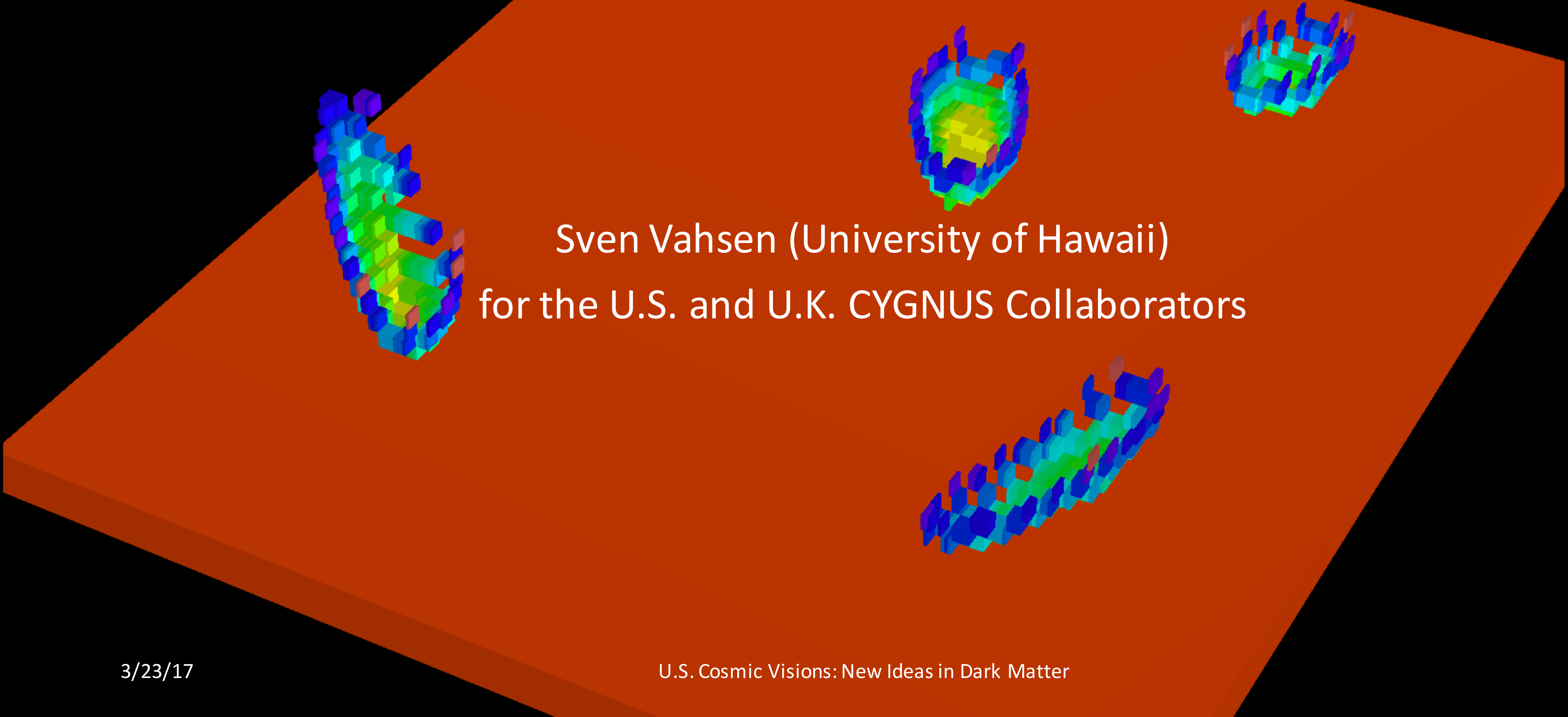
CYGNUS HD10

A low-mass dark matter search with directional sensitivity via charge cloud tomography

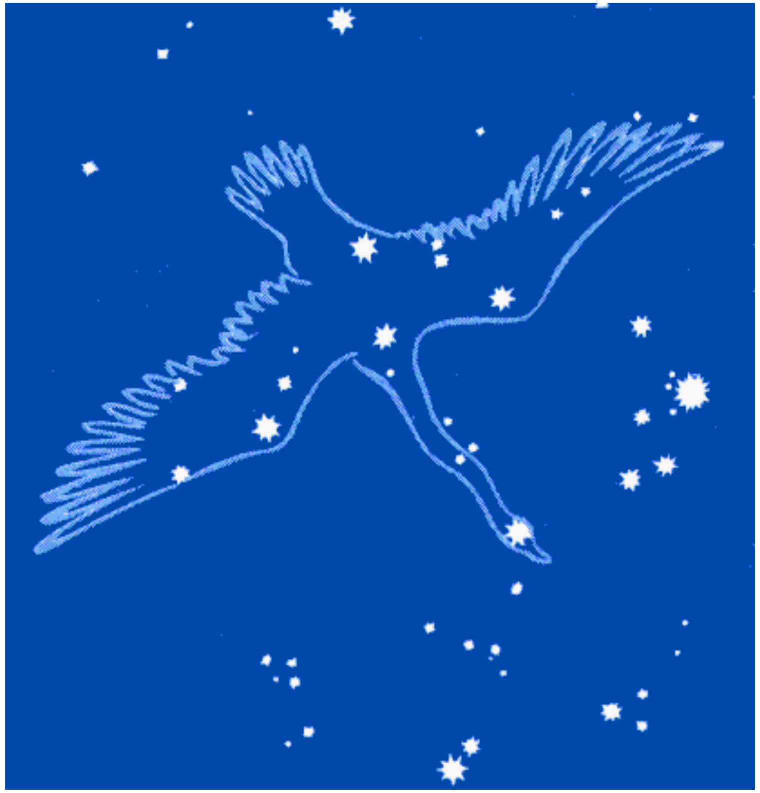


Sven Vahsen (University of Hawaii)

for the U.S. and U.K. CYGNUS Collaborators

The CYGNUS Collaboration

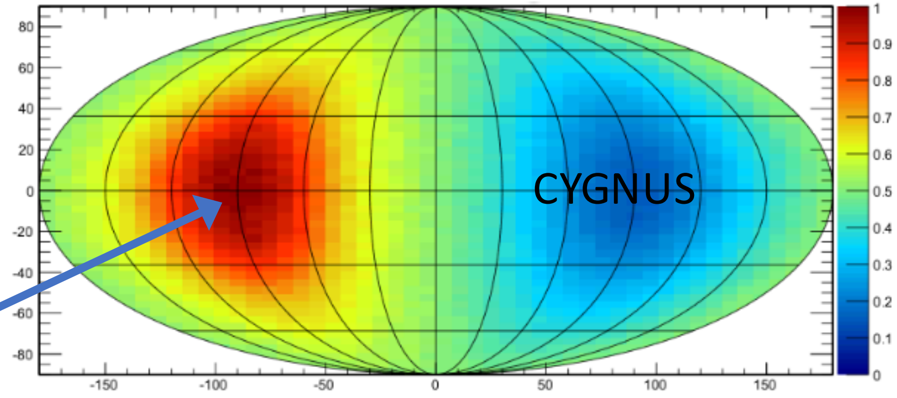
- Recently, many of the groups working on directional dark matter detection formed a new international proto-collaboration: CYGNUS
- 44 signed members from the US, UK, Japan, Italy, Spain, China
- Steering group:
  - Neil Spooner (Sheffield, UK)
  - Sven Vahsen (Hawaii, USA)
  - Kentaro Miuchi (Kobe, Japan)
  - Elisabetta Baracchini (Frascati, Italy)
  - Elisabetta Barberio (Melbourne, Australia)
- Four working groups, monthly meetings: https://indico.phys.hawaii.edu/categoryDisplay.py?categId=34
- Outcome and namesake of bi-annual CYGNUS workshop on directional dark matter detection, held since 2007.
- This year, in Xichang, Sichuan, China http://www.tir.tw/conf/cygnus2017/



The dark matter wind is expected to come from the constellation Cygnus.

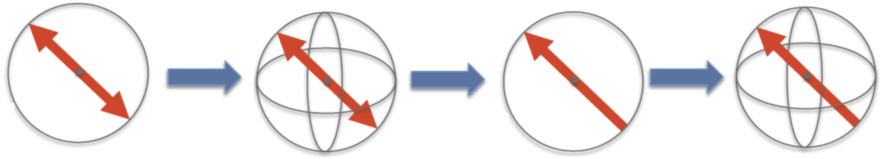
CYGNUS vision and long-term goal

- Build large-scale (>1000 m^3) nuclear recoil detector capable of
  - Observing Dark Matter via diurnal directional oscillation (⇔ Dipole in galactic coordinates)
  - Detecting solar neutrinos
  - Efficiently penetrating the ν floor
  - Measuring DM particle properties and physics
  - WIMP astronomy
  - *A review of the discovery reach of directional Dark Matter detection*, Physics Reports 627 (2016)



Sky map in galactic coordinates of recoils from 100 GeV WIMPs on ^{19}F, E>50 keV

Jeremy P. Lopez, MIT 2

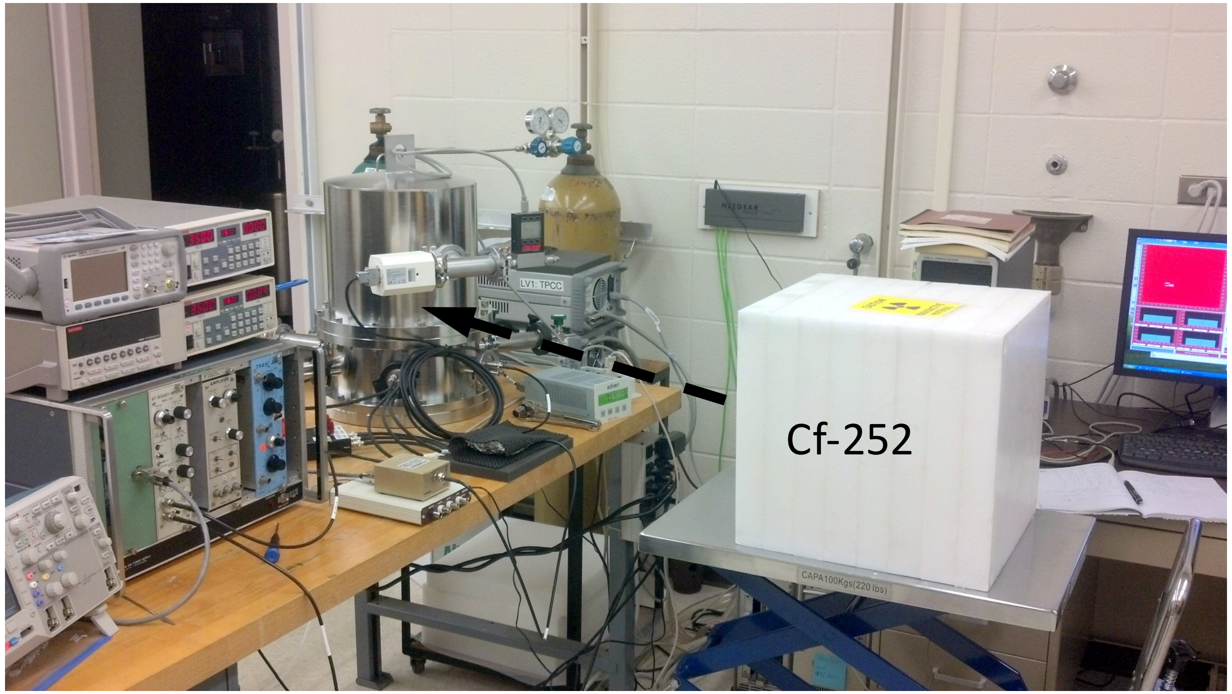


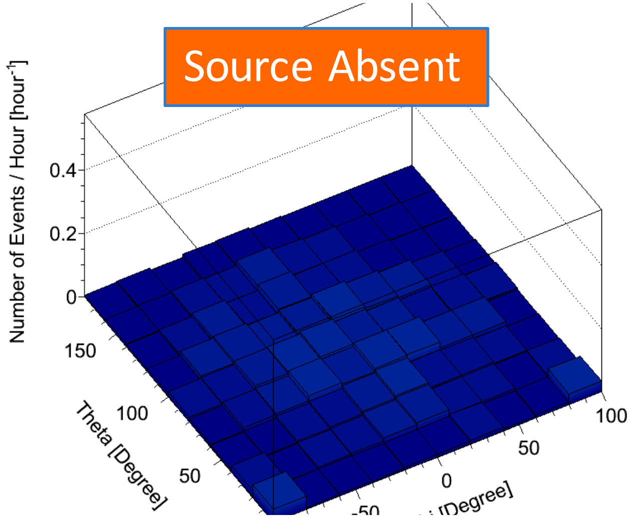
Good → Best

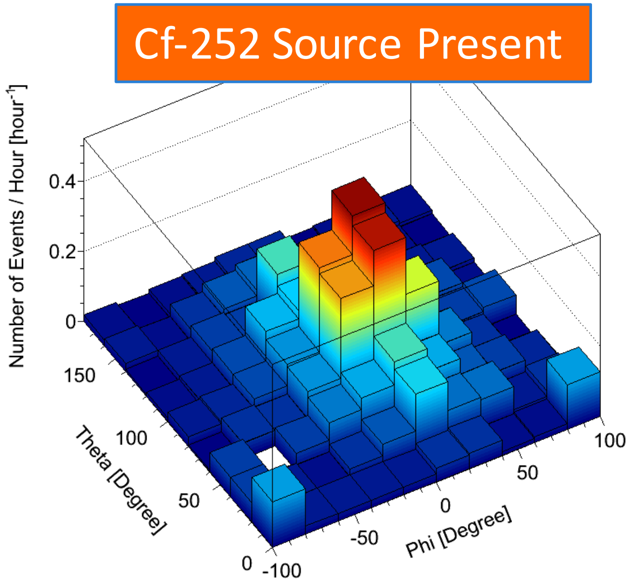
but most costly and challenging

- 3D readout w/ head-tail requires the fewest events to identify the recoil dipole.
- Of order 10 events (versus order 1000/100 for 1D/2D)

Detecting the Neutron Wind - in 3D

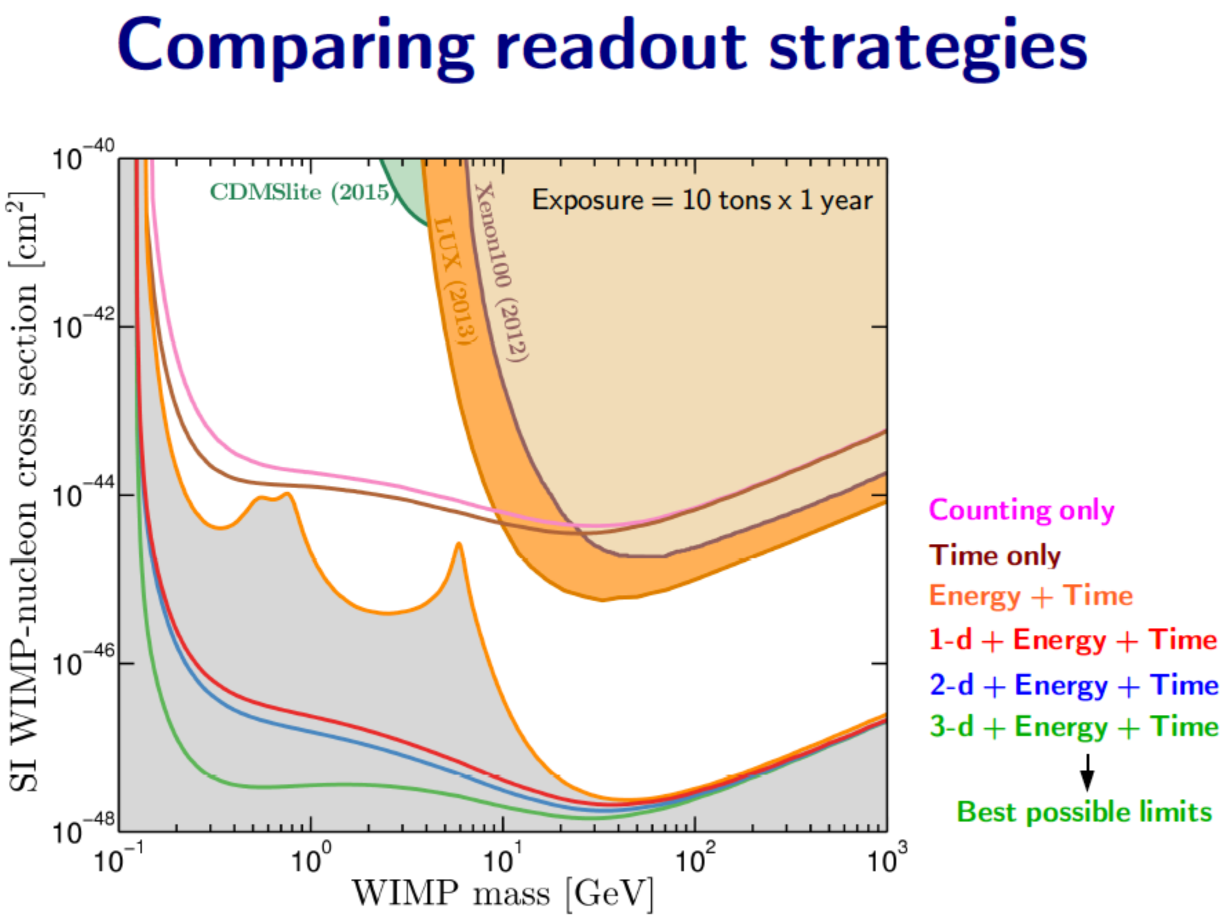






27-sigma evidence for "neutron wind" in Hawaii!
Recoils point back to source, in 3D.

Types of directionality: 1D, 2D, 3D

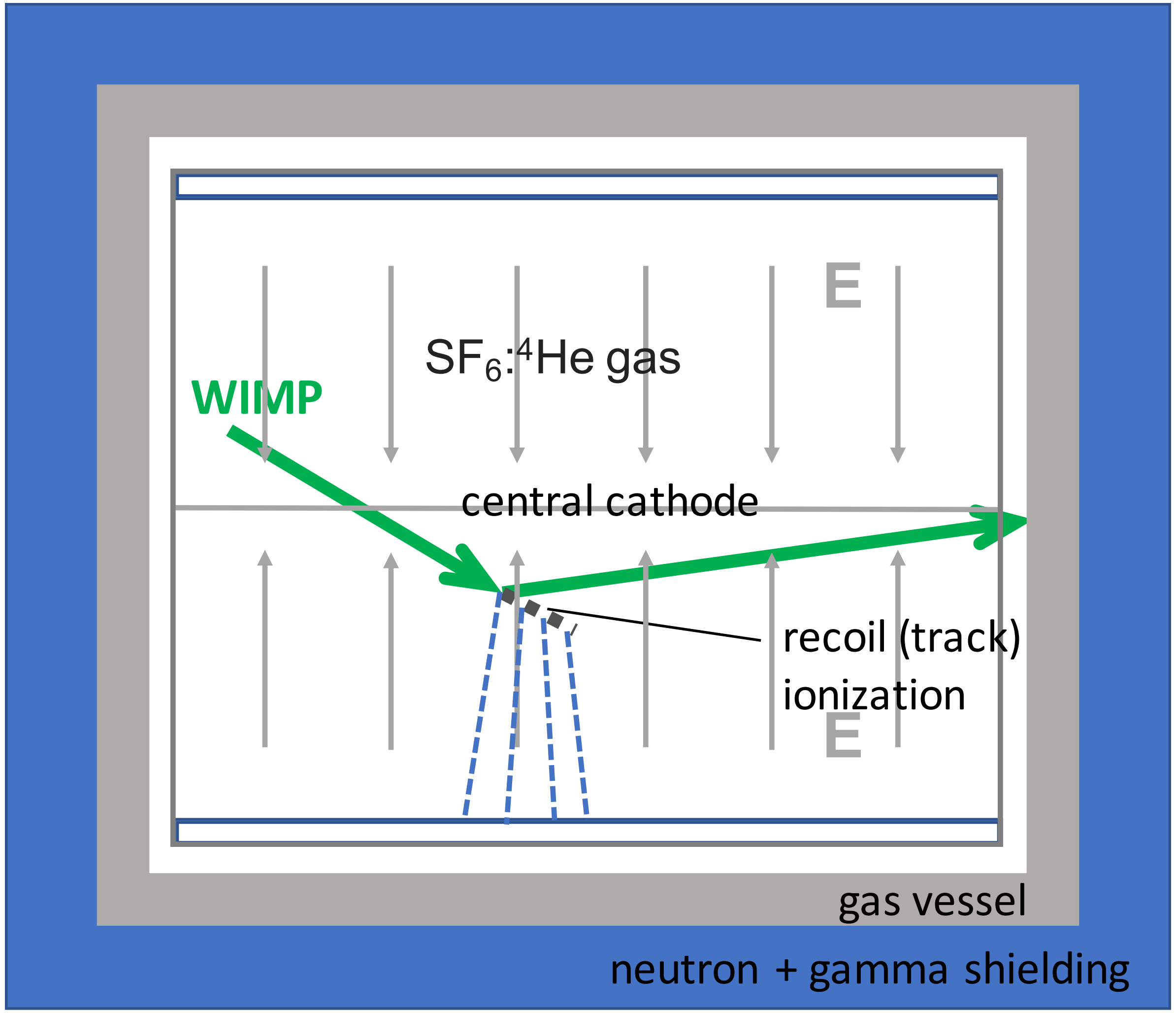


- 3D recoil reconstruction also best for penetrating the neutrino floor, though advantage here is smaller
- Caveat: Such studies typically *do not include energy dependence of detector performance* (such as angular resolution, efficiency, head/tail reconstruction).
- These are major effects. CYGNUS collaboration working on a comprehensive technology comparison. Anticipating the outcome of this work, we propose CYGNUS HD10…

Readout strategies for directional dark matter detection beyond the neutrino background
Ciaran A. J. O'Hare, Anne M. Green, Julien Billard, Enectali Figueroa-Feliciano, Louis E. Strigari

CYGNUS HD10: Experimental Approach

- Gas Time Projection Chamber, 10 m^3
- Gas mixture: SF_6:^4He, p~1 atm
  - Possibility of switching from atmospheric pressure (search mode) operation to low pressure operation for (improved) directional confirmation of WIMP signal
- Reduced diffusion via negative Ion drift (SF_6)
- Charge amplification via Micromegas
- HD – high resolution charge readout via x/y strips (200 μm pitch) for improved
  - 3D directionality with head-tail sensitivity
  - Electron event rejection
  - Fiducialization
- Redundant 3D fiducialization
  - SF_6 minority carriers
  - charge cloud profile
- Helium target
  - Improved sensitivity to low mass WIMP
  - Longer recoil tracks, extending electron event discrimination to lower energies through Helium target

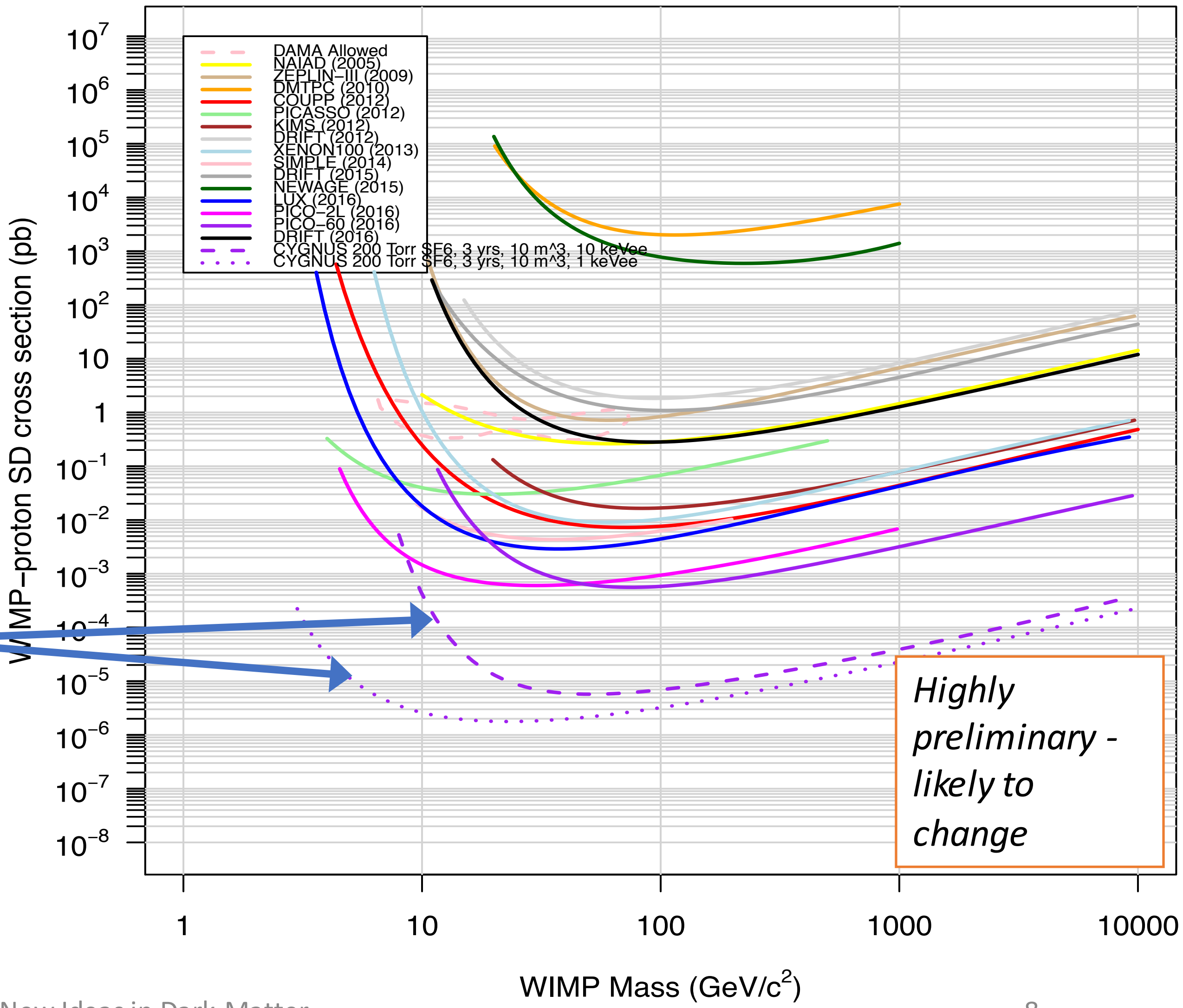


CYGNUS HD10: Proponents

- CYGNUS P.I.s from U.S. and U.K.
  - James Battat – Wellesley
  - Dinesh Loomba – New Mexico
  - Neil Spooner – Sheffield
  - Dan Snowden-Ifft – Occidental
  - Sean Paling – Boulby Underground Laboratory
  - Sven Vahsen – Hawaii

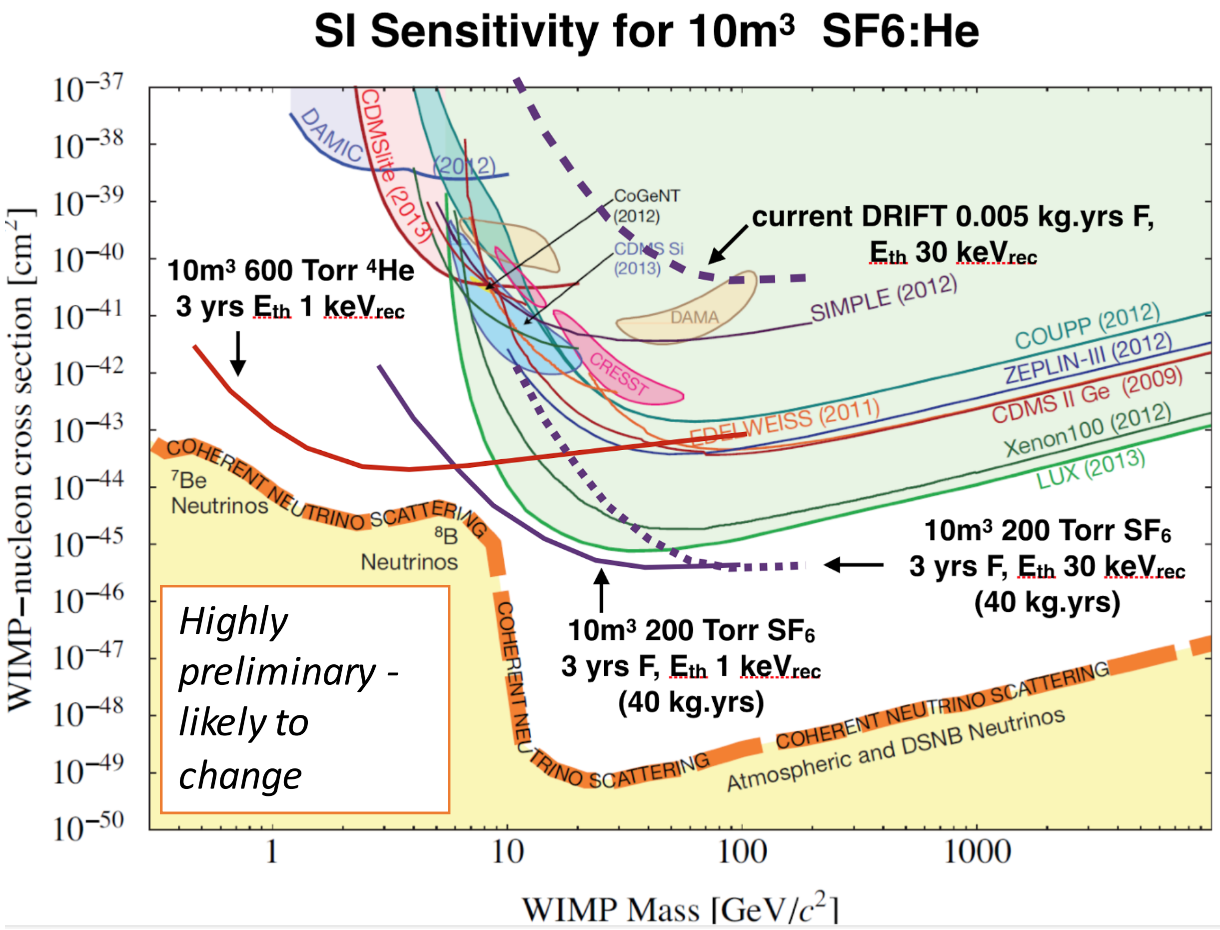
CYGNUS HD10: SD Sensitivity

- Search mode: p=1 atm
  - 200 torr SF_6, 600 torr ^4He
- SD sensitivity due to Fluorine
- 3 years of running time
  - Potential for SD reach slightly better than LZ / PICO-60 projections (not shown)
  - But will depend on discrimination threshold (see later slide)
- Discoveries can be investigated with improved directionality in low-pressure mode (~0.1 atm)



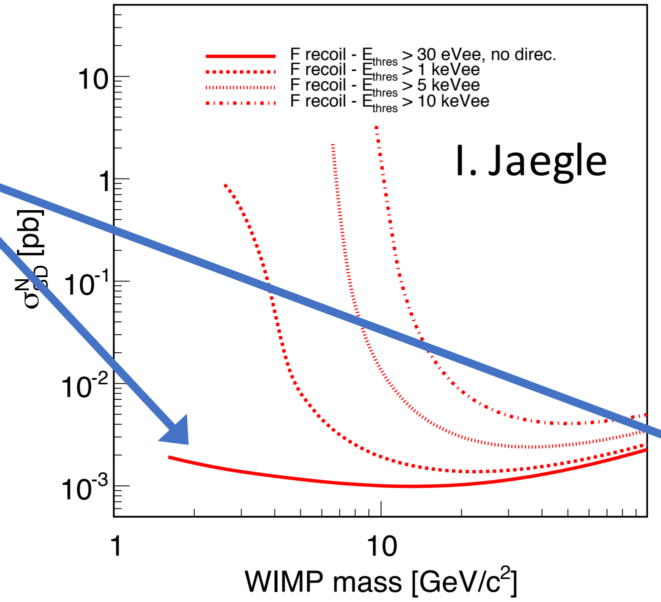
CYGNUS HD10: SI Sensitivity

- Search mode: p=1atm
  - 200 torr SF_6, 600 torr ^4He
- 3 years of running time
  - Good SI reach for m_{WIMP}<1 GeV due to He target
  - Similar to SuperCDMS HV detectors, but with electron event discrimination
  - May see first solar neutrino events
- Discoveries can be investigated with improved directionality in low-pressure mode (~0.1 atm)

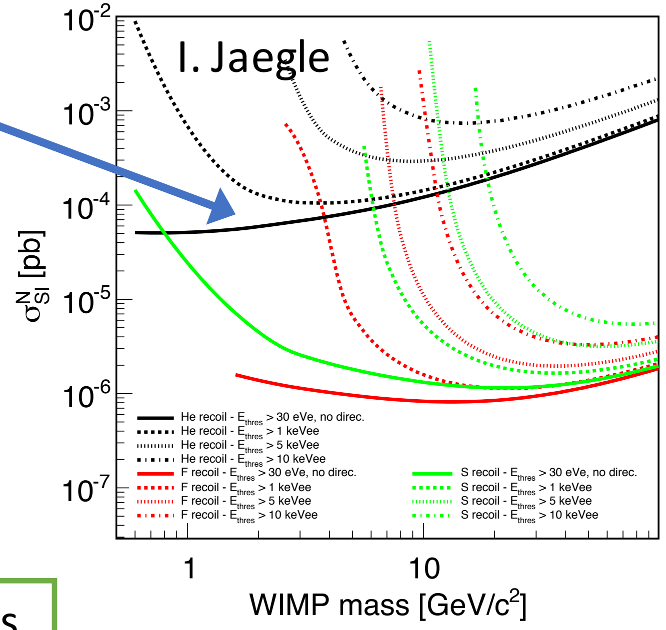


Three types of energy thresholds in a Gas TPC

- Ionization threshold
  - as low as ~30 eVee - depends achievable gain, readout segmentation→capacitance → noise floor, and diffusion/drift length
- Electron discrimination threshold
  - order 10 keVee (depends on gain, S/N, readout dimensionality, segmentation, drift length, gas density, target nucleus)
- Directional threshold
  - depends on same factors as discrimination threshold
  - but tends to be higher



10 torr of SF6
+ 50 torr of He
1 event detected
1000 days exposure
1 m³
60cm drift length
track length / sigma(drift distance) > 3



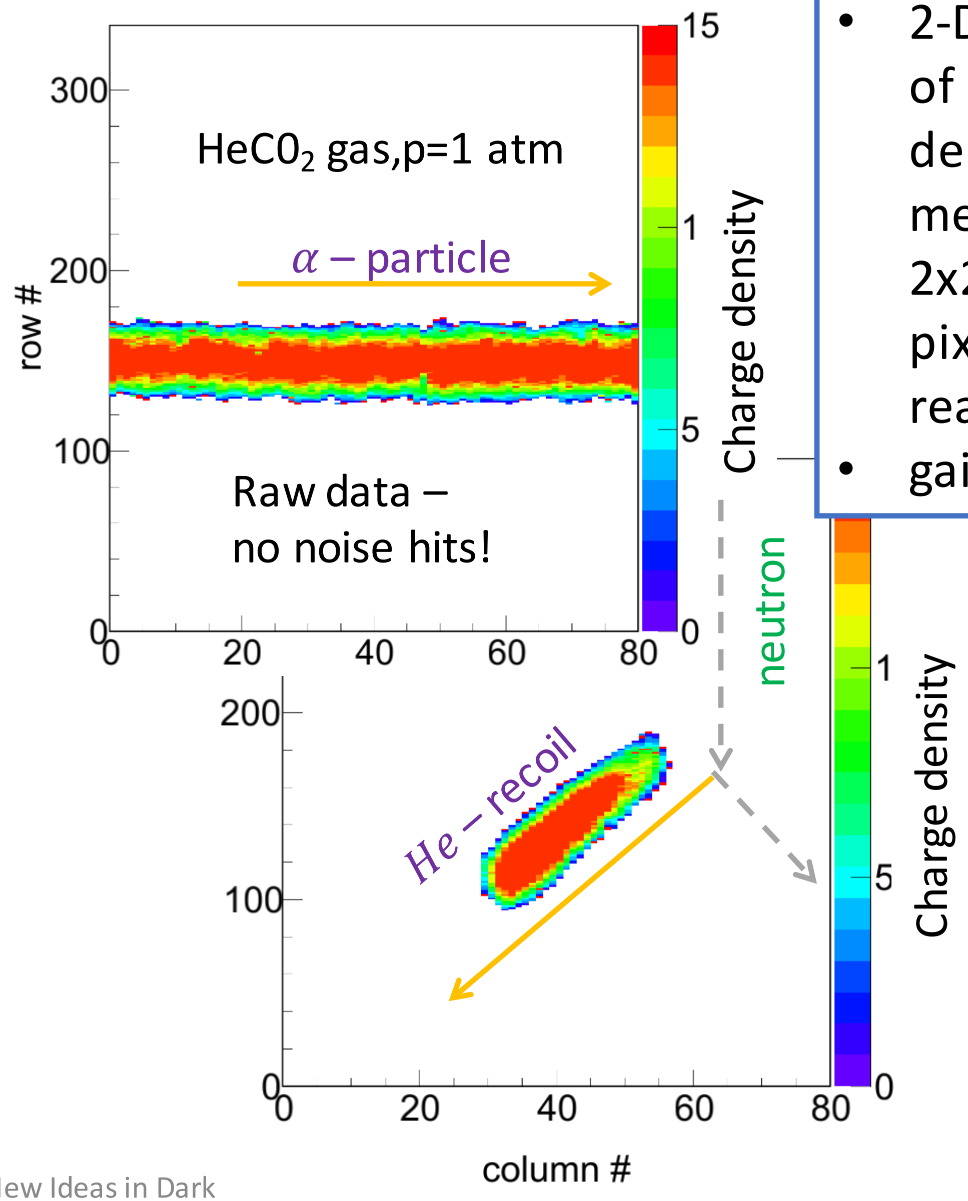
Highly preliminary - likely to change

Each of these thresholds is lowest with 3D charge readout --- pixels or strips.

3D Charge Readout pixels and strips

- Pixel readout: ultimate in performance
  - 3D: 50μm x250 μm x 40 MHz
  - Small readout pads → lower detector capacitance → lower noise → lower charge threshold
    - Can detect single electrons (30 keVee) with high efficiency at gain > 20k
  - Improved separation of electron and recoil events → lower discrimination threshold
  - Lower directional threshold
  - Fiducialization via charge cloud profile
- But
  - High cost – of order \$100k / m^2
  - Low radio-purity
  - Tedious to construct - each chip is only 2x2 cm

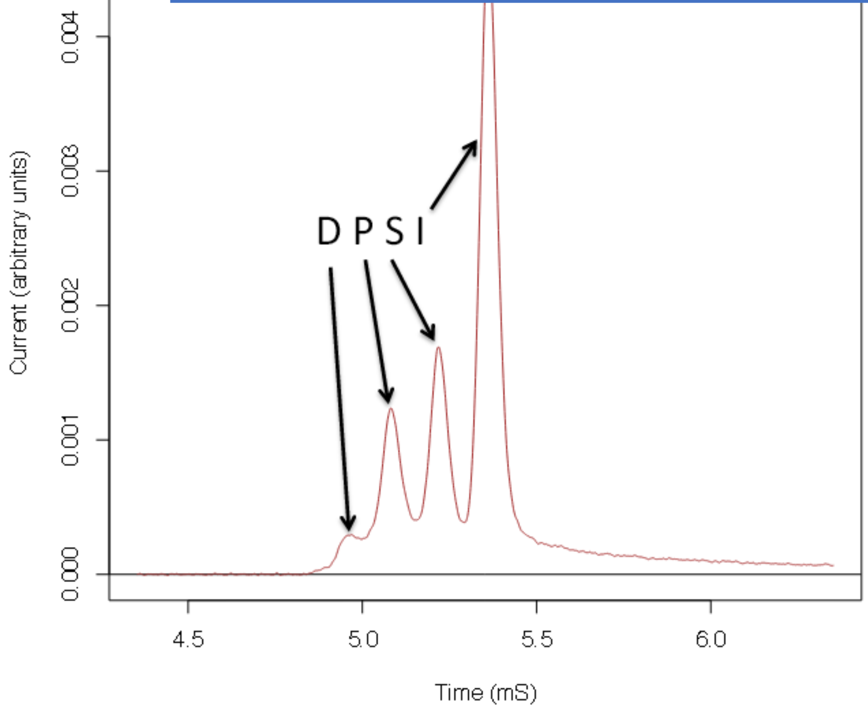
→ Best compromise
  - Resistive Micromegas readout with integrated x/y strips (available from CERN
  - Cost of order \$10k / m^2
  - Large - up to 1m x 2m!
  - Higher noise floor and thus ionization threshold

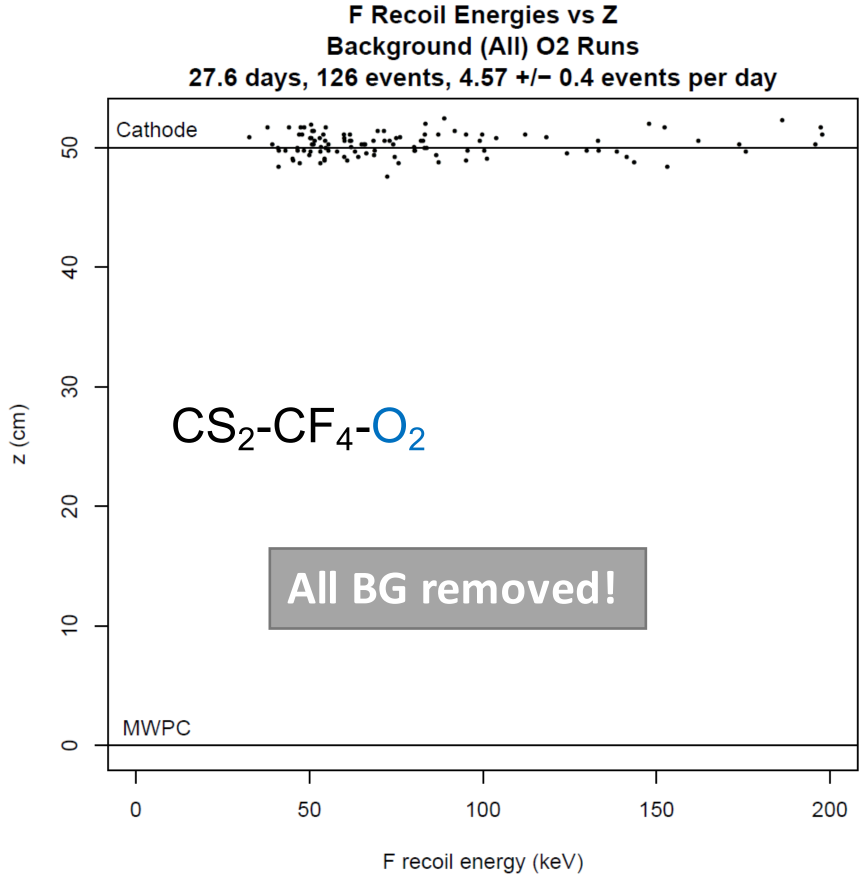


- 2-D projection of ionization density, measured w/ 2x2 cm ATLAS pixel chip readout
- gain ~ 3000

3D Fiducialization I: Minority Carriers

Discovery of Multiple, Ionization-Created Anions in Gas Mixtures Containing CS2 and O2
Daniel P. Snowden-Ifft http://arxiv.org/abs/1308.0354





- Game changer for directional WIMP search via gas TPC
- Utilizes timing - works with any charge readout (1D,2D,3D)
- More recently - Minority carriers also discovered in SF_6
- Incredibly lucky: SF_6 is also non-toxic, non-flammable, not corrosive, has gain, and is a good SD target (!)

The novel properties of SF_6 for directional dark matter experiments

N.S. Phan, R. Lafler, R.J. Lauer, E.R. Lee, D. Loomba, J.A.J. Matthews and E.H. Miller
Published 17 February 2017 • © 2017 IOP Publishing Ltd and Sissa Medialab srl
Journal of Instrumentation, Volume 12, February 2017

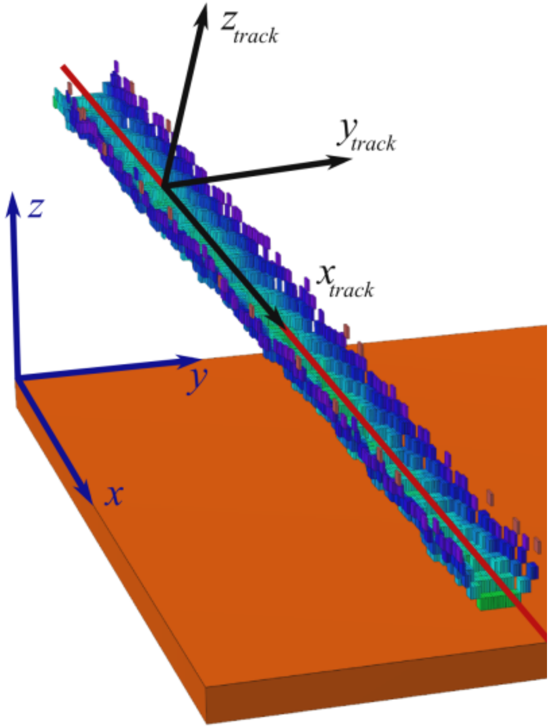
3D Fiducialization II: Charge Cloud Reconstruction

Nuclear Instruments and Methods in Physics Research A 789 (2015) 81–85

P.Lewis

- Measurement of charge-profile (*not width*) of track, enables accurate measurement of transverse diffusion, which depends on drift length

→ obtain absolute position in drift direction



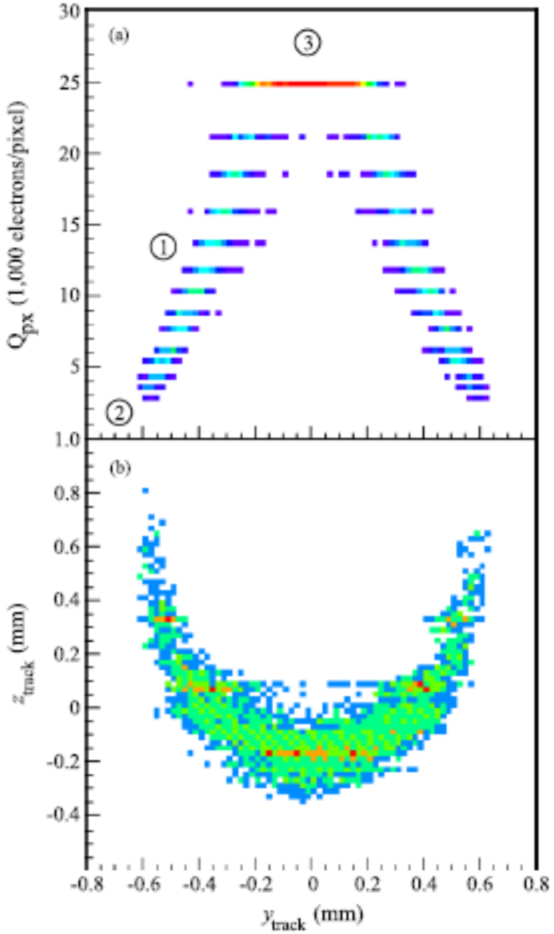


Fig. 2. Corrected pixel charge (Q_{px}) profile (a) and shell coordinates (b) for a single horizontal track from the near alpha source. Label 1 of the profile plot (a) corresponds to the Gaussian, label 2 to the threshold, and label 3 to the saturation regions of the profile. The U-shaped shell in plot (b) is very roughly the bottom half of the track in space, described in Section 2.1. These plots are two-dimensional histograms where the counts per bin are encoded by brightness: the outside points of each distribution (blue online) have the lowest count number, the center points (yellow and red online) have higher count numbers. (References to color apply to the web version of this article.)

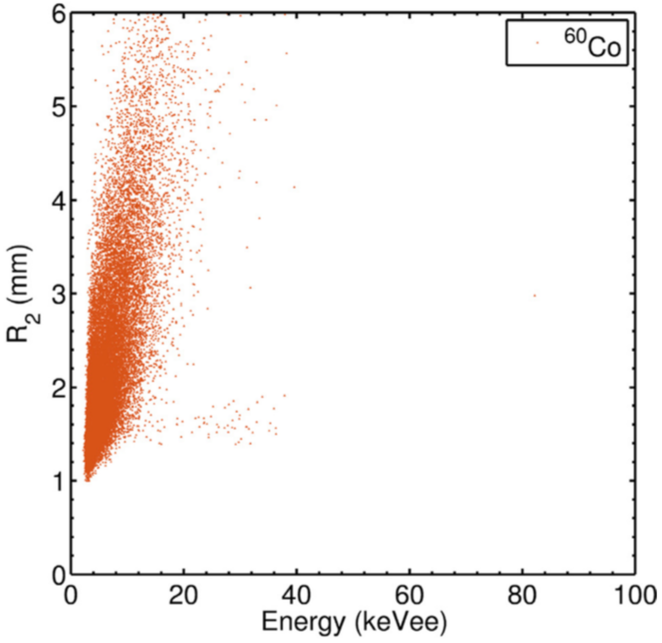
- Requires high resolution readout of charge density → only 2D, 3D
- However, should work with any gas
- Published version utilized “chopped” alphas, but has since been extended by grad student to also work with recoil events (unpublished)

Electron event rejection

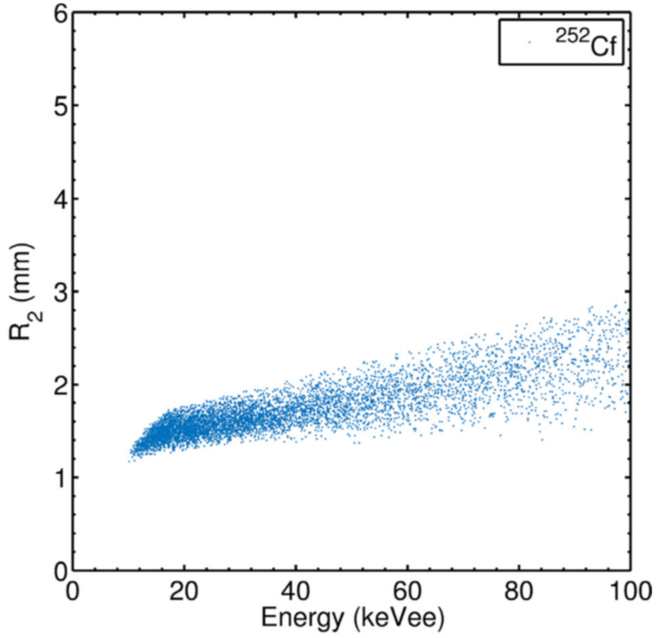
- On right: 2D optical readout in 100 torr CF_4
  - F versus electron recoils
  - $\sigma = 0.35$ mm readout resolution, incl. diffusion
  - Using range-energy signature, electron event rejection factor < 3.9 x 10^{-5} around 10 keVee
  - *It's a limit – all available electron events rejected*!
- Extrapolating to CYGNUS HD10 (Helium recoils drifting in SF_6 via negative ion drift)
  - 3D readout (better discrimination)
  - In 200 torr SF6 + 560 torr Helium, Helium recoils (higher pressure, but longer recoils)
  - Assuming 50 cm of thermal drift ($\sigma = 0.55$ mm)

→more than half the detector volume should have excellent electron discrimination at ~5 keVee and below.

- Should improve with 3D charge *cloud tomography, i.e.*, going beyond range-energy signature.
- *Follow-up experimental work with 3D readout needed.*



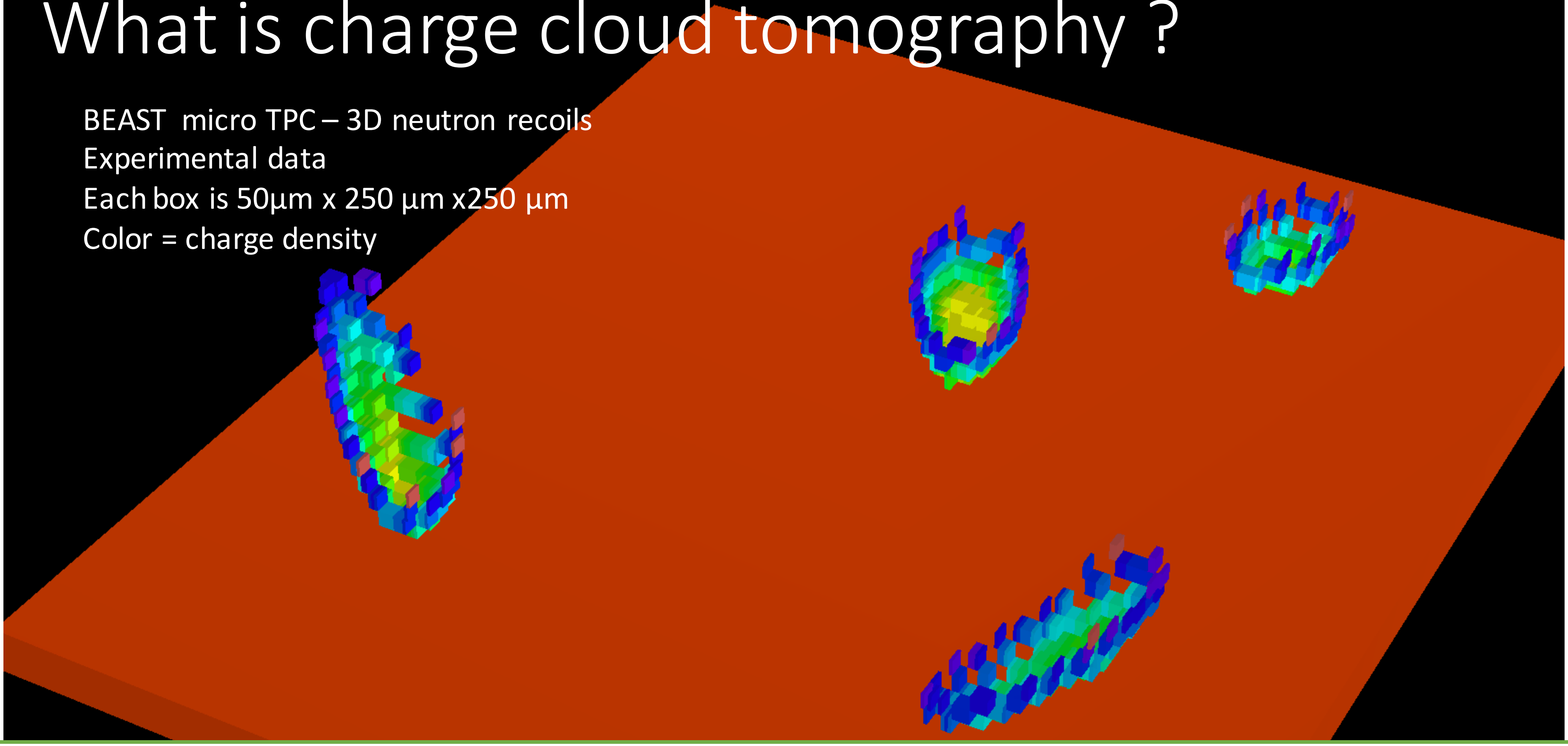
(b) ^{60}Co data post CCD cuts



(b) ^{252}Cf data post selection cuts

GEM-based TPC with CCD imaging for directional dark matter detection
N.S. Phan, et. al., roparticle Physics, 84 (2016)

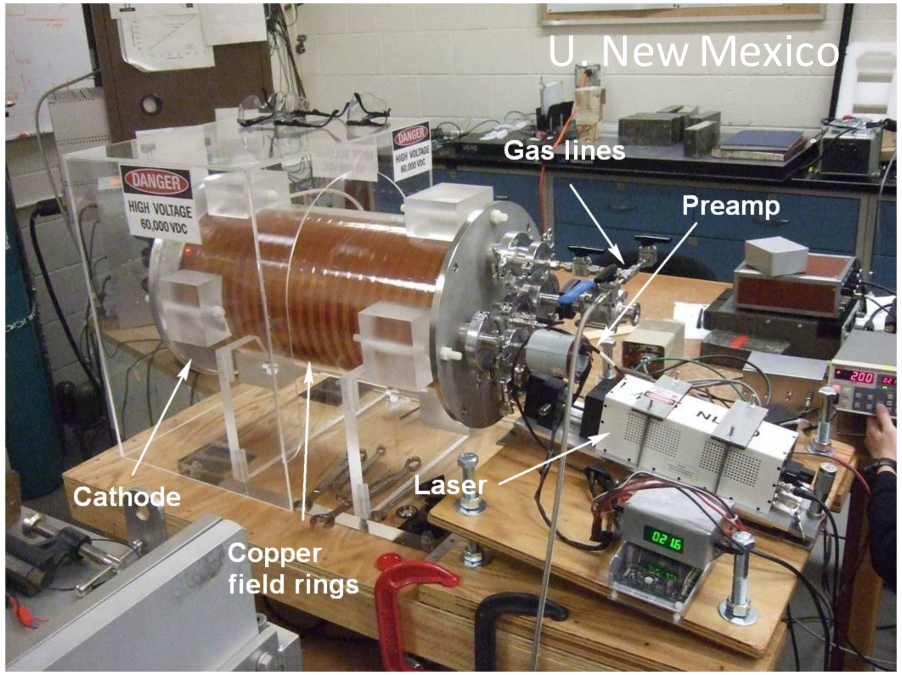
What is charge cloud tomography ?

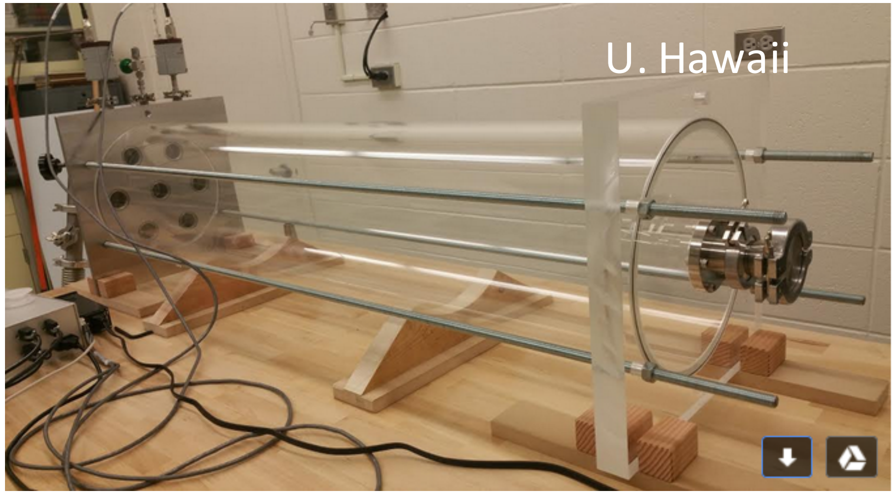


- Above: In electron drift gases, 3D event that is a surface. In a negative ion drift gas, may obtain full 3D charge density.
- Extract full information content available -> improved electron rejection and energy resolution (electron counting).
- Detailed imaging of the event topology also sensitive to exotic models, e.g. DM* N -> DM N +gamma [Browder, Petrov] (”weak priors” corner of *priorhedron* – see talk by N. Weiner this morning)

Technological Readiness

- Several 1 m^3-scale gas TPCs already built (DRIFT, DMTPC) or under construction (NEWAGE, MIMAC)
- The proposal here represents a modest factor 10 scale-up, but aims for drastically enhanced performance
- The key new technologies and techniques have already been experimentally demonstrated by CYGNUS collaboration members, but *individually*
- Must be demonstrated in the same detector, with the proposed gas mixture.
- Extension of electron/recoil separation to <= 5 keVee energies via 3d readout and He recoils needs experimental demonstration
- Acrylic gas vessels may be required at >10m^3 – prototypes exist





Backgrounds, cost, underground lab

- Detector would be constructed in the U.S.
- Boulby underground laboratory has offered to host CYGNUS detectors in a dedicated cavern
- Possibility of laboratory support (infrastructure, manpower for operations)
- Preliminary simulation show that we can get the rock and cosmogenic neutron background at Boulby down to < 0.5 events
- Gamma shielding under investigation, depends on readout discrimination power and radio-purity
- Expect US cost of order $2-3M (excludes manpower)

Underground at Boulby

Timeline & Synergies

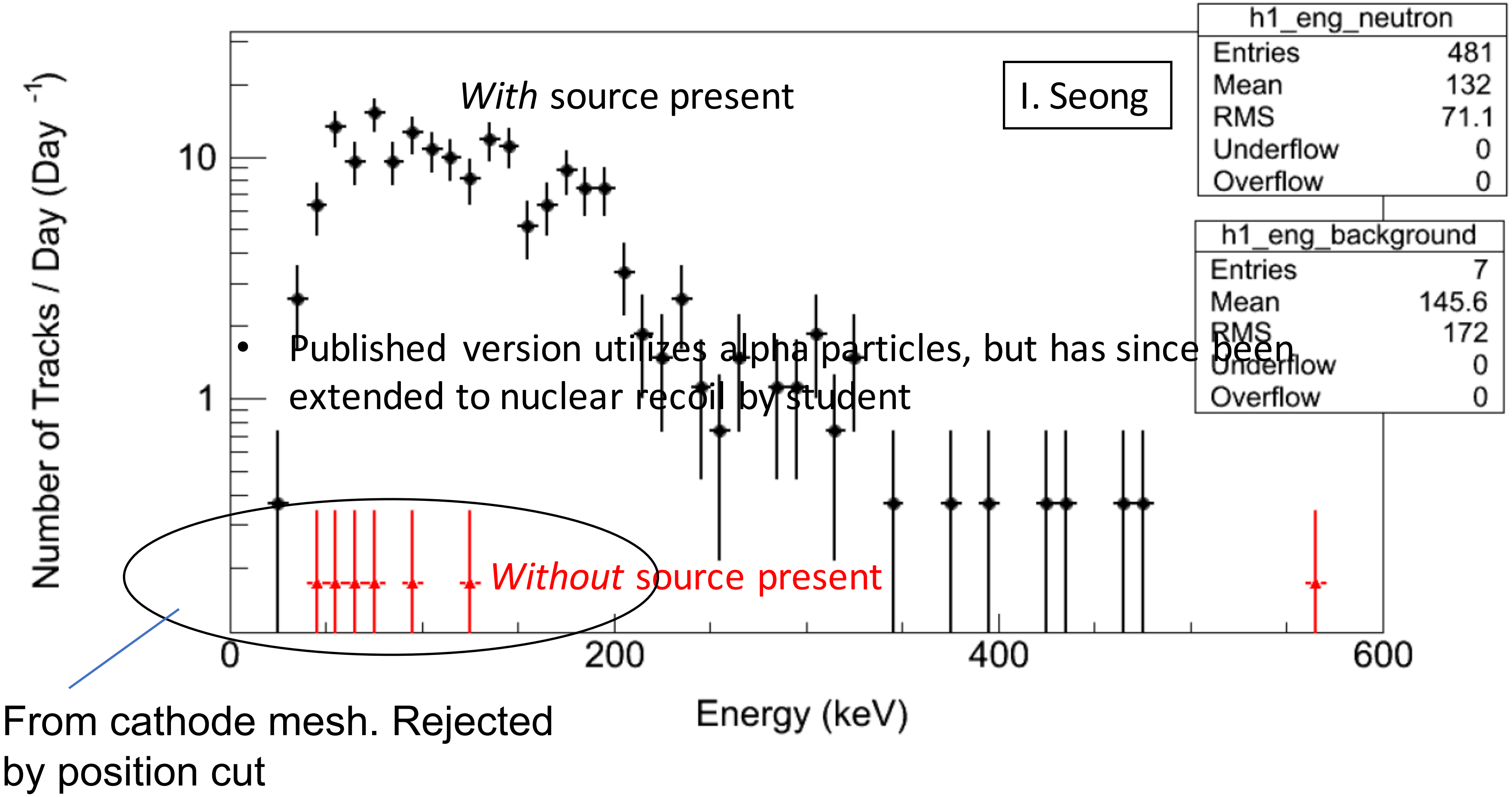
- Collaboration working on conceptual design paper, to be completed in time for CYGNUS 2017 conference in June
- First US funding proposals to be submitted this year
- 1 m^3 detector construction could start soon
- 10 m^3 clean detector needs more careful planning of timeline
- Programmatic synergies
  - Directional Neutron Detection
  - A smaller proof-of-principle detector with limited radio-purity could be built first, and utilized to measure coherent neutrino scattering at a neutrino source (COHERENT)
  - High-channel-count, high S/N, pixelated charge readout is also of interest to the US neutrino community (NOvA)

Conclusion & Summary

- CYGNUS HD-10 is a newly proposed, 10 m^3, U.S. built gas TPC
- Leverages recent advances in Micropattern Gaseous Detectors to achieve 3D HD charge readout (most powerful option) of large volumes at reasonable cost
- DM sensitivity beyond G2 experiments in both SD (cross section) and SI (mass), in a single detector, with improved electron rejection expected at low masses
- Proposed gas mixture is a starting point - *could be optimized to target only one of SD or (low-mass) SI - with further improvements in sensitivity*
- Detailed imaging of ionization sensitive to wider class of DM models
- Highly flexible with respect to target
- First step towards a large-scale directional detector, capable of
  - unambiguously demonstrating the cosmological origin of a putative WIMP signal
  - effectively penetrating the neutrino floor
  - eventually, WIMP astronomy

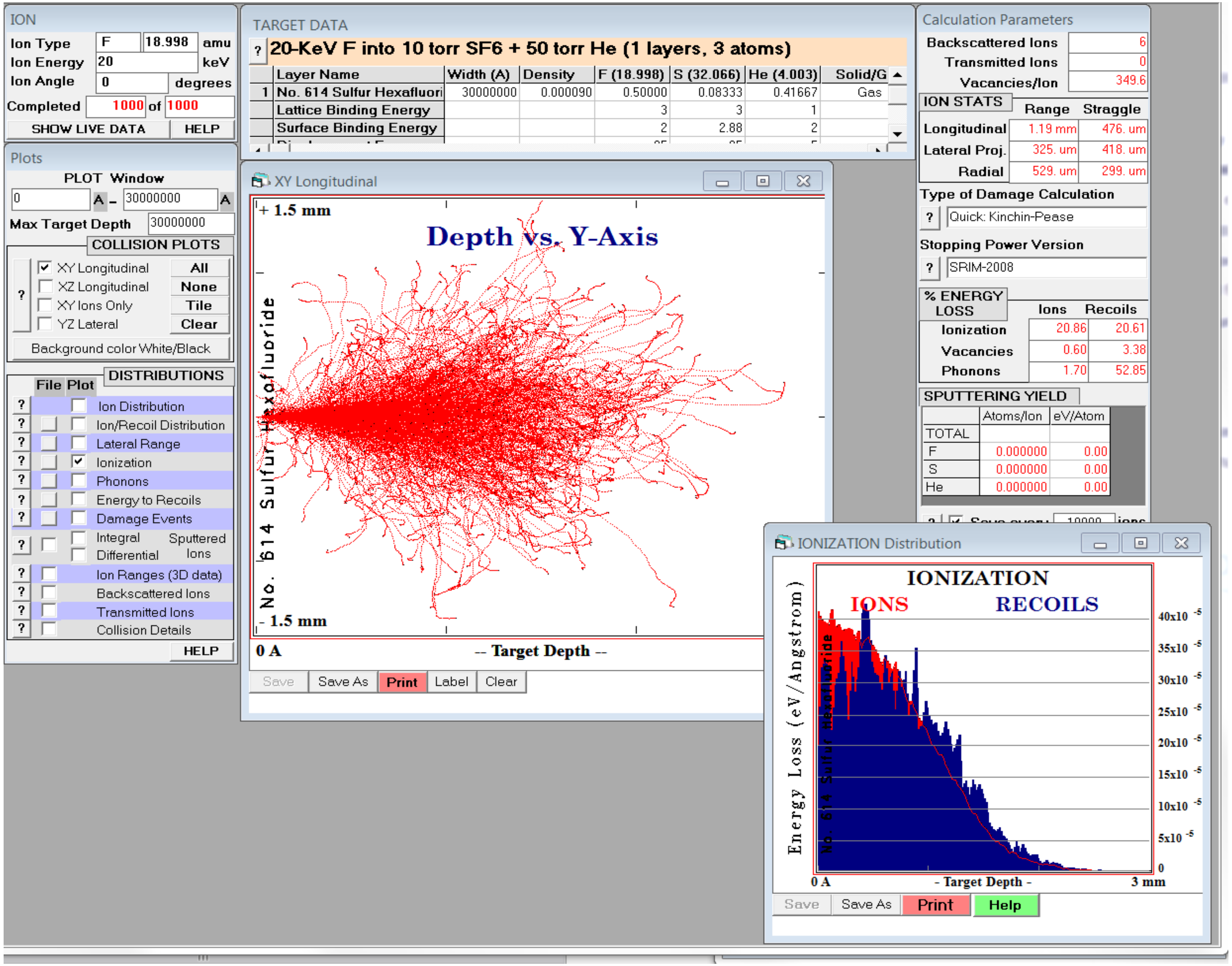
BACKUP SLIDES

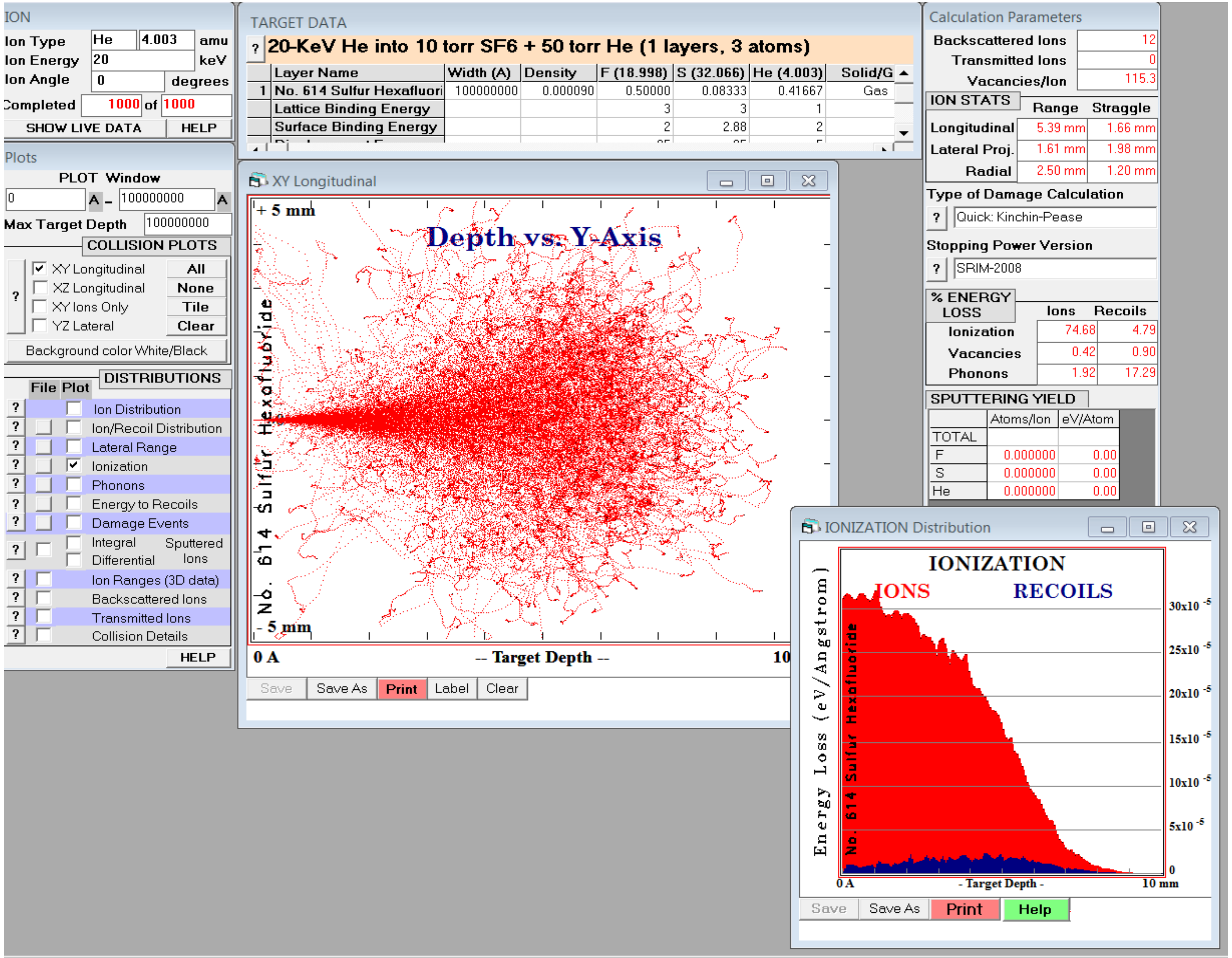
Cf-252 data, recoil ionization energy spectrum, before position cut



- Published version utilizes alpha particles, but has since been extended to nuclear recoil by student

Detector is essentially background free for high-energy neutron recoil events.


ION
Ion Type F 18.998 amu
Ion Energy 20 keV
Ion Angle 0 degrees
Completed 1000 of 1000
SHOW LIVE DATA
HELP
TARGET DATA
20-KeV F into 10 torr SF6 + 50 torr He (1 layers, 3 atoms)
Layer Name | Width (A) | Density | F (18.998) | S (32.066) | He (4.003) | Solid/G
1 No. 614 Sulfur Hexafluori | 30000000 | 0.000090 | 0.50000 | 0.08333 | 0.41667 | Gas
Lattice Binding Energy | 3 | 3 | 1
Surface Binding Energy | 2 | 2.88 | 2
Calculation Parameters
Backscattered Ions 6
Transmitted Ions 0
Vacancies/Ion 349.6
ION STATS Range Straggle
Longitudinal 1.19 mm 476. um
Lateral Proj. 325. um 418. um
Radial 529. um 299. um
Type of Damage Calculation
Quick: Kinchin-Pease
Stopping Power Version
SRIM-2008
% ENERGY LOSS Ions Recoils
Ionization 20.86 20.61
Vacancies 0.60 3.38
Phonons 1.70 52.85
SPUTTERING YIELD
Atoms/Ion eV/Atom
TOTAL
F 0.000000 0.00
S 0.000000 0.00
He 0.000000 0.00
Plots
PLOT Window
0 A - 30000000 A
Max Target Depth 30000000
COLLISION PLOTS
XY Longitudinal All
XZ Longitudinal None
XY Ions Only Tile
YZ Lateral Clear
Background color White/Black
File Plot DISTRIBUTIONS
Ion Distribution
Ion/Recoil Distribution
Lateral Range
Ionization
Phonons
Energy to Recoils
Damage Events
Integral Sputtered
Differential Ions
Ion Ranges (3D data)
Backscattered Ions
Transmitted Ions
Collision Details
HELP
XY Longitudinal
+ 1.5 mm
Depth vs. Y-Axis
No. 614 Sulfur Hexafluoride
- 1.5 mm
0 A
-- Target Depth --
Save Save As Print Label Clear
IONIZATION Distribution
IONIZATION
IONS
RECOILS
Energy Loss (eV/Angstrom)
40x10 -5
35x10 -5
30x10 -5
25x10 -5
20x10 -5
15x10 -5
10x10 -5
5x10 -5
0
0 A
- Target Depth -
3 mm
Save Save As Print Help


ION
Ion Type He 4.003 amu
Ion Energy 20 keV
Ion Angle 0 degrees
Completed 1000 of 1000
SHOW LIVE DATA
HELP
Plots
PLOT Window
0 A - 100000000 A
Max Target Depth 100000000
COLLISION PLOTS
XY Longitudinal
XZ Longitudinal
XY Ions Only
YZ Lateral
All
None
Tile
Clear
Background color White/Black
DISTRIBUTIONS
File Plot
Ion Distribution
Ion/Recoil Distribution
Lateral Range
Ionization
Phonons
Energy to Recoils
Damage Events
Integral
Differential
Sputtered Ions
Ion Ranges (3D data)
Backscattered Ions
Transmitted Ions
Collision Details
HELP
TARGET DATA
20-KeV He into 10 torr SF6 + 50 torr He (1 layers, 3 atoms)
Layer Name | Width (A) | Density | F (18.998) | S (32.066) | He (4.003) | Solid/G
1 No. 614 Sulfur Hexafluori | 100000000 | 0.000090 | 0.50000 | 0.08333 | 0.41667 | Gas
Lattice Binding Energy | 3 | 3 | 1
Surface Binding Energy | 2 | 2.88 | 2
Calculation Parameters
Backscattered Ions 12
Transmitted Ions 0
Vacancies/Ion 115.3
ION STATS
Range Straggle
Longitudinal 5.39 mm 1.66 mm
Lateral Proj. 1.61 mm 1.98 mm
Radial 2.50 mm 1.20 mm
Type of Damage Calculation
Quick: Kinchin-Pease
Stopping Power Version
SRIM-2008
% ENERGY LOSS
Ions Recoils
Ionization 74.68 4.79
Vacancies 0.42 0.90
Phonons 1.92 17.29
SPUTTERING YIELD
Atoms/Ion eV/Atom
TOTAL
F 0.000000 0.00
S 0.000000 0.00
He 0.000000 0.00
XY Longitudinal
Depth vs. Y-Axis
+ 5 mm
- 5 mm
No. 614 Sulfur Hexafluoride
0 A
-- Target Depth --
10
Save
Save As
Print
Label
Clear
IONIZATION Distribution
IONIZATION
IONS
RECOILS
Energy Loss (eV/Angstrom)
No. 614 Sulfur Hexafluoride
30x10^-5
25x10^-5
20x10^-5
15x10^-5
10x10^-5
5x10^-5
0
0 A
- Target Depth -
10 mm
Save
Save As
Print
Help

Existing Directional Detectors

- Most, but not all, groups focused on Time Projection Chambers at < $1m^3$ scale:
  - Newage (1 m^3 funded)
  - DRIFT (1 m^3 operating)
  - DMTPC (1 m^3 constructed)
  - MIMAC ($1m^3$ funded)
  - D^3 (small prototypes)
  - NITECH (small prototypes)