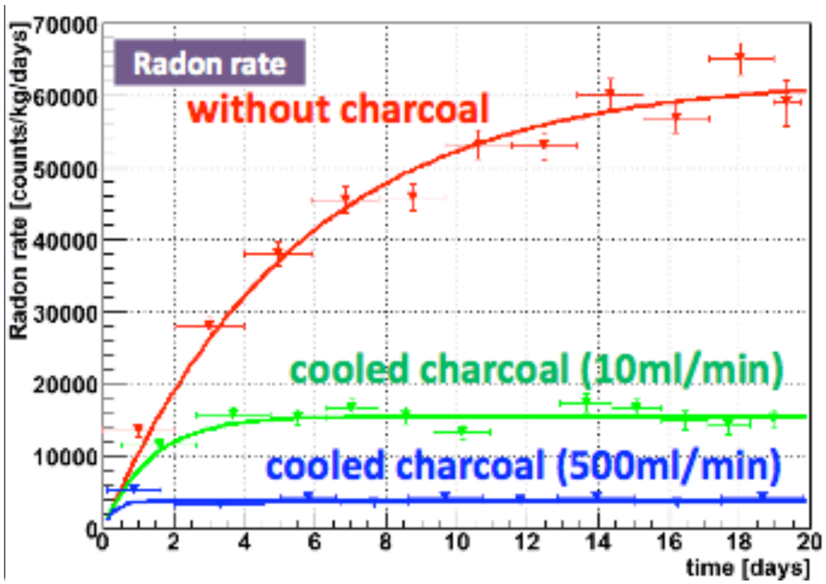


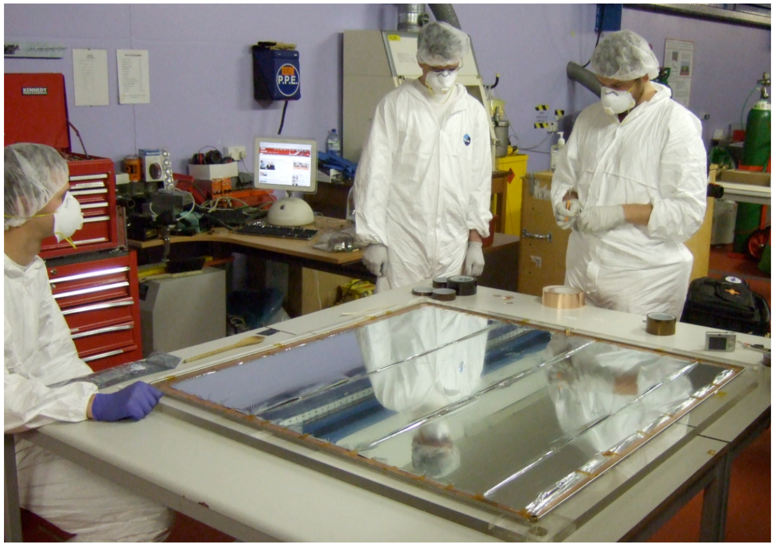
Limits nonetheless



Radon/RPR reduction

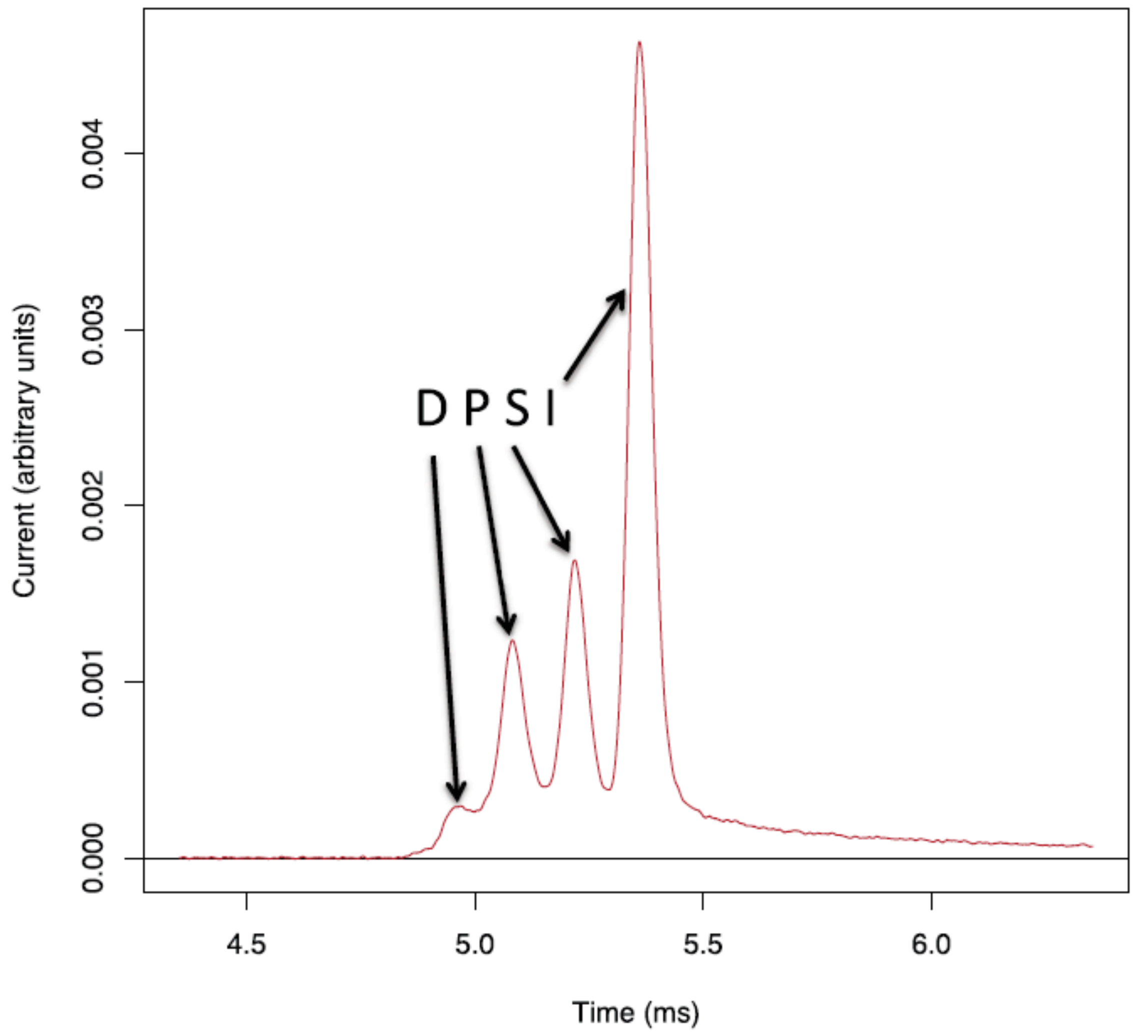
- Identifying and eliminating radon emanating materials
- Recirculation thru cooled charcoal (NEWAGE)
- Development of thin film cathodes to improve efficiency of vetoing RPRs (DRIFT)





Z Fiducialization: the "holy grail"

Discovery of "minority peaks" in CS_2^* $+O_2$ mixtures:

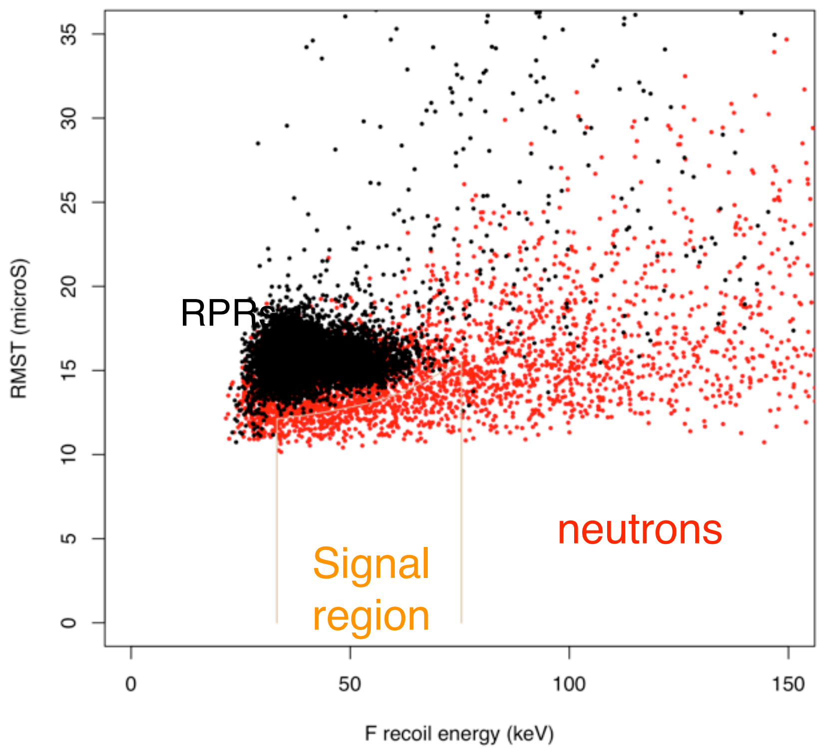


* elixir: a magical liquid that can cure illness or extend life

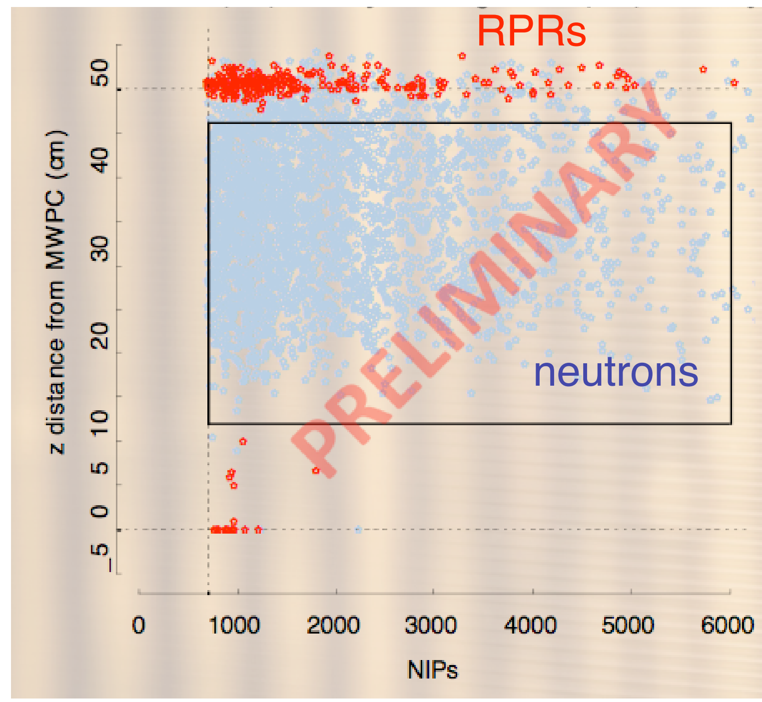
D.P.S-I, Rev. Sci. Instrum. (2014)

For DRIFT: an expanded signal region and **zero** backgrounds

Before



After



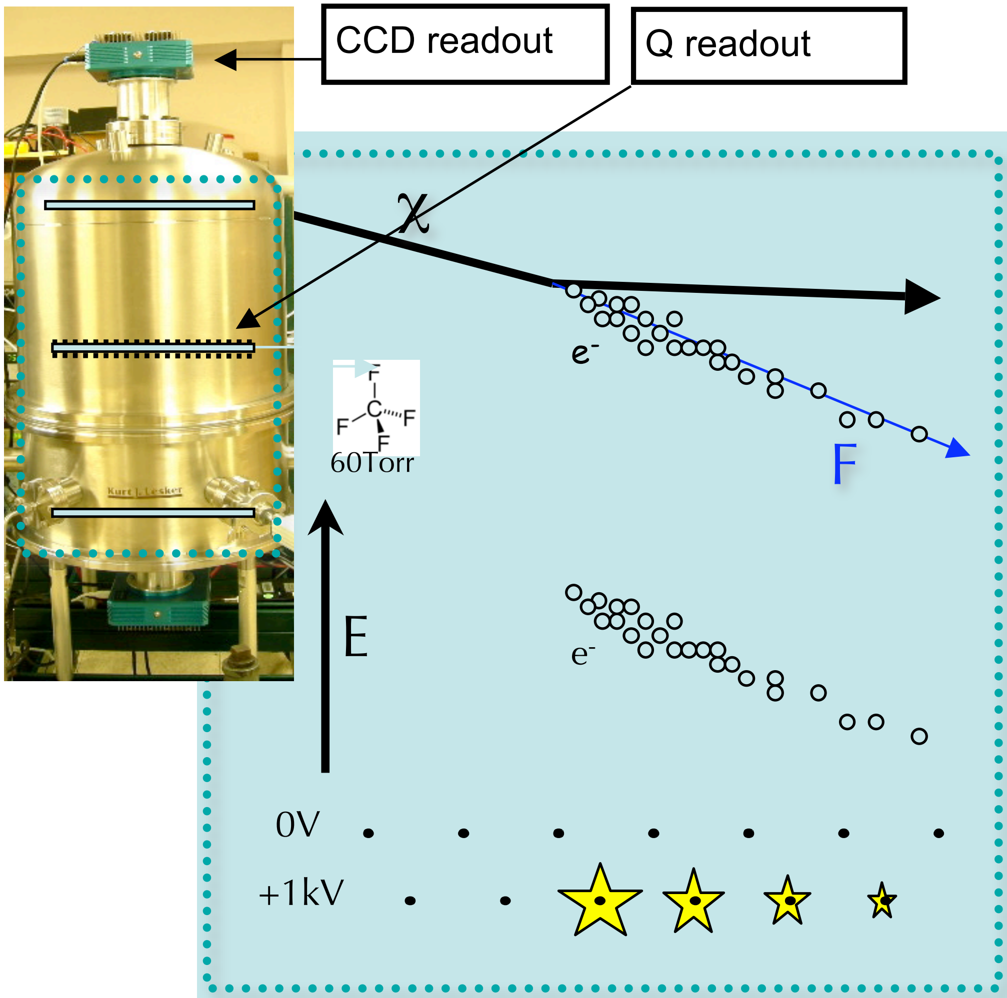
Both are from ~50 day dark matter runs at Boulby

(See Neil Spooner's talk)


RPR
(1901-2013)

Directional Experiments

Dark Matter Time Projection Chamber



DMTPC Collaboration

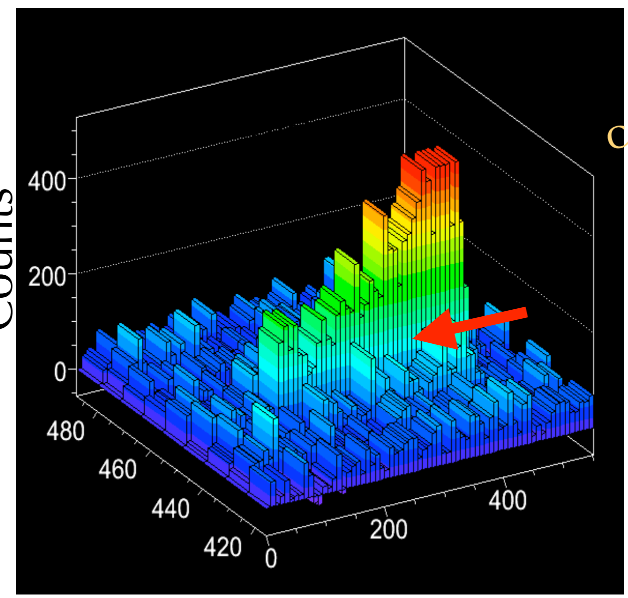
Brandeis University
A. Dushkin, H. Wellenstein*

Bryn Mawr/Wellesley
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)
G. Druitt, R. Eggleston, P. Giampa, J. Monroe*



calibration neutron beam

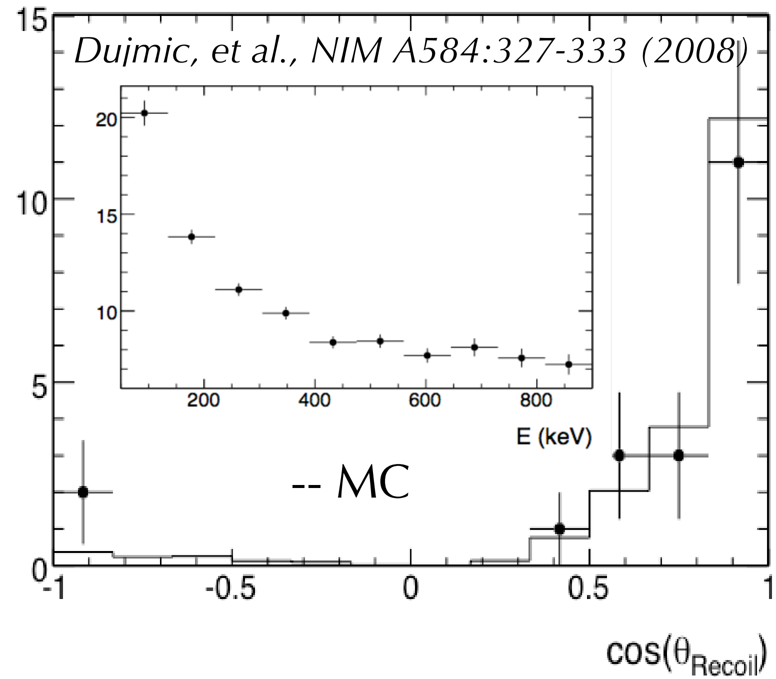
light and charge readout for tracking & backgrounds

D. Dujmic, et al., NIM A 584:337 (2008)

Directionality

- 2D angle + head-tail from fitting light asymmetry (measure skewness)
- Require range/width > 3 for ID
- Diffusion has a big impact! Therefore working to lower pressure
- R&D for 3D proceeding

cosine (E>200 keVr), 5 cm drift



Future: DMTPCino 1m^3 Detector

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

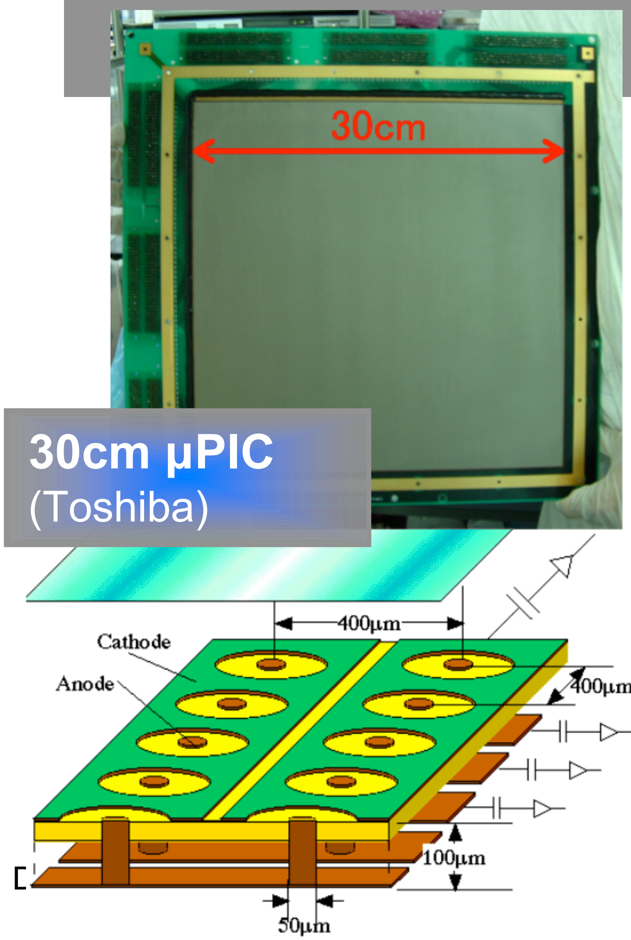
Detector under construction now, vacuum vessel acceptance test May 2014, commissioning Fall 2014

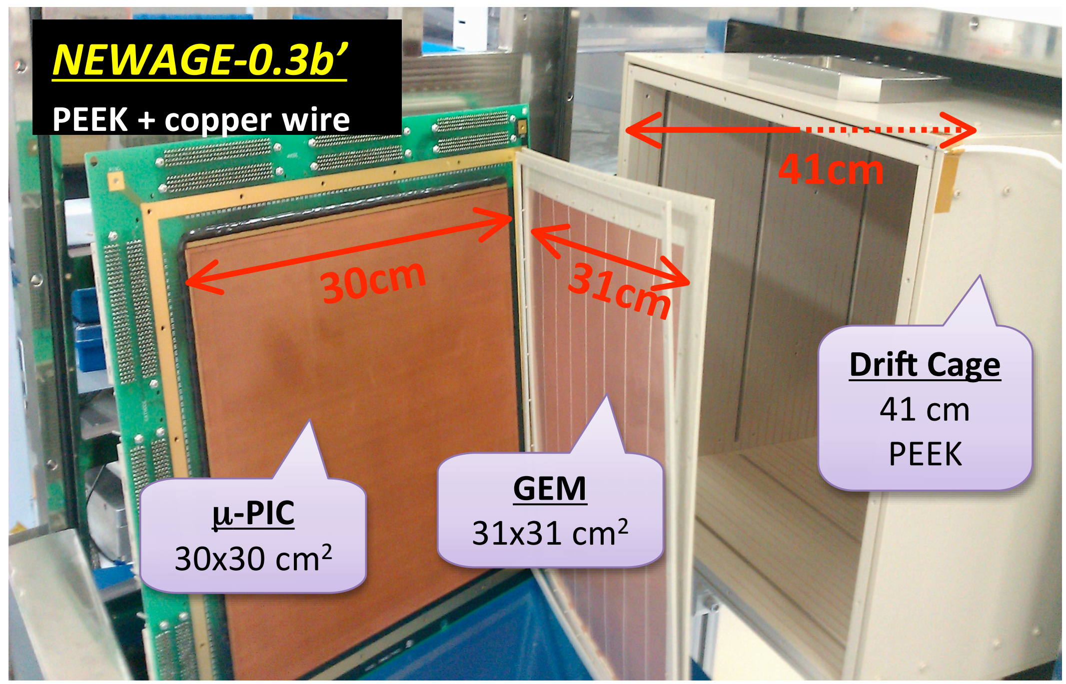
NEWAGE - New generation WIMP search with an advanced gaseous tracker experiment)

- 2D imaging device:
  μ-PIC (gas gain 5000)
  - 400mm pitch
  - 30×30㎝²

Readout electronics
- Digital ”3D-HIT” (track) +charge (energy)

PI: K. Muichi (Kobe)





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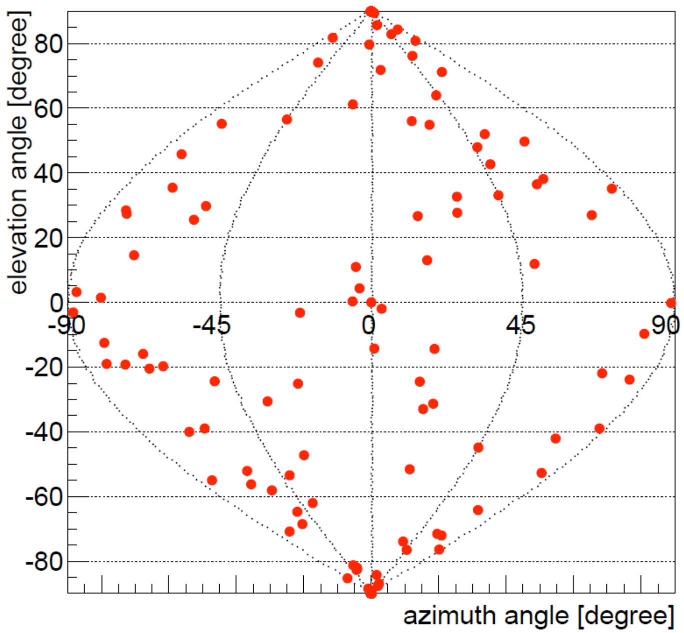
NEWAGE 2013 results

- NEWAGE−0.3b
  - larger × 2 (23 … m^3)
  - lower threshold … V (152⇒76torr)
  - low BG: γ reje… 0^{-5}@50-100keV
    radon red… : 1/50

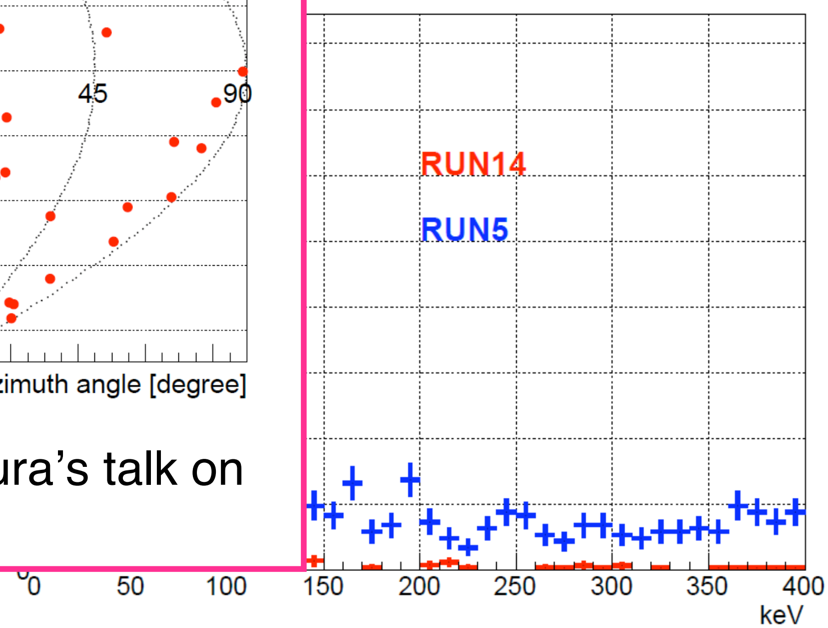
NEWAGE KamiokaR…

- Kamioka (2700m.w.e.)
- period : 2013/7/20-8/1…
- live time : 31.6 days
- fiducial volume : 28x24…
- mass : 10.36g
- exposure : 0.327 kg･da…

New directional limits!



Come to K. Nakamura's talk on Friday



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)

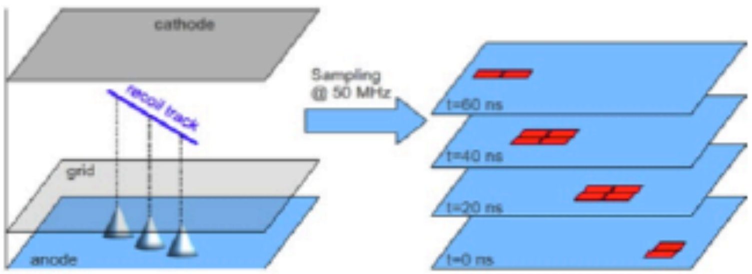
CCPM (Marseille): J. Busto, Ch. Tao, D. Fouchez, J. Brunner (Radon filtering)

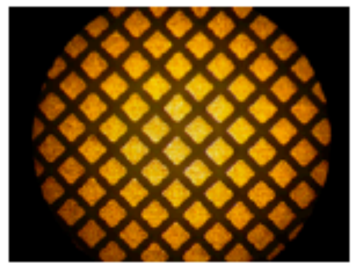
Neutron facility (AMANDE) :
IRSN (Cadarache): L. Lebreton, D. Maire (Ph. D.)

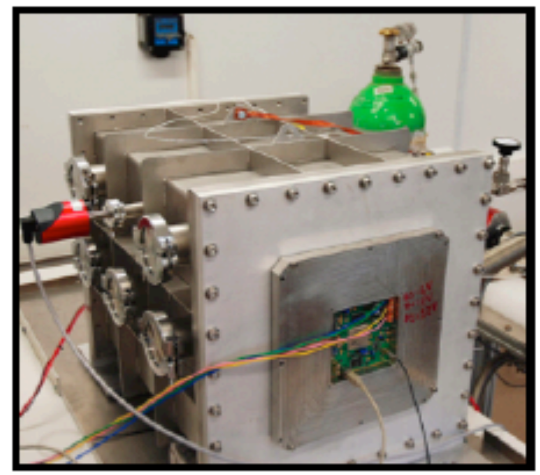
Concept: low pressure CF_4, CHF_3 and H with charge readout via Micromegas + pixel technology

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

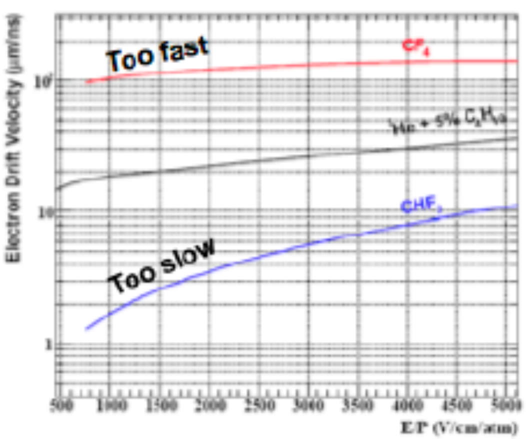
Bi-chamber module 2 x (10.8x10.8x25 cm^3)





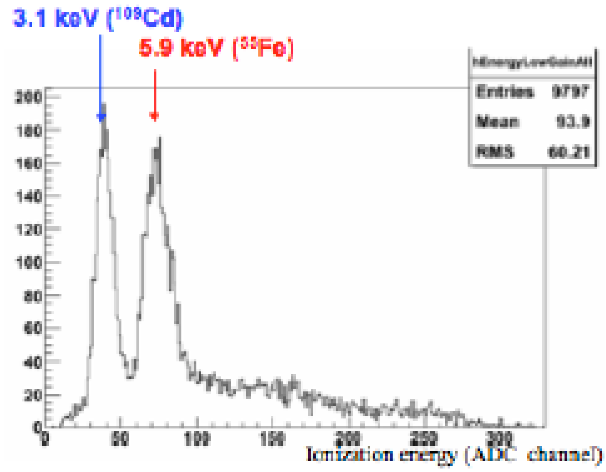


Pixel micromegas from IRFU (Saclay) - 200 µm

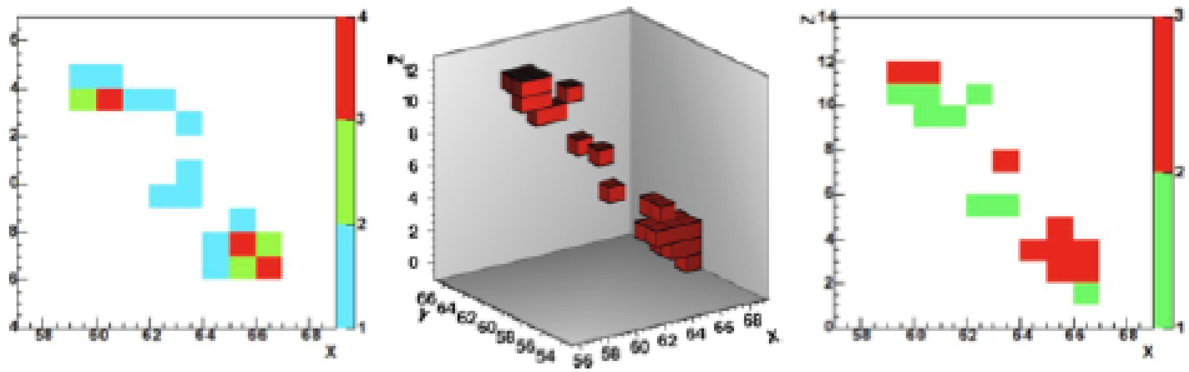


New mixed gas MIMAC target needed to slow drift velocity to match speed of electronics time slicing : CF4 + 30% CHF3

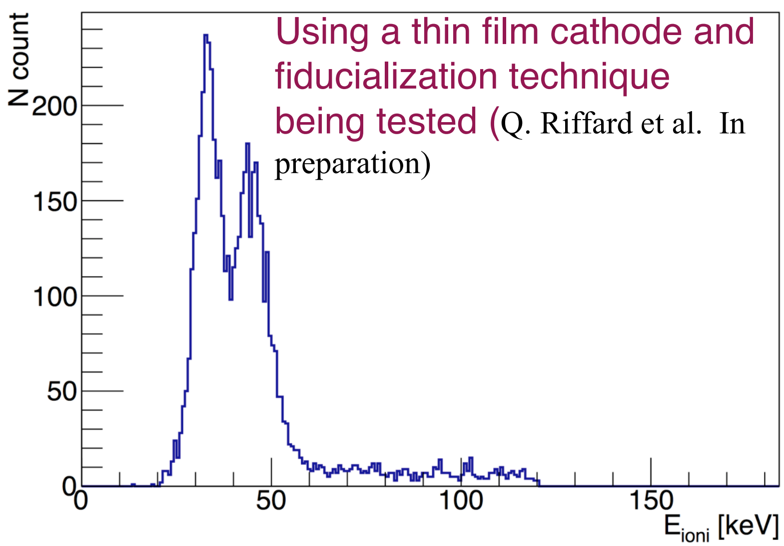
Underground in Modane since 2013



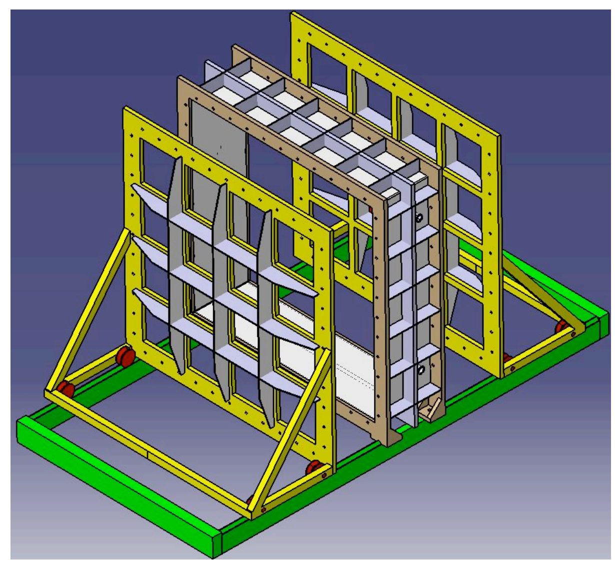
A 5.9 keV electron track in 350 mbar 95% 4He + C4H10



RPRs! Rn-222 daughter spectra:

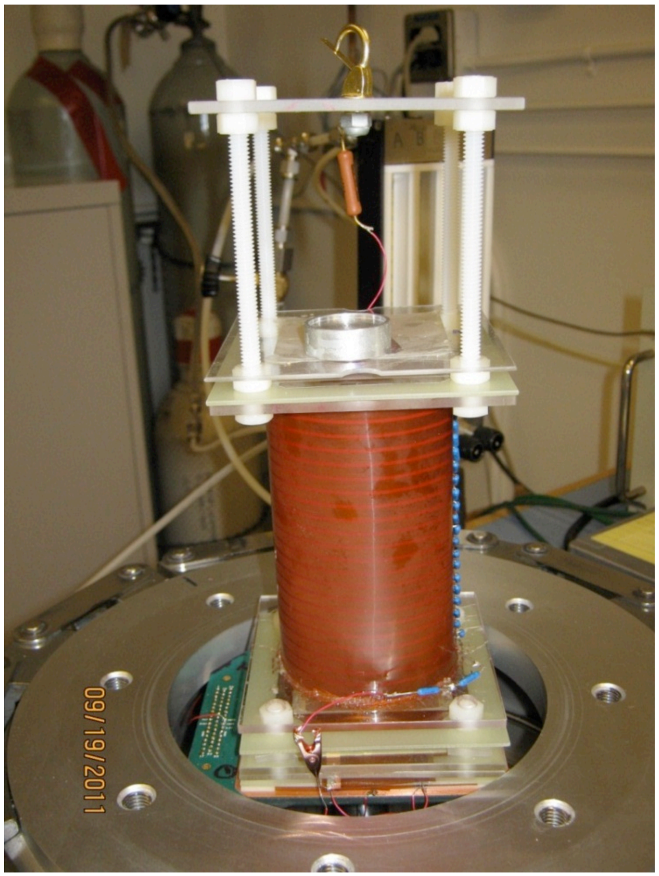


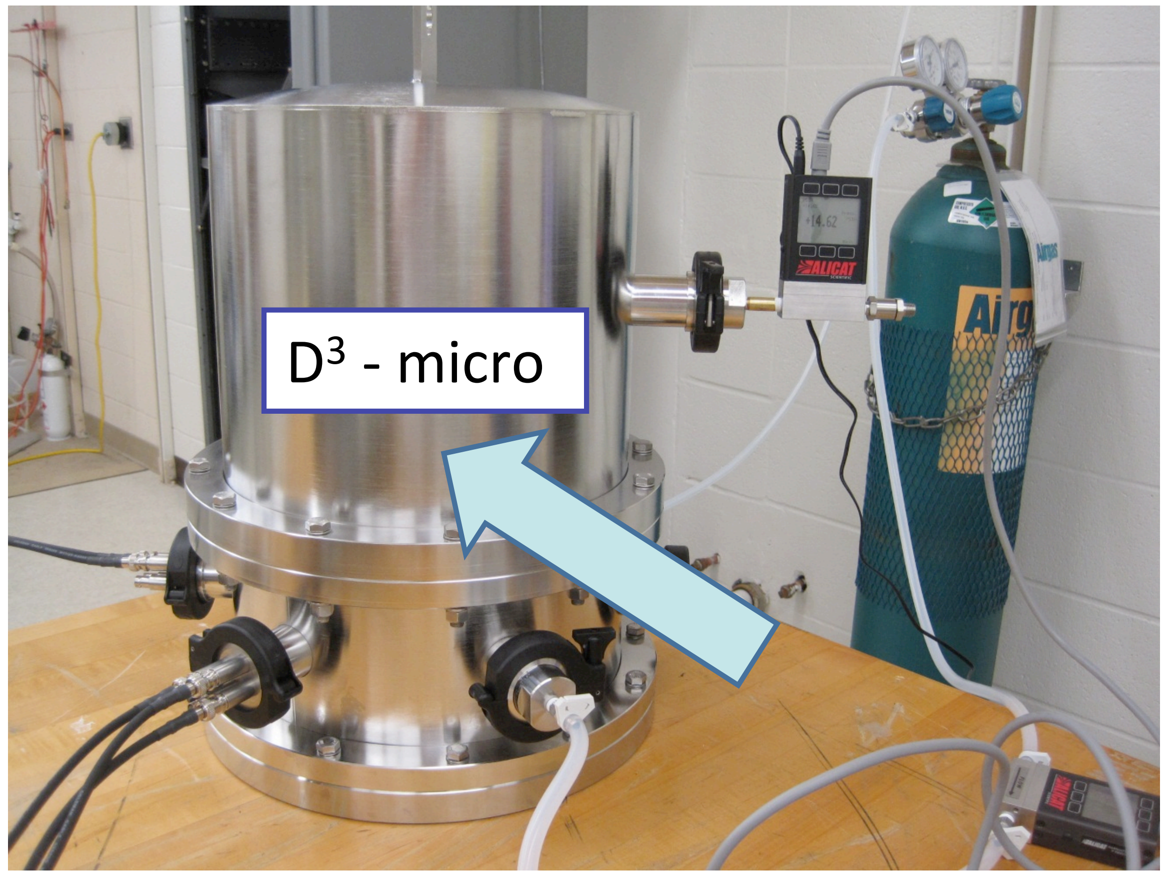
Future: MIMAC – 1m^3 = 16 bi-chamber modules (2x 35x35x25.5 cm^3)



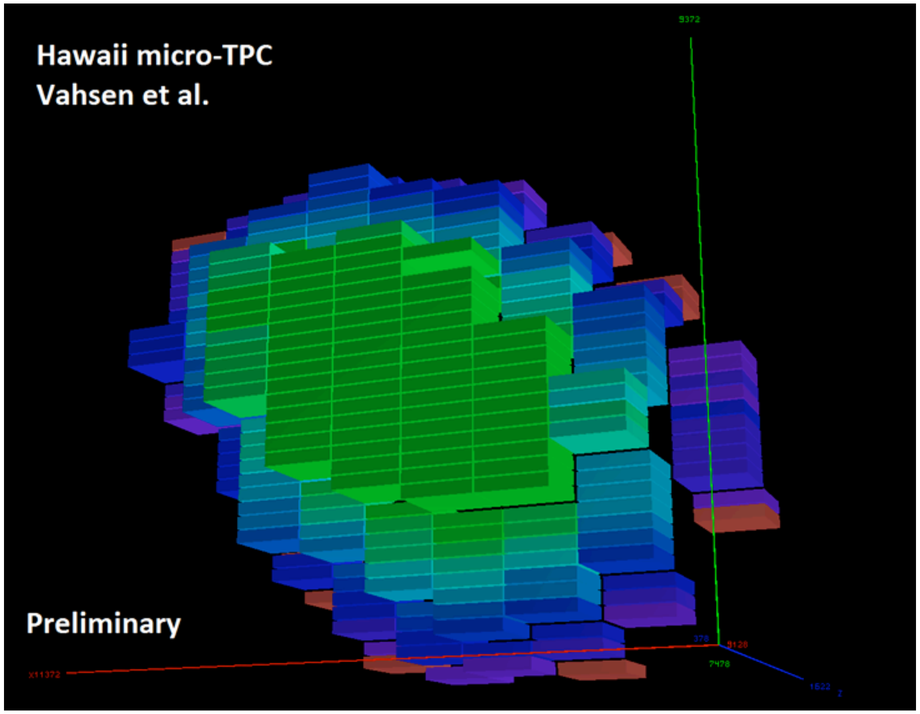
D^3 - Directional Dark Matter Detector

- Investigating feasibility of directional DM search w/ micro-pattern gas detectors
- Technology also of interest for detecting neutrons and charged particles
- Small (1-60 cm^3) prototypes built at LBNL (PI: JA Kadyk) and U. Hawaii (PI: S. Vahsen)
- Ongoing since ~Fall 2010



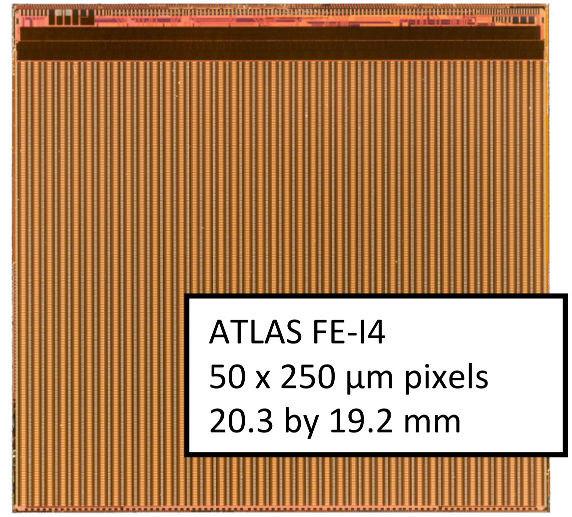


3D tracks: ~25 keVee recoiling He nucleus

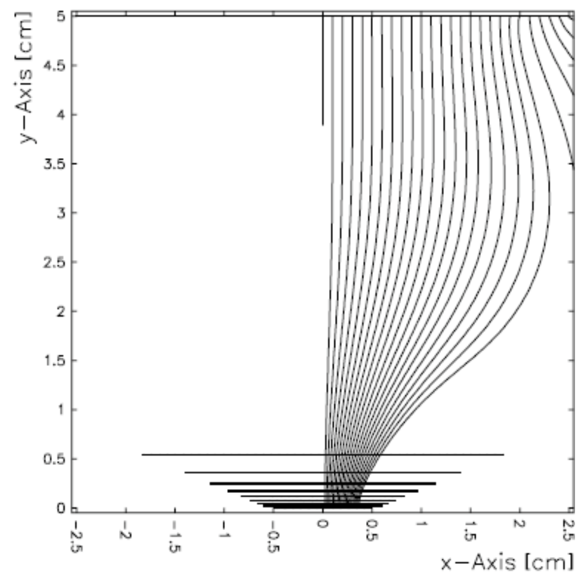


- each block: 50x250x250 μm^3
- Color: ionization density

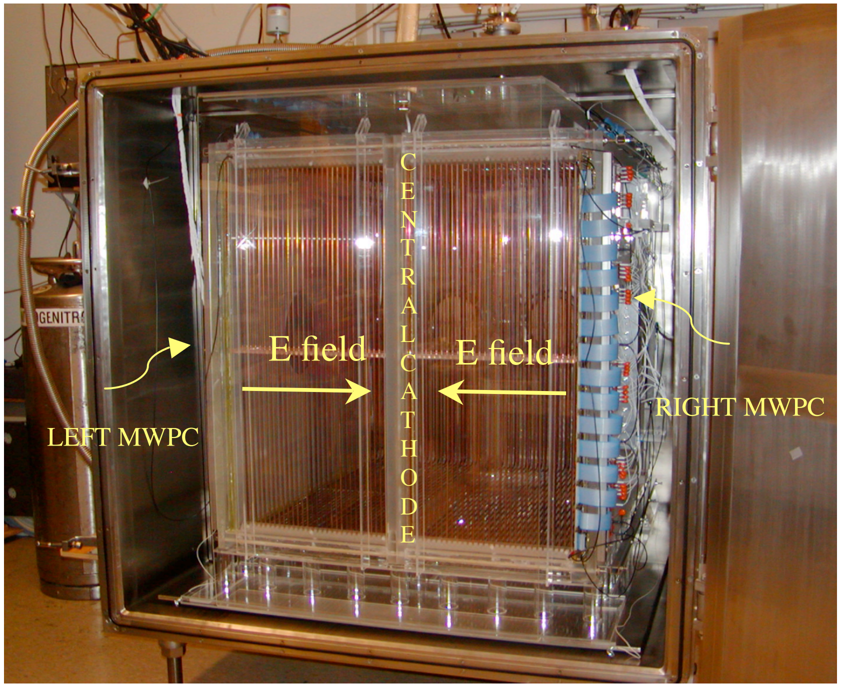
How to reduce # chips: larger ATLAS chips + focusing



S. Ross et al., "Charge-Focusing Readout of Time Projection Chambers", proceedings of IEEE NSS 2012



DRIFT - Directional Recoil Identification From Tracks



- $1m^3$ Negative Ion TPC with 30+10 Torr CS_2+CF_4
- MWPC readouts
- Operating in Boulby for >10 years
- Operating with ZERO backgrounds for >50 days!

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

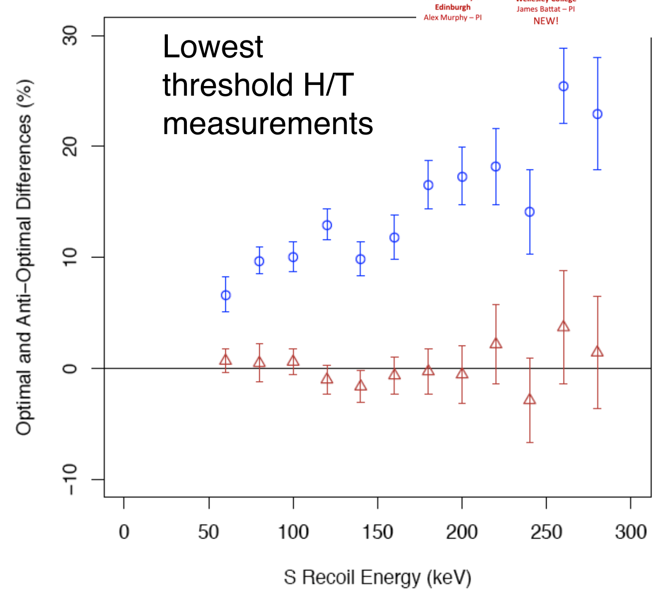
University of New Mexico
Dinesh Loomba - PI
Michael Gold – PI
John Matthews - PI
Eric Lee
Eric Miller
Nguyen Phan
Randy Lafler

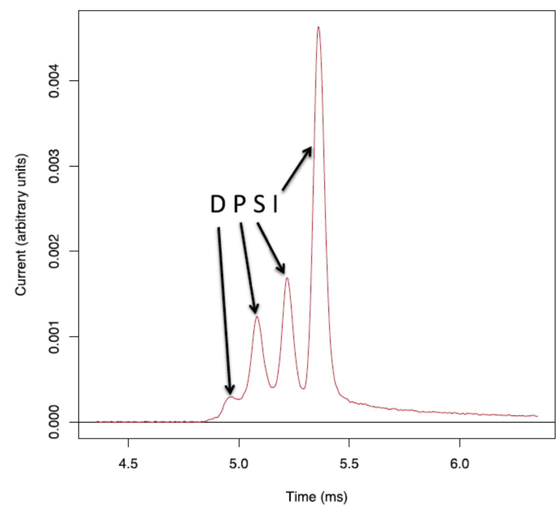
The University of Edinburgh
Alex Murphy – PI

Wellesley College
James Battat – PI
NEW!

University of Hawaii
Sven Vahsen – PI
NEW!

Boulby Mine
Sean Paling – PI
Emma Meehan
Louise Yeoman

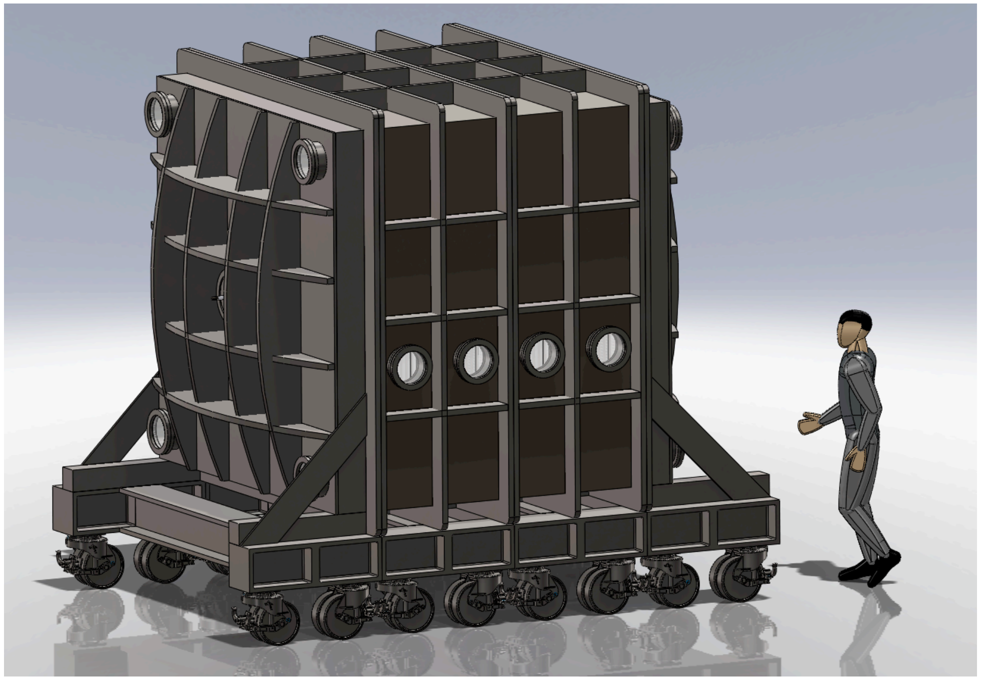




Future goals

- Deploy 2nd DRIFT-II detector with transparent MWPCs capable of reading from both sides
- Higher signal-to-noise every-wire readout
- R&D on high resolution readout (GEM/Micromegas + strips/pixels)
- R&D on directionality for low-mass WIMPs

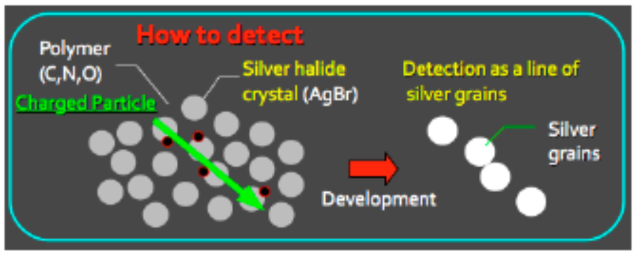
DRIFT has now entered a new phase, going from being background limited, to being volume limited. Ready to scale up by ~30 to the DRIFT-III detector:



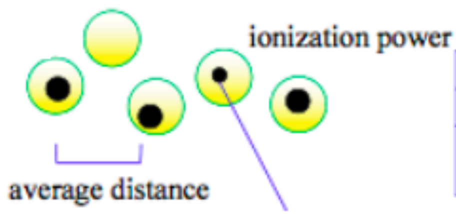
Emulsion Dark Matter Search Project

Nagoya (T. Naka),
Napoli, Padova, LNGS

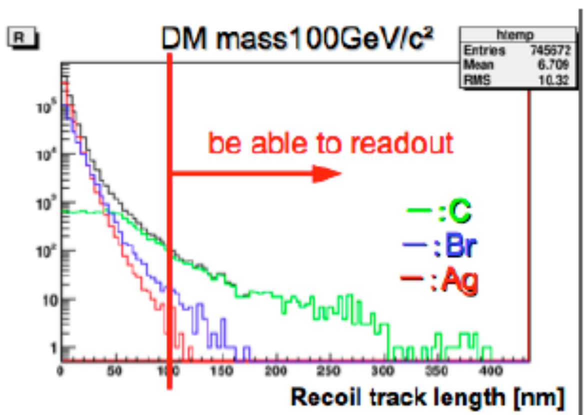
Concept (1): Use of emulsion film to give 3D tracking - solid detector (3g/cc), high spatial resolution, low cost, target Ag(46%), Br(34%), C(N,O) (19%)



- Track produces line of silver grains

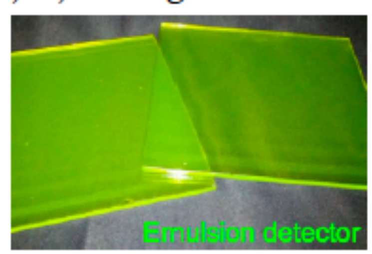


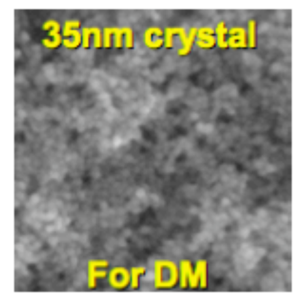
crystal size	45nm
crystal distance	85nm
crystal sensitivity for alpha-ray	>20% (not sensitized)



- 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

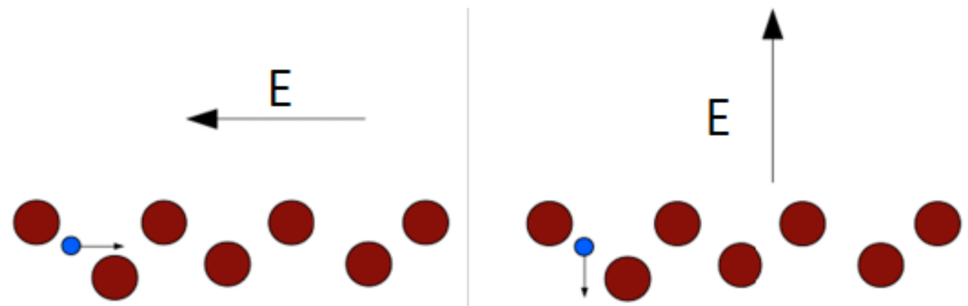




- Progress made to produce stable very fine crystals by using the PVA techniques

Columnar recombination in HPXe

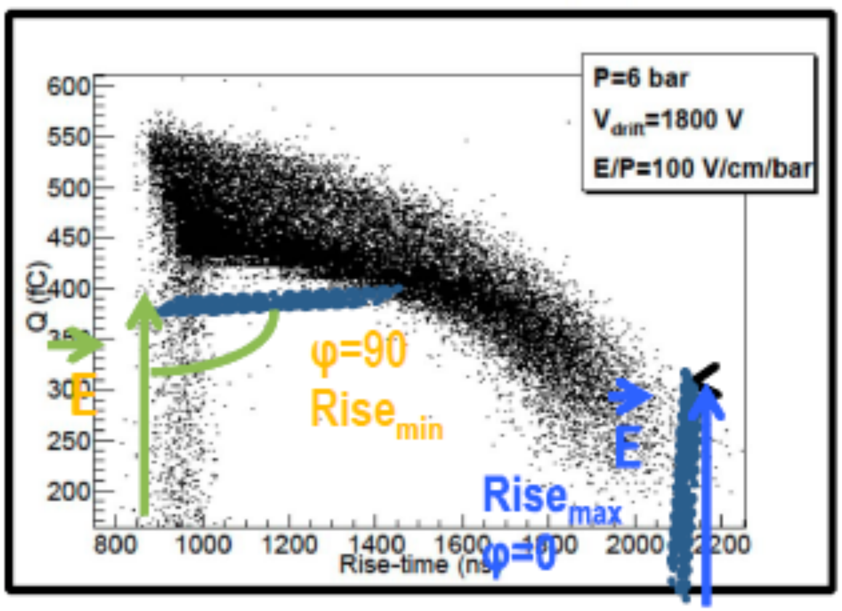
D. Nygren (LBNL)+ others
at Zaragoza

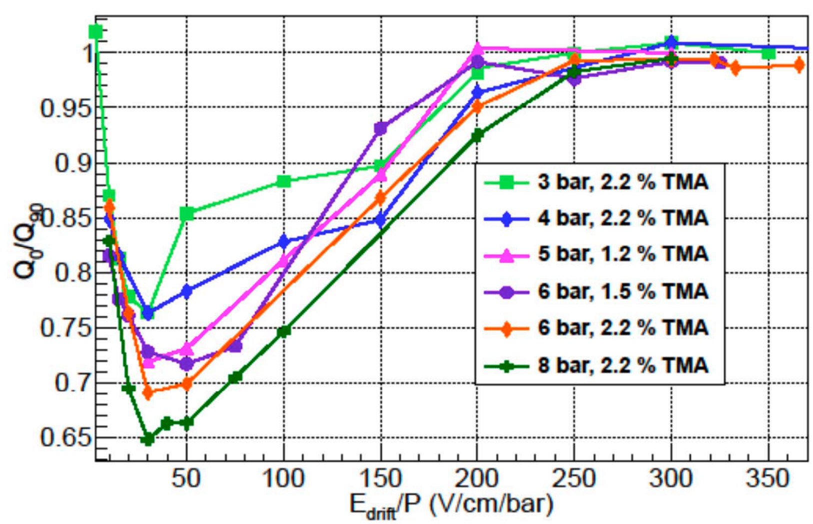


Case 1:
More Recombination

Case 2:
Less Recombination

Effect seen in 5.5 MeV alphas, R&D on nuclear recoils underway





Summary

- Experimental effort have demonstrated and improved their directionality. We are approaching the simulated predictions on strength of signature.
- Discrimination with range vs energy is excellent. But good signal-to-noise and resolution will be needed as we push to lower thresholds.
- Flexibility of technology enables numerous approaches for probing a wide range of WIMP parameters.
- The RPR problem has a solution that works.
- Experiments are all getting larger, but we are volume limited and need to scale up.
- Many new groups entering field, some with novel ideas in solids-state and high pressure gas


Cygnus