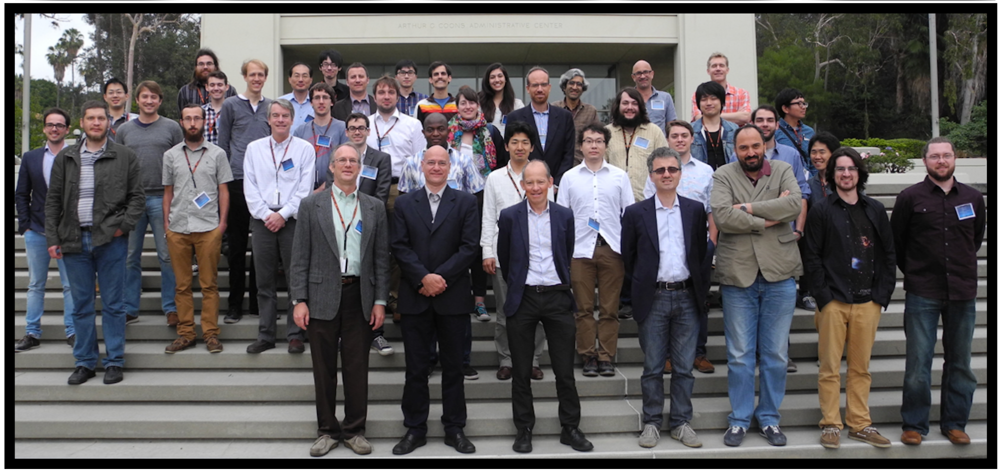
CYGNUS@CEvNS2019

Coherent Neutrino Scattering with Directionality

Neil Spooner, University of Sheffield

Australia, China, France, Italy, Japan, UK, US…



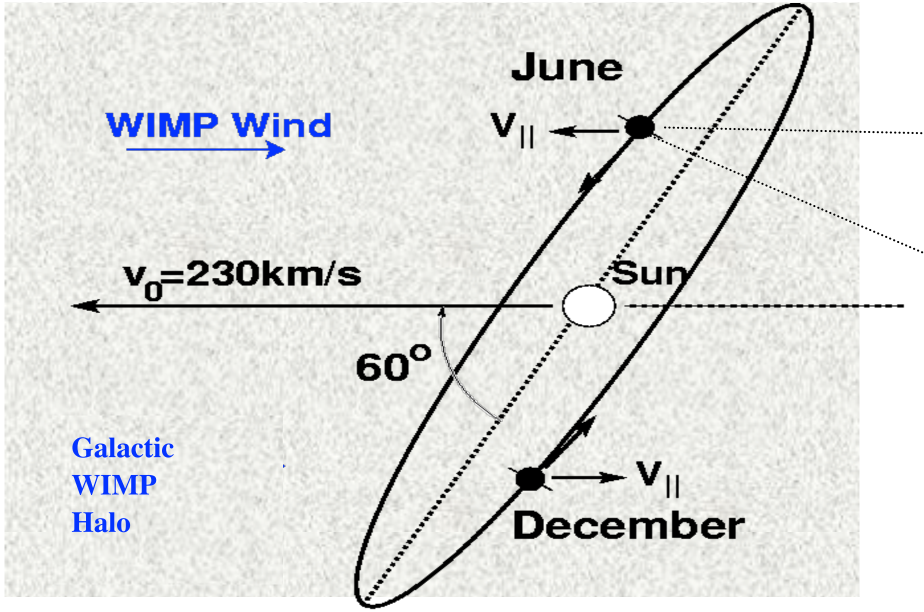
AIM

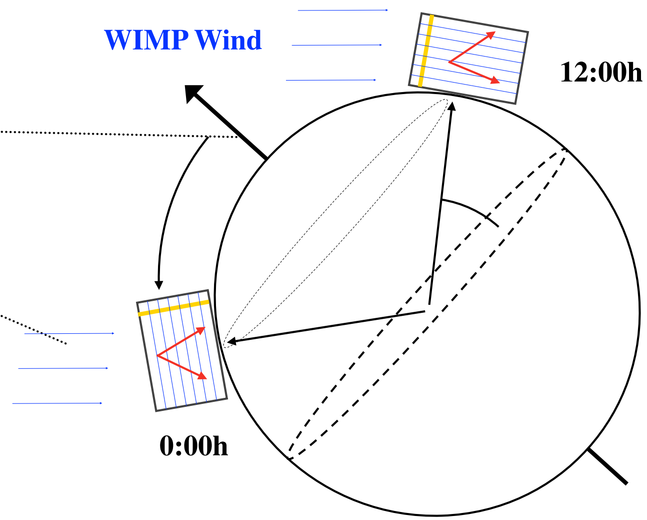
A WIMP dark matter search using gas TPC technology to record nuclear recoil directions and hence probe below the neutrino floor.

- CYGNUS introduction
- Electron background rejection simulations and R&D (Sheffield work)
- Hartlepool reactor neutrino prospects

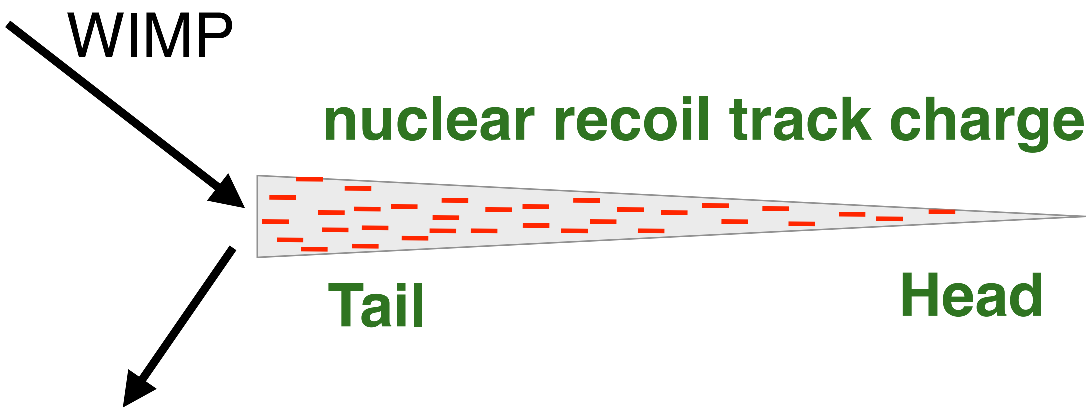
Directionality - A Real DM Signal

- A directional recoil signal is a very powerful proof





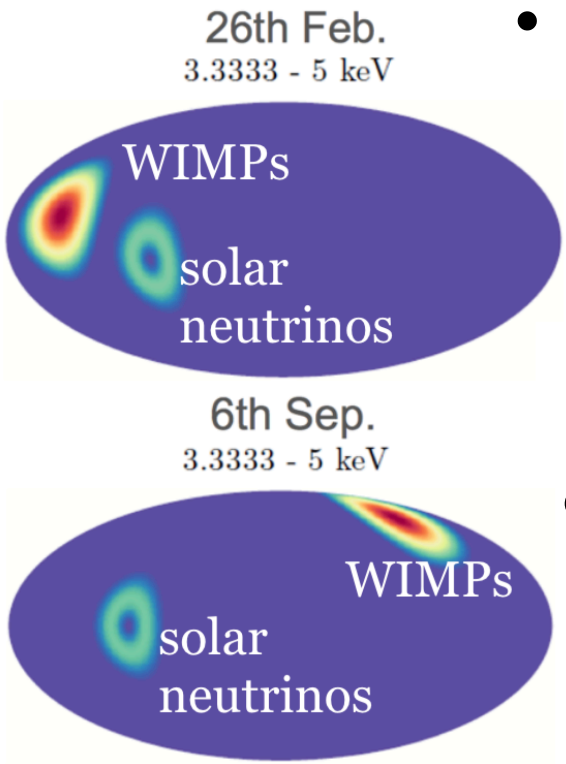
- Measure the nuclear recoil track itself and determine the head from tail or sense



CYGNUS Science

- Search for low WIMP mass
  - -Nuclear recoils AND Electron recoils
- Observe galactic dipole, directionality
- Detecting solar neutrinos
- Penetrate the neutrino floor
- Measure DM particle properties and physics
- Measure Geoneutrinos
- WIMP Astronomy

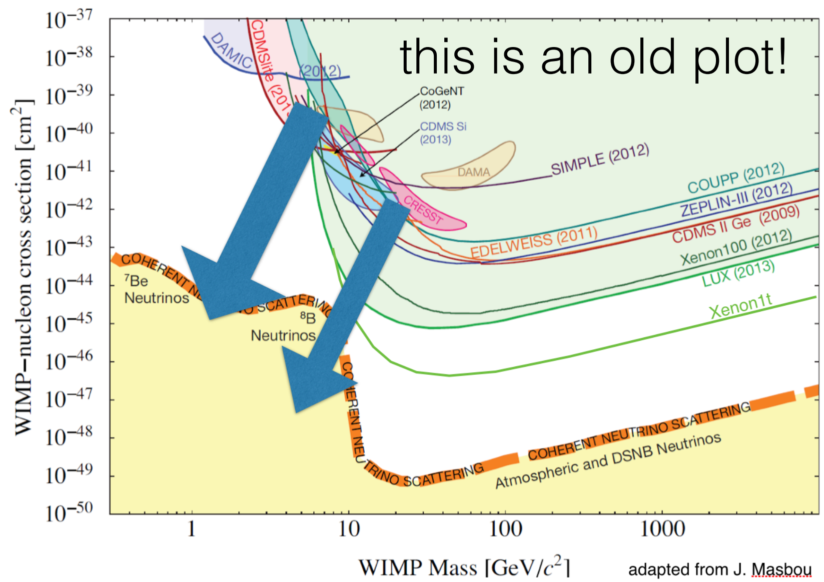
exposure



- position of Sun never coincides with Cygnus

Mollweide projections of the WIMP plus ^{8}B neutrino angular differential event rate

C.J.G. O'Hare 1505.08061



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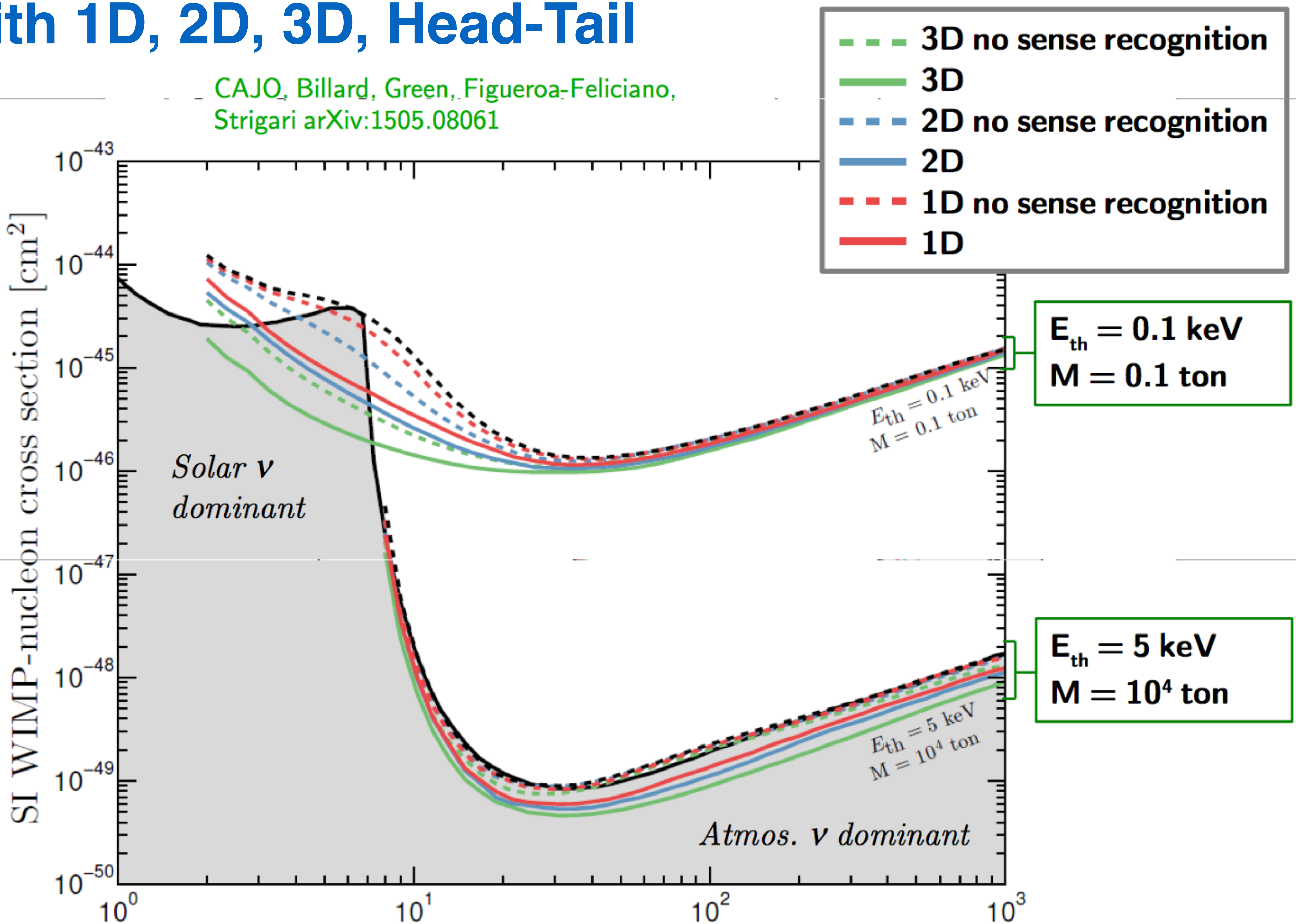
Below the Neutrino Floor

with 1D, 2D, 3D, Head-Tail



thanks to O'Hare et al.

CYGNUS paper draft

CYGNUS: Feasibility of a nuclear recoil observatory with directional sensitivity to dark matter and neutrinos

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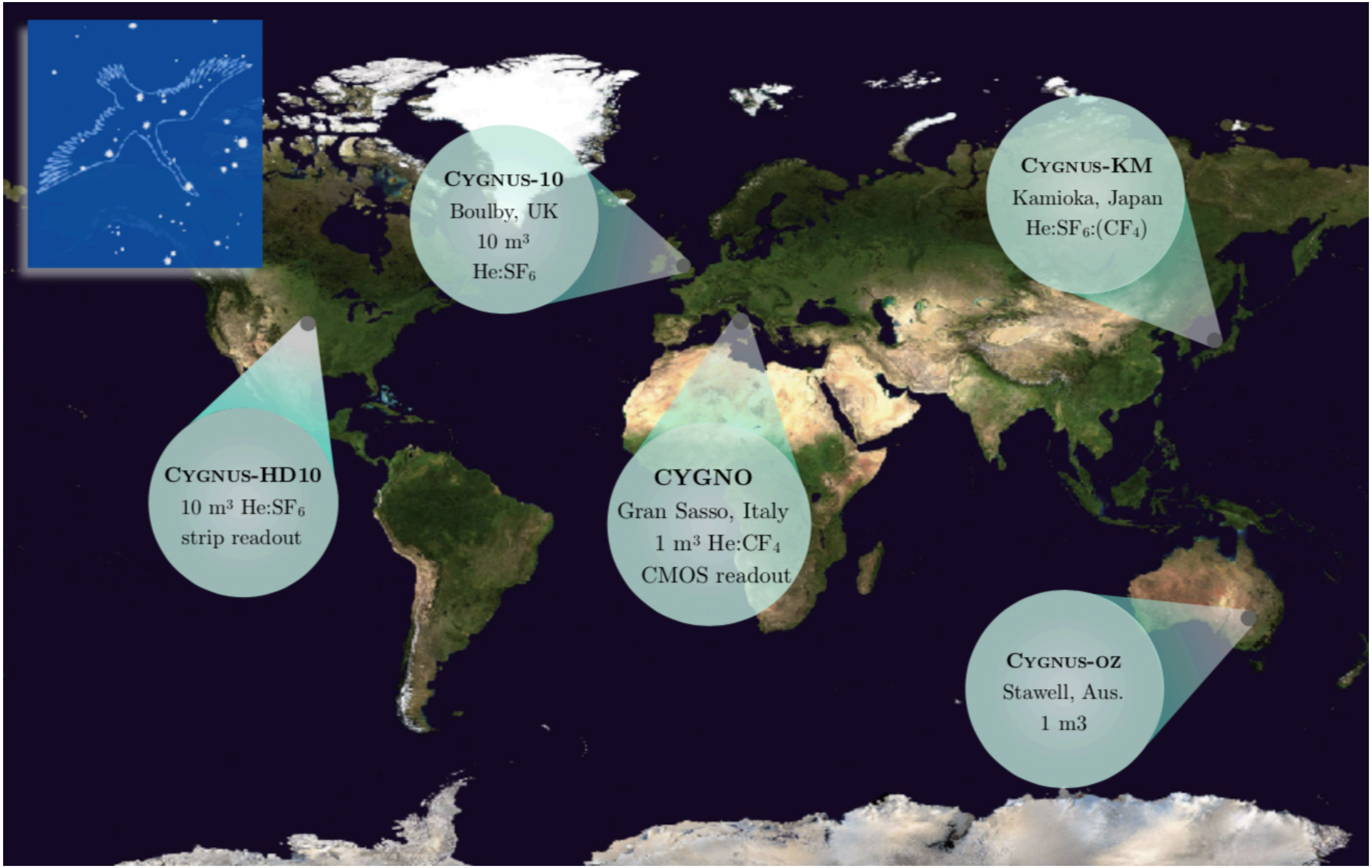
(Dated: July 10, 2019)

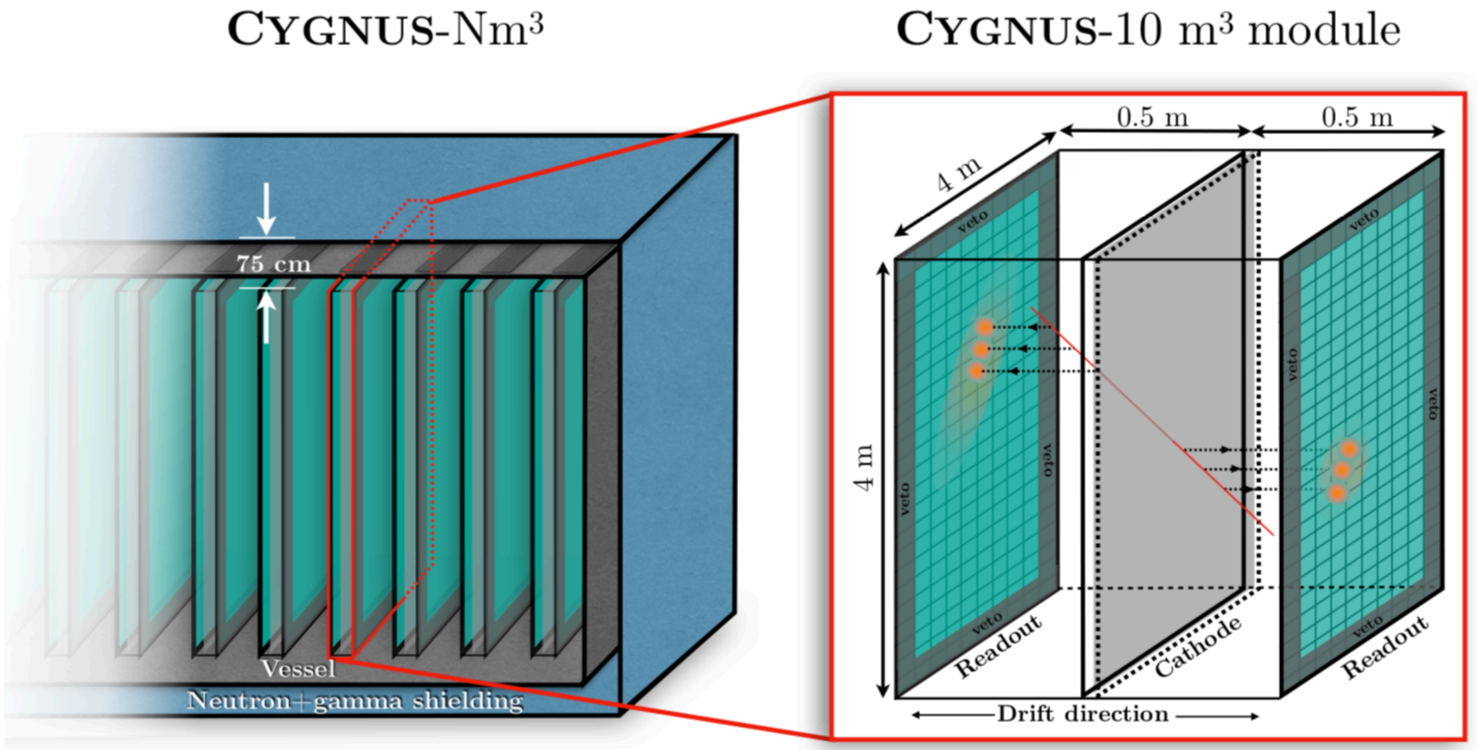
CYGNUS Multi-site R&D

A multi-site Galactic Nuclear Recoil Observatory



CYGNUS TPC for CEvNS Advantages?

- Recoil directionality (track reconstruction 2D, 3D..)
- Multiple targets possible
  - *Ar, C, F, He, S….*
- Electron discrimination
- Modular construction
- Low background
- Fiducialisation by minority carriers SF_6, CS_2 (-ve ion TPC)
- No cryogenics



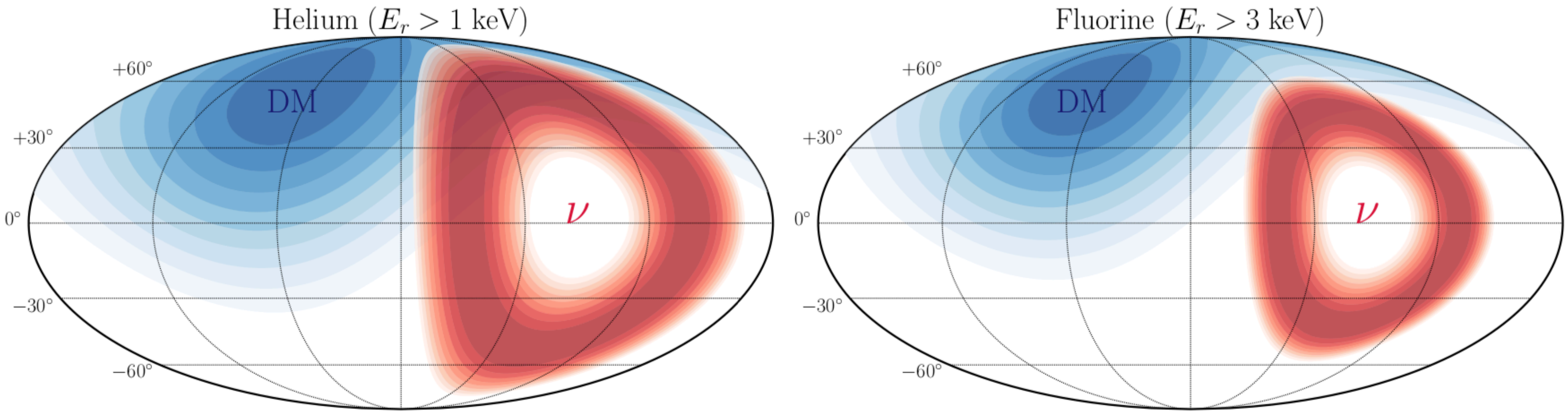
- **Gas of choice**

20 Torr SF_6

740 Torr He

Power of Directionality

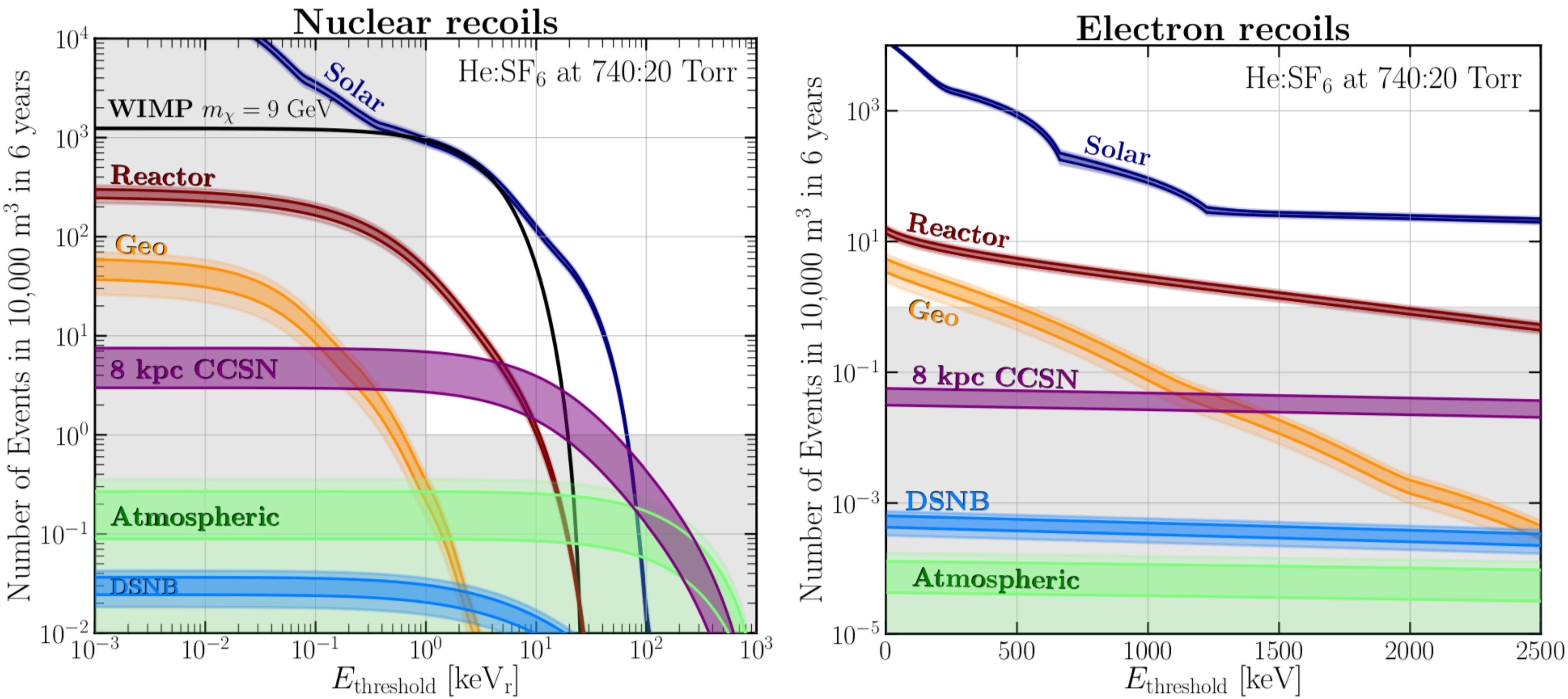
Penetrating the neutrino floor



Mollweide projections of the WIMP plus ^{8}B neutrino angular differential event rate

projection of the total angular distribution of a 10 GeV WIMP (blue) and solar neutrinos (red), with a fluorine (left) and a helium (right) assumed target. We show the projection in the laboratory coordinate system (North-West- Zenith) at 18:00 on September 6 in UK. The central horizontal axis is the horizon and the centre of each maps points South. Both distributions have been rescaled by their maximum values and displayed to show the region of the sky that they occupy.

Neutrino event rates



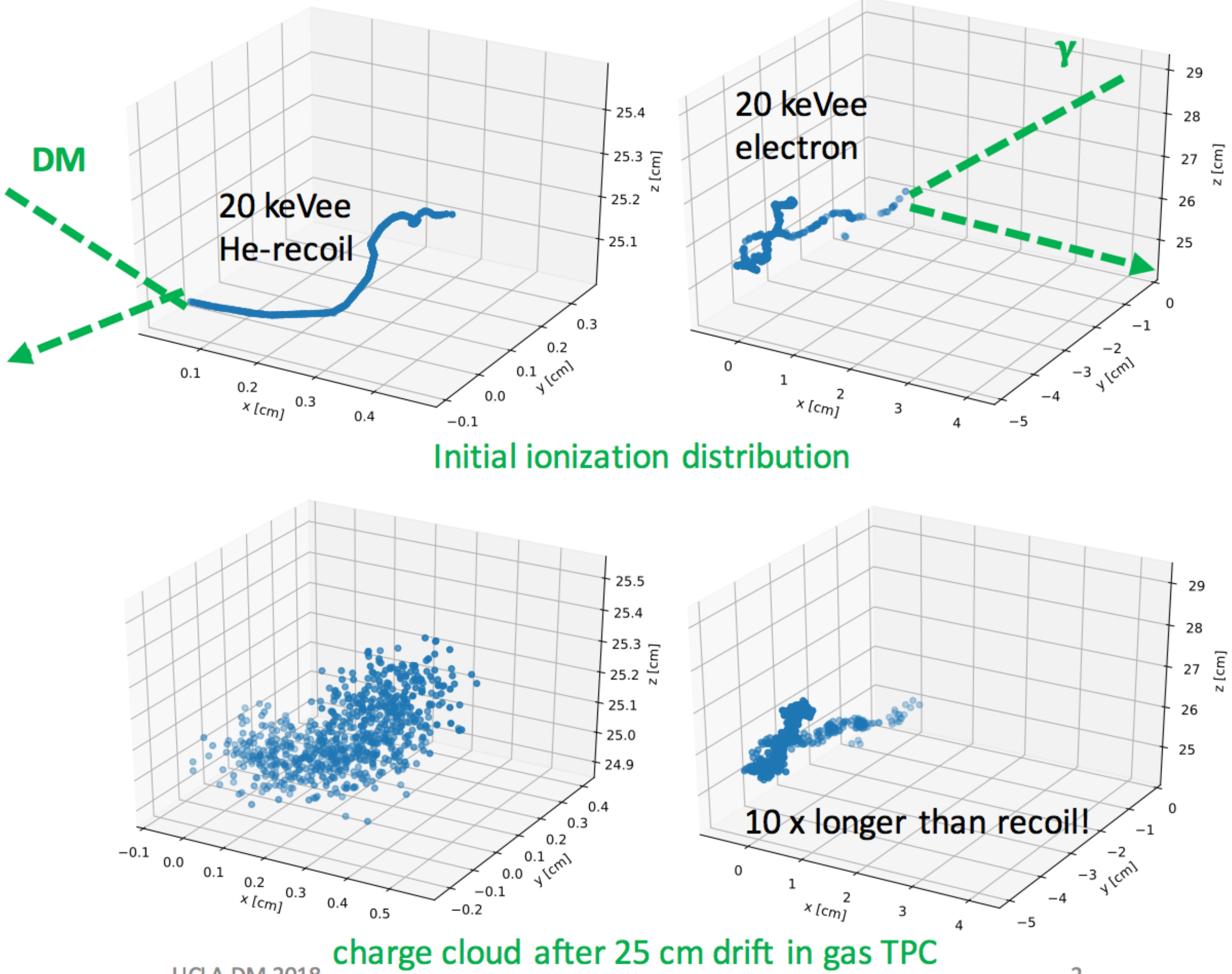
Number of neutrino events observed in a CYGNUS-10k m^3 detector filled with atmospheric pressure He:SF$_6$ at a 740:20 Torr ratio (the event rates are summed over each target nuclei). The left hand panel corresponds to nuclear recoils whereas the right hand panel is for electron recoils. We calculate the expected number of observed events by integrating the event rate for each background component above a lower energy threshold $E_{\rm threshold}$. The background components are shown as darker and lighter shaded regions indicating the 1 and 2σ uncertainties from the predicted flux. For comparison we also show the nuclear recoil event rate expected from a $m_\chi = 9$ GeV WIMP with a SI WIMP-proton cross section of $\sigma_p^{\rm SI} = 5 \times 10^{-45}$ cm^2 as a black line. For the reactor and geoneutrinos we assume CYGNUS is located at Boulby, UK. The purple region indicates the range expected number events from the neutrino bursts from supernovae of stars with masses between 11 and 27 $M_\odot$ located 8 kpc away from Earth. To add further clarity we shade in gray parts of the plot which give fewer than one event in this exposure, and (in the left hand panel) fall below the lowest nuclear recoil energy included in later simulations.

Gas Time Projection Chamber (TPC) Offers Detailed Information

- Measure spatial ionisation distribution resulting from nuclear recoils

- Advantages:
    - Axial Directionality
    - **<u>Head/tail</u>**
    - Background rejection
    - Particle ID
    - 3D fiducialization
- Technologically challenging, but now achievable via multiple technologies

- ‣ Key is intrinsic low background
- ‣ High ER/NR discriminations
- ‣ Low threshold (keV)



Sven Vahsen et al. (Hawaii)

Example GEANT4 et al. simulations

- 10 keV electron in 20 Torr SF_6

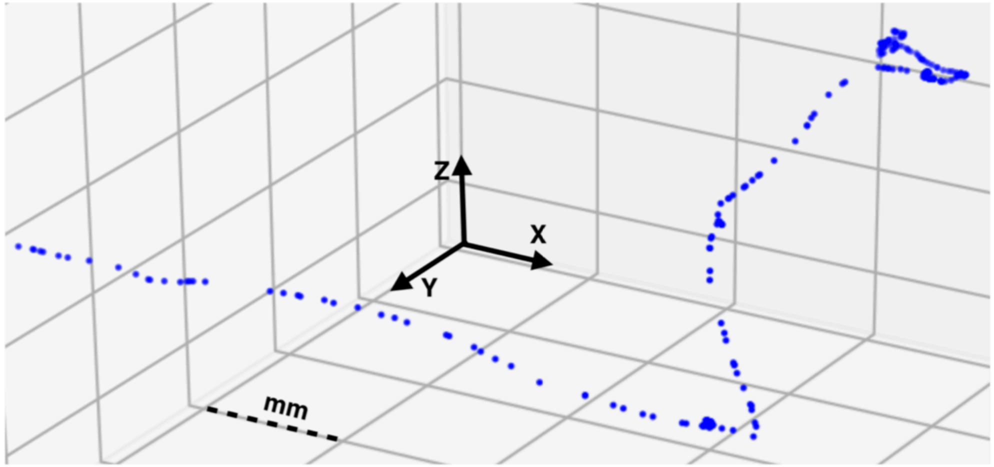


Figure 3.2: Ionisation from a 10 keV electron recoil in 20 Torr SF_6, simulated using GEANT4.

- 50 keV fluorine in 20 Torr SF_6

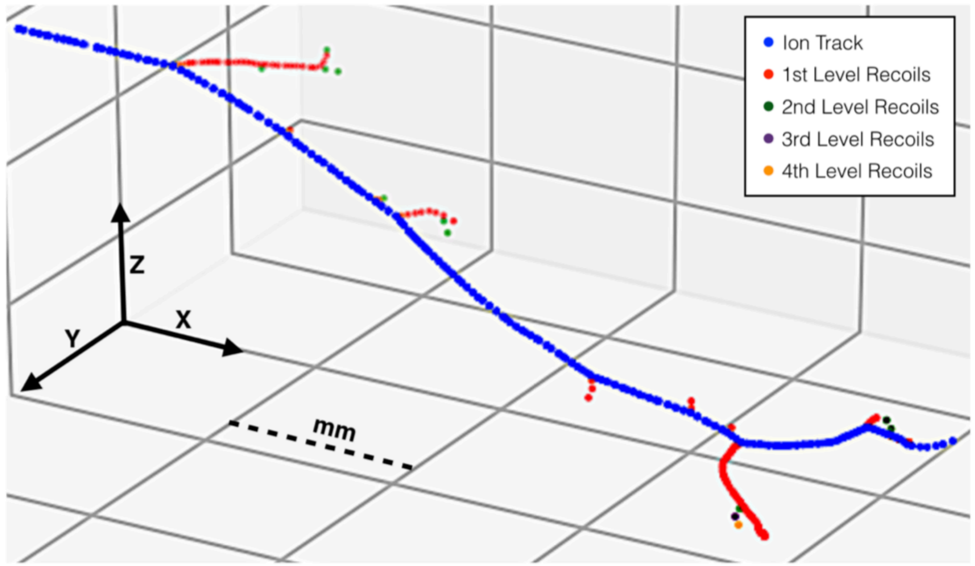


Figure 3.1: Ionised electrons, form the primary, 1st, 2nd, 3rd and 4th level of recoils, for a 50 keV$_r$ fluorine track in 20 Torr of SF_6 gas.

What Directional TPC Technology?

Several possibilities, CYGNUS is comparing them
1D, 2D, 3D; backgrounds; cost

Readout	Experiment	Target[8]	Granularity x, y, z[9]	Area m^2 [10]	Fiducial Volume[11]	Gas Gain[12]	Energy resolution[13]	Enery threshold[14]	Angular resolution	Sense recognition threshold
MWPC	DRIFT	NI CS_2 CS_2:CF_4 CS_2:CF_4:O_2	2 mm NA 1 μs	2×2	0.8 m^3	~1000	42% [242]	50 keV_r [64] 30 keV_r [243]	unpublished	50 keV_r [64] 40 keV_r [243]
Micromegas	MIMAC	EG Mix of CF_4, CHF_3, and C_4H_{10}	0.42 mm 0.42 mm 20 ns	2×1	5 L	2×10^4	22% [130]	~1 keV_{ee} [134]	unpublished	unpublished
μPIC	NEWAGE	EG CF_4	0.4 mm 0.4 mm 10 ns	0.3×0.3	36 L	1000	23% [142] 47% at 50 keV_{ee} [150]	50 keV_{ee} (directional) [150]	40° at 50 keV_{ee} [150]	75 keV_{ee} [244]
ATLAS Pixel chips	D^3	EG He+CO_2 NI SF_6 [245]	0.05 mm 0.25 mm 25 ns	NA[15]	50.4 cm^3	NA	20%, 100 Torr CF_4 [165]	1–10 primary e^- [164]	$\frac{\sqrt{12}\sigma}{L\sqrt{N}}$ radians [166][16]	unpublished
Optical	DMTPC	EG CF_4	0.3-0.6 mm 0.3-0.6 mm NA[17]	NA[18]	20 L (1 m^3)	NA	35% at 80 keV_r [220]	20 keV_{ee} [205]	15° at 20 keV_{ee} [205]	40 keV_{ee} [205]
Emulsions	NEWS	Solid emulsion	10 nm 10 nm 0.1 μm	100 g[19]	NA	NA	unpublished	35 keV_r Carbon [227]	13° for 100 keV_r Carbon [227]	unpublished

CYGNUS Technology study

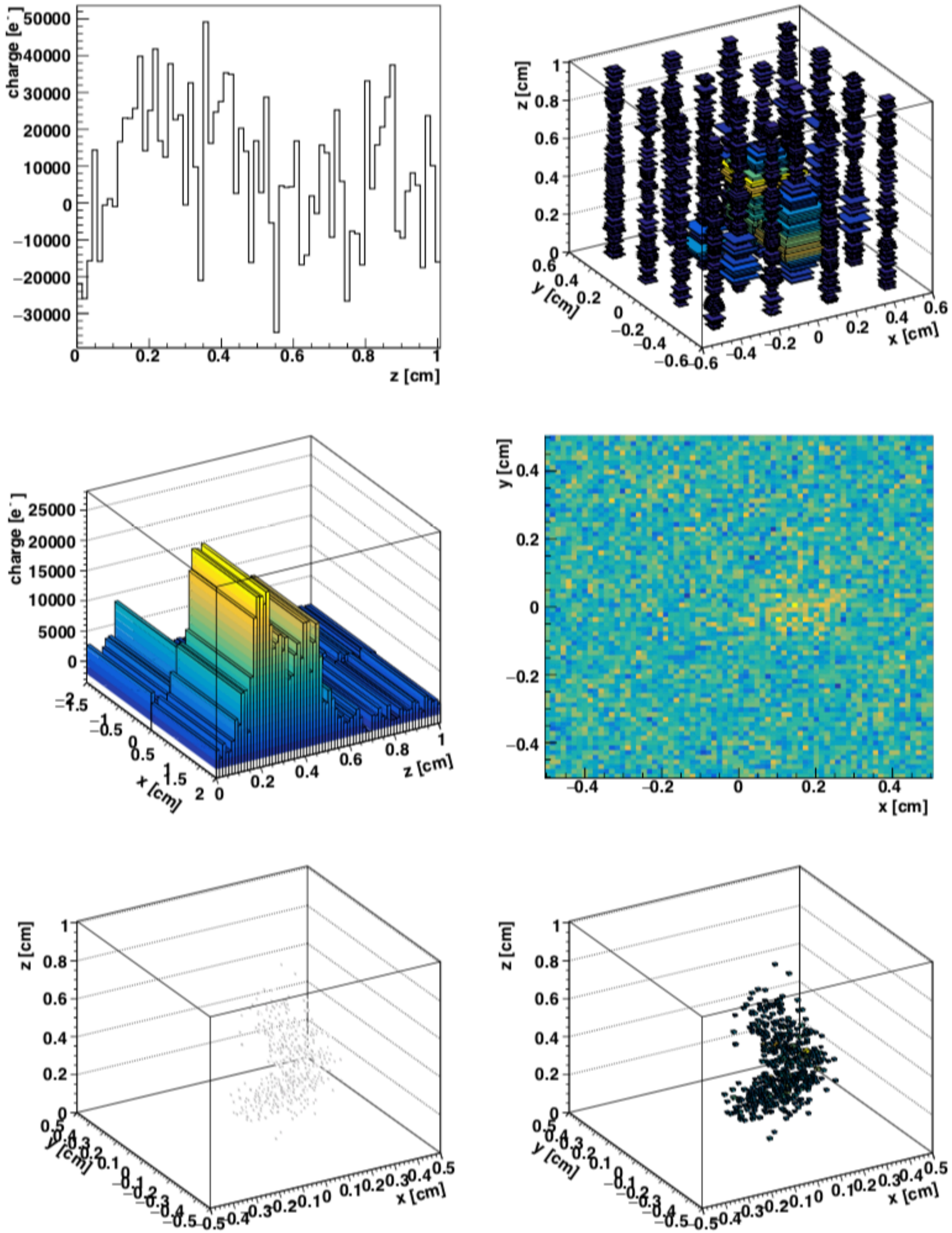
planar, pad, wire, CCD, strip, pixel readout

Signal from 20 keVr helium recoil in 20 Torr of SF_6 gas after 25 cm of drift.

From top left to bottom right: planar, pad, wire, CCD, strip, and pixel readout.

For the first four readouts, all simulated effects except charge thresholds have been applied.

For strips and pixels only, detector thresholds have also been applied, otherwise noise hits in the 3d display would obscure the signal.



Example study with BDT

Warren Lynch (Sheffield)

- 100 µm resolution
- 25 cm diffusion
- 20 Torr SF_6
- 6 keV e^-

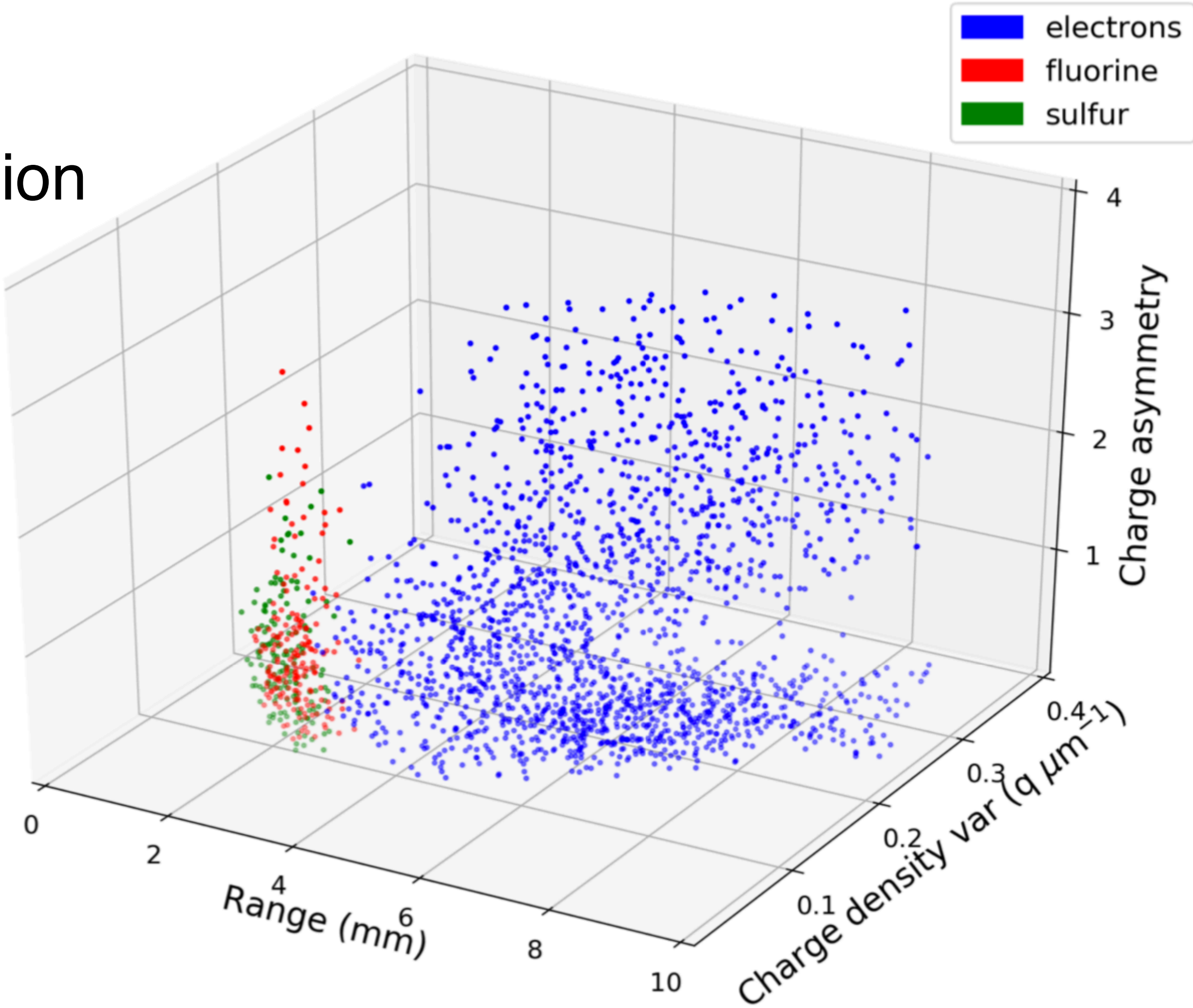


Figure 3.9: Parameter space made up of the parameters: range, charge asymmetry and charge density variation. For a spatial resolution of 100 μm and after 25 cm diffusion. Fluorine, sulfur and electron recoils of 6 $\pm$0.5 keV$_{ee}$ in 20 Torr SF_6 are shown as red, green and blue points respectively.

Diffusion issues

Warren Lynch (Sheffield)

- 10 keV e⁻
- 20 Torr SF_6^-

- 10 µm resolution
- 20 µm resolution
- 50 µm resolution

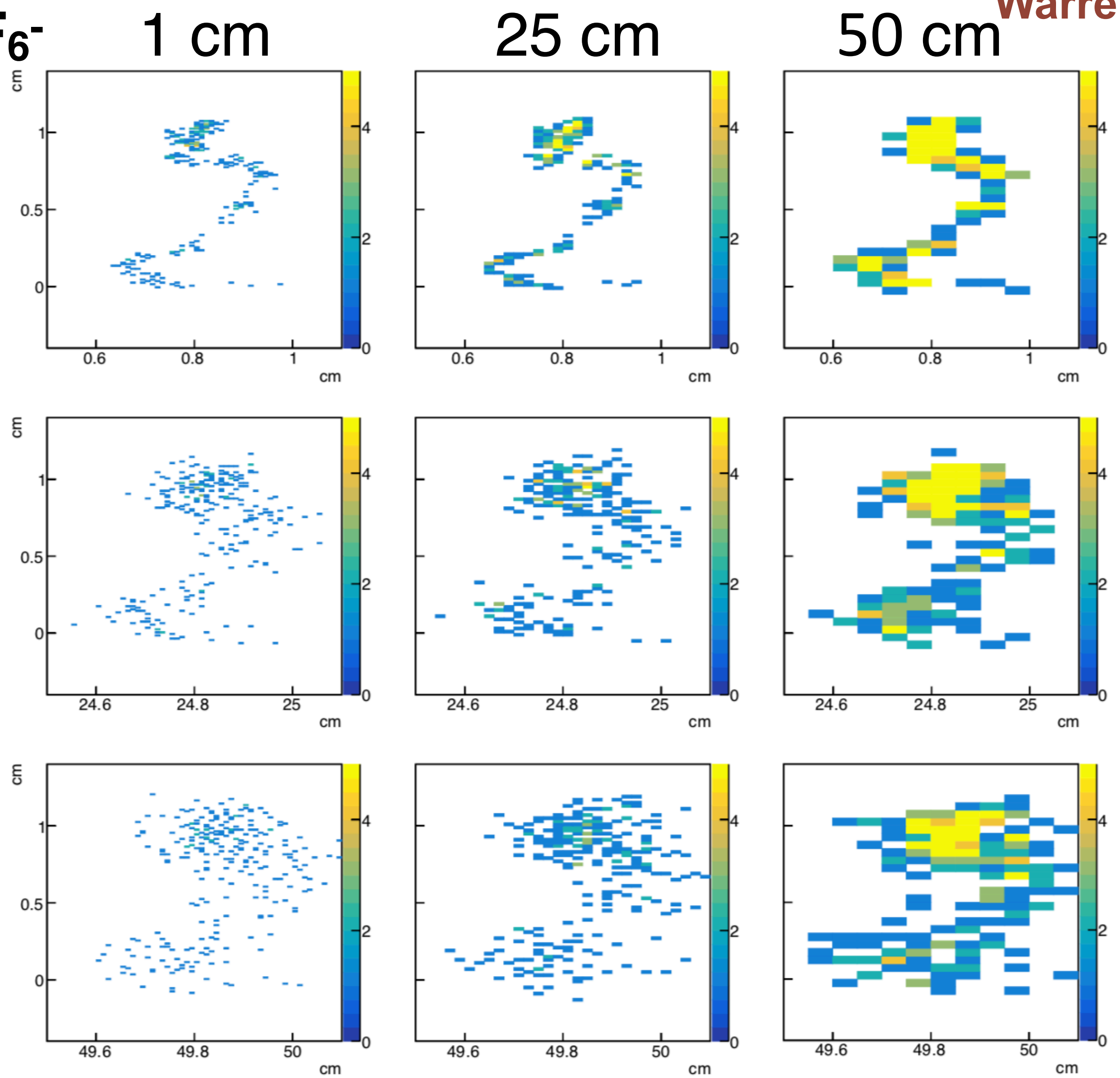


Figure 3.5: The effects of diffusion and spatial resolution on a 10 keV electron track in 20 Torr SF_6. Diffusion lengths of 1, 25 and 50 cm are shown increasing from top to bottom and spatial resolutions of 10, 20 and 50 μm are shown increasing from left to right. The key indicates the electron density per bin.

Electron rejection with BDT

Warren Lynch (Sheffield)

- e.g. 99% rejection at 4 KeV_{ee} with 25 cm diffusion and 600 µm resolution, 50% detection efficiency

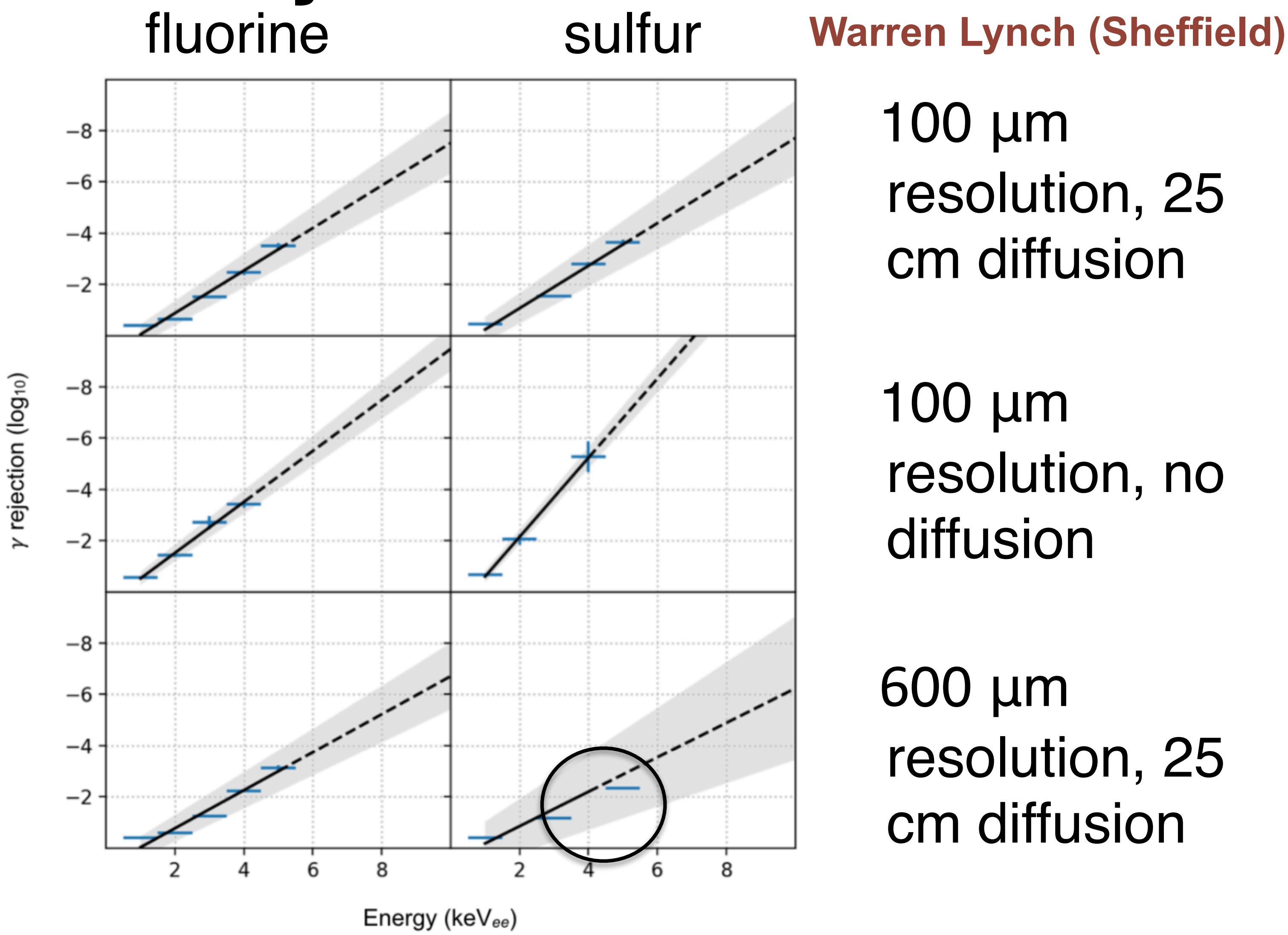
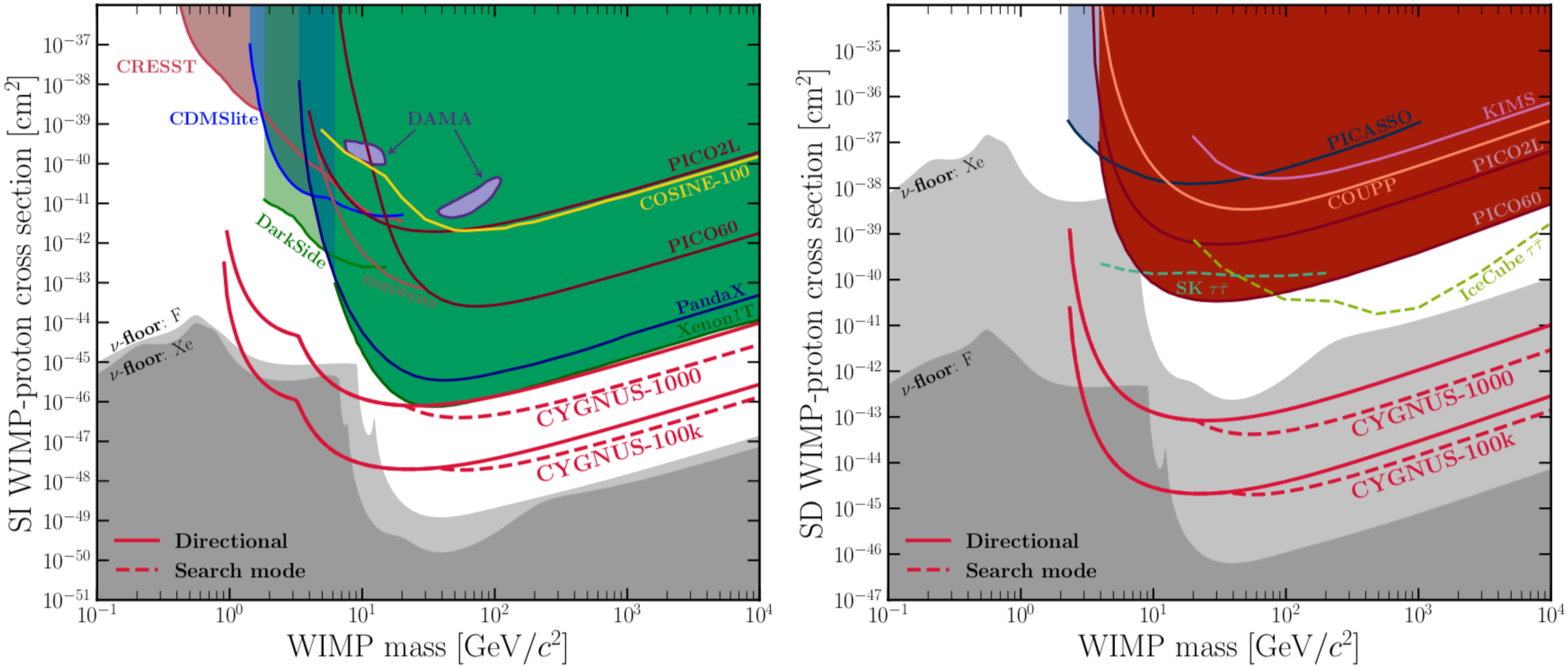


Figure 3.14: Gamma rejection at 50% detection efficiency for fluorine and sulfur recoils with energies between 1-10 keV_{ee}, given for different diffusion lengths and spatial resolutions. The blue points with error bars were extrapolated from the data shown in Figure 3.13 and the solid line is a fit to these points. The dotted lines are predictions of the rejection factors. The shaded region shows 1 σ deviation from the fitted lines.

WIMP Sensitivity aims

- This requires detection of solar neutrinos via coherent scattering, i.e. nuclear recoils, with directional information



Constraints on the spin-independent WIMP-nucleon (left panel) and spin-dependent WIMP-proton (right panel) cross sections versus WIMP mass. We show the existing constraints and detection regions for various experiments as labeled (see text for the relevant references). With red dashed and dotted lines we show our projected limits for the CYGNUS experiment operating with 1000 m^3 (dot-dashed) and 100,000 m^3 (dotted) of He:SF_6 gas. The SF_6 gas is assumed to be at 20 Torr with a nuclear recoil threshold of 3 keV, whereas for He we assume 740 Torr and a 1 keV nuclear recoil threshold. For each detector volume we show both the limit assuming directional recoil measurements (thicker lines) and the limit for a 'search mode' experiment with 200 Torr SF_6 (thinner lines), this would have reduced discrimination power but higher exposure by a factor of 10. Below these limits we display the neutrino floor for fluorine as well as for reference the often quoted floor for xenon. This is the lower limit to standard direct detection searches that CYGNUS is designed to circumvent, we discuss this in Sec. II B 2.

CYGNUS-1000

Warren Lynch (Sheffield)

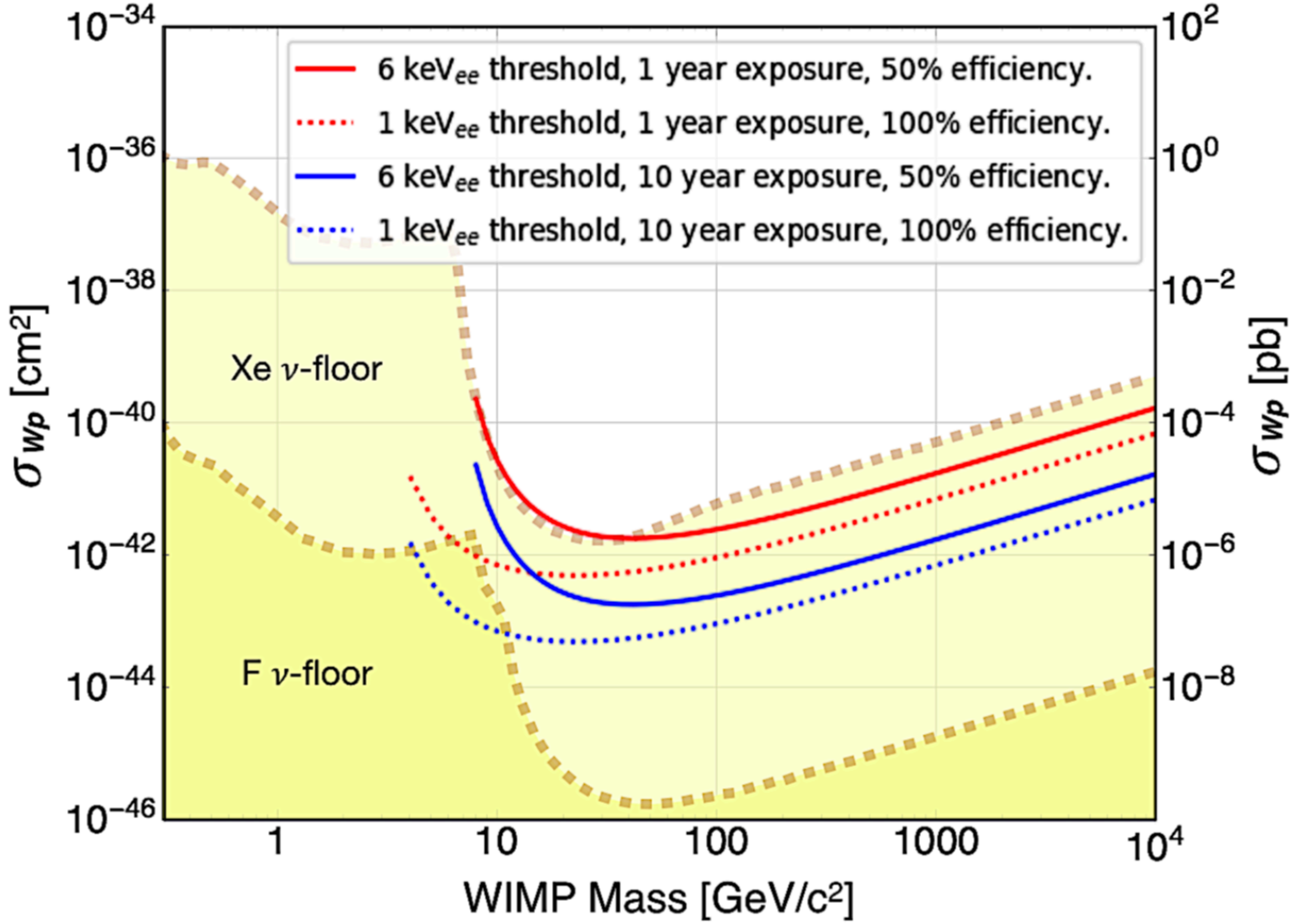
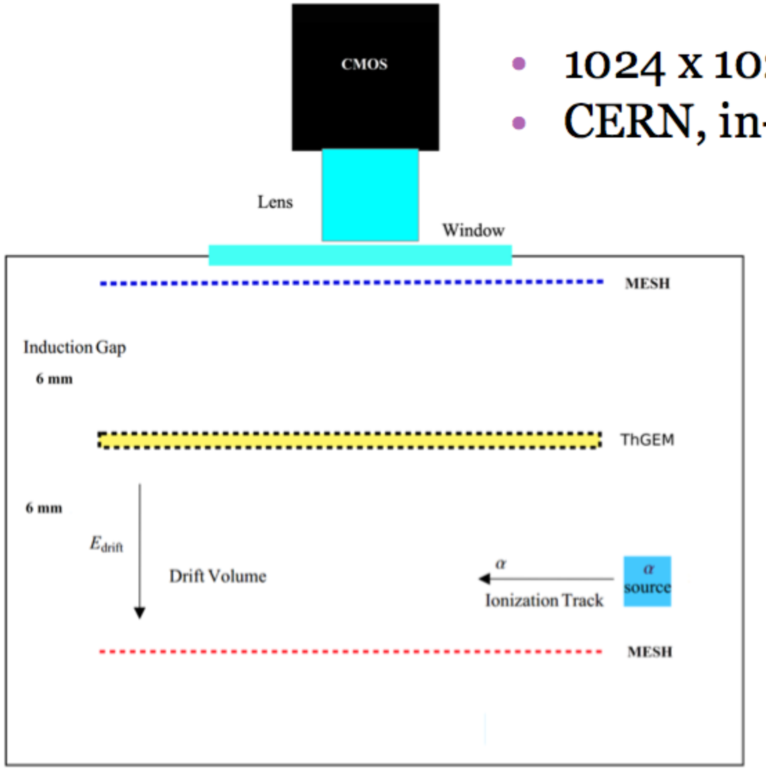


Figure 5.9: CYGNUS-1000 search reach after 1 (red) and 10 (blue) year exposures, for a 6 keV$_{ee}$ threshold and 50% detection efficiency (solid line) and for a 1 keV$_{ee}$ threshold and 100% detection efficiency (dotted line).

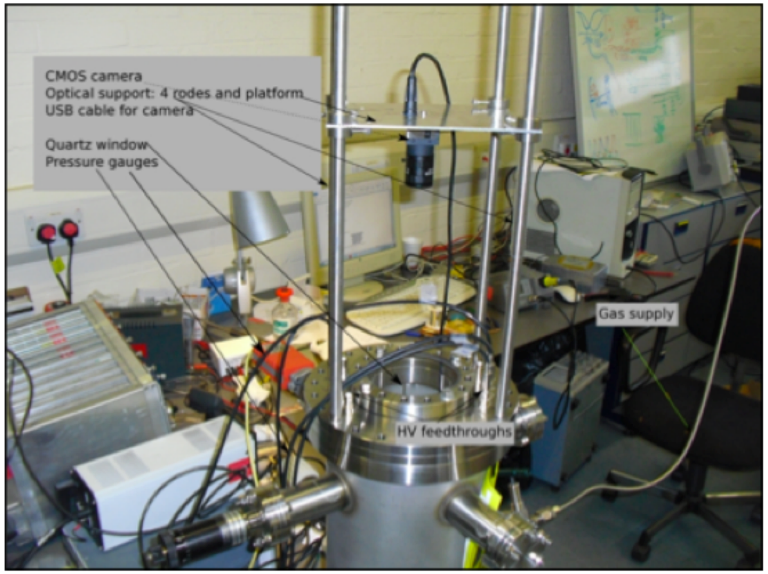
Sheffield R&D - CCD + Thick GEMs

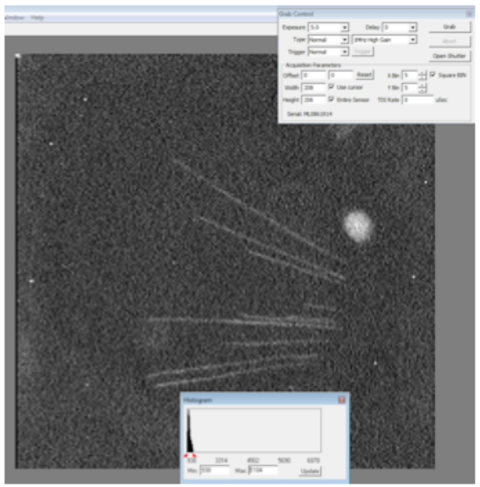
Concept: low pressure **CF_4 and SF_6 with Thick GEMs and CCD** readout

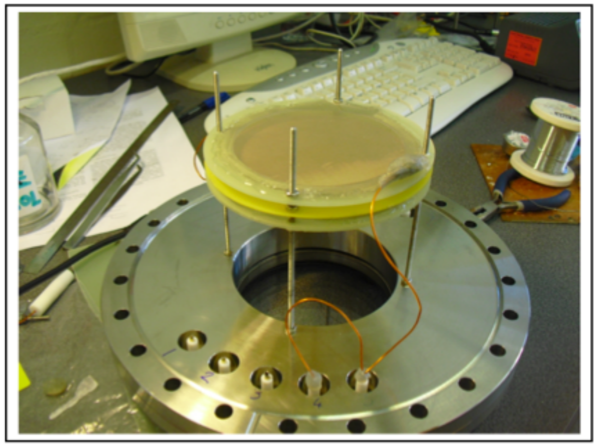
N. Spooner et al.,

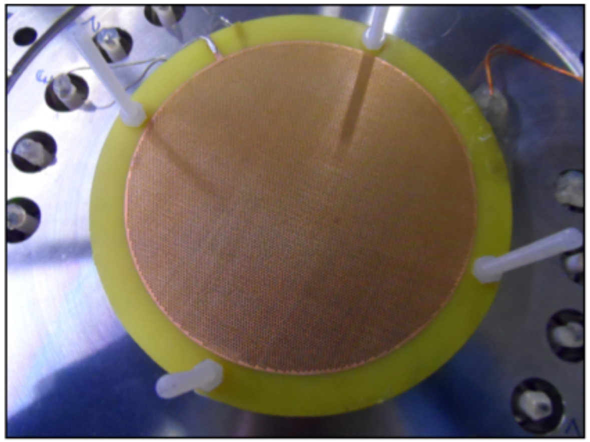


- 1024 x 1024, 24μm microline ML1001E camera
- CERN, in-house and AWE design Thick GEMs



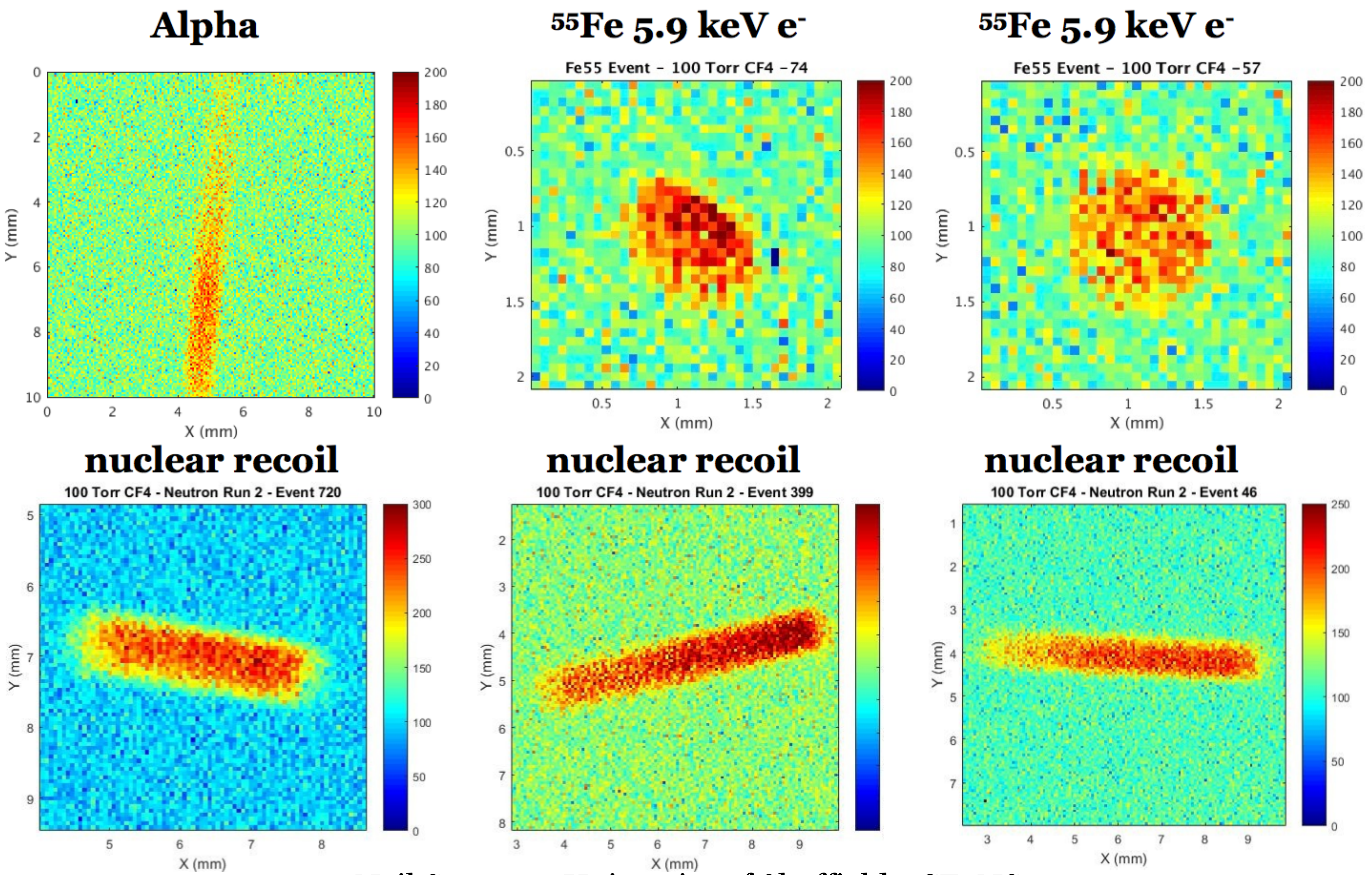






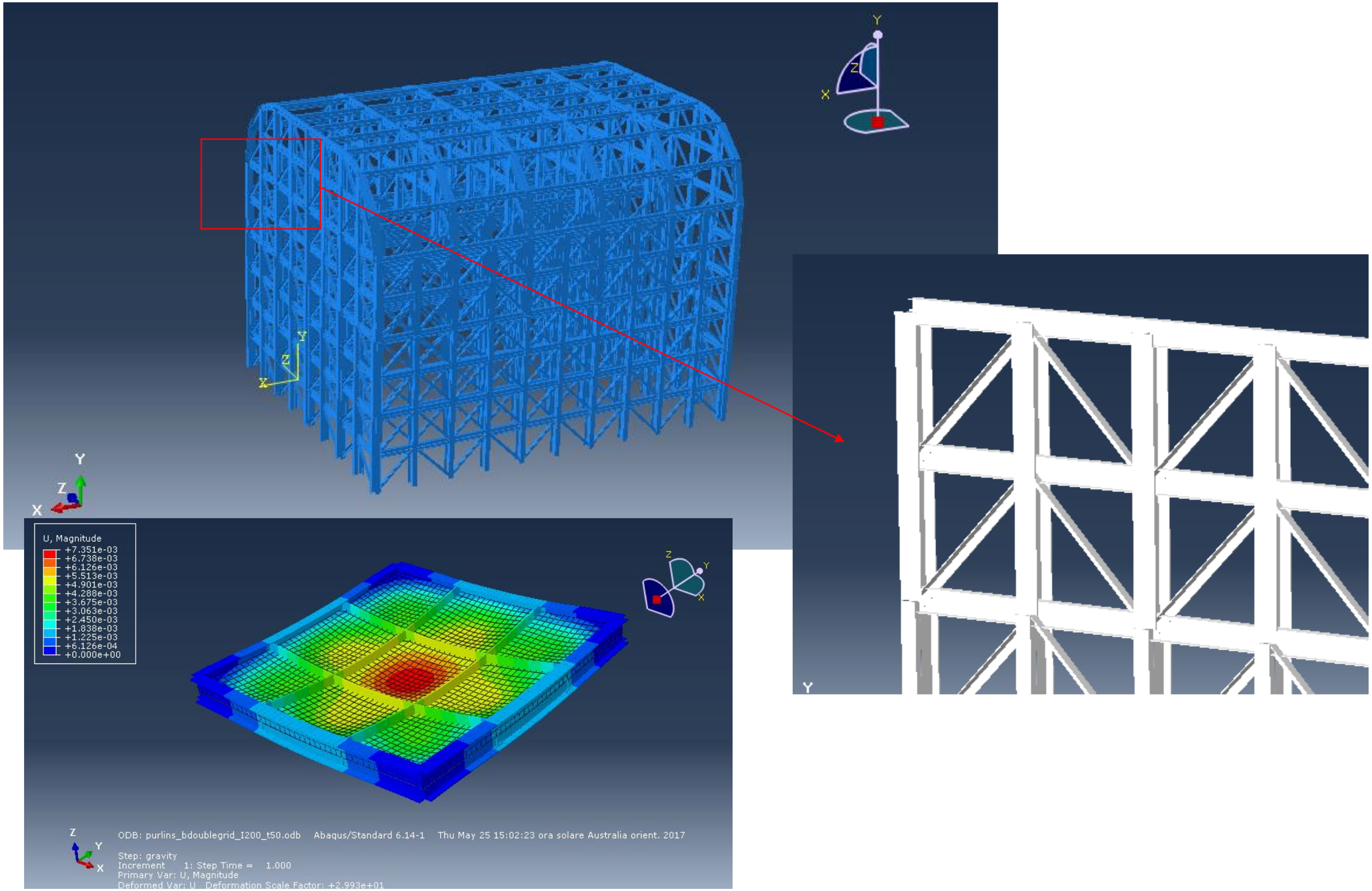
Sheffield R&D - CCD + Thick GEMs

Track images with 100 Torr CF_4 with Thick GEMs and CCD readout



Eventually will need large structure with low background "simple" Readout

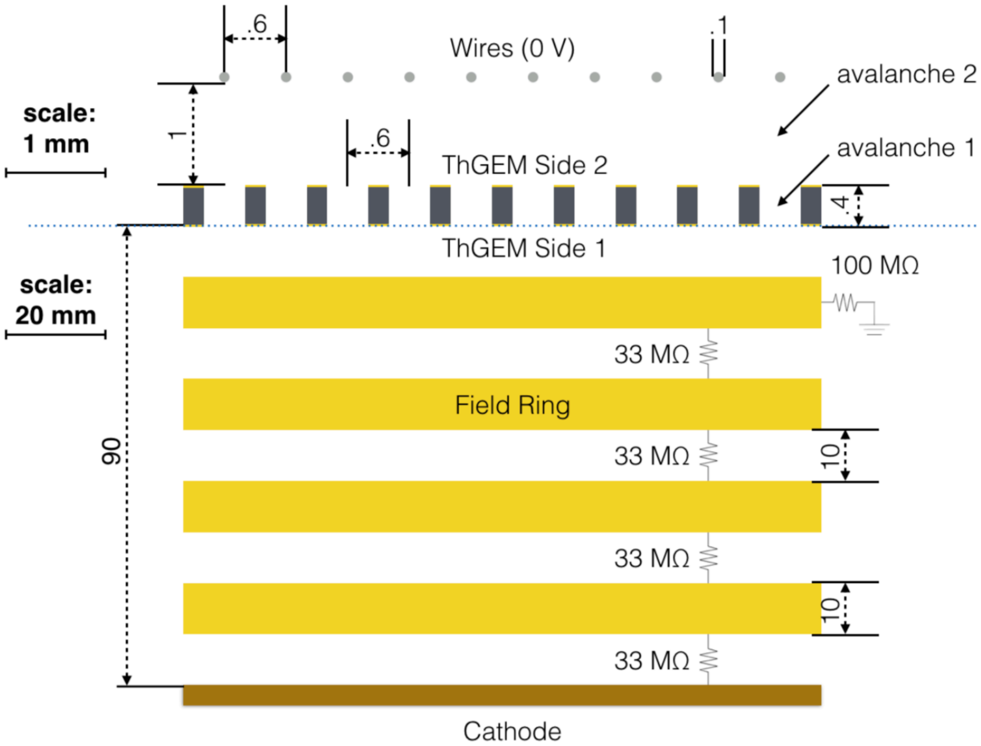
Tiziano Baroncelli (Melbourne)



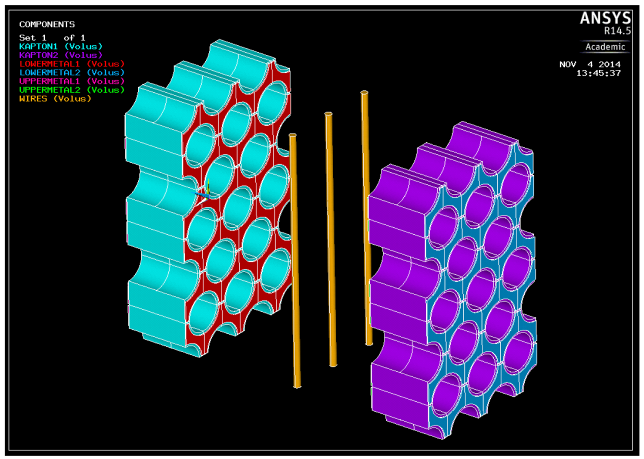
Example - Hybrid GEM+Wired

Sheffield group

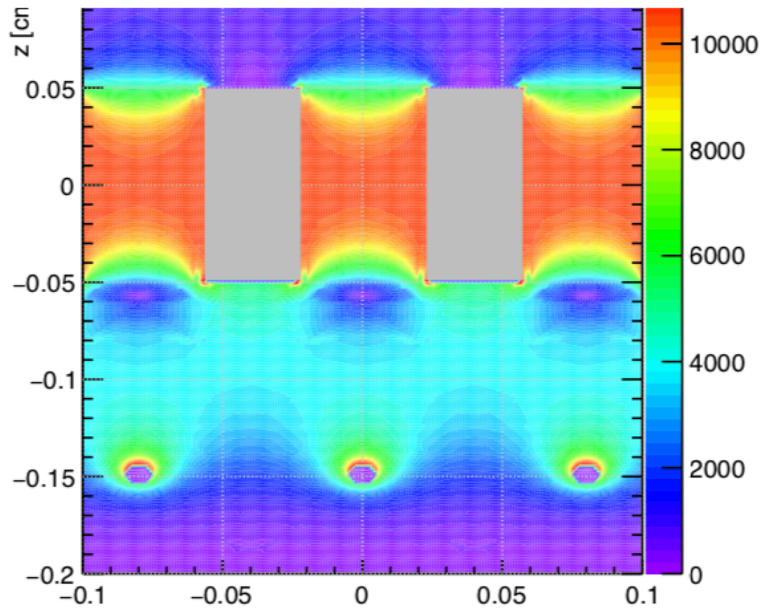
- What is the lowest background readout that might just work?



- Novel concept is simple (CERN) ThGEM + MWPC combination
- High gain (10^6) from GEM, low noise from wires (600 µm pitch)



low background just 20 µm wires,Cu and acrylic



Electric field contour around three ThGEM holes and wires obtained with a Garfield simulation by biasing the induction and charge transfer sides of the ThGEM, read-out wires and drift field to +600 V, 450 V, 0 and 700 V cm^{1} , respectively.

Example - SF_6 Hybrid GEM+Wired

Sheffield group

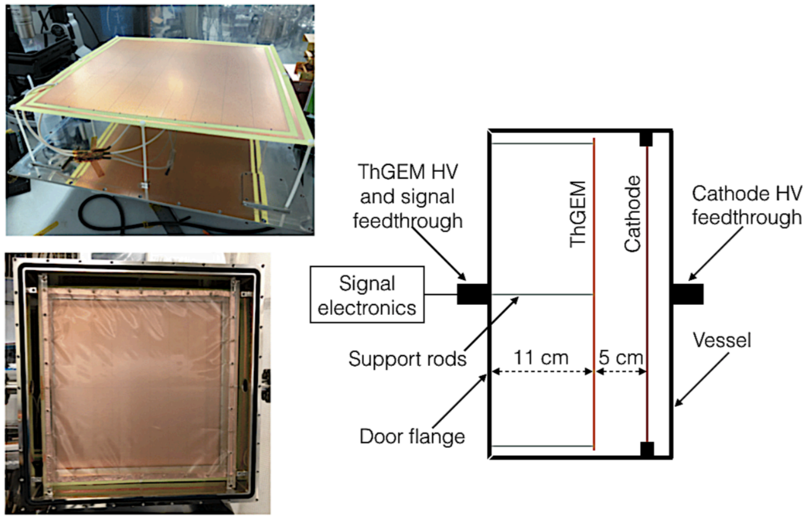
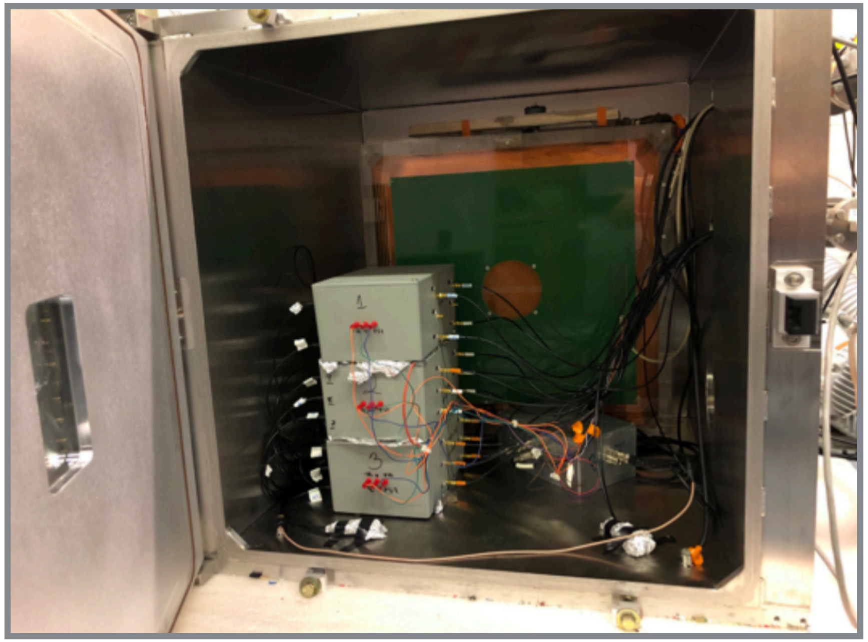
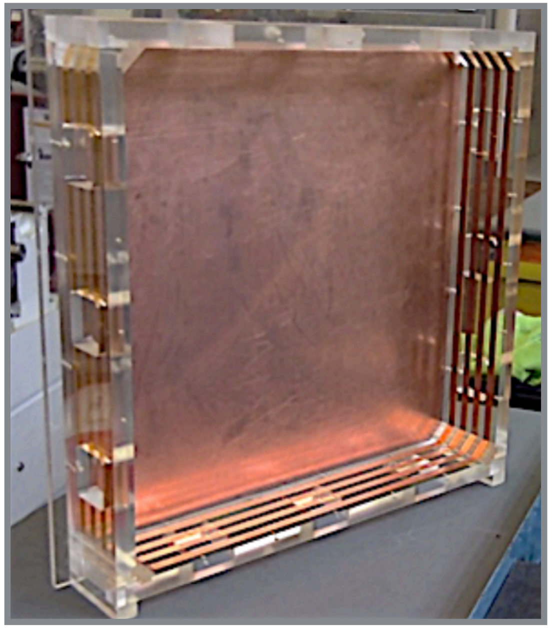
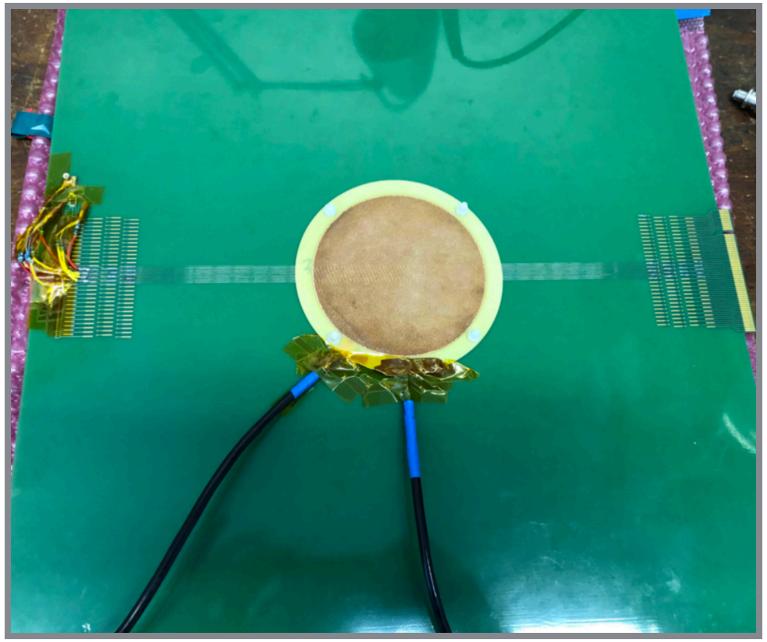
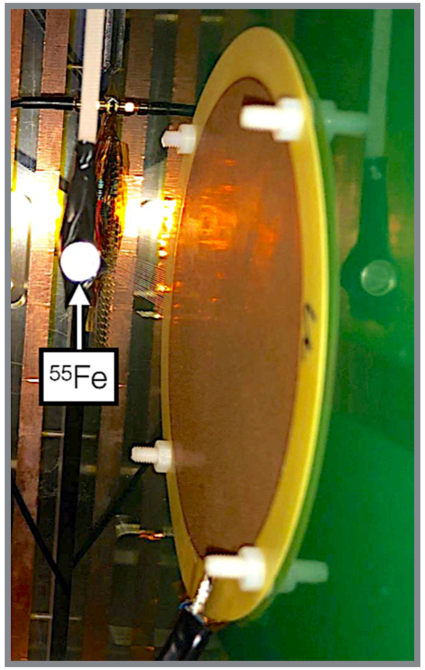


Figure 8.4: Top left: Cern ThGEM installed onto the test vessel door flange. Bottom left: Thin film Mylar cathode installed inside the test vessel. Right: Sketch (not to scale) of the ThGEM and cathode configuration inside the CYGNUS-KM prototype vessel.









Example - SF_6 Hybrid GEM+Wires

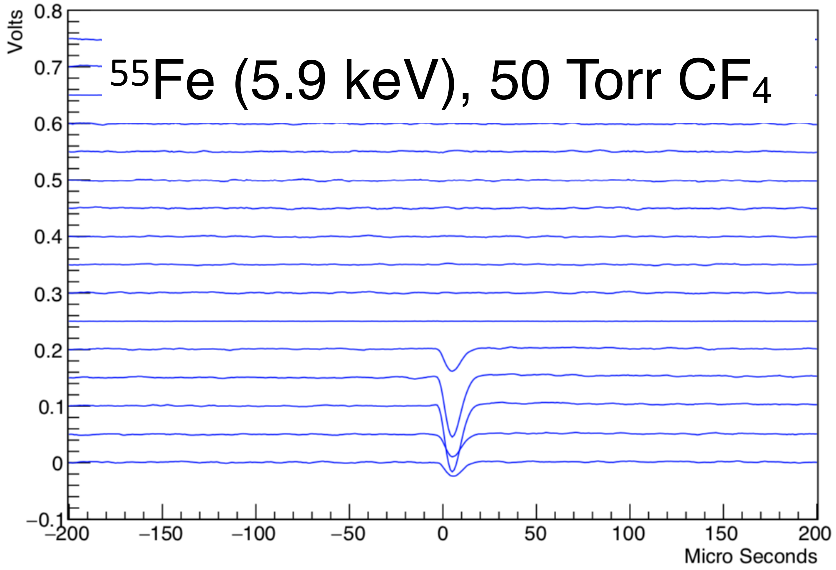


Figure 7.11: ^{55}Fe signal, in 50 Torr of CF_4, showing response across five wires.

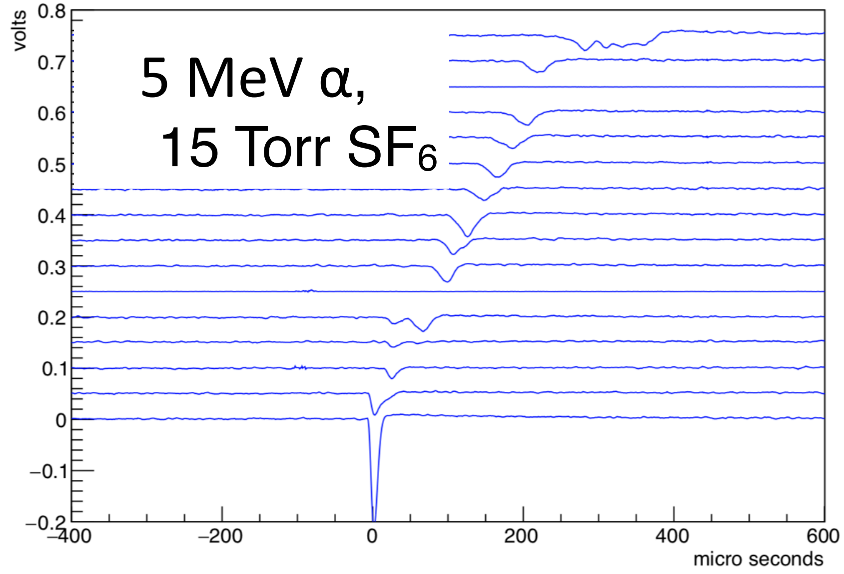


Figure 7.13: Alpha track in 15 Torr of SF_6, showing signal delay between each wire. The two wires showing no response were purposely disconnected due to a high noise level observed on those wire.

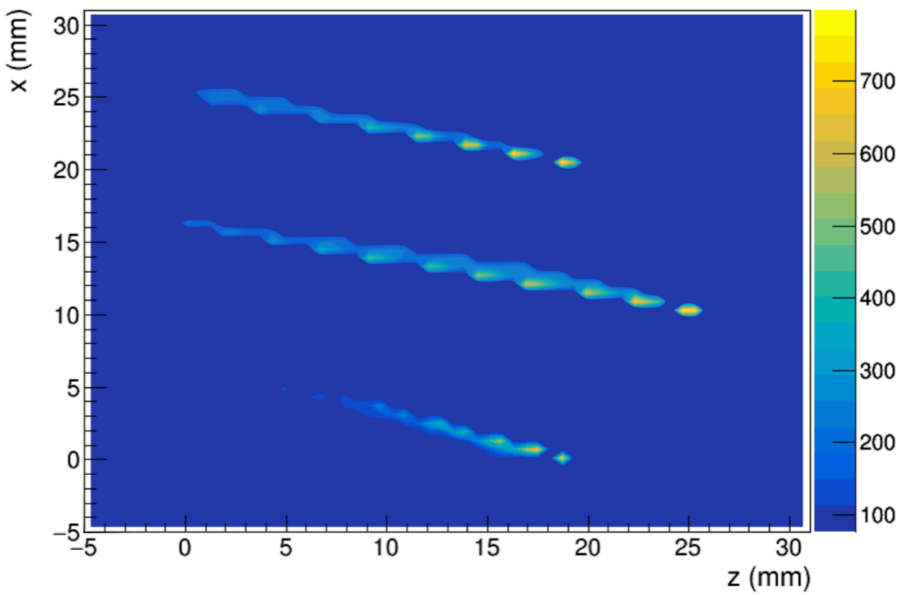


Figure 7.15: Contour plot of alpha ionisation in 15 Torr SF_6. The key gives the electron density.

- Alpha tracks in 15 Torr SF_6 -ve ion drift, readout by wires (no gain) with ThGEM providing gain stage.

A.C. Ezeribe et al., arXiv:1909.13881

AIT-WATCHMAN

(Advanced Instrumentation Testbed – WATer CHerenkov Monitor of ANtineutrinos)

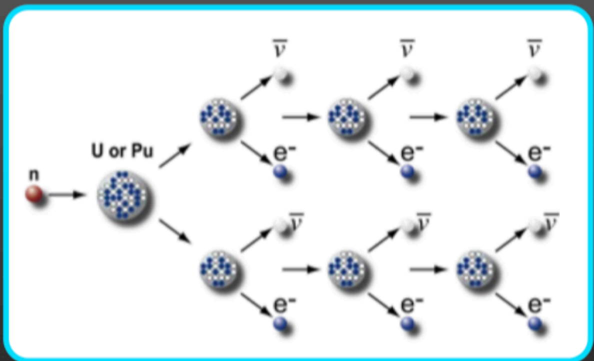
May provide near-field opportunity to demonstrate coherent elastic neutrino-nucleus scattering

Can neutrinos be used to monitor distant reactors?

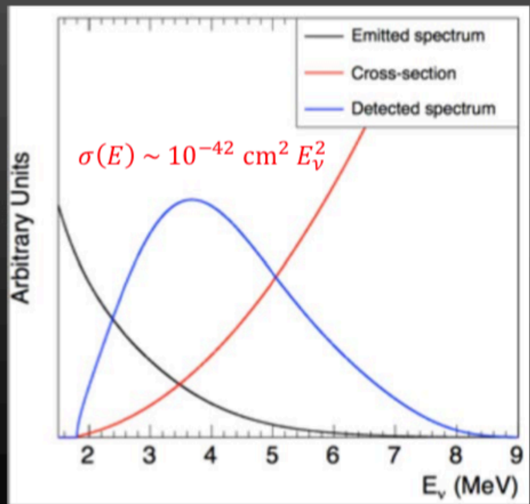
Roughly 6 $\bar{\nu}_e$ released per fission and ~10^{21} fissions per second in a typical 3 GW_t power reactor, means that you have ~10^{22} $\bar{\nu}_e$ per second isotropic emission

Inverse Beta Decay (IBD):

$$\bar{\nu}_e + p \rightarrow e^+ + n$$



25 km stand-off



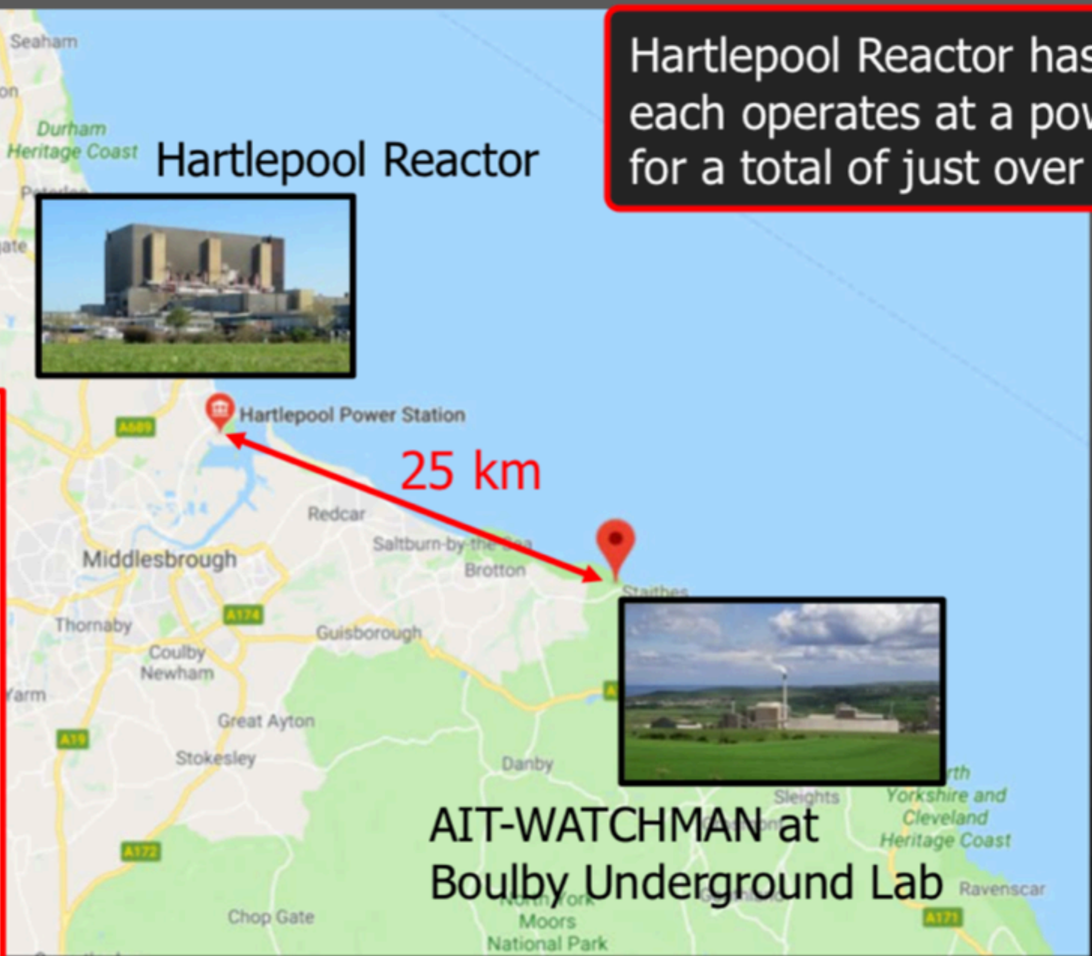
Can expect "several" interactions per kiloton of water per day at 25 km distance

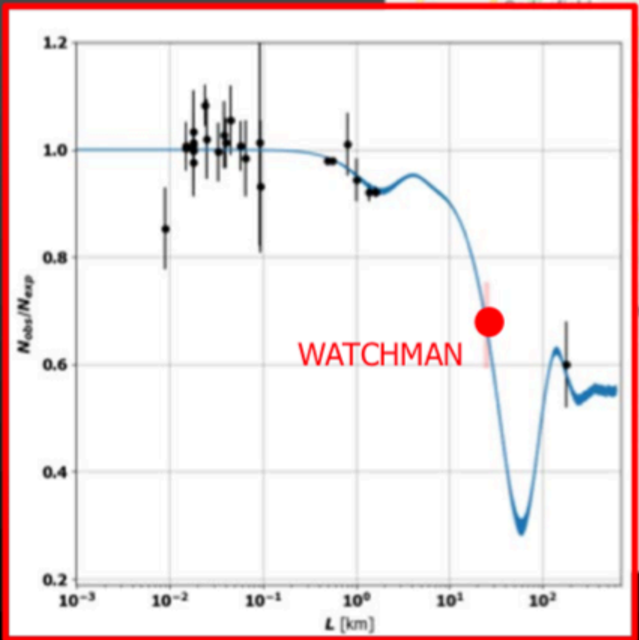
20 Institutions and 96 Collaborators from the US and UK

AIT-WATCHMAN

(Advanced Instrumentation Testbed – WATer CHerenkov Monitor of ANtineutrinos)

Hartlepool Reactor has two cores, each operates at a power of 1.5 GW_t for a total of just over 3 GW_t





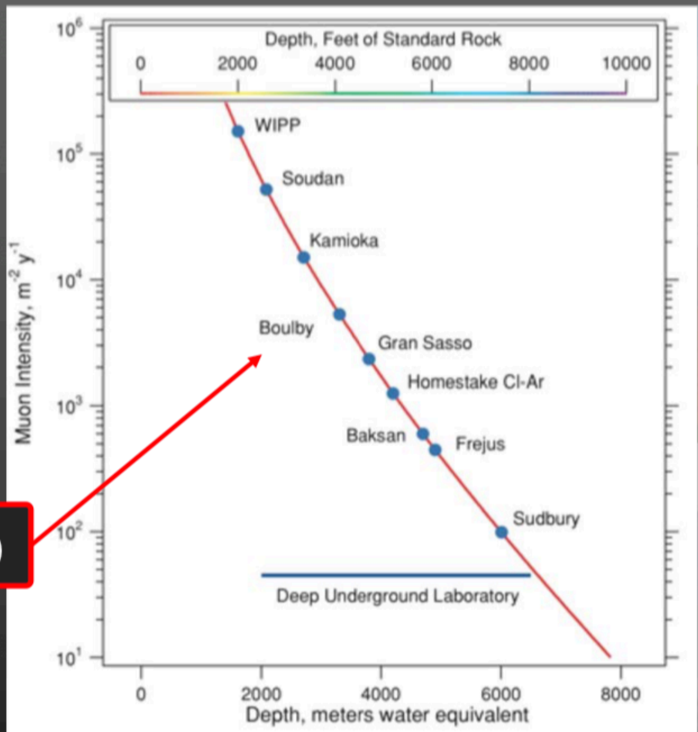
AIT-WATCHMAN

(Advanced Instrumentation Testbed – WATer CHerenkov Monitor of ANtineutrinos)

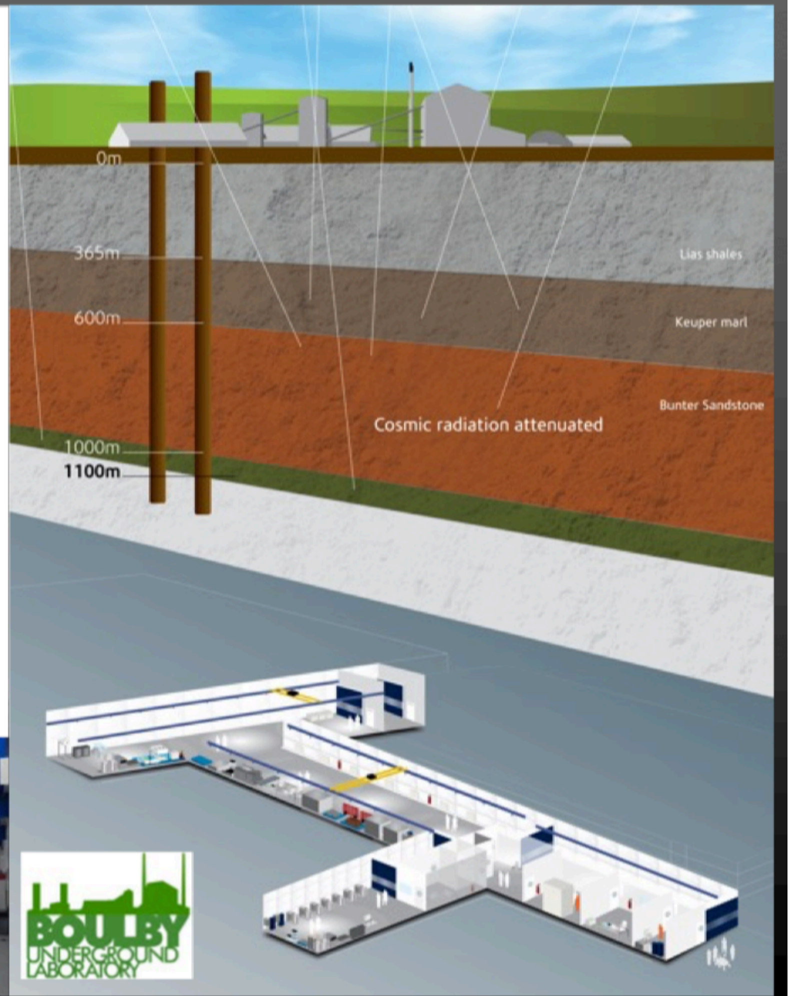
Boulby Underground Laboratory

This facility is well-established, hosting a variety of low-background particle physics experiments and other multidisciplinary projects

Depth of 1.1 km (2805 mwe)



Cleanliness in the underground lab will reduce the impact of dust and other environmental contamination



Coherent Neutrino Scattering at Hartlepool Reactor?

- Goal of CYGNUS is coherent solar neutrino detection
- Can we, should we, test this feasibility using a reactor (~same spectrum)?
- We have negotiated access to the HP civil reactor
    - 1.5 GW thermal, 2 AGR reactors
    - 25 km from Boulby
    - Access to space at ~10-40m from reactor
    - Background survey campaign planned on Jan 2020

Hartlepool Estimates

Callum Eldridge (Sheffield)

- We can estimate the spectrum and flux (see ref below)
- Potential labs at between 10m and 40m from reactor core
- 1.5 GW
- Backgrounds in the lab are normal natural levels

Reactor Neutrino Spectra

Anna C. Hayes,[1] and Petr Vogel[2]

[1]T-2 Theoretical Division MS283, Los Alamos National Laboratory, Los Alamos, NM 8545, USA ; email: anna_hayes@lanl.gov
[2]Kellogg Radiation Laboratory 106-38, California Institute of Technology, Pasadena, CA 91125, USA ; email: pvogel@caltech.edu

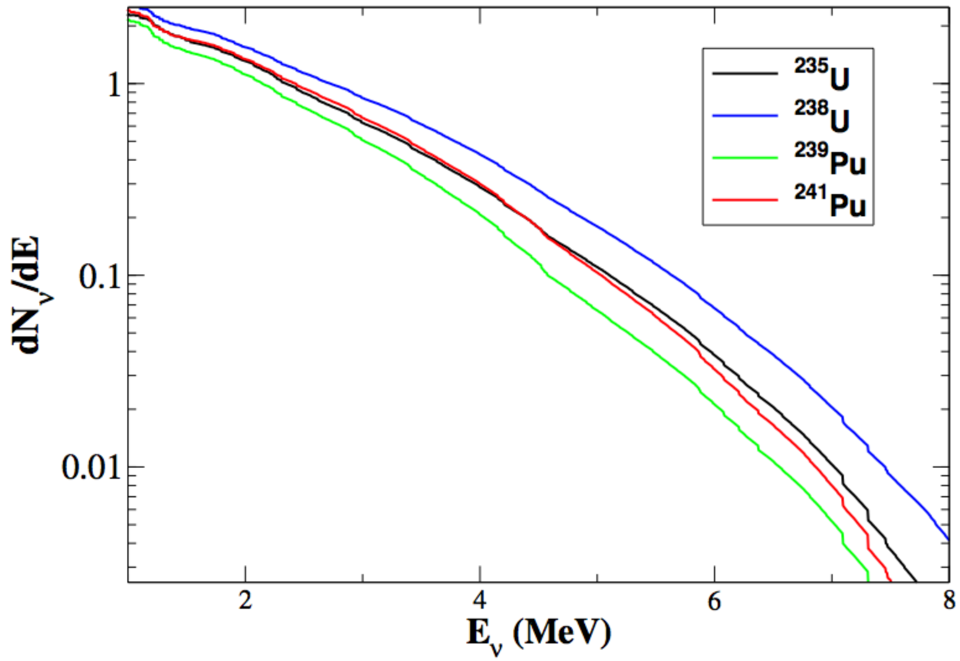


Figure 3

The antineutrino spectra for the four actinides determining the total antineutrino flux emitted from reactors. The fission yields were taken from JEFF-3.1.1 and the decay data, included the modeled data for unmeasured spectra, from ENDF/B-VII.1.

Hartlepool Estimates

Callum Eldridge (Sheffield)

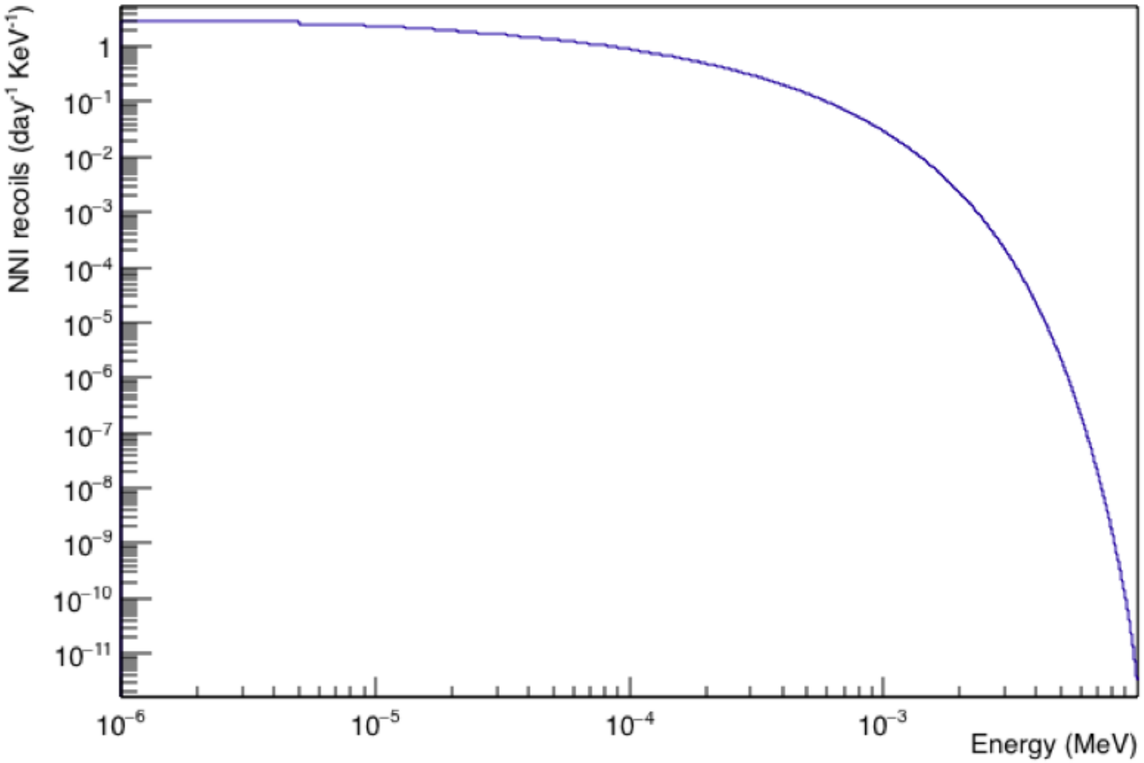


Figure 8: Energy spectrum of CEνNS nuclear recoils in one litre of Argon at STP 10 m from Hartlepool reactor.

- 1lt Ar gas, STP, 10m
- from one reactor centre

at 1 keV - SF_6 rate is 0.0589, 2 keV = 0.015

- ~3,300 per year in 1 m³ of SF_6 = 13 per day (from the two reactors)

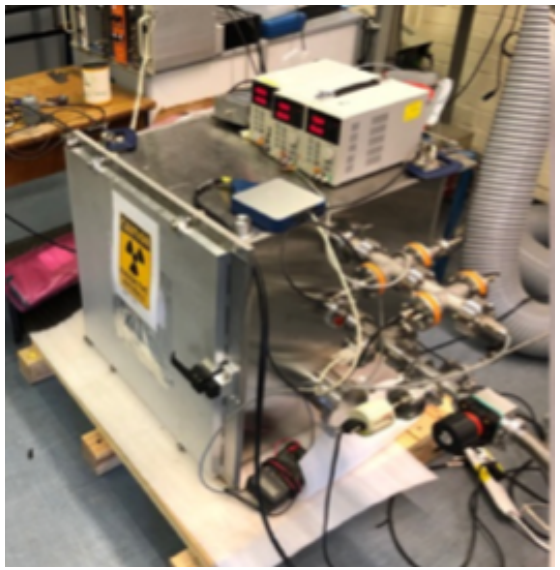
Table 2: Number of detectable interactions per litre per day for different gasses at atmospheric pressure 10 m from Hartlepool reactor.

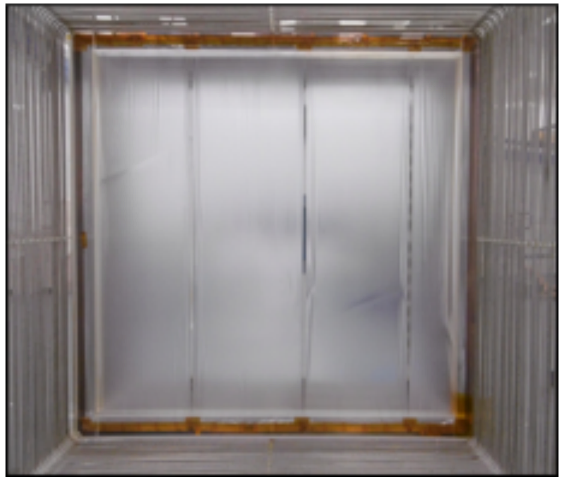
Target Gas	**CEνNS rate with E_{rec} >0.5 keV**
He	0.002
Ne	0.022
Ar	0.046
Xe	0.029
CF_4	0.097
SF_6	0.161
CO_2	0.045

Basic Requirements

Maybe better to place at a spallation source

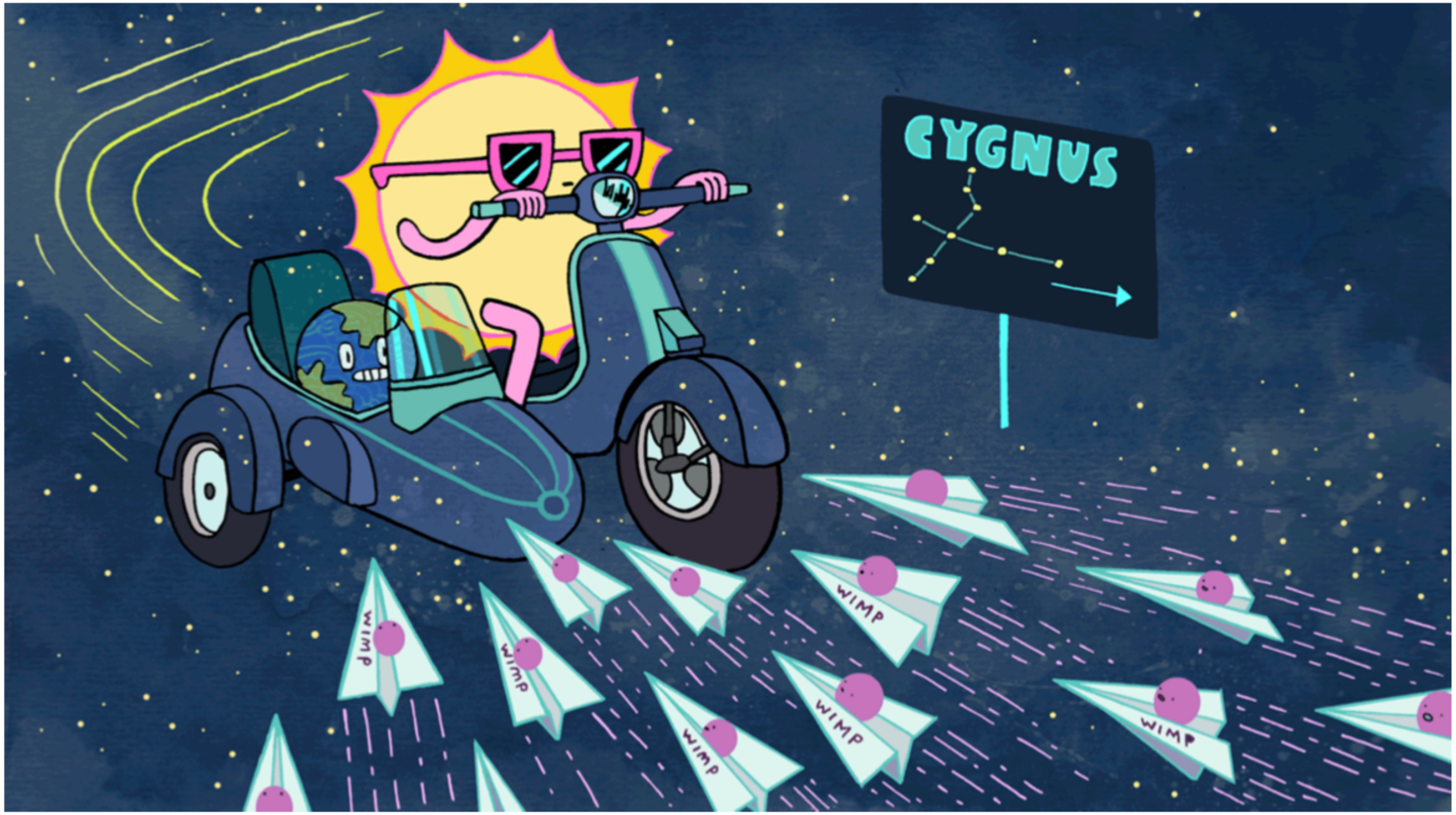
- Space for gas vessel - probably pressure vessel but could be 1 atm
- Size - ~ 1.5 x 1.5 x 1.5 m (test vessel is 0.6 x 0.6 x 0.6)
- Gas supplies, He, Ar, SF_6 (looking at recirculation to avoid dumping)
- No cryogenics, no water, minimal power to run DAQ, internet
- Likely muon/neutron plastic veto (needs background study)
- Needs to be as close to reactor as possible





Conclusions

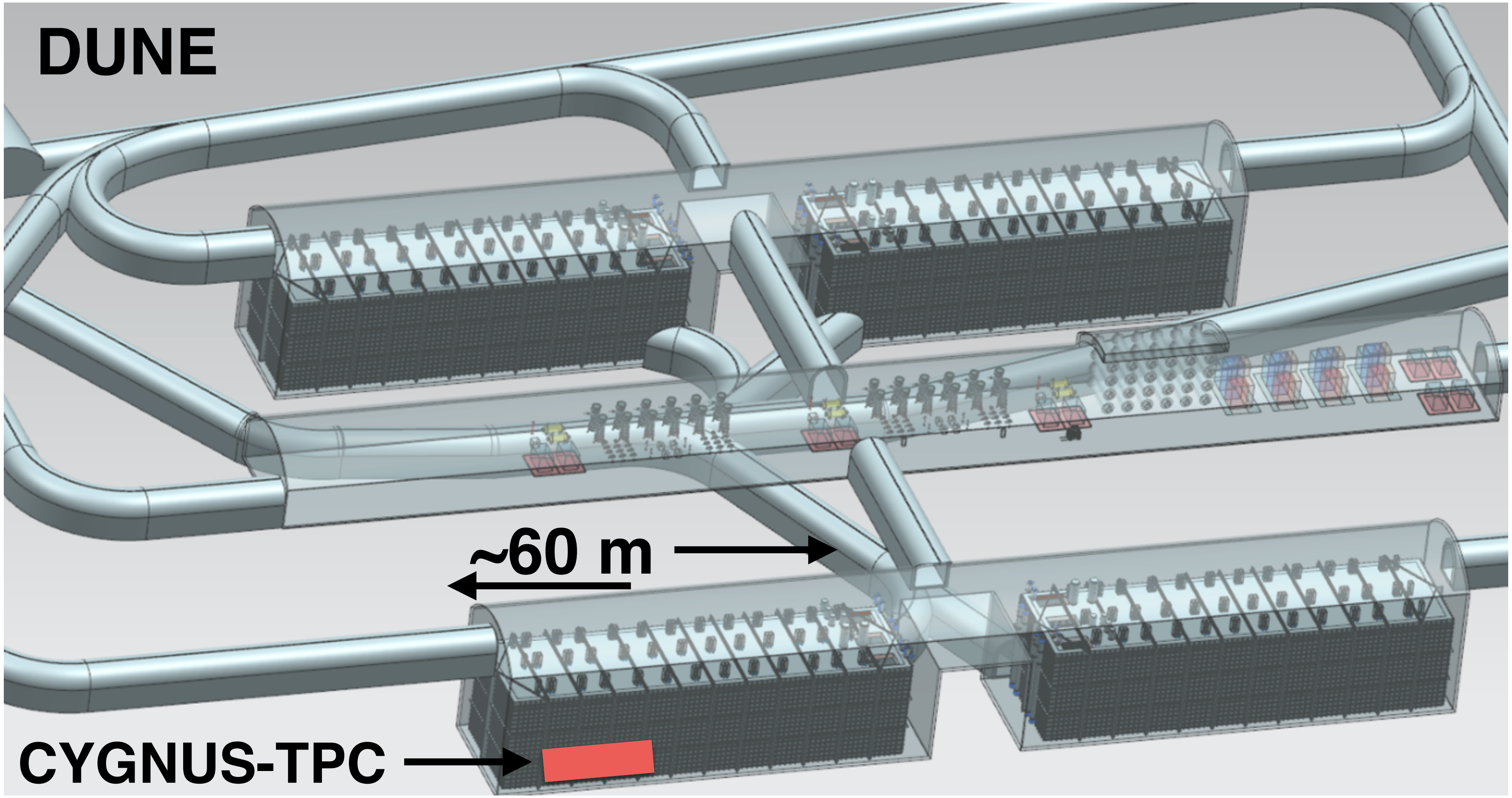
- The directional community has expanded and forming a larger collaboration - CYGNUS - a global directional network
- Enormous progress has been made on all key technical issues
- CEvNS experiments provide an opportunity for synergy



http://www.symmetrymagazine.org/article/wimps-in-the-dark-matter-wind

Backup

How Not to be Afraid of Larger TPCs



- Size is ~ 100th scale of proposed DUNE liquid argon TPC
- But would also be spread on multiple sites

Low Energy Discrimination Measurements

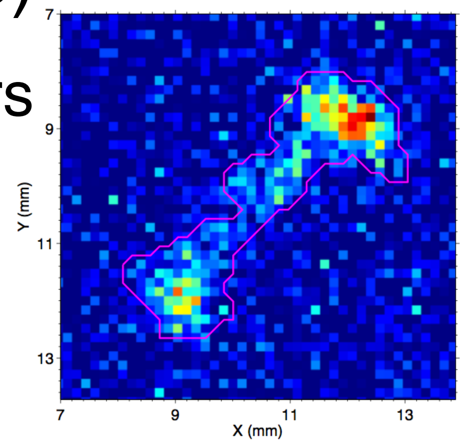
- Recoil discrimination below 10 KeV_{ee} looks feasible
- Growing evidence from several groups

(e.g. UNM group)

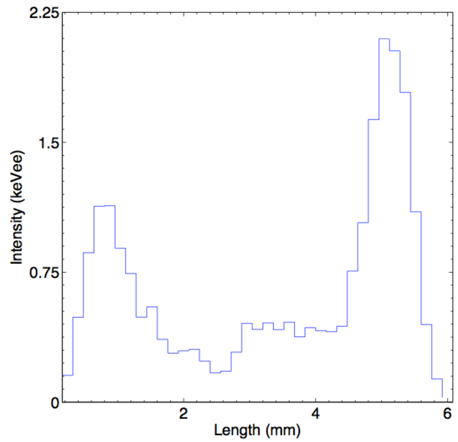
claim 10^5 at 10keV (100 Torr CF4)

- Simple parameters
- separation at 6 keVee in 100 Torr CF_4

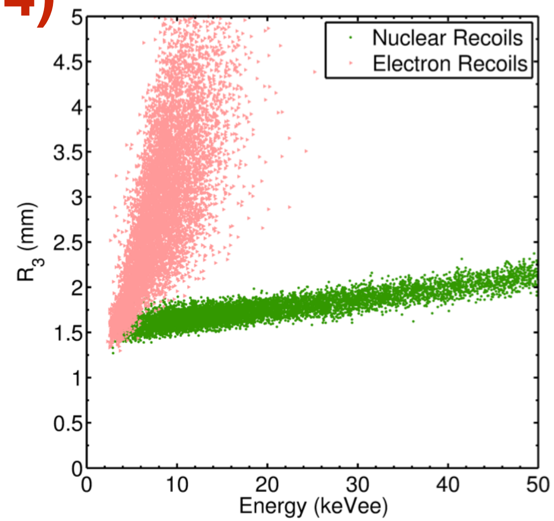
arXiv:1510.02170v3



(a) Electron Recoil



(b) Projected Bragg Curve



(b) 3D Reconstruction

(e.g. MIMAC group)

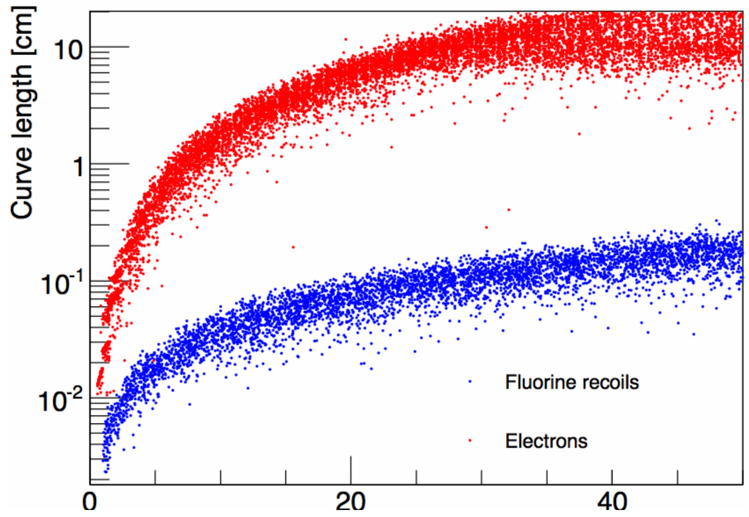
- Simulations with complex multi parameter fits

70% CF_4 and 30% de CHF_3 at 50 mbar

claim 10^5 at 5 keV

arXiv:1205.0973v2

Variable	Type
Minimals	
$S[0]$	Pulse-shape
Track is outside	Track
Clustering	Track
$\Delta X > 1$ or $\Delta Y > 1$	Track
Discriminanting	
N_{Coinc}	Track
$\rho_{track}/\Delta t_{slot}$	Track
N_{Strip}	Track
A_{peak}	Pulse-shape
ρ_{track}	Track
NIS	Track
τ	Pulse-shape
t^{start}_{slot}	Track
Δt_{slot}	Track
$t^{pulse}_{start} - t^{start}_{slot}$	Both
X^{2}_{peak}	Pulse-shape
σ_{Long}	Track
μ_{peak}	Pulse-shape
τ/E_{ioni}	Pulse-shape
L_C	Track
$V(\Delta X \Delta Y)$	Track
E_{ioni}	Pulse-shape
$\sigma^{(1)}_{Trans} - \sigma^{(2)}_{Trans}$	Track



22 observables built using the MIMAC readout.... and more ...
(Q. Riffard et al. arXiv: 1602.01738 (2016))