CYGNUS-TPC Directional Dark Matter Search

Neil Spooner, University of Sheffield

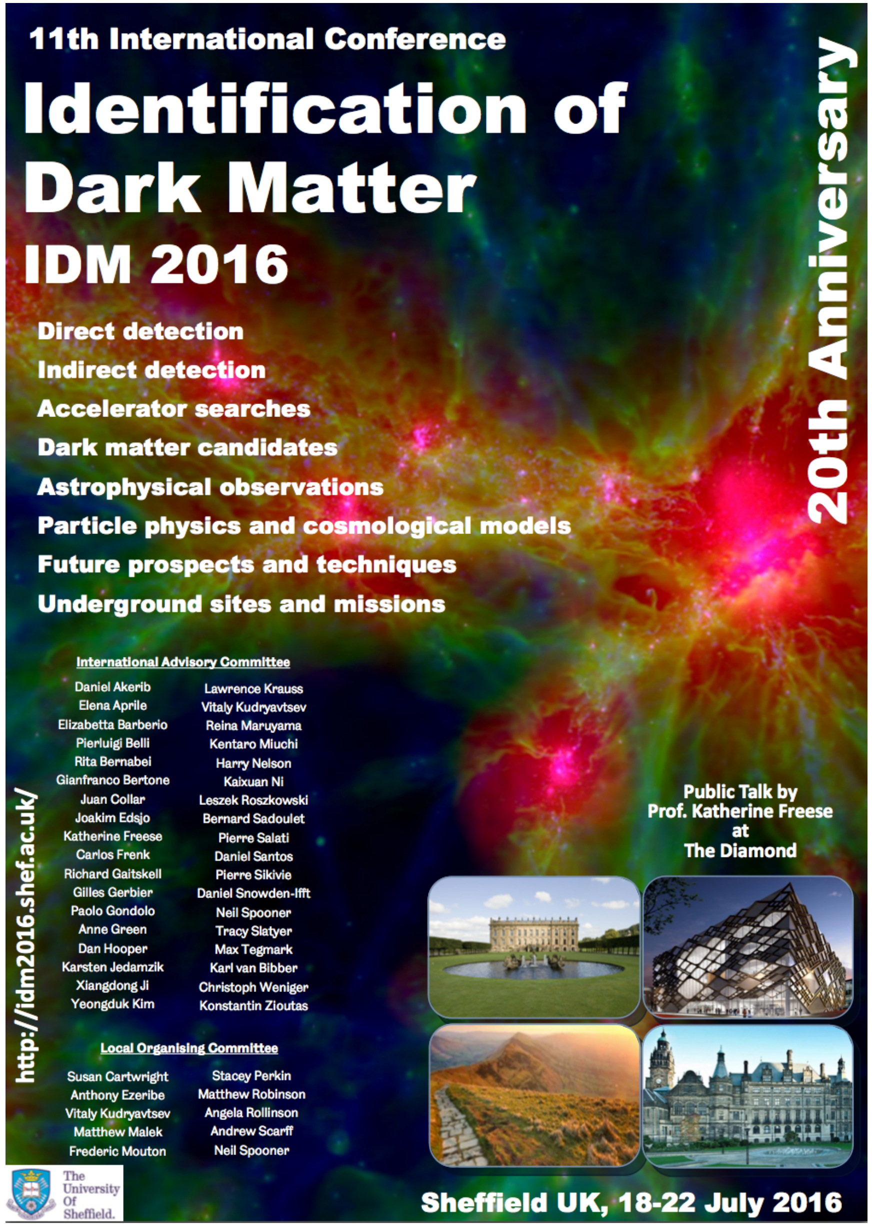
- WIMP Dark Matter Detection and Signal Identification
- Power of Directionality and the gas TPC
- Gas TPC Strategy and Latest Highlights (with DRIFT bias)
- What is CYGNUS-TPC

Thanks to those from whom I have borrowed slides and info

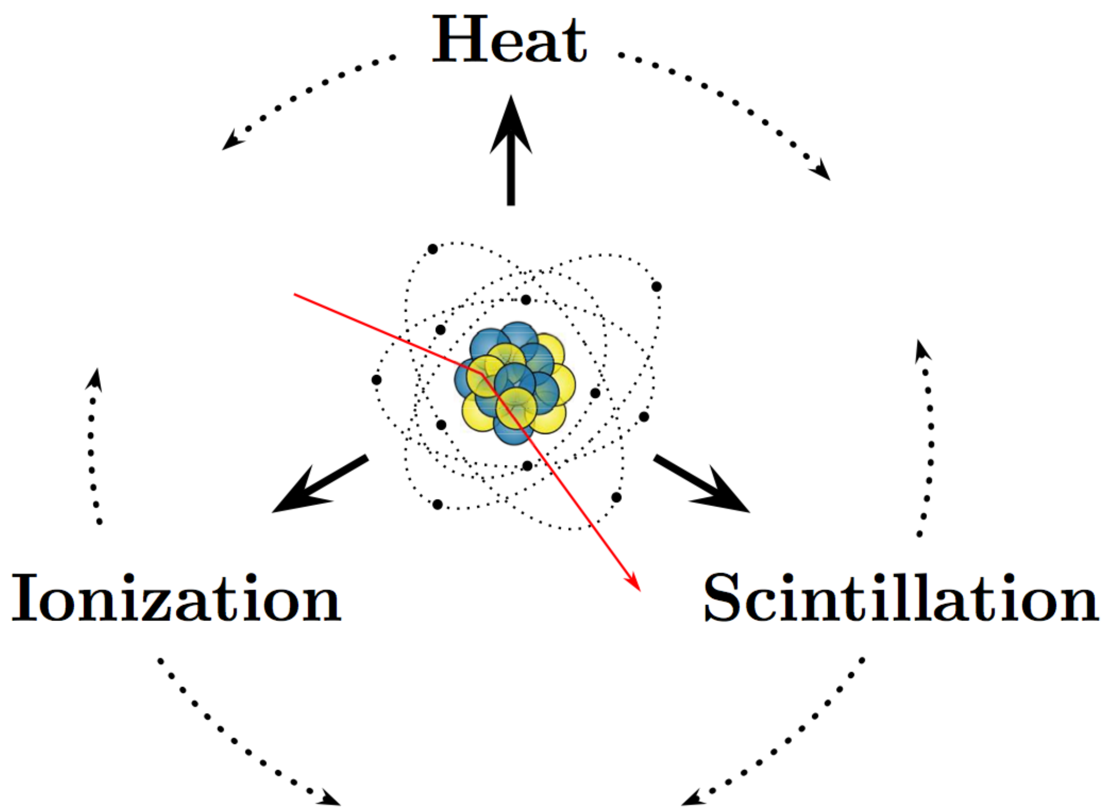
Sorry not to cover all directional experiments

For the Latest Come to IDM2016

- To know more —> IDM2016
- Sheffield, 18-22 July
- mini-CYGNUS, 23rd July



The Normal Route to WIMP Detection



~Current Situation

- **at High Mass**

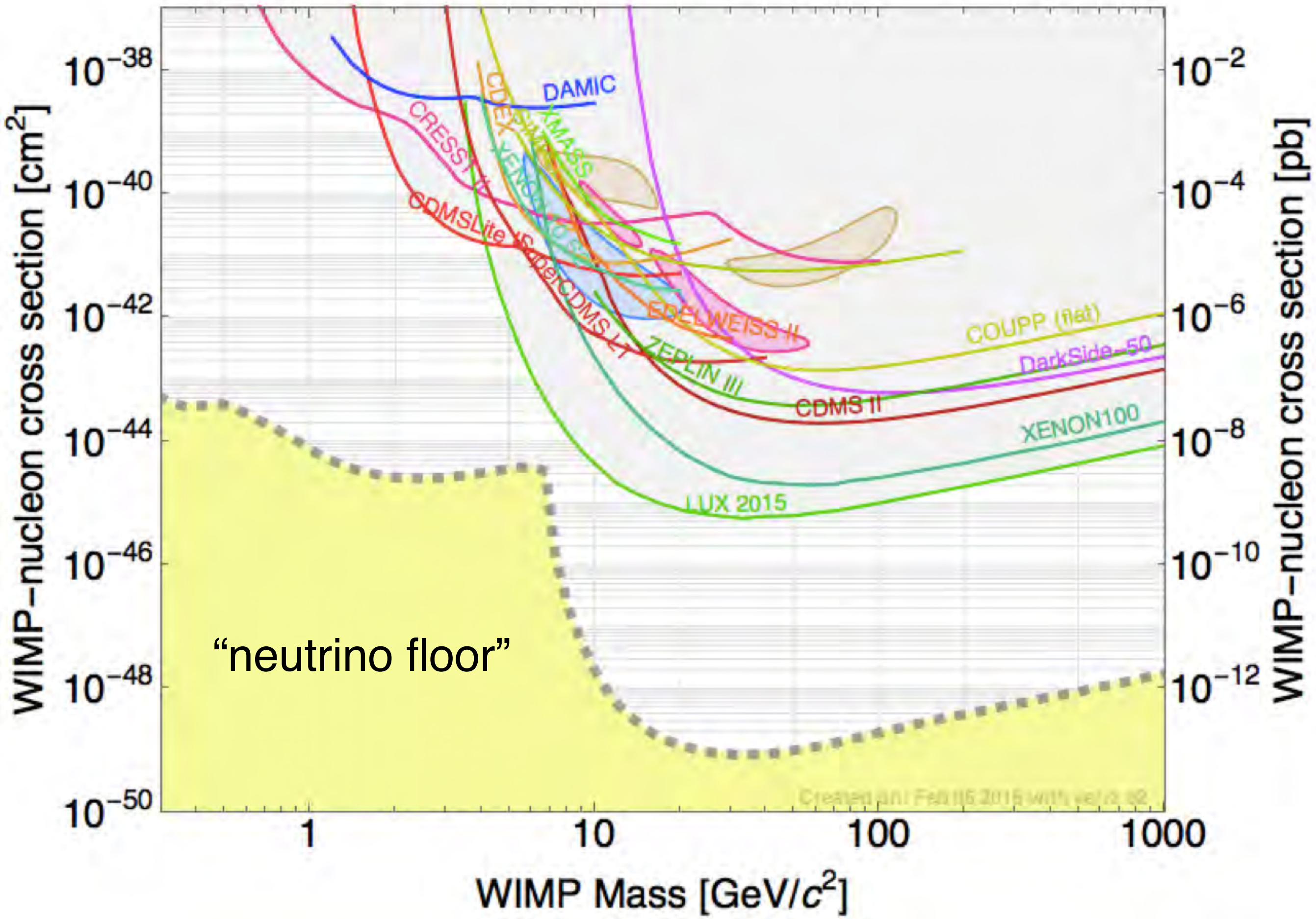
Nothing so far
Consistent with the absence of SUSY@LHC

- **at Low Mass**

Some closed contours, and strong limits

What is going on?

- **Are the closed regions a hint or just unreliable calibration**



WIMPs?

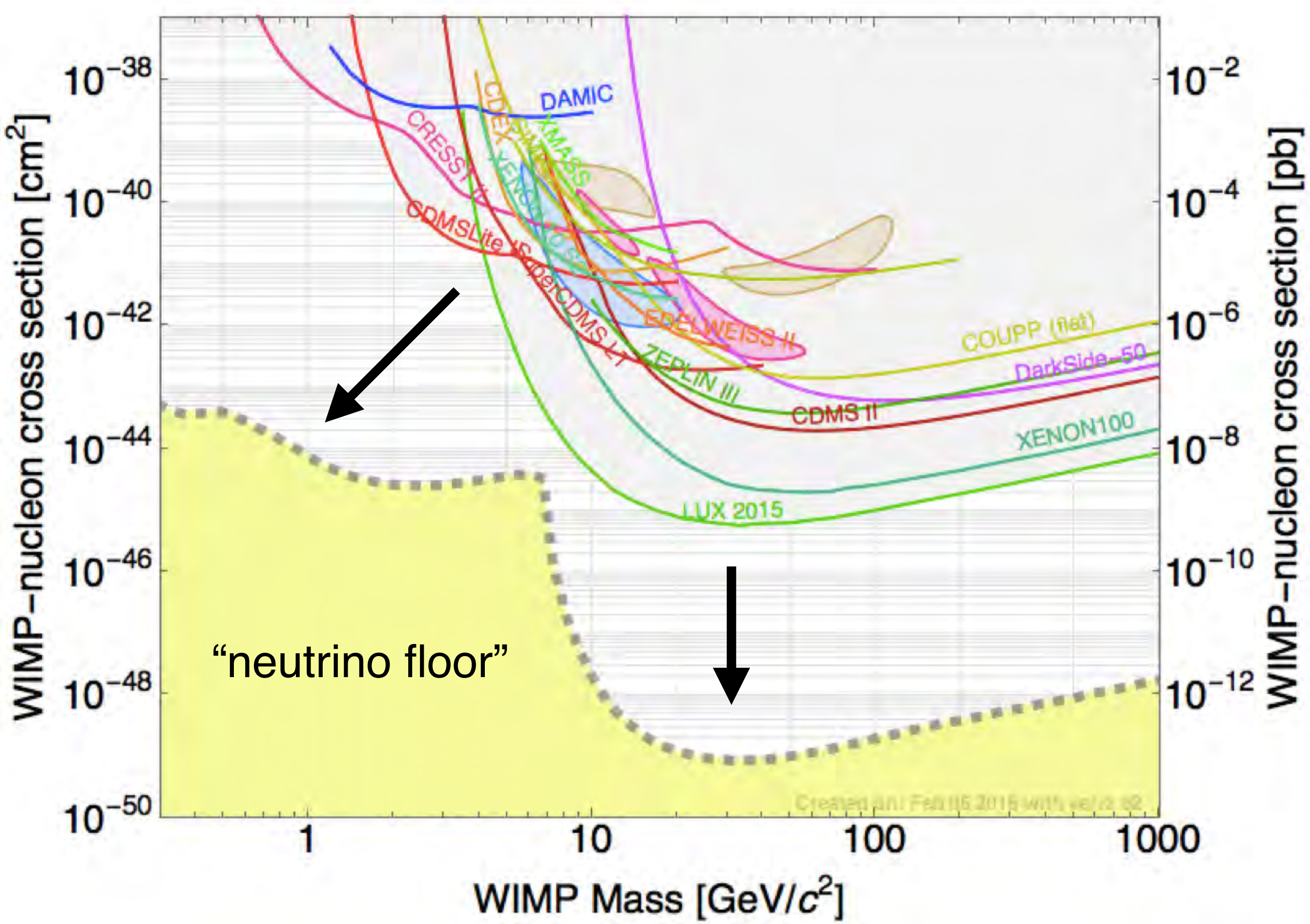
"I can't tell you what's in the dark matter sandwich. No one knows what's in the dark matter sandwich."

Many Recent Technical Advances

but oh dear, what to do?:

- try low WIMP mass
- try bigger targets for high WIMP mass
- double check old “signals”
- seek better signal —> CYGNUS-TPC

~Current Situation



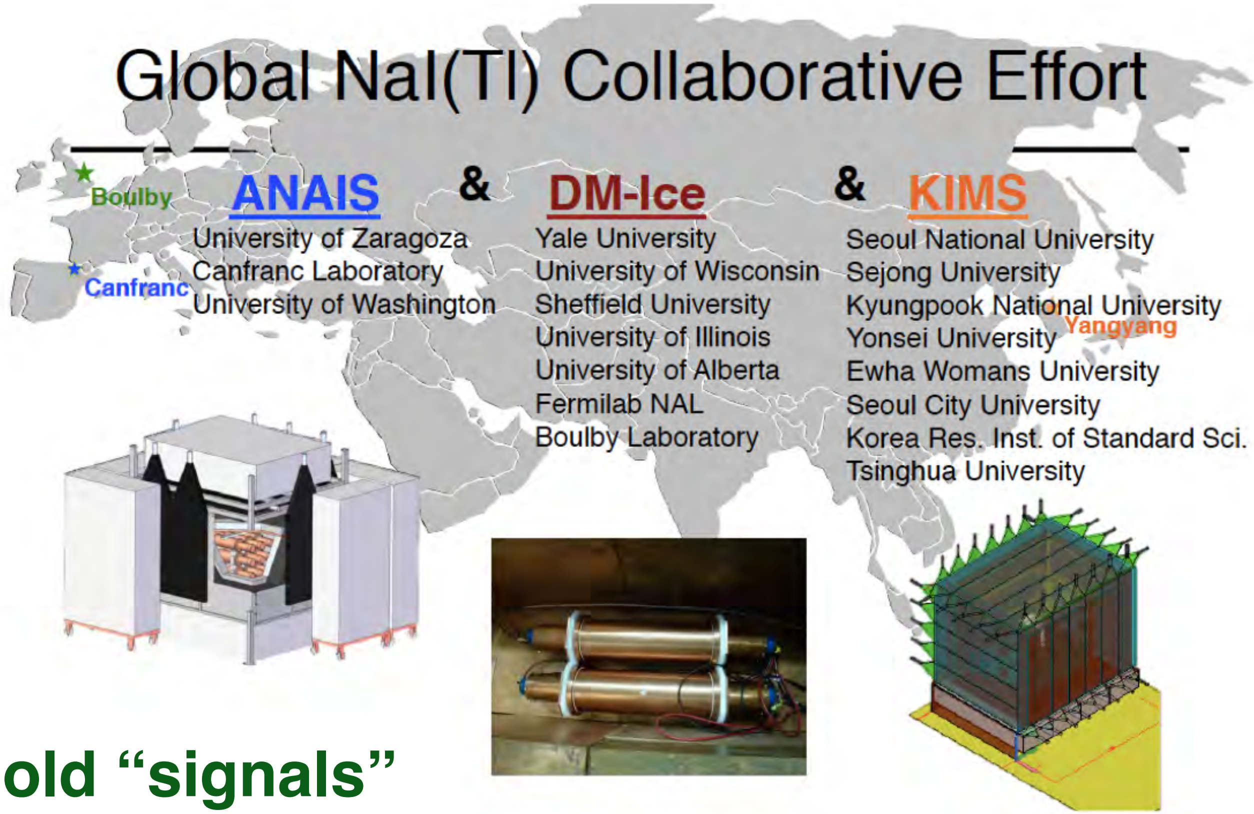
▸ **Strategy**

1. Improve sensitivity at low mass (lower the threshold)
2. Improve sensitivity at large mass (increase target mass)

Annual Modulation Attack

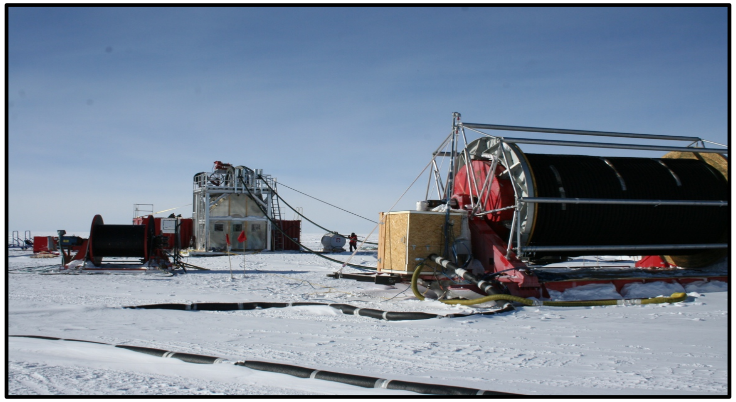
- Renewed global efforts of annual modulation in NaI
  - ANAIS (Spain)
  - DM-ICE (US-UK)
  - KIMS (S. Korea)
  - Sabre (US-Italy)

→ COSINE (joint analysis)

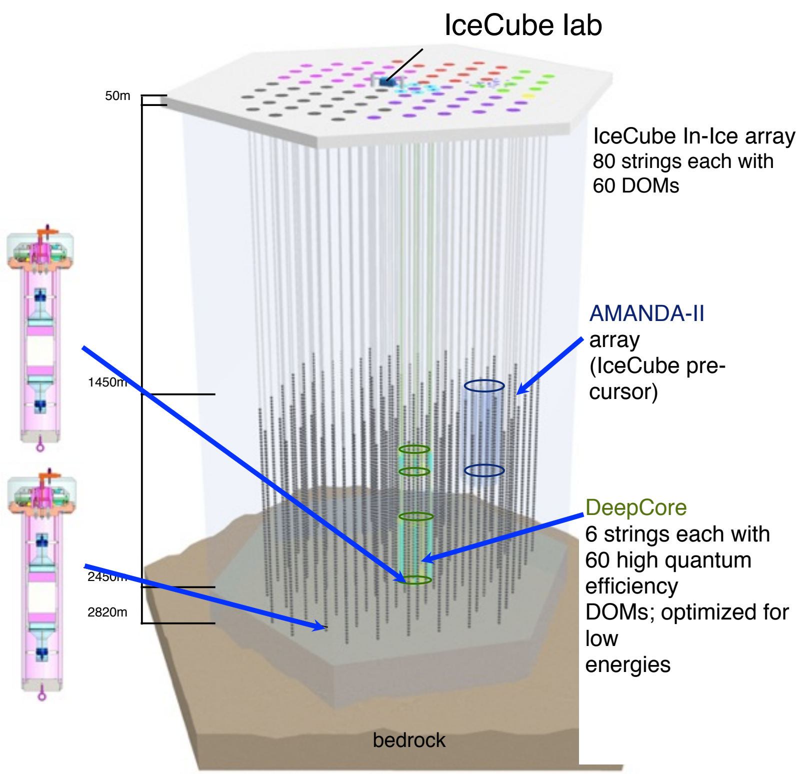


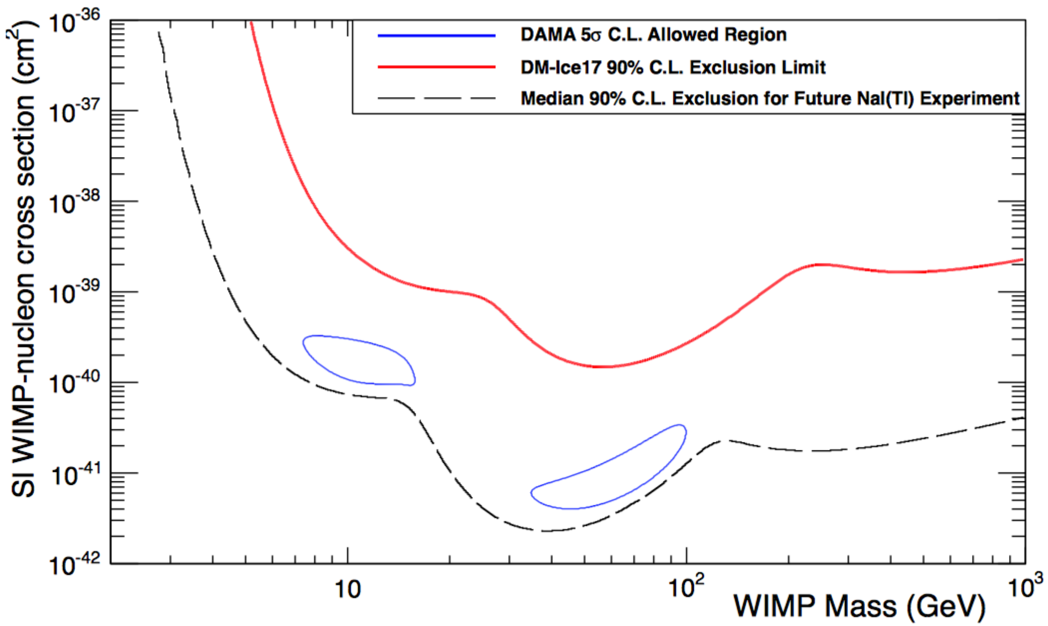
- double check old "signals"

First DM-ICE Result Just Published



- 17 kg, 2.5 km below South Pole
- Original UK NAIAD experiment NaI crystals from Boulby





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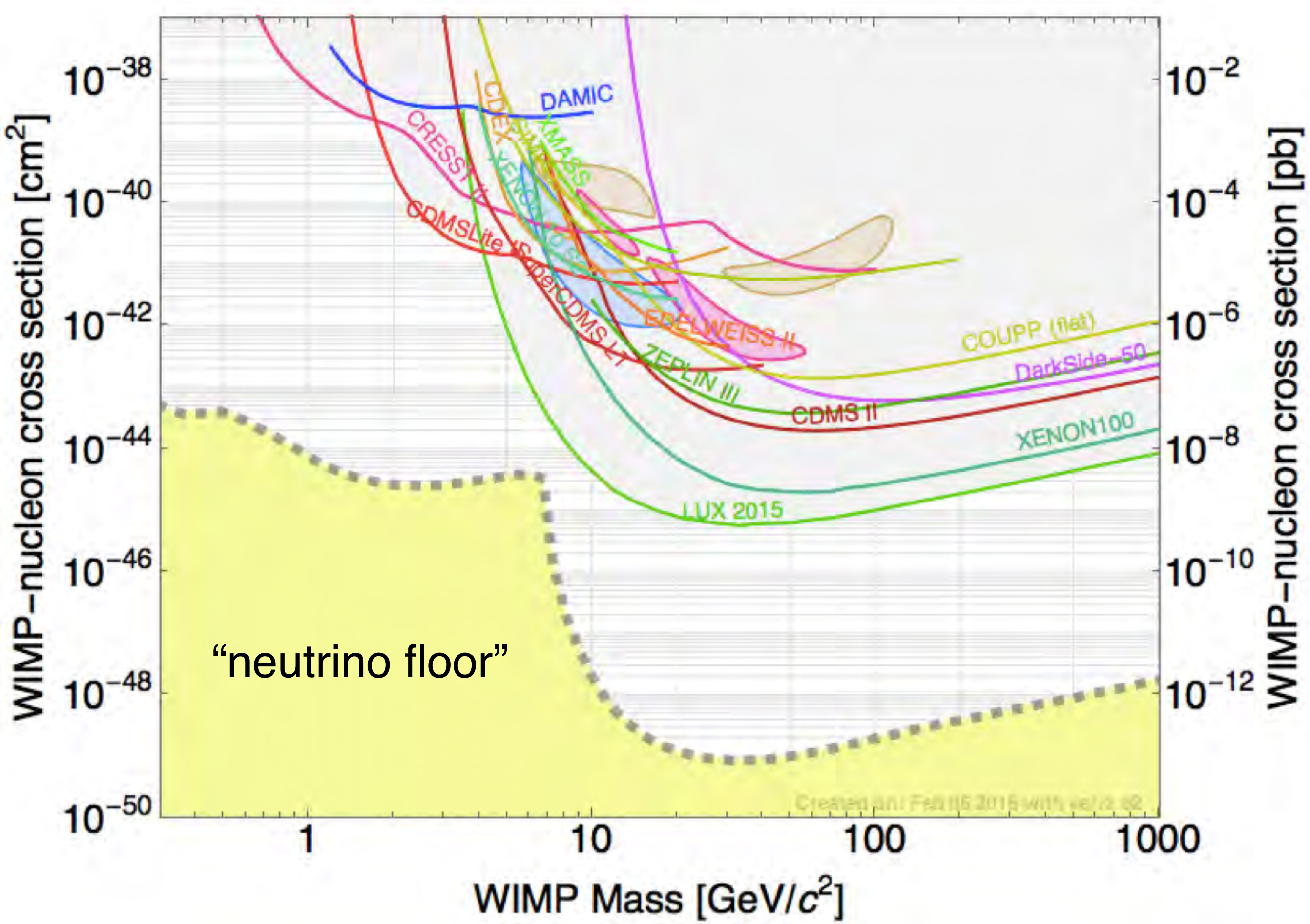
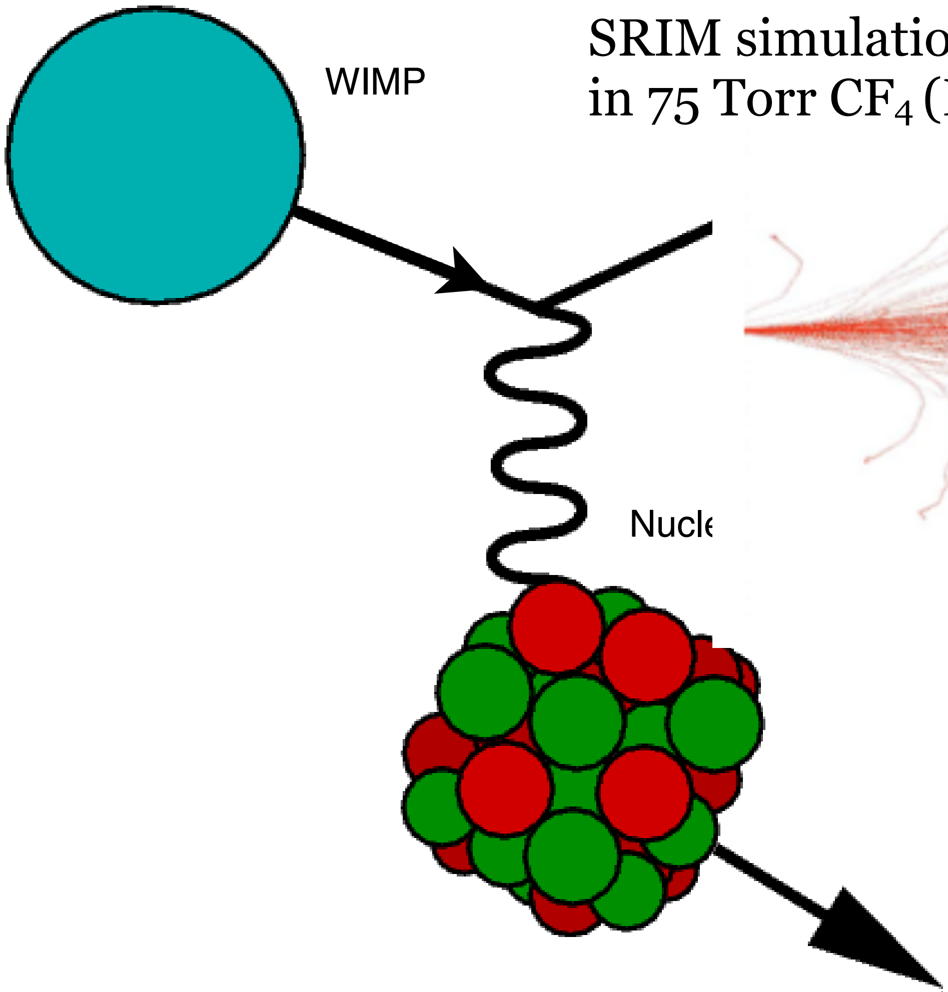
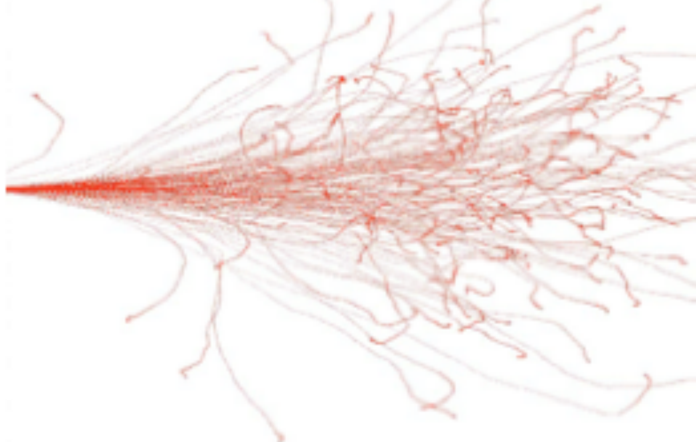


What a WIMP Does



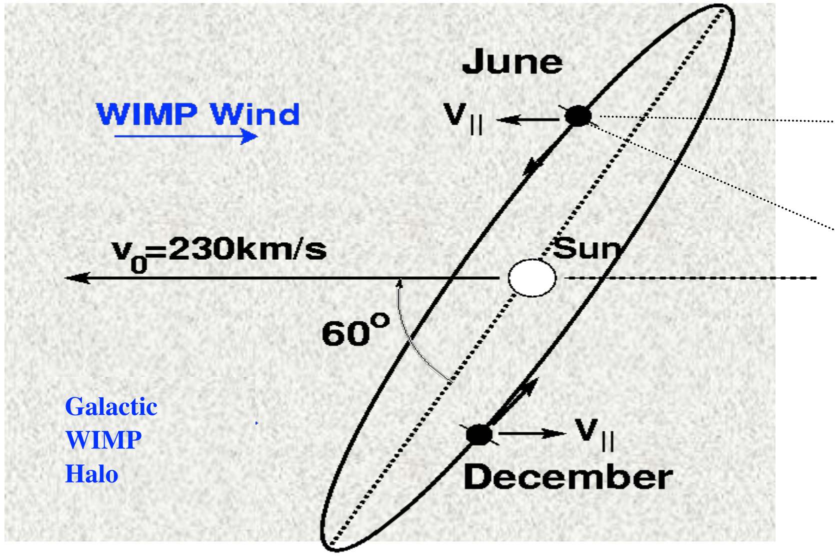
SRIM simulation - 100 keV F recoil in 75 Torr CF_4 (D3 collaboration)

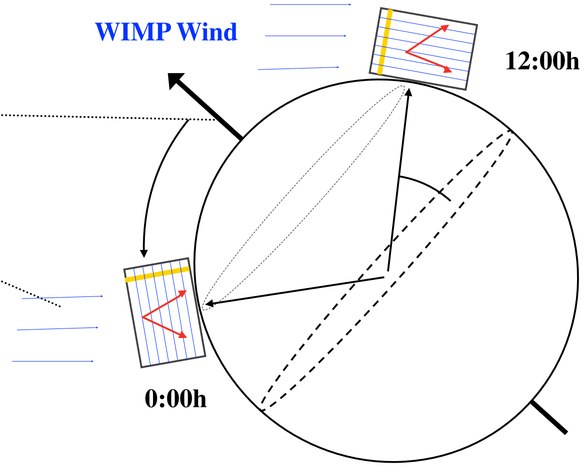


- **seek better signal —> CYGNUS-TPC**

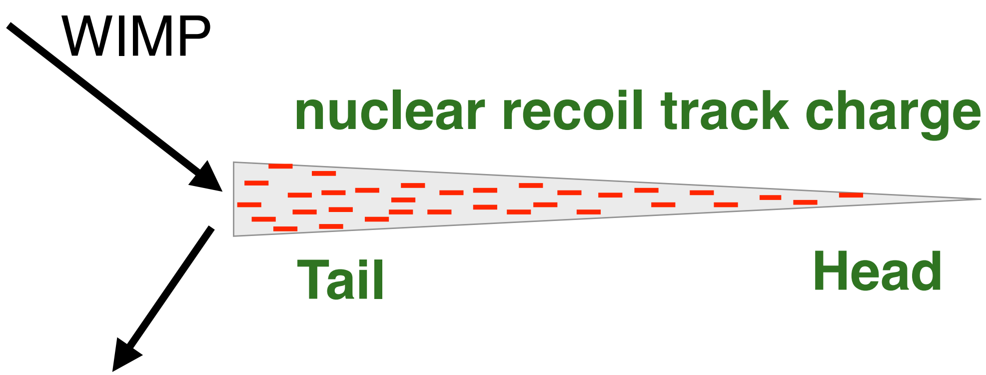
What About a Signal for WIMPs?

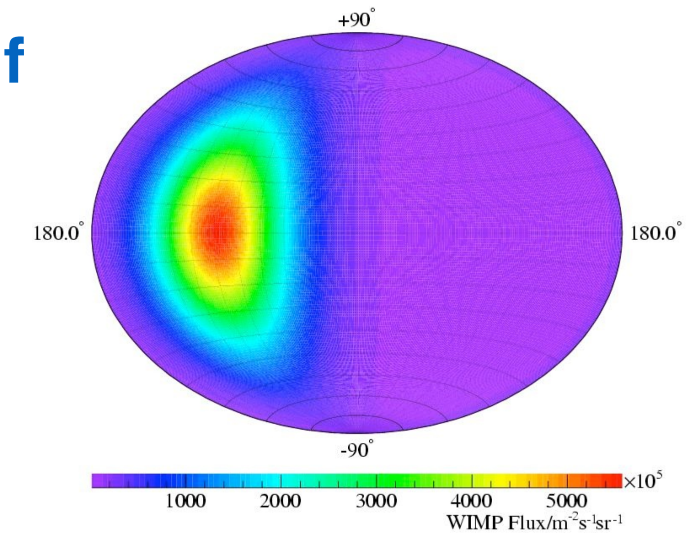
- A directional recoil signal is a very powerful proof
- Lets be prepared!





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





CYGNUS Collaboration

- **Changing from workshop into a collaboration**

2007 Boulby, UK
2009 MIT, US
2011 Modane, France
2013 Toyama, Japan
2015 Occidental, US

- Recognise the challenge of scale-up
- Consider many techniques

Solid vs. Gas?

- **CYGNUS includes both, but focus here is gas TPC**

A directional technology with higher density would be nice? But a long history of looking has not so far produced much success.

- Nuclear Emulsions
- $ZnWO_4$
- Carbon nanotubes
- Columnar recombination

non-gas

Currently low pressure gas remains most promising

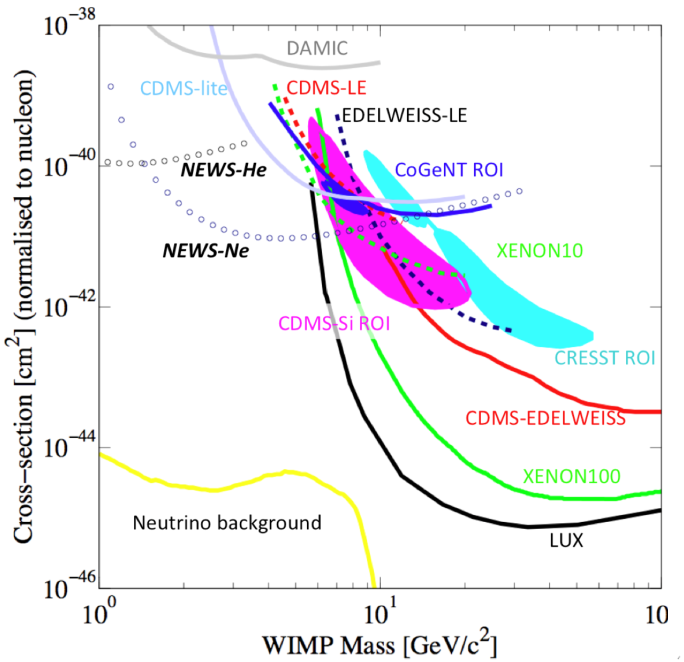
- D3
- DM-TPC
- DRIFT
- MIMAC
- NEWAGE
- *ITALY*

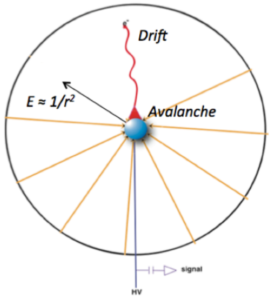
gas

Low Mass Non-Directional TPCs

- Interest in gas TPCs just for low mass WIMPs with no directionality is growing

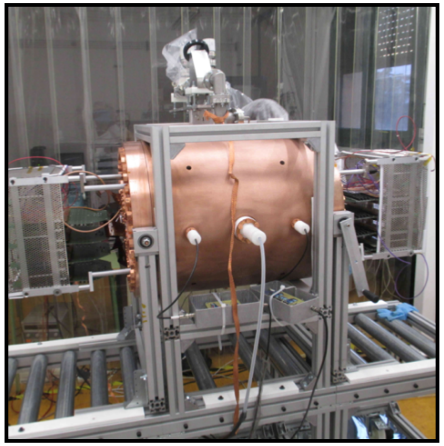
- Low threshold gas TPC





NEWS
(SNOLAB)

TREX
(~CANFRANC)

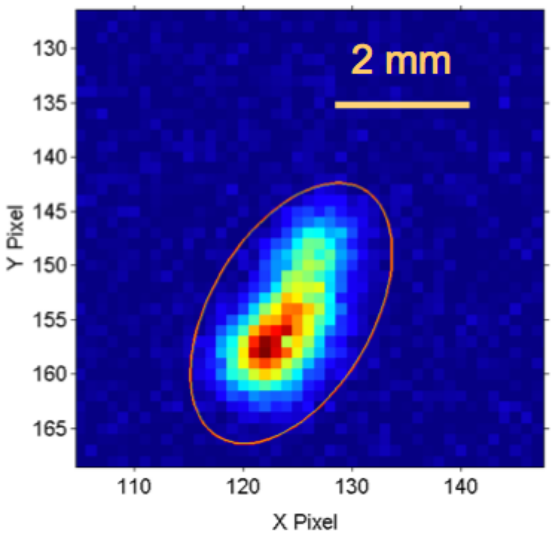


- Low aim for low energy threshold, ~no discrimination

Power and "Vision" of Directionality

- Strong particle identification from topology

  (at least in a gas TPC)



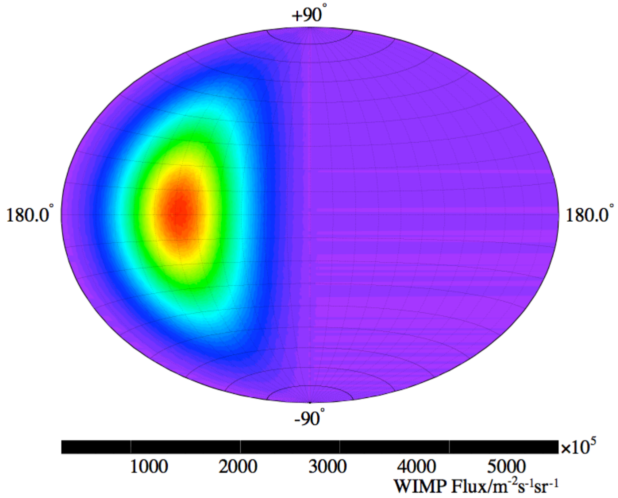
example high energy F recoil in optical TPC (D. Loomba et al.)

- Total ionisation
- Particle range
- dE/dX topology
- Track orientation (axial)
- Track sense (head-tail)(vector)

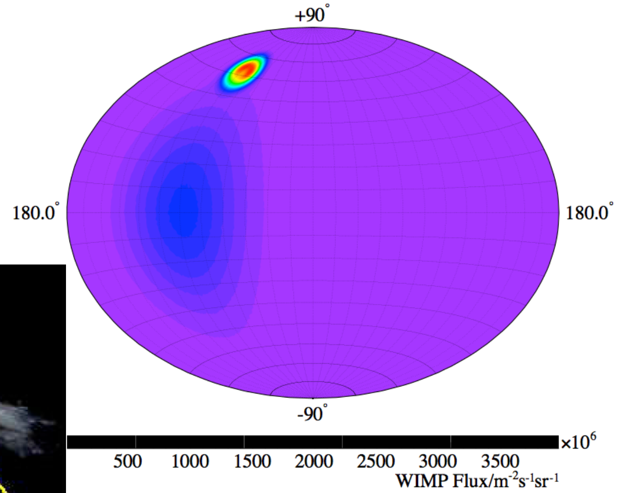
Power of Directionality

- Potential for WIMP "Astronomy"

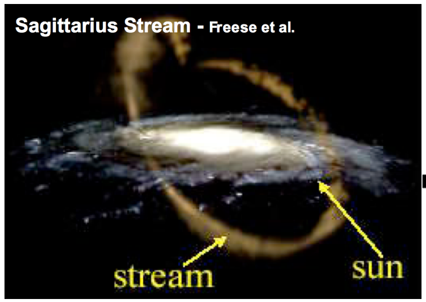
Standard Halo



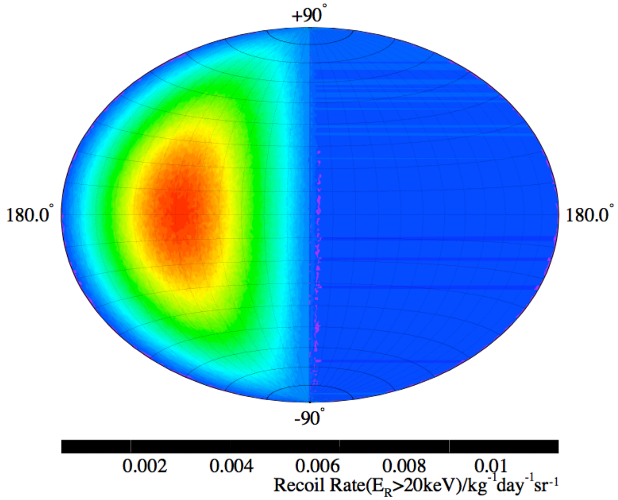
With Sagittarius Stream

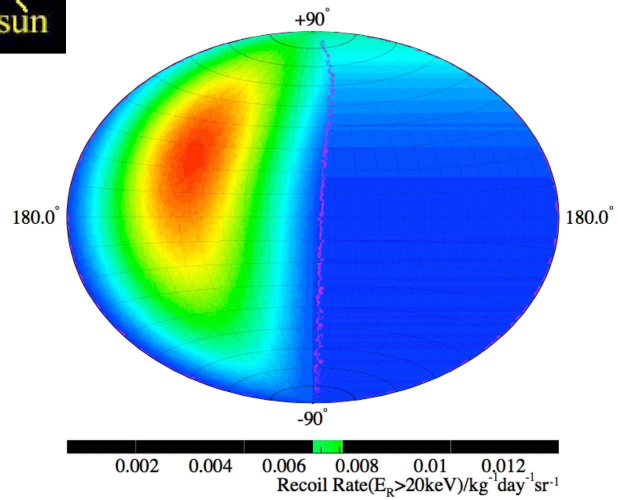


WIMP flux



S recoil flux

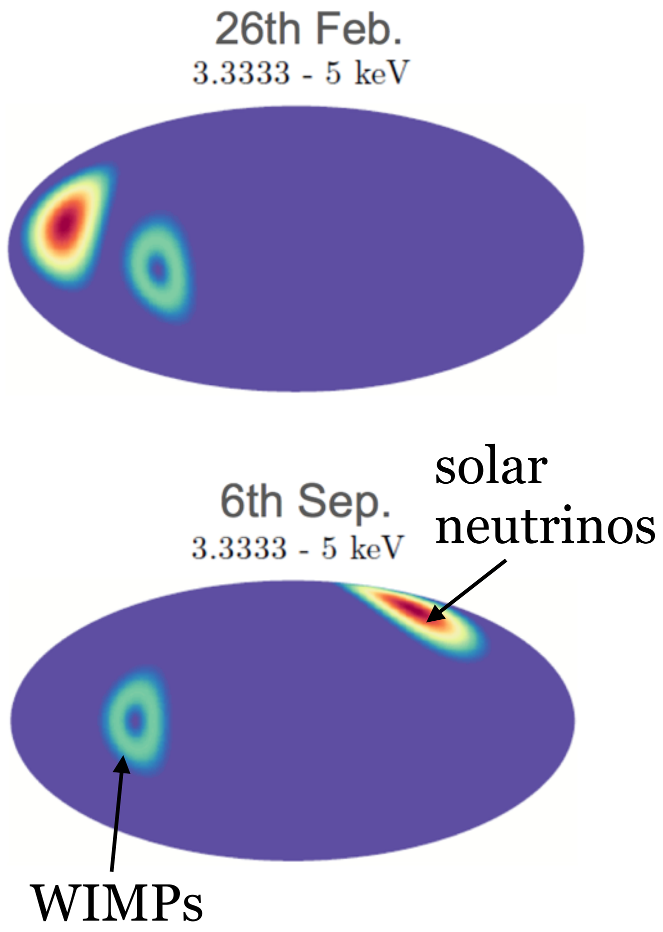


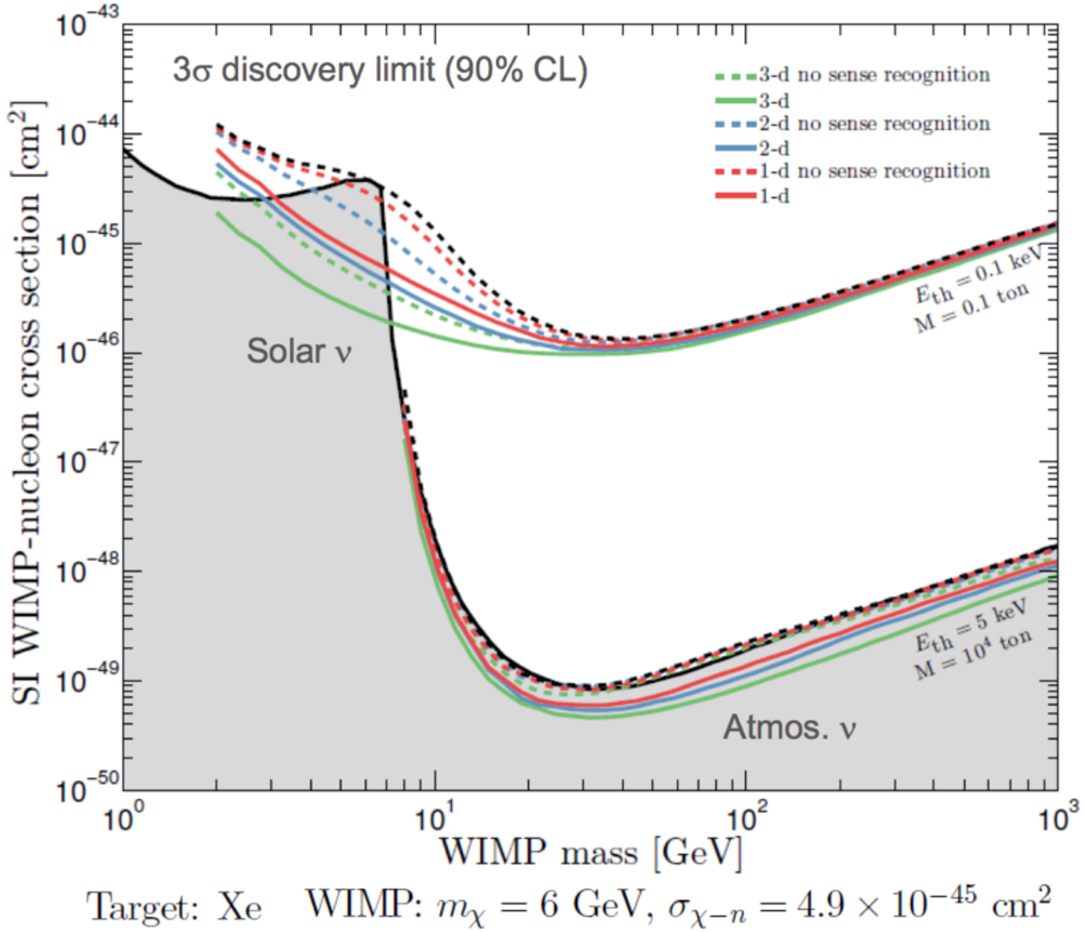


simulations by Ben Morgan (Sheffield)

Power of Directionality

- Potential to go beyond the “neutrino floor”





- position of Sun never coincides with Cygnus

e.g. C.J.G. O’Hare 1505.0806

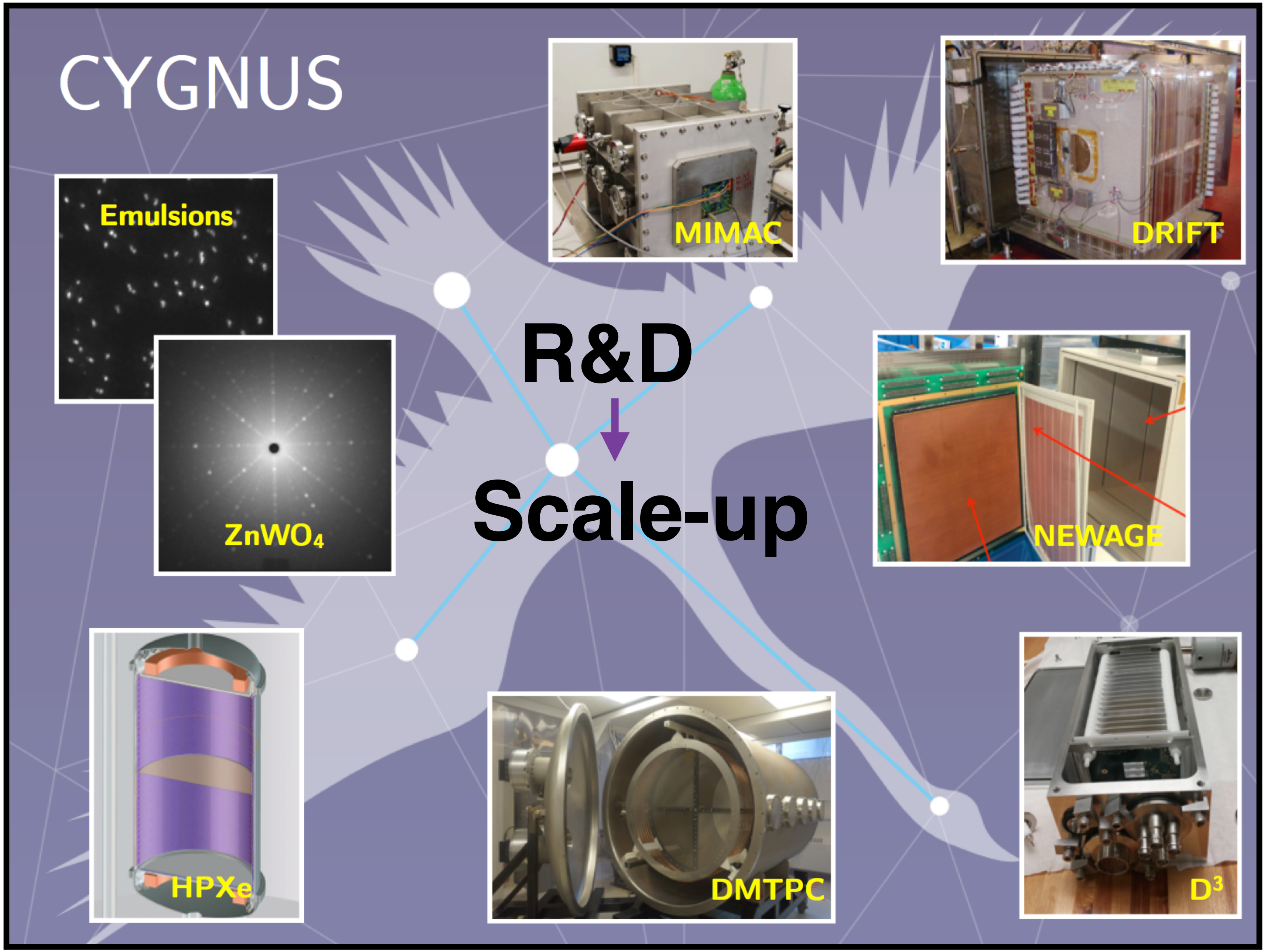
Galactic Recoil Observatory

(1) Dark matter distribution in the galaxy

(2) Directional Coherent scattering of astrophysical neutrinos

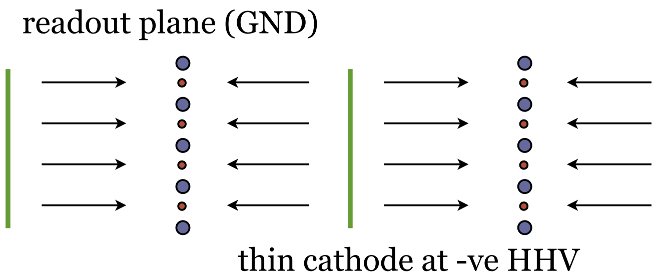
This is ambitious - but not impossible?

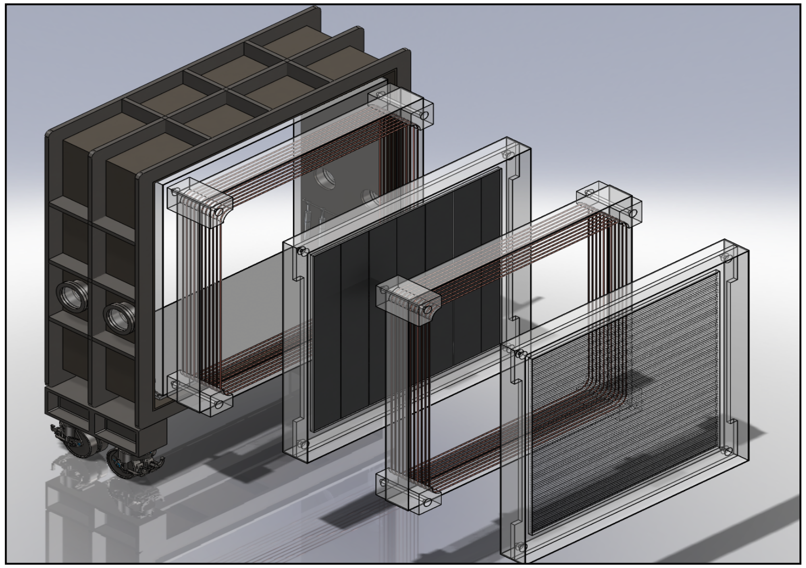
CYGNUS Groups

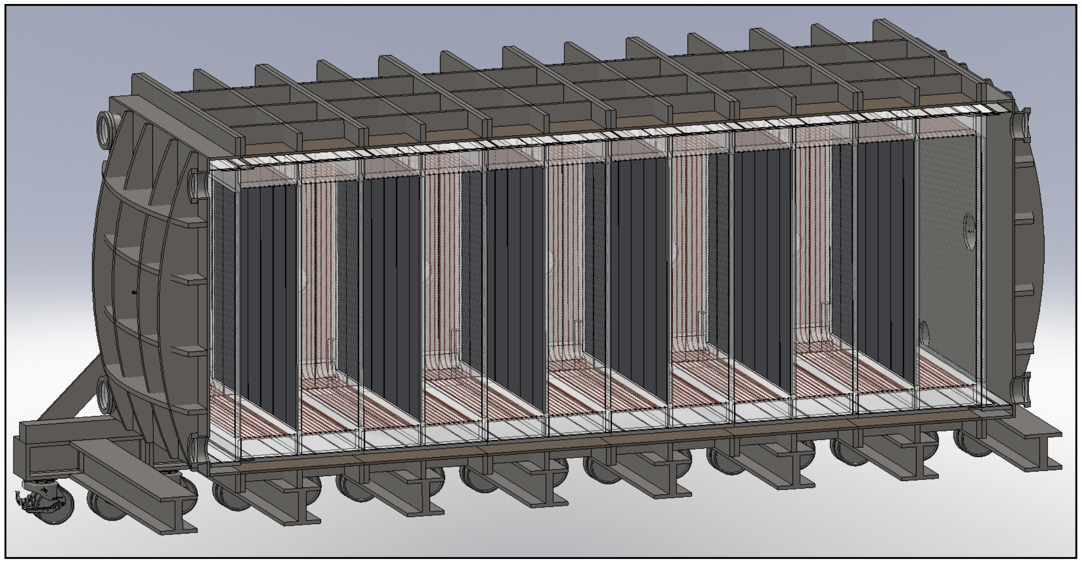


DRIFT Scale-up Concepts

- 3 modules of 8 m^3
- 4 kg target mass
- Water shield
- Simplified MWPC







What Directional TPC Technology?

- What is optimum readout and DAQ?
- What is optimum gas mixture (-ve ion?)
- Can backgrounds be controlled (radon, neutron)?
- What is optimum TPC structure and vessel design?
- Can we benefit from multiple underground site(s)

Optimising Detectors

How many WIMPs are needed to get a directional (non-isotropic) signal?:

A. Green et al., AstroP 27 (2007) 142

difference from baseline configuration	N_{90}	N_{95}
none	7	11
$E_T = 0$ keV	13	21
no recoil reconstruction uncertainty	5	9
$E_T = 50$ keV	5	7
$E_T = 100$ keV	3	5
$S/N = 10$	8	14
$S/N = 1$	17	27
$S/N = 0.1$	99	170
3-d axial read-out	81	130
2-d vector read-out in optimal plane, raw angles	18	26
2-d axial read-out in optimal plane, raw angles	1100	1600
2-d vector read-out in optimal plane, reduced angles	12	18
2-d axial read-out in optimal plane, reduced angles	190	270

upgraded and unrealistic

assuming perfect angular resolution

A conclusion

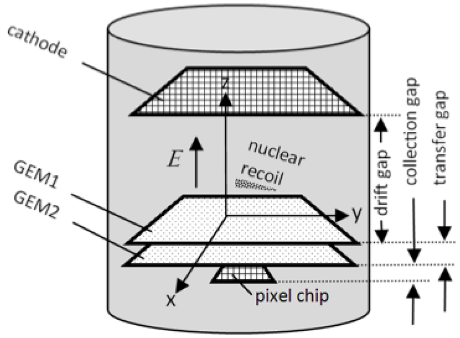
head-tail discrimination ("vector") may be more important than 3D reconstruction (however, 3D may be important for background rejection).

What Directional TPC Technology?

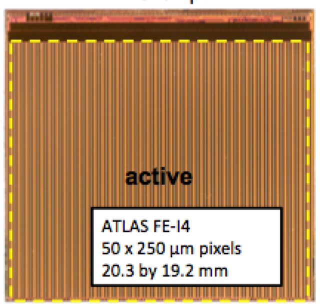
"high definition - 3D"

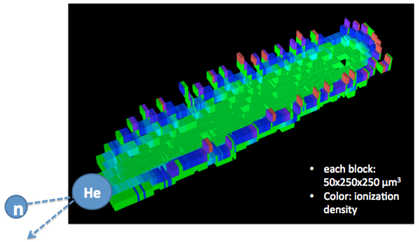
e.g. D3 - pixel e.g. DM-TPC - CCD

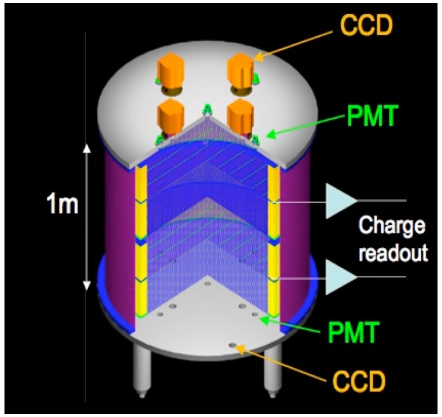
small volume R&D

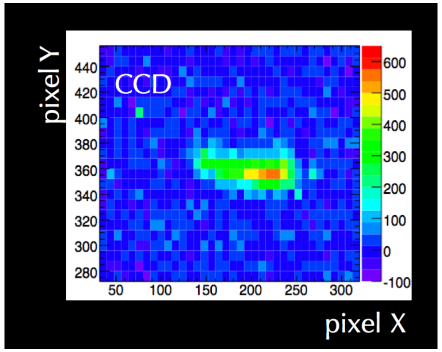


Pixel chip:





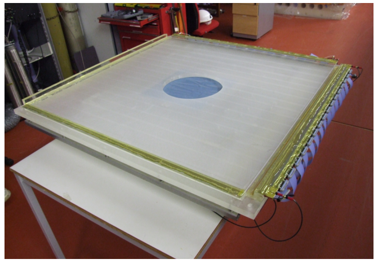


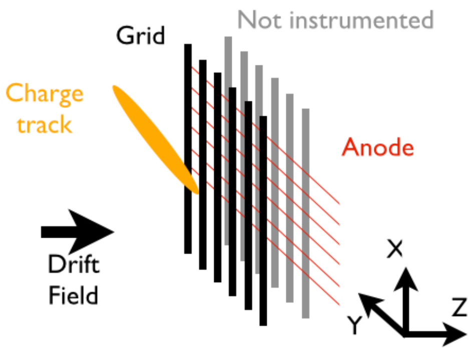


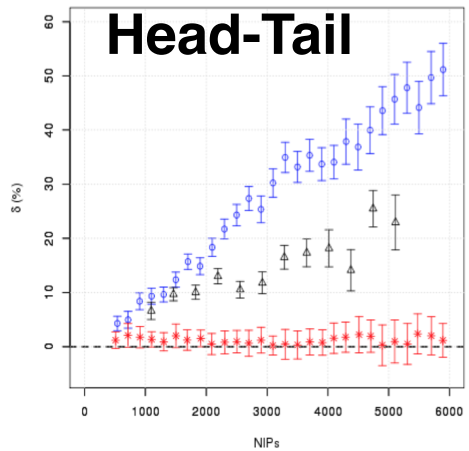
"low definition ~ 1.5D"

e.g. DRIFT - wires

larger volume R&D, low background







What Directional TPC Technology?

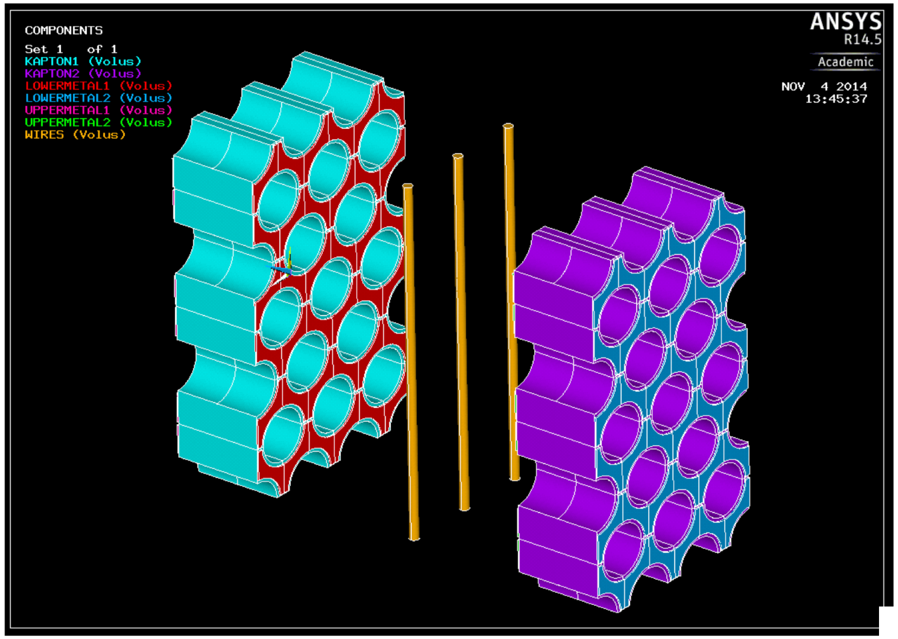
Trade-offs

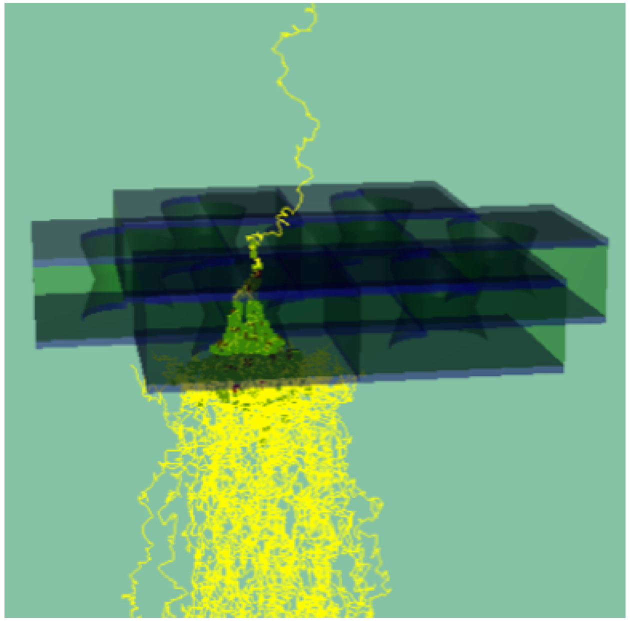
High Definition 3D	⟷	Low Definition 1D with HT
Higher cost/volume	⟷	Lower cost/volume
Lower WIMP mass	⟷	Higher WIMP mass
Lower target mass	⟷	Higher target mass

Is there a compromise?

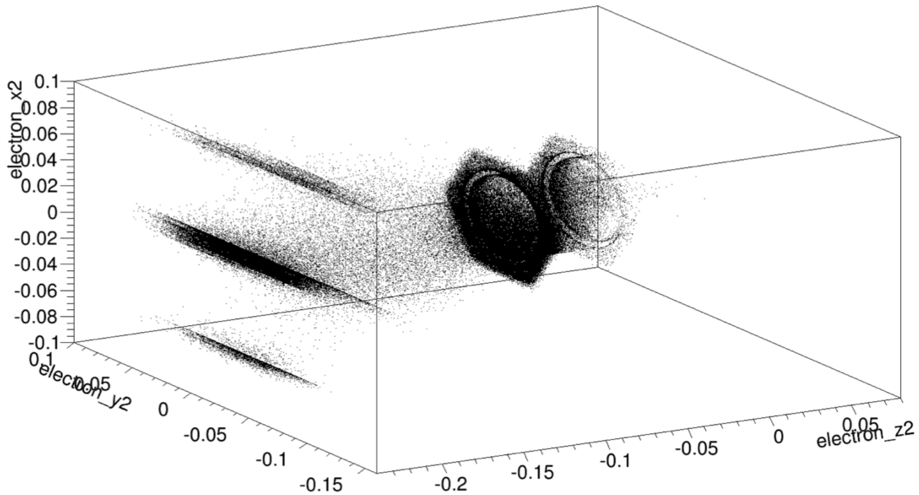
MWPC-GEM Hybrid?

Dan walker (Sheffield)





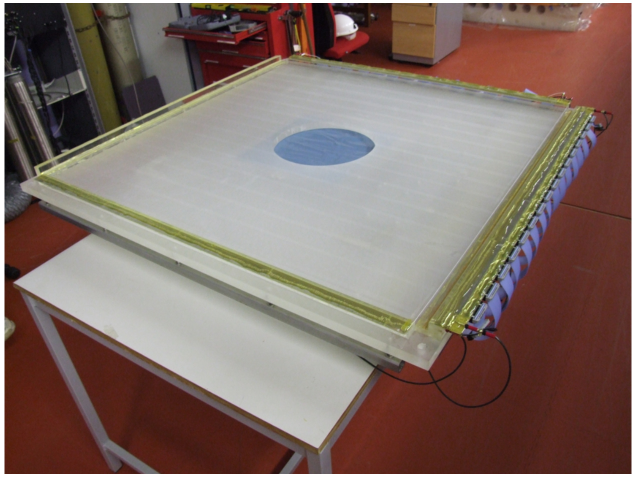
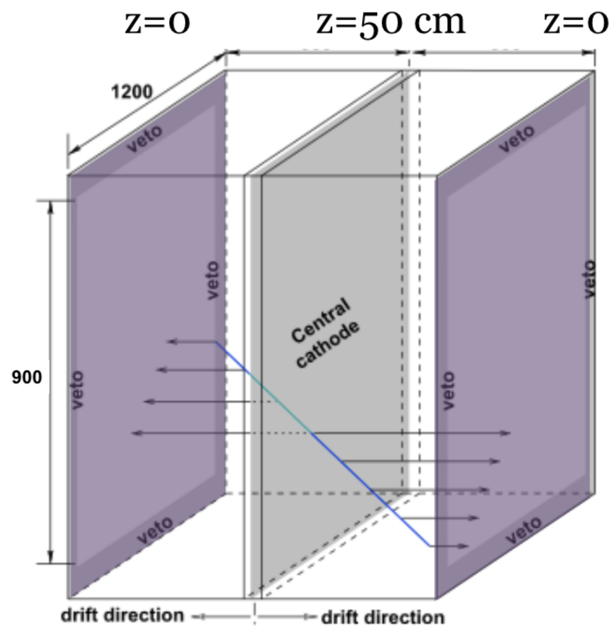
Final positions of the avalanche electrons



- Use GEMs at amplifier stage for wires
- Garfield++ simulations

Some Exciting Advances - DRIFT

- Use low pressure negative ion gas

Significant advances recently:

- Z-fiducialisation using minority carriers in CS_2:CF_4:O_2

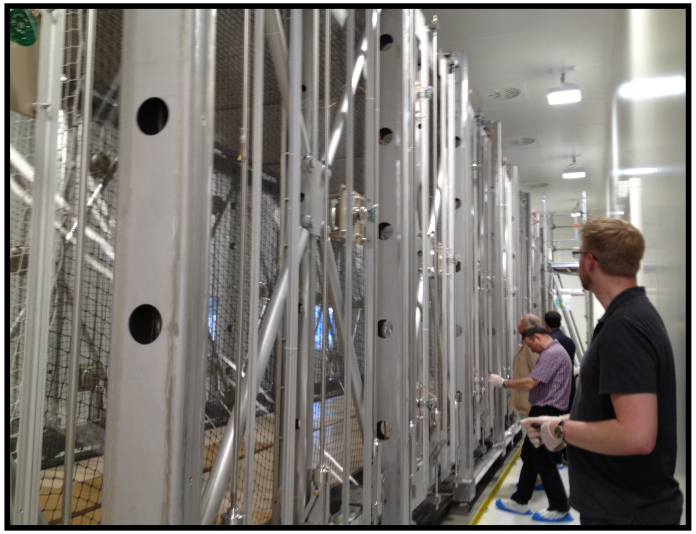
  Real prospects for “zero” background

- Head-tail sensitivity with this mixture
- Use of SF_6 -ve ion drift - improved target mass (UNM)
- Large volume TPCs are quite feasible

How Not to be Afraid of Large TPCs

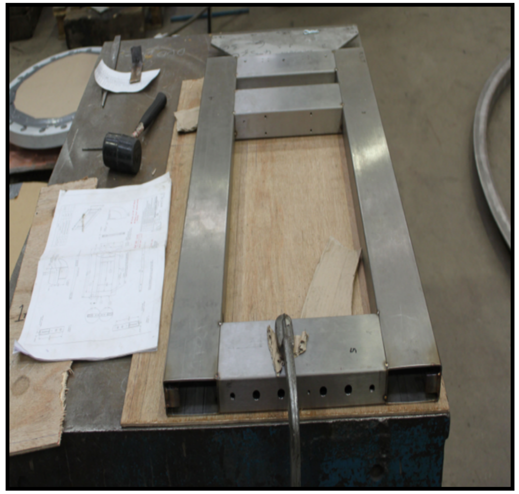
- Example - something the size of ICARUS (used for LAr)
- Size: 2 x ~18 x 3 x 3 m, central cathode, 1.5m drift
- **Would contain ~ 0.5 Tonne Fluorine (SF_6) @ 200 Torr**
- **Size of full CYGNUS-TPC is <100th scale of proposed DUNE liquid argon TPC**



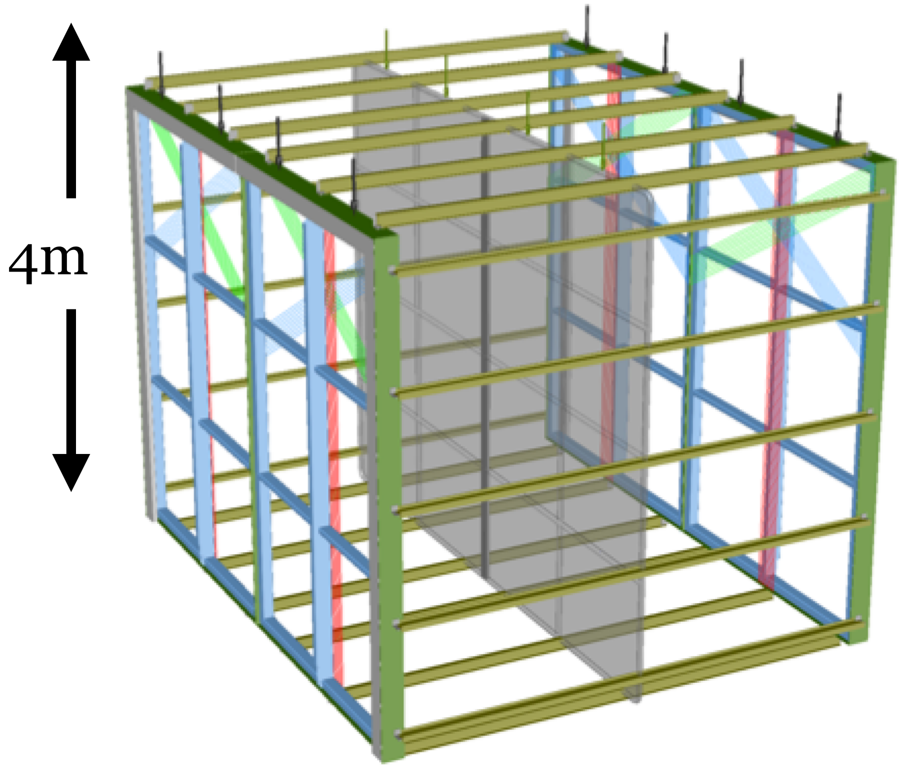


How Not to be Afraid of Large TPCs

- We can learn from the UK-US funded Liquid Argon neutrino TPC community at FNAL
- Proposed DUNE TPC is ~ x100 bigger than a full CYGNUS-TPC



- SBND experiment new TPC - UK construction

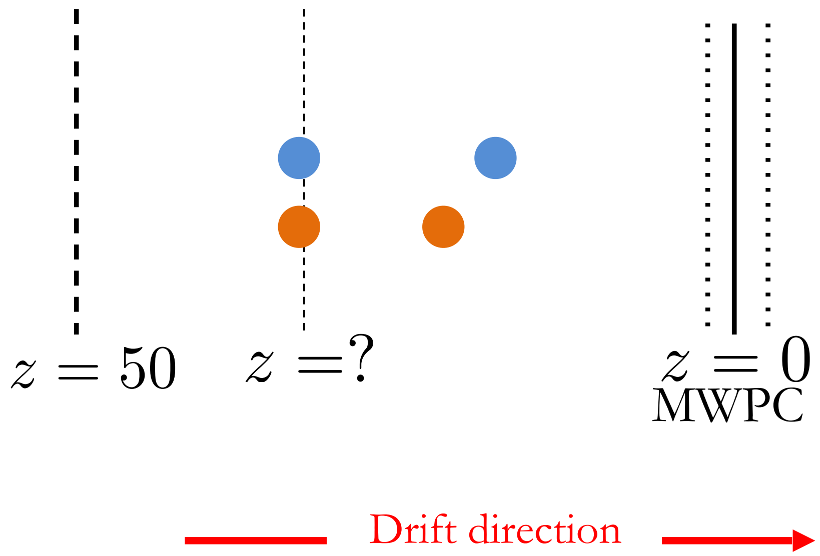


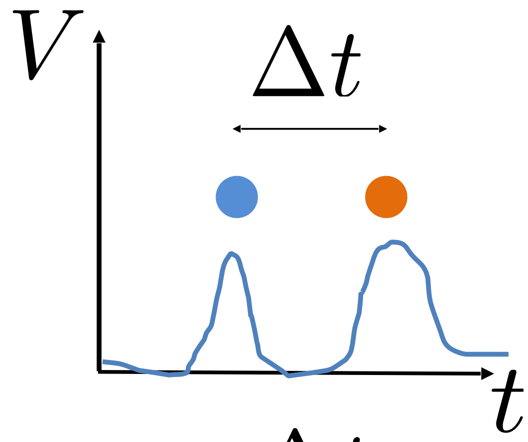
- Tests of steel and carbon fibre

- Sheffield is building the Anode Plane Frames

z-Fiducialization

- Use of different drift speeds of carriers





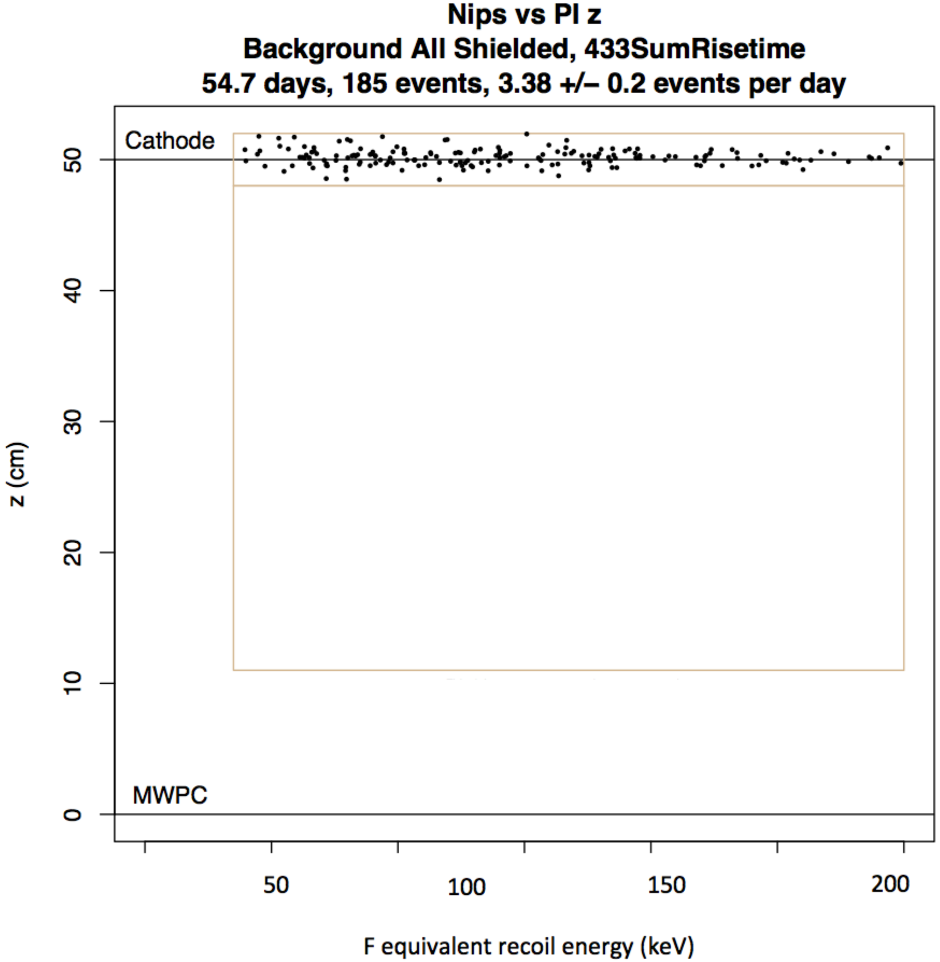
$z \propto \Delta t$

Proportionality constant can be measured for various gas mixtures, or calibrated in-situ.

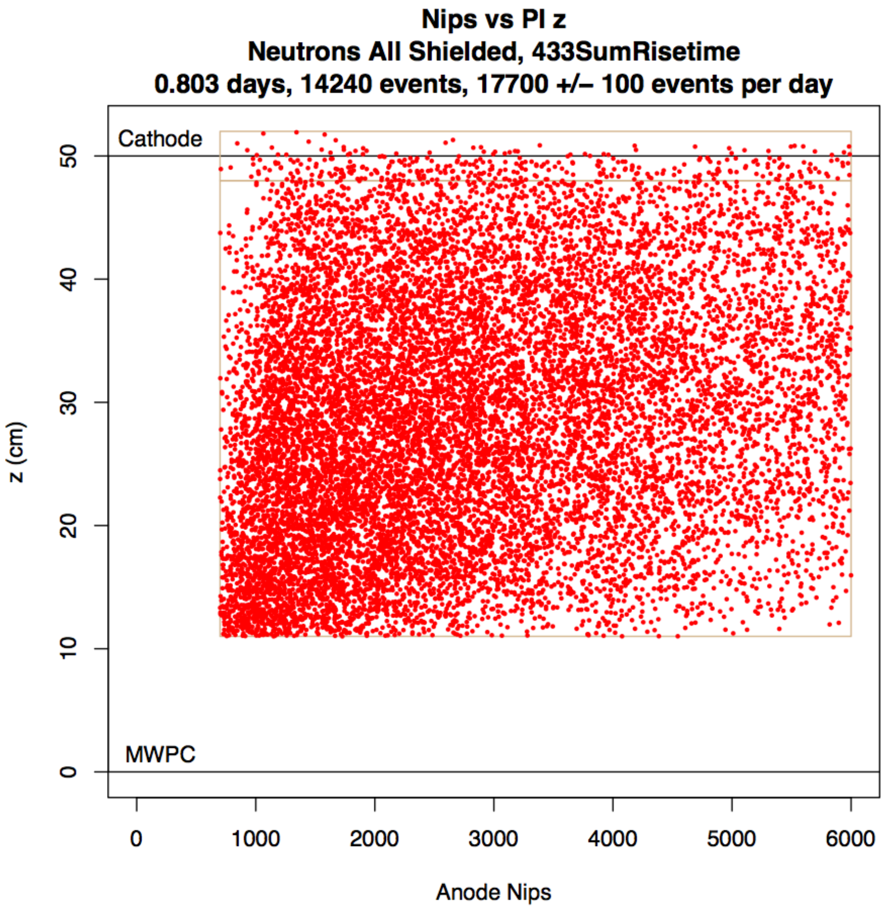
DRIFT - 3D Fiducial with Head-Tail

- DRIFT-IId now runs zero background, only volume limited

Shielded 30-10-1 CS_2-CF_4-O_2 Data

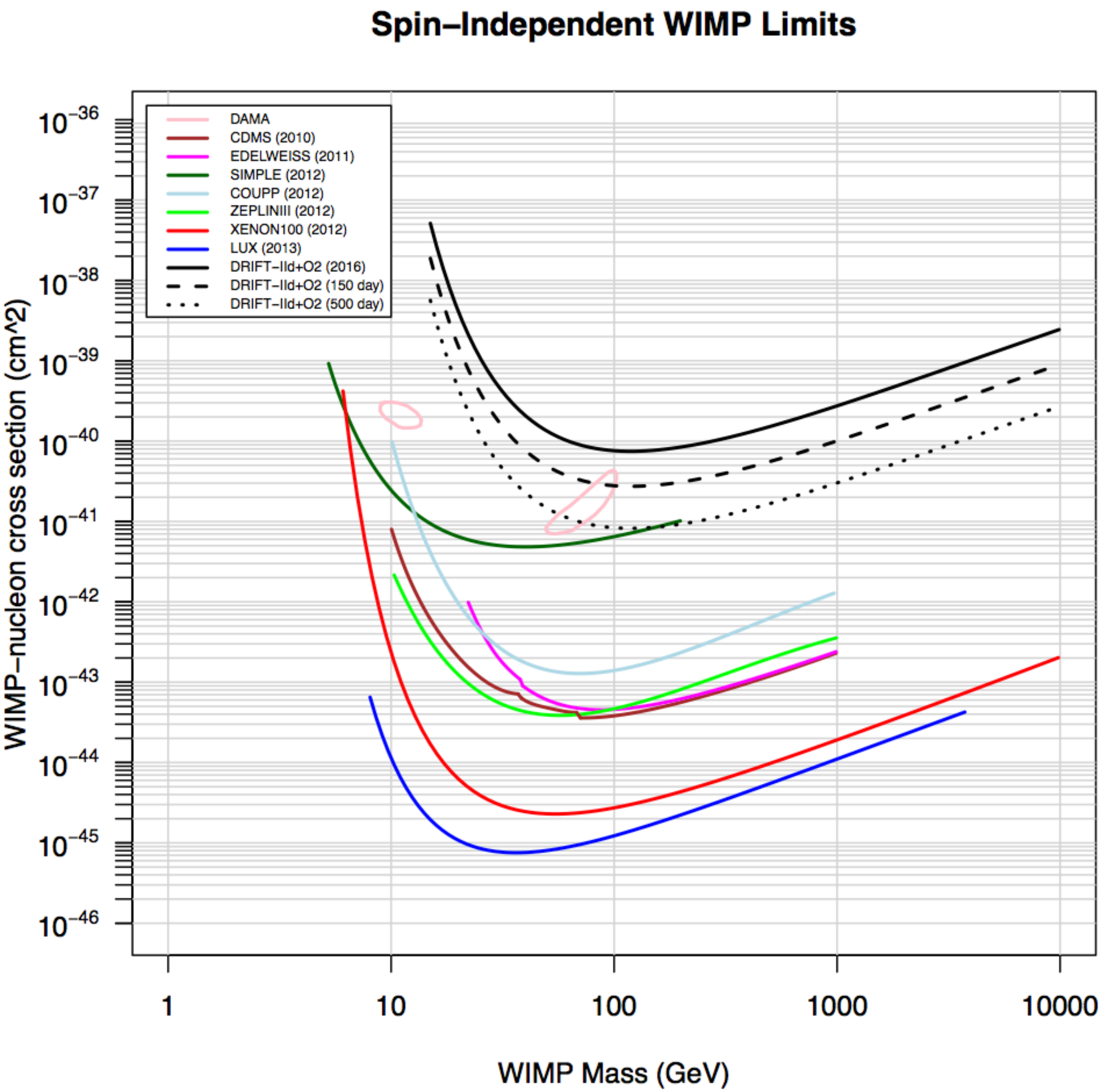


Cf-252 Neutron Calibration Data



DRIFT-II - 3D Fiducial with Head-Tail

- **Towards ruling out DAMA <u>- with 1 m³</u>**

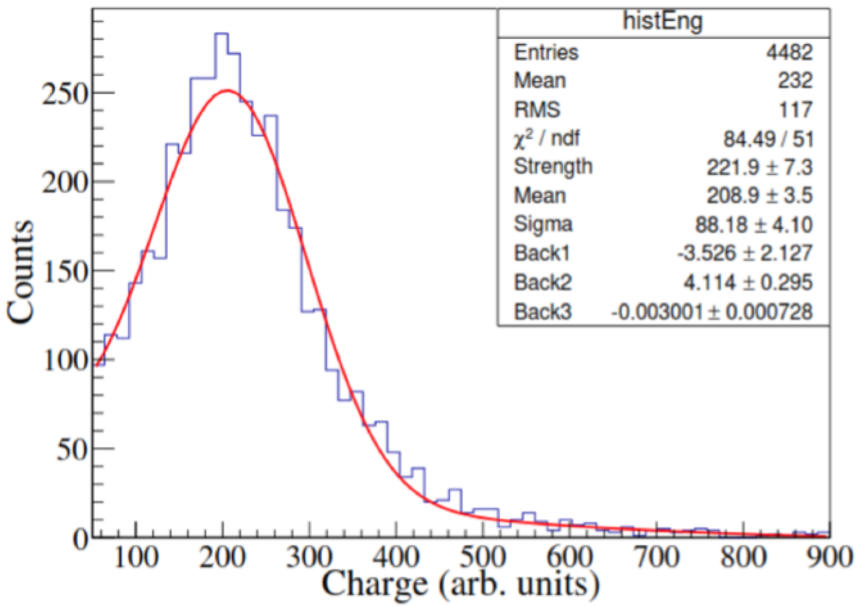


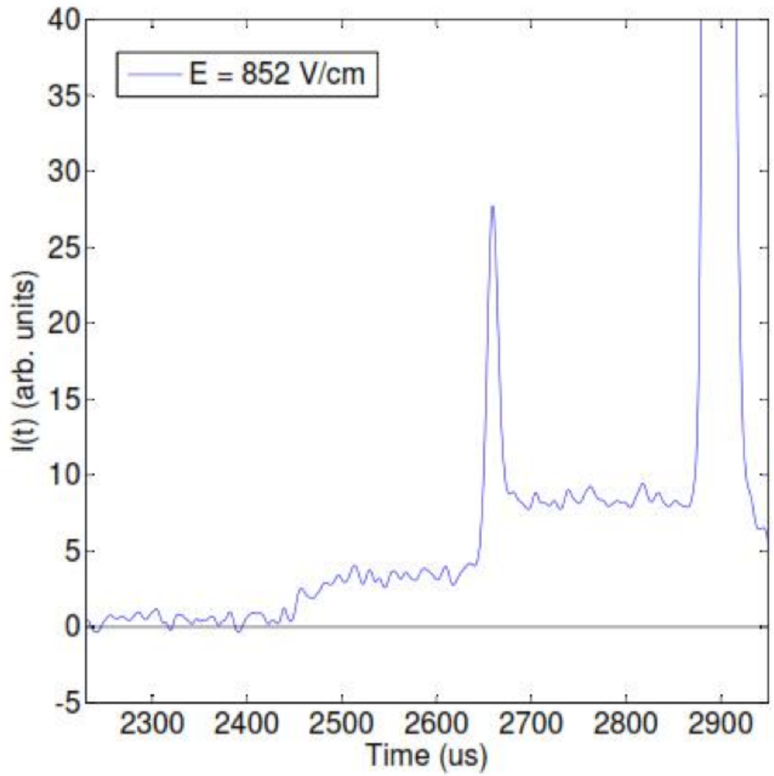
- **Achieved with ~130 g target**

New SF_6 Breakthrough

N. Phan, University of New Mexico

- First demonstration of SF_6 as a -ve gas (with GEMs)
  - ^{55}Fe spectrum in 40 Torr SF_6 with 0.4mm GEM
  - Gain curves up to 2.5×10^4
  - z-fidusialization with SF_5^- shown (20 Torr, laser events)





CYGNUS Proposal MOU

The CYGNUS Galactic Nuclear Recoil Observatory
Memorandum of Understanding for a new International Experiment

1. Motivation and Proposed Experiment

There has been major progress world-wide in recent years in the development of ultra-sensitive, low background gaseous time projection chambers (TPCs) capable of recording the direction of sub-100 keV nuclear recoils induced by elastic scattering from incident neutral particles. Much of this work has been undertaken in the context of the international CYGNUS collection of groups interested in directional detection of dark matter. However, such powerful recoil direction sensitive technology, when combined with the prospect of deployment of large devices in multiple underground sites at different latitudes on Earth, opens the unique prospect of building a global **Galactic Nuclear Recoil Observatory** facility with multiple science goals. Such an observatory would for instance have ability not only to search for a directional signal from particle dark matter, thought to be incident on Earth from the direction of the Cygnus constellation, but simultaneously to detect and measure a directional signal due to coherent scattering of neutrinos from the Sun. The directional capability would provide a route to a definitive signal for dark matter particles not feasible with conventional non-directional dark matter experiments and allow a powerful first detection of solar neutrinos by elastic scattering correlated with the position of the Sun.

This memorandum sets the basis for formation of a new collaboration, we call CYGNUS, to construct a TPC-based observatory aimed firstly at these two exciting new goals. We envisage the ultimate CYGNUS TPC to be an experiment of 10-ton target mass distributed in five underground sites in both northern and southern hemispheres. This would incorporate full 3D reconstruction of elastic nuclear recoil events and full event fiducialisation in x, y, and z dimensions, necessary to achieve zero background. It is already possible to contemplate constructing such an experiment based on current technology and available space in underground sites. However, we foresee advantage in a staged programme towards CYGNUS comprising two "pathfinder" projects, CYGNUS-P1 and CYGNUS-P2. These pathfinders are aimed at down-selecting and optimising the readout and engineering concepts respectively, whilst also providing intermediate and world-leading science sensitivity on shorter timescales prior to deployment of the full CYGNUS facility.

2. The CYGNUS Galactic Nuclear Recoil Observatory

As stated the ultimate CYGNUS experiment will include 3D reconstruction capability for recoil events and incorporate full event fiducialisation in x, y and z dimensions. Both heavy and light target nuclei would be used, notably F, He and Xe, with the possibility to vary both the composition and pressure up to 1 atmosphere. This will allow directional sensitivity covering the region equivalent to 1-1000 GeV mass for dark matter particles with cross section around and below the "knee" in the coherent neutrino spectrum in the region around 10 keV recoil energy. A simple modular and elongated detector design with room temperature operation will enable installation in multiple underground sites in both northern and southern hemispheres, suitable for both mine-type sites and road tunnel-type sites. Correlation of the direction of recoils in galactic coordinates from sites at different Earth latitudes facilitated by this is a ground-breaking feature of CYGNUS. It provides a route to exceptional control over systematic errors arising from terrestrial daily and seasonal phenomena and improves 3D sensitivity. However, it also allows broadening of participation to new nations, maximis access to the Earth's available underground space and ensures a better spread of bot construction and analysis costs across participating nations. The prime science aims are:

(a) Discovery of a SD directional DM particle signal in the 1-1000 GeV region correlated t galactic motion, including SD cross section below the so-called neutrino floor level
(b) Discovery of coherent solar neutrino events with direction correlated to the motion o the Sun

The dark matter objective requires ~100 DM particle events to be observed at the neutrin floor. This is equivalent to a detection-only cross section of ~1 x 10^{-6} pb in 50 Torr C compatible also with the solar neutrino objective we envisage.

3. The CYGNUS Pathfinder Experiments

The vision for CYGNUS is bold and ground-breaking, aiming to be the first observato capable of using the direction of elastically scattering nuclei as a new probe of neutr penetrating particles in our local Universe. It will also be the first substantial Partic Astrophysics experiment to require united support by multiple underground laboratories d to the need for multi-site deployment. Much of the technology required for is alrea available. However, prior to construction we envisage a two-stage pathfinder effort. This w allow down-select and optimisation of the readout and engineering designs necessary optimise better the costs, whilst also providing world-leading science sensitivity on short timescales. A key aspect of the pathfinders will be confirmation that the necessa background levels can be achieved as the scale increases. It is expected that 3D readout cos will continue to reduce with time. The staged project recognizes this by enabling a gradu transition from basic 1D MWPC/ThGEM readout towards use of strips, optical or pixel forms.

3.1 CYGNUS-P1 -The Readout Pathfinder Experiment

The first pathfinder experiment, CYGNUS-P1, is designed primarily to test and select scalab low background readout technologies for CYGNUS and to establish the first coordinated mult site operation. The main focus will initially be towards the mass range where the neutri floor has the highest cross section. To achieve this we envisage CYGNUS-P1 will compri 25 m^3 total volume. This will comprise 1 m^3 instrumented with High Definition readout (H including full 3D capability comparing strip, optical and pixel readout, plus 24 m^3 in a simpl but Large Volume (LV) 1D vector configuration with recoil head-tail sensitivity usi MWPC/ThGEM technology. This will be made of made of 3 x 8 m^3 or 4 x 6 m^3 units common design. The modular approach of HD and LV allows for location and construction multiple sites, namely in North America, Australia, Japan/Asia and Europe. A four-ye timescale for construction is envisaged for CYGNUS-P1. In each case a standard readout un tile size of 50 x 50 cm is envisaged for the HD parts, so that 4 units make a single reado plane of 1 x 1m. The HD unit would include two readout planes of 1 x 1 m each, allowing variety of pixel and strip-readout concepts from different groups to be incorporated an directly compared in the same field cage and gas configurations. The LV planes are envisa to have 2 x 2m unit sizes.

The focus for the science of the HD component will be to provide competitive sensitivity the low mass elastic scattering energy regime, whilst also providing a route to down-select the technology through a *figure of merit* criteria based on cost per unit sensitivity. The L component would use already demonstrated MWPC/ThGEM readout plane technology. T science focus for LV would be towards the high-energy region, up to 1000 GeV, whilst al allowing demonstration of key engineering aspects required for the final experiment. Th includes demonstration of gas recirculation, low background vacuum vessel engineerin active veto shielding and multi-site operation. The science objectives of CYGNUS-P1 are:

(a) To reach for the first time with directional sensitivity cross sections for SI particle dark matter below both the DAMA-LIBRA allowed regions (at ~10 GeV and ~50 GeV) – an improvement of x100 over current directional sensitivity
(b) To achieve competitive SD sensitivity in the particle DM region below 15 GeV
(c) To set first directional limits on coherent neutrino scattering from the Sun
(d) To complete first searches for other exotic candidates including kk axions

This first pathfinder stage P1 will determine which technology has the best *figure of merit*. This will likely depend on the recoil energy or WIMP mass range considered. It is therefore recognized that a cost optimal design may involve more than one readout technology. This approach also allows for some technical redundancy and for the potential to benefit from any relative change in the cost effectiveness of different readout technologies with time.

3.2 CYGNUS-P2 -The Engineering Pathfinder Module Experiment

A major technical goal for the first pathfinder CYGNUS-P1 will be down-select of the readout technology to be used for the observatory, based on the performance comparisons made in each mass range and backed by the agreed cost effectiveness *figure of merit*. CYGNUS-P2 is then cited to demonstrate and optimise use of this readout in an engineering scale-up at 1/20th scale of the full CYGNUS Galactic Nuclear Recoil Observatory, reaching a target mass of ~0.5 tonnes. This experiment will thus also provide the first single module building block of the proposed full observatory. The scientific goal for the Stage II pathfinder will be:

(a) A further factor 100 improvement in SD and SI dark matter directional sensitivity, extending this to the low mass range below 10 GeV
(b) First detection in a direction sensitive experiment of events due to coherent scattering of solar neutrinos

3. Collaboration Agreement, Contributions and Underground Sites

Members of the new collaboration here agree to pool expertise and resources on a best-efforts basis to work towards the agreed goal of building the CYGNUS Galactic Nuclear Recoil Observatory, including participation in the pathfinder steps as outlined here. This should include contributions and participation both to construction of the initial LV components vital to the engineering design as well as the HD readout parts as appropriate.

Whilst the focus here is on TPCs it is recognised that development of emulsion-based and other non-gaseous directional concepts are underway, notably the emulsion-based NEWS programme. It is agreed that researchers working in these areas are encouraged to participate in the proposal here in the context of cultivating the wider CYGNUS community to include non-gaseous techniques. The CYGNUS collaboration as a whole aims to work together towards the common goals, regardless of technology used.

A unique aspect of our CYGNUS observatory is the distributed nature of the instrument across multiple underground sites and the opportunities this gives for inter-site cooperation in a first truly global particle astrophysics experiment. The multi-site aspect is essential to allow a convincing measurement of the sought after non-terrestrial signals and to optimise sensitivity in the likely event that detectors do not have a fully isotropic directional sensitivity in galactic coordinates.

4. Signatures

We the undersigned agree to work together on the CYGNUS programme outline above:

Institute or laboratory	responsible person	date

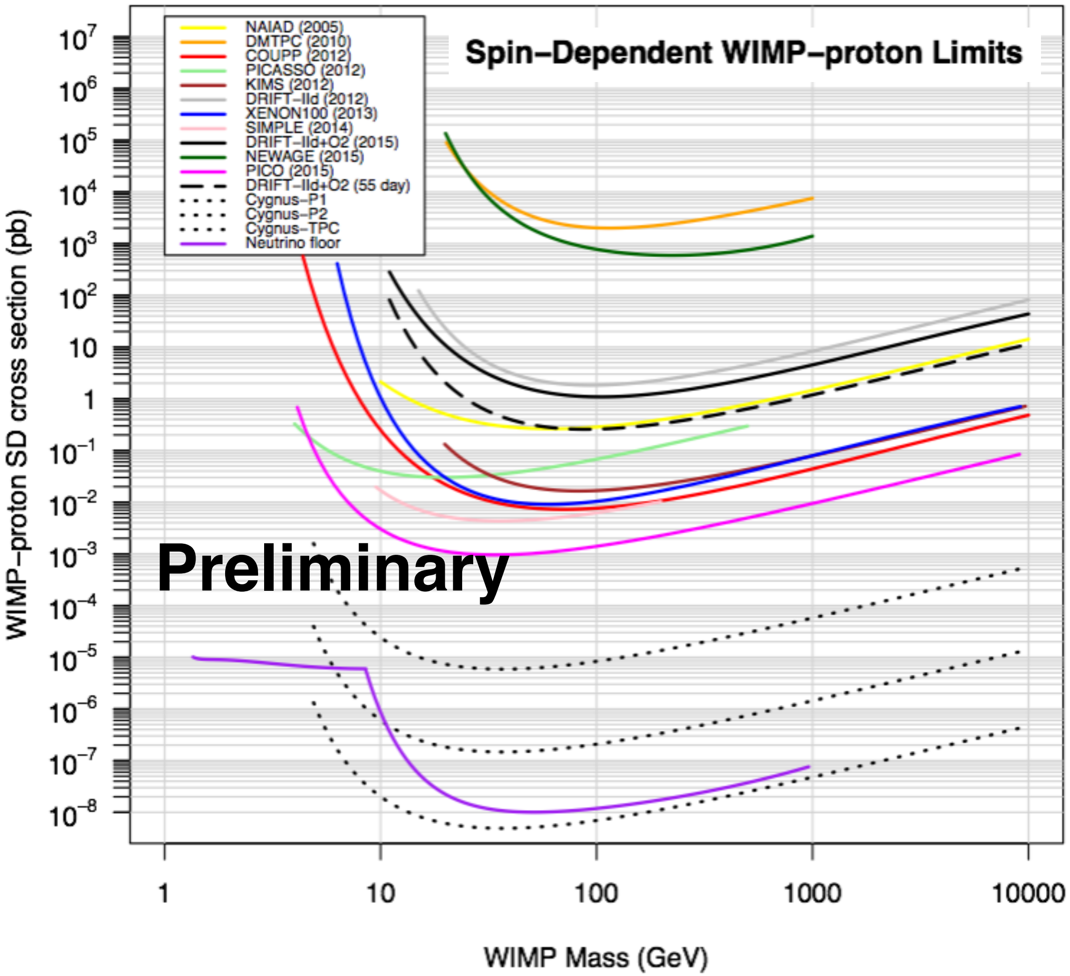
CYGNUS-TPC Proposal, MOU

General Strategy

- Multi-site across the globe
  - Allows leverage of resources, maximises underground space
  - Allows control of systematics for a galactic signal
- Include HD pixel/optical component
  - Compare technologies and down-select at first stage ~ $1m^3$
- Include LD larger scale TPC
- A staged approach
  - **Pathfinder 1**
  - **Pathfinder 2**
  - **CYGNUS-TPC**

CYGNUS-TPC Concept and Reach

- Fiducialisation, -ve ion drift, head-tail sensitivity
- Multi-tonne, multi-underground site,
- Staged programme - low WIMP mass, high WIMP mass



potential interest
Australia, China, France, Italy, Japan, UK, US

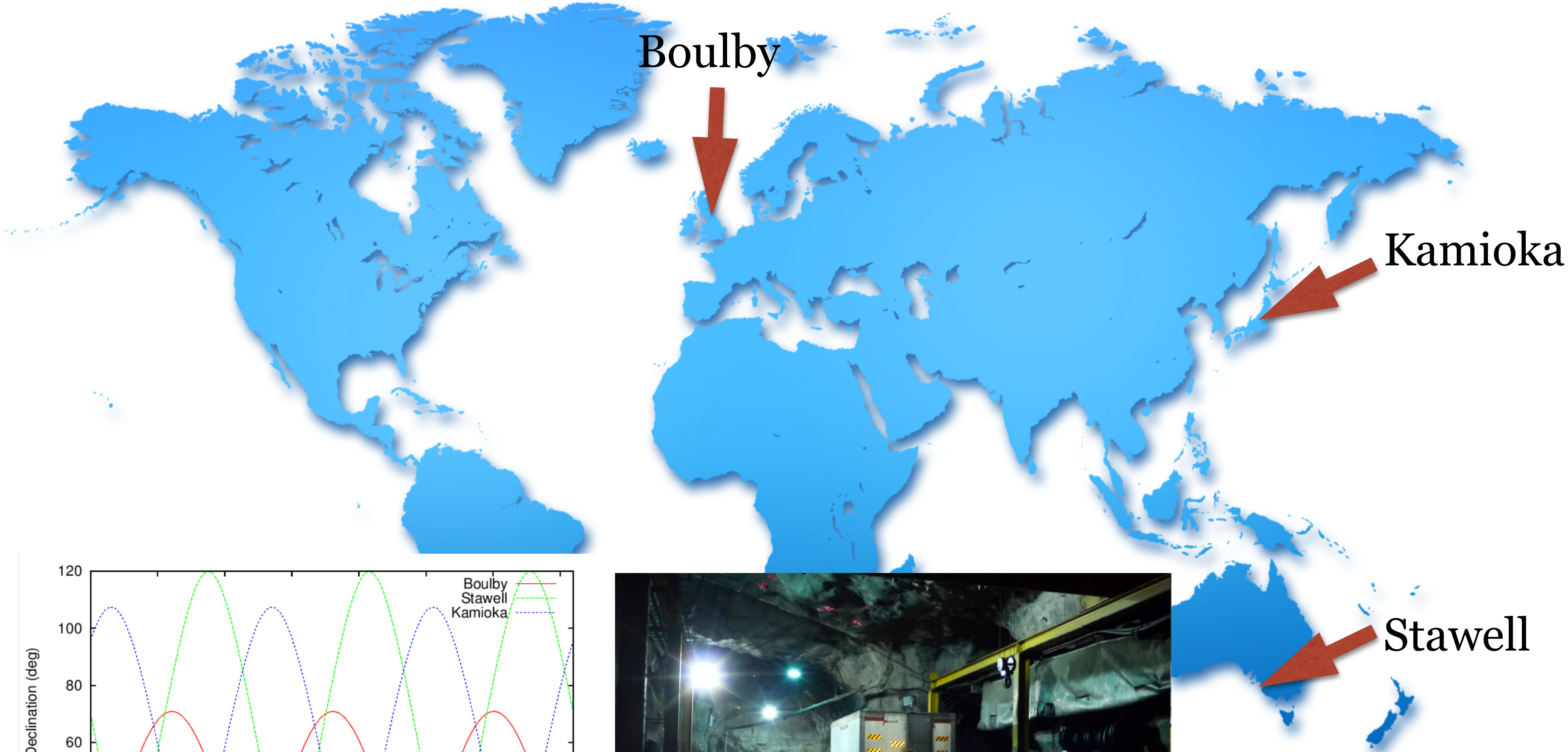
~Current state

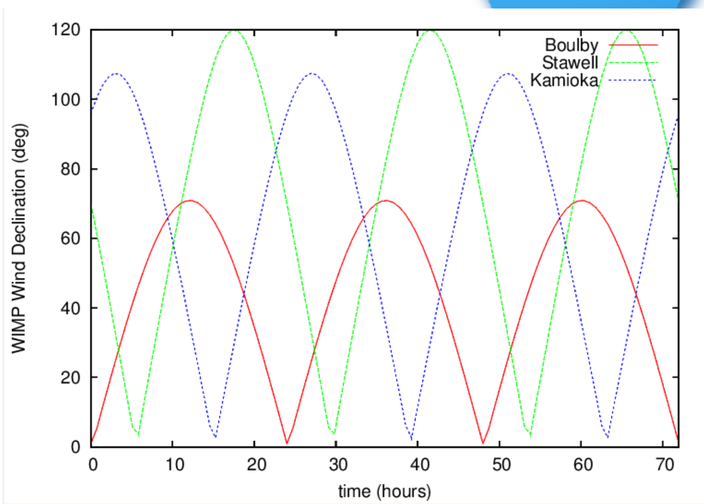
CYGNUS - Pathfinder 1

CYGNUS - Pathfinder 2

CYGNUS - TPC

CYGNUS-TPC - Multiple Sites





new lab funded in Australia

A CYGNUS Site at New Boulby Lab

CYGNUS Proposal MOU Objectives

The CYGNUS Galactic Nuclear Recoil Observatory
Memorandum of Understanding for a new International Experiment

- **Objectives**

(1) Discovery of a SD directional DM particle signal in the 1-1000 GeV region correlated to galactic motion, including SD cross section below the so-called neutrino floor level

(2) Discovery of coherent solar neutrino events with direction correlated to the motion of the Sun

CYGNUS Proposal MOU

The CYGNUS Pathfinder Experiments

CYGNUS-P1 -The Readout Pathfinder Experiment

(a) To reach for the first time with directional sensitivity cross sections for SI particle dark matter below both the DAMA-LIBRA allowed regions (at ~10 GeV and ~50 GeV) – an improvement of x100 over current directional sensitivity

(b) To achieve competitive SD sensitivity in the particle DM region below 15 GeV

(c) To set first directional limits on coherent neutrino scattering from the Sun

(d) To complete first searches for other exotic candidates including kk axions

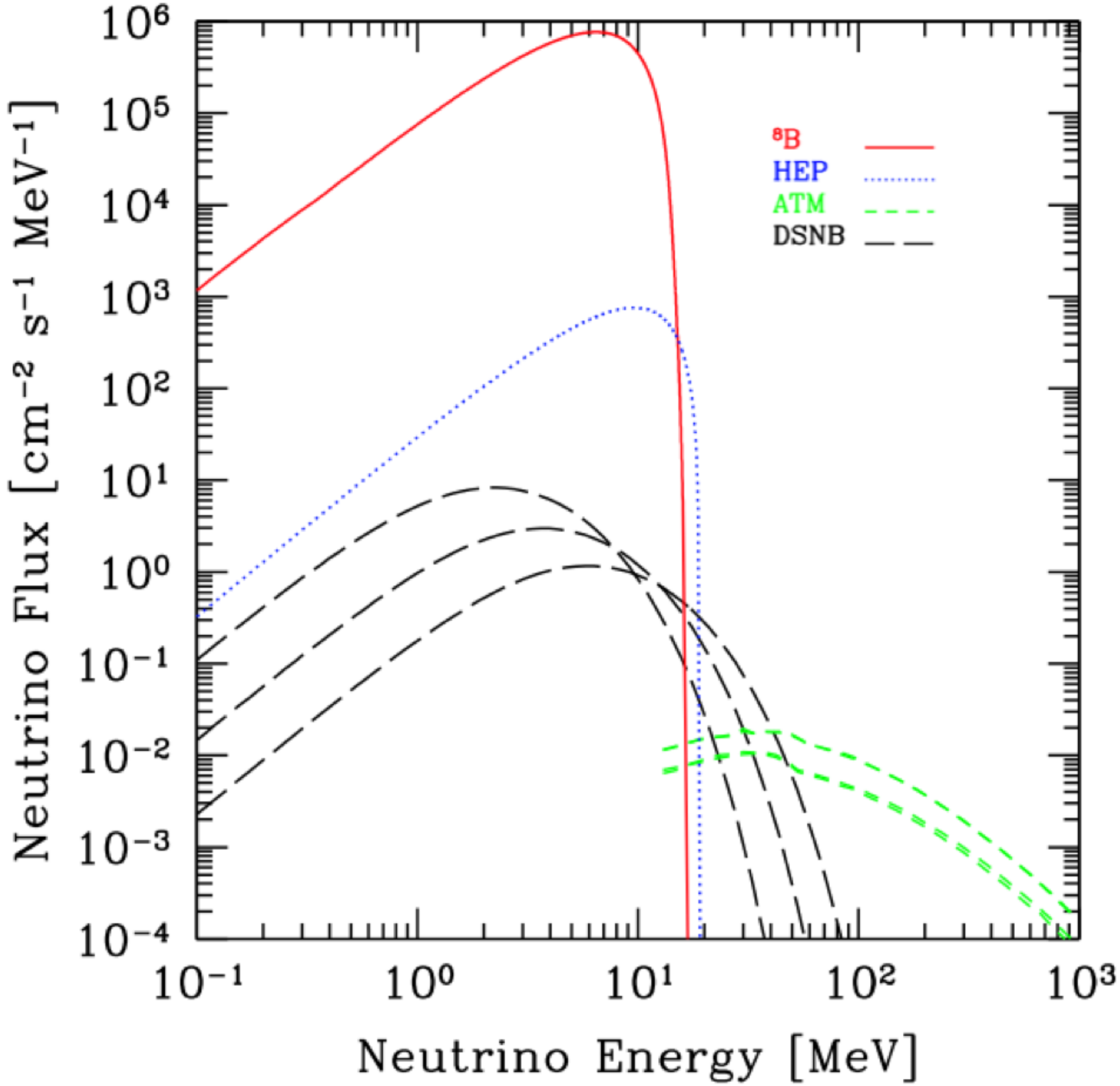
CYGNUS-P2 -The Engineering Pathfinder Module Experiment

(a) A further factor 100 improvement in SD and SI dark matter directional sensitivity, extending this to the low mass range below 10 GeV

(b) First detection in a direction sensitive experiment of events due to coherent scattering of solar neutrinos

Coherent Neutrino Scattering

- **Solar Neutrino Spectrum**



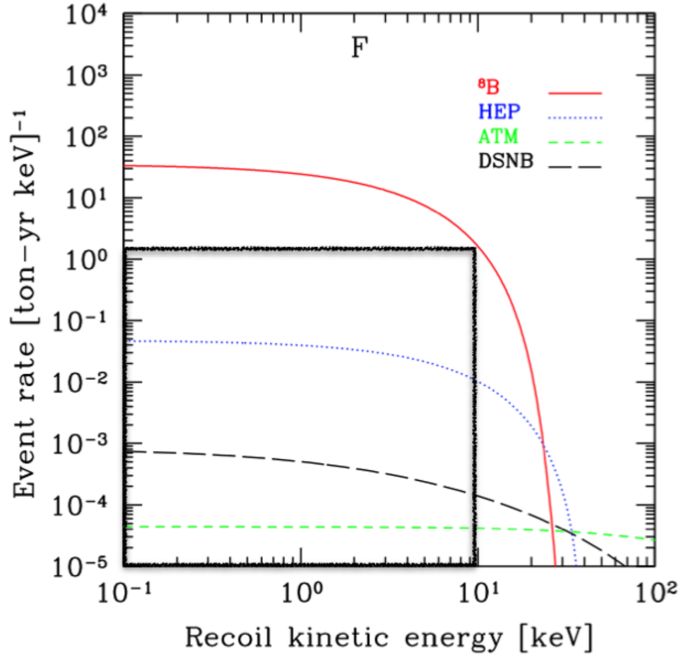
ν type	E_ν^{max} (MeV)	$E_{r_{Ge}}^{max}$ (keV)	ν flux (cm^{-2}.s^{-1})
pp	0.42341	5.30×10^{-3}	$5.99 \pm 0.06 \times 10^{10}$
^{7}Be	0.861	0.0219	$4.84 \pm 0.48 \times 10^{9}$
pep	1.440	0.0613	$1.42 \pm 0.04 \times 10^{8}$
^{15}O	1.732	0.0887	$2.33 \pm 0.72 \times 10^{8}$
^{8}B	16.360	7.91	$5.69 \pm 0.91 \times 10^{6}$
hep	18.784	10.42	$7.93 \pm 1.27 \times 10^{3}$
DSNB	91.201	245	85.5 ± 42.7
Atm.	981.748	27.7×10^{3}	10.5 ± 2.1

TABLE II: Relevant neutrino fluxes to the background of direct dark matter detection experiments. Also shown are the respective maximum neutrino energy, maximum recoil energy on a Ge target, and overall fluxes and uncertainties [22–24].

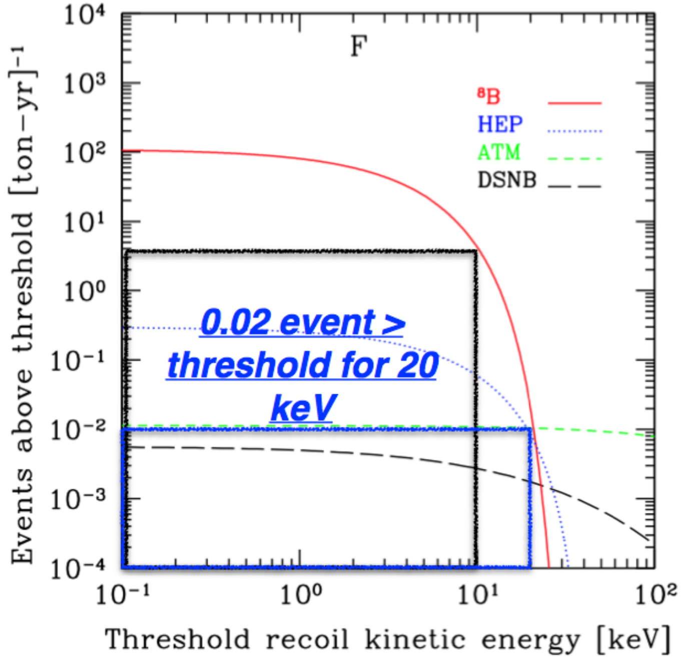
Coherent Neutrino Scattering

from Slac pub 15817, arXiv:0903.3630.

nuclear recoil event rate due to coherent neutrino scattering from the Sun



nuclear recoil events due to coherent neutrino scattering from the Sun above threshold



3 events/ton/year above 10 keV for each Fluorine atom

18 (12) events/ton/year above 10 keV for SF_6 (CF_4)

with perfect efficiency

Conclusion

We want to build a Global Galactic Recoil Observatory

(1) Dark Matter Directionality (2) Coherent Astrophysical Neutrino

Trying to develop in WIMP “telescope” is fascinating and challenging…

It will be needed to determine a definitive detection of WIMP dark matter

It is not harder than non-directional, it’s different

It needs more minds….and a global effort

Join CYGNUS