CYGNUS-Oz development of directional dark matter detection capabilities using a gaseous time projection chamber

Ferdos Dastgiri, L.J. Bignell, L.J. McKie, P.C. McNamara, G.J. Lane, Z. Slavkovská, and V. Bashu (ANU)

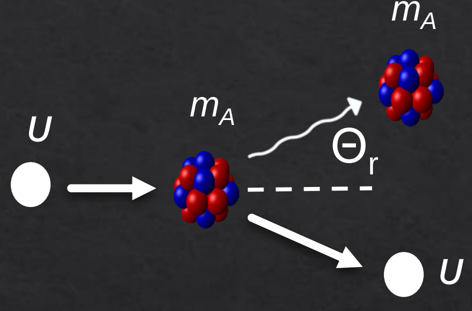
Dark Side of the Universe

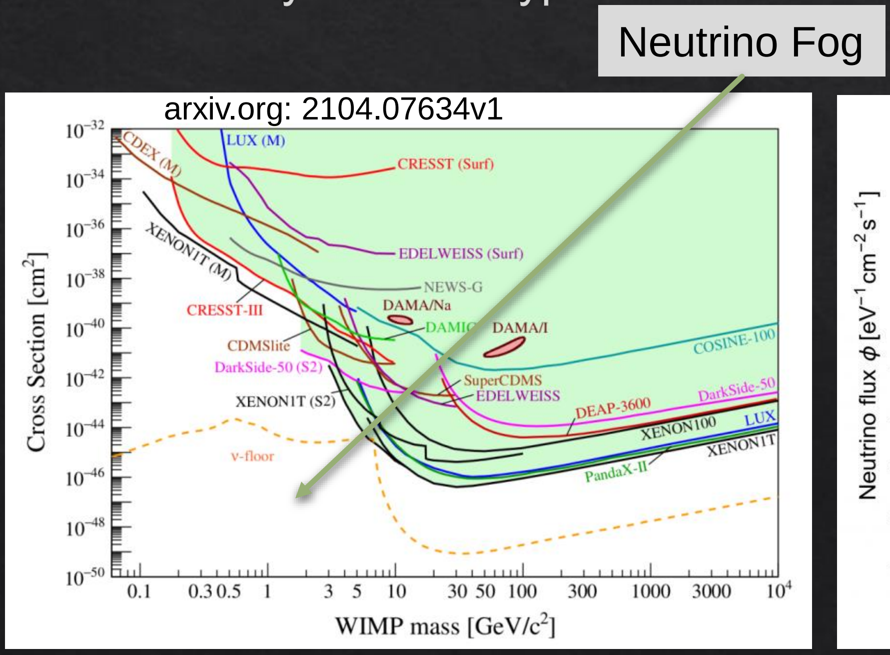
On behalf of Cygnus-Oz

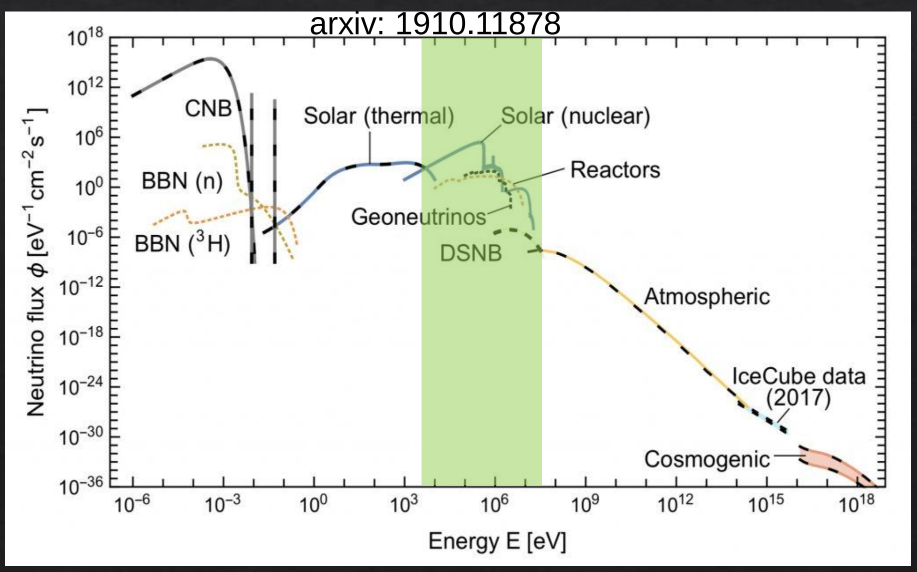
06 December 2022

Dark Matter case

- Next huge challenge: Coherent Elastic neutrino Nuclear Scattering (CEυNS)
  - Weakly interacting
  - Mimic WIMP signals
  - Many different types

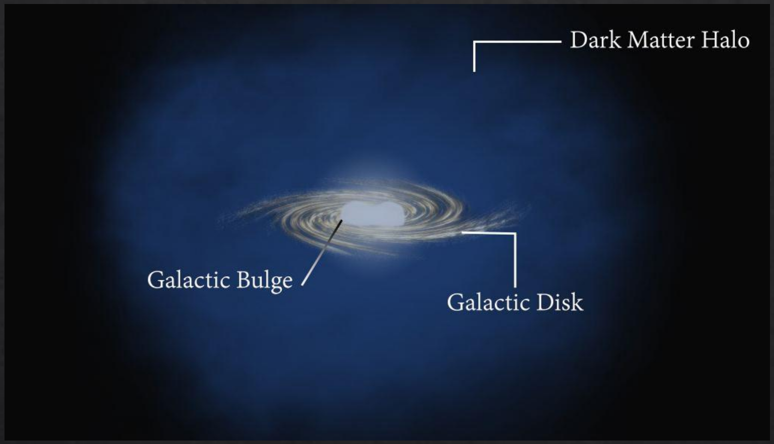




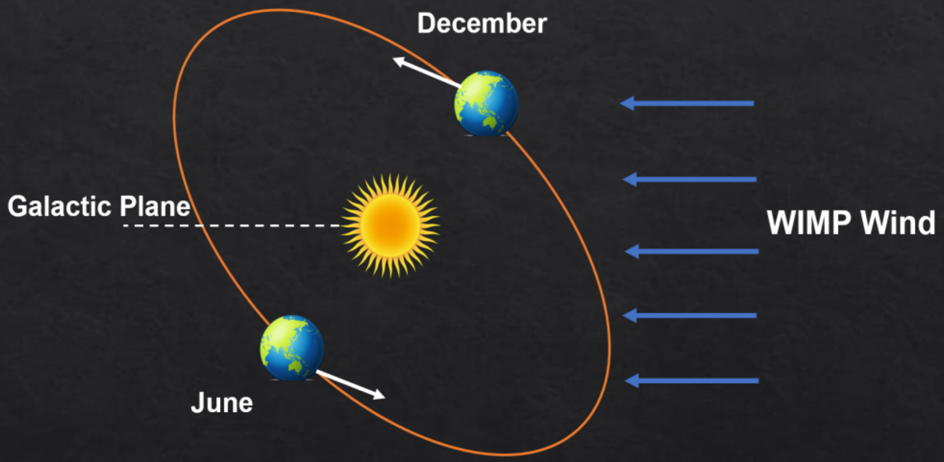


Galactic Halo Annual Modulation

- Modern cosmology of structure formation hypothesises a DM halo surrounds our galaxy
- Experiments classically look for annual modulation



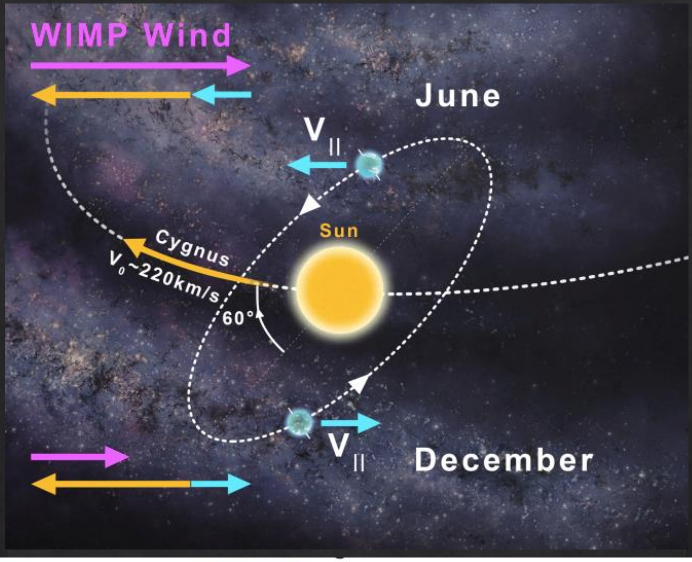
Credit: L Jaramillo and O Macias, Virginia Tech
https://www.universetoday.com/153460/stars-getting-kicked-out-of-the-milky-way-can-help-us-map-its-dark-matter-halo/

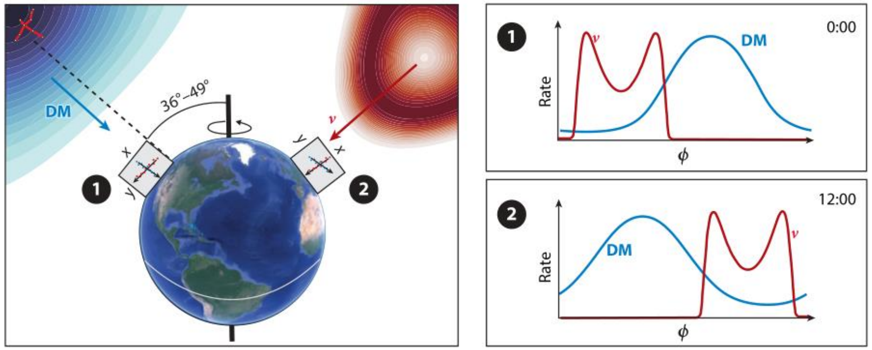


WIMP Wind peak in June – toward wind
WIMP Wind low in December – away from the wind

Directionality

- Average WIMP 'wind' originates from the Cygnus constellation.
- WIMP and neutrinos distinguished based on angle of recoil
  - Definitive DM WIMP signature
  - Look for neutrinos



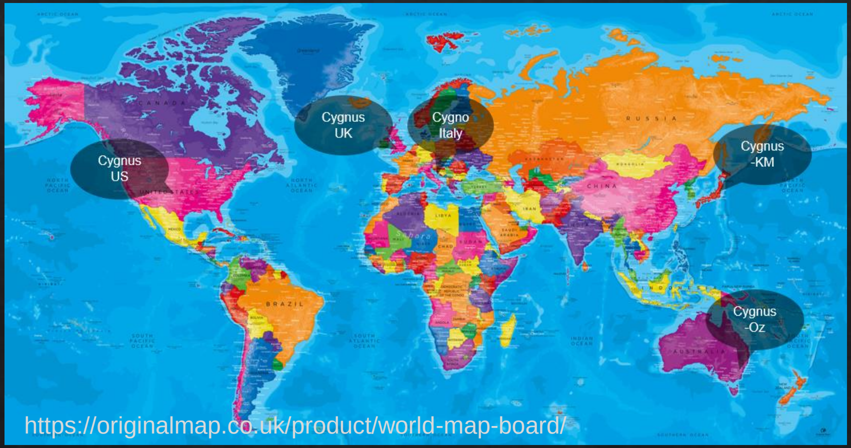


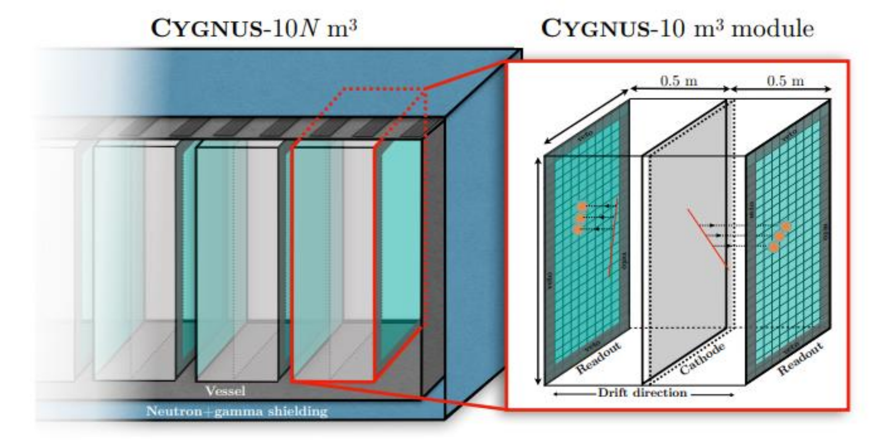
Diurnal modulation

arxiv: 2102.04596v2

CYGNUS Collaboration

- International collaboration for directional dark matter detection
  - Network of gas TPCs worldwide ~ 10 N m^3
  - US, UK, Italy, Japan and Australia





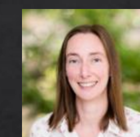
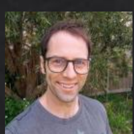
Vahsen, S. et al. arxiv: 2008.12587

CYGNUS-Oz Collaboration

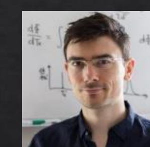
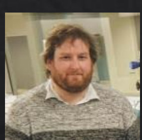
Australian National University | THE UNIVERSITY OF ADELAIDE AUSTRALIA | THE UNIVERSITY OF SYDNEY | THE UNIVERSITY OF MELBOURNE

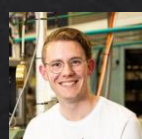
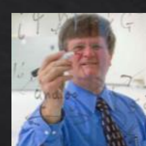


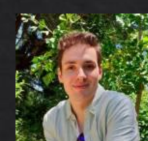






Institutional Board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CYGNUS-Oz Collaboration

Australian National University

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THE UNIVERSITY OF SYDNEY

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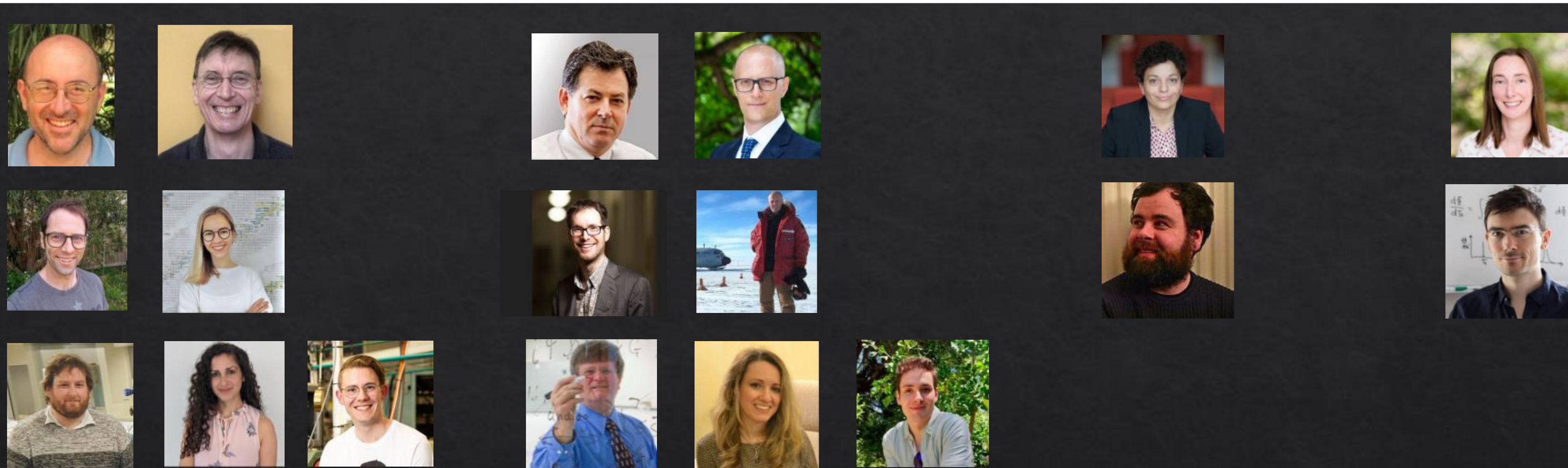
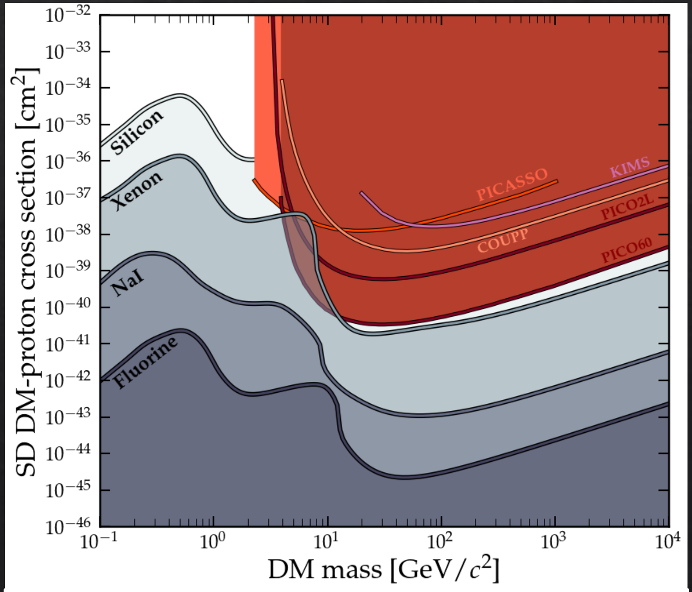


Working groups:

- Experiment
- Theory
- Simulation/Analysis

Case for Gas TPC

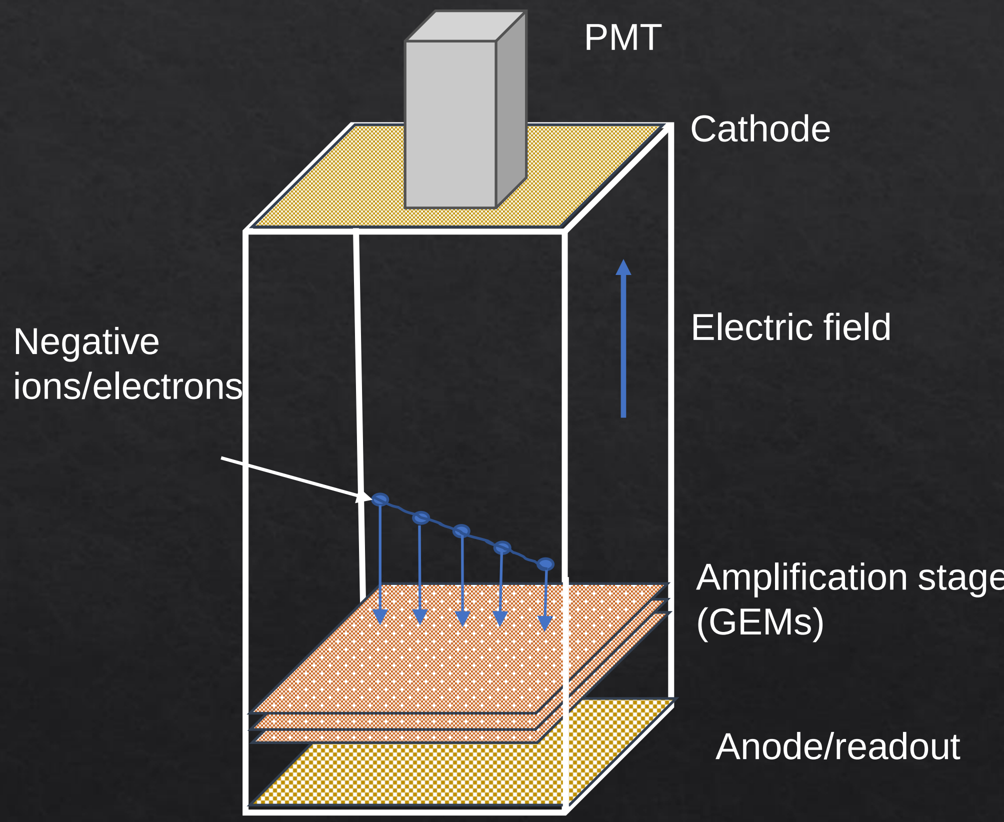
- Directionality to confirm WIMP signals
- Low threshold < 1 keV_{ee}
- Multitude of targets:
  - Set competitive spin-dependent sensitivity – 10 m^3
  - He target – low mass WIMP
- Background rejection capability
  - Electron Recoil vs Nuclear Recoil
- Neutrinos physics – ER/NR
  - 100 m^3 solar neutrinos NR
  - 10 m^3 solar neutrinos ER
- Measurement of Migdal effect
- Directional neutron detection



O'Hare, C. arXiv:2109.03116

Gaseous Time Projection Chamber (TPC)

- Measure ionisation
  - Nuclear recoil (NR) or Electron recoil (ER)
- Ionisation drifted by an applied electric field – experience **diffusion**



TPC Schematic

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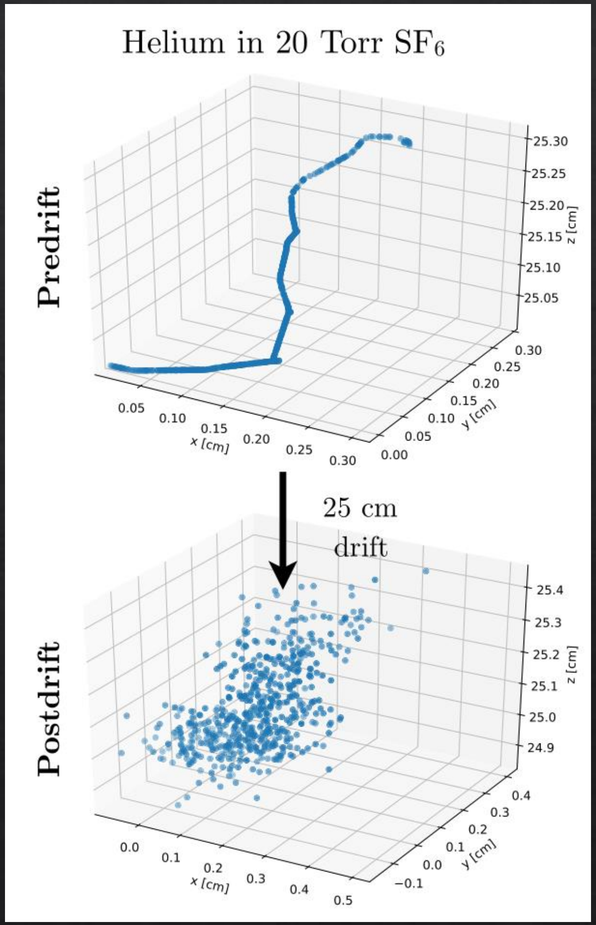

Vahsen, S. and O'Hare, C. arXiv:2008.12587

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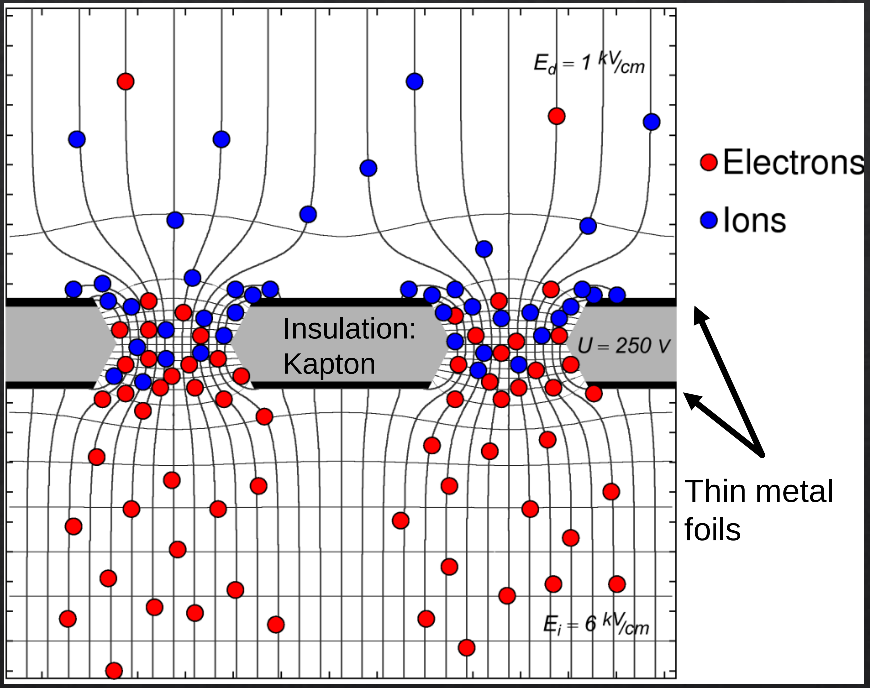

DESY: flc.desy.de/tpc/basics/gem/index_eng.html

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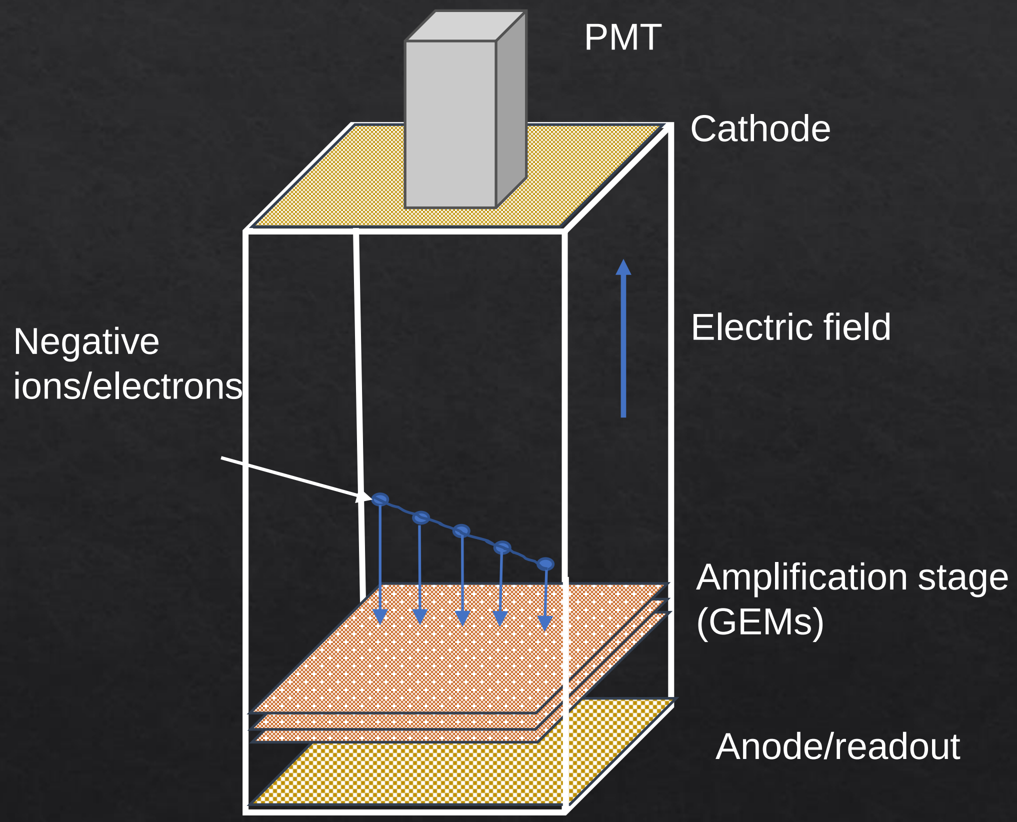
- 3D – calculate z by time of drift
- characteristics E_r and Θ_r



TPC Schematic

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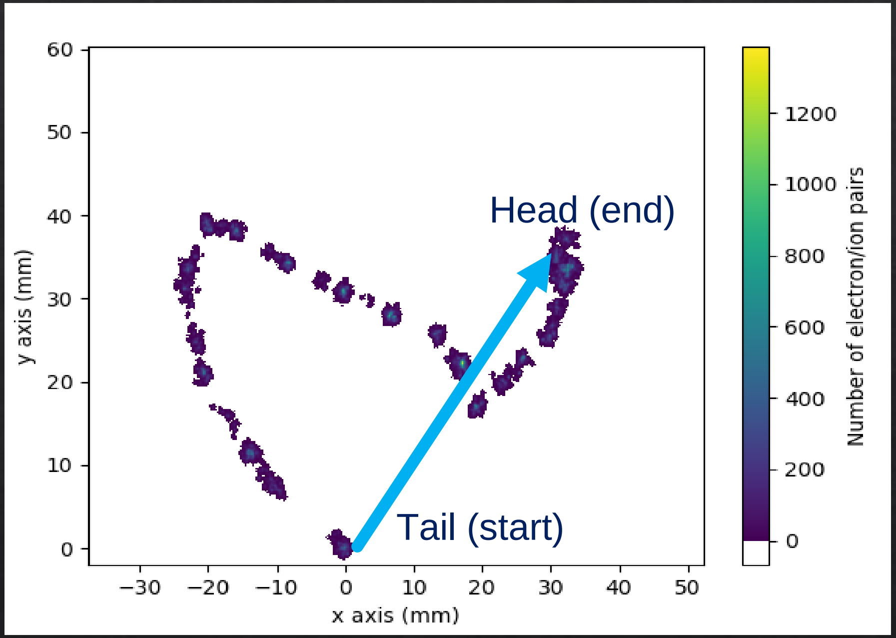
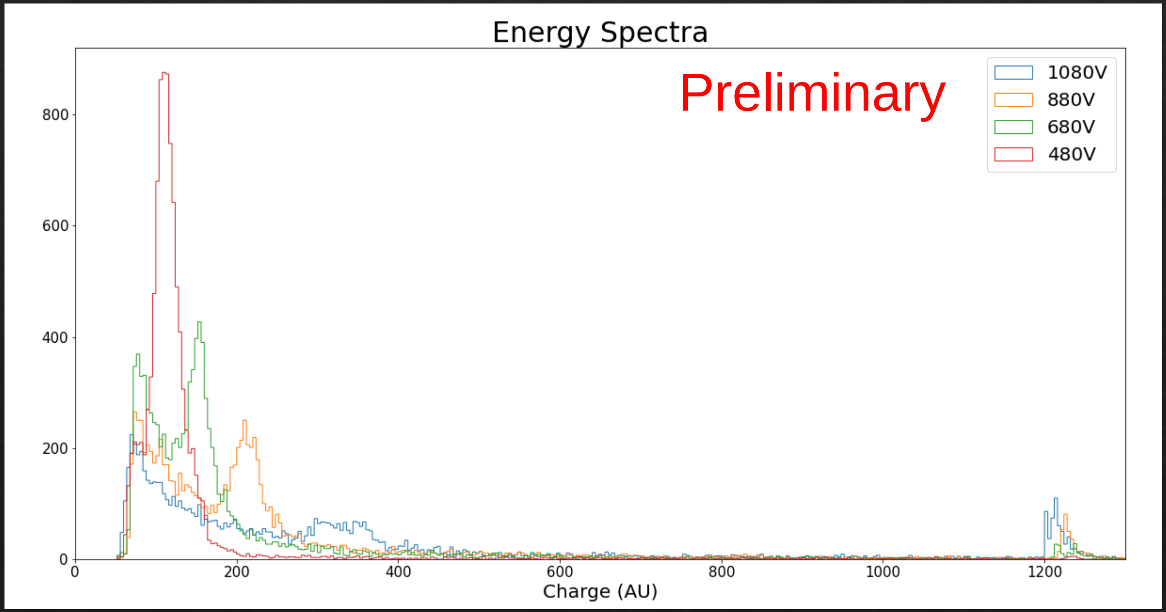
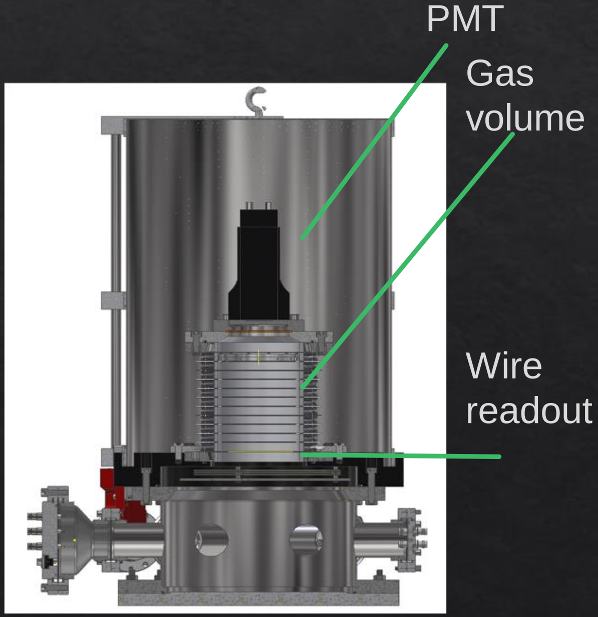
- characteristics E_r and Θ_r
- determine Head-Tail



Experiment: Detector Development

- 7 L Gas volume, Ar:CO_2
- Current measurements on wires, limited to α tracks
- Some setbacks: HV supply failure, DAQ, GEM failures





Credit: Thomas Tunningley, ANU

Experiment: Detector Development

- 7 L Gas volume, Ar:CO_2
- Current measurements on wires, limited to α tracks
- Some setbacks: HV supply failure, DAQ, GEM failures
- Challenge: optimisation of prototype

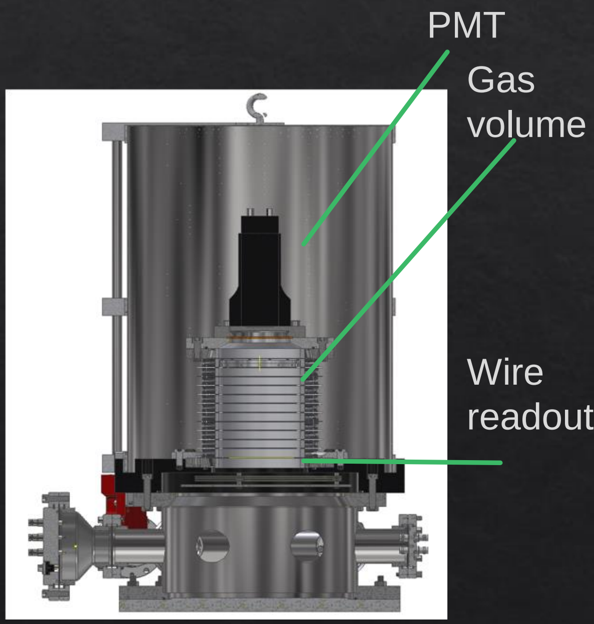
Detector set-up

Gas mixtures
Pressures
Electric field
Amplification
Readout
Reconstruction

↔

Optimise

Diffusion
Energy threshold
Angular resolution
Head/tail
Particle ID



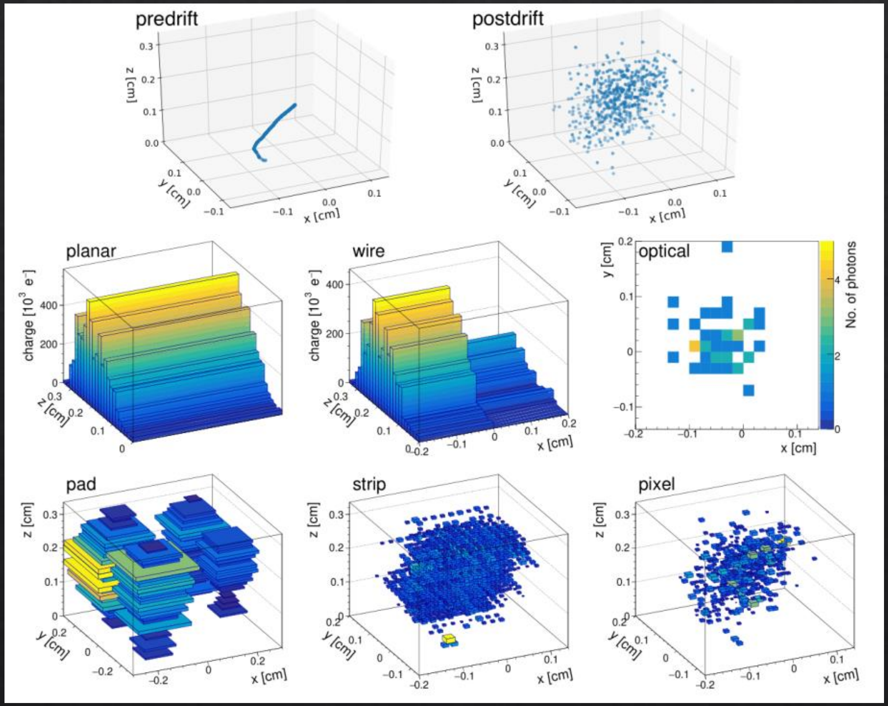
Credit: Thomas Tunningley, ANU

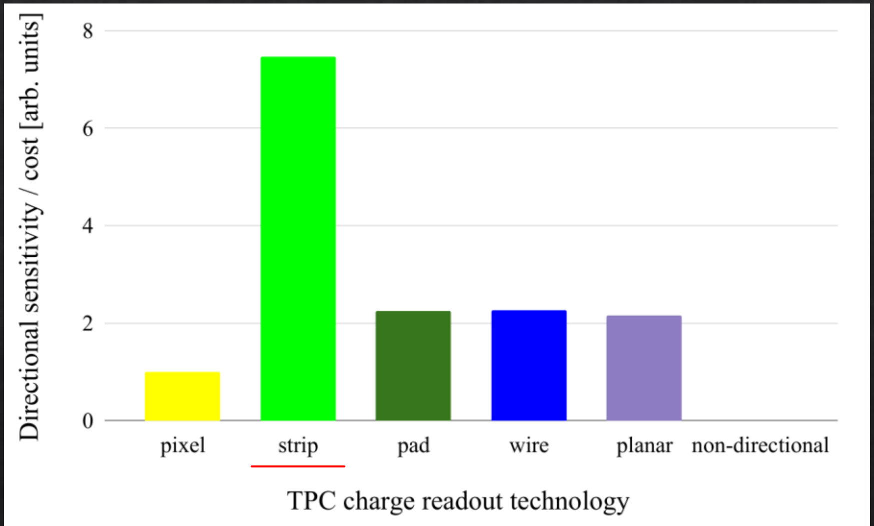
Detector Development

- Gas mixtures:
  - Maximise gain, minimise diffusion, lower recoil thresholds
  - Negative Ionising Drift gases
  - Optimal pressure to control diffusion and maximise track length (< atm)
  - Scintillation for PMT readout
- Optimise gain from GEMs

Detector Development

- Choose readout feasible in a large detector ($$)
  - Affects angular and energy resolution

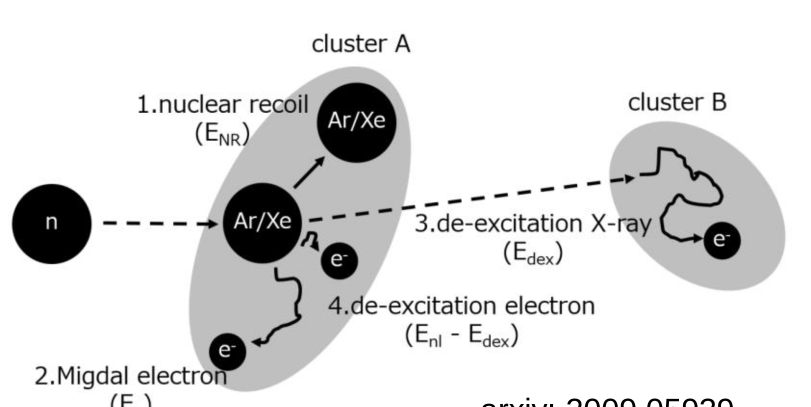




Vahsen, S. and O'Hare, C. arXiv:2008.12587

Theory

- CYGNUS WIMP Feasibility case (Vahsen, O'Hare, et al. in arxiv: 2008.12587)
- Migdal effect:
  - Theorised effect of nuclear recoil
  - Improve DM sensitivity at low masses
  - Studies in liquid TPC (Bell, et al. in arxiv: 2112.08514)
  - Extend this to gas TPC (such as arxiv: 2009.05939)



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  - Extend this to gas TPC (such as arxiv: 2009.05939)
- CYGNUS solar neutrino feasibility

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

S. E. Vahsen,[1] C. A. J. O'Hare,[2] W. A. Lynch,[3] N. J. C. Spooner,[3] E. Baracchini,[4,5,6] P. Barbeau,[7] J. B. R. Battat,[8] B. Crow,[1] C. Deaconu,[9] C. Eldridge,[3] A. C. Ezeribe,[3] M. Ghrear,[1] D. Loomba,[10] K. J. Mack,[11] K. Miuchi,[12] F. M. Mouton,[3] N. S. Phan,[13] K. Scholberg,[7] and T. N. Thorpe[1,6]

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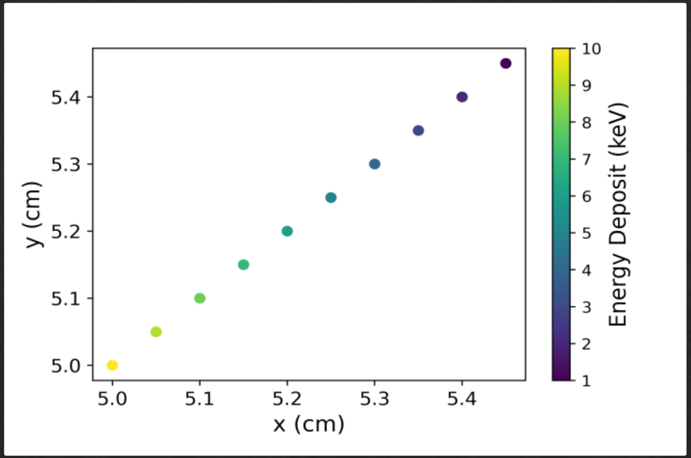
Observing the Migdal effect from nuclear recoils of neutral particles with liquid xenon and argon detectors

Nicole F. Bell, James B. Dent, Rafael F. Lang, Jayden L. Newstead, and Alexander C. Ritter
Phys. Rev. D **105**, 096015 – Published 17 May 2022

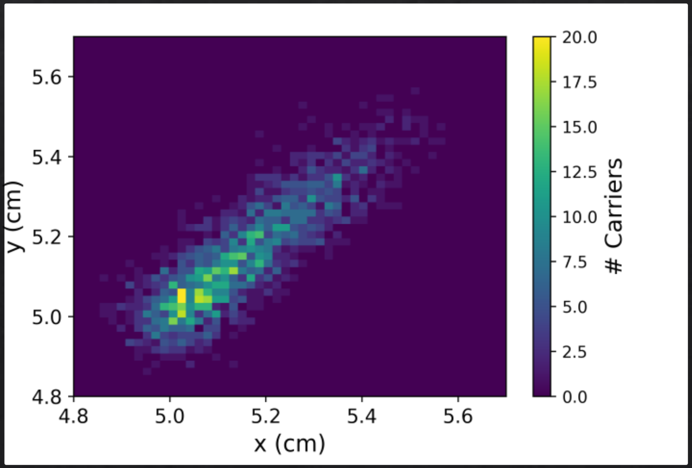
Simulations

- Aim to model ionisation, amplification and readout

1. Primary track generation
ER/ NR
GEANT4, HEED, etc



2. Drift and diffusion
Principles of charge transfer in gases



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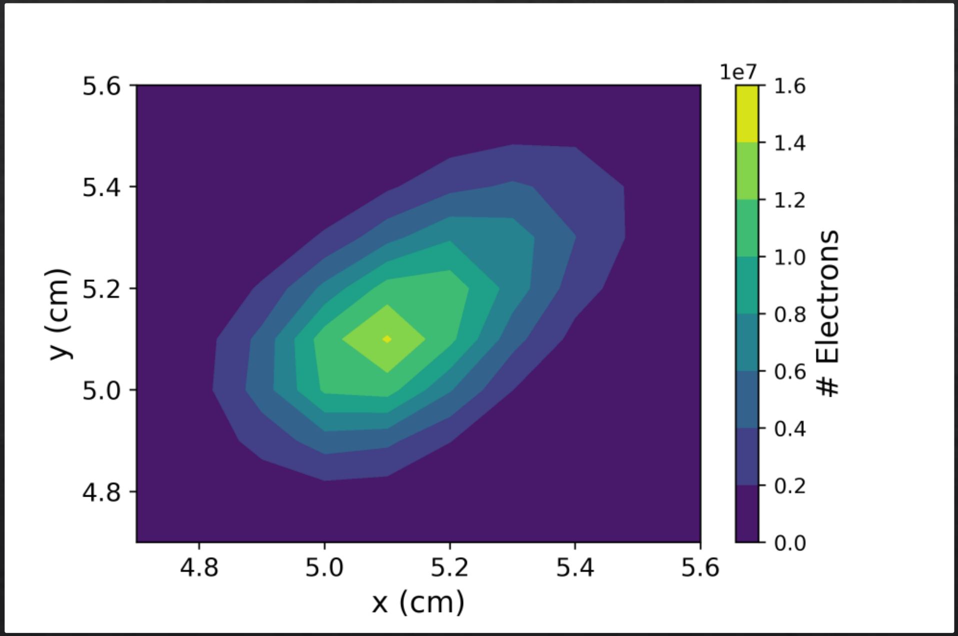
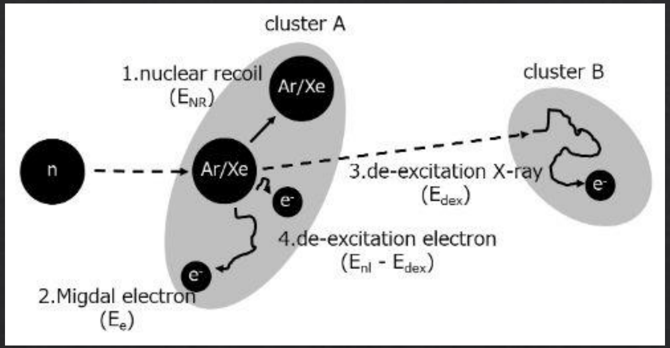
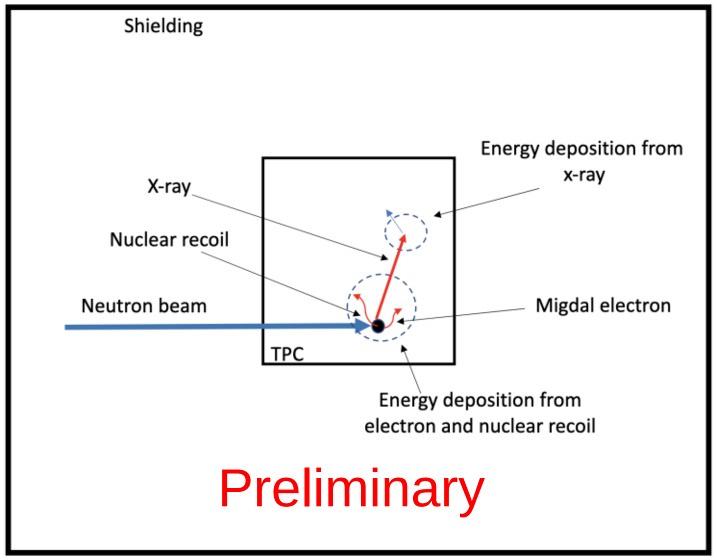
3. Amplification, diffusion and readout

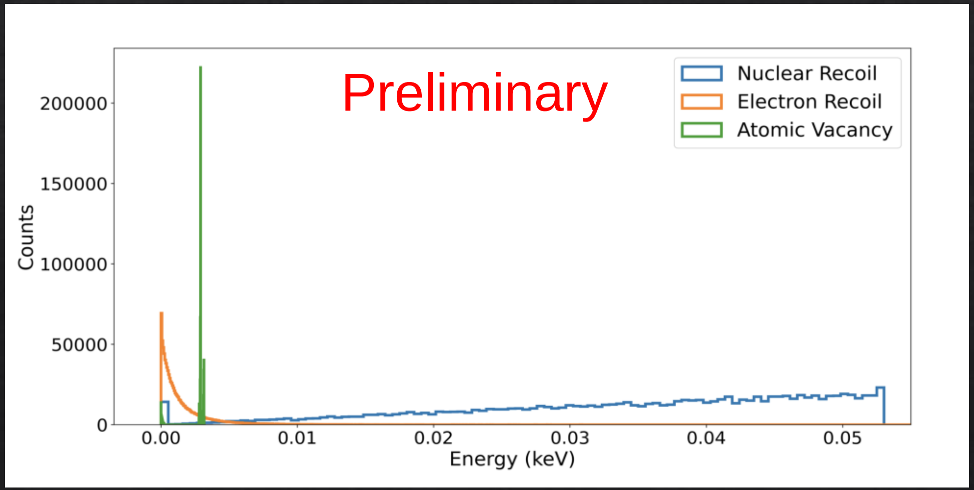


Simulations

- Migdal simulations
  - 1 atm Ar TPC
  - Generate three recoil species







Credit: Bashu, V. and Newstead, J.

Future

Detector

- CYGNUS-1 : upgrade gain stage, investigate optical readout. Take P < 1 atm measurements and add F target
- Possible experimental work at Adelaide
- Medium term : O(m^3) detector underground

Theory

- Solar neutrino case
- Electron Recoil feasibility
- Migdal physics in gas TPC development

Simulations/Reconstruction

- ANSYS detector electric field
- Head-tail reconstruction algorithms

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

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Australian National University

THE UNIVERSITY OF MELBOURNE

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THE UNIVERSITY OF SYDNEY

THE UNIVERSITY OF WESTERN AUSTRALIA

ANSTO

DST GROUP

INTERNATIONAL PARTNER ORGANISATIONS:

CALIFORNIA INSTITUTE OF TECHNOLOGY

INFN LNGS

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

UNIVERSITET STOCKHOLMS

UNI FREIBURG

UNIVERSITEIT VAN AMSTERDAM

The University Of Sheffield.

UNIVERSITY OF WASHINGTON

Back-up CYGNUS R&D

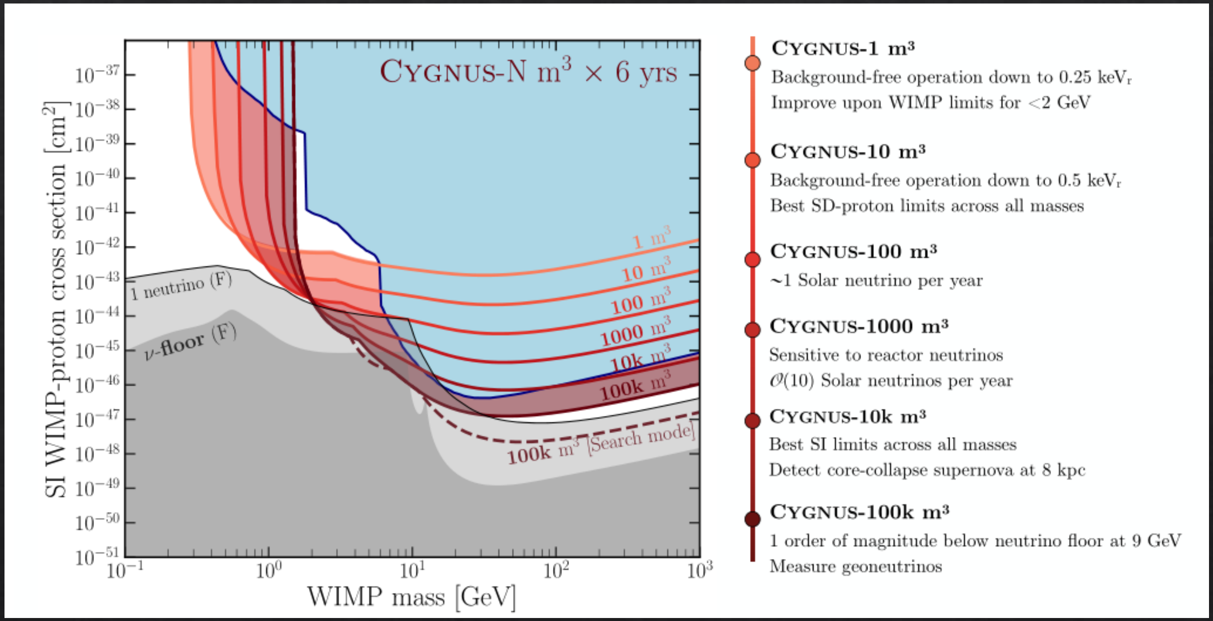
	Established readout & directionality	Established gas	R&D readout	R&D gas	Largest detector realised	Detector under development
DRIFT	MWPC 1.5 D	CS_2:CF_4:O_2 @ 0.05 bar	THGEM + wire/ micromegas	SF_6:(CF_4) @ 0.05 bar	1 m^3 (underground)	10 m^3 (under study)
NEWAGE	GEM + muPIC 3D	CF_4 @ 0.1 bar	GEM + muPIC	SF_6 @ 0.03 bar	0.04 m^3 (underground)	1 m^3 (vessel funded)
D^3/CYGNUS-HD	2 GEMs + pixels 3D	Ar/He:CO_2 @ 1 bar	Strip micromegas	He:CF_4:X @ 1 bar	0.0003 m^3	40 L + 1 m^3 (under construction)
New Mexico	THGEM + CCD 2D	CF_4 @ 0.13 bar	THGEM + CMOS	CF_4:CS_2/SF_6 @ 0.13 bar	0.000003 m^3	
CYGNO	3 GEMs + CMOS + PMT 2D + 1 D	He:CF_4 @ 1 bar	3 GEMs + CMOS + PMT	He:CF_4:SF_6 @ 0.8-1 bar	0.05 m^3 (underground)	0.4 m^3 (funded)
CYGNUS-OZ			3 GEMs + PMT + charge	He:CF_4:(SF_6) @ 0.05-0.1 bar		100 mL (funded)
CYGNUS			All of the above	Helium-Fluorine @ 1 bar		1000 m^3

Electron drift ***Negative ion drift*** ***Charge readout*** ***Optical readout***

Spooner, N. Annual CDM Meeting 2022.

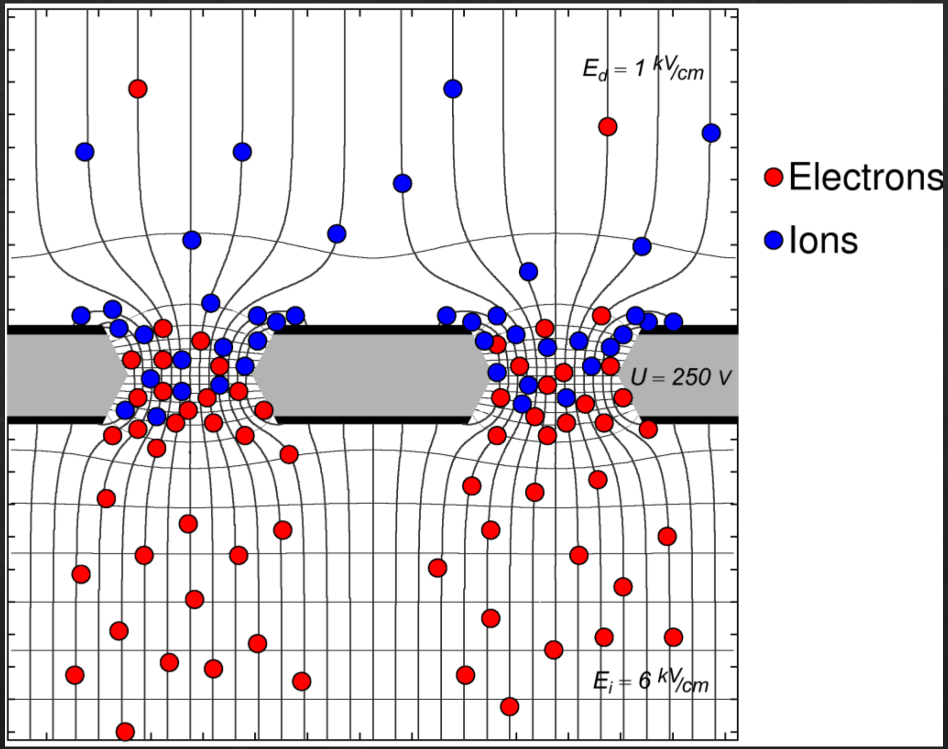
Expected Capability

- A 1000 m^3 detector should be able to see excess of O(10) nuclear recoils and O(100) electron recoil from solar neutrinos every year.
- Competitive with Borexino

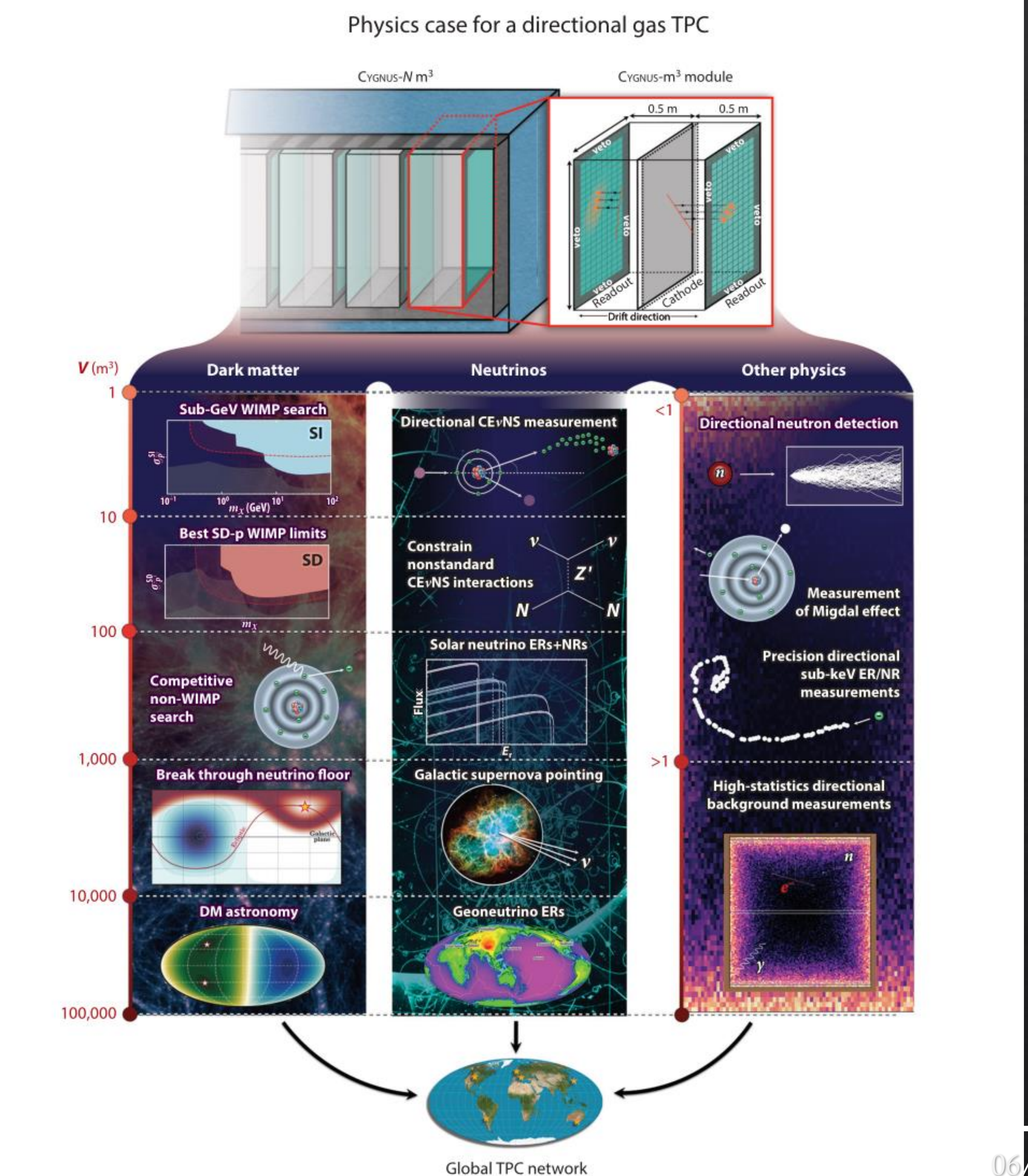


GEMs

1. Gas Electron Multipliers or GEMs – polymer foils with metal coating.
2. Create avalanche of electrons



DESY:
flc.desy.de/tpc/basics/gem/index_eng.html



Annu. Rev. Nucl. Part. Sci. 2021. 71:189–224

NID and Neutrinos

- Via neutrino-electron scattering, electron recoils allow probing of pp, pep, ^{7}Be and CNO.
- 1000 m^3 competitive with Borexino

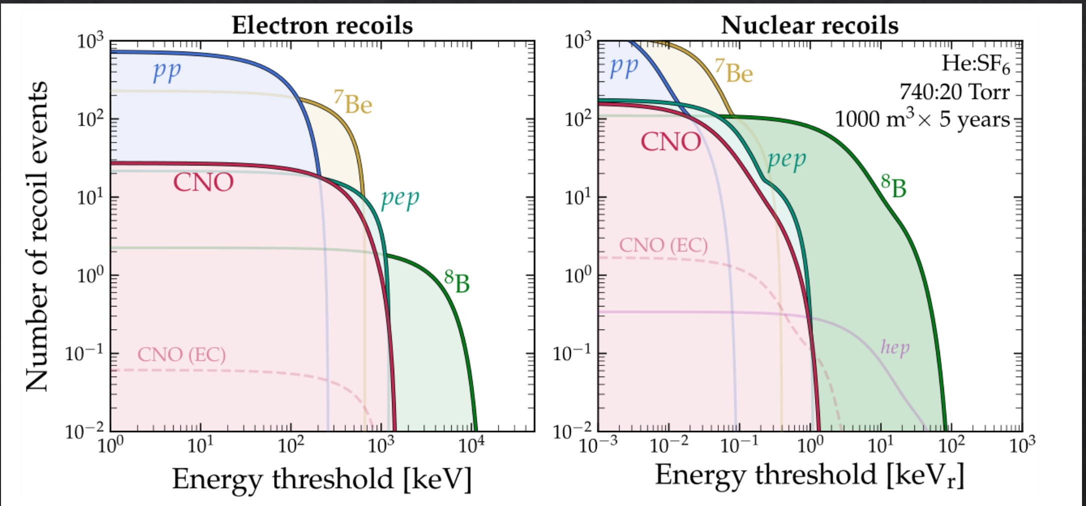


FIG. 3. Expected number of recoil events as a function of the energy threshold above which dR/dE_r is integrated. We show the rates for electron events on the left, and nuclear recoils on the right, both assuming a He:SF$_6$ gas mixture at 1 atmosphere, with a 740:20 pressure ratio. We assume a volume of 1000 m^3 and a total data-taking time of 5 years.

Credit C. O'Hare