Galactic Signatures and Directional Detection of Dark Matter Particles - CYGNUS & probing below the neutrino floor

The University Of Sheffield.

Neil Spooner, University of Sheffield

- Direct Search Update
- Annual Modulation and Directionality
- from DM-ICE and DRIFT to COSINE-NaI and CYGNUS-TPC

Thanks to those from whom I have borrowed slides and info

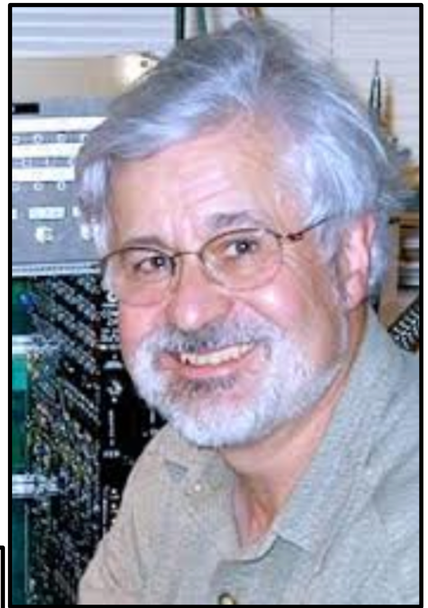
Characters of Discovery

Leo Stodolski

Rita Bernabei

Peter Smith

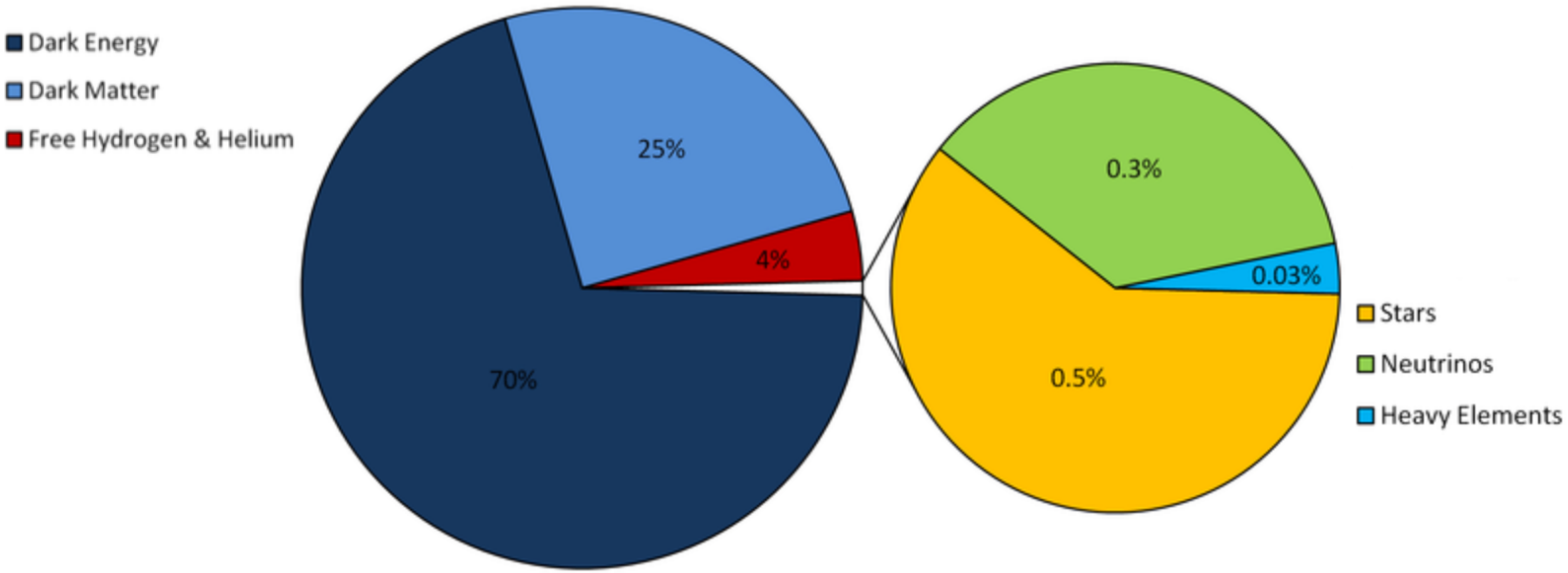
Bernard Sadoulet



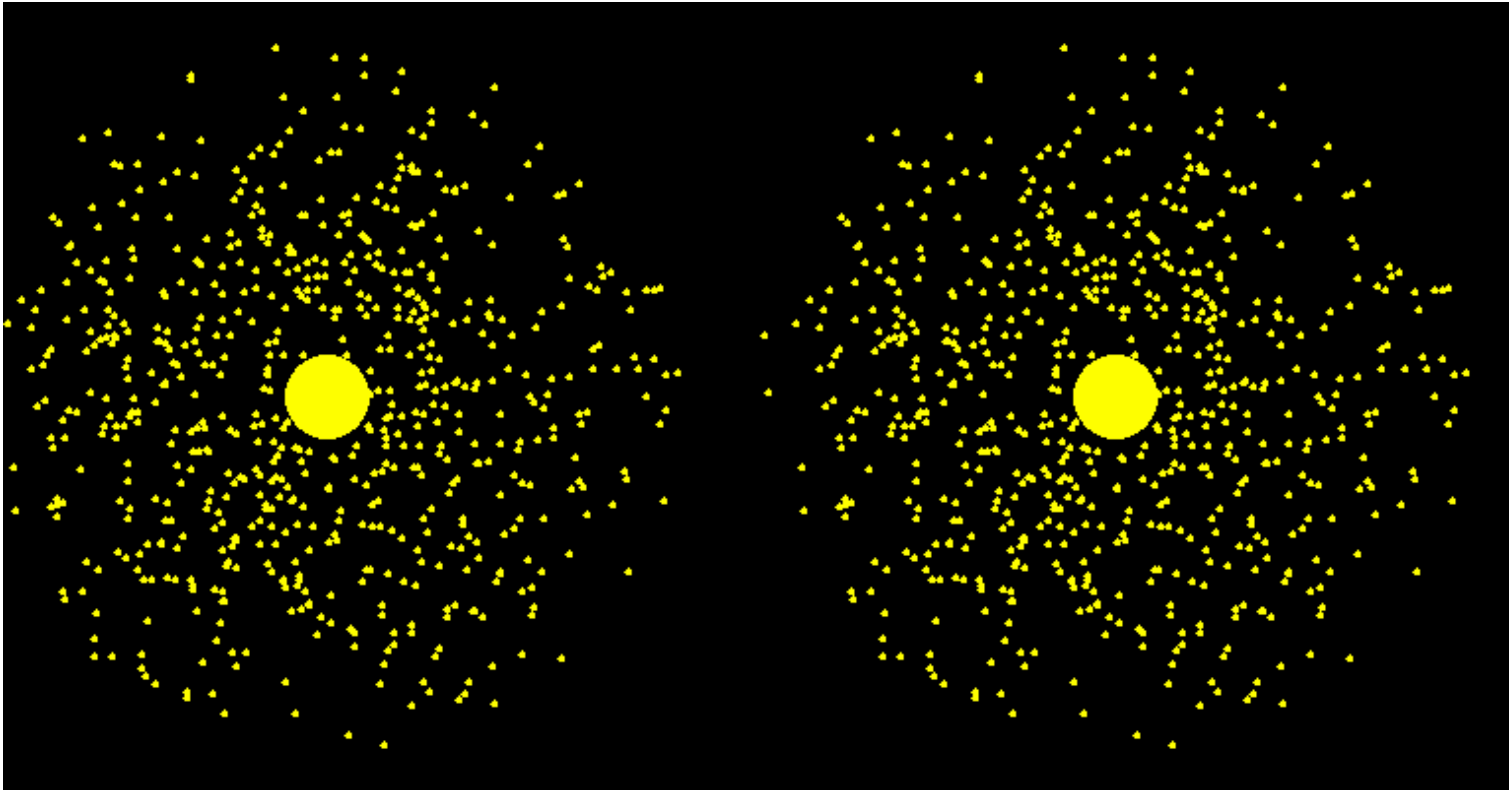
Katie Freese

Elena Aprile

The Composition of the Universe



Which Galaxy is most like we observe?



So Galaxies are 90% Dark Matter

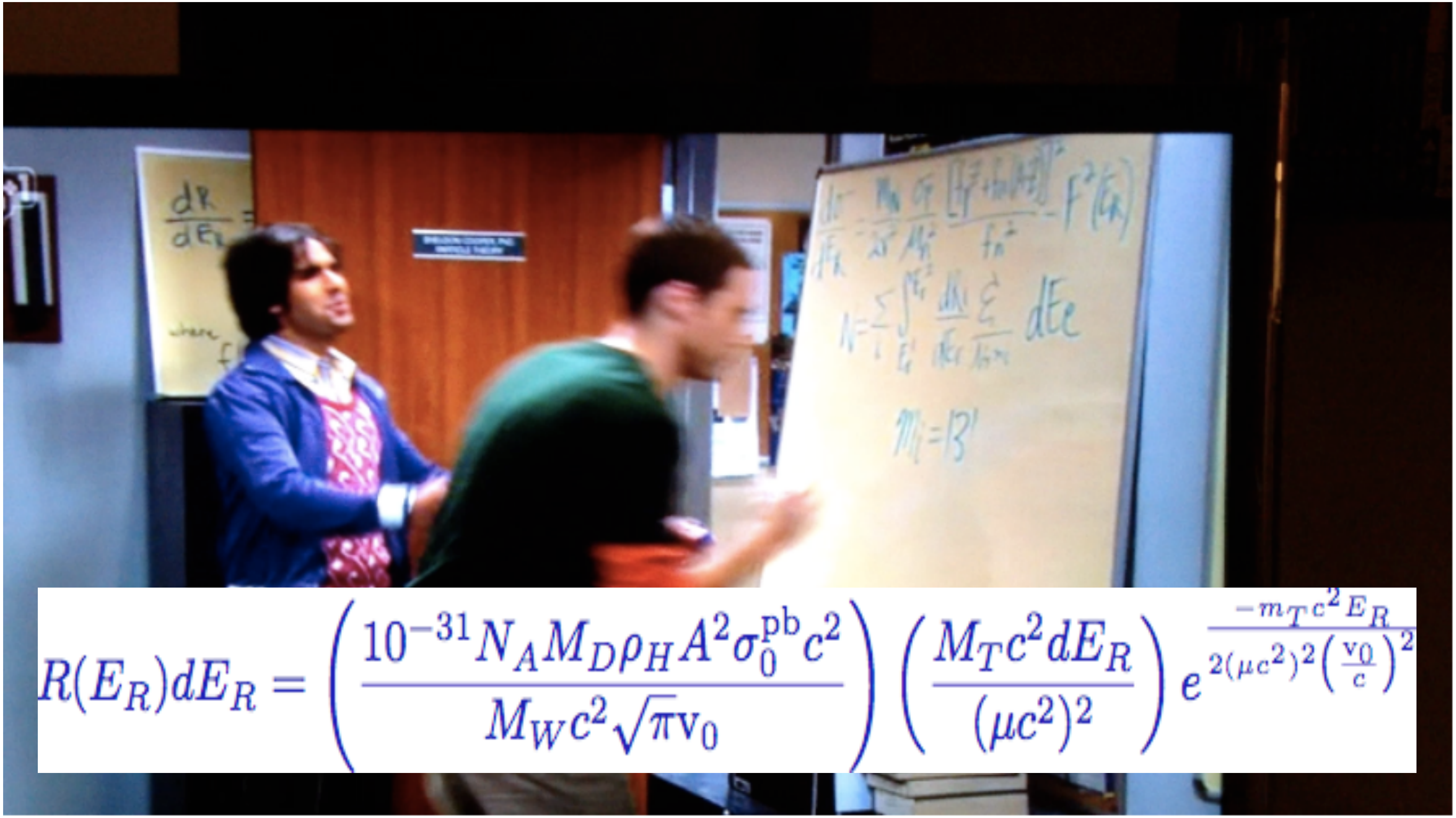
"I can't tell you what's in the dark matter sandwich. No one knows what's in the dark matter sandwich."

WIMPs!

What a WIMP Does

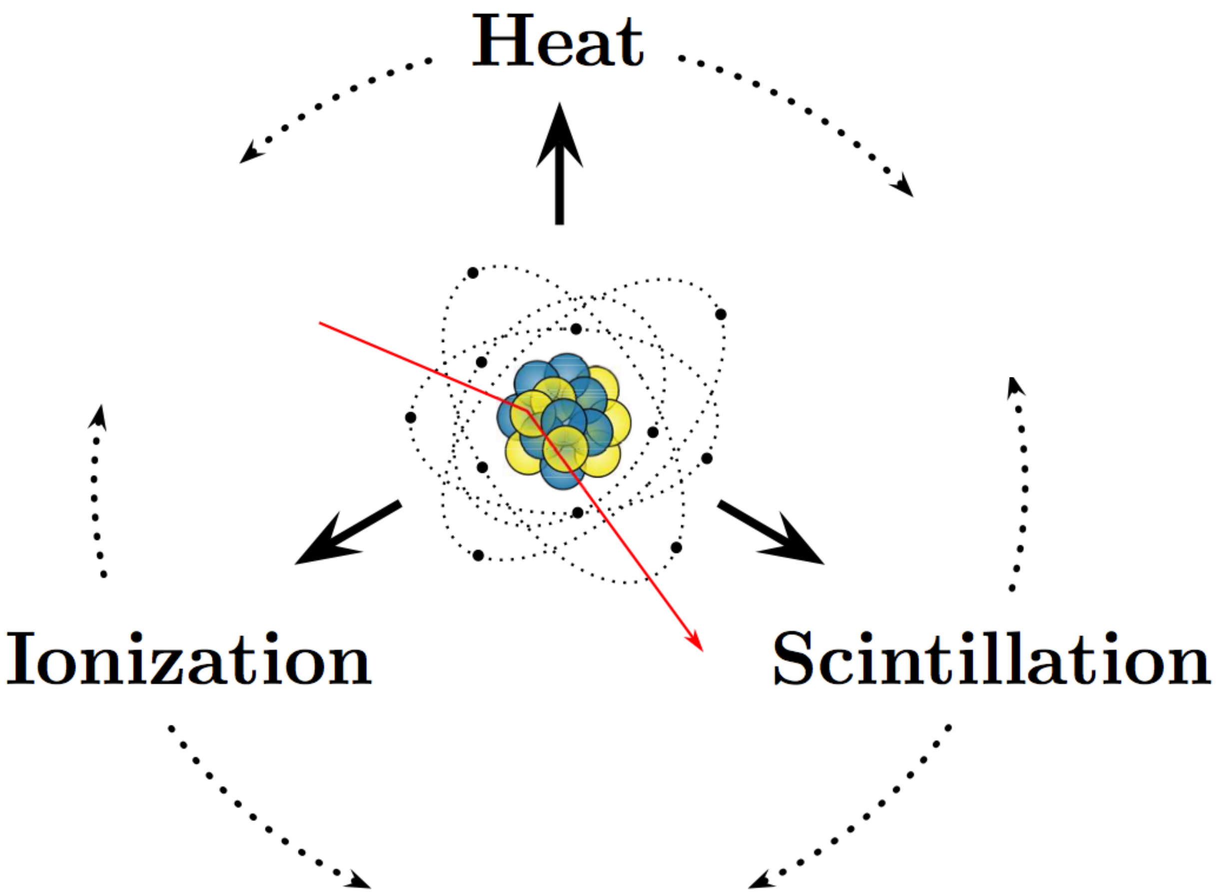
atom

The Recoil Equation



$$R(E_R)dE_R = \left(\frac{10^{-31} N_A M_D \rho_H A^2 \sigma_0^{\mathrm{pb}} c^2}{M_W c^2 \sqrt{\pi} \mathrm{v}_0}\right)\left(\frac{M_T c^2 dE_R}{(\mu c^2)^2}\right) e^{\frac{-m_T c^2 E_R}{2(\mu c^2)^2 \left(\frac{\mathrm{v}_0}{c}\right)^2}}$$

Conventional WIMP Direct Detection



Dealing with backgrounds drives the technology

- Alpha, beta, gamma, neutron, cosmic rays
- U, Th, K….   radon
- Go underground to get away from cosmic rays

~Current WIMP Situation

- **at High Mass**

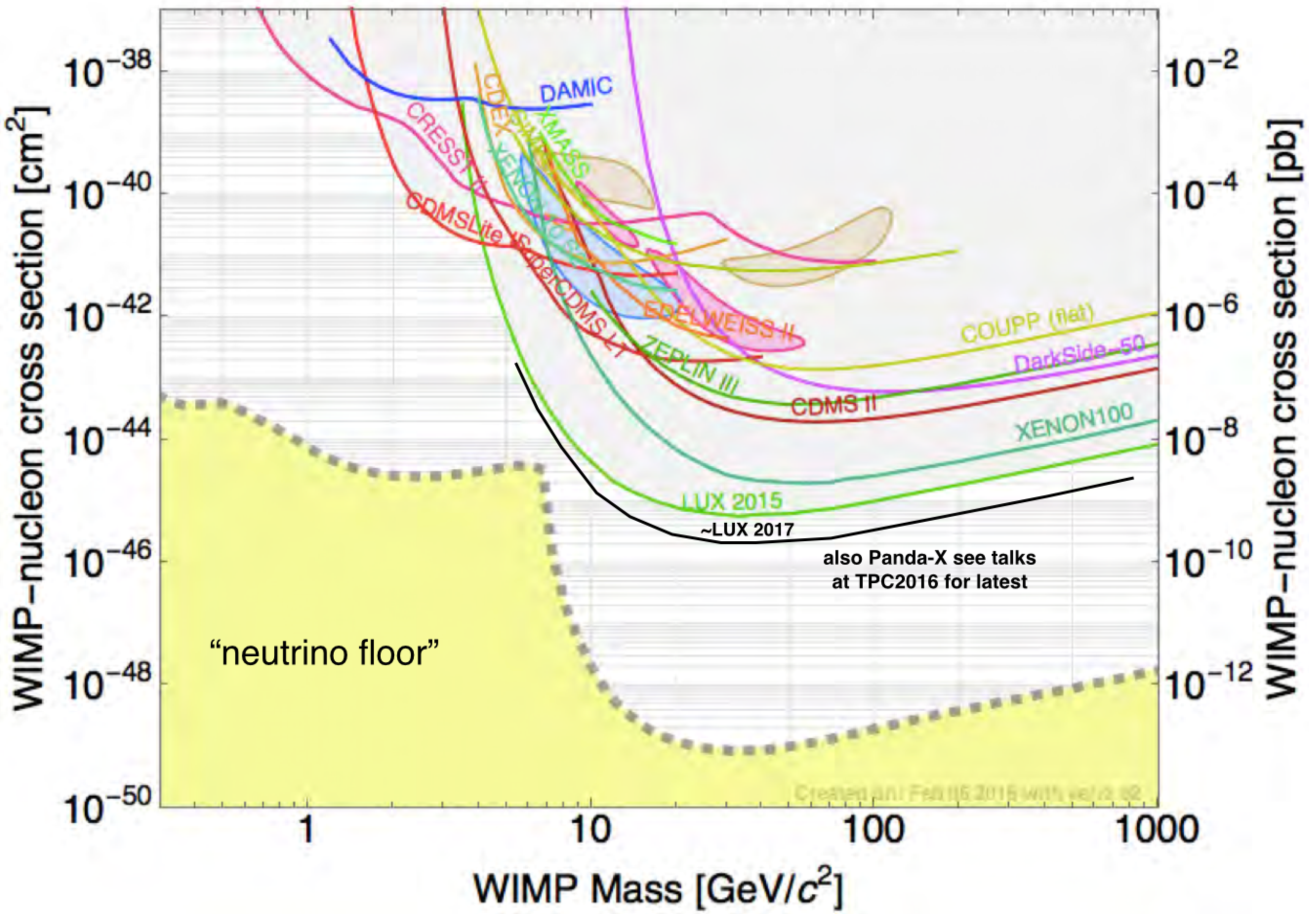
Nothing so far
Consistent with the absence of SUSY@LHC

- **at Low Mass**

Some closed contours, and strong limits

What is going on?

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



Many Recent Technical Advances

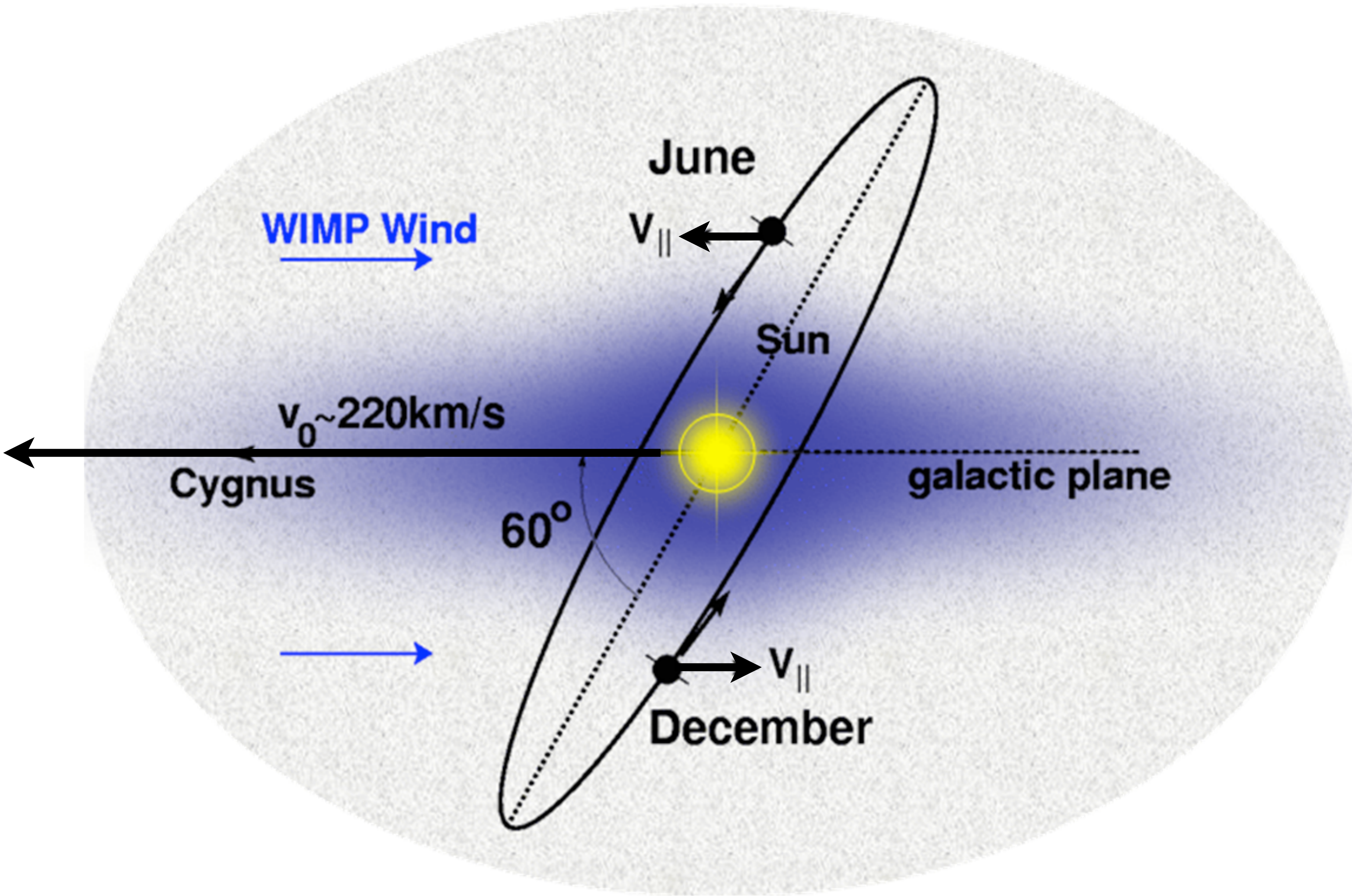
but oh dear, no clear signal?, what to do?:

Many Recent Technical Advances

but oh dear, no clear signal?, what to do?:

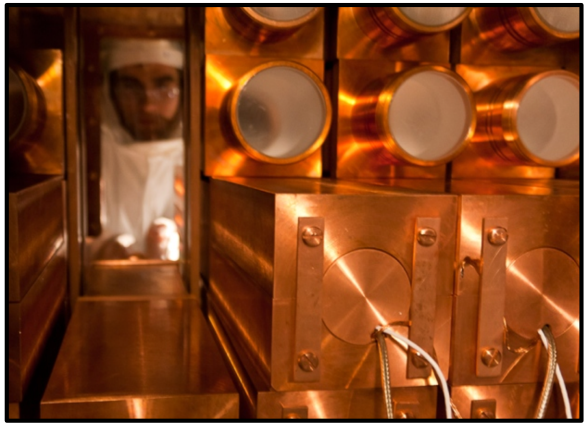
- try low WIMP mass
- try bigger targets for high WIMP mass
- double check old “signals”
- seek better signal
- try something else!

What could the Signal be for WIMPs?

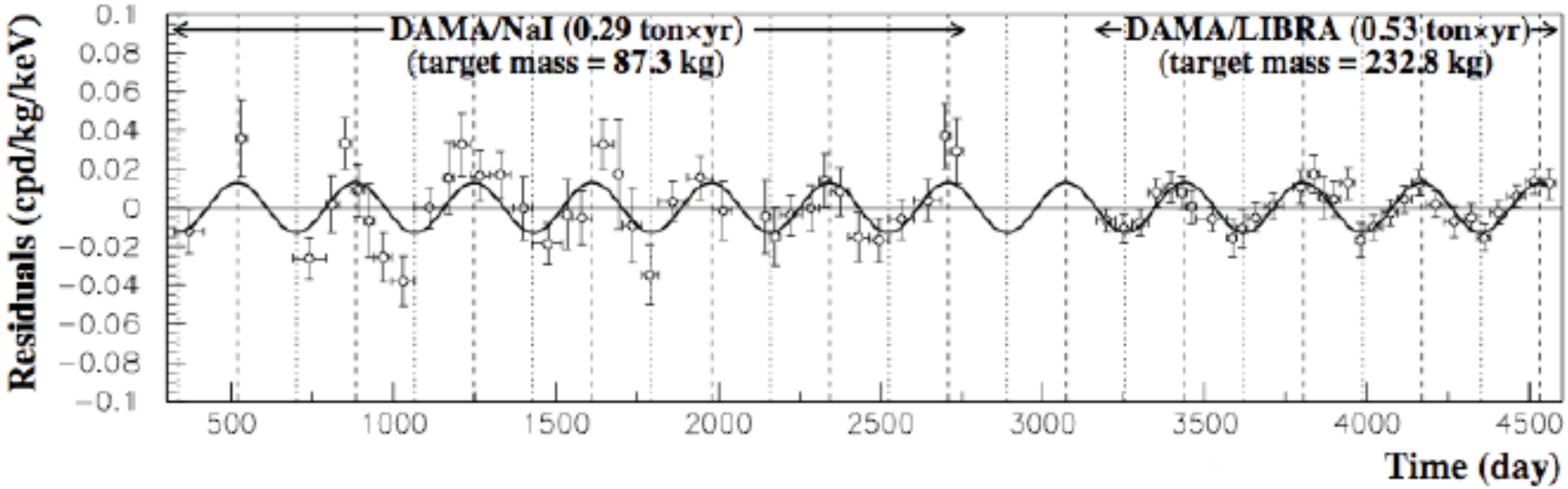


WIMPs Found? or Not?

- DAMA collaboration in Italy see an Annual Modulation and claim it is WIMPs!
- Changed Phototubes to high QE - Results 2017?



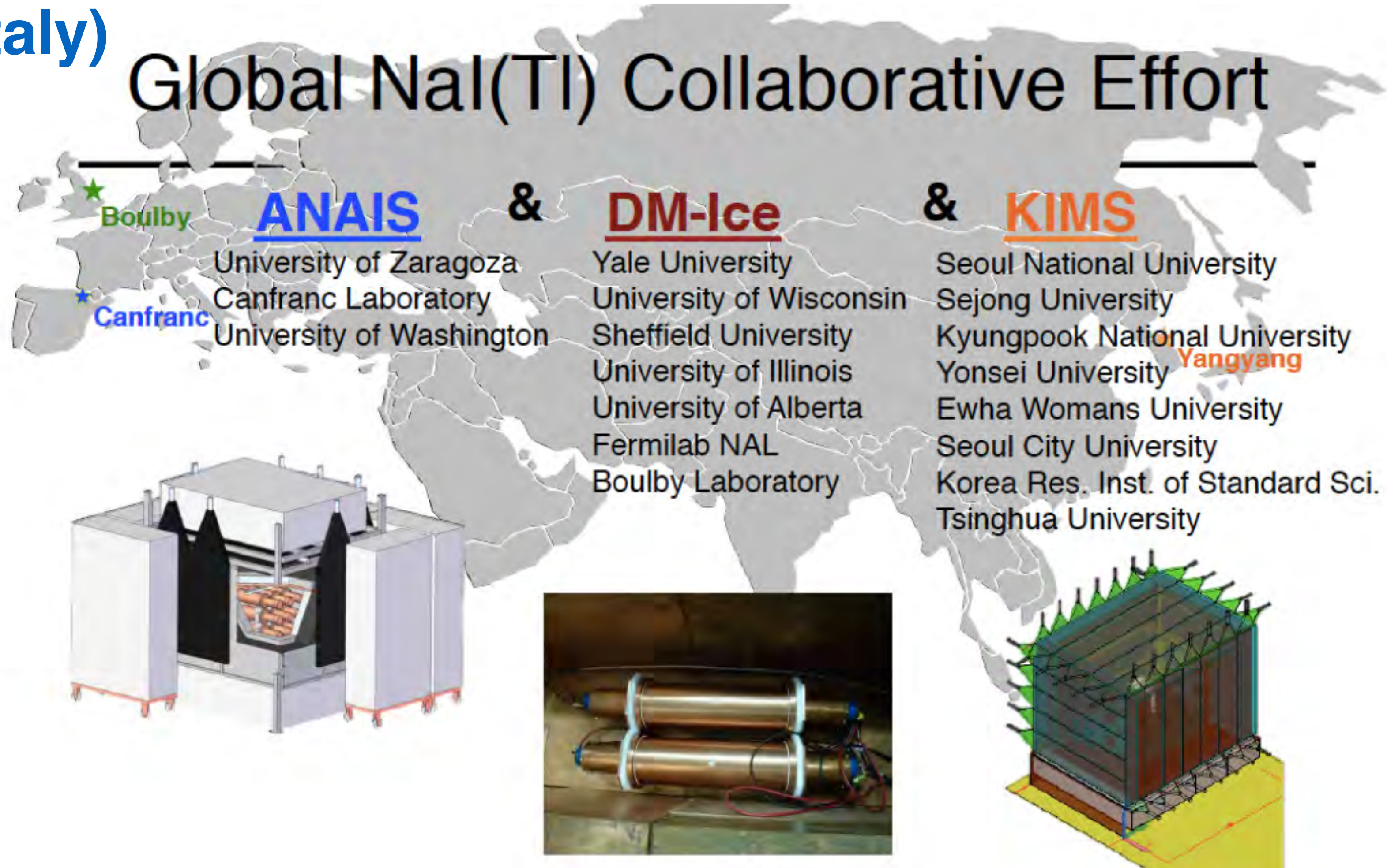
Rita Bernabei



New Annual Modulation Attack

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

COSINE-NaI



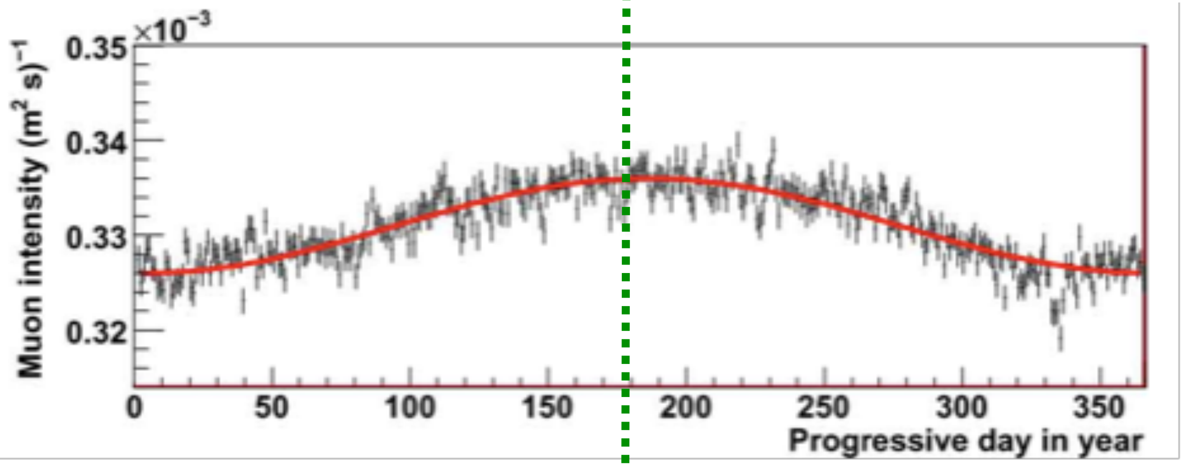
e.g. Muon Modulation North vs. South

Gran Sasso

summer

- LVD:

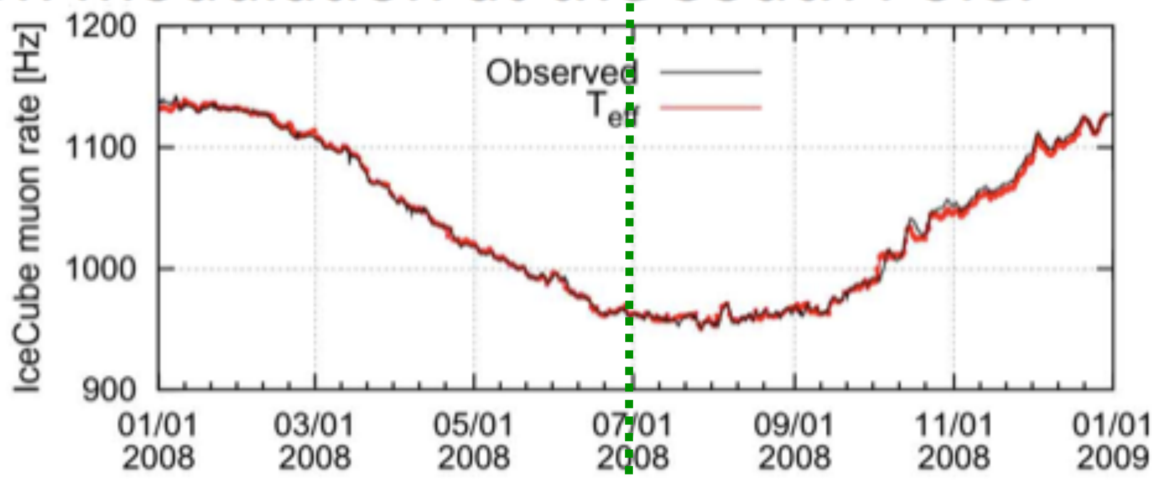
Selvi, Proc. 31st ICRC. (2009)



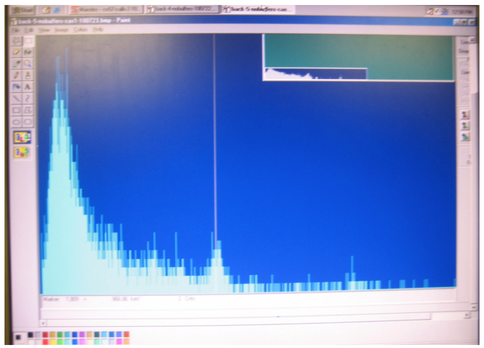
South Pole

- Opposite Muon modulation at the South Pole:

Tilav, Proc. 31st ICRC. (2009)



DM-ICE17 Tests at Boulby, UK

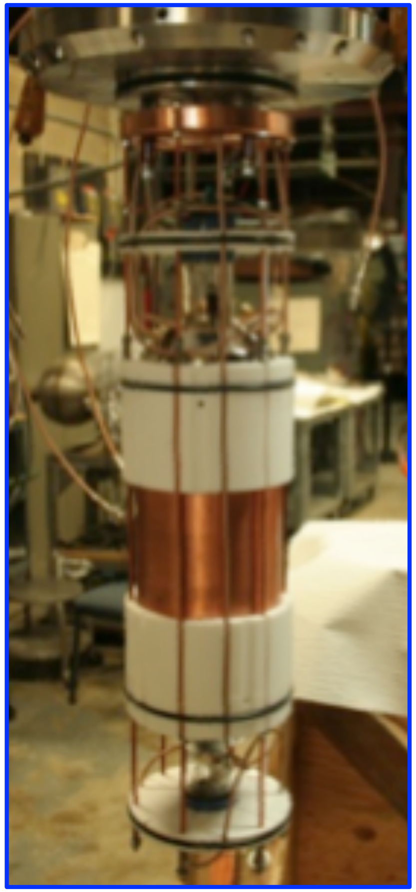


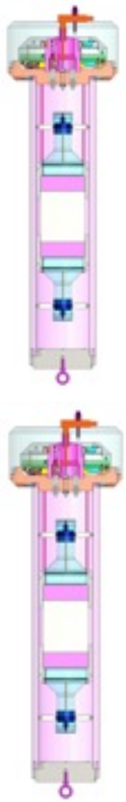
- Two crystals originally used in the NaIAD dark matter experiment

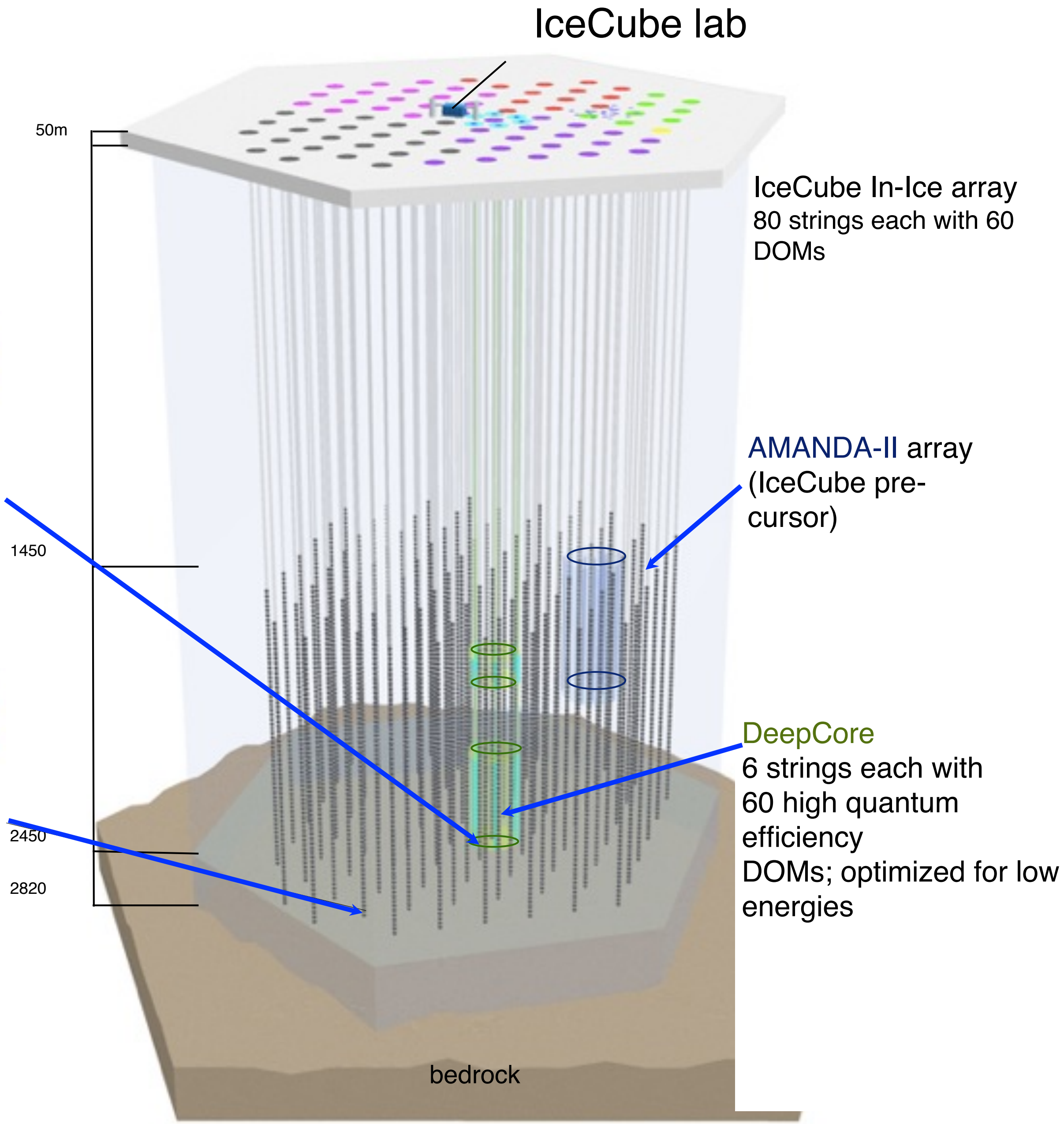
DM-ICE17 Location and Runs

Deployed Dec. 2010

- Two 8.5 kg NaI detectors recycled from the original NAIAD experiment at Boulby
- Operation from Feb. 2011
- Data run from June 2011





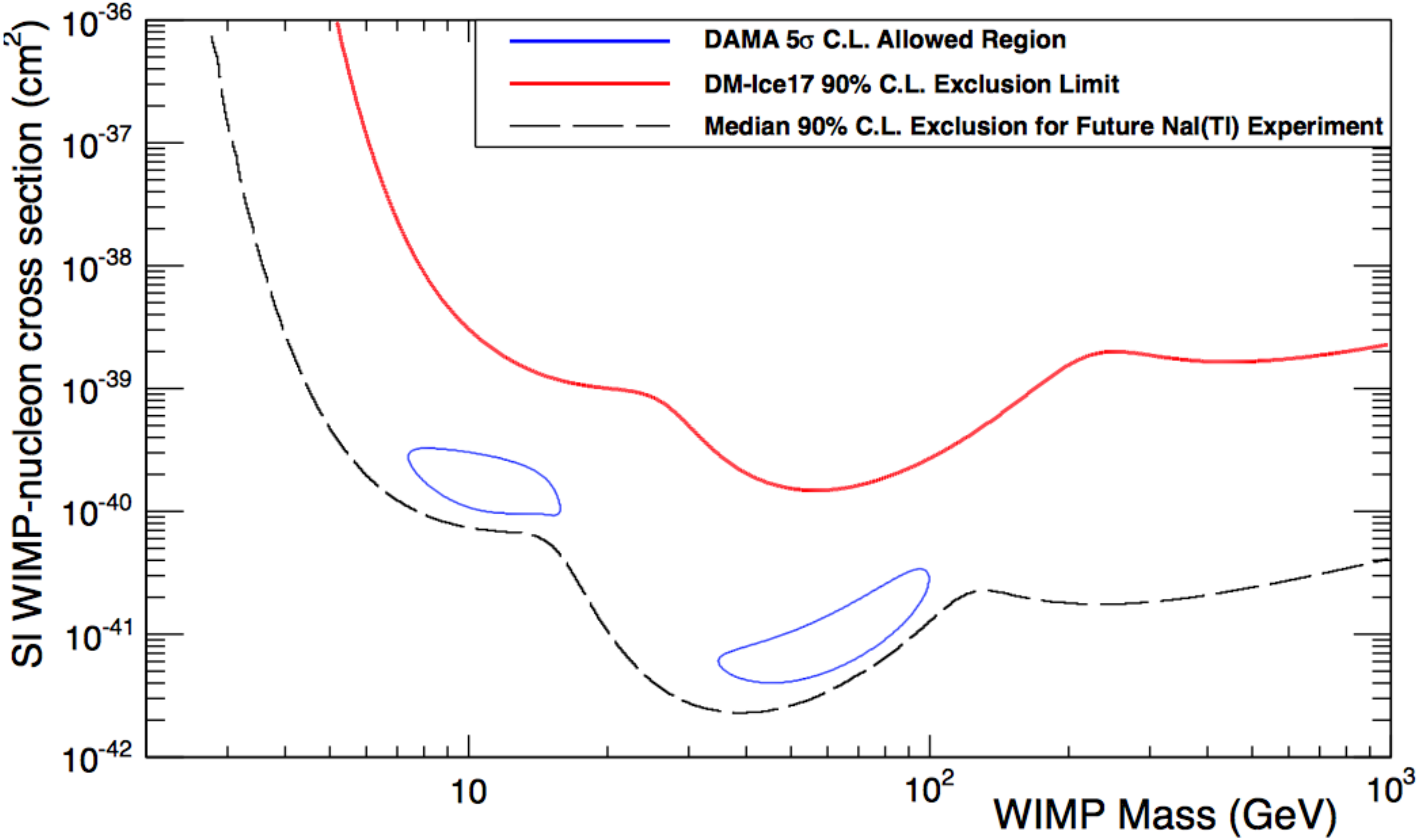


First DM-ICE Result Just Published

- 17 kg, 2.5 km below South Pole

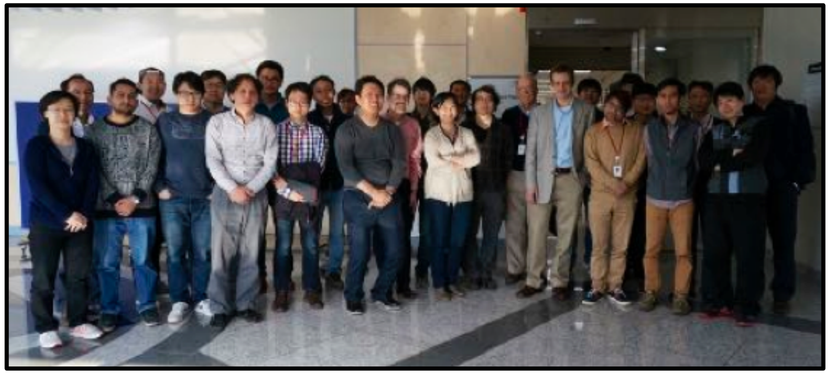
Phys. Rev. D 95, 030001 (2017)

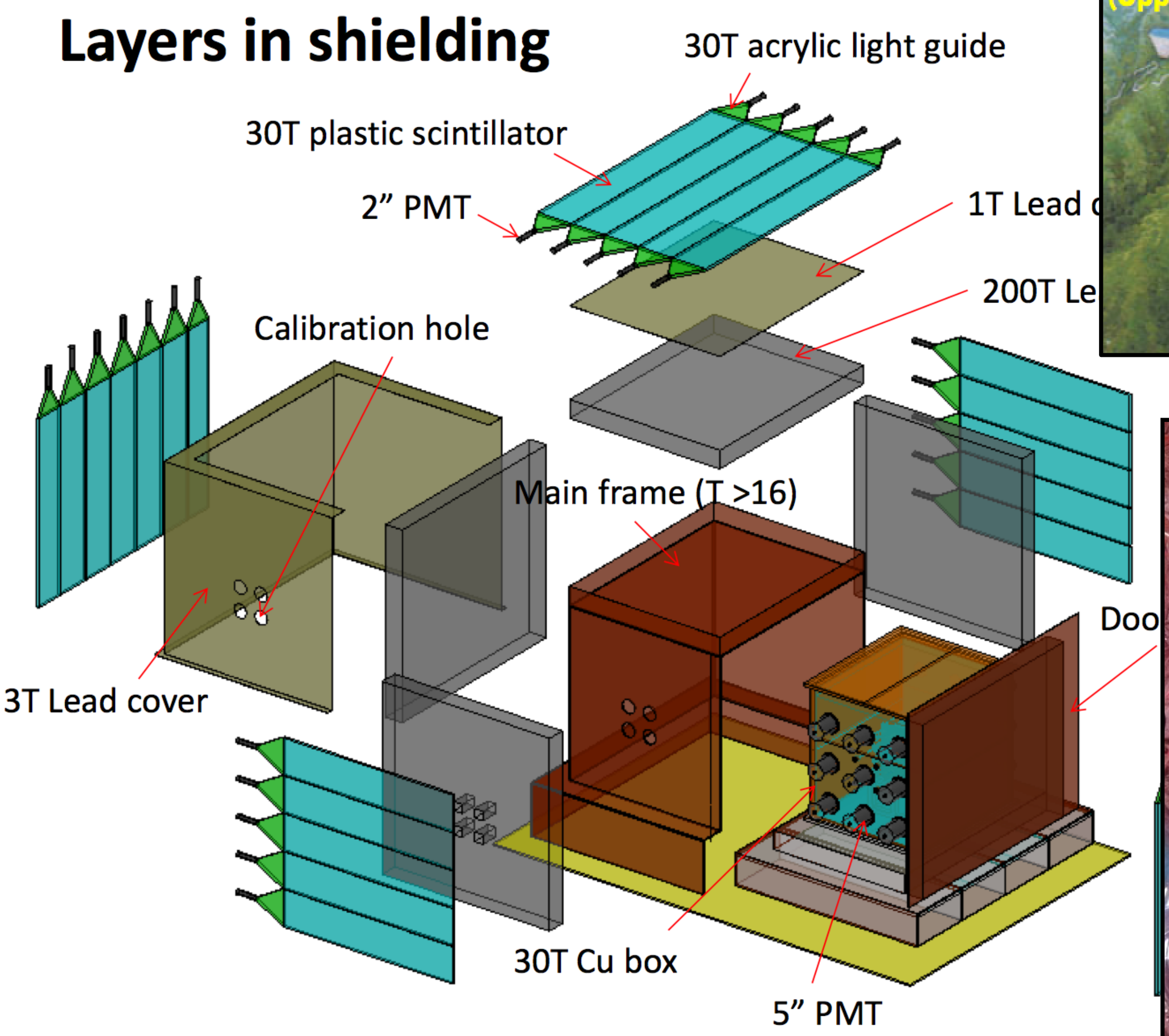
- First southern hemisphere dark matter result

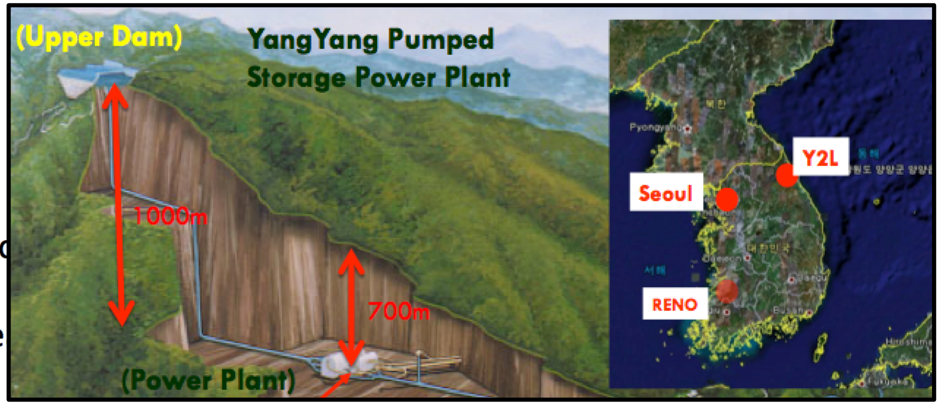


COSINE-100

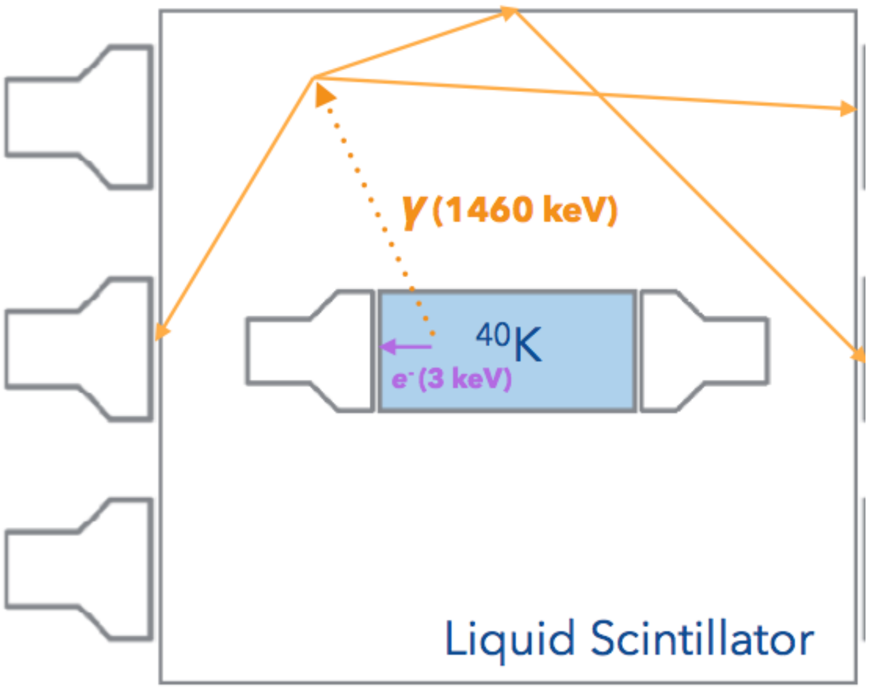
- Combined DM-ICE/KIMS, YanyYang
- Data taking since 09/2016
- 14 Institutes

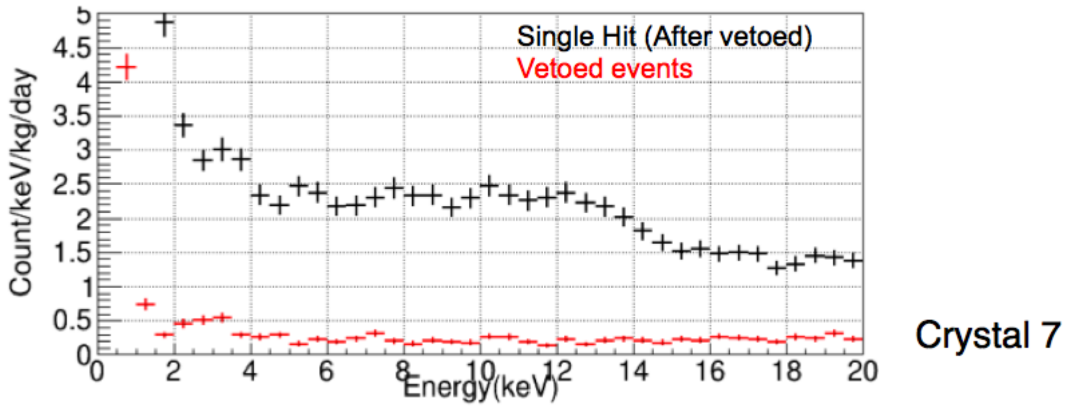


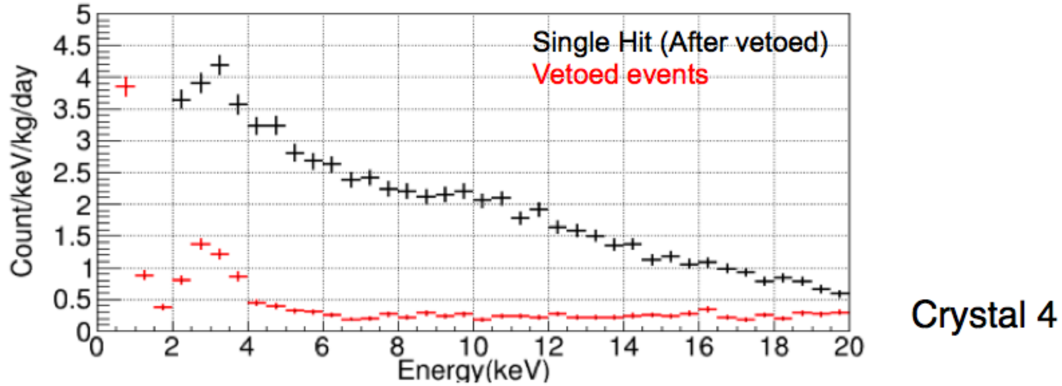




COSINE-100 First Data





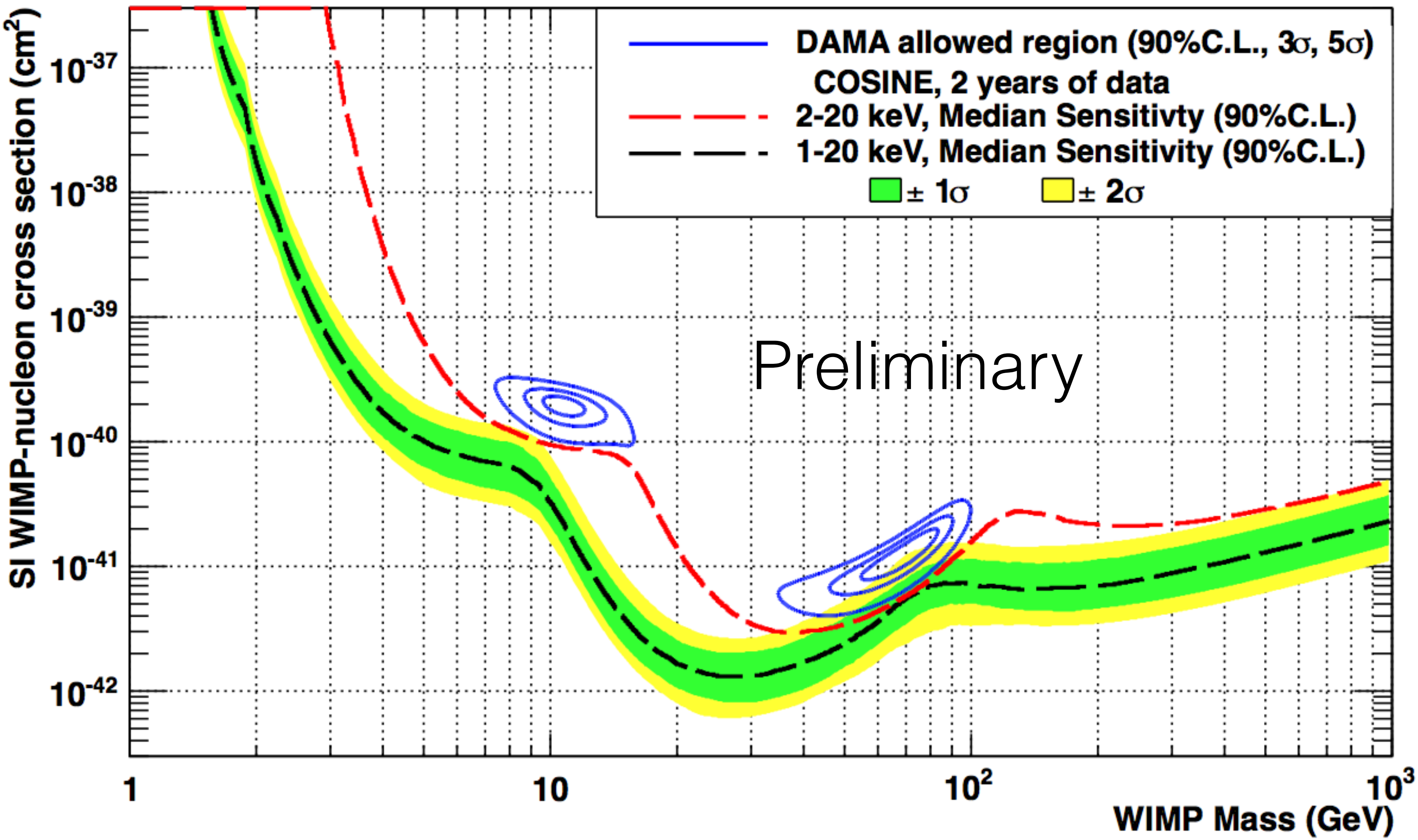


^{40}K Tagging 1460 keV events with LS enables to veto 3 keV background events

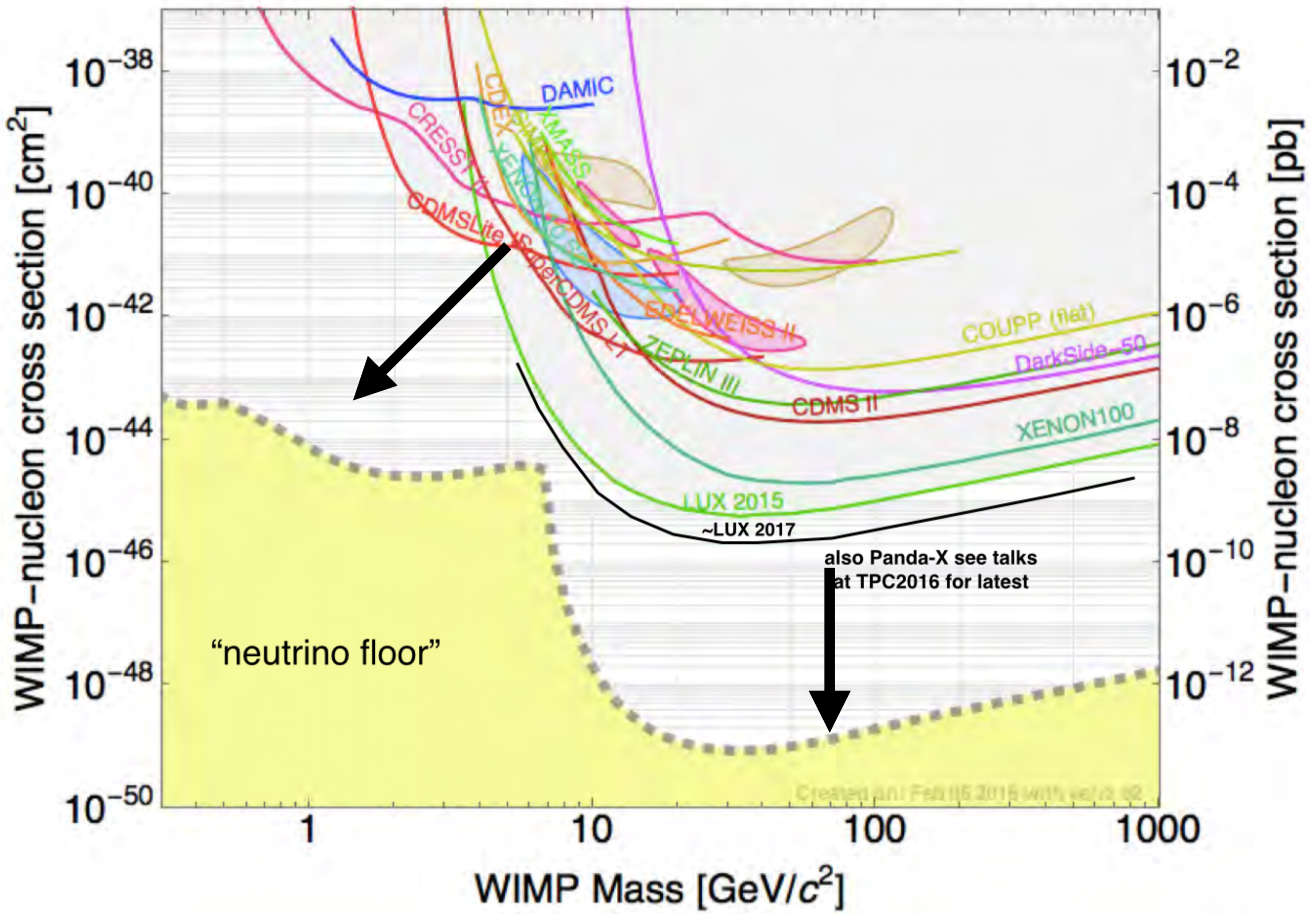
Surface ^{210}Pb is suspected to be the dominant background, followed by ^{40}K internal to crystal

COSINE-100 Projections

- 100 kg, 1 keV threshold, combined DM-ICE/KIMS at YanyYang



Back to Current WIMP Situation



- **Mainstream strategy**

1. Improve sensitivity at low mass (lower the threshold): **e.g. CDMS, CRESST, DAMIC.**
2. Improve sensitivity at large mass (increase target mass): **e.g. LZ, Xenon nT…**

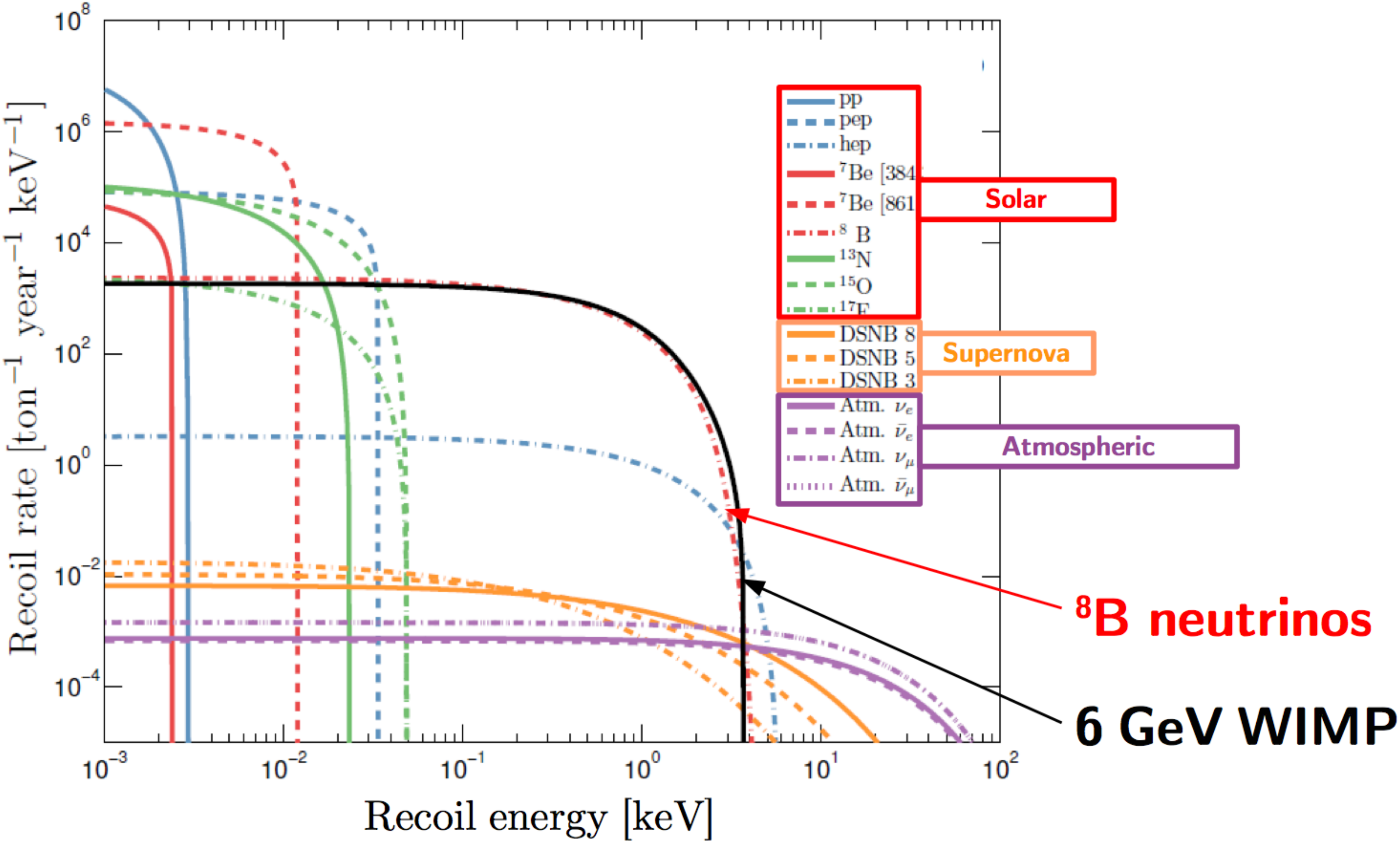
Is there a Better Signal for WIMPs?

Can we get below the neutrino floor?

- Neutrinos may increasingly shape the future of direct detection
- There is some focus on reaching the neutrino floor but this should shift to studying the neutrinos
- Then start to do neutrino/solar physics

Neutrino Coherent Background

Coherent neutrino-nucleus scattering rates on a Xenon target:

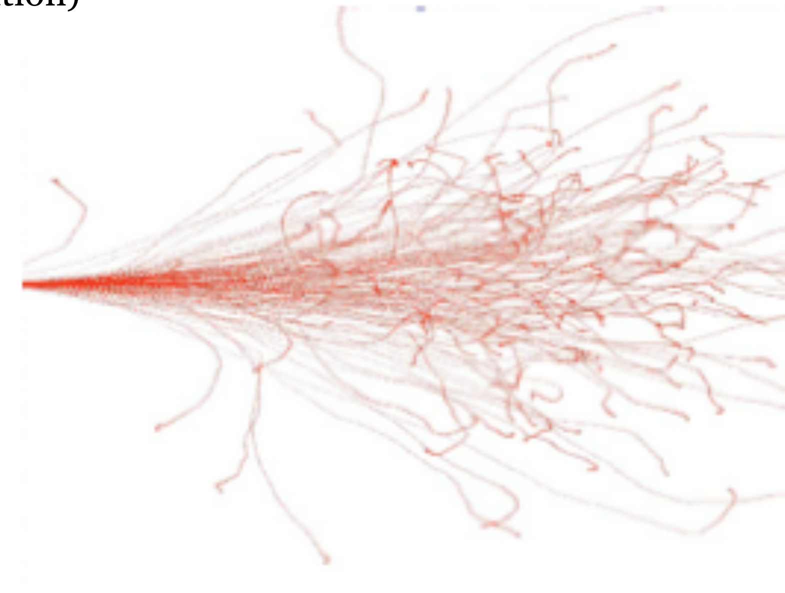


thanks to O'Hare et al.

What a WIMP Does

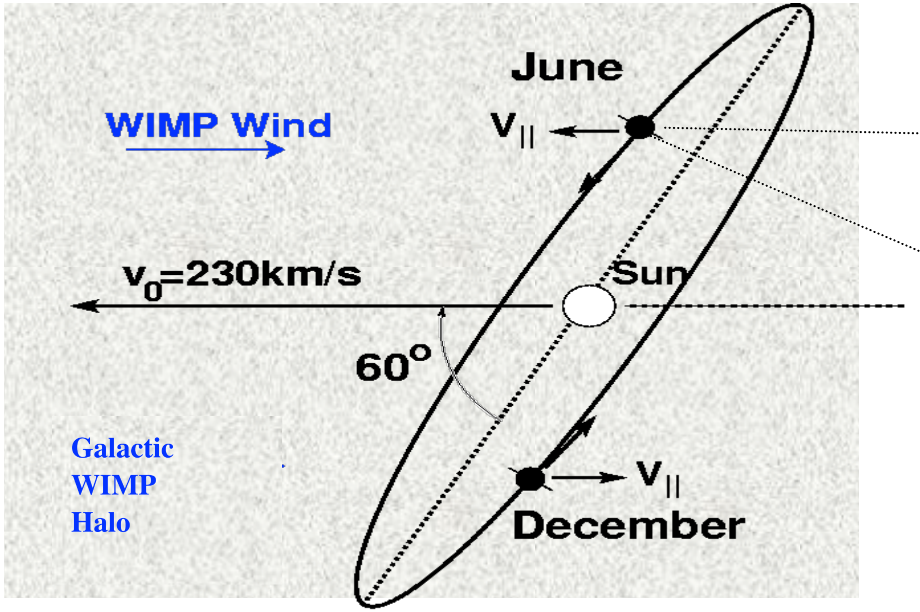
atom

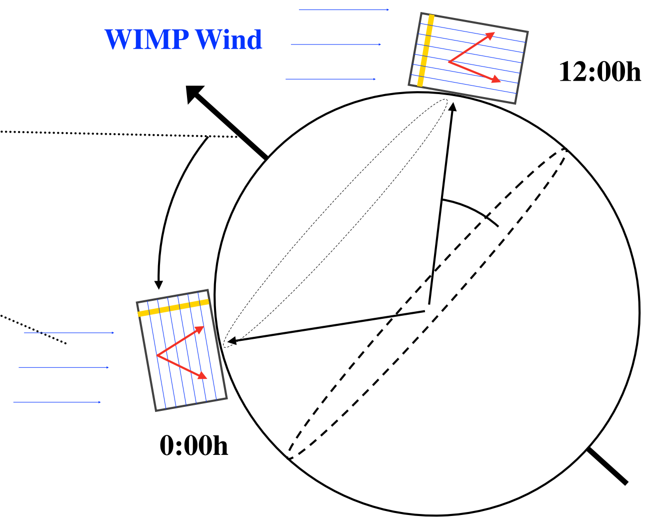
SRIM simulation - 100 keV F recoil in 75 Torr CF_4 (D3 collaboration)



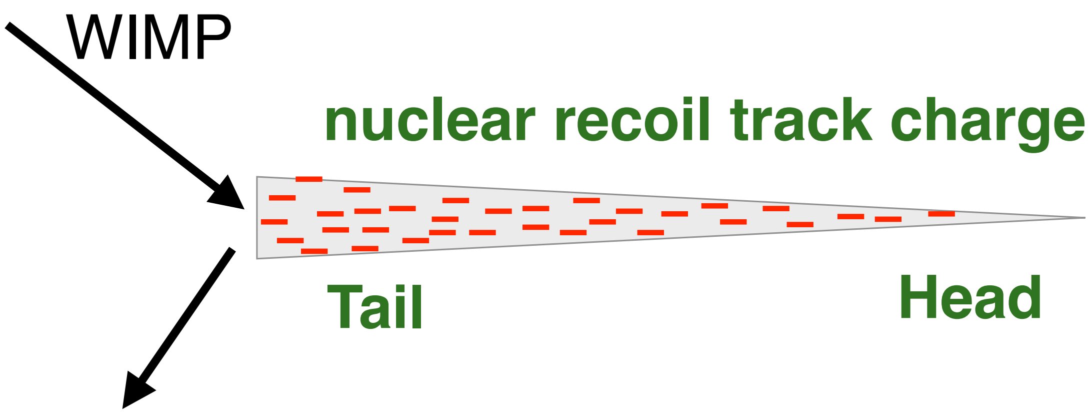
Directionality - A Better WIMP Signal

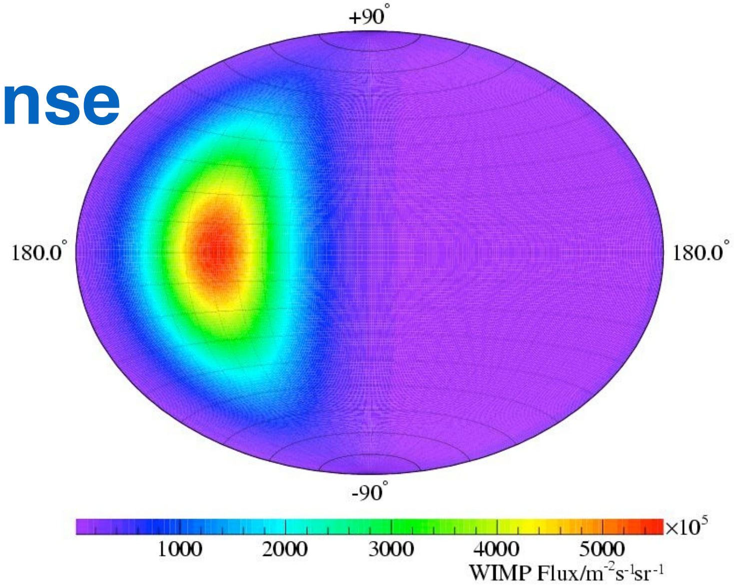
- A directional recoil signal is a very powerful proof
- Lets be prepared!





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





Directional Strategies and CYGNUS

(1) High Density Targets Solid, Liquids

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

Old work

Stilbene
Rotons in Lq He
Phonon focussing
Multilayers....

But recent work is progressing...

Anisotropic scintillators
Emulsions
Columnar recombination in Xe/Ar
Carbon nano-tubes

(2) Low Pressure TPCs

DRIFT
DM-TPC
MIMAC
NEWAGE
D^3
Italy R&D
Australia R&D
others..

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(2) Low Pressure TPCs

DRIFT
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MIMAC
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Australia R&D
others..

CYGNUS

(1) DM below neutrino floor (2) Coherent solar neutrinos

CYGNUS - Agreement

CYGNUS agreement includes Solid and TPC technology

The CYGNUS Galactic Directional Recoil Observatory
Proto-Collaboration Agreement

Now that conventional WIMP dark matter searches are approaching the neutrino floor, there has been a resurgence of interest in the possibility of introducing recoil direction sensitivity into the field. Such directional sensitivity would offer the powerful prospect of reaching below this floor, introducing both the possibility of identifying a clear signature for dark matter particles in the galaxy below this level but also of exploiting observation of coherent neutrino scattering from the Sun and other sources with directional sensitivity. There has also been significant progress recently in development of technology able to record the directional information from nuclear recoils at low energy (sub-100 keV) necessary for these goals. This includes progress on improving the sensitivity of low pressure gas time projection chamber technology but also on novel ideas with higher density targets, such as ultra-fine grain emulsions, scintillation materials, columnar recombination with noble gas targets and concepts using nano-technology. Such world-wide directional expertise, if pooled together and directed at converging on an optimised design, likely at multiple underground sites and different latitudes, could allow creation of a global **Galactic Nuclear Recoil Observatory**. Such a distributed multi-site facility would thus open a new window on the Universe with multiple science goals – the observation of a directional signal from particle dark matter, likely incident on Earth from the direction of the Cygnus constellation, a first means to detect and measure a directional signal due to coherent scattering of non-terrestrial neutrinos including from supernovae and the Sun, correlated with the position of the Sun, and also a novel means to search for exotic new particles including axions.

For several years there has been growing cooperation and exchange between most world groups working on recoil directional technology, including through a series international meetings called CYGNUS. This proto-collaboration agreement now sets the basis for taking this cooperation forward towards formation of a full collaborative experiment to realise construction of a global Galactic Directional Recoil Observatory, which we call the CYGNUS experiment. Signatories to this agreement hence forward agree to work together towards this common goal and to the formation of the CYGNUS collaboration, recognising that cooperation brings mutual benefits to all. Specifically in this regard, we the undersigned, on a best efforts basis, agree to work on the following goals:

(1) to establish the science case for CYGNUS, working with external experts as required
(2) to establish the feasibility and technology choices for CYGNUS, coordinating R&D activities, resources and joint publications as necessary
(3) to form an Institute Board including remit to prepare an organisational structure in readiness for launch of the collaboration
(4) to write an experiment LOI as basis for formation of the collaboration based on (1-3)
(5) to launch the collaboration at an appropriate date to be decided by us

The CYGNUS proto-collaboration will be coordinated by an interim steering group (ISG) with remit to facilitate activities of the proto-collaboration and organise technical meetings. The ISG will guide transition to launch of the collaboration but will be disbanded at that time.

(includes common analysis)
(broad aim - below neutrino floor, high and low mass)

CYGNUS proto-collaboration agreement (Sep. 2016-)
- 50 signatures (as of Nov. 2016)
- Steering group
- 4 working groups, monthly TV meeting
  - Engineering WG (N. Spooner)
  - Simulation WG (S.Vahsen)
  - Neutron WG (E. Baracchini)
  - Gas R&D WG (K. Miuchi)

Power of TPC Directionality

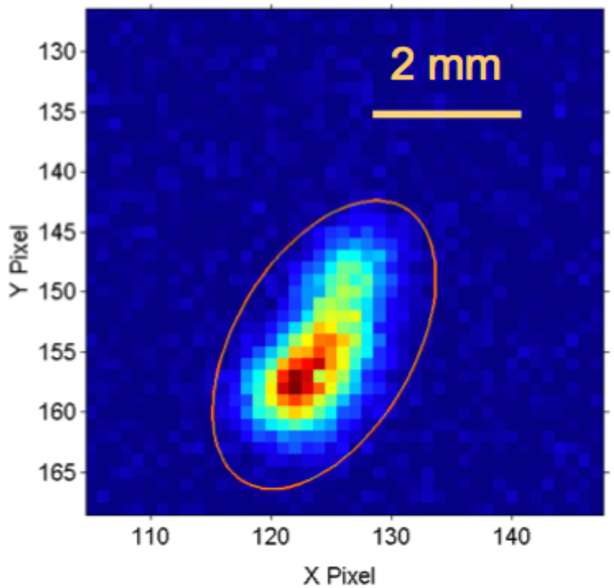
- **Only TPCs have the advantage of accessing head-tail information and sensitivity to the start of the recoil track**

- Head-Tail Sensitivity
- Axial Sensitivity

Power of TPC Directionality

- **Only TPCs have the advantage of accessing head-tail information and sensitivity to the start of the recoil track**

- Head-Tail Sensitivity
- Axial Sensitivity

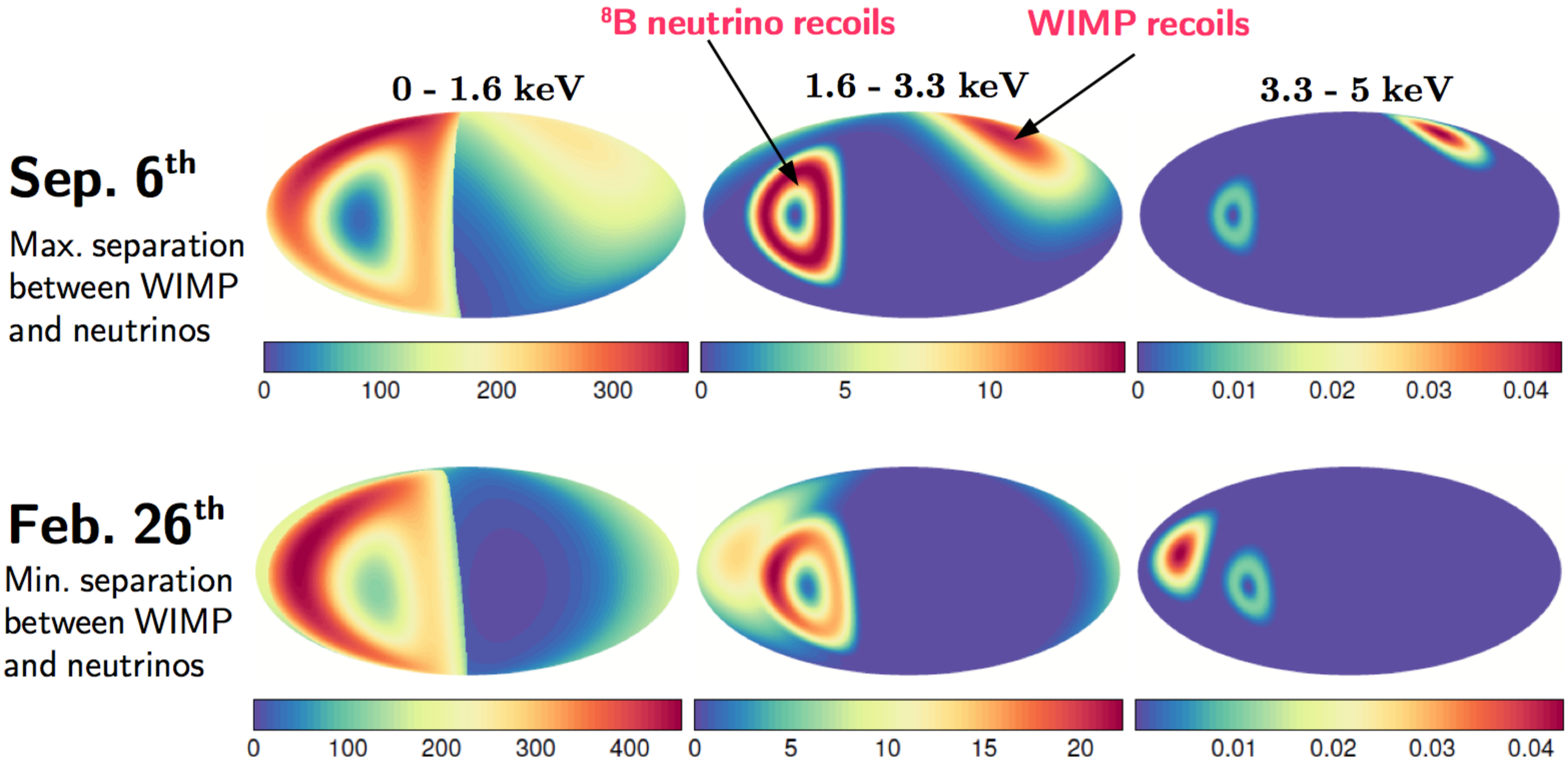


Example high energy F recoil in optical TPC (D. Loomba et al.)

- **How many WIMPs to get a directional (non-isotropic) signal?**

Power of Directionality - Solar Neutrinos

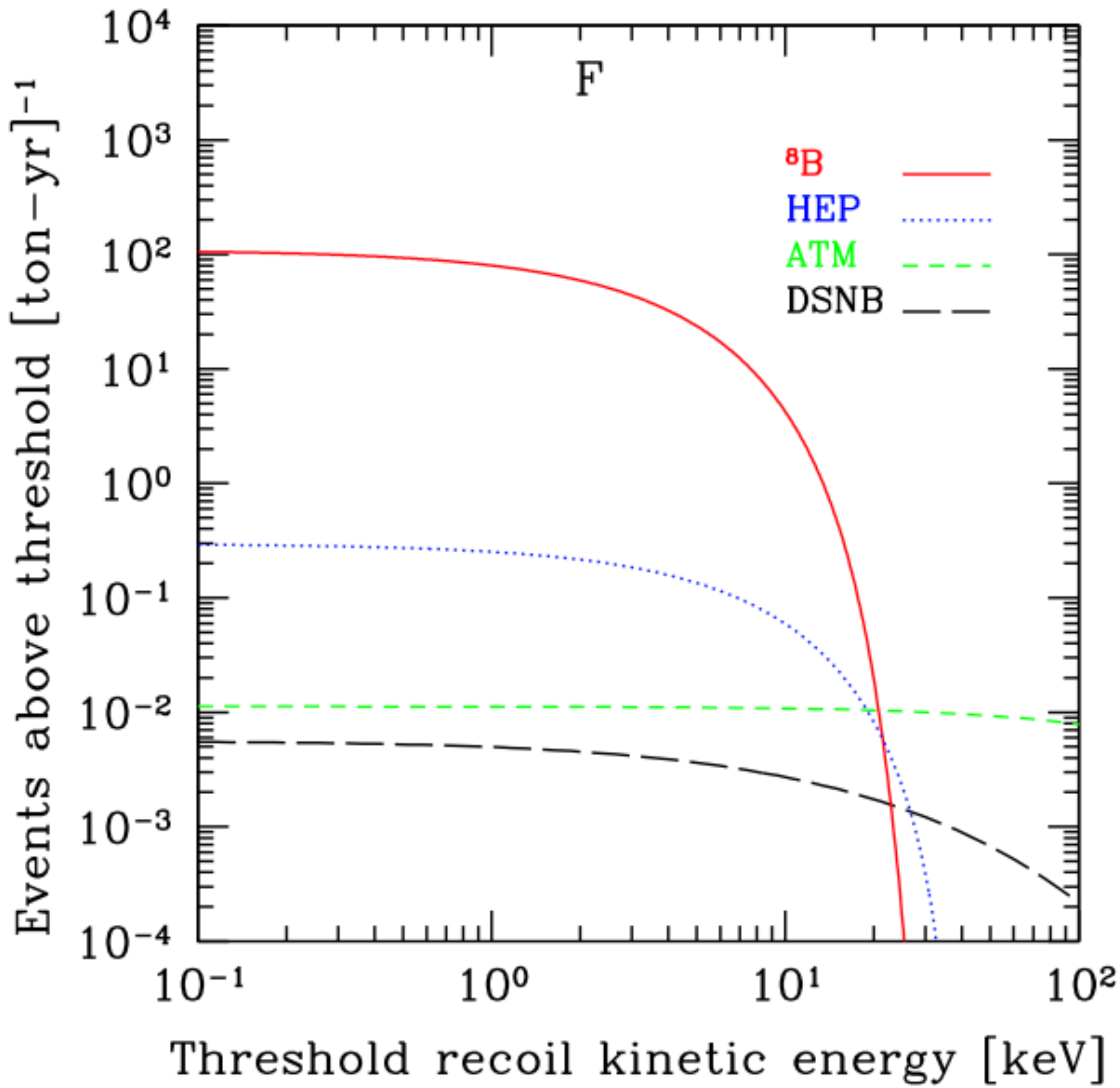
- Sun does not coincide with peak WIMP direction at any time
- It should be possible to distinguish the two signals at any time

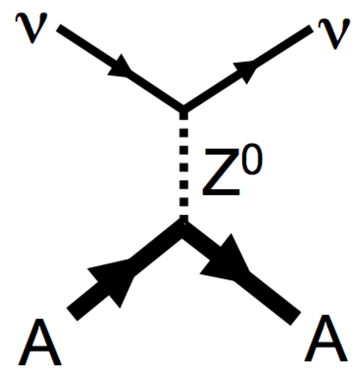


CAJ O'Hare *et al* [1505.08061]

Neutrino Coherent Rates, Fluorine

Louis E. Strigari arXiv: 0903.3630v2



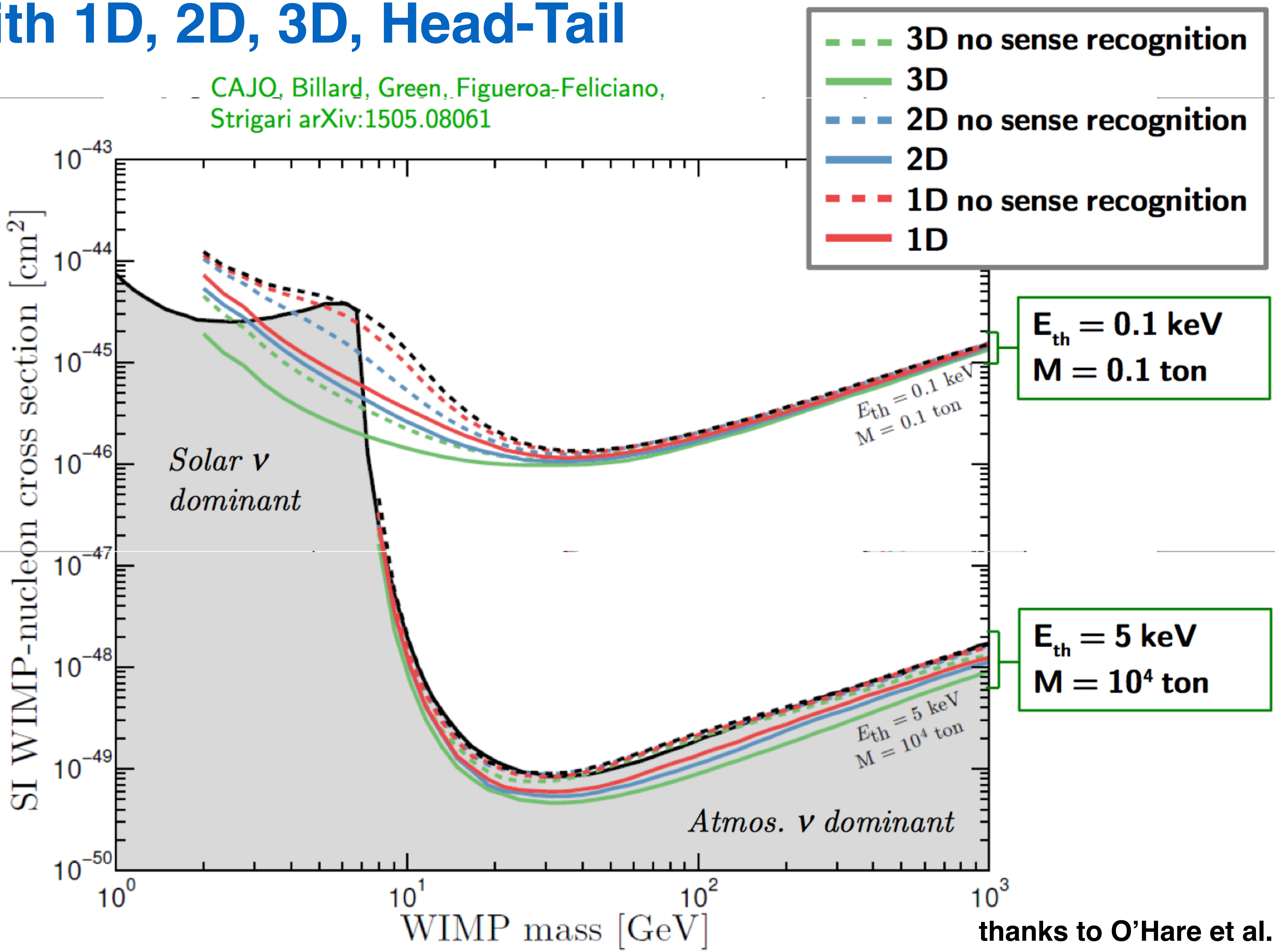


1keV$_{rec}$ threshold —> ~70 events per ton year

10m^3 SF_6 at 200 torr for 3 years operation yields 4 neutrinos.

Below the Neutrino Floor

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

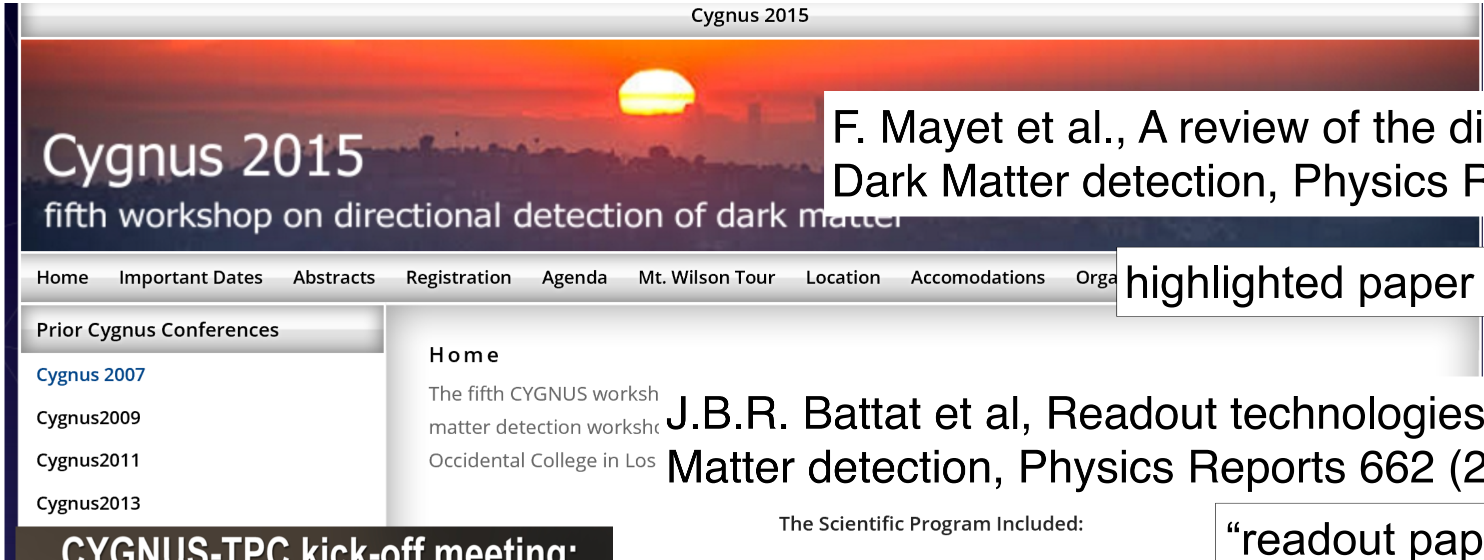


thanks to O'Hare et al.

CYGNUS Activities

"CYGNUS" : from workshop to collaboration

- biannual workshop for directional detection of dark mater (2007-)
- two related papers (2010, 2016, 2016), another is ongoing
- proto-collaboration agreement (Sep. 2016-)



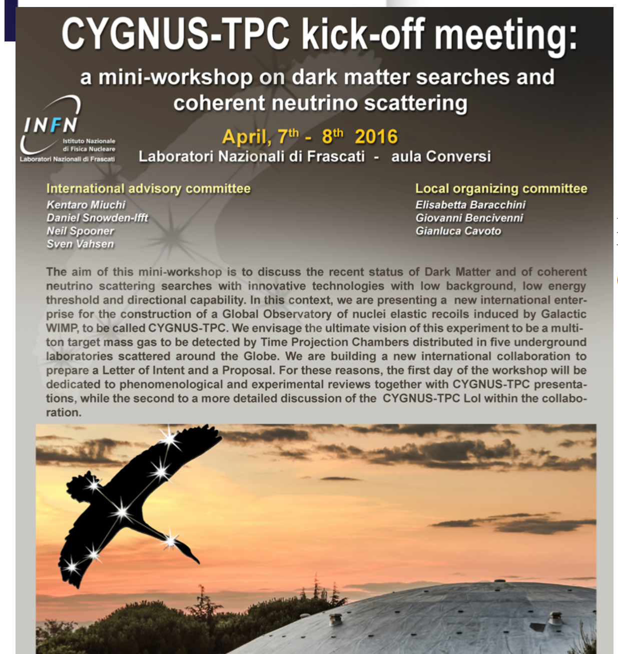
F. Mayet et al., A review of the discovery reach of directional Dark Matter detection, Physics Reports 627 (2016) 49

highlighted paper

"physics paper" 16 authors

J.B.R. Battat et al, Readout technologies for directional WIMP Dark Matter detection, Physics Reports 662 (2016) 46

"readout paper" 93 authors



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Readout technologies for directional WIMP Dark M
detection

"white paper" 112 authors

Physics Reports

homepage: www.elsevier.com/locate/physrep

THE CASE FOR A
DIRECTIONAL DARK MATTER DETECTOR AND
THE STATUS OF CURRENT EXPERIMENTAL EFFORTS

Readout technologies for directional WIMP Dark Matter
detection

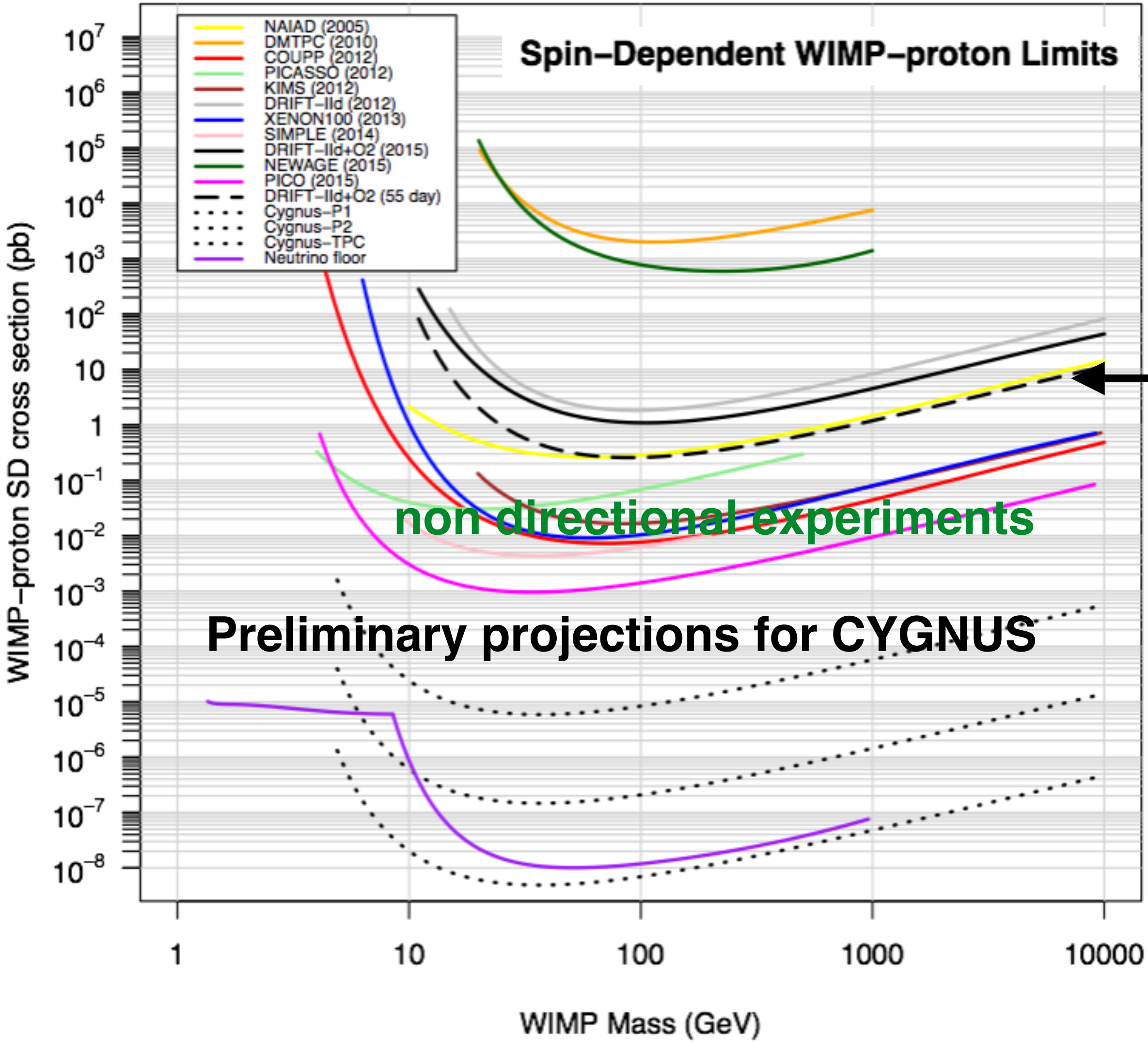
CYGNUS - Multiple Sites

Directionality benefit from multiple sites at different latitude

new lab funded in Australia

CYGNUS-TPC Baseline Concepts/Aim

- SF_6 target (~x5 more F per volume than current)
- Fiducialisation, -ve ion drift, head-tail sensitivity
- Multi-tonne, multi-underground site,
- Staged programme - low WIMP mass, high WIMP mass



The Pathfinder Strategy

~Current directional experiment state

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

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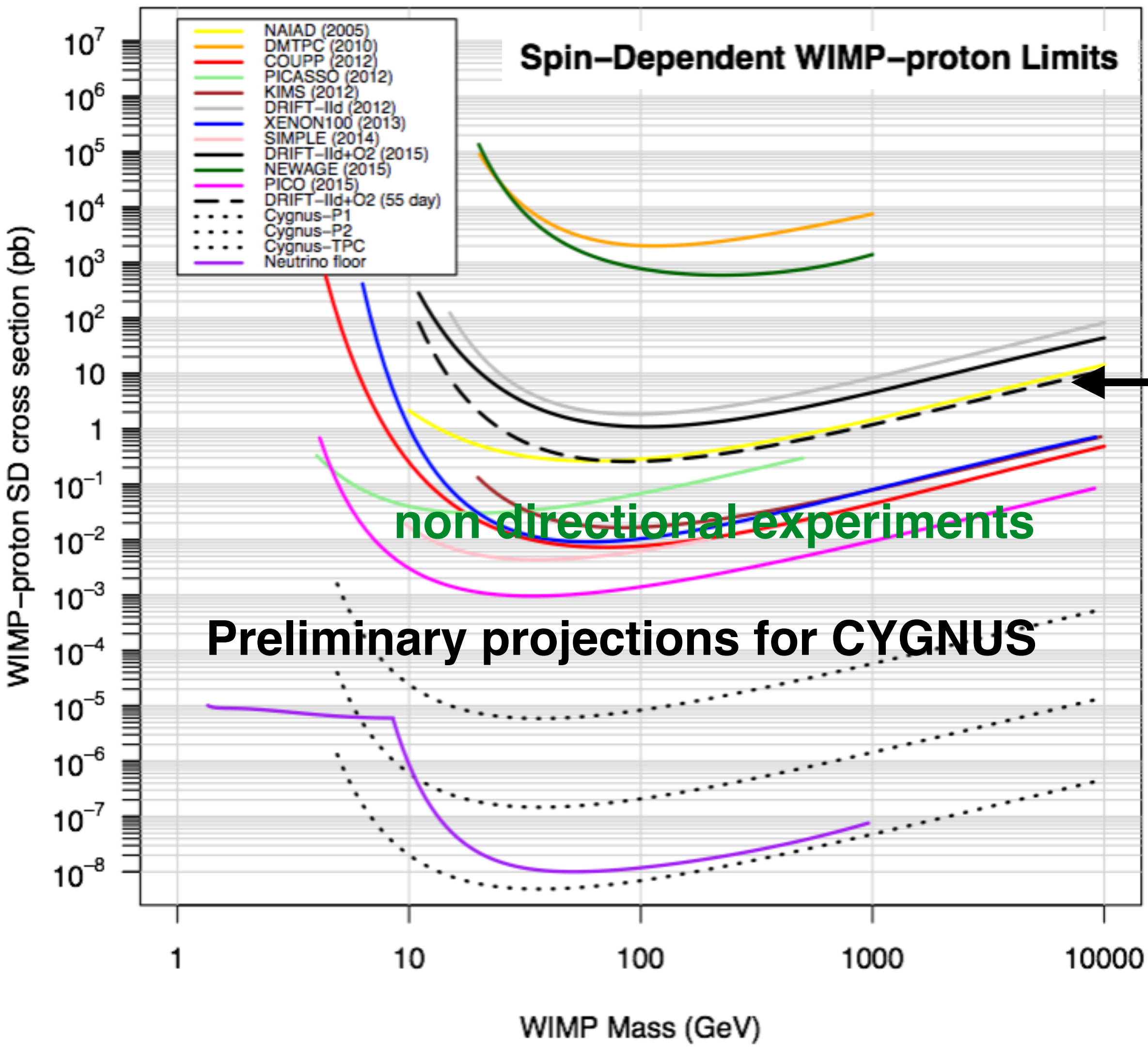


The Pathfinder Strategy

~Current directional experiment state

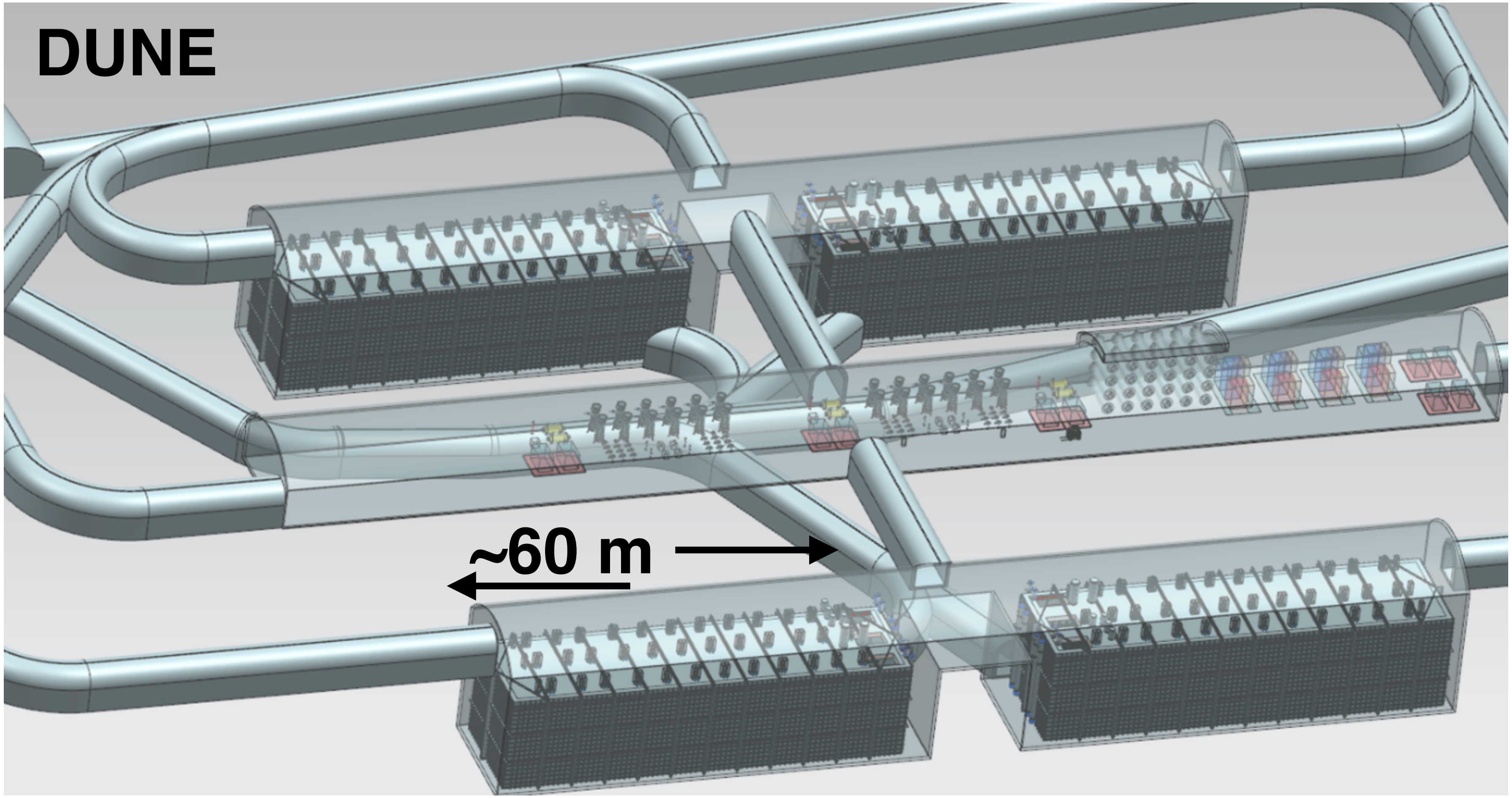
CYGNUS - Pathfinder 1

CYGNUS - Pathfinder 2

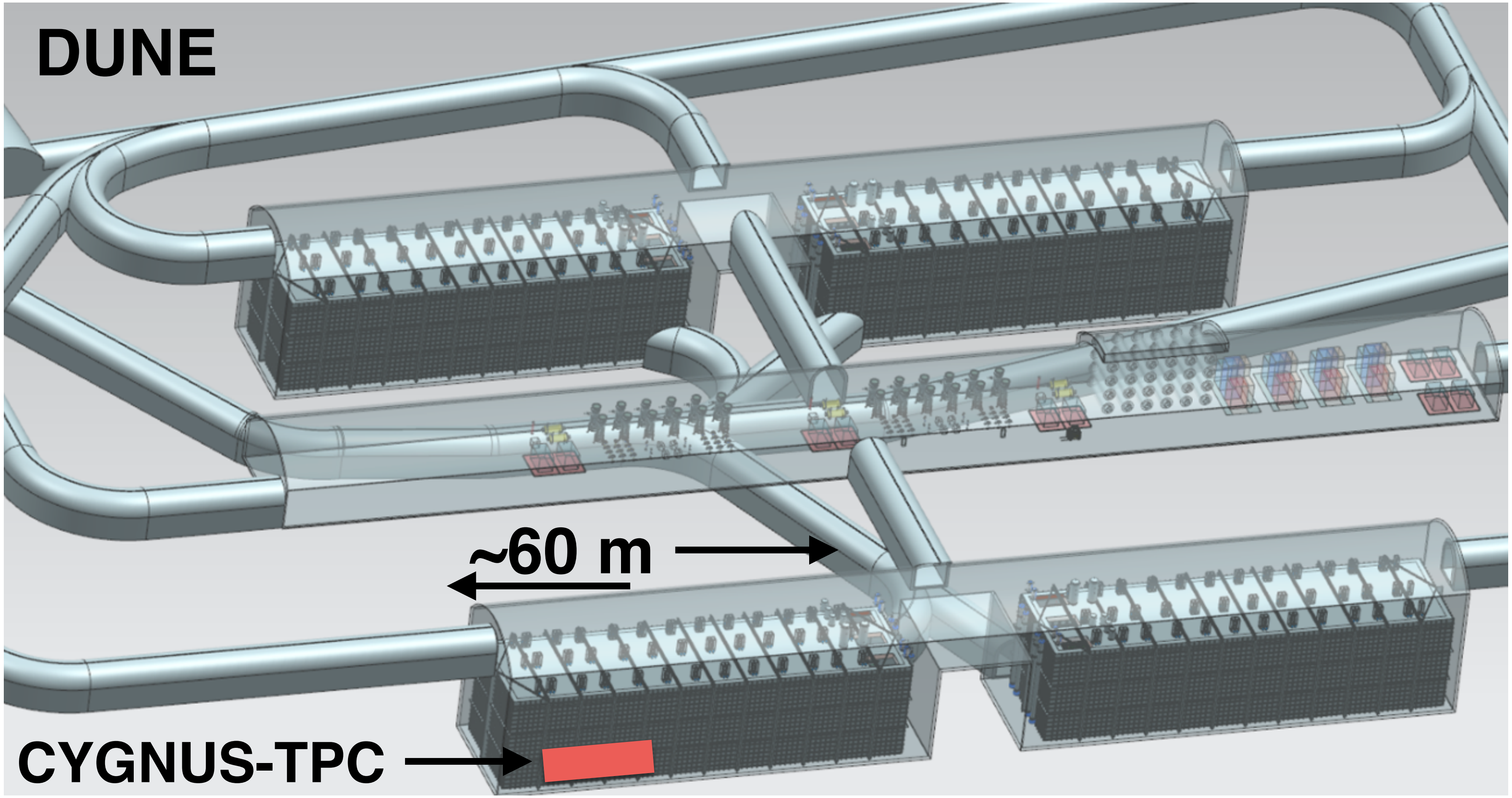
CYGNUS - TPC

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

How Not to be Afraid of Larger TPCs



How Not to be Afraid of Larger TPCs



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

CYGNUS NOW

Stage 1 Vision

(1) CYGNUS-TPC-South (10 m3 vessel….readout 1)
(2) CYGNUS-TPC-North (10 m3 vessel….readout 2)
(3) R&D at 1 m3 (CYGNUS-Japan, DRIFT…

North - Boulby, LNGS, Kamioka?
South - Stawell?

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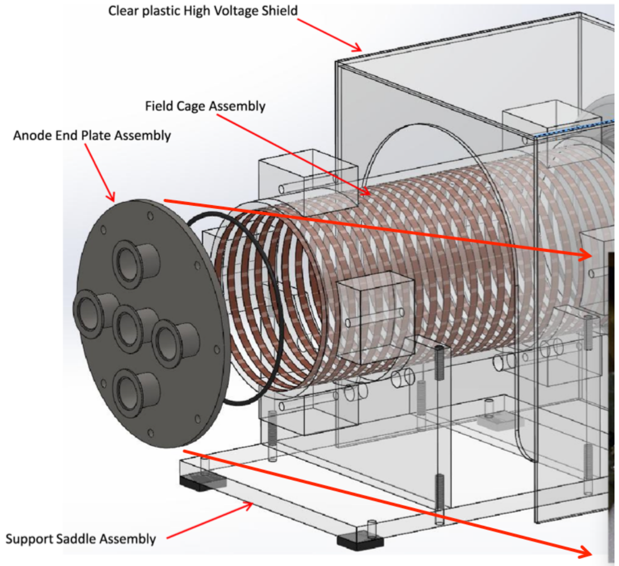
South - Stawell?

CYGNUS-TPC Optimisation - key issues

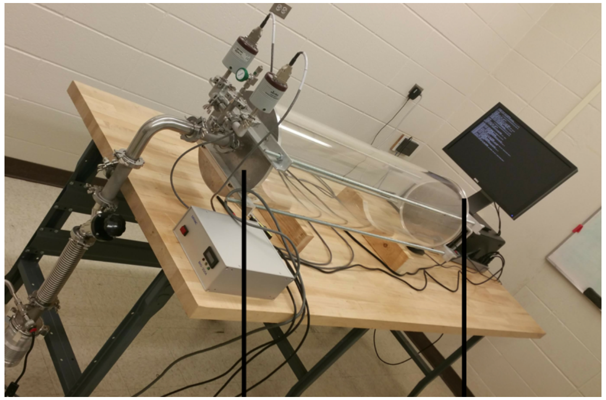
- What directional capability is optimal - 1D, 2D, 3D + HT vs cost?
- What directional sensitivity can there be <20 keV_{recoil}?
- Can we use multiple underground sites
- What gas - can SF_6 work well enough for fiducialisation?
- Can zero background be achieved (particularly neutrons)?

New Studies - Funded Activity

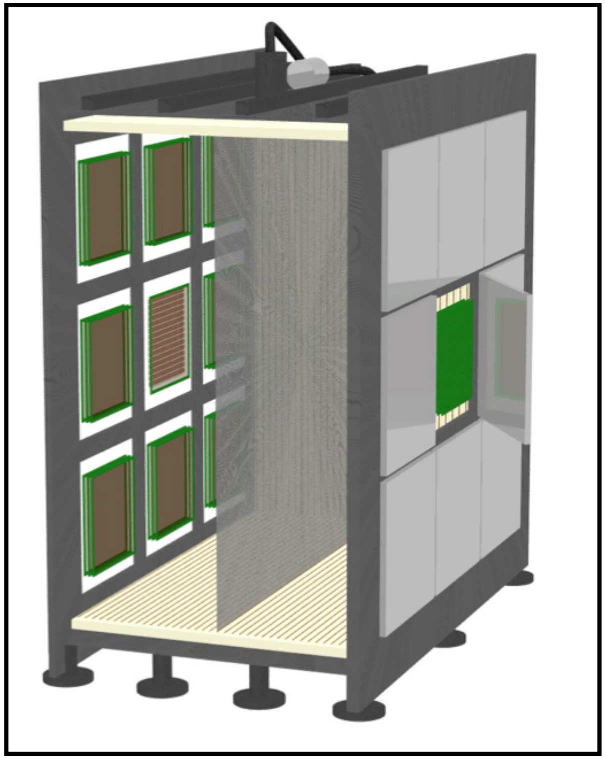
UNM acrylic (USA)



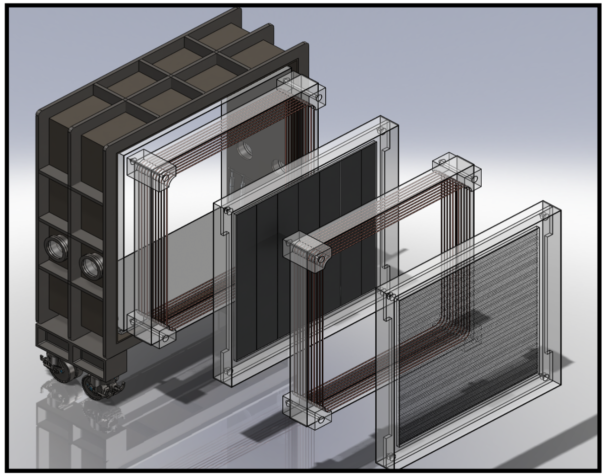
Hawaii D3 (USA)

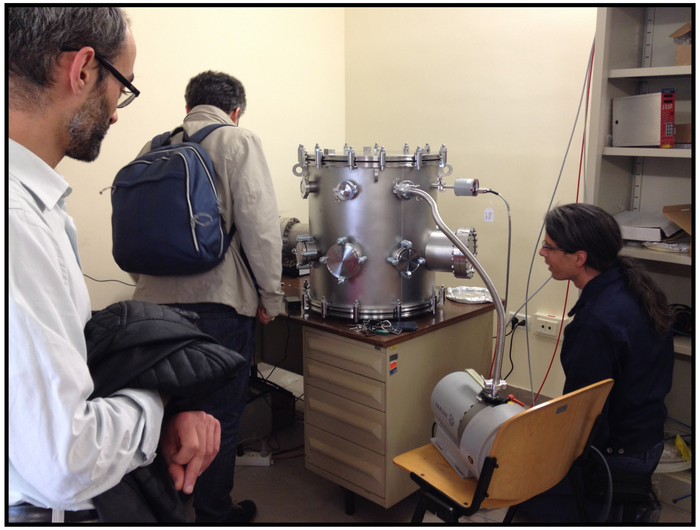


1 m3 CYGNUS test vessel (Japan) →

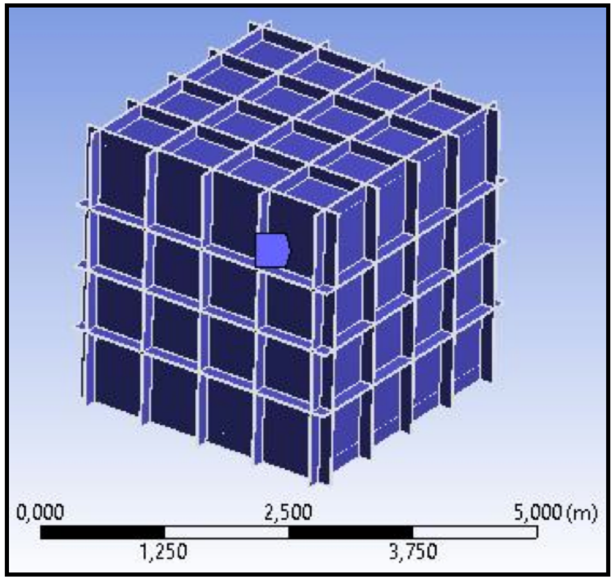


10 m^3 designs (US, UK)





SF_6 R&D, Frascati, (Italy)

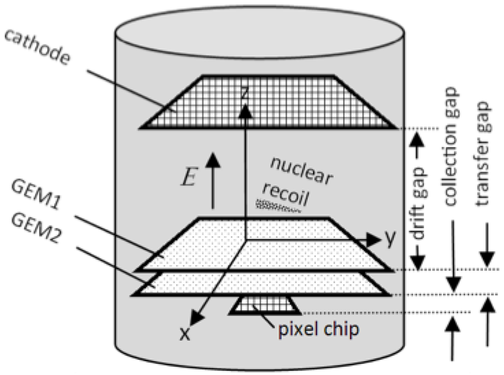


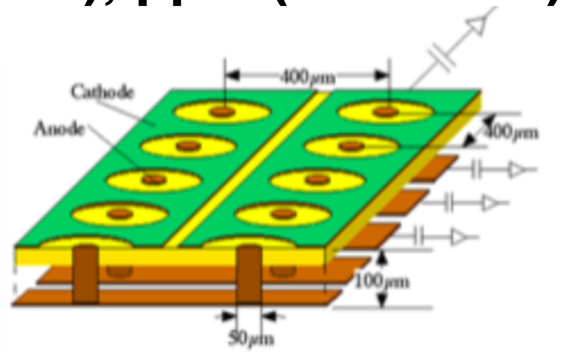
10 m^3 vessels (Australia)

What Directional TPC Technology?

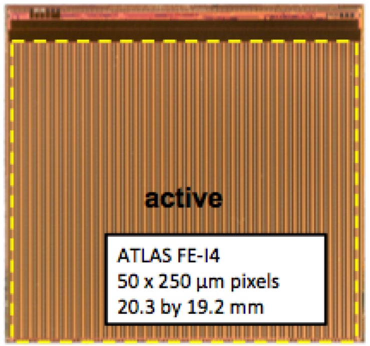
"high definition - 3D"

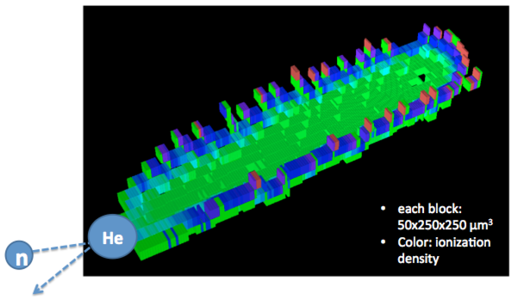
Pixel (D3), CCD (DM-TPC), Micromegas (MIMAC), μpic (NEWAGE)

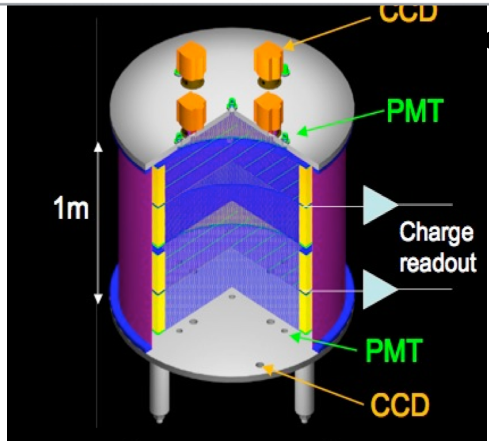


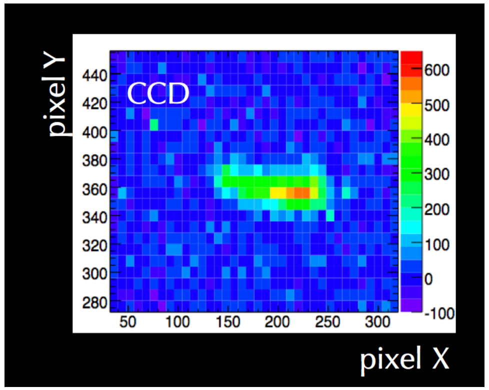


Pixel chip:



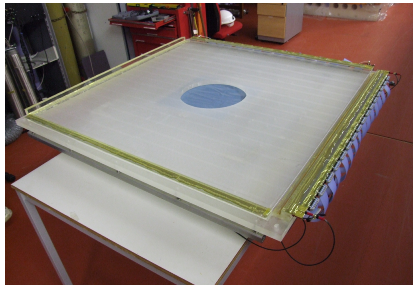


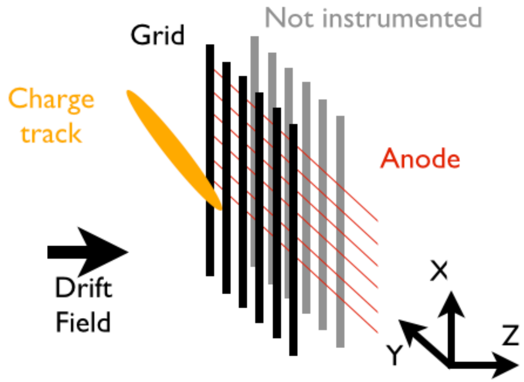


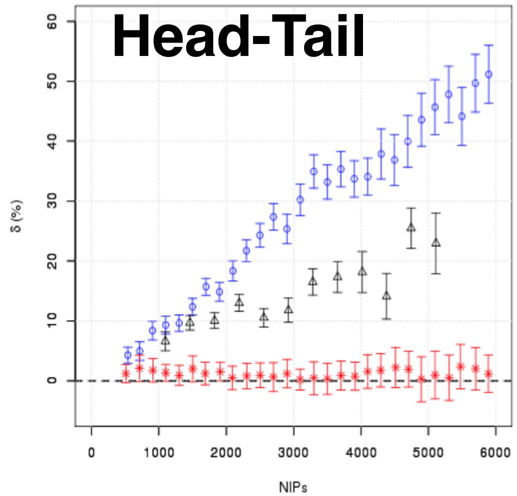


"low definition ~ 1.5D"

MWPC wires (DRIFT)



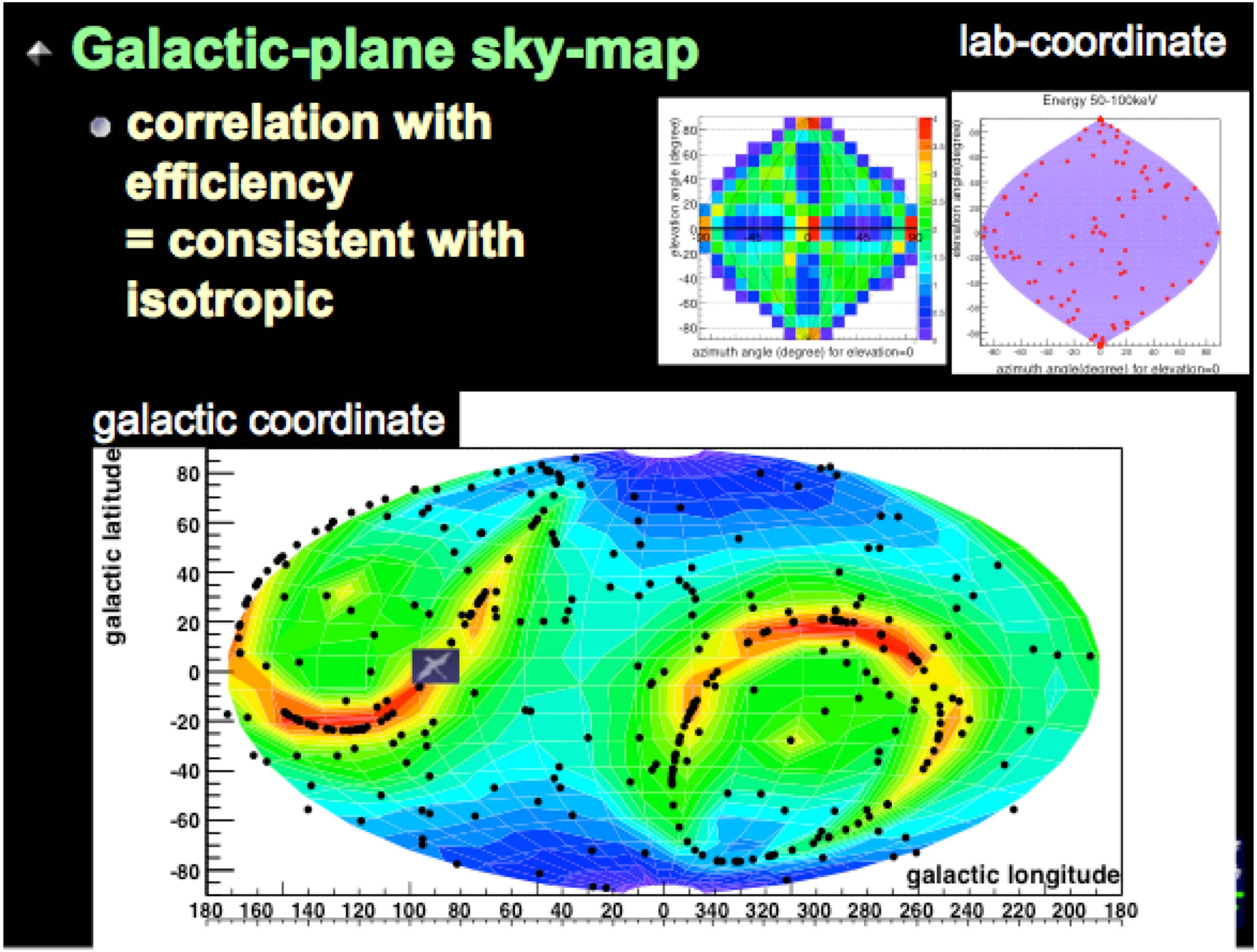




NEWAGE Experiment (Japan)

K. Muichi et al.

- **First demonstration in use of 3D to produce sky maps**



CYGNUS Next Paper

- **Next CYGNUS paper underway will address issue of cost-benefit of readout options**

Feasibility of a Nuclear Recoil Observatory with Directional Sensitivity to WIMPs and Solar Neutrinos

Contents

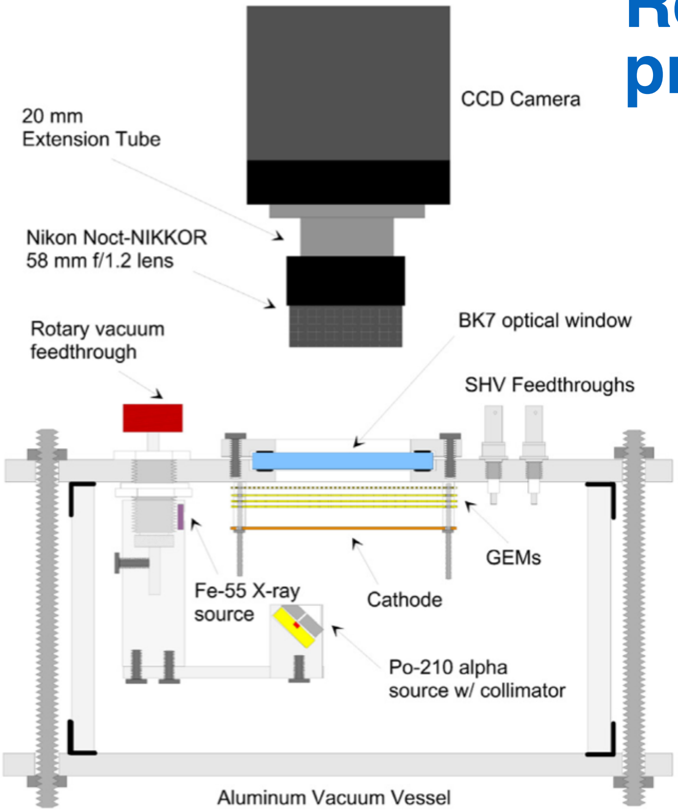
Sven Vahsen (Hawaii) is coordinating

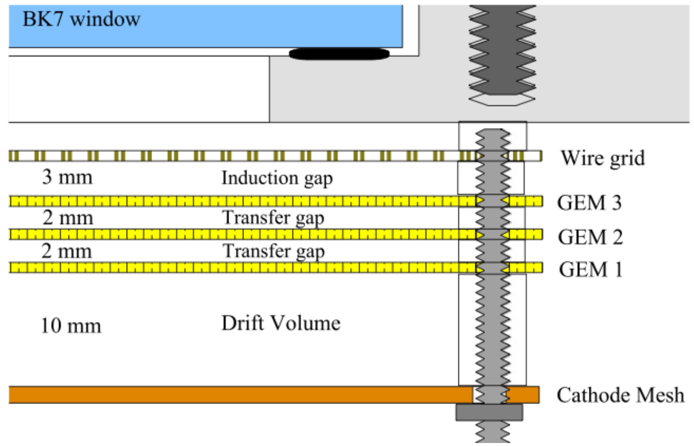
Low Energy Directionality Seen (UNM)

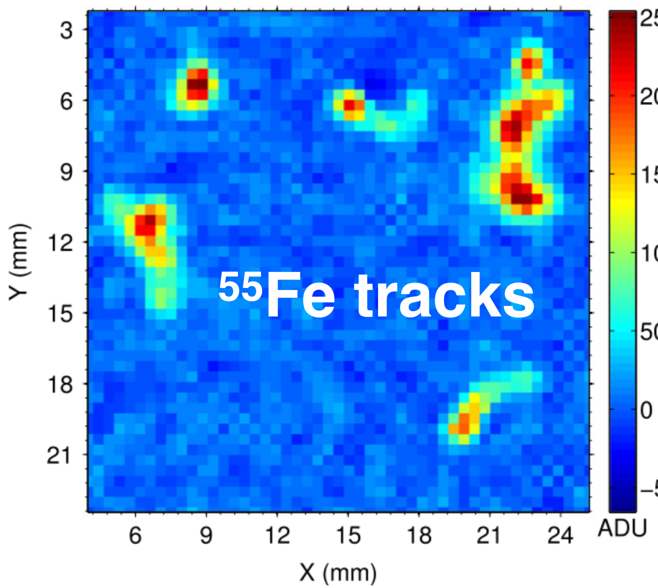
D. Loomba et al.,

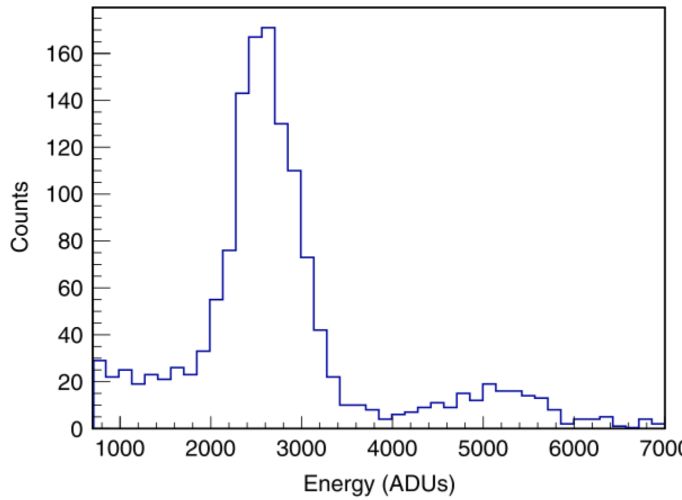
Recoil Directionality R&D is now probing <20 keV region

- CCD + triple GEM optical readout
- e.g. ^{55}Fe tracks resolved
- see upcoming papers by UNM

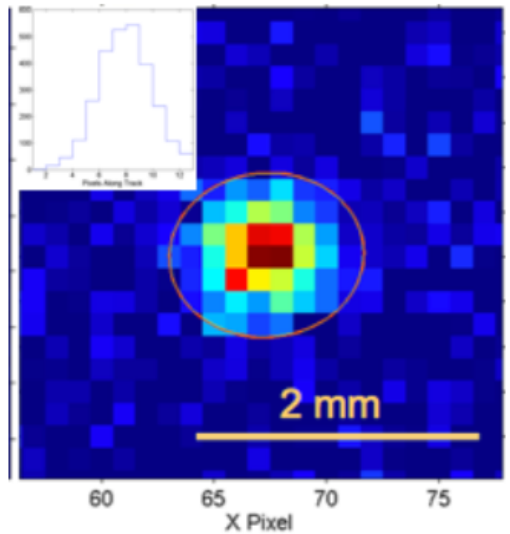








F recoil event of 10 keV_{ee} (23 keV_{rec}) still shows direction

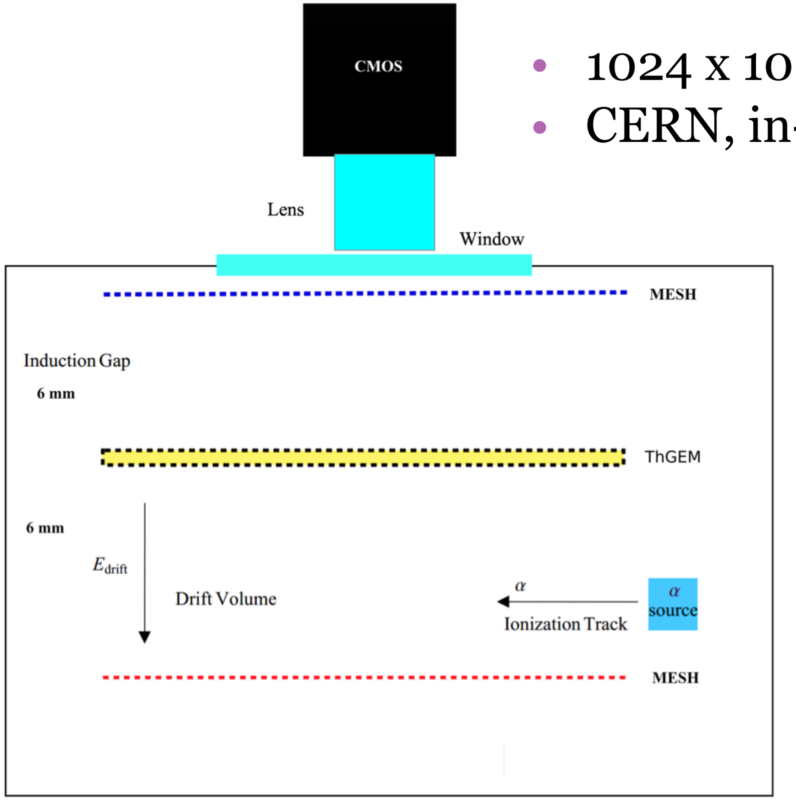


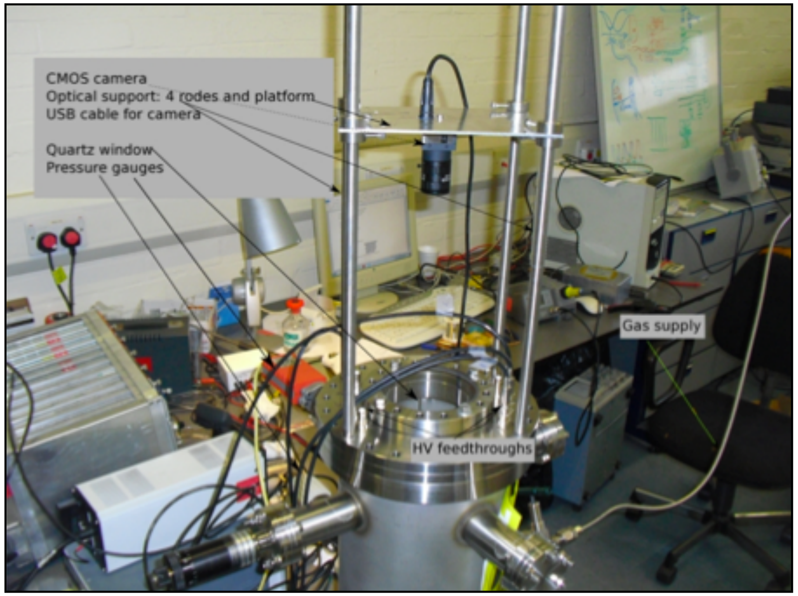
Sheffield R&D - CCD + Thick GEMs

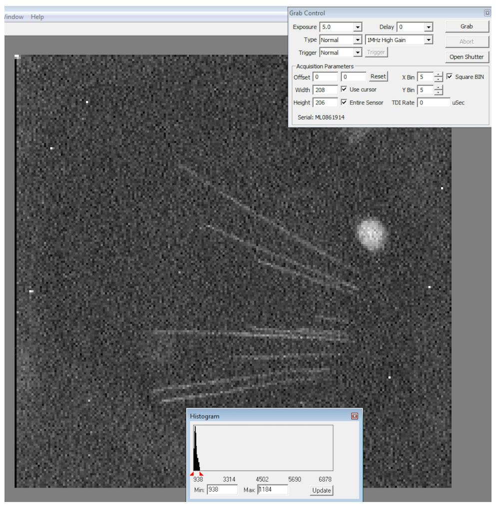
Concept: low pressure **CF_4 and SF_6 with Thick GEMs and CCD** readout

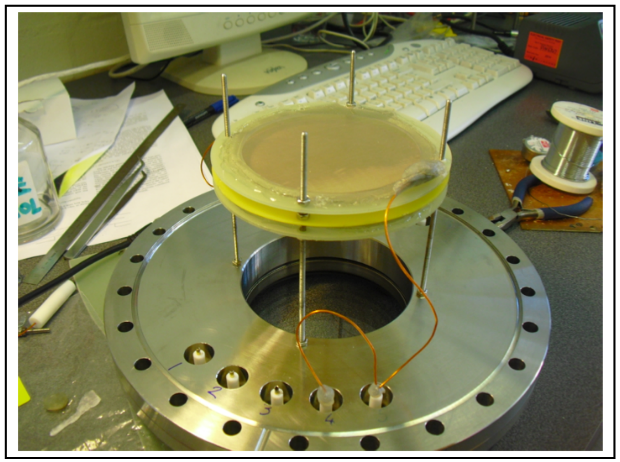
N. Spooner et al.,

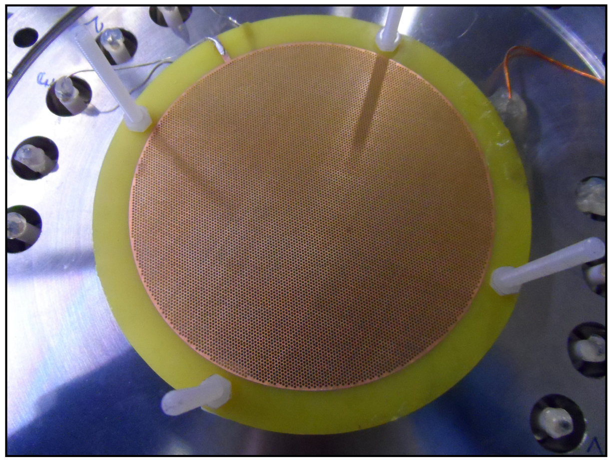
- 1024 x 1024, 24μm microline ML1001E camera
- CERN, in-house and AWE design Thick GEMs







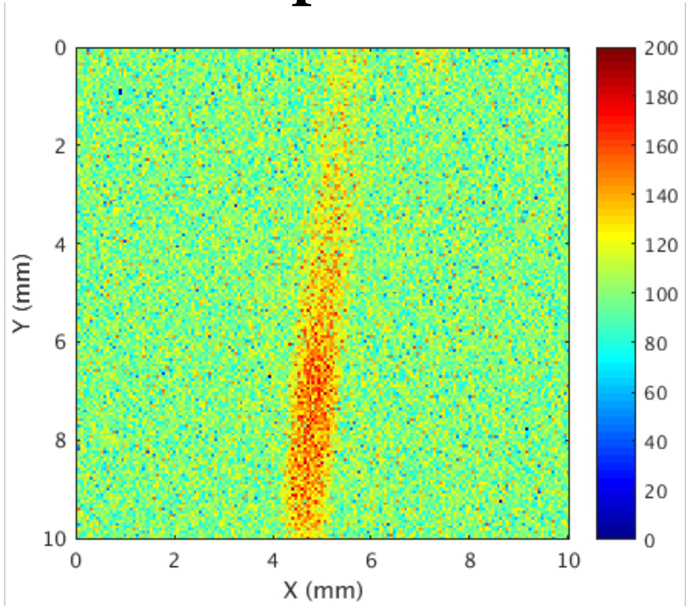




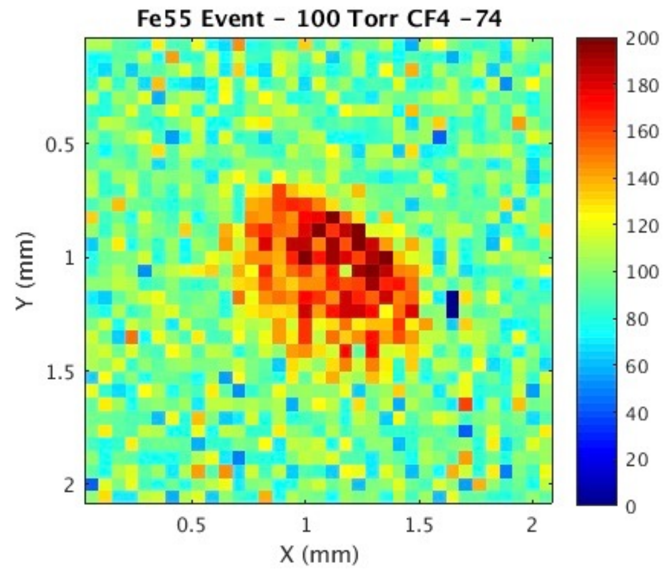
Sheffield R&D - CCD + Thick GEMs

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

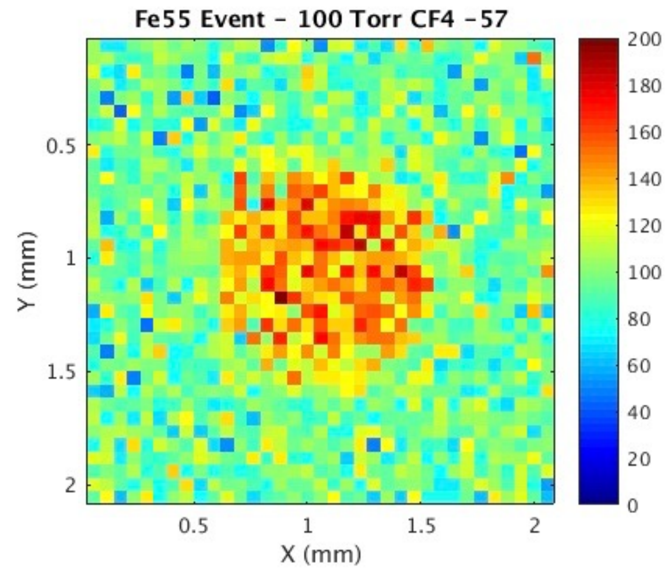
Alpha



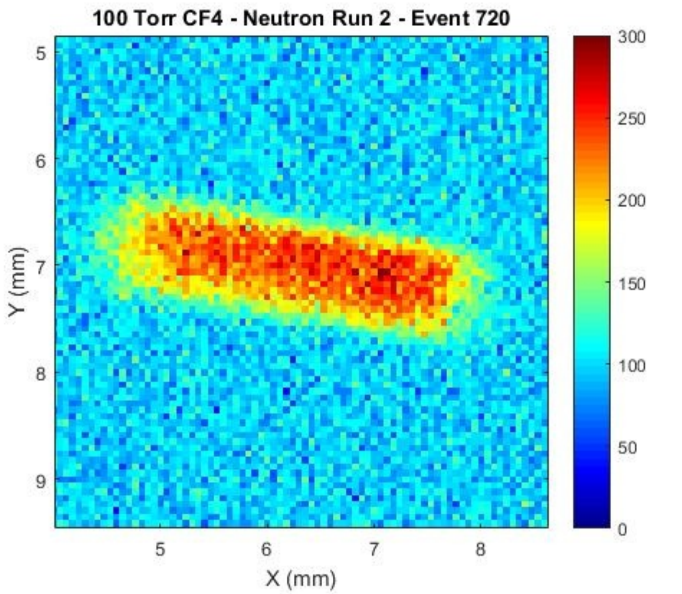
^{55}Fe 5.9 keV e^-



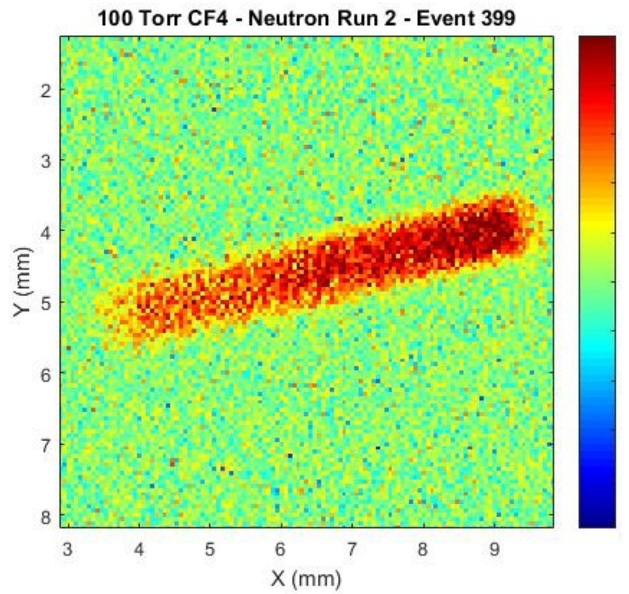
^{55}Fe 5.9 keV e^-



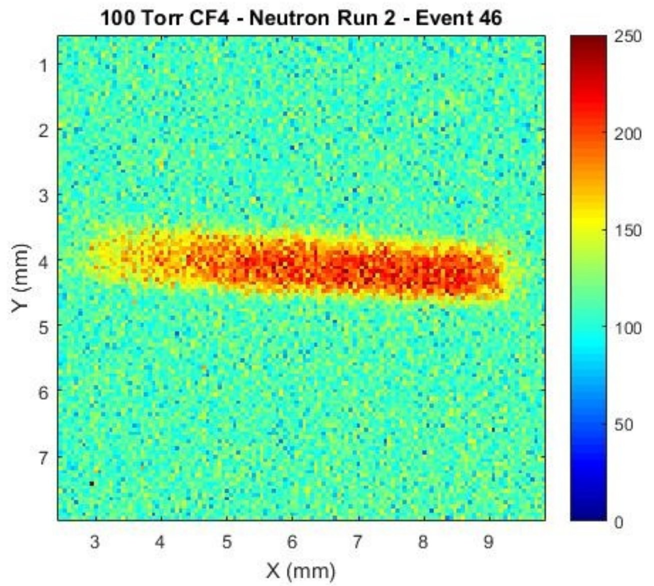
nuclear recoil



nuclear recoil



nuclear recoil



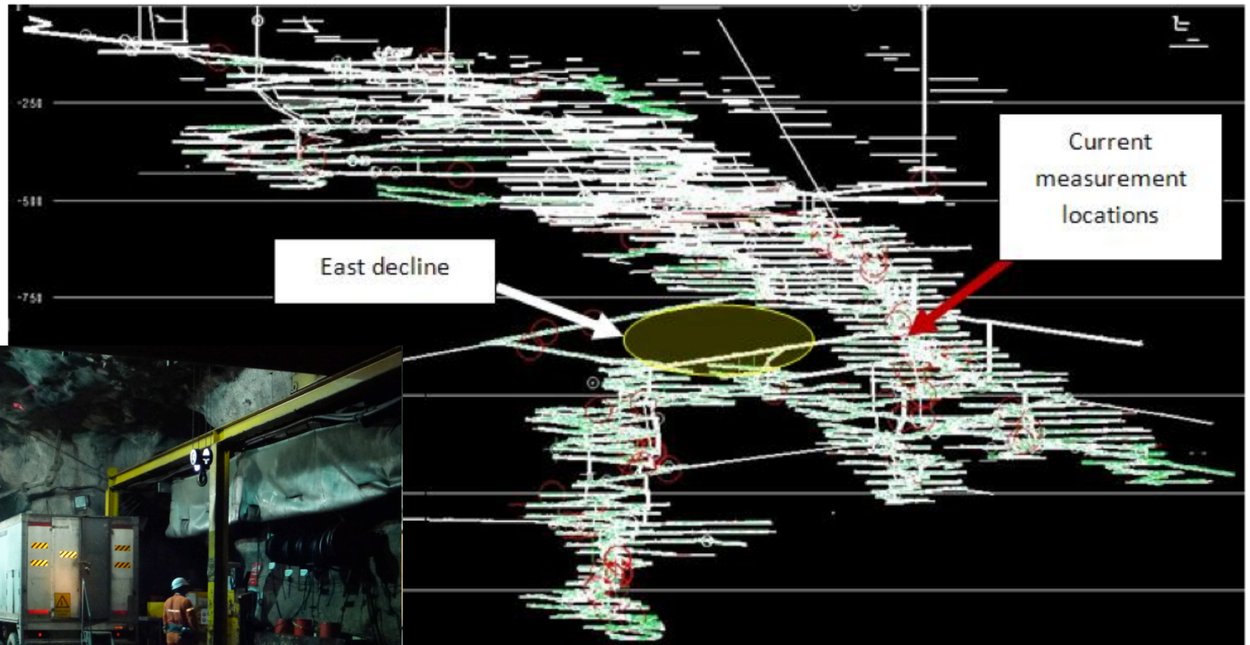
New Site Infrastructure

Stawell, Australia new site

- **New site funded by Australian government - 1 km depth**

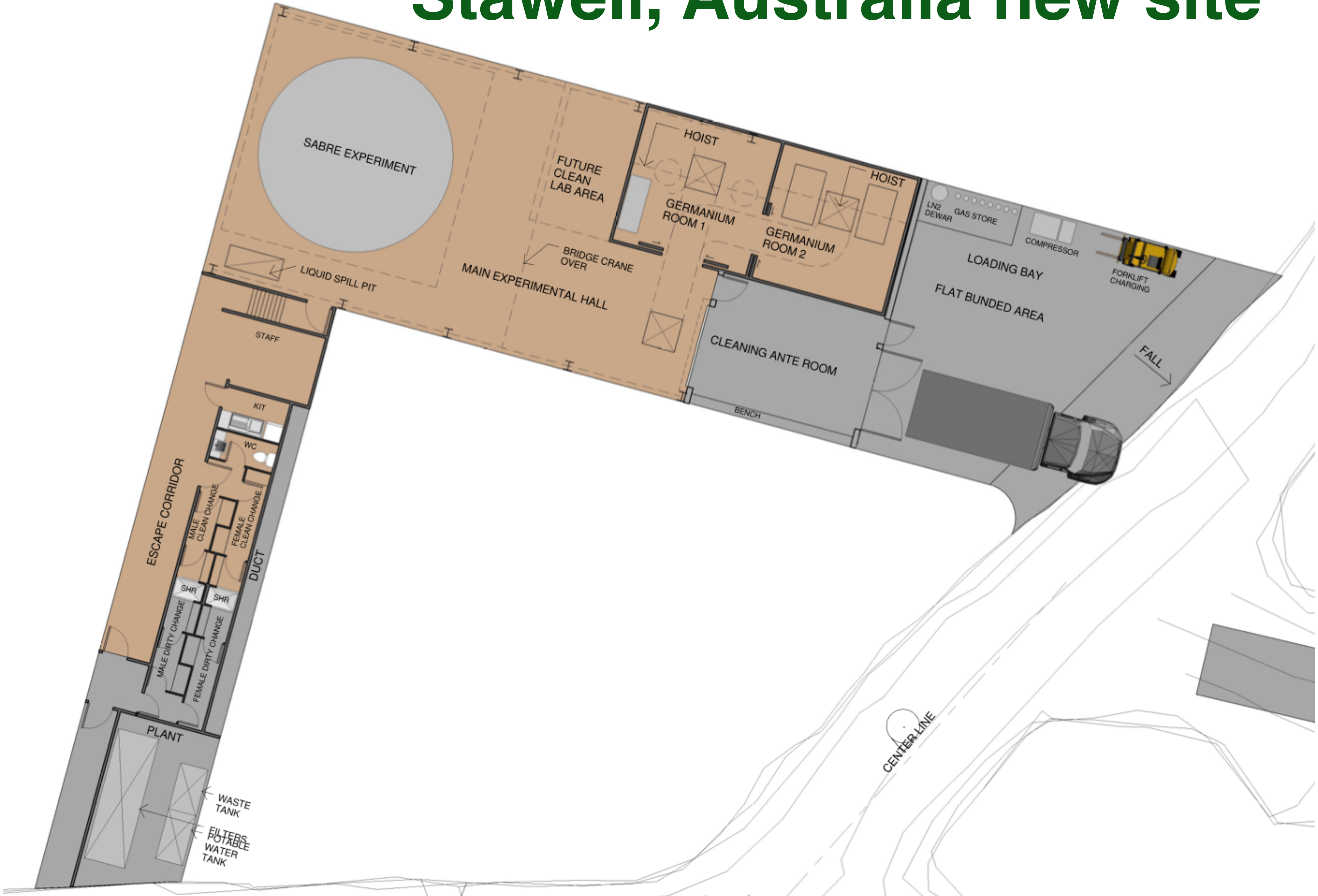
Stawell gold mine ~240 km west of Melbourne,
could be the first underground laboratory in the Southern hemisphere.

Decline mine, 1.6 km deep, with many caverns.
All sites served with electricity, optical fibre,
reached by car/truck.



New Site Infrastructure

Stawell, Australia new site

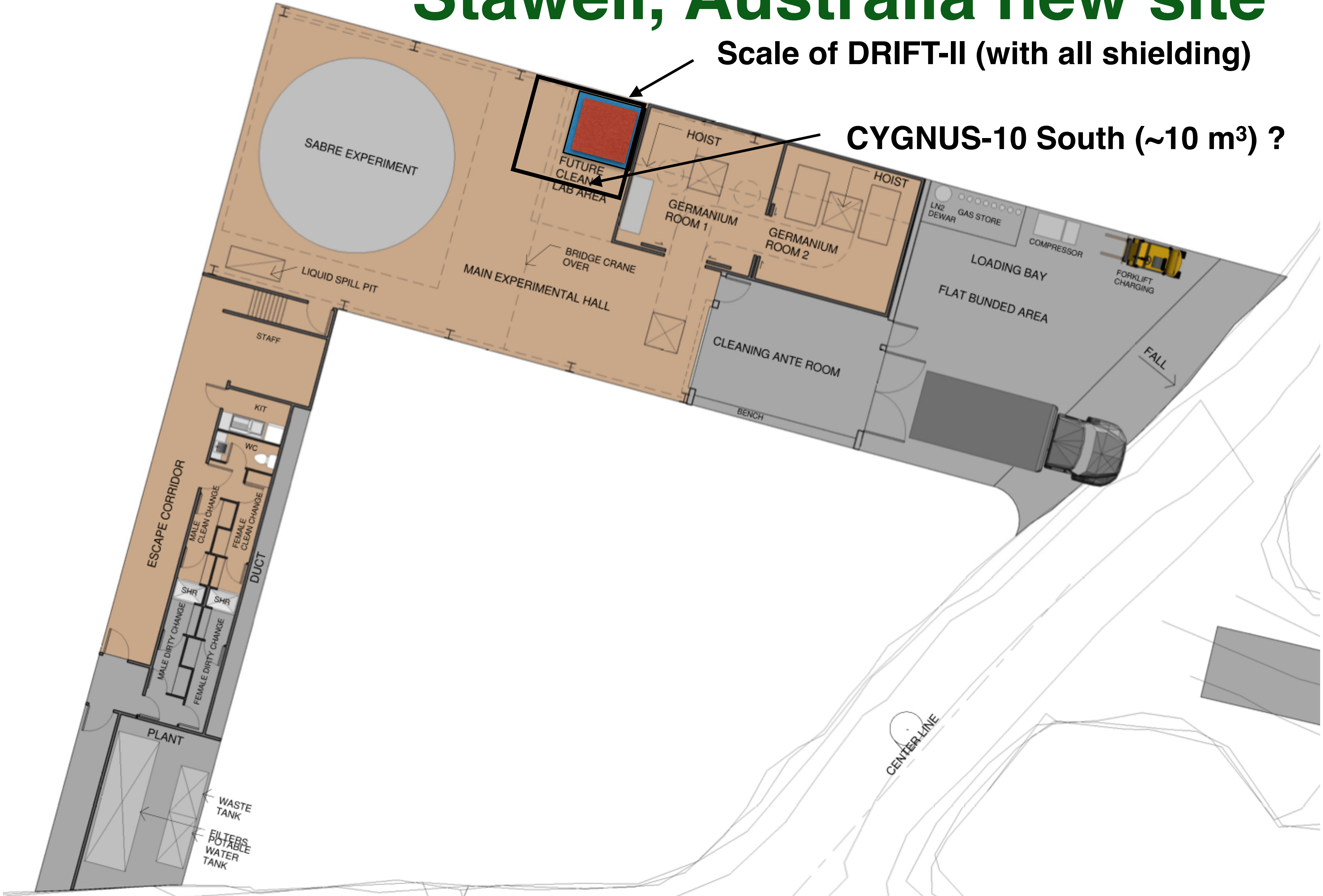


New Site Infrastructure

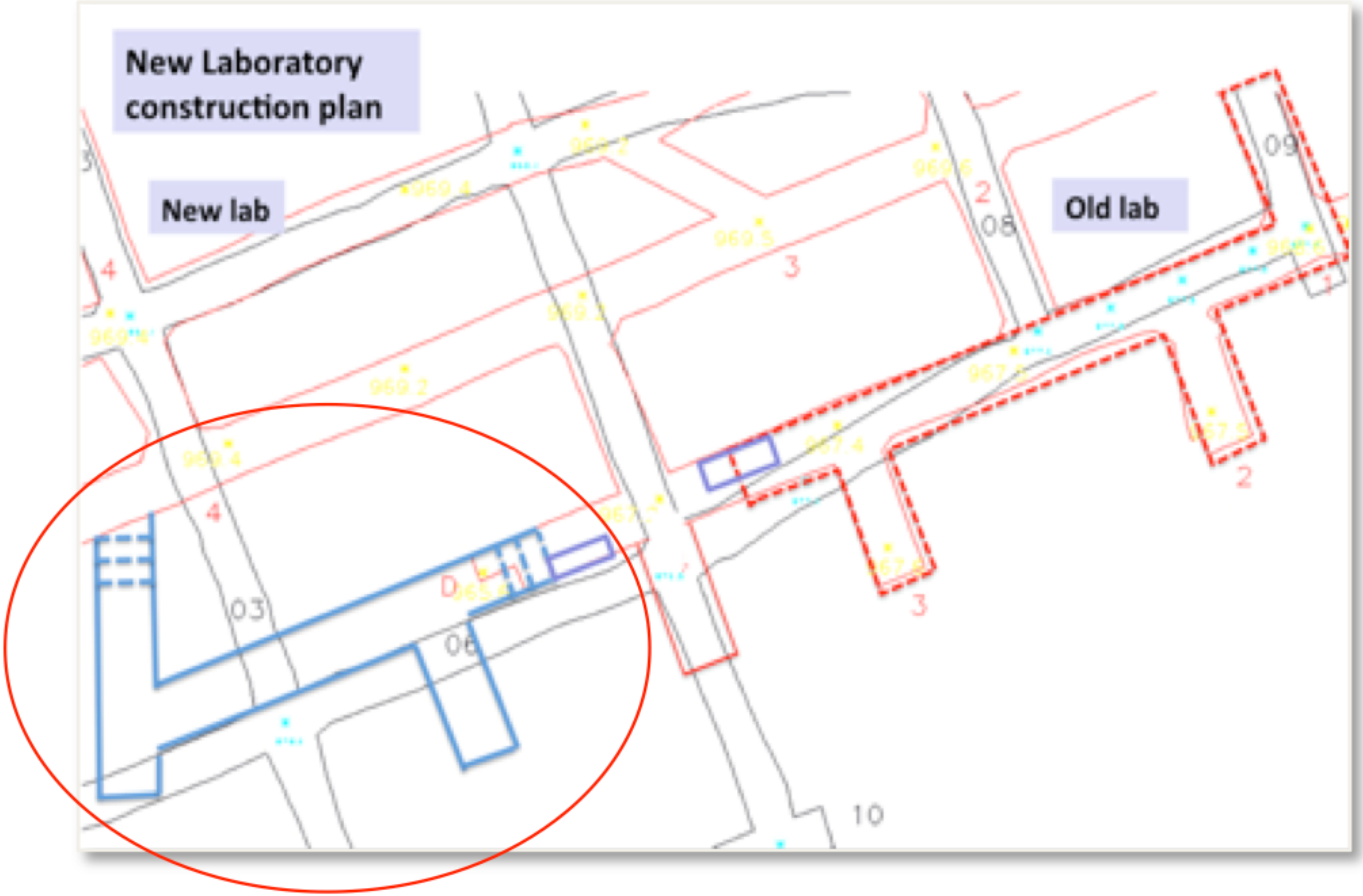
Stawell, Australia new site

Scale of DRIFT-II (with all shielding)

CYGNUS-10 South (~10 m³) ?



New Site Infrastructure
Boulby Laboratory, UK

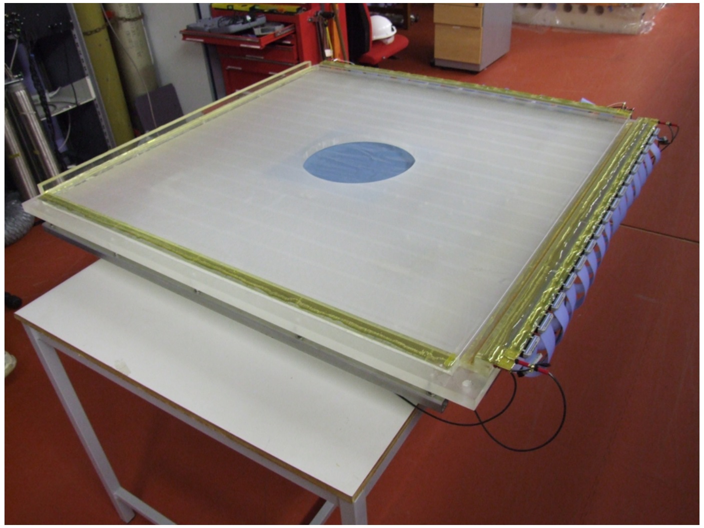


Underground Research Laboratory
Boulby

CYGNUS site at New Boulby Lab, UK

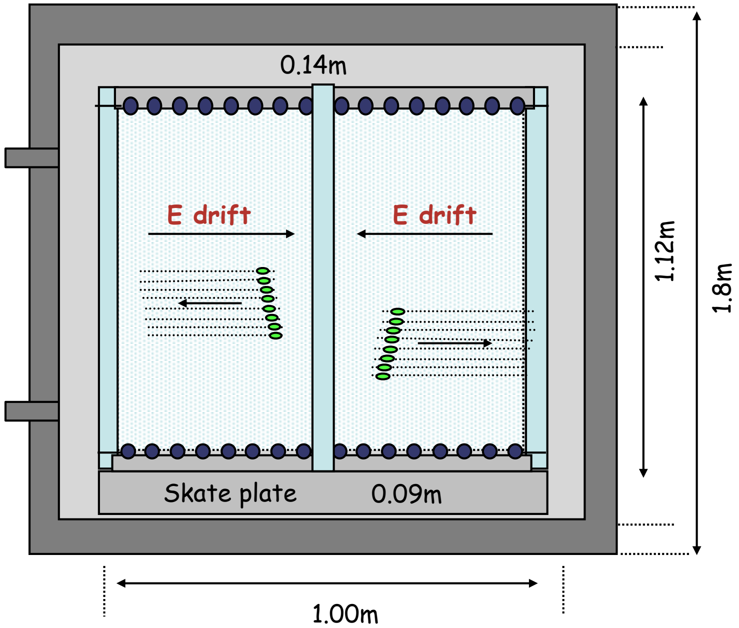
DRIFT IId & DRIFT IIe at Boulby

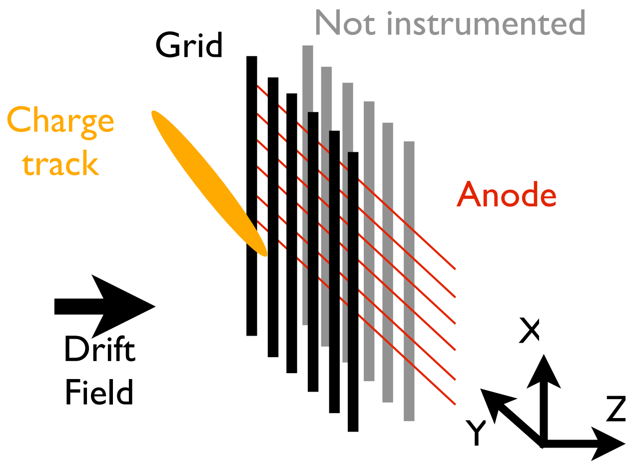
DRIFT is Pioneer (US-UK) at Boulby

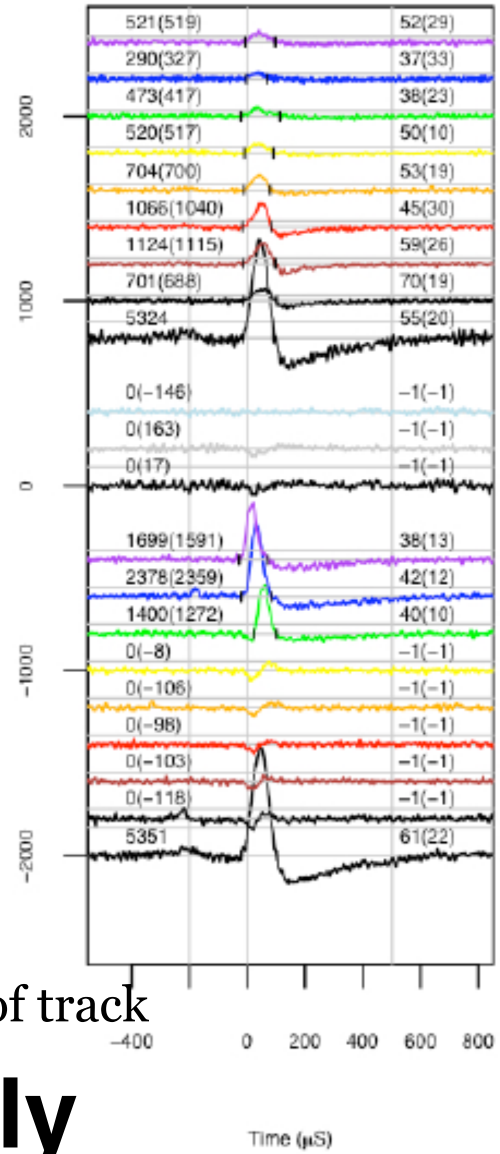


Directional Recoil Identification From Tracks (DRIFT)

DRIFT IIa, b, c, d, e



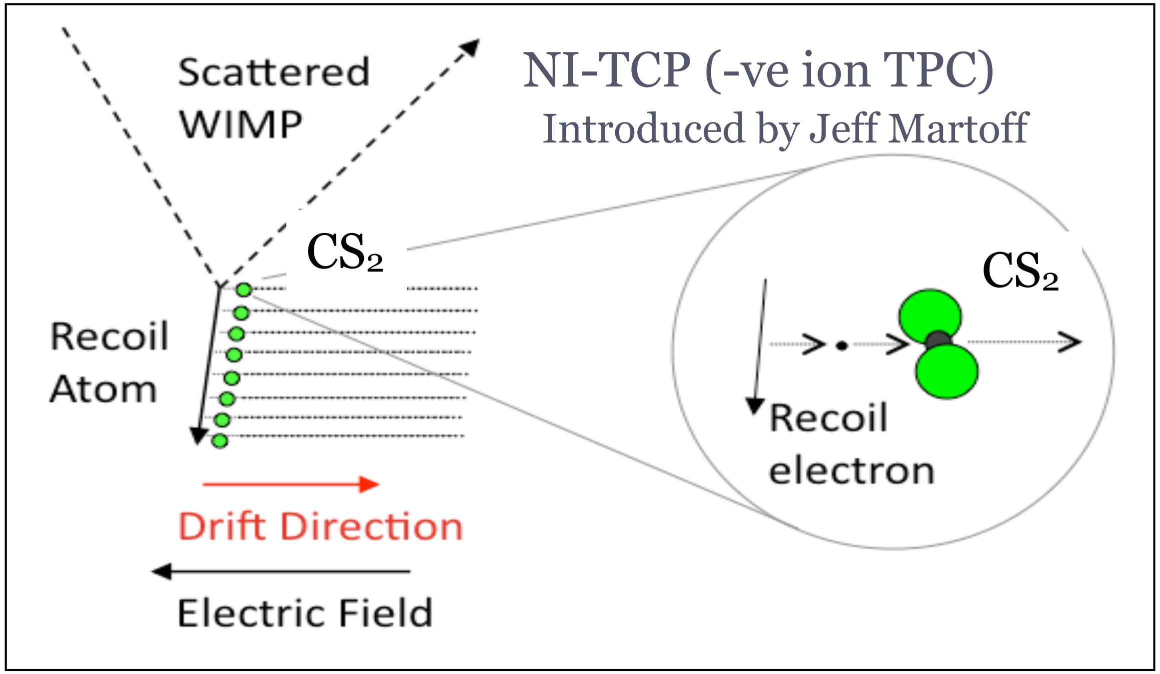




ΔX: Number of anode wires crossed
ΔY: Progression across grid wires
ΔZ: Drift time between start and end of track

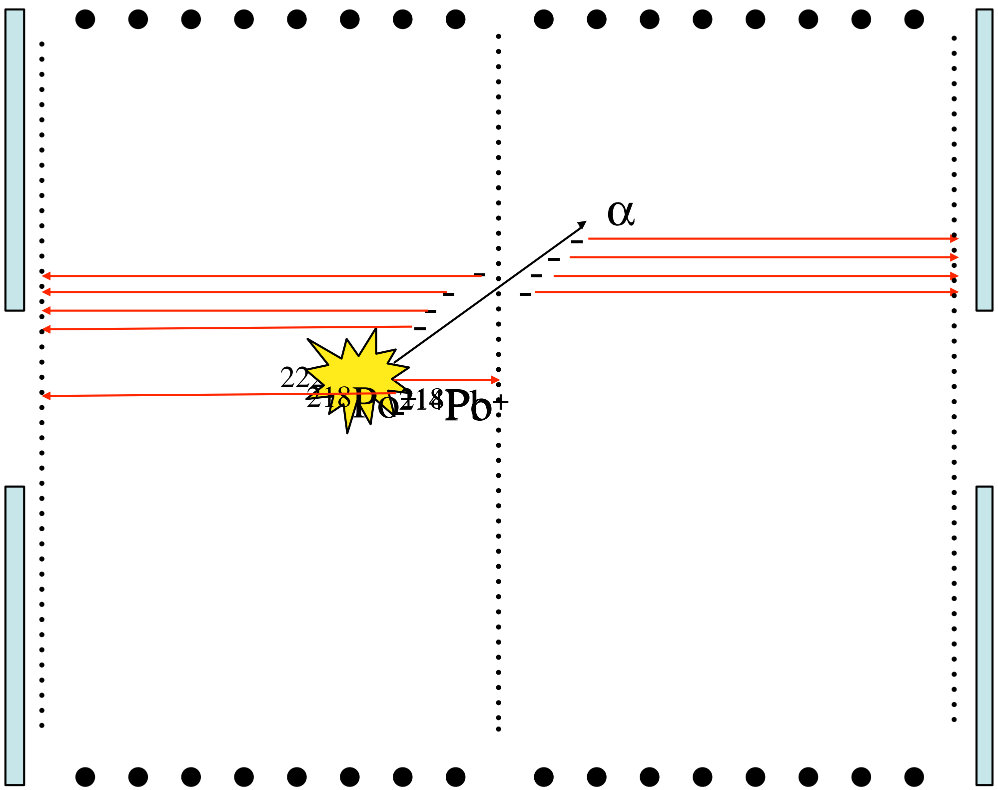
Significant advances recently

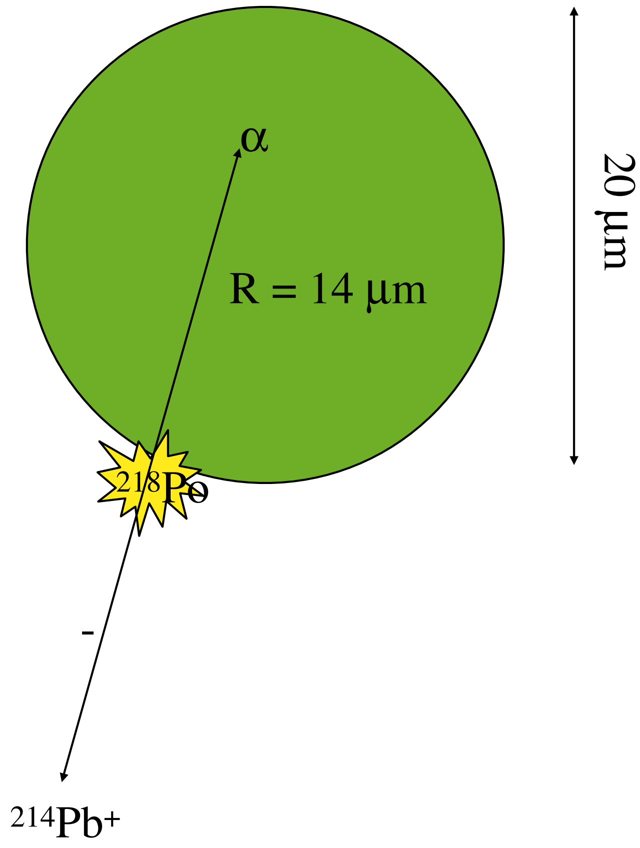
Negative Ion Drift



Towards Zero Background

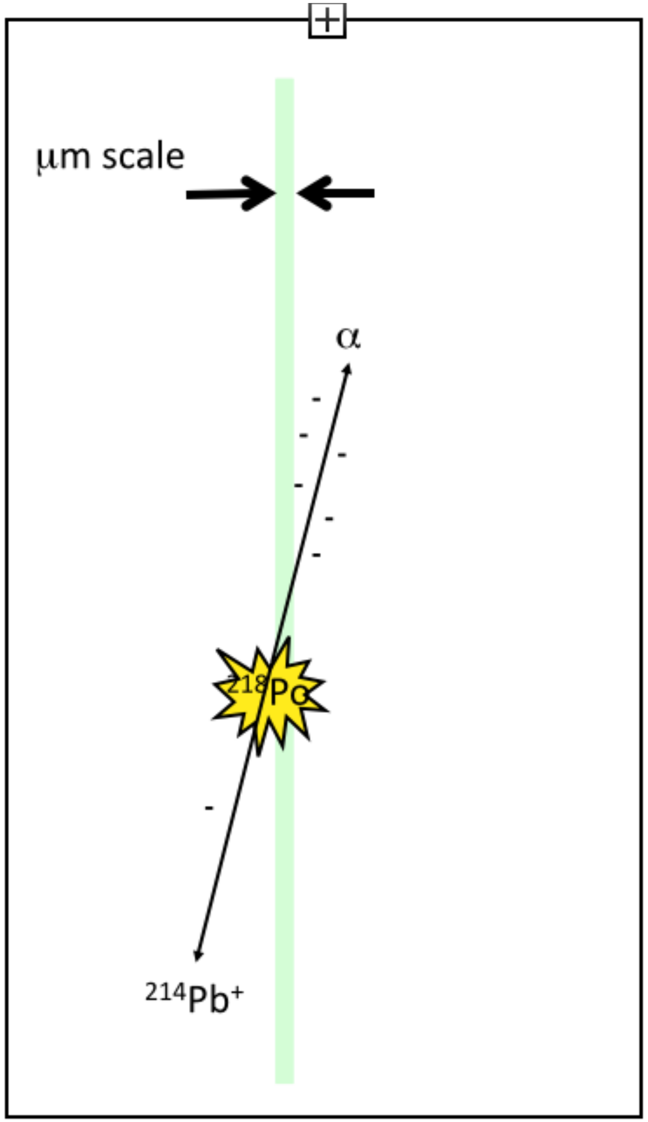
Radon Progeny Recoils





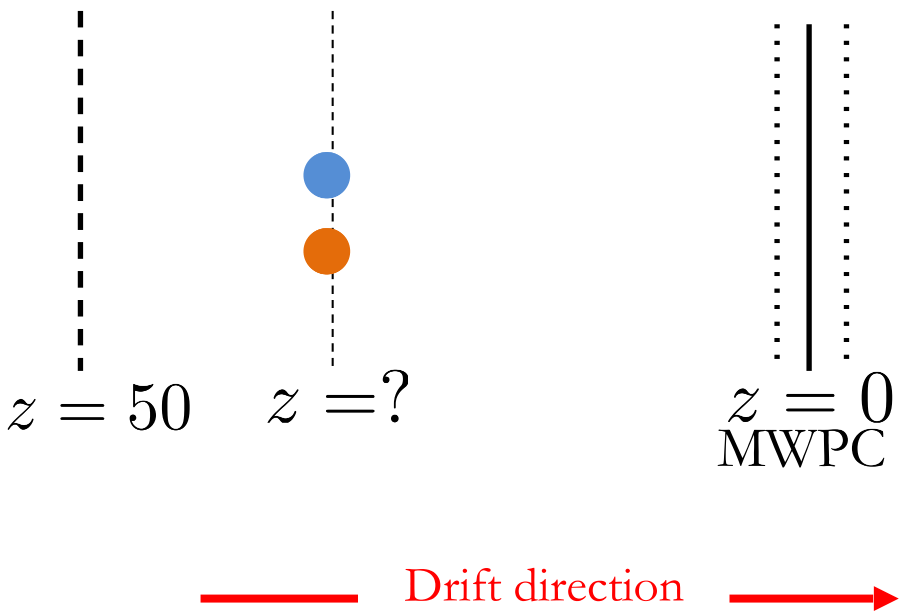
Ultra-thin Cathode

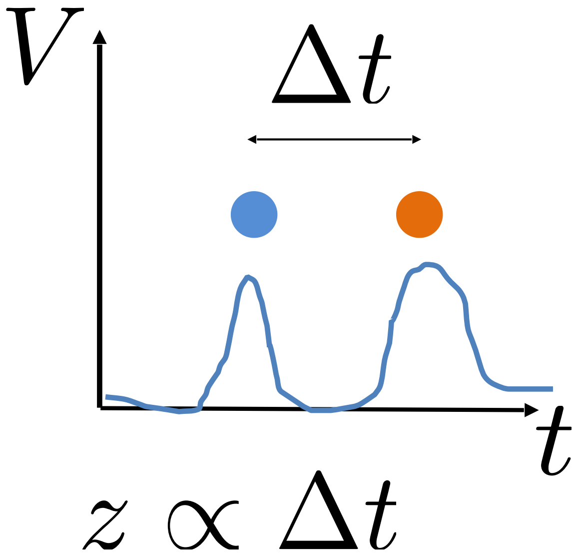
- 0.9μm textured thin cathode reduces radon events



z-Fiducialization Breakthrough

- Discovery of minority carrier gas mixtures CS_2:CF_4:O2
- Use of different drift speeds of carriers





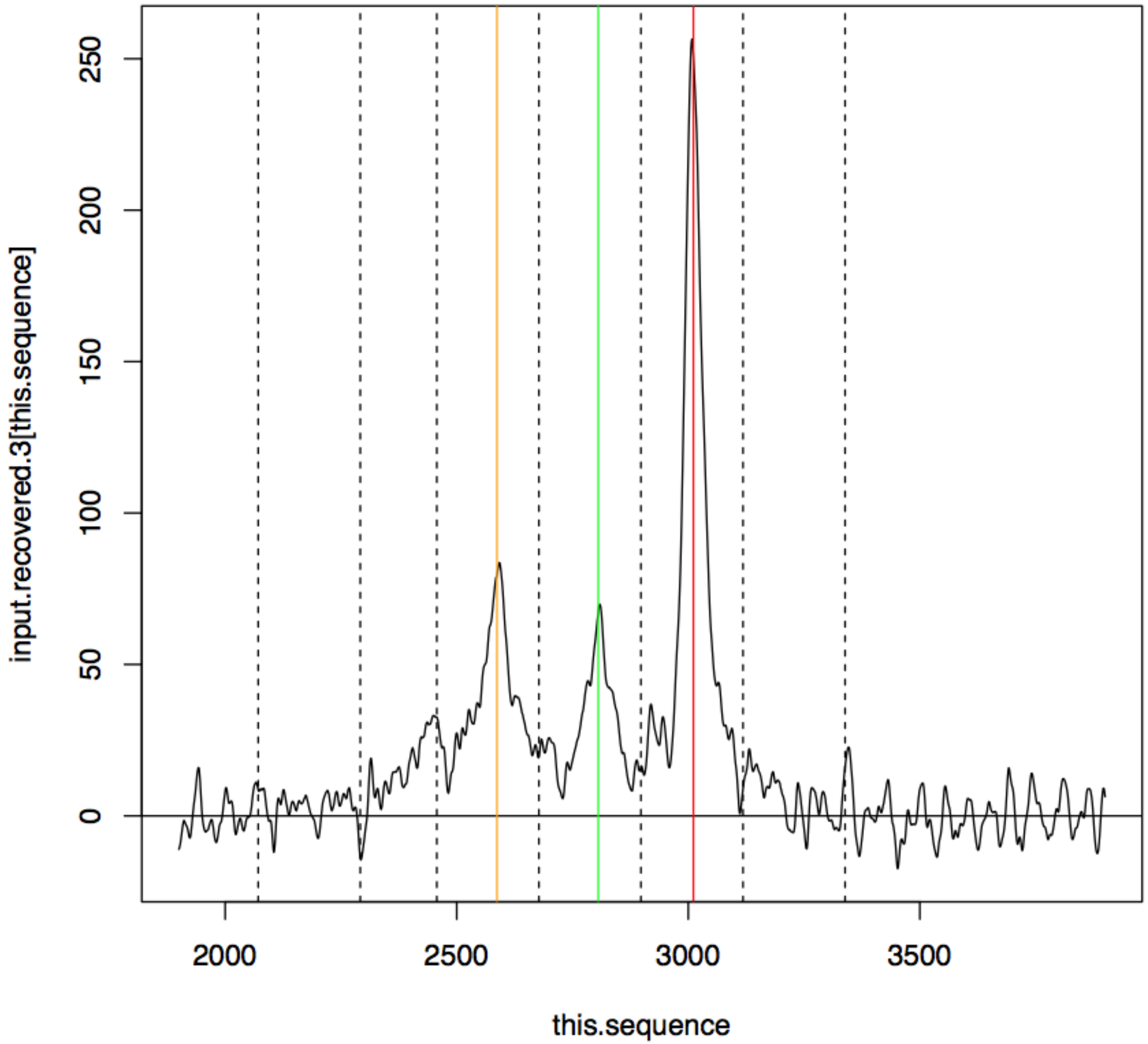
Proportionality constant can be measured for various gas mixtures, or calibrated in-situ.

thanks to D. Snowden-Ifft

z-Fiducialization

Examples

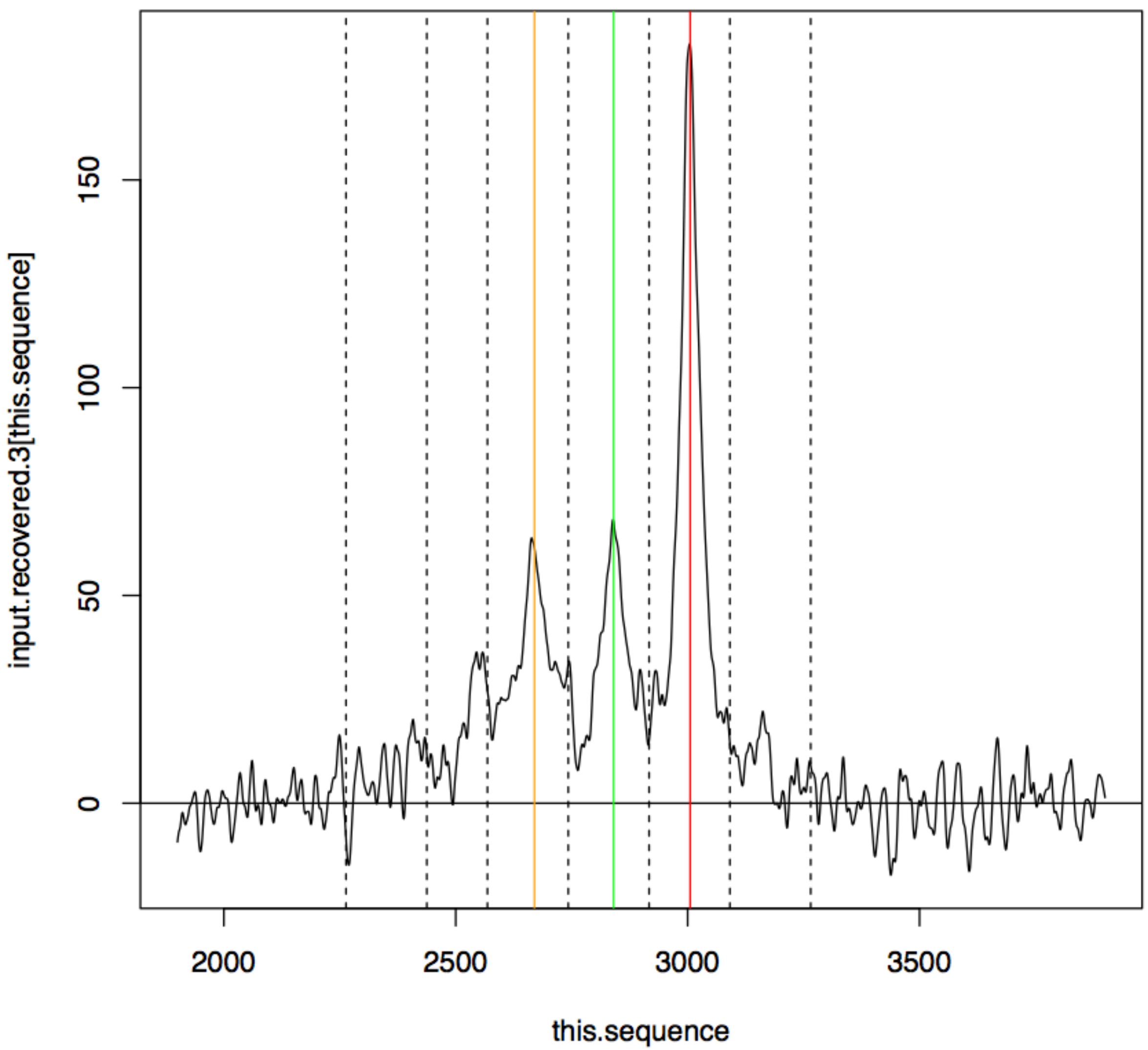
z = 49.7 cm



z-Fiducialization

Examples

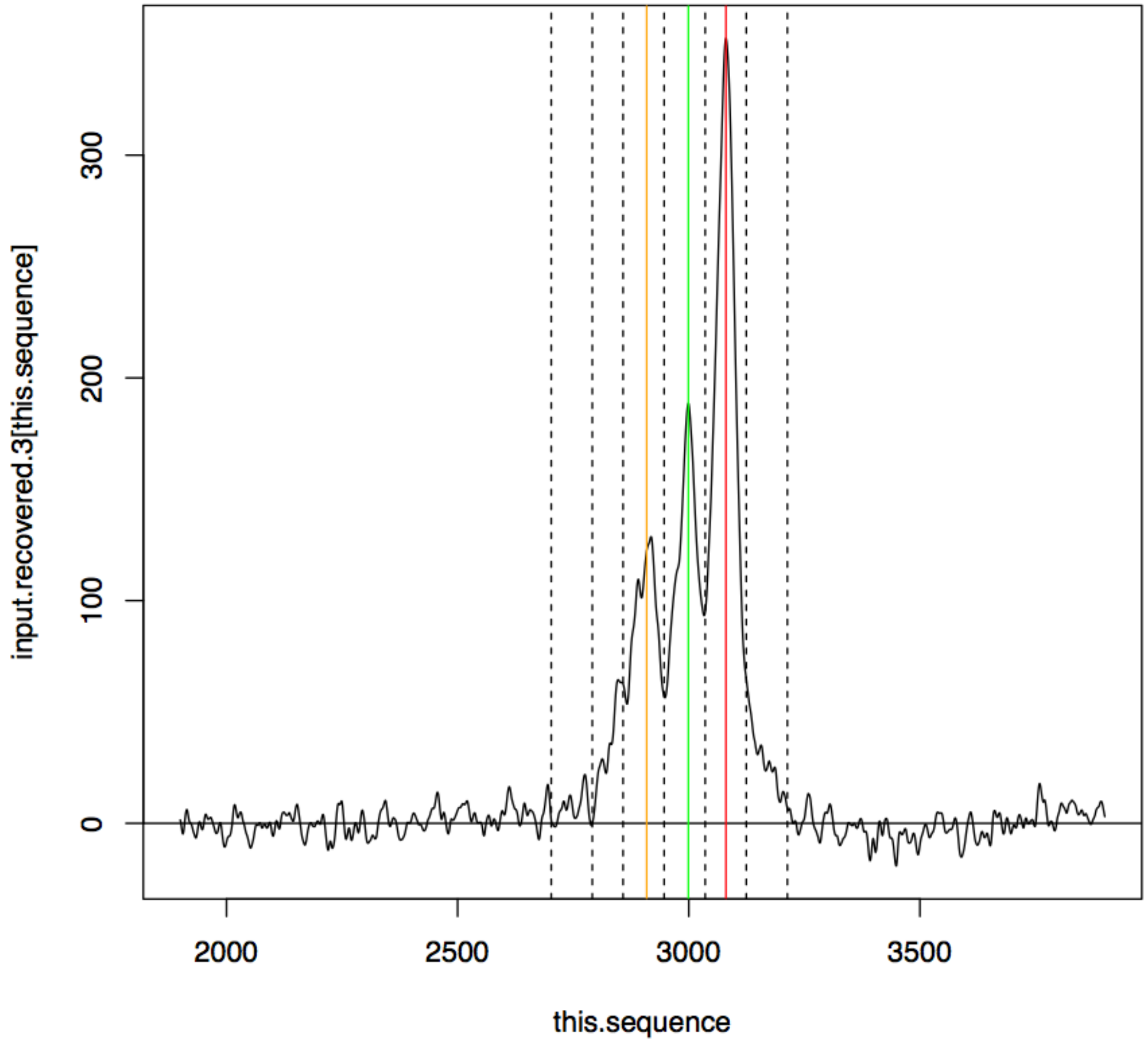
z = 39.3 cm



z-Fiducialization

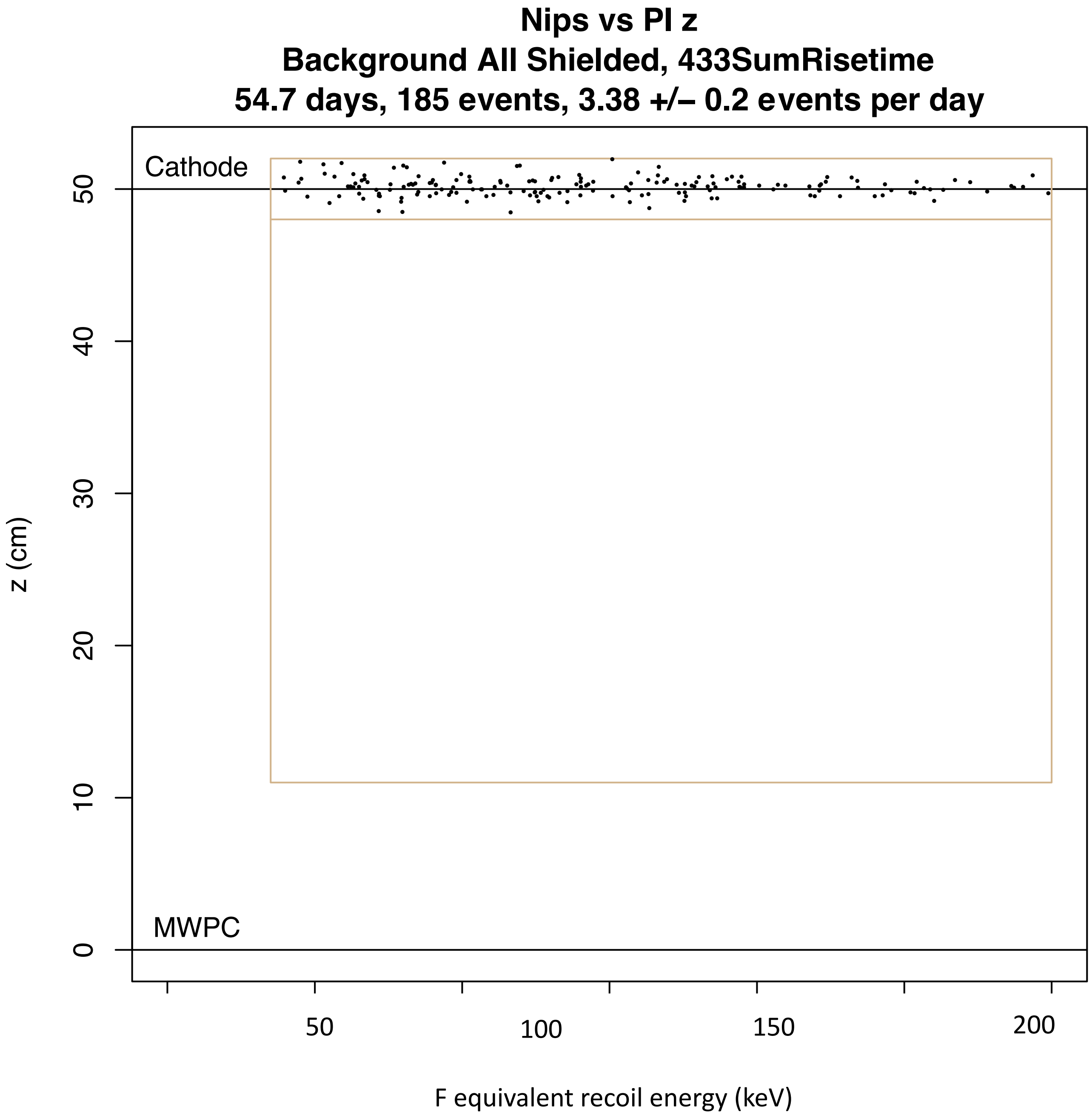
Examples

$z = 20.1$ cm



DRIFT WIMP Analysis

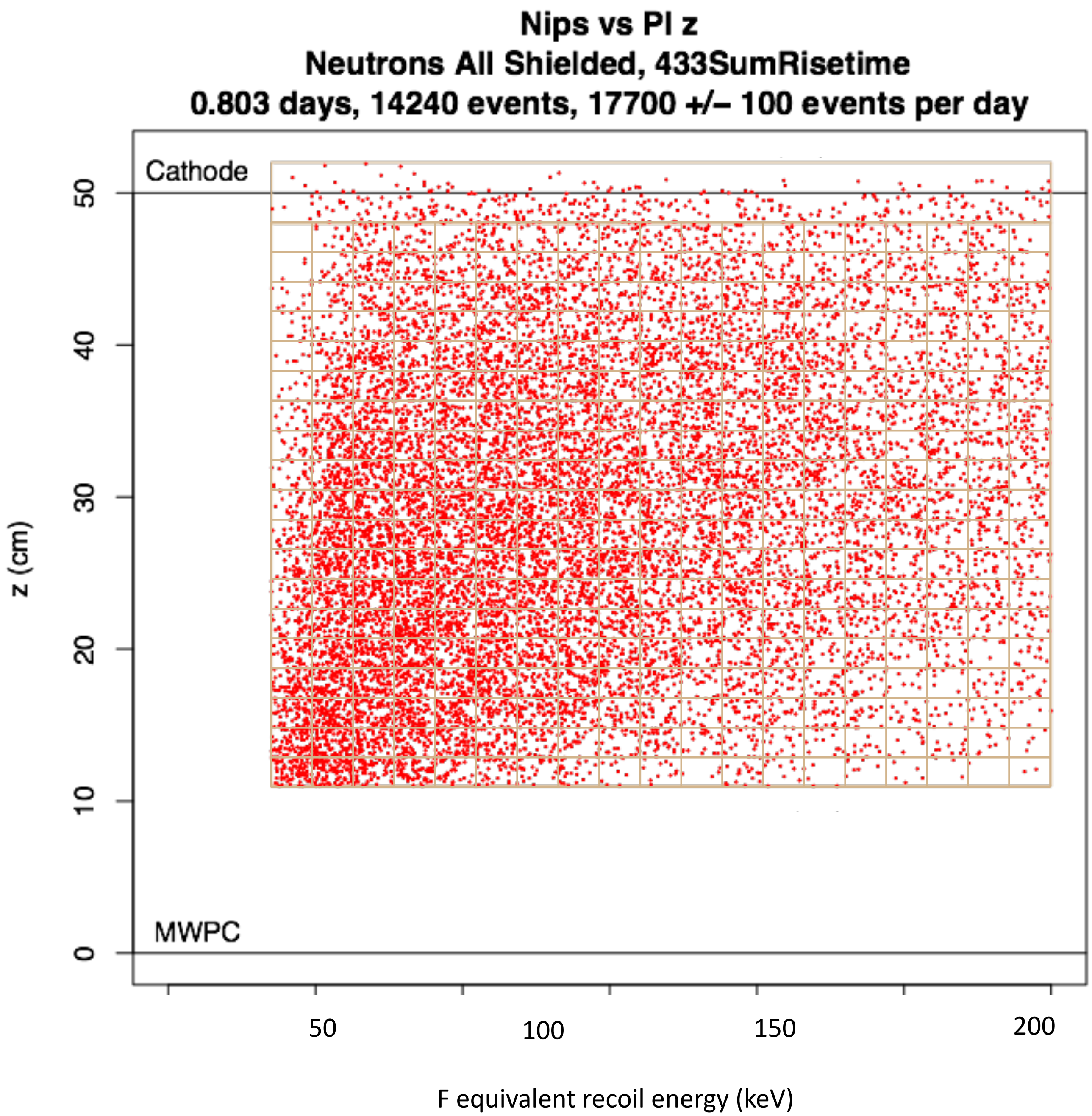
Shielded 30-10-1 CS_2-CF_4-O_2 Data



- 54.7 days of data analyzed
- 185 events found but as expected all were located at 50 cm away from the detector, i.e. on the central cathode.
- Define a background-free fiducial region.
- In order to interpret this as a limit need to calibrate the detector…

DRIFT WIMP Analysis

Cf-252 Neutron Calibration Data



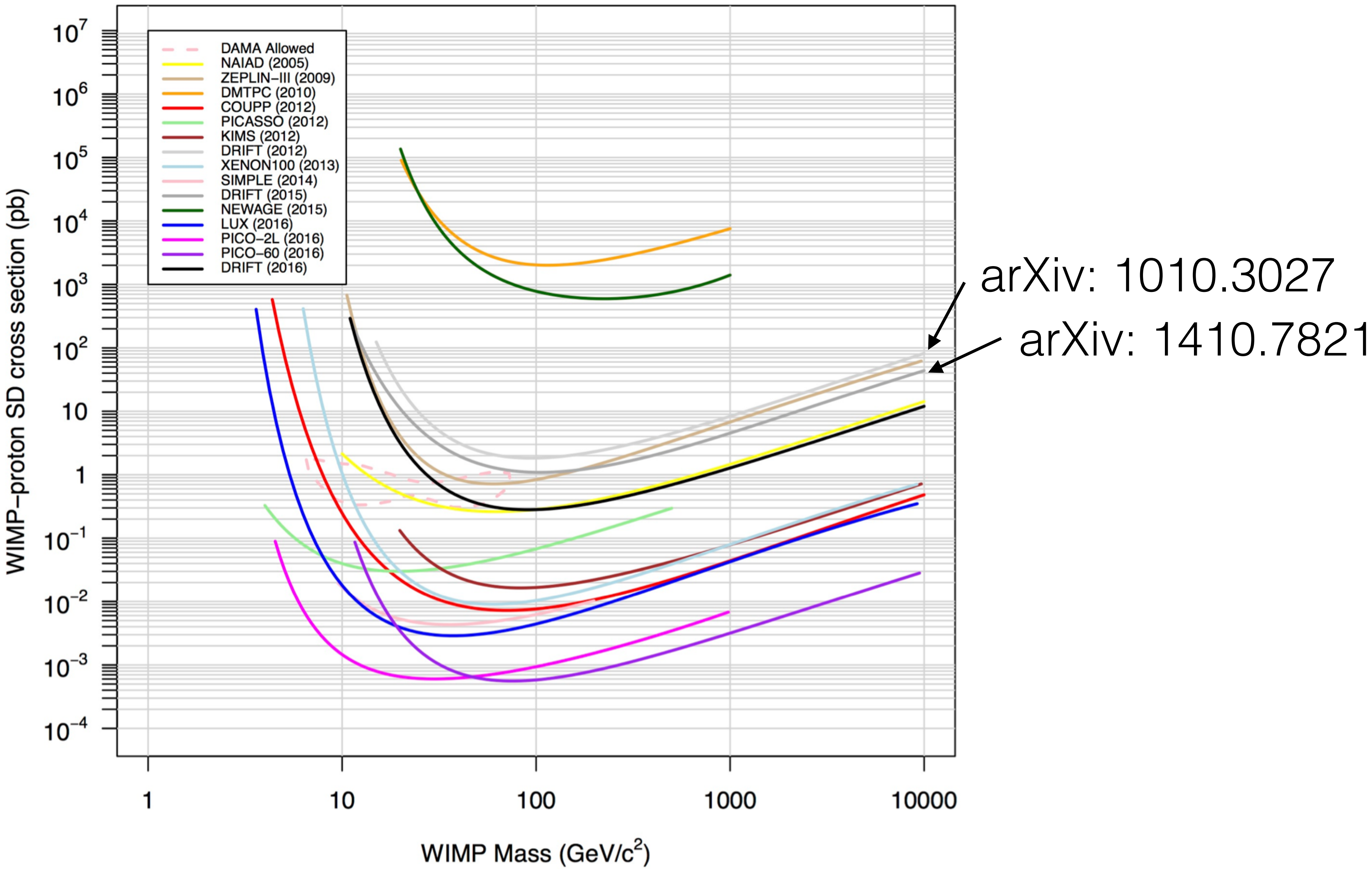
- **Exposed the detector to a CF-252 neutron source**
- **As expected the neutrons distributed themselves more or less uniformly in *z* within the fiducial region**
- **Since neither the distribution in *z* nor *NIPs* (ionization) is truly uniform need to do this carefully…**

- **Did the same for the experimental data.**

New Result (zero background)

New result (CAASTRO2017) including reduced threshold analysis

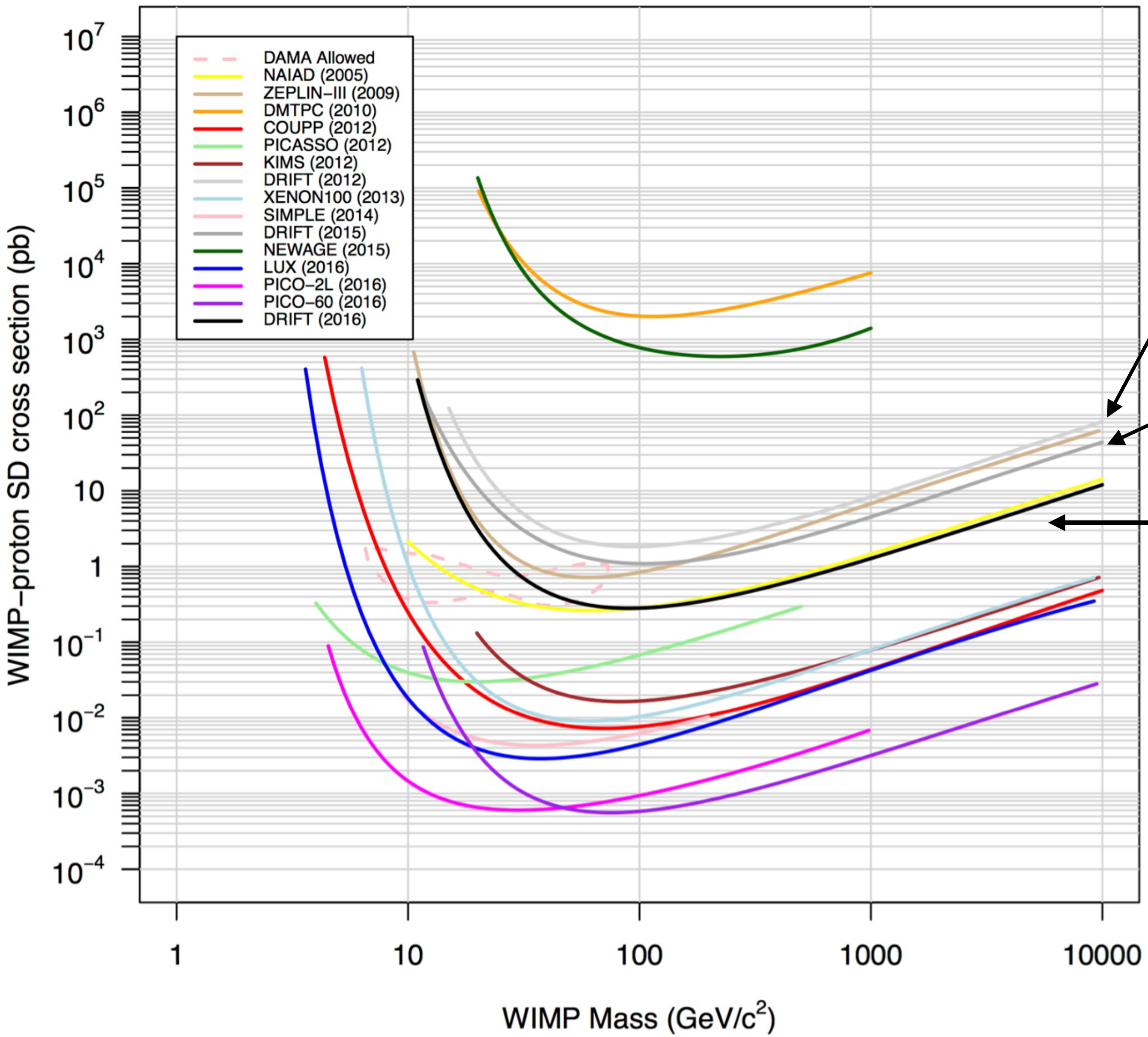
First result in “DAMA Region” with directional sensitivity”



New Result (zero background)

New result (CAASTRO2017) including reduced threshold analysis

First result in "DAMA Region" with directional sensitivity"



arXiv: 1010.3027

arXiv: 1410.7821

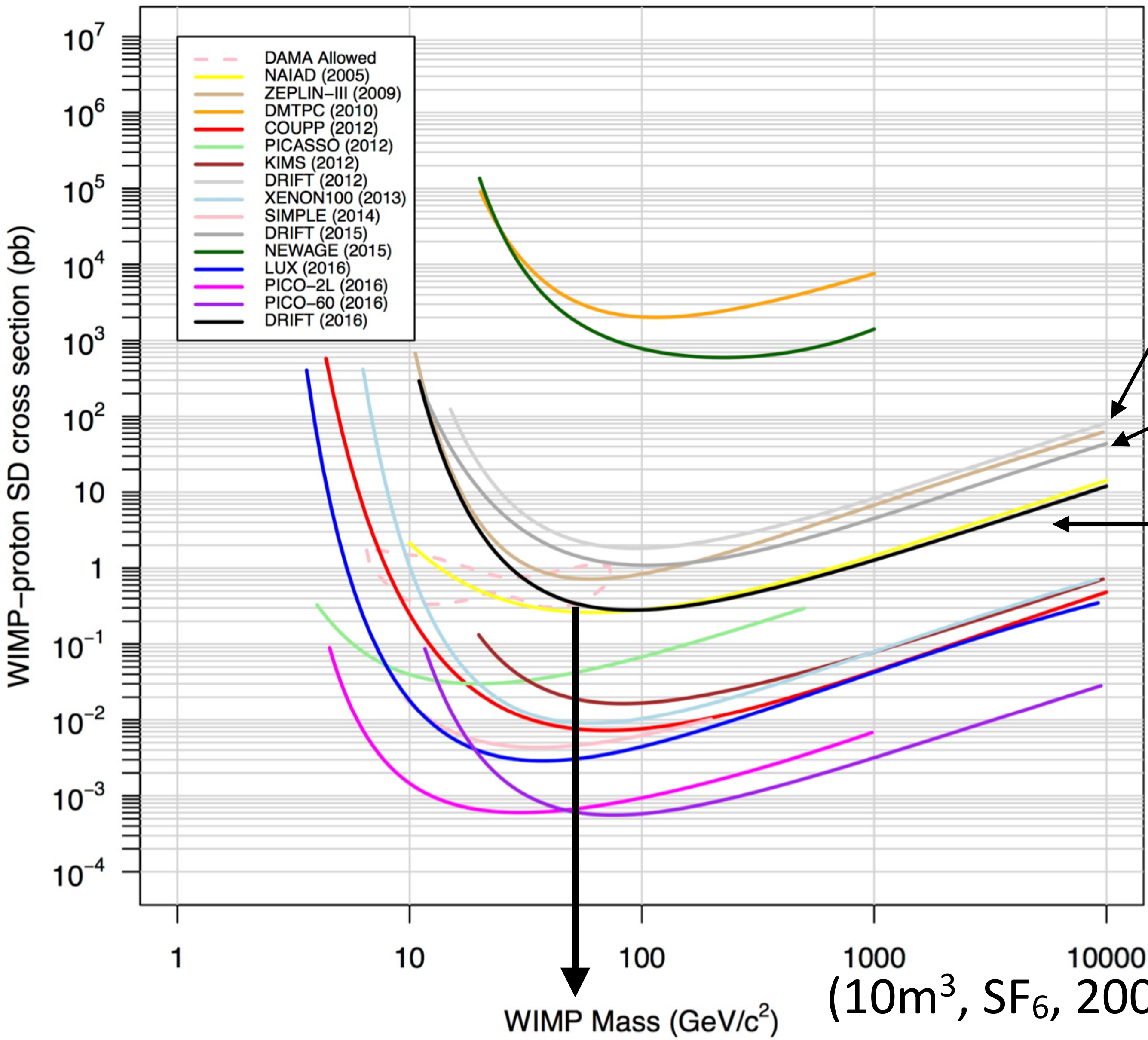
arXiv: 1701.00171

(31 gram F, 40 Torr, ~50 days, zero background)

New Result (zero background)

New result (CAASTRO2017) including reduced threshold analysis

First result in "DAMA Region" with directional sensitivity"



arXiv: 1010.3027

arXiv: 1410.7821

arXiv: 1701.00171

(31 gram F, 40 Torr, ~50 days, zero background)

(10m^3, SF_6, 200 Torr, 3 years days, zero background)

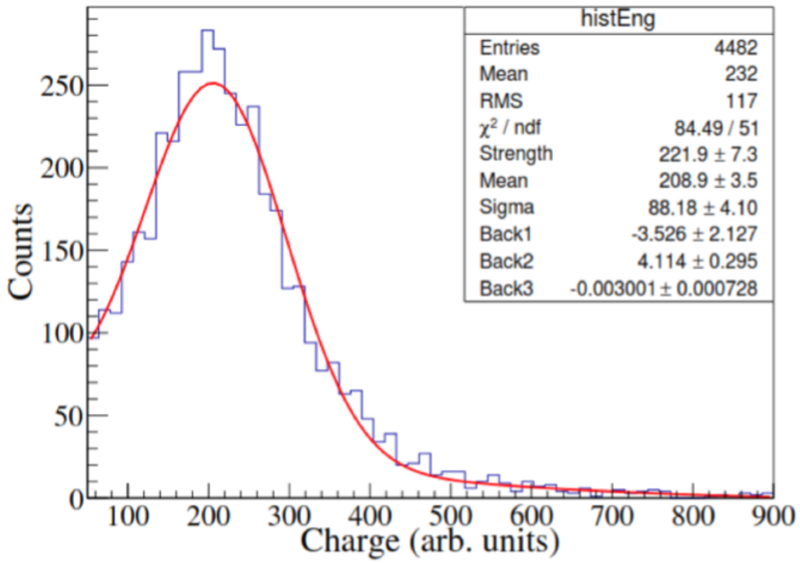
SF_6 Breakthrough at UNM

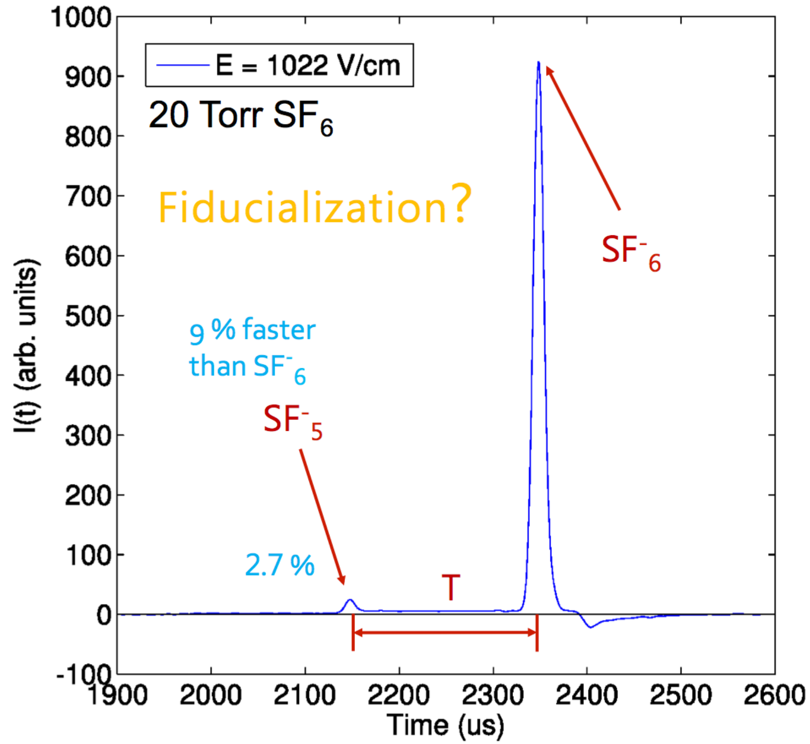
-ve ion with minority carrier and increased target mass

N. Phan, University of New Mexico

- **Replacement for CS_2**
- **First demonstration of SF_6 as -ve on gas (with GEMs)**
- **Potential for x5 more mass, with fiducialisation?**
- **This has been a revelation**

  - ^{55}Fe spectrum in 40 Torr SF_6 with 0.4mm GEM
  - Gain curves up to x3000
  - z-fidusialization with SF_5^- shown (20 Torr)





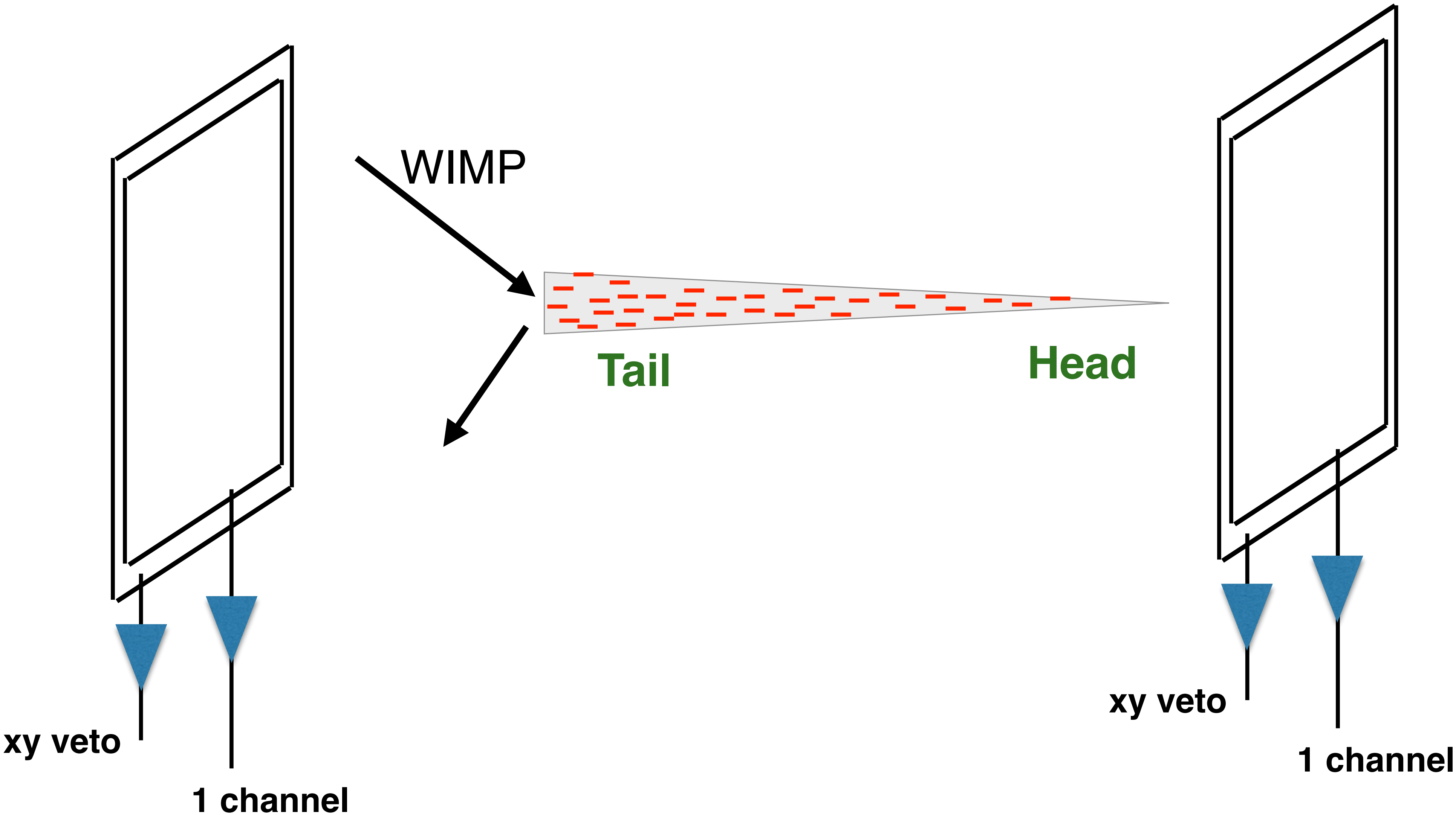
- **Activity now in many groups**
- **Frascati, Kobe, UNM, Sheffield**

Is a Simpler "1D-HT" Readout Possible?

CYGNUS R&D activity at Boulby

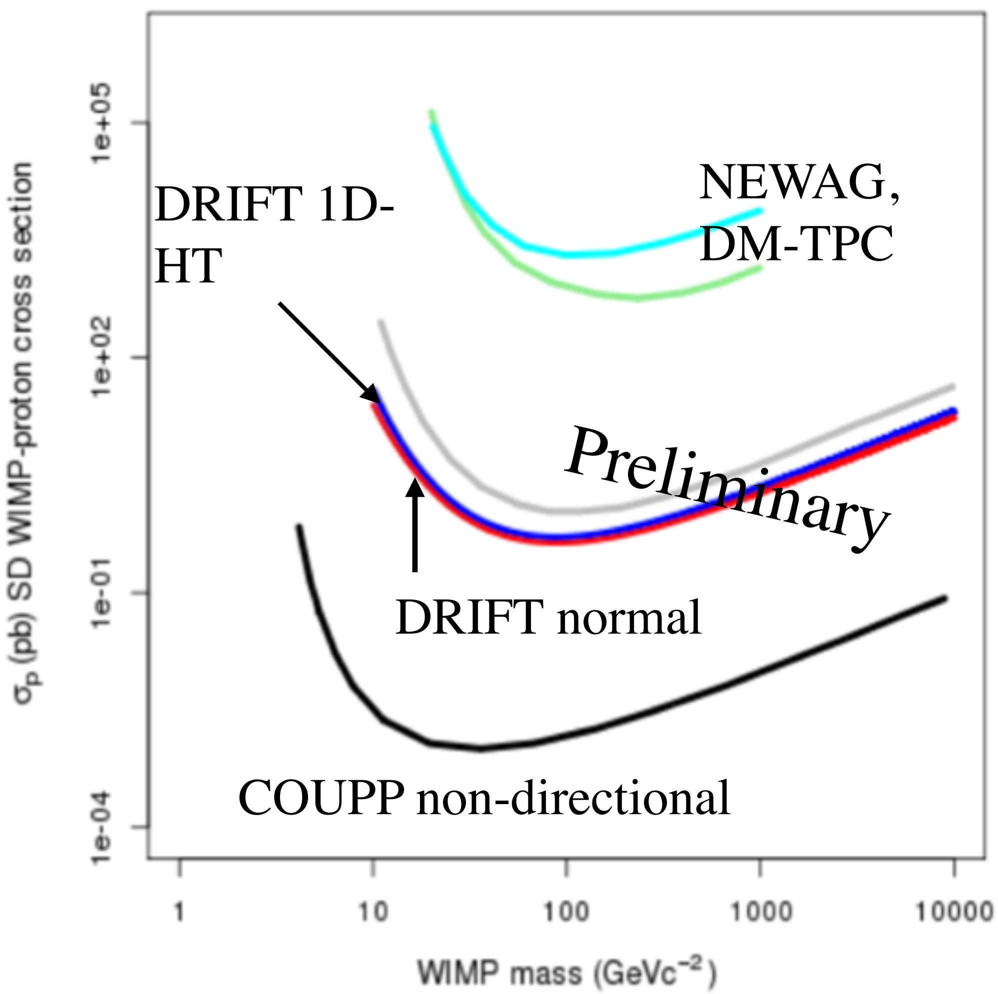
N. Spooner, University of Sheffield

- **What is the simplest possible readout that might just work?**



“1D-HT” Test using DRIFT Data

- experiment with DRIFT-IId xy information switched off, just z and head-tail data analysed, like a 1 x 1m single channel.

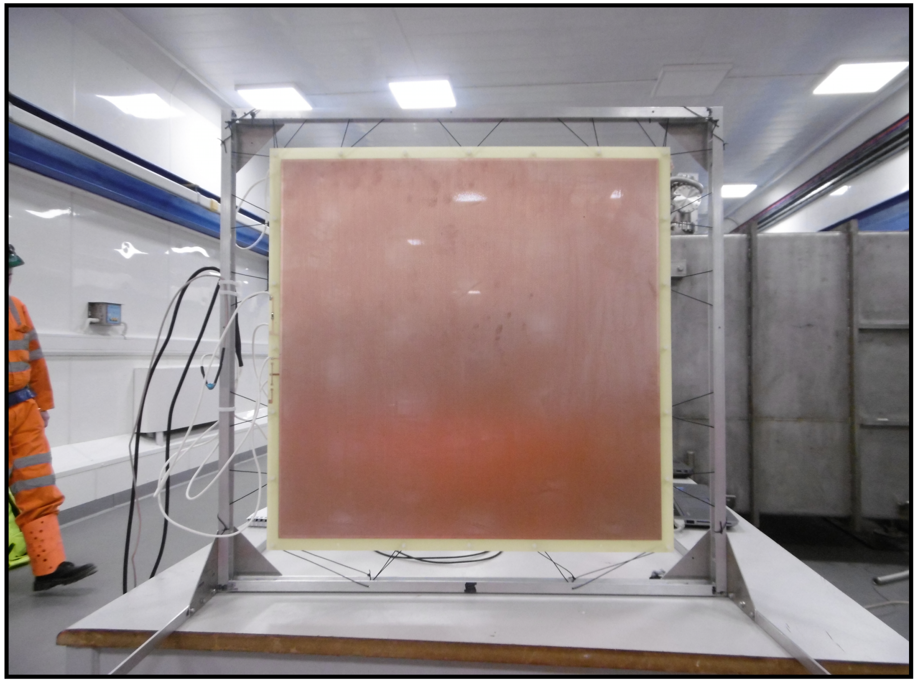


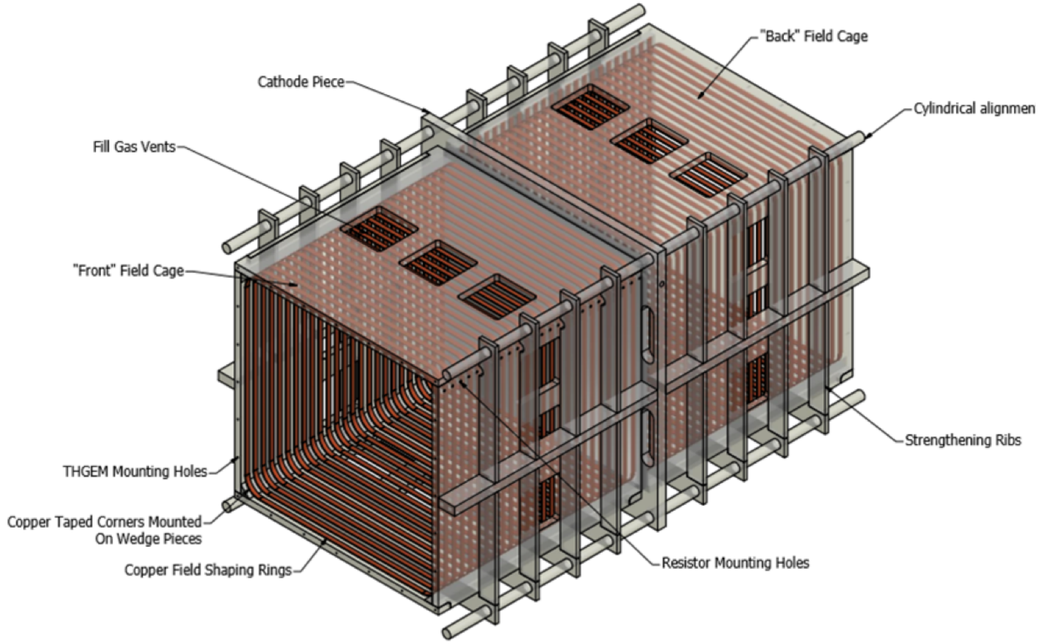
Paper in preparation

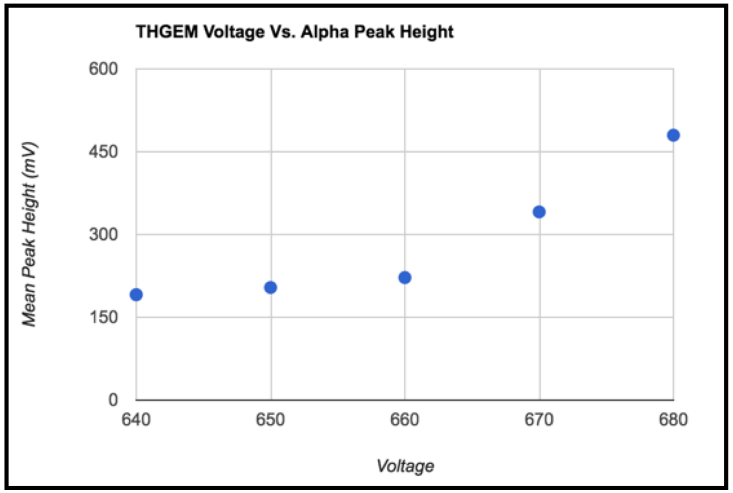
Simpler "1D-HT" Readout Concept

N. Spooner, University of Sheffield

- ThGEM 0.4mm hole dia., pitch 1mm, first data from alpha interactions - 2cm drift gap, 300 V/cm. 100 Torr CF_4

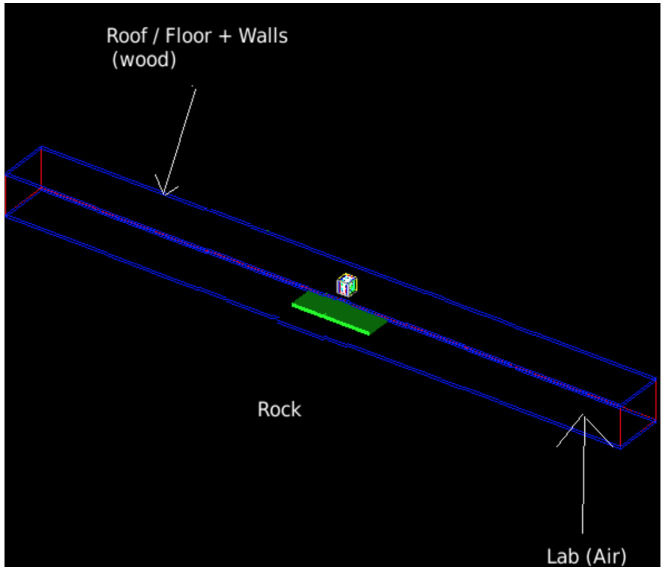


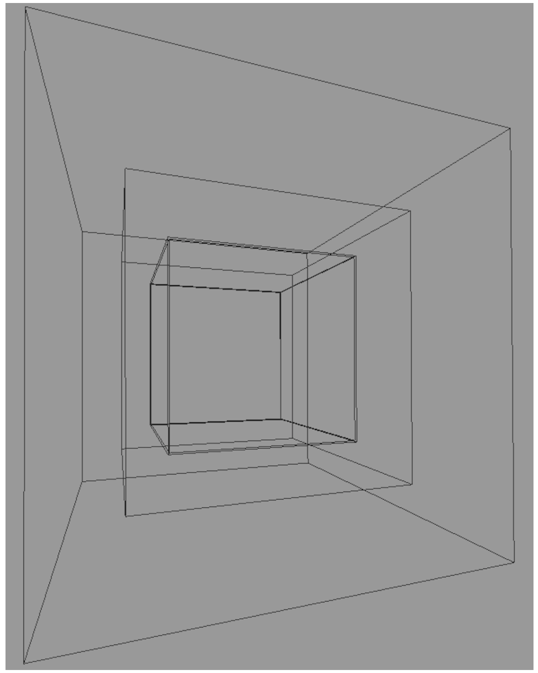




TPC Vessels & Neutron Backgrounds

- **Neutron backgrounds in a 10 x 10 x 10m TPC required to achieve < 1 neutron in 3 years operation**
- **GEANT4 simulations**
  - **Rock neutrons**
  - **Muon neutrons**
  - **Internal neutrons**
  - **Vessel types: steel, acrylic, steel + internal plastic shield**
  - **e.g. steel vessel 100 tons, acrylic vessel 20cm thick**





Highlight results

- **Steel has typically x10^3-10^4 times too much U/Th**
- **"SNO/DEAP" acrylic (~ 39 microBq/kg Th = 9.6 x 10^{-3}ppb), is suitable**
- **Steel plus ~50 cm internal acrylic shield, is suitable**
- **Ceramic components - maximum allowed total mass ~30-50g**

CYGNUS-10 Proposal for Boulby

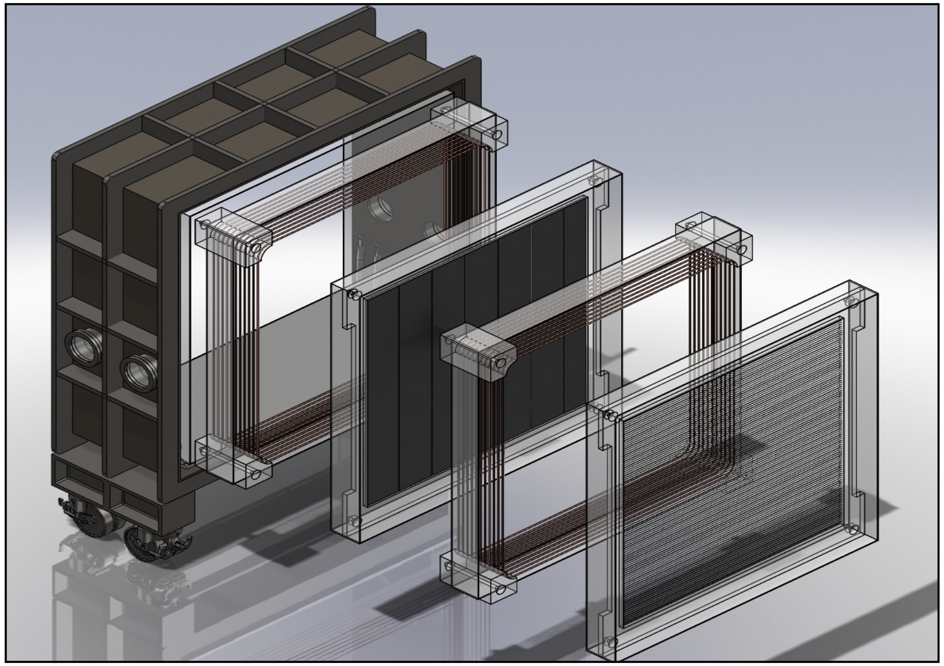
- $10\ m^3$ vessel, 75 cm poly neutron shield, simple veto
- Two modes of operation:

  (1) High pressure

  (200 Torr SF_6 : 500 Torr He)

  13 kg F, 1 kg He

  (2) Low pressure, directional (40 Torr SF_6)



- Science

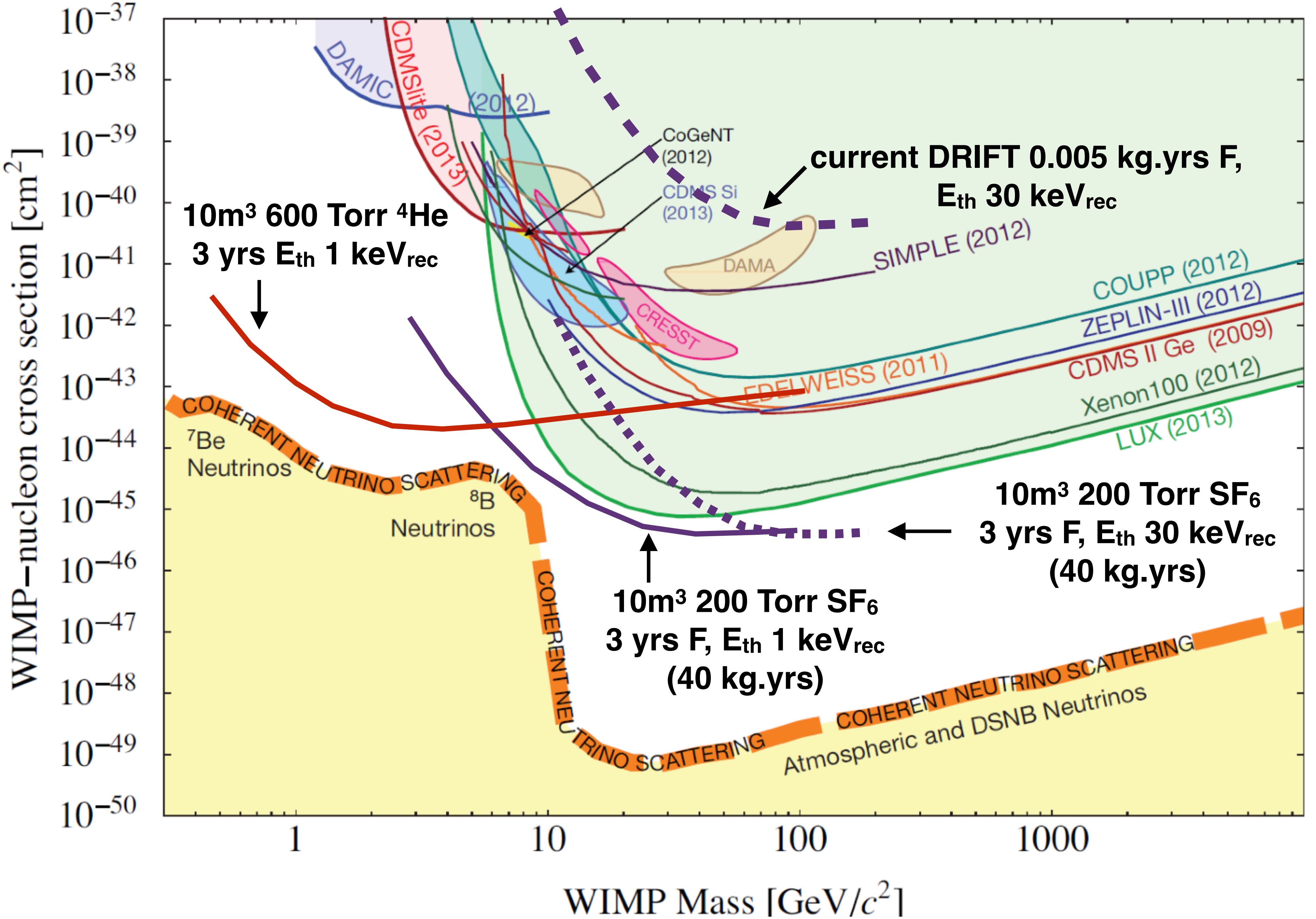
(1) directional sensitivity at 1×10^{-4} pb in high mass SD WIMP (~50 GeV), x 2000 below DAMA

(2) non-directional at 2×10^{-5} pb in high mass SD WIMP regime (~50 GeV), x 10000 below DAMA

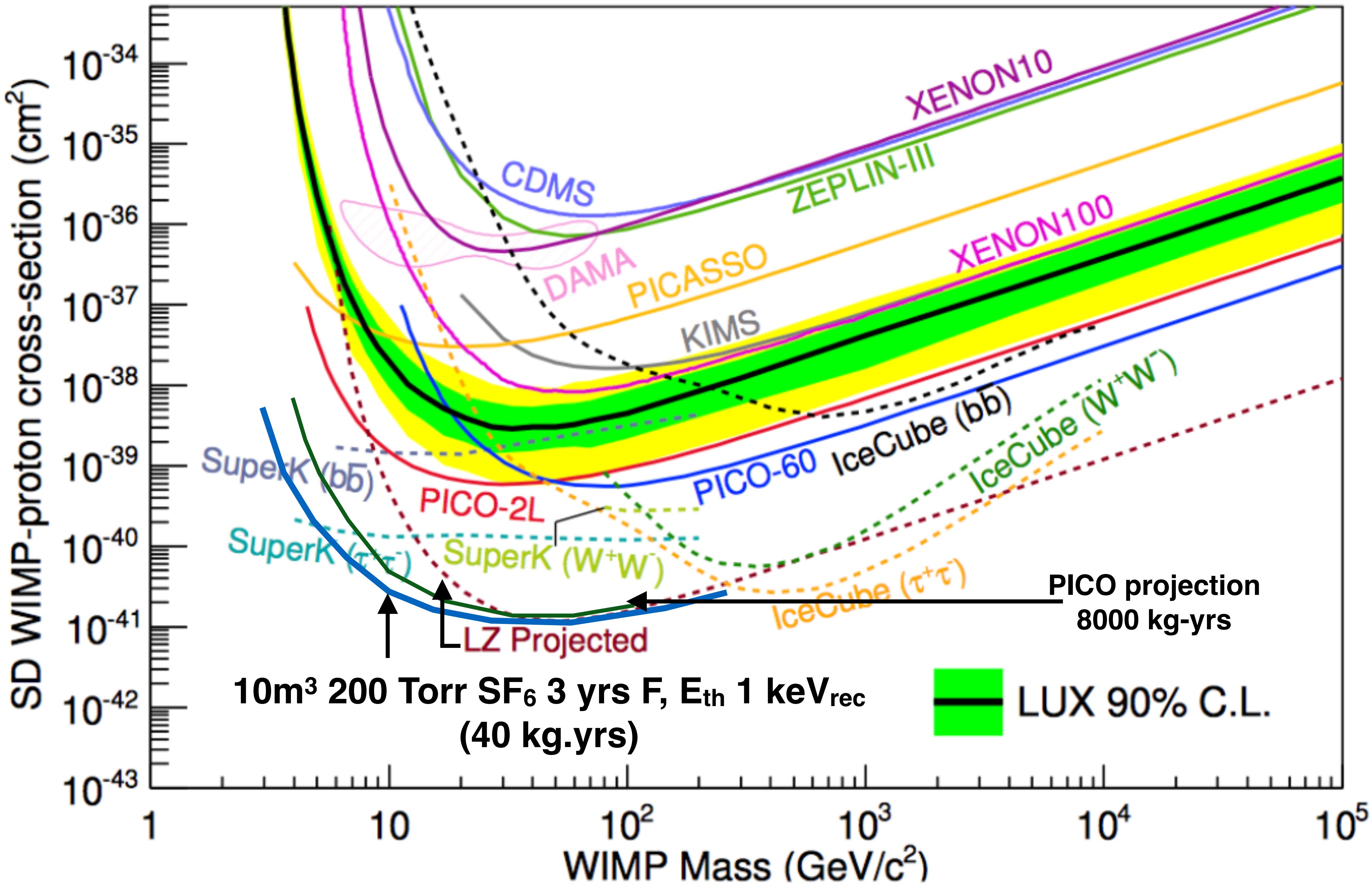
(3) for 10 GeV region sensitivity at 10^{-6} Pb SI

(4) 4 ^{8}B neutrinos detected with direction sensitivity on

SI Sensitivity for 10m³ SF6:He



SD Sensitivity for 10m³ SF6:He



Conclusion

Idea of a Global Galactic Recoil Observatory

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

Significant progress made recently

(1) Low energy directionality, (2) fiducialisation, (3) SF_6, (4) new lab..

Proto-collaboration underway and growing

Please join in!

CYGNUS Astrophysics and Neutrino Workshop

Jan 30th - Feb 2nd 2017
Melbourne, Australia

CYGNUS2017 Full Workshop

Jun 13th - Jun 15th 2017
Jinping, China