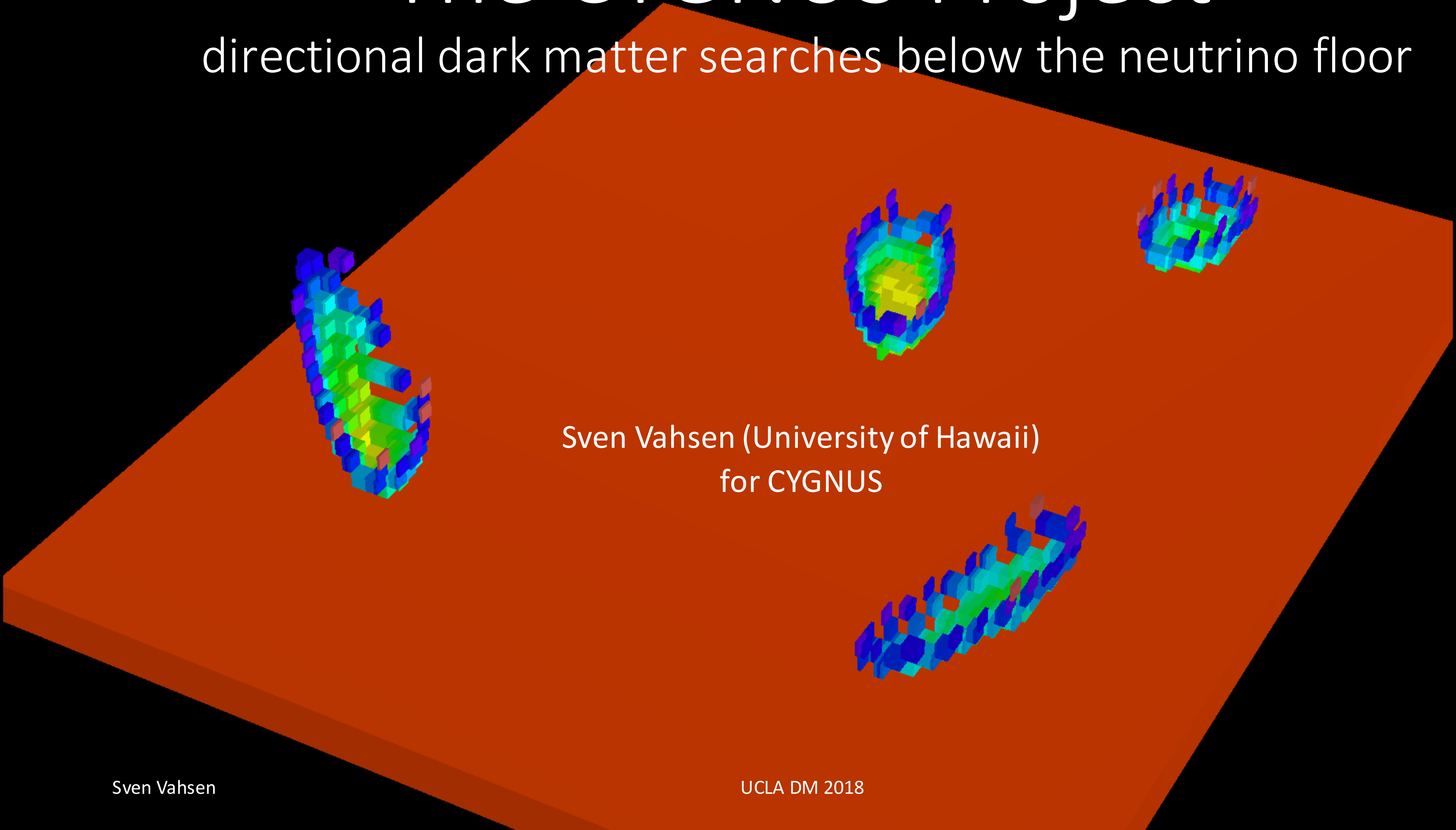
The CYGNUS Project

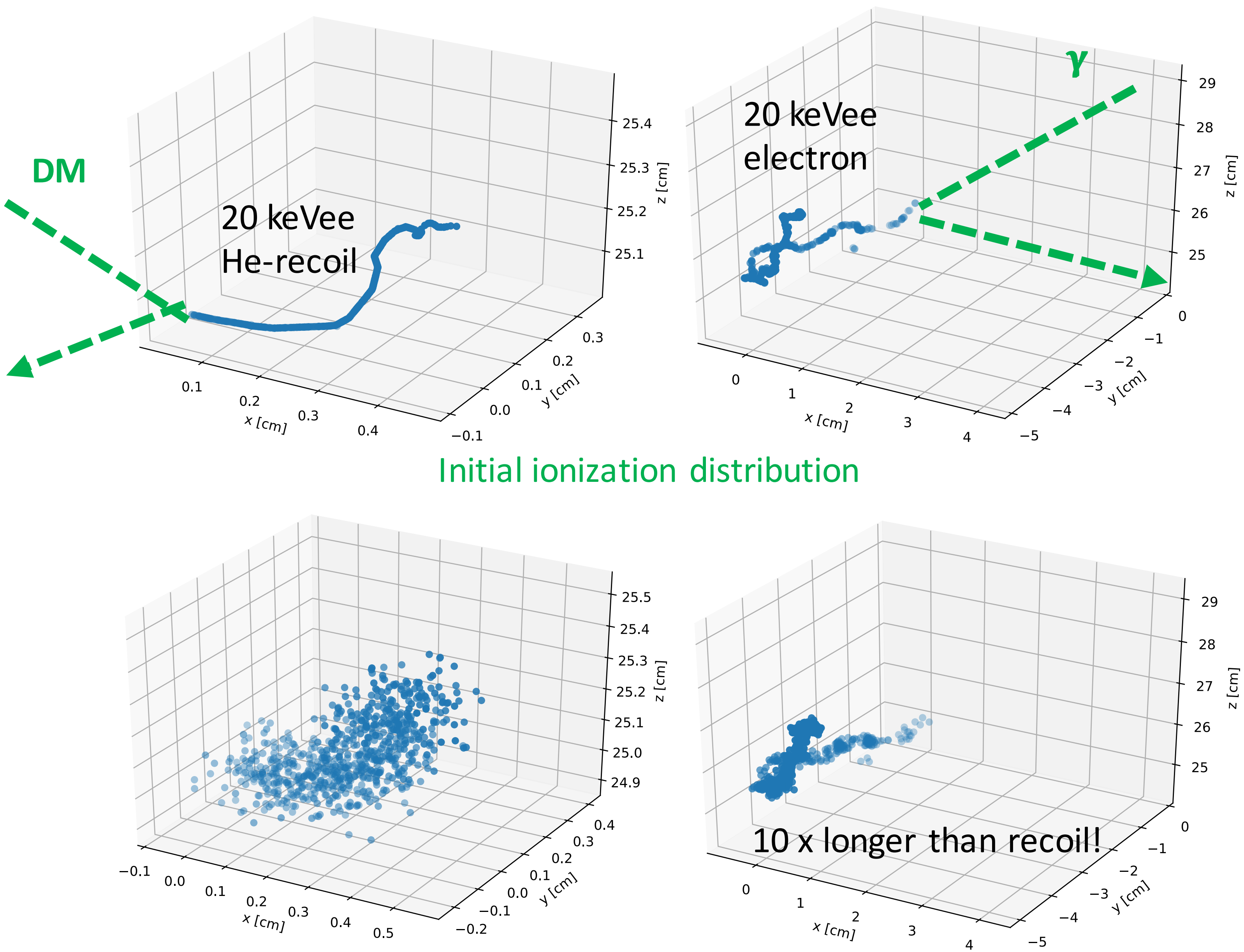
directional dark matter searches below the neutrino floor



Sven Vahsen (University of Hawaii)
for CYGNUS

The main idea

- Direct DM detection
- Gas based TPCs
- Measure spatial ionization distribution resulting from nuclear recoils
- Advantages:
  - Axial Directionality
  - Head/tail
  - Background rejection
    - Particle ID
    - 3D fiducialization
- Technologically challenging, but now achievable via multiple technologies

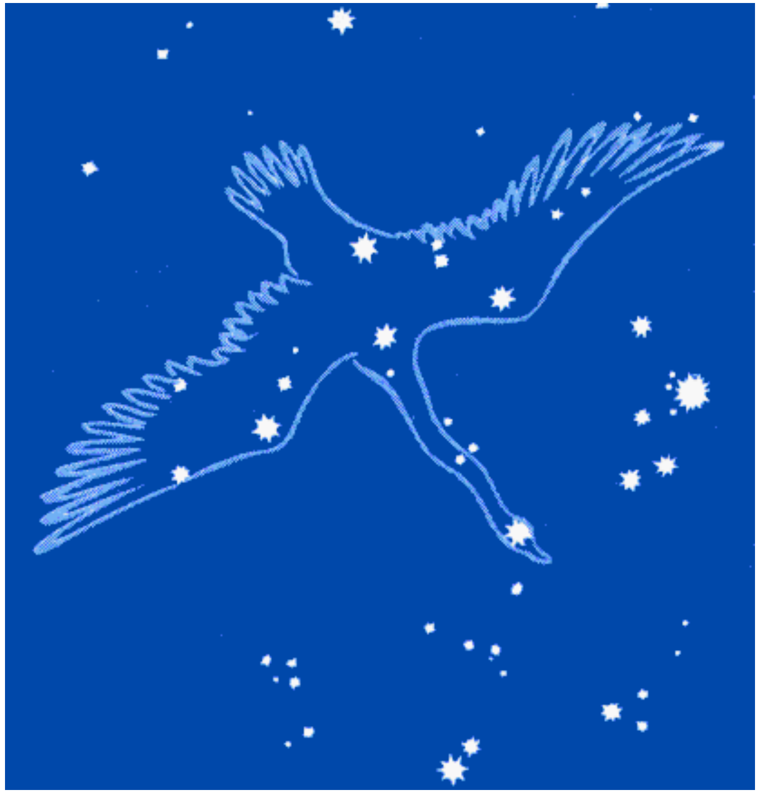


Initial ionization distribution

charge cloud after 25 cm drift in gas TPC

The CYGNUS Collaboration

- Recently, many of the groups working on directional dark matter detection formed CYNUS
- 45 signed members from the US, UK, Japan, Italy, Spain, China, Australia
- Steering group:
  - Neil Spooner (Sheffield, UK)
  - Sven Vahsen (Hawaii, USA)
  - Kentaro Miuchi (Kobe, Japan)
  - Elisabetta Baracchini (GSSI/INFN, Italy)
  - Elisabetta Barberio (Melbourne, Australia)



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

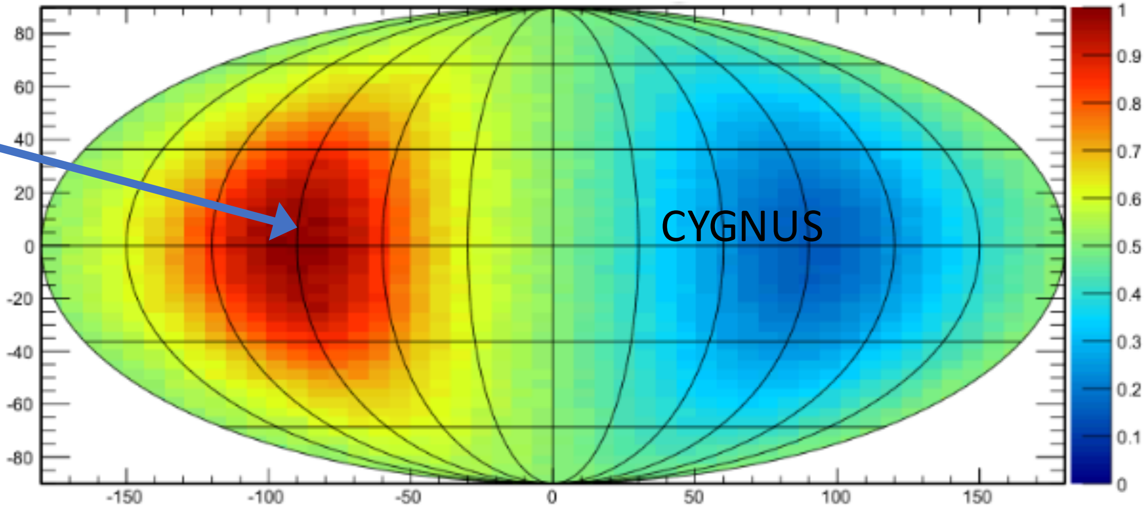
CYGNUS vision and long-term goal

> 1000 m^3 directional nuclear recoil detector capable of

exposure

- Setting competitive DM limits
- Observing galactic dipole ⇔ diurnal oscillation in lab
- Detecting solar neutrinos
- Efficiently penetrating the ν floor
- Measuring DM particle properties and physics
- Measuring Geoneutrinos
- WIMP astronomy

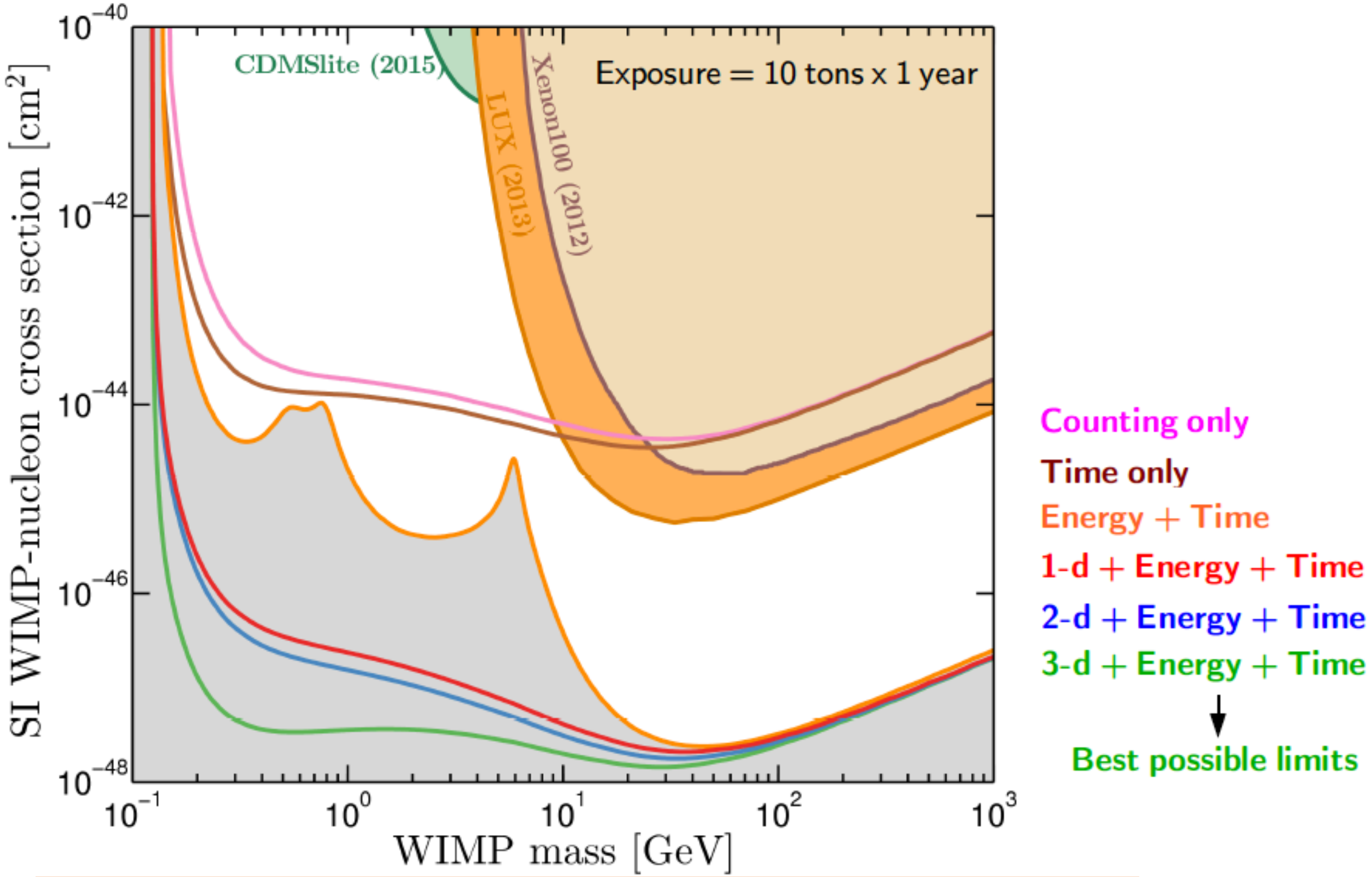
A review of the discovery reach of directional Dark Matter detection
Physics Reports 627 (2016)



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

Galactic dipole: - strongest predicted direct detection signature
- unambiguous proof of cosmological origin

Penetrating the neutrino floor

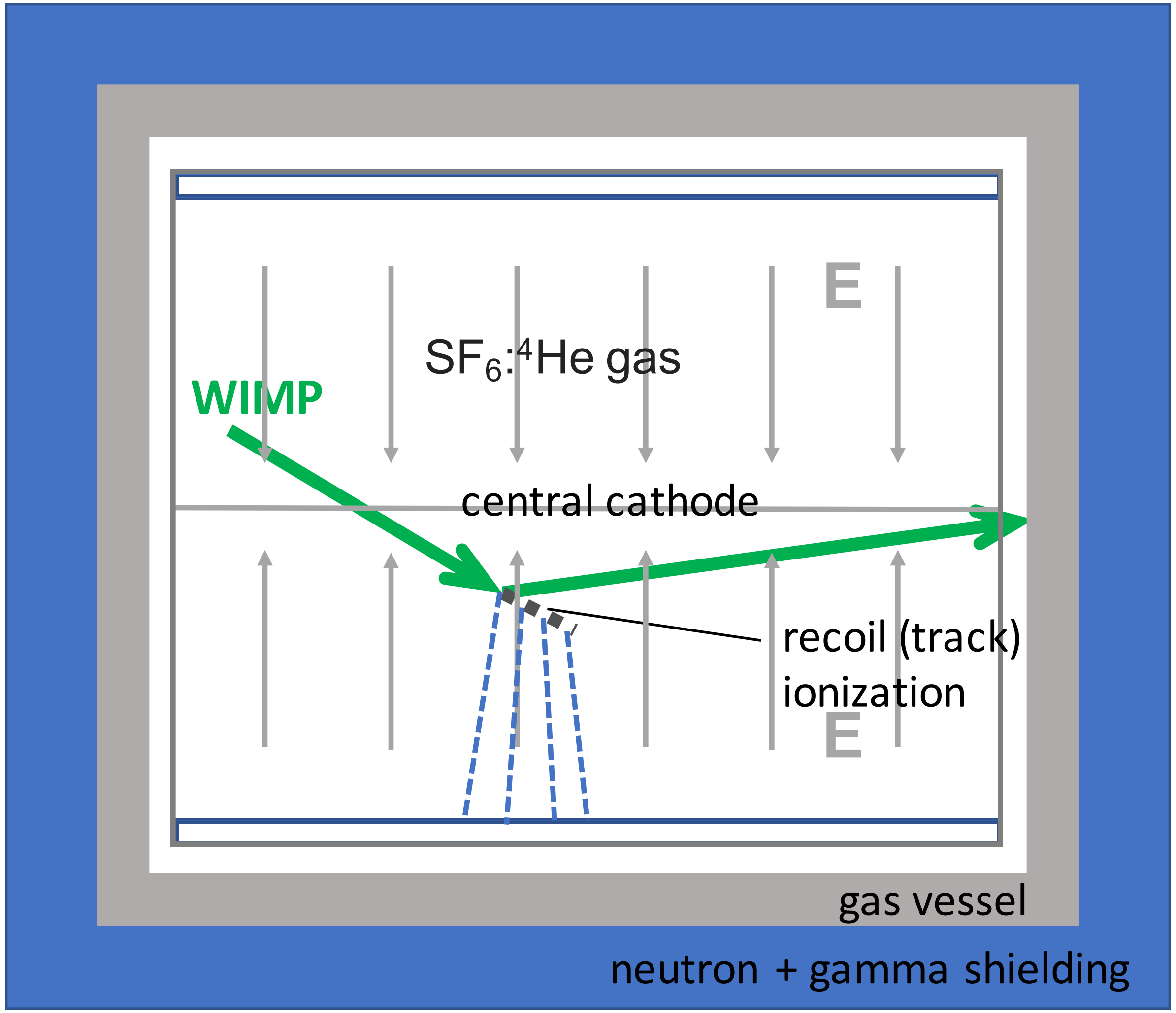


Readout strategies for directional dark matter detection beyond the neutrino background
Ciaran A. J. O'Hare, Anne M. Green, Julien Billard, Enectali Figueroa-Feliciano, Louis E. Strigari

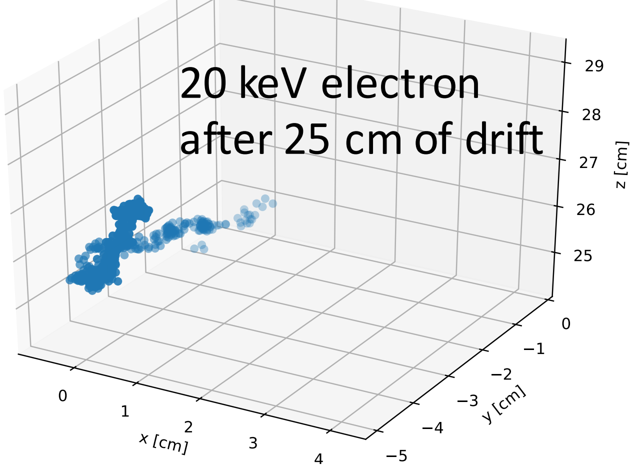
- >= 3 orders of magnitude greater DM sensitivity below neutrino floor w/ with directionality
- 3D “best”, but also most costly
- True Figure of Merit: sensitivity / unit cost.
- CYGNUS currently working on a comprehensive technology + cost comparison to finalize conceptual design of 1000 m^3 detector.

CYGNUS: Experimental Approach

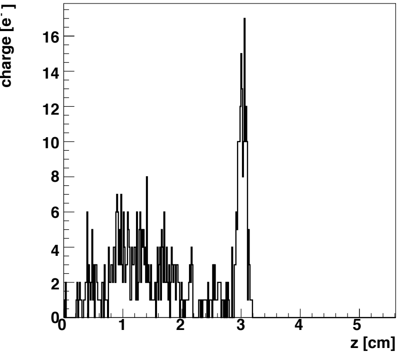
- Gas Time Projection Chamber
- Gas mixture: SF_6:^{4}He, p~1 atm
  - Possibility of switching between higher density (search mode) gas and lower density gas mixtures for (improved) directional confirmation of WIMP signal
- Reduced diffusion via negative Ion drift (SF_6 gas)
- Redundant 3D fiducialization
  - SF_6 minority carriers
  - charge cloud profile
- Helium target
  - Improved sensitivity to low mass WIMP
  - Longer recoil tracks, extending directionality to lower energies
- Multiple readout plane options have been successfully demonstrated



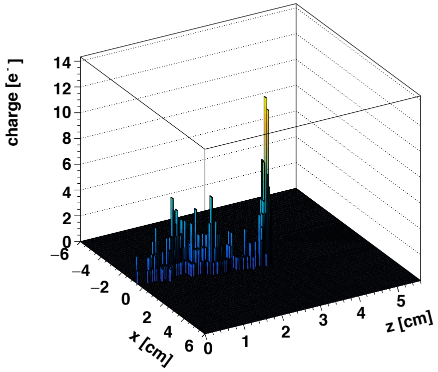
Six types of TPC charge readouts



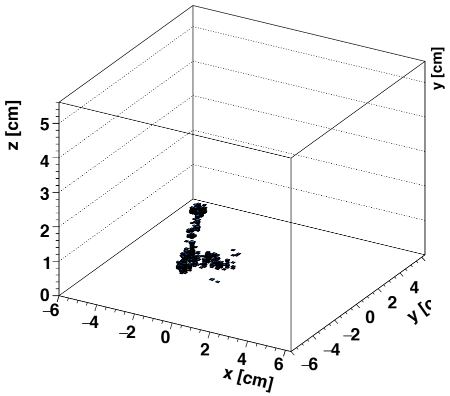
20 keV electron
after 25 cm of drift



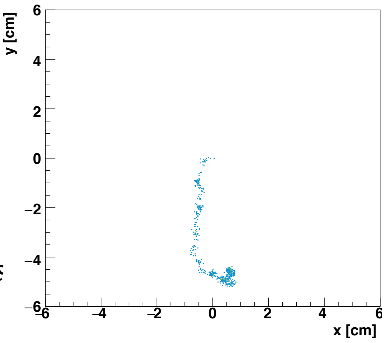
1D GEM



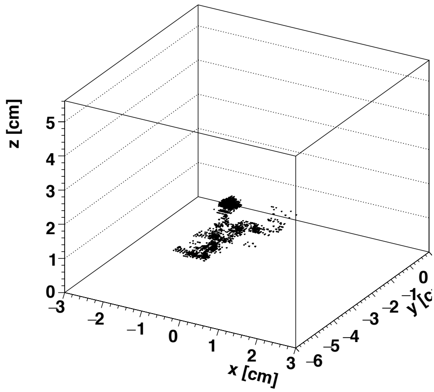
1.5 D: wires



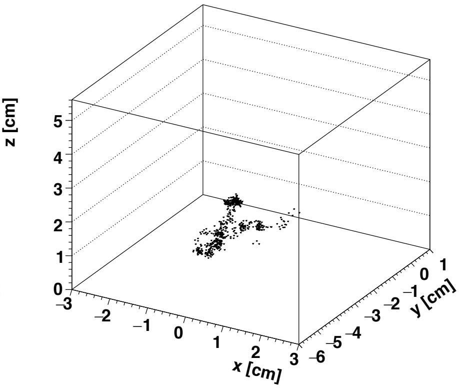
3D pads



2D optical



3D strips



3D pixels

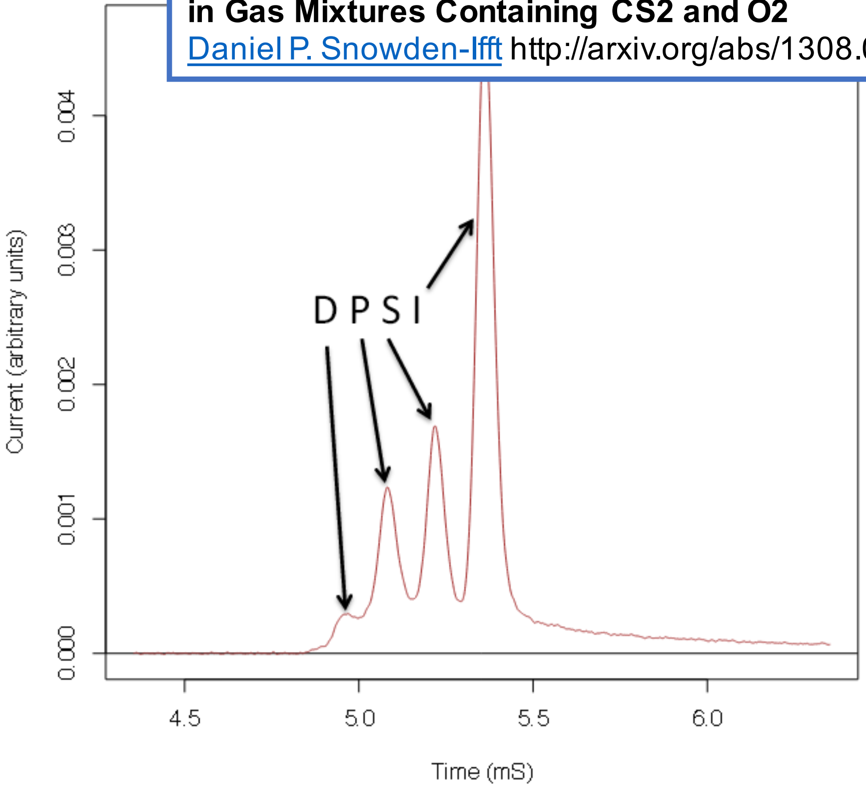
Worse performance
Lower cost

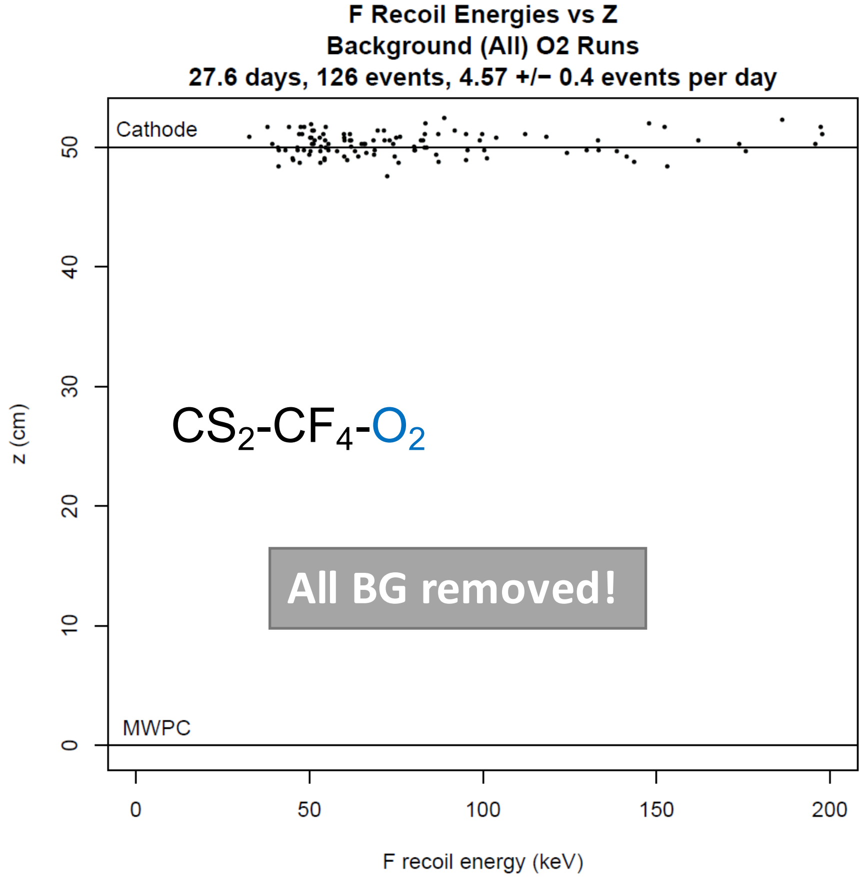
Best compromise? Simulation study ongoing.

Better performance
Higher cost

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





CS_2-CF_4-O_2

All BG removed!

- Game changer for directional WIMP search via gas TPC
- Utilizes timing - works with any charge readout (1D,2D,3D)
- First discovered in CS_2
- Now also demonstrated in pure SF_6 & CF4 + SF_6 mixtures
- Incredibly lucky: SF_6 is also non-toxic, non-flammable, not corrosive, has gain, thermal diffusion, 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

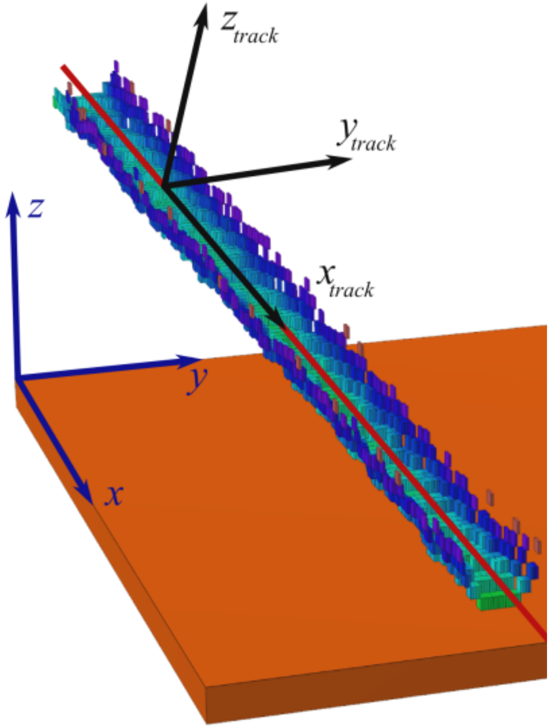
3D Fiducialization II: Charge Cloud Reconstruction

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

P.Lewis (U. Hawaii)

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

→ obtain absolute position in drift direction



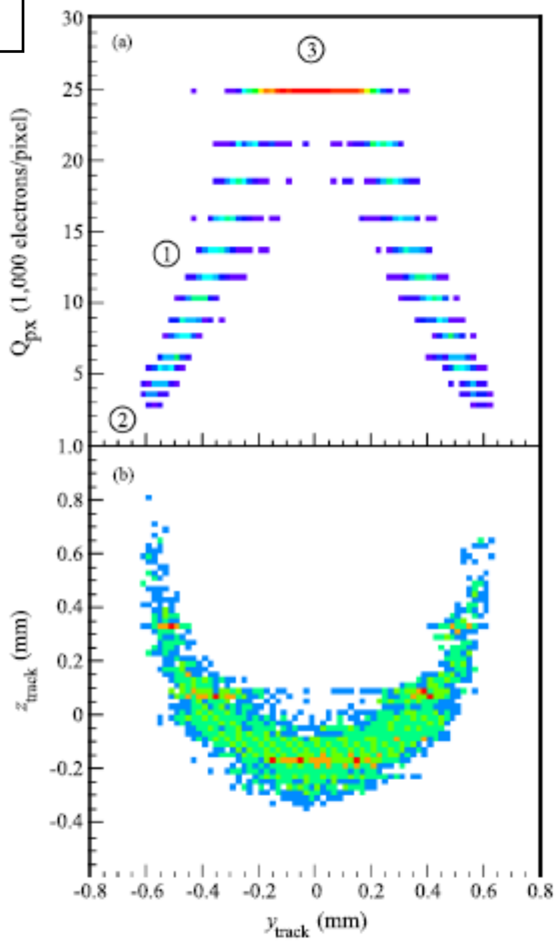


Fig. 2. Corrected pixel charge (Q_{px}) profile (a) and shell coordinates (b) for a single horizontal track from the near alpha source. Label 1 of the profile plot (a) corresponds to the Gaussian, label 2 to the threshold, and label 3 to the saturation regions of the profile. The U-shaped shell in plot (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.)

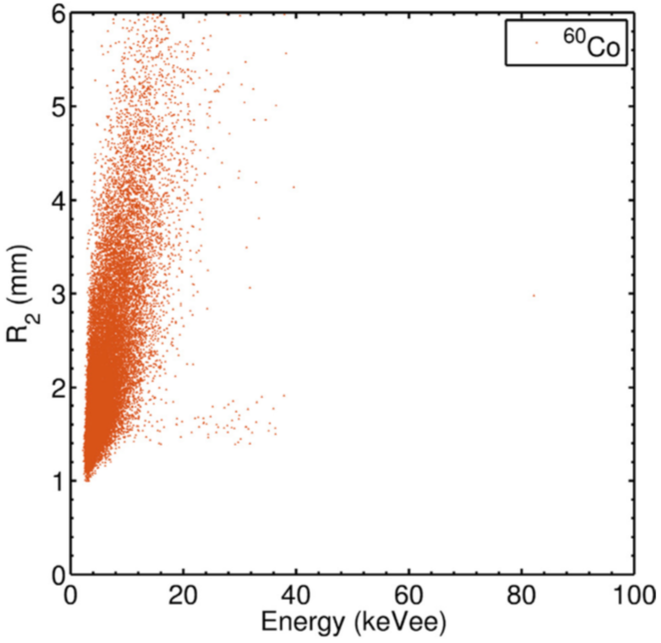
- Requires high resolution readout of charge density → only 2D, 3D
- However, should work with any gas
- Published version utilized "chopped" alphas, but has since been extended by grad student to also work with recoil events (unpublished)

2D electron rejection (experiment)

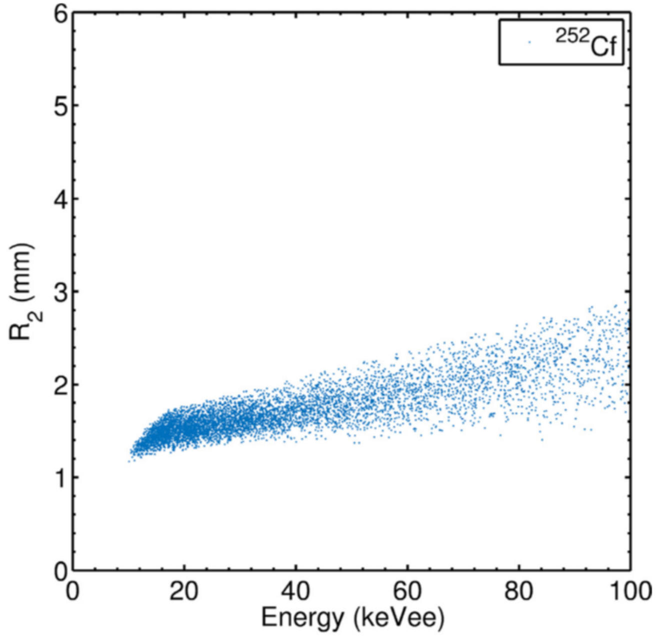
- On right: 2D optical readout in 100 torr CF_4
  - F versus electron recoils
  - $\sigma = 0.35$ mm readout resolution, incl. diffusion
  - Using range-energy signature, electron event rejection factor < 3.9 x 10^{-5} around 10 keVee
  - *It's a limit – all available electron events rejected*!
- Extrapolating to CYGNUS
  - 20 torr SF6 + 740 torr Helium: 50% longer tracks
  - 50 cm of thermal drift ($\sigma = 0.55$ mm): 50% higher

→expected same discrimination in CYGNUS

- Should improve with 3D charge *cloud tomography, i.e.*, going beyond range-energy signature.
- *Follow-up experimental work with 3D readout needed.*
- *Both directionality and BG rejection are strongly gas density dependent. Can operate in search mode (higher density) and confirmation mode (lower density)*



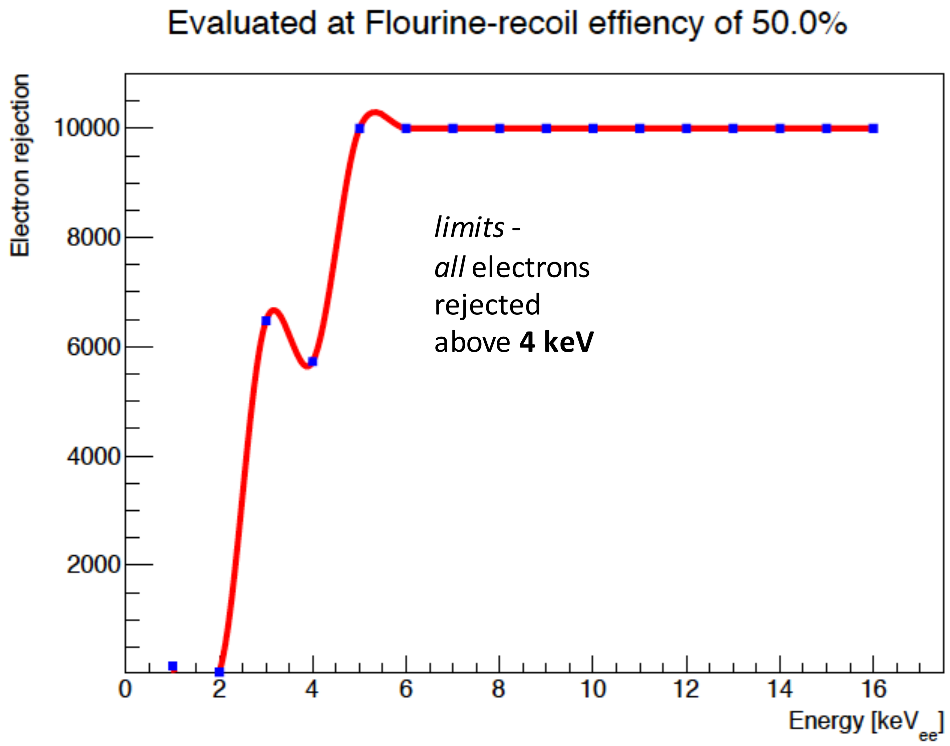
(b) ^{60}Co data post CCD cuts



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

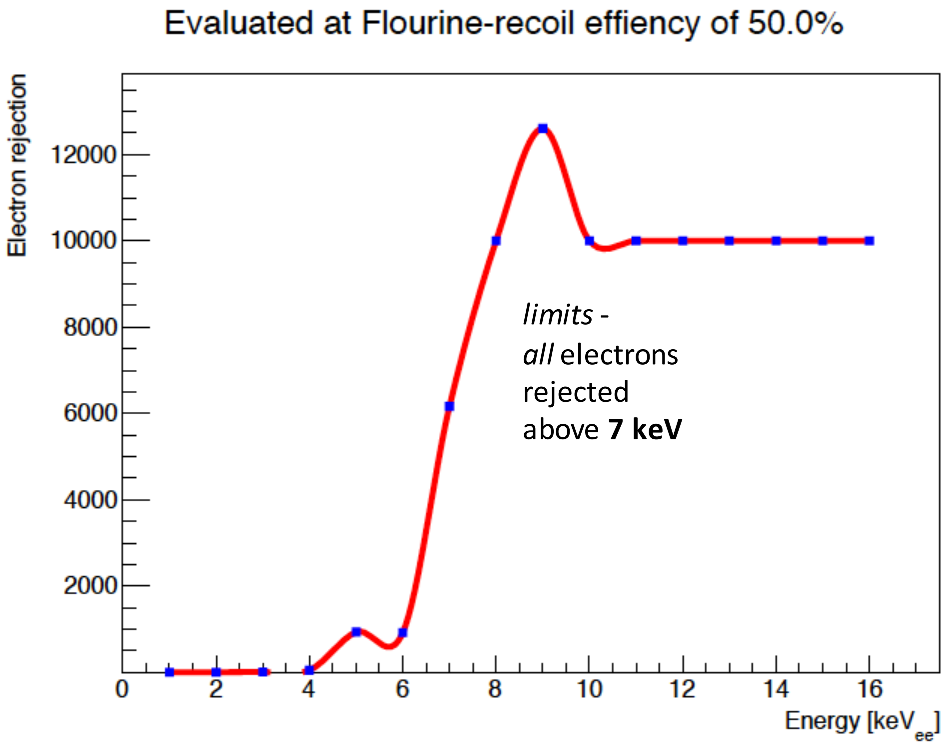
GEM-based TPC with CCD imaging for directional dark matter detection
N.S. Phan, et. al., Astroparticle Physics, 84 (2016)

3D electron rejection (simulation) per 1keVee



limits -
all electrons
rejected
above **4 keV**

No drift



limits -
all electrons
rejected
above **7 keV**

25 cm drift

By range versus energy signature alone, excellent electron rejection down to 3-7 keV (depending on drift length)

Backgrounds, underground lab

- Boulby underground laboratory has offered to host CYGNUS detectors in a dedicated cavern
- Also interest from new Stawell Underground Laboratory (SUPL) in Victoria Australia
- We ultimately envision a distributed network of underground detectors
- Simulations show that we can get the rock and cosmogenic neutron background at Boulby down to < 0.5 events/year for a 1000 m detector
- After copper shielding, expect ~10^5 gammas/year < 10 keV → matches expected discrimination

Underground at Boulby

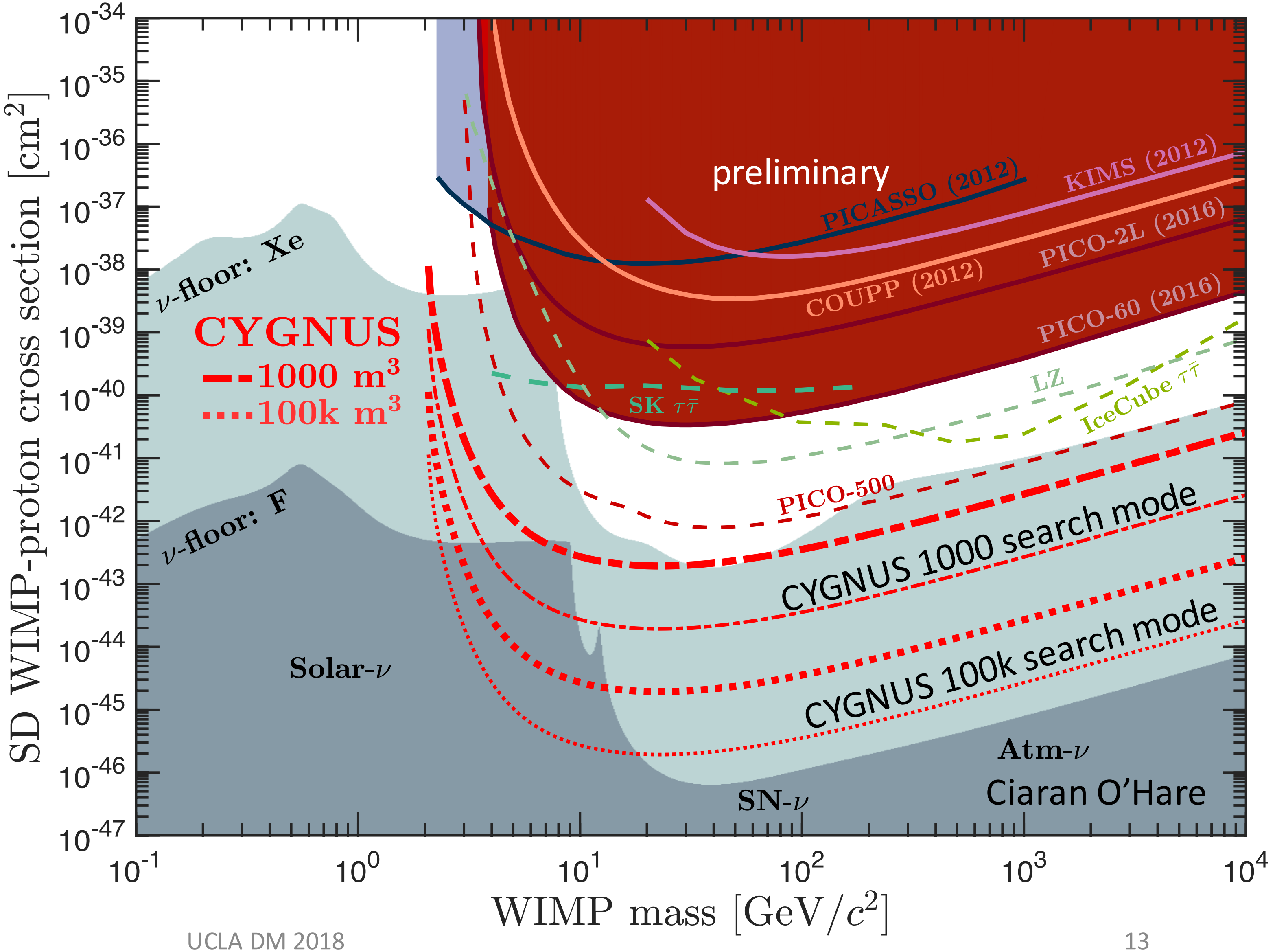
CYGNUS SD Sensitivity

CYGNUS 1000: 10m x 10m x 10m
CYGNUS 100k: ~2 x DUNE target volume

- Assumptions
  - 3 years of running time
  - 3 keVr F threshold
  - 1 keVr He threshold
  - Directional mode:

    20 torr SF_6
    740 torr 4-He
  - Search mode:

    200 torr SF_6
    740 torr 4-He
- Should see solar ν events
- Discoveries can be investigated in directional mode

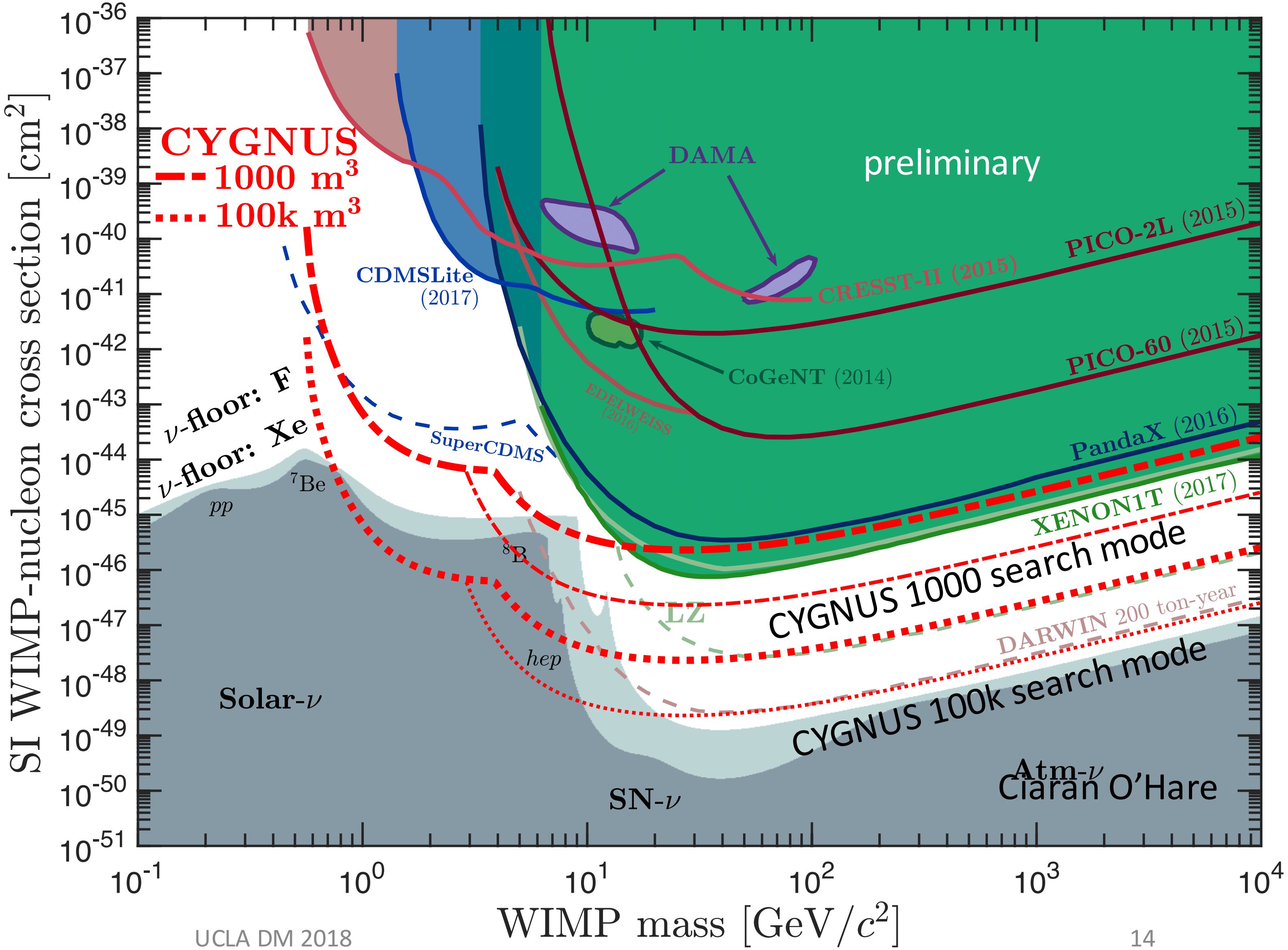


CYGNUS SI Sensitivity

- Assumptions
  - 3 years of running time
  - 3 keVr F threshold
  - 1 keVr He threshold
  - Directional mode:

    20 torr SF_6
    740 torr 4-He
  - Search mode:

    200 torr SF_6
    740 torr 4-He
- Should see solar ν events
- Discoveries can be investigated in directional mode

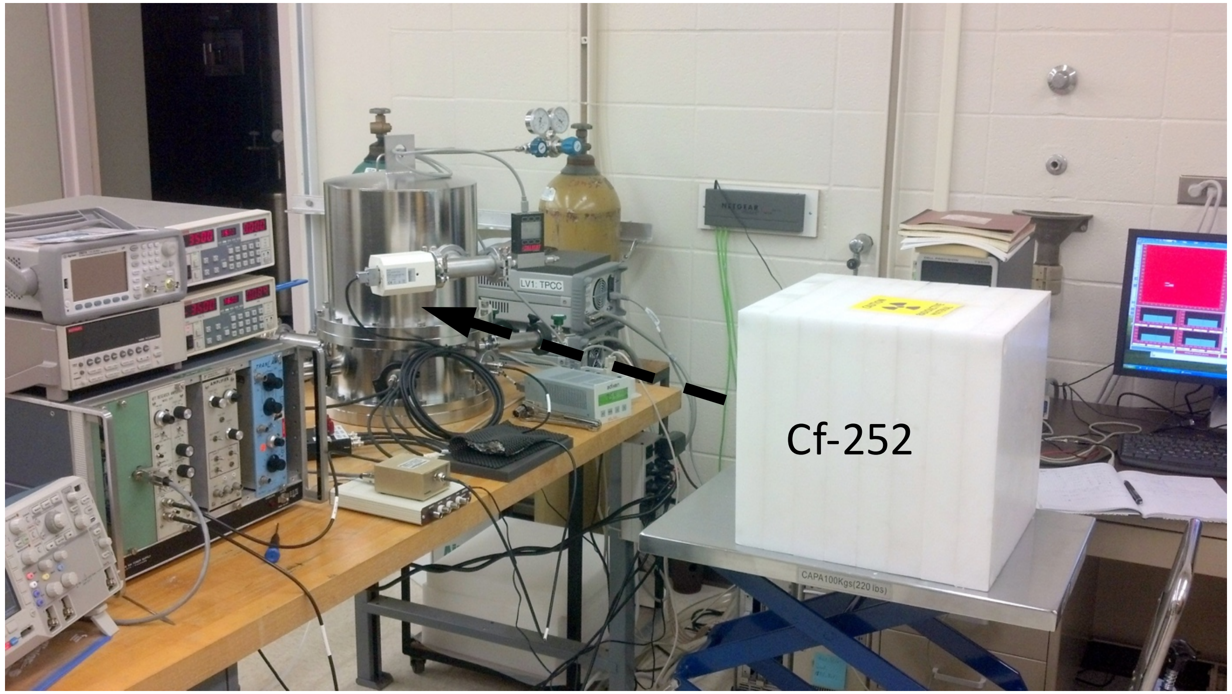


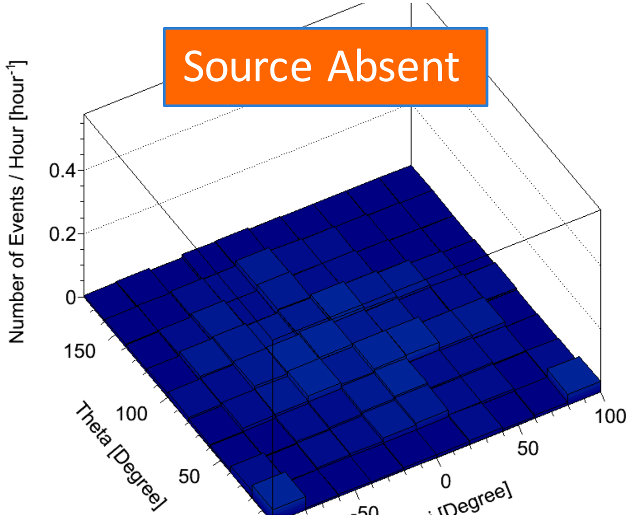
Conclusion & Summary

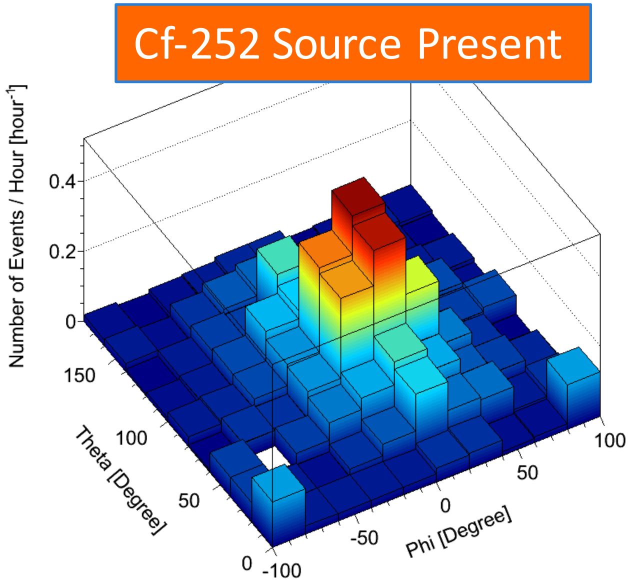
- Directional detection via imaging of recoils
  - provides a new handle on otherwise irreducible backgrounds in WIMP searches
  - improves what can be learned from a WIMP signal
- Much of worldwide directional detection community merged into CYGNUS
- Work on conceptual design of 1000 m^3 detector nearly complete
  - 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
- First step towards a large-scale, distributed recoil observatory, capable of
  - unambiguously demonstrating the cosmological origin of a putative WIMP signal
  - effectively penetrating the neutrino floor
  - eventually, WIMP astronomy
- Look for conceptual design paper soon

BACKUP SLIDES

Detecting the *Neutron* Wind - in 3D

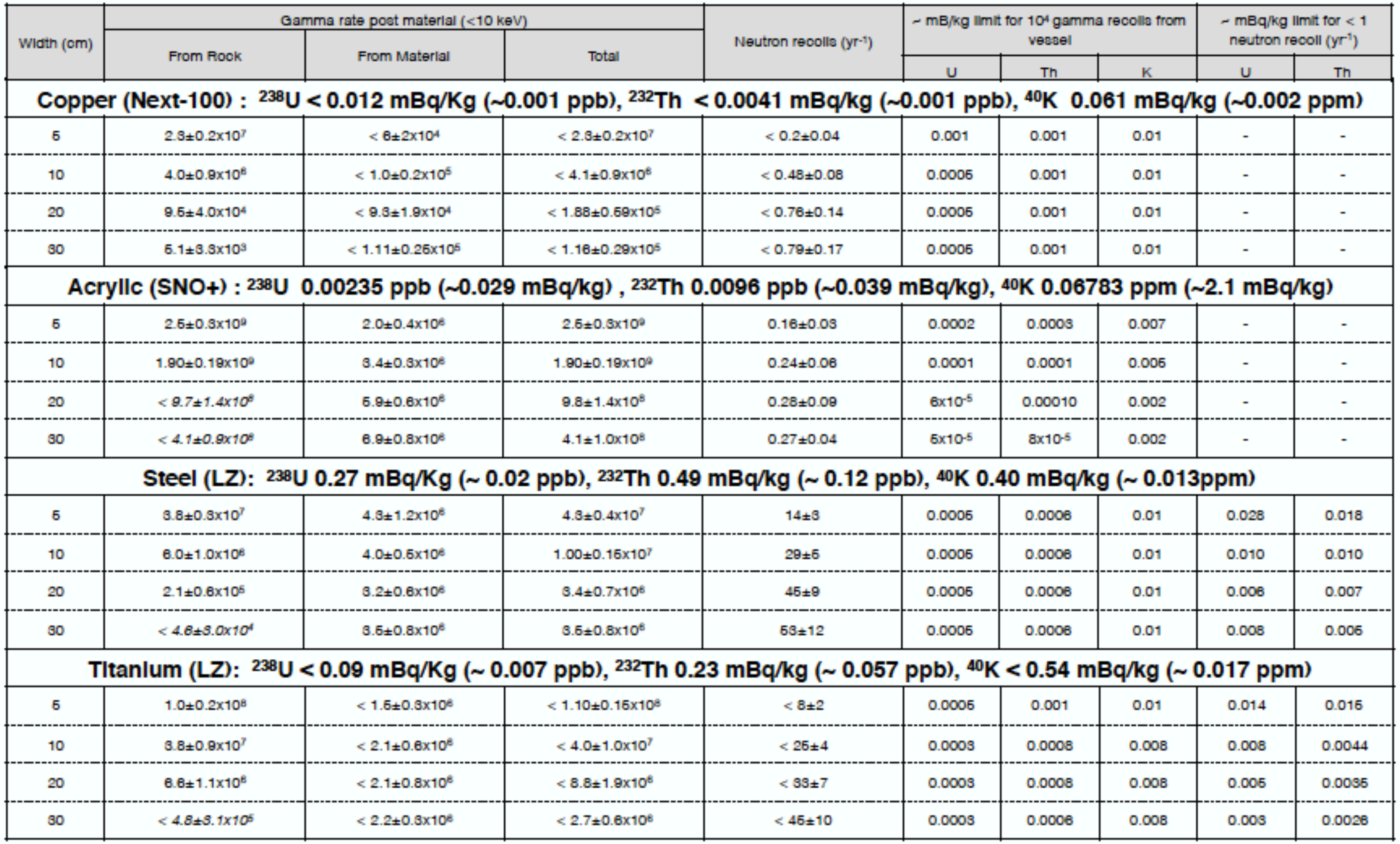



Source Absent


Cf-252 Source Present

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

Vessel Material Backgrounds



Width (cm)	Gamma rate post material (<10 keV)			Neutron recoils (yr^{-1})	~ mB/kg limit for 10^4 gamma recoils from vessel			~ mBq/kg limit for < 1 neutron recoil (yr^{-1})	
	From Rock	From Material	Total		U	Th	K	U	Th
Copper (Next-100) : ^{238}U < 0.012 mBq/Kg (~0.001 ppb), ^{232}Th < 0.0041 mBq/kg (~0.001 ppb), ^{40}K 0.061 mBq/kg (~0.002 ppm)									
5	$2.3 \pm 0.2 \times 10^7$	$< 6 \pm 2 \times 10^4$	$< 2.3 \pm 0.2 \times 10^7$	$< 0.2 \pm 0.04$	0.001	0.001	0.01	-	-
10	$4.0 \pm 0.9 \times 10^6$	$< 1.0 \pm 0.2 \times 10^5$	$< 4.1 \pm 0.9 \times 10^6$	$< 0.48 \pm 0.08$	0.0005	0.001	0.01	-	-
20	$9.5 \pm 4.0 \times 10^4$	$< 9.3 \pm 1.9 \times 10^4$	$< 1.88 \pm 0.59 \times 10^5$	$< 0.76 \pm 0.14$	0.0005	0.001	0.01	-	-
30	$5.1 \pm 3.3 \times 10^3$	$< 1.11 \pm 0.25 \times 10^5$	$< 1.16 \pm 0.29 \times 10^5$	$< 0.79 \pm 0.17$	0.0005	0.001	0.01	-	-
Acrylic (SNO+) : ^{238}U 0.00235 ppb (~0.029 mBq/kg) , ^{232}Th 0.0096 ppb (~0.039 mBq/kg), ^{40}K 0.06783 ppm (~2.1 mBq/kg)									
5	$2.5 \pm 0.3 \times 10^9$	$2.0 \pm 0.4 \times 10^6$	$2.5 \pm 0.3 \times 10^9$	0.16 ± 0.03	0.0002	0.0003	0.007	-	-
10	$1.90 \pm 0.19 \times 10^9$	$3.4 \pm 0.3 \times 10^6$	$1.90 \pm 0.19 \times 10^9$	0.24 ± 0.06	0.0001	0.0001	0.005	-	-
20	*$< 9.7 \pm 1.4 \times 10^8$*	$5.9 \pm 0.6 \times 10^6$	$9.8 \pm 1.4 \times 10^8$	0.28 ± 0.09	6×10^{-5}	0.00010	0.002	-	-
30	*$< 4.1 \pm 0.9 \times 10^8$*	$6.9 \pm 0.8 \times 10^6$	$4.1 \pm 1.0 \times 10^8$	0.27 ± 0.04	5×10^{-5}	8×10^{-5}	0.002	-	-
Steel (LZ): ^{238}U 0.27 mBq/Kg (~ 0.02 ppb), ^{232}Th 0.49 mBq/kg (~ 0.12 ppb), ^{40}K 0.40 mBq/kg (~ 0.013ppm)									
5	$3.8 \pm 0.3 \times 10^7$	$4.3 \pm 1.2 \times 10^6$	$4.3 \pm 0.4 \times 10^7$	14 ± 3	0.0005	0.0006	0.01	0.028	0.018
10	$6.0 \pm 1.0 \times 10^6$	$4.0 \pm 0.5 \times 10^6$	$1.00 \pm 0.15 \times 10^7$	29 ± 5	0.0005	0.0006	0.01	0.010	0.010
20	$2.1 \pm 0.6 \times 10^5$	$3.2 \pm 0.6 \times 10^6$	$3.4 \pm 0.7 \times 10^6$	45 ± 9	0.0005	0.0006	0.01	0.006	0.007
30	*$< 4.6 \pm 3.0 \times 10^4$*	$3.5 \pm 0.8 \times 10^6$	$3.5 \pm 0.8 \times 10^6$	53 ± 12	0.0005	0.0006	0.01	0.008	0.005
Titanium (LZ): ^{238}U < 0.09 mBq/Kg (~ 0.007 ppb), ^{232}Th 0.23 mBq/kg (~ 0.057 ppb), ^{40}K < 0.54 mBq/kg (~ 0.017 ppm)									
5	$1.0 \pm 0.2 \times 10^8$	$< 1.5 \pm 0.3 \times 10^6$	$< 1.10 \pm 0.15 \times 10^8$	$< 8 \pm 2$	0.0005	0.001	0.01	0.014	0.015
10	$3.8 \pm 0.9 \times 10^7$	$< 2.1 \pm 0.6 \times 10^6$	$< 4.0 \pm 1.0 \times 10^7$	$< 25 \pm 4$	0.0003	0.0008	0.008	0.008	0.0044
20	$6.6 \pm 1.1 \times 10^6$	$< 2.1 \pm 0.8 \times 10^6$	$< 8.8 \pm 1.9 \times 10^6$	$< 33 \pm 7$	0.0003	0.0008	0.008	0.005	0.0035
30	*$< 4.8 \pm 3.1 \times 10^5$*	$< 2.2 \pm 0.3 \times 10^6$	$< 2.7 \pm 0.6 \times 10^6$	$< 45 \pm 10$	0.0003	0.0006	0.008	0.003	0.0026

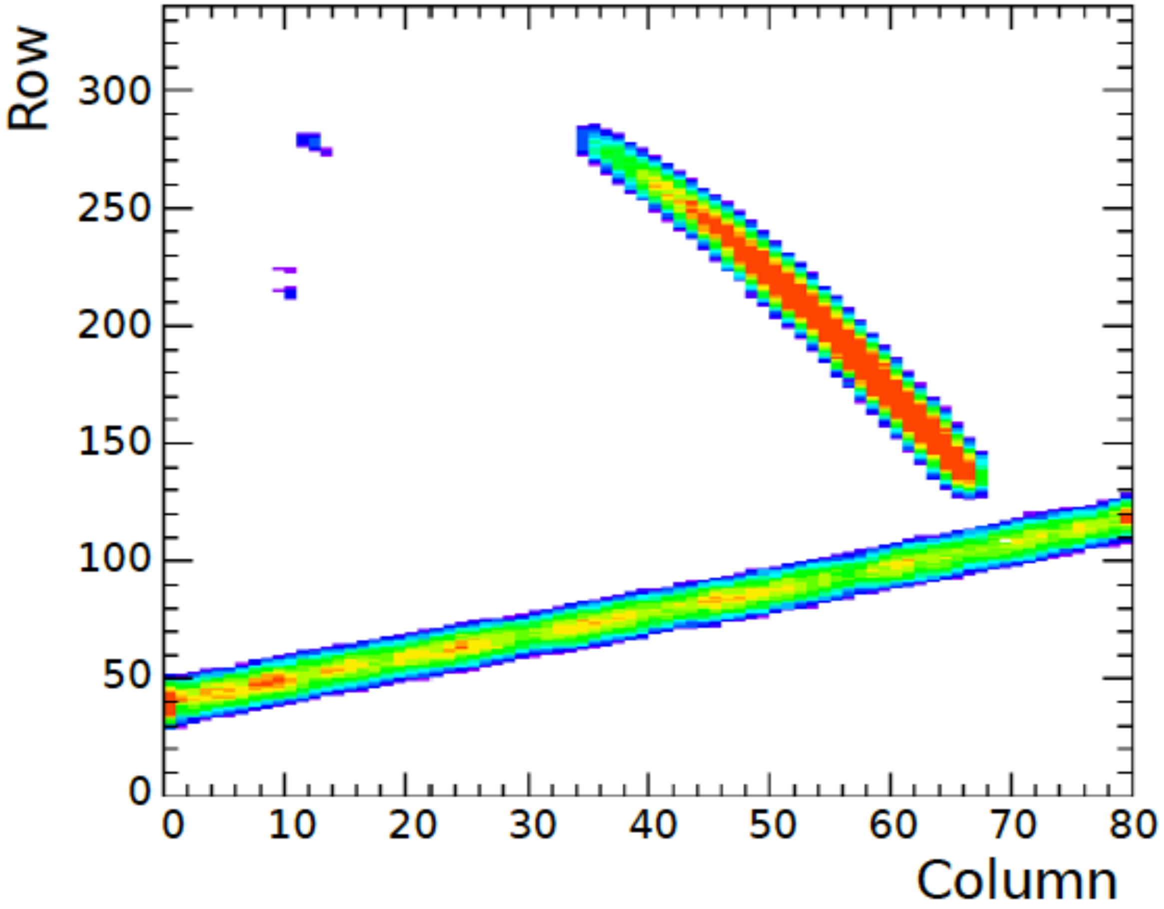


Figure 30: (color online) Three separate events detected by a TPC, superimposed in the same event display. The display is an occupancy plot of all of the pixels that triggered in the events, organized by row and column number. The color indicates the amount of charge collected in each pixel. The small isolated clusters are from X-rays, the long continuous track spanning the entire width of the pixel chip is from an MeV energy-scale alpha particle emitted from a ^{210}Po calibration source. The track completely contained within the chip area is our signal: the resulting nuclear recoil from a fast neutron elastically scattering off of a nucleus in the target gas.

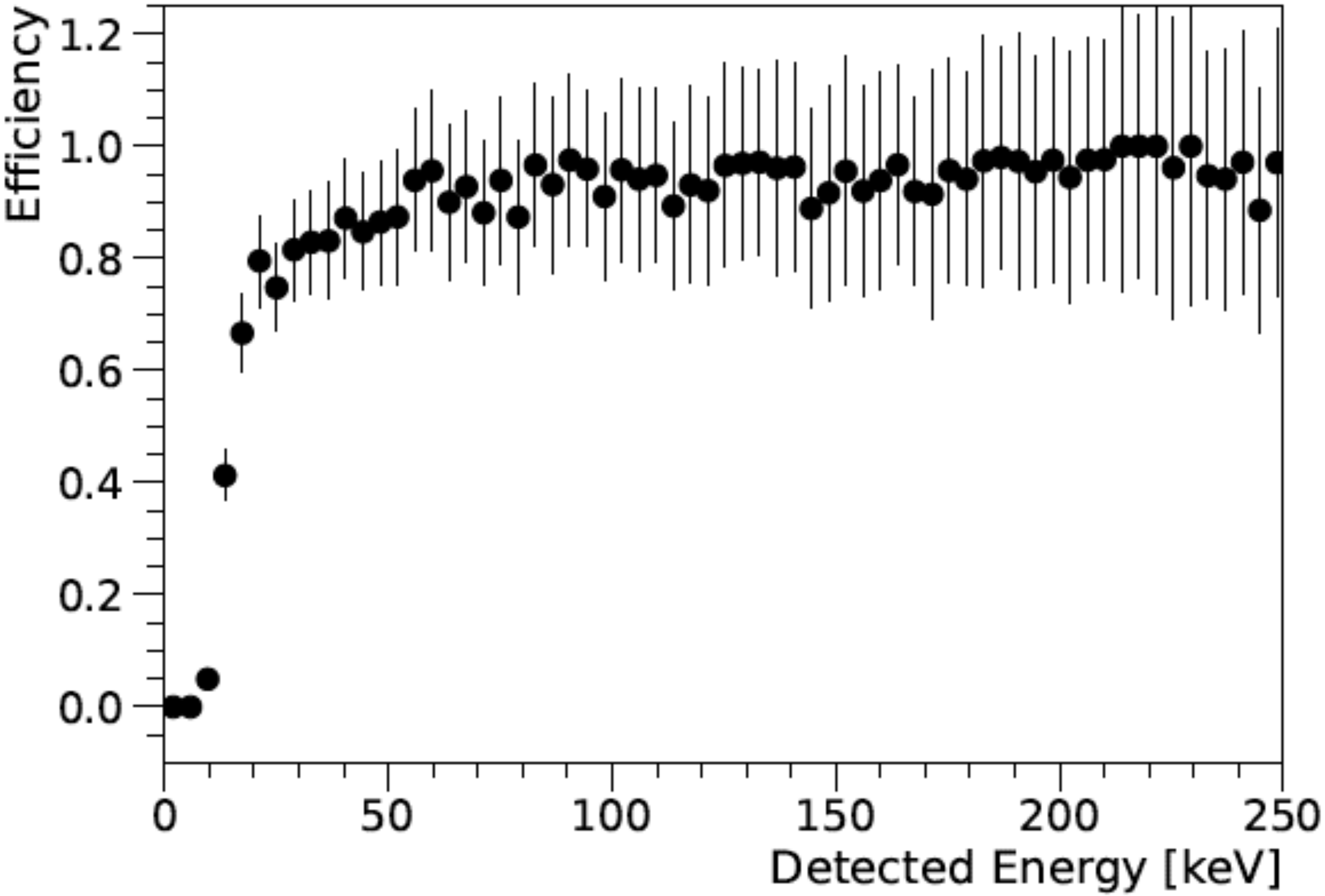
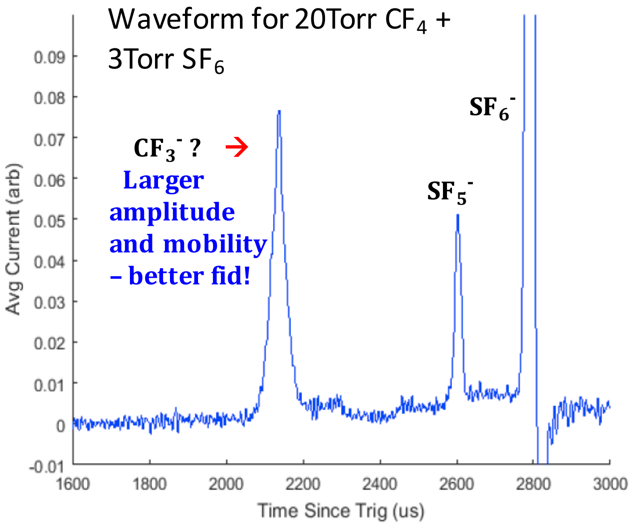
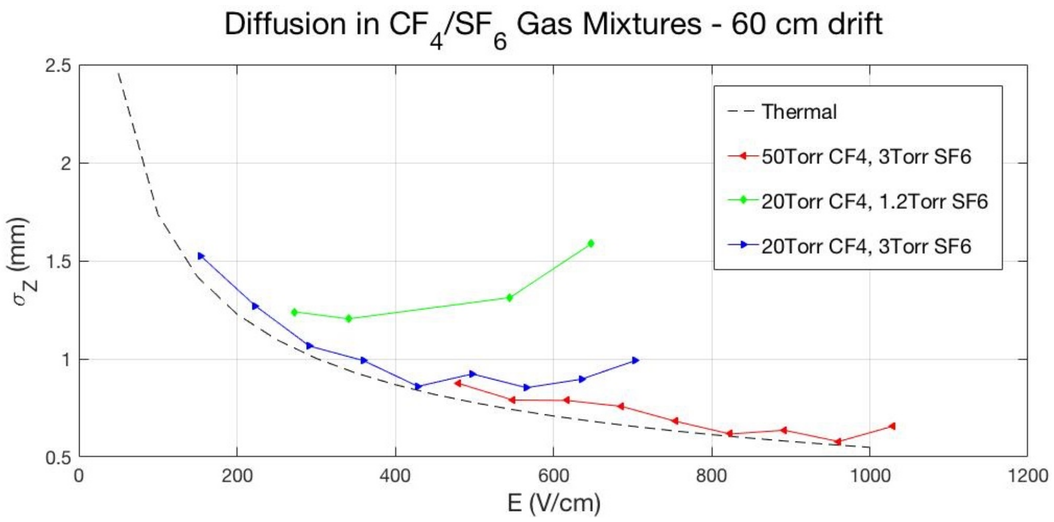


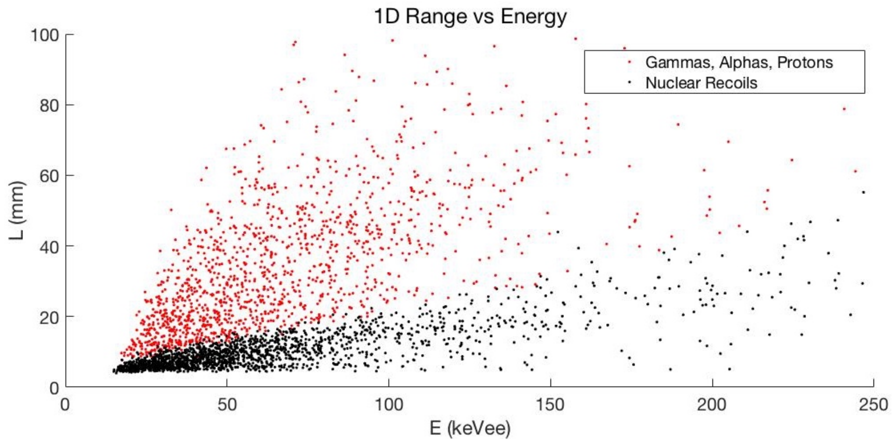
Figure 100: Efficiency of TPC neutron selections described in Table 35 versus detected energy in experimental data. Efficiency of 50% occurs at approximately 15 keV. The error bars show statistical uncertainties only.

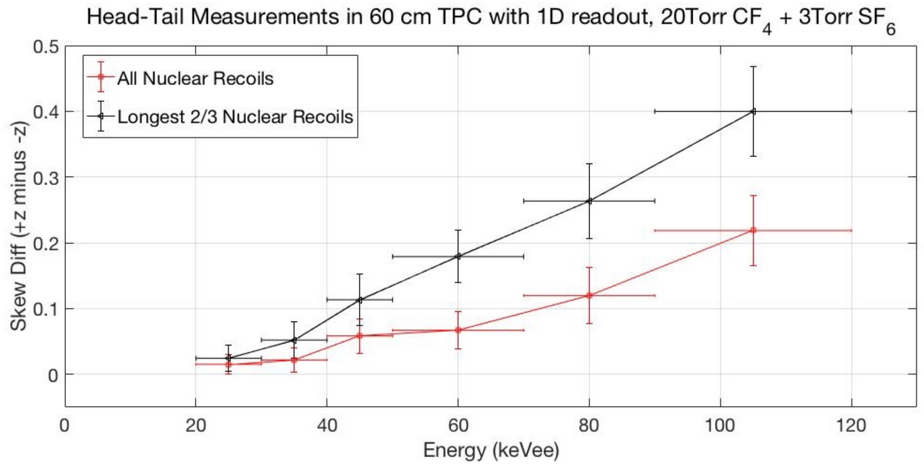
Recent progress at UNM (Randy Lafler, D. Loomba)

- Studies on **SF_6** demonstrated: **gas gain**, **negative-ion drift**, **thermal diffusion** and a secondary charge carrier enabling **fiducialization**. (Phan et al, 2017 *JINST* 12 P02012)
- These properties make it a near-ideal SD gas for directional DM searches
- In the past year we have extended this work to **CF_4/SF_6 gas mixtures**, which exhibit the same benefits as pure SF_6 but with the advantage of a **tunable minority charge carrier for fiducialization**.





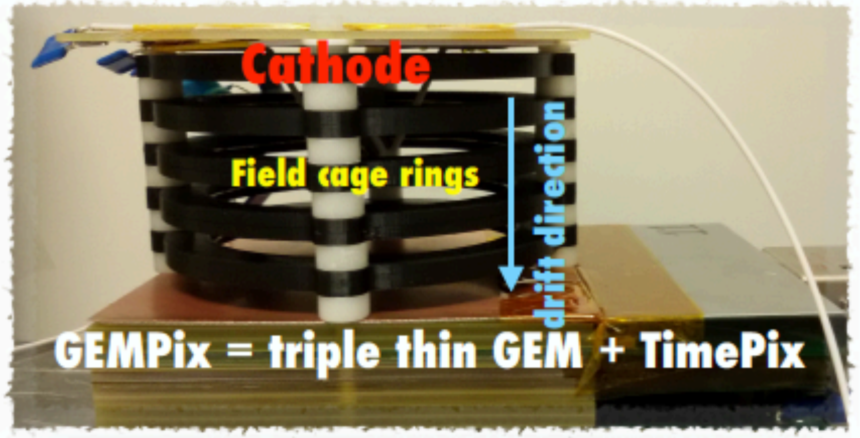




CYGNUS-RD detectors

2015

NITEC: Negative Ion Time Expansion Chamber



Individual Fellowship Marie Sklodowska-Curie

3 x 3 x 5 cm^3

0.045 Liters

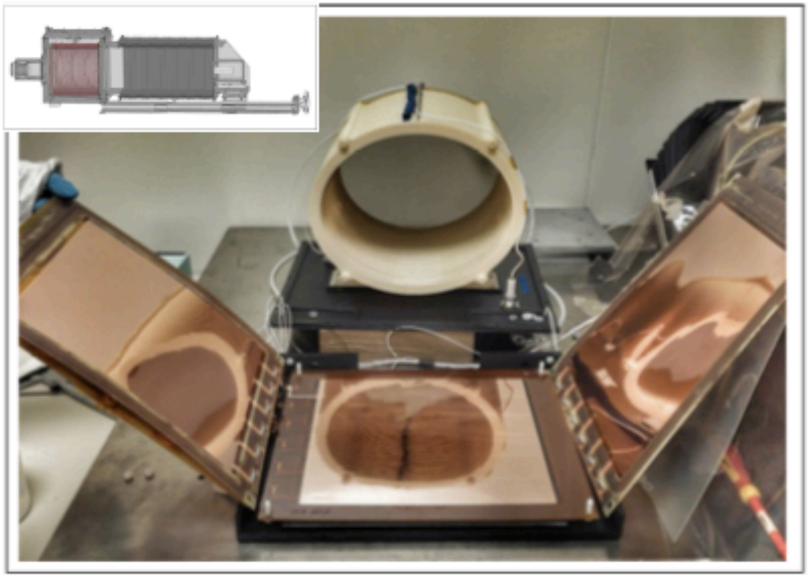
Triple thin GEMs

Timepix pixel 50 x 50 um^2

charge readout

2017

LEMOn: Large Elliptic Module Optically readout



24 x 20 x 20 cm^3

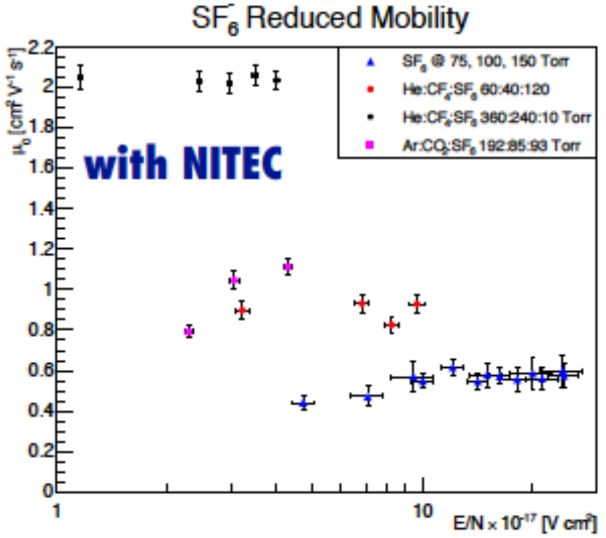
9.6 Liters

Triple thin GEMs

CMOS & PMT optical readout of the light produced in the GEM avalanches

CYGNUS-RD results

**E. Baracchini et al.,
arXiv:1710.01994, under review by JINST**

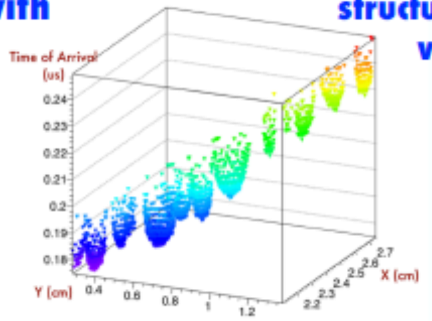

SF$_6^-$ Reduced Mobility

with NITEC

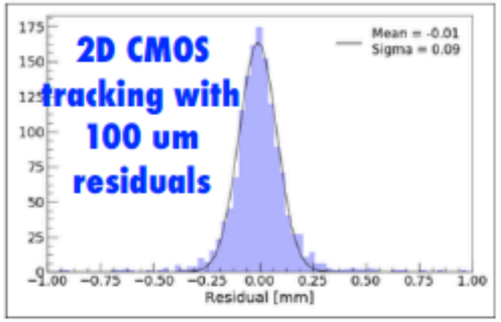
**SF$_6$ negative ion drift up to 610 Torr
with He:CF$_4$-based gas mixtures**

**CR recorded
in NITEC with
Ar:CO$_2$**

**Ionization clusters
structures clearly
visible**

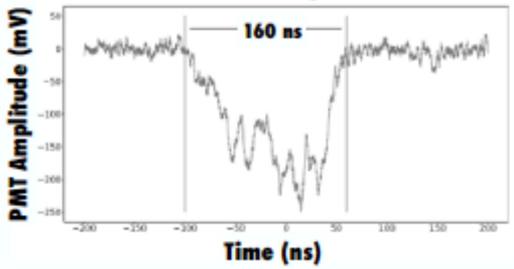


**D. Pinci et al.,
EPS-HEP 2017 Proceedings**

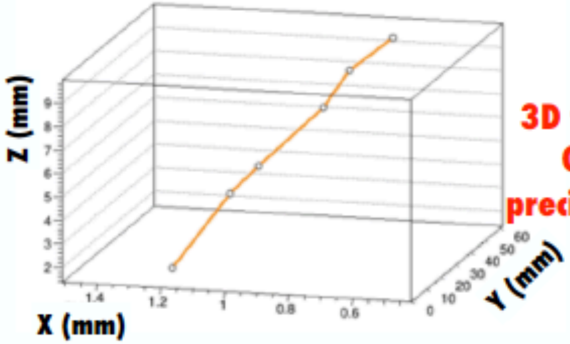

**2D CMOS
tracking with
100 um
residuals**

**G. Mazzitelli et al.,
IEEE 2017 Proceedings**

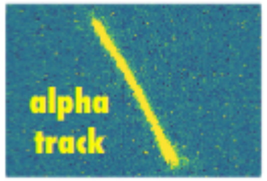
**combined to light time profile
measured by PMT**

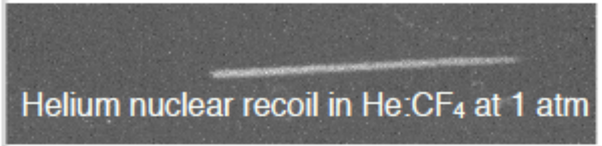


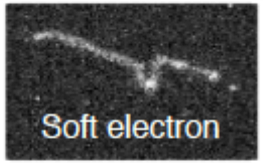
**Optical
negative ion
operation soon**

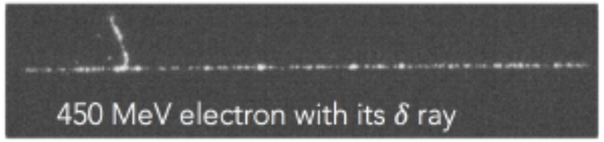


**3D tracking with
O(100) um
precision in He:CF$_4$
at 1 atm**


alpha
track

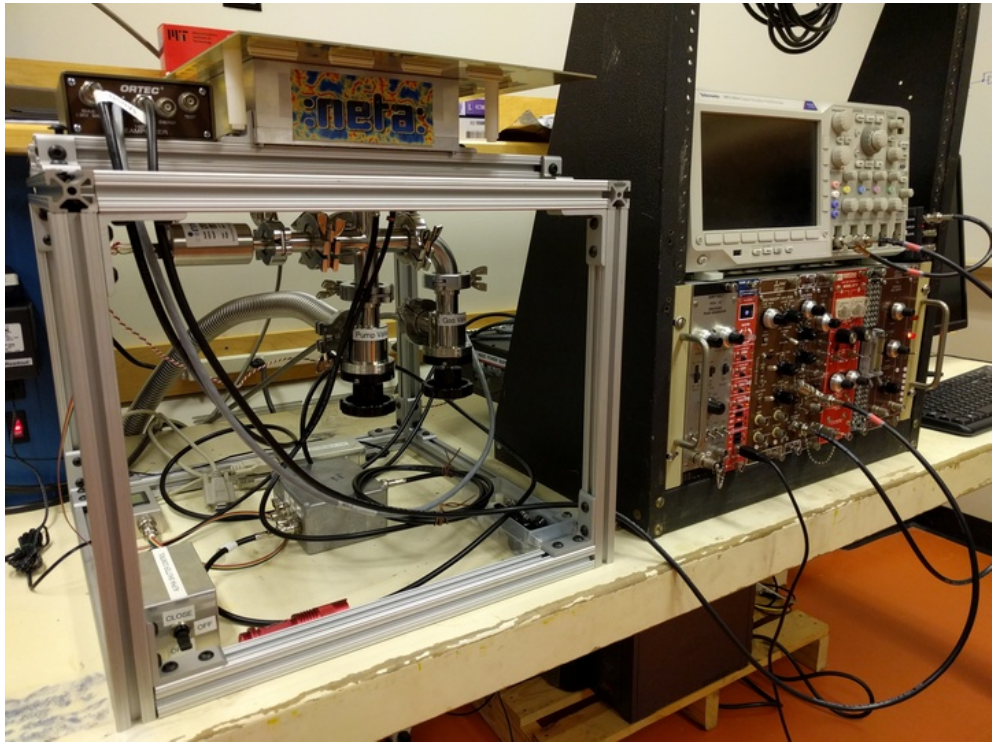

Helium nuclear recoil in He:CF$_4$ at 1 atm


Soft electron

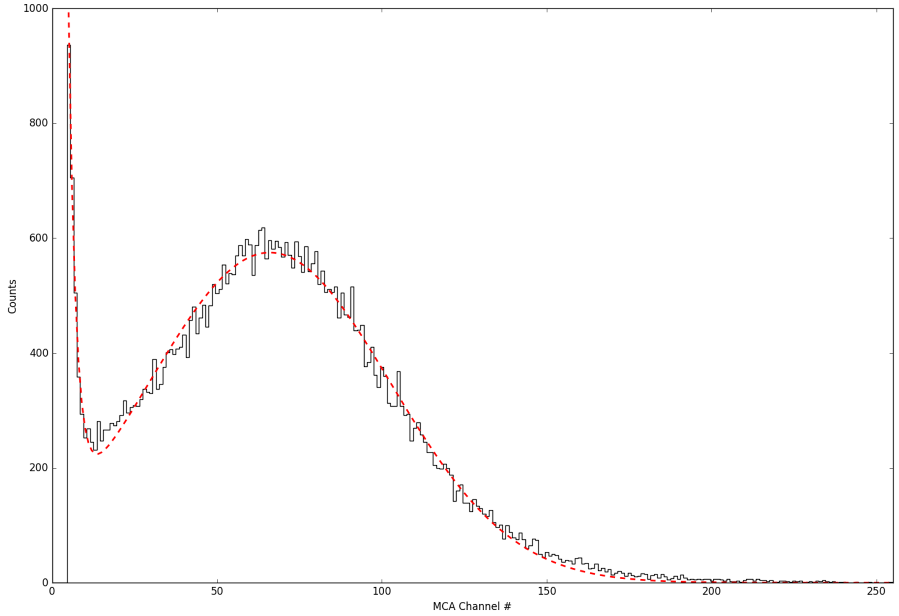

450 MeV electron with its δ ray

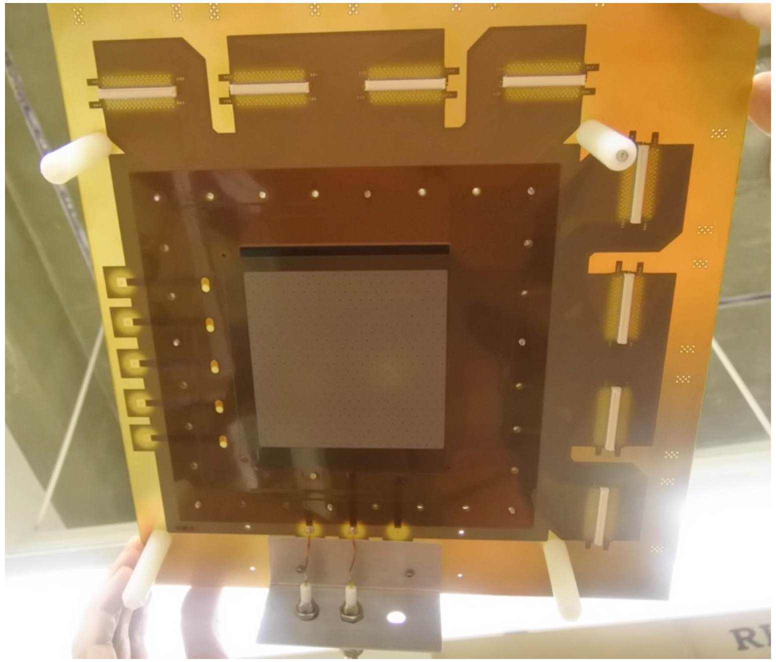
SF$_6$ studies at Wellesley College

Battat & Nicoloff



- Operation from 20-60 Torr
- Gas gain ~300
- CERN Micromegas:
  - 128, **256**, 512um amplification gap
  - 10 x 10 cm^2 active area
- Adapting BNL DUNE readout electronics (LArASIC preamp and digitizer) for track reconstruction (in collaboration with Martin Herbordt at Boston University)

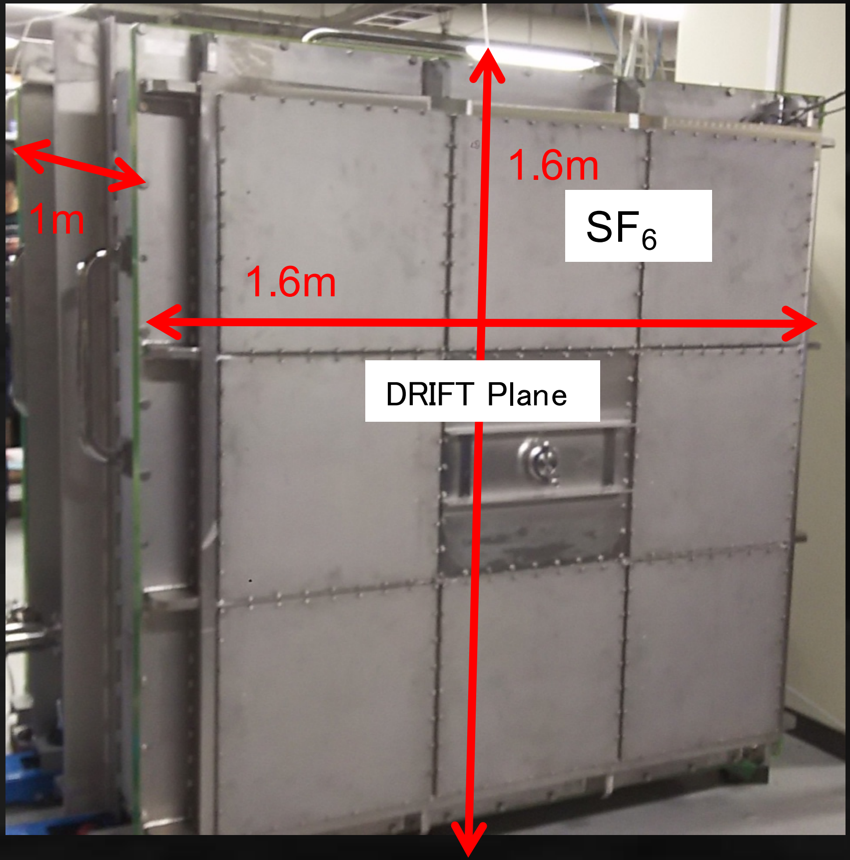




Scaling-up: modulated chamber

- μ-PIC, GEMs, micromegas, pixels, MWPCs…

HV



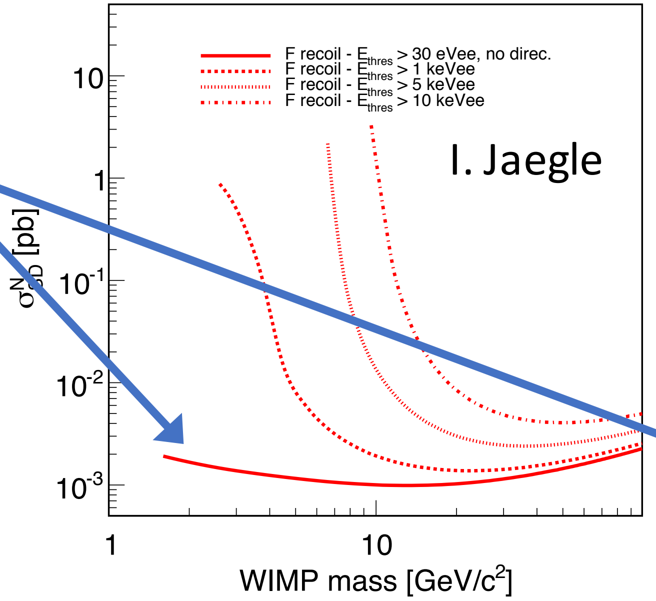
1.6m

CYGNUS/NEWAGE vessel
40 × 40cm^2 modules

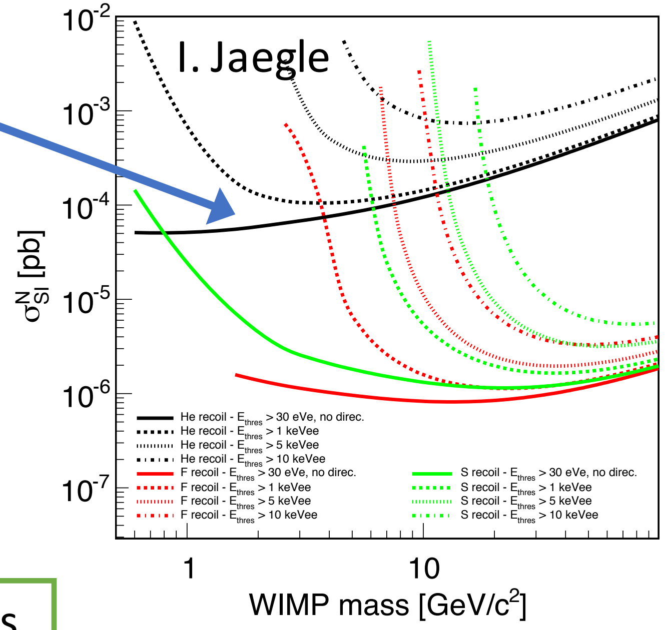
1.6m

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



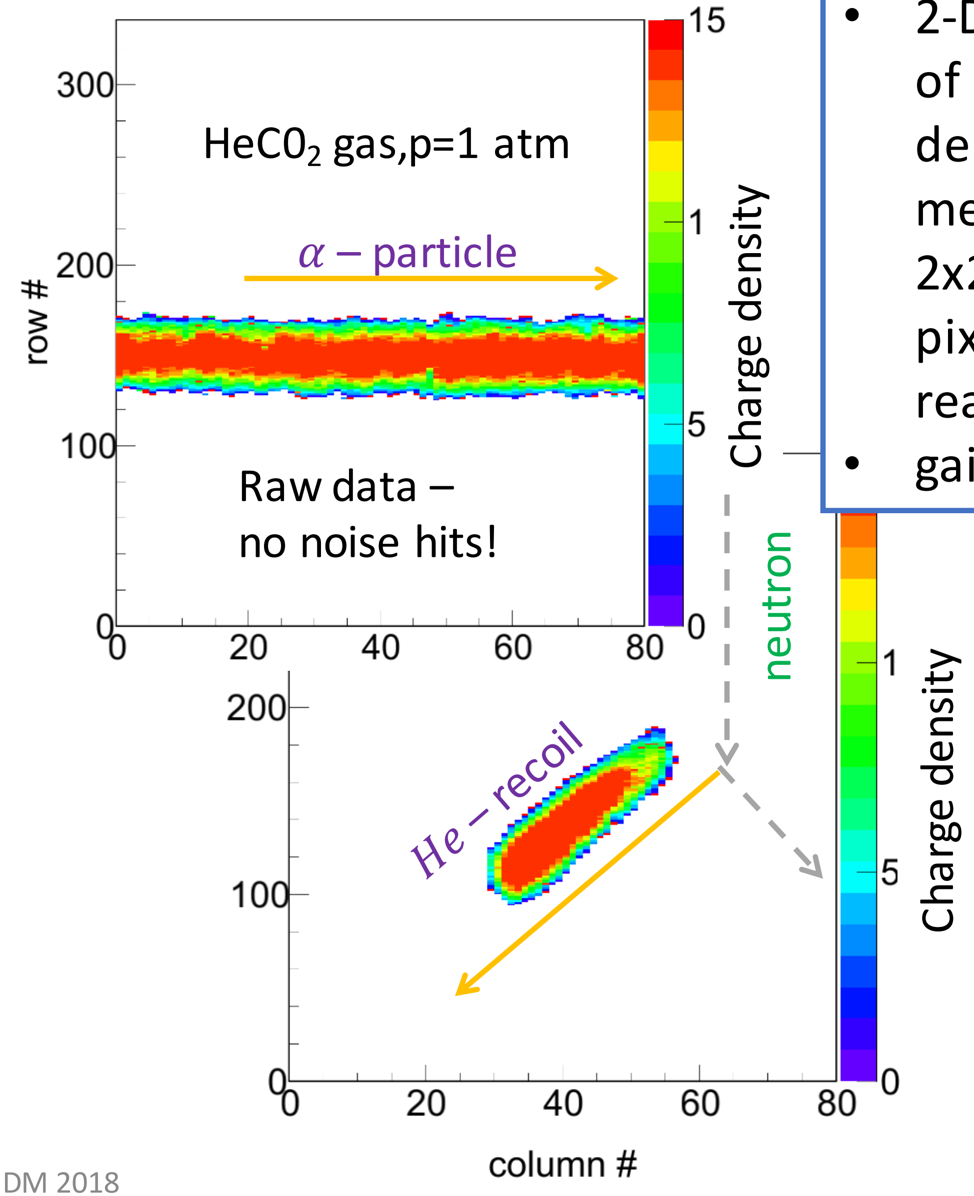
Highly preliminary - likely to change

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

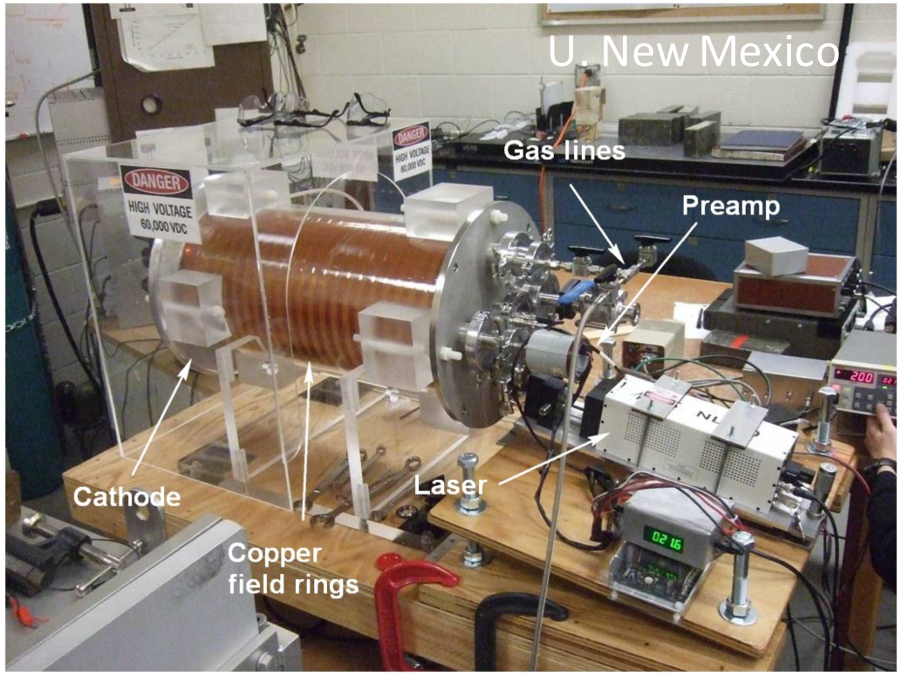
→ Best compromise
  - Resistive Micromegas readout with integrated x/y strips (available from CERN
  - Cost of order \$10k / m^2
  - Large - up to 1m x 2m!
  - Higher noise floor and thus ionization threshold

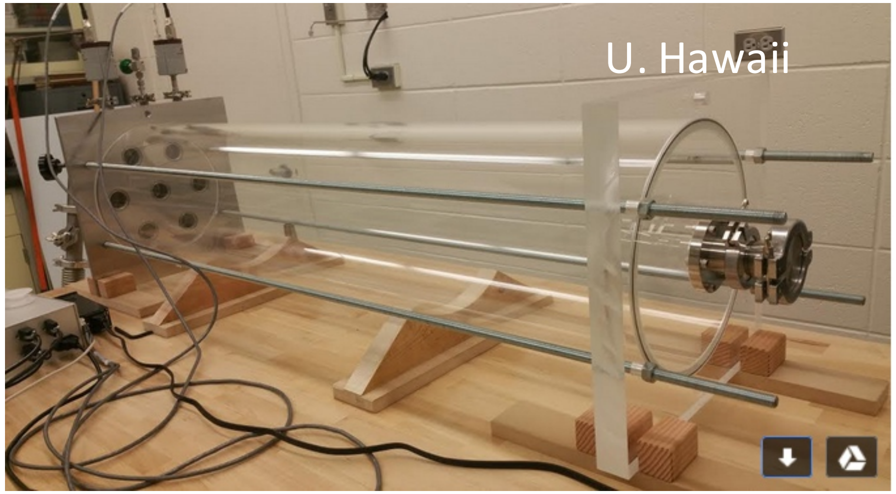


- 2-D projection of ionization density, measured w/ 2x2 cm ATLAS pixel chip readout
- gain ~ 3000

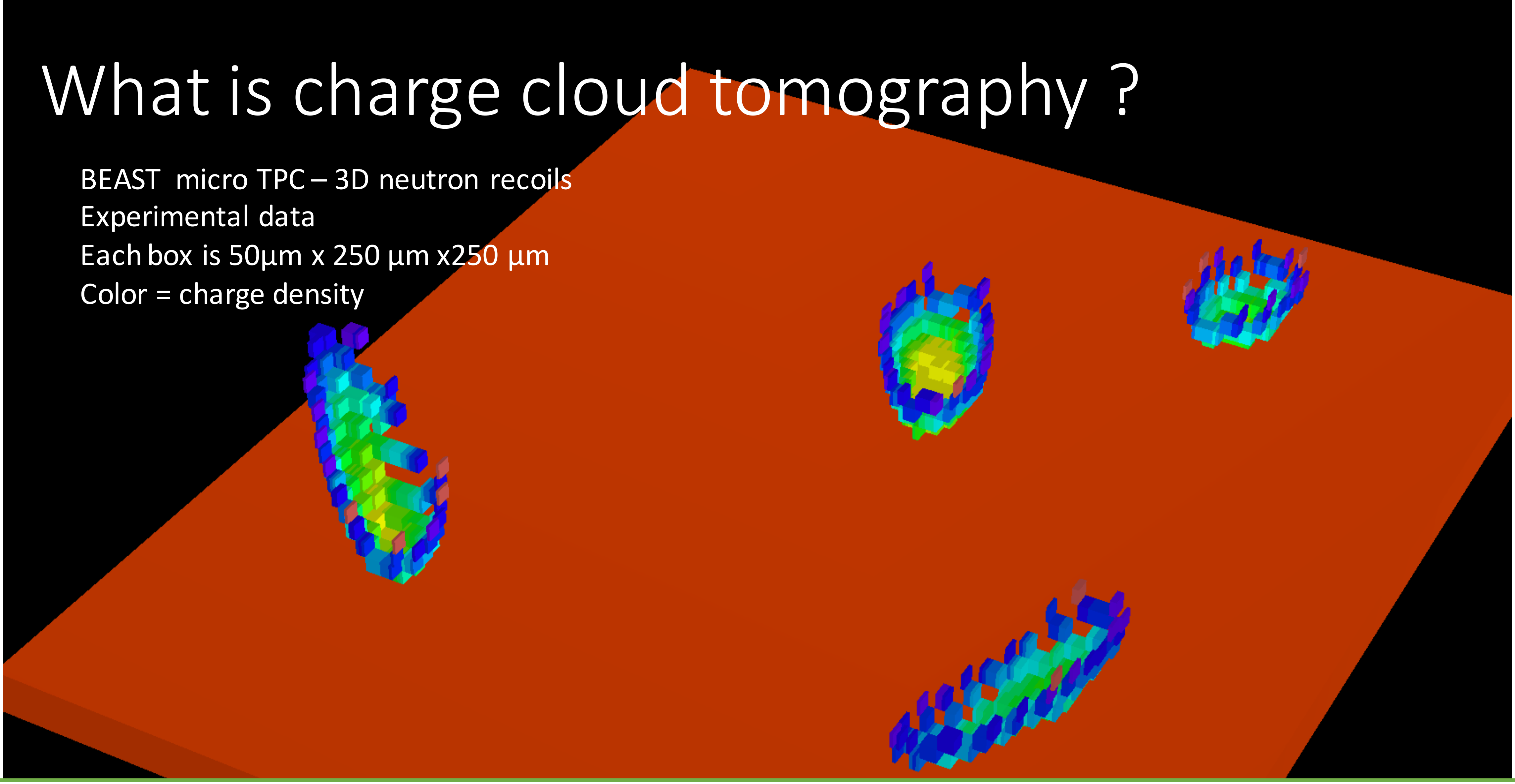
Technological Readiness

- 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





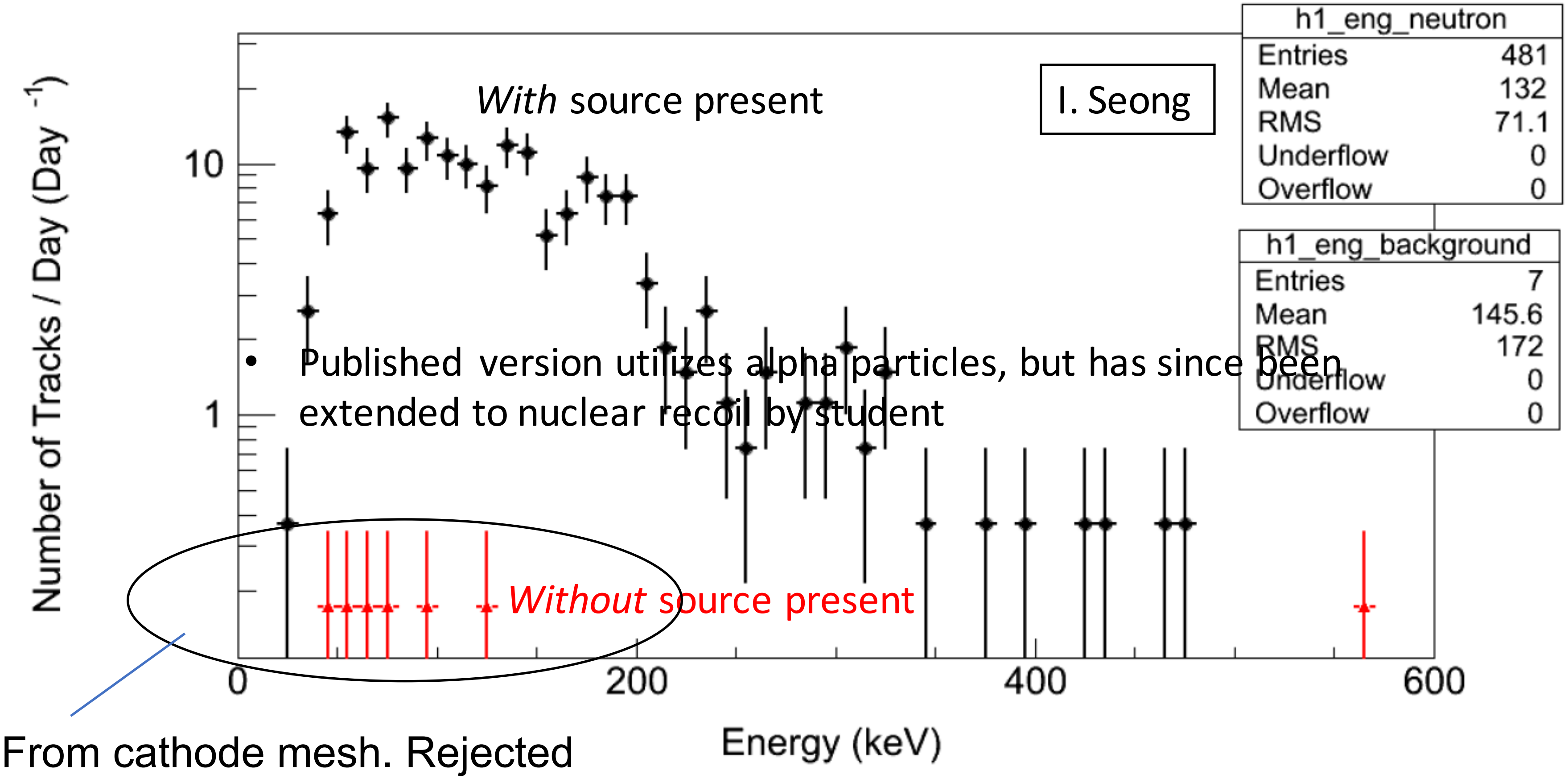
What is charge cloud tomography ?



BEAST micro TPC – 3D neutron recoils
Experimental data
Each box is 50µm x 250 µm x250 µm
Color = charge density

- 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)

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

From cathode mesh. Rejected by position cut

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