Roma International Conference on AstroParticle Physics RICAP-24

Directional Dark Matter searches and the CYGNUS project

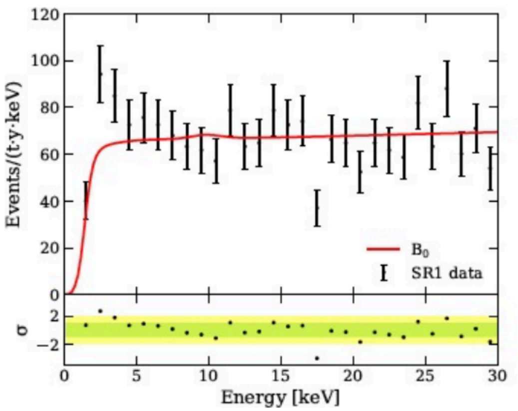
Elisabetta Baracchini

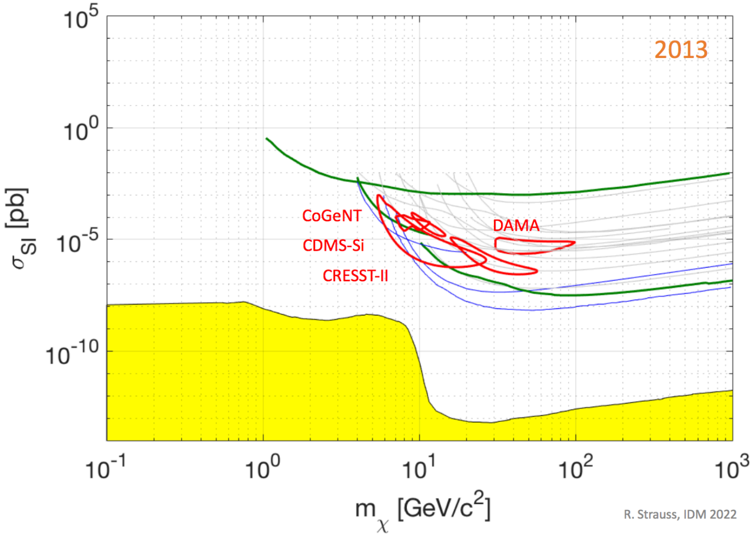
on behalf of the CYGNUS proto-collaboration

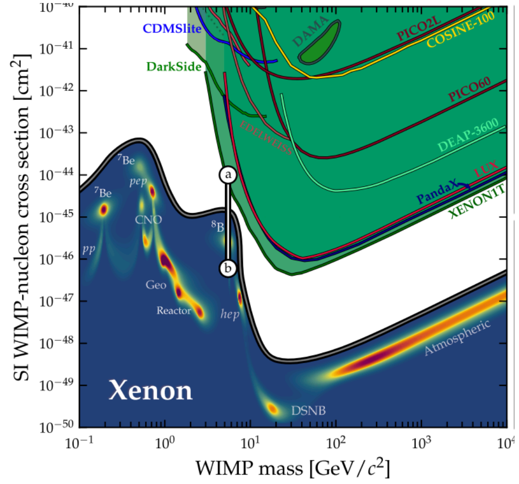
Dark Matter: a search hampered by many false promises…

i.e. many things can look like a signal if you don't know where they are coming from

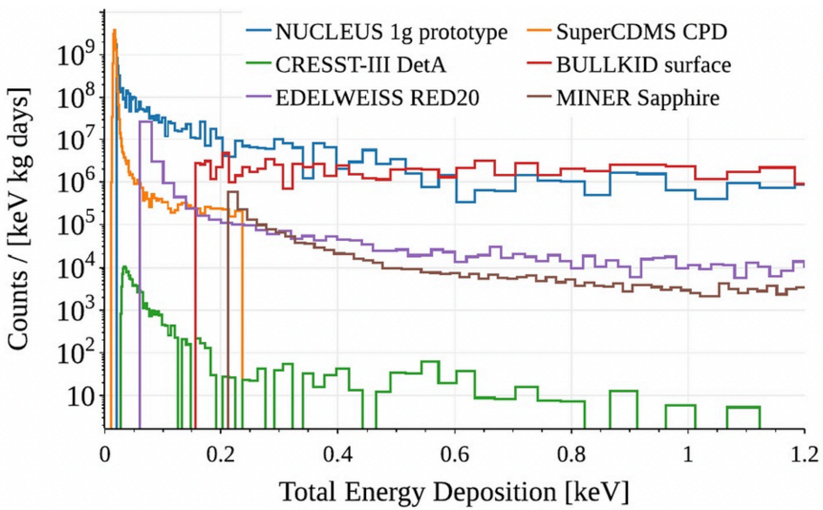
Direction is the only way







[The Low Energy Excess (LEE) SciPost Phys.Proc. 9 (2022) 001]



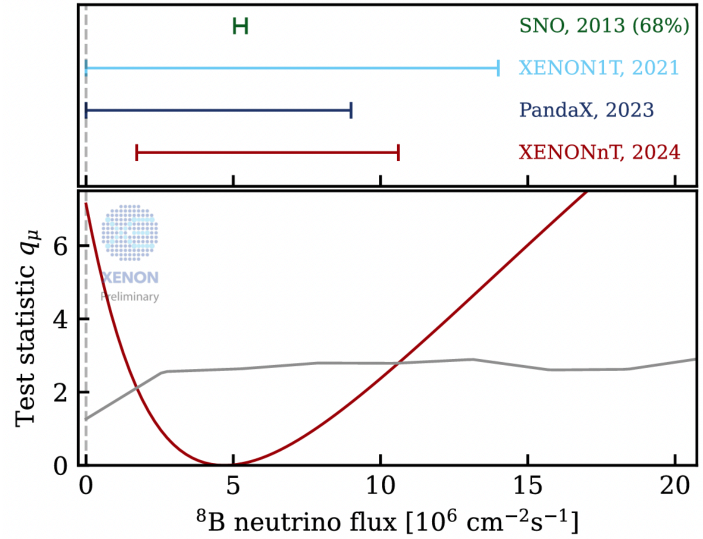
- huge difference in rate between above ground and underground measurements
- CRESST observes by far the lowest LEE rate
- more underground measurements needed to identify the nature of the residual LEE

[From C. Strandhagen IDM 2024 Plenary Talk "The Low Energy Excess(es) in Cryogenic Detectors"]

...and one certainty: the Neutrino Fog

R. Biondi
Tue 15.25

XenonNT arXiv:2408.02877

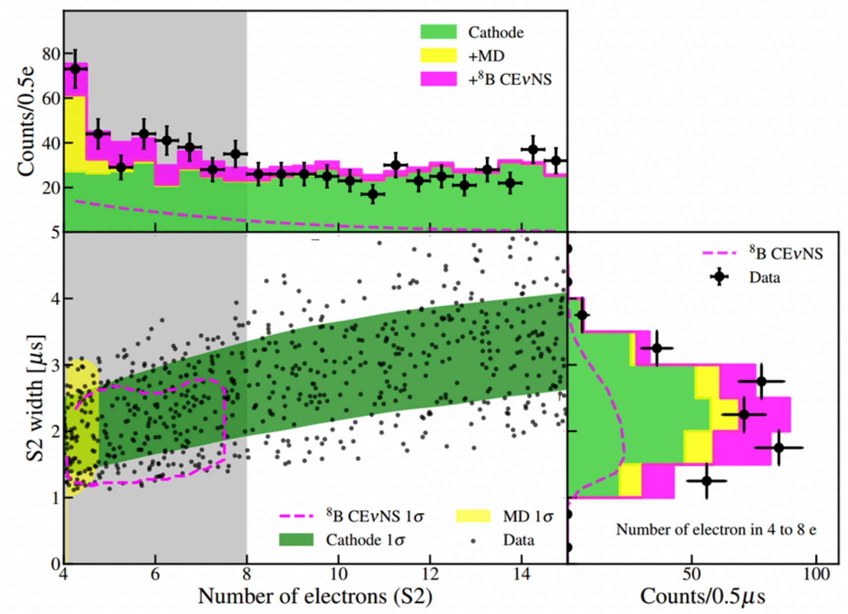


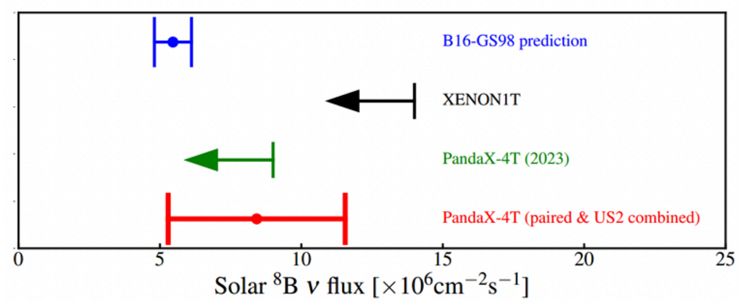
Component	Background only fit	Background + ^{8}B fit	Nominal Expectation
AC - SR0	7.55	7.36	7.48 ± 0.52
AC - SR1	18.26	17.90	17.77 ± 1.23
ER	0.74	0.54	0.68 ± 0.68
NR	0.50	0.45	0.47 ± 0.32
Total Background	27.05	26.24	26.4 ± 1.5
^{8}B	-	10.71	11.9 ± 3.1
Observed		37	

The background-only hypothesis is disfavored at 2.73σ

X. Cui
Tue 15.08

Panda-X arXiv:2407.10892





- Reject bkg-only hypothesis with significance of 2.64σ, with best-fit B8 events is 75±28 (US2) and 3.5±1.3 (paired);

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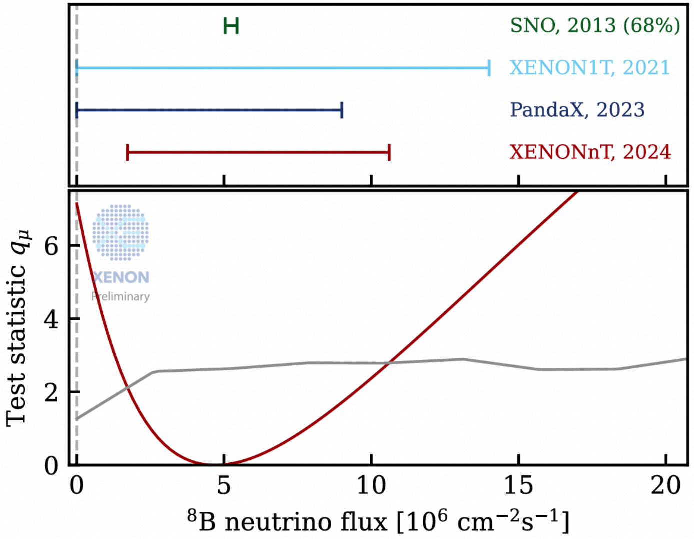

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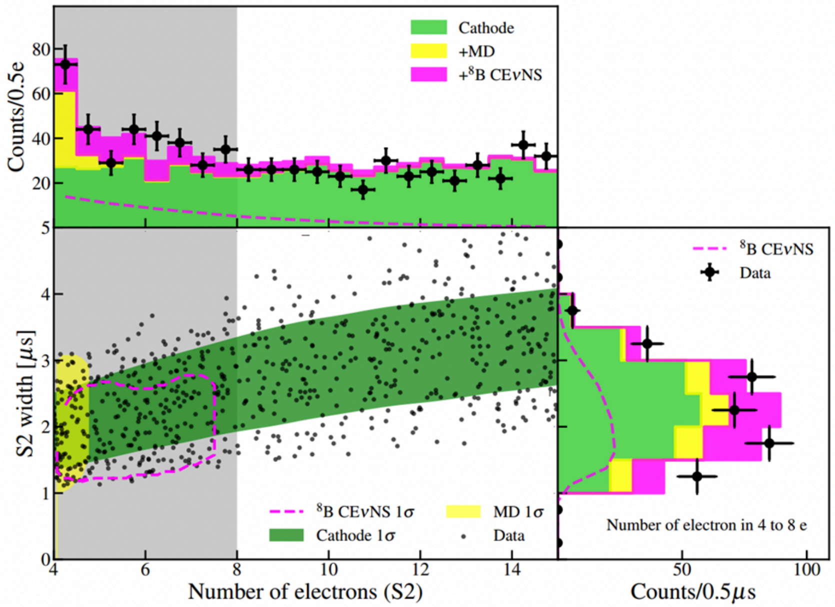
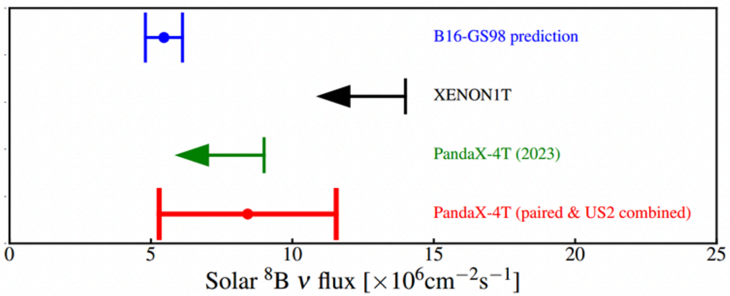




- Reject bkg-only hypothesis with significance of 2.64σ, with best-fit B8 events is 75±28 (US2) and 3.5±1.3 (paired);

A provocative question: where is the positive proof that these are not 6 GeV WIMPs?

The Neutrino Fog future

D. S. Akerib et al., 2022 Snowmass Summer Study, arXiv:2203.08084

C. A. J. O'Hare, Phys. Rev. Lett. 127 (2021) 25, 251802

- **Discovery limit as function of the observed *N* neutrino background events and uncertainty δΦ on neutrino fluxes**

Background free

$$N < 1, \sigma \propto 1/N$$

Poissonian background subtraction

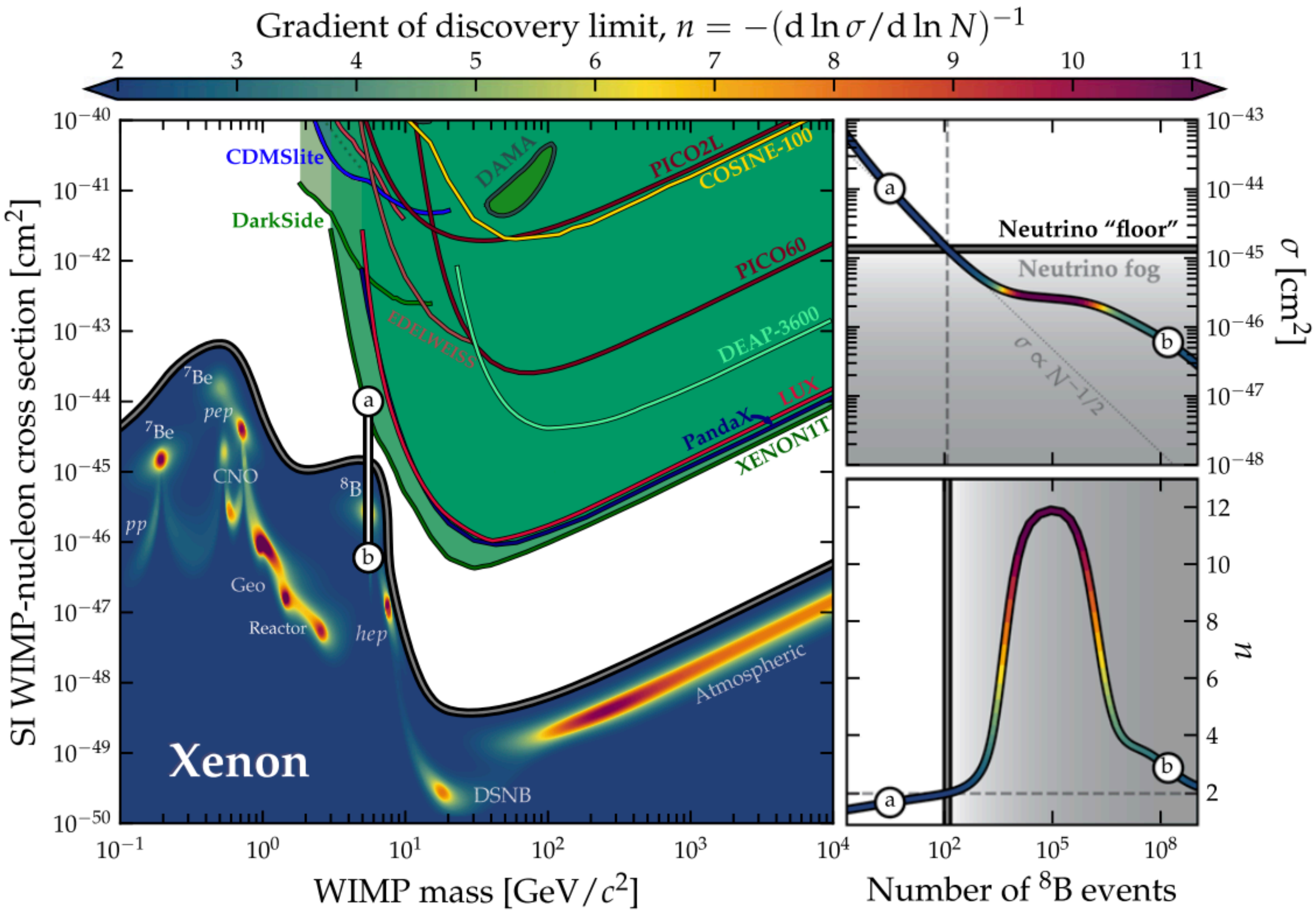
$$N\delta\Phi^2 \ll 1, \sigma \propto 1/\sqrt{N}$$

Purely dominated by systematics

$$N\delta\Phi^2 \gg 1, \sigma \propto \sqrt{(1 + N\delta\Phi^2)/N}$$

- ***n*** **is defined so that *n = 2* under normal Poissonian subtraction, and *n > 2* when there is saturation**
  - **The value of the cross section *σ* at which *n* crosses 2 is defined as the neutrino floor.**

$$n = -\left(\frac{d \log \sigma}{d \log MT}\right)^{-1}$$



Reducing the sensivity of an experiment by a factor *x* requires an increas in the exposure by *at least x^n*

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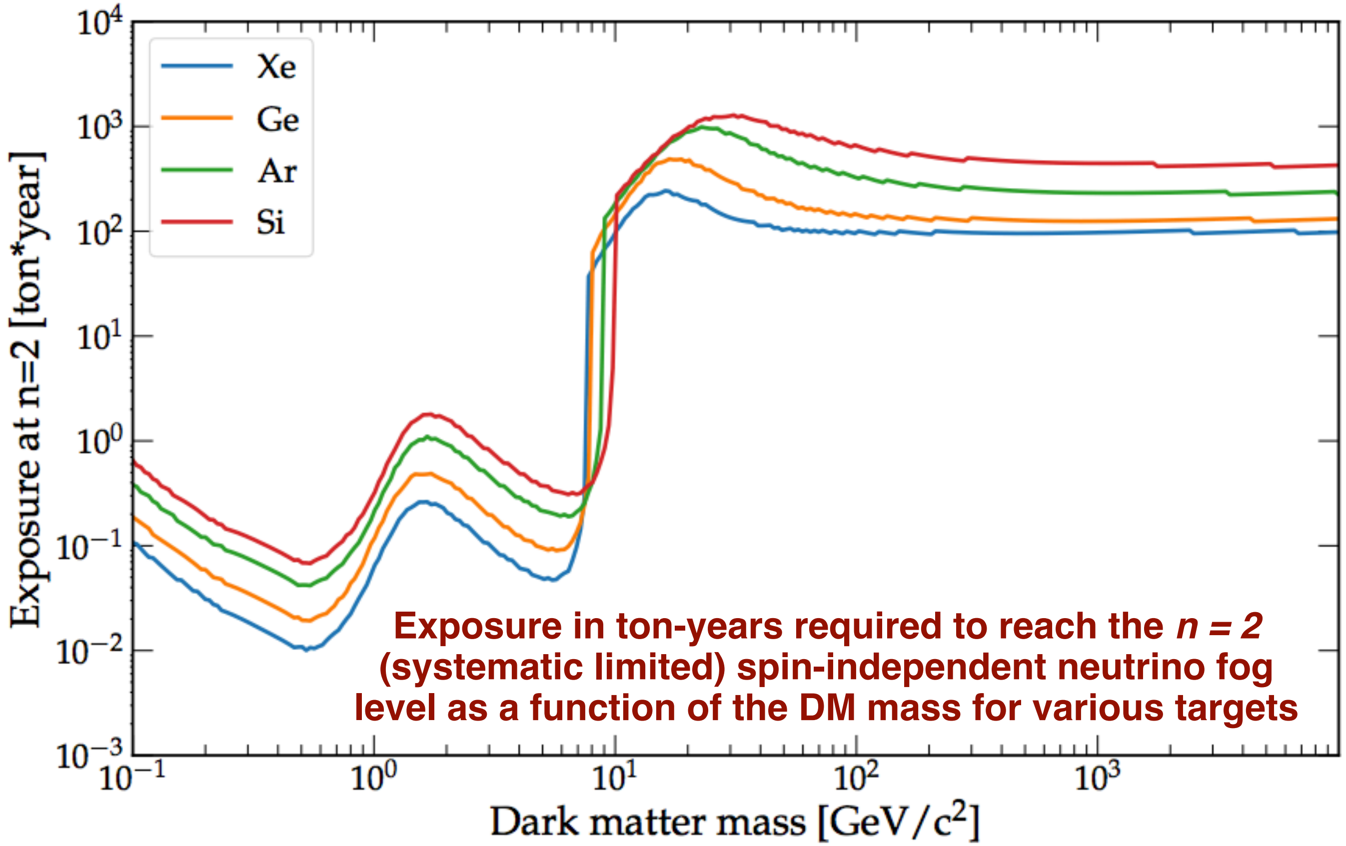
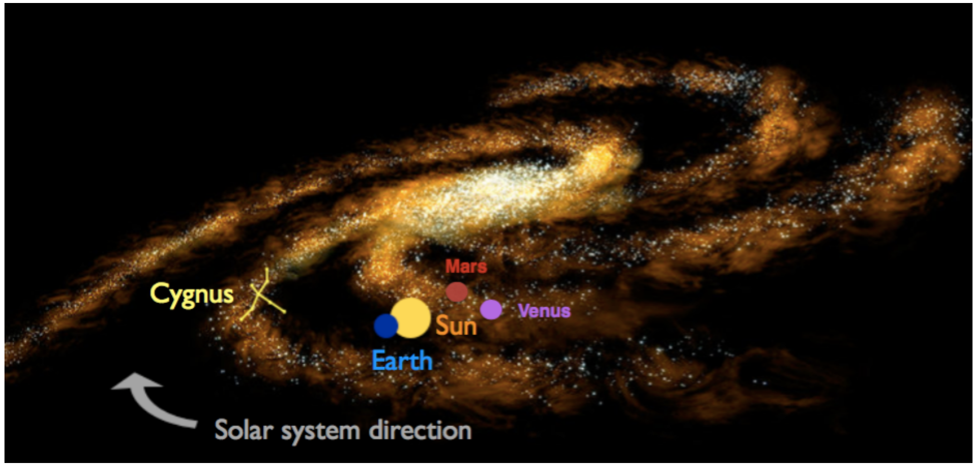
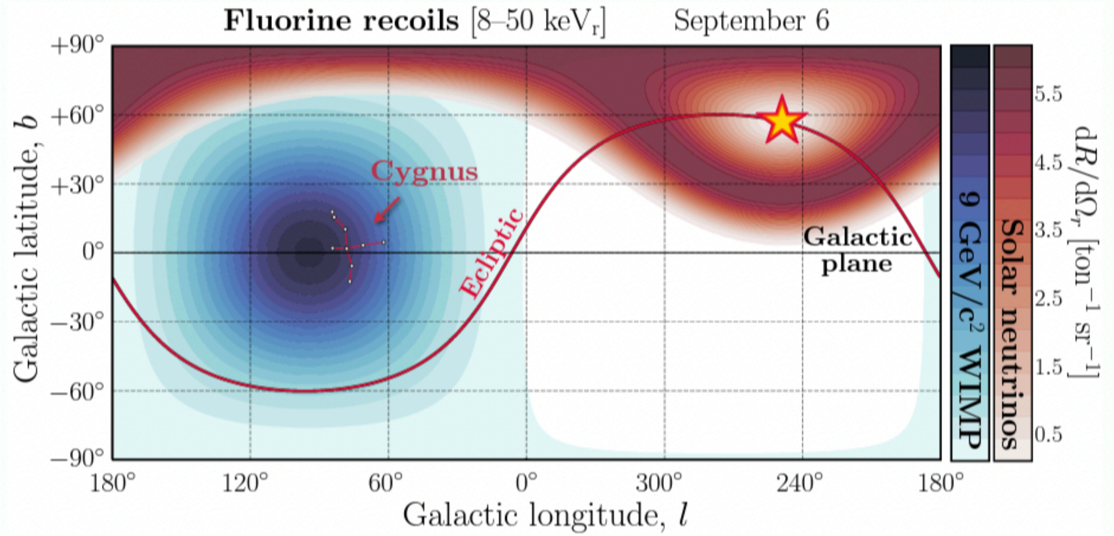


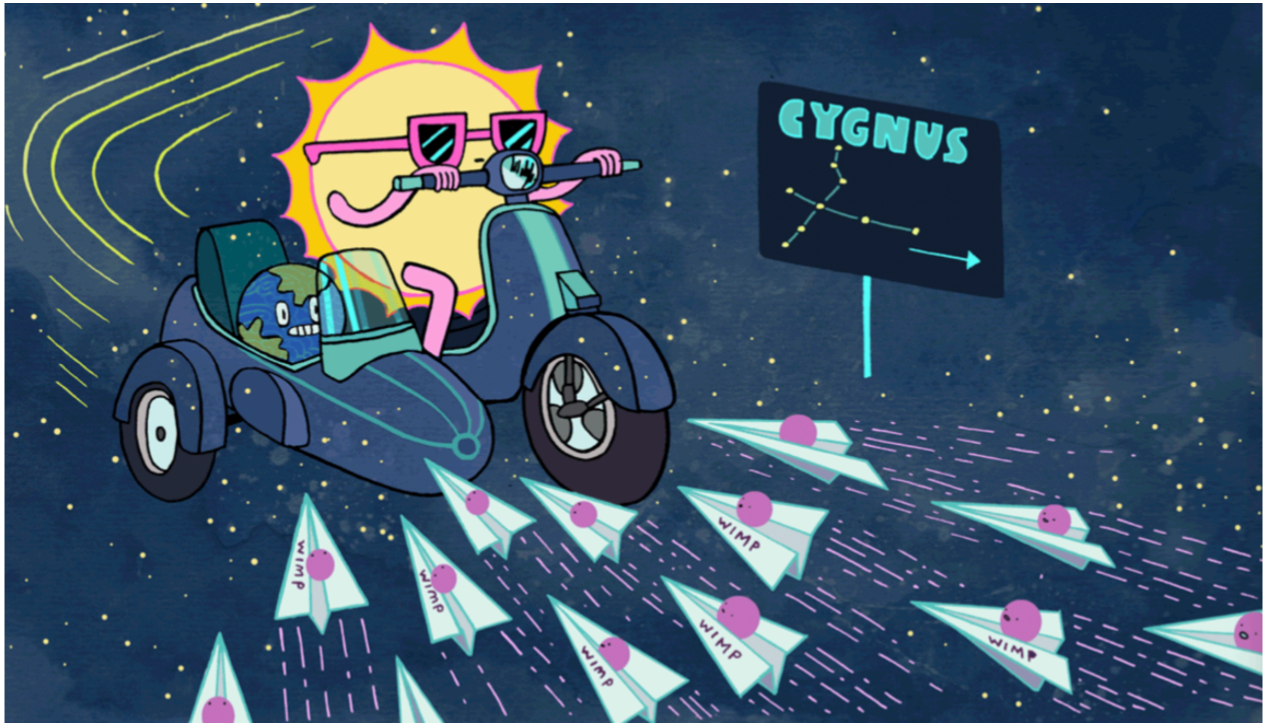
Reducing the sensivity of an experiment by a factor *x* requires an increas in the exposure by *at least* x^n

The return on investment becomes no more favourable

Driving towards CYGNUS with a DM wind blowing in our hairs

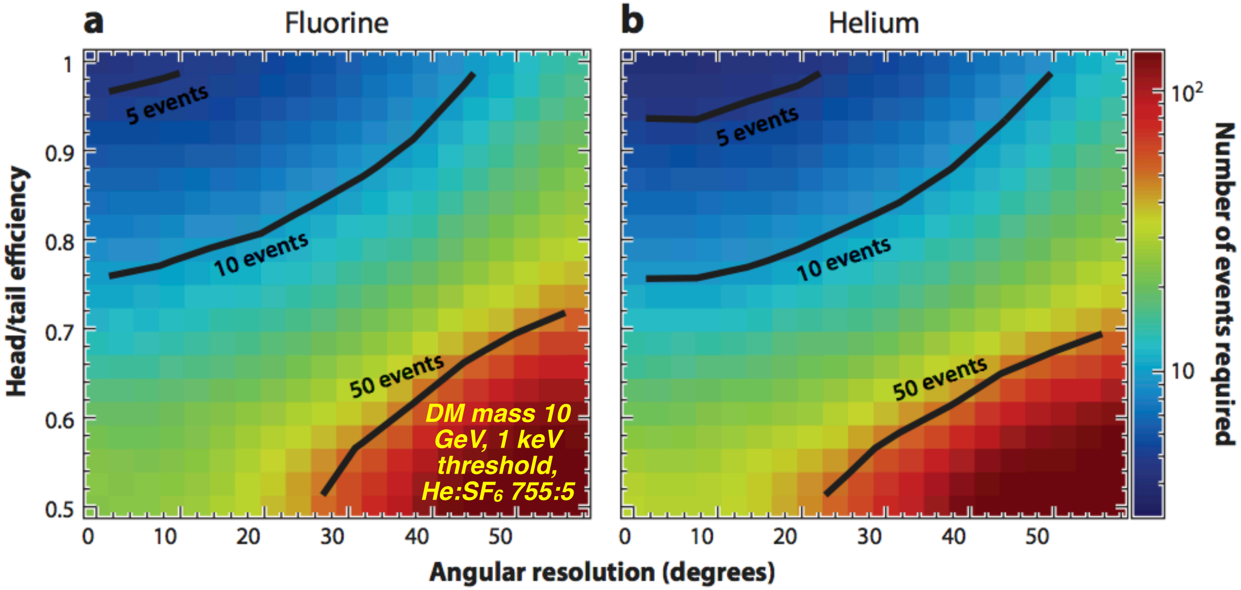






Diving into the neutrino fog with directionality

Required number of detected He and F recoils to exclude solar neutrinos at 90% C.L. vs angular resolution and head-tail efficiency



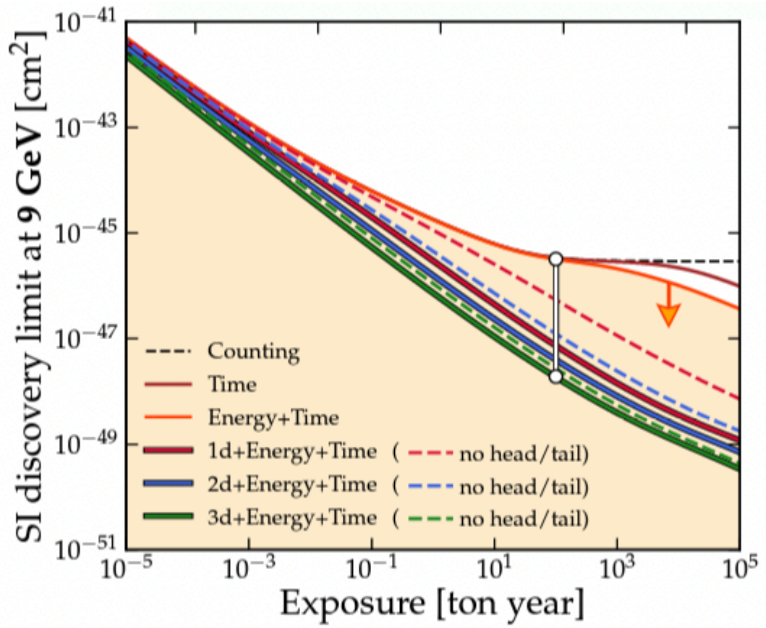
- Angular resolution <30°
- Correct head / tail >75% of the time
- Fractional energy resolution < 20%

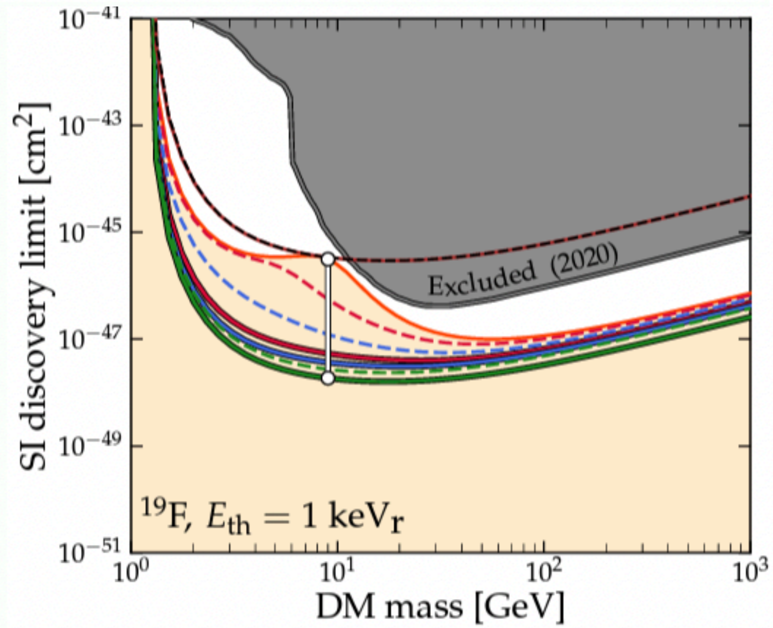
If you don't achieve these then directionality adds nothing to the sensitivity (in the context of the ν fog)

And achieved…

- At the level of individual events
- In as high a density target as possible
- Below <10 keVr
- With a timing resolution better than a few hours

Full recoil imaging needed!



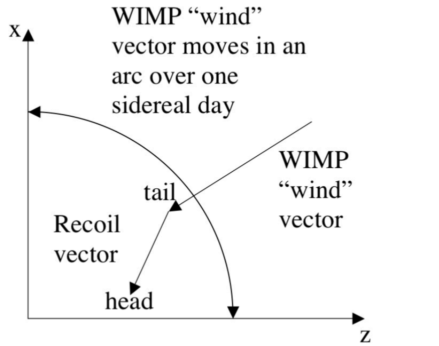


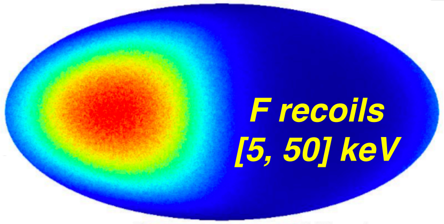
C. A. J. O'Hare, Phys. Rev. Lett. 127 (2021) 25, 251802

S. Vahsen et al., Ann. Rev. Nucl. Part. Sci. 71 (2021) 189-224

Positive discovery

signal events to reject isotropy == to claim positive discovery





M=100 GeV

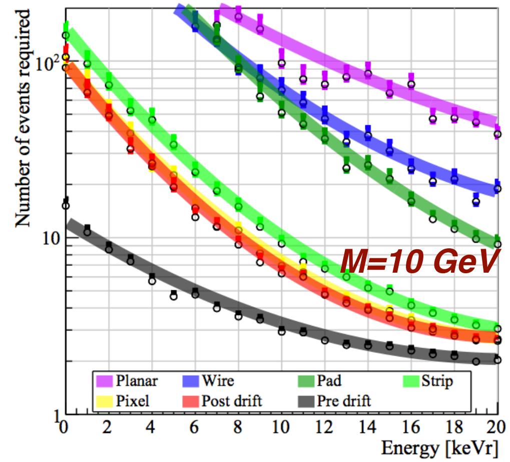
Baseline == 3D, 20 keV energy threshold and no background

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

A. M. Green and B. Morgan, Astropart. Phys. **27** (2007) 142

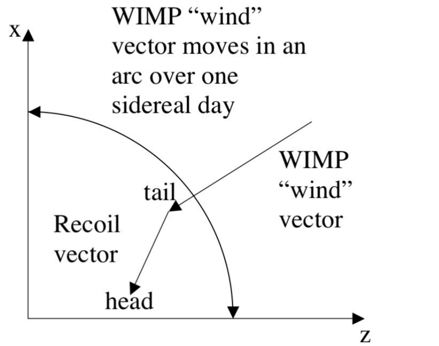
for various level of tracking capabilities & backgrounds

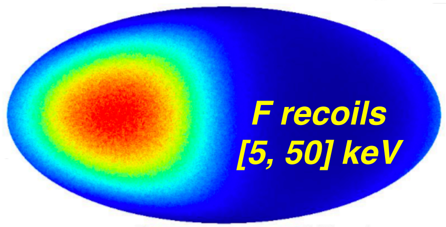
arXiv:2008.12587



for gaseous TPC with various readout

Positive discovery, identification





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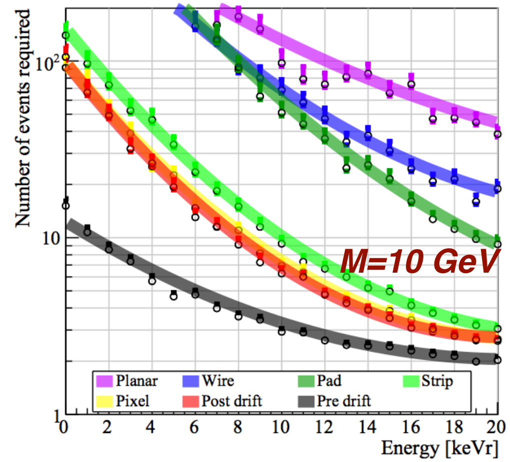

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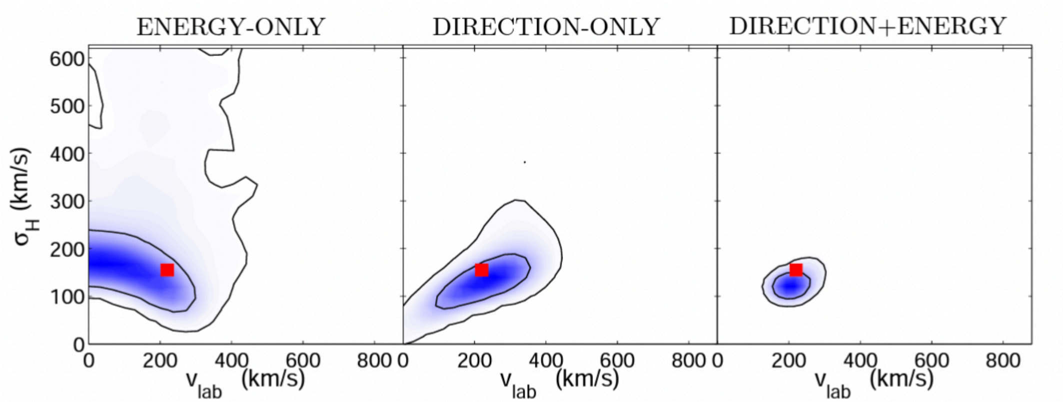
Phys.Rept. 627 (2016) 1-49



Positive discovery, identification & astronomy

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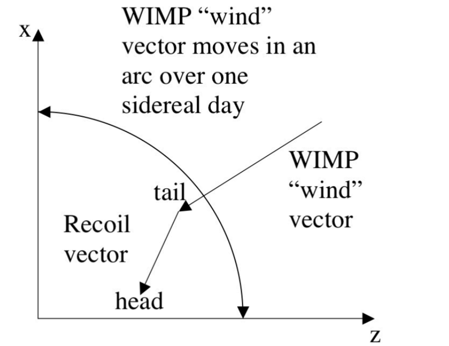

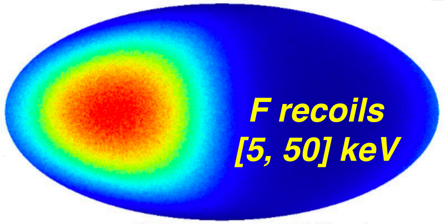

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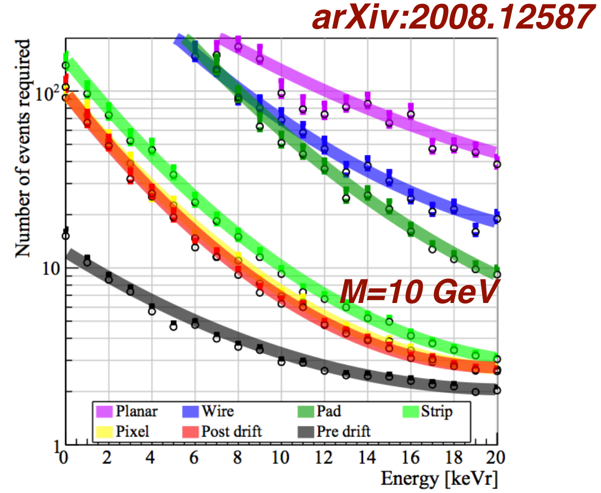

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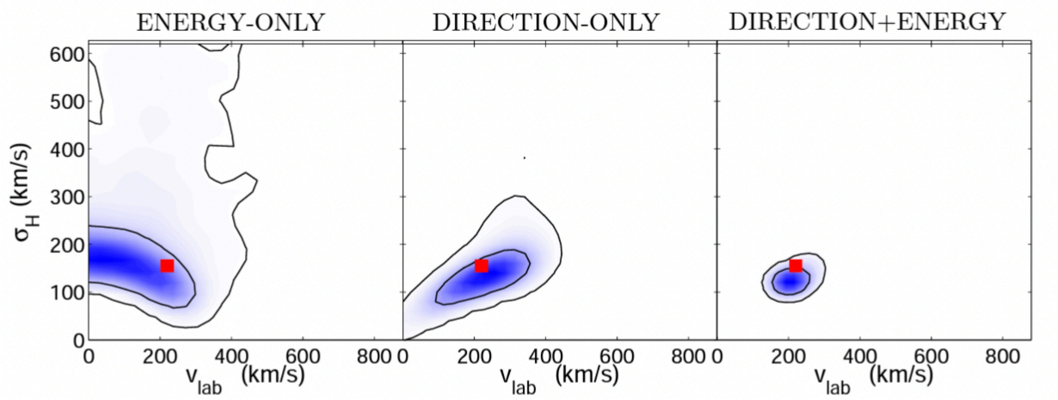
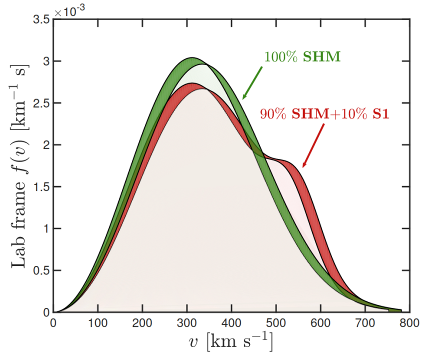
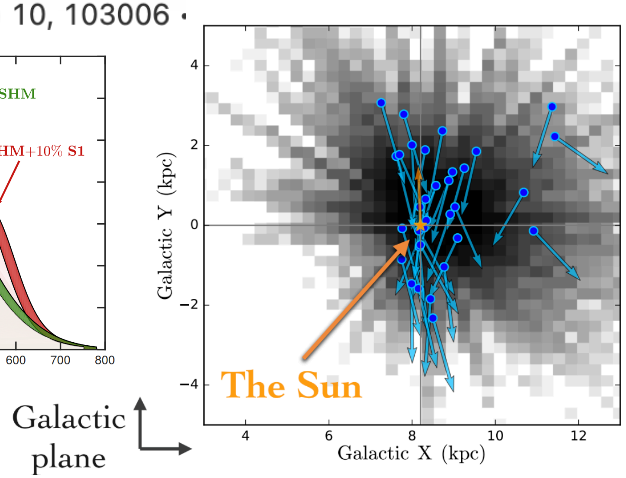


Phys.Rev.D 98 (2018) 10, 103006





Detector classes by directional information

S. Vahsen et al., Ann. Rev. Nucl. Part. Sci. 71 (2021) 189-224 revisited

Indirect | **Recoil imaging**

Statistical | **Event-level**

Modulation-based directionality → Indirect recoil event directionality → Time-integrated recoil imaging → Time-resolved recoil imaging

A. Leoncini
Tue 17.17

Anisotropic scintillators
- No event-level directions
- Exploits modulation of DM with respect to crystal axes

Carbon nanotubes (ER directionality)

Anisotropic energy threshold in Ge (MeV DM)

Columnar recombination
- Event-level 1d directions
- No head/tail
- Direction and energy are not independent

Nuclear emulsions
- 2d recoil tracks, without head/tail
- No event times recorded

DNA detector
- 3d recoils without head/tail
- No event times recorded

Gas TPC
- Head/tail measurable
- 1d, 2d or 3d
- Independent energy/direction measurement

Crystal defects
- 3d track topology
- Head/tail measurable

Levitated optomechanics (DM nuggets)

Demonstrated (green)
R&D (blue)
Proposed (red)
New proposal @ IDM 2022 (yellow)

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<u>*S. Vahsen et al., Ann. Rev. Nucl. Part. Sci. 71 (2021) 189-224 revisited*</u>

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Levitated optomechanics (DM nuggets)

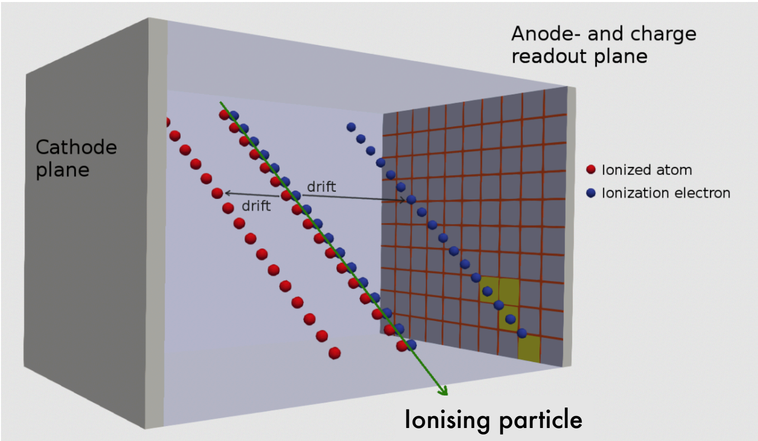
Nuclear emulsion needs an Equatorial Telescope to dive into the Neutrino Fog due to lack of timing information

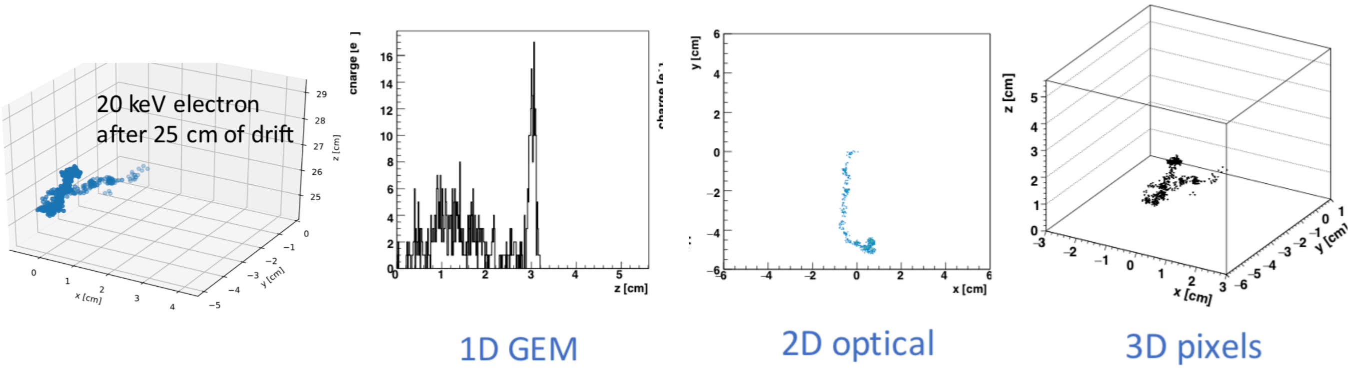
Gas TPC is the only demonstrated technology able to provide positive discovery within the Neutrino Fog

Demonstrated
R&D
Proposed
New proposal @ IDM 2022

Gaseous TPC experimental approach

Depending on the anode segmentation (x-y) and time sampling (z), tracks can be reconstructed in 1D, 2D or 3D





Energy + particle ID + 3D position + recoil angle + vector sense

Less event information → **More event information**

Improved background discrimination
More physics cases per exposure

The CYGNUS project

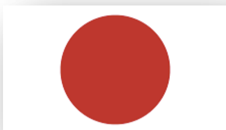
Since fall 2016

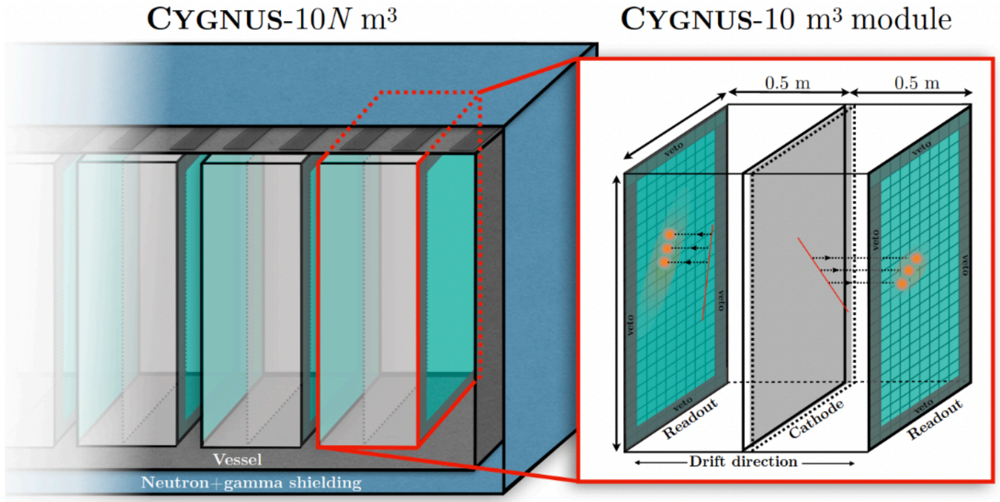
CYGNUS proto-collaboration vision

A multi-site, multi-target Galactic Directional Nuclear and Electron Recoil Observatory at the ton-scale to probe Dark Matter below the Neutrino Floor and measure solar Neutrinos

- About 70 members
- Steering group:
  - Elisabetta Baracchini (GSSI/INFN, Italy)
  - Greg Lane (Canberra, Australia)
  - Dinesh Loomba (New Mexico, USA)
  - Kentaro Miuchi (Kobe, Japan)
  - Ciaran O'Hare (Sidney, Australia)
  - Neil Spooner (Sheffield, UK)
  - Sven Vahsen (Hawaii, USA)



- **Helium/Fluorine gas mixtures at 1 bar**
  - **Sensitivity to O(GeV) WIMP for both SI & SD couplings**
- **Reduced diffusion**
  - **Through negative ion drift or "cold" gases (CF_4)**
- **3D fiducialization**
  - **Through minority carriers or fit to diffusion**
- **Directional threshold at O(keV)**
- **Full background rejection at O(keV)**
- **Both electronic and optical charge readout investigated**

arXiv:2008.12587

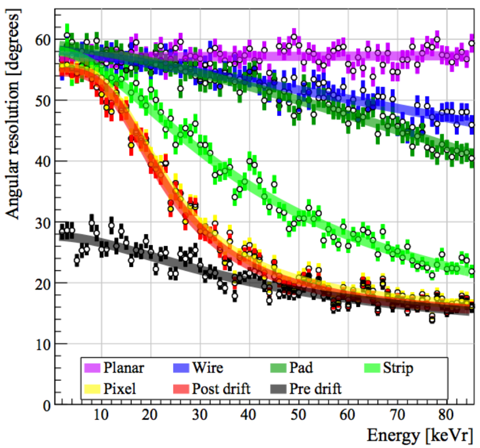
Cygnus: Feasibility of a nuclear recoil observatory with directional sensitivity to dark matter and neutrinos

S. E. Vahsen,[1] C. A. J. O'Hare,[2] W. A. Lynch,[3] N. J. C. Spooner,[3] E. Baracchini,[4,5,6] P. Barbeau,[7] J. B. R. Battat,[8] B. Crow,[1] C. Deaconu,[9] C. Eldridge,[3] A. C. Ezeribe,[3] M. Ghrear,[1] D. Loomba,[10] K. J. Mack,[11] K. Miuchi,[12] F. M. Mouton,[3] N. S. Phan,[13] K. Scholberg,[7] and T. N. Thorpe[1,6]

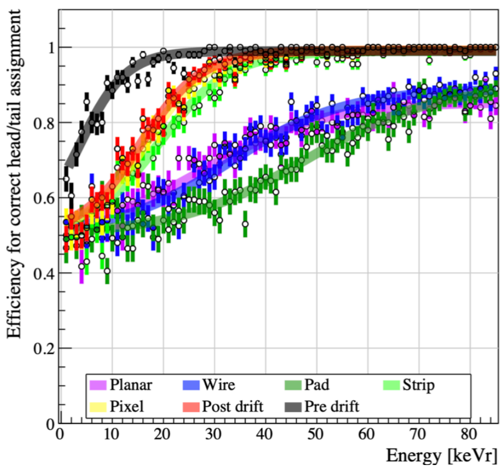
- **Extensive concept paper on 1000 m^3 gaseous NITPC detector focused on technical feasibility and WIMP searches through nuclear recoils**
- **Detailed simulation of seven readout options with with a cost/benefit FOM**
- **Background discrimination studies**
- **Detailed simulation and study of all internal and external backgrounds**
- **Engineering studies for a 1000 m^3 detector**

Negative ion drift in He:SF_6 755:5 Torr

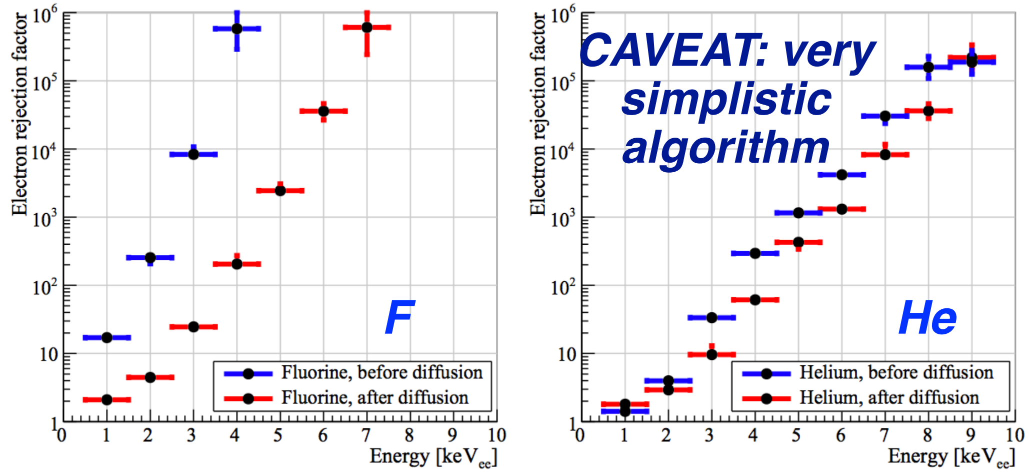
Angular resolution



Sense recognition



Electron recoil rejection

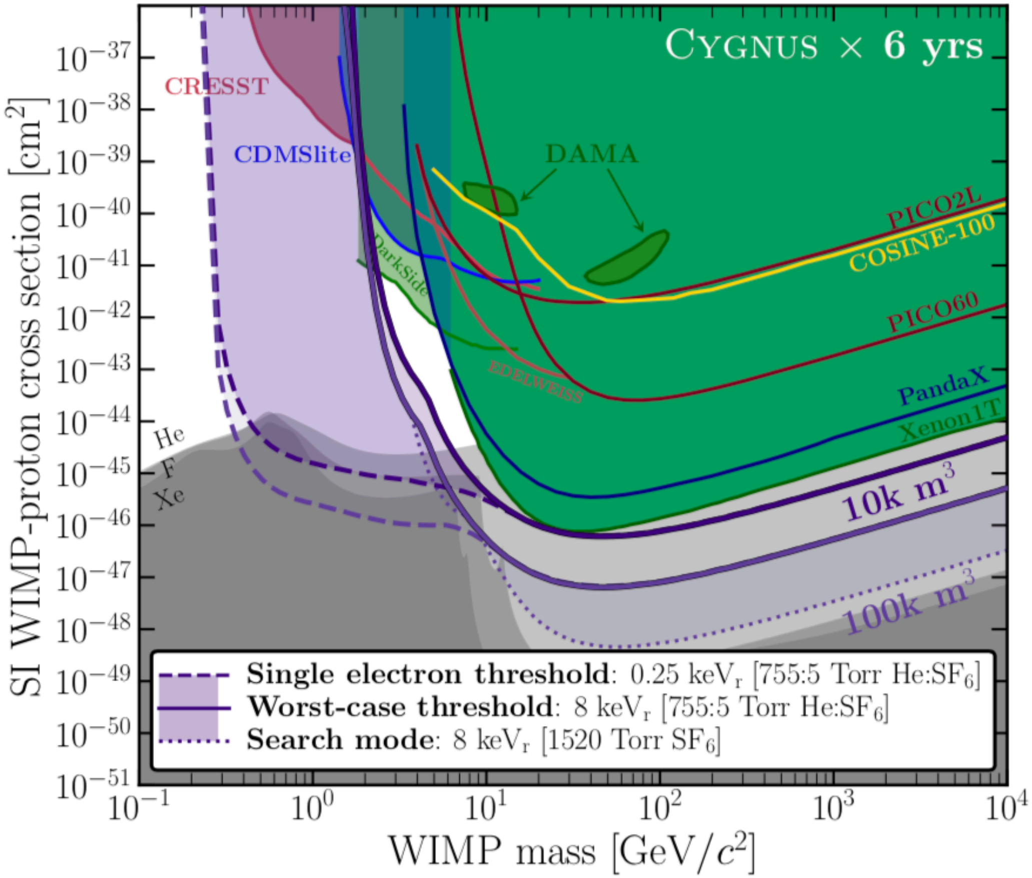


- **Pixels extract the entire directional information left after diffusion**
- **Strips readout perform almost as pixels, but at much lower costs**
- **Rejection at O(keV) possible, > 10^6 at 10 keV_{nr}**

CYGNUS 1 ton WIMP searches expected sensitivity

NID operation

He:SF_6 755:5

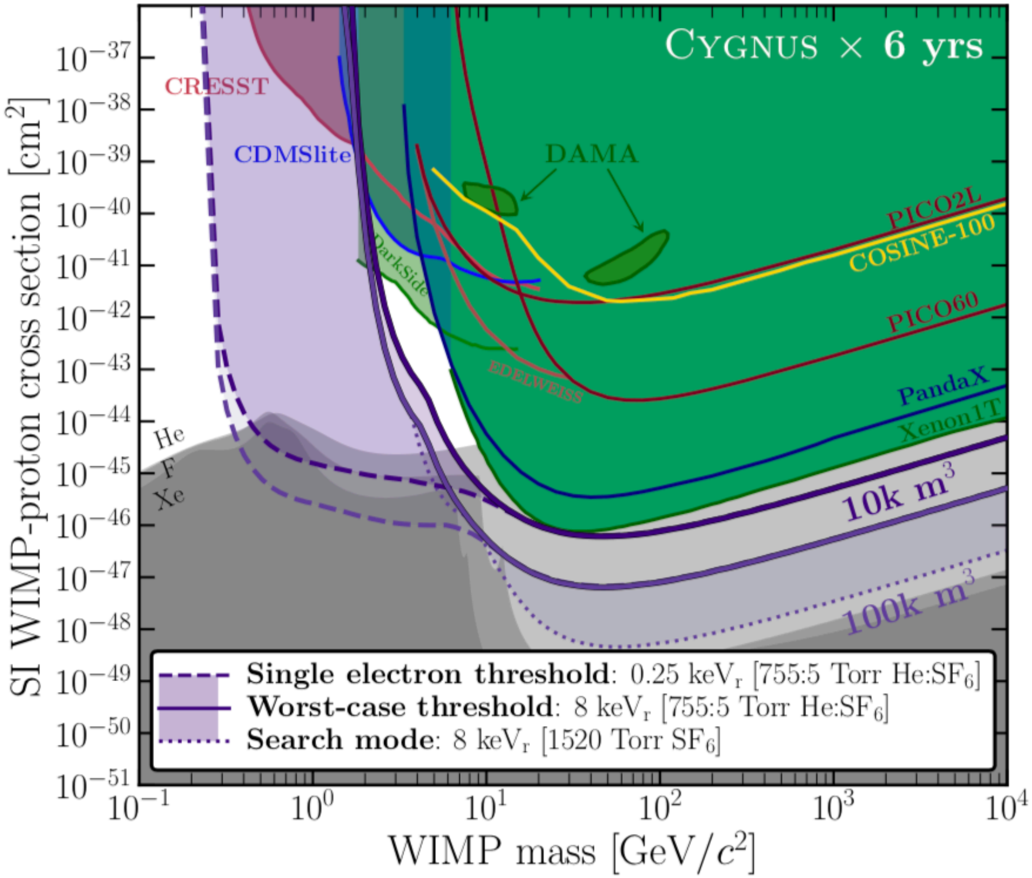


Significant improvement in SI in the low WIMP mass region, expect 10-50 IDENTIFIED neutrino nuclear recoil events

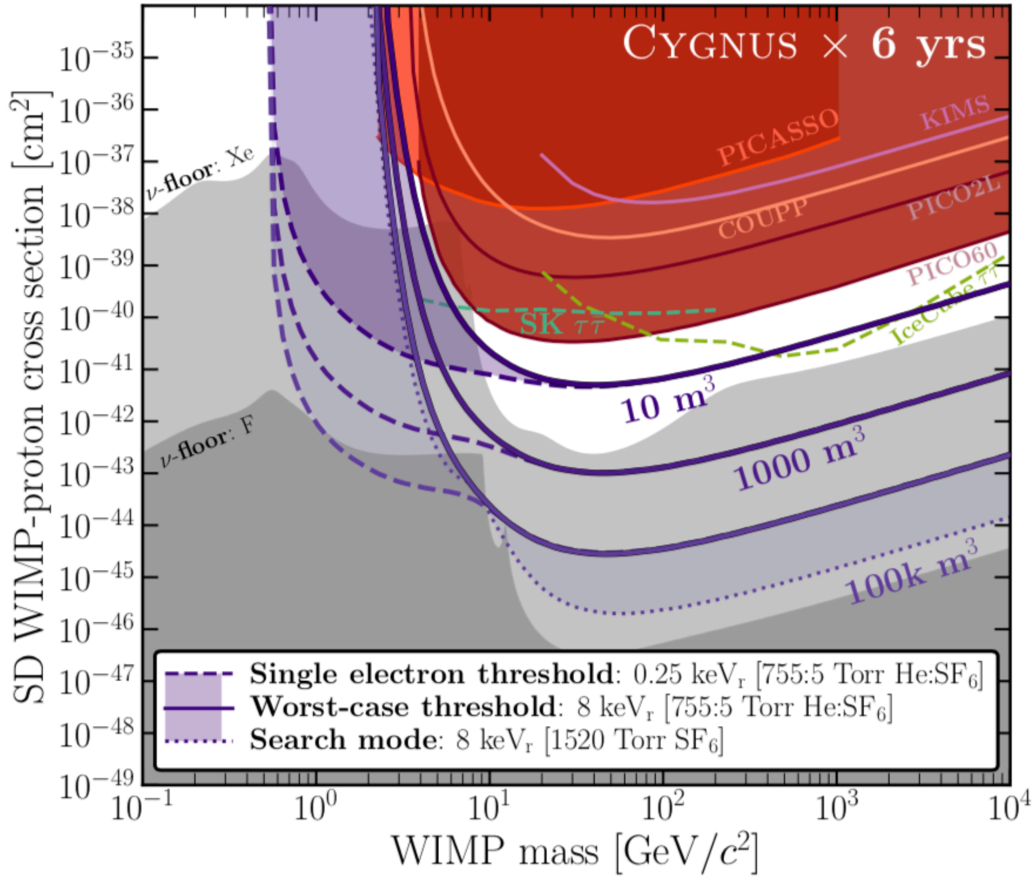
CYGNUS 1 ton WIMP searches expected sensitivity

NID operation

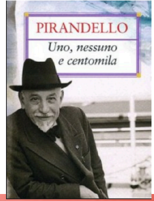
He:SF_6 755:5



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



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

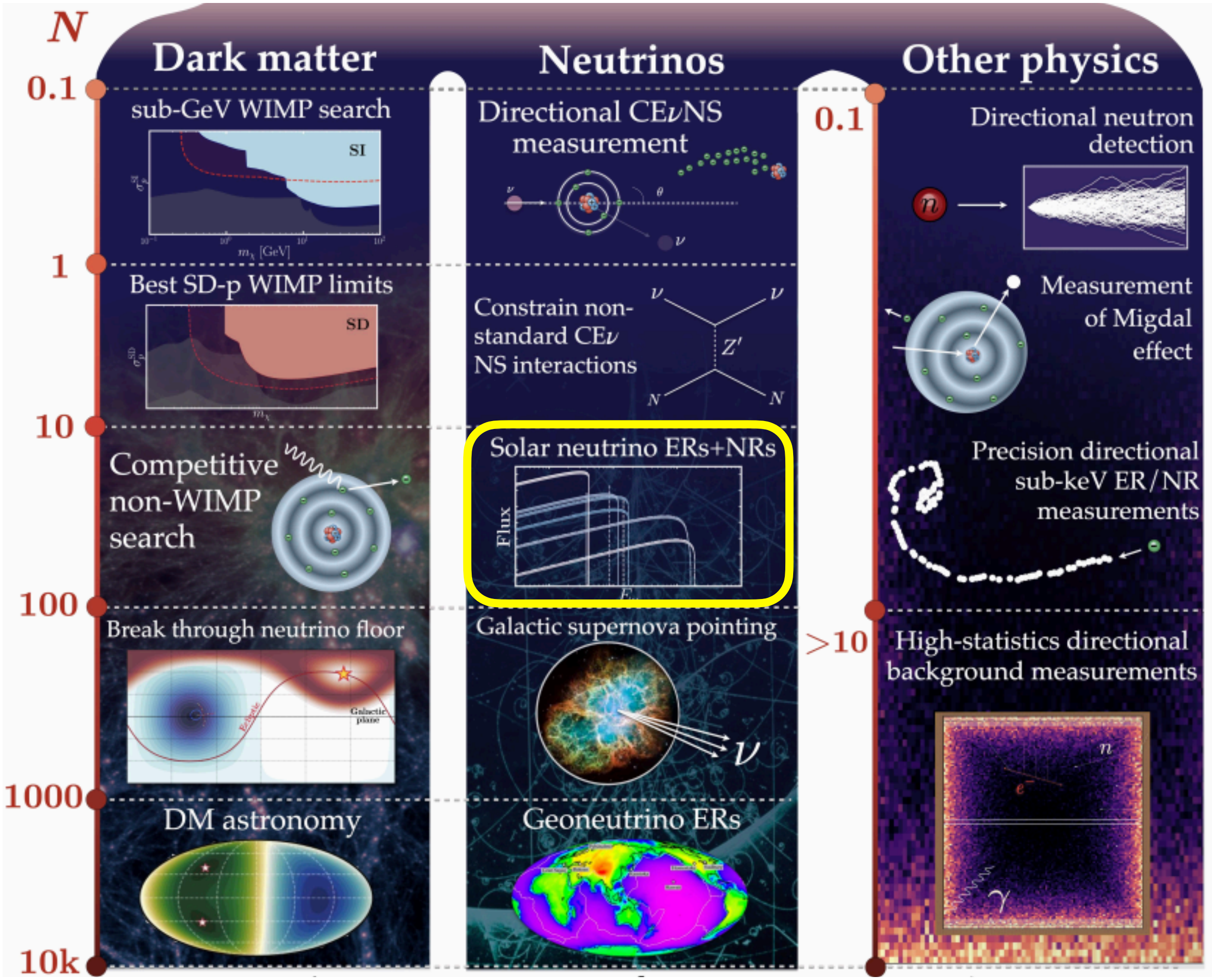


One, no one, one hundred thousand ;) physics cases for directional TPCs

Directionality

"a tool for all seasons"

[S. Vahsen et al., Ann. Rev. Nucl. Part. Sci. 71 (2021) 189-224]



N = volume in m³ assuming 1 atm operation

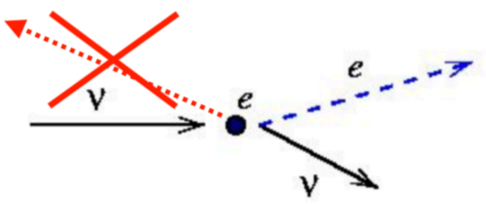
Solar neutrinos spectroscopy through elastic scattering on electrons in CYGNUS: promoting background to signal

Original idea by Seguinot et al (1992)

C. A. J. O'Hare et al., 2022 Snowmass Summer Study, arXiv:2203.05914

NEW! arXiv:2404.03690v1

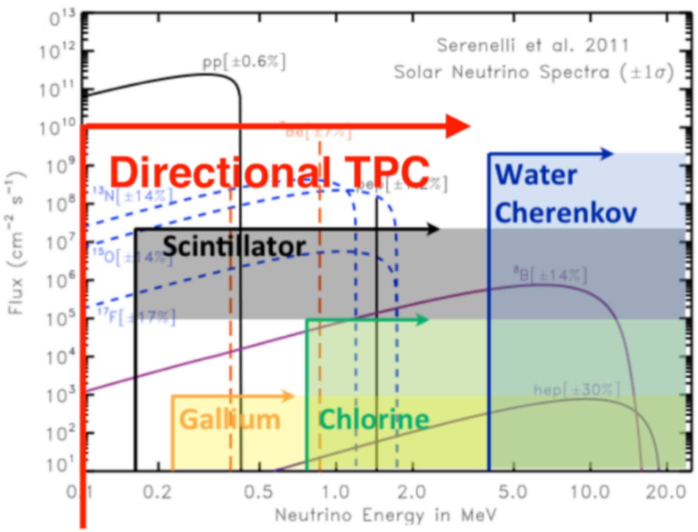
Given the Sun position, recoils in opposite direction are kinematically forbidden



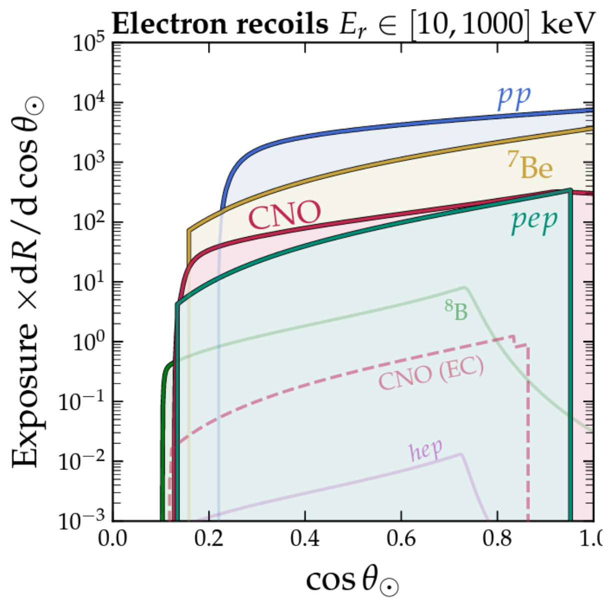
Differently from WIMPs, background can be measured on sidebands data

Neutrinos reconstruction performances and sensitivity dependend on:

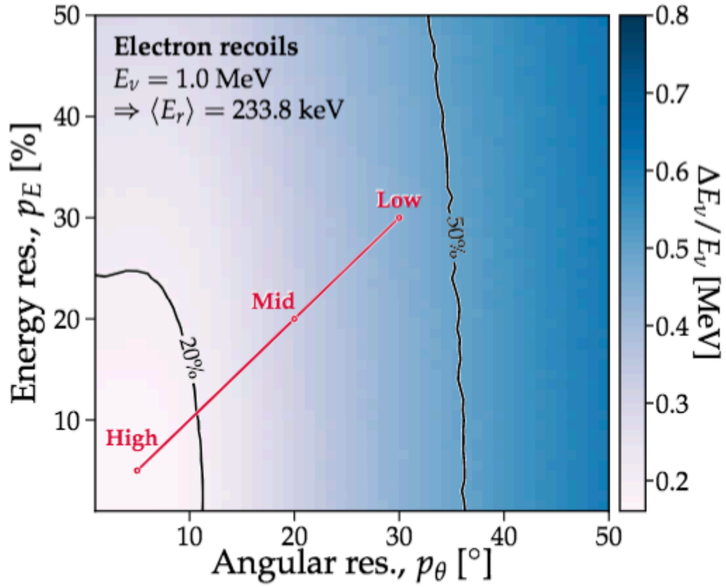
1) *ER energy resolution*
2) *ER angular resolution*
3) *non-neutrino ER background level*



Energy thresholds of solar neutrino detection techniques



Expected number of electron recoil events as a function of the cosine of the angle away from the Sun (He:CF₄ 60:40 1000 m³)

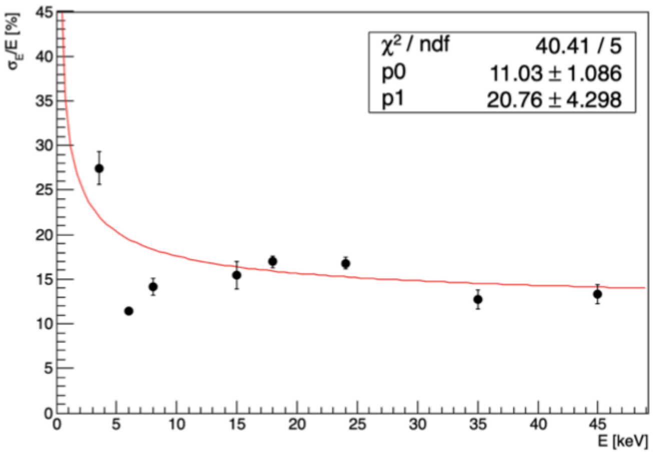


Neutrino energy reconstruction accuracy as a function of electron recoil energy and angular resolutions

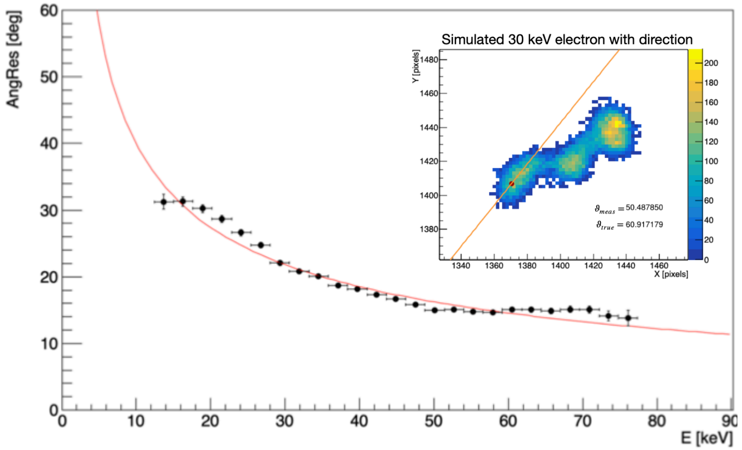
GSSI

Directional solar neutrino detection: a realistic feasibility study

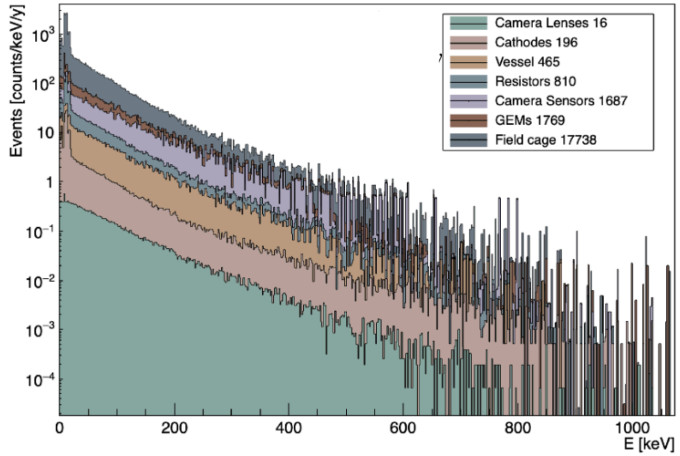
INFN



Energy resolution from 50 L detector data (Eur.Phys.J.C 83 (2023) 10, 946)



Angular resolution from extensively validated full MC simulation and dedicated low energy ER directional algorithm



Geant-4 simulation of expected backgrounds assuming most radiopure materials as of today

- **ER energy threshold (with directionality) at 10 keV, translating into 55 keV neutrinos energy threshold**
  - **Borexino pp measurement energy threshold = 300 keV**
- **Solar pp cycle detection feasibile at 3 σ sensitivity with 5.5 years of CYGNO 30 m³ exposure with a background over signal of 60**
  - **Borexino pp measurement background over signal ± 2**
- **Given the current expected ER background in CYGNO 30 m³, only a factor 3 reduction would be needed to achieve this goal**

An O(10) m³ directional TPC could extend Borexino pp measurement to lower threshold while tolerating a background 30 times higher

CYGNO-100 and CYGNO-1000 (i.e. CYGNUS) potentialities for solar neutrinos spectral measurements

arXiv:2404.03690v1

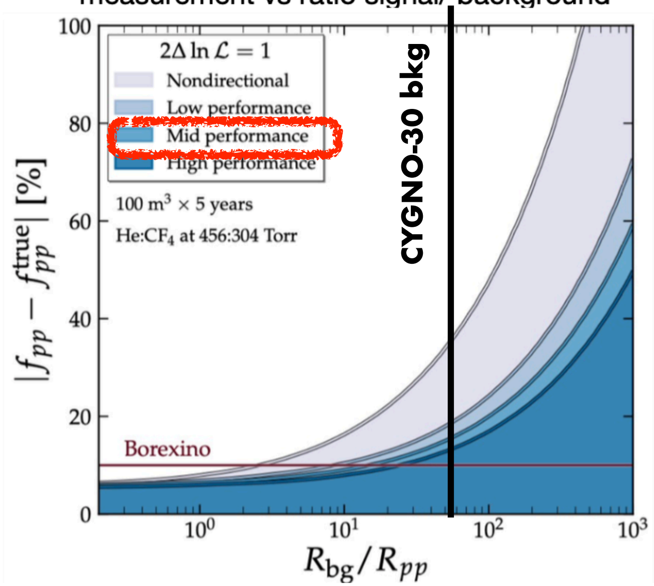
CYGνS: Detecting solar neutrinos with directional gas time projection chambers

Chiara Lisotti,[1,a] Ciaran A. J. O'Hare,[1,b] Elisabetta Baracchini,[2,3] Victoria U. Bashu,[4] Lindsey J. Bignell,[4] Ferdos Dastgiri,[4] Majd Ghrear,[5] Gregory J. Lane,[4] Lachlan J. McKie,[4] Peter C. McNamara,[6] and Samuele Torelli[2,3]

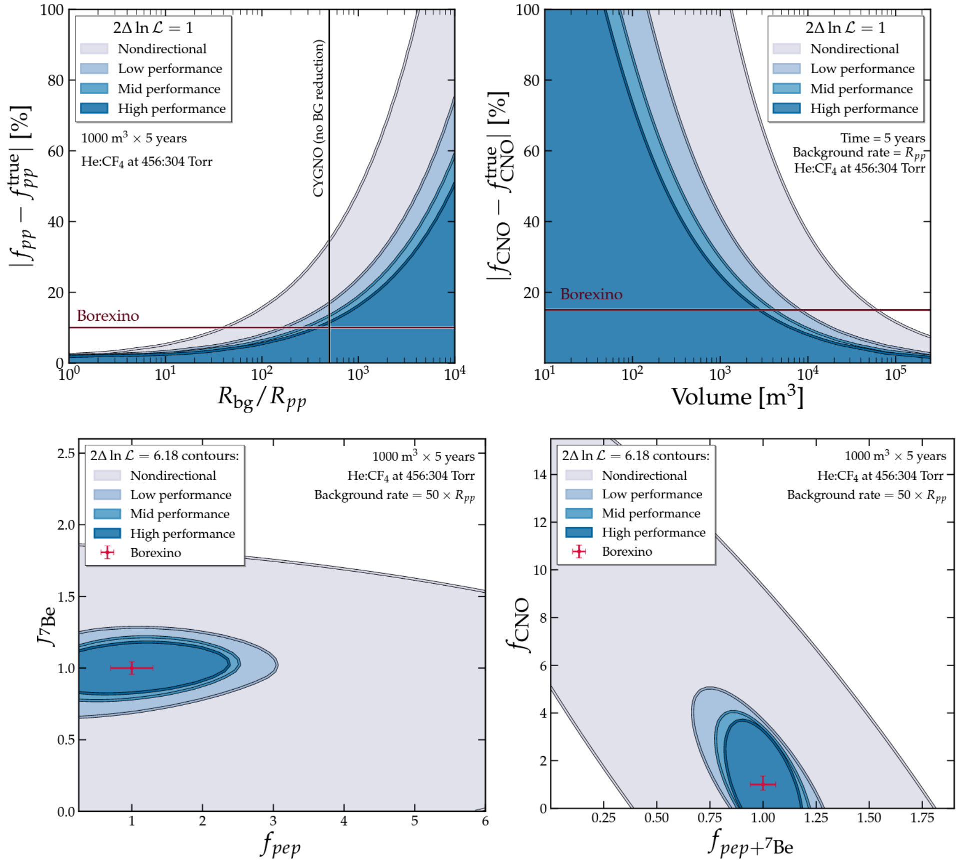
CYGNO approach used as benchmark for CYGNUS

CYGNO 30 m³ feasibility study ER reconstruction capabilities consistent with Mid performances

Expected precision on pp flux measurement vs ratio signal/ background



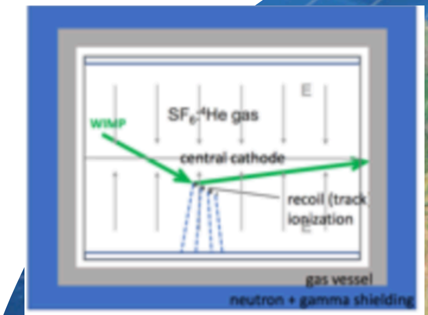
CYGNO-100



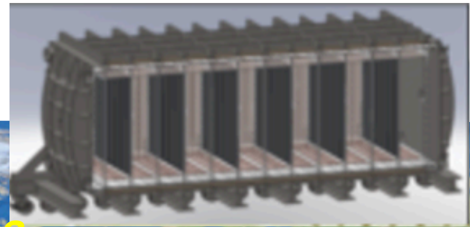
CYGNO-1000

CYGNUS 1000 m³ could measure the CNO cycle by breaking the degeneracy with pep + ⁷Be fluxes through directionality

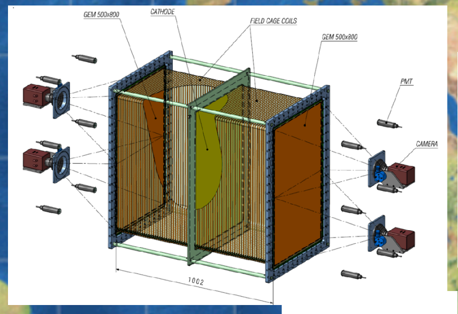
CYGNUS projects in the world



CYGNUS-HD10
Strip micromegas
He:CF_4:X
40 L + 1 m^3 R&D detectors under construction



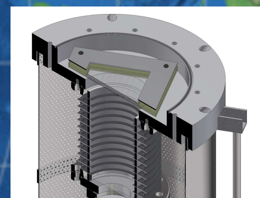
CYGNUS-10
10 m^3, GEMs + wires
He:SF_6
Boulby, UK
R&D ongoing on 1 m^3



European Research Council
Established by the European Commission

CYGNO/INITIUM
GEMs + sCMOS + PMT
He:CF_4 (:SF_6)
LNGS, Italy
0.4 m^3 demonstrator under construction towards 30 m^3 experiment

CYGNUS-KM
1 m^3, GEMs + 2D strips
SF_6/CF_4
Kamioka, Japan
R&D ongoing on 1 m^3



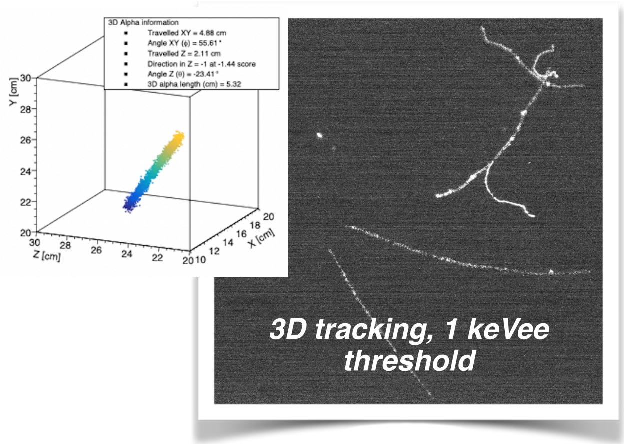
ARC CENTRE OF EXCELLENCE FOR DARK MATTER

CYGNUS-OZ
Stawell, Australia
GEMs + CCDs for gas studies
Small prototype under development

CYGNO/INITIUM latest news

Eur.Phys.J.C.83 (2023) 10, 946

GEMs + sCMOS + PMTs

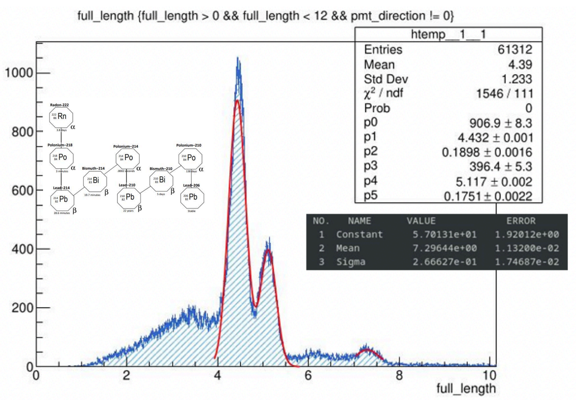


Extensive underground characterisation of 50 L detector @ LNGS about 2.6 kg days exposure with full shielding scheme

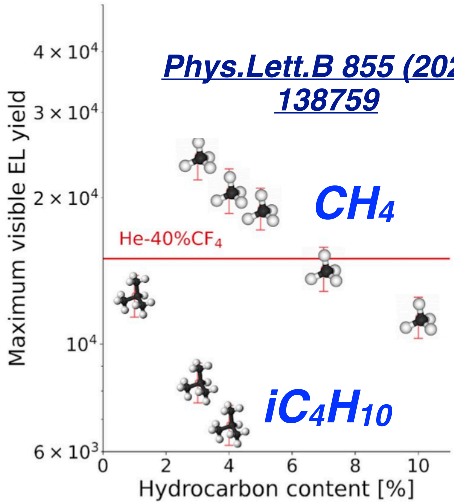
	Shielding	Number of bkg pictures	Event rate	Period
Run1	none	4×10^5	35 Hz	Oct 2022
Run2	4 cm Cu	4.5×10^5	3.5 Hz	Jan-Mar 2023
Run3	10 cm Cu	2.7×10^6	1.3 Hz	May-Nov 2023
Run4	10 cm Cu + 40 cm H_2O	2.8×10^6	0.9 Hz	Dec 2023-Apr 2024
Run5	10 cm Cu	$O(10^7)$	O(1) Hz	May-Dec 2024

STAY TUNED

Alphas RPR in 3D to study Rn contamination

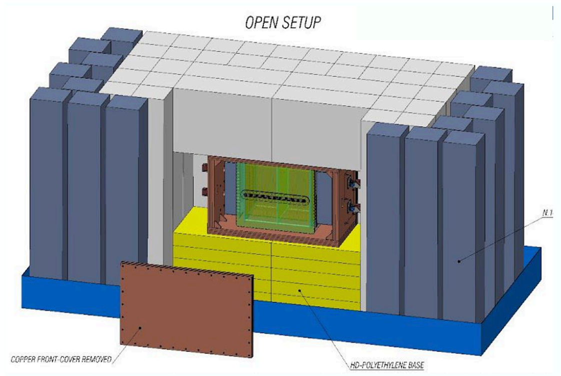


Hydrogen-rich gases to enhance O(GeV) WIMP sensitivity



Phys.Lett.B 855 (2024) 138759

0.4 m³ detector underground under costruction @ LNGS

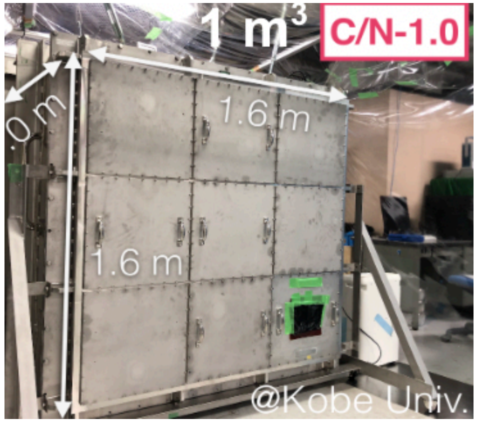


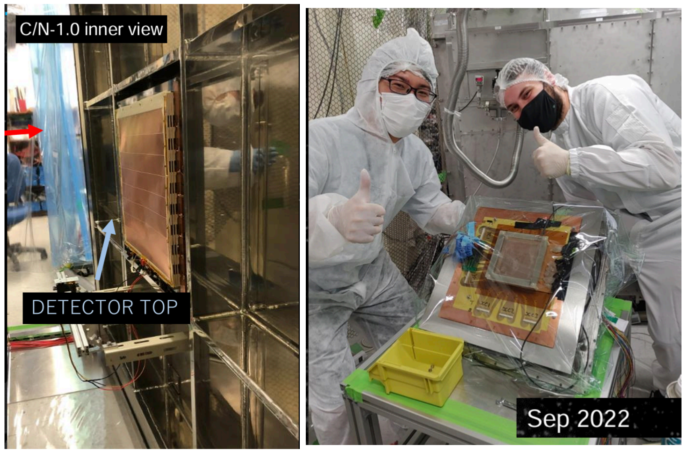
CYGNO TDR, DOI:10.15161/oar.it/76967

NEWAGE latest news

3D tracking, 50 keVee threshold

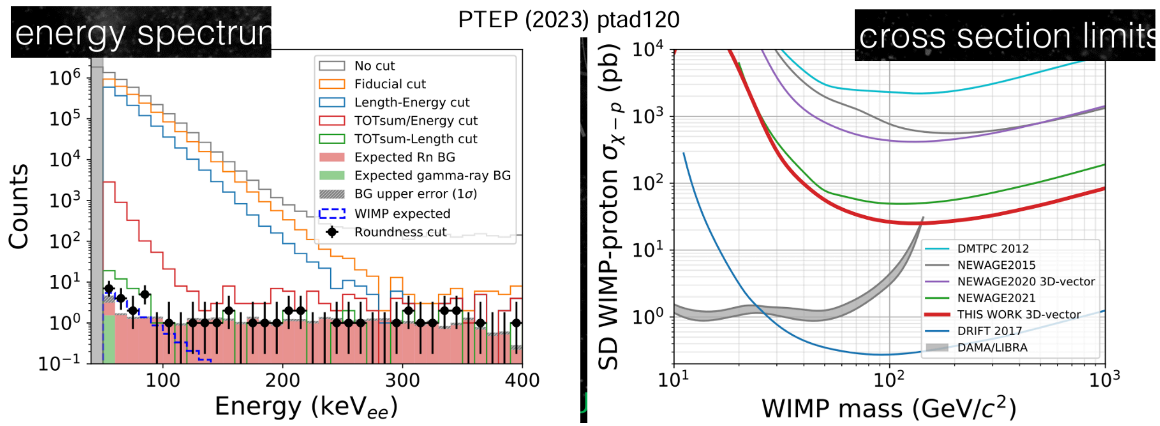
GEMs + muPIC



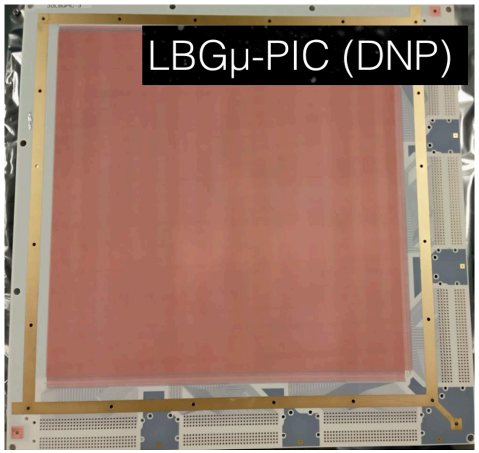


1 m³ vessel @ Kamioka as test bench for readout modules (also with DRIFT/CYGNUS-10 group)

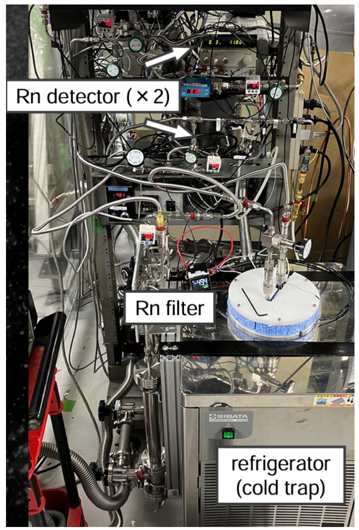
PTEP 2023 (2023) 10, 103F01



Latest limits with low background muPIC
3.2 kg days exposure



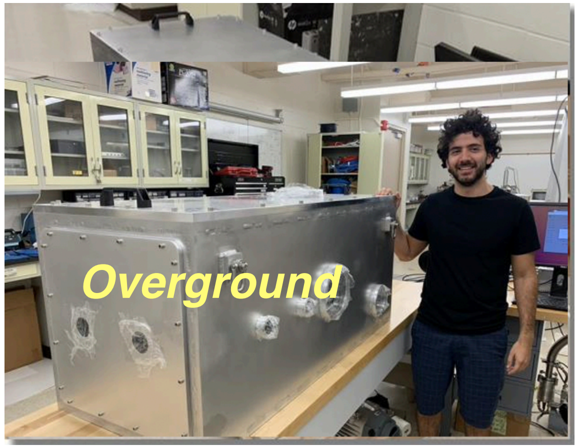
Low background muPIC: quartz + resin instead of polymide + glass cloth, x20 reduction



Gas recirculation system with low radioactivity Rn filters

CYGNUS HD latest news

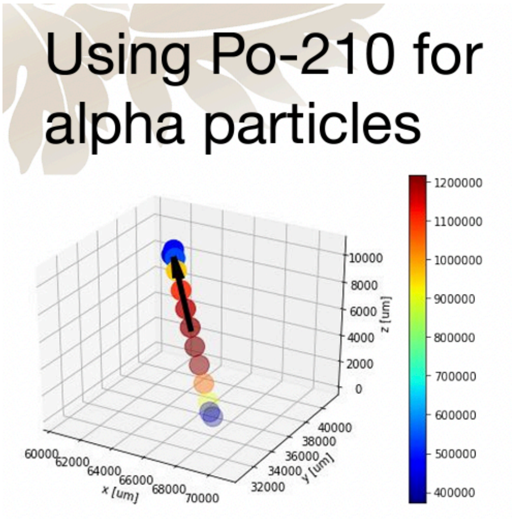
CERN strip Micromegas + SRS



0.04 m^3 under construction

1 m^3 detector project

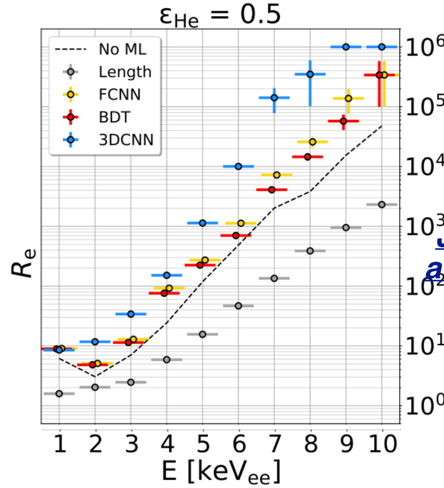
Micromegas models readout comparison



± 10^4 gain with 60-100 um position resolution

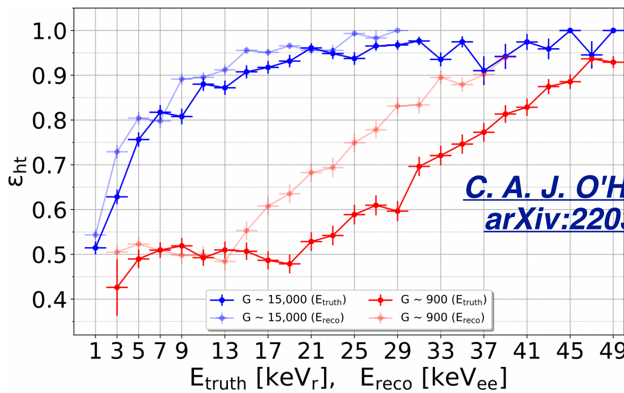
3D tracking, 1 keVee threshold

Machine Learning on simulated data with pixel readout (CYGNUS-HD)



J. Schuler et al, arXiv:2206.10822

O(10^5) ER rejection on simulated data below 10 keV achievable @ 60 Torr

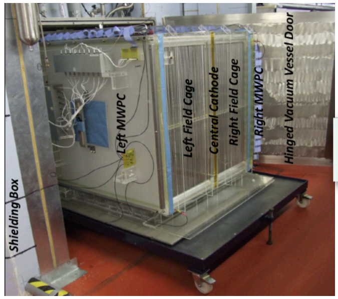


C. A. J. O'Hare et al, arXiv:2203.05914

Head-tail on simulated data at 1 keV achievable at 1 atm!

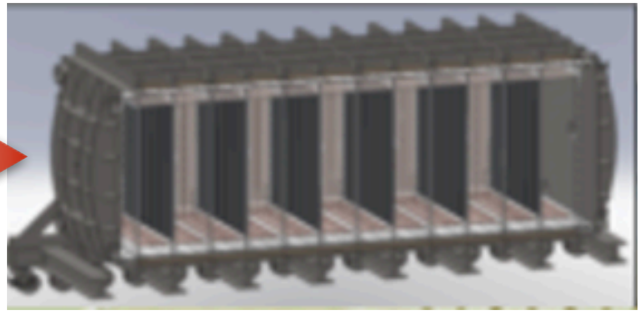
DRIFT/CYGNUS-10 latest results

DRIFT (UK)

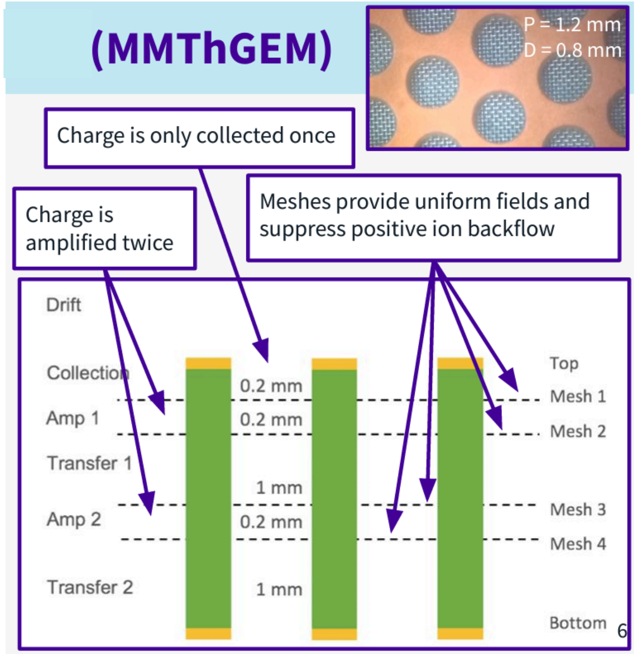


1 m^3 experiment

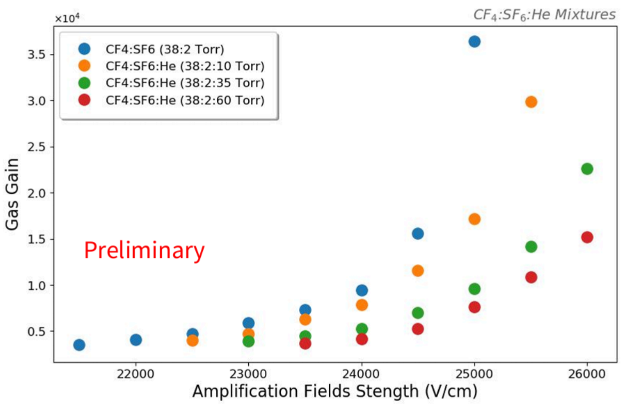
MWPC —> MMThickGEM

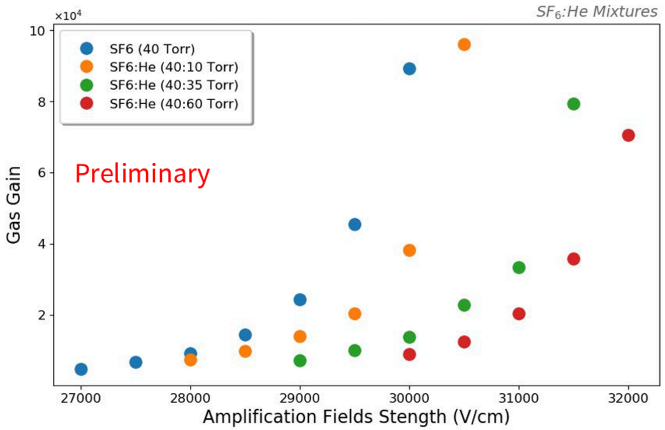


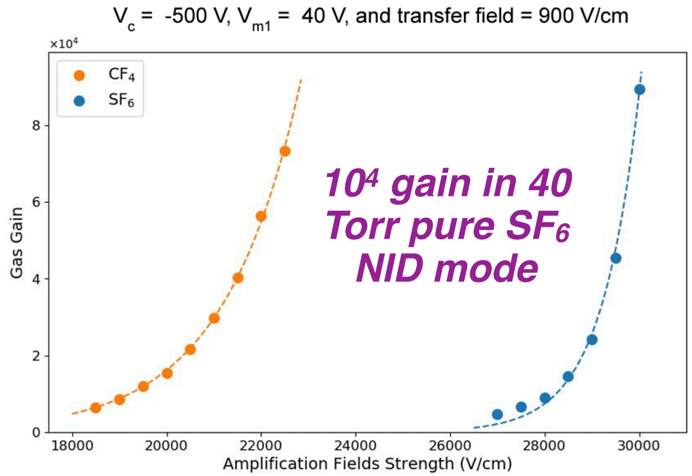
O(10) m^3 detector concept



10^4 gain in 100 Torr (He:)CF_4:SF_6 NID mode







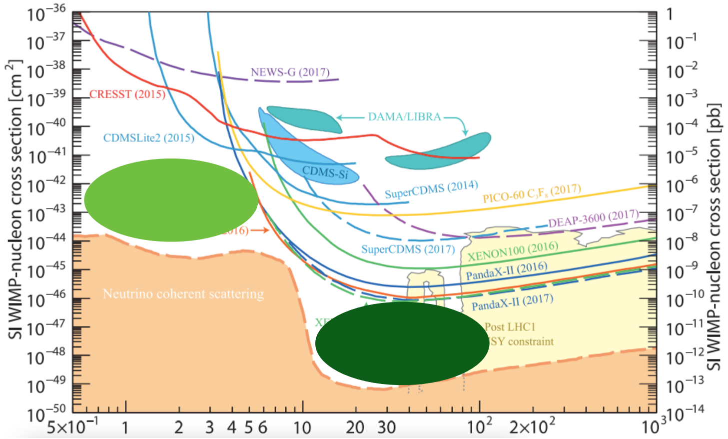
10^4 gain in 40 Torr pure SF_6 NID mode

With CYGNO Collaboration JINST 19 (2024) 06, P06021

A.G. McLean et al, JINST 19 (2024) 03, P03001

Direct DM search future

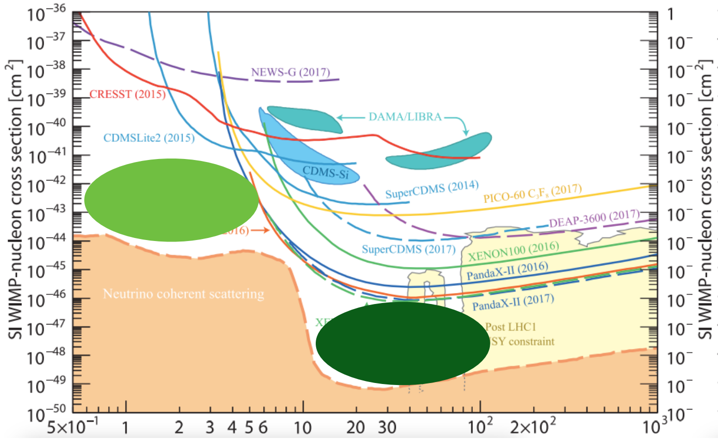
Old limits, only illustrative purpose

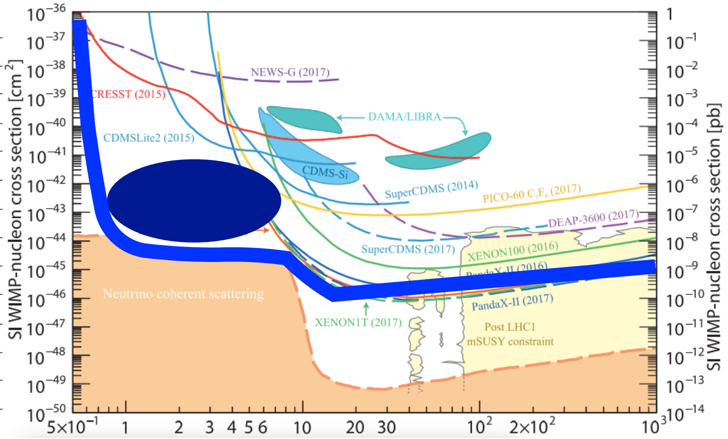


DM is claimed:
only a directional experiment can confirm the galactic origin of the observed signal

Direct DM search future

Old limits, only illustrative purpose





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only a directional experiment can test the galactic origin of the observed signal

Direct DM search future

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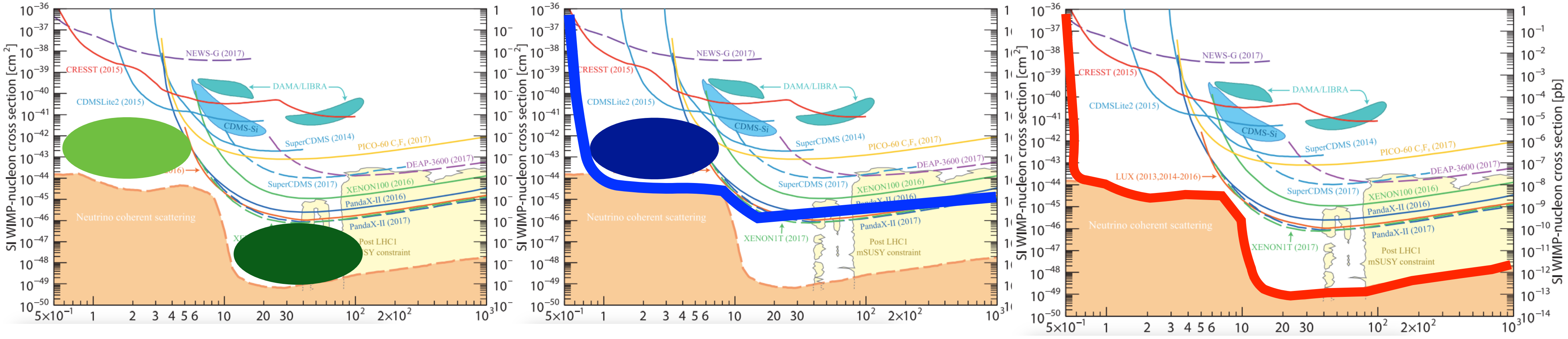


DM is claimed:
only a directional experiment can confirm the galactic origin of the observed signal

Incompatible results:
only a directional experiment can test the galactic origin of the observed signal

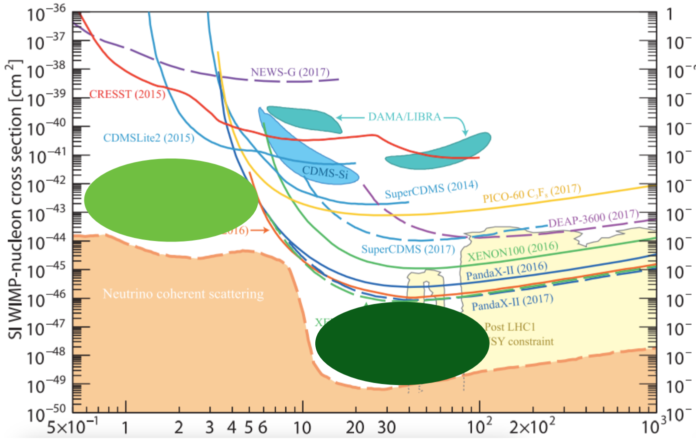
DM is excluded to the Neutrino Fog:
only a directional experiment can continue DM searches and study neutrinos

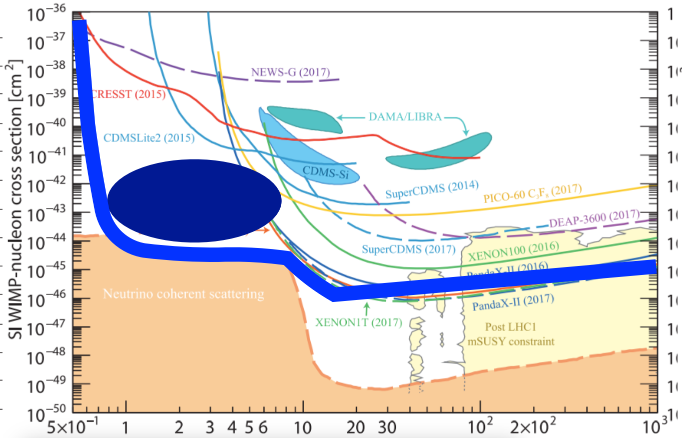
*Or we "hit" some new other irreducible background

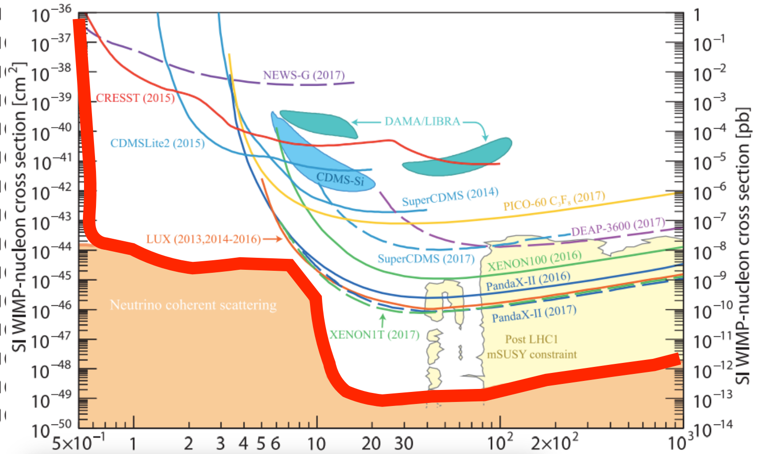
Direct DM search future

Old limits, only illustrative purpose

....kind of already here..







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only a directional experiment can continue DM searches and study neutrinos

*Or we "hit" some new other irreducible background

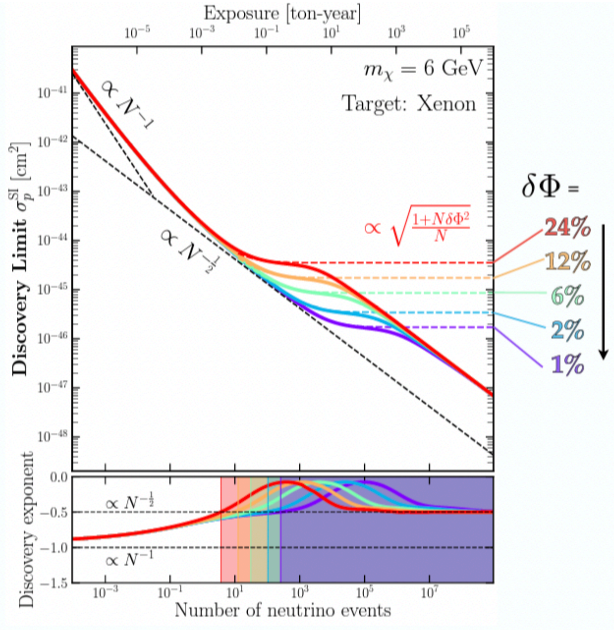
Directional DM community in CYGNUS ready for the challenge!

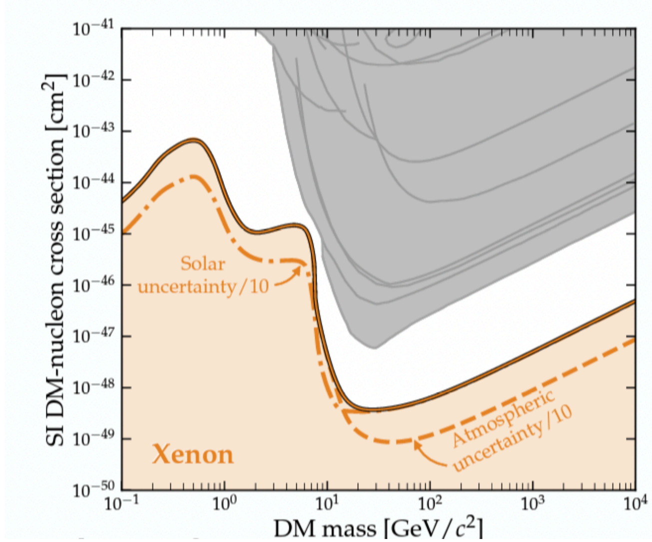
Backup slides

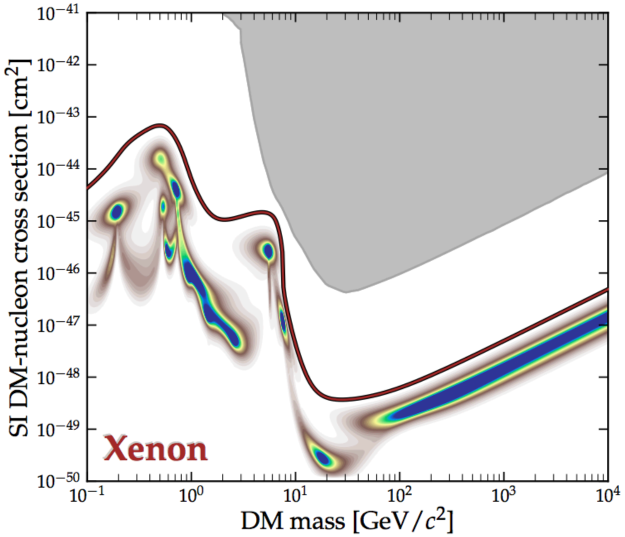
Neutrino fog: neutrino flux uncertainties & targets complementarity

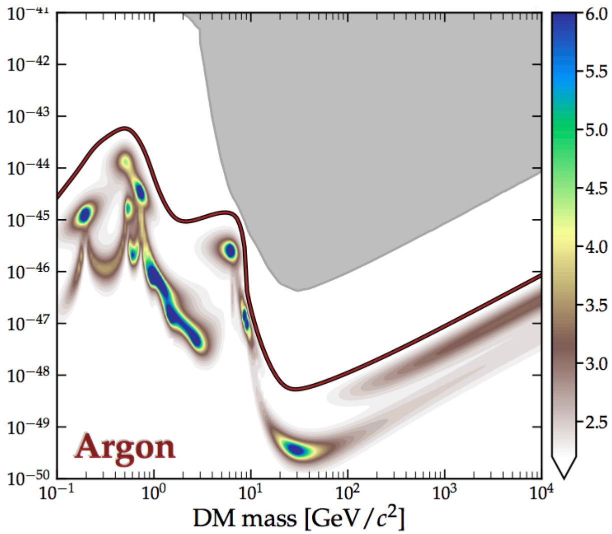
With a smaller neutrino flux uncertainty, the onset of the neutrino fog is pushed to lower cross sections

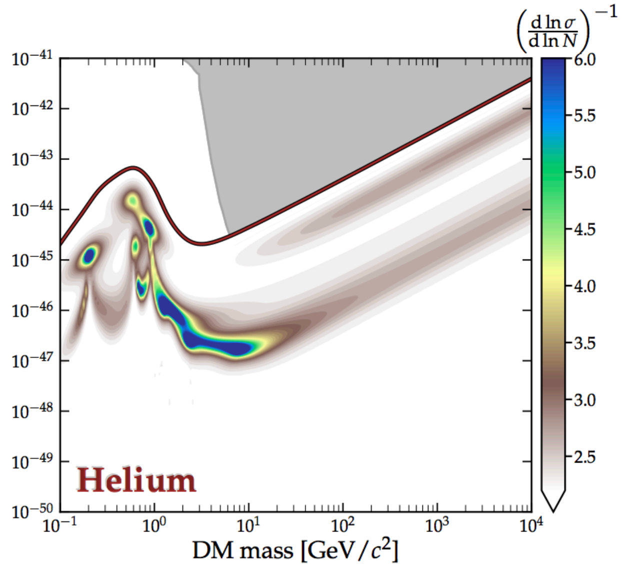
i.e. if you go in with a better prior knowledge of the background, you can tolerate more of it before it starts to impact your sensitivity











ER angular resolution from full simulation of 2D optical readout within the CYGNO project

Simulations: [S. Torelli PhD Thesis within CYGNO Collaboration, paper in prepration]

- Electron recoils simulated in GEANT4
- Angular resolution evaluated on MC simulated sCMOS images that take into account GEM gain fluctuations, photon production, sensor calibration and diffusion during drift as evaluated on LIME. PMT waveforms information can further improve this scenario (on going work)

- First part of the algorithm: search for the beginning of the track with:
  - Skewness
  - Distance of pixels from barycenter (farthest pixels)

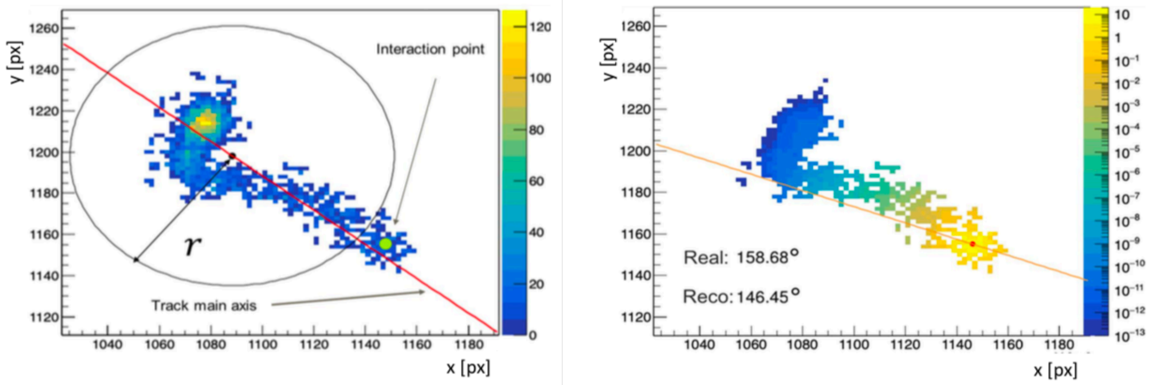
- Second part of the algorithm aims to find the direction:
  - Track point intensity rescalad with the distance from the interaction point: $W(d_{ip}) = exp(-d_{ip}/w)$
  - Direction taken as the the main axis of the rescaled track passing from the interaction Point
  - Orientation given following the light in the Pixels

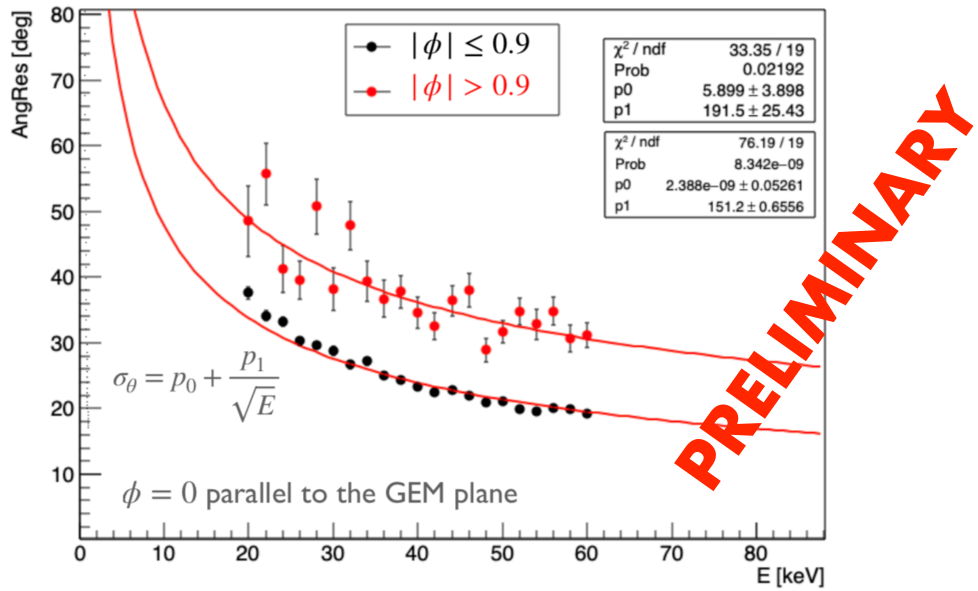
- Algorithm adapted from X-ray polarimetry:

"Measurement of the position resolution of the Gas Pixel Detector"
Nuclear Instruments and Methods in Physics Research Section A, Volume 700, 1 February 2013, Pages 99-105

LIME detector (now underground @ LNGS):
50 L volume (33 x 33 cm² for 50 cm drift)

$He:CF_4$ 60:40 1 bar





Fit expectation for 70 keV ER compatible with prediction from previous slide and in the "Mid-performance" range

Comparison of "neutrino floors"

C. A. J. O'Hare, Phys. Rev. Lett. 127 (2021) 25, 251802

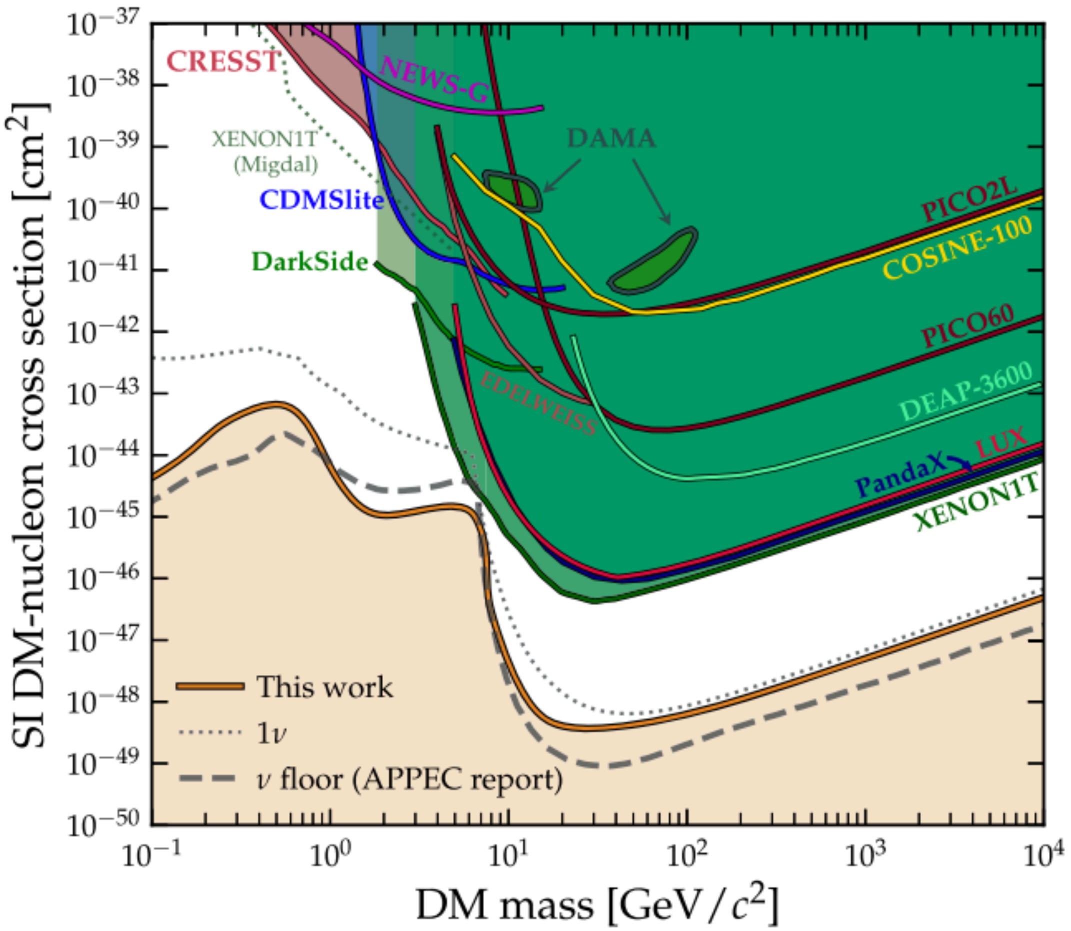


FIG. 1. Present exclusion limits on the spin-independent DM-nucleon cross section (assuming equal proton or neutron couplings) [7,58–71]. Beneath these limits we show three definitions of the neutrino floor for a xenon target. The previous discovery-limit-based neutrino floor calculation shown by the dashed line is taken from the recent APPEC report [72] (based on the technique of Ref. [32]). The envelope of 90% C.L. exclusion limits seeing one expected neutrino event is shown as a dotted line. The result of our work is the solid orange line. We define this notion of the neutrino floor to be the boundary of the neutrino fog, i.e., the cross section at which any experiment sensitive to a given value of m_χ leaves the standard Poissonian regime and begins to be saturated by the background.

Not only WIMP Dark Matter: potentialities for discovery of MeV DM from SN with directionality

Discovering supernova-produced dark matter with directional detectors #1

Elisabetta Baracchini (GSSI, Aquila and Gran Sasso), William Derocco (Stanford U., ITP), Giorgio Dho (GSSI, Aquila and Gran Sasso) (Sep 18, 2020)

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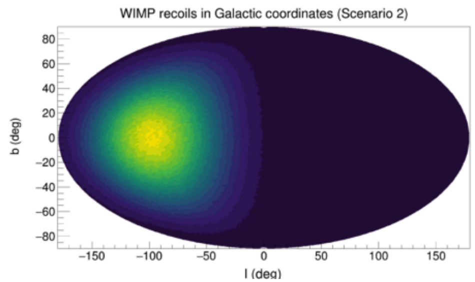
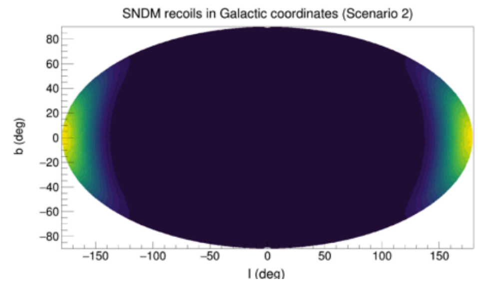
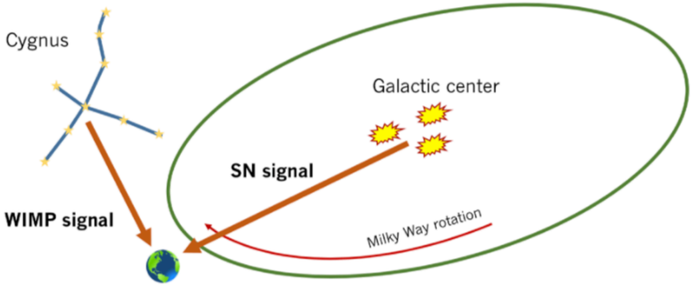
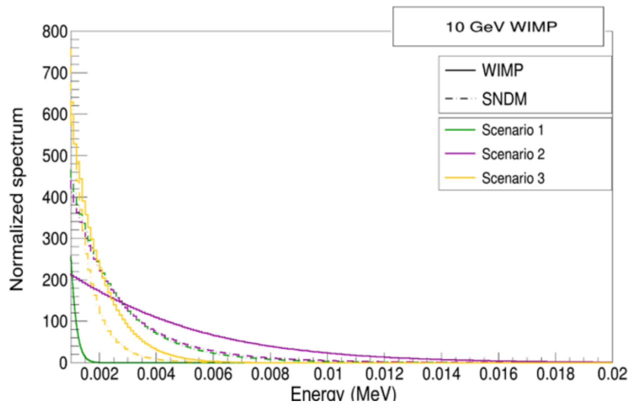
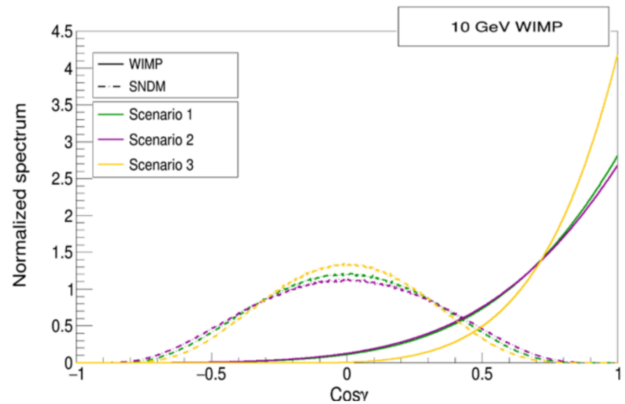
W. DeRocco, P. W. Graham, D. Kasen, G. Marques-Tavares, and S. Rajendran, Phys. Rev. D **100**, 075018 (2019).

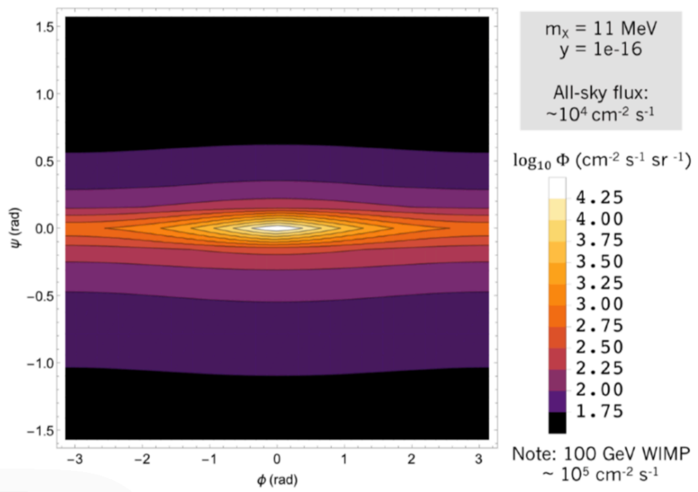


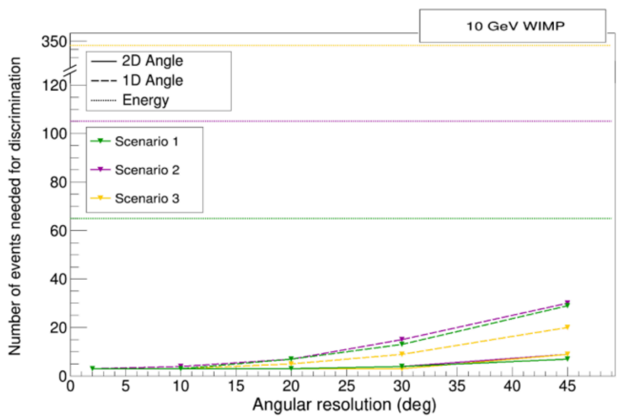


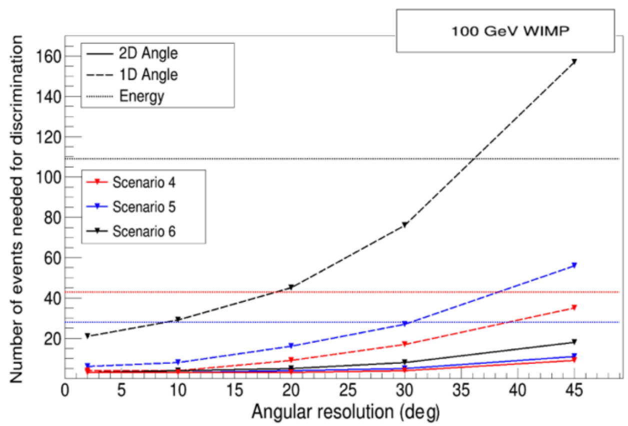






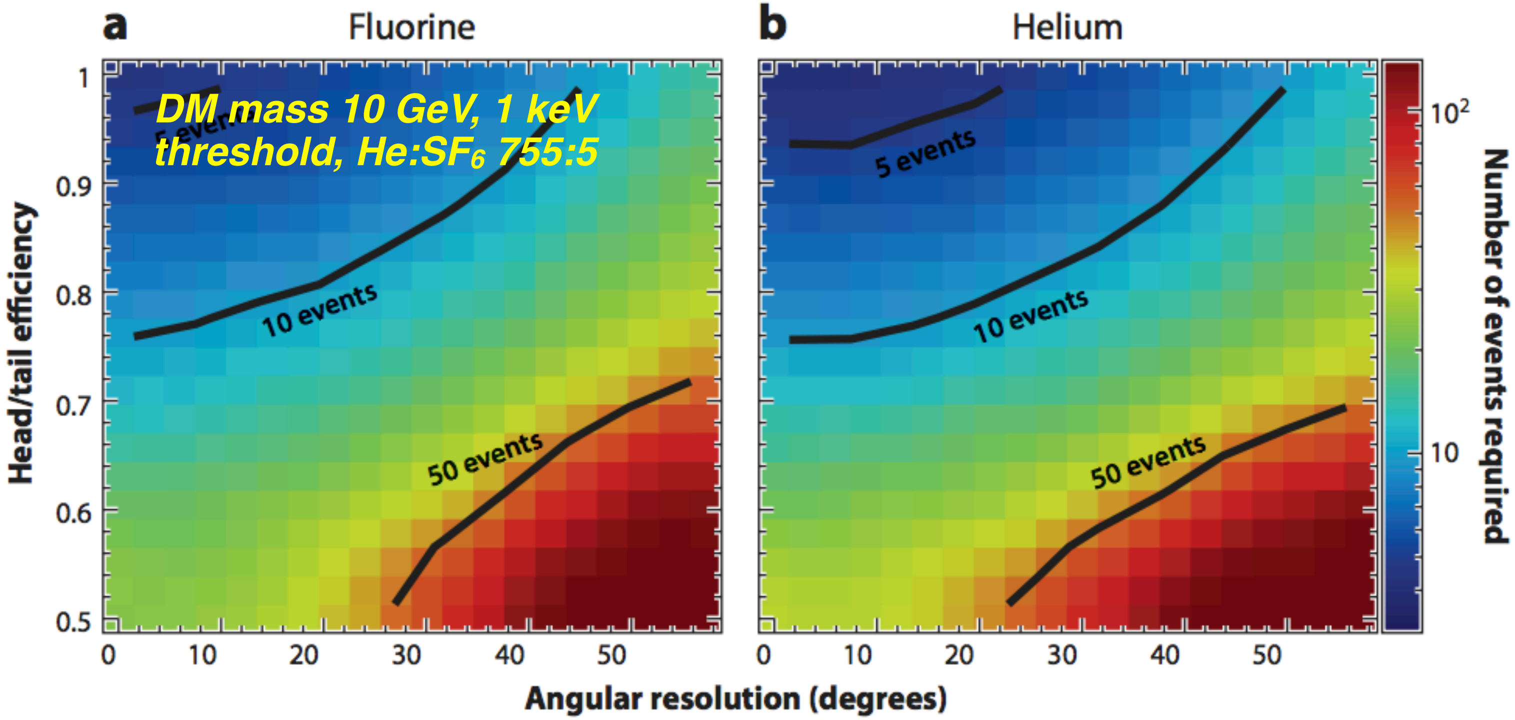






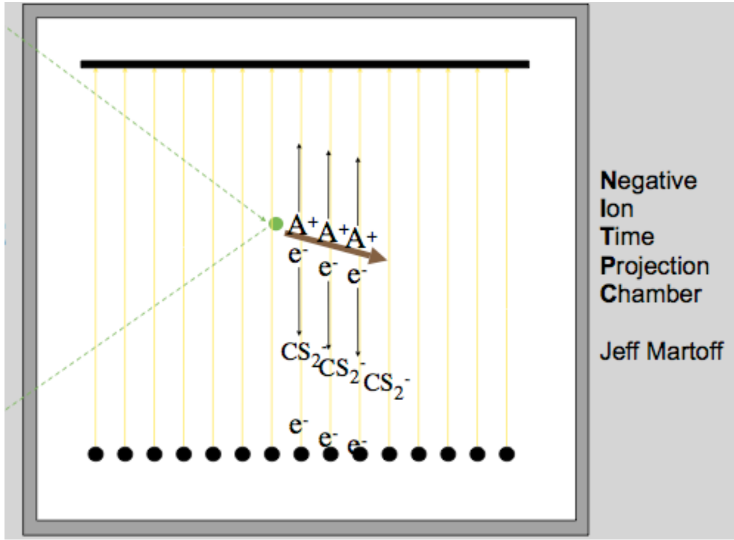
The importance of HT

Required number of detected He and F recoils to exclude solar neutrinos at 90% C.L. vs angular resolution and head-tail efficiency



Negative ion drift (NID): improved tracking

Reduced diffusion = improved tracking



- Electronegative dopant in the gas mixture (CS_2, SF_6, CH_3NO_2, ...)
- Primary ionization electrons captured by electronegative gas molecules at O(100) um
- Anions drift to the anode acting as the effective image carrier instead of the electrons and reducing both longitudinal and transverse diffusion to thermal limit

$$\sigma = \sqrt{\frac{2kTL}{eE}} = 0.7\,\mathrm{mm}\left(\frac{T}{300\,\mathrm{K}}\right)^{1/2}\left(\frac{580\,\mathrm{V/cm}}{E}\right)^{1/2}\left(\frac{L}{50\,\mathrm{cm}}\right)^{1/2}$$

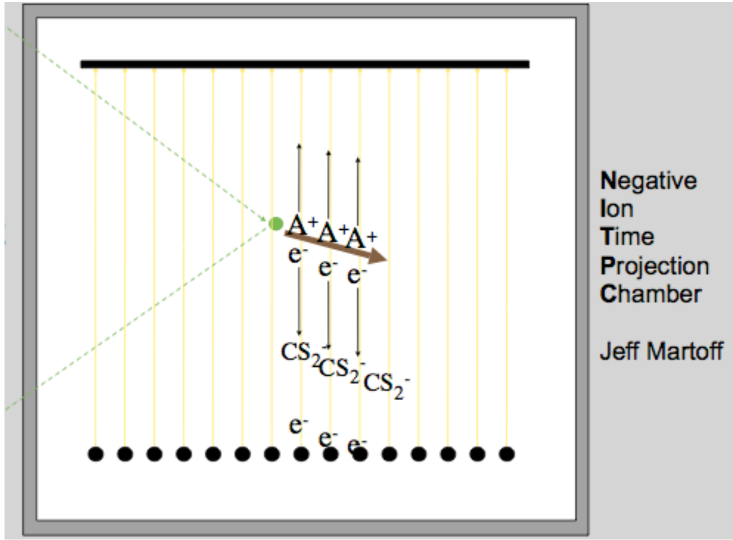
low diffusion increases active volume per readout area

T. Ohnuki et al., NIM A 463

J. Martoff et al., NIM A 440 355

Negative ion drift (NID): improved tracking & full fiducialization

Reduced diffusion = improved tracking



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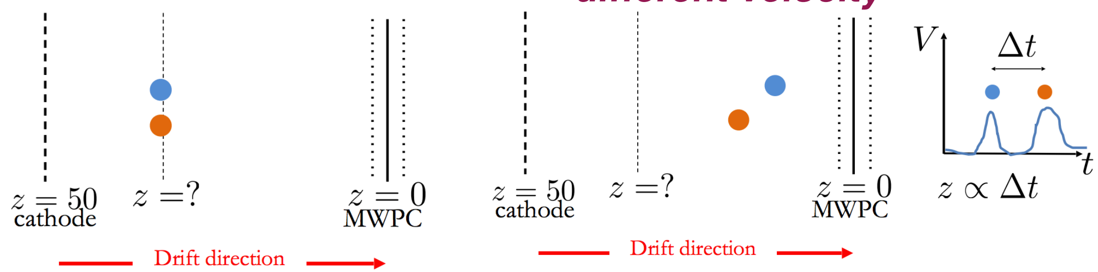
T. Ohnuki et al., NIM A 463

J. Martoff et al., NIM A 440 355

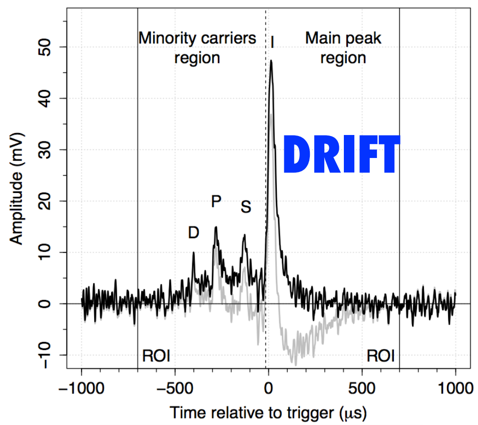
Multiple charge carriers = fiducialization!!

start together … *…but drift at different velocity*



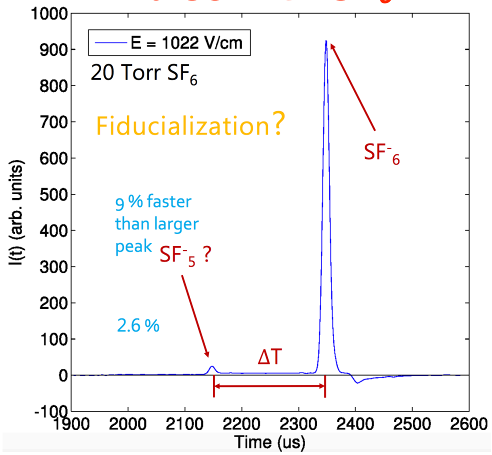
$$z = (t_m - t_p)\frac{v^m_{drift} v^p_{drift}}{v^m_{drift} - v^p_{drift}}$$

- CS_2:CF_4:O_2 30:10:1 Torr



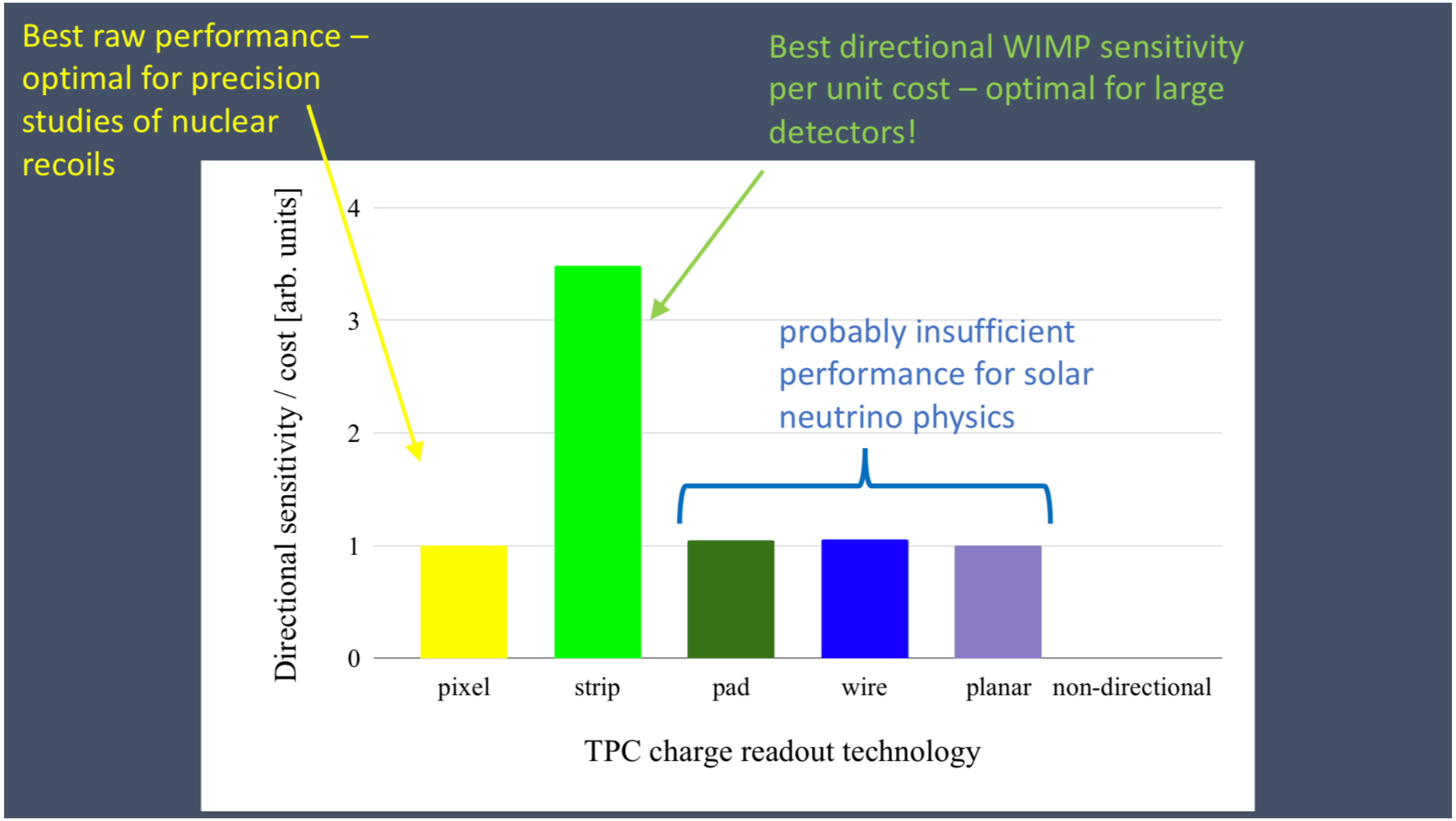
D. Snowden-Ifft, Rev. Sci. Instrum. 85 (2014) 013303

From 2015 demonstrated also with SF_6



N.S.Phan et al., JINST 12 (2017) no.02, P02012

Cost vs benefit study result (for NID operation)



For He:SF_6 755:5 with negative ion drift, strips results the best choice in terms of costs versus performances, radiation budget and engineering cosiderations

Cost benefit study and gas optimisation for electron drift with both charge and optical readout under development

Gaseous TPCs for directional DM landscape

	Established readout & directionality	Established gas	R&D readout	R&D gas	Largest detector realised	Detector under development
MIMAC	Micromegas + FADC 3D	CF_4:CHF_3:C_4H_{10} @ 0.05 bar			0.05 m^3 (underground)	1 m^3 (under study)
DRIFT	MWPC 1.5 D	CS_2:CF_4:O_2 @ 0.05 bar	THGEM + wire/ micromegas	SF_6:(CF_4) @ 0.05 bar	1 m^3 (underground)	10 m^3 (under study)
NEWAGE	GEM + muPIC 3D	CF_4 @ 0.1 bar	GEM + muPIC	SF_6 @ 0.03 bar	0.04 m^3 (underground)	1 m^3 (vessel funded)
D^3/CYGNUS-HD	2 GEMs + pixels 3D	Ar/He:CO_2 @ 1 bar	Strip micromegas	He:CF_4:X @ 1 bar	0.0003 m^3	0.04 m^3 (under construction)
New Mexico	THGEM + CCD 2D	CF_4 @ 0.13 bar	THGEM + CMOS	CF_4:CS_2/SF_6 @ 0.13 bar	0.000003 m^3	
CYGNO	3 GEMs + CMOS + PMT 2D + 1 D	He:CF_4 @ 1 bar	3 GEMs + CMOS + PMT	He:CF_4:SF_6 @ 0.8-1 bar	0.05 m^3 (underground)	0.4 m^3 (under construction)

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

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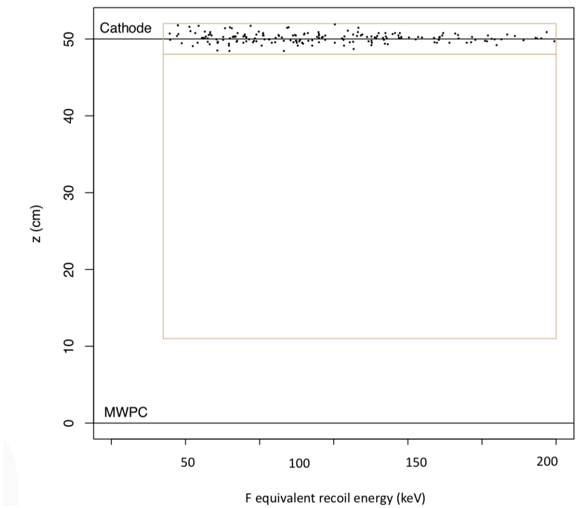
CYGNUS			All of the above	Helium-Fluorine @ 1 bar		1000 m^3

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

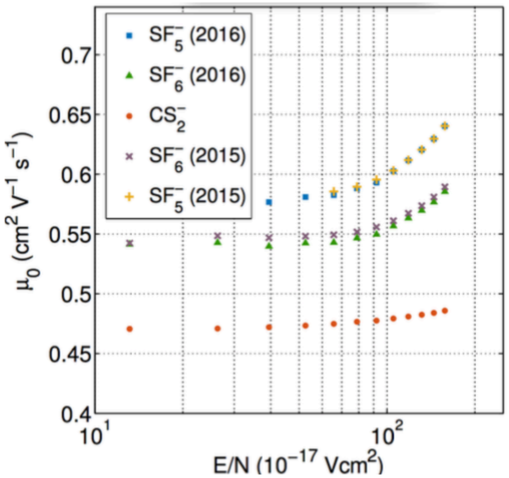
CYGNUS R&D: negative ion drift (NID), amplification & readouts

DRIFT background-free limit by fiducialization through CS_2 NID minority carriers @ 40 Torr



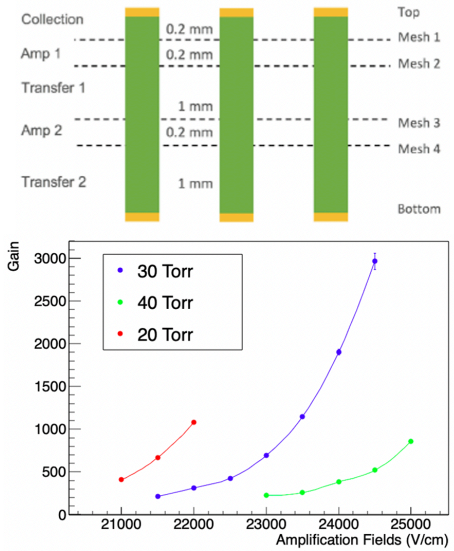
[*Phys. Dark Univ. 9-10 (2015)*]

NID operation with SF_6 20-40 Torr, much safer and easier to handle than CS_2



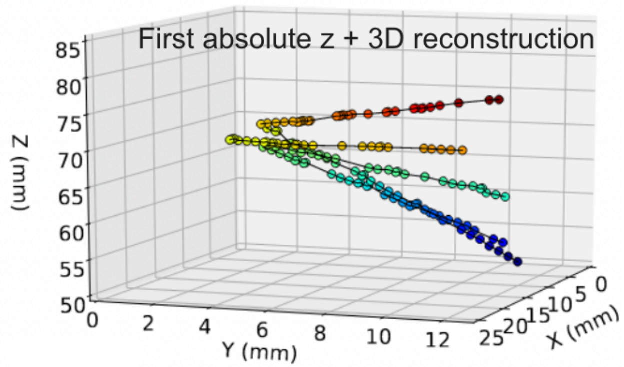
[*JINST* 12 (2017) 02, P02012]

Dedicated amplification structure MMThickGEM 20-40 Torr



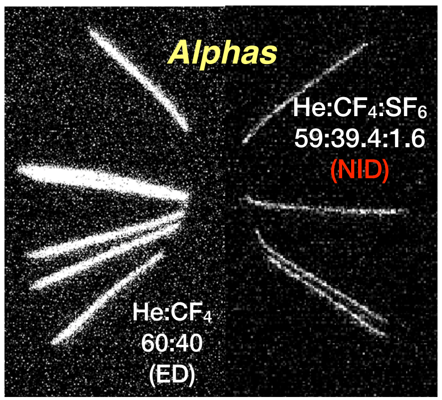
[*JINST* 18 (2023) 08, P08021]

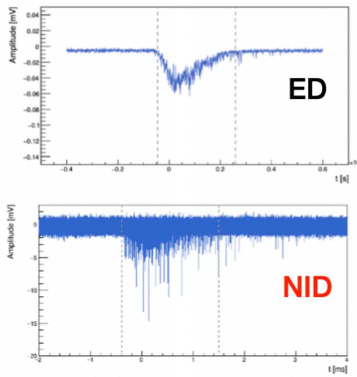
Absolute Z + 3D tracking @ 20 Torr

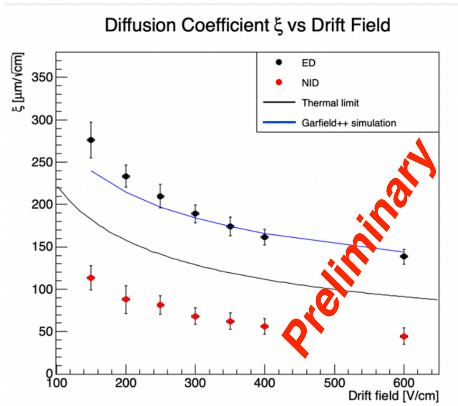


[*JINST* 15 (2020) 07, P07015]

NID with optical readout with both sCMOS and PMT at atmospheric pressure!







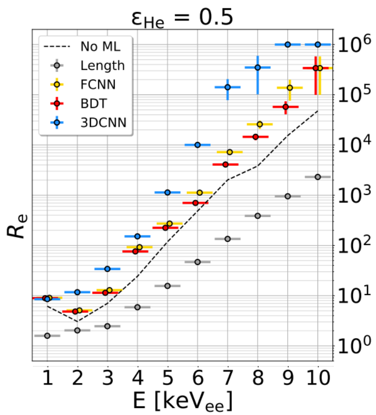
[*Paper in preparation*]

CYGNUS R&D: data challenges

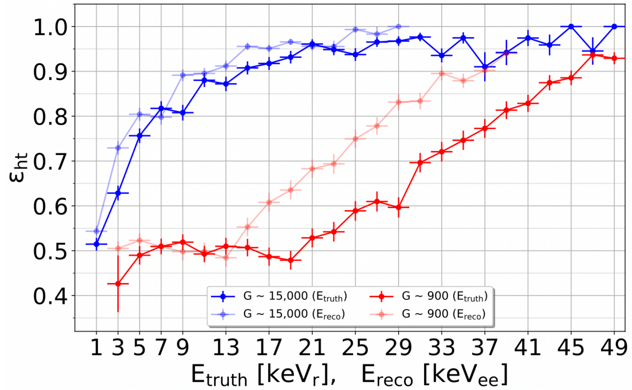
Machine Learning on simulated data with pixel readout (CYGNUS-HD)

Diffusion & quantization included

J. Schuler et al, arXiv:2206.10822



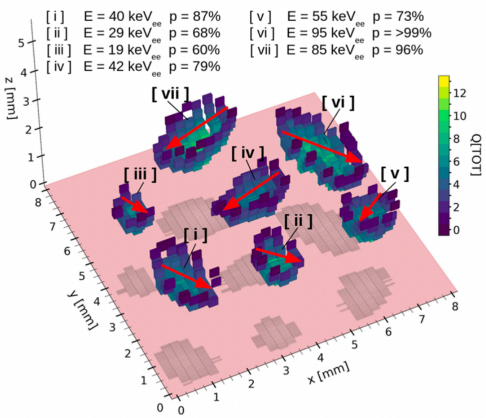
C. A. J. O'Hare et al, arXiv:2203.05914



O(10^5) ER rejection on simulated data below 10 keV achievable @ 60 Torr

Head-tail on simulated data at 1 keV achievable at 1 atm!

DETECTED He recoils at 1 atm with pixel readout



Machine Learning on simulated data with optical readout (CYGNO)

Full simulation of detector effects

Preliminary

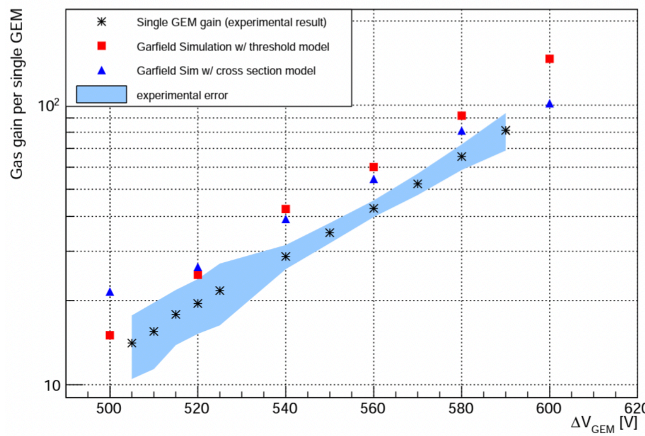
Models	Signal Efficiency [ϵ^S]%	Bkg. Rej. Efficiency [1-ϵ^B]%
RFC	40	99.1
	50	97.5
GBC	40	98.3
	50	96.5
DNN	40	96.6
	50	93.5

Paper in preparation

See A. Prajapati talk on CYGNO Thu 14.20

O(10^3) ER rejection in the 1-35 keV @ 1 atm

GEM SF_6 NID amplification Garfield++ simulation



J. Phys. Conf. Series 1498 (2020) 1, 012018