Directional Detection & the CYGNUS Project

Neil Spooner, University of Sheffield

- **Motivations for nuclear recoil directional sensitivity**
- **The CYGNUS concept and proto-collaboration**
- **Progress and challenges for a large directional TPC**
- **Recent results from the Boulby CYGNUS/DRIFT programme**

Sorry for some bias towards my pet interests

Thanks to those from whom I have borrowed slides and info

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

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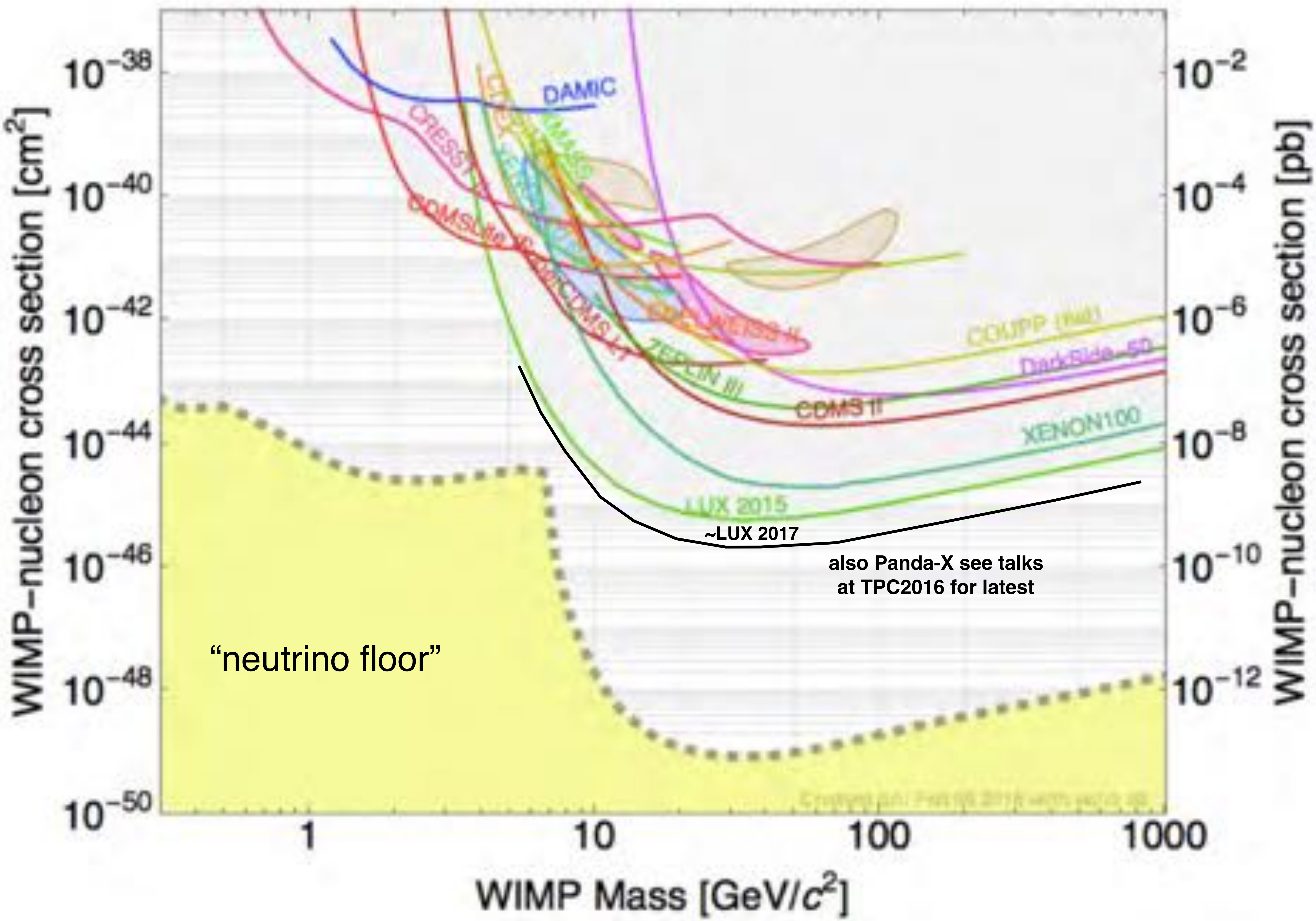
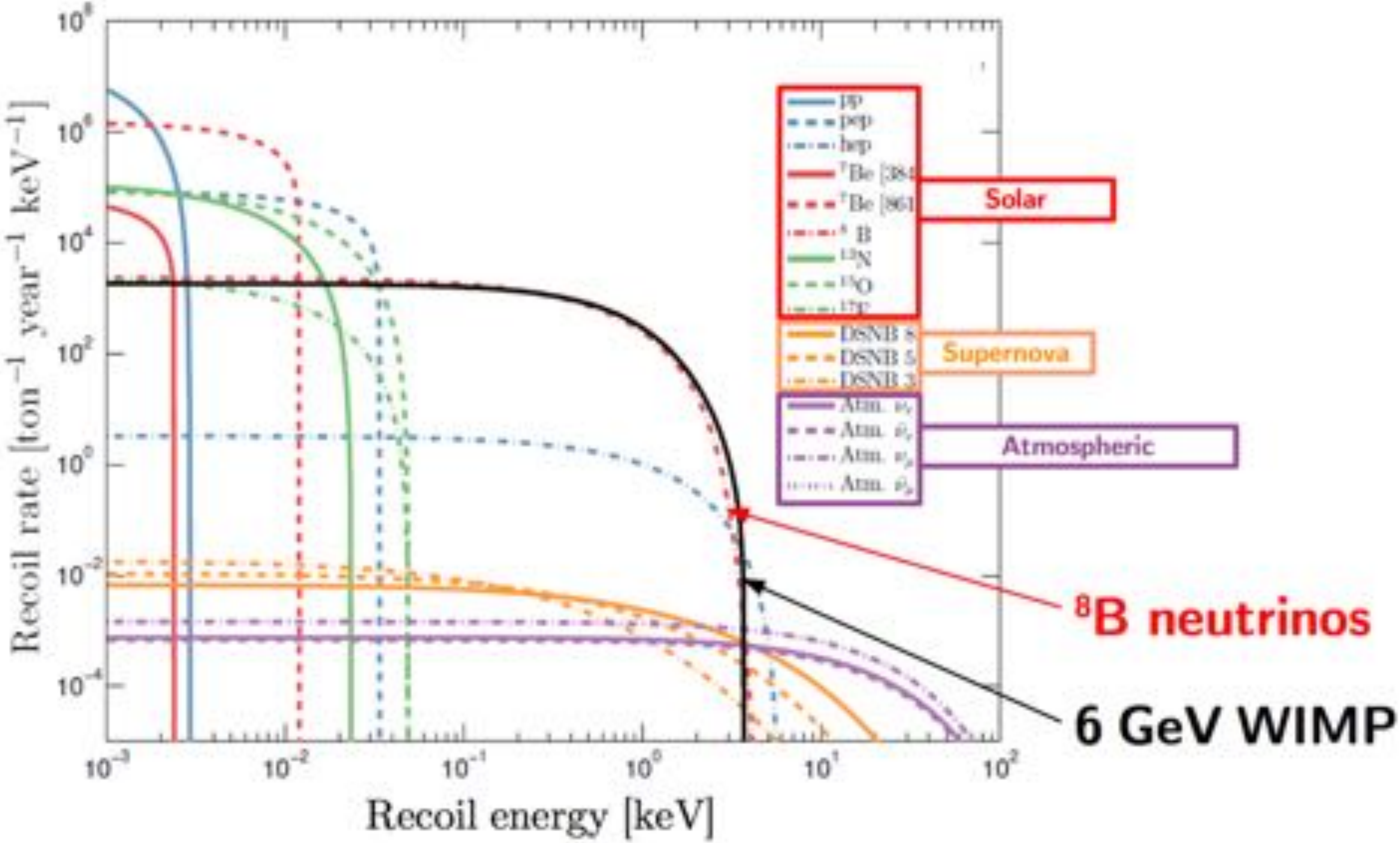
WIMPs!

~Current WIMP Situation



Neutrino Coherent Background

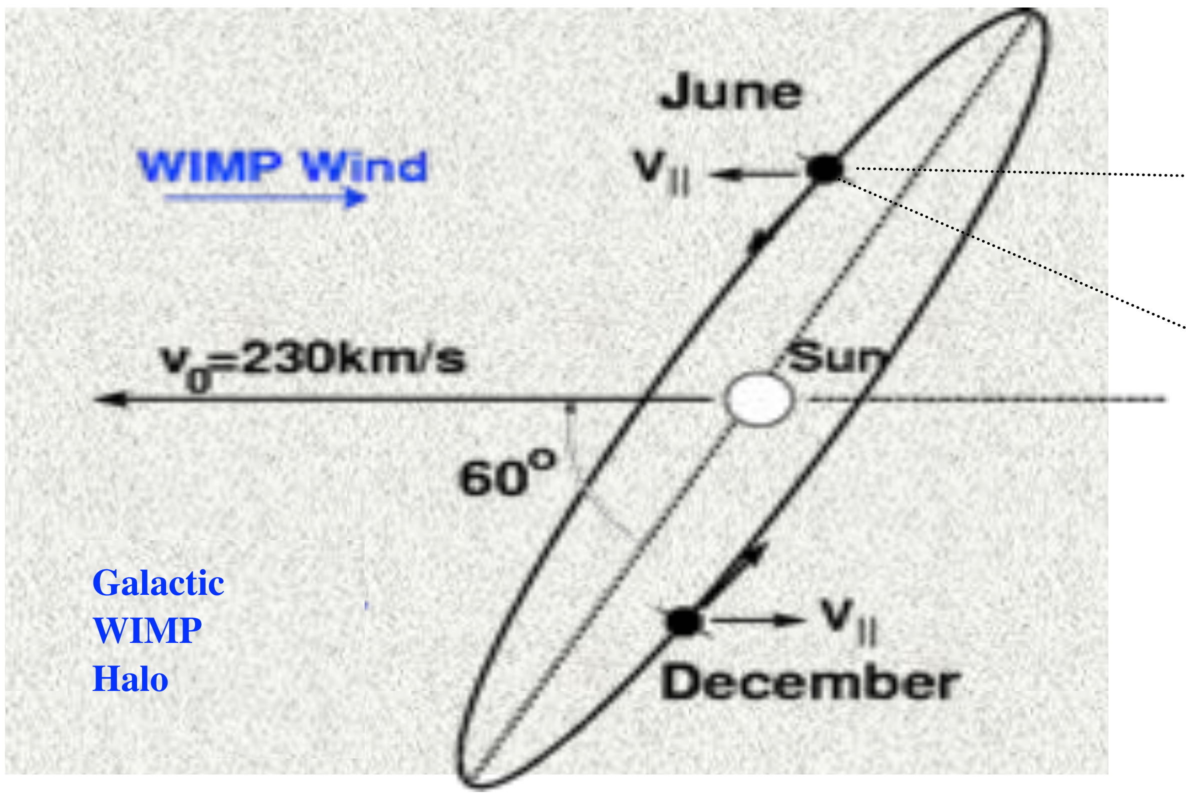
Coherent neutrino-nucleus scattering rates on a Xenon target:

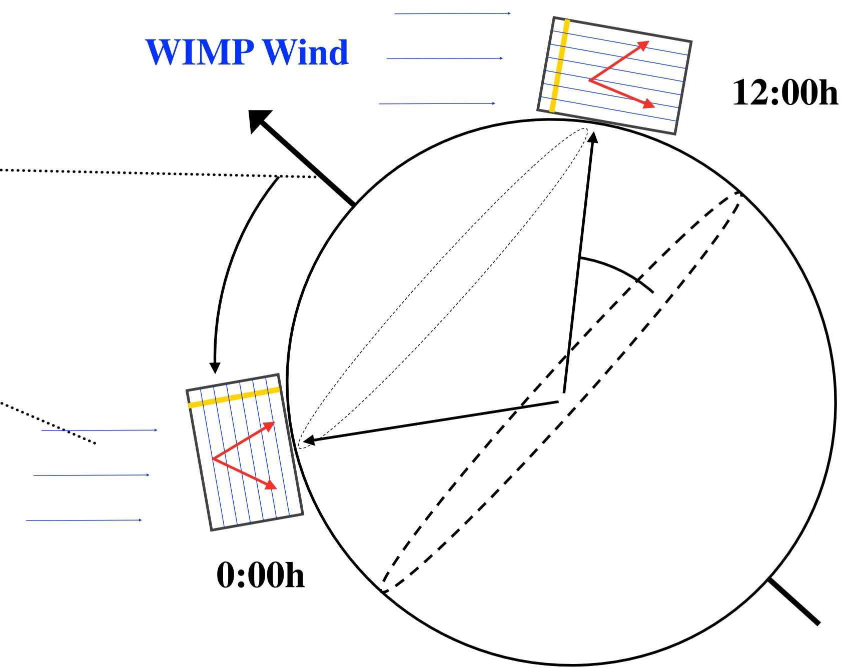


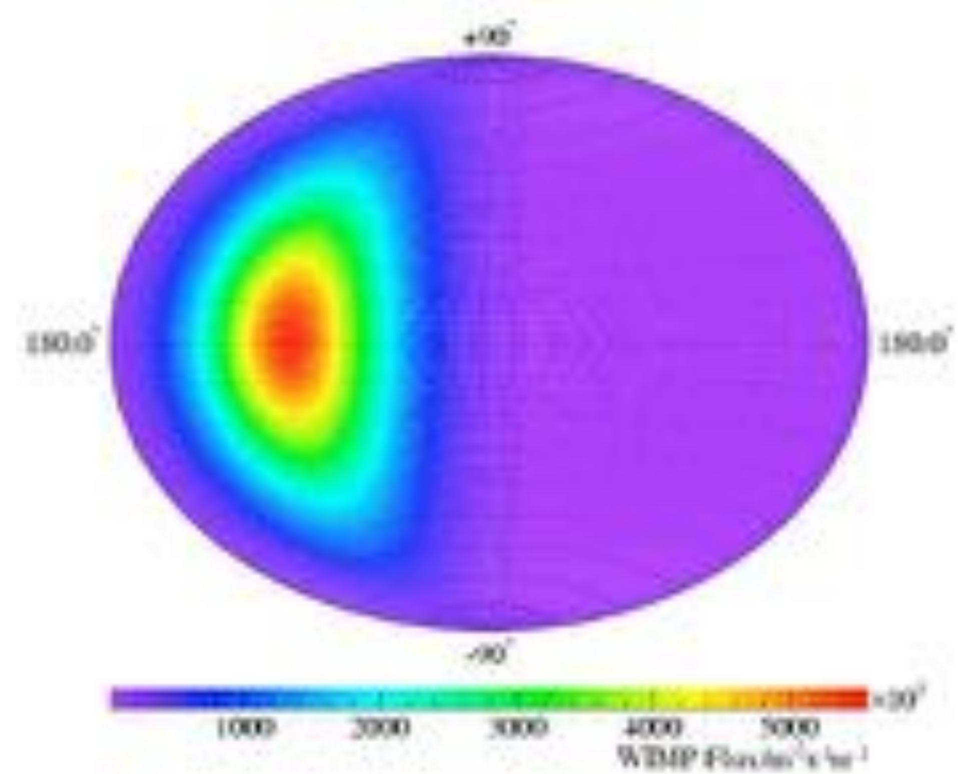
thanks to O'Hare et al.

Directionality - A Better Signal

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







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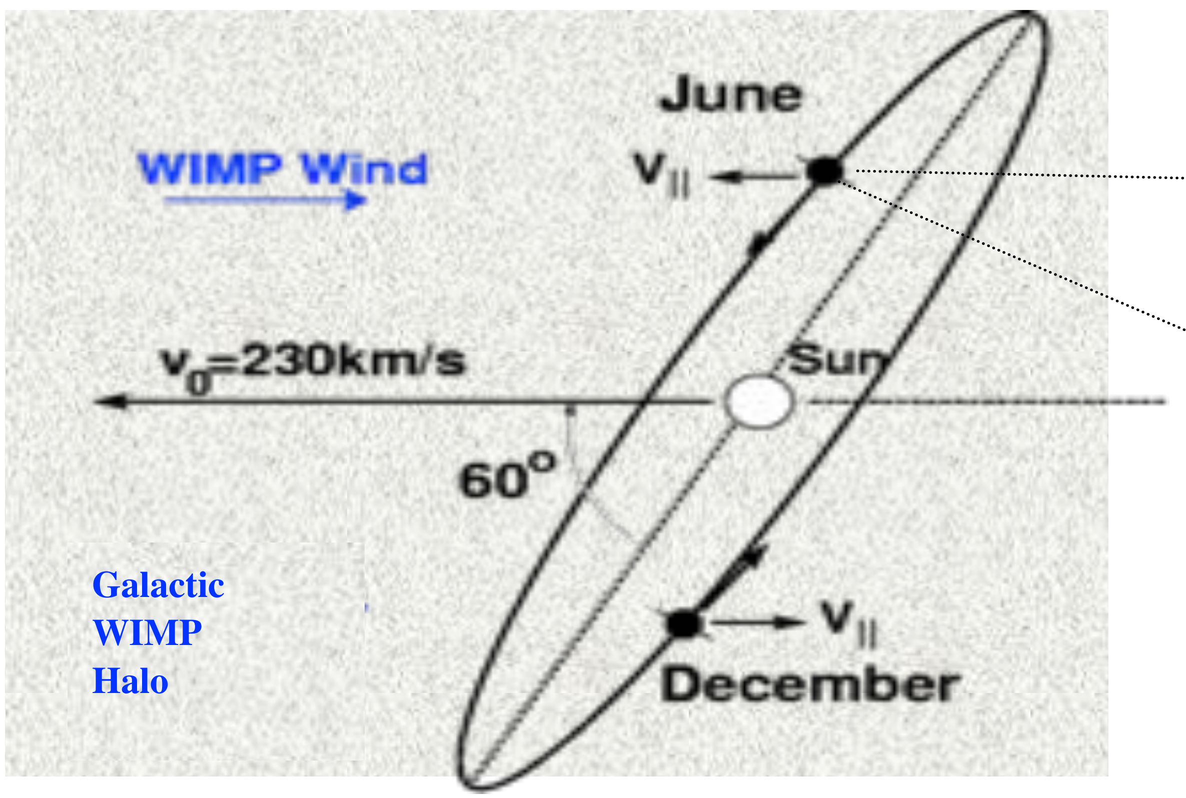
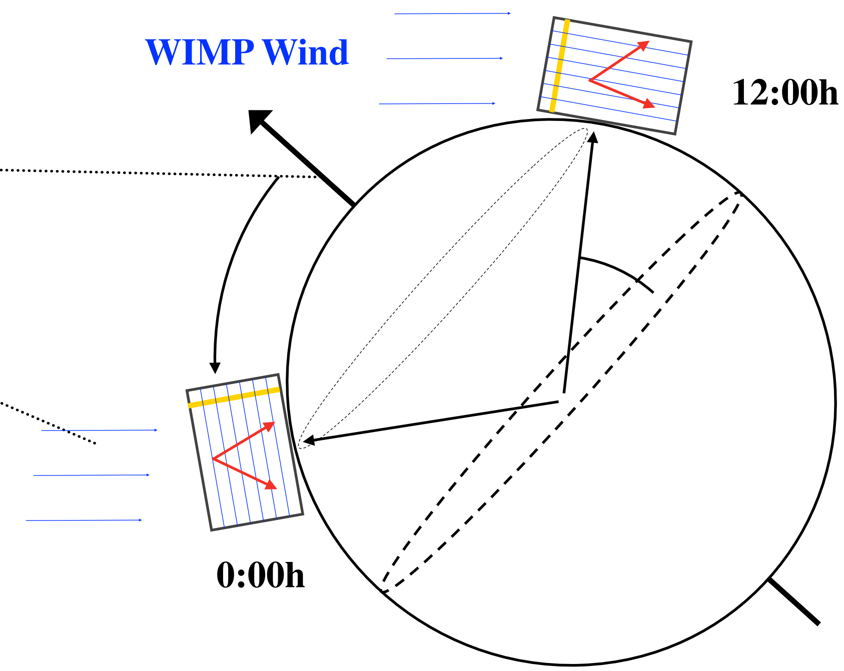
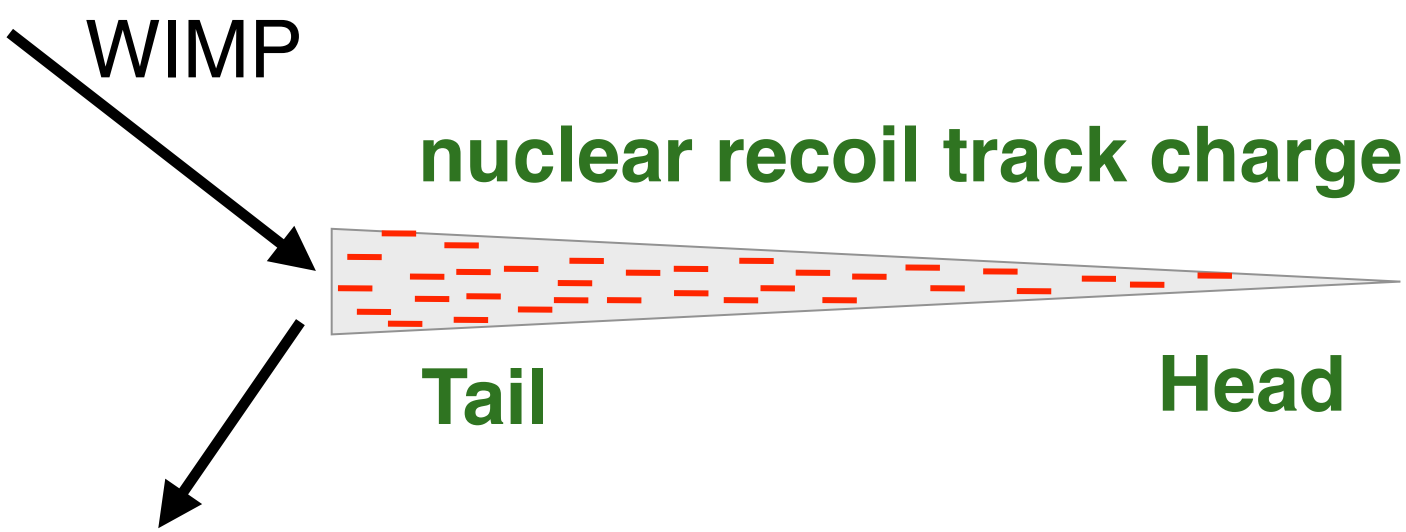
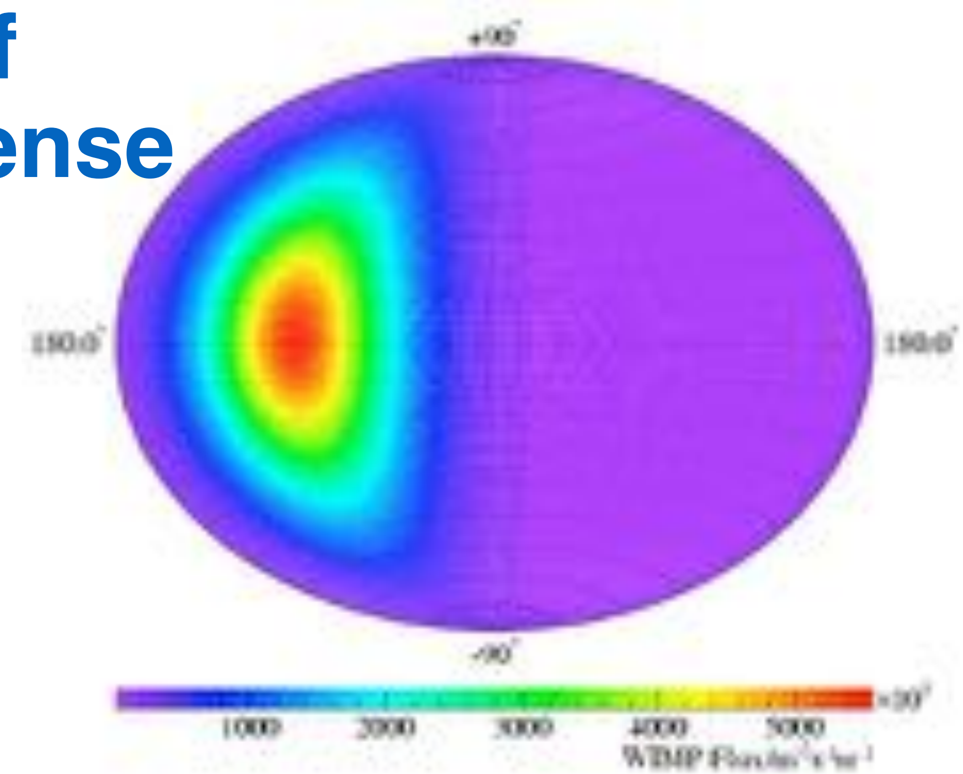




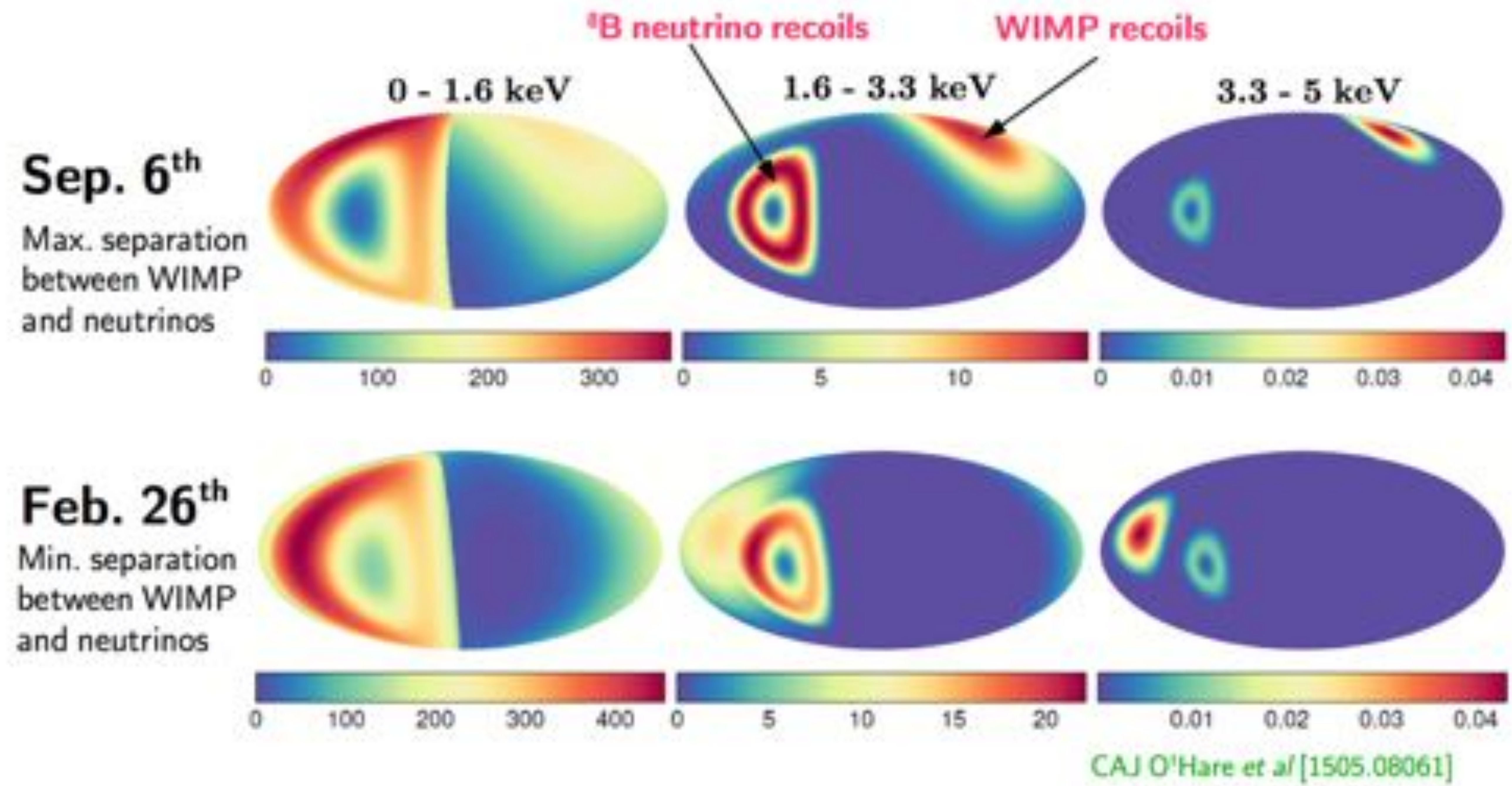
- Measure the nuclear recoil track itself and determine the head from tail or sense





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



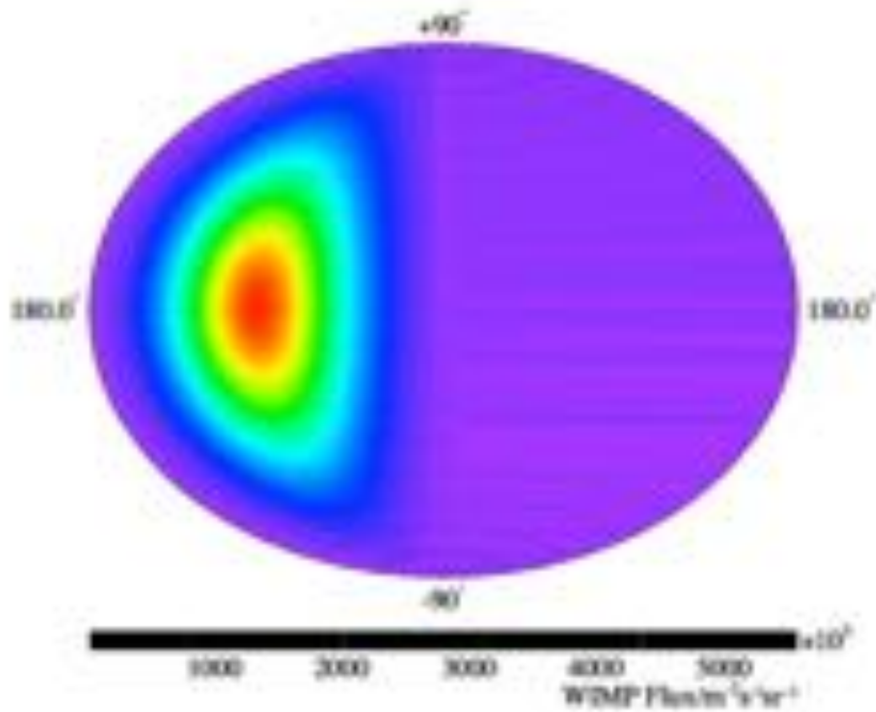
Power of Directionality - Astrophysics?

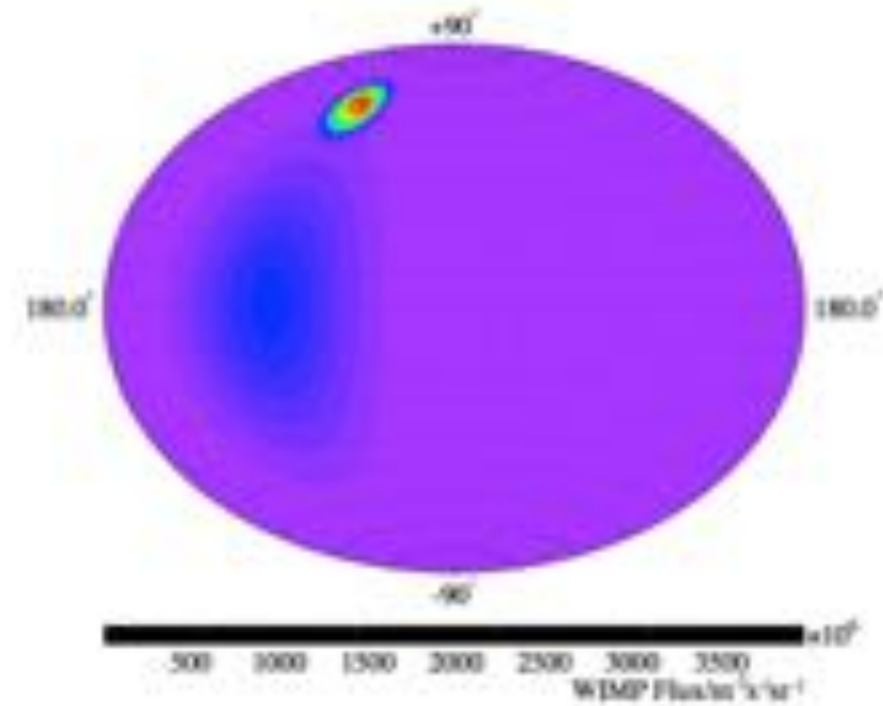
- Potential for WIMP “Astronomy”

Standard Halo

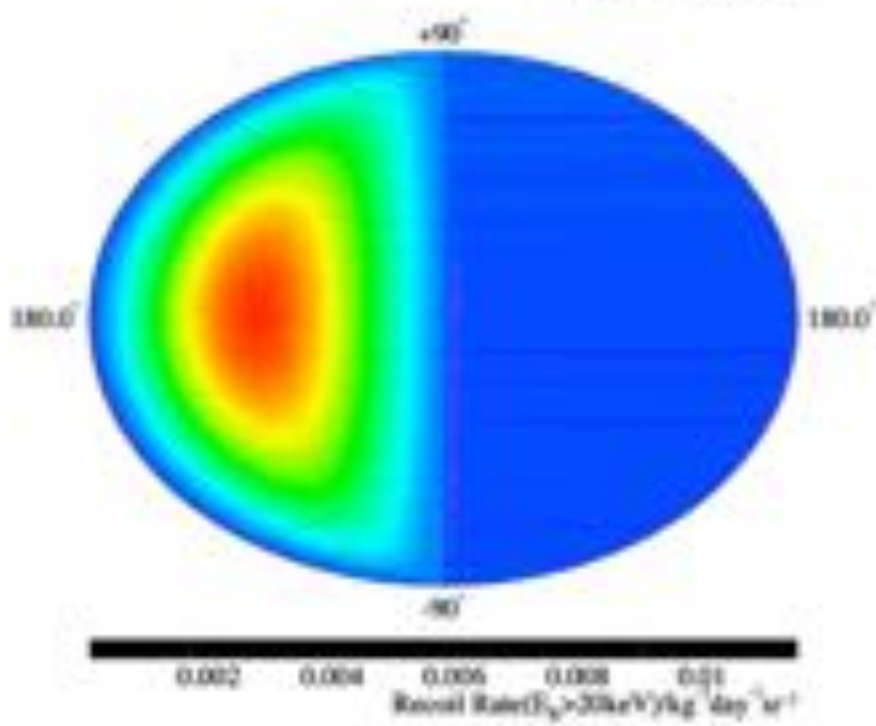
With Sagittarius Stream

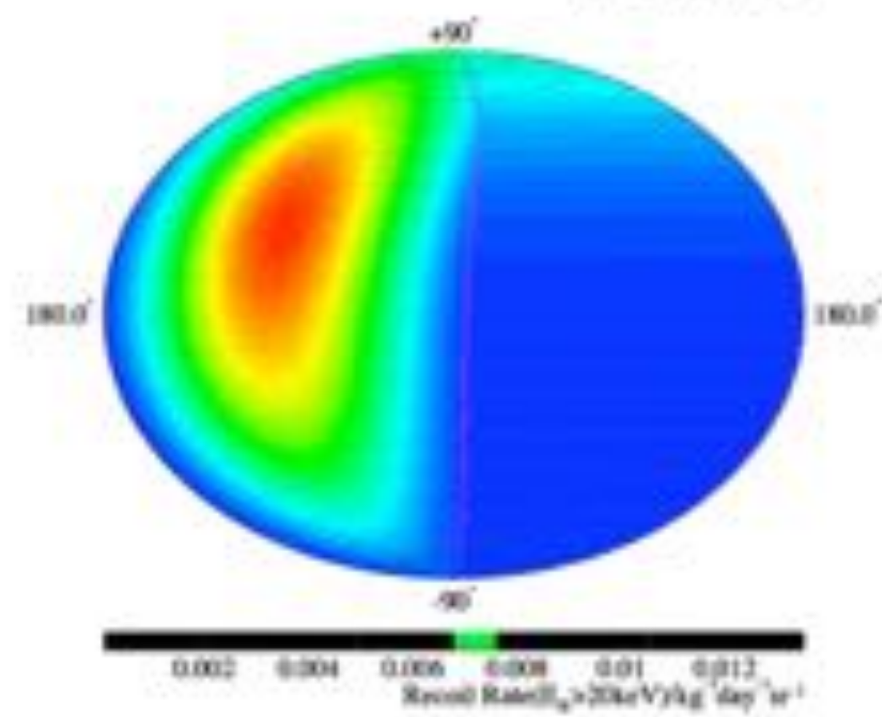
WIMP flux





S recoil flux

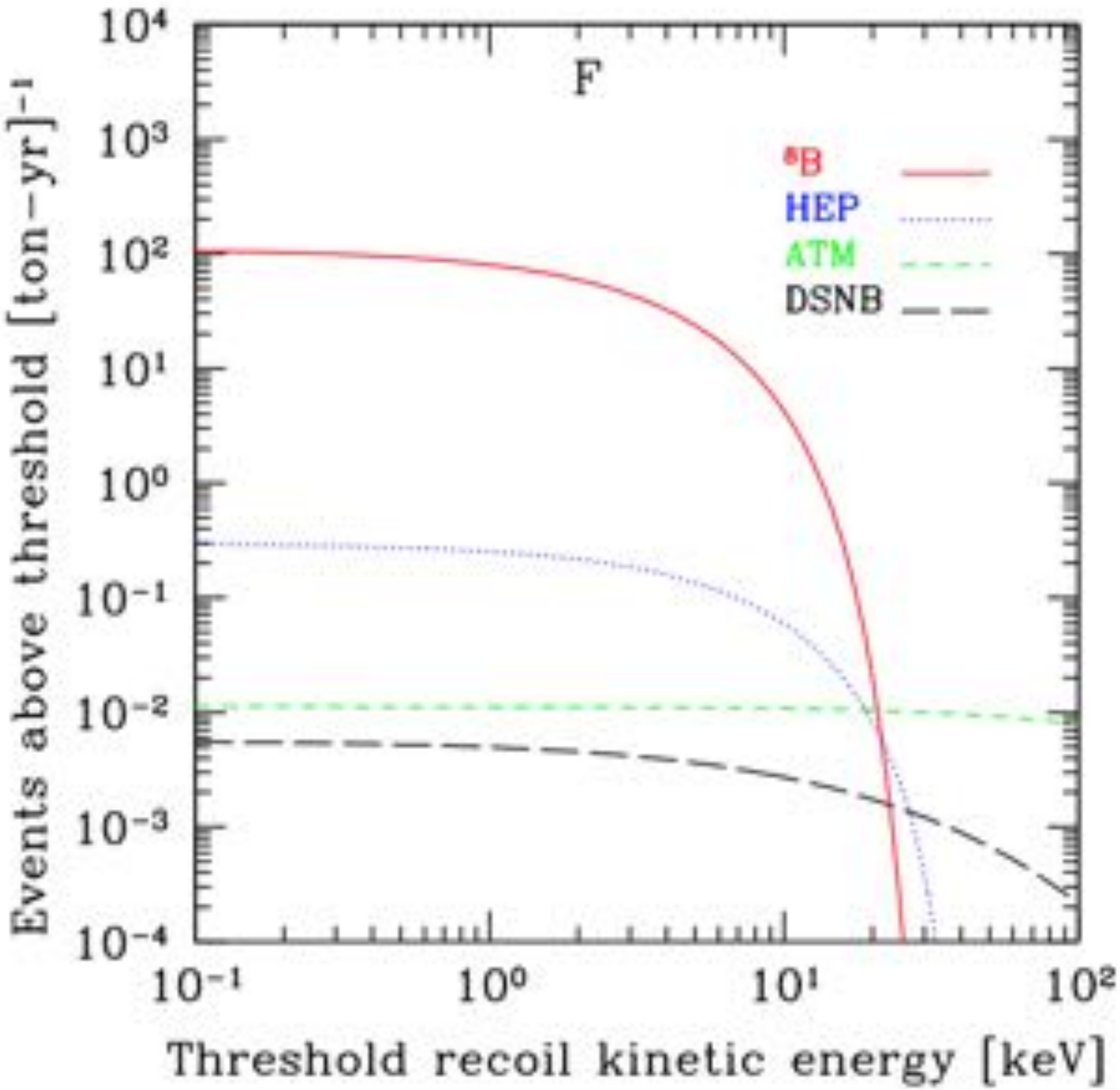


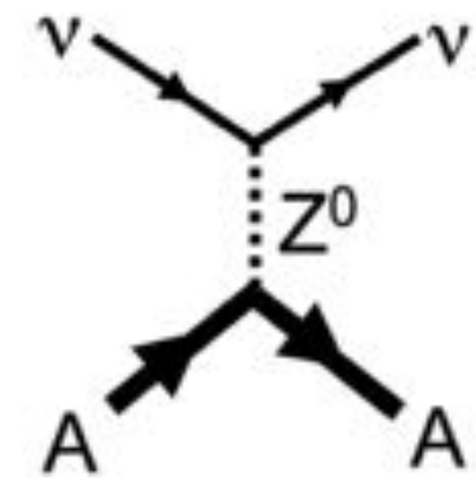


simulations by Ben Morgan (Sheffield)

Neutrino Coherent Rates, Fluorine

Louis E. Strigari arXiv: 0903.3630v2



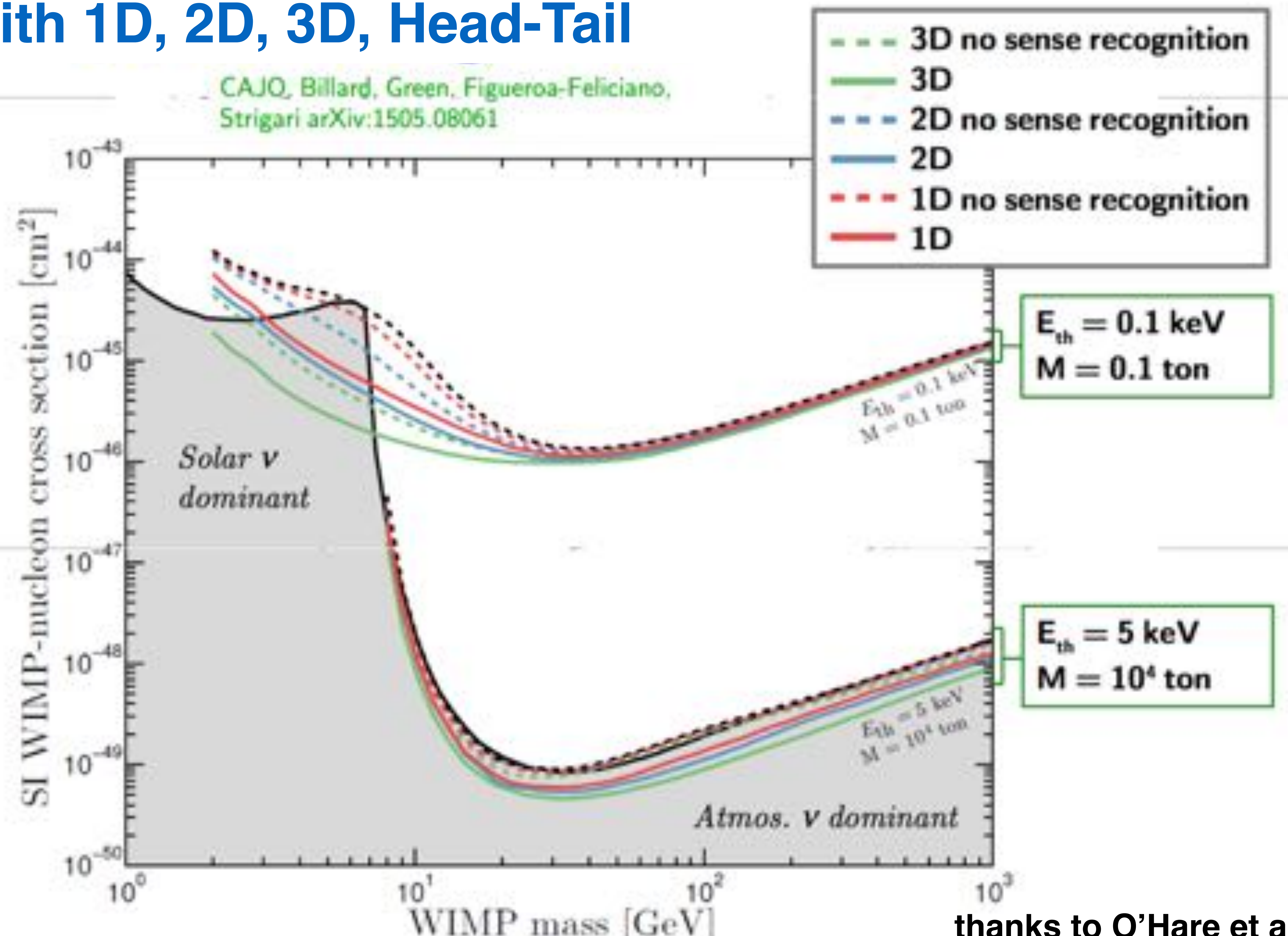


1keV$_{rec}$ threshold —> ~70 events per ton year

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.

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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- others..

CYGNUS

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

CYGNUS - Agreement

CYGNUS agreement includes Solid and TPC technology

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)

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

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-)

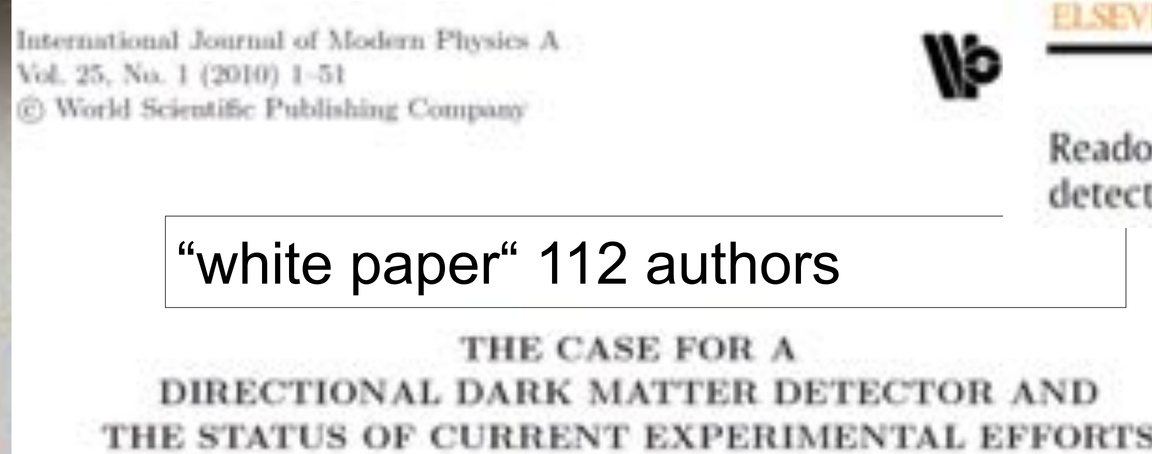
F. Mayet et al., A review of the discovery reach of directional Dark Matter detection, Physics Reports 627 (2016) 49

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


International Journal of Modern Physics A
Vol. 25, No. 1 (2010) 1–51
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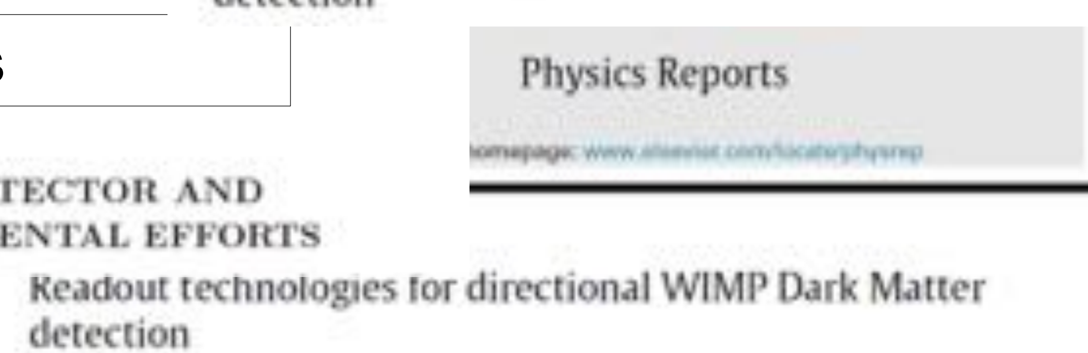
THE CASE FOR A
DIRECTIONAL DARK MATTER DETECTOR AND
THE STATUS OF CURRENT EXPERIMENTAL EFFORTS

"white paper" 112 authors



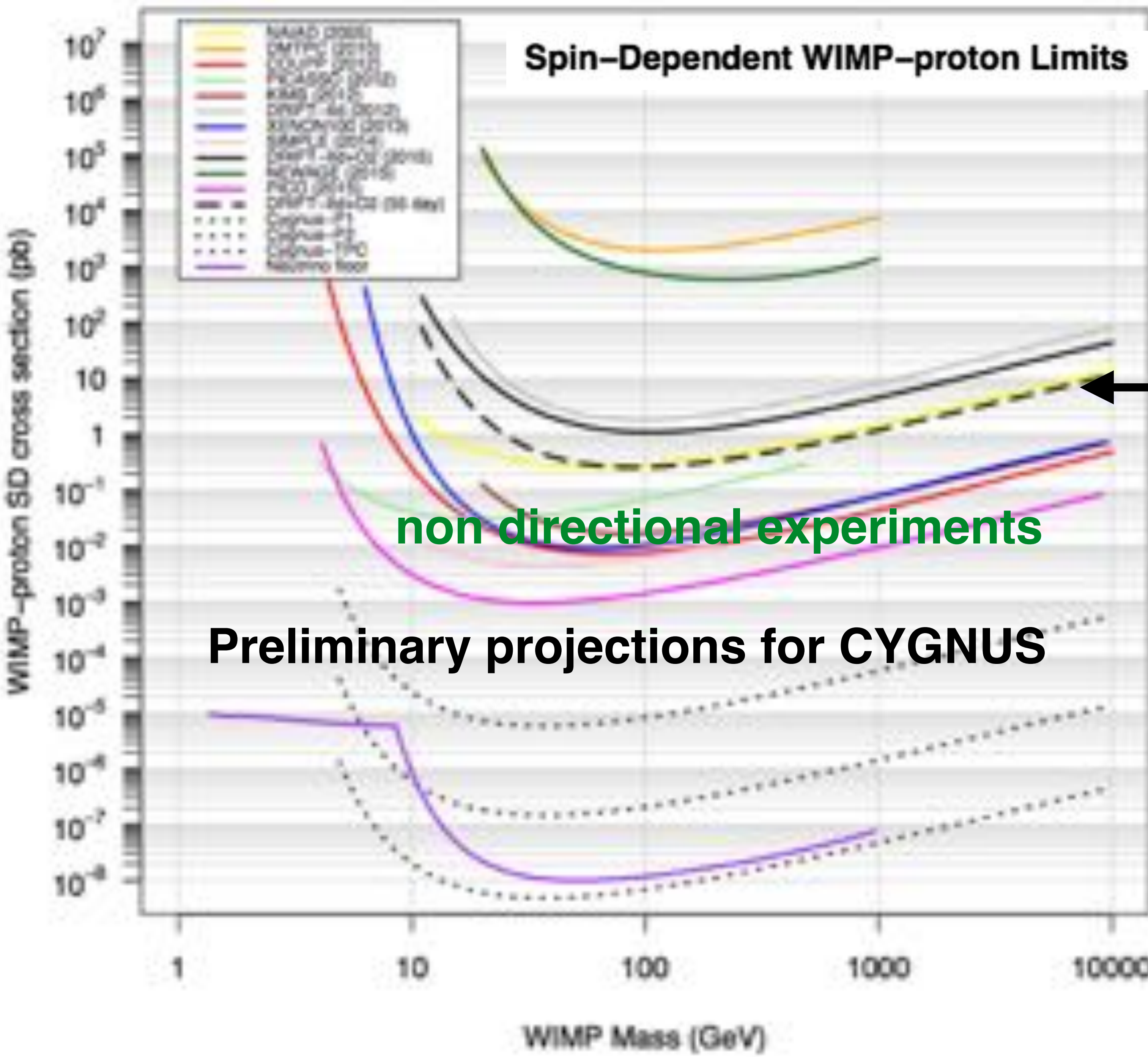
CYGNUS - Multiple Sites

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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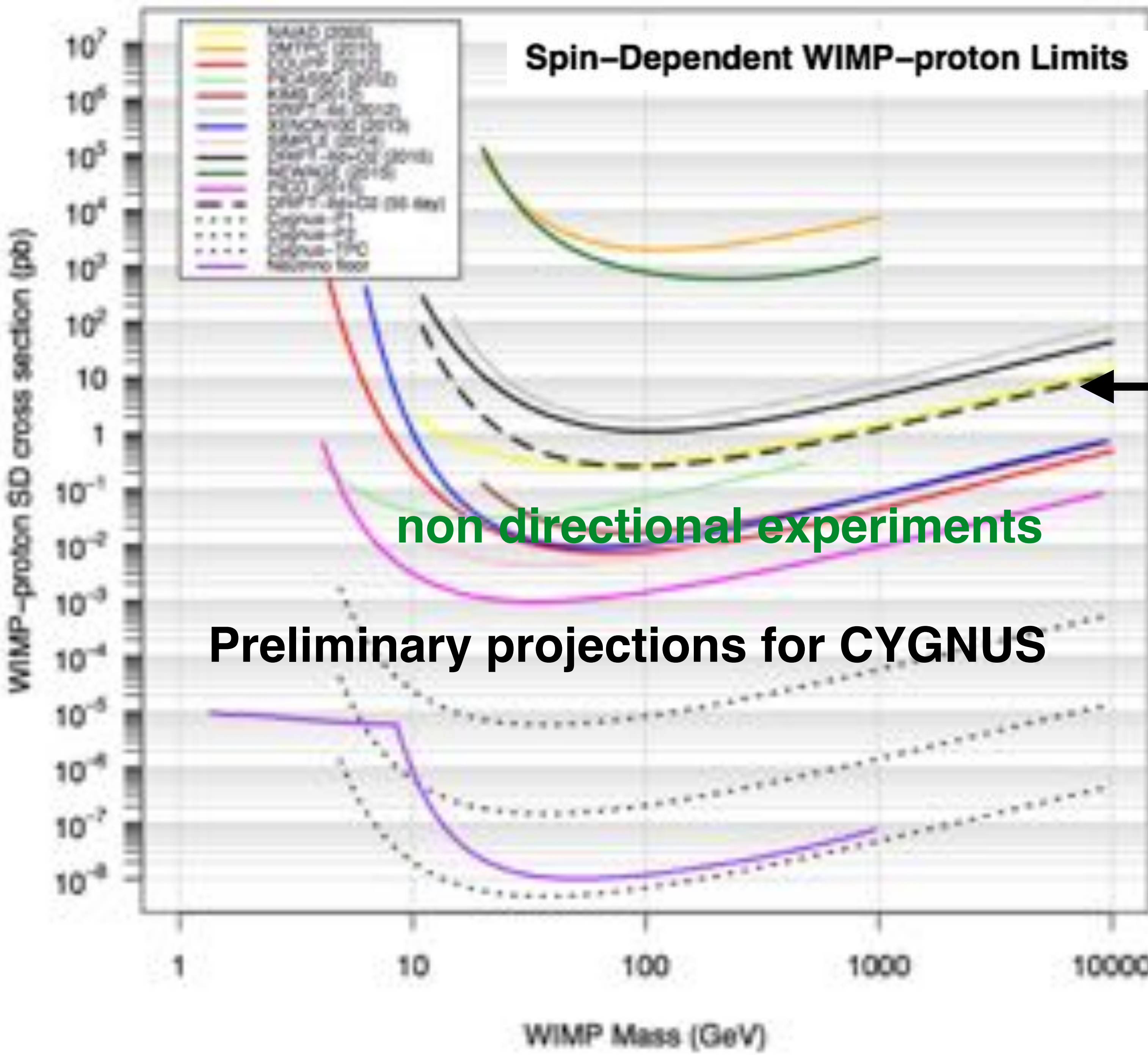


The Pathfinder Strategy

~Current directional experiment state

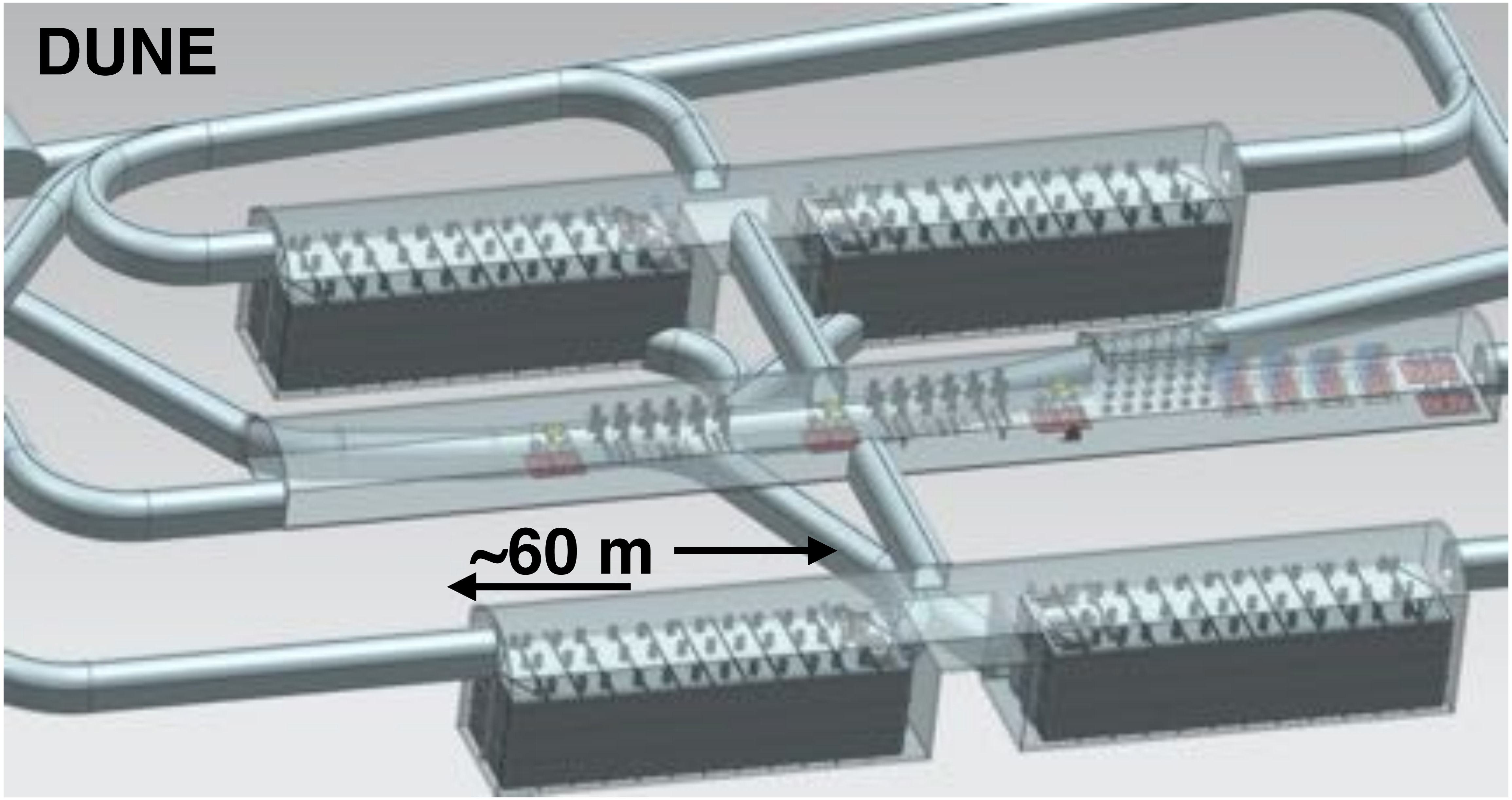
CYGNUS - Pathfinder 1

CYGNUS - Pathfinder 2

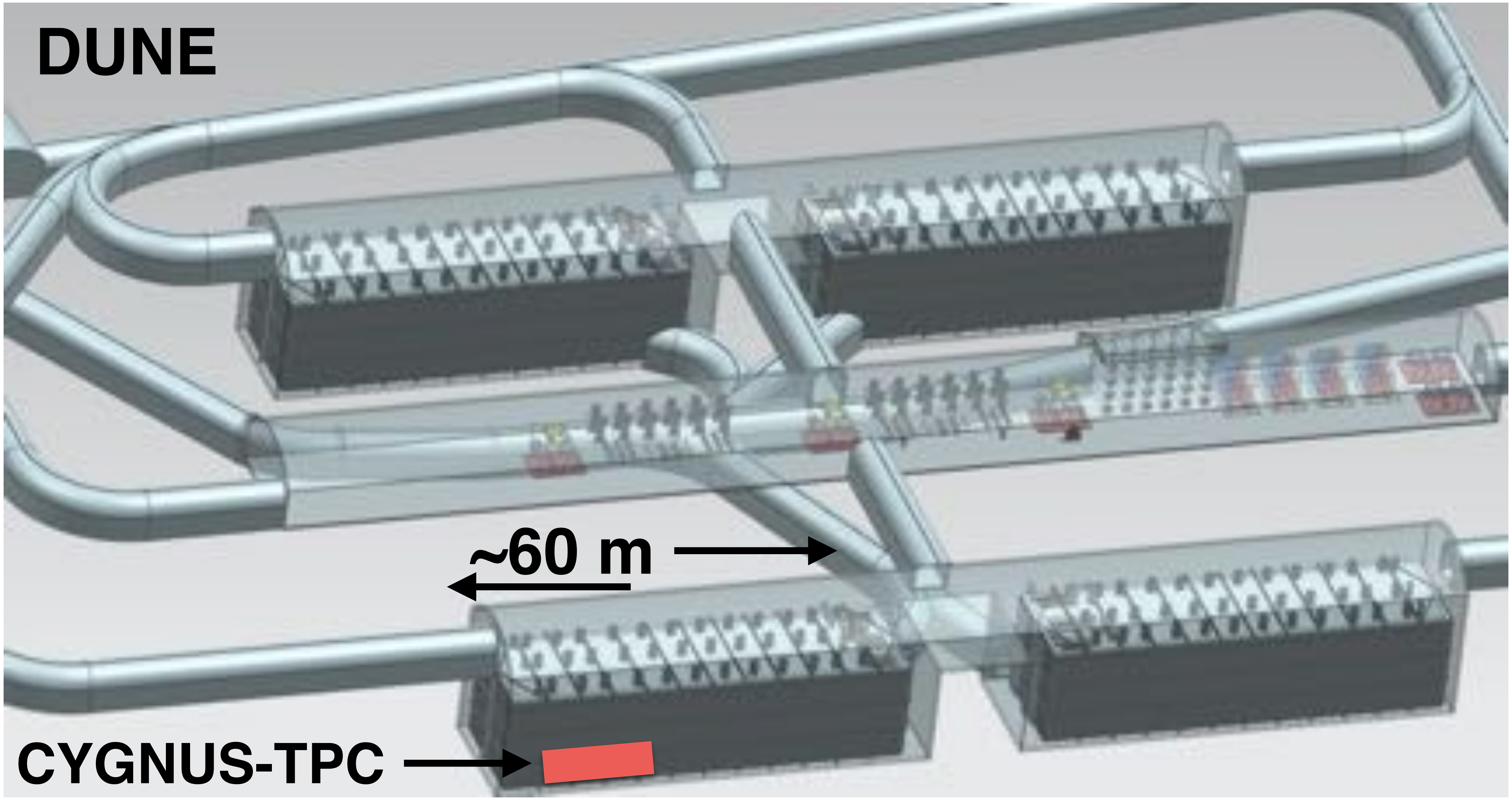
CYGNUS - TPC

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?

CYGNUS NOW

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(3) R&D at 1 m3 (CYGNUS-Japan, DRIFT…

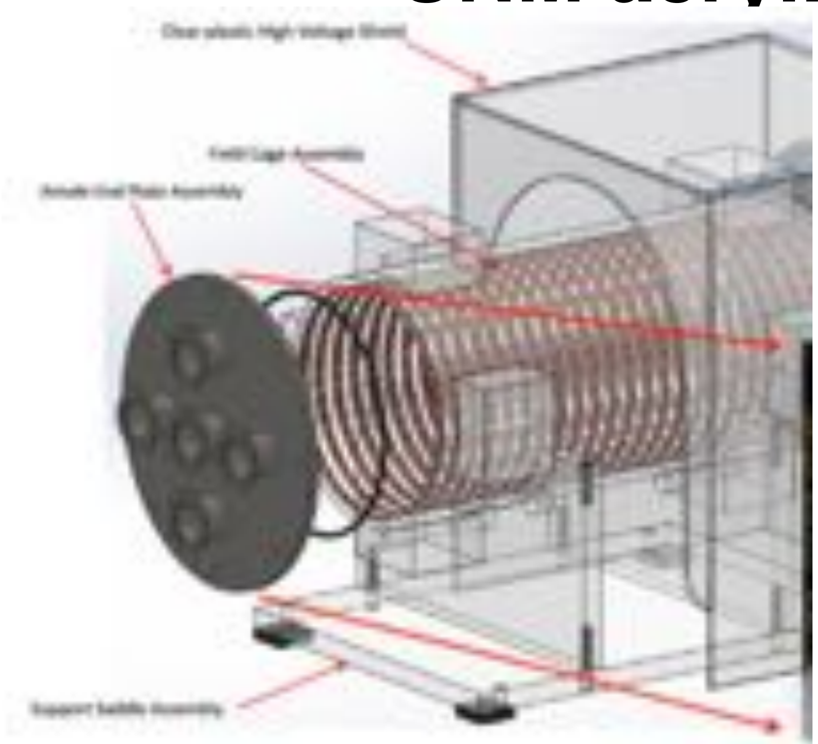
North - Boulby, LNGS, Kamioka?
South - Stawell?

CYGNUS-TPC Optimisation

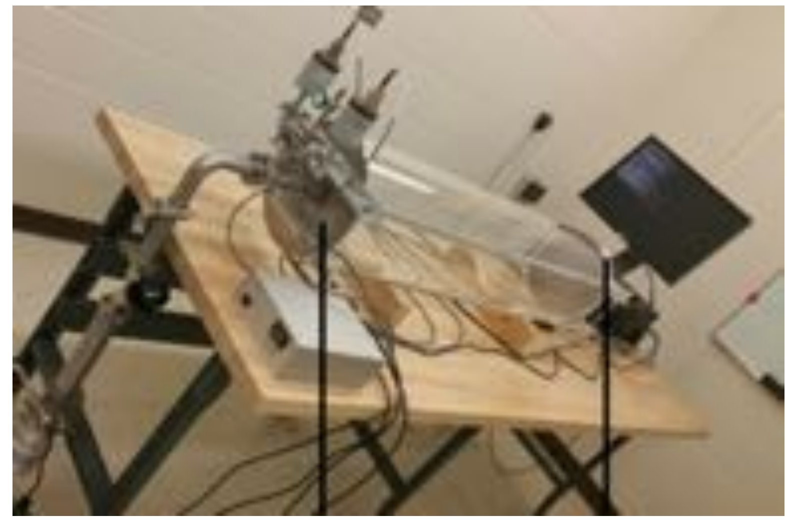
- What directional capability is optimal - 1D, 2D, 3D + HT vs cost?
- What gas - can SF_6 work well enough for fiducialisation?
- What directional sensitivity can there be <20 keV_{recoil}?
- Can zero background be achieved (particularly neutrons)?
- Can we use multiple underground sites

New Studies - Funded Activity

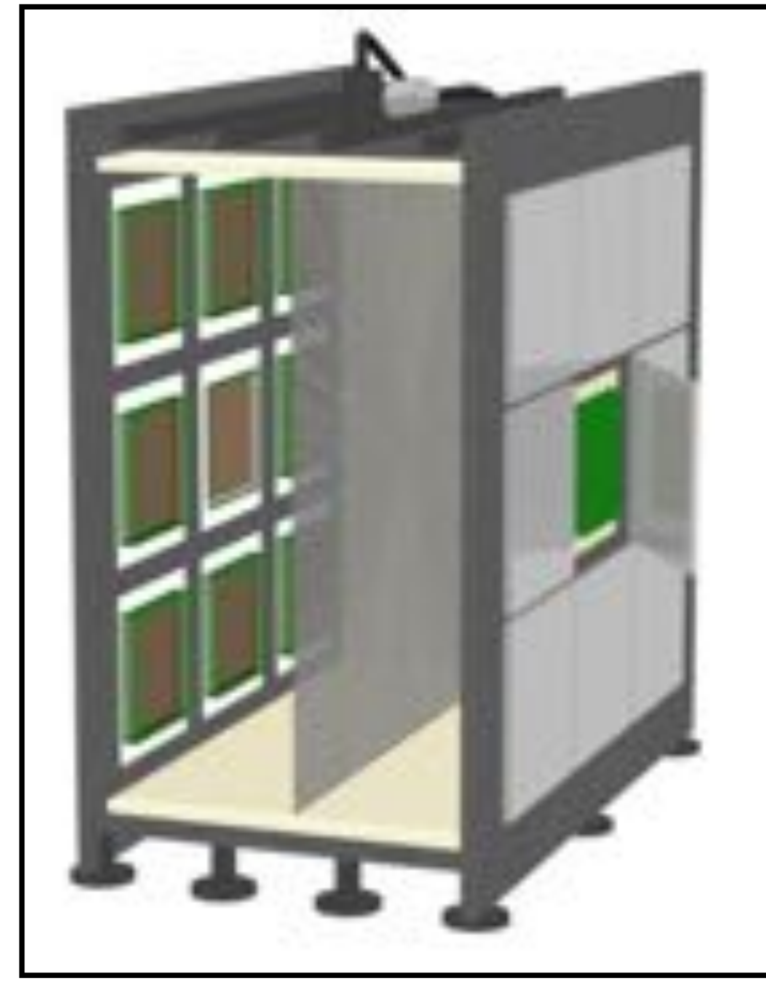
UNM acrylic (USA)



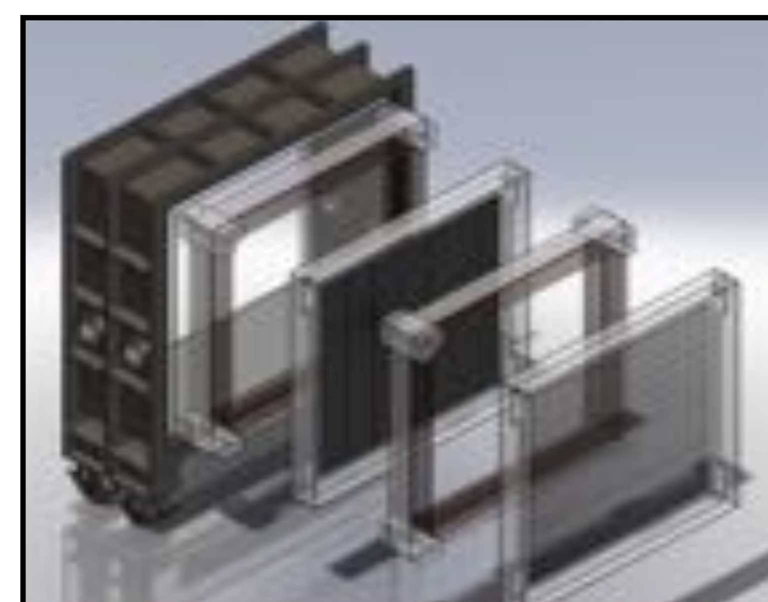
Hawaii D3 (USA)



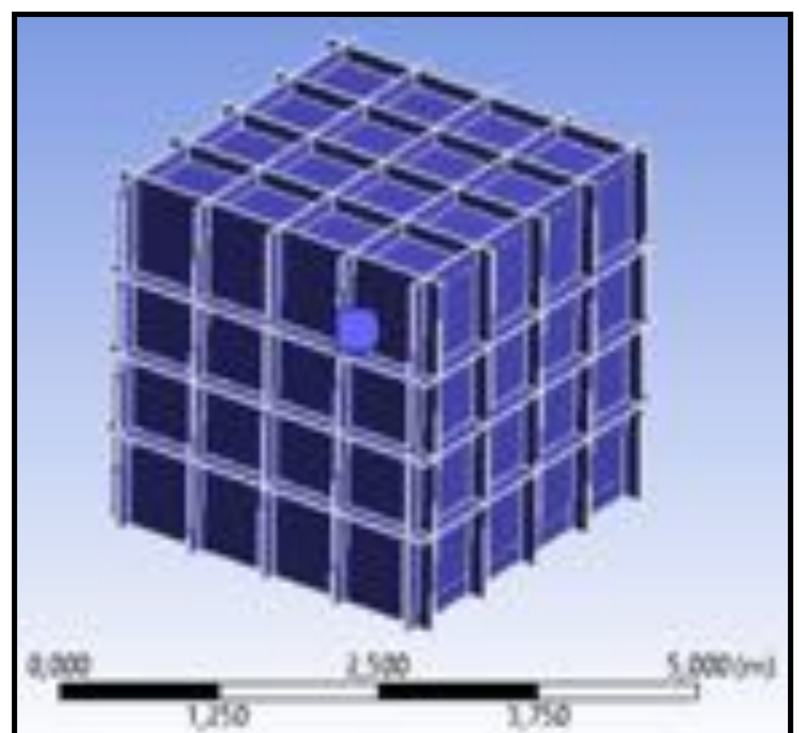
1 m3 CYGNUS test vessel (Japan) →



10 m^3 designs (US, UK)



SF_6 R&D, Frascati, (Italy)



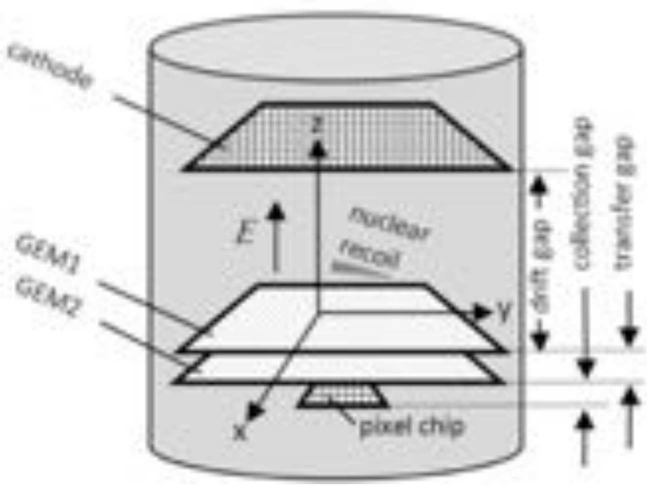
10 m^3 vessels (Australia)

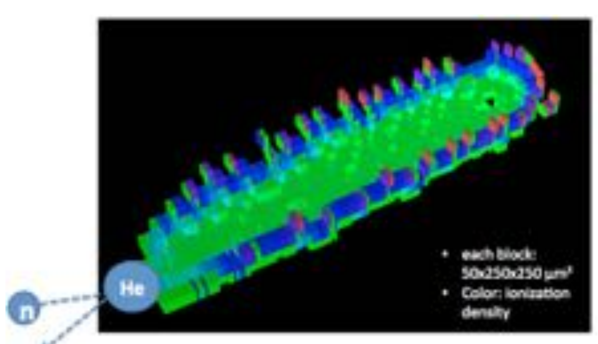
What Directional TPC Technology?

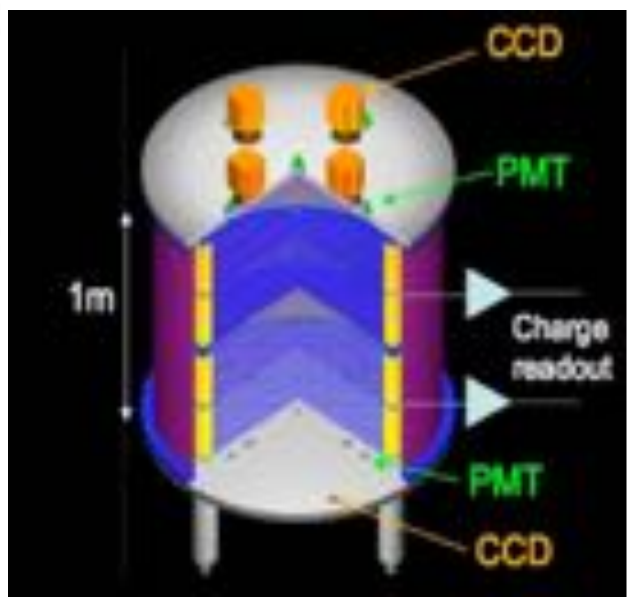
"high definition - 3D"

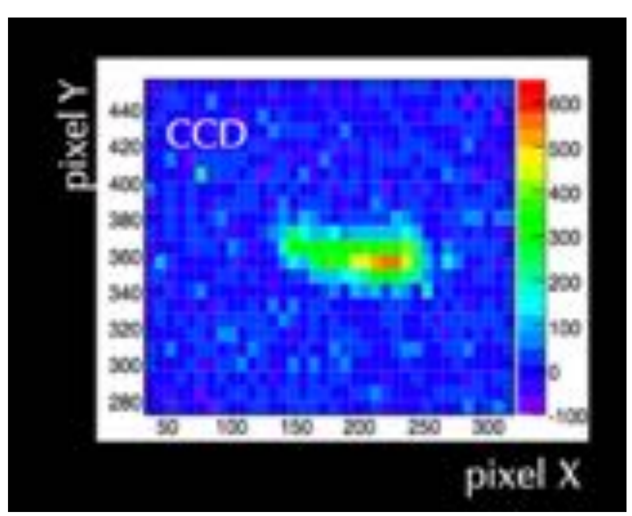
e.g. D^3 - pixel **e.g. DM-TPC - CCD**

small volume R&D





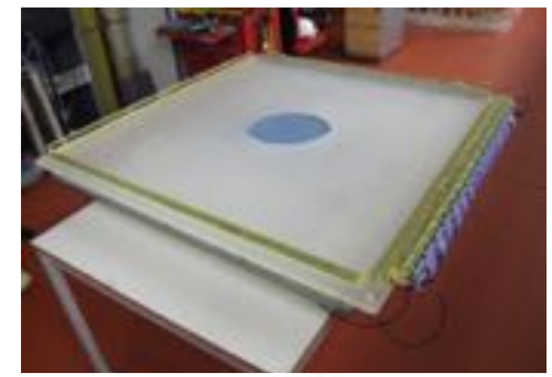


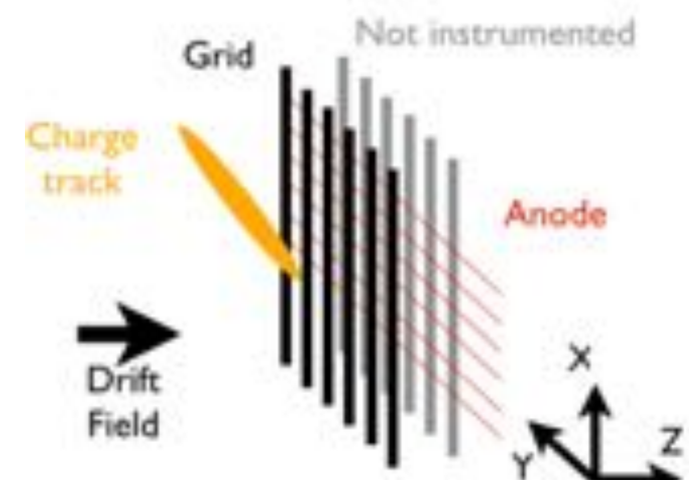


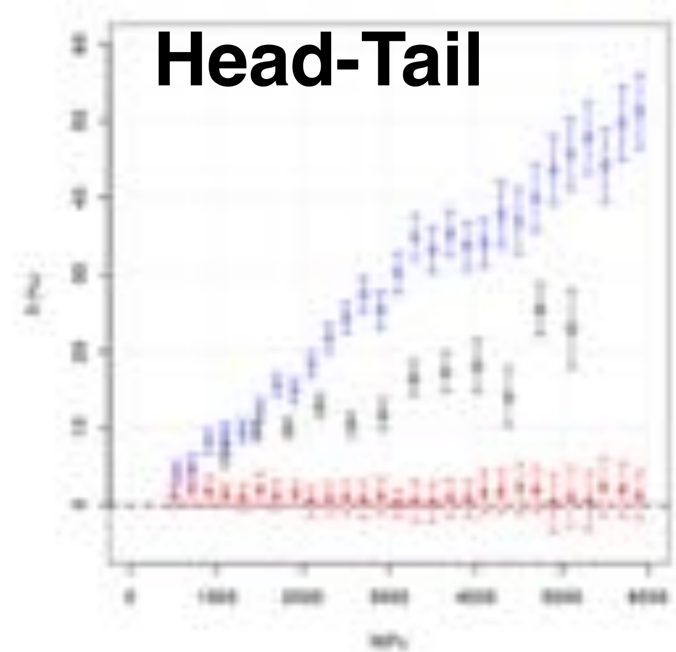
"low definition ~ 1.5D"

e.g. DRIFT - wires

larger volume R&D, low background







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

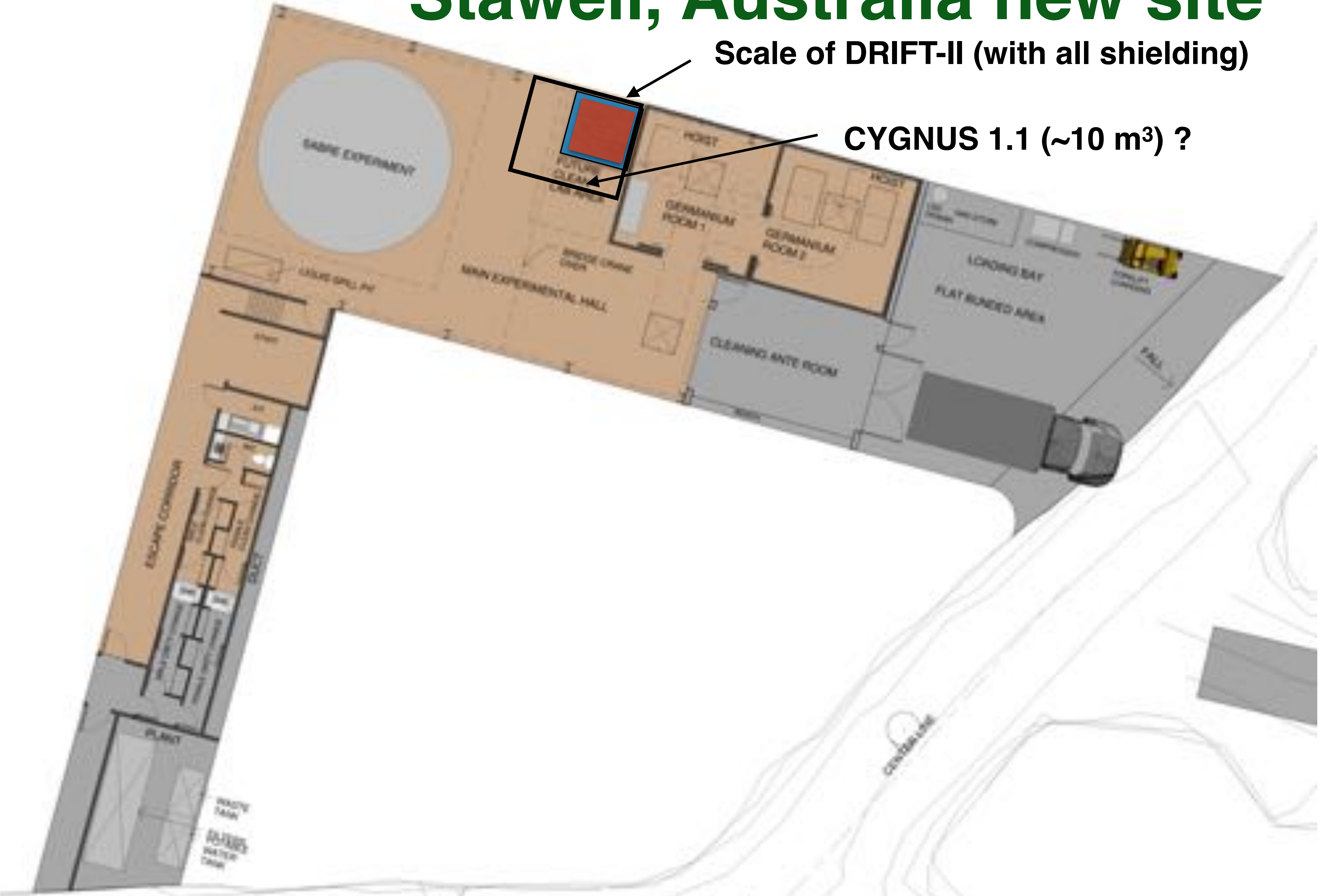
Sven Vahsen (Hawaii) is coordinating

New Site Infrastructure

Stawell, Australia new site

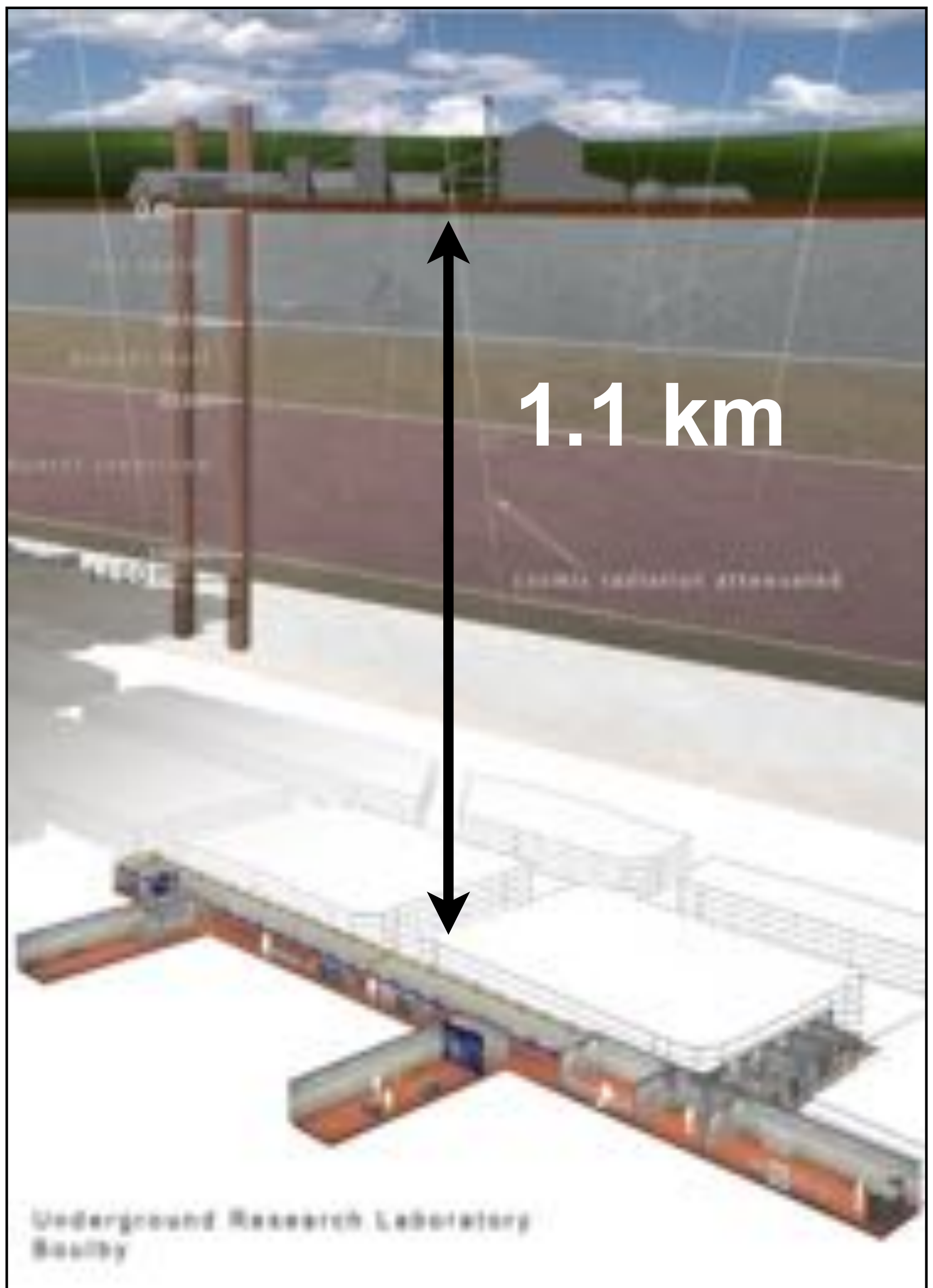
New Site Infrastructure

Stawell, Australia new site



New Site Infrastructure
Boulby Laboratory, UK

- Here is the old laboratory
- 1.1 km deep in very low background salt rock
- New lab now constructed, completed in 2017



CYGNUS R&D at New Boulby Lab

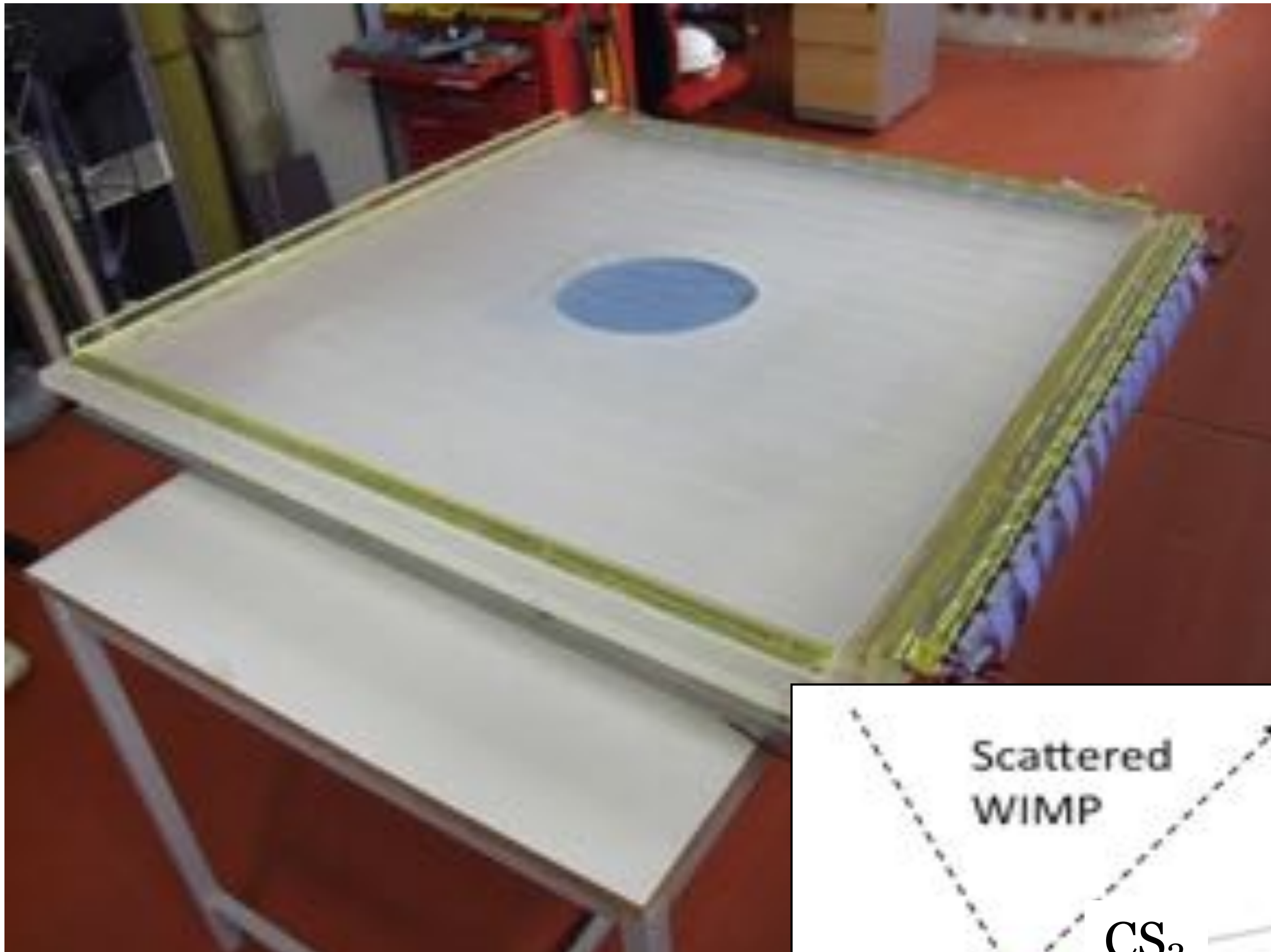
DRIFT IId & DRIFT IIe at Boulby

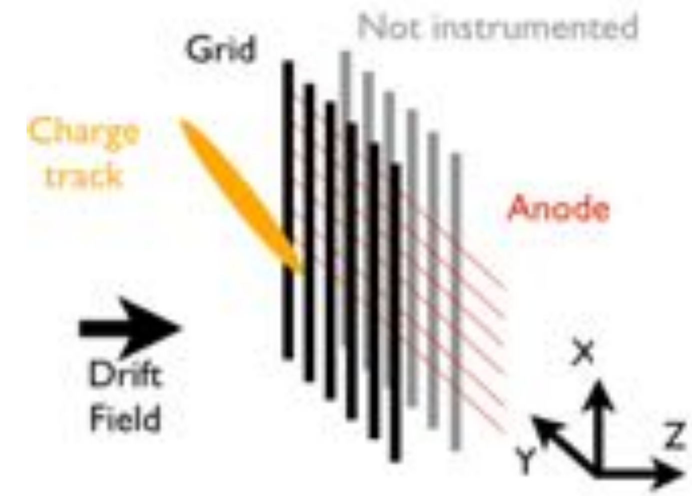
Studies of Low Background, DRIFT

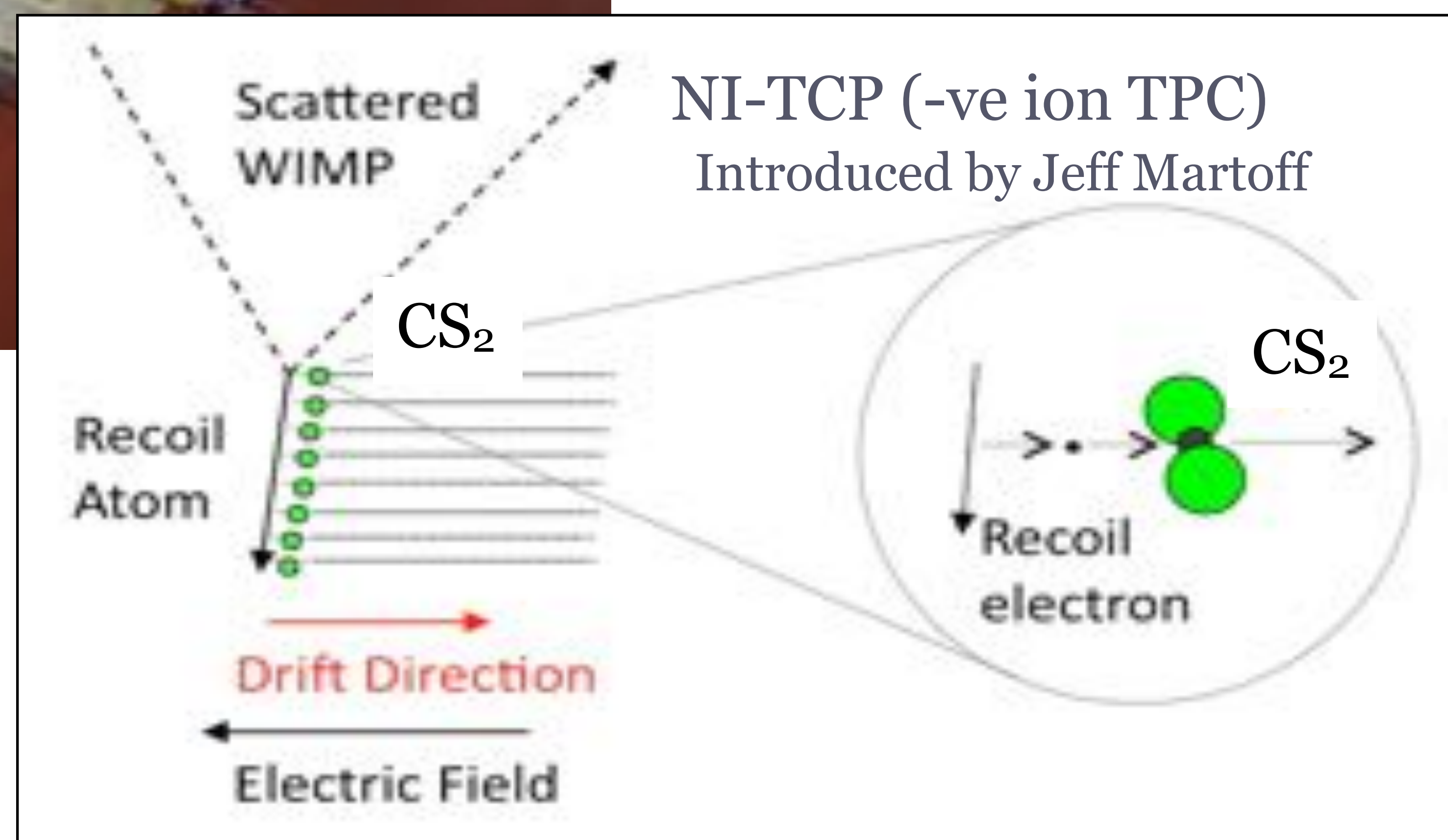
Key Issues: (i) Full Fiducialisation

(ii) Neutron Backgrounds at ton scale

DRIFT MWPC 1 x 1m, -ve ion drift



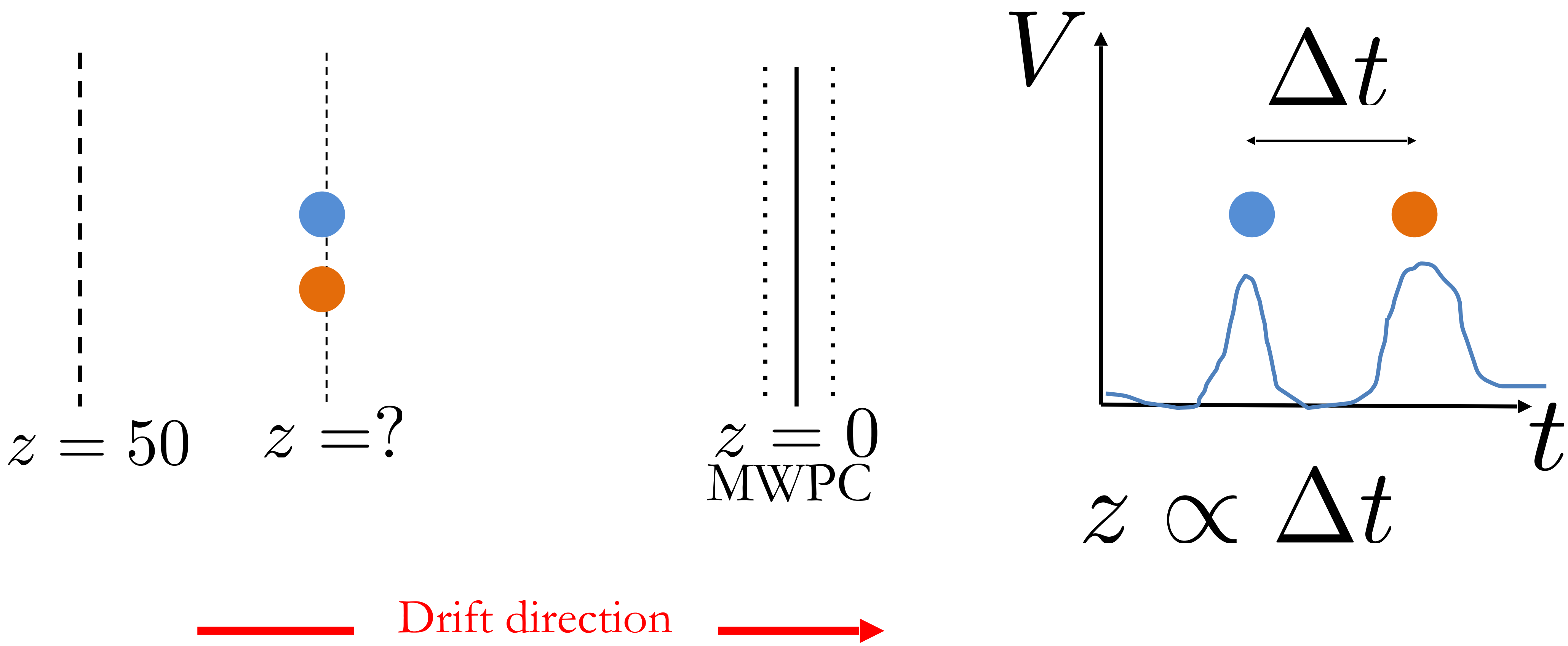




- Discovery of minority carrier gas mixtures CS_2:CF_4:O2

z-Fiducialization Breakthrough

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

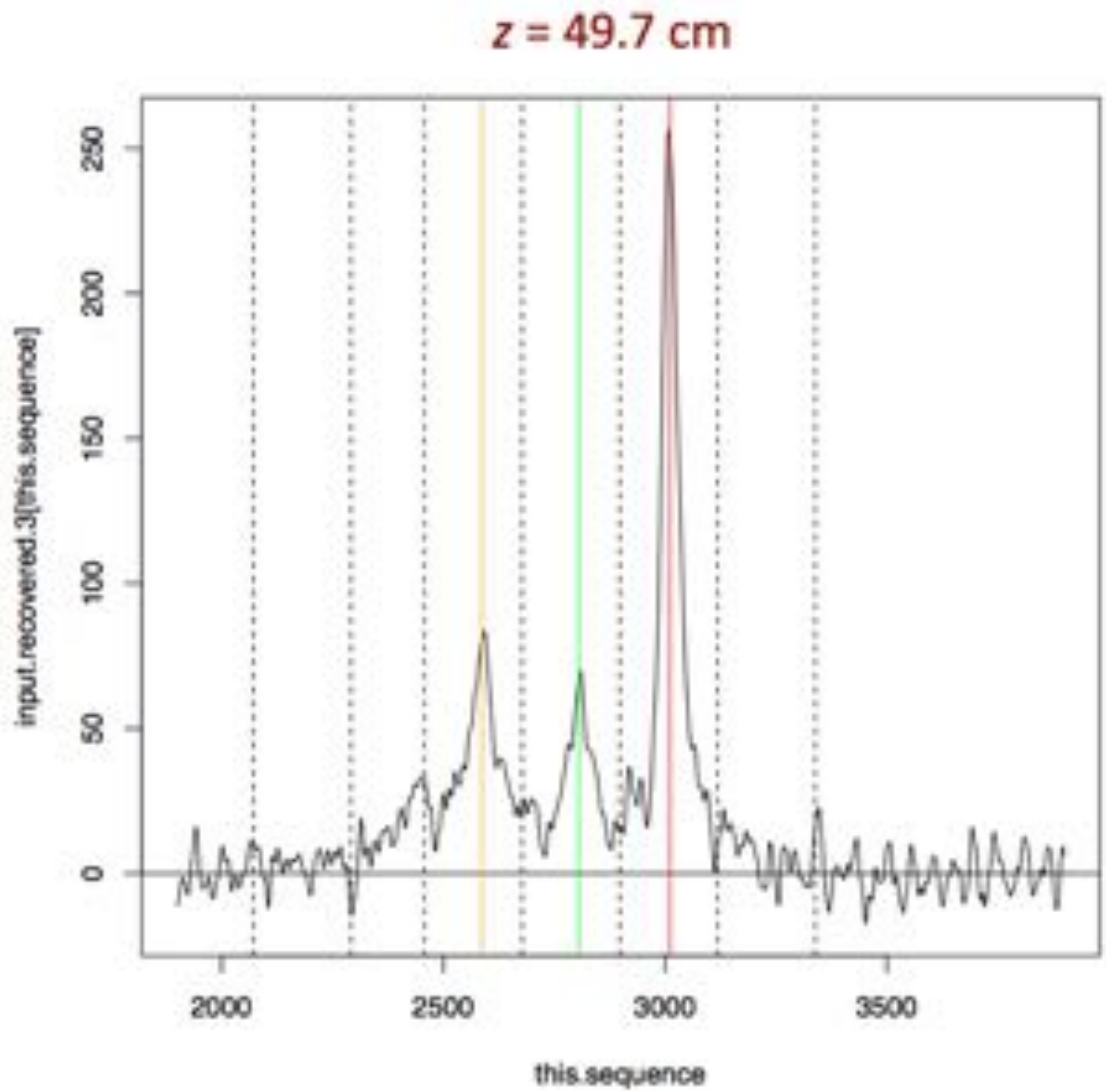


Proportionality constant can be measured for various gas mixtures, or calibrated in-situ.

thanks to D. Snowden-Ifft

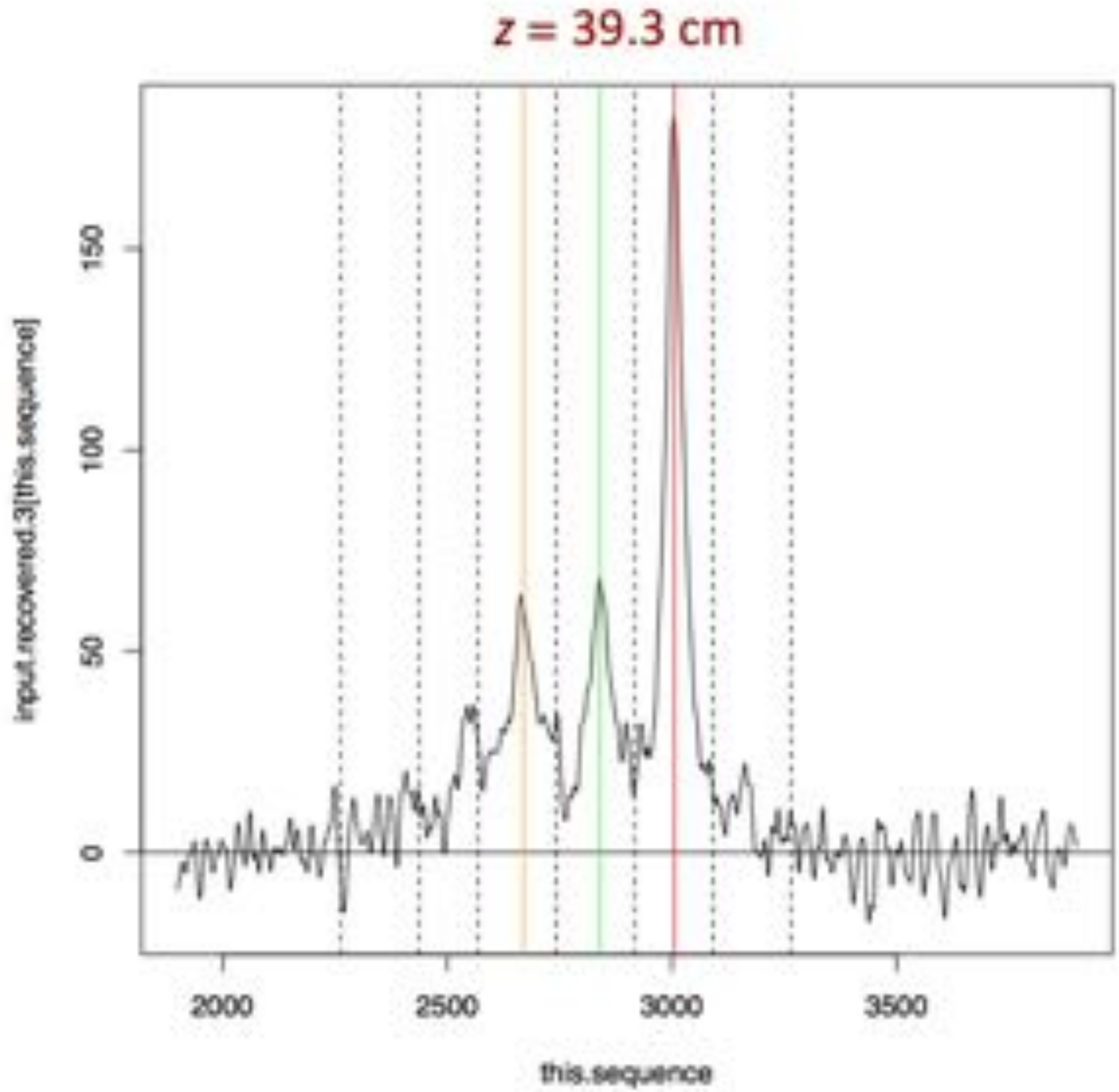
z-Fiducialization

Examples



z-Fiducialization

Examples



z-Fiducialization

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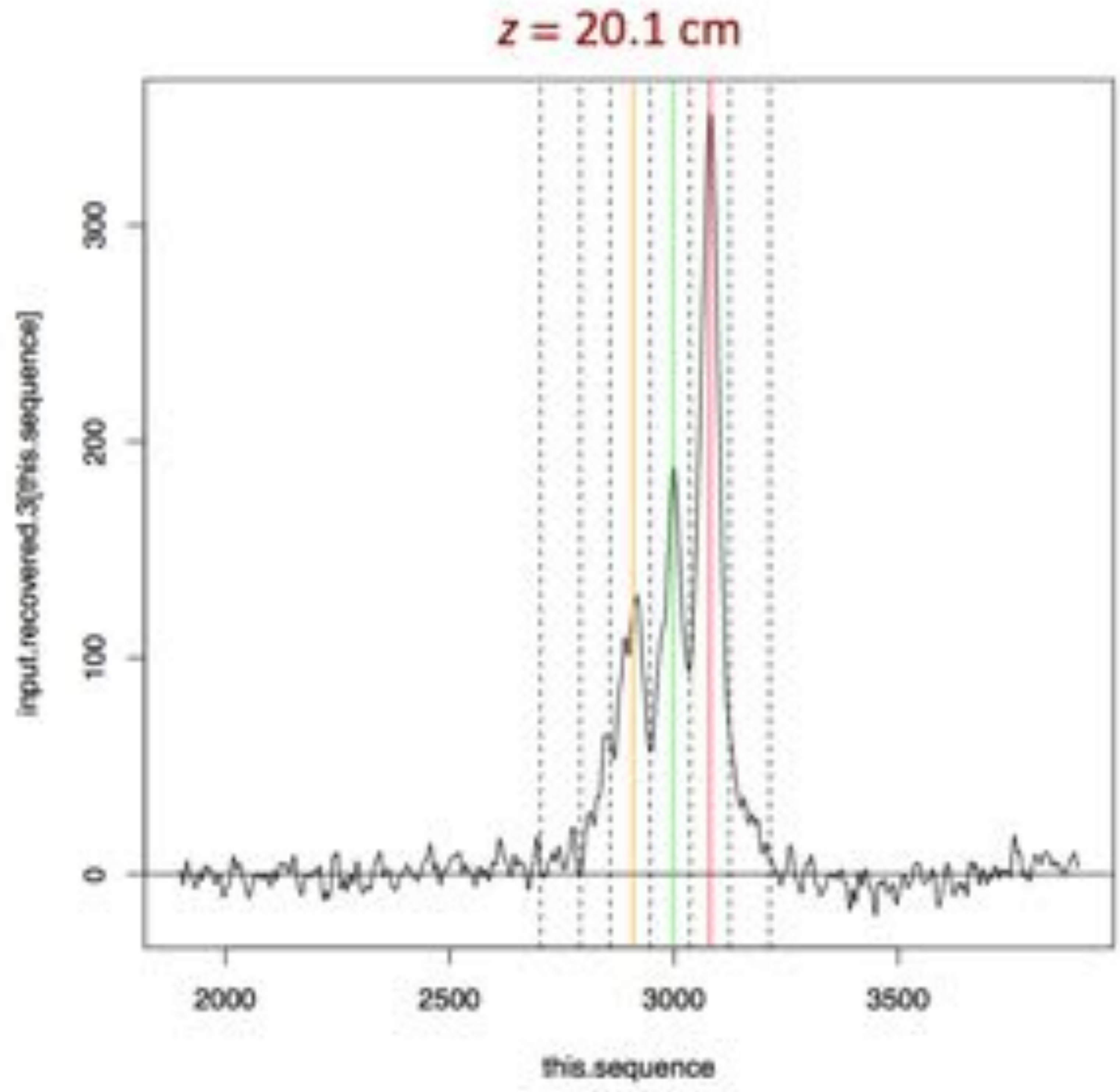
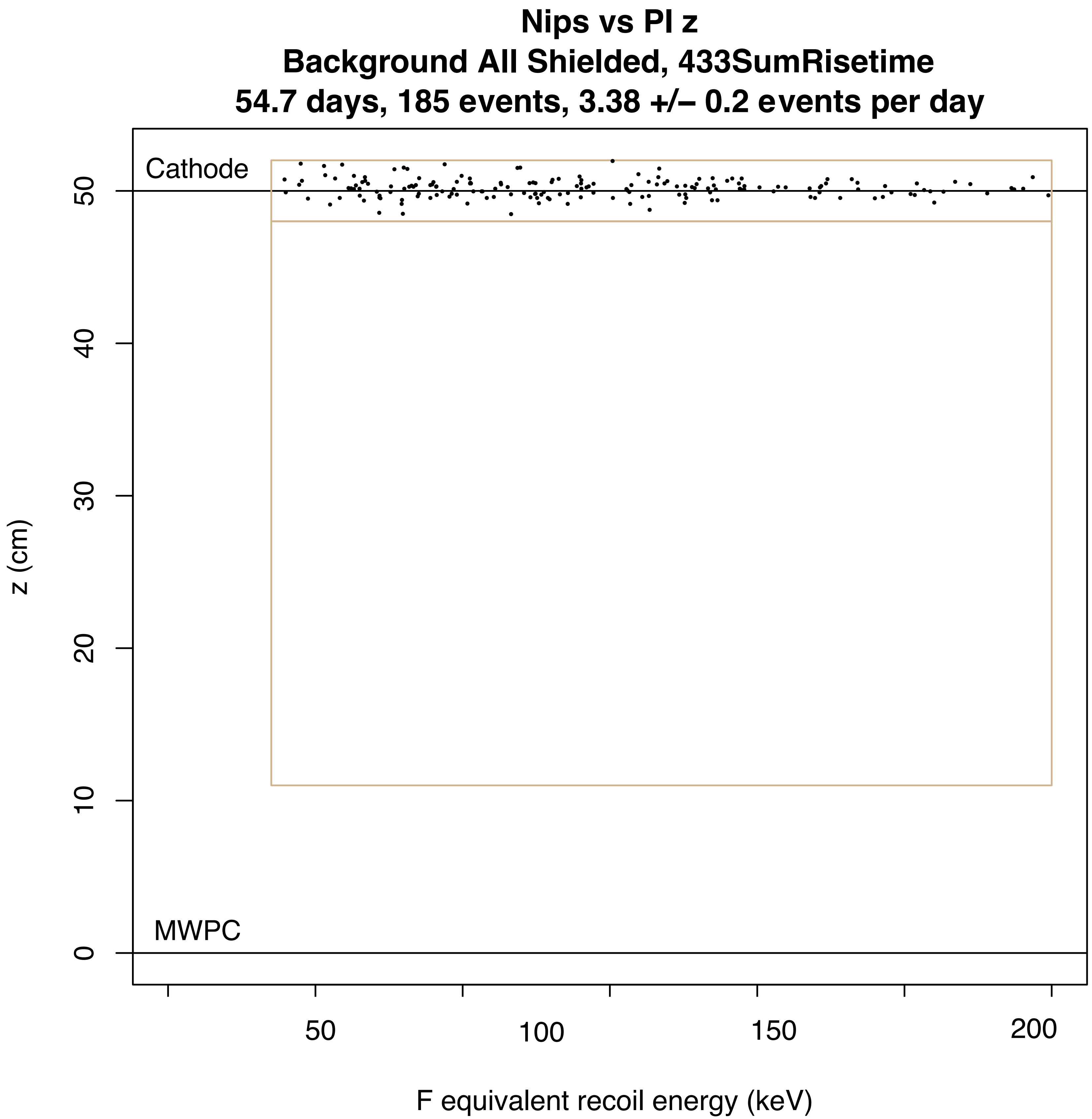


DRIFT WIMP Analysis

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

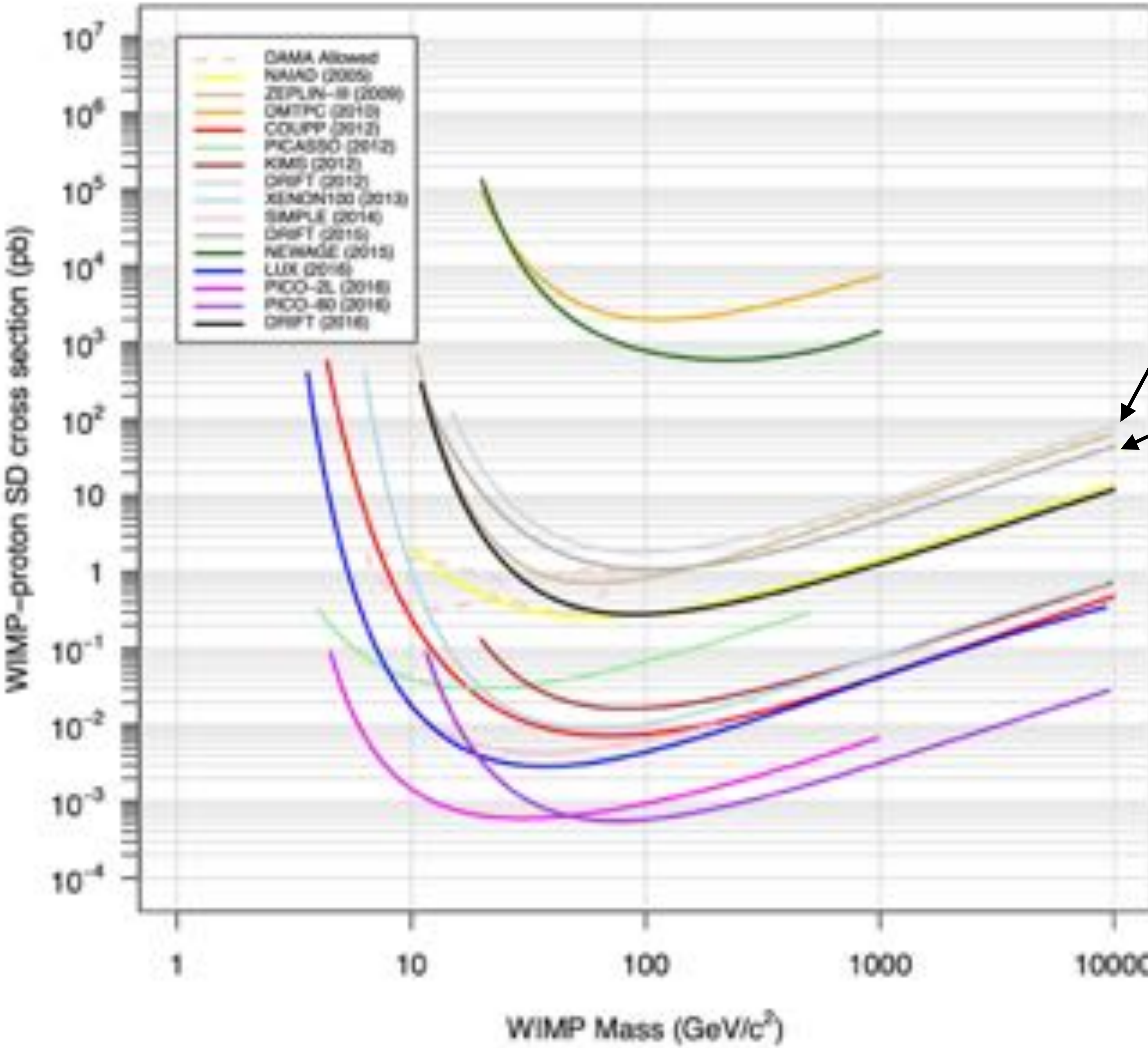


- 54.7 days of data analyzed
- 185 events found but as expected all were located at 50 cm away from the detector, i.e. on the central cathode.
- Define a background-free fiducial region.
- In order to interpret this as a limit need to calibrate the detector…

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

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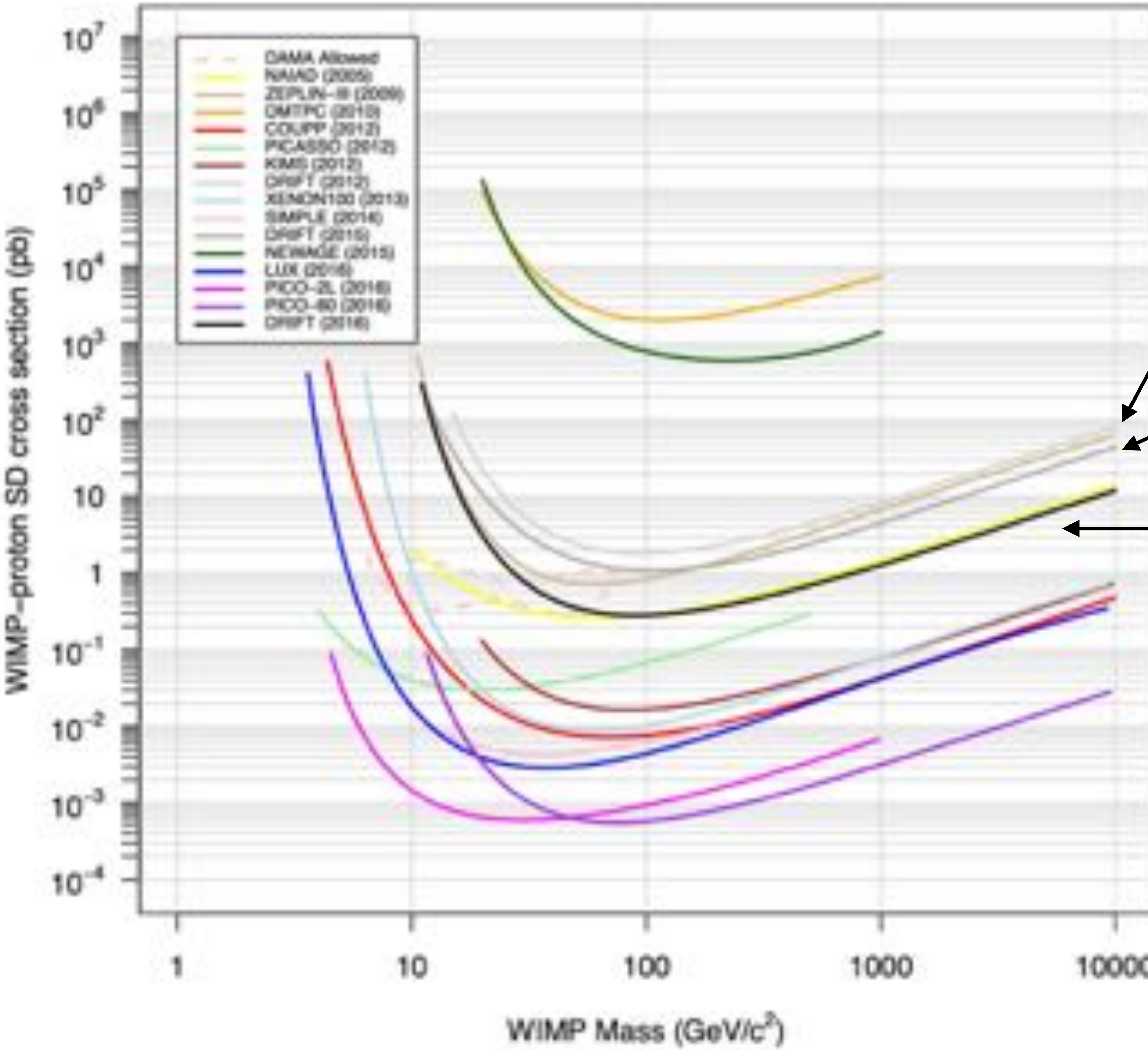

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arXiv: 1701.00171

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

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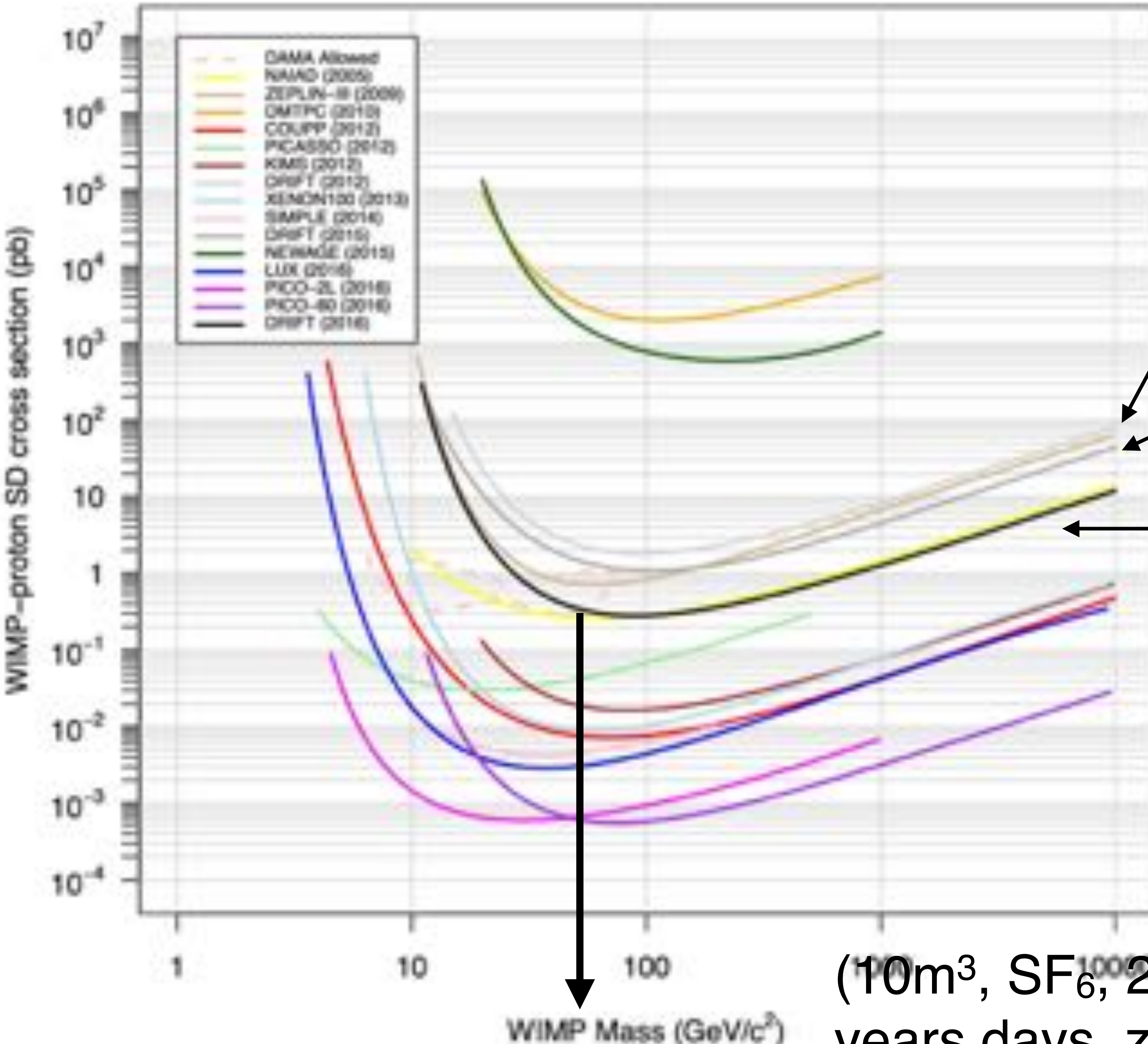

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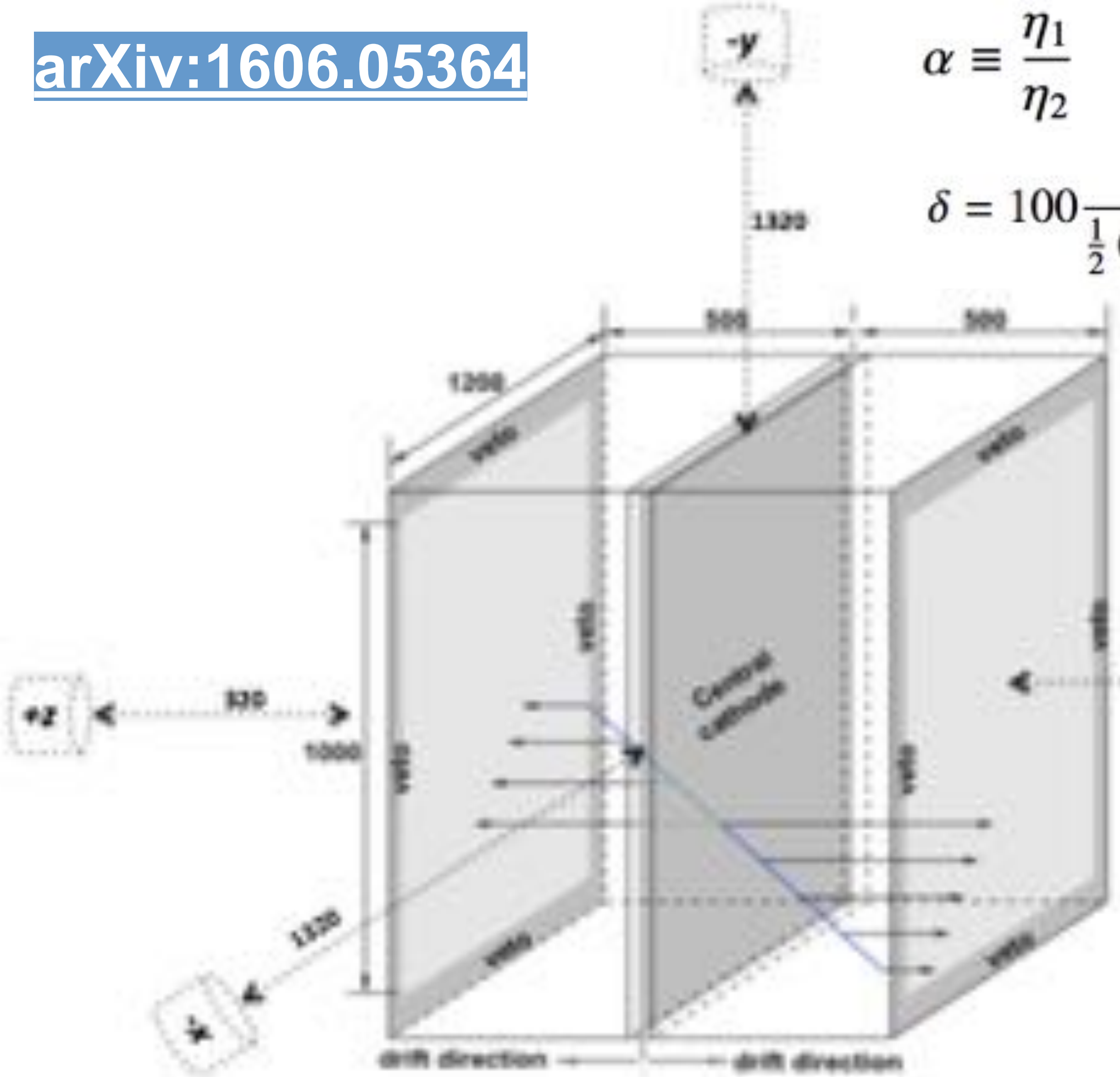
(31 gram F, 40 Torr, ~50 days, zero background)

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

Head-Tail Directionality Maintained

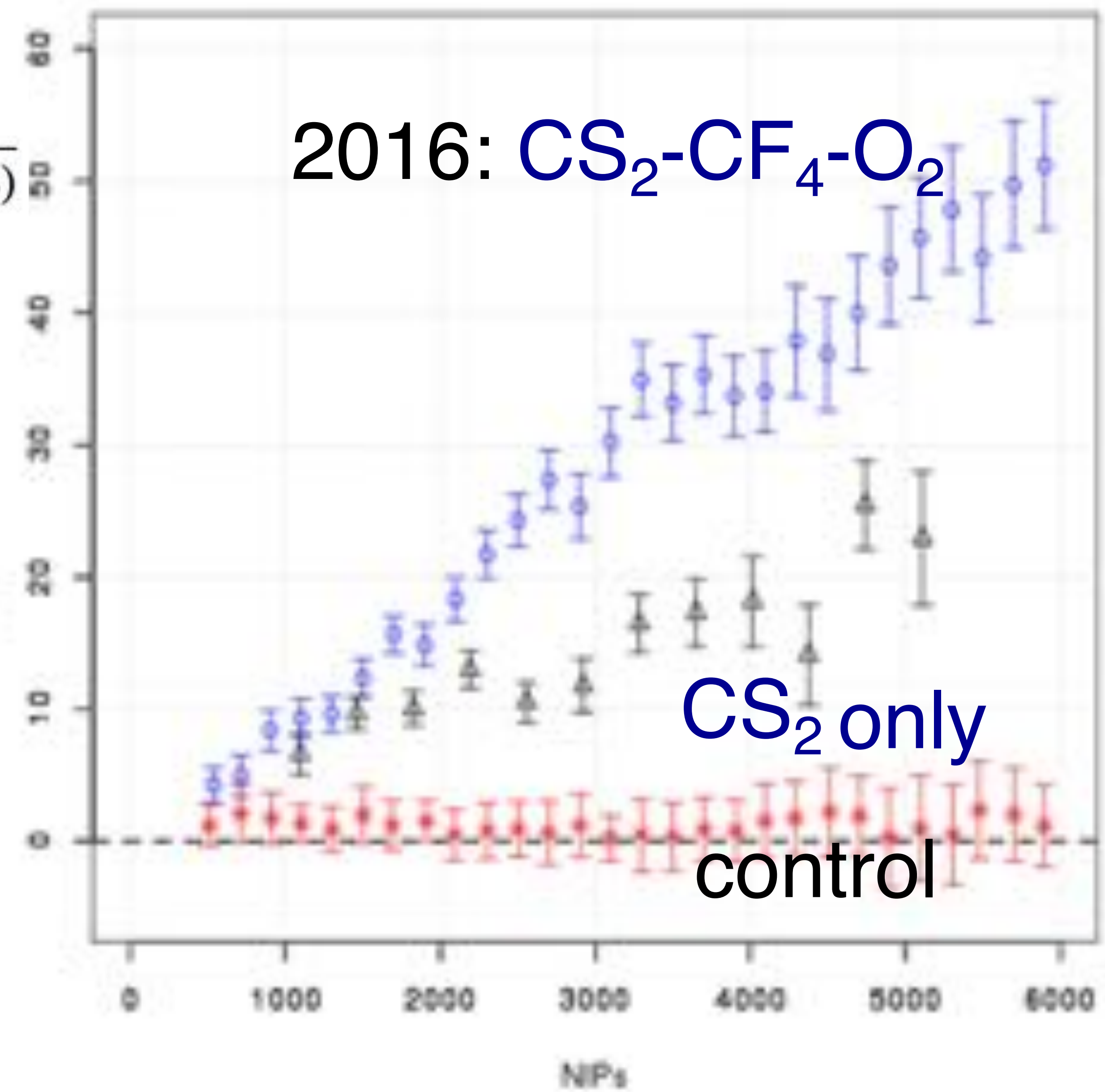
- **Directional Head-Tail sensitivity with z-fiducialisation**

arXiv:1606.05364



$$\alpha \equiv \frac{\eta_1}{\eta_2}$$

$$\delta = 100\frac{|\Delta\alpha|}{\frac{1}{2}(\langle\alpha\rangle_L + \langle\alpha\rangle_R)}$$



- **DRIFT sensitivity to HT in the new gas mode was investigated.**
- **Method of extracting the HT parameter from Astropart. Phy., 31 (2009) 261.**
- **Analyzed 7 days of directed source neutron data.**
- **Event by event measurement of the HT parameter was done using η_1 to η_2 ratio.**
- **Can now study HT *z*, thanks to fiducialization.**

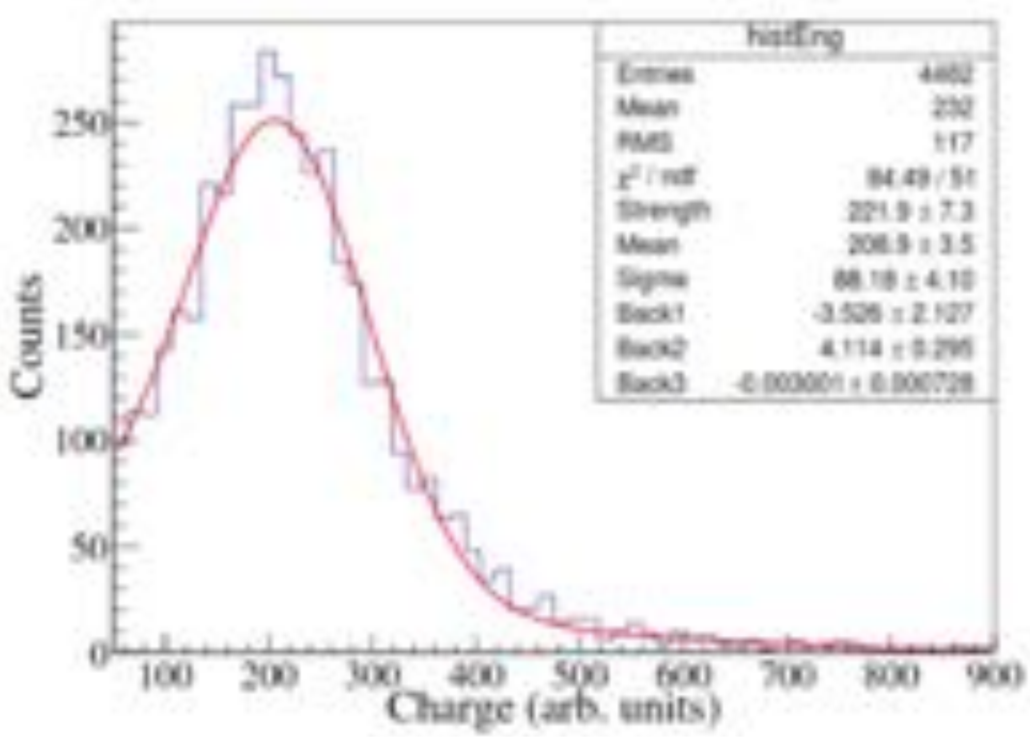
SF_6 Breakthrough at UNM

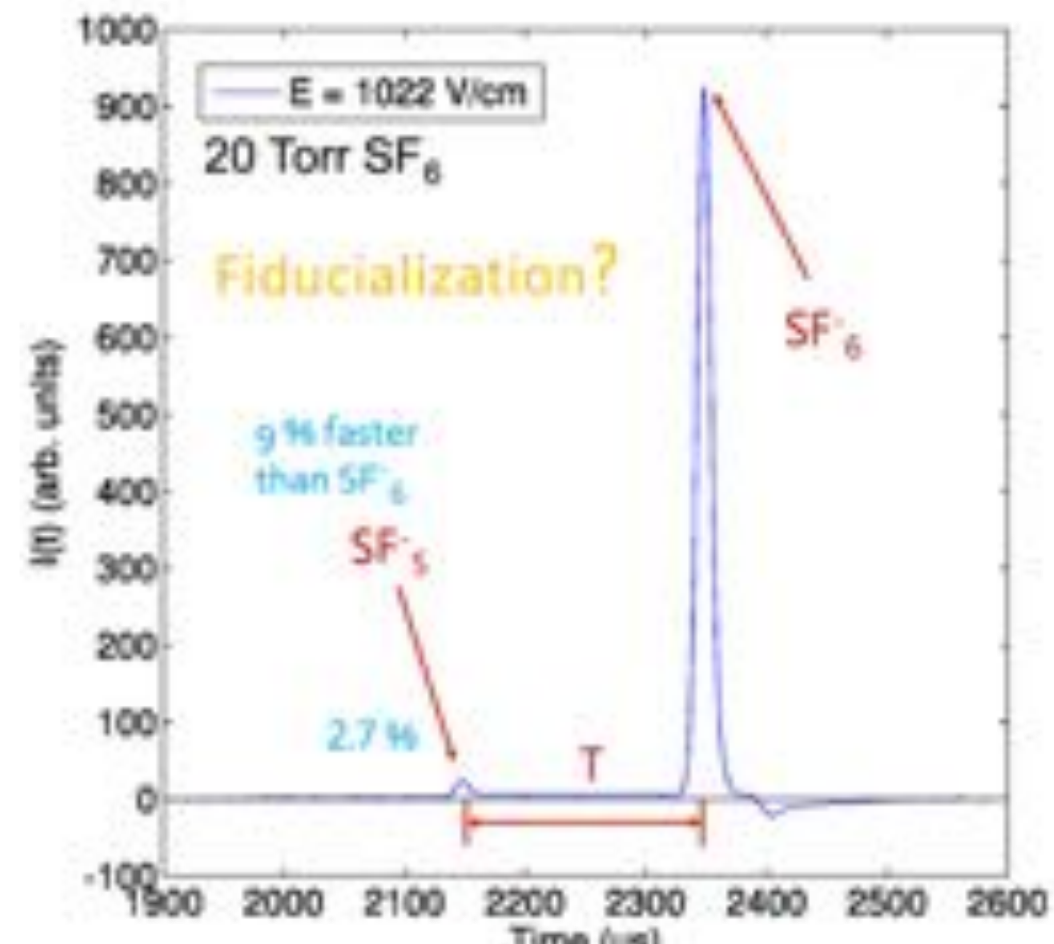
-ve ion with minority carrier and increased target mass

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)

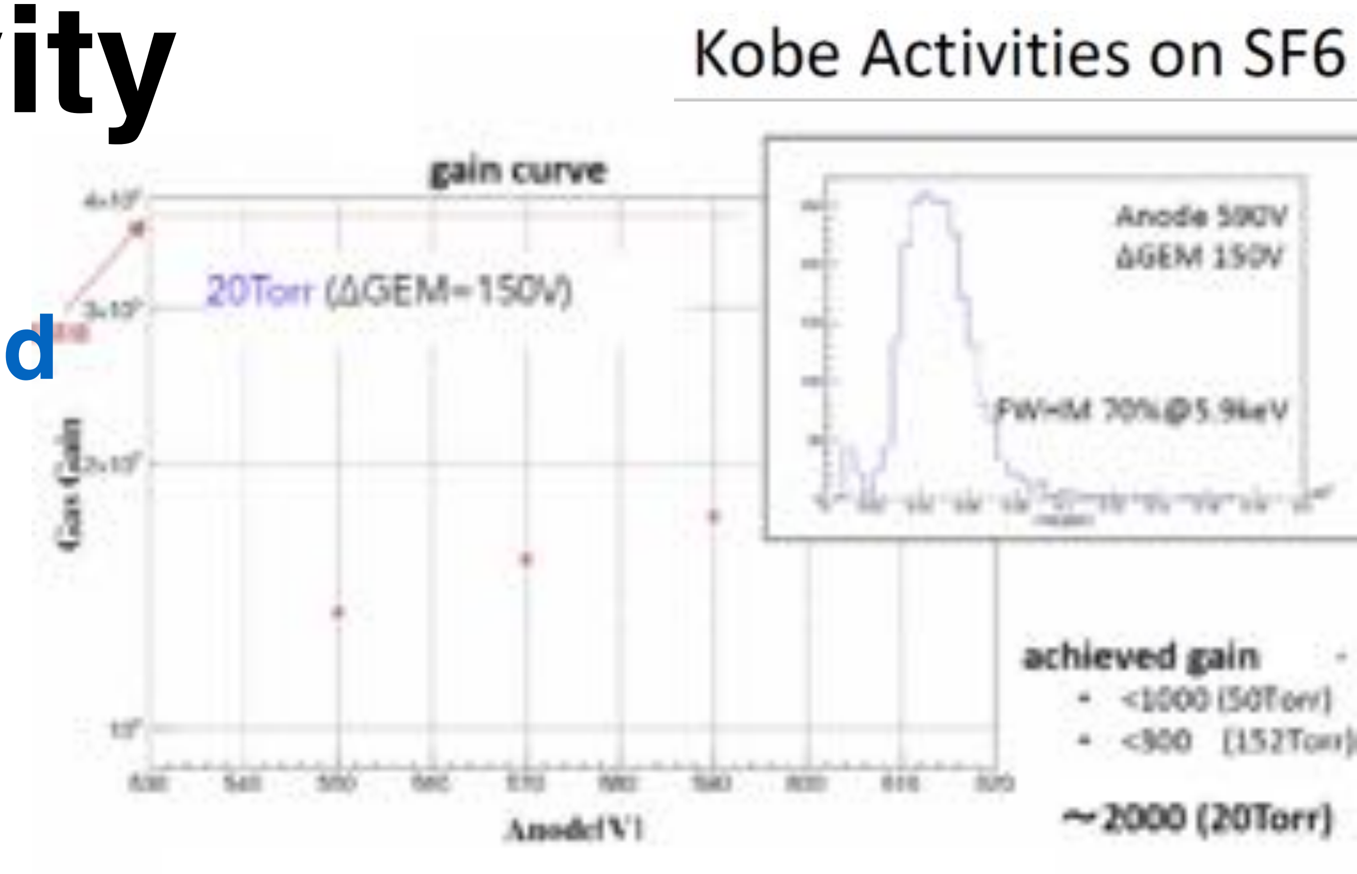


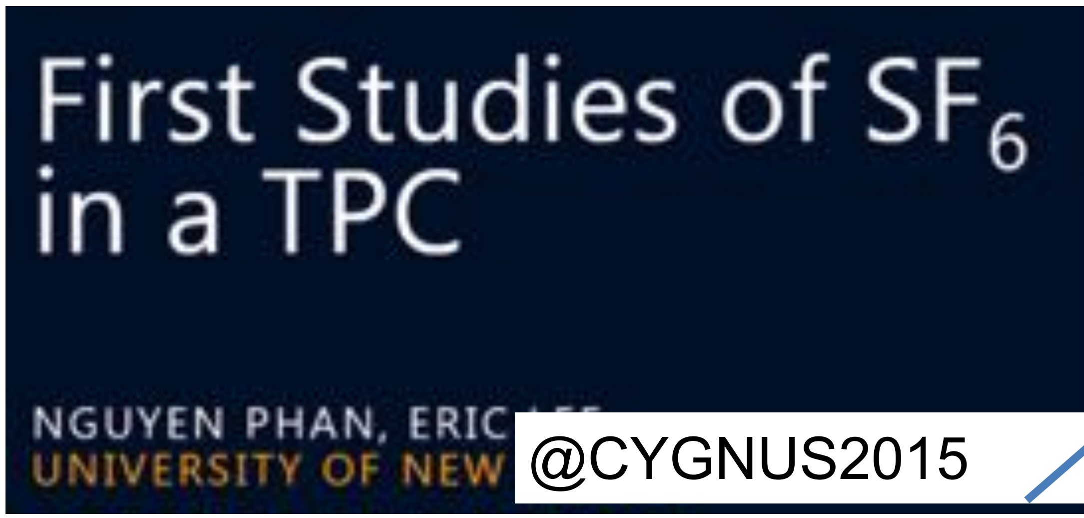


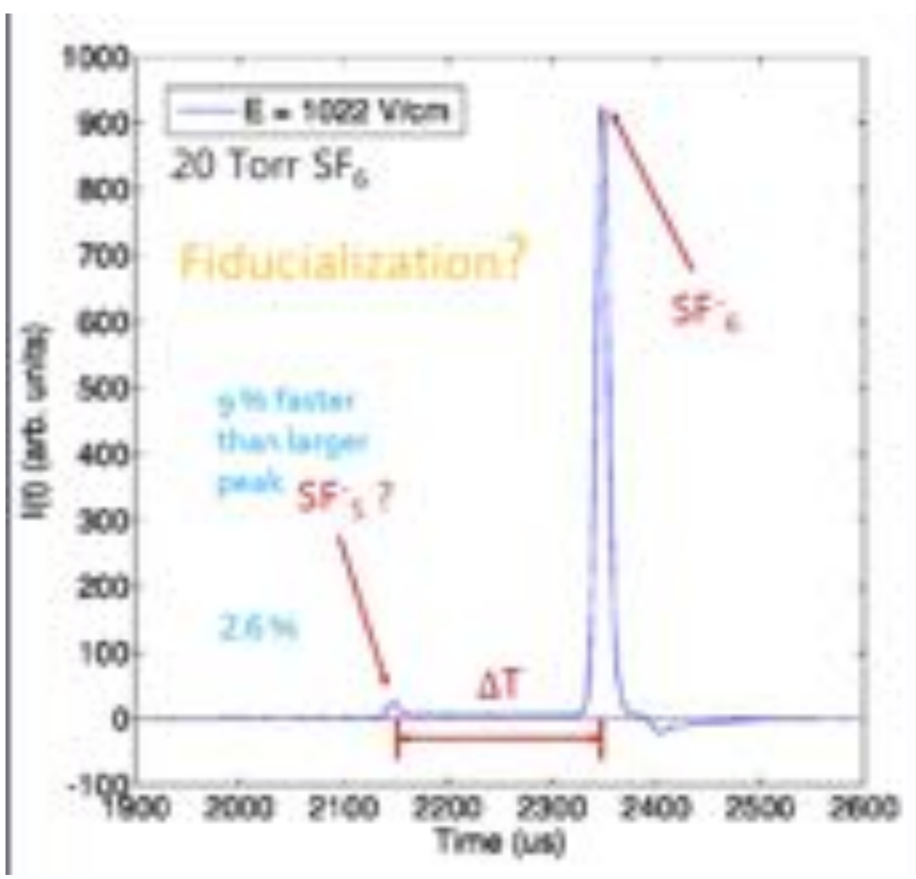
- **Activity now in many groups**
- **Frascati, Kobe, UNM, Sheffield**

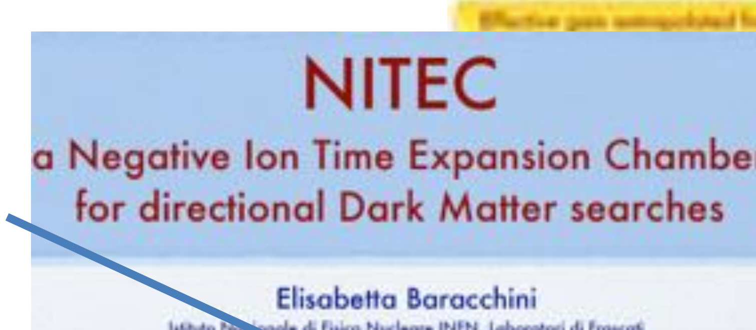
CYGNUS SF_6 Activity

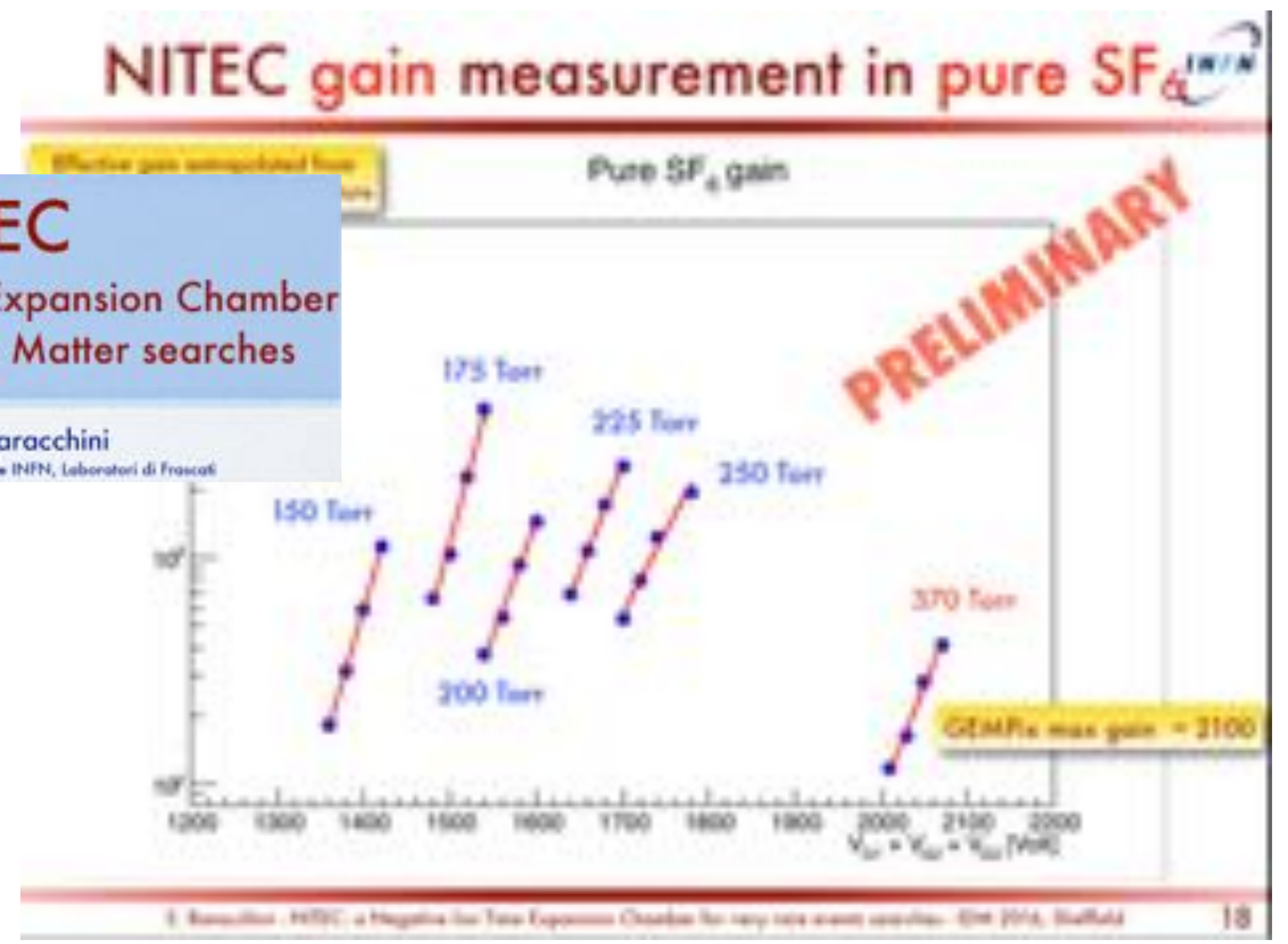
- Activity now in many groups
- Frascati, Kobe, UNM, Sheffield







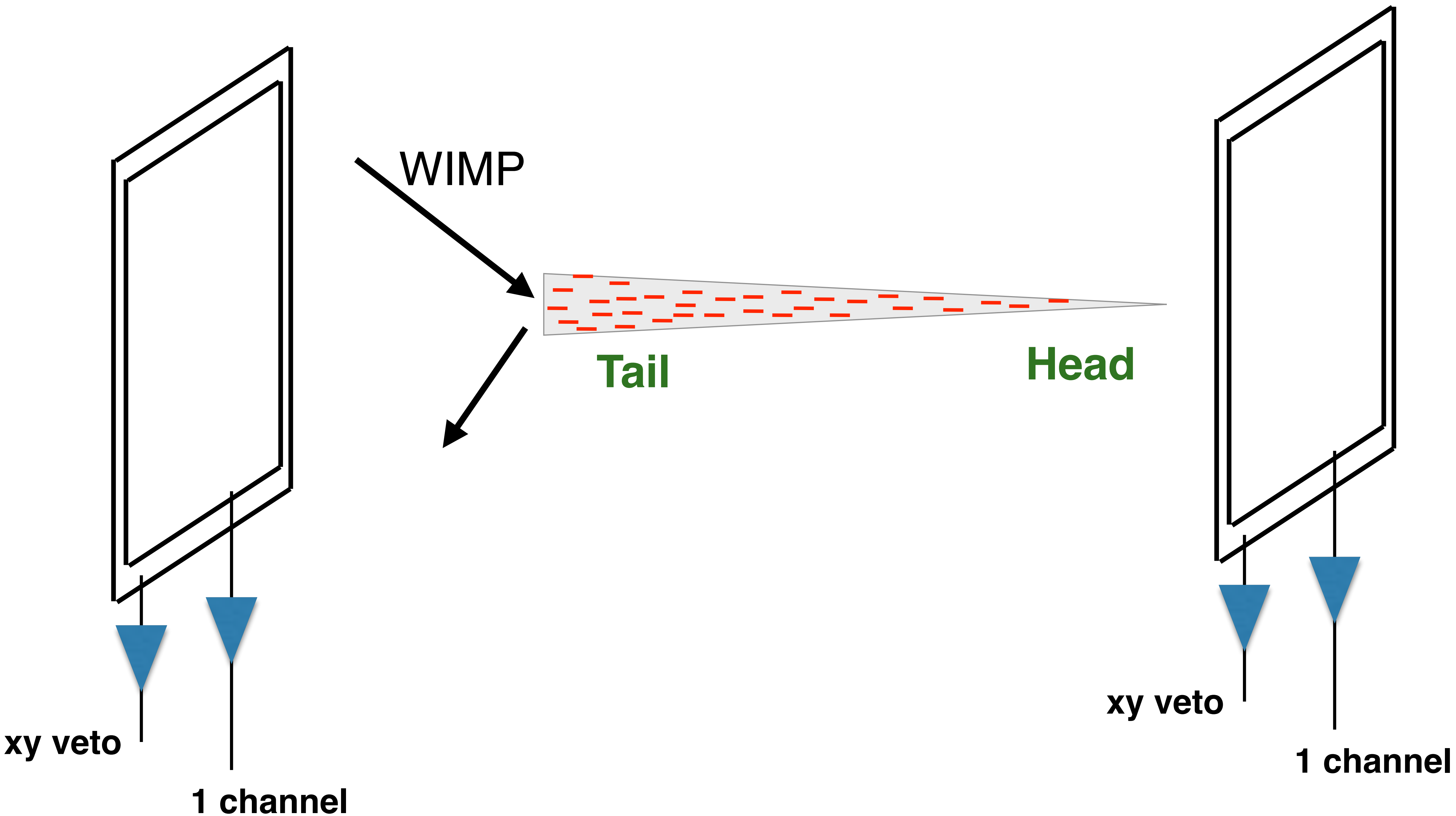




Is a Simpler “1D-HT” Readout Possible?

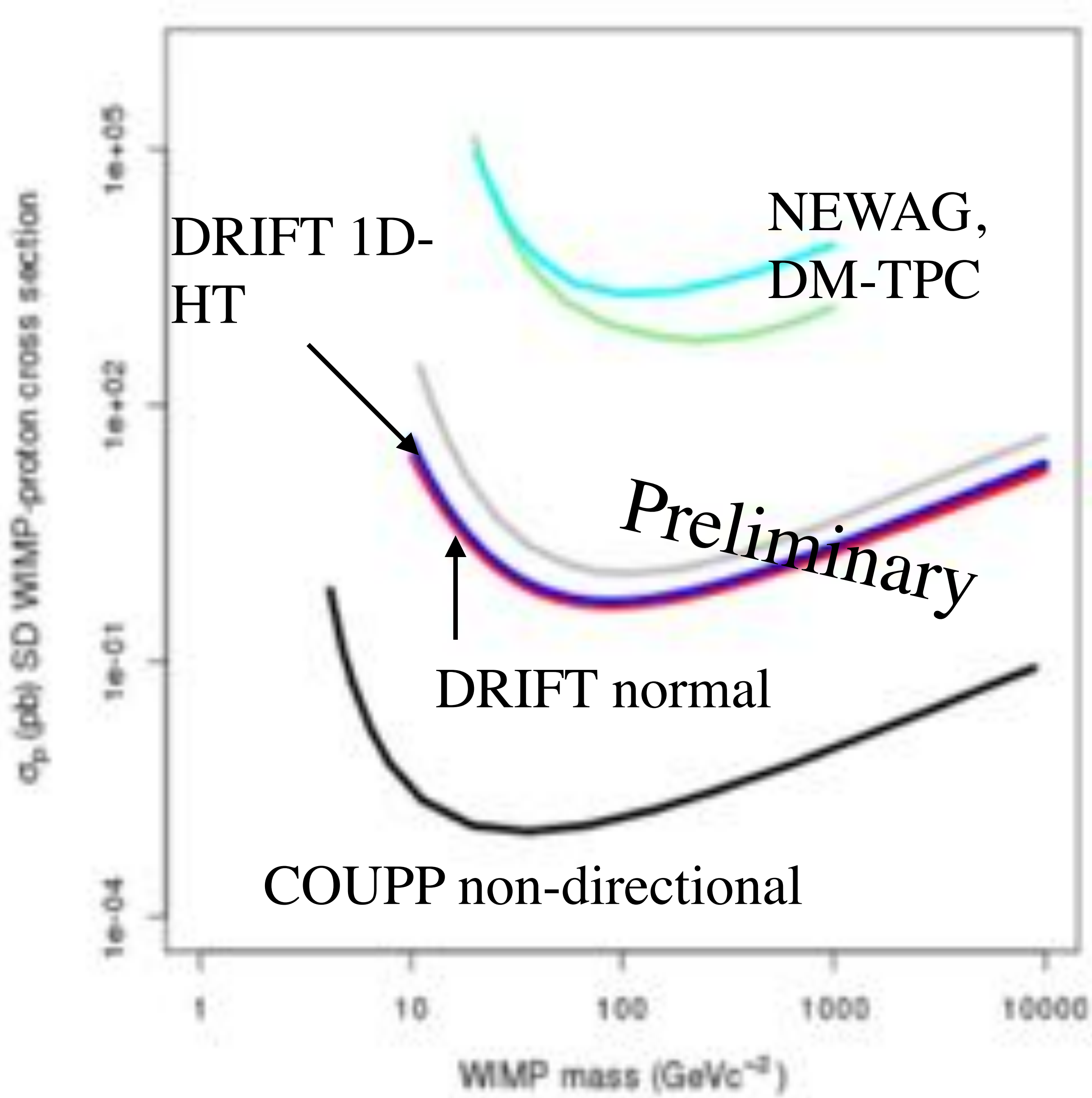
CYGNUS R&D activity at Boulby

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



“1D-HT” Test using DRIFT Data

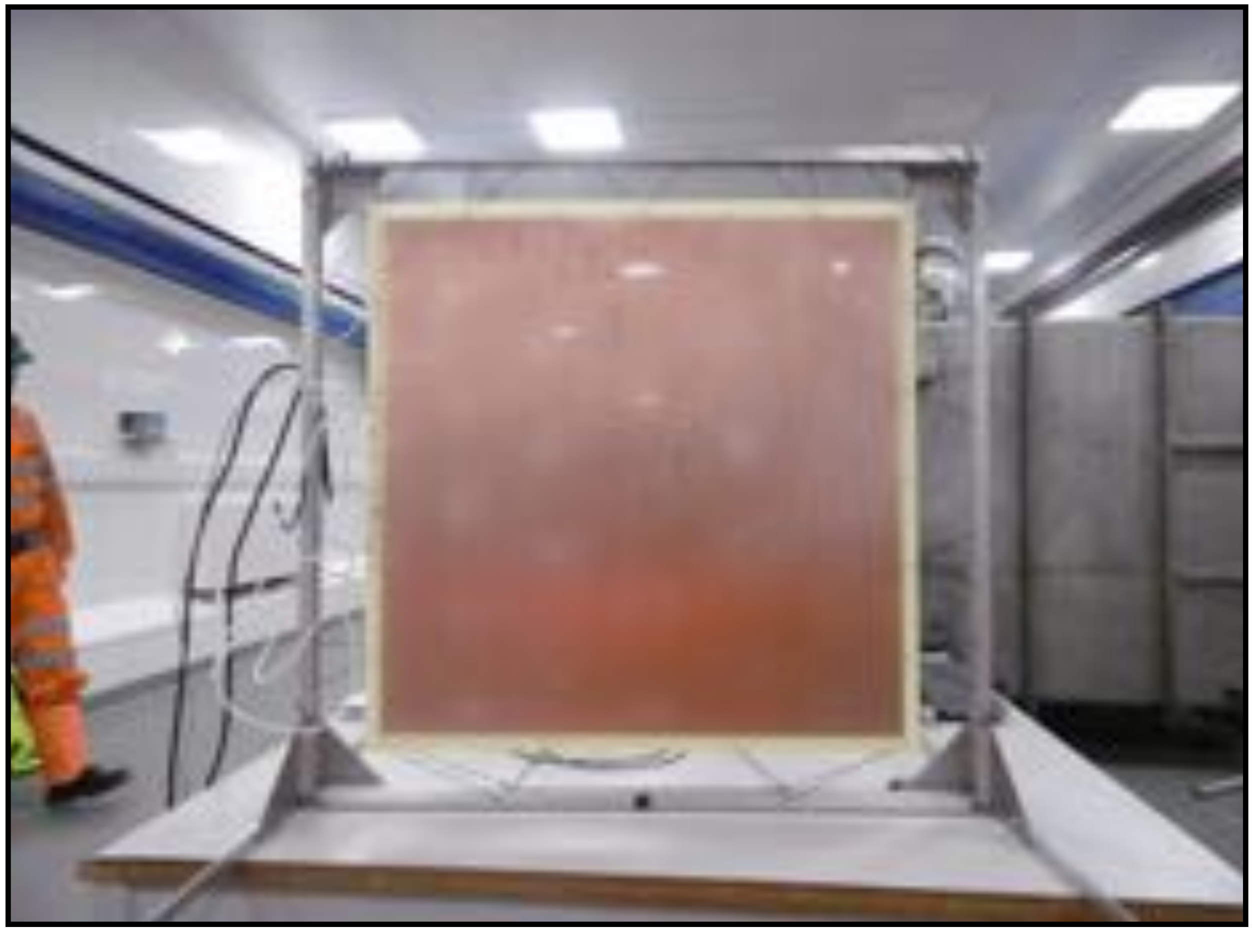
- experiment with DRIFT-IId xy information switched off, just z and head-tail data analysed, like a 1 x 1m single channel.

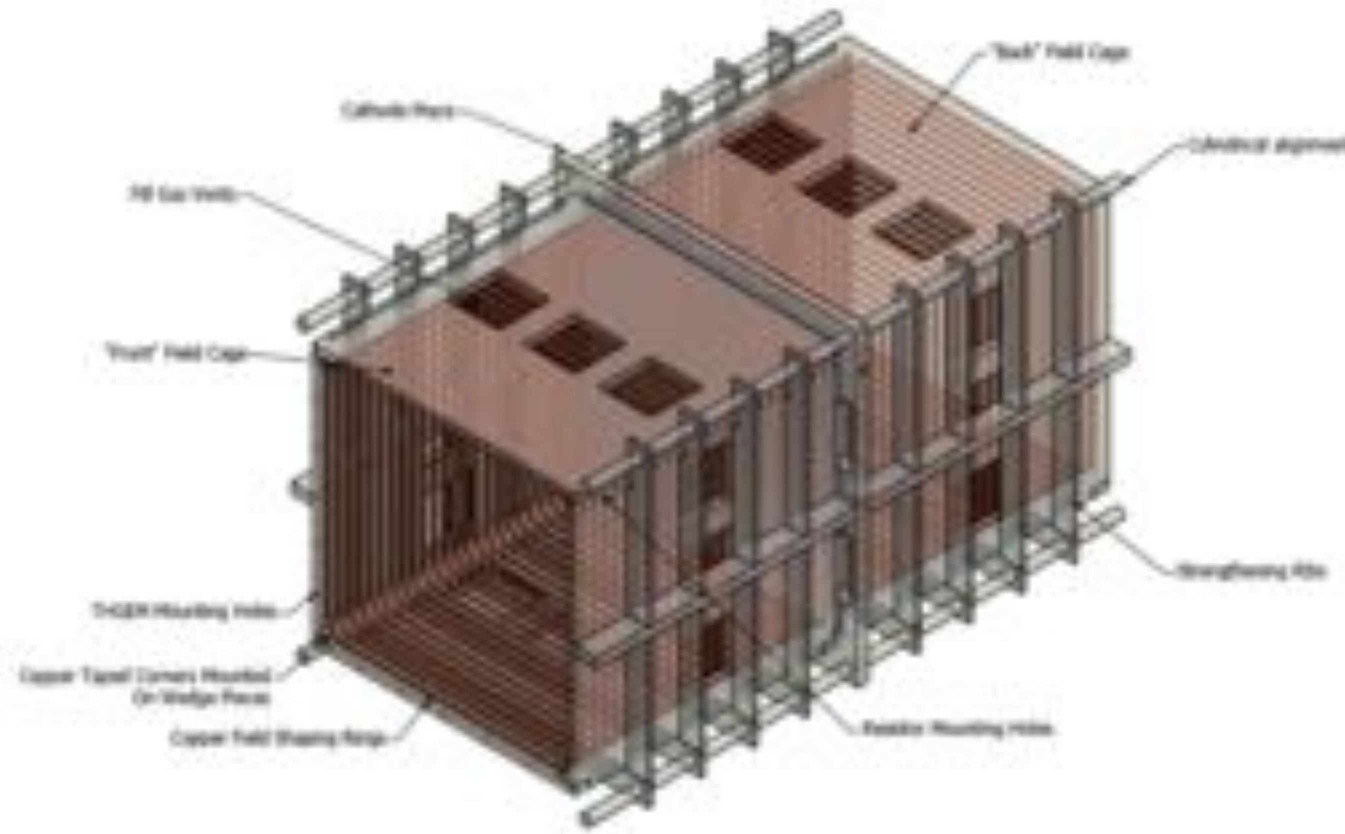


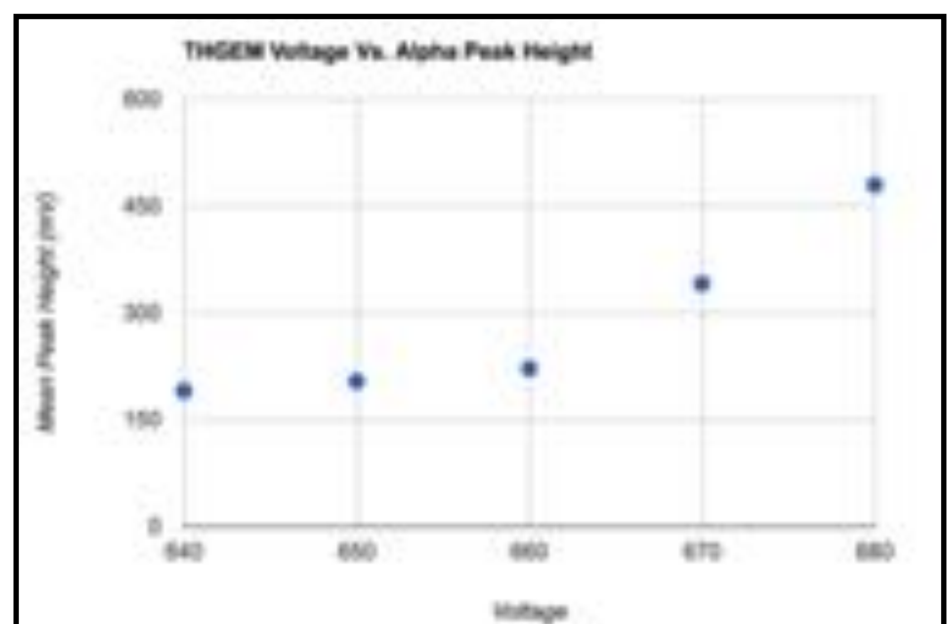
Paper in preparation

Simpler “1D-HT” Readout Concept

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

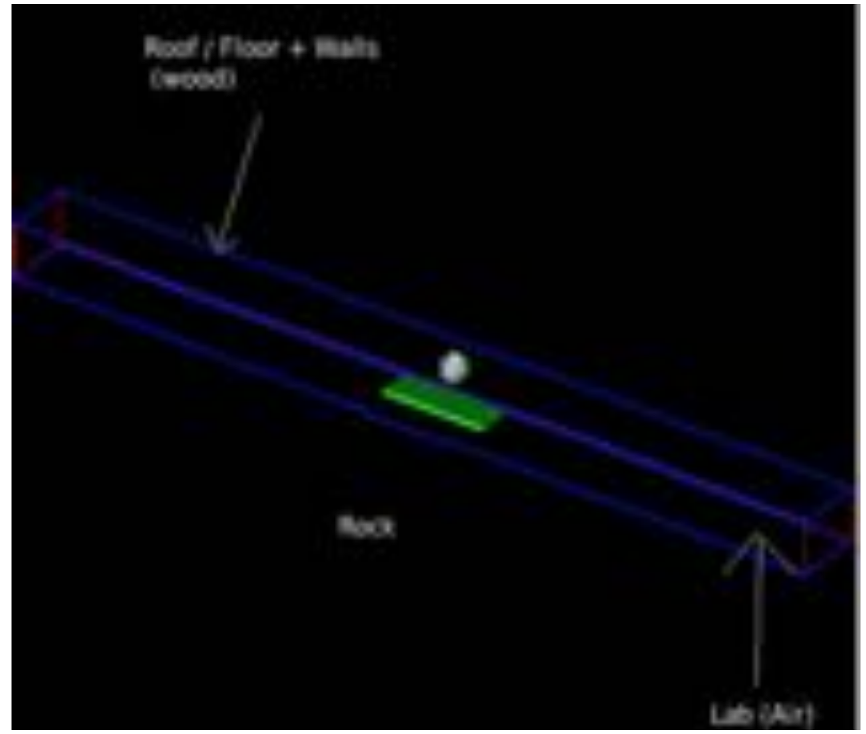


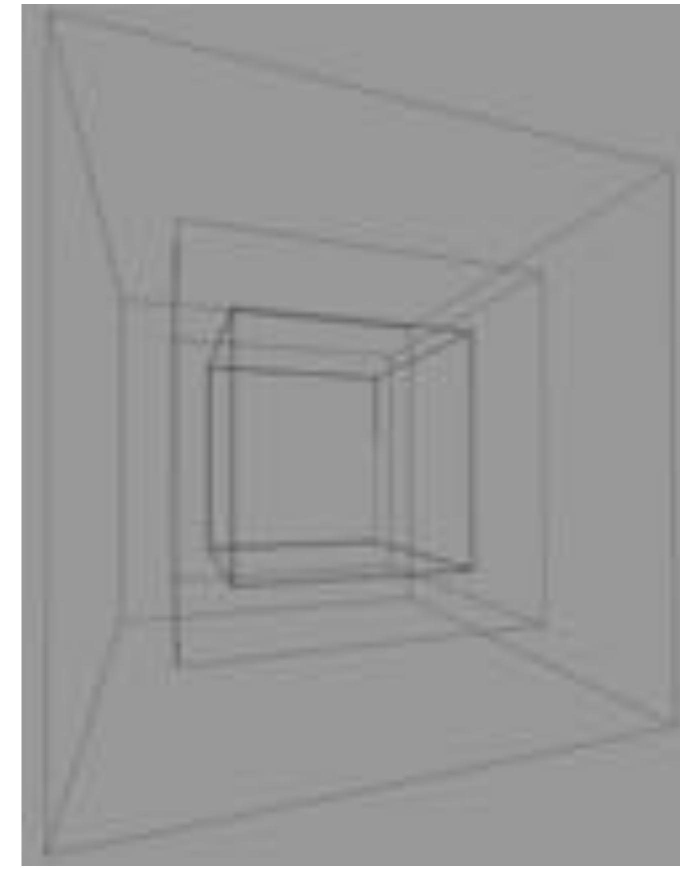




TPC Vessels & Neutron Backgrounds

- 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

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

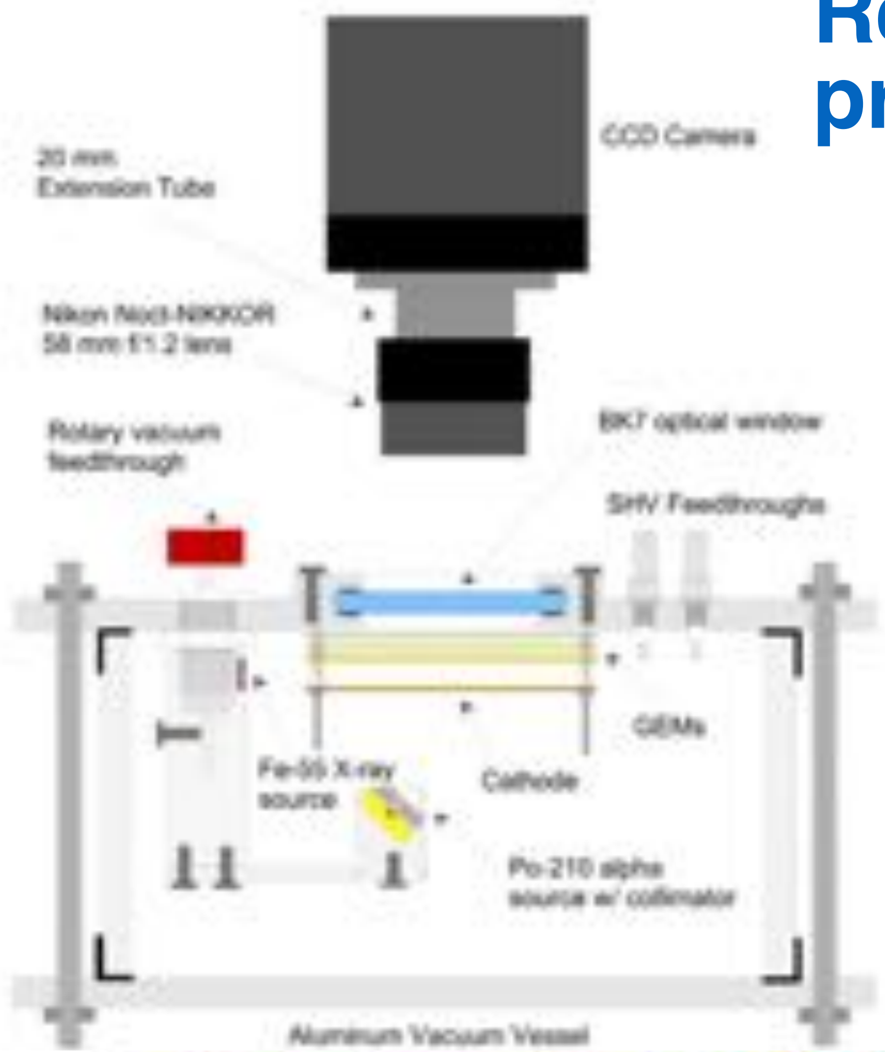
Backup Slides

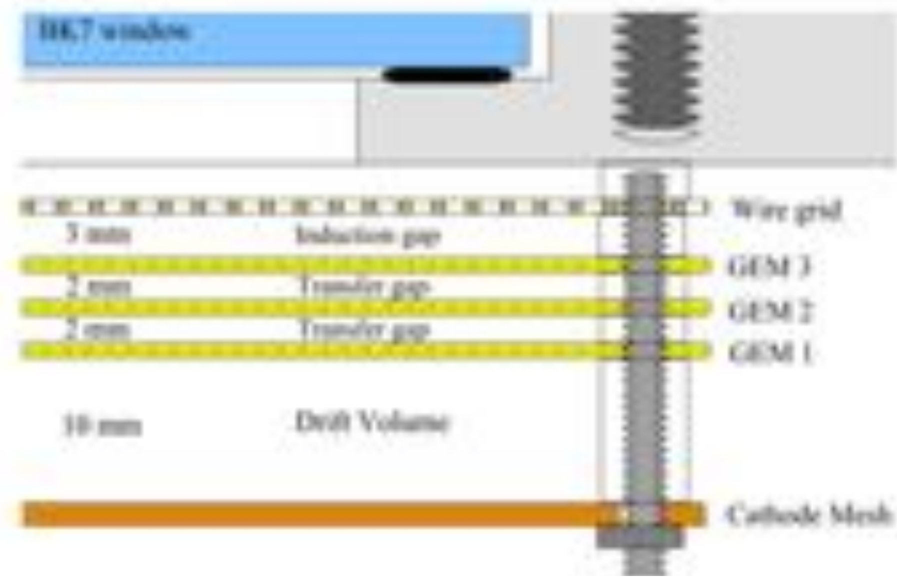
Low Energy Directionality Seen (UNM)

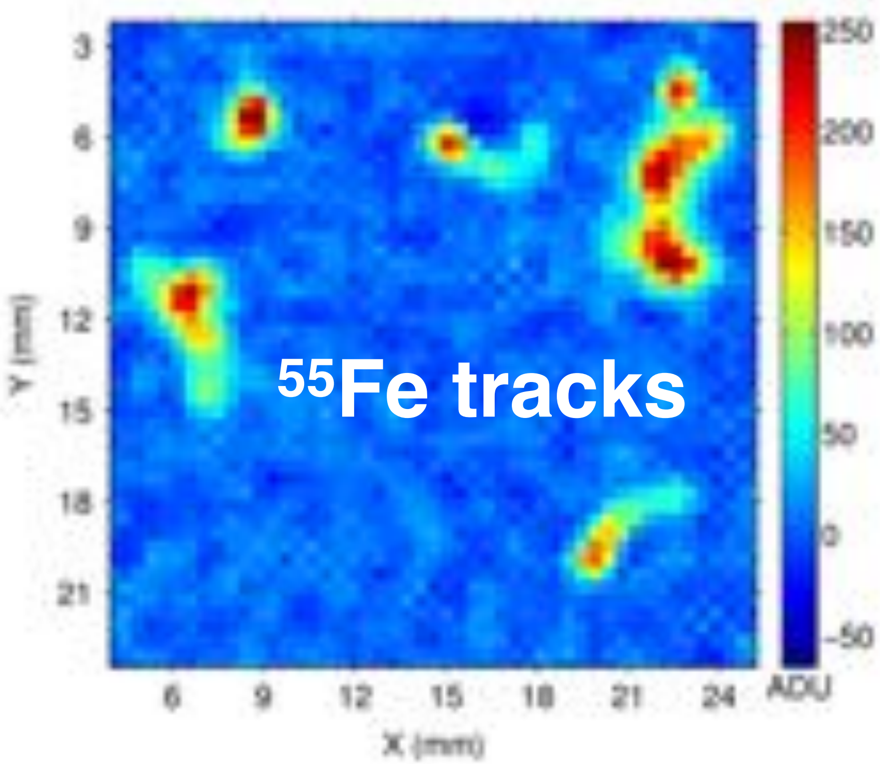
D. Loomba et al.,

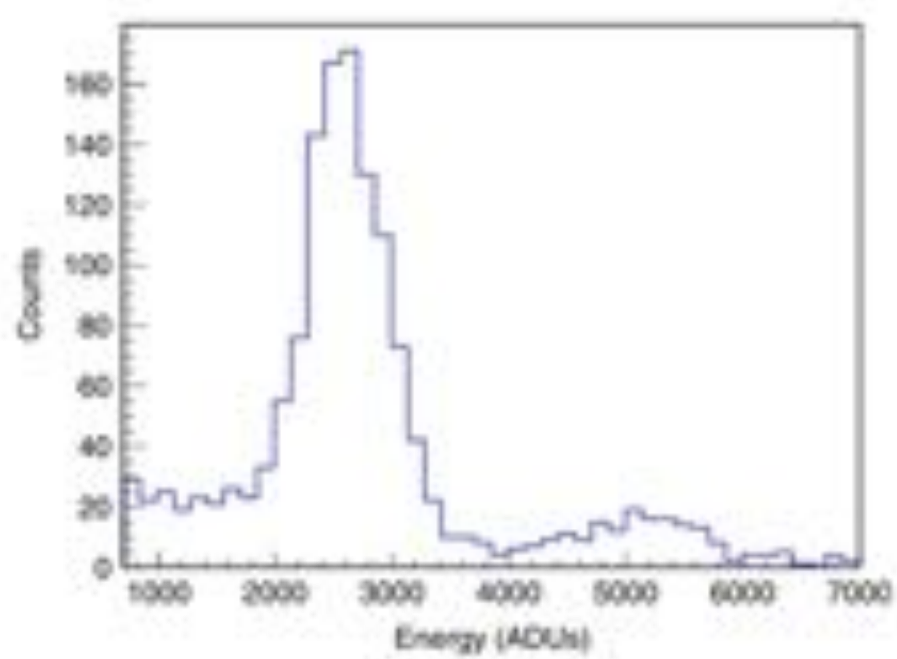
Recoil Directionality R&D is now probing <20 keV region

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

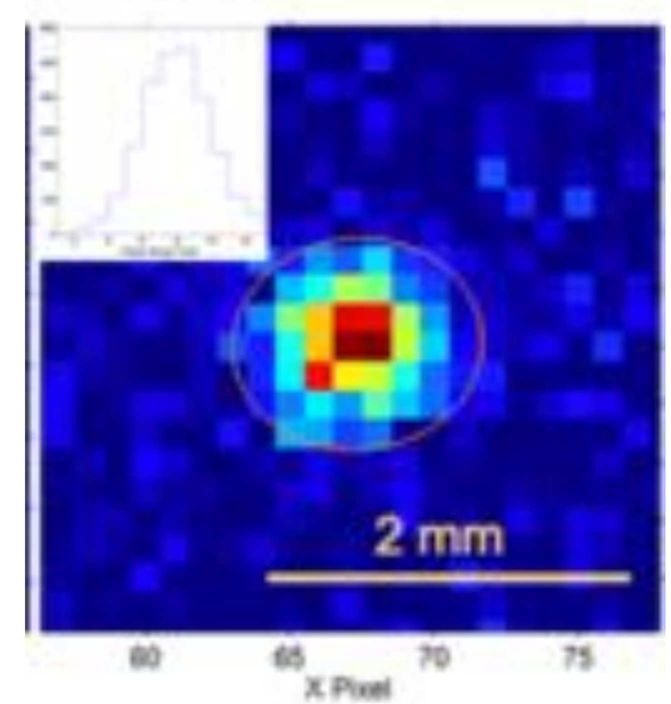








F recoil event of 10 keV_{ee} (23 keV_{rec}) still shows direction



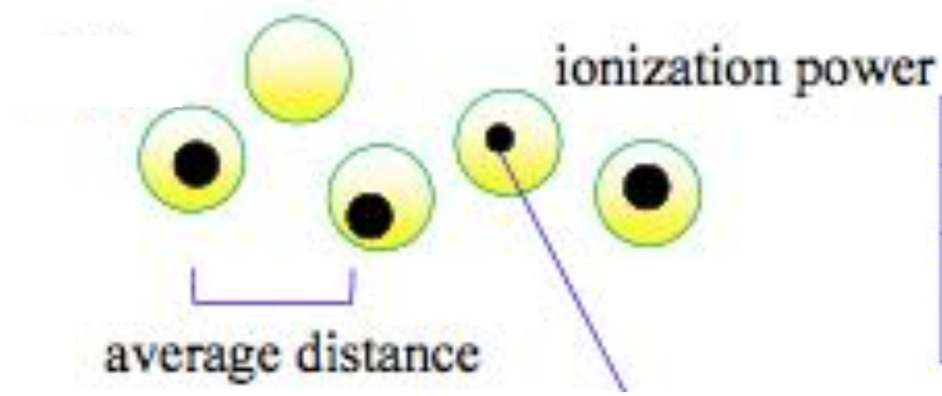
Nuclear Emulsions - NEWS

Also working in CYGNUS - Giovanni de Lellis (Napoli) and Nagoya University, OPERA…

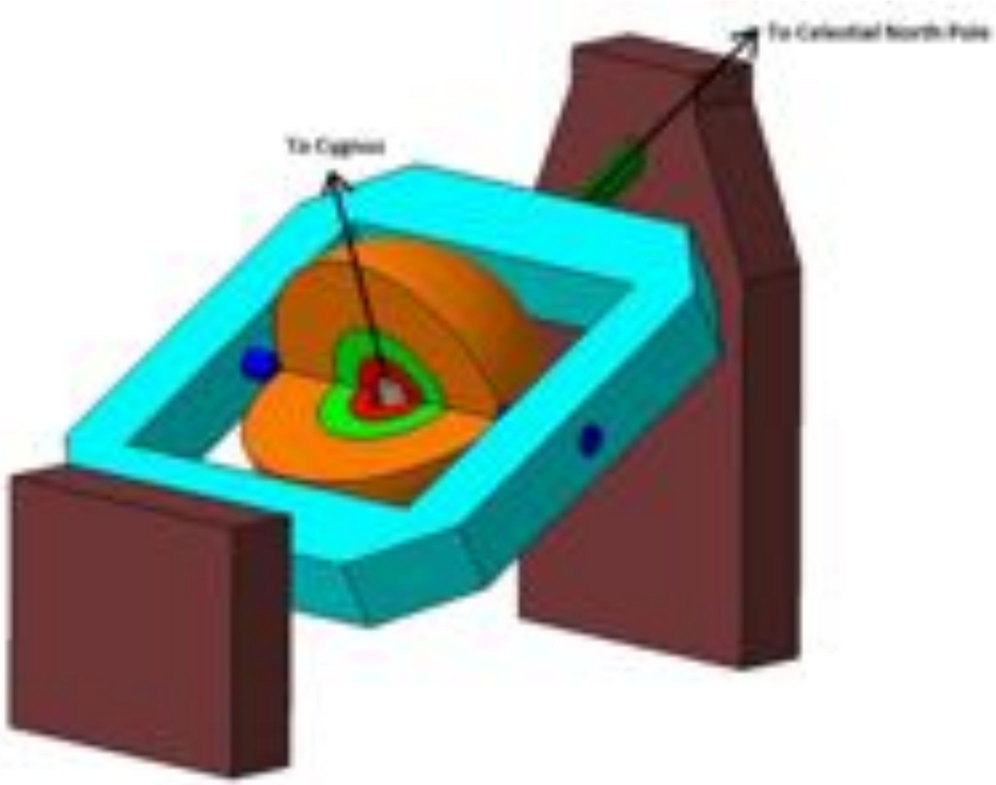
Concept: Use of emulsion film to give 3D tracking

Solid (3g/cc), high spatial resolution, low cost, target Ag(46%), Br(34%), C(N,O) (19%)

- Track produces line of silver grains

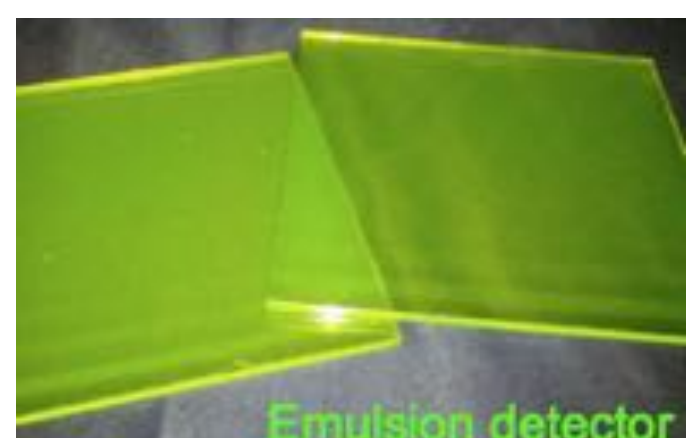


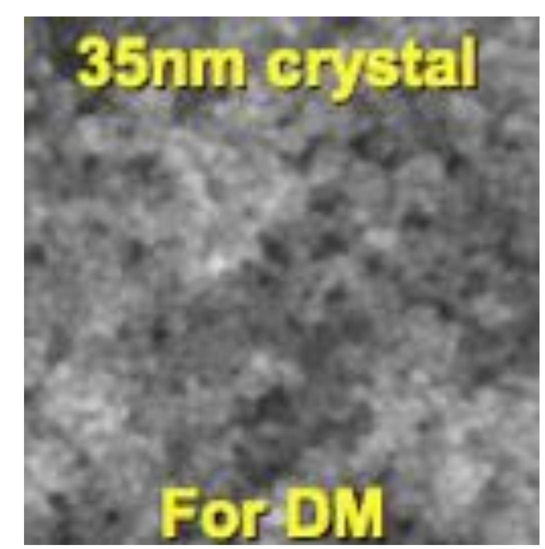
crystal size	45nm
crystal distance	85nm
crystal sensitivity for alpha-ray	>20% (not sensitized)



- Challenge is to get: (i) small grains <40nm (OPERA had 200 nm), (ii) closely packed, and (iii) sensitive to low ionisation

- Typical recoils are order 100nm - Ag, Br likely produce tracks too short so need to use C, N, O target





- ▸ **R&D funded towards 1kg experiment**

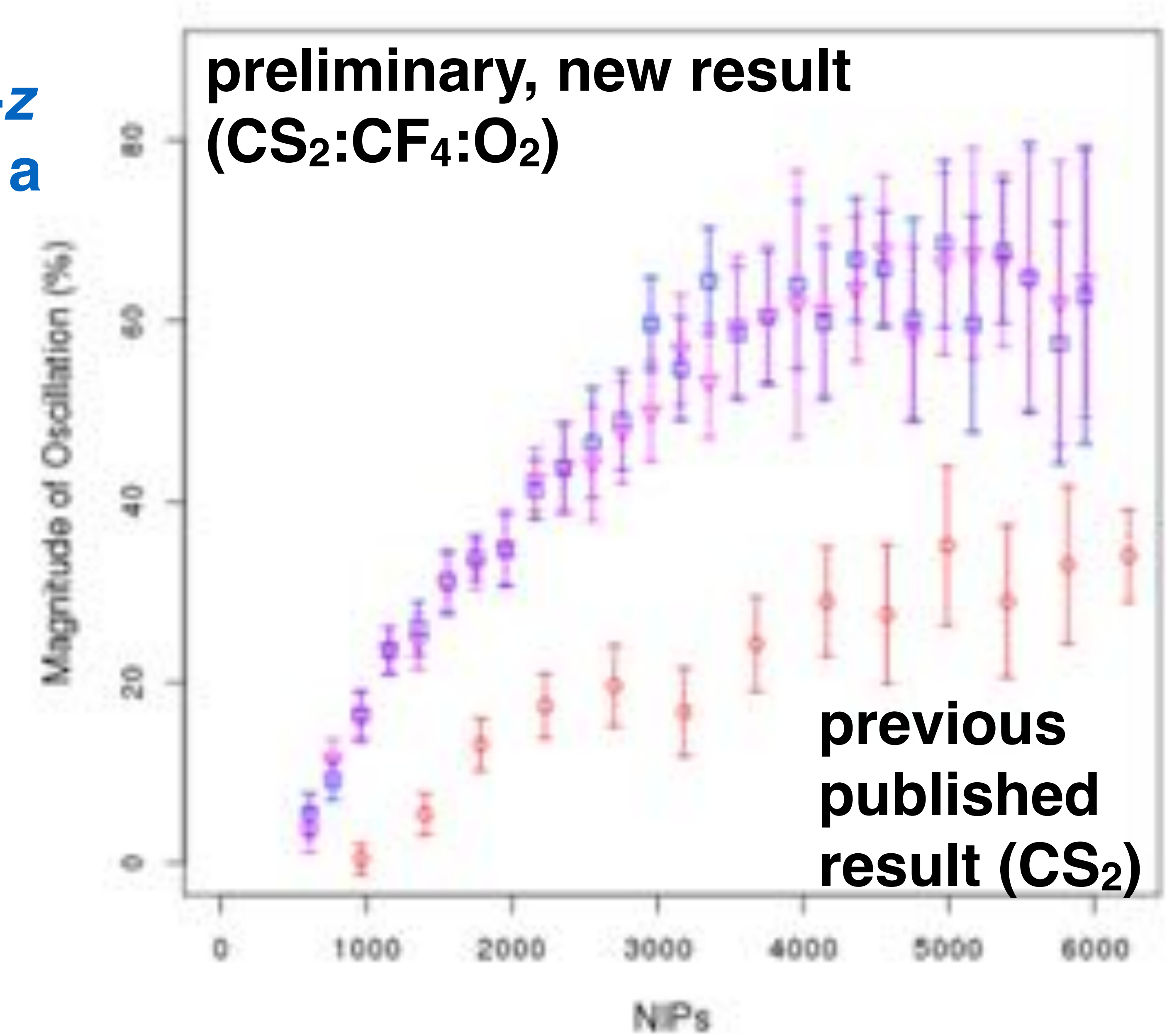
Axial Directionality also Maintained

- **Axial Directional sensitivity with z-fiducialisation**

Magnitude of "oscillation" as neutron source is moved from *+z* to *x* and from *z* to *x* (A_{ozx} %) as a function of nuclear recoil NIPs equivalent energy:

$$\overline{\frac{\Delta z}{\Delta x}} = \frac{\sum_{a=1}^{n}\left(\frac{\Delta z_a}{\Delta x_a}\right)}{n}$$

$$A_{o_{zx}} = \left(\frac{\overline{\frac{\Delta z}{\Delta x_z}} - \overline{\frac{\Delta z}{\Delta x_x}}}{\frac{1}{2}\left(\overline{\frac{\Delta z}{\Delta x_z}} + \overline{\frac{\Delta z}{\Delta x_x}}\right)}\right)100$$



(blue) this analysis average values in bins of 200 NIPs interval square points for *+z* to *x* oscillation, (pink) triangular points from *z* to *x* oscillation. Red circle points are results obtained with only ^{32}S recoil tracks.

Power of TPC Directionality

- **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

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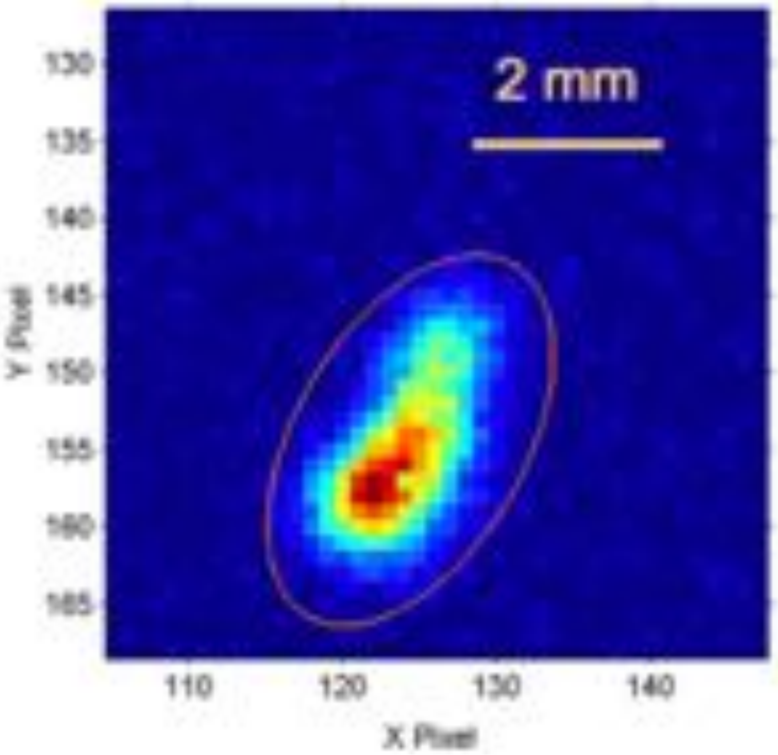
- Head-Tail Sensitivity
- Axial Sensitivity

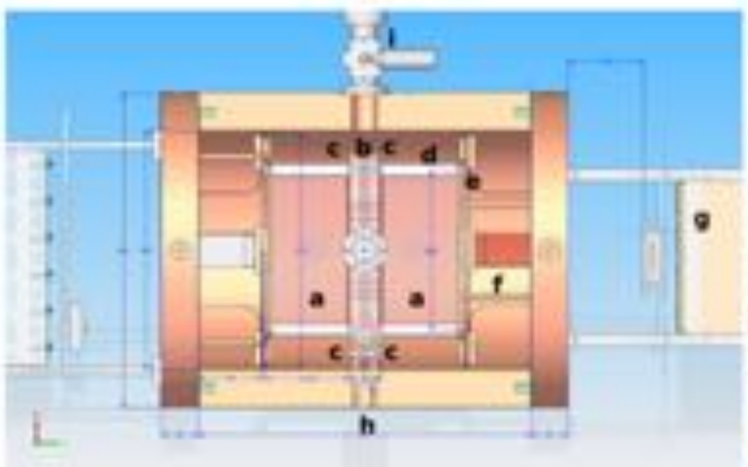


Example high energy F recoil in optical TPC (D. Loomba et al.)

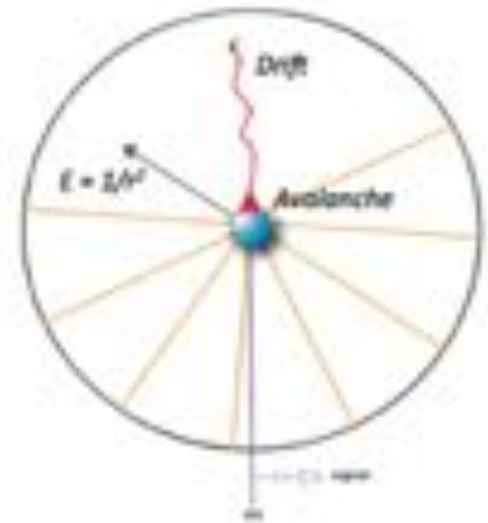
Power of TPC Directionality

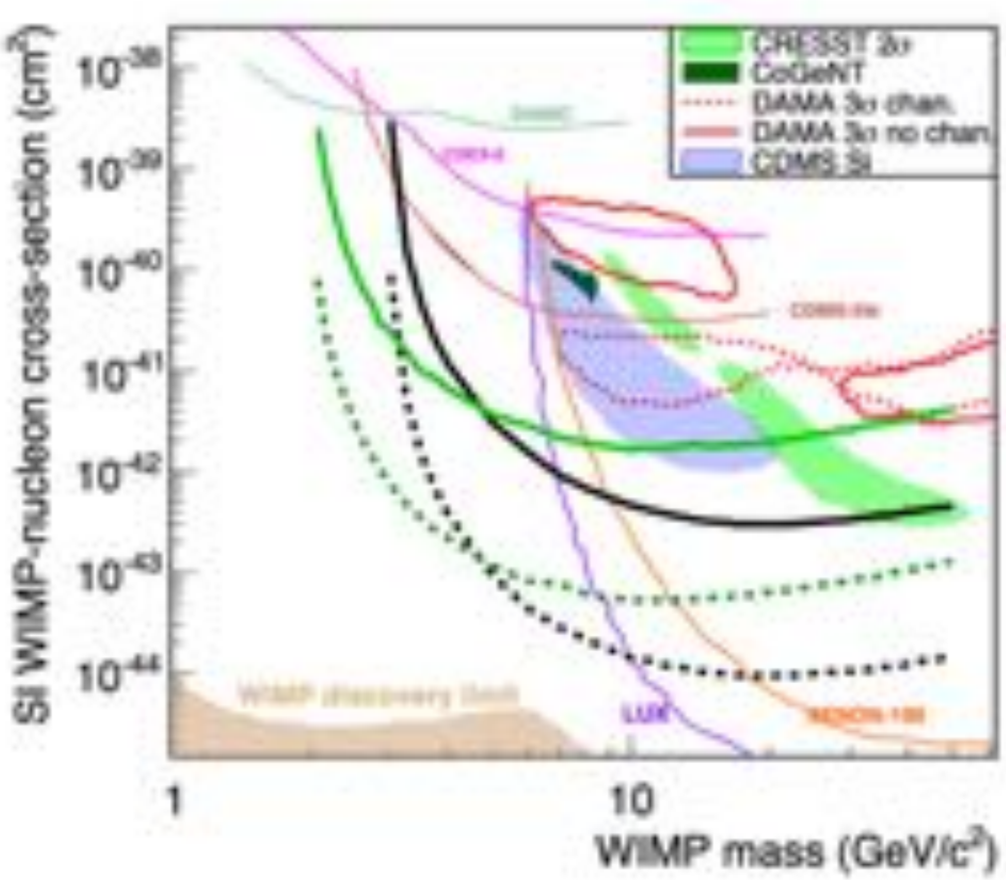
- **Note TPCs have excellent particle ID anyway, so also good for low mass, non-directional, WIMP searches at higher pressure**

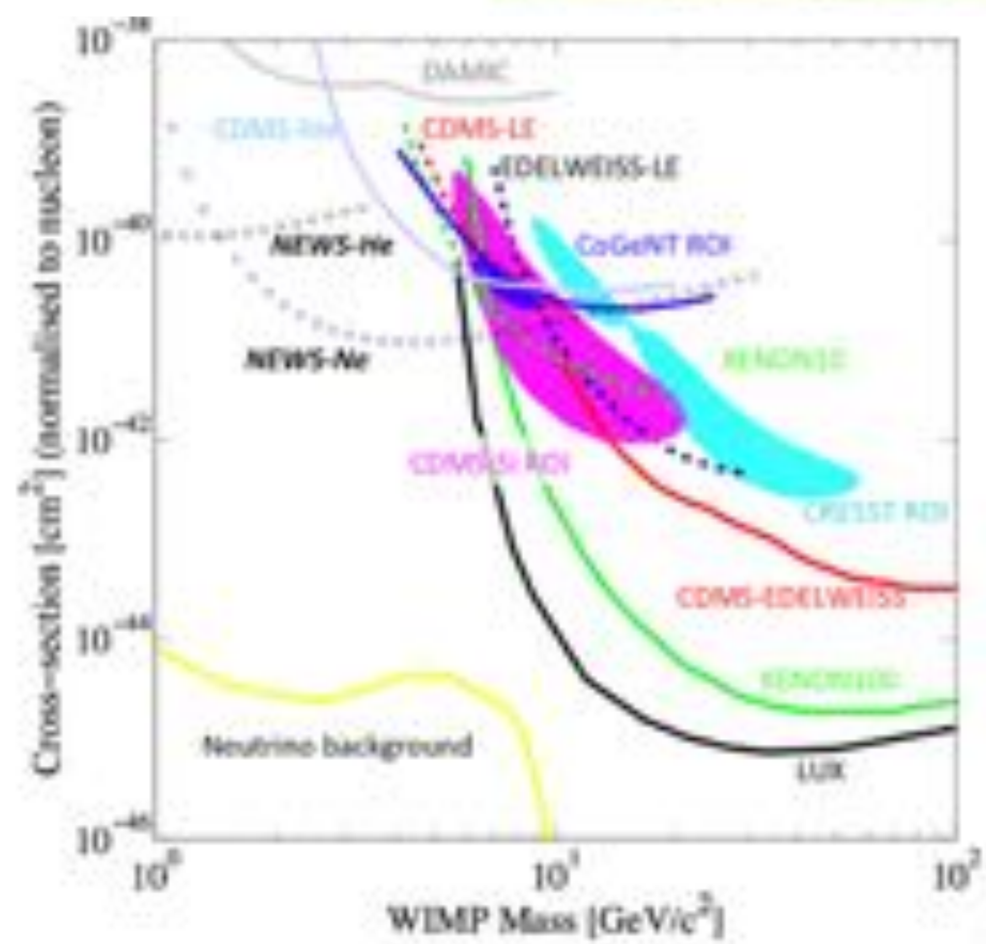
- TREX-DM



- NEWS

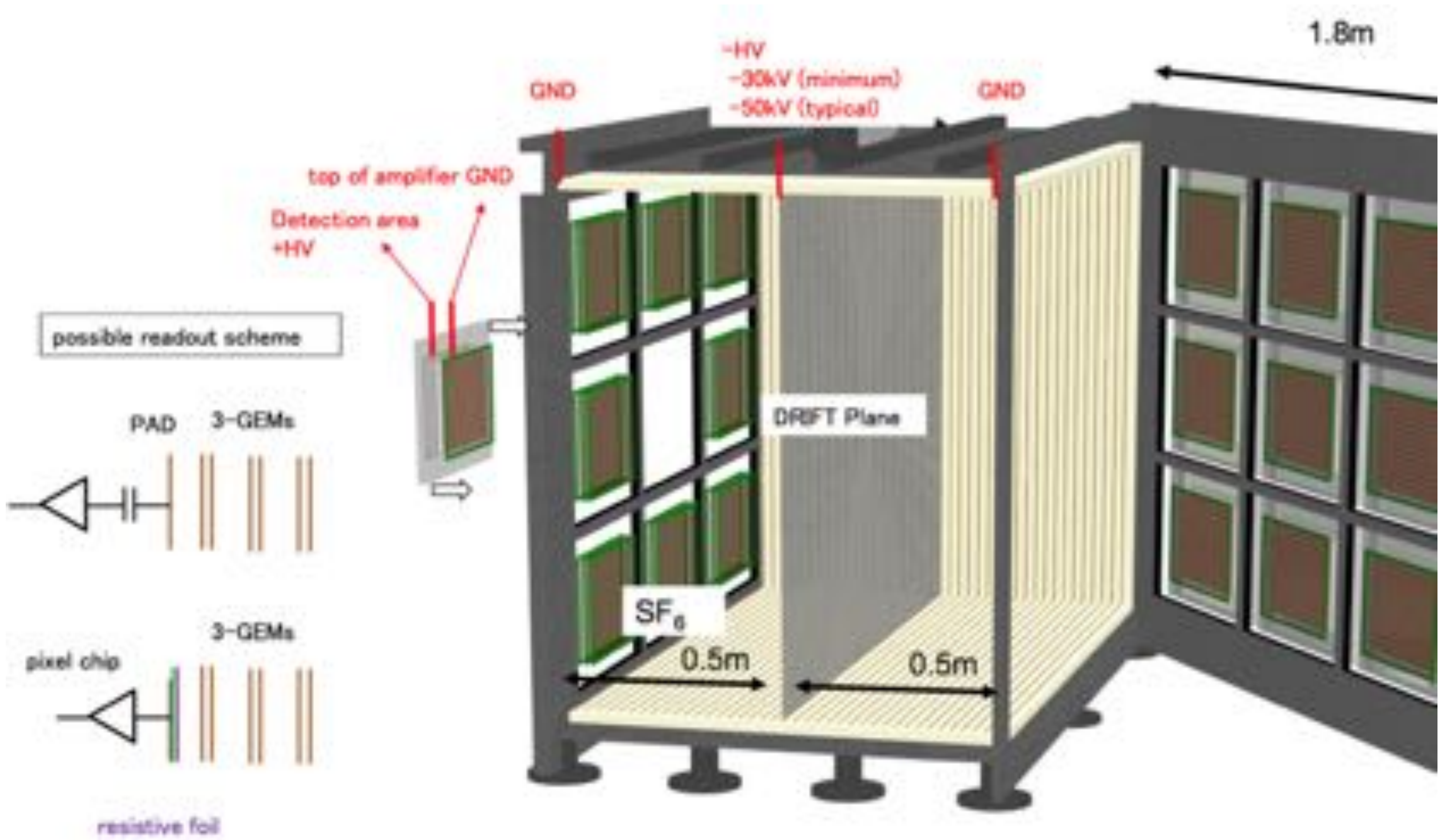




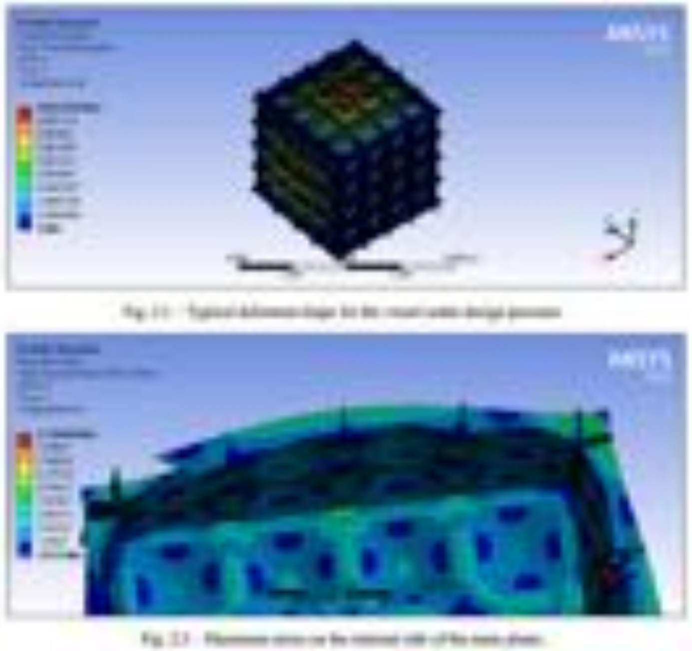


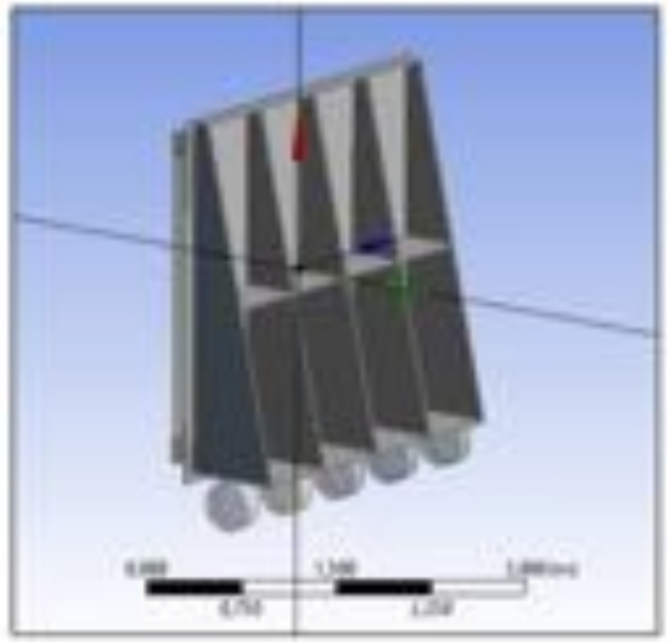
Other New Studies - Funded Activity

1 m^3 CYGNUS test vessel (Japan)

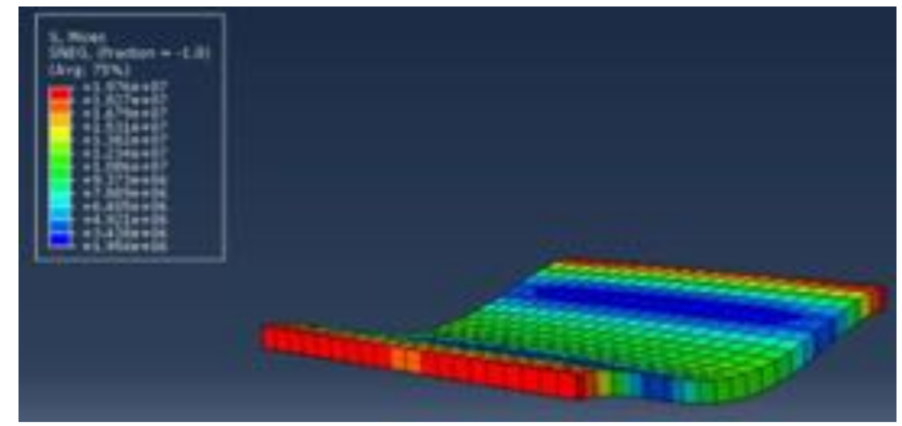


Other New Studies - Funded Activity

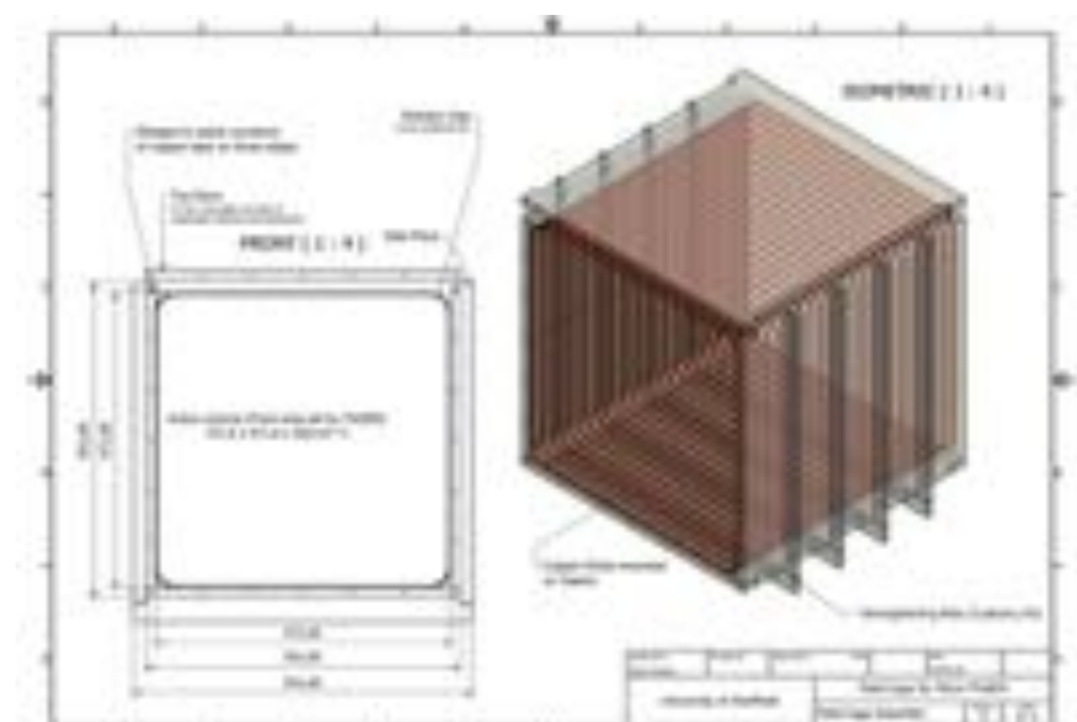


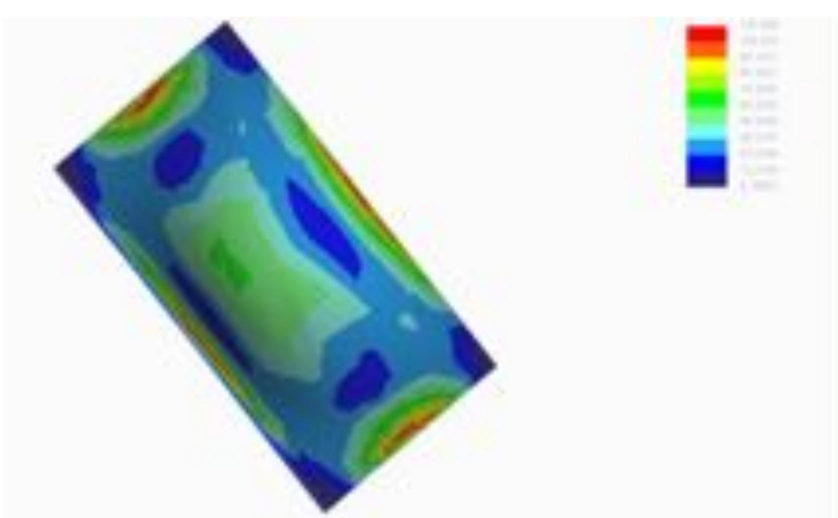


2.2 x 2.2 x 2.2 m Steel vessel (Australia)



Water block neutron shielding (as for DRIFT-IId upgrade) (UK)



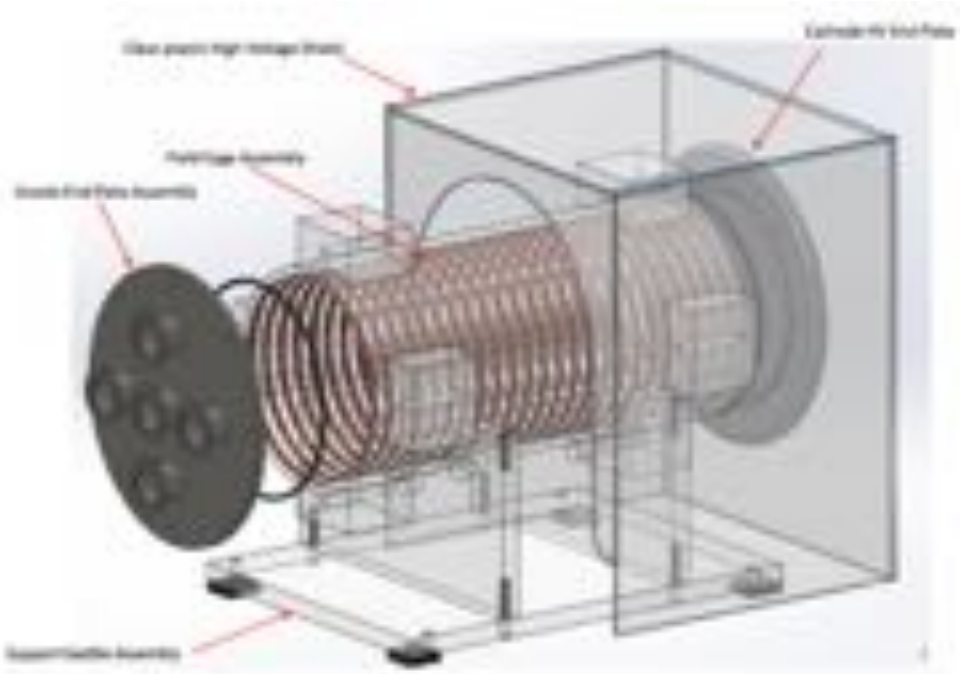


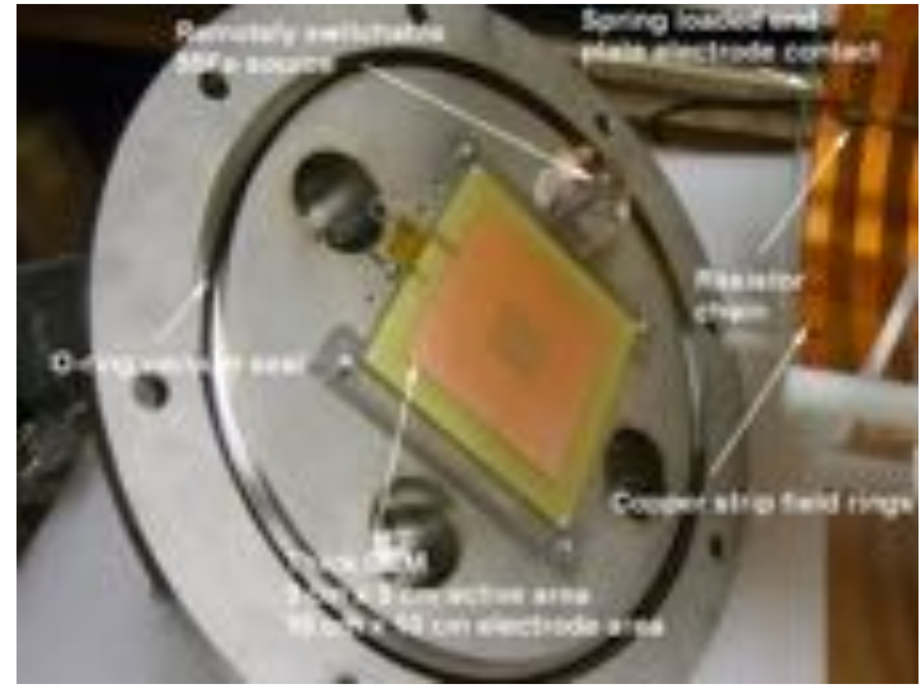
Low background Basic field cage design (UK)

CYGNUS SF_6 Activity at UNM

N. Phan, D. Loomba
University of New Mexico

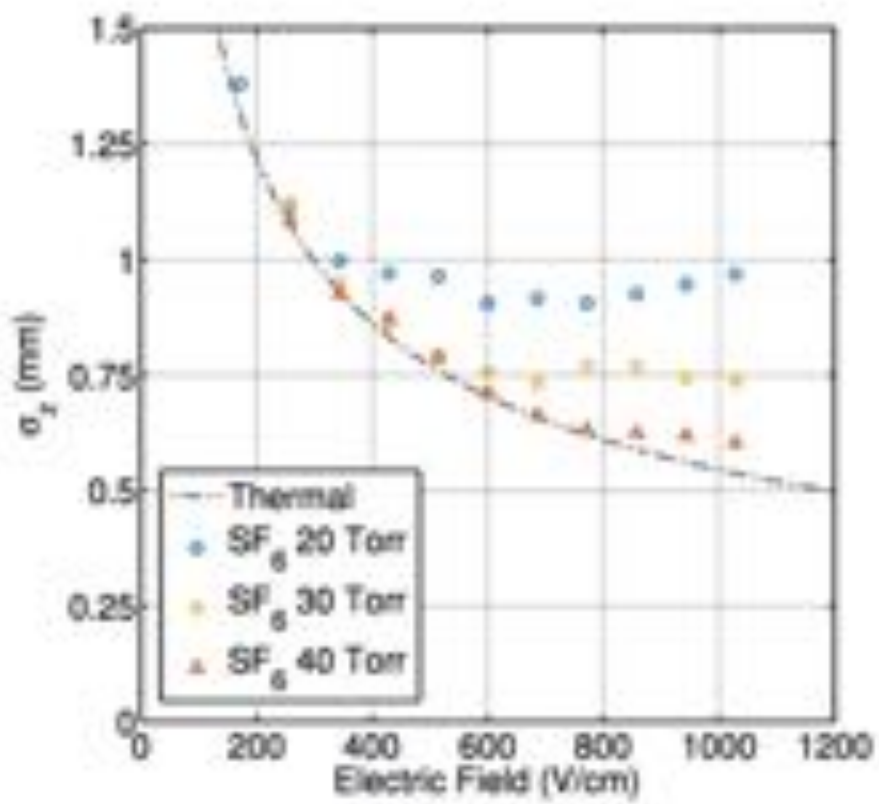
- **Demonstration of 2000-3000 gain in ThGEM**



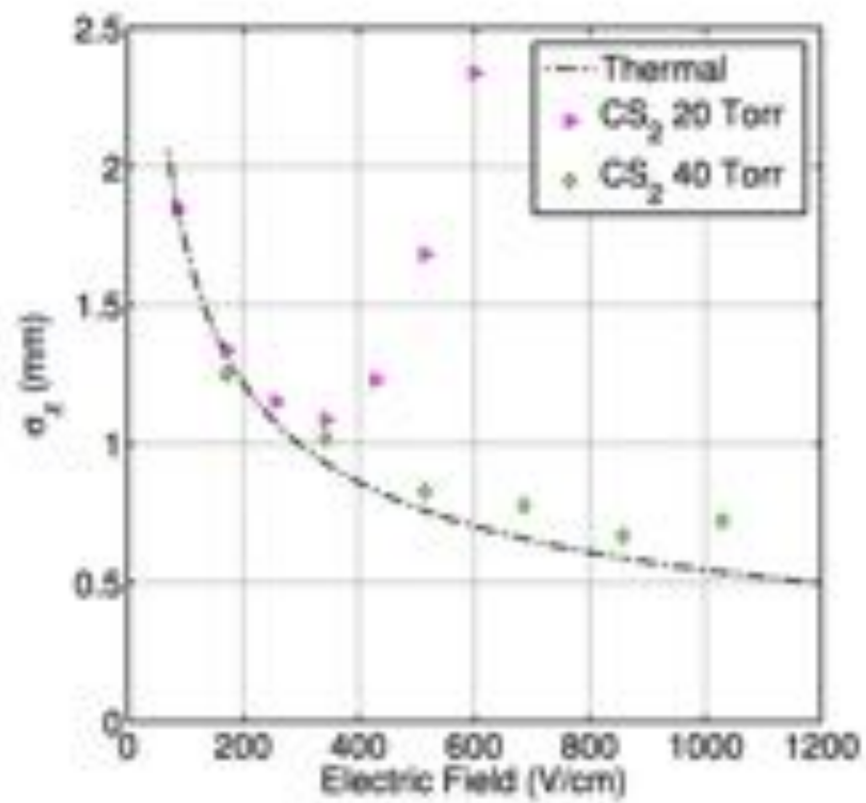


- **Diffusion measurements**

arXiv: 1609.05249



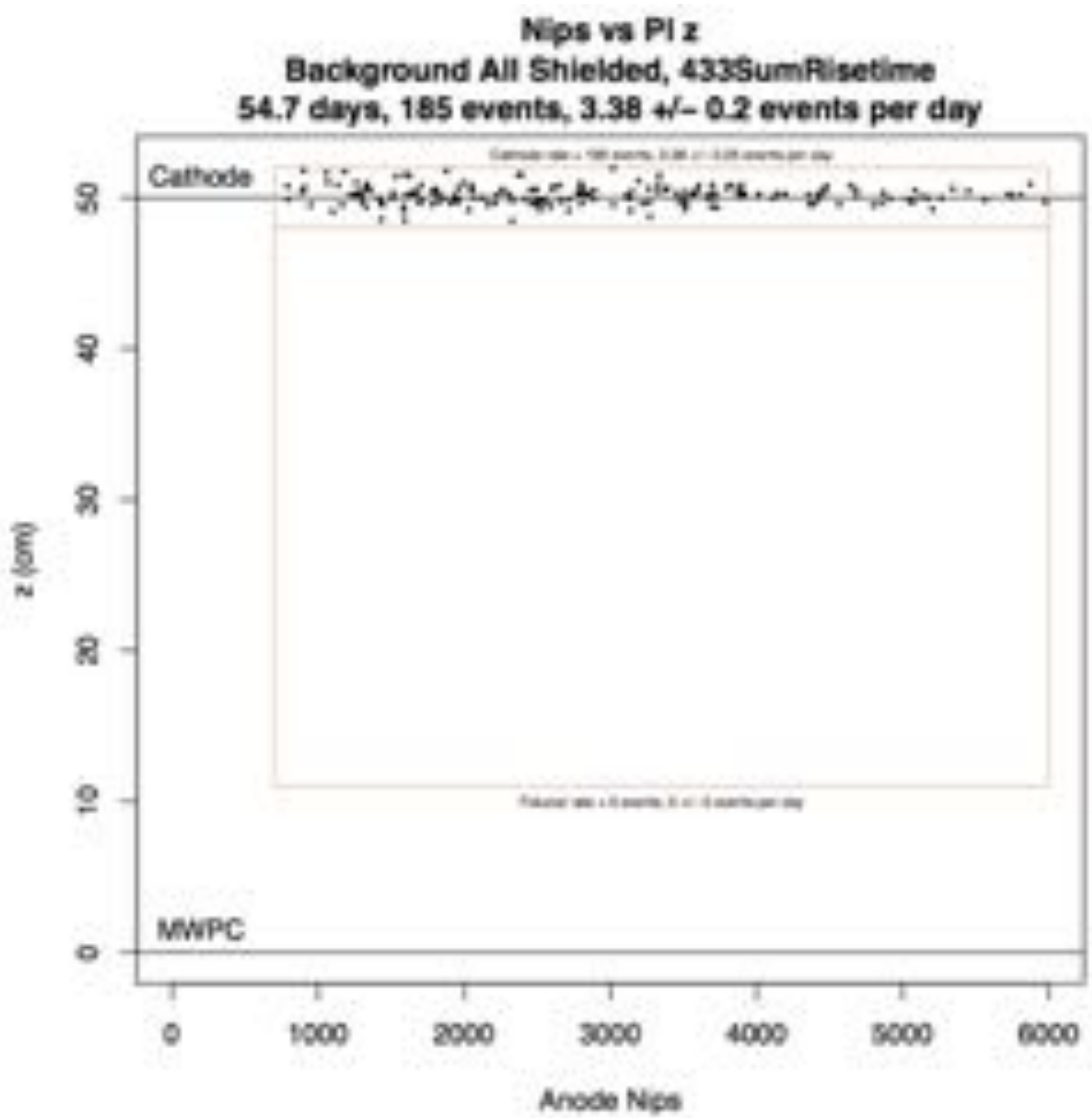
(a) SF_6 diffusion



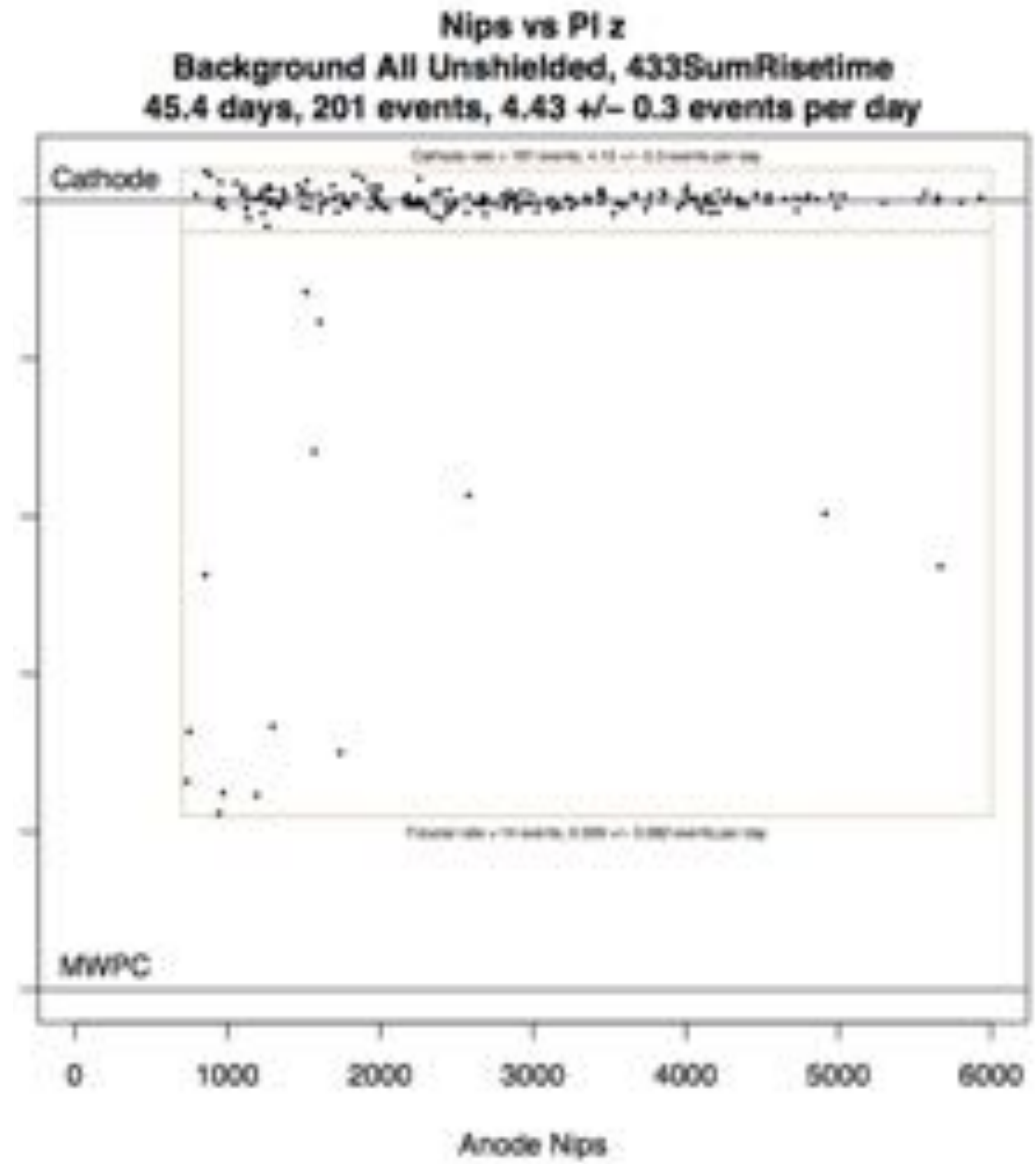
(b) CS_2 diffusion

Neutron Background & Directionality

- 54.7 day shielded run - no events seen



- 45.4 day unshielded run - see 14 fast rock neutrons



- Consistent with Boulby neutron flux of 7 x 10^{-7} n/cm^2/s

What Directional TPC Technology?

“high definition - 3D”

Readout	Experiment	Target[8]	Granularity x, y, z[9]	Area m^2 [10]	Fiducial Volume[11]	Gas Gain[12]	Energy resolution[13]	Enery threshold[14]	Angular resolution	Sense recognition threshold
MWPC	DRIFT	NI CS_2 CS_2:CF_4 CS_2:CF_4:O_2	2 mm NA 1 μs	2 × 2	0.8 m^3	~1000	42% [242]	50 keV, [64] 30 keV, [243]	unpublished	50 keV, [64] 40 keV, [243]
Micromegas	MIMAC	EG Mix of CF_4, CHF_3, and C_4H_{10}	0.42 mm 0.42 mm 20 ns	2 × 1	5 L	2×10^4	22% [130]	~1 keV_{ee} [134]	unpublished	unpublished
μPIC	NEWAGE	EG CF_4	0.4 mm 0.4 mm 10 ns	0.3 × 0.3	36 L	1000	23% [142] 47% at 50 keV_{ee} [150]	50 keV_{ee} (directional) [150]	40° at 50 keV_{ee} [150]	75 keV_{ee} [244]
ATLAS Pixel chips	D[3]	EG He+CO_2 NI SF_6 [245]	0.05 mm 0.25 mm 25 ns	NA[15]	50.4 cm^3	NA	20%, 100 Torr CF_4 [165]	1–10 primary e^- [164]	$\frac{\sqrt{12}\sigma}{L\sqrt{N}}$ radians [166][16]	unpublished
Optical	DMTPC	EG CF_4	0.3-0.6 mm 0.3-0.6 mm NA[17]	NA[18]	20 L (1 m^3)	NA	35% at 80 keV, [220]	20 keV_{ee} [205]	15° at 20 keV_{ee} [205]	40 keV_{ee} [205]
Emulsions	NEWS	Solid emulsion	10 nm 10 nm 0.1 μm	100 g[19]	NA	NA	unpublished	35 keV, Carbon [227]	13° for 100 keV, Carbon [227]	unpublished