



The CYGNUS Project

Lindsey Bignell for the CYGNUS proto-collaboration



Australian
National
University



Why Directionality?

Less Event
Information

energy + particle ID + position + **recoil angle + vector sense**

More Event
Information

Improved background discrimination
more physics per exposure

Why Directionality?

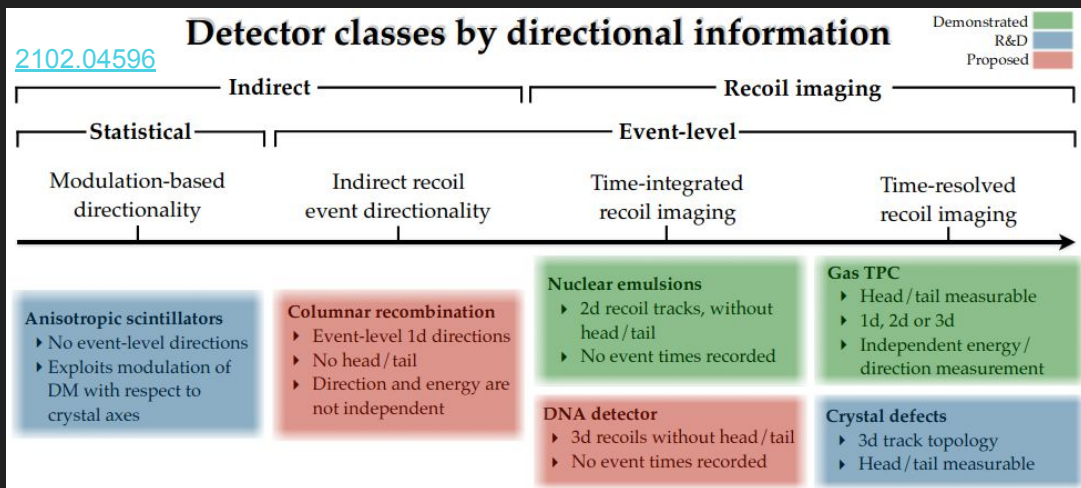
Less Event Information

energy + particle ID + position + **recoil angle** + **vector sense**

More Event Information

Improved background discrimination

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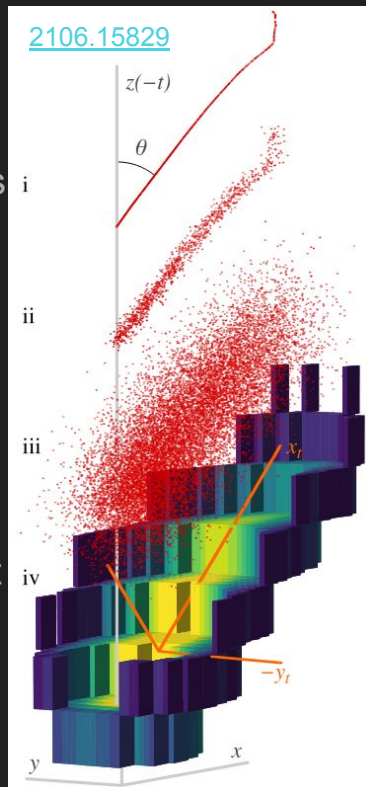


Recoiling nucleus i

Drift ii

Gas Amplification iii

Readout iv



Gas time projection chamber offers most mature event-by-event directionality

Why Directionality? The Neutrino Fog

Less Event Information

energy + particle ID + position + **recoil angle + vector sense**

More Event Information

Improved background discrimination
more physics per exposure



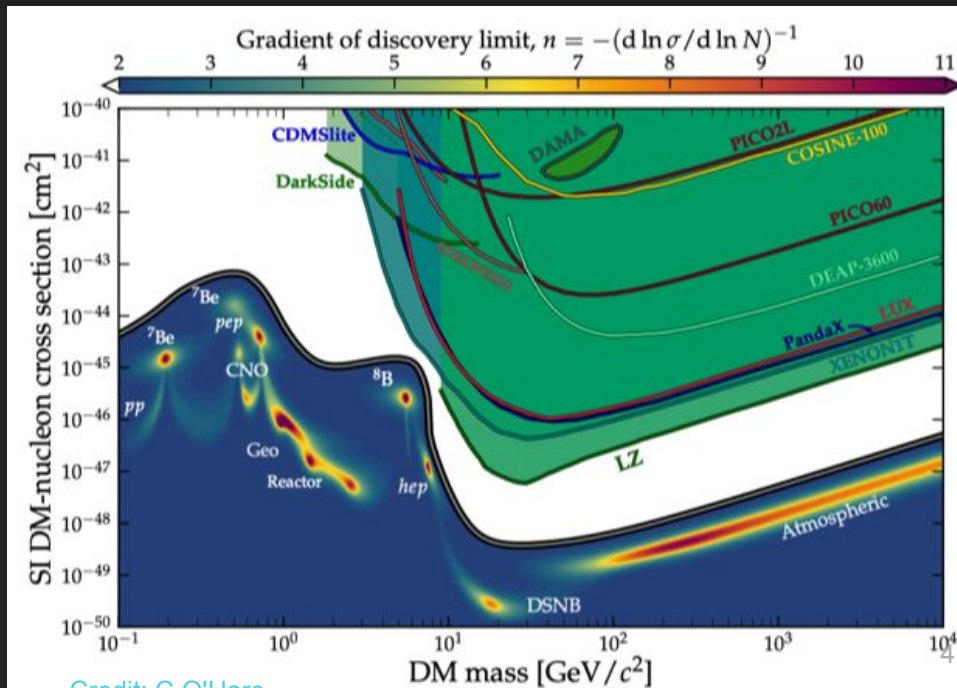
Neutrino Fog

CEvNS degenerate with WIMP signal.

BG free: $\sigma_{\text{Min}} \sim (\text{Exposure})^{-1}$

Distinguishable BG: $\sigma_{\text{Min}} \sim (\text{Exposure})^{-1/2}$

Degenerate BG: $\sigma_{\text{Min}} \sim (\text{Exposure})^{-1/N}$
 $N > 2$

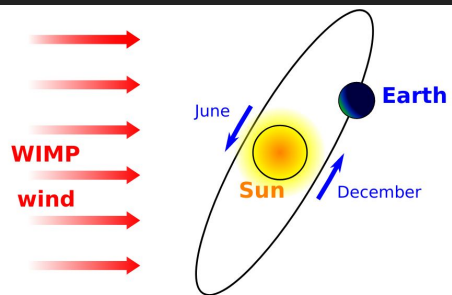


Credit: C O'Hare

Why Directionality? Dark Matter Discovery

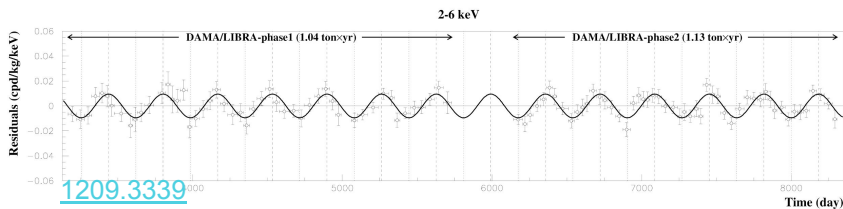
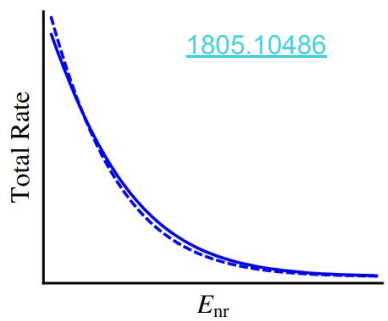
Must tie a signal excess to astrophysics to prove it is dark matter.

Annual Modulation

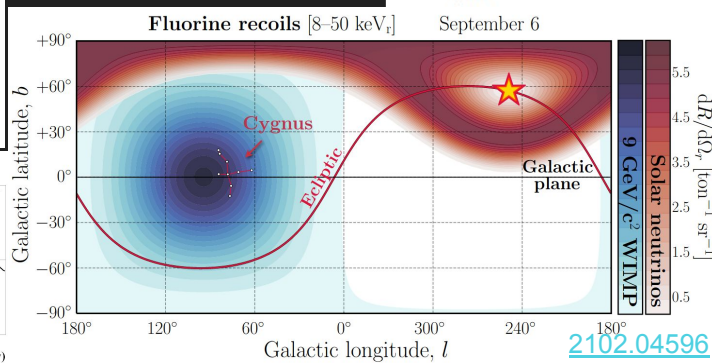
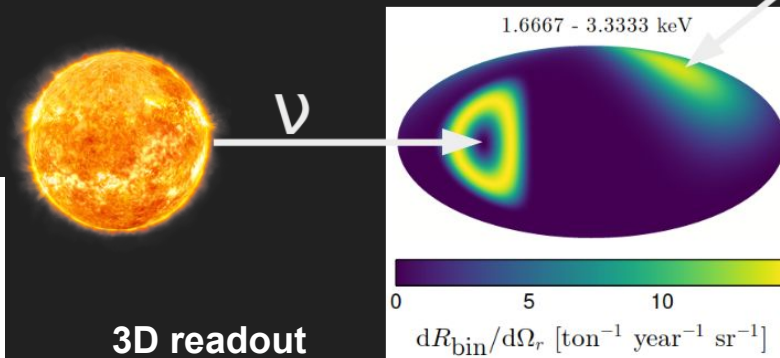


Modulations

Very subtle spectrum
Subtle ($\sim 1\%$) rate

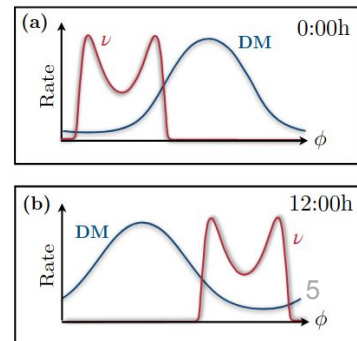


Directionality

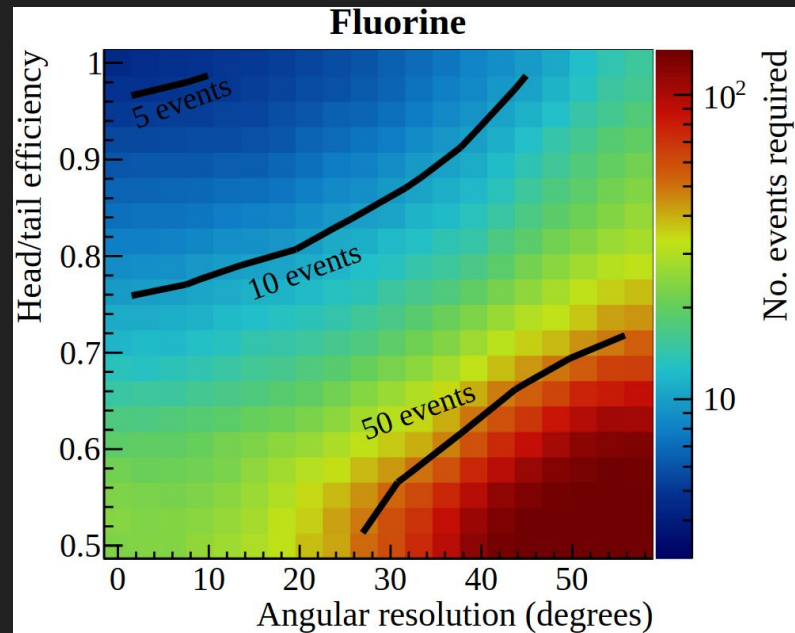
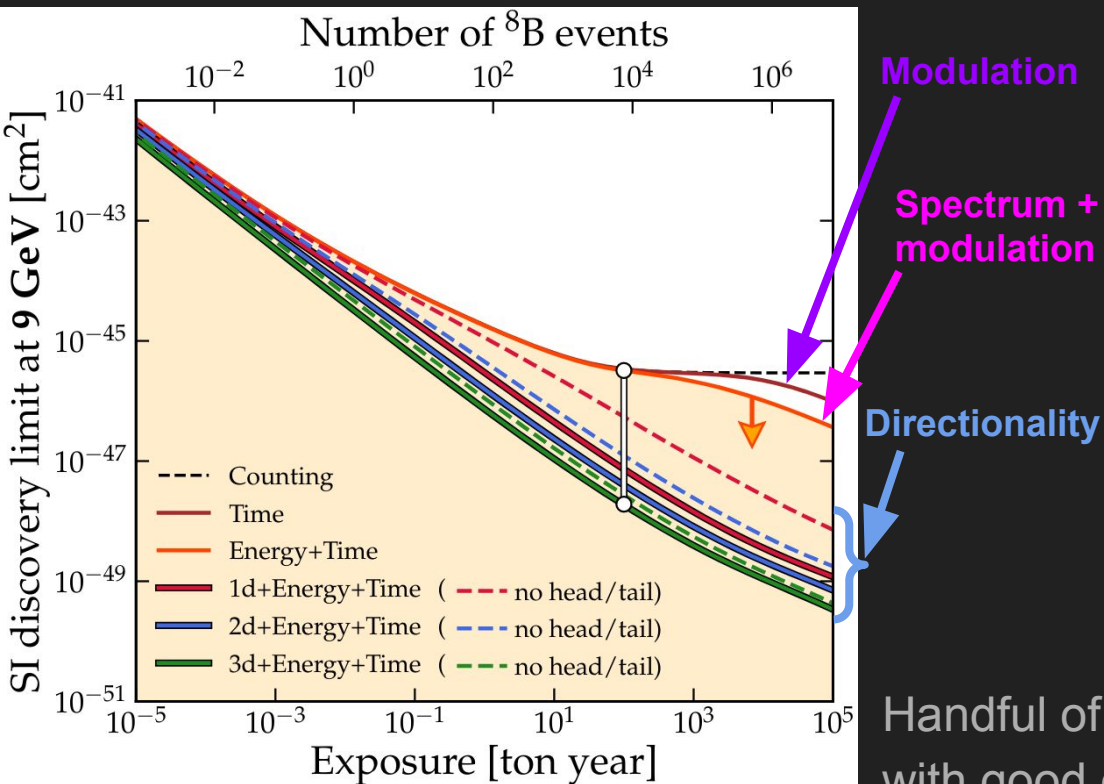


1602.03781

2D readout



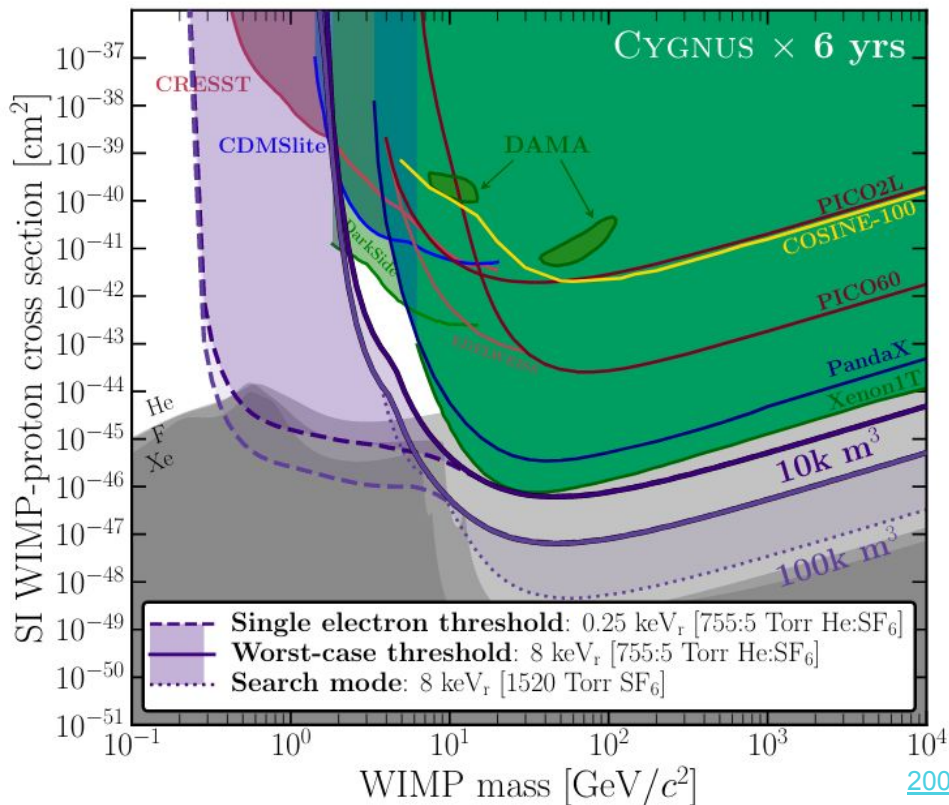
Why Directionality? Dark Matter Discovery



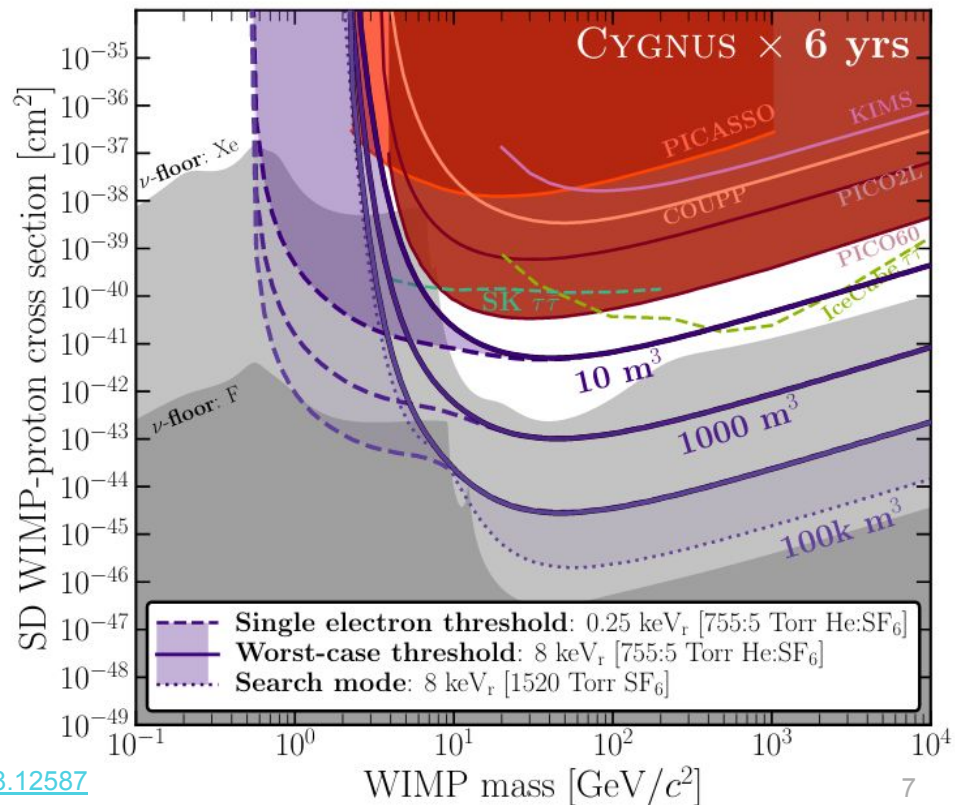
Handful of events can exclude neutrinos (90%)
with good enough directionality

Why Directionality? Dark Matter Discovery

Search the ν fog with a large detector



Leading SD sensitivity for $\sim 10 \text{ m}^3$ detector

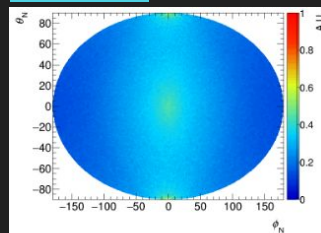


Why Directionality? Dark Matter Astronomy

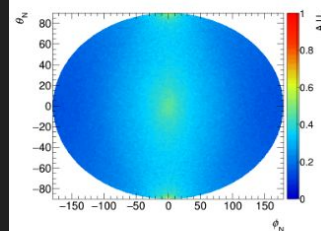
Anisotropies further increase sensitivity relative to non-directional detectors

- Can extract information about the WIMP velocity distribution/streams (1807.09004)
- Sensitive to boosted dark matter (2211.13399)
- Extract DM halo properties (1012.3960)

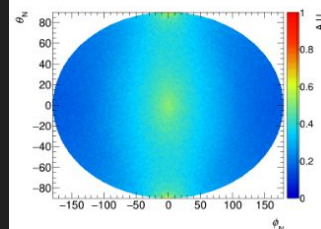
2211.13399



NFW, $m_\chi = 100$ MeV

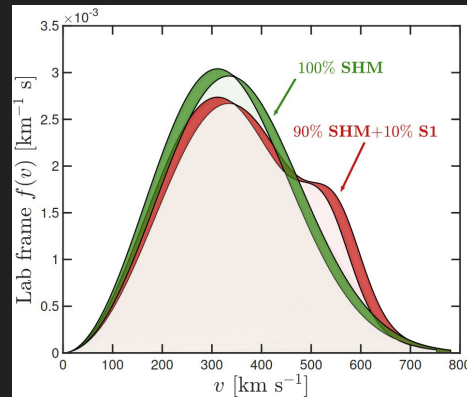


NFW, $m_\chi = 10$ MeV



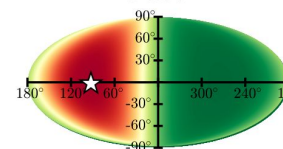
NFW, $m_\chi = 1$ MeV

1807.09004

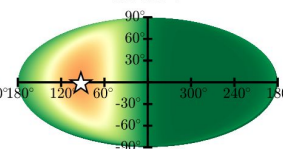


SHM

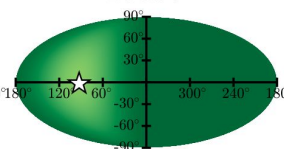
5 keV



10 keV

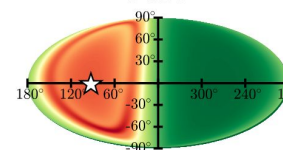


20 keV

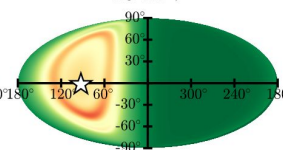


90% SHM + 10% S1

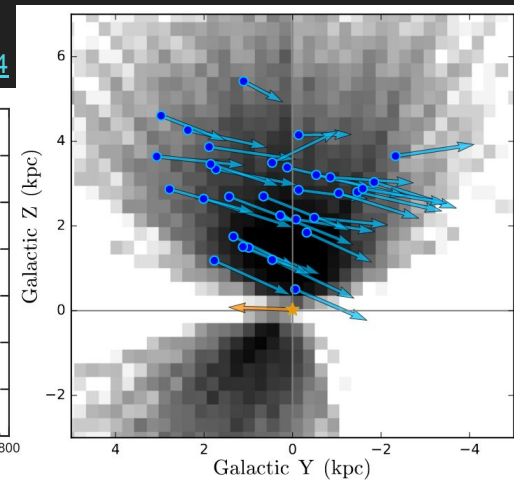
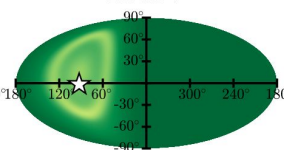
5 keV



10 keV



20 keV



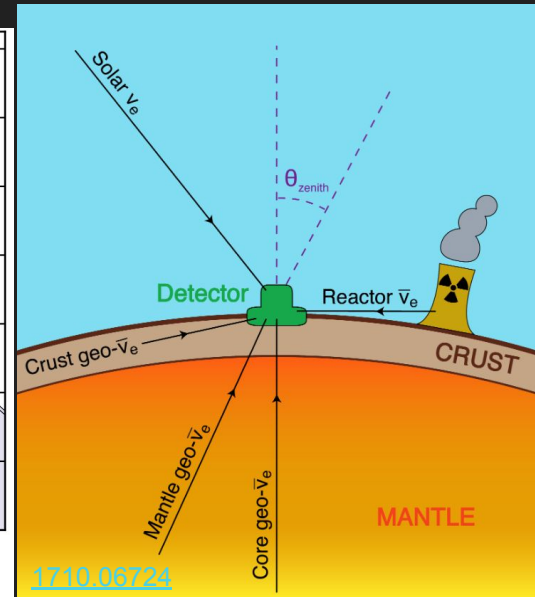
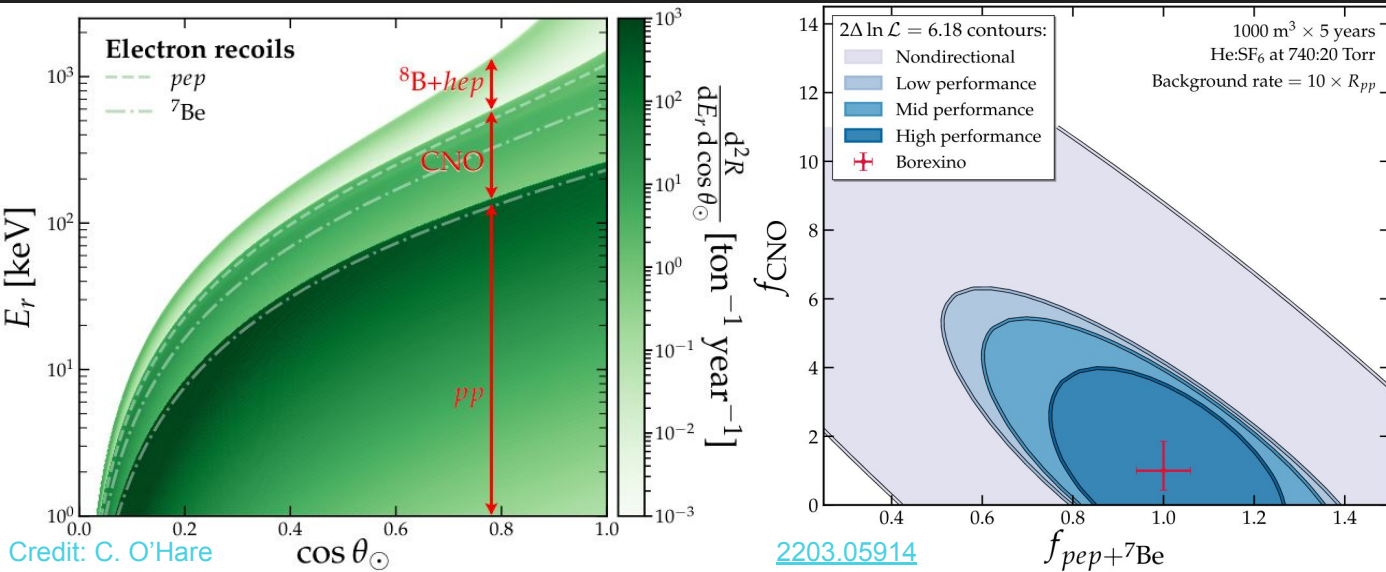
Angular resolution = 0°

Why Directionality? Neutrinos

Solar Neutrinos: ν -e scattering (higher rate than CEvNS) – directionality allows neutrino spectrum measurement and allows inference of CNO fraction.

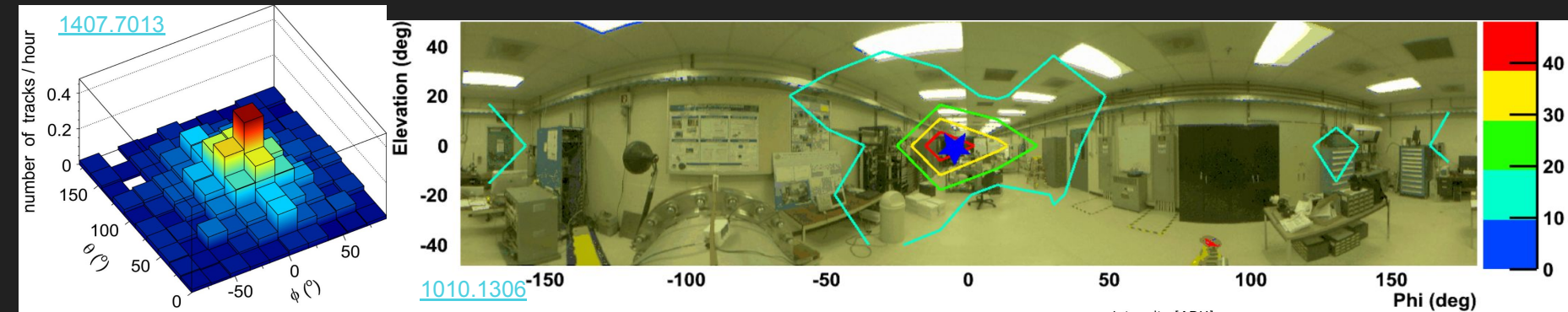
K-40 Geoneutrinos: 10 T ($\sim 10^3 - 10^4$ m³ gas) for 10 years (1710.06724)

CEvNS: spallation source (2003.11510), LBNF (2103.10857)



Why Directionality?

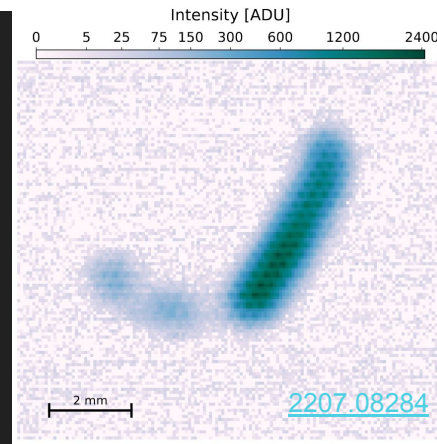
Neutron directionality: applications such as homeland security or underground background characterisation



Migdal Effect: Never experimentally measured

Track topologies make laboratory measurement feasible (2207.08284)

cf. Pawel Majewski's talk yesterday

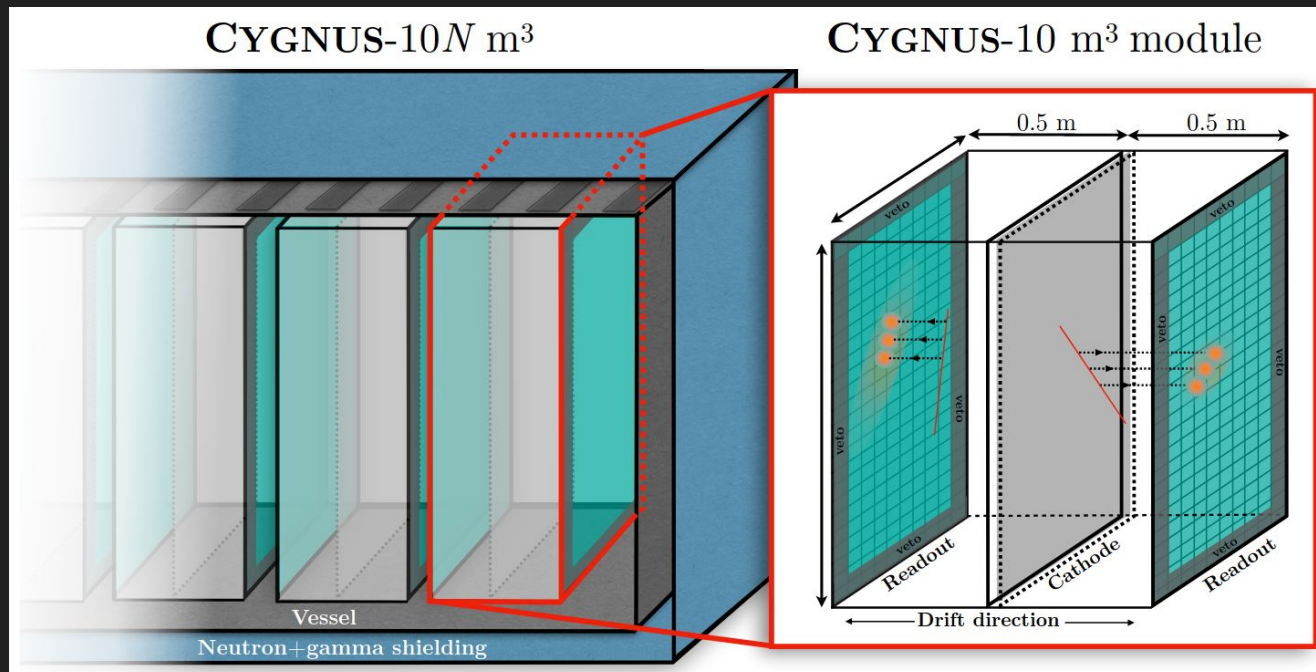


CYGNUS Vision

Large gas time projection chamber with low-energy directionality.

Modular detector, distributed across multiple underground labs, flexible implementation.

R&D challenges: minimising diffusion and backgrounds, optimising performance for WIMP and/or other physics.



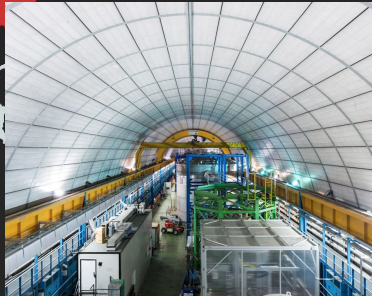
The CYGNUS proto-collaboration



CYGNUS-HD10
Lead, USA



CYGNUS-10
Boulby, UK



CYGN0
Gran Sasso, Italy



CYGNUS-KM
Kamioka, Japan



CYGNUS-Oz
Stawell, Aus

Stawell Underground Physics Laboratory

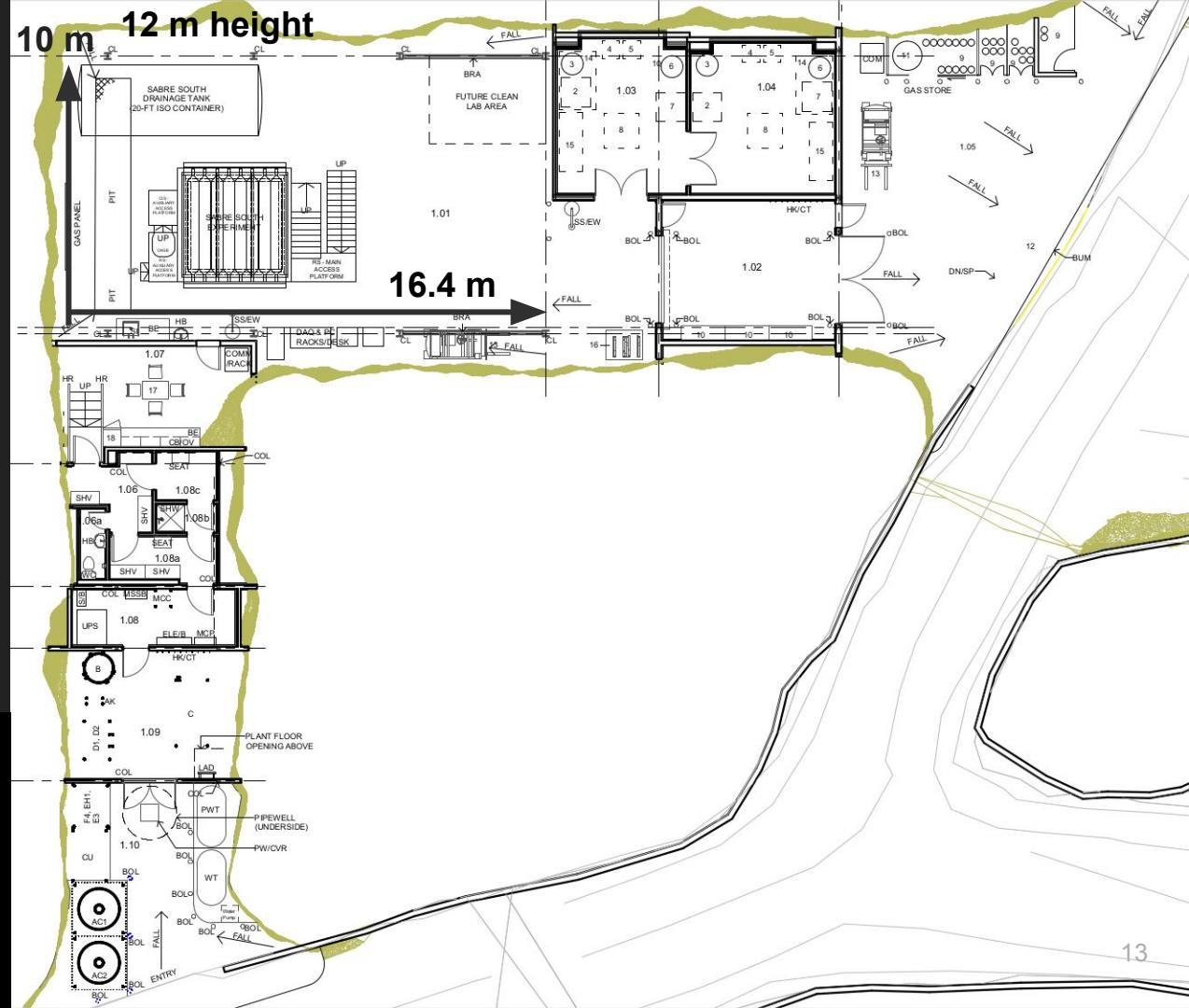
First general purpose underground laboratory in the Southern Hemisphere

1025 m overburden, similar muon flux to LNGS.

Planned location for CYGNUS-Oz



STAWELL
UNDERGROUND
PHYSICS LAB



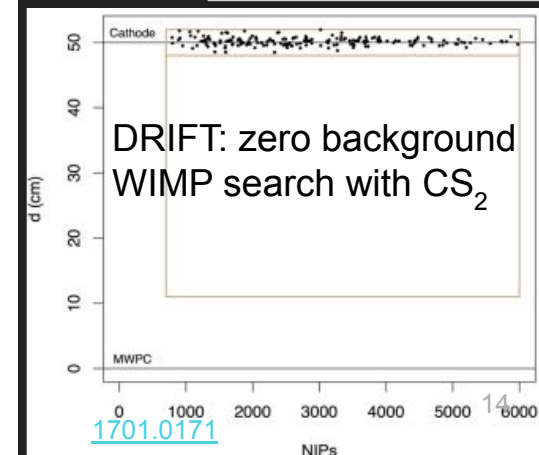
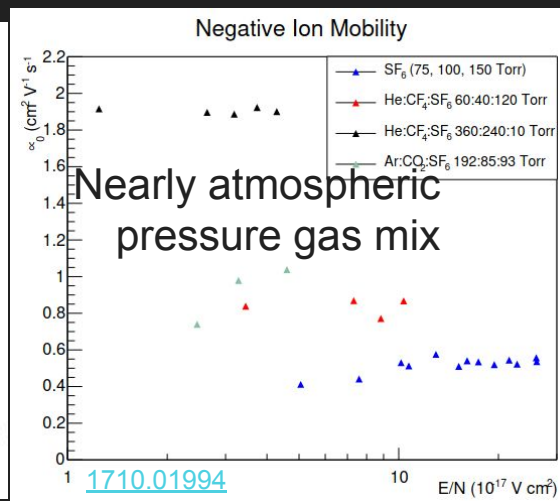
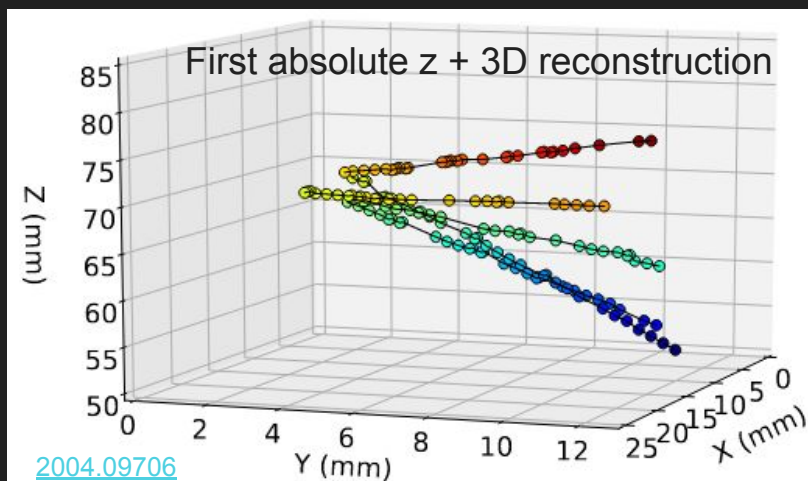
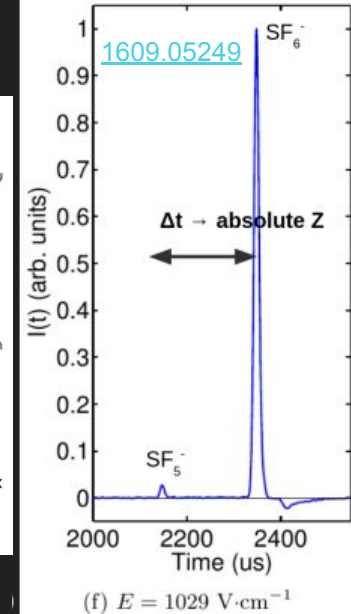
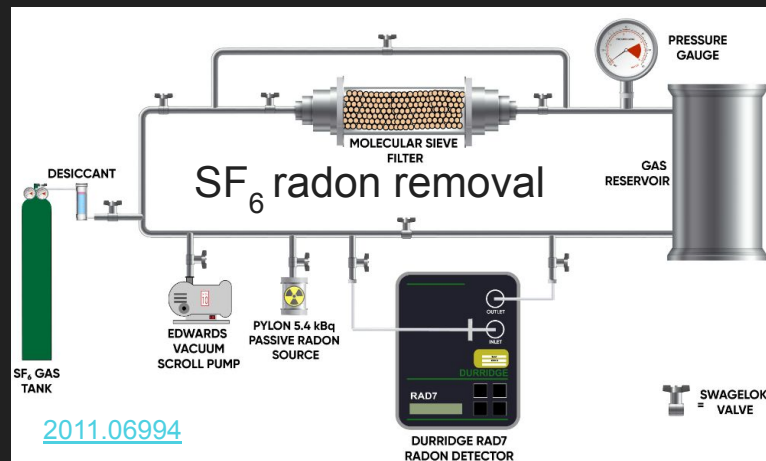
CYGNUS R&D: Negative Ion Gases

$\text{CS}_2 + \text{O}_2$, or SF_6 main focus

10^3 slower drift speeds
→ slower (cheaper) readout

Diffusion at thermal limit
→ larger volumes feasible

Minority carriers → fiducialisation

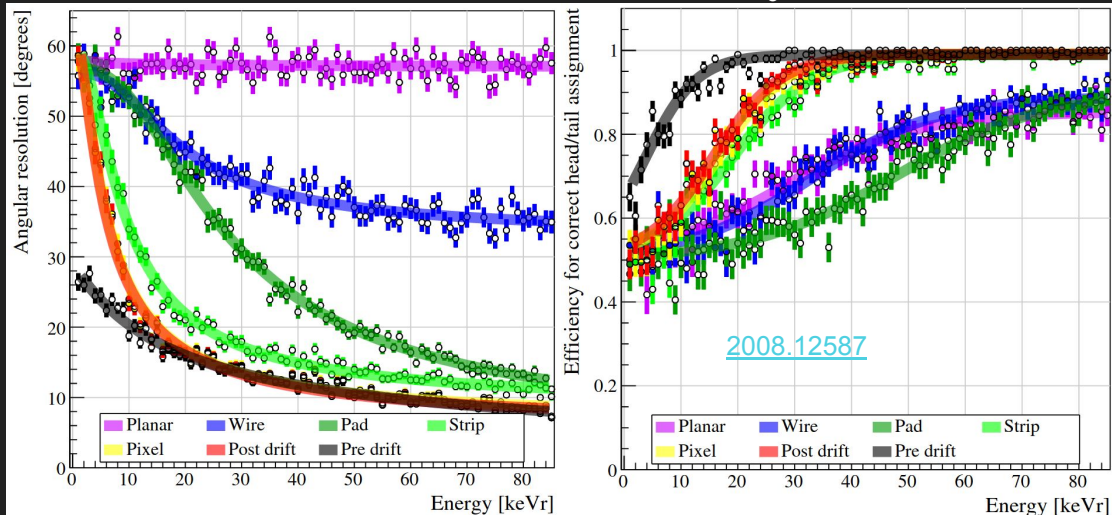


CYGNUS R&D: Micropatterned Readout

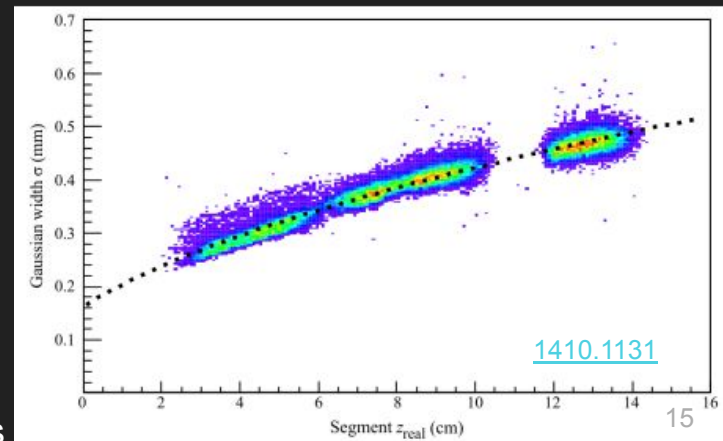
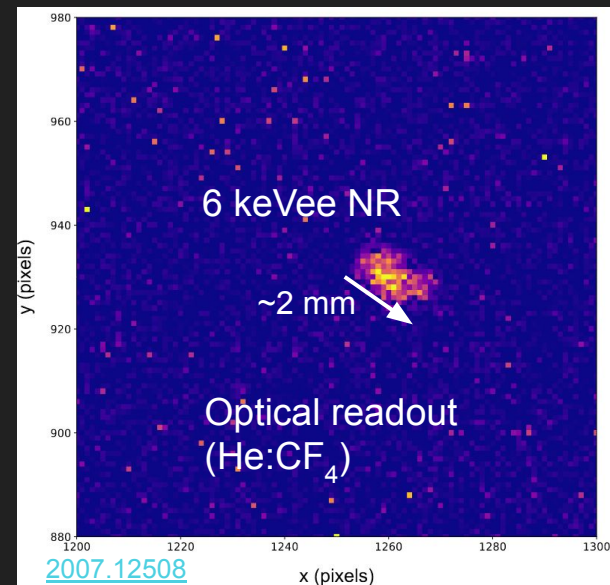
Required for 3D directionality and
particle ID/topological event information

Charge and optical readout options

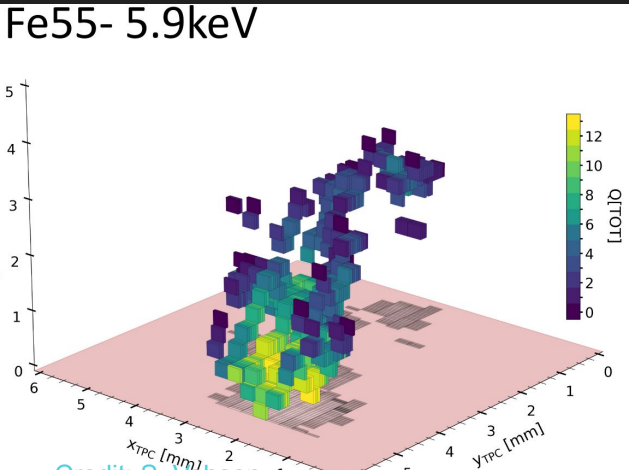
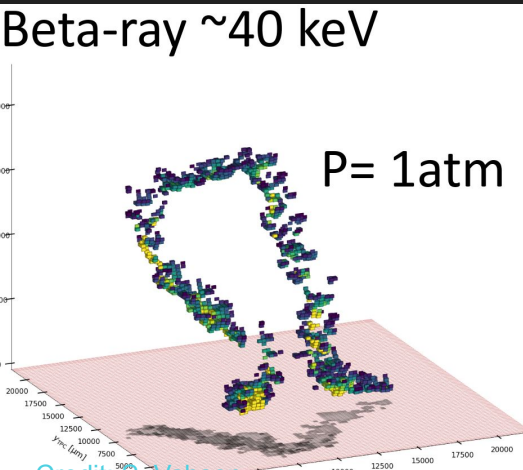
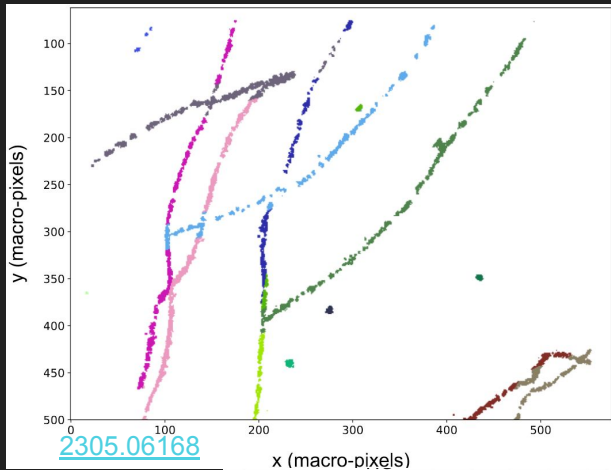
He recoils in 755:5 Torr He:SF₆



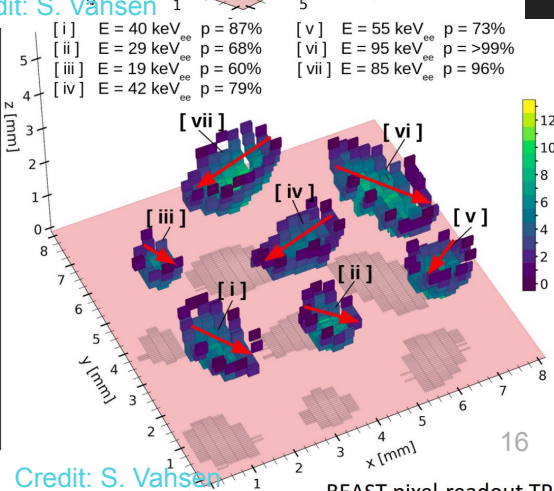
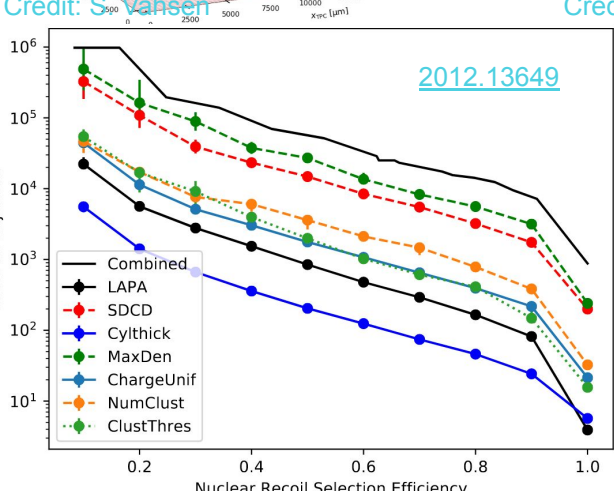
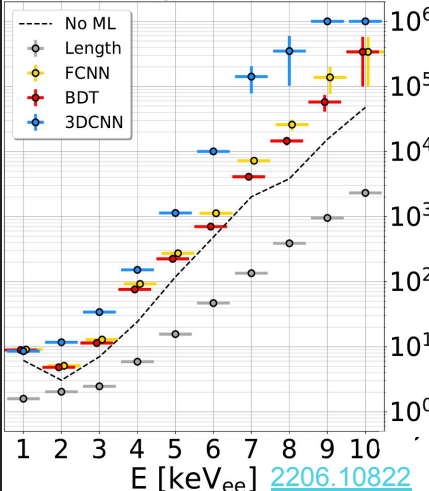
Alternate fiducialisation method:
transverse diffusion of drifting electrons



CYGNUS R&D: Data Challenges

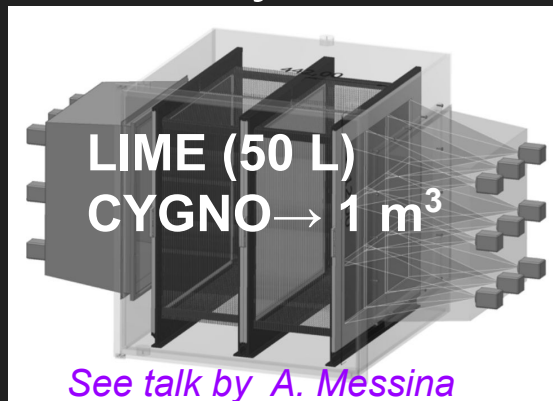


Rich data,
ripe for
ML-based
analyses

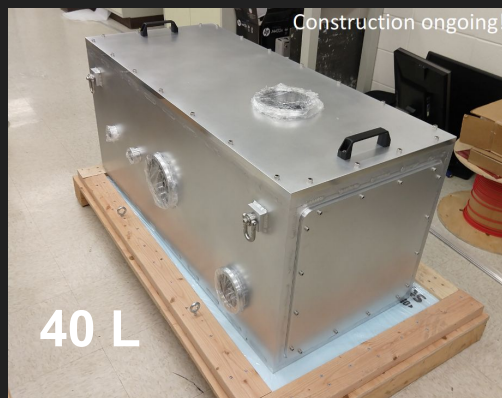


CYGNUS R&D: Status

Italy

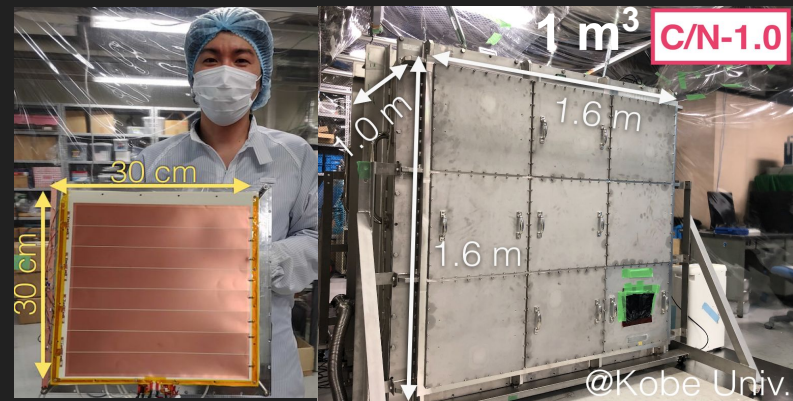


USA

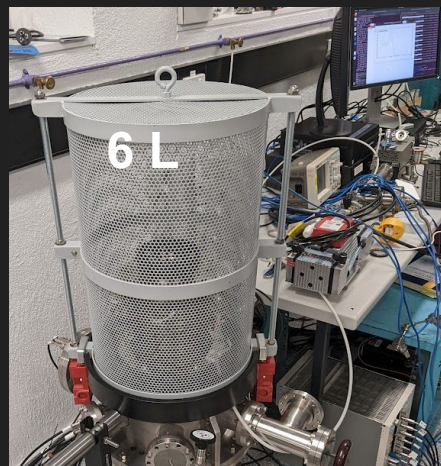
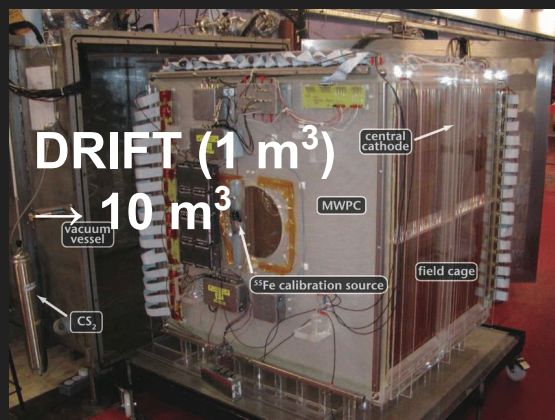


See talk by S. Higashino

Japan



UK



Australia

New formal collaboration:
CYGNUS-Oz, 20 members
4 institutions.

Conclusion

Directional TPCs are a promising platform for rare event DM/neutrino physics

R&D challenges remain, but scale-up appears feasible and is already beginning.



8th CYGNUS Workshop on Directional Recoil Detection

Sydney,
11-15 Dec 2023

Free registration!

<https://indico.cern.ch/event/cygnus2023>

- Directional detection of dark matter
- Directional neutrino detection
- Directional neutron detection
- Gas TPCs and MPGDs
- Novel directional detection technologies
- Recoil simulation tools
- Detection of rare nuclear decays

Physics case for a directional gas TPC

