

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



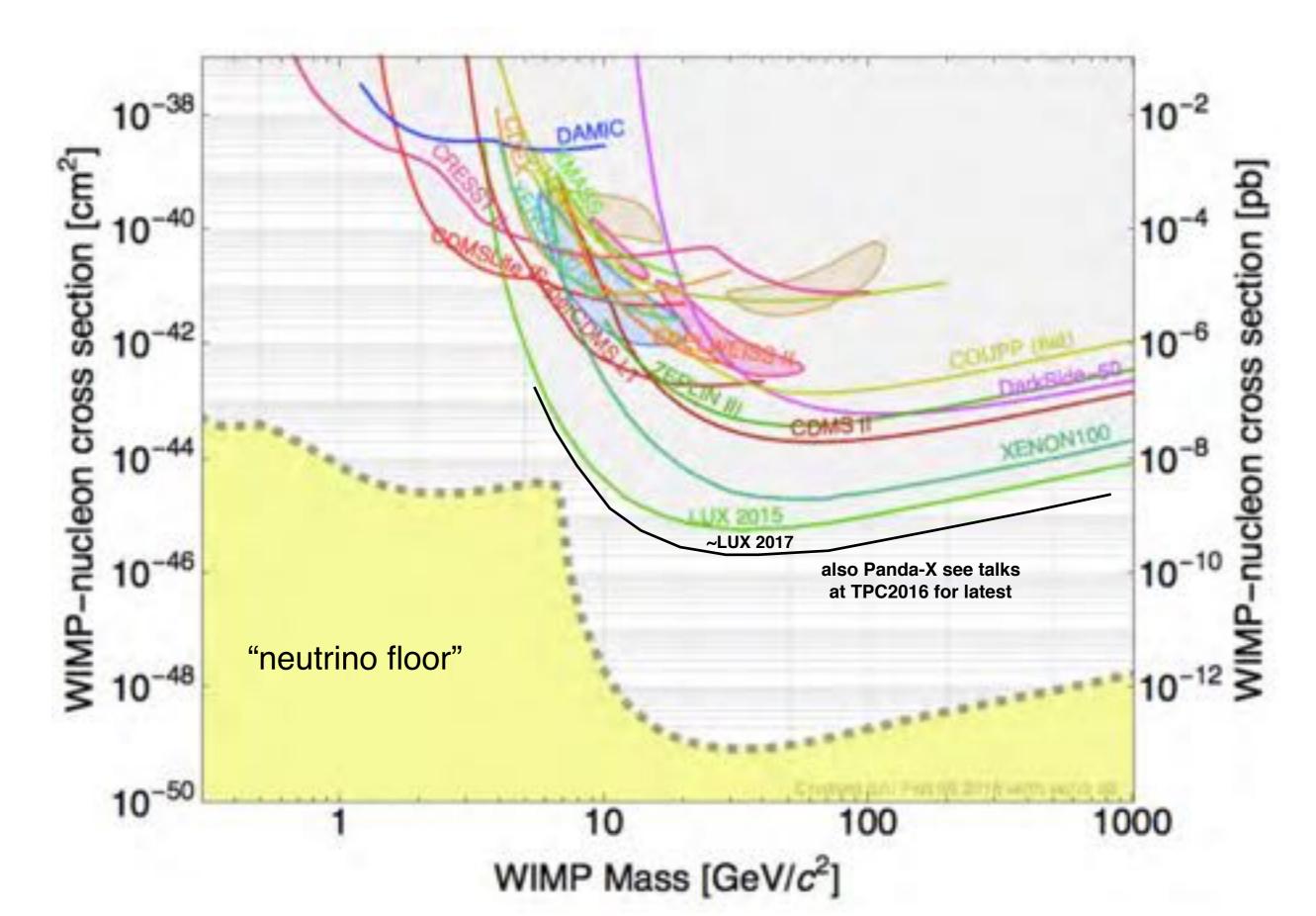
"I can't tell you what's in the dark matter sandwich. No one knows what's in the dark matter sandwich."



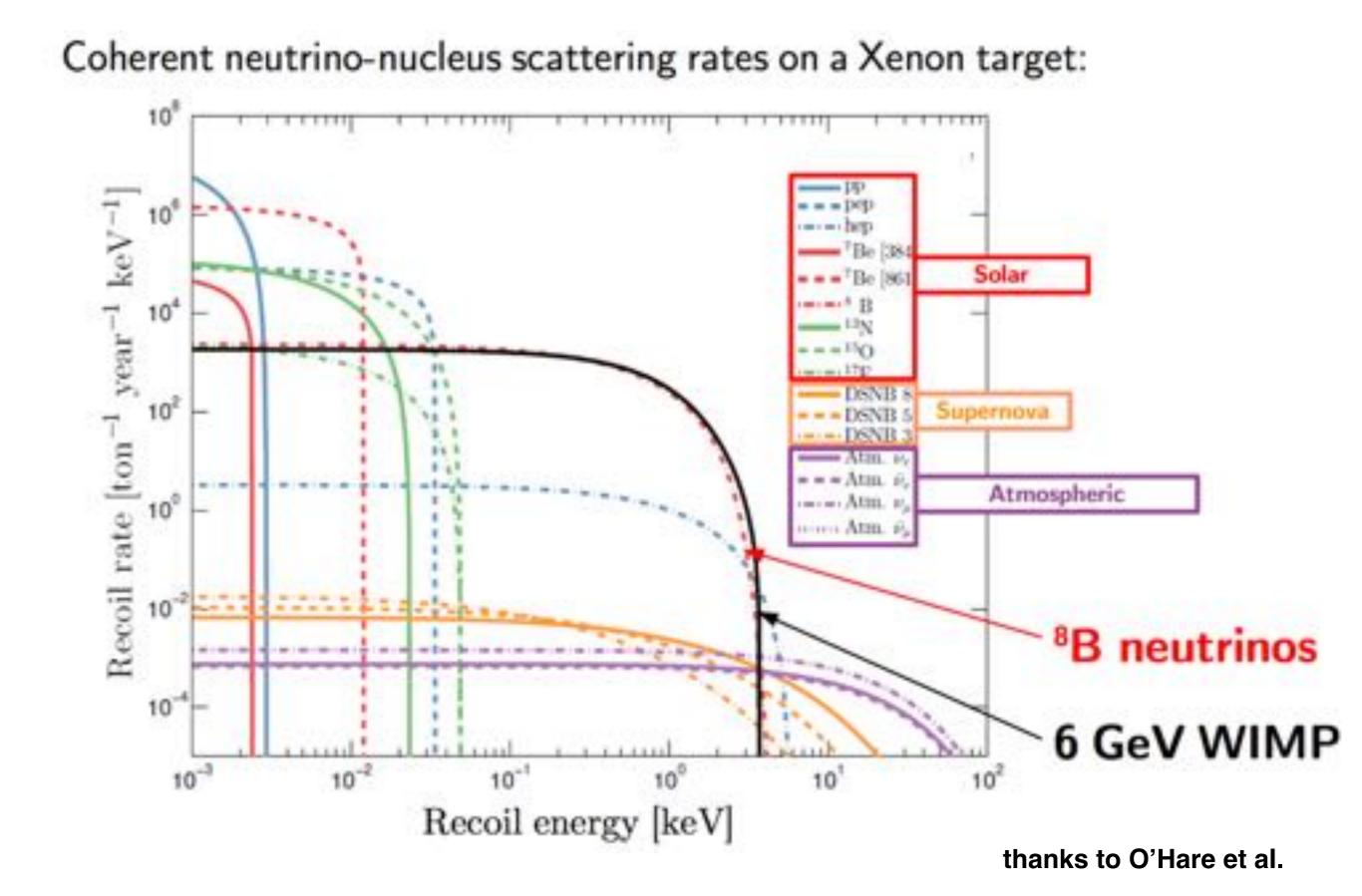
"I can't tell you what's in the dark matter sandwich. No one knows what's in the dark matter sandwich."



~Current WIMP Situation

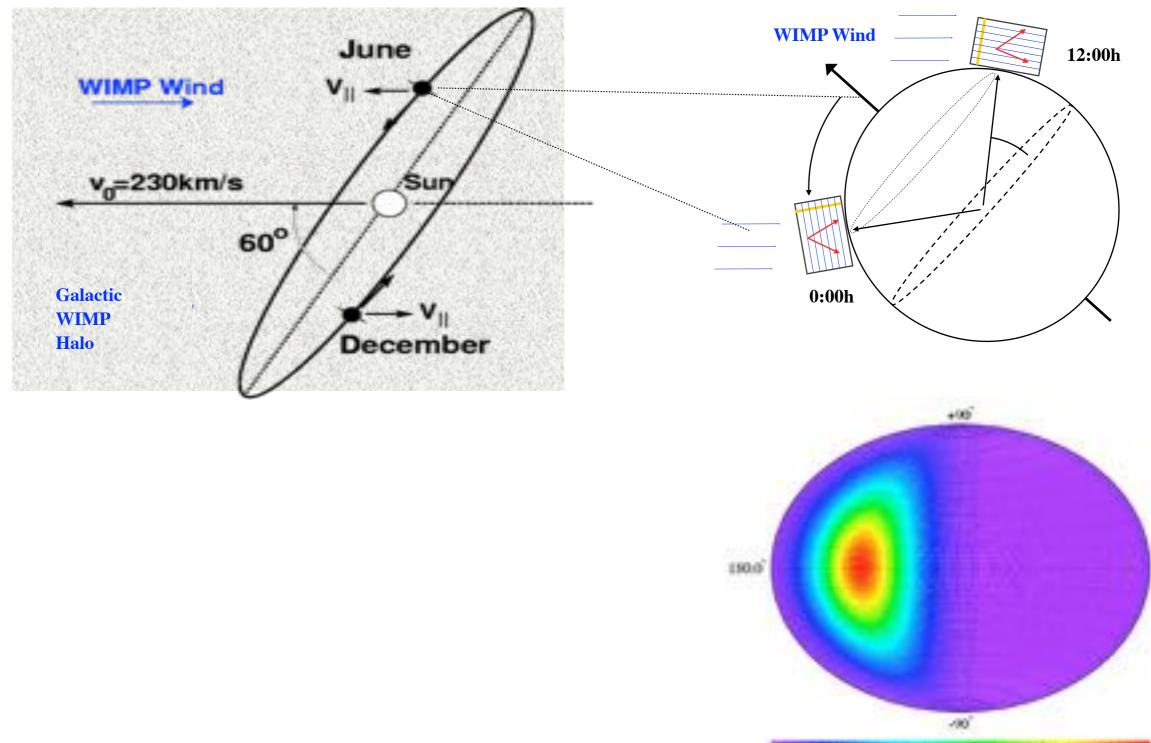


Neutrino Coherent Background



Directionality - A Better Signal

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



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WIMP Forder's w

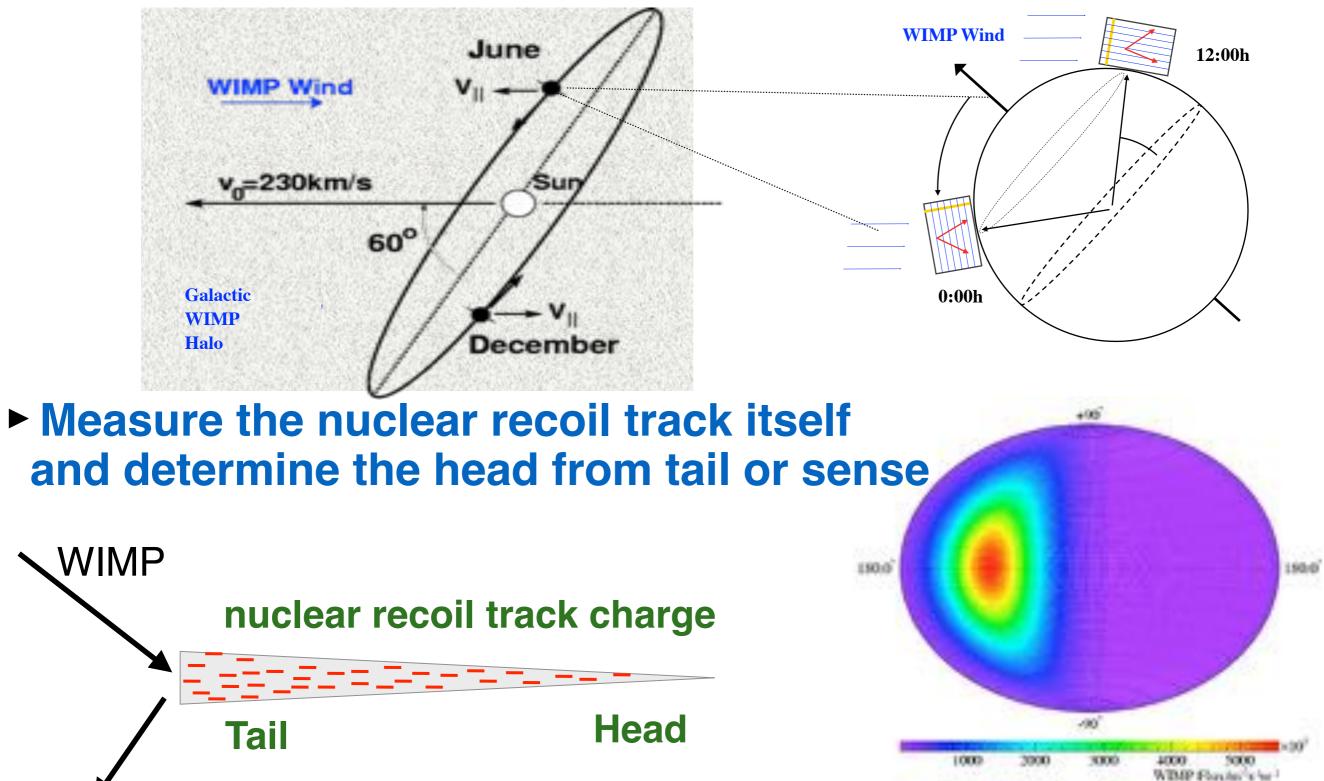
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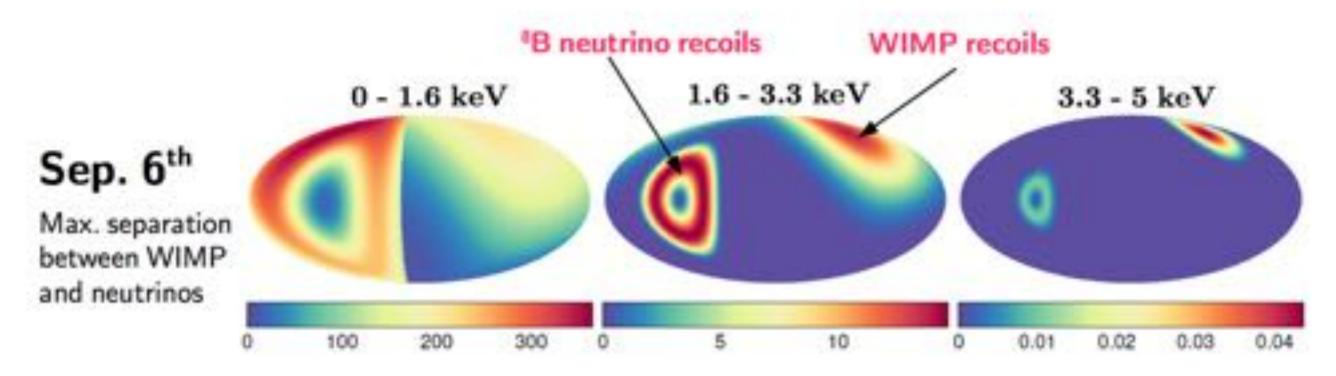
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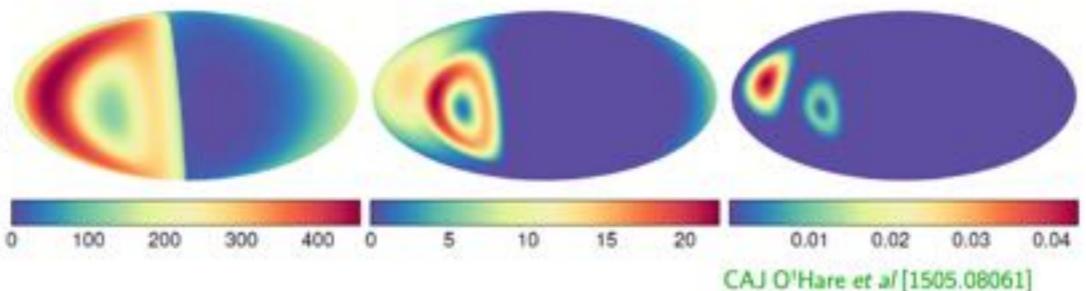


Power of Directionality - Solar Neutrinos

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

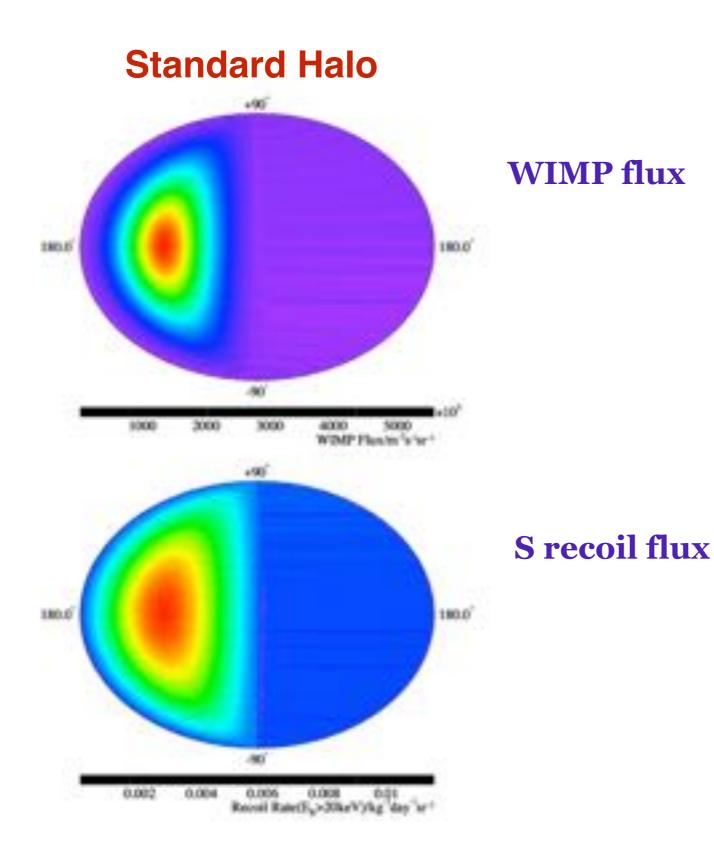


Feb. 26th Min. separation between WIMP and neutrinos

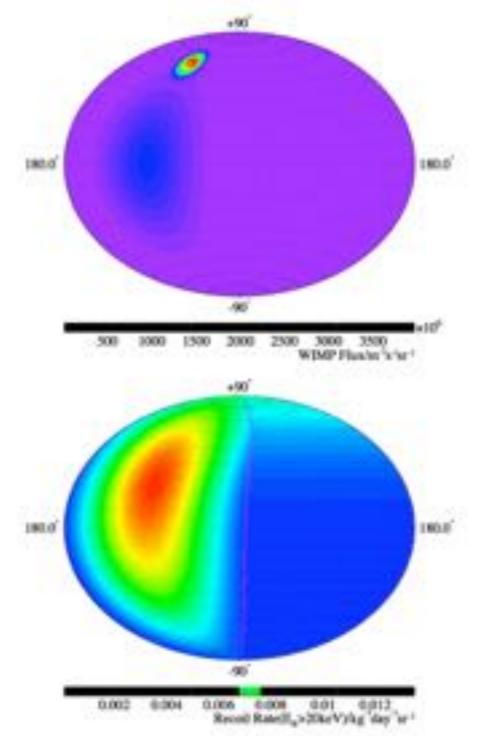


Power of Directionality - Astrophysics?

Potential for WIMP "Astronomy"



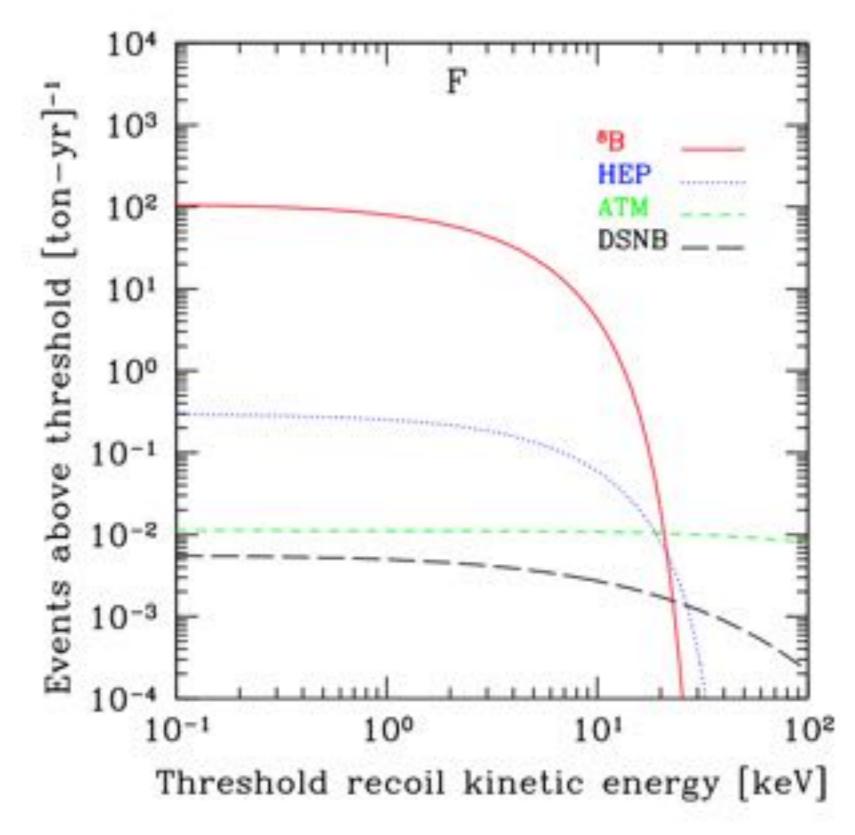
With Sagittarius Stream

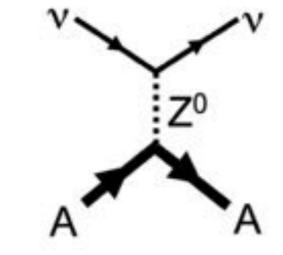


simulations by Ben Morgan (Sheffield)

Neutrino Coherent Rates, Fluorine

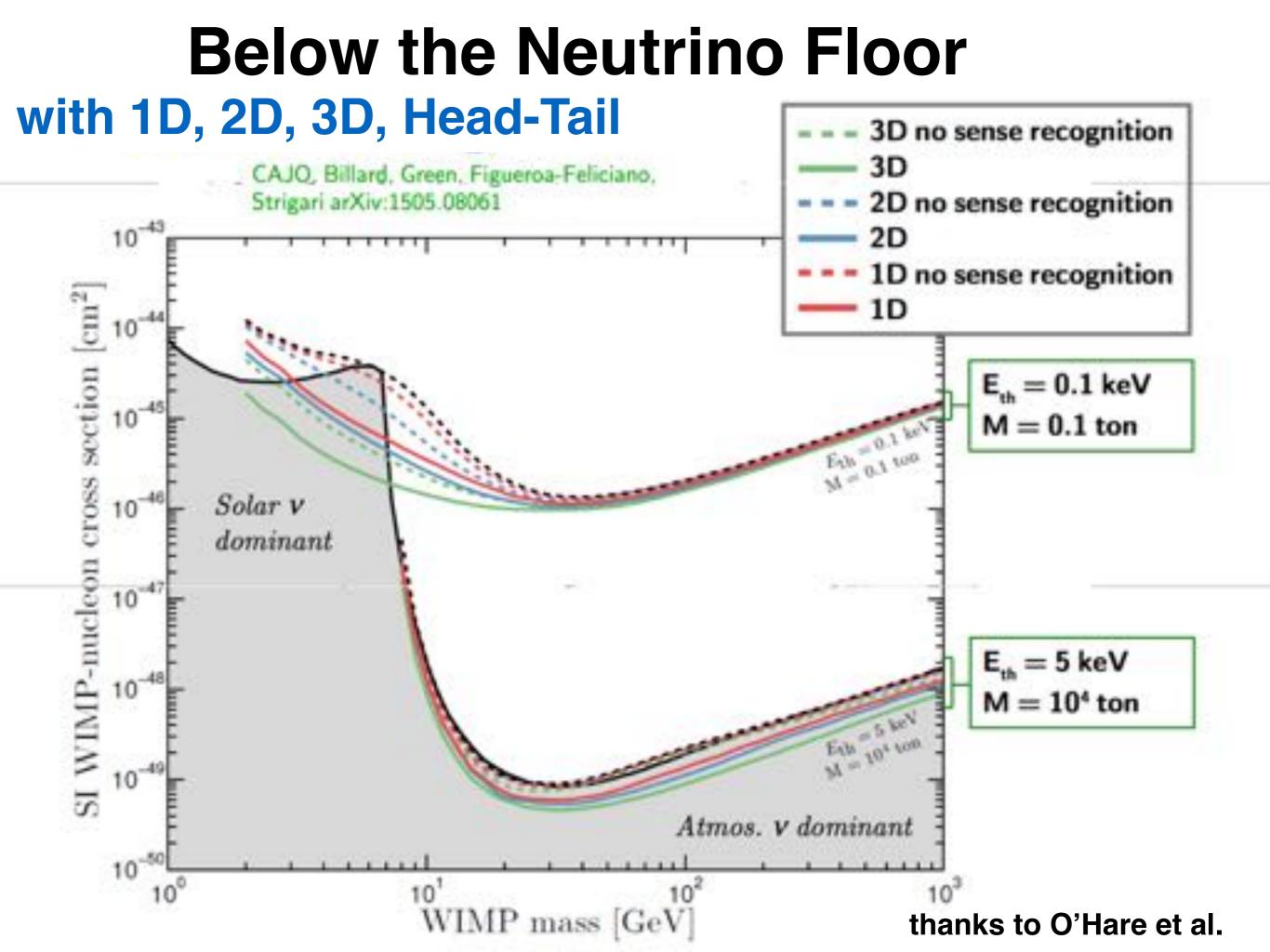
Louis E. Strigari arXiv: 0903.3630v2





1keV_{rec} threshold —> ~70 events per ton year

10m³ SF₆ at 200 torr for 3 years operation yields 4 neutrinos.



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 D³ Italy R&D Australia R&D others..

Directional Strategies and CYGNUS

(1) High Density Targets Solid, Liquids

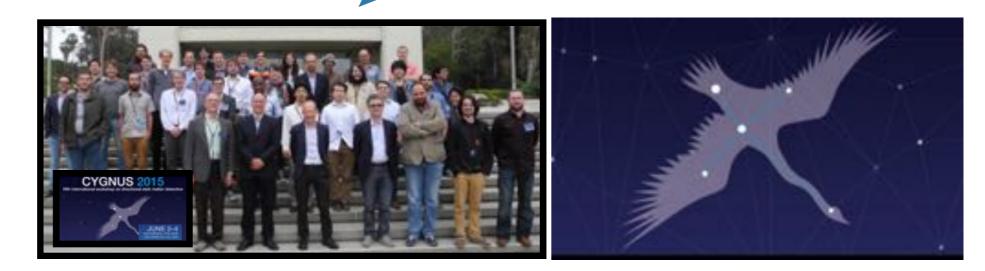
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Columnar recombination in Xe/Ar
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CYGNUS

(2) Low Pressure TPCs

DRIFT DM-TPC MIMAC NEWAGE D³ Italy R&D Australia R&D others..



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

CYGNUS - Agreement

CYGNUS agreement includes Solid and TPC technology



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(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)

Man jage Continues

Main Page



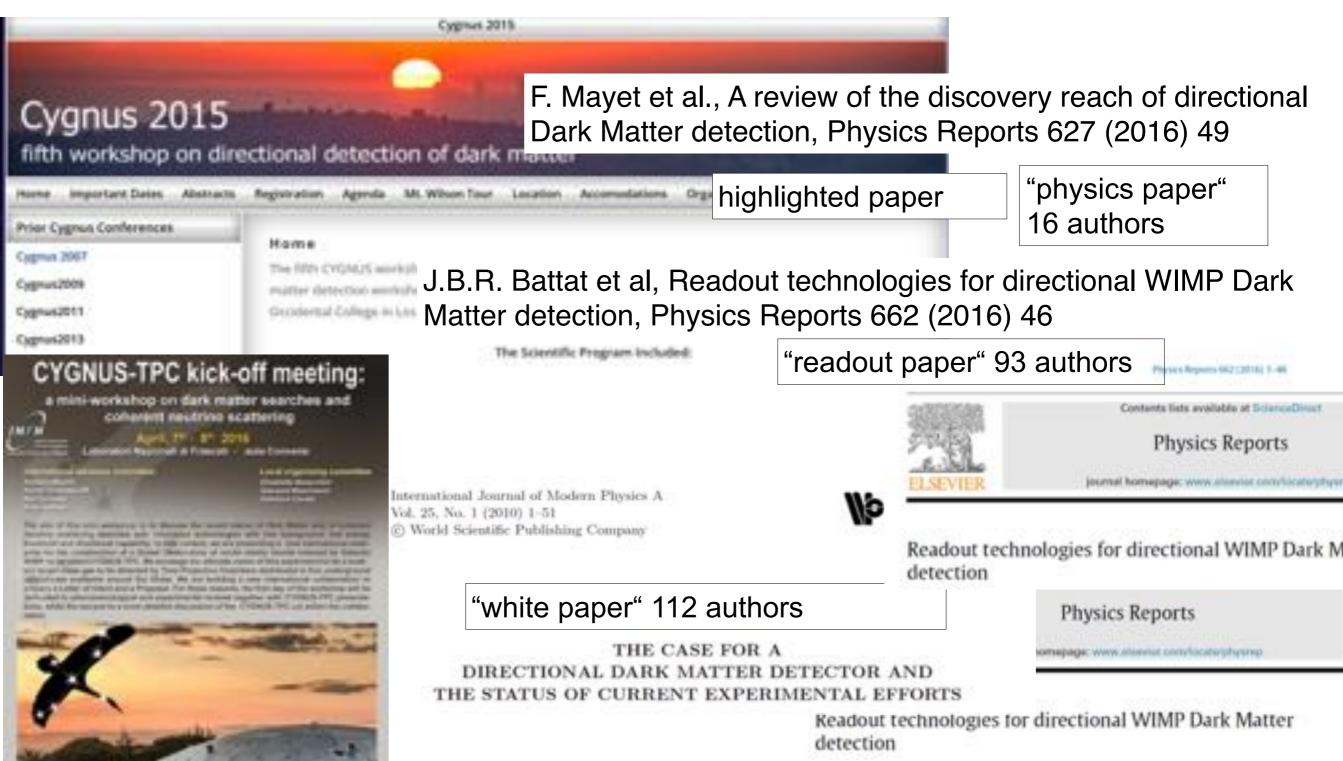
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CYGNUS Activities

"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-)



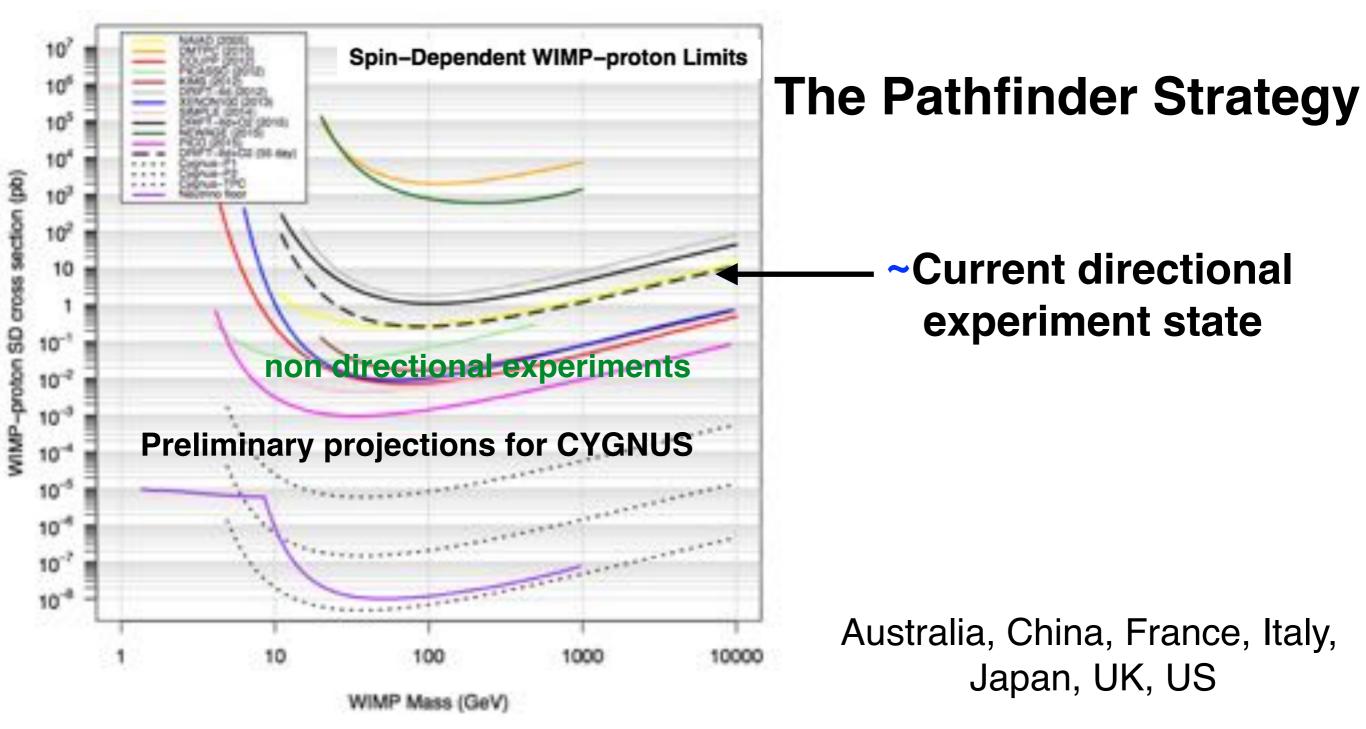
CYGNUS - Multiple Sites

Directionality benefit from multiple sites at different latitude



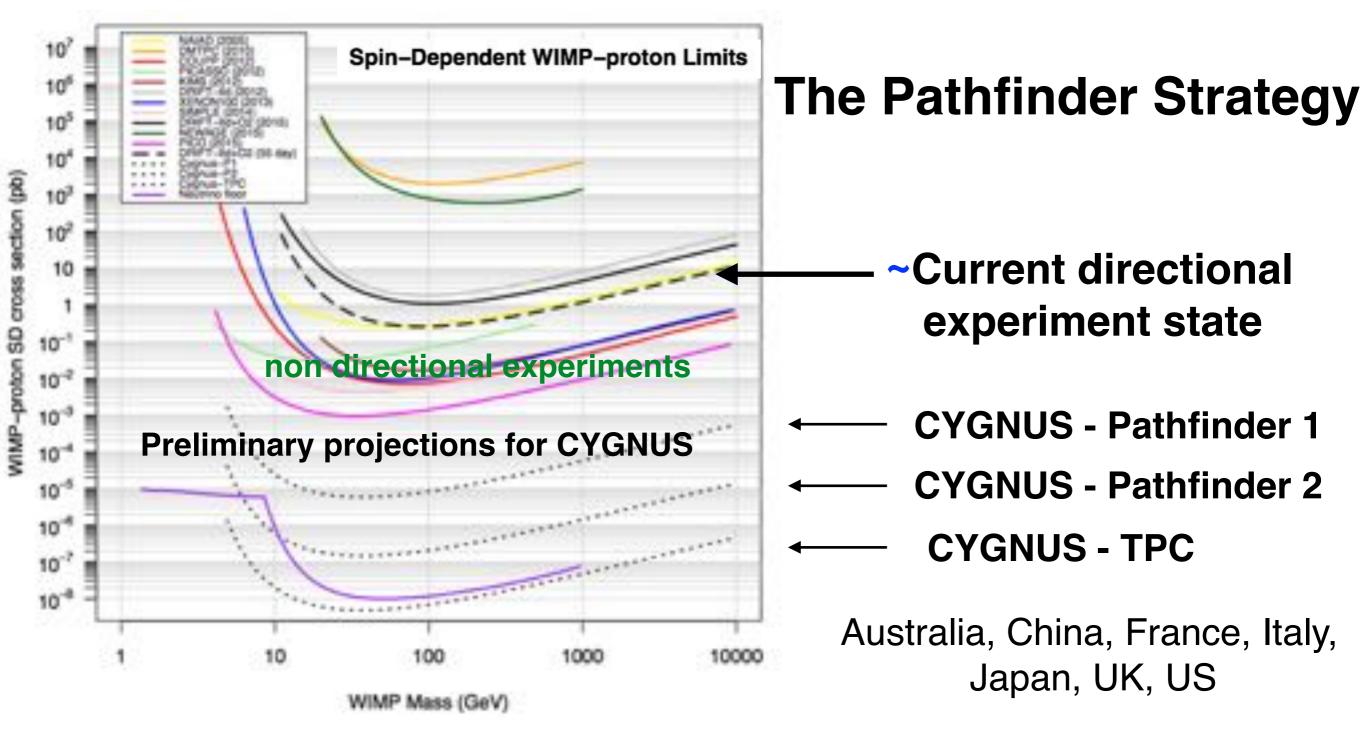
CYGNUS-TPC Baseline Concepts/Aim

- ► SF₆ 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

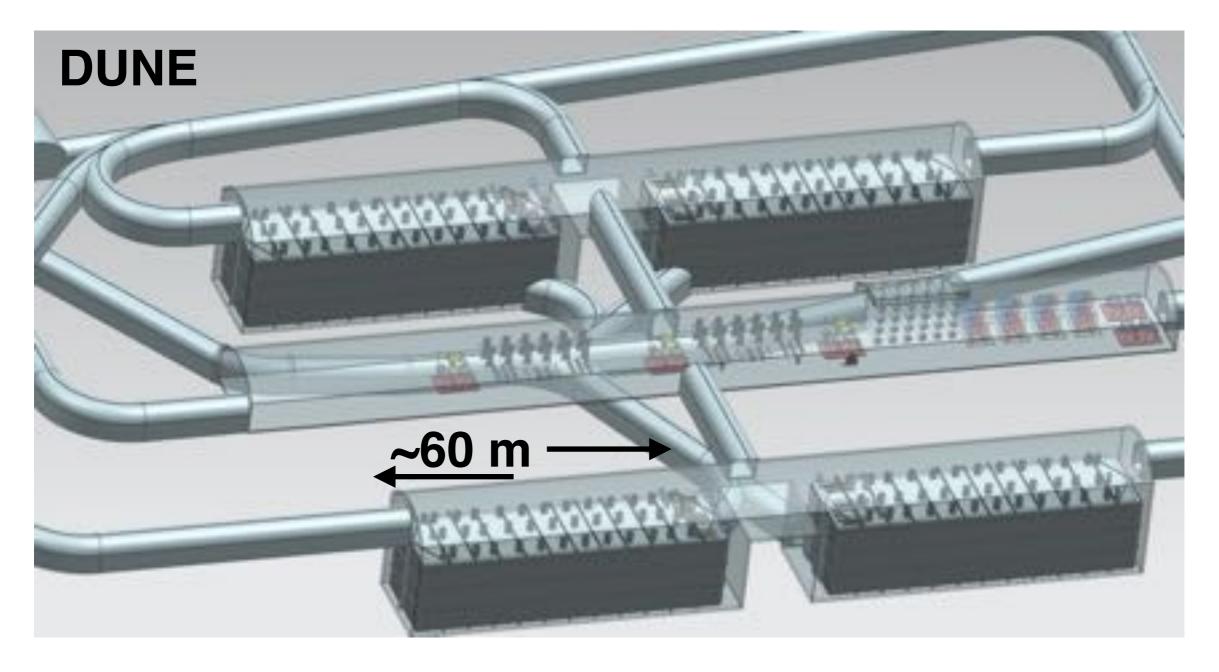


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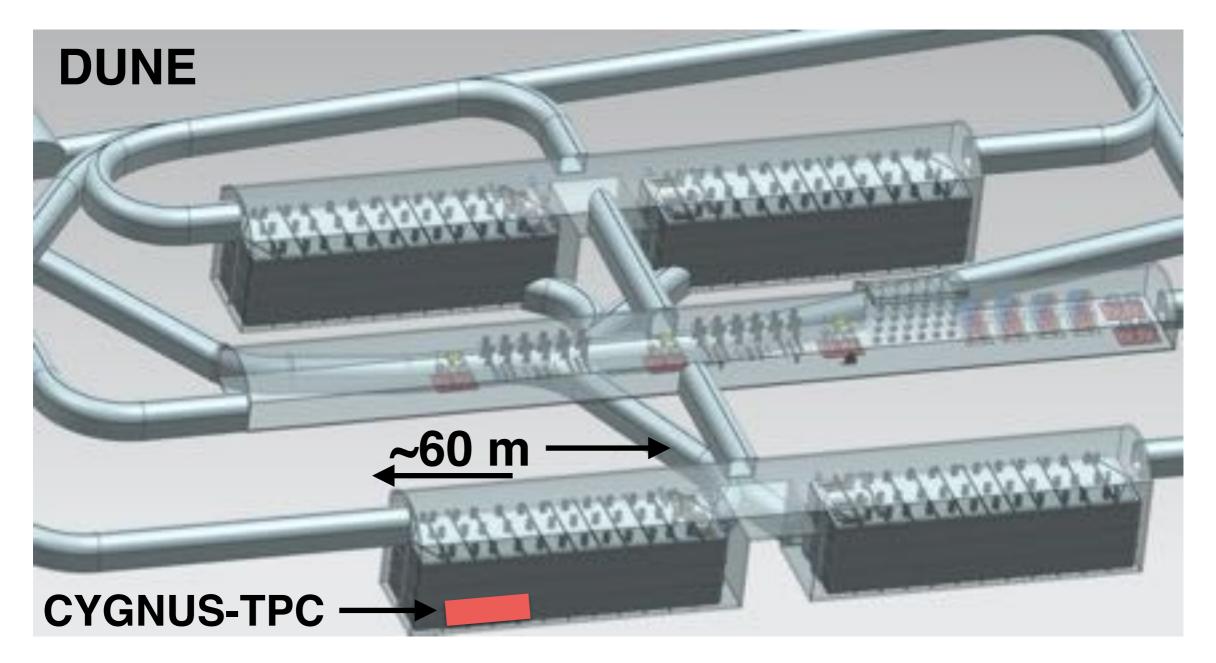
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- Multi-tonne, multi-underground site,
- Staged programme low WIMP mass, high WIMP mass



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

Stage 1 Vision

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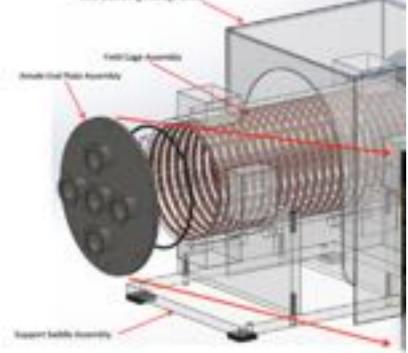
CYGNUS-TPC Optimisation

- What directional capability is optimal 1D, 2D, 3D + HT vs cost?
- What gas can SF₆ 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)

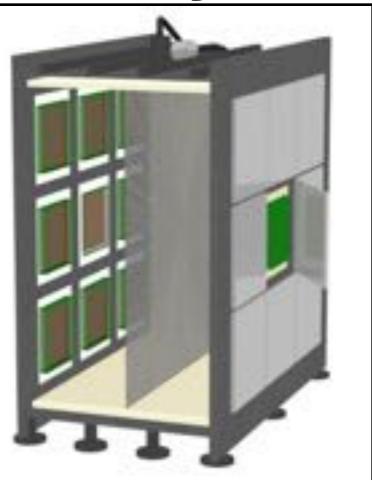
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Hawaii D3 (USA)

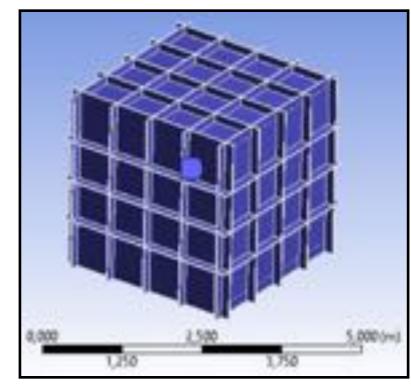


1 m3 CYGNUS test vessel (Japan) →



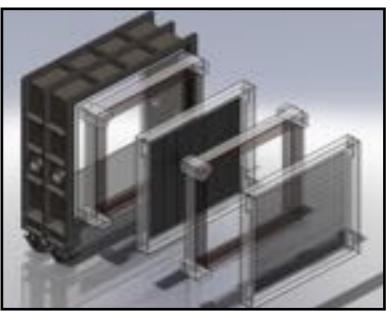


SF₆ R&D, Frascati, (Italy)

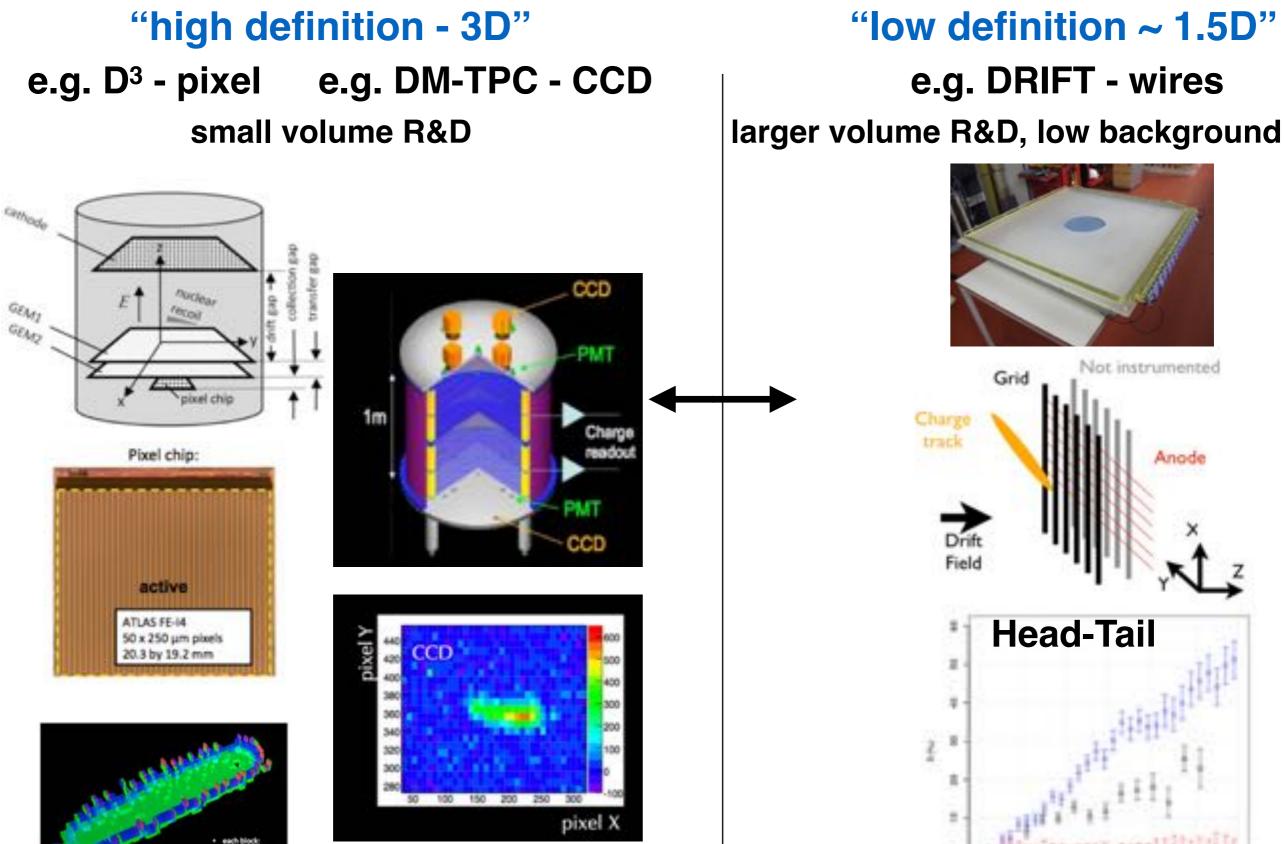


10 m³ vessels (Australia)

10 m³ designs (US, UK)



What Directional TPC Technology?



 each bli Sou250 Color: k density

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

0	ontents		
1	Introduction		
2	Science Case for a large Nuclear Recoil Observatory 2.1 WIMPs 2.2 Solar Neutrinos 2.3 Other Physics	3 3 3 3	
3	Existing Directional Detection Technologies		
•	Quantitative Comparison of Directional WIMP and Solar Neutrino Sensitivity 4.1 Simulation of nuclear recoils 4.2 Simulation of detectors and readouts 4.3 Algorithms to extract directional signals 4.4 Directional power of detectors versus recoil energy 4.5 Directional WIMP and Solar Neutrino Sensitivity 4.6 Figure of Merit for Specific Science Goals 4.7 Conclusion on Technology Choices		
5	Zerv Background Feasibility 5.1 Fidacialization 5.2 Neutron Backgrounds 5.2.1 Laboratory and TPC Geometry 5.2.2 Rock Neutrons and Passive Shielding 5.2.3 Vessel and TPC Neutrons 5.2.4 Maon-induced neutrons and active vetoing 5.2.5 Neutron Conclusion	566778888	
	5.3 Gamma Backgrounds 5.4 Radon and Radon Progeny Backgrounds 5.5 Surface and other Backgrounds 5.6 Comparison of Technologies for low background	999	
6	Underground Sites and Engineering		
7	Conceptual Design Strategy		
8	Conclusion		

Sven Vahsen (Hawaii) is coordinating

New Site Infrastructure Stawell, Australia new site

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New Site Infrastructure Stawell, Australia new site

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Scale of DRIFT-II (with all shielding)

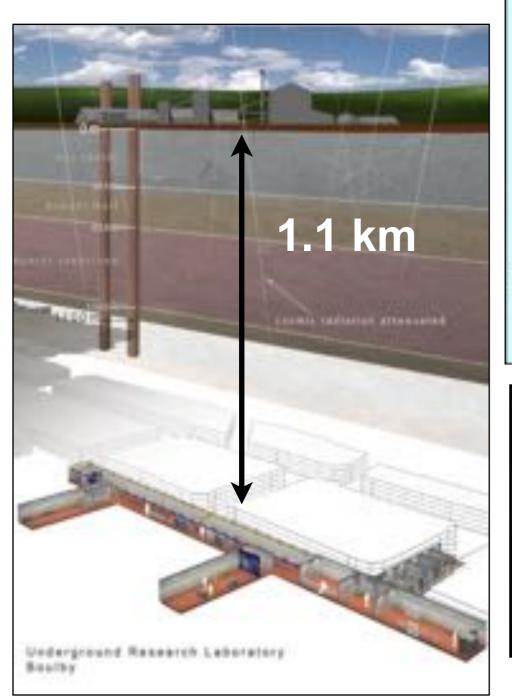
CYGNUS 1.1 (~10 m³) ?

CADING BAY

PLAT BARE OR AND

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



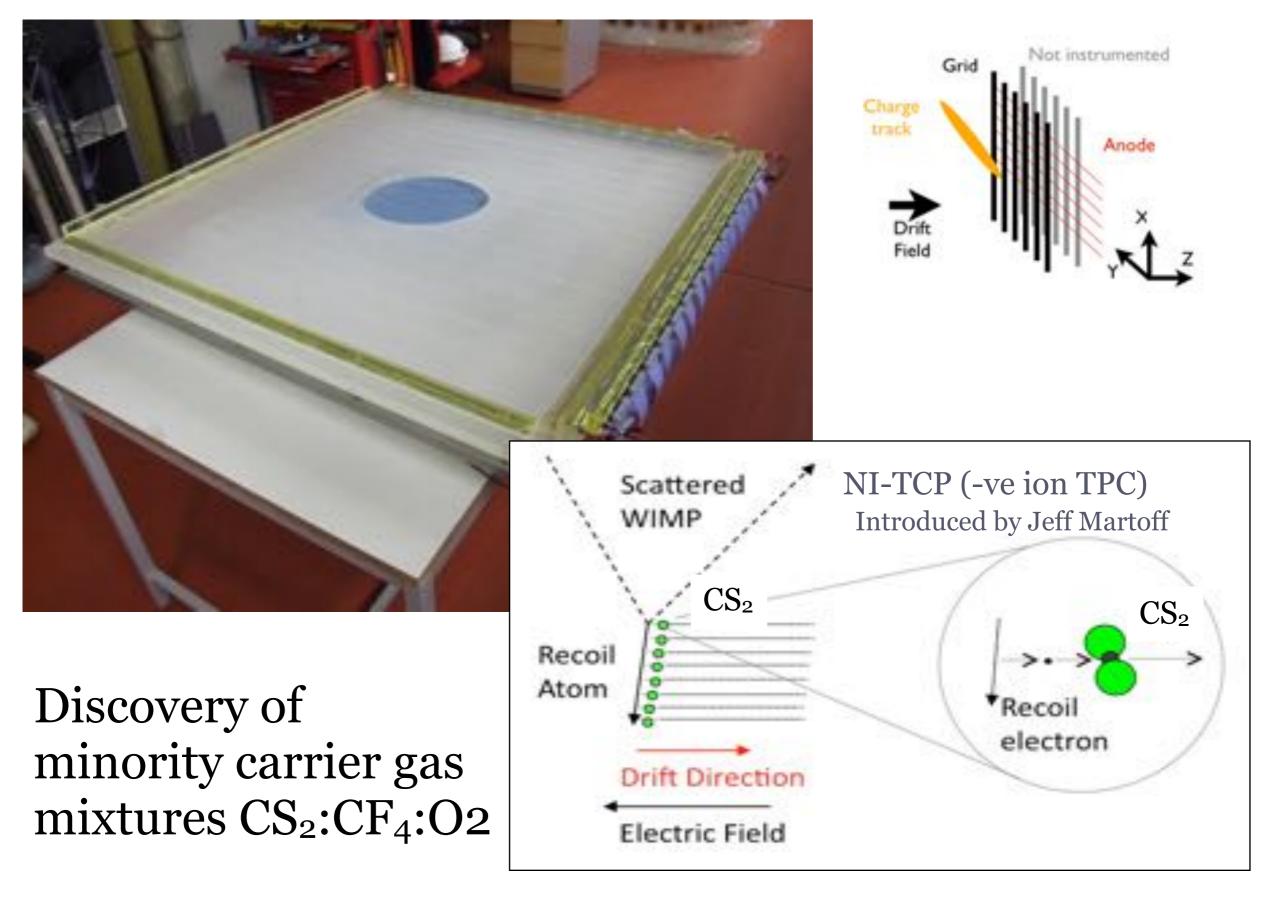
Studies of Low Background, DRIFT

Key Issues: (i) Full Fiducialisation

(ii) Neutron Backgrounds at ton scale

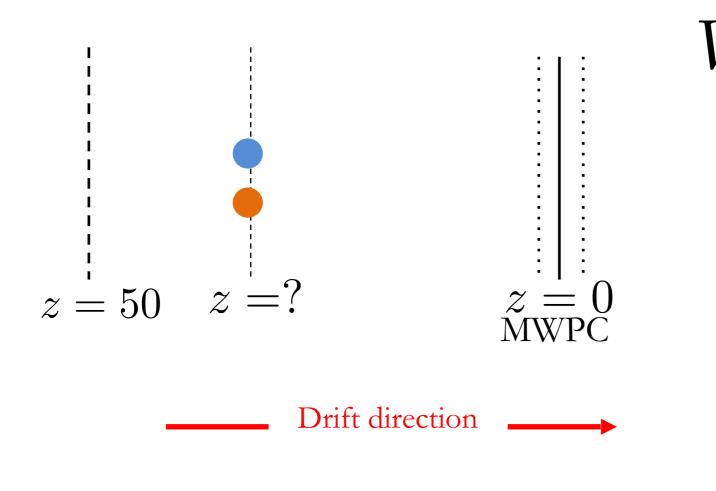


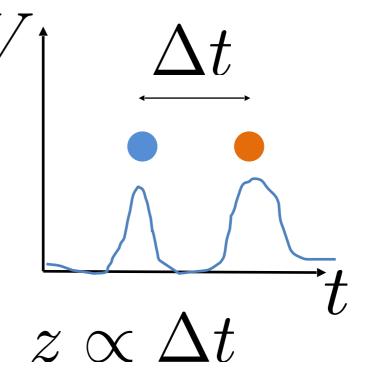
DRIFT MWPC 1 x 1m, -ve ion drift



z-Fiducialization Breakthrough

- Discovery of minority carrier gas mixtures CS₂:CF₄:O2
- Use of different drift speeds of carriers





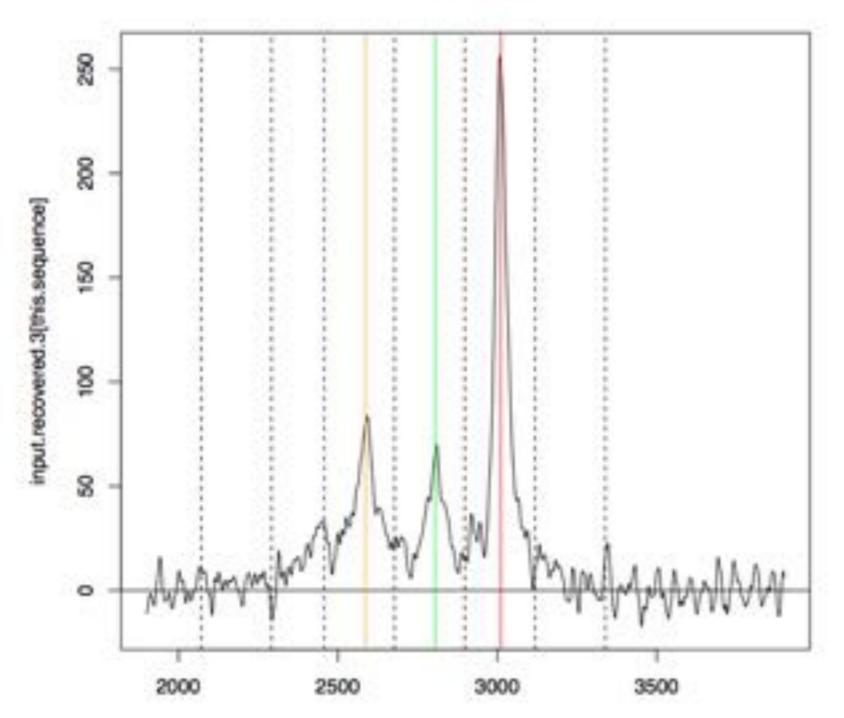
Proportionality constant can be measured for various gas mixtures, or calibrated in-situ.

thanks to D. Snowden-Ifft

z-Fiducialization

Examples

z = 49.7 cm



this sequence

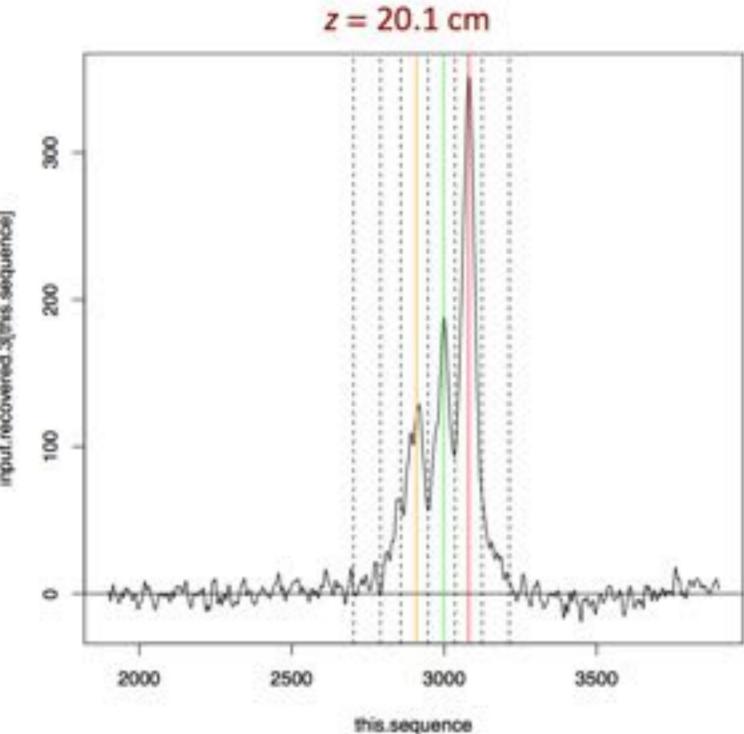


z-Fiducialization

z = 39.3 cm input recovered 3[this.sequence] WWAMIN

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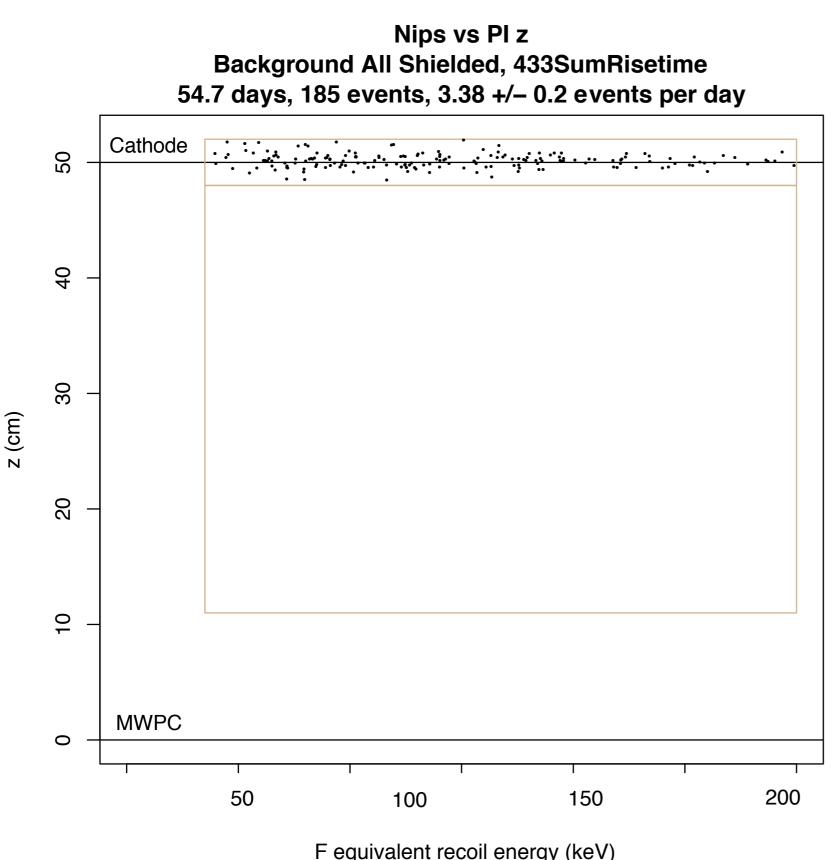
z-Fiducialization



input.recovered.3[this.sequence]

Examples

DRIFT WIMP Analysis Shielded 30-10-1 CS₂-CF₄-O₂ Data

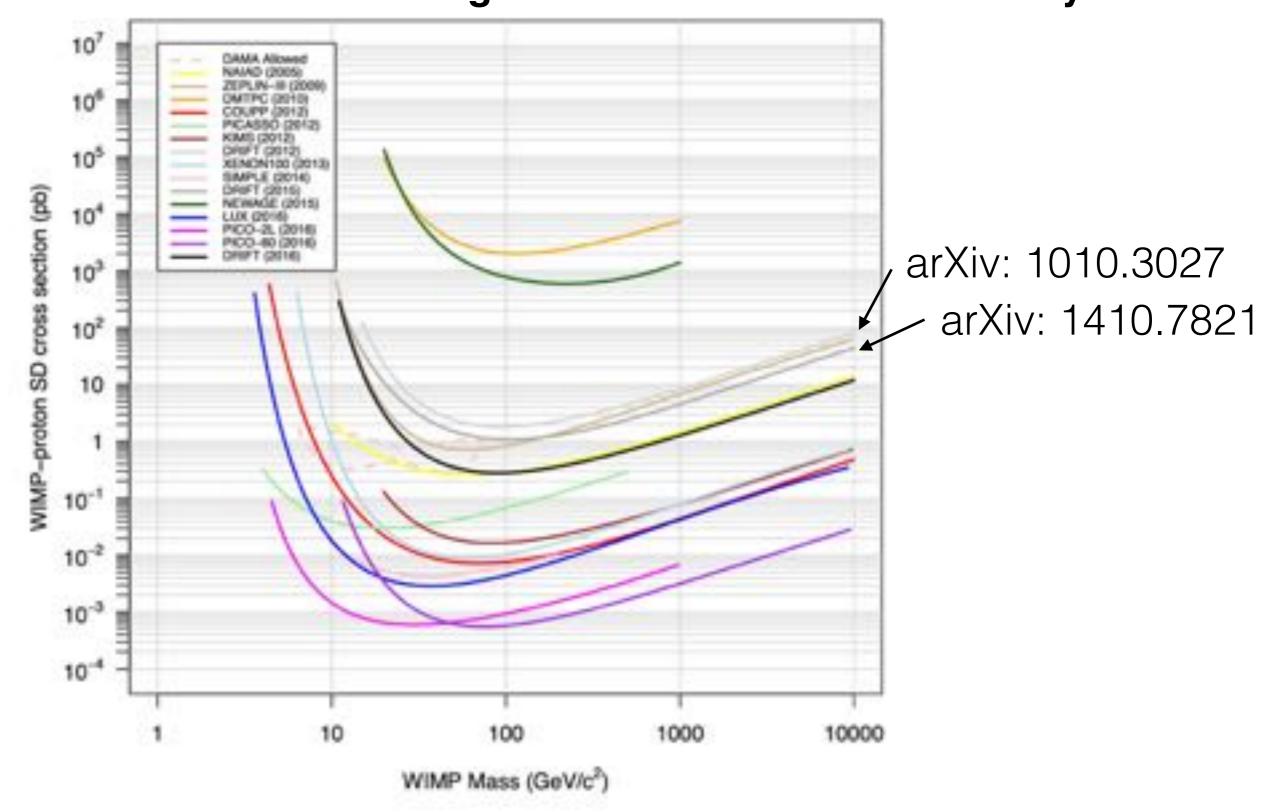


• 54.7 days of data analyzed

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

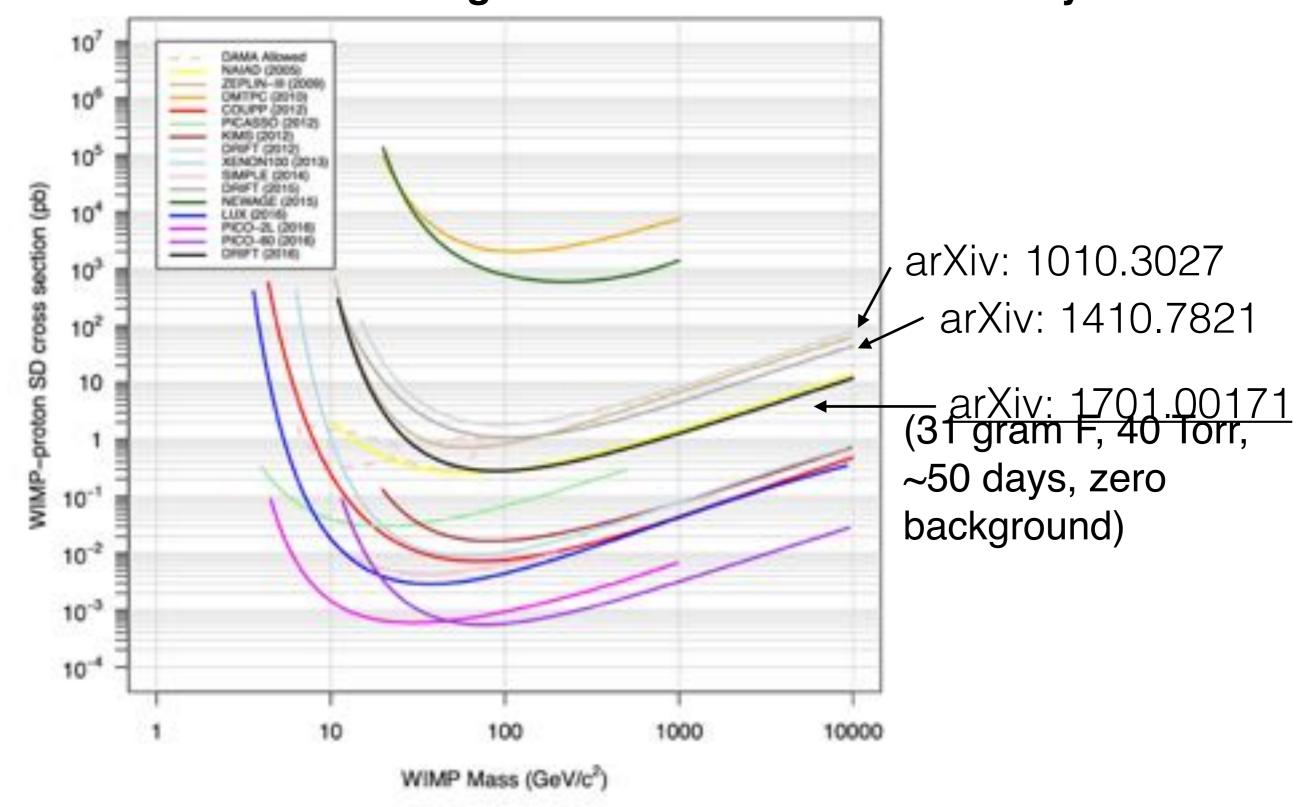
New Result (zero background)

New result (CAASTRO2017) including reduced threshold analysis First result in "DAMA Region" with directional sensitivity"



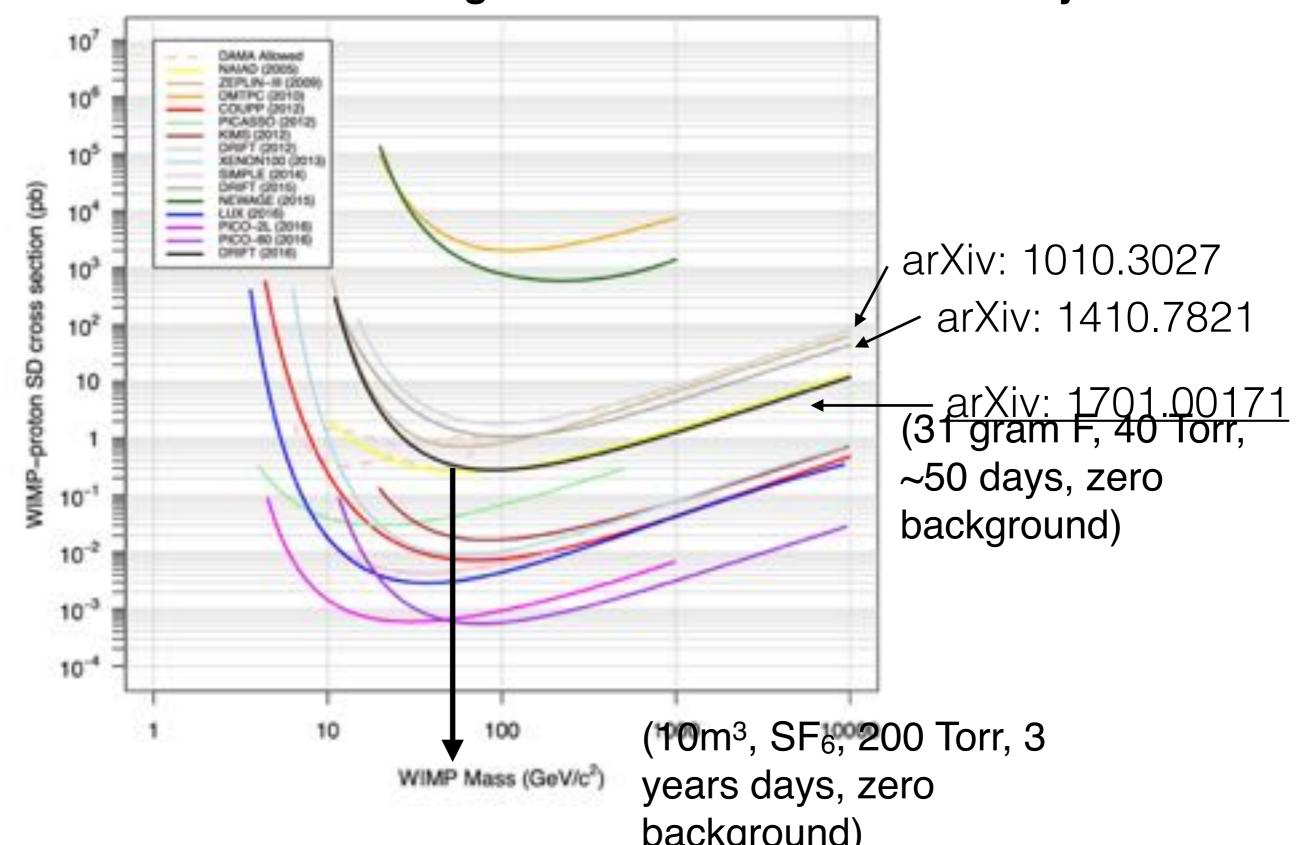
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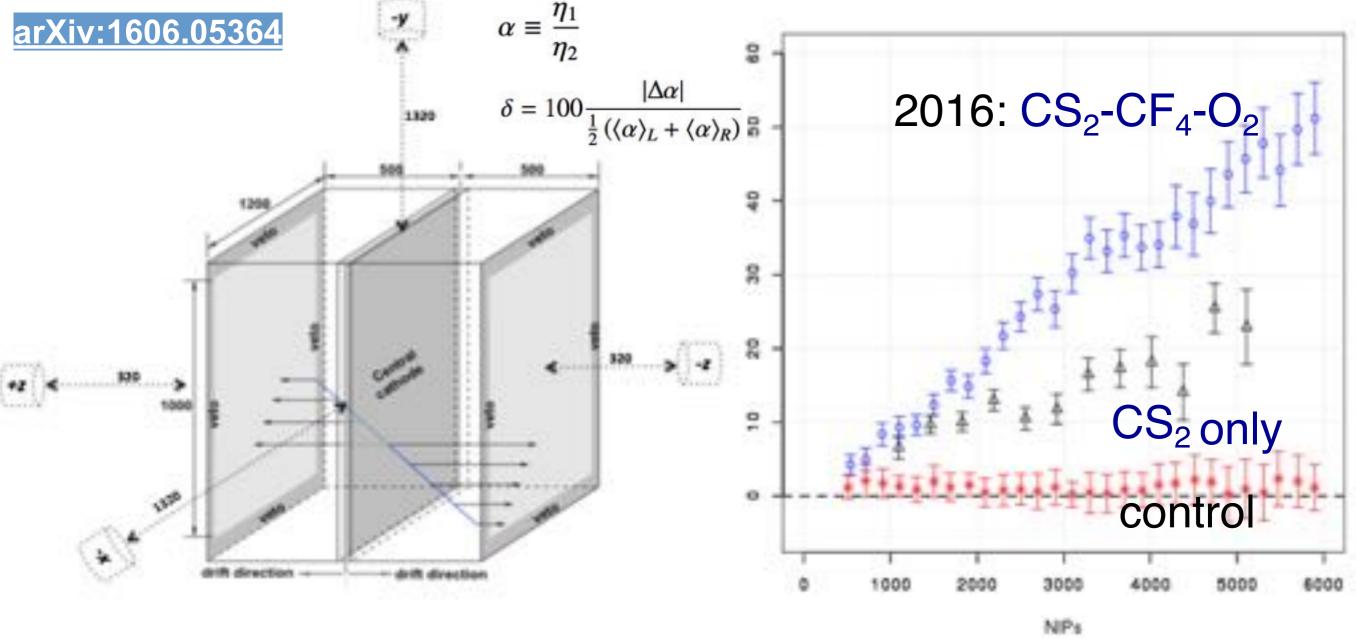
New Result (zero background)

New result (CAASTRO2017) including reduced threshold analysis First result in "DAMA Region" with directional sensitivity"



Head-Tail Directionality Maintained

Directional Head-Tail sensitivity with z-fiducialisation

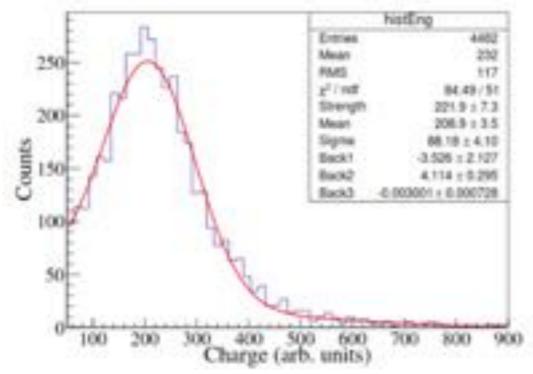


- DRIFT sensitivity to HT in the new gas mode was investigated.
- Method of extracting the HT parameter from Astropart. Phy., 31 (2009) 261.
- Analyzed 7 days of directed source neutron data.
- Event by event measurement of the HT parameter was done using η_1 to η_2 ratio.
- Can now study HT *z*, thanks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

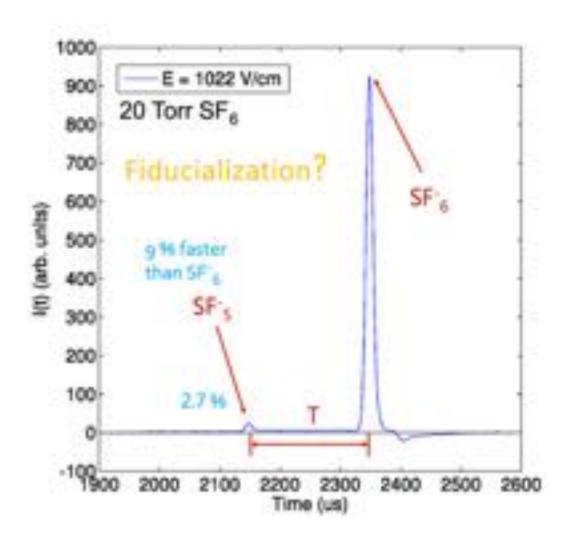
SF₆ Breakthrough at UNM

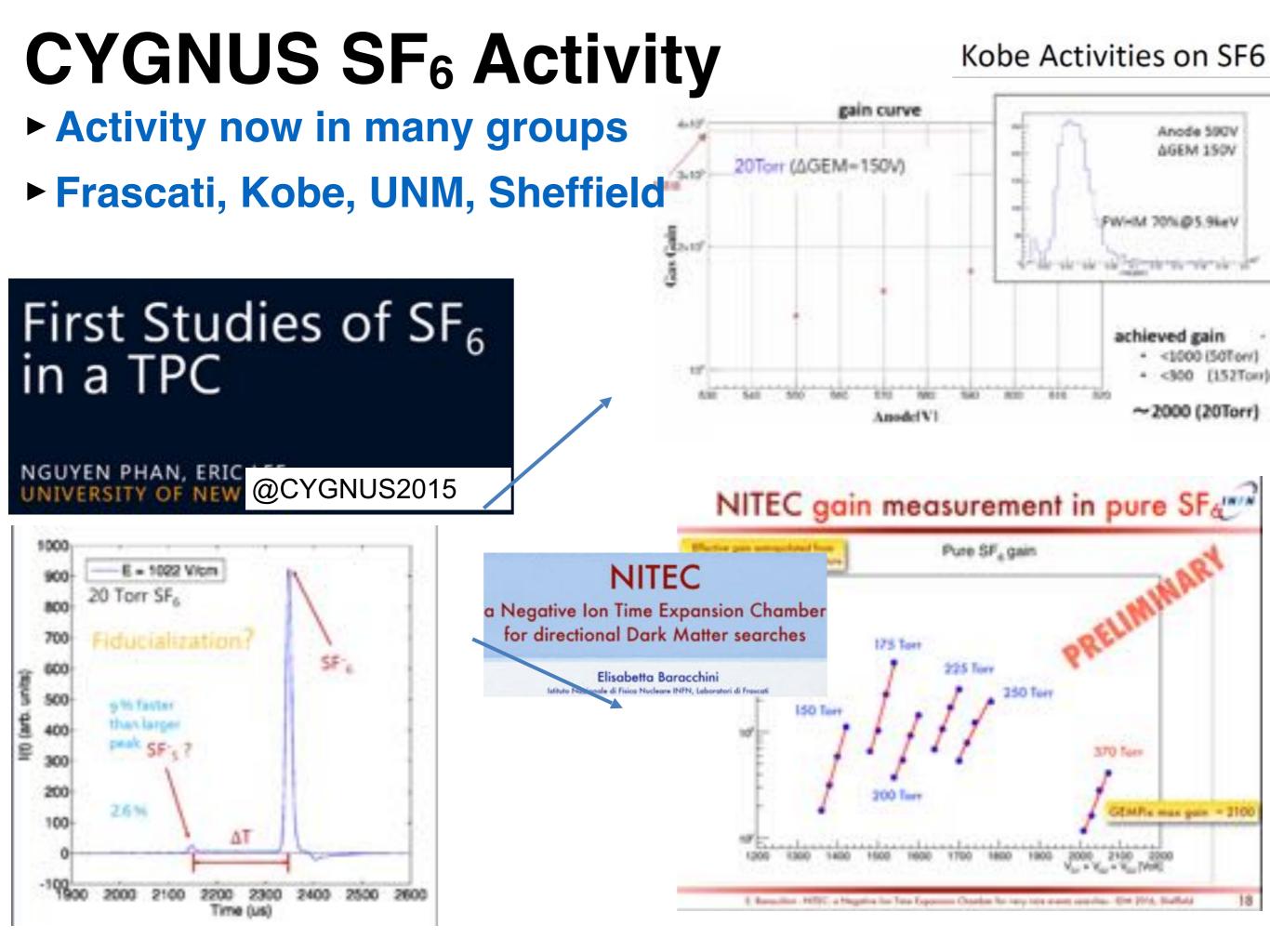
-ve ion with minority carrier and increased target mass

- Replacement for CS₂
 N. Phan, University of New Mexico
- First demonstration of SF₆ as -ve on gas (with GEMs)
- Potential for x5 more mass, with fiducialisation?
- This has been a revelation
 - ⁵⁵Fe spectrum in 40 Torr SF₆ with 0.4mm GEM
 - Gain curves up to x3000
 - z-fidusialization with SF₅⁻ shown (20 Torr)



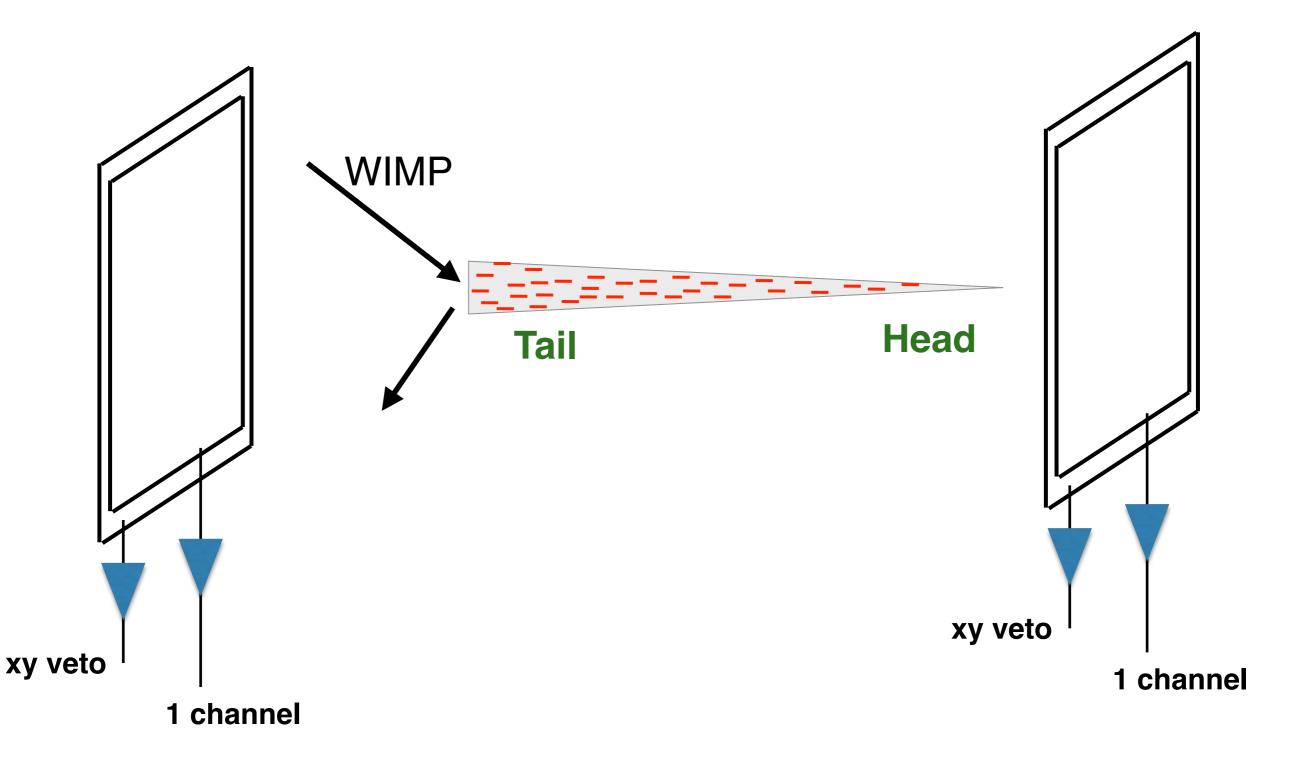
Activity now in many groups
 Frascati, Kobe, UNM, Sheffield





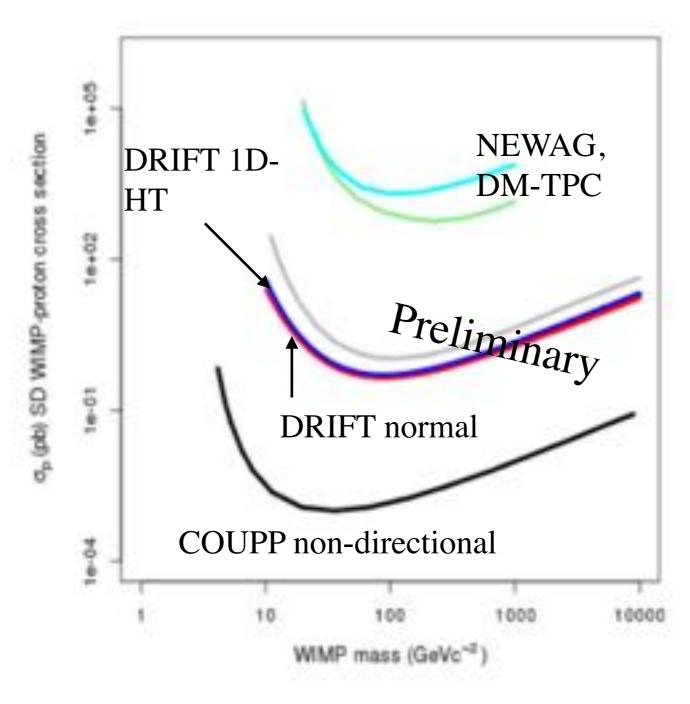
Is a Simpler "1D-HT" Readout Possible? CYGNUS R&D activity at Boulby

What is the simplest possible readout that might just work?



"1D-HT" Test using DRIFT Data

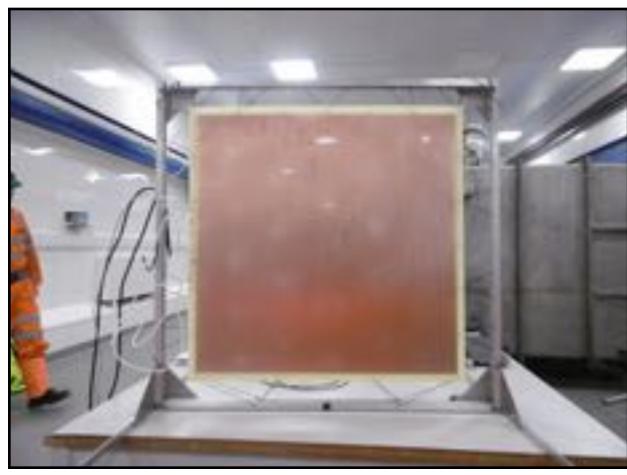
experiment with DRIFT-IId xy information switched off, just z and head-tail data analysed, like a 1 x 1m single channel.

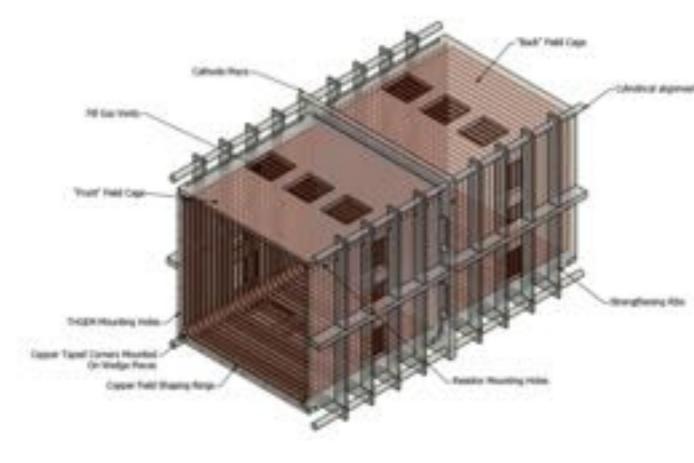


Paper in preparation

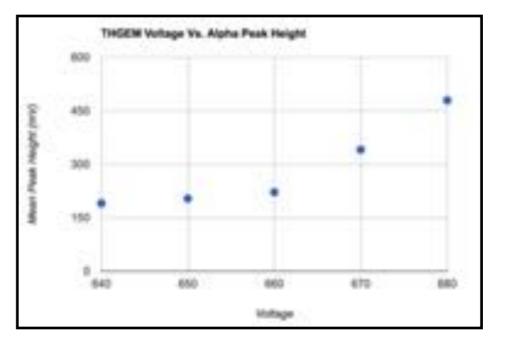
Simpler "1D-HT" Readout Concept

ThGEM 0.4mm hole dia., pitch 1mm, first data from alpha interactions - 2cm drift gap, 300 V/cm, 100 Torr CF₄,



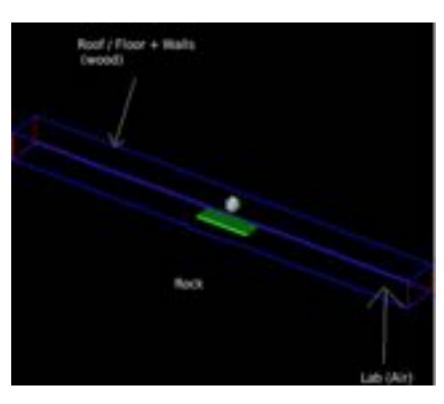


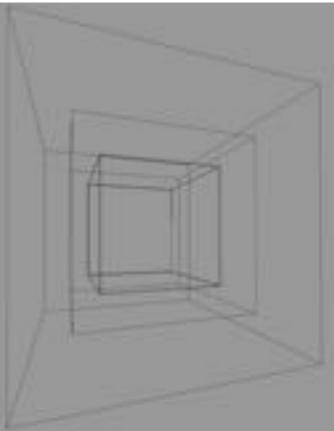




TPC Vessels & Neutron Backgrounds

- Neutron backgrounds in a 10 x 10 x 10m TPC required to achieve < 1 neutron in 3 years operation</p>
- 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 x10³-10⁴ times too much U/Th
- "SNO/DEAP" acrylic (~ 39 microBq/kg Th = 9.6 x 10⁻³ppb), 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) SF₆, (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

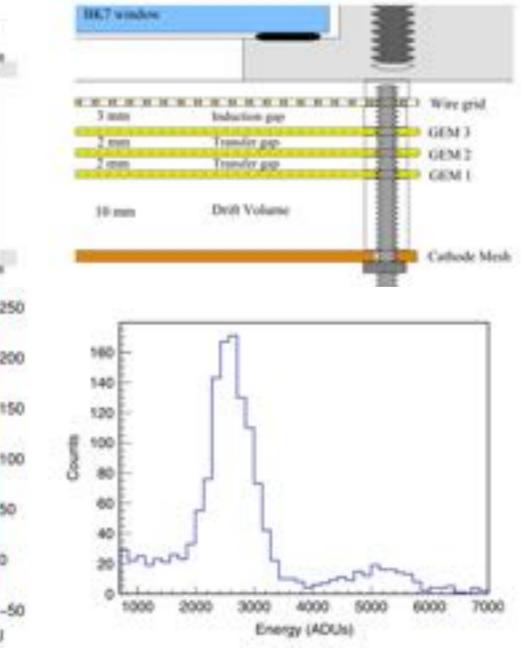


Backup Slides

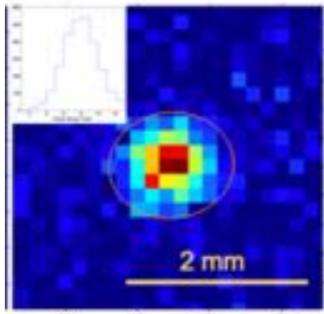
Low Energy Directionality Seen (UNM)

Recoil Directionality R&D is now D. Loomba et al., probing <20 keV region

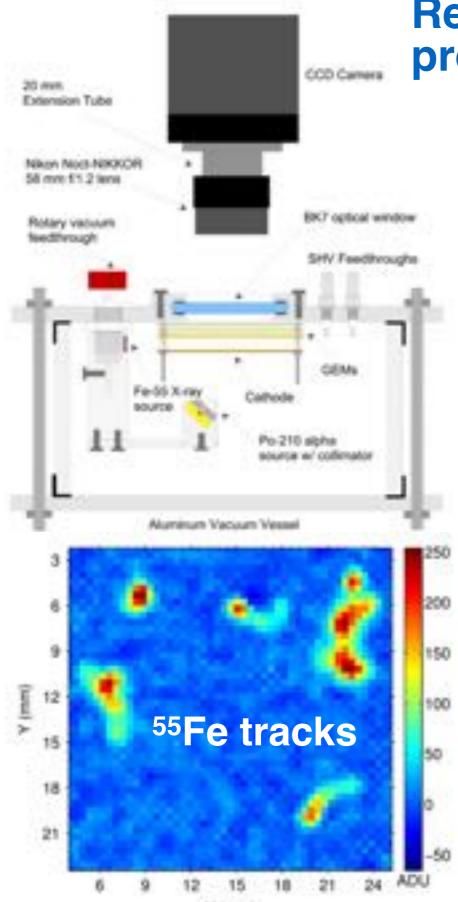
- CCD + triple GEM optical readout
 e.g. ⁵⁵Fe tracks resolved
- see upcoming papers by UNM



F recoil event of 10 keVee (23 keVrec) still shows direction



60 65 70 75 X Pixel



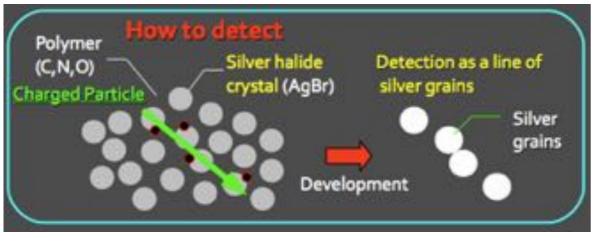
X (mm)

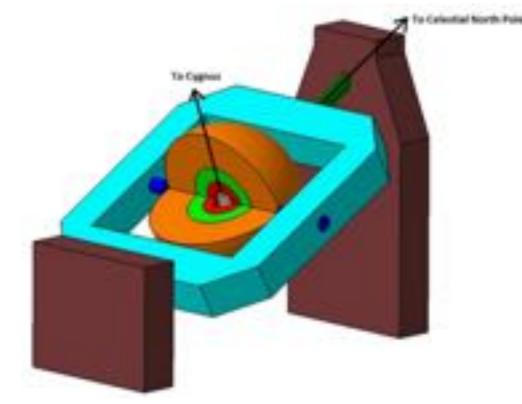
Nuclear Emulsions - NEWS

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

Concept: Use of emulsion film to give 3D tracking

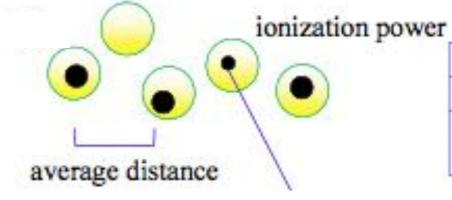
Solid (3g/cc), high spatial resolution, low cost, target Ag(46%), Br(34%), C(N,O) (19%)





R&D funded towards 1kg experiment

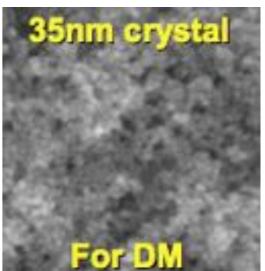
Track produces line of silver grains



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

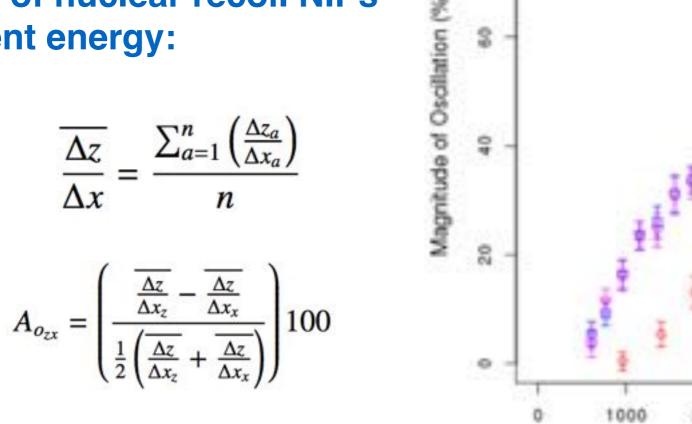
- Challenge is to get: (i) small grains <40nm (OPERA had 200 nm), (ii) closely packed, and (iii) sensitive to low ionisation
- Typical recoils are order 100nm Ag, Br likely produce tracks too short so need to use C, N, O target

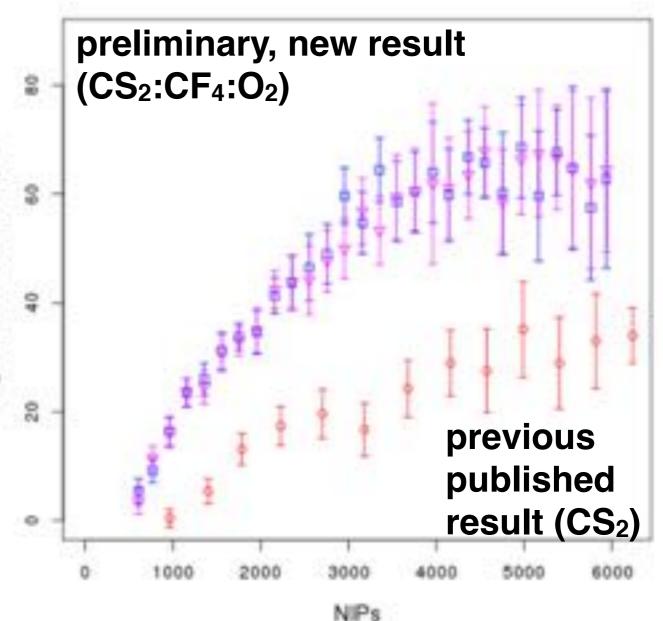




Axial Directionality also Maintained • Axial Directional sensitivity with z-fiducialisation

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





(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 ³²S recoil tracks.

Power of <u>TPC</u> Directionality

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



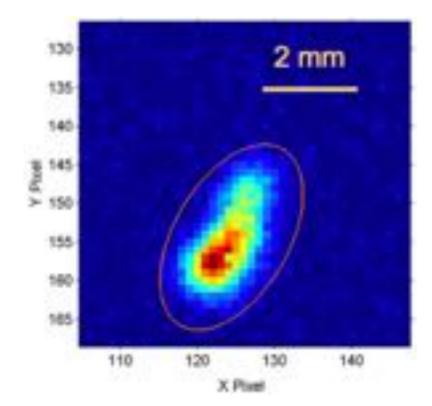
- Head-Tail Sensitivity
- Axial Sensitivity

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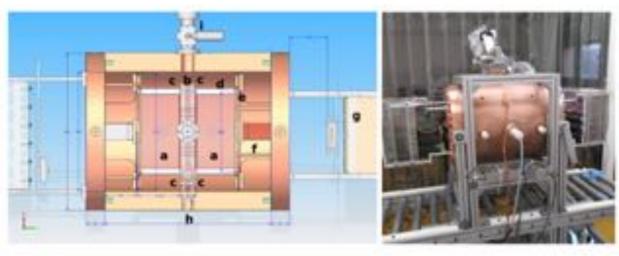
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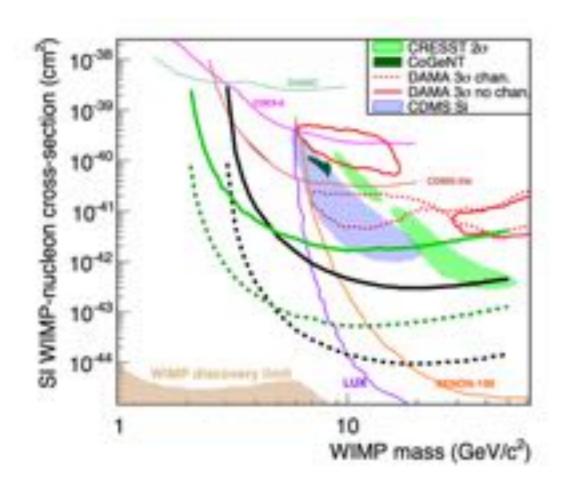


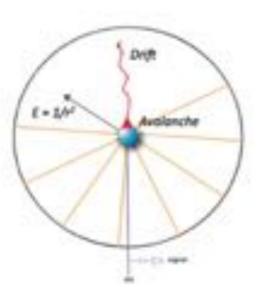
Example high energy F recoil in optical TPC (D. Loomba et al.)

Power of <u>TPC</u> Directionality

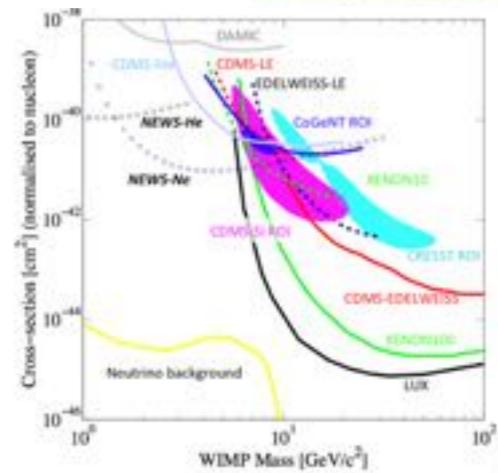
- Note TPCs have excellent particle ID anyway, so also good for low mass, non-directional, WIMP searches at higher pressure
 TDEX DM
 - TREX-DM





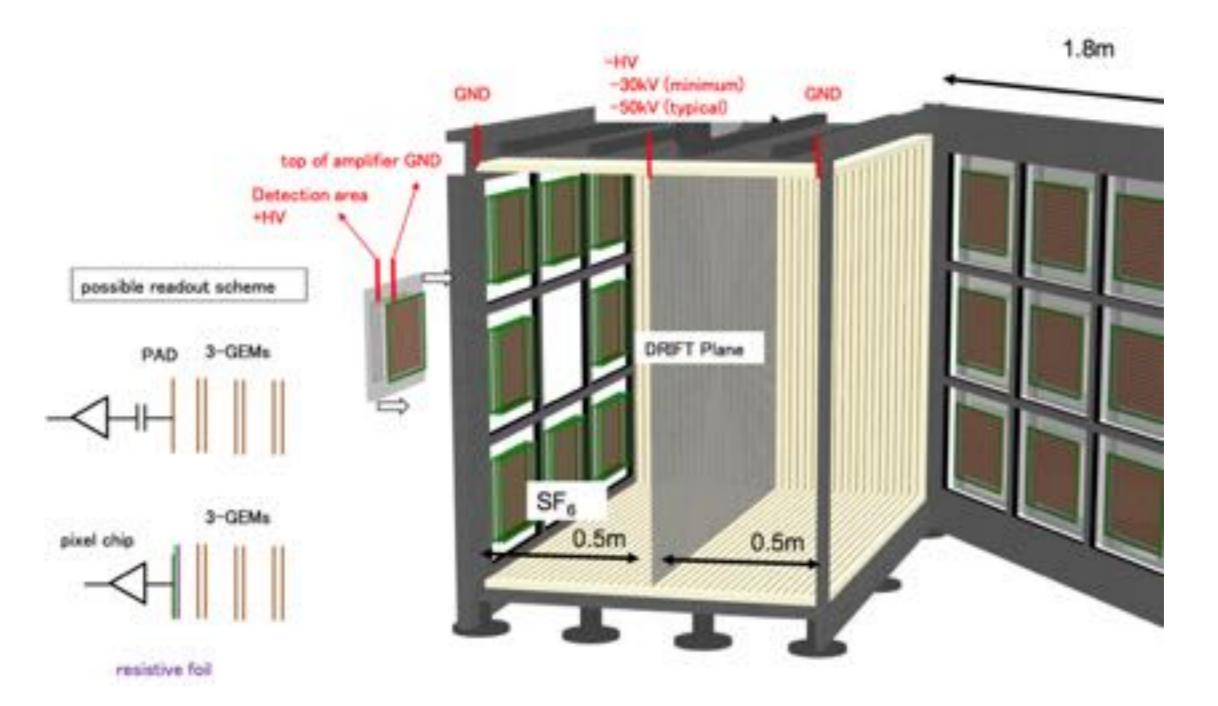




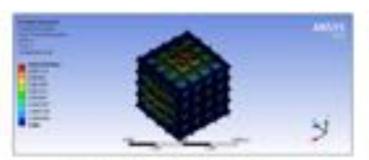


Other New Studies - Funded Activity

1 m³ CYGNUS test vessel (Japan)



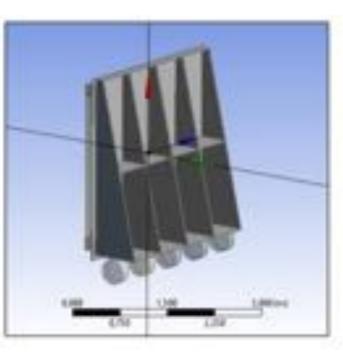
Other New Studies - Funded Activity



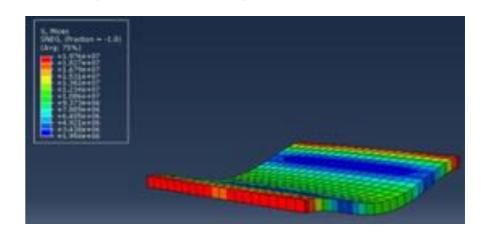
Tay, 3.1. "Applical deformationing in the International design process



Fig. 2.1. Fileness street or by control off of No Anti-Anti-



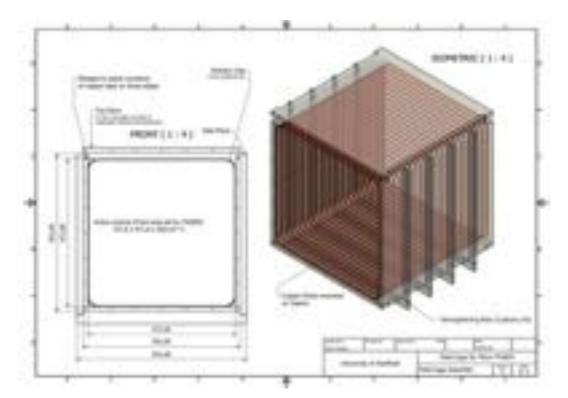
2.2 x 2.2 x 2.2 m Steel vessel (Australia)

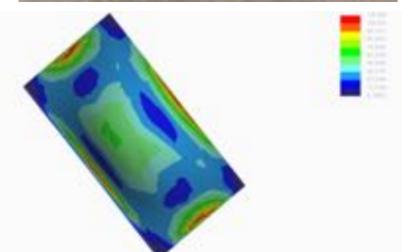






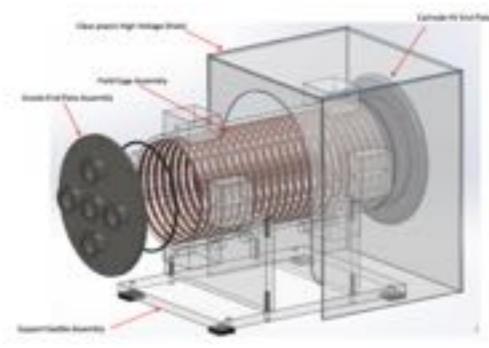
Water block neutron shielding (as for DRIFT-IId upgrade) (UK)

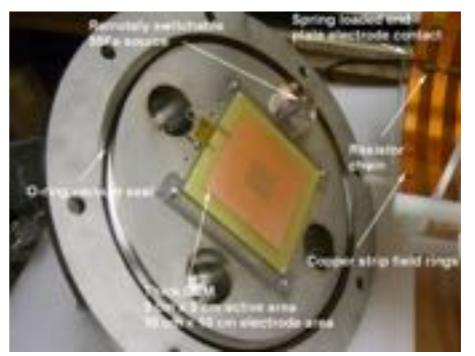




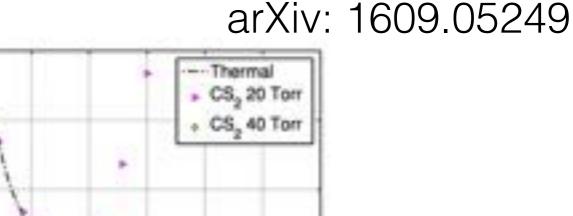
Low background Basic field cage design (UK)

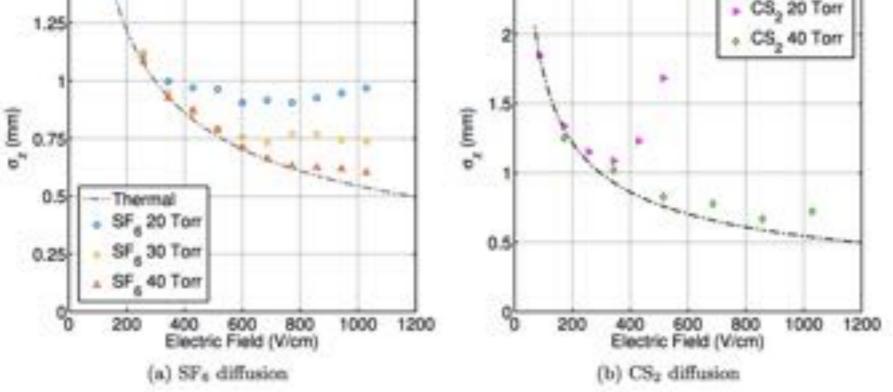
CYGNUS SF₆ Activity at UNM ► Demonstration of 2000-3000 gain in ThGEM N. Phan, D. Loomba University of New Mexico





Diffusion measurements





2.5

Neutron Background & Directionality

45.4 day unshielded run -

see 14 fast rock neutrons

54.7 day shielded run no events seen

Nips vs Pl z Nips vs Pi z Background All Unshielded, 433SumRisetime Background All Shielded, 433SumRisetime 45.4 days, 201 events, 4.43 +/- 0.3 events per day 54.7 days, 185 events, 3.38 +/- 0.2 events per day Cathode ب دار در دور و در و در و در و در در 2 윻 2 z (0m) 8 2 sharker' will a 10 metric. If all 10 metrics per sta secondary of the local second s MWPC MWPC 0 1000 2000 4000 5000 6000 3000 5000 1000 2000 4000 6000 Anode Nips Anode Nips

Consistent with Boulby neutron flux of 7 x 10⁻⁷ n/cm²/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 resolu- tion ¹³	Enery thresh- old ¹⁴	Angular resolution	Sense recog- nition threshold
MWPC	DRIFT	NI CS ₂ CS ₂ :CF ₄ CS ₂ :CF ₄ :O ₂	2 mm ΝΑ Ι μs	2×2	0.8 m ³	~1000	42% [242]	50 keV, [64] 30 keV, [243]		50 keV, [64] 40 keV, [243]
Micromegas	MIMAC	EG Mix of CF4, CHF3, and C4H20	0.42 mm 0.42 mm 20 ns	2×1	5 L.	2 × 10 ²	22% [130]	~1 keV _{ee} [134]	unpublished	unpublished
μPIC	NEWAGE	EG CF4	0.4 mm 0.4 mm 10 ns	0.3×0.3	36L	1000	23% [142] 47% at 50 keV _{ce} [150	50 keV _{ee} (directional) [150]	40° at 50 keV _{se} [150]	75 keV _{et} [244
ATLAS Pixel chips	D3	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]	$\frac{\sqrt{12}\sigma}{L\sqrt{N}}$ radi- ans [166] ¹⁶	unpublished
Optical	DMTPC	EG CF4	0.3- 0.6 mm 0.3- 0.6 mm NA ¹⁷	NA ¹⁸	20L (1 m ³)	NA	35% at 80 keV, [220]	20 keV _{ee} [205]	15° at 20 keV _{re} [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