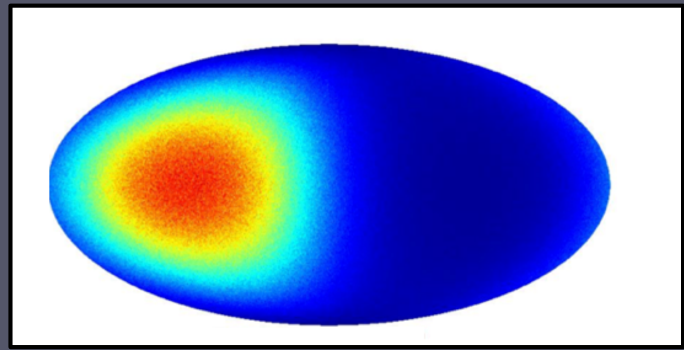
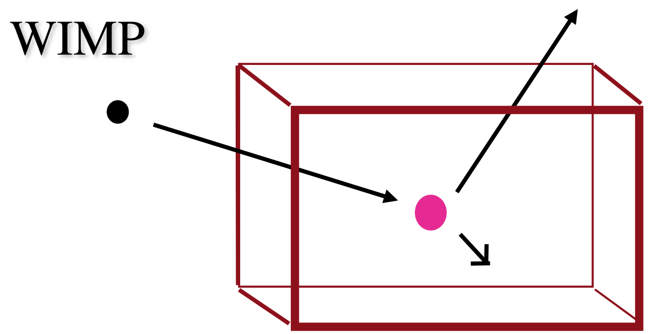
Dark Matter Directions

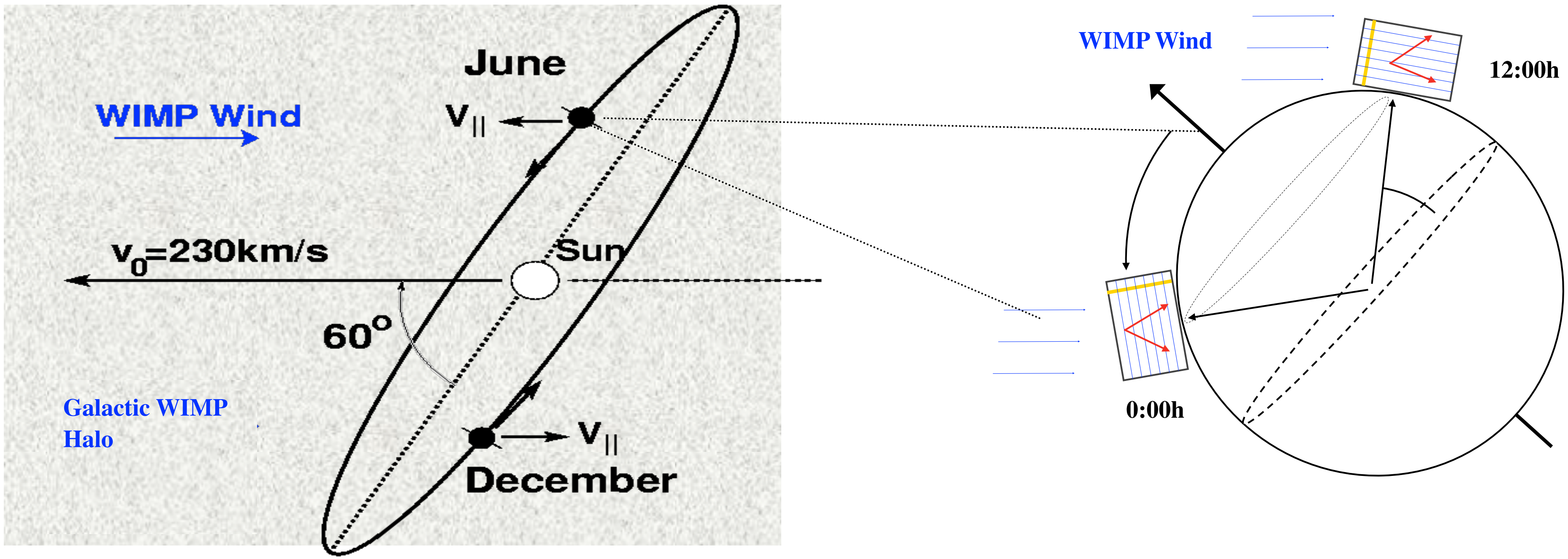


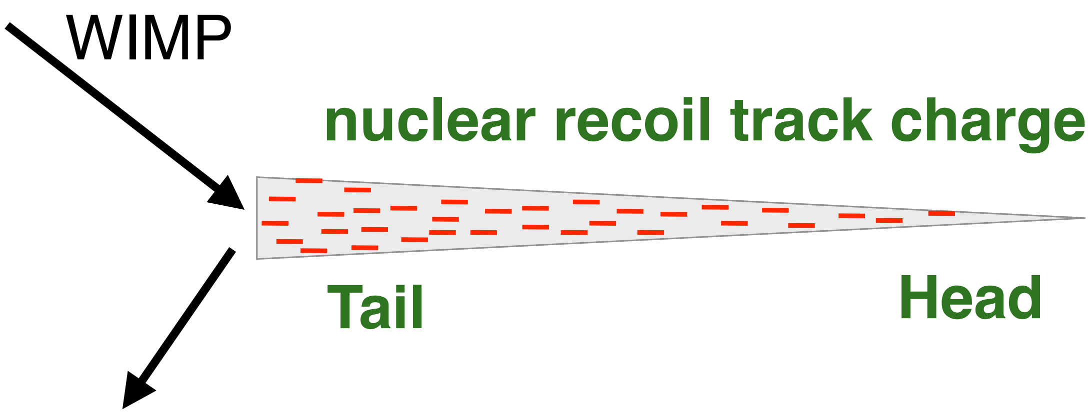
Neil Spooner, University of Sheffield

- Motivations for WIMP dark matter searches with directionality
- Historical perspectives, tactics, Boulby
- CYGNUS, scale-up studies and prospects



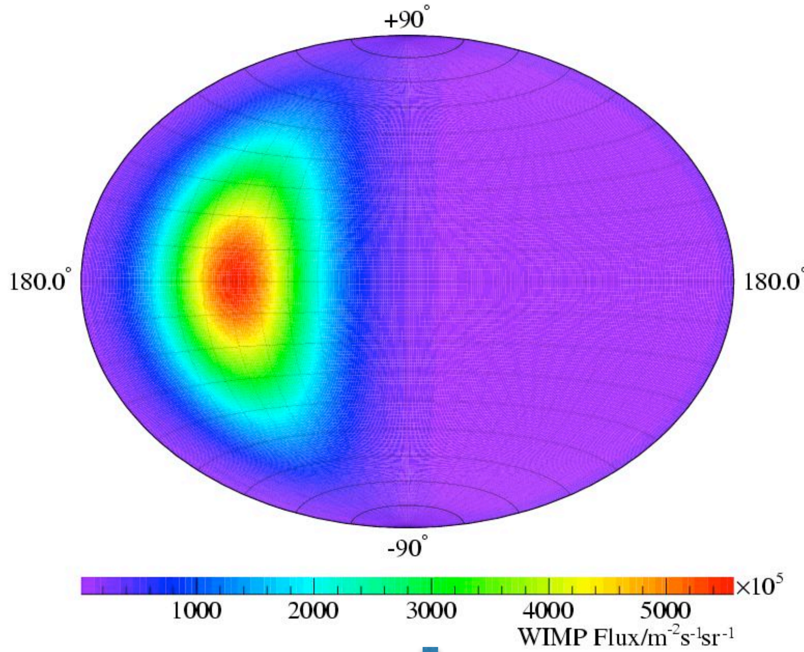
A Galactic Signal for DM!



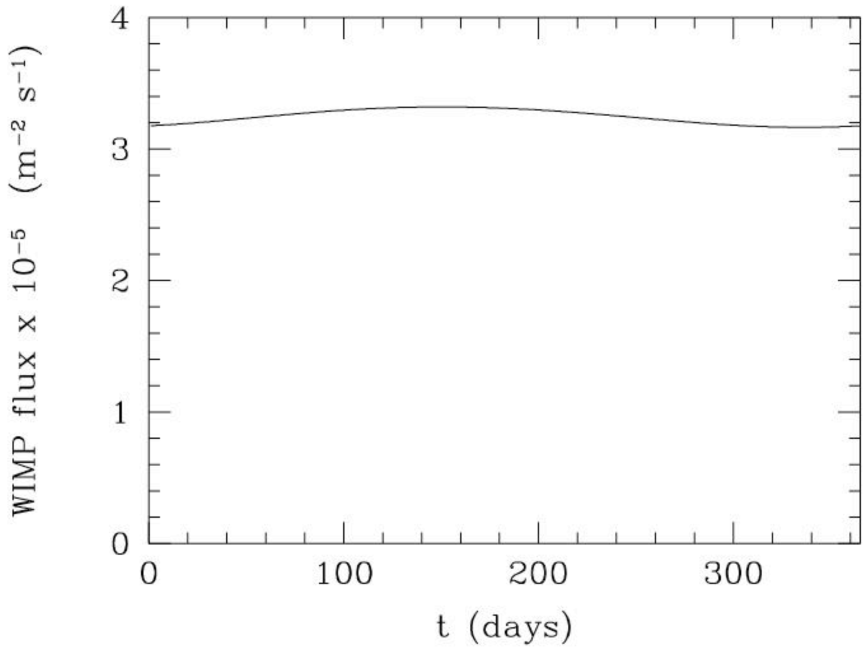


What Galactic Signature?
Directional vs. Annual Modulation

Directional signal



Annual modulation signal



Hard for a background to mimic the directional signal.

Signal could *(in principle)* be detected with of order 10 events.

Thresholdinos - it's "easy" to find DM

- Many examples of past experiments "finding" DM due to lack of information on events?

e.g. CDMS 2013

Silicon Detector Dark Matter Results from the Final Exposure of CDMS II

R. Agnese *et al.* (CDMS Collaboration)
Phys. Rev. Lett. **111**, 251301 – Published 16 December 2013

physicsworld

dark matter and energy

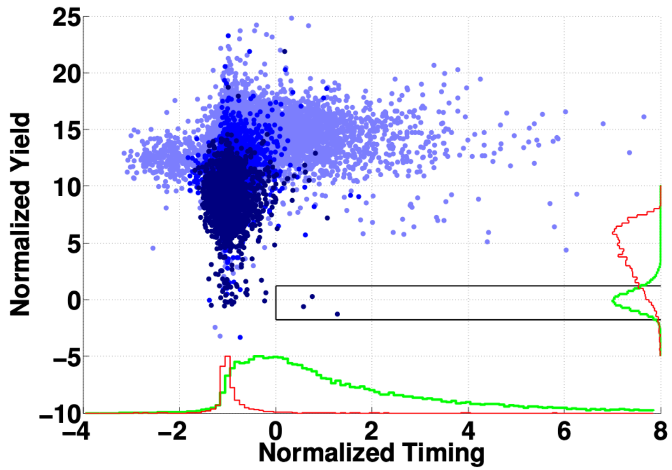
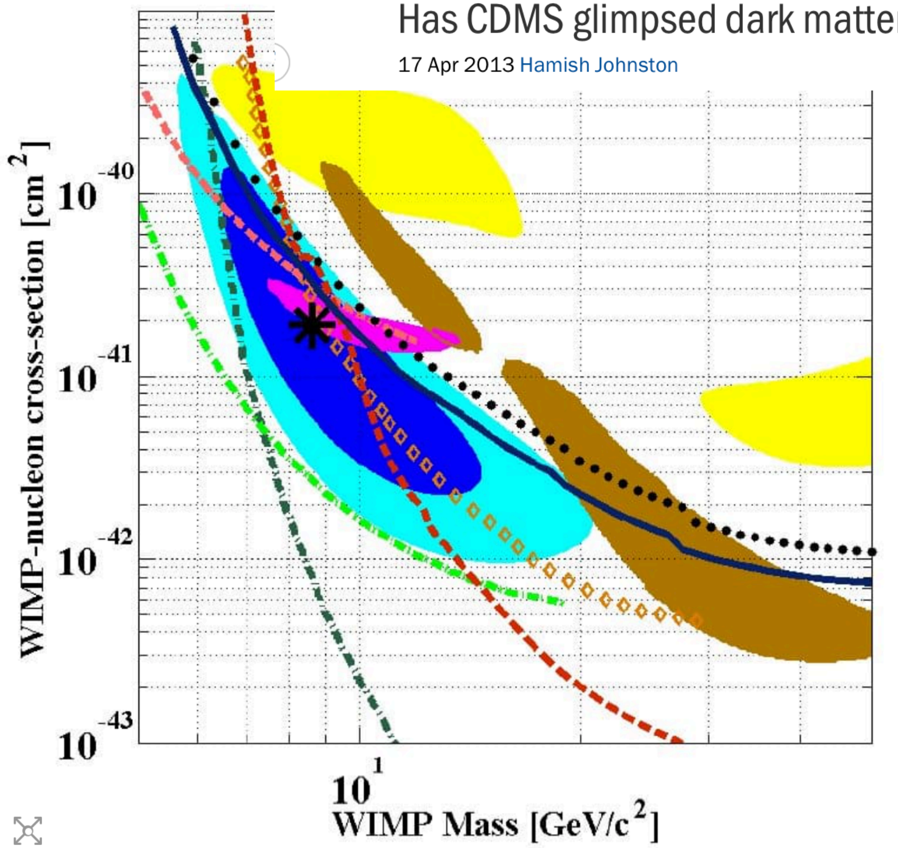


FIG. 3. Normalized ionization yield (standard deviations from the nuclear recoil band centroid) versus normalized phonon timing parameter (normalized such that the median of the surface event calibration sample is at -1 and the cut position is at 0) for events in all detectors from the WIMP-search data set passing all other selection criteria. The black box indicates the WIMP candidate selection region. The data are colored to indicate recoil energy ranges (dark to light) of 7–20, 20–30, and 30–100 keV. The thin red curves on the bottom and right axes are the histograms of surface events from ^{133}Ba calibration data, while the thicker green curves are the histograms of nuclear recoils from ^{252}Cf calibration data.

DARK MATTER AND ENERGY | BLOG

Has CDMS glimpsed dark matter?

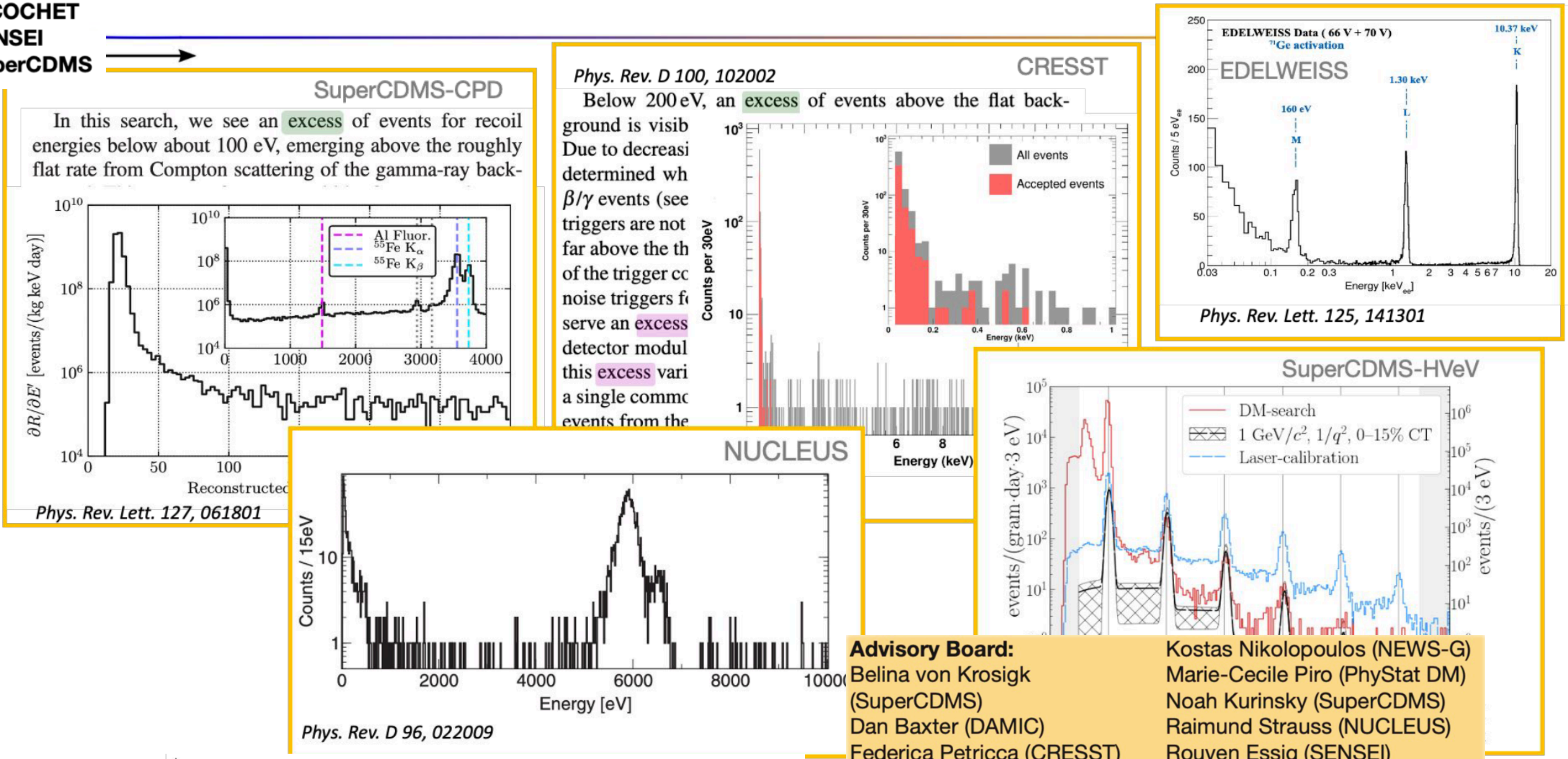
17 Apr 2013 Hamish Johnston



Latest Thresholdino Industry (2022)

CONNIE
CRESST
DAMIC
EDELWEISS
MINER
NEWS-G
NUCLEUS
RICOCHET
SENSEI
SuperCDMS

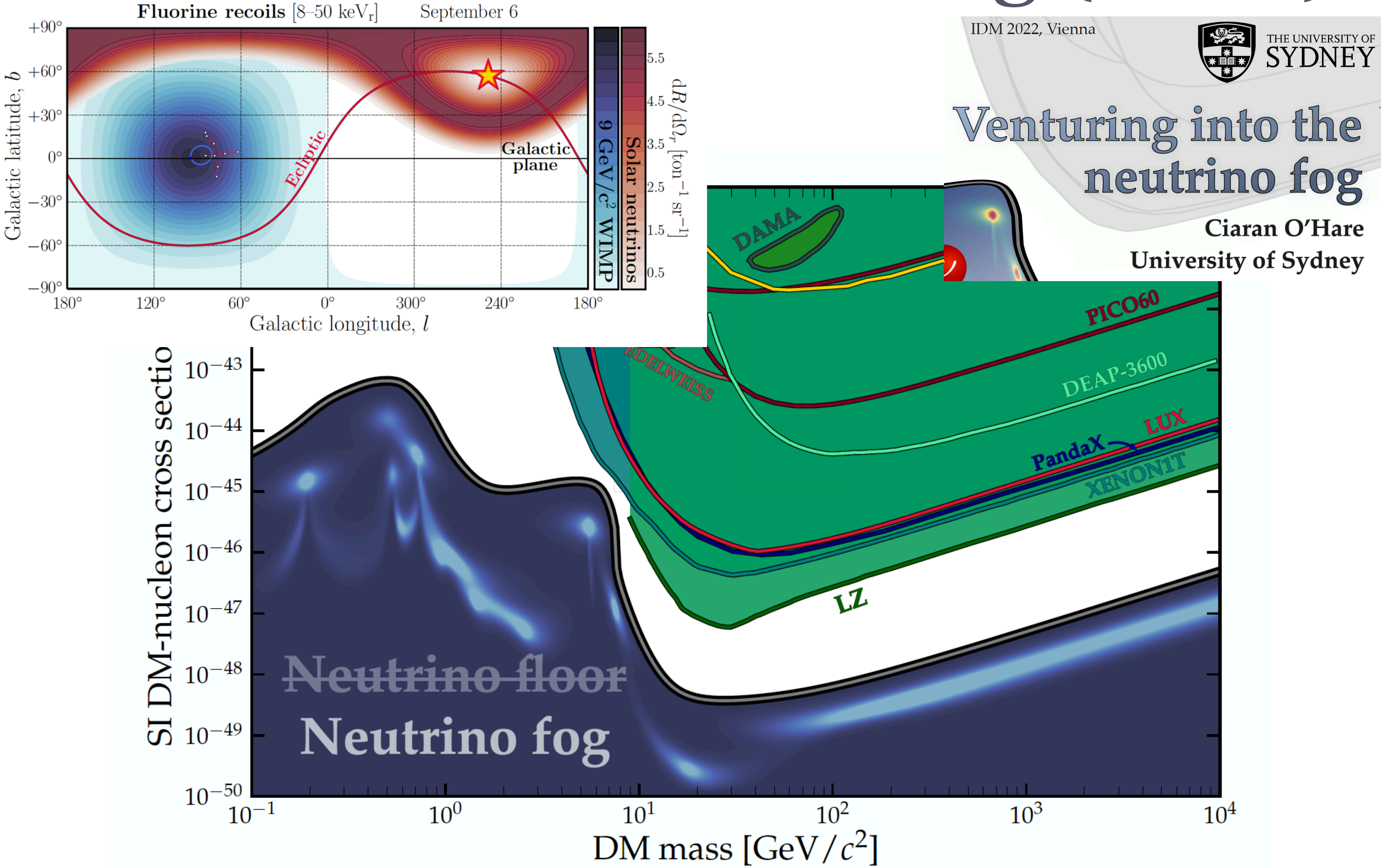
After reaching the sub-kev energy thresholds multiple solid-state experiments observe unexplained sharply rising event rates below a few hundred eV with various sensor technologies, different materials, above and below ground.



Advisory Board:
Belina von Krosigk (SuperCDMS)
Dan Baxter (DAMIC)
Federica Petricca (CRESST)
Guillaume Giroux (NEWS-G)
Guillermo Fernandez Moroni (CONNIE/Skipper-CCD)
Jules Gascon (EDELWEISS)
Julien Billard (RICOCHET)
Kostas Nikolopoulos (NEWS-G)
Marie-Cecile Piro (PhyStat DM)
Noah Kurinsky (SuperCDMS)
Raimund Strauss (NUCLEUS)
Rouven Essig (SENSEI)
Rupak Mahapatra (MINER)
Vasile Ghete (NUCLEUS)

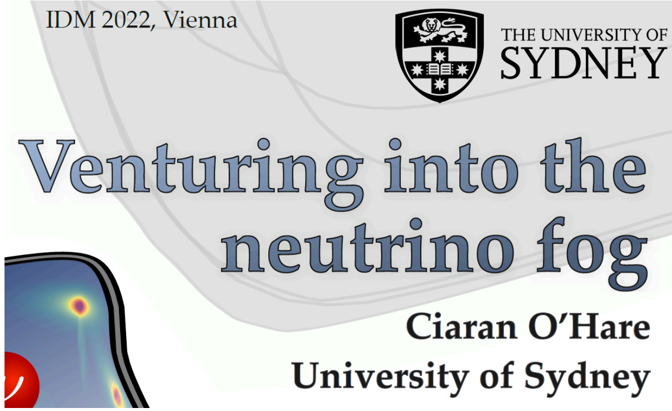
EXCESS workshop 2021

Into the Neutrino Fog (2022)



What's needed (IDM2022)?

- IDM2022 - Ciaran O'Hare...



How to venture into the neutrino fog:

5 methods, ordered (sort of) in increasing effectiveness

~~1. Detect *a lot* of events~~

~~2. Use annual modulation~~ ← Not really good enough

~~3. Have multiple target nuclei~~

4. Improve neutrino flux measurements ← Good, but not up to us

5. Use directional detectors

What is required to clear the neutrino fog?

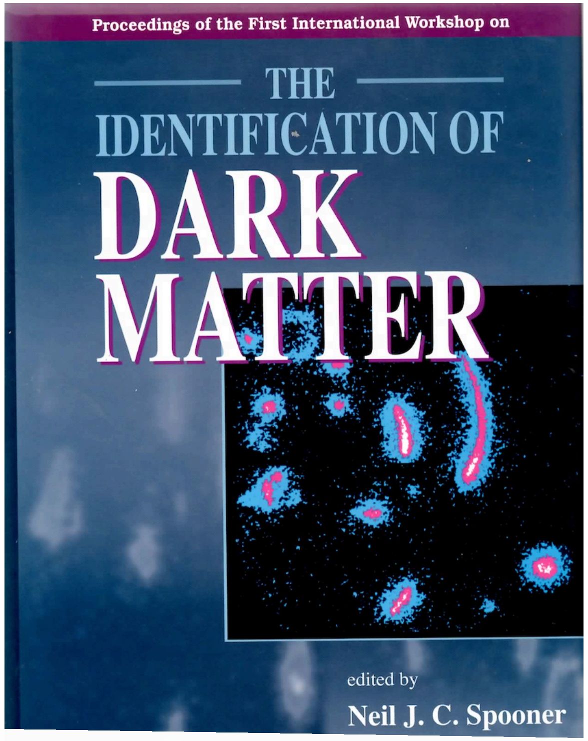
(see our review [2102.04596] and Snowmass WP [2203.05914] for reasoning)

- Angular resolution **<30°**
- Correct head / tail **>75%** of the time
- Fractional energy resolution < **20%**

} If you don't achieve these then directionality adds nothing to the sensitivity (in the context of the ν fog)

Directional Ideas - IDM1996

- Several concepts explored in early 1990's



Participants in the International Conference on the Identification of Dark Matter
Sheffield, 8–12 September, 1996

Session C3b: WIMP Detectors — Prospects for Directional Sensitivity

Directional Ideas - 1996

- Superfluid He
- Gas TPC (with CCD)
- Anisotropic scintillator

RECOIL DIRECTION SENSITIVITY IN A SUPERFLUID HELIUM PARTICLE DETECTOR

J.S. ADAMS, S.R. BANDLER[1], R.E. LANOU, H.J. MARIS, T. MORE[2], G.M. SEIDEL
Department of Physics, Brown University, Providence, RI 02912, USA

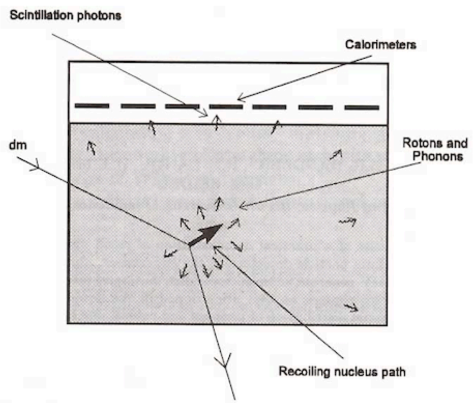


Figure 1: Schematic arrangement for detection of dark matter using superfluid helium.

LOW-PRESSURE TPC FOR DARK MATTER SEARCHES: FUTURE DIRECTIONS

K.N. BUCKLAND, M.J. LEHNER, G.E. MASEK
UCSD Dept. of Physics, La Jolla, CA 92093-0319 USA

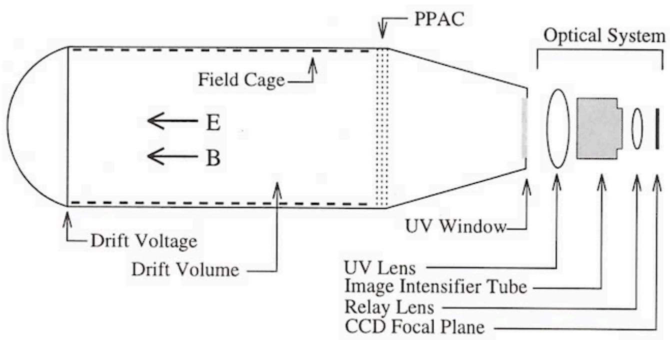
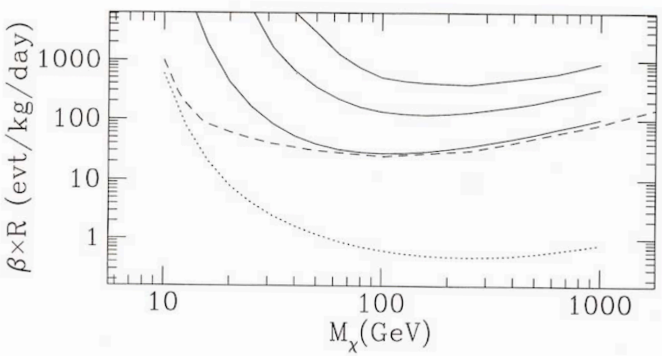


Figure 1: Schematic view of the optically imaged low pressure TPC system. The superconducting magnet which contains the detector is not shown.



MEASUREMENTS OF CARBON RECOIL SCINTILLATION EFFICIENCY AND ANISOTROPY IN STILBENE FOR WIMP SEARCHES WITH DIRECTION SENSITIVITY

N.J.C.SPOONER, J.W.ROBERTS, D.R.TOVEY
Department of Physics, University of Sheffield, Hicks Building, Hounsfield Road, Sheffield S3 7RH

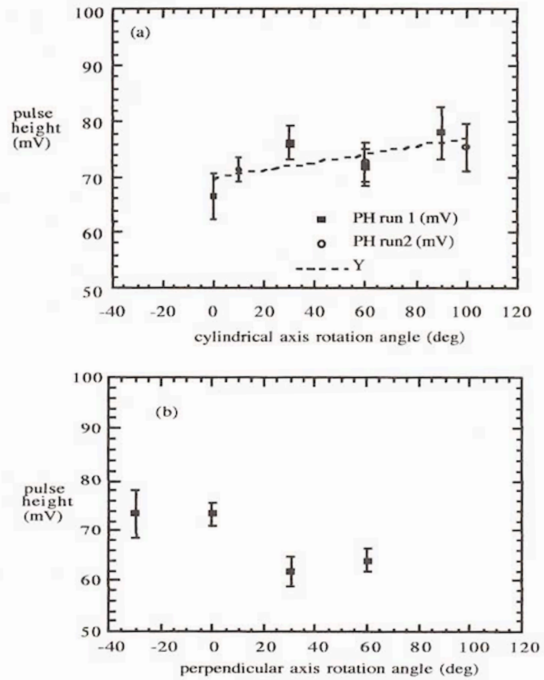


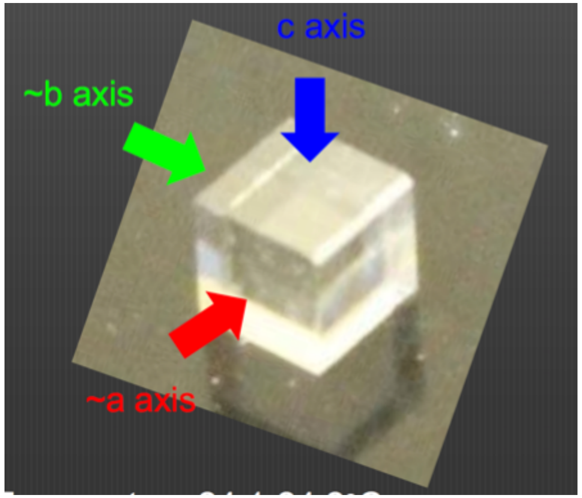
Figure 3: Relative carbon recoil scintillation efficiency taken at 48 keV recoil energy vs. crystal orientation for (a) rotation about the cylindrical axis and (b) rotation about the perpendicular axis.

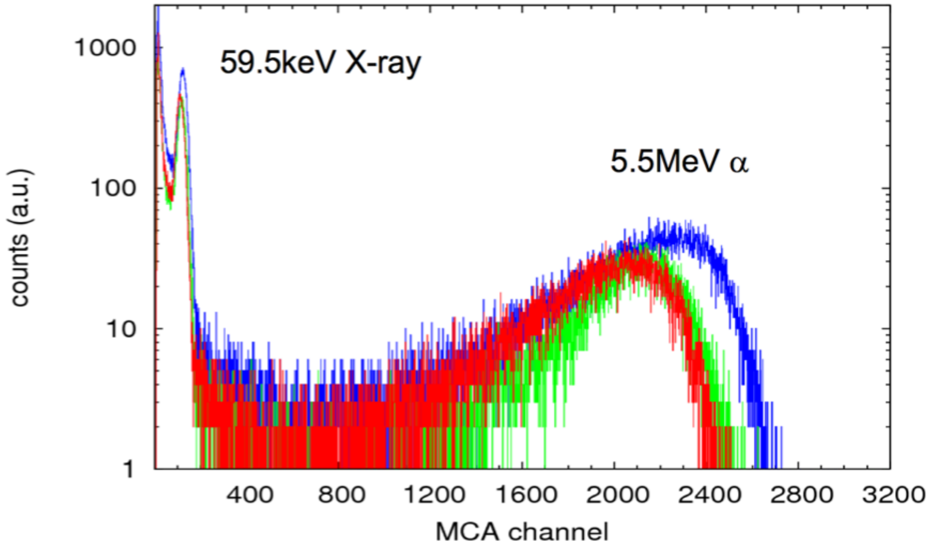
- Problems: too complex, scalability, mass, surface area, quench factor/poor directionality....

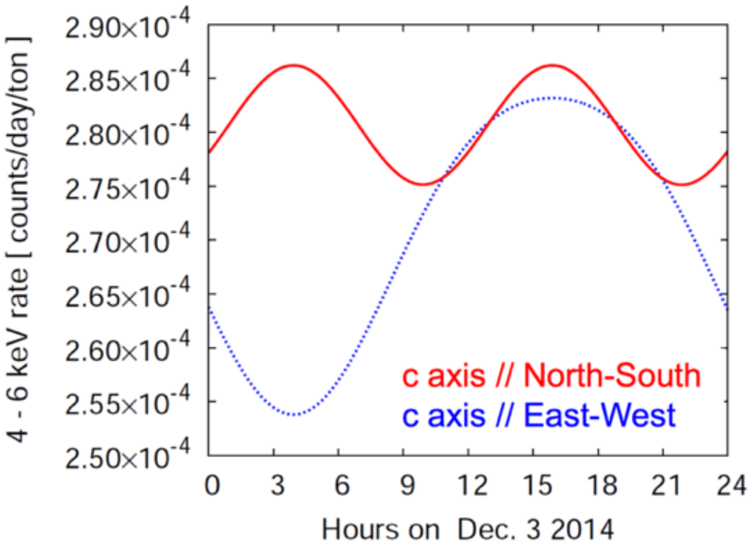
Anisotropic ZnWO4 (ICRR)

Hiroyuki Sekiya et al, ICRR, IMR…

- Look for directional asymmetry in light output







- 12% difference in alpha peaks vs direction
- Signal prediction (10 tons, 1000 days) assumes 7% difference at 5 keV

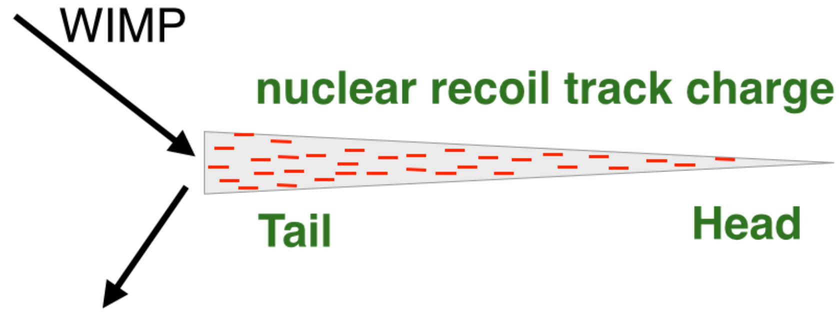
Challenges:

- Low energy response not known
- Backgrounds
- **No head-tail**

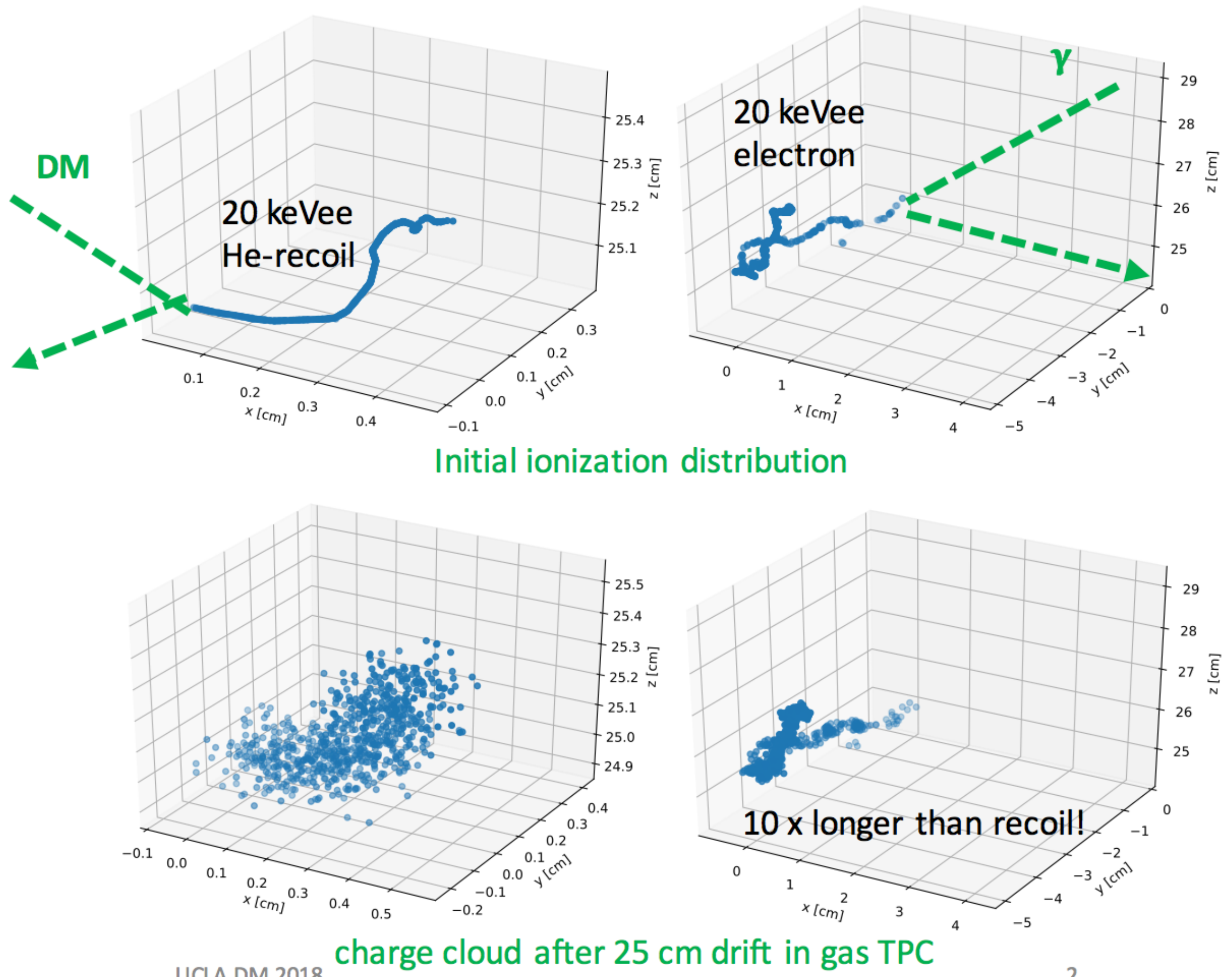
see also **F. Cappella et al. (DAMA)** and others…

Gas TPC offers detailed information

- Measure spatial ionisation distribution resulting from nuclear recoils



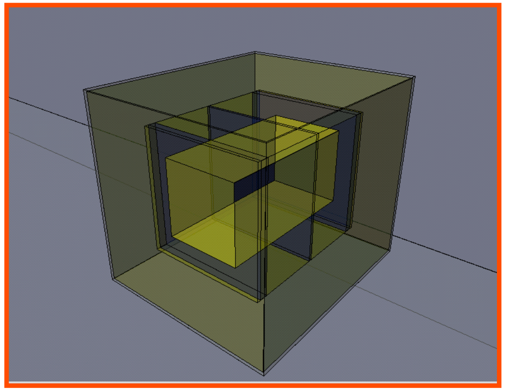
- Advantages:
    - Axial Directionality
    - **<u>Head/tail</u>**
    - Background rejection
    - Particle ID
    - 3D fiducialization

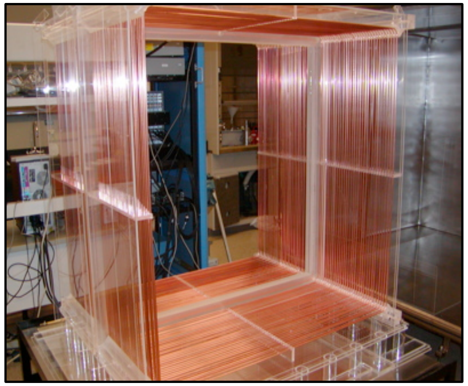
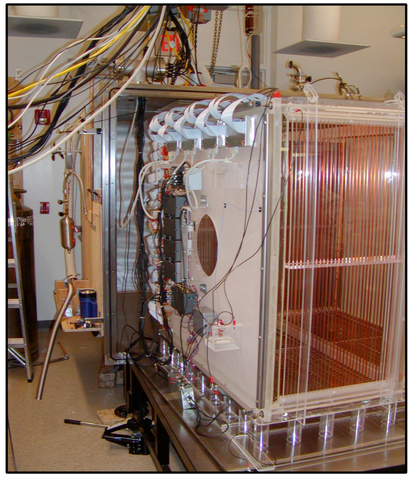


- Technologically challenging, **but maximum potential to avoid <u>thresholdinos</u>!**

DRIFT II a-d (BOULBY 2005...)

Pioneering Negative Ion Drift




New Boulby Laboratory

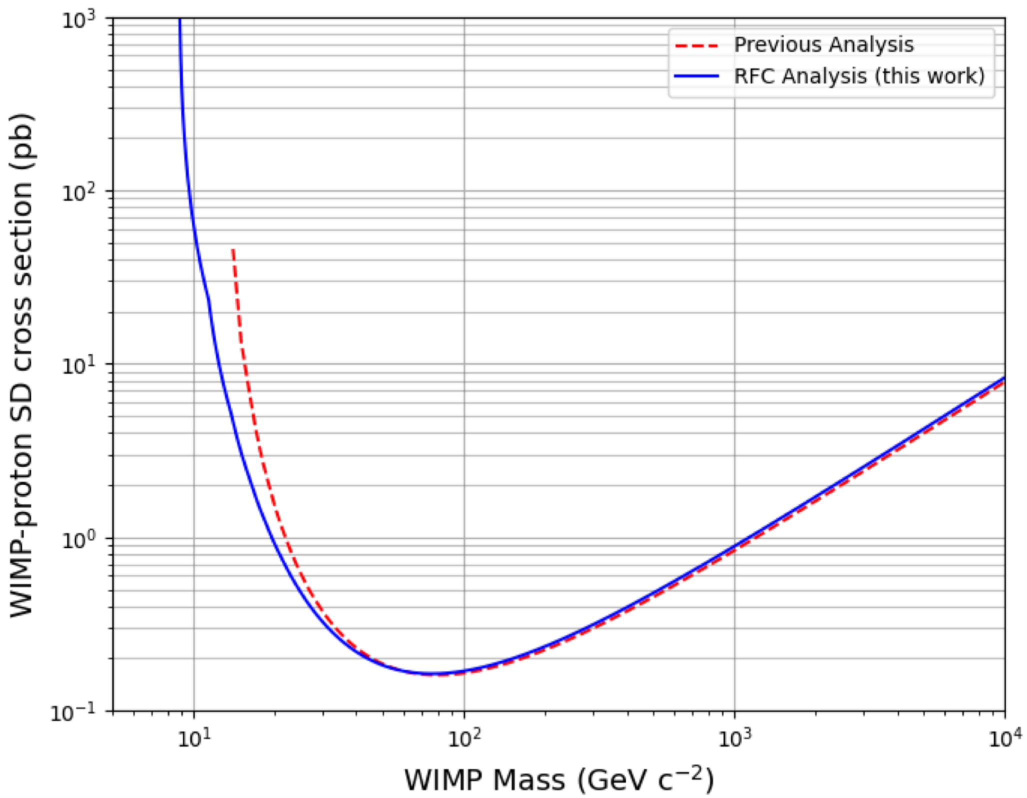
Use of ML for low mass WIMPs

FIG. 25. DRIFT-IId interlocking acrylic block shielding surrounding the detector and containing water, located at Boulby underground laboratory.

Improved sensitivity of the DRIFT-IId directional dark matter experiment using machine learning

The DRIFT collaboration, J.B.R. Battat[1], C. Eldridge[2], A.C. Ezeribe[2], O.P. Gaunt[1], J.-L. Gauvreau[3], R.R. Marcelo Gregorio[2], E.K.K. Habich[1], K.E. Hall[1], J.L. Harton[4]

Journal of Cosmology and Astroparticle Physics, Volume 2021, July 2021

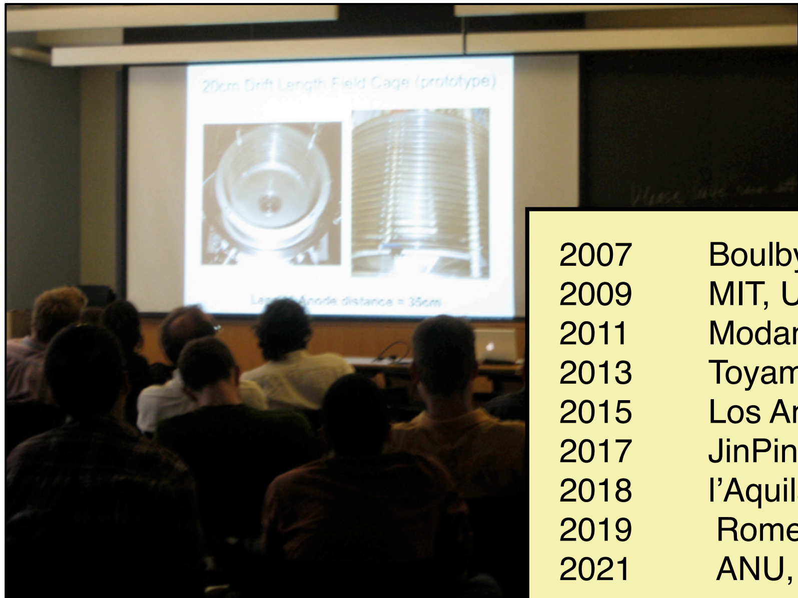


CYGNUS workshops (2007-..)

- CYGNUS Cooperation links most groups interested in directional detection from 2007
  - Interest in directional detection rapidly increasing
  - DRIFT (US-UK), MIMAC (France), (CAST), NEWAGE (Japan), DMTPC (US), Emulsions (Japan)
  - Theory groups....

CYGNUS2007 meeting
22-24 July 2007, Boulby, UK

CYGNUS2009
11-13 June 2009, Boston, USA



2007	Boulby, UK
2009	MIT, US
2011	Modane, France
2013	Toyama, Japan
2015	Los Angeles, USA
2017	JinPing, China
2018	l'Aquila, Italy
2019	Rome, Italy
2021	ANU, Australia

Solids Revisited?

- Can we find a directional technology with higher density?

It would be nice! But a long history of looking has not so far produced much

It is hard...but recent work...

Anisotropic Scintillators

Nuclear Emulsions

High pressure Xe, LAr - columnar recombination

DNA strands

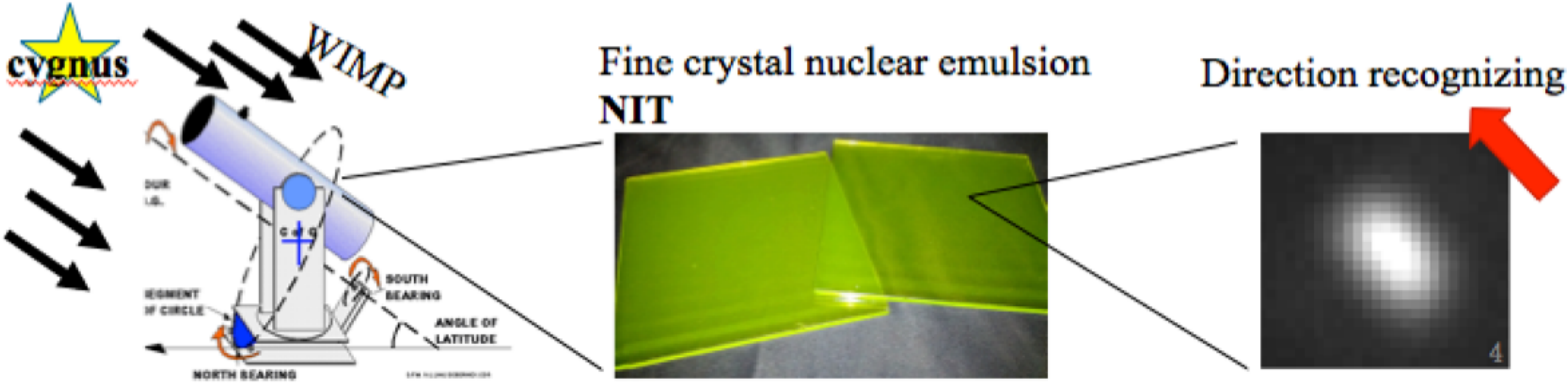
Carbon nanotubes

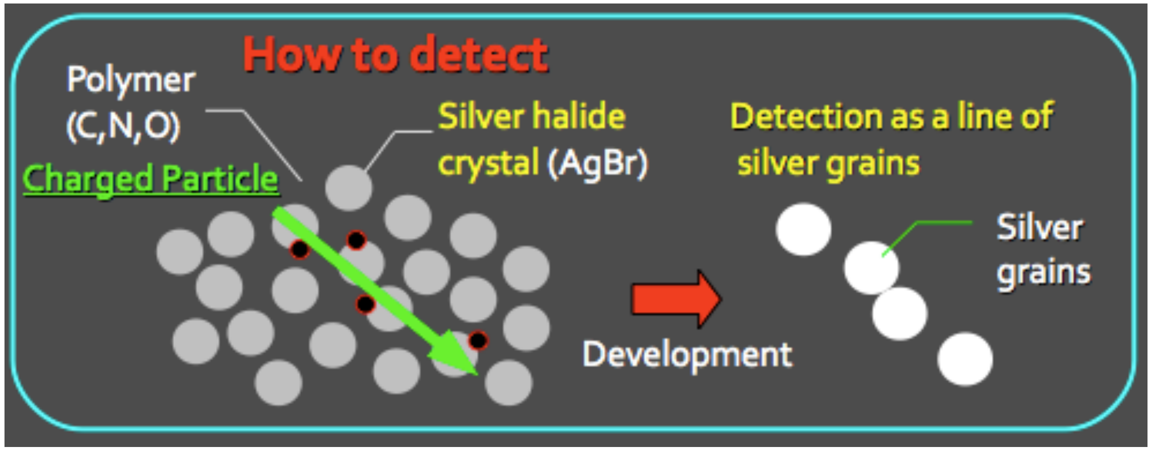
Diamonds

Nuclear Emulsions - NEWS-DM

Nagoya University, OPERA…

- Look for tracks in emulsion grains <40 nm





Challenges:

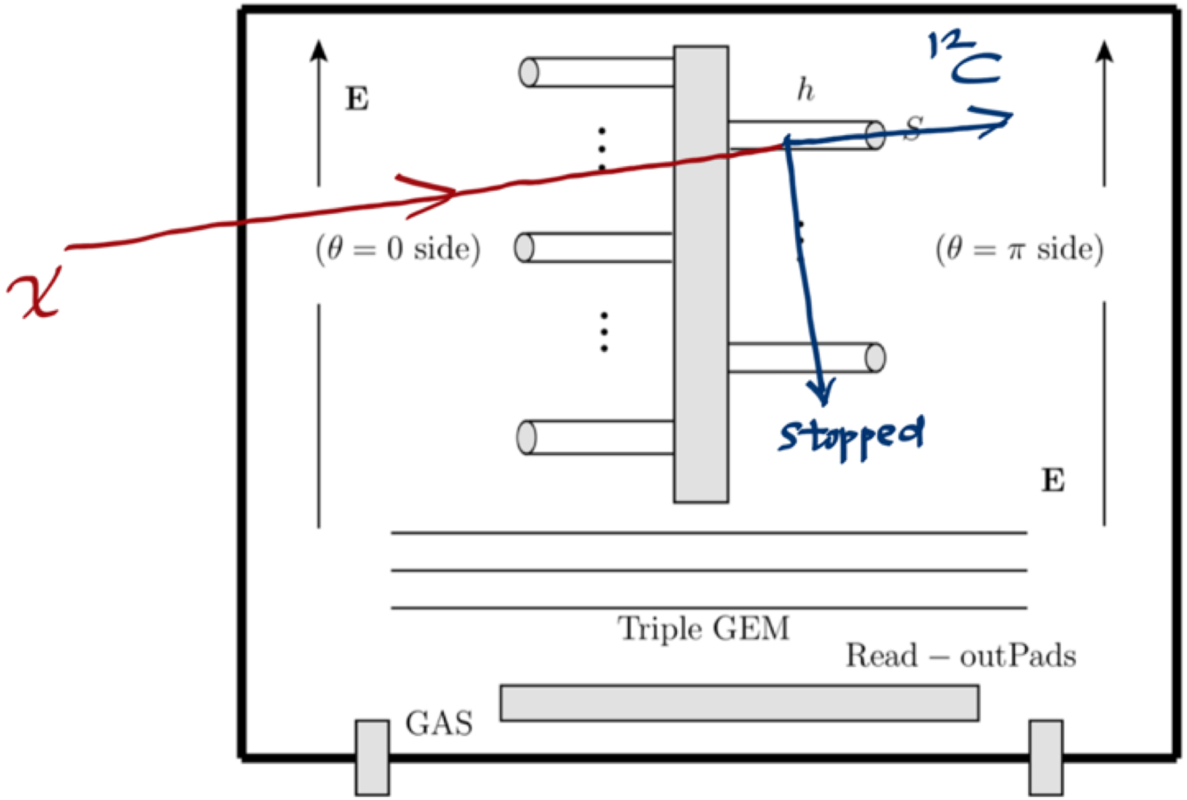
- **no head-tail**
- small grains <40nm (OPERA had 200 nm),
- closely packed, and
- sensitive to low ionisation

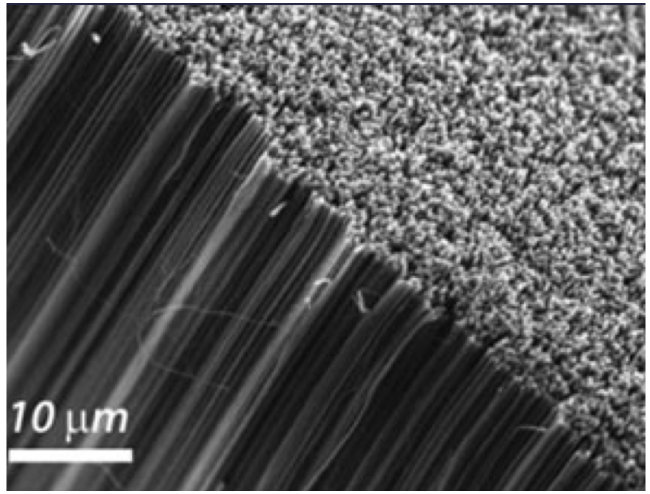
- Progress made to produce stable very fine crystals by using the PVA techniques

Carbon Nanotubes (CNT)

L. Capparelli et al., Rome Sapienza

- Channel C-recoils from nano-tube to GEM readout





Challenges for CNT and other fibre technologies:

- Need for low cost mass-production with correct encoded properties
- Assembly into bulk detector of ton-scale
- Is there a way to do head-tail discrimination
- Can surface backgrounds be controlled

Can we push Anisotropic Scint.?

- Old thoughts from 1990's - CASPAR - CaF(Eu) grains in RI

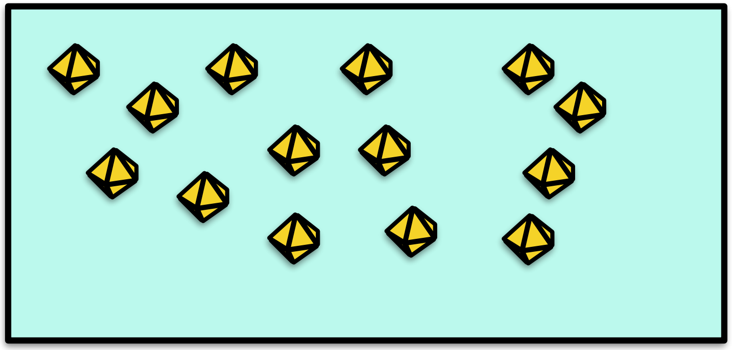
N.J.C. Spooner, D.R. Tovey, C.D. Peak, J.W. Roberts

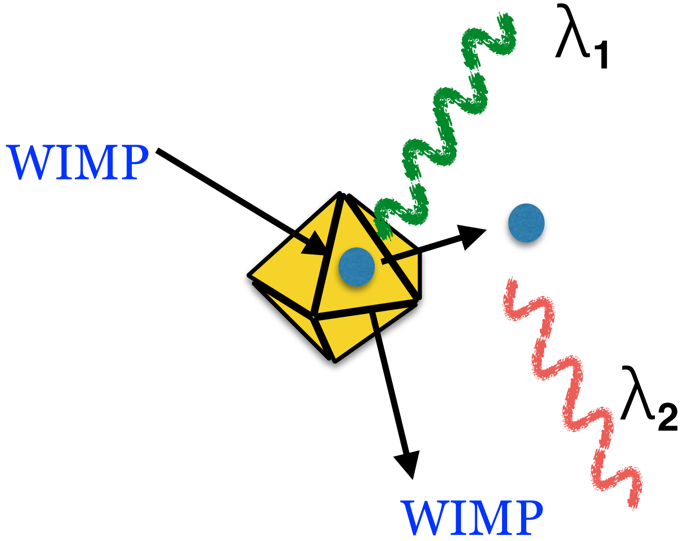
ELSEVIER

Astroparticle Physics
Volume 8, Issues 1–2, December 1997, Pages 13-19

Demonstration of nuclear recoil discrimination using recoil range in a mixed CaF_2 + liquid scintillator gel detector for dark matter searches

N.J.C. Spooner, D.R. Tovey, C.D. Peak, J.W. Roberts





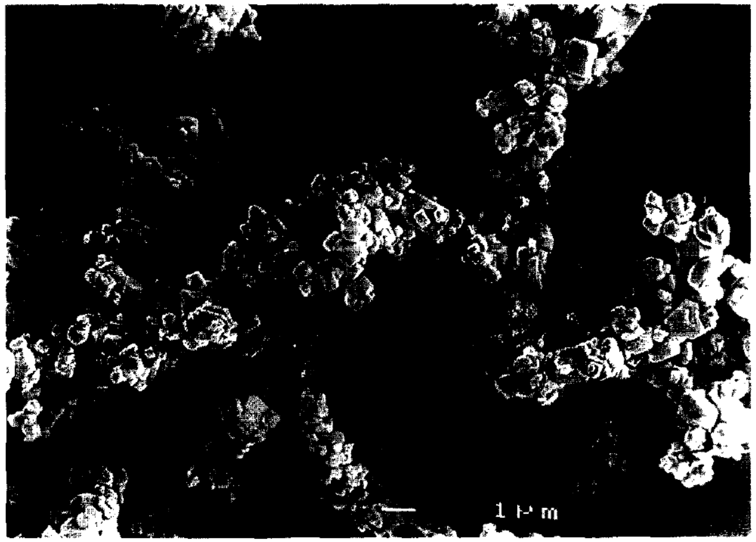


Fig. 1. Electron microscopy photograph of a typical CaF_2 precipitate sample.

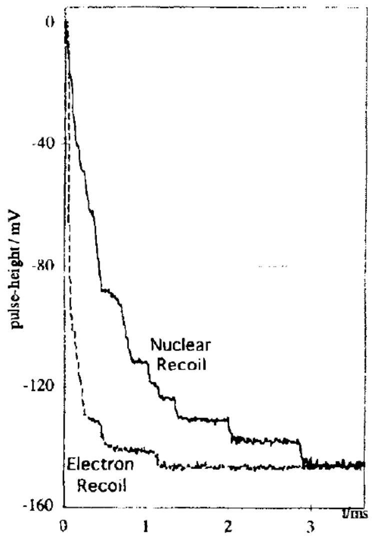


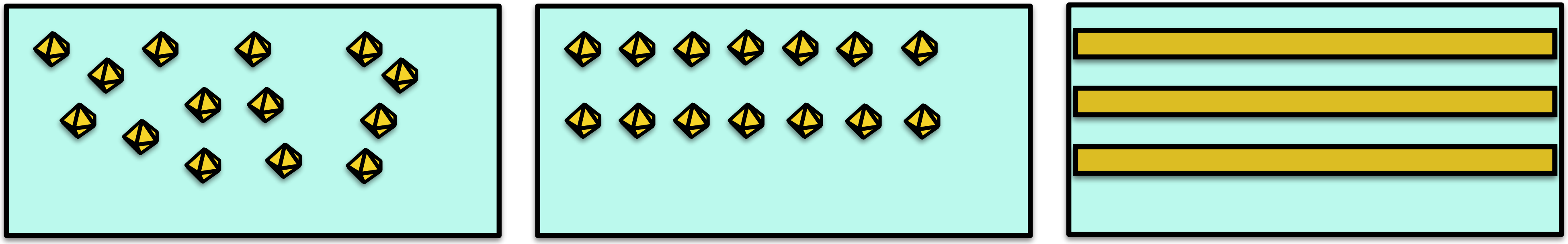
Fig. 3. Example pulses from CASPAR for: (a) nuclear recoils within grains and (b) electron recoils.

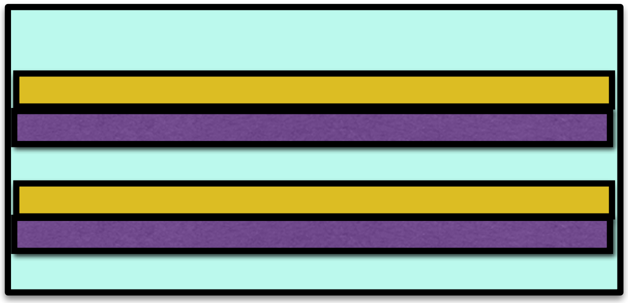
Can we push Anisotropic Scint.?

- Multilayer scintillator construction for directionality

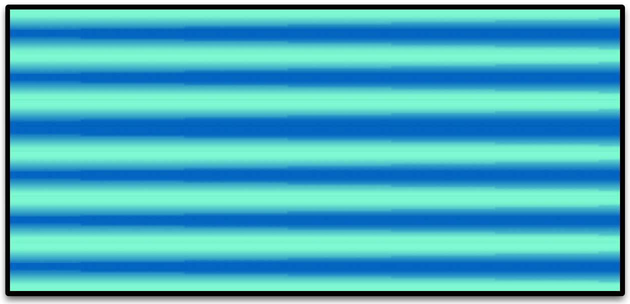
N.J.C. Spooner

- encoding stronger directionality in a bulk purpose-grown scintillator

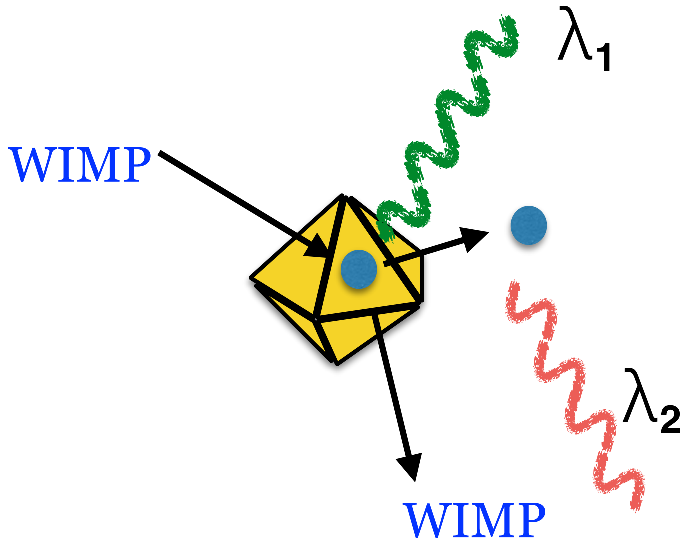




- multi-layer with head-tail directionality



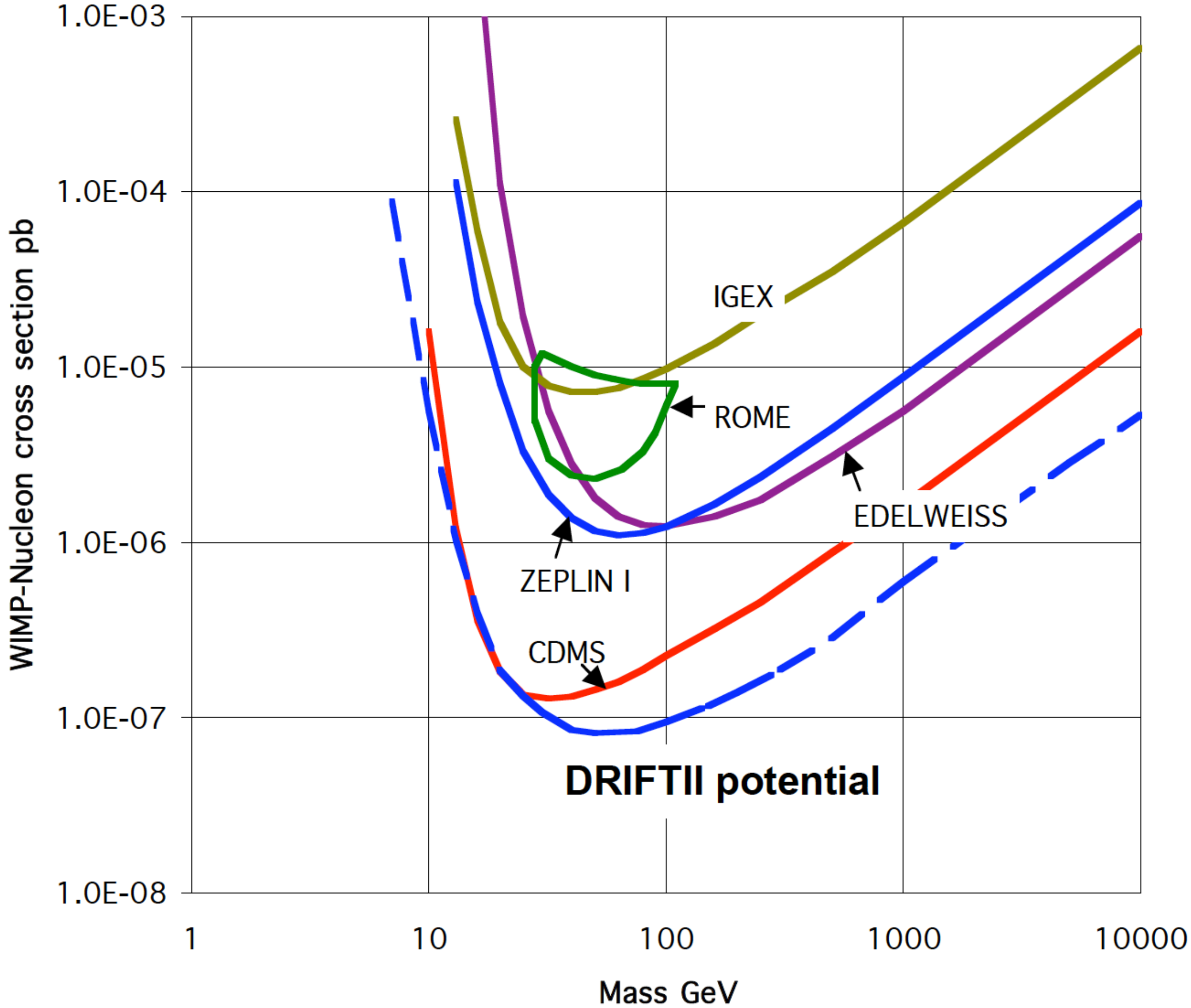
- modulating Tl doing in NaI(Tl) crystal?



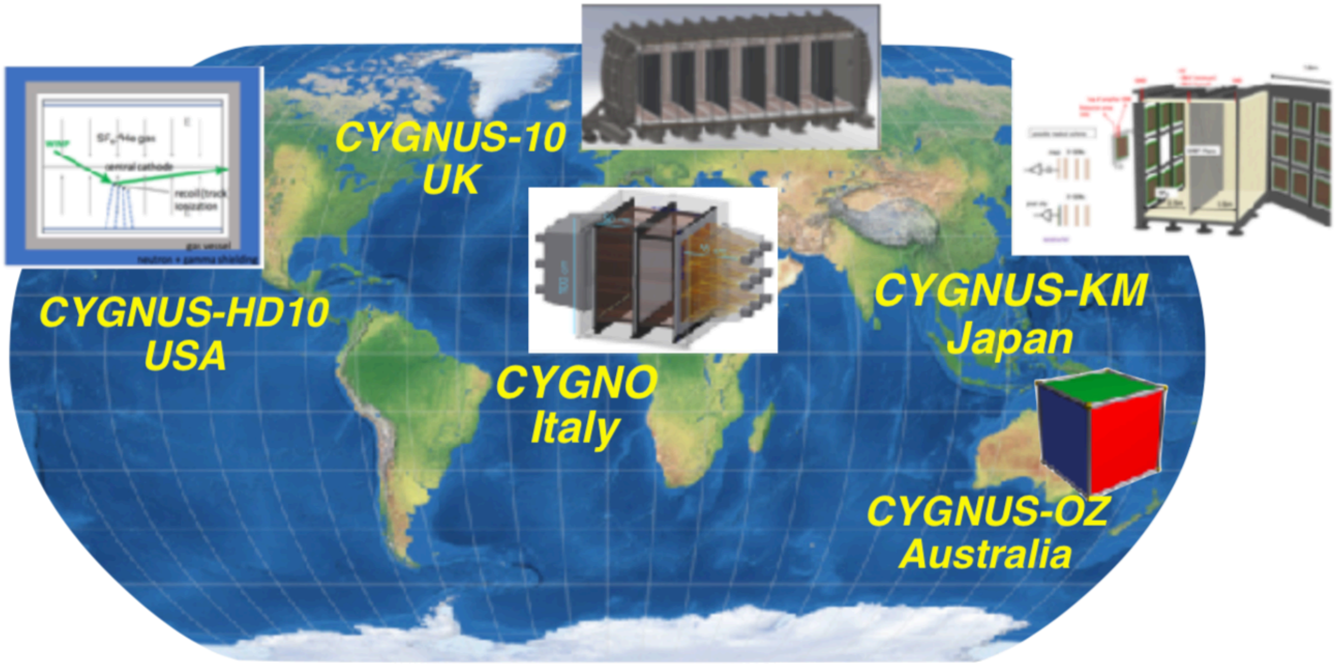
But Surprising Potential of Gas

- DRIFT predictions 2007..

  $3m^3$ of CS_2 - 3.4 years - 40 Torr - 20 keV S recoil energy



CYGNUS Collaboration Vision (TPC)



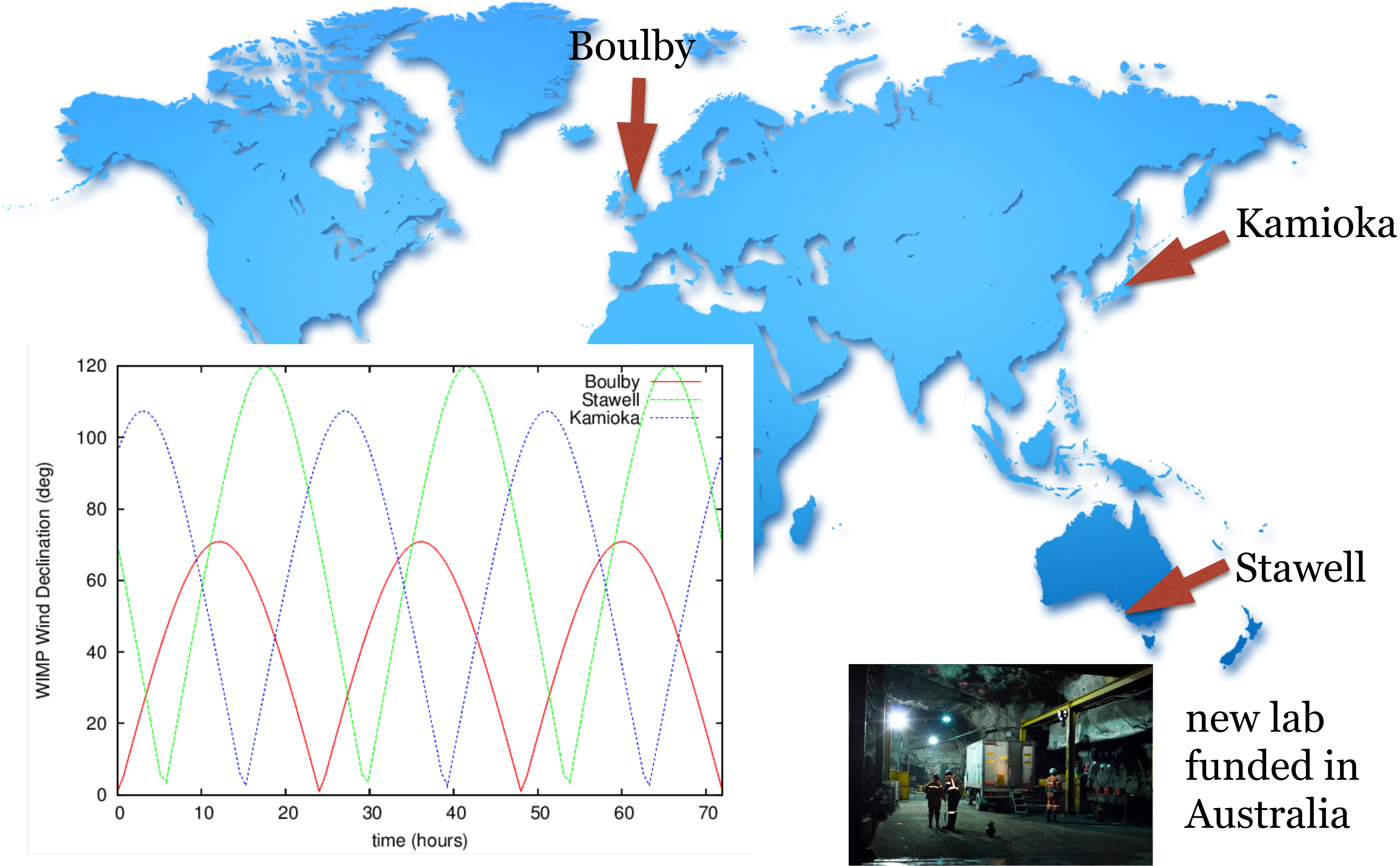
A multi-site Galactic Nuclear Recoil Observatory

Probe Dark Matter below the Neutrino Floor

Measure ^{8}B solar neutrinos with directionality

Extend searches to low mass with electron and nuclear recoils

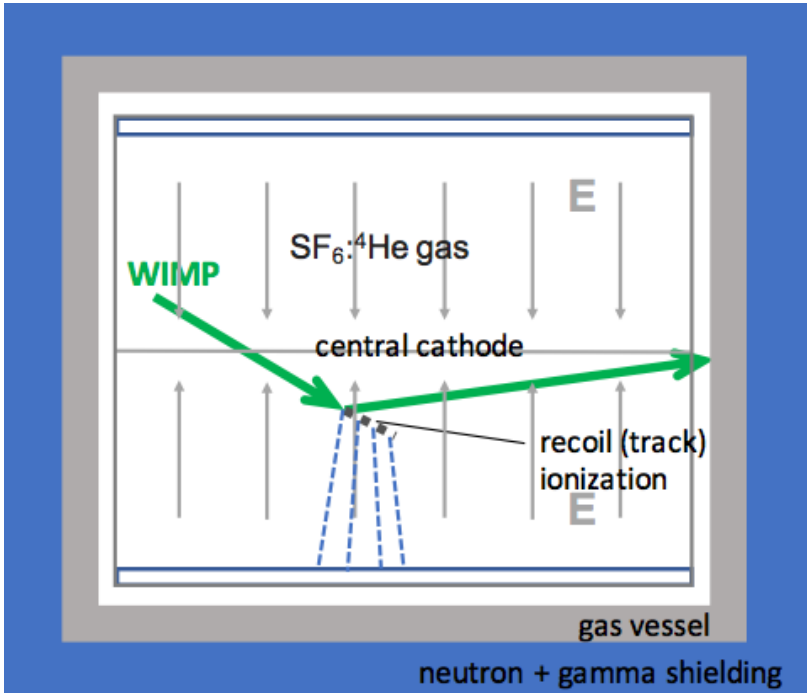
Multiple Sites for directionality

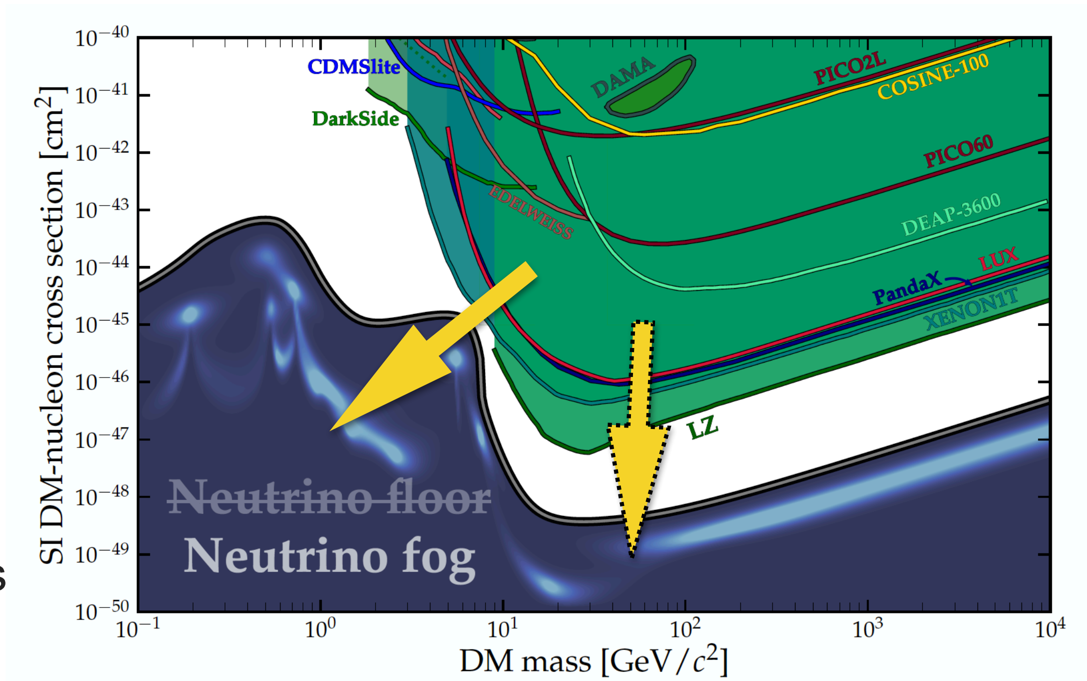


new lab funded in Australia

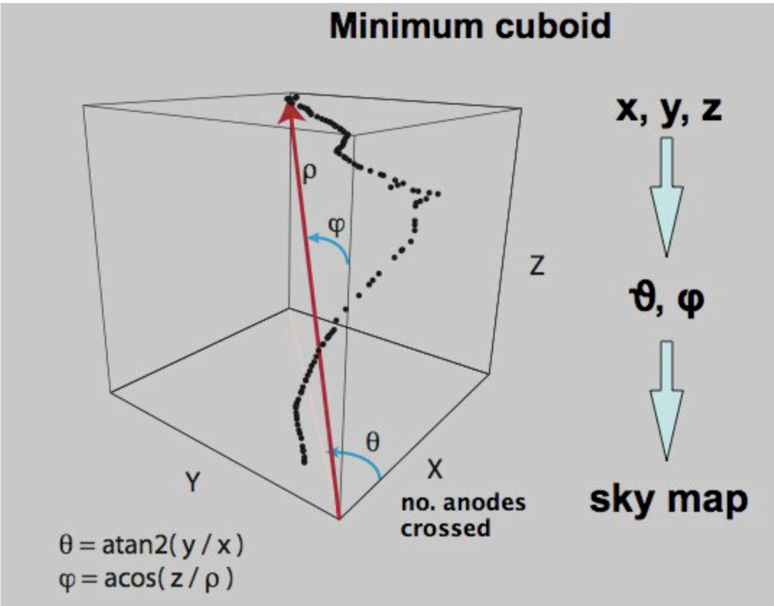
CYGNUS: Gas TPC Concept

- **Detector volumes 10-<u>1000</u> m^3….**
- **Gases: SF_6:He, CF4:SF6:He (1atm)**
  - Can switch between higher density (search mode) and lower density gas for (improved) directional confirmation of WIMP signal
- **Threshold at <1 keV$_e$**
  - Use of high gain stages
  - Ultimate is W~30 eV
- **Electron rejection at ~GeV**
- **Reduced diffusion -ve ion drift**
- **3D Fiducialisation**
  - SF_6 minority carriers
  - charge cloud profile
- **He target**
  - Improved sensitivity to low mass WIMP
  - Extending directionality to lower energies





Challenge - find optimum cost/benefit



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

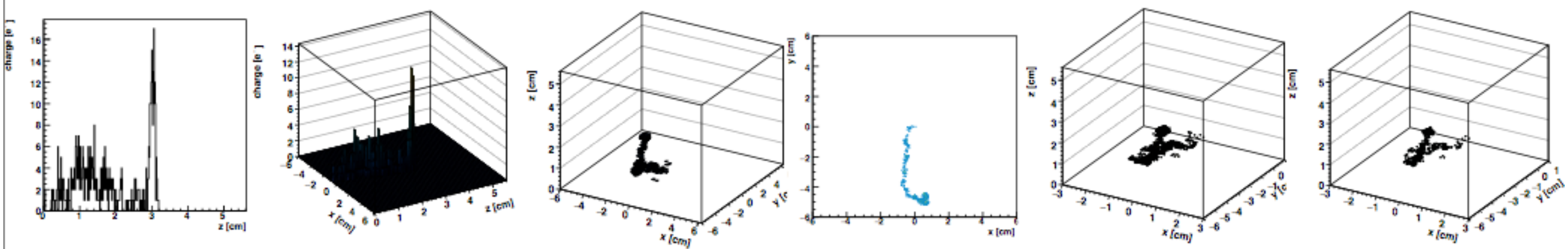
S.E. Vahsen (Hawaii U.), C.A.J. O'Hare (Sydney U.), W.A. Lynch (Sheffield U.), N.J.C. Spooner (Sheffield U.), E. Baracchini (Frascati and INFN, Rome and Gran Sasso) et al. (Aug 28, 2020)

e-Print: 2008.12587 [physics.ins-det]

Challenges:
(1) Readout
(2) Background
(3) Engineering

→ **Sensitivity per Unit Cost**

simulated examples of a 20 keV electron track 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

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

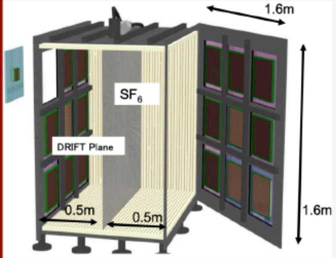
Electron drift ***Negative ion drift*** ***Charge readout*** ***Optical readout***

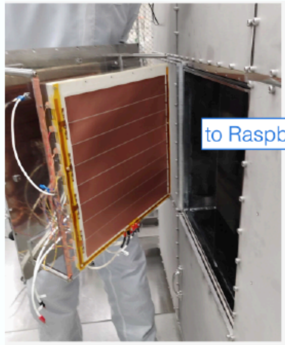
CYGNUS Detectors

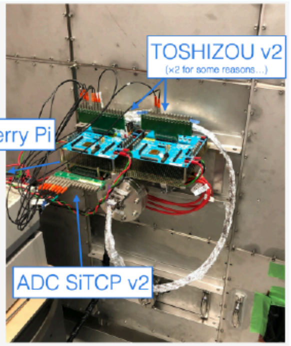
CYGNUS-KM / NEWAGE (C/N-1.0)
(Kamioka)

- 18 modules capable 1 m^3 chamber

➡ placed in Kobe University

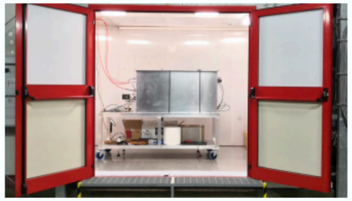


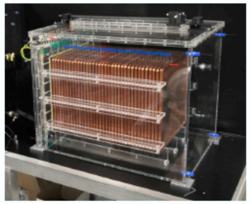


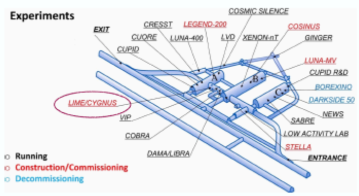


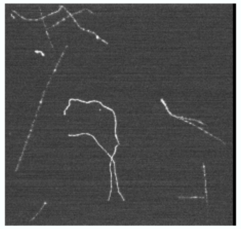
- **A single 30 x 30 cm^2 module for 50 cm drift length commissioning the chamber at Kobe University**
  - **Goal: detect SF_6^- and SF_5^- peaks**
- **After commissioning, to be moved to underground Kamioka Mine**

LIME - CYGNO PHASE 0
1 sCMOS + 4 PMT + 3 GEMs
33 x 33 cm^2 readout area
50 cm drift length

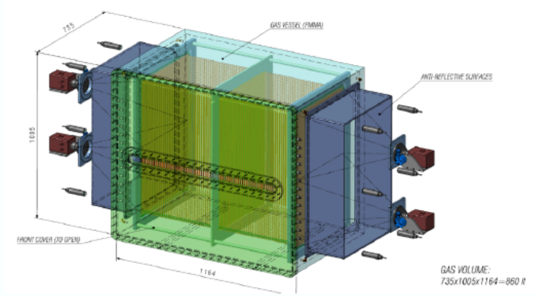






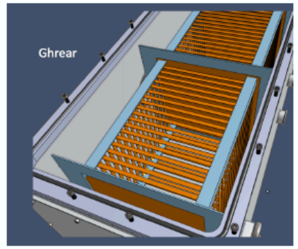


Base module design for PHASE 1 @ underground LNGS taking data



CYGNO PHASE 1 0.4 m^3 detector & shielding TDR submitted to INFN

CYGNUS HD "Keiki"
CERN strip Micromegas + SRS
20 x 20 cm^2 readout area
50 cm drift length x 2 (double sided)



Under construction
Goal: evaluation of components for follow-on 1 m^3 detector

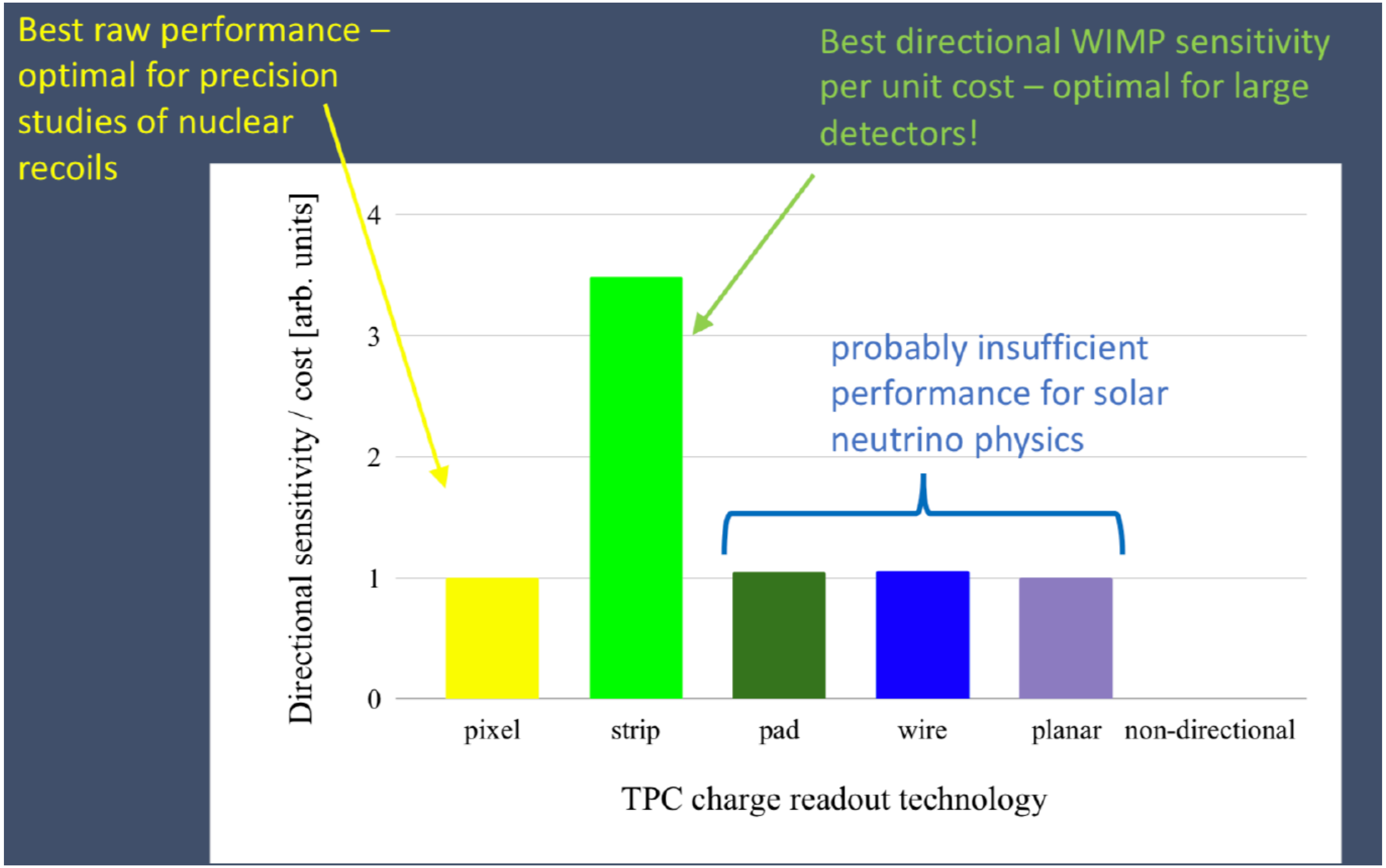
1 m^3 vessel design completed

CYGNUS Readout "Conclusions"

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

S.E. Vahsen (Hawaii U.), C.A.J. O'Hare (Sydney U.), W.A. Lynch (Sheffield U.), N.J.C. Spooner (Sheffield U.), E. Baracchini (Frascati and INFN, Rome and Gran Sasso) et al. (Aug 28, 2020)

e-Print: 2008.12587



For He:SF6 755:5 with negative ion drift
strips results the best choice in terms of costs versus performances

CYGNUS Background Conclusions

We have aimed to determine the feasibility of limiting electron recoils to a rate of 10^4 recoils keV^{-1} yr^{-1} in the energy range 1–10 keV_{ee}, and nuclear recoils to a rate of < 1 yr^{-1} between 1–100 keV. These numbers are compatible with zero electron background

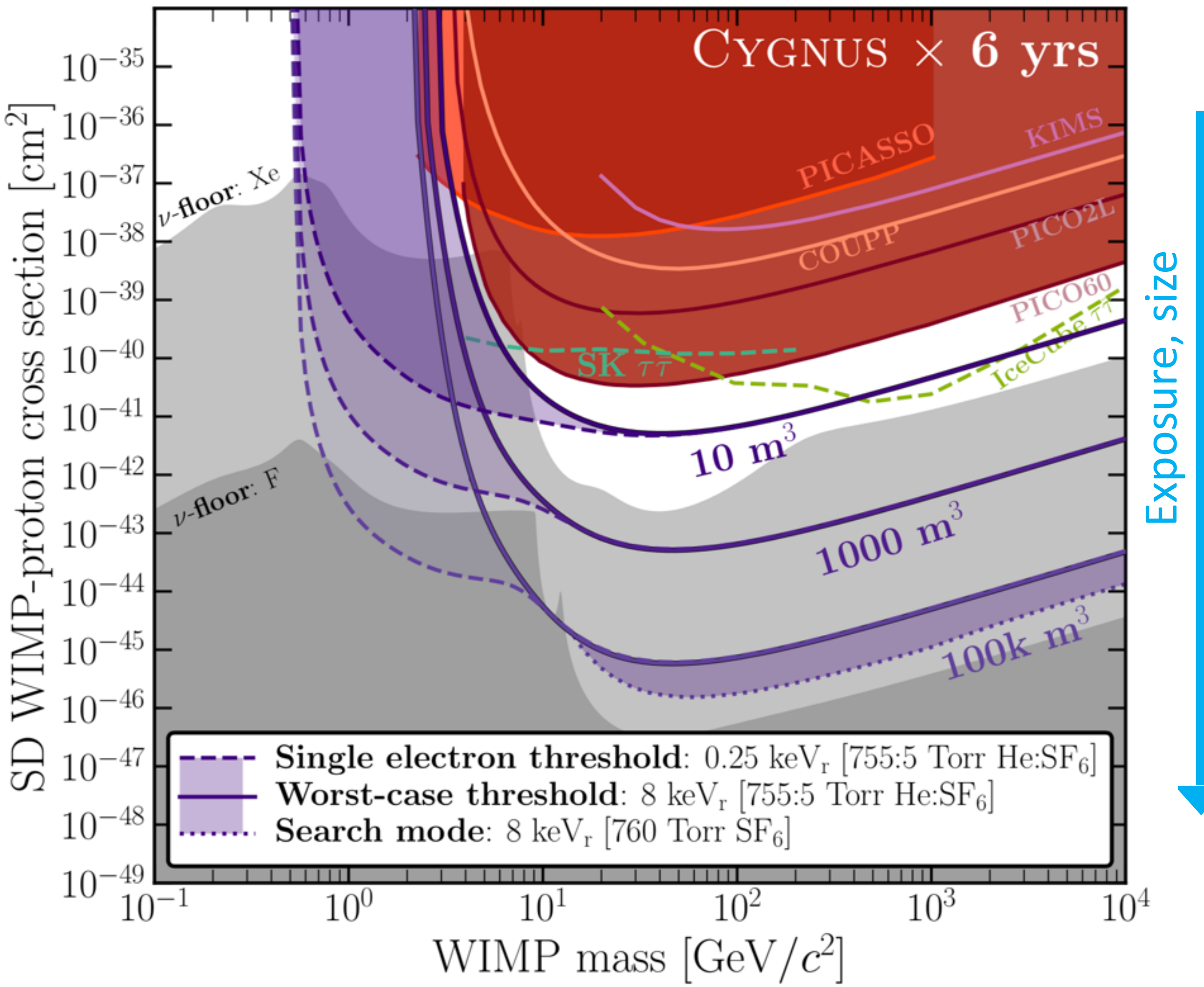
Readout	Material (width)	γ recoils (keV^{-1} yr^{-1})	U limit (mBq kg^{-1})	Th limit (mBq kg^{-1})	K limit (mBq kg^{-1})
Gain stages:					
THGEM	Acrylic (1 mm)	$3.3\pm0.7\times10^4$	✓	✓	0.54
	Copper (0.1 mm ×2)	$< 1.5\pm0.3\times10^3$	✓	✓	✓
GEM	Kapton (50 microns)	$1.57\pm0.02\times10^5$	✓	✓	3.65
Readout stages:					
Strip	Acrylic-Cu (1 mm)	$3.4\pm0.7\times10^4$	✓	✓	0.54
Wires	Steel (50 μm)	1.8 ± 0.3	✓	✓	✓
	Acrylic (2 cm × 1 cm)	$2.4\pm0.1\times10^4$	✓	✓	0.88
Pixel chip	Silicon (400 μm)	$< 2.55\pm0.19\times10^5$	0.26	0.29	0.46
	Copper (3.9 μm)	$< 24\pm2$	✓	✓	✓
	Aluminum (4.5 μm)	$< 937\pm77$	✓	✓	✓
Other:					
μ-PIC	Polyimide (1 mm)	$< 1.3\pm0.2\times10^7$	0.12	0.09	0.12
Resistors	Ceramic	$2.5\pm1.3\times10^4$	0.13	✓	✓

TABLE IX. Readout gamma recoil rates in 20 Torr SF_6 for different readout materials and the ^{238}U, ^{232}Th, and ^{40}K radiopurity required to achieve 10^4 recoils keV^{-1} yr^{-1} (as well as the materials which already satisfy this requirement).

Electron background and electron discrimination should take priority in future work.

CYGNUS outlook

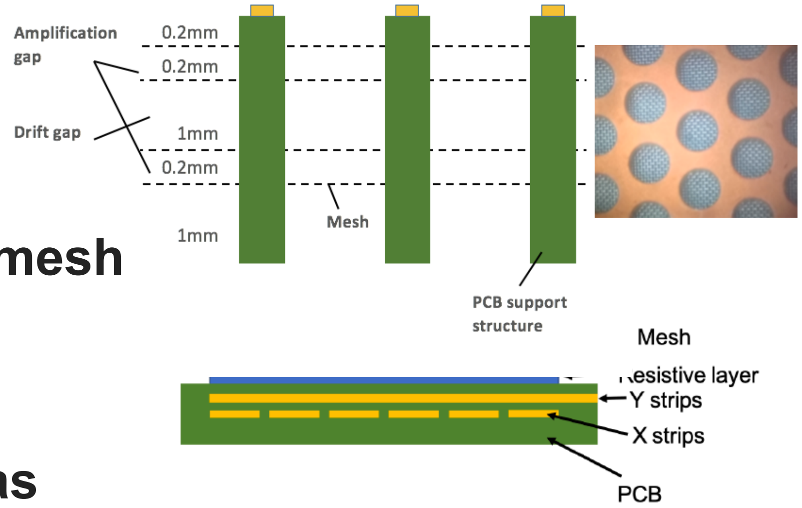
More than dark matter - Strawman design paper: arXiv:2008.12587

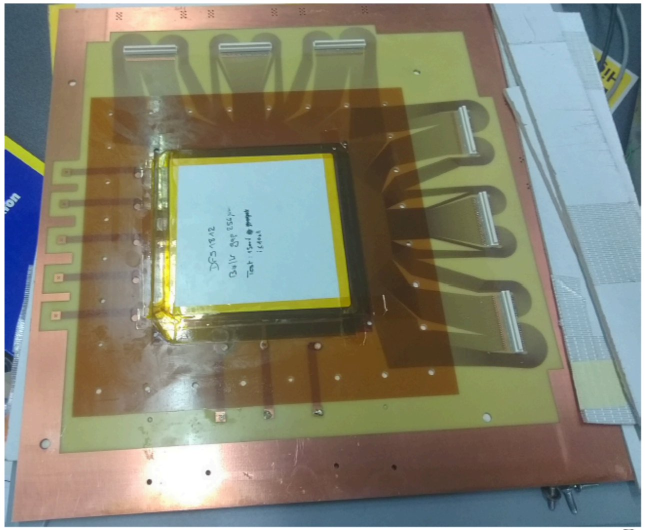


- Migdal Effect measurement
- Coherent Elastic Neutrino-Nucleus Scattering (CEvNS) at either NuMI or DUNE
- Competitive DM limits in SI and SD
- CEvNS from solar neutrinos
- Efficiently penetrating the neutrino floor
- Observing galactic DM dipole
- Measuring DM particle properties and physics
- Geoneutrinos
- WIMP astronomy

SF_6 Gas Gain on Strips ~10^5

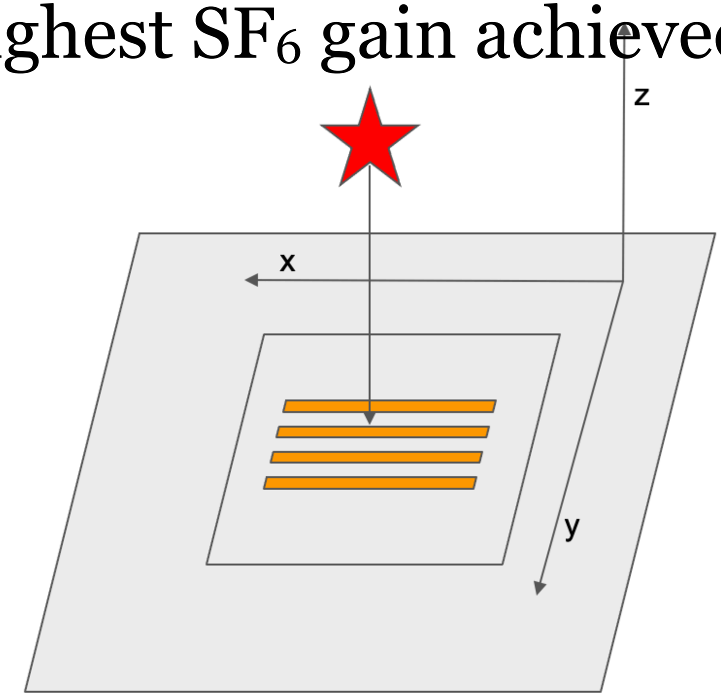
- Sheffield update: Ali McLean, Callum Eldridge

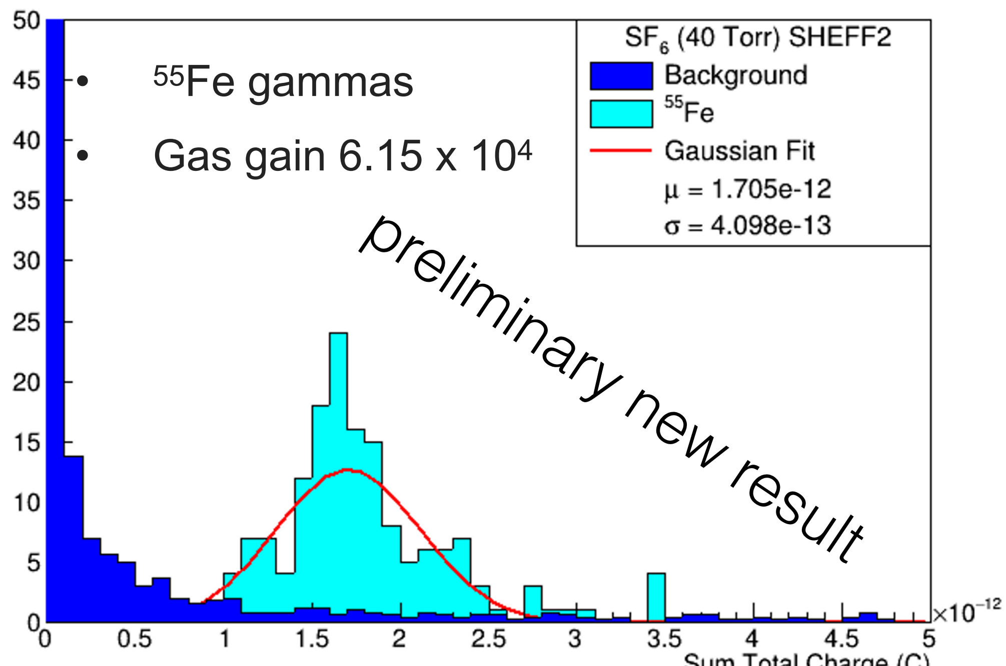




- **new multi-mesh gain stage**
- **CERN micromegas**

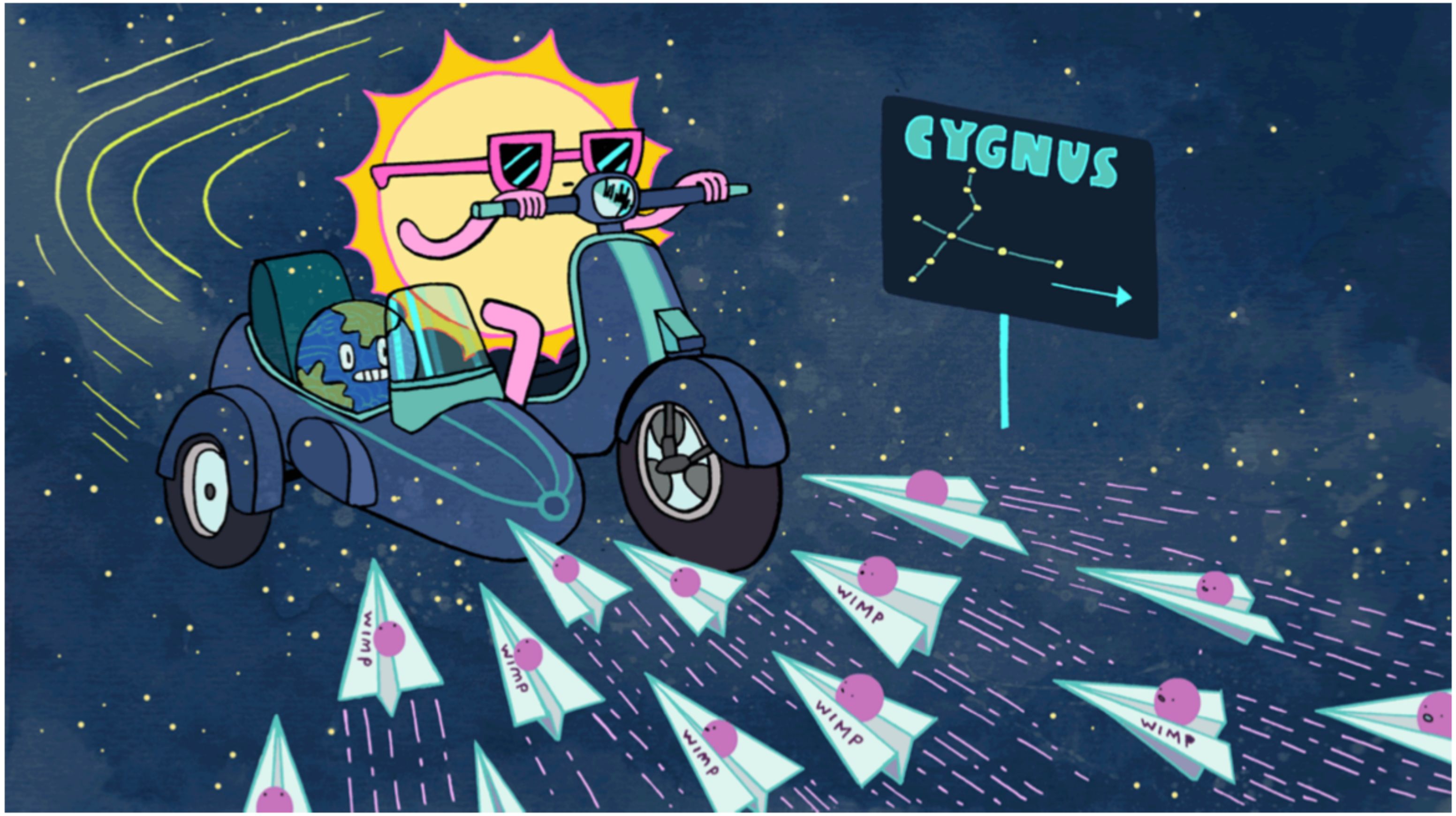
- Highest SF_6 gain achieved so far - upto x 10^5





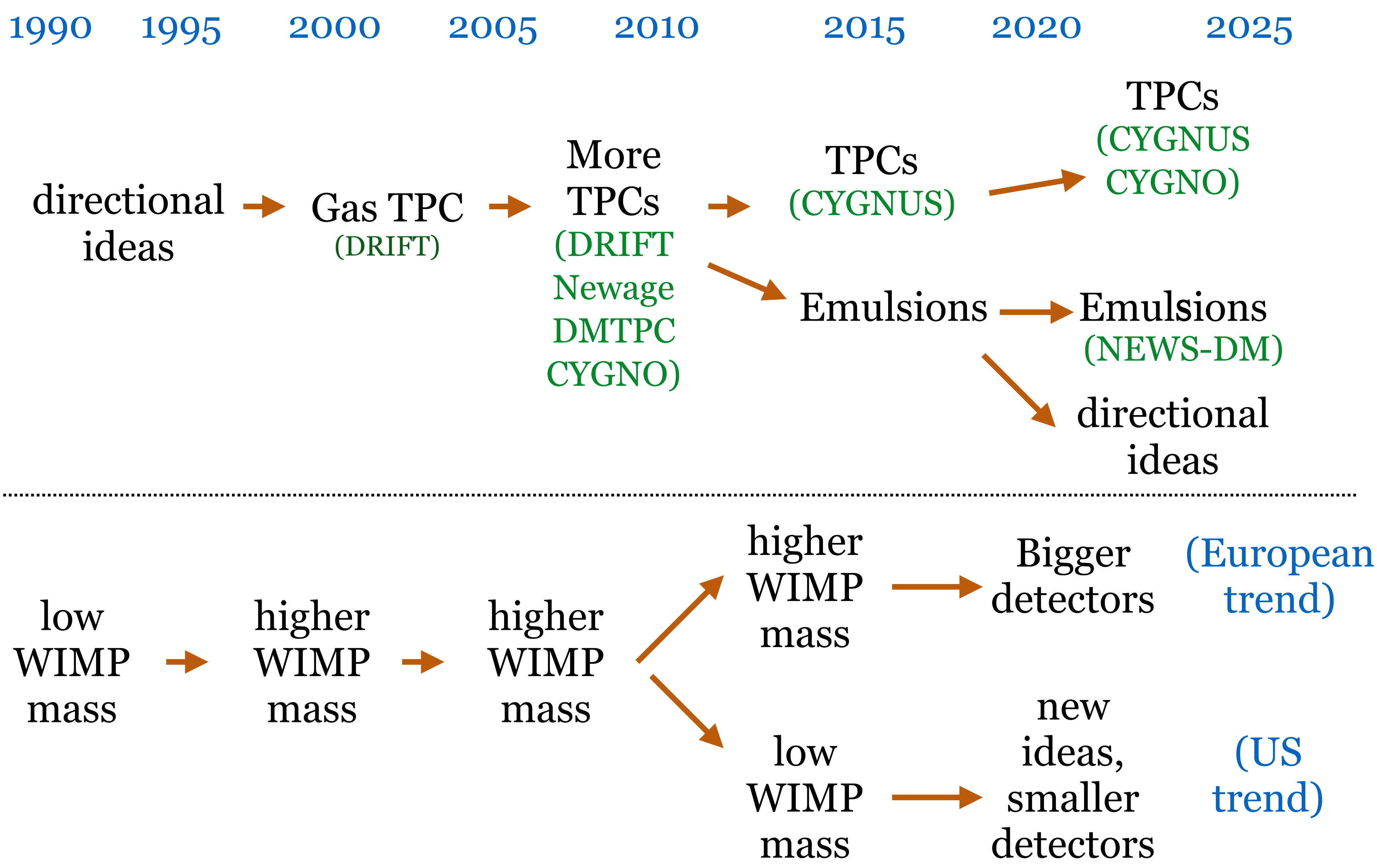
Conclusions

- The directional community has expanded to form a collaboration CYGNUS - using gas to avoid thresholdinos
- Much recent progress on many key technical issues
- Help us proceed to build the next phase - into the neutrino fog



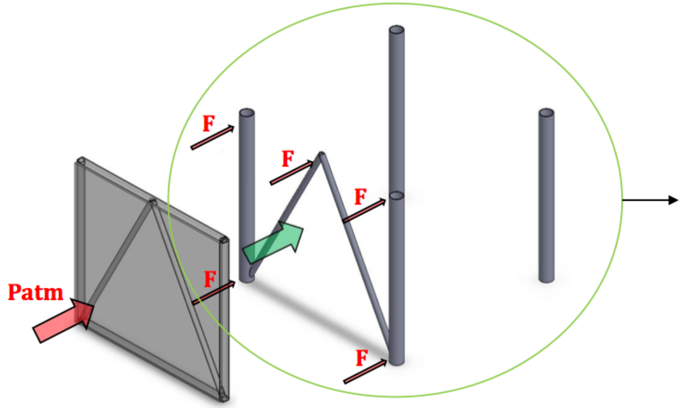
http://www.symmetrymagazine.org/article/wimps-in-the-dark-matter-wind

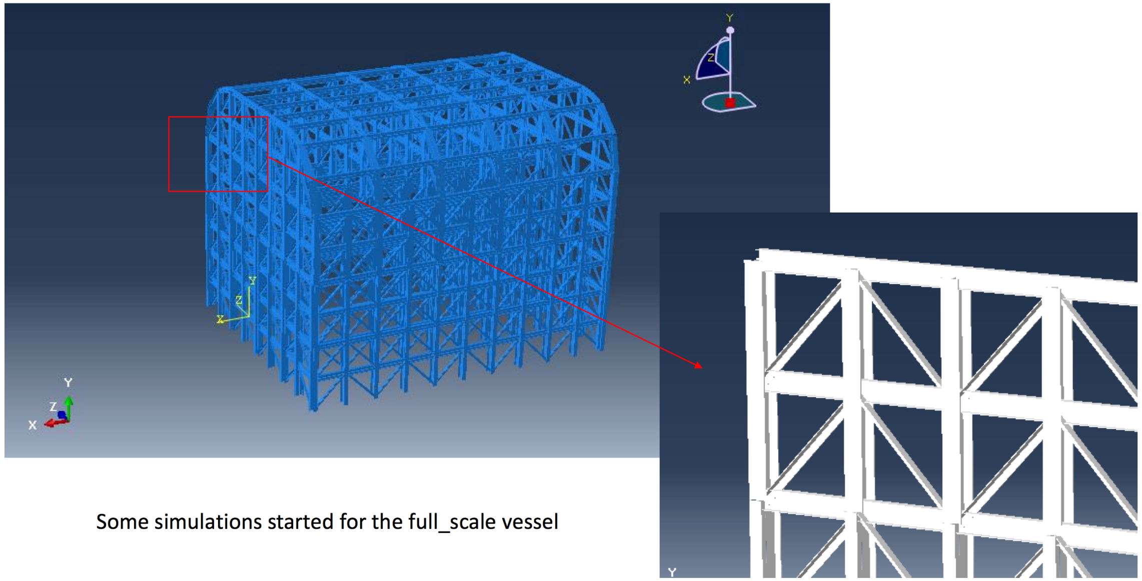
Directional Trends



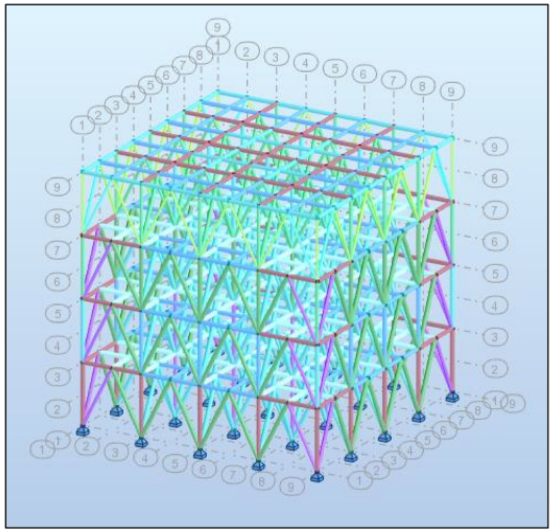
CYGNUS Engineering Conclusions

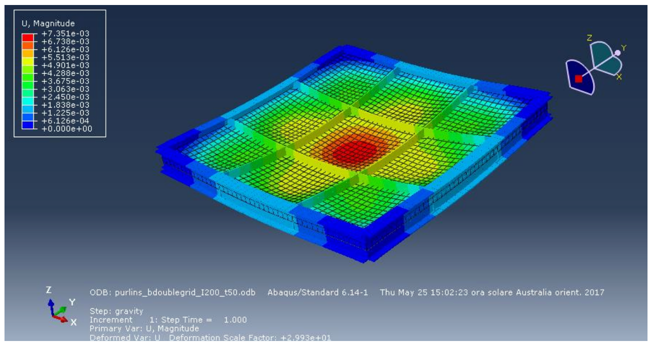
- Key intrinsic background issue is low energy electrons from the vessel and readout (GEANT4, Sheffield group).
- Needs new vessel design, **possible 1 atm. operation** will help this.
- Light truss structure design (Ti + Acrylic) looks best.





Some simulations started for the full_scale vessel

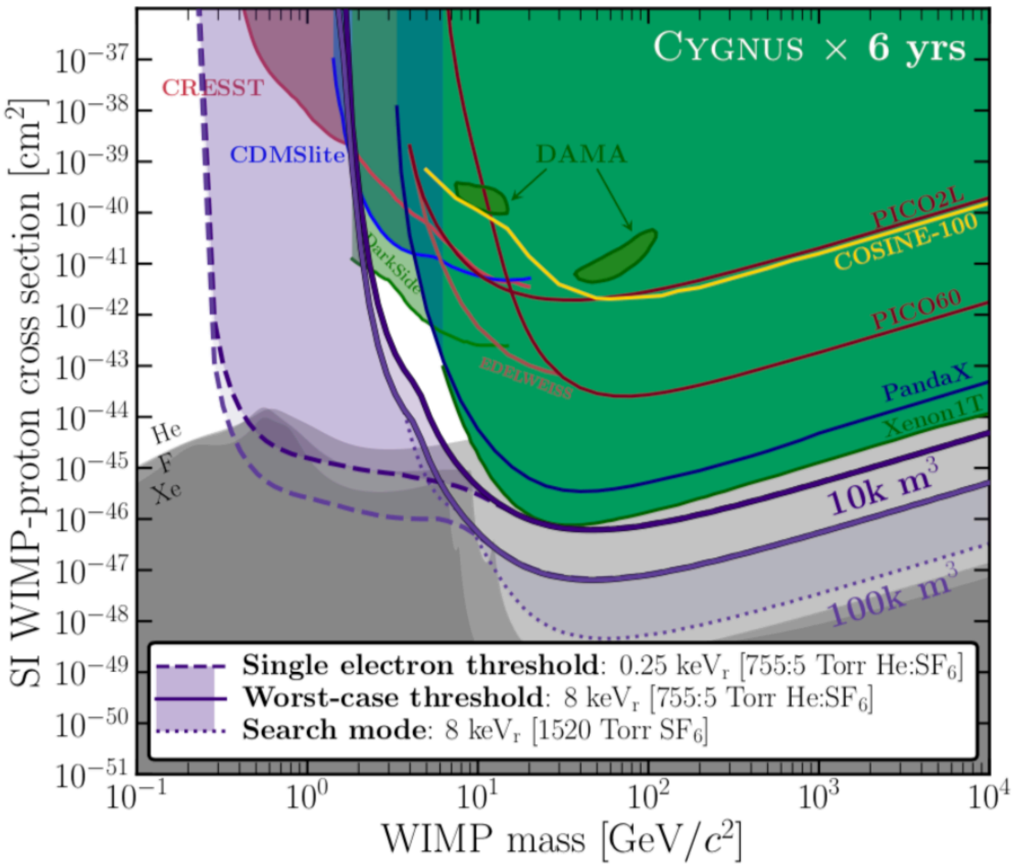


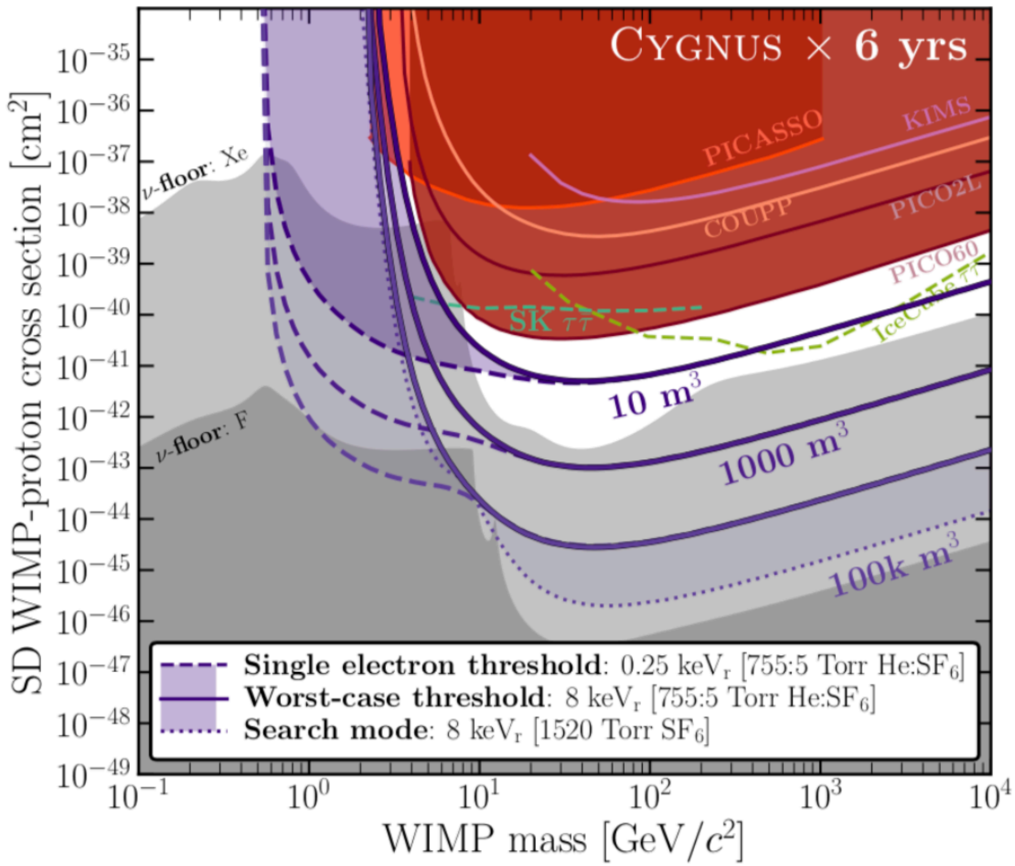


Tiziano Baroncelli (Melbourne group)

One Tonne CYGNUS sensitivity

He:SF_6 755:5





Significant improvement in SI in the low WIMP mass region, expect 10-50 IDENTIFIED neutrino nuclear recoil events

Significant improvement in SD reach over existing experiments for all WIMP masses, a 10 m³ detector can already breach the Xe neutrino floor