A Hunt for Dark Matter: a Tale of Direction and Sensitivity

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University of New Mexico

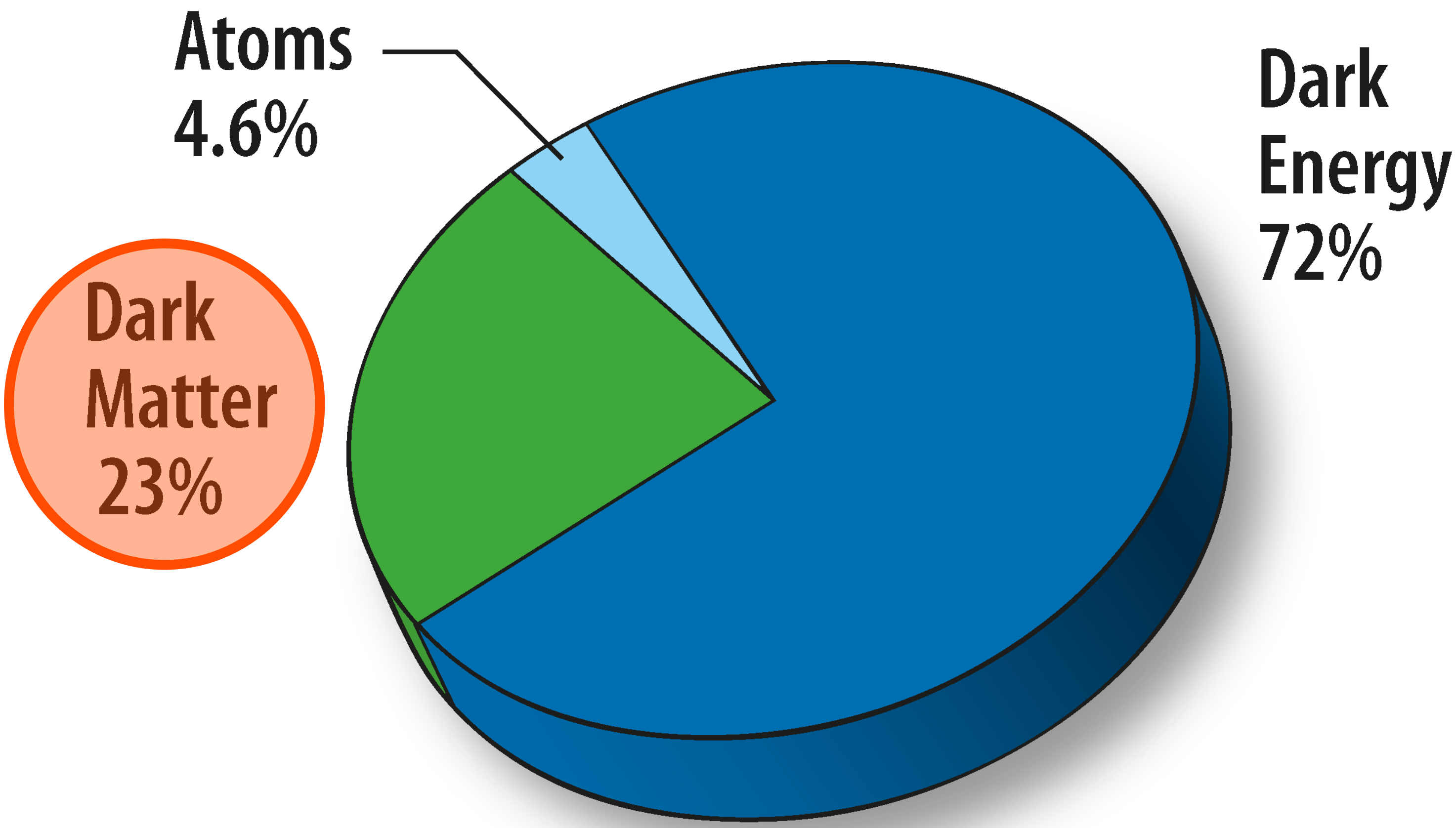
INFN Seminar

December 19 2017

Outline

- Intro to Dark Matter
- The case for directionality in DM searches:
  - a “smoking gun” signature for discovery
  - to reach beyond the “neutrino floor”
- Direction-sensitive Time Projection Chambers
- The DRIFT experiment – its pros and cons
- R&D towards improved sensitivity for DM and directionality

The Cosmic Pie - a precise measure of the known unknowns



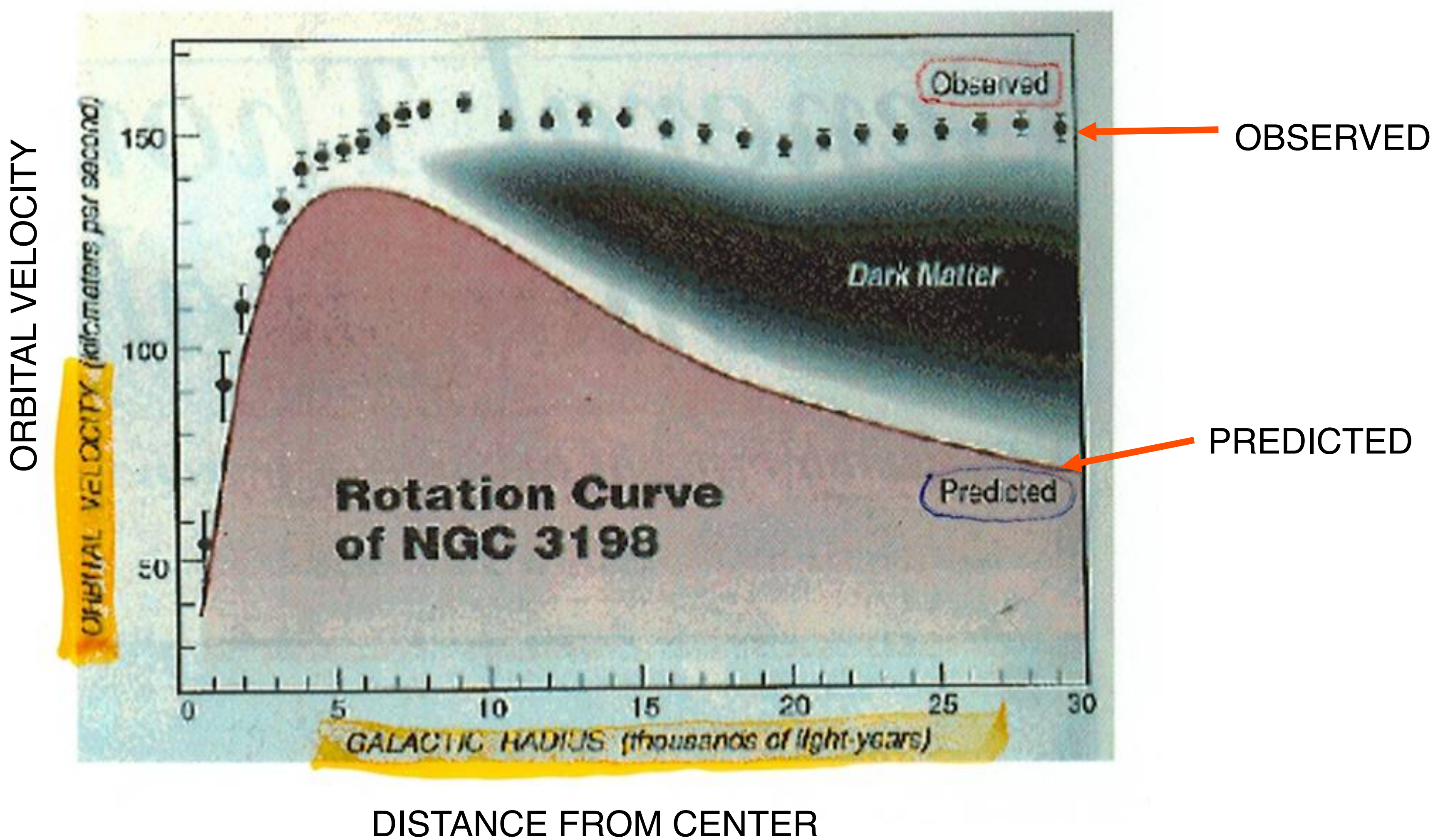
TODAY

map.gsfc.nasa.gov

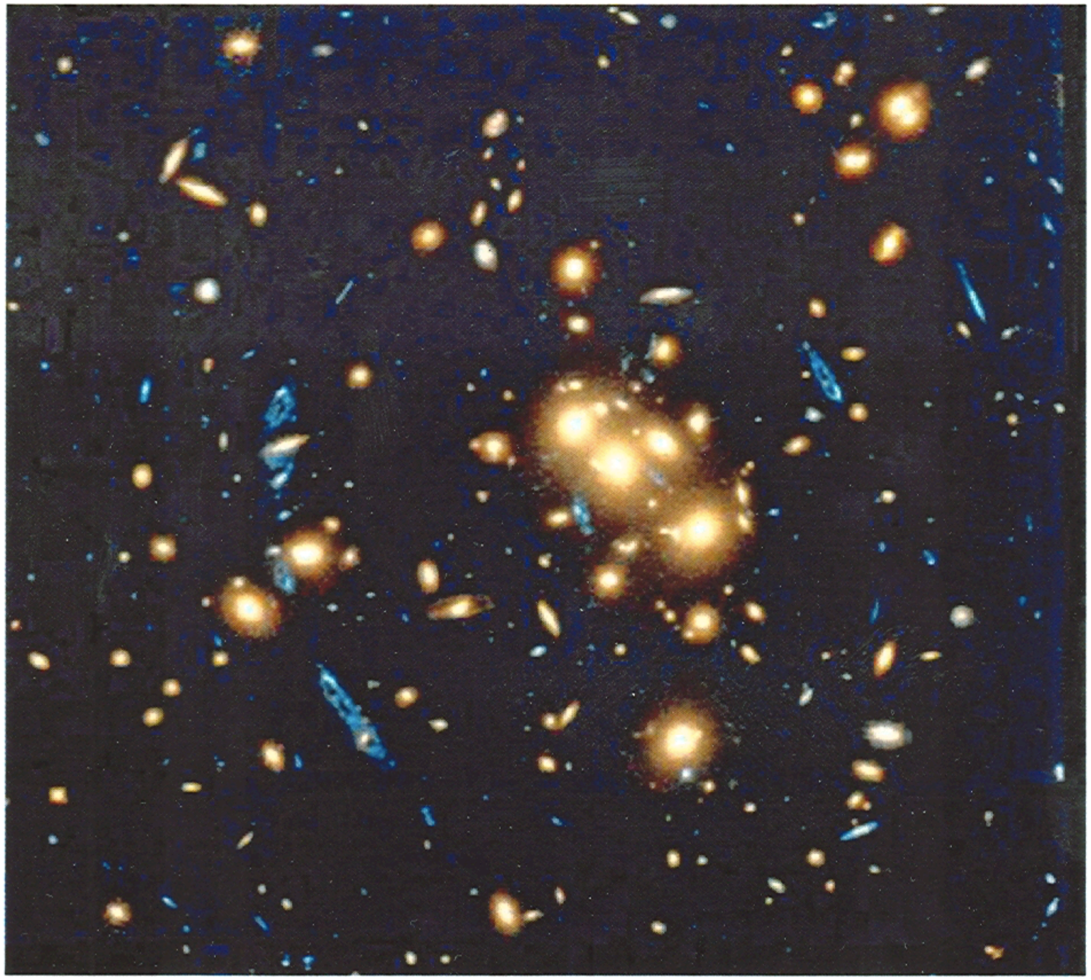
Evidence for dark matter exists on all scales, from···

…galaxies like our own, where…

…the data DISAGREES with Newton…



…to clusters of galaxies, where…

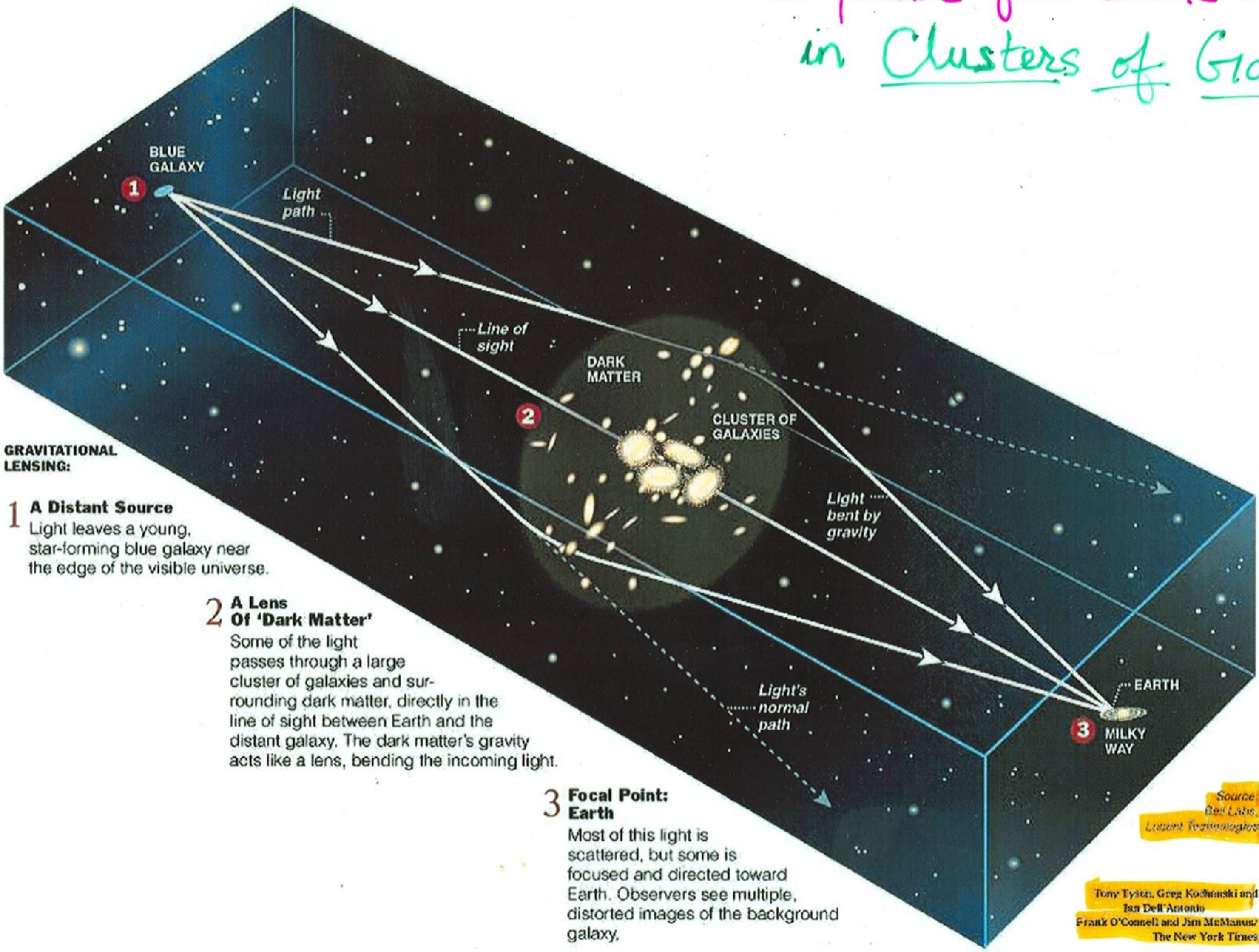


Foreground cluster at z = 0.39, lensed galaxy at z ≳ 1.2

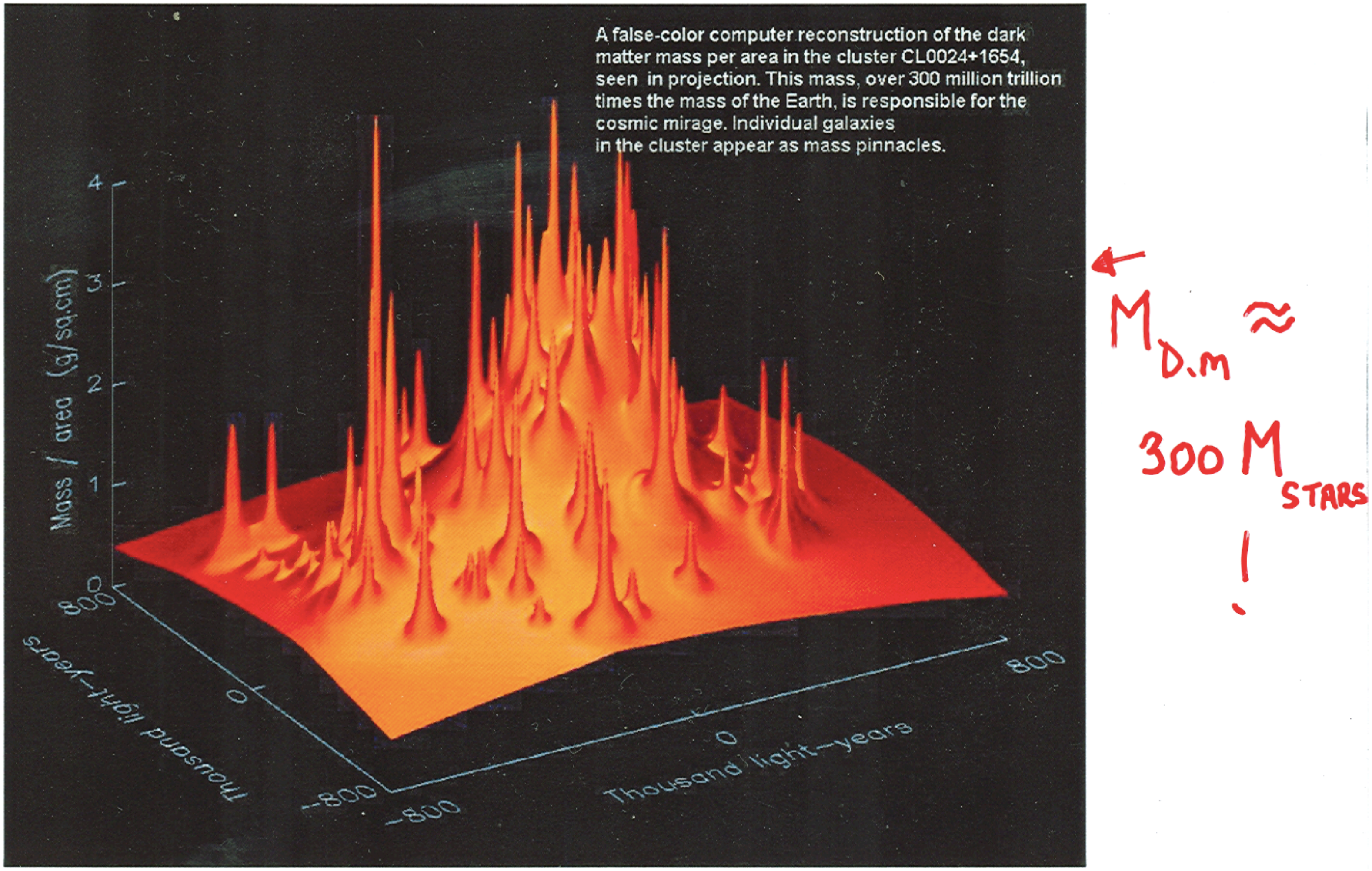
A Hubble Space Telescope image of a gravitational lens formed by the warping of images of objects behind a massive concentration of dark matter. Warped images of the same blue background galaxy are seen in multiple places. (Colley, Tyson, Turner ApJ **461** L83 (1996)).

…we use gravitational lensing
to constrain the mass…

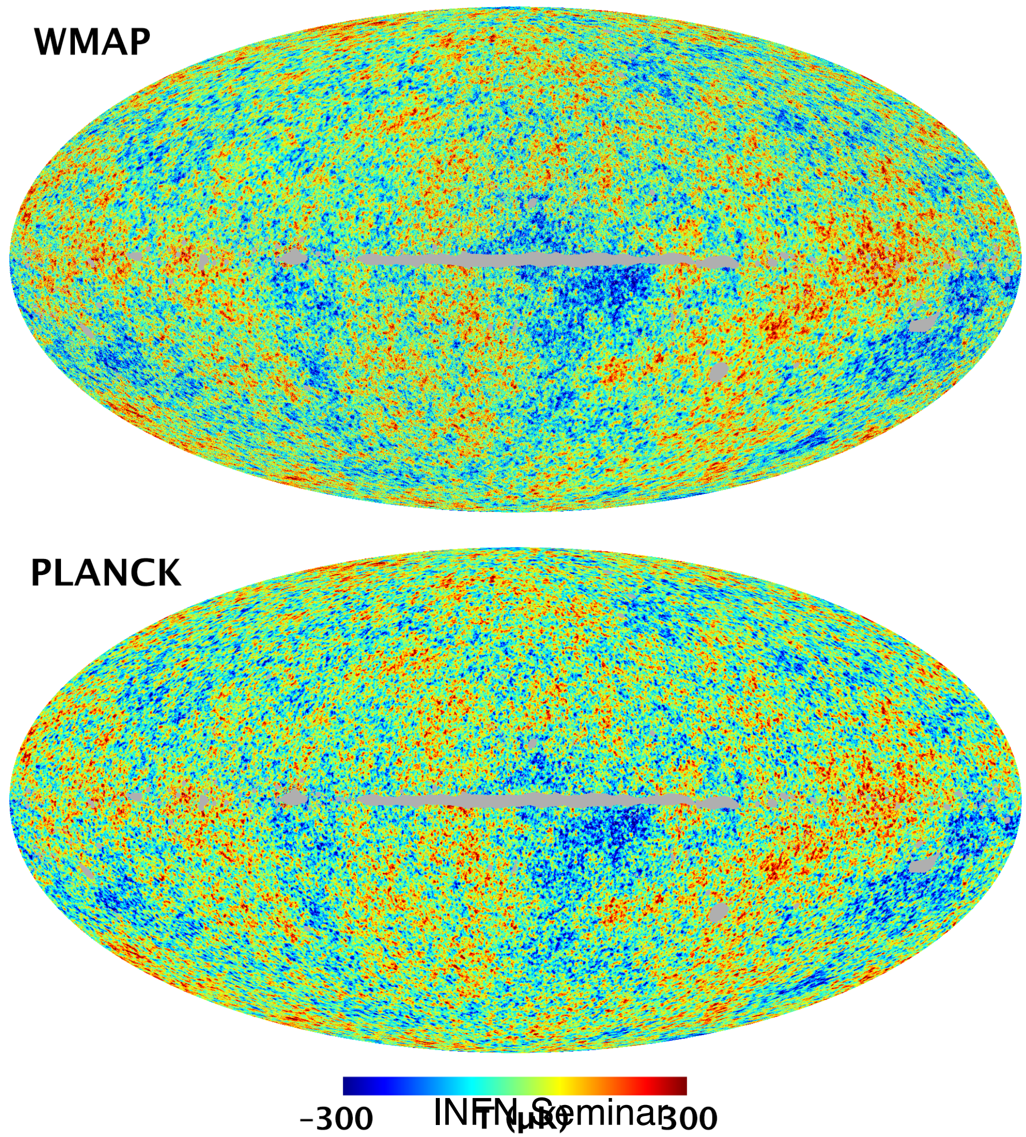
GRAVITATIONAL LENSING,
a probe for Dark Matter
in Clusters of Galaxies

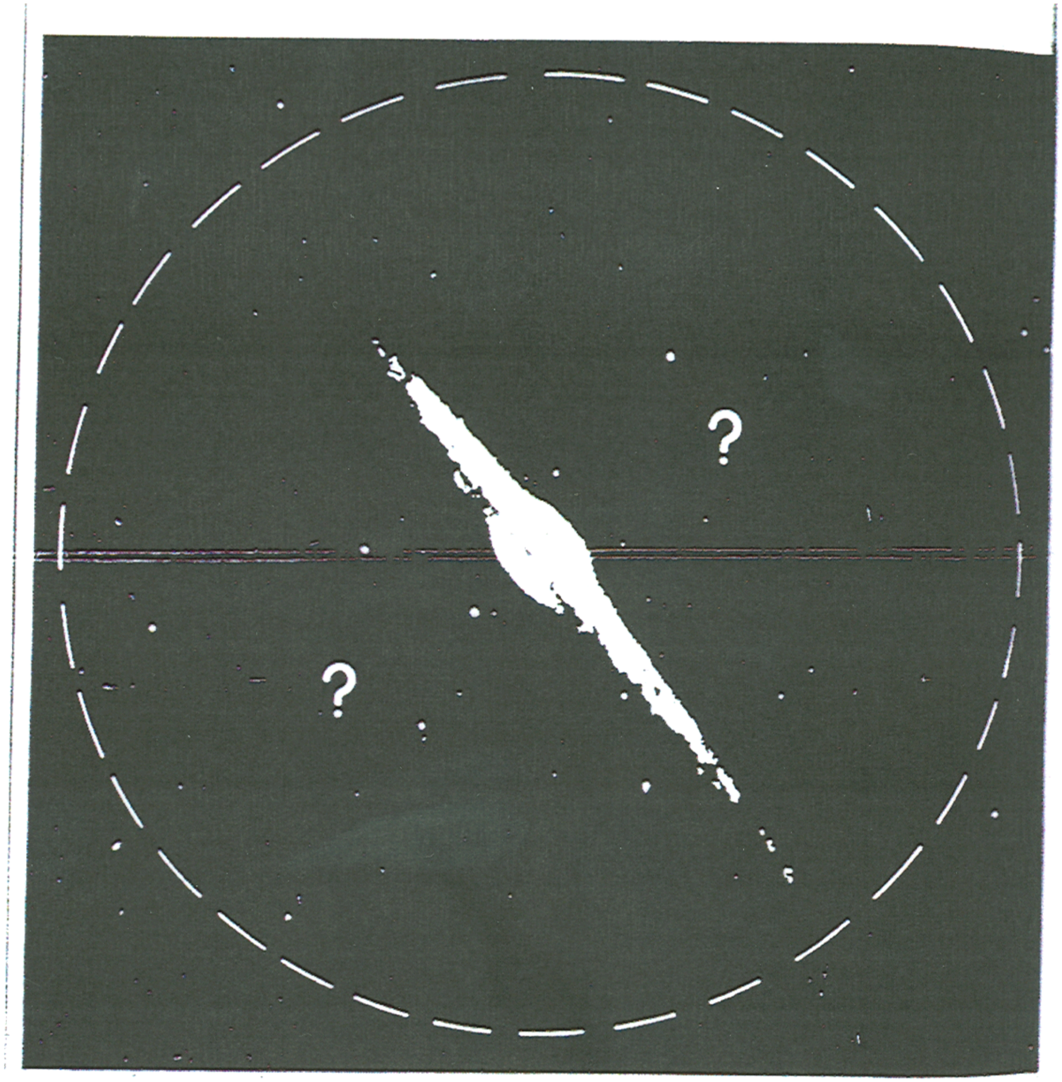


…the data again disagrees with theory



Finally, on the largest scales, we use the CMB



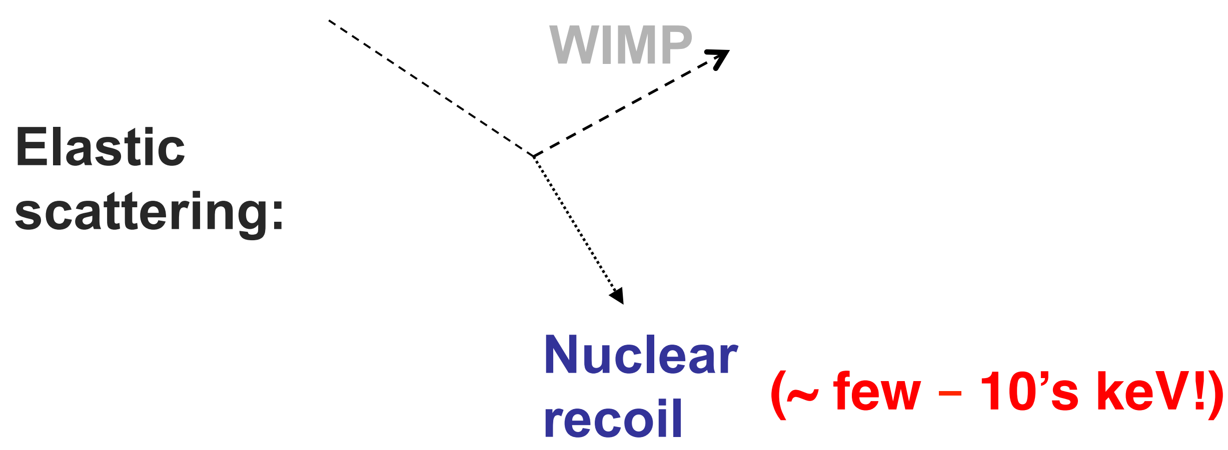


NGC4565

So, what is it??

We believe it is a new elementary particle which we call the WIMP for Weakly Interacting Massive Particle

There is a large effort all over the world aimed at detecting the WIMP and determining its nature

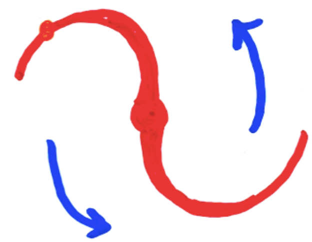


The Challenge: Signal vs Background

- The backgrounds: our detector triggers at a rate of a few Hz even a 1km underground
- The expected signal: we expect a WIMP interaction at a rate < 1 per 10 kg.yr (!)

To look for the rare signals from WIMPs an ideal detector should reject backgrounds and measure a signature pointing to the Galactic origin of the signal

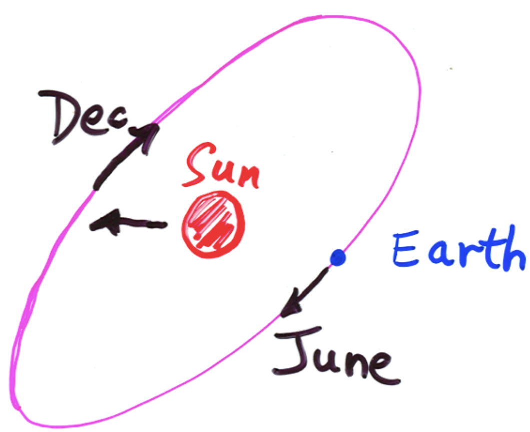
GALAXY



DM extends out to 10x the extent of luminous part of Milky Way!

DM Halo "Stationary" w.r.t MILKY WAY

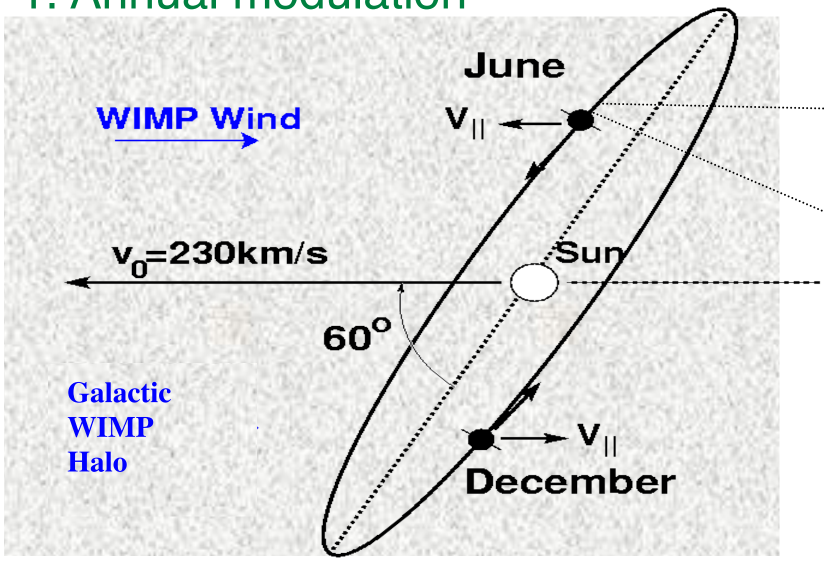
WIMP WIND

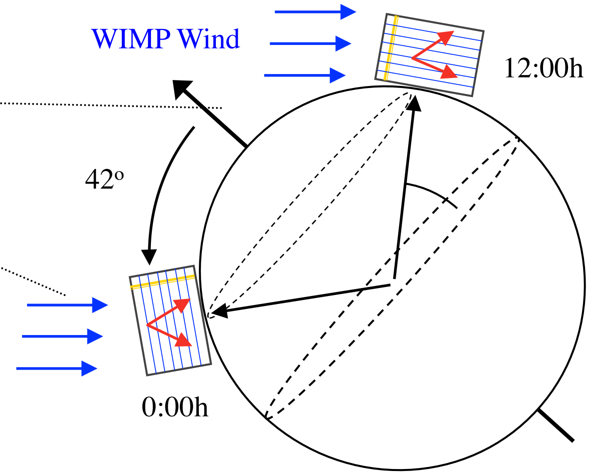


Textbook WIMP signatures

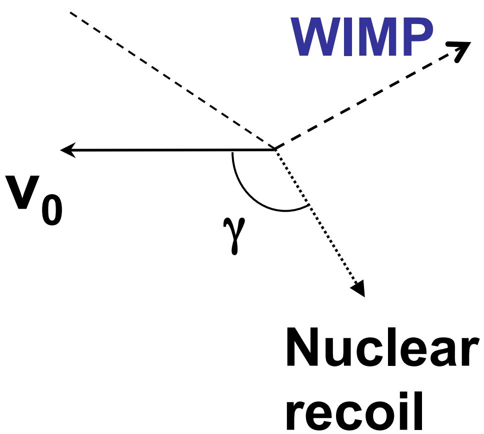
1. Annual modulation

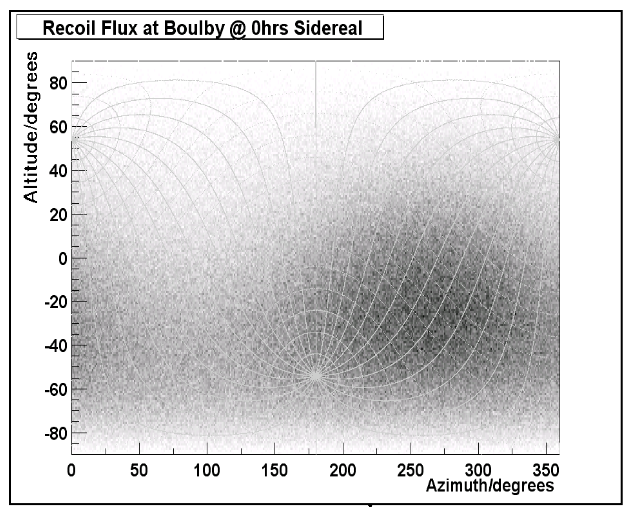
Cygnus





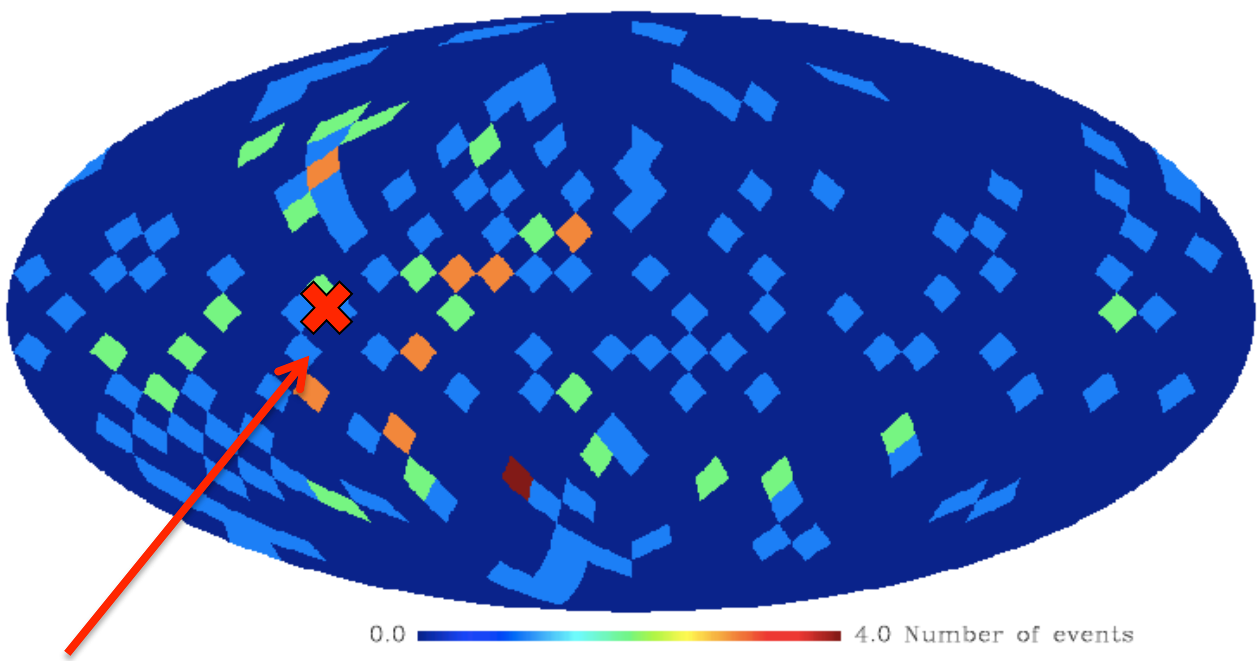
2. Sidereal modulation





Directionality is powerful even with backgrounds…

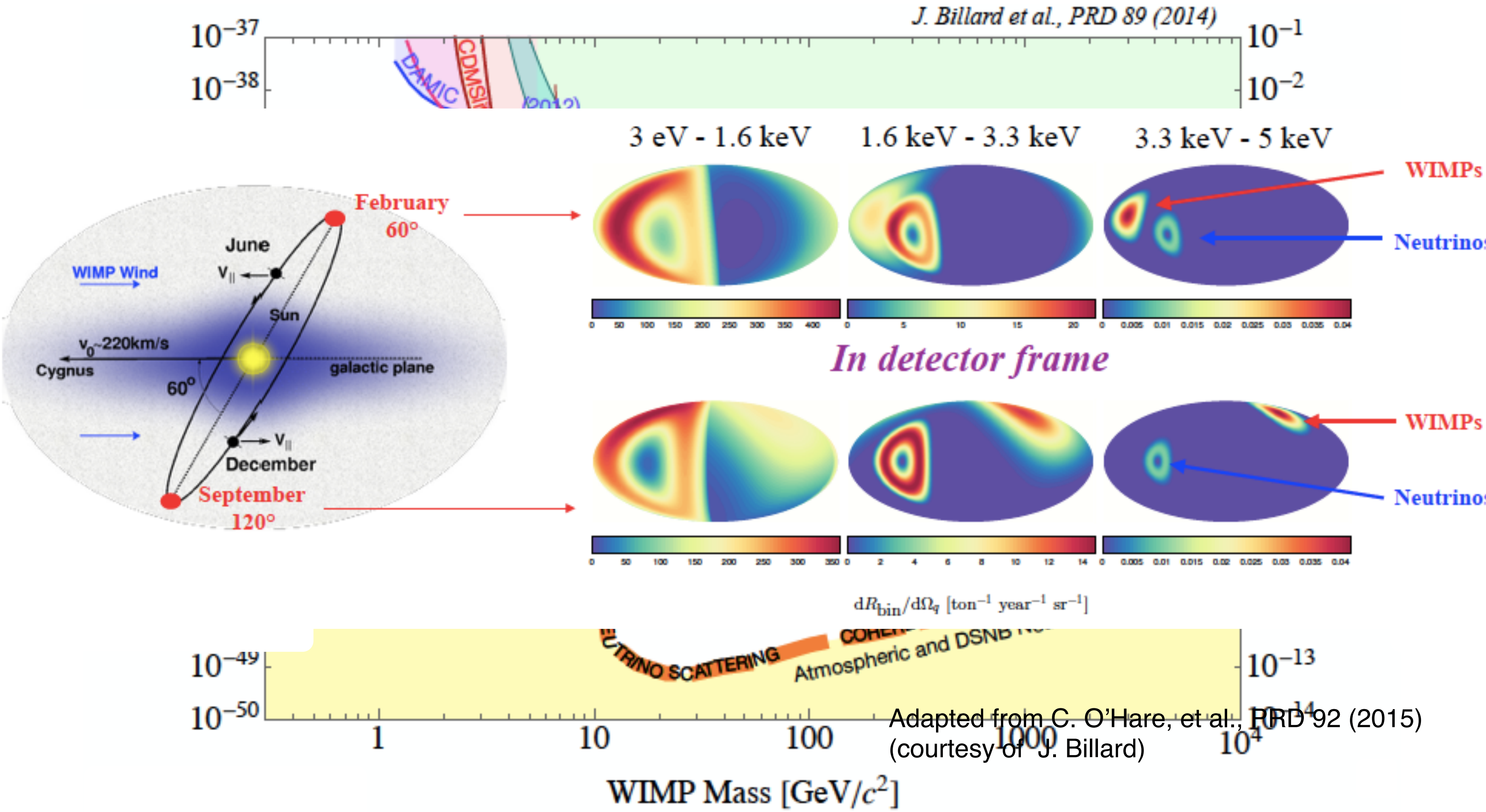
100 WIMP + 100 isotropic Bkgd events



Cygnus Constellation (l = 90°,b = 0°)

J. Billard, F. Mayet, J.F. Macías-Pérez, D. Santos, PLB 691 (2010)

…which is critical for going below the neutrino floor:



Adapted from C. O'Hare, et al., PRD 92 (2015)
(courtesy of J. Billard)

Courtesy of J. Billard

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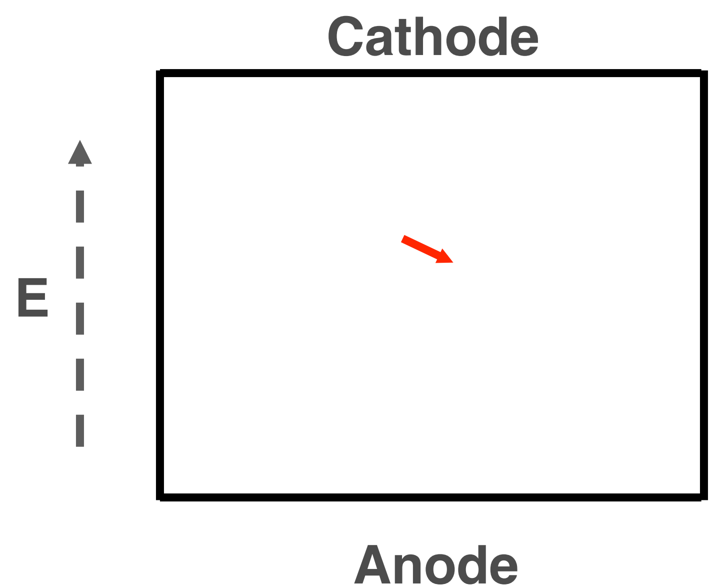
Directional Technologies

- Anisotropic scintillators
- Emulsions
- Low pressure gas TPCs
- Plus lots of recent R&D on more speculative technologies, e.g., columnar recombination, carbon-nanotubes, etc

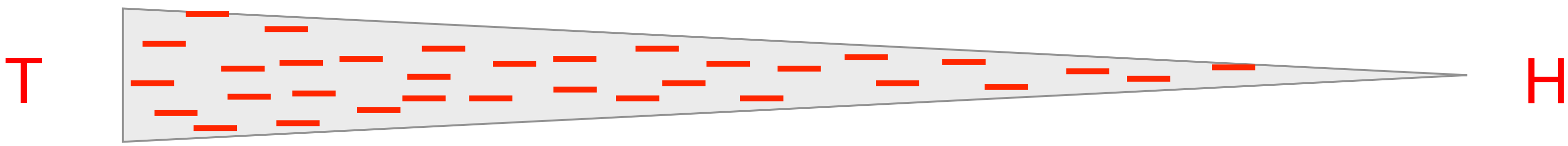
The Experimental Challenges to Measuring Recoil Tracks

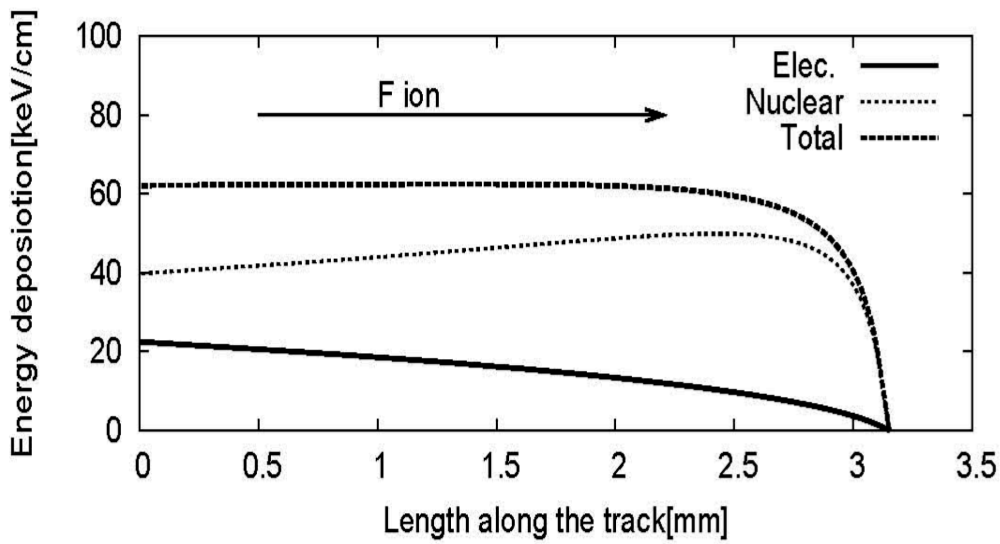
Most experiments use low pressure gas TPCs:



The challenge: reconstructing ~mm tracks in cubic meter volume TPCs

Zoom in on the recoil:



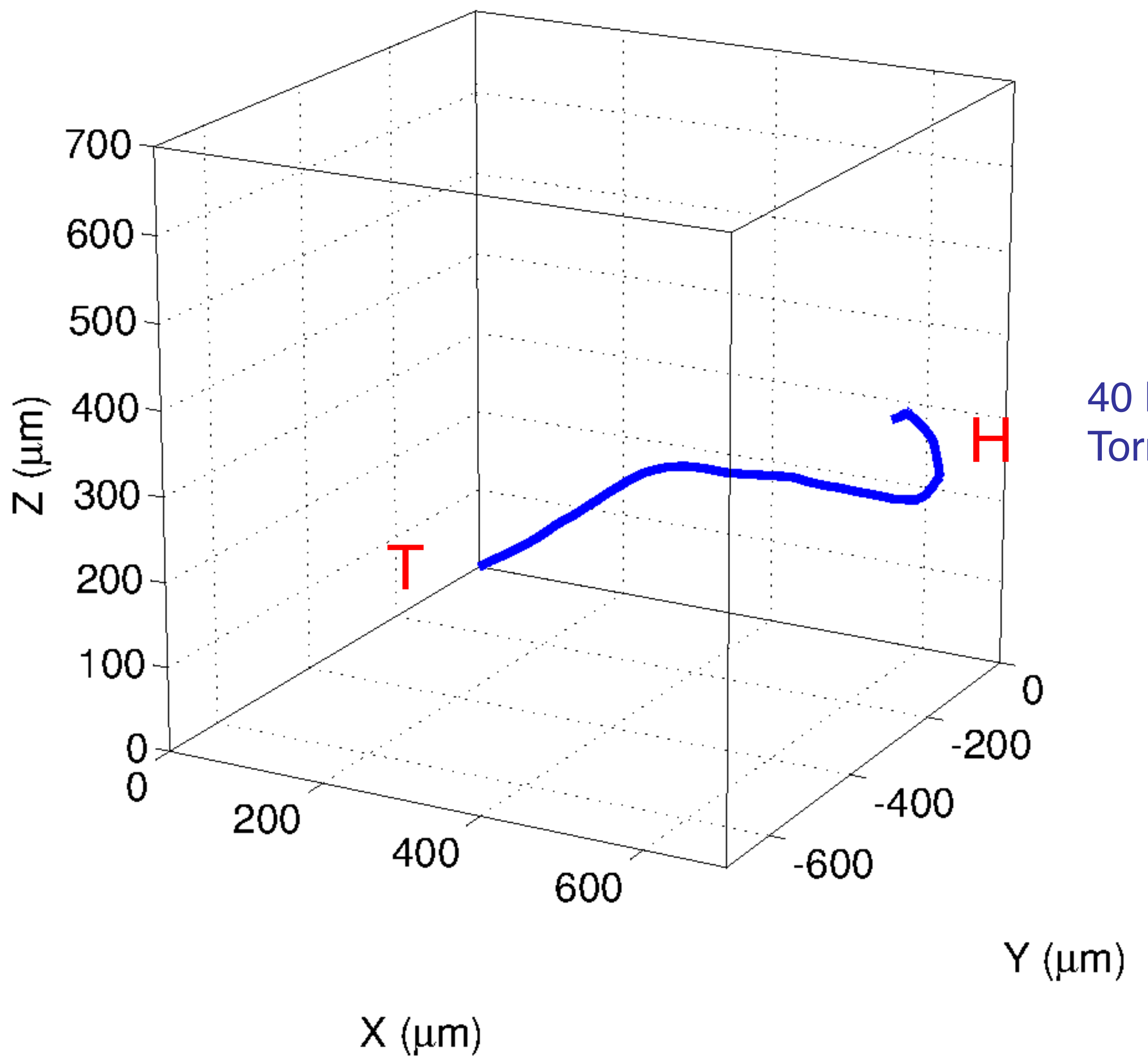


Importance:

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

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

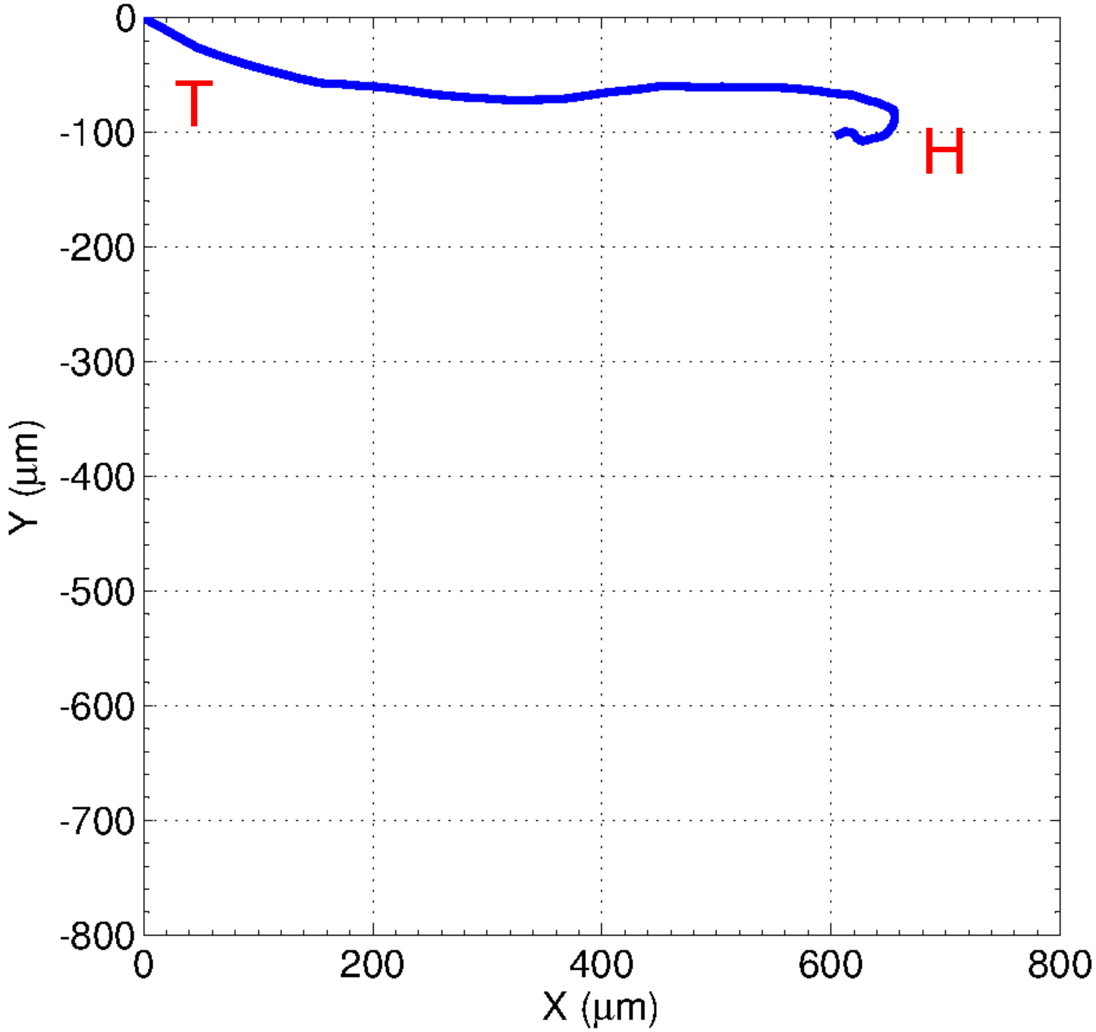
A real recoil has straggling:



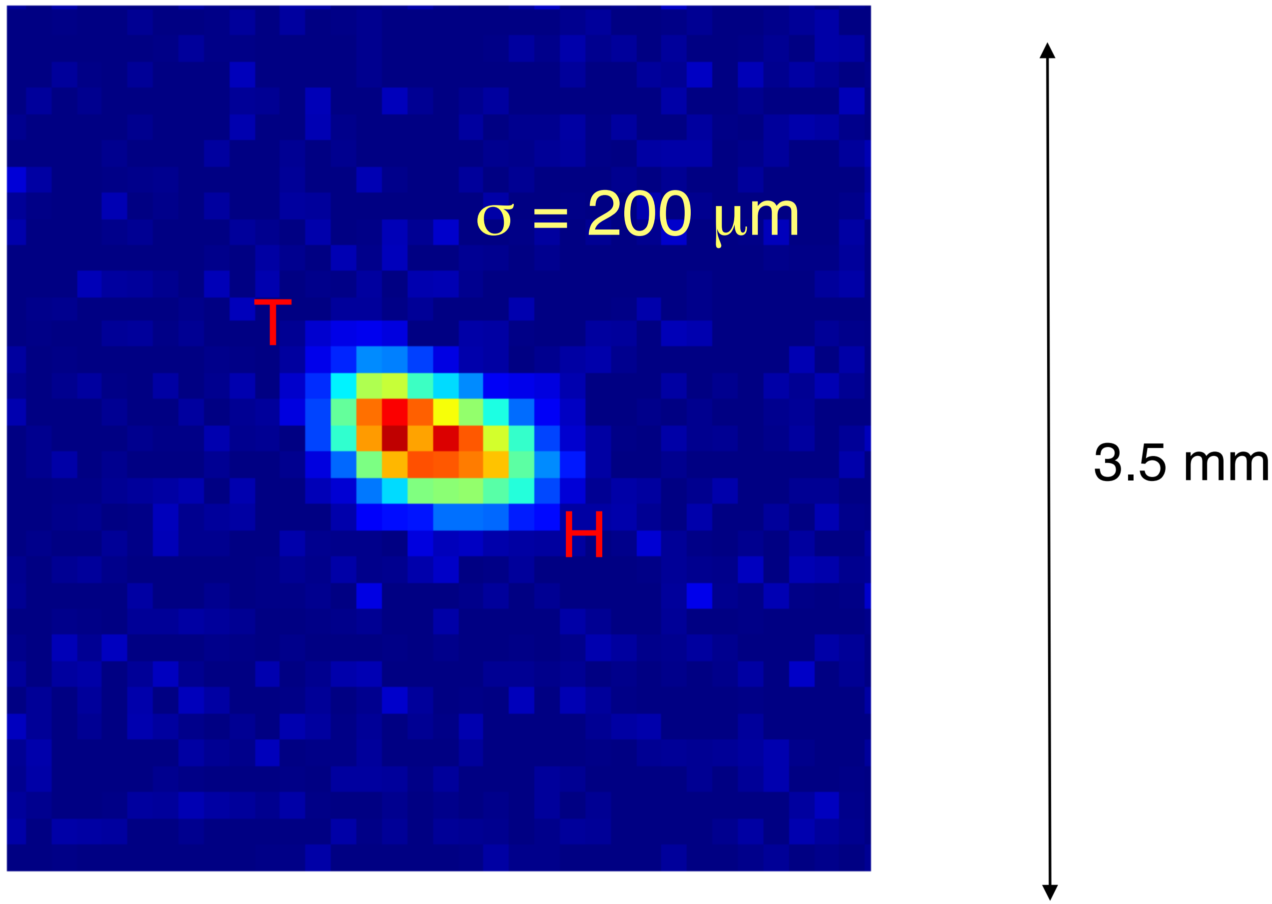
40 keV F in 100 Torr CF_4

SRIM

Projection (2D or 3D):

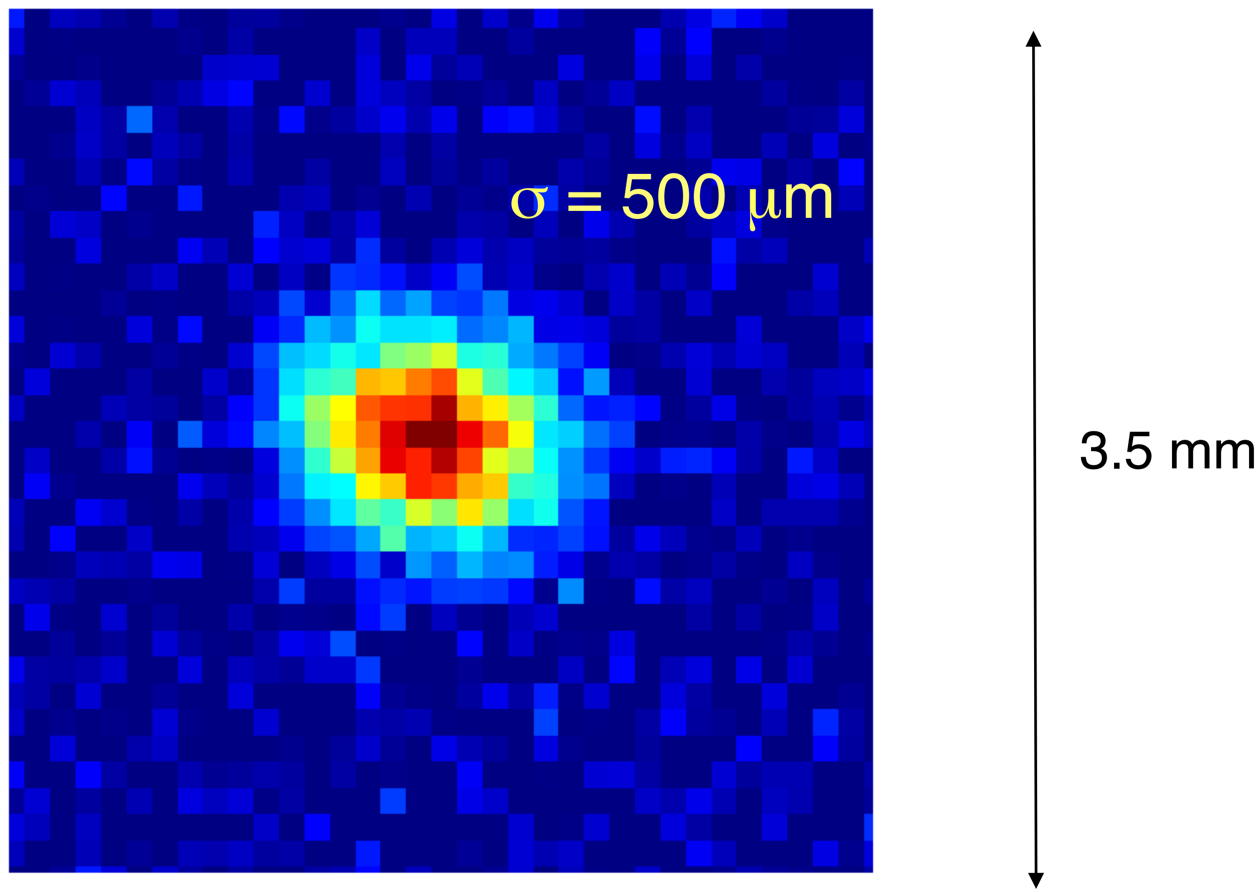


Diffusion:



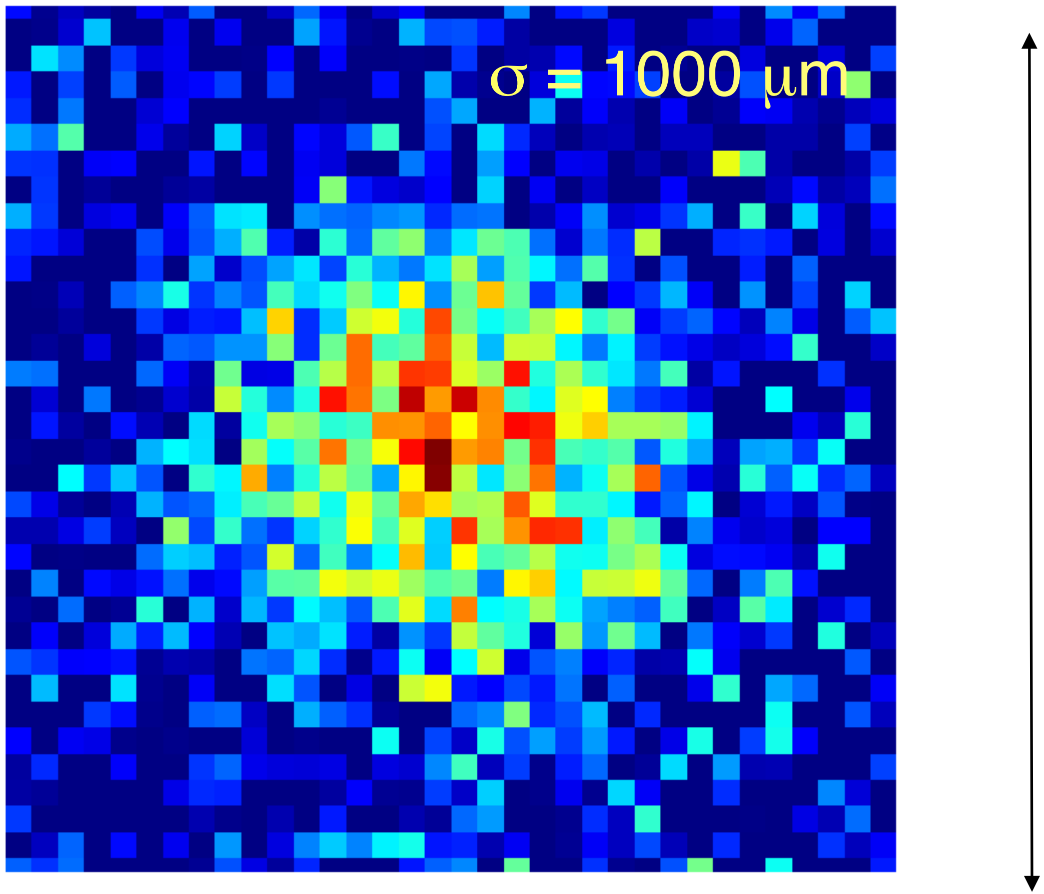
100 μm pixel readout

Diffusion:



100 μm pixel readout

Diffusion: you need to keep it low!!

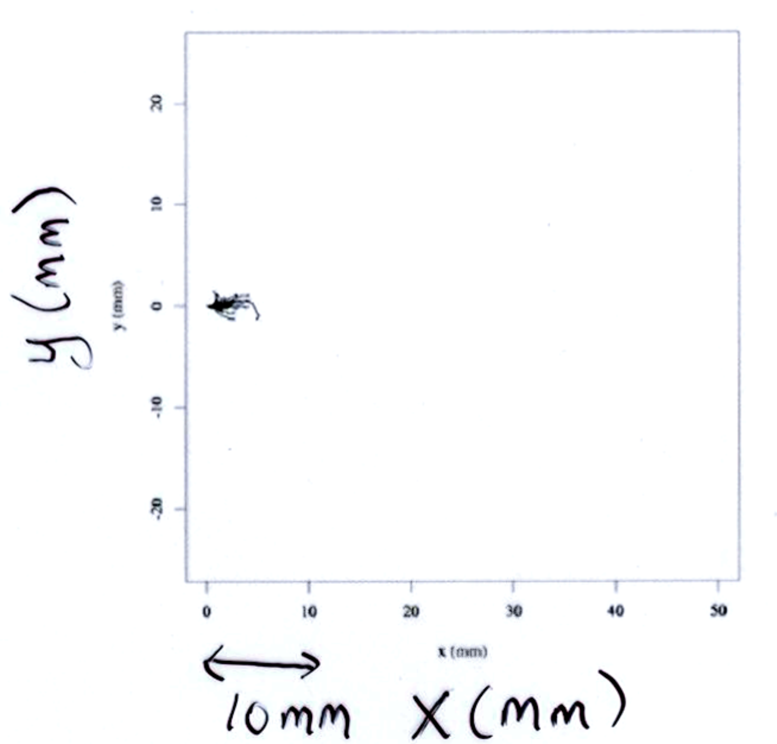


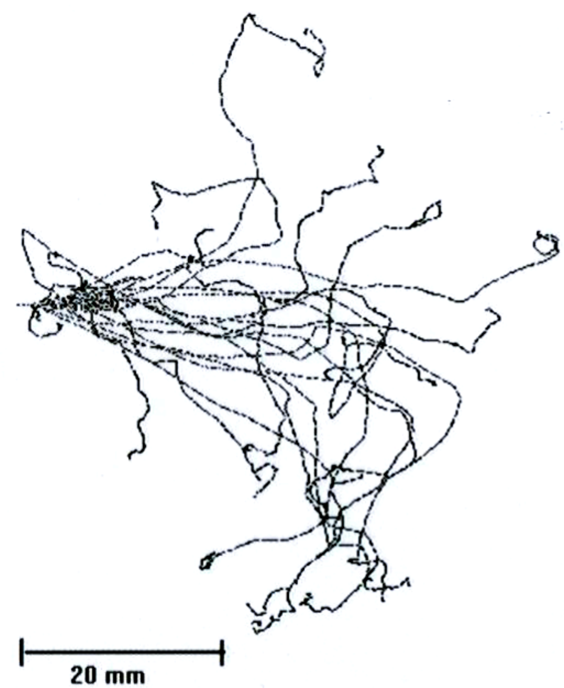
100 μm pixel readout

Tracks also provide background discrimination

Each deposits the same detectable energy (~500 electron-ion pairs) in the gas

40 KeV Ar recoils	13 KeV electrons





Simulations from SRIM97, EGS4/ Presta

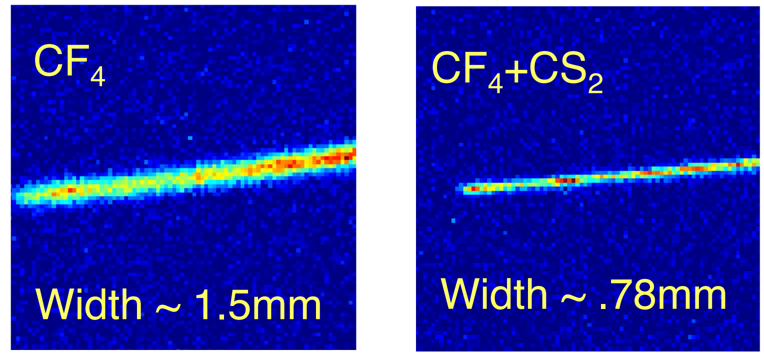
Advantages of gas TPCs: flexibility

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

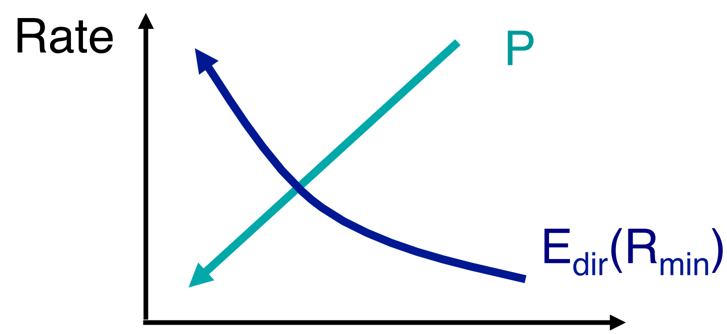
• Negative ion drift: target $+CS_2$ mixtures (or SF_6) enable drift with thermal diffusion (Martoff).

vs

Shorter drift distance



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



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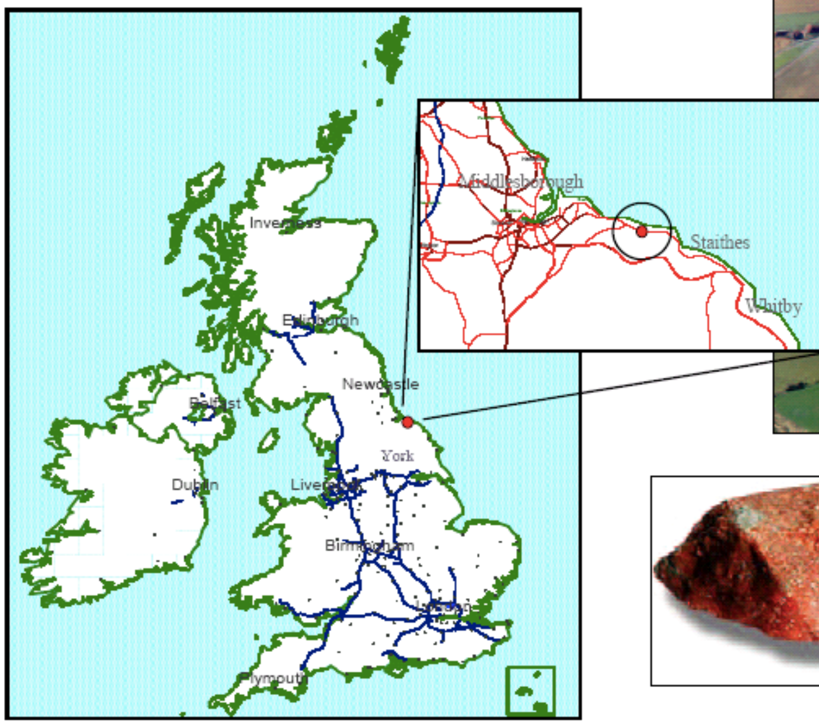
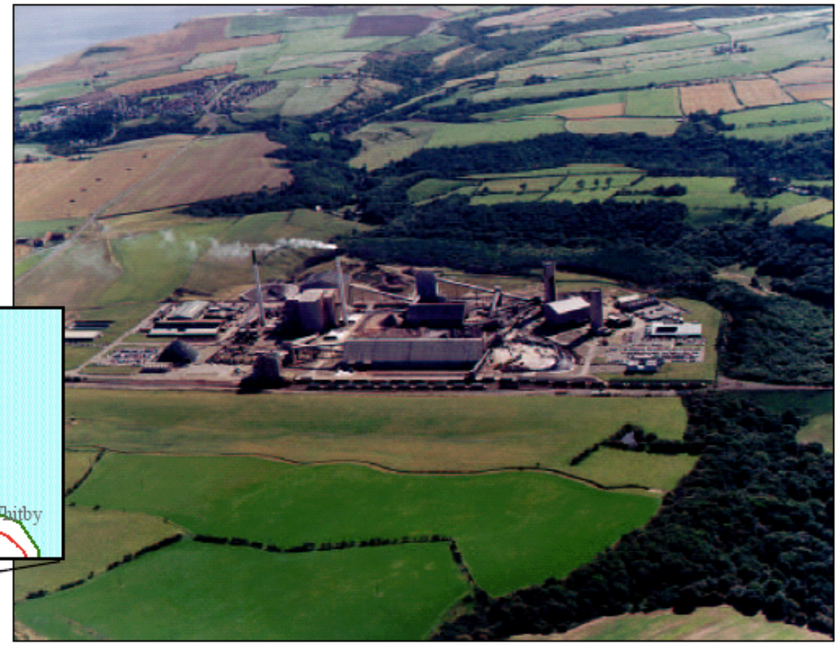
DRIFT is located in the Boulby Mine in UK

- Working Potash mine
- Deepest mine in Britain
- 850m to 1.3km deep





Sylvanite

CLEVELAND POTASH

DRIFT - Directional Recoil Identification From Tracks

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

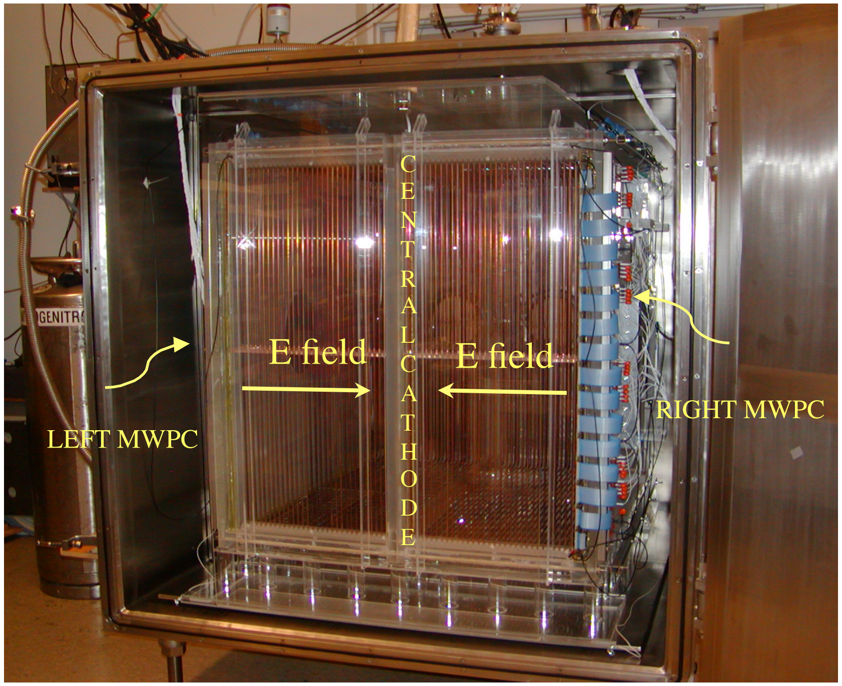
University of New Mexico
Dinesh Loomba - PI
Michael Gold – PI
John Matthews - PI
Eric Lee
Eric Miller
Nguyen Phan
Randy Lafler

The University of Edinburgh
Alex Murphy – PI

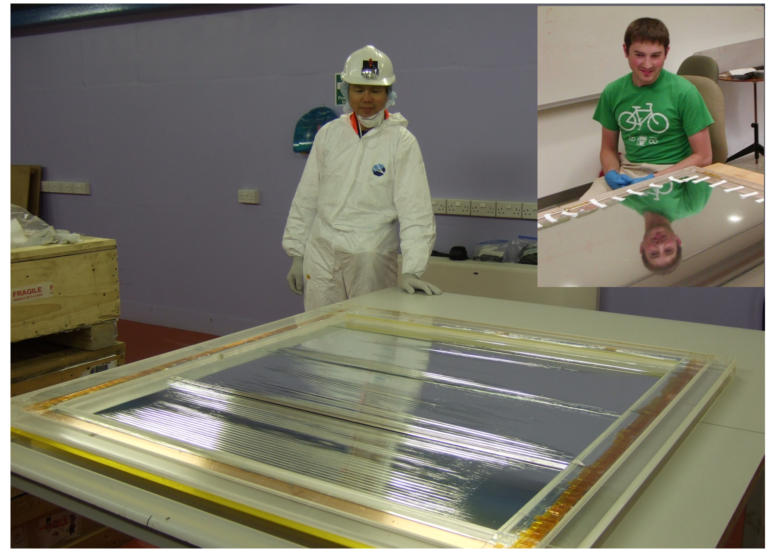
Wellesley College
James Battat – PI
NEW!

University of Hawaii
Sven Vahsen – PI
NEW!

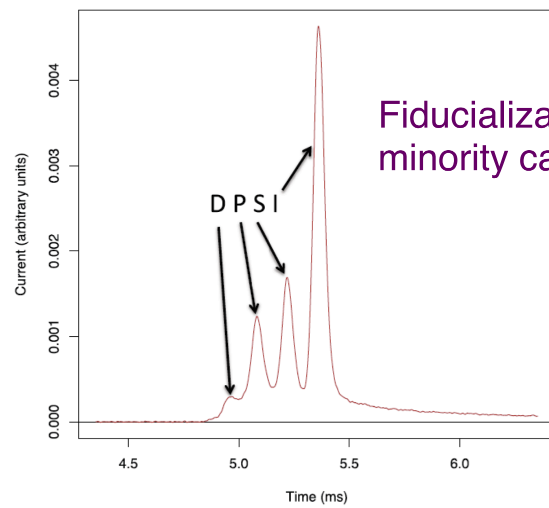
Boulby Mine
Sean Paling – PI
Emma Meehan
Louise Yeoman



0.9 μm thin cathode



- $1m^3$ Negative Ion TPC with 30+10+1 Torr $CS_2+CF_4+O_2$
- MWPC readouts
- Operating in Boulby for >10 years
- **Operated with ZERO backgrounds for > 100 days!**

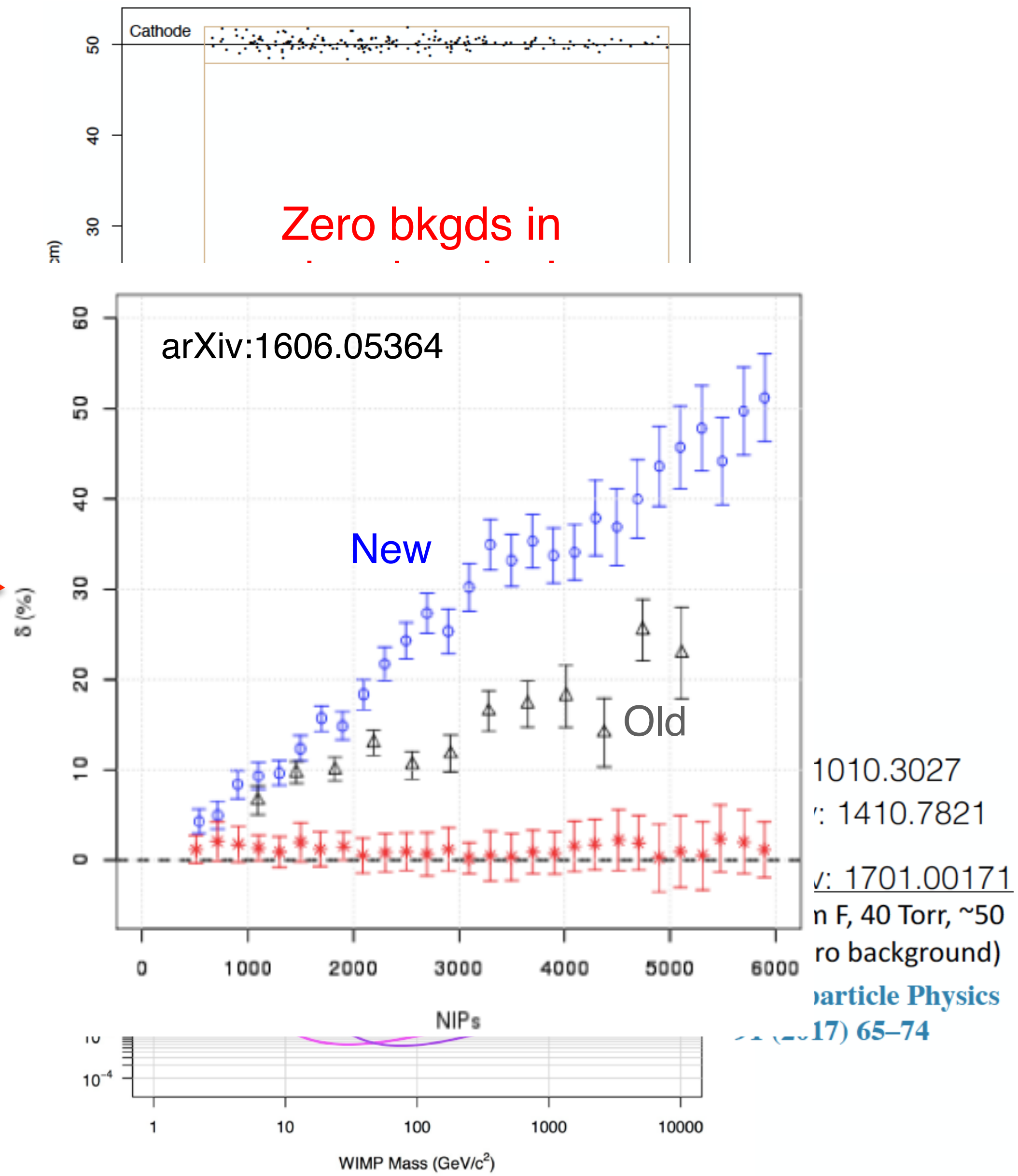


Fiducialization with minority carriers

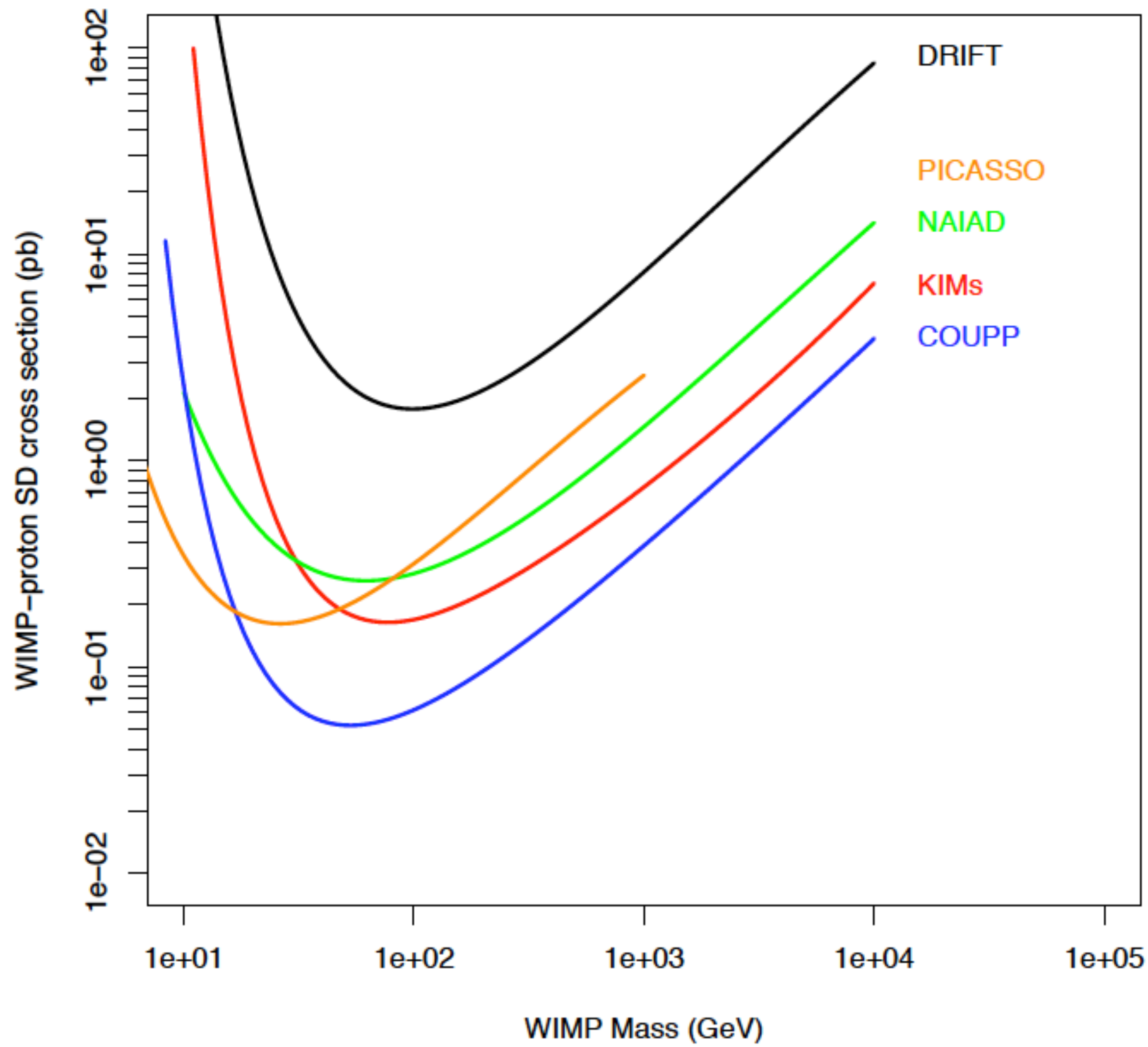
Latest Results:

- gamma rejection better than ~ 2×10^{-7} (90% CL)
- **zero backgrounds thanks to thin-film cathode and fiducialization, resulting in new limits**
- better (1D) directionality

- DRIFT has entered a new phase, going from being background limited, to being volume limited.

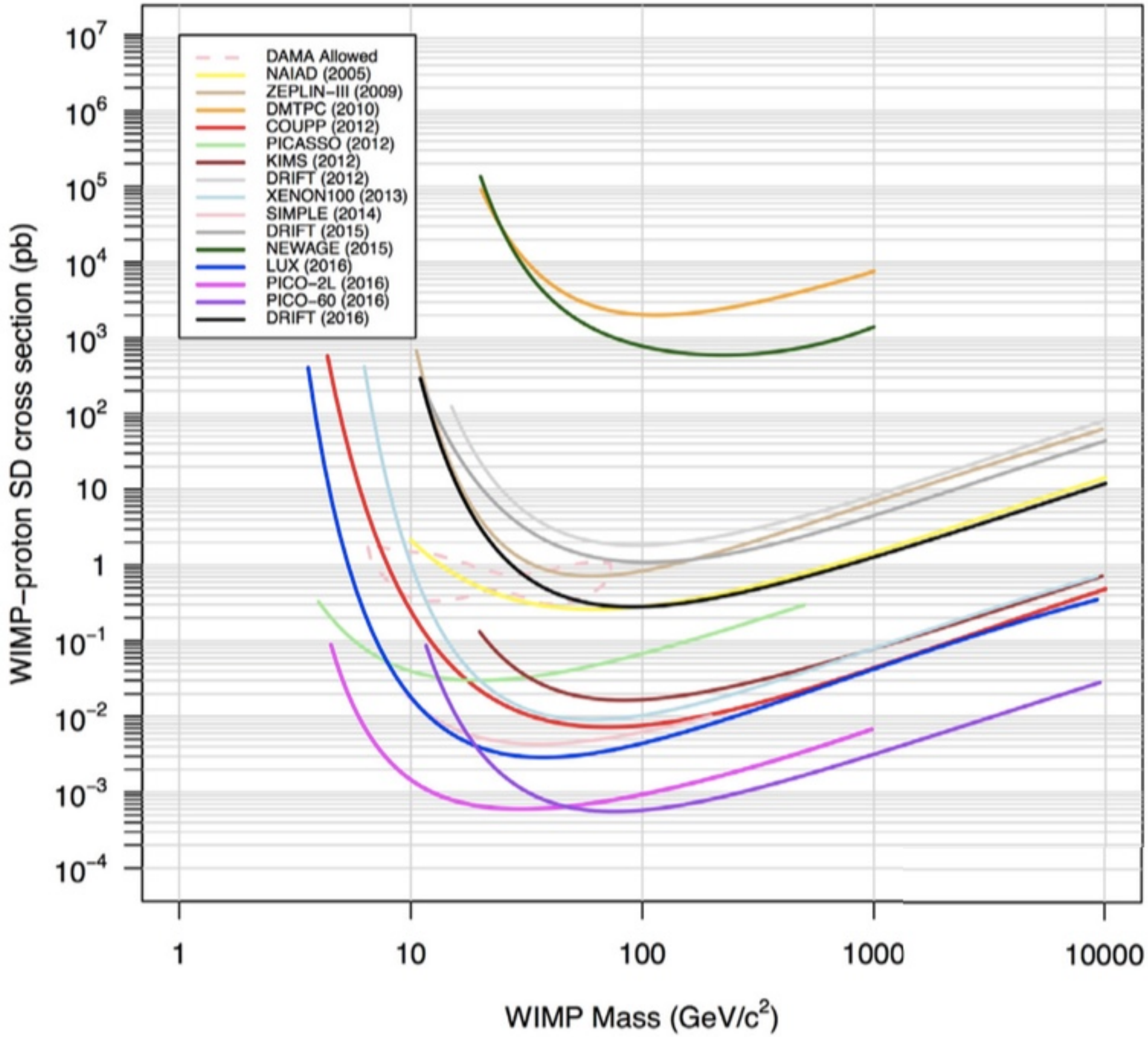


DRIFT set competitive SD WIMP-p limits early on:



Astropart. Phys. 35 (**2012**) 397

DRIFT limits today – non-directional experiments have lept forward!



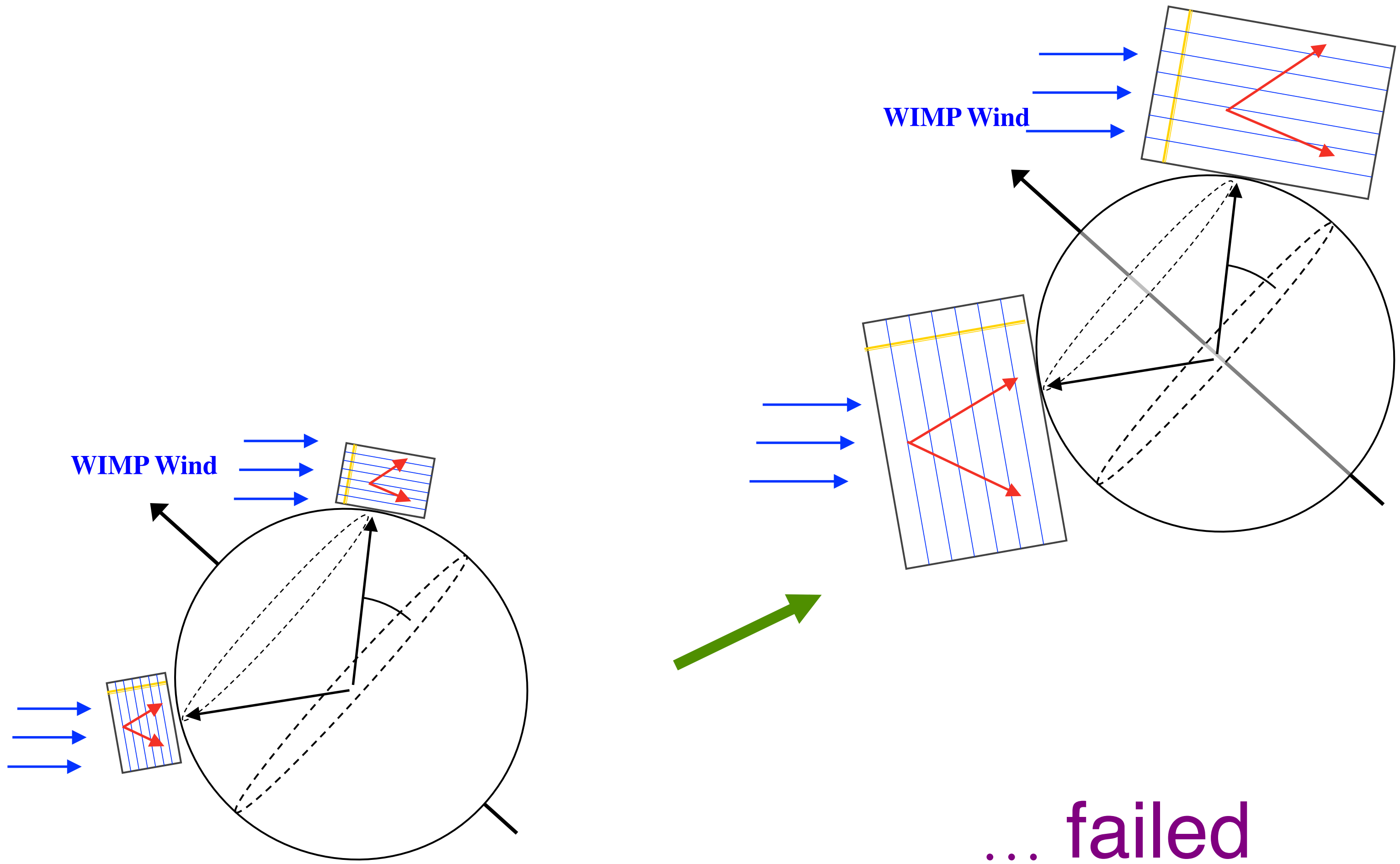
Astropart. Phys. 91 (**2017**) 61

How can we improve DRIFT's sensitivity?

- **Limit-setting sensitivity**
  - Target mass fraction. DRIFT's gas mixture, 30/10/1 $CS_2/CF_4/O_2$ has **only ~33 g of F**
  - Energy threshold (discrimination & directional). DRIFT's current threshold for both is ~40 keV recoil energy F

- **Directional sensitivity**
  - DRIFT's directional signature requires **≥ 440 events** to rule out isotropy. Can we approach the theoretical limit of few 10's of events?
  - Can the directional threshold be lowered below **~40 keVr** F? **→ low mass WIMPs + ν-floor!**

The brute force solution…



… failed

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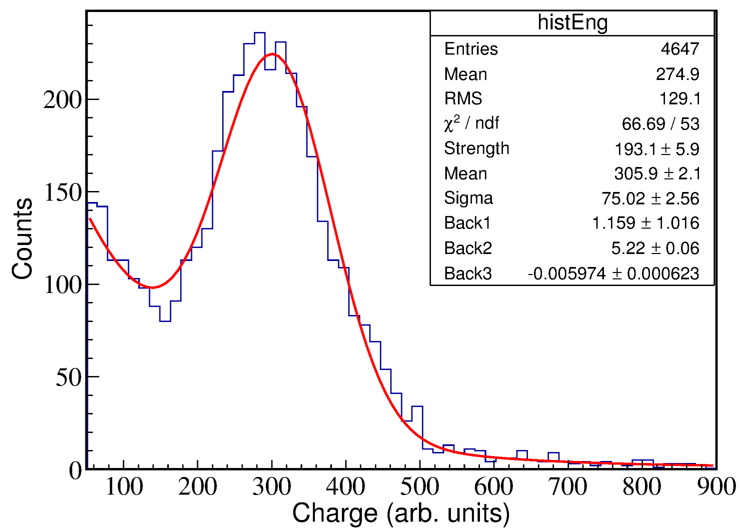
R&D at UNM to address these issues

- Gas studies to search for new gases with the benefits of CS_2 (thermal diffusion), O_2 (z-fiducialization) and CF_4 (F-rich for SD interactions)
- Study basic properties of electronic and nuclear recoils to understand limitations on directionality and discrimination

Gas Studies

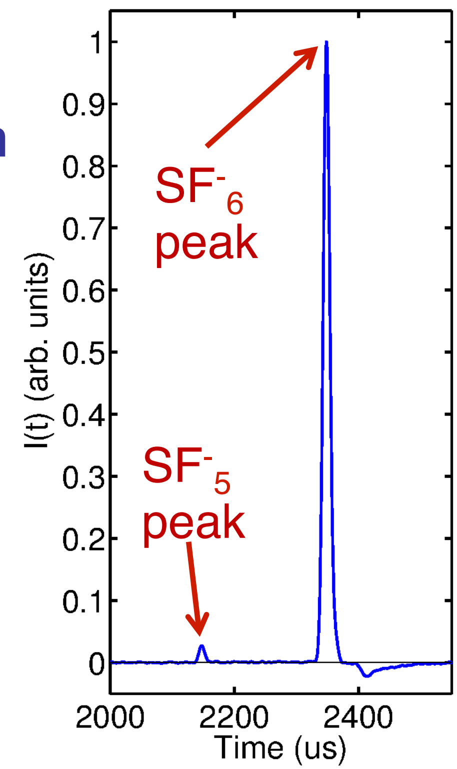
- What single gas has all of the benefits of the DRIFT mixture:
  - CS_2 (thermal diffusion)
  - O_2 (z-fiducialization)
  - CF_4 (F-rich for SD interactions)
- What about SF_6?
  - Highly electronegative
  - F-rich
  - Z-fiducialization?

Does it sustain gas amplification?

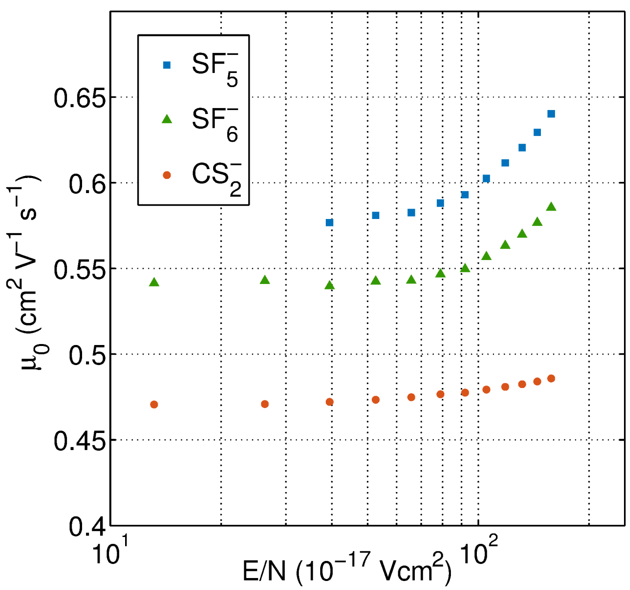


^{55}Fe energy spectrum in 30 Torr SF_6 using 0.4 mm THGEM – G ~ 3000

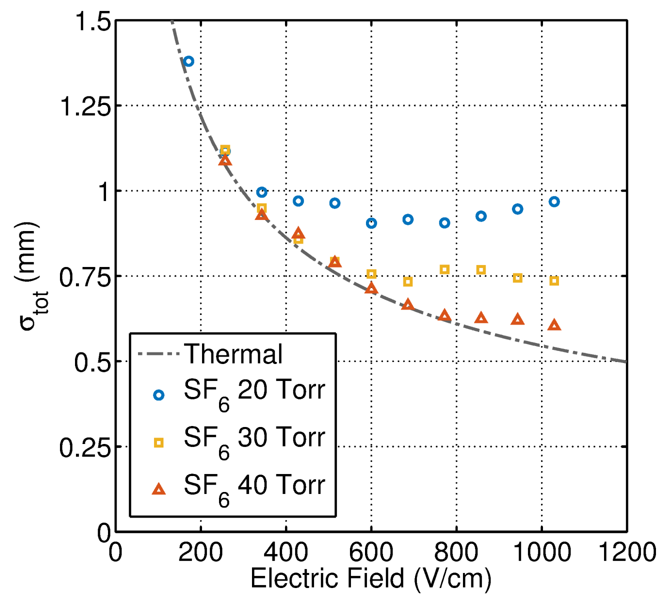
- **gas gain**
- **Thermal diffusion**
- **fiducialization**
- **8X target mass of DRIFT at same pressure**



Waveform has Multiple Peaks



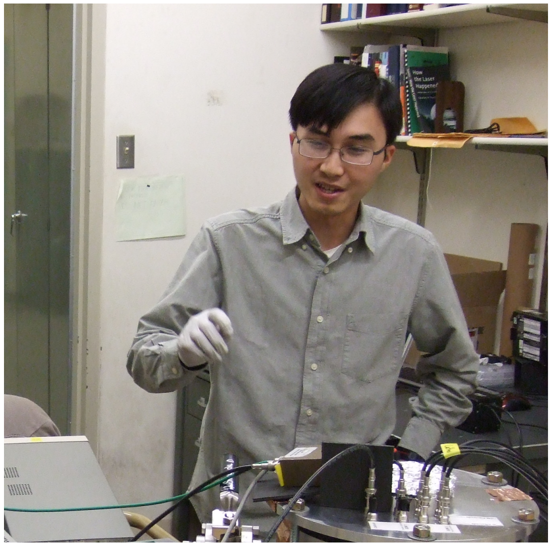
Reduced Mobility



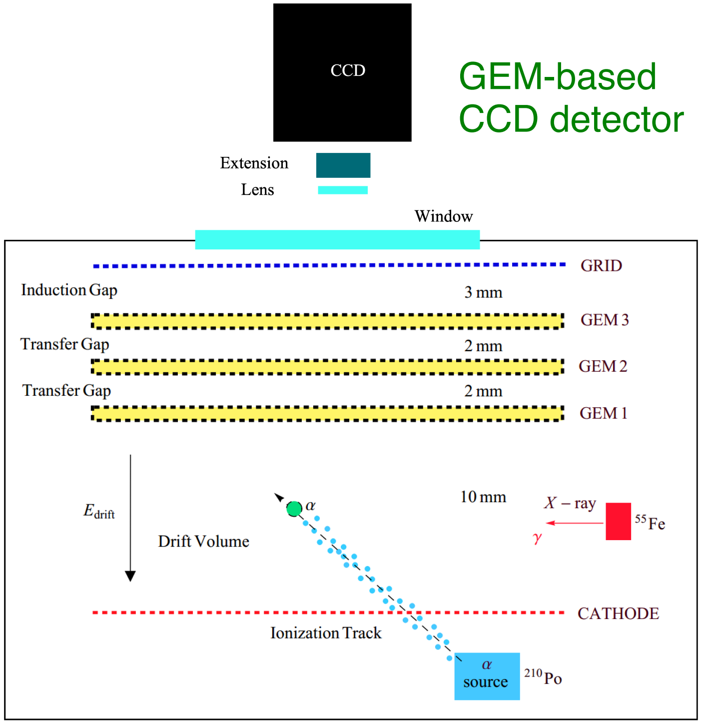
Diffusion

N.S. Phan, et al, *JINST 12*, P02012, 2017.
(arXiv:1609.05249)

UNM R&D: study limitations on discrimination and directionality with an optimized detector



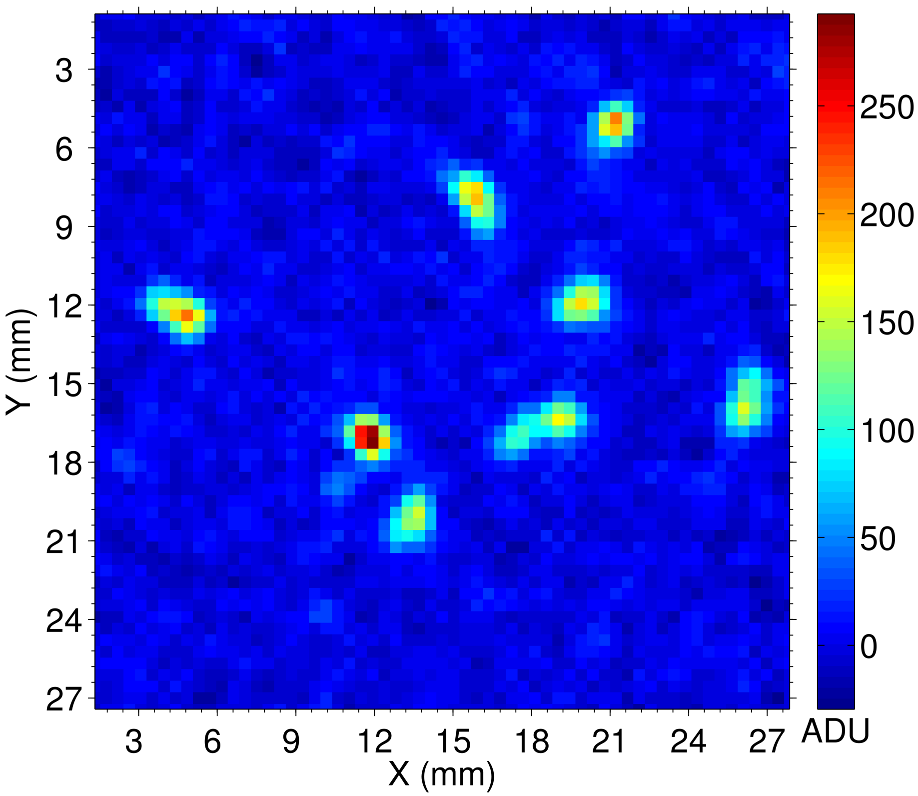
Nguyen Phan (PhD student, UNM)

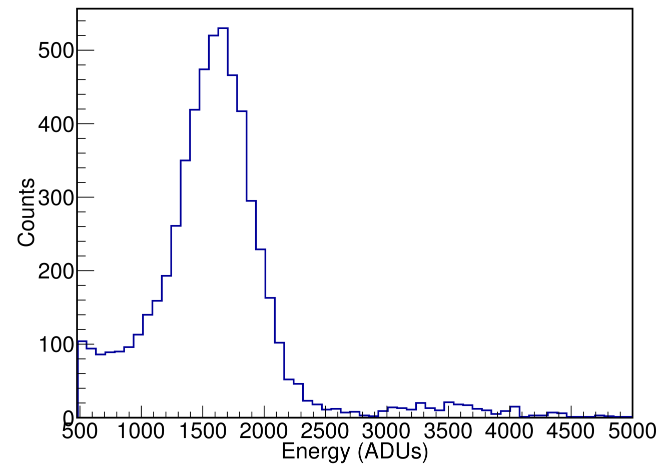


GEM-based CCD detector

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

Very high S/N allows us to optically resolve Fe-55 tracks:



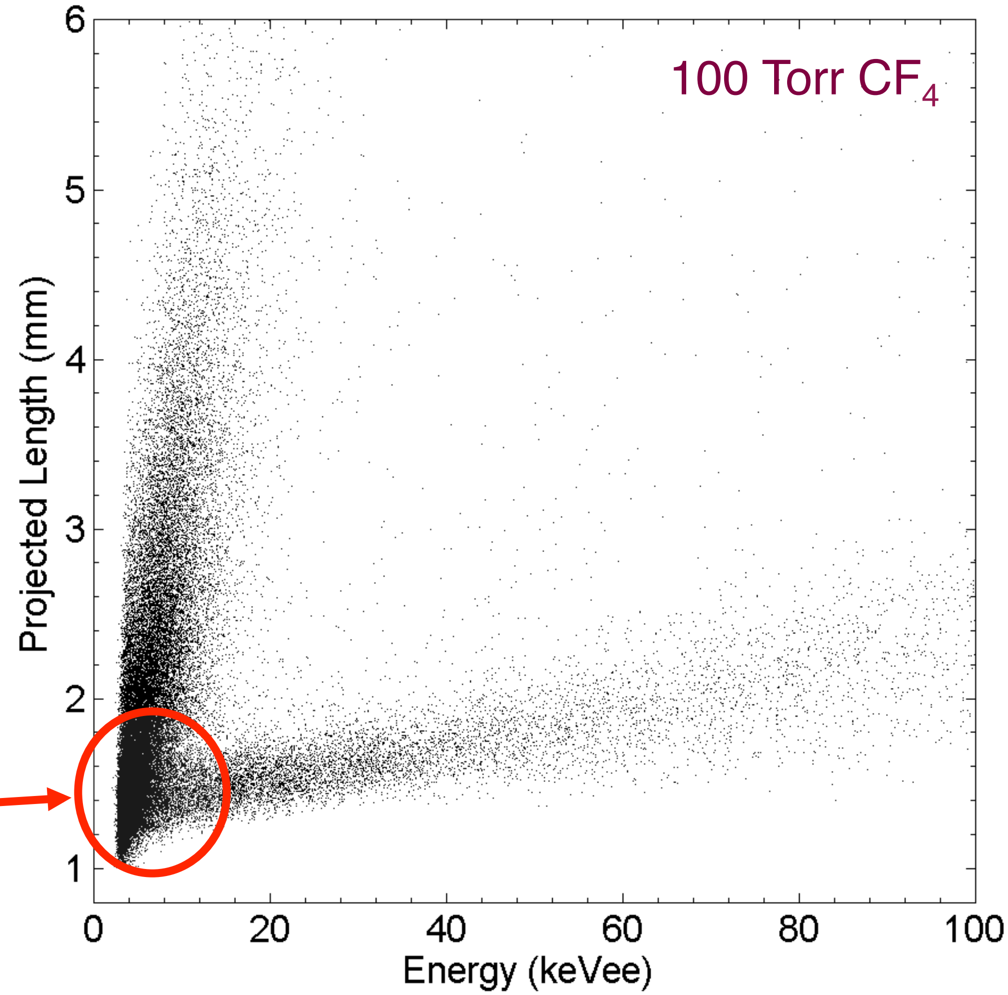


To our knowledge, this is the first optical ^{55}Fe spectrum (FWHM energy resolution 38%).

Phan, et al. arXiv:1703.09883

Discrimination with Range vs Energy

Low dE/dx:
γ's

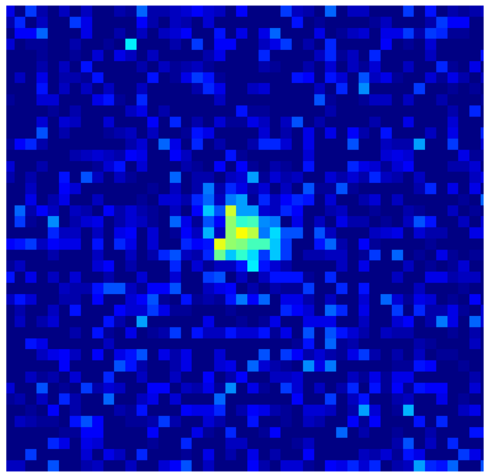


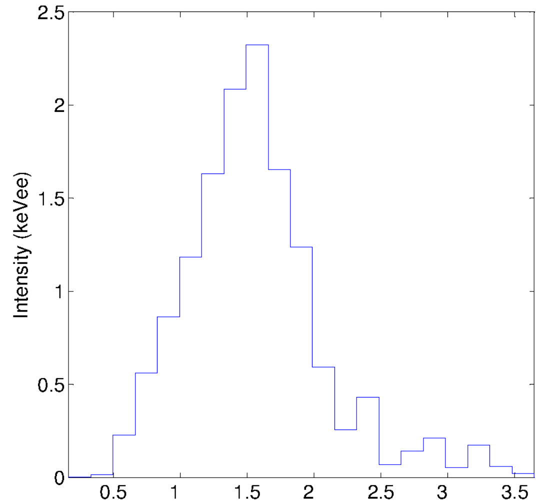
High dE/dx:
nuc. recoils

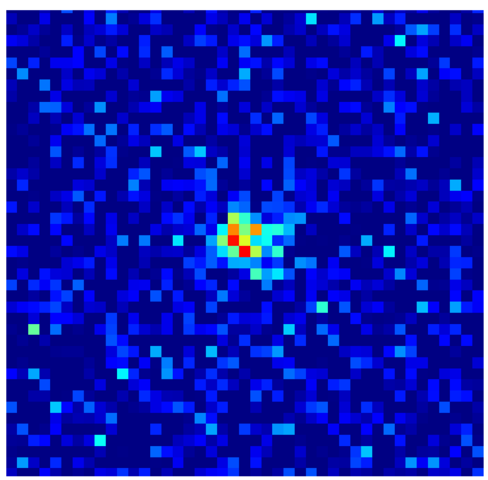
Diffusion +
S/N

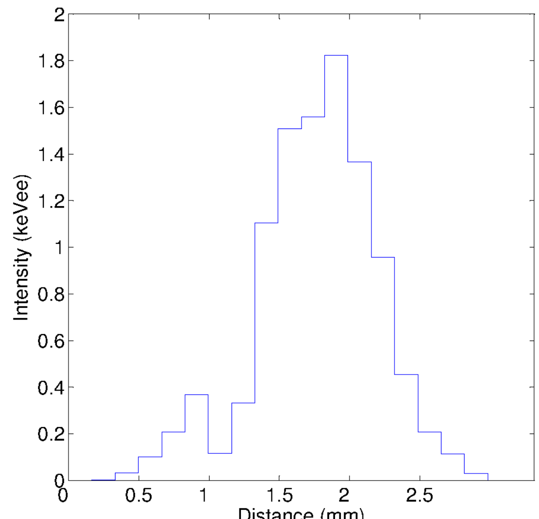
Data from Cf-252 - Phan, et al.
Astro Part Phys (2016)

Gamma backgrounds have small dE/dx, large fluctuations:

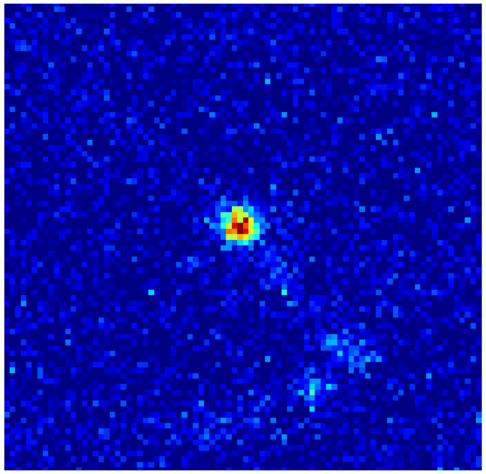


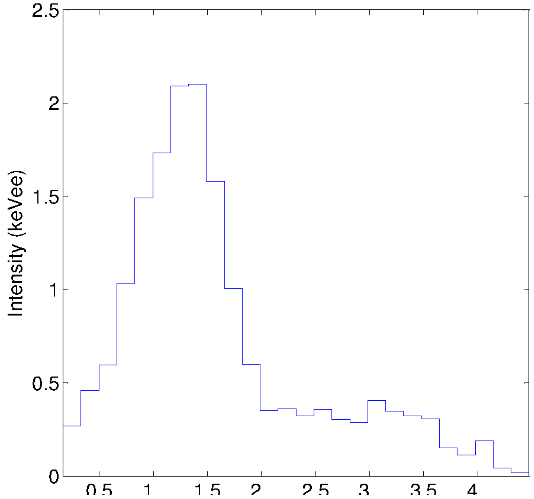


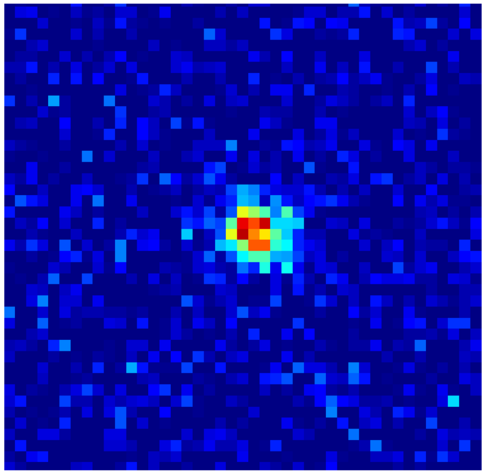


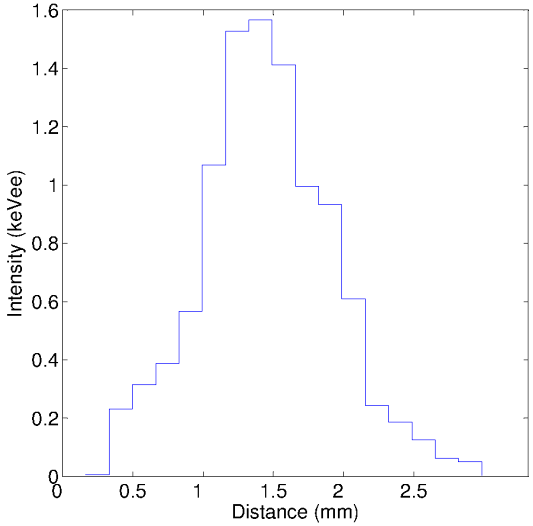


Gamma backgrounds have small dE/dx, large fluctuations:



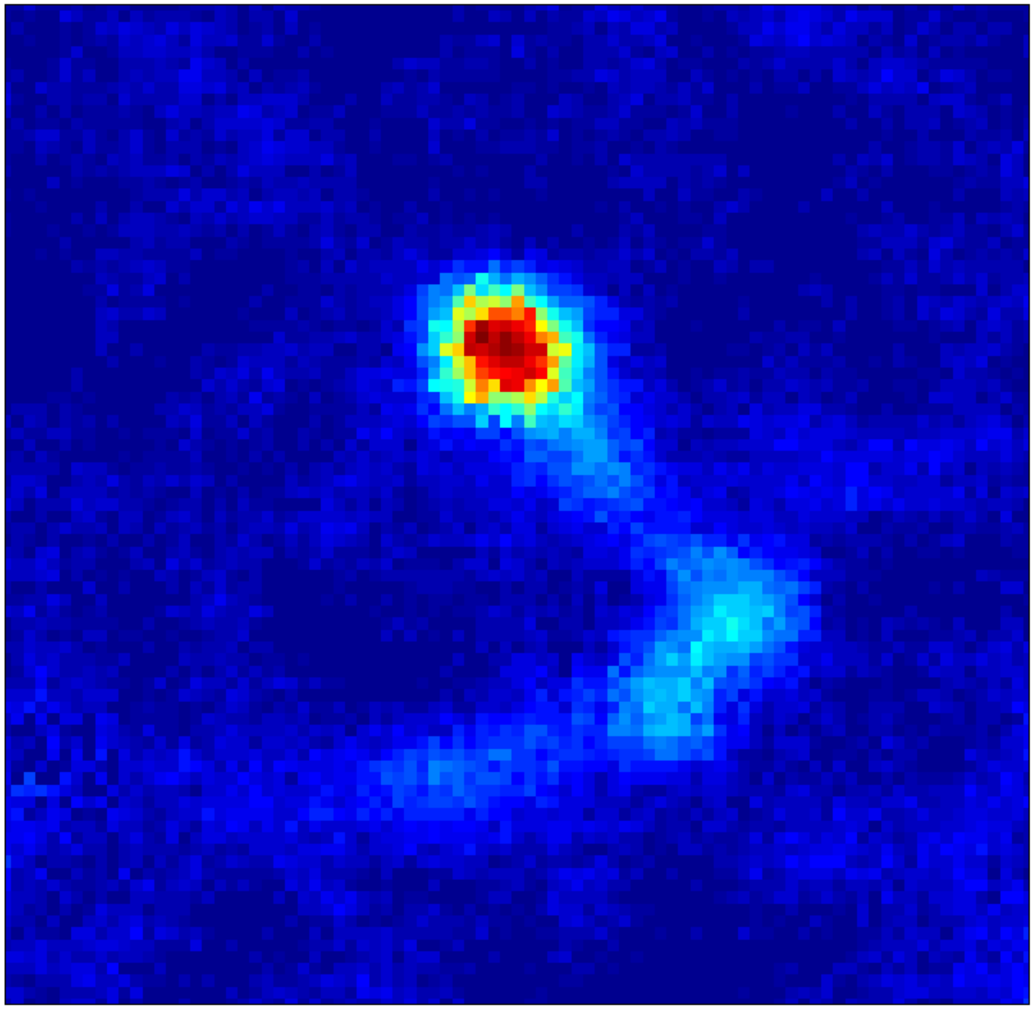






Gamma backgrounds have small dE/dx, large fluctuations:

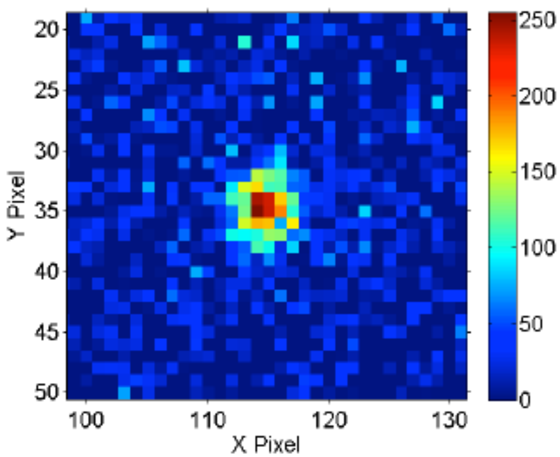
high signal-to-noise is important!



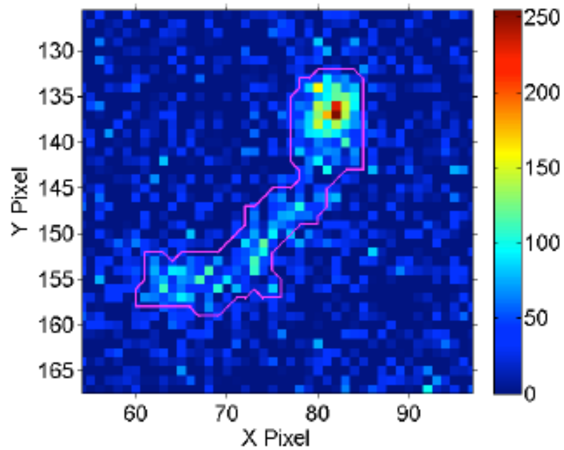
And 3D should help

D Loomba, U of New M

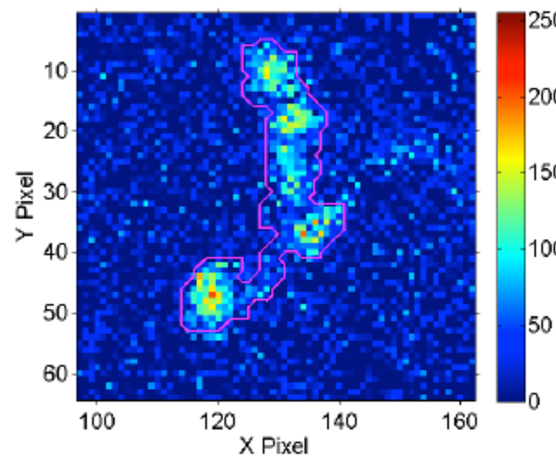
Images of Electronic & Nuclear Recoils in 100 Torr CF_4



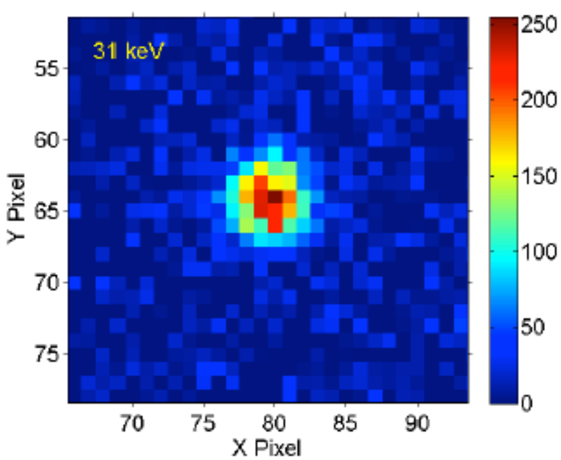
(a) 8 keV electronic recoil



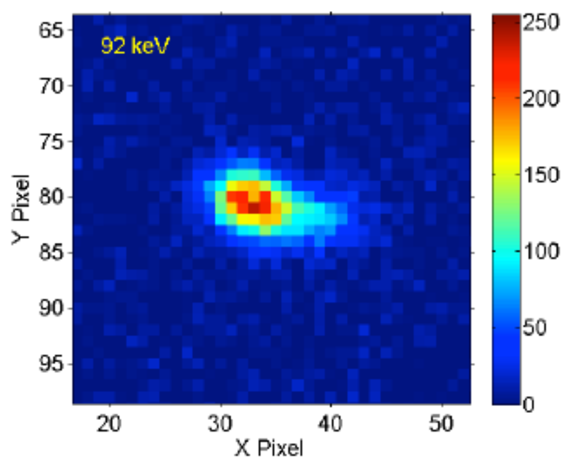
(b) 17 keV electronic recoil



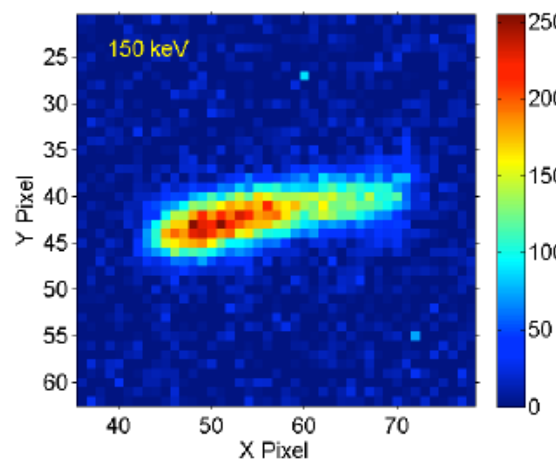
(c) 39keV electronic recoil



(d) 31 keV nuclear recoil



(e) 92 keV nuclear recoil

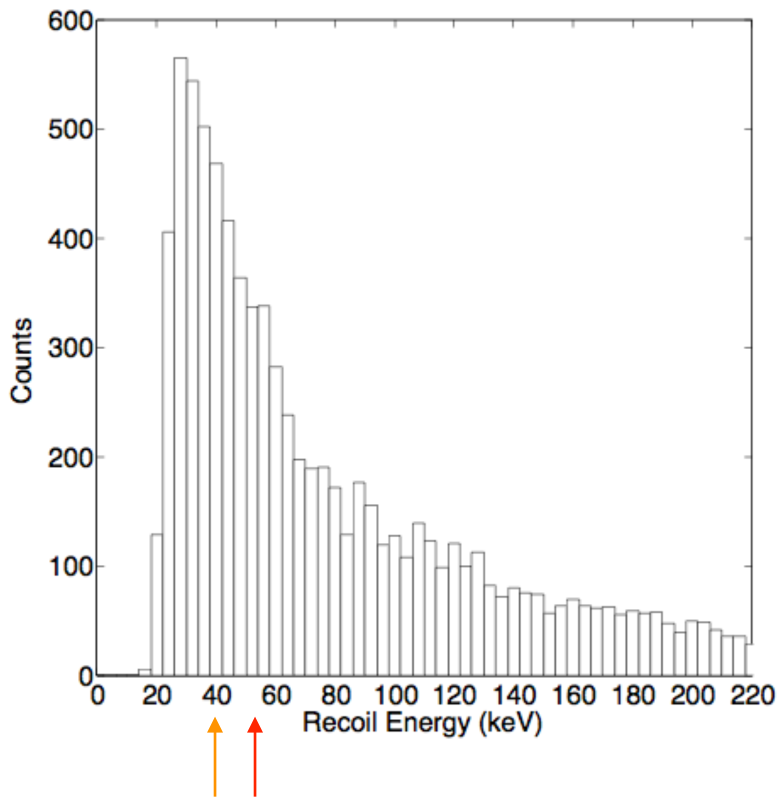


(f) 150 keV nuclear recoil

Data from Co-60 & Cf-252 - Phan, et al. Astro Part Phys (2016)

Results from Cf-252 exposure:

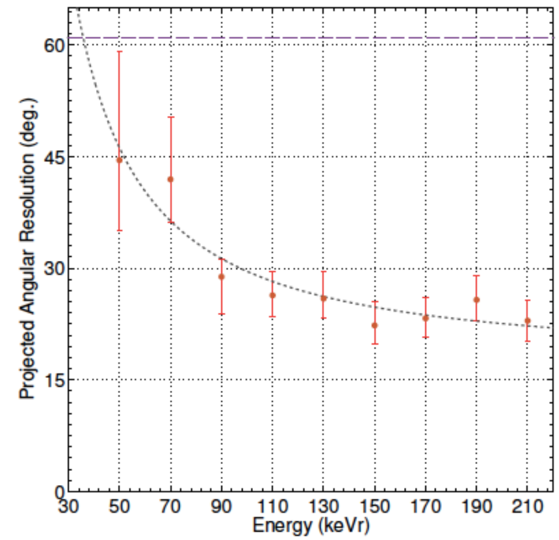
Nuclear recoil energy spectrum

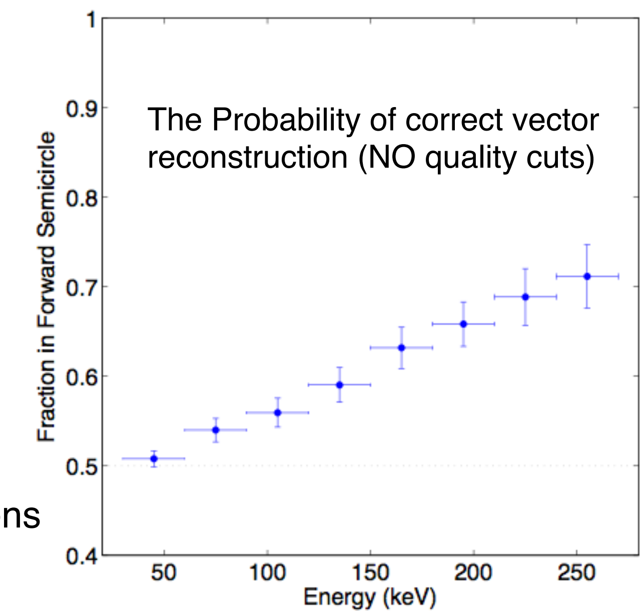


Directionality threshold:
axial, vector

Results are conservative: neutrons scatter, WIMPs don't

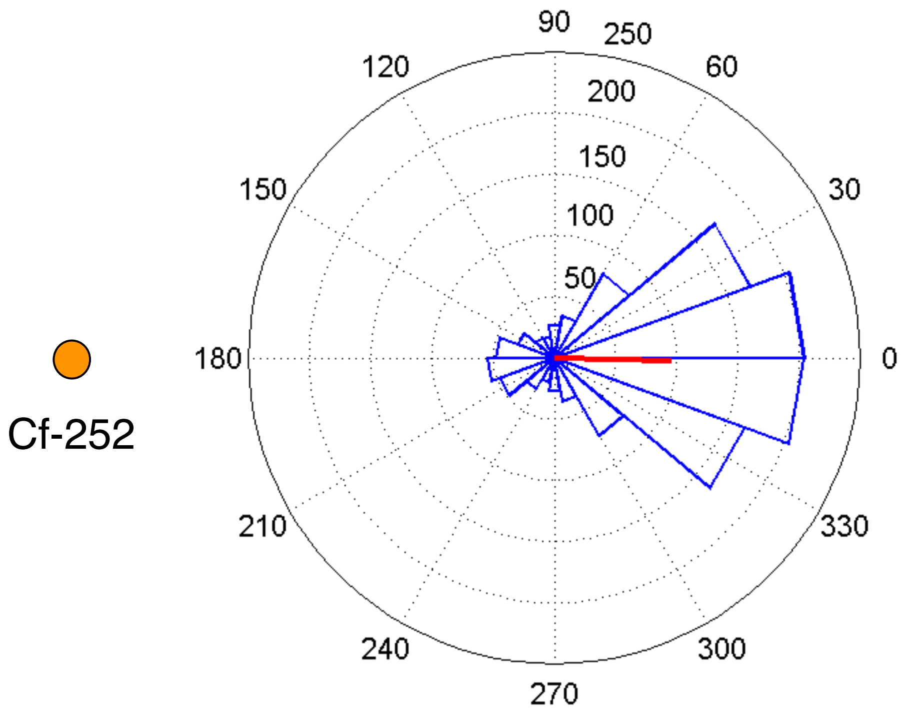
2D angular resolution



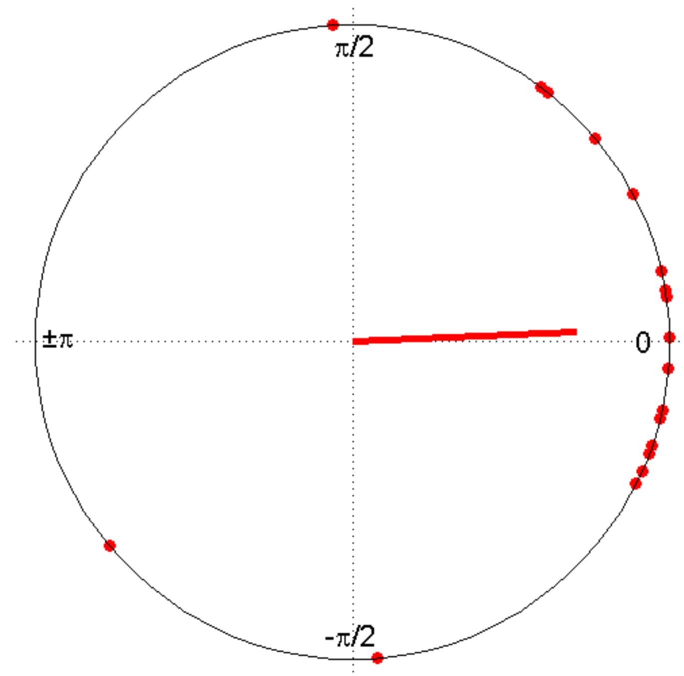


Results from Cf-252 exposure (cont.):

2D circular histogram of vector recoil directions, after cuts



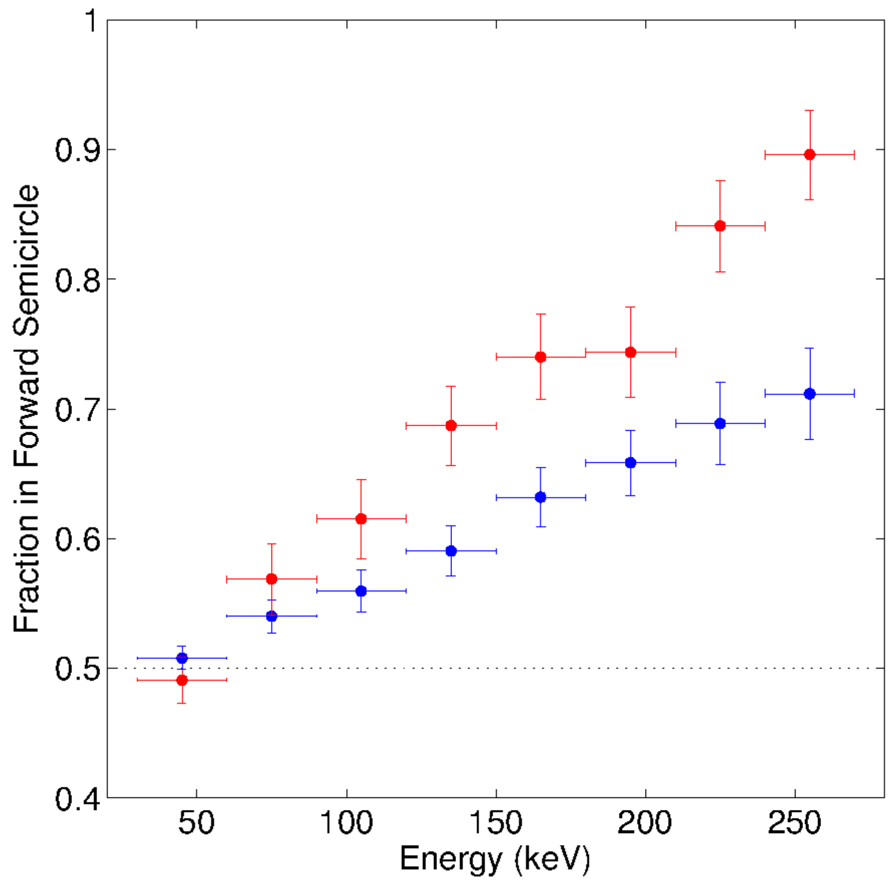
~18 events (90% CL) needed to point back to the source…



…after quality cuts on ~40 events randomly chosen from dataset.

For a 100 GeV WIMP, these results imply that ~54 events are needed for discovery.

The Probability(correct) of vector sense reconstruction (NO quality cuts):



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, pressure, plus the ability to vary target A. So one can lower the directionality threshold, e,g, for a low mass WIMP search.

So, did we improve DRIFT's sensitivity?

Comparing the limit setting and directional sensitivity of our CCD-based GEM detector to DRIFT's:

- Our results are in 100 Torr, DRIFT's were in 40 Torr (10 Torr of CF_4, containing SD fluorine target);
- Discrimination threshold is ~25 keV recoil energy, vs. ~40 keV for DRIFT
- Directionality is ~10X better than DRIFT's

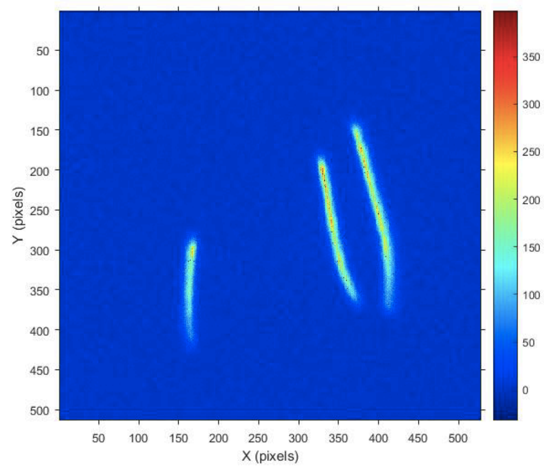
At the same (e.g. 40 Torr) pressure, the CCD detector requires ~30X less exposure than DRIFT to reach a given x-section, and ~80X less exposure for discovery with directionality

*** NOTE: this is not a fair comparison!**

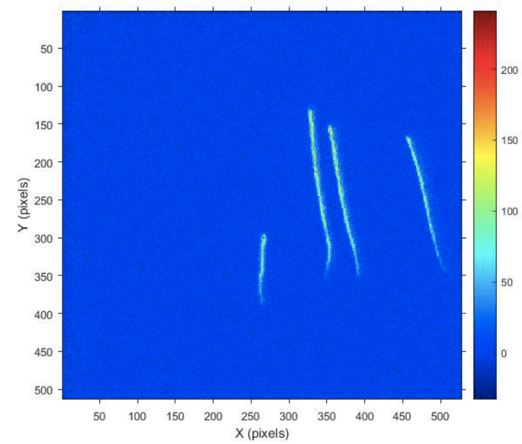
Other tools that could help

- Our CCD results are for electron drift…negative-ion drift has many advantages as shown by DRIFT and our SF_6 studies:

Alphas

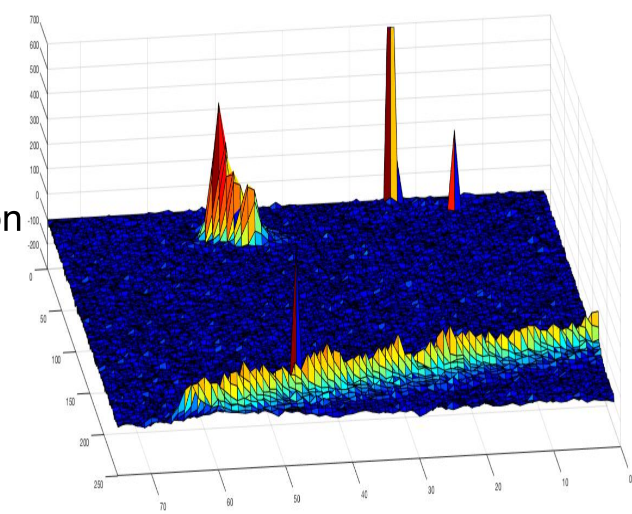


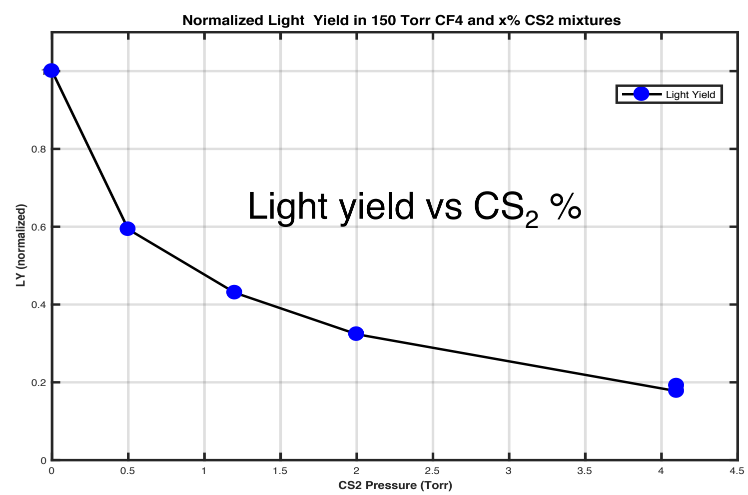
150 Torr CF_4, **σ ~ 450 um**



150 Torr CF_4 + 5.9 Torr CS_2, **σ ~ 150 um**

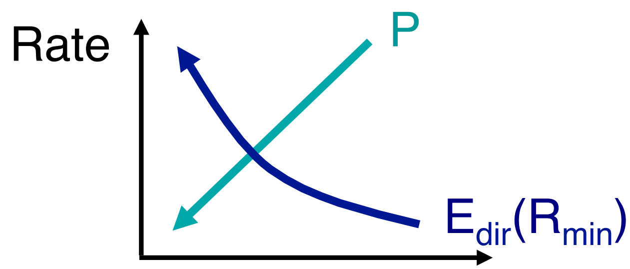
F recoil, proton and CRs in CF_4+CS_2



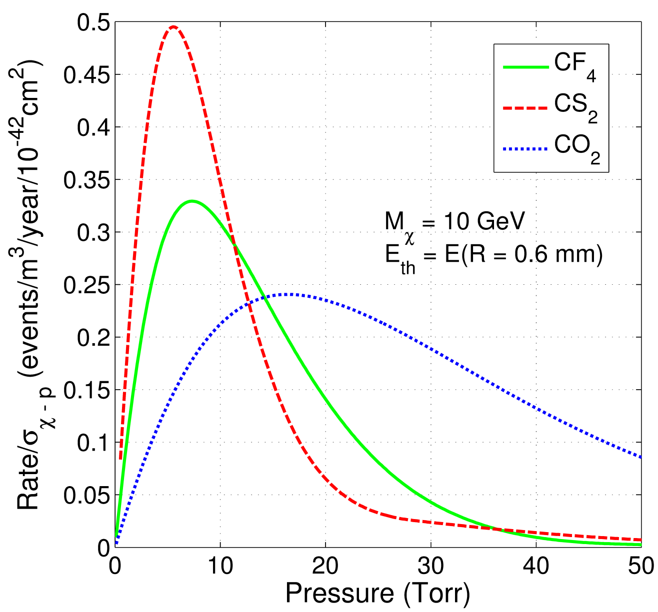


- And lower the pressure to make longer tracks at same recoil E:

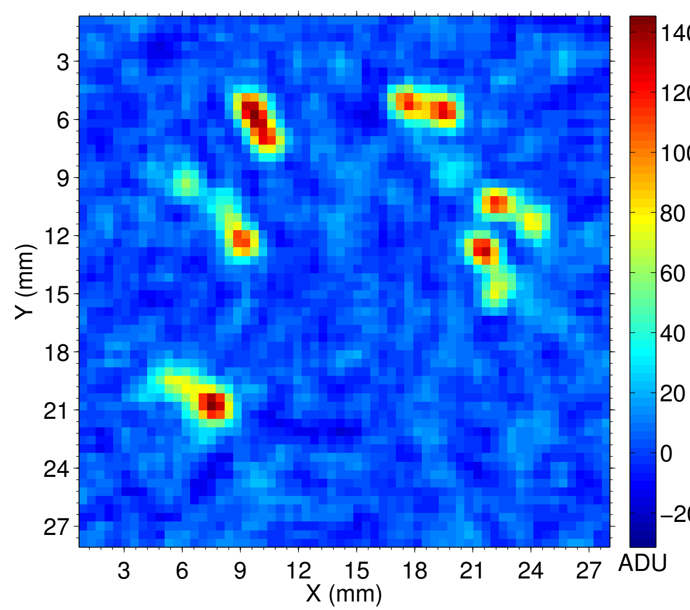
Pressure is tunable: given a minimum resolvable track-size, R_{min}, one can vary the directionality threshold E_{dir} by lowering pressure:



Optimal Pressure for 10 GeV WIMP with R_{min} = 0.6 mm:



R_{min} = 0.6 mm in 10 Torr CF_4 → E_{dir} =6 keV

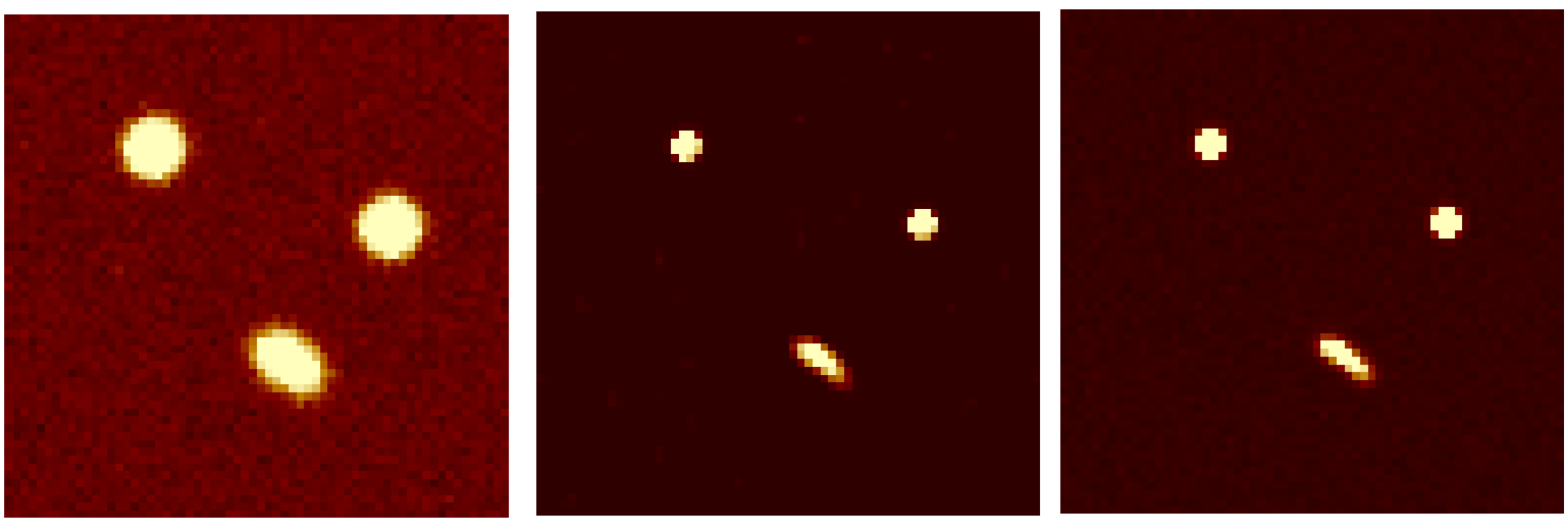


5.9 keV electron tracks in 50 Torr CF4:

- If we have z-fiducialization, we can use deconvolution techniques from astronomy:

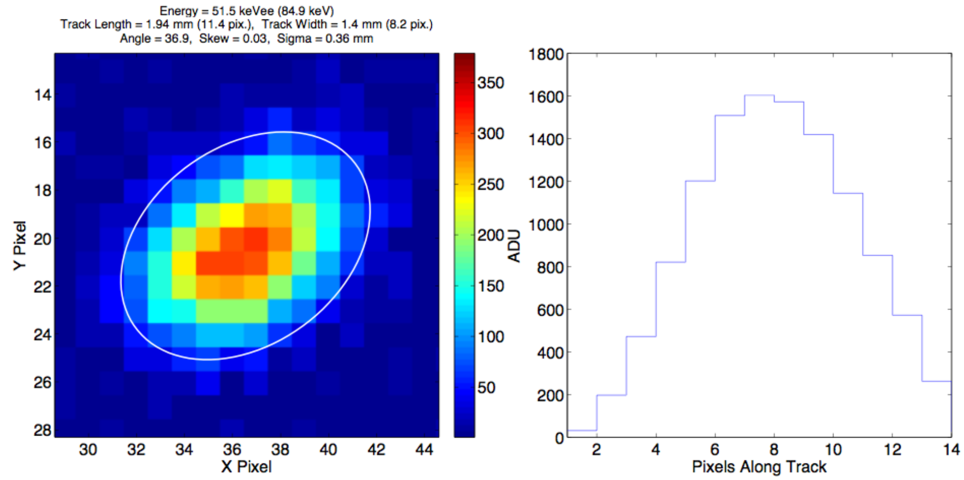
50 keVee fluorine with Cf-252 source to the left, in 100 Torr CF_4:

- Right image is truth (PSF's have to satisfy Nyquist/Shannon/etc and are 2 pixels wide, or Gaussian sigma = 150 um)
- Left image is what Nguyen's detector would see
- Middle image is deconvolved image

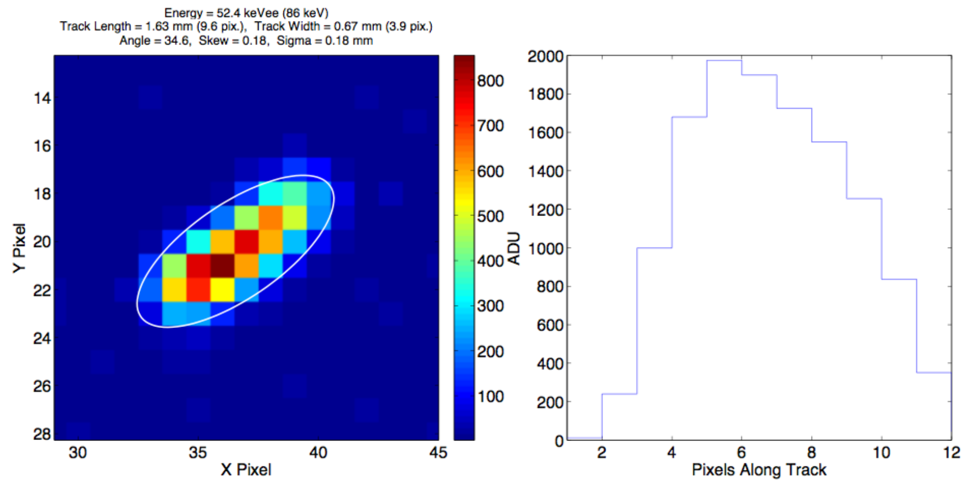


50 keVee:

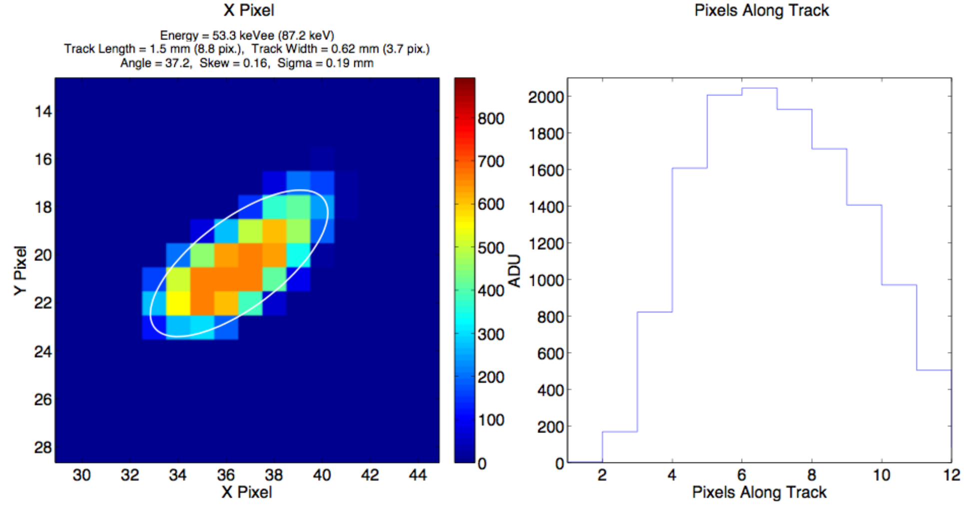
Nguyen's detector sees:



Truth:

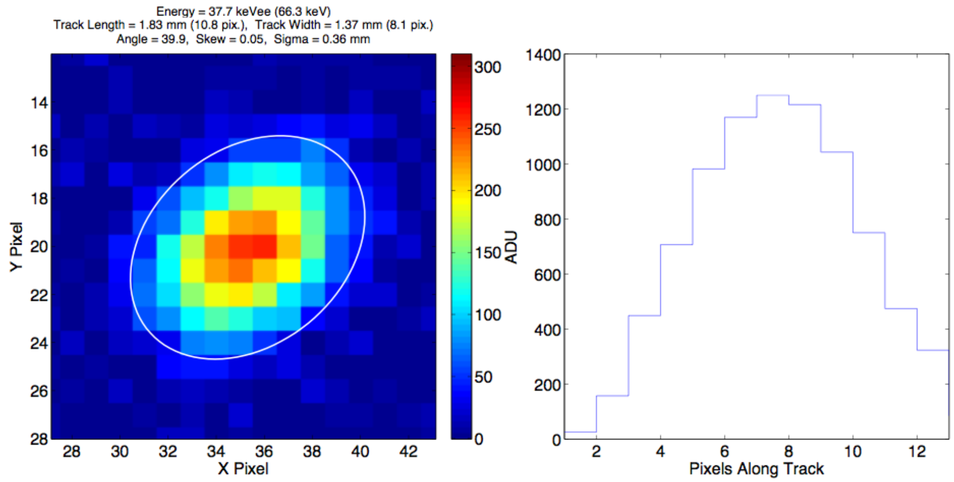


Deconvolved:

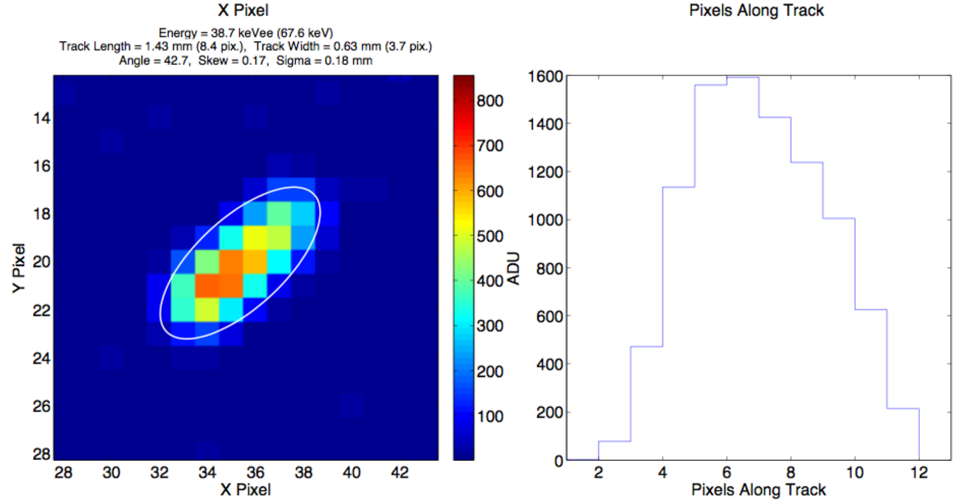


38 keVee:

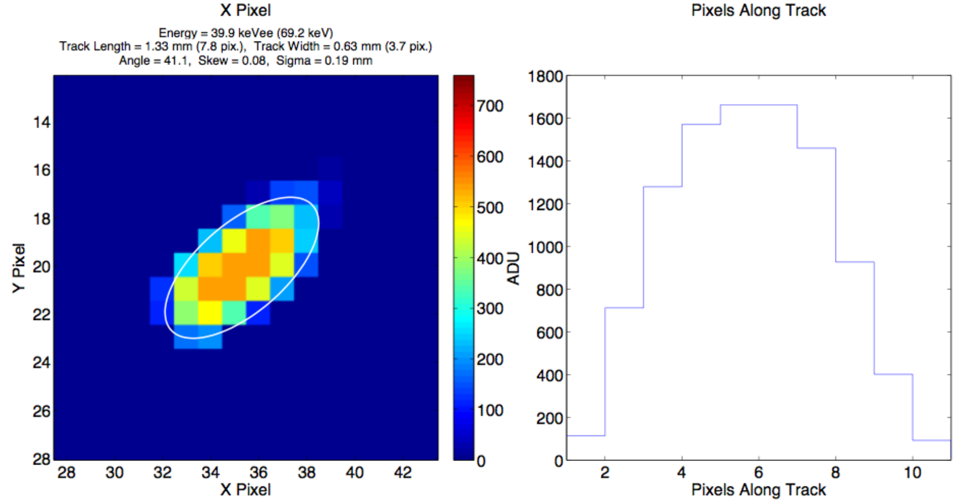
Nguyen's detector sees:



Truth:

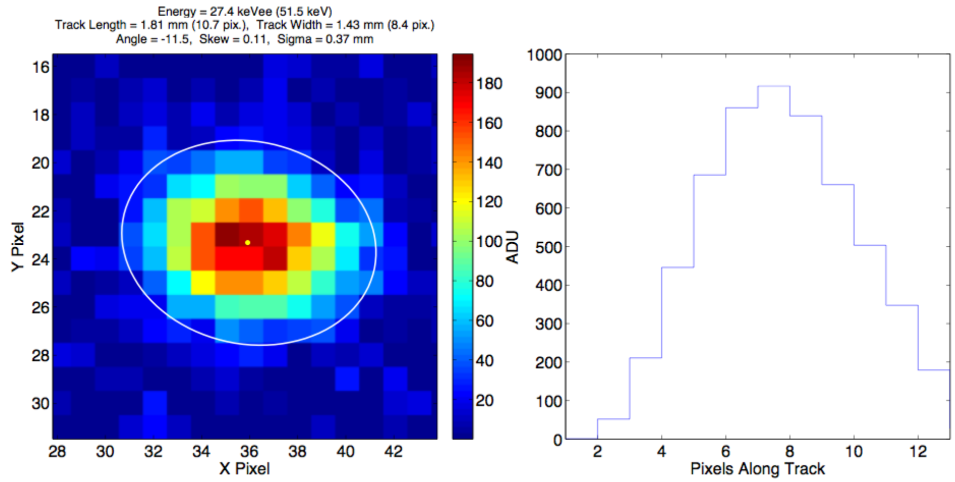


Deconvolved:

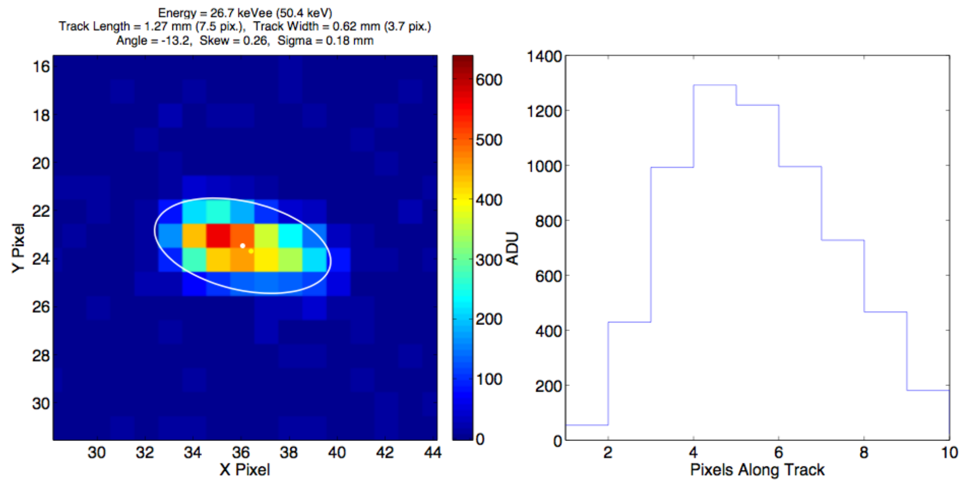


26 keVee:

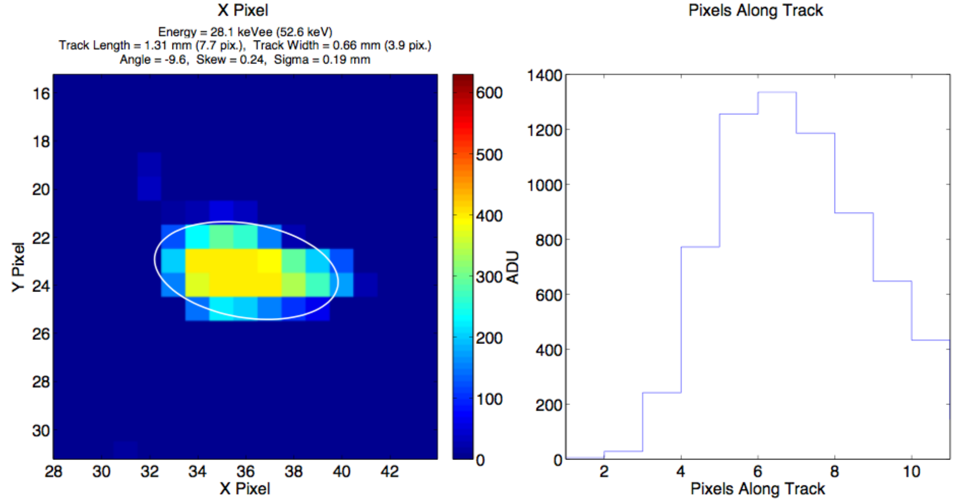
Nguyen's detector sees:



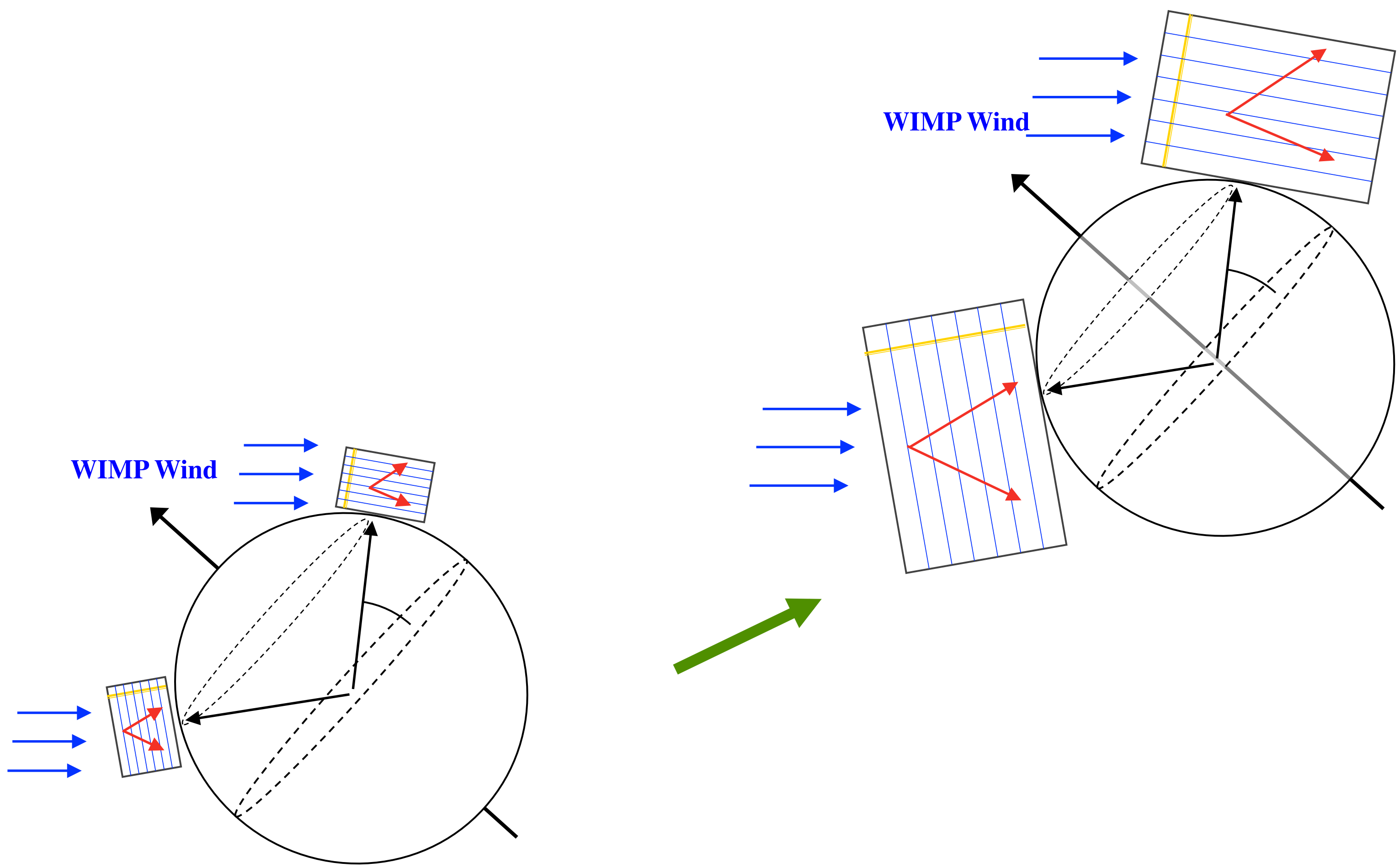
Truth:



Deconvolved:



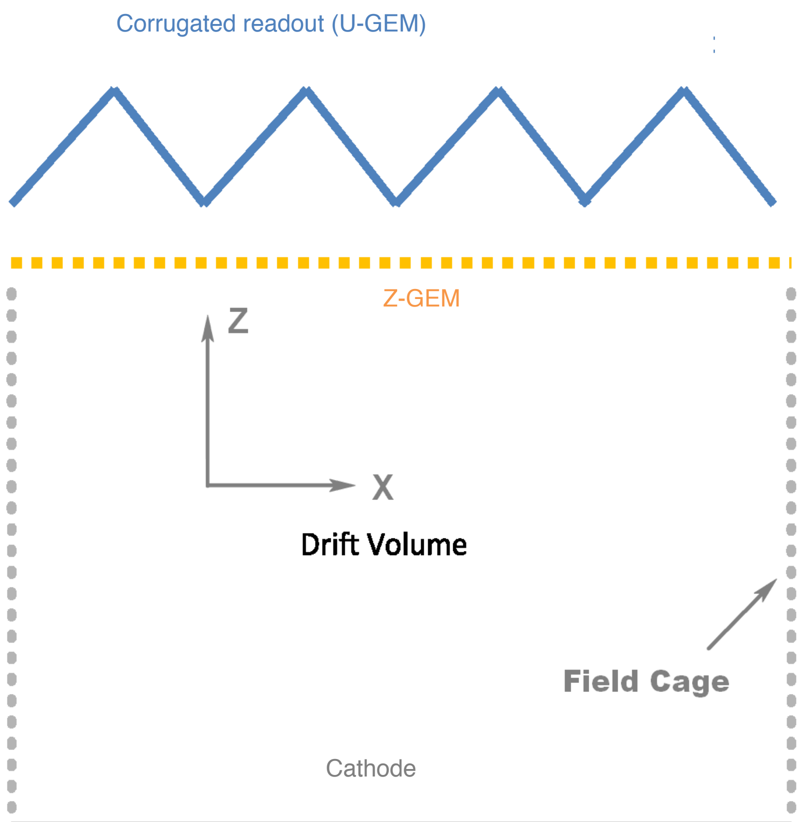
Back to the question of scale-up…

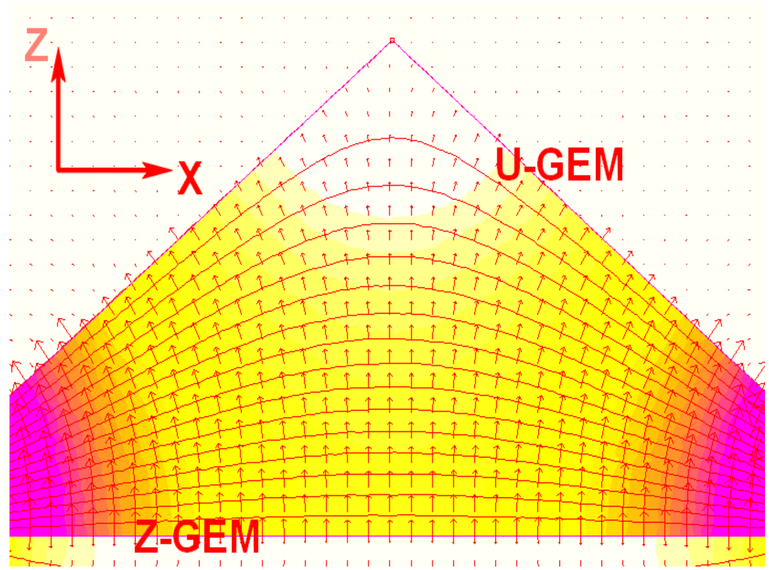


For the detector volumes required for directional DM in low-pressure TPCs, a cheap, robust, low-background, scale-able technology is the goal

This led to a novel idea by Nguyen Phan, a former UNM graduate student who is now at Los Alamos National Labs …

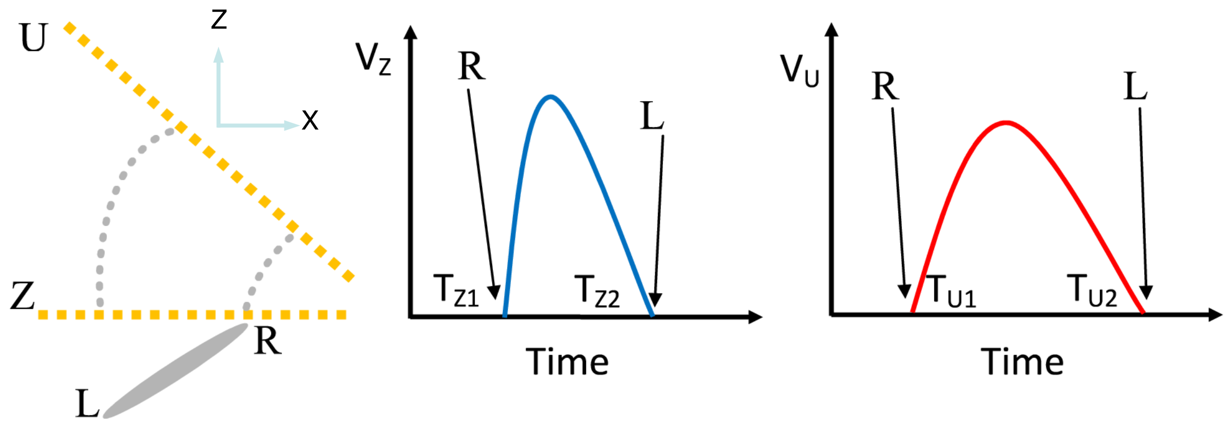
A novel high-res 2D readout

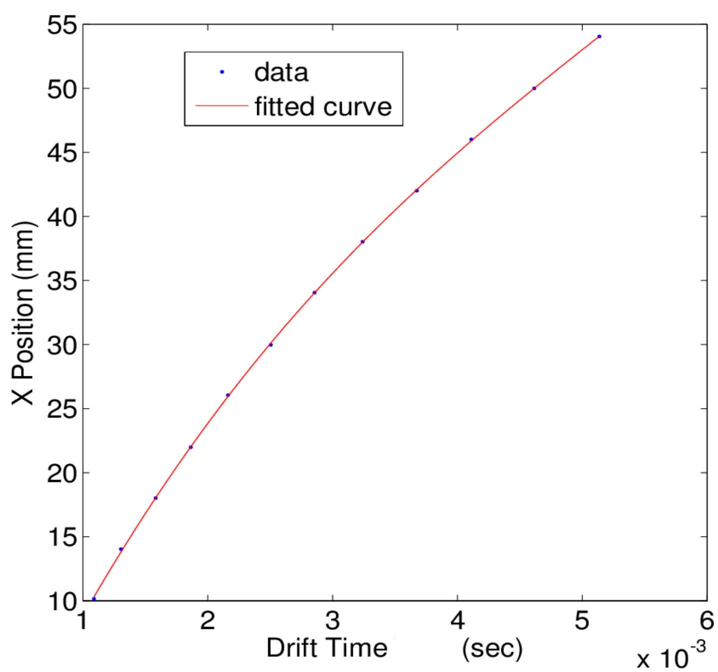




Use timing to detect both Z and X components of the range of a track!

X determination using timing: there's a 1-to-1 mapping between X and ΔT, the drift time between Z and U GEMs





← Calibration of X(T) with alphas

$$X_1 = X(T_{U1} - T_{Z1})$$

$$X_2 = X(T_{U2} - T_{Z2})$$

$$\Delta X = X_2 - X_1 < 0$$

$$\Delta Z = T_{Z2} - T_{Z1}$$

Low-cost, robust scale-up with this high-res 2D readout?

- We have demonstrated some of the basic ideas at the 10 cm by 10 cm readout scale
- With a negative ion gas, the z-pixel size is <100 um; we expect a comparable size for the x-pixel
- Only 2 readout channels were required, vs 100's – 1000's for a standard strip readout of comparable pitch
- Next steps are to demonstrate track resolution and directionality/discrimination for a readout of this size

If this works, it could provide a low-cost, robust, scalable path for very large directional DM TPCs

Summary

- The sidereal modulation of the directionality expected from DM is a “smoking gun” signature for discovery
- With the neutrino floor on the horizon for the next generation DM experiments (LZ, Xenon, etc), directionality has seen a resurgence
- R&D to make large improvements in sensitivity underway:
  - High-res, high S/N readouts lower the directional energy threshold and improve directional signature
  - A simple, low-cost 2D high-res readout shows promise
  - Probing the low energy regime is especially critical to broaden the search for low mass WIMPs


Johanna Turk, PhD 2008


Eric Miller, PhD 2015

Christina Hagemann, PhD 2008

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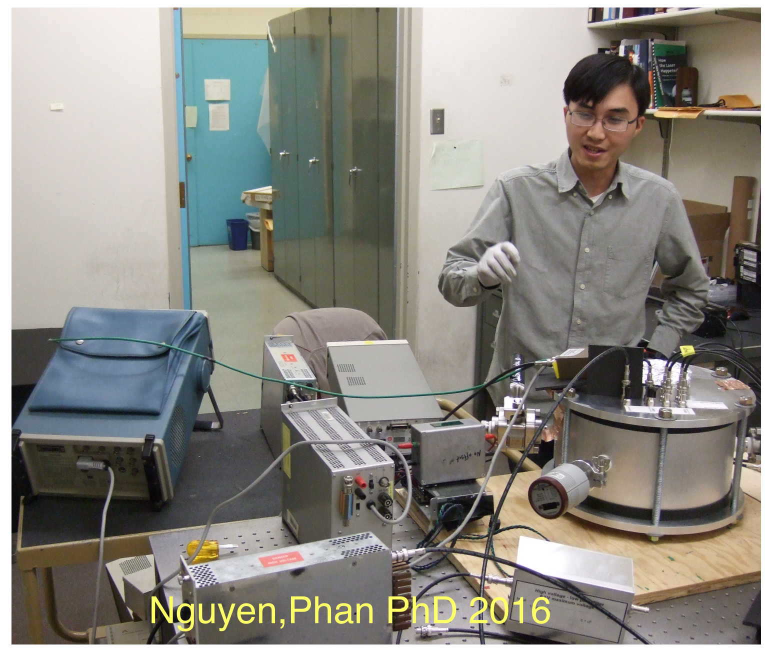
Nguyen,Phan PhD 2016

- Undergrads: A. Burghart, T. Wang, M. Perry, J. Martin, Z. Castillo, M. Avery, A. Vaitkus, D. Berenger-Russell
- Grad students: shown + N.Sanghi, R. Lafler, A. Mills