TeV Particle Astrophysics Conference 2023
Napoli, 13th September 2023

The CYGNUS project

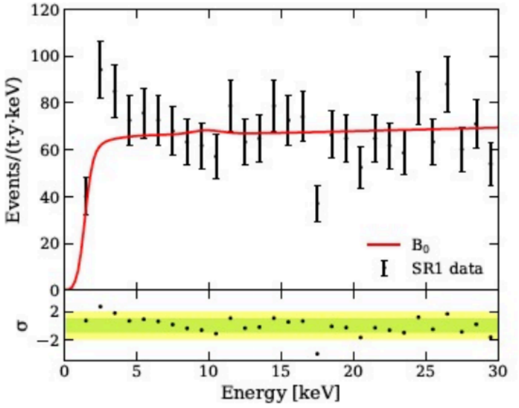
Elisabetta Baracchini

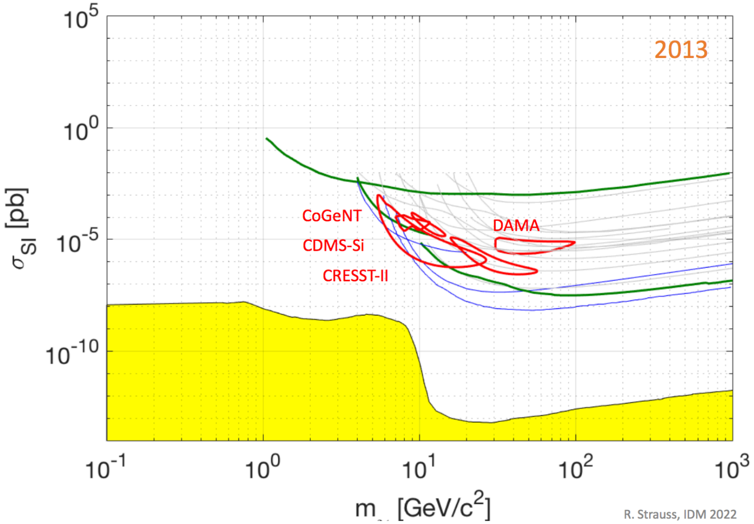
on behalf of the CYGNUS proto-collaboration

A search hampered by many false promises

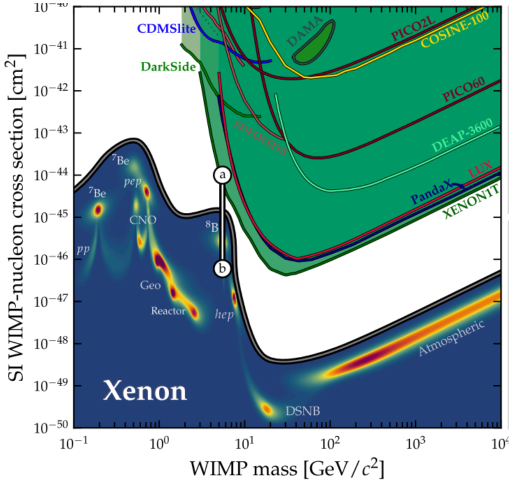
i.e. many things can look like a signal if you don't know where they are coming from

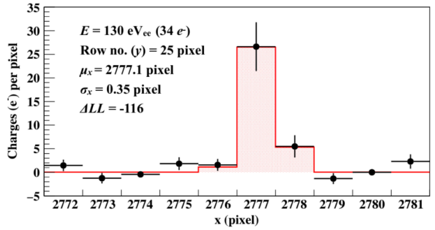
Direction is the only way

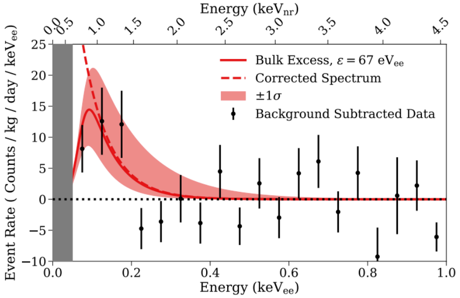




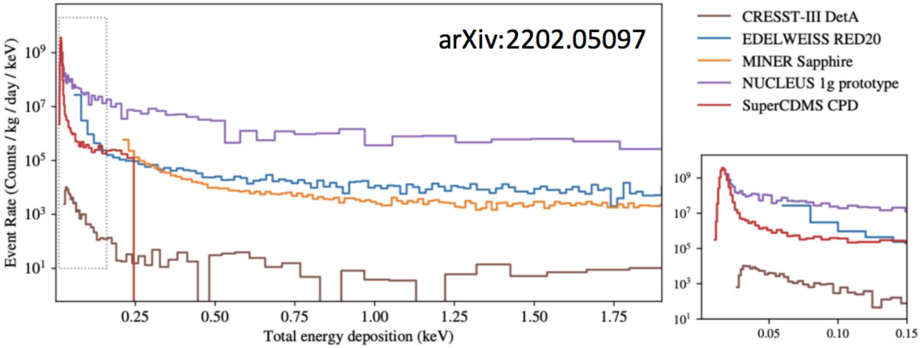
R. Strauss, IDM 2022







Exponentially rising background towards lower energies



Currently limiting the sensitivity globally !

Origin still unknown, but a lot of R&D is going on …

From neutrino floor to neutrino fog

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

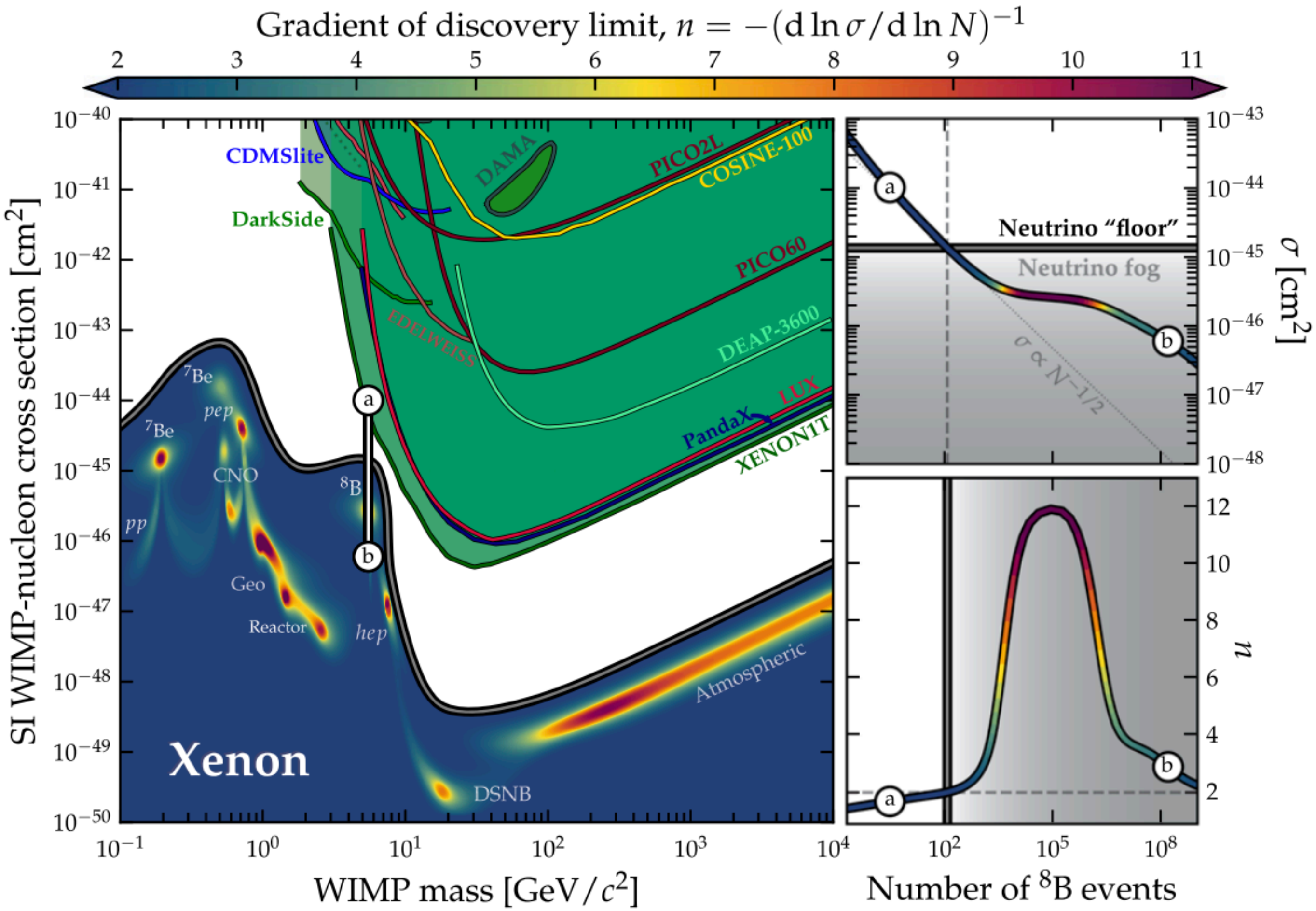
$$N\delta\Phi^2 \ll 1, \sigma \propto 1/\sqrt{N}$$

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*

See also J. Monroe Wed 9.00

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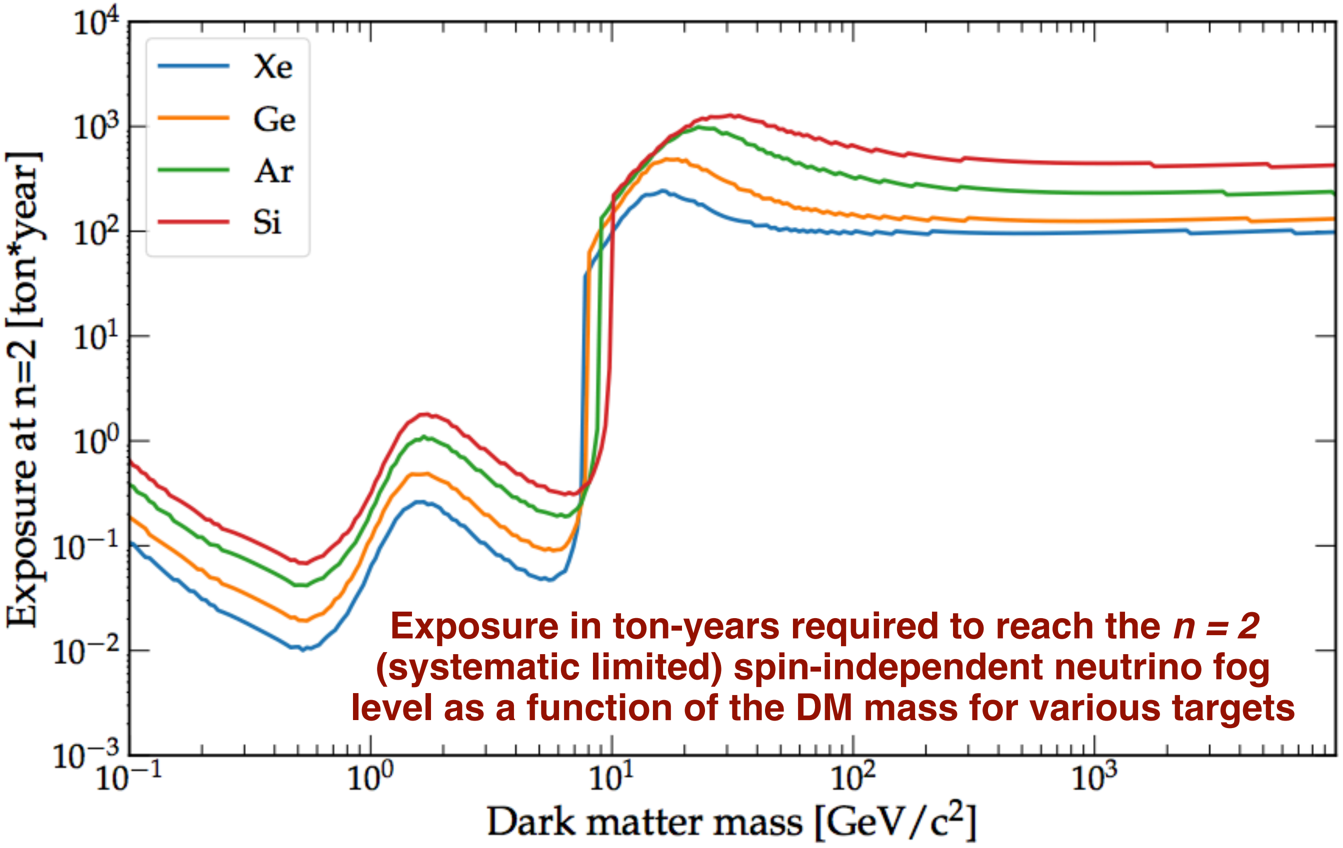
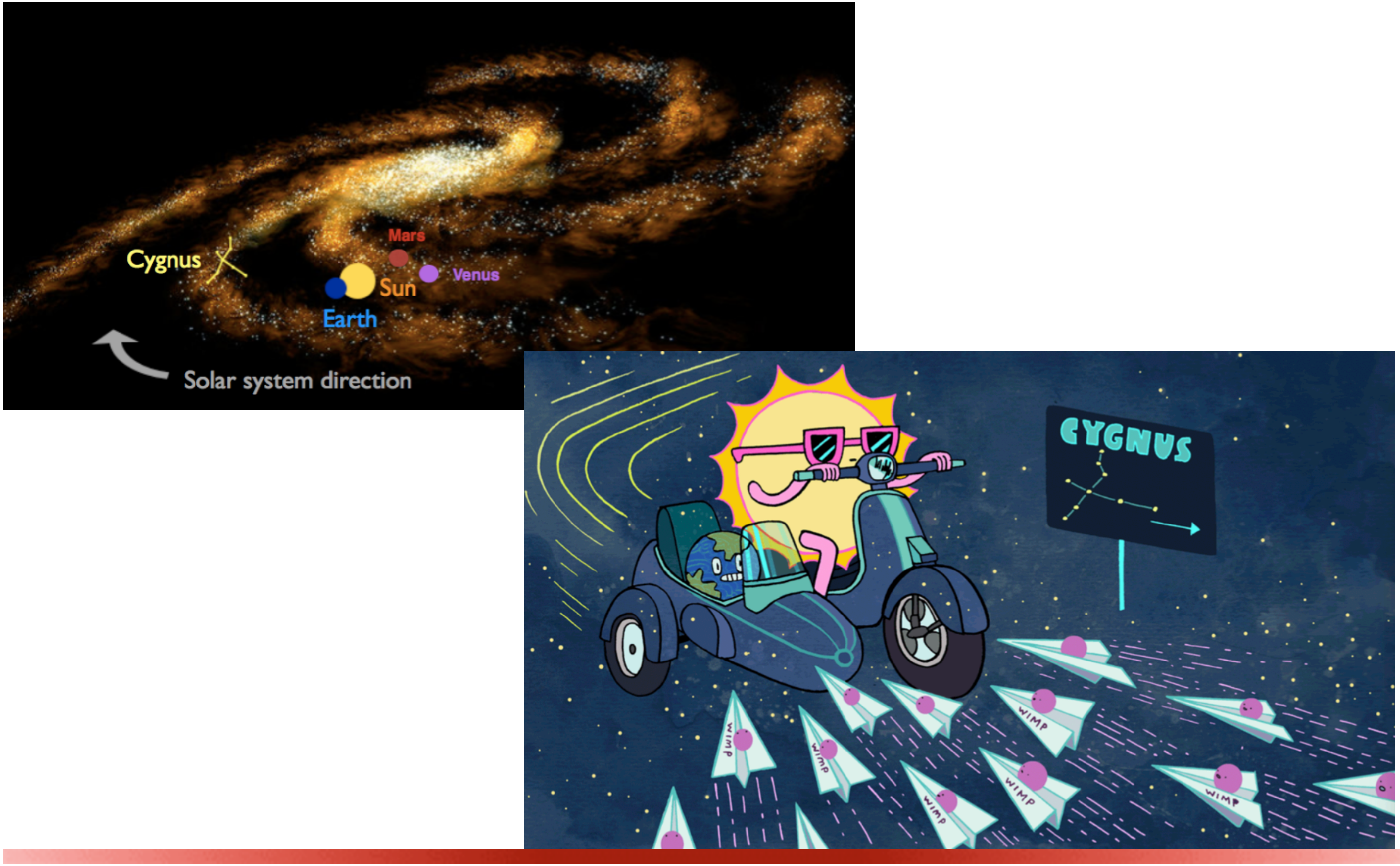


Exposure in ton-years required to reach the $n = 2$ (systematic limited) spin-independent neutrino fog level as a function of the DM mass for various targets

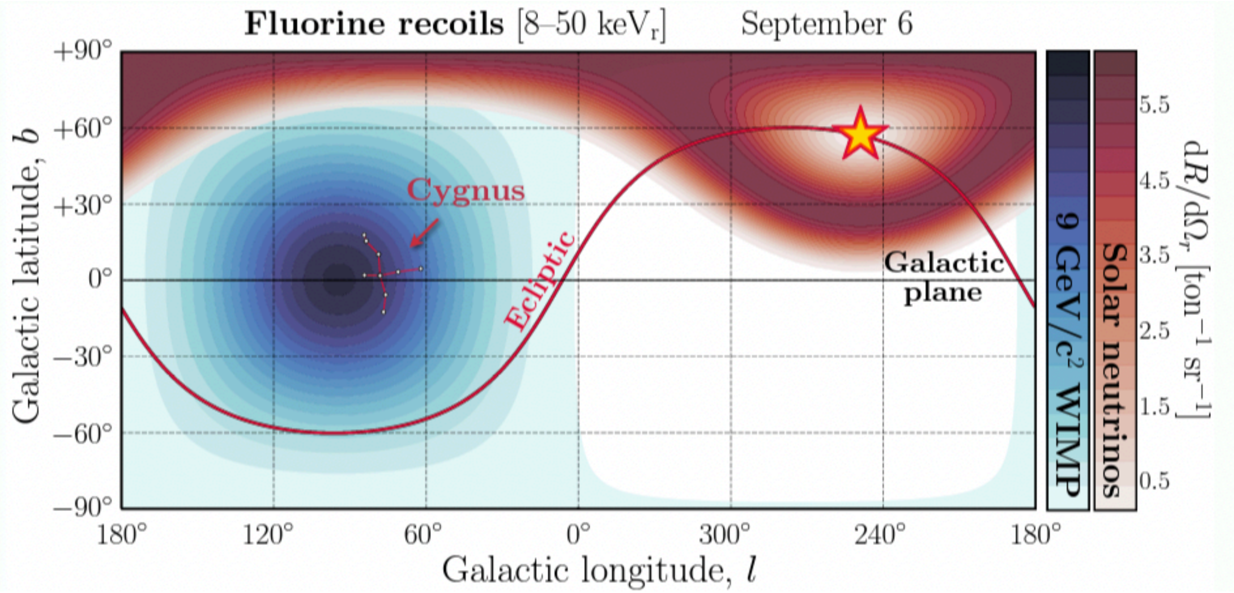
Reducing the sensivity of an experiment by a factor *x* requires an increas in the exposure by *at least x^n*

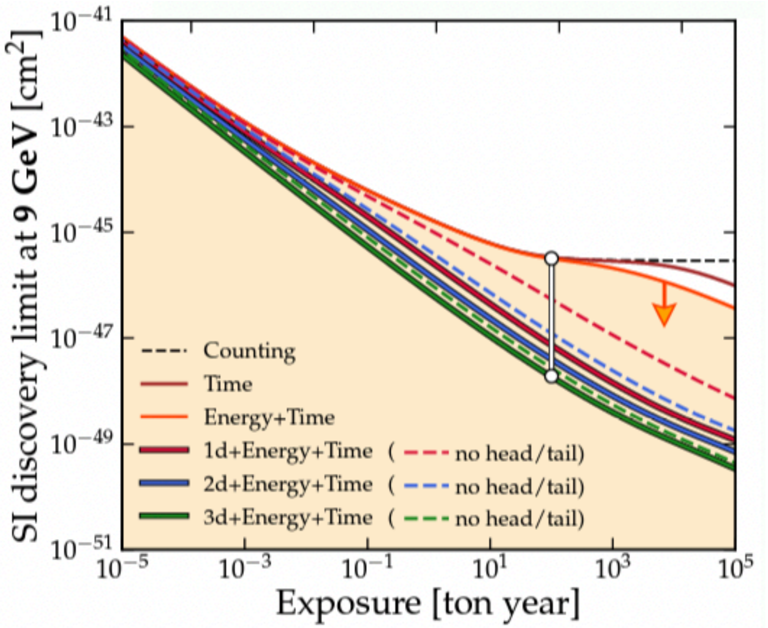
The return on investment becomes no more favourable

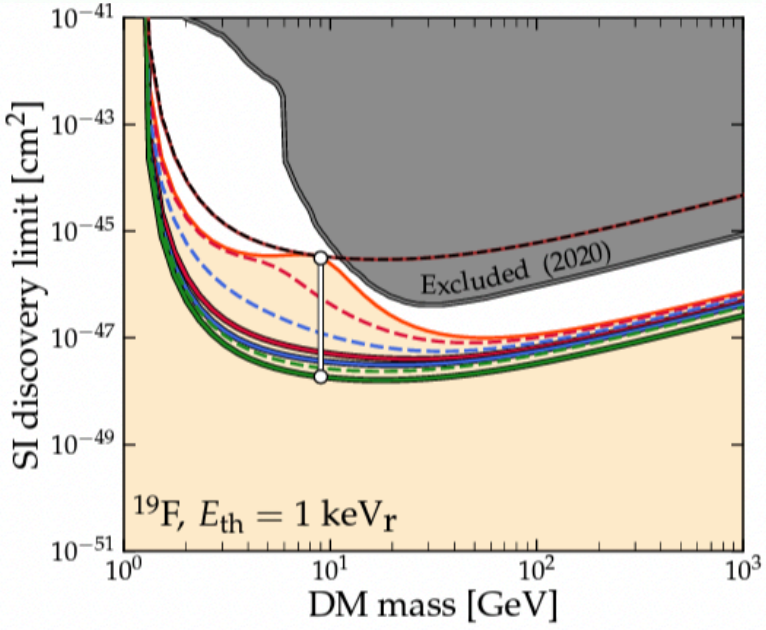
Driving towards CYGNUS with a DM wind blowing in our hairs



Diving into the neutrino fog with directionality







- 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…

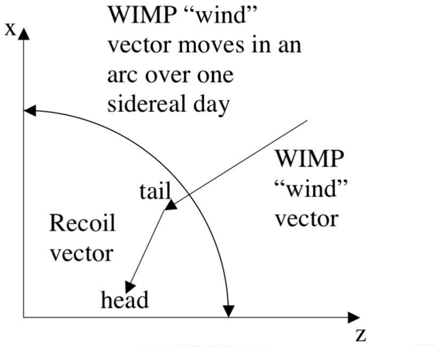
- At the level of individual events
- In as high a density target as possible
- Below <10 keVr
- With a timing resolution better than a few hours

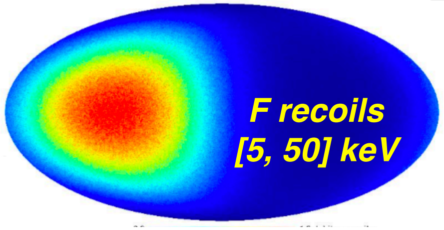
Full recoil imaging needed!

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

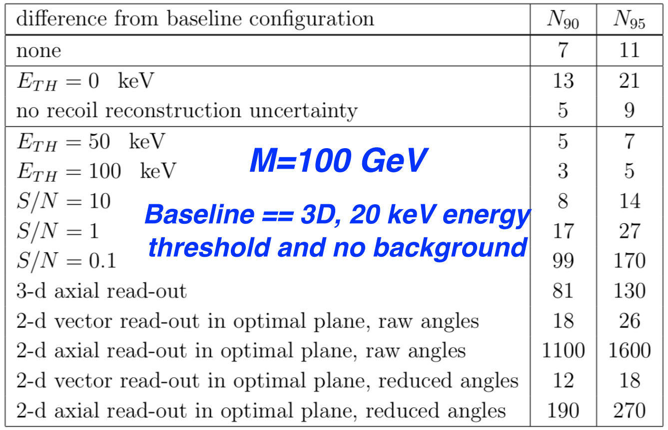
Positive discovery, identification & astronomy





F recoils [5, 50] keV

signal events to reject isotropy == to claim positive discovery



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

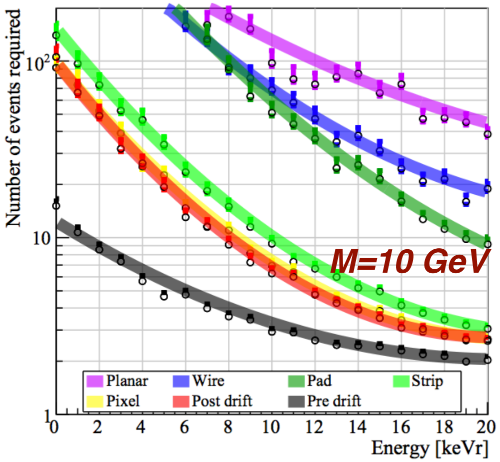
M=100 GeV

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

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

for various level of tracking capabilities & backgrounds

arXiv:2008.12587

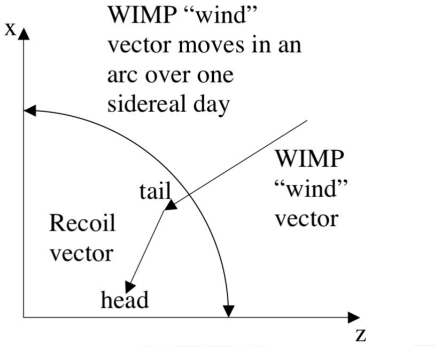


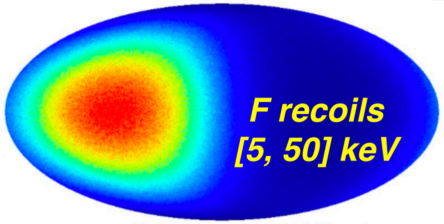
M=10 GeV

for gaseous TPC with various readout

Positive discovery, identification & astronomy

signal events to reject isotropy == to claim positive discovery

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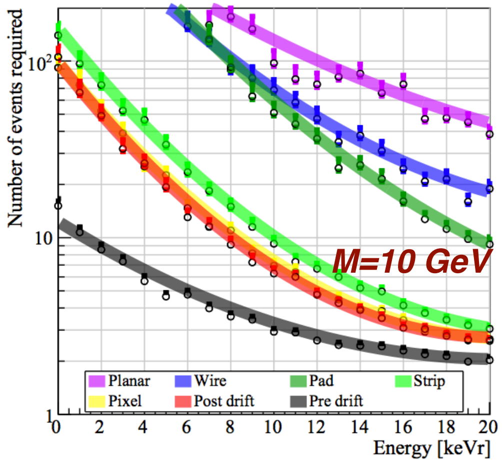
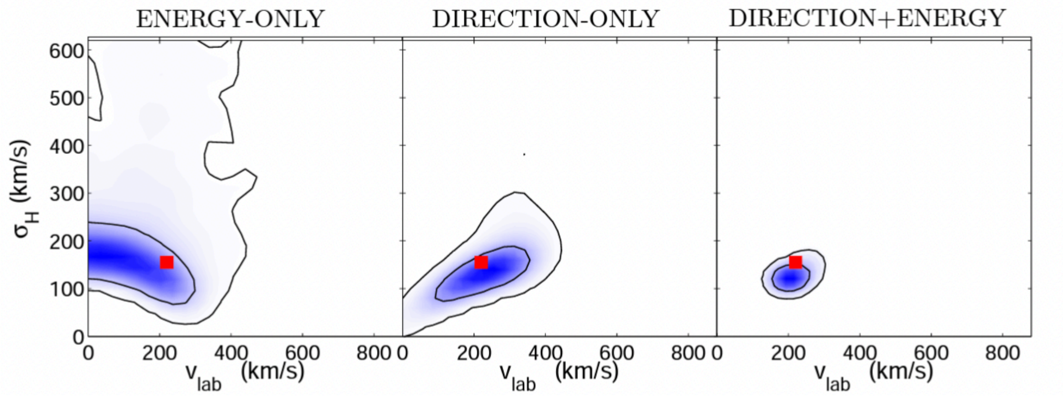
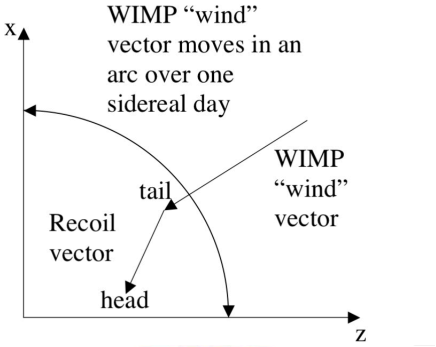


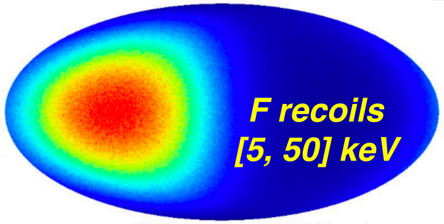
for gaseous TPC with various readout

Phys.Rept. 627 (2016) 1-49



Positive discovery, identification & astronomy





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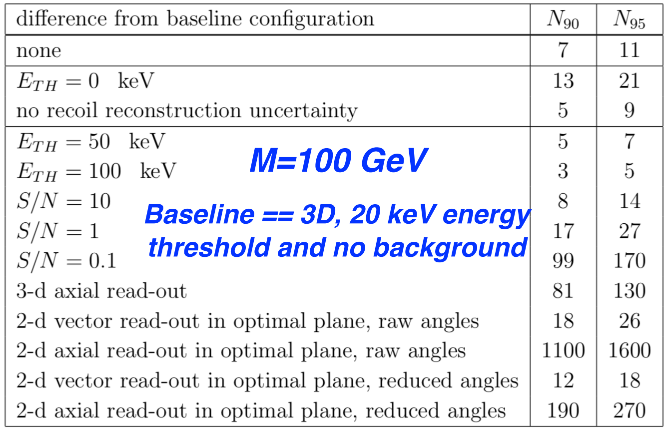

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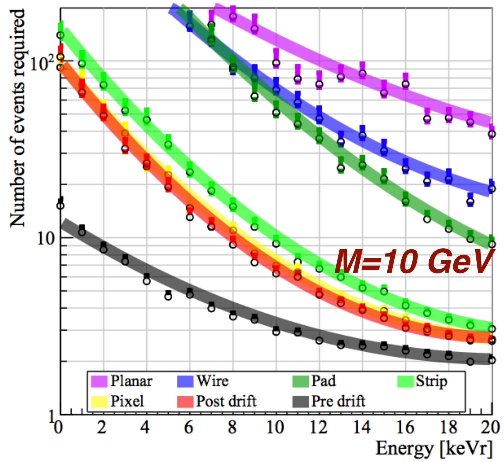

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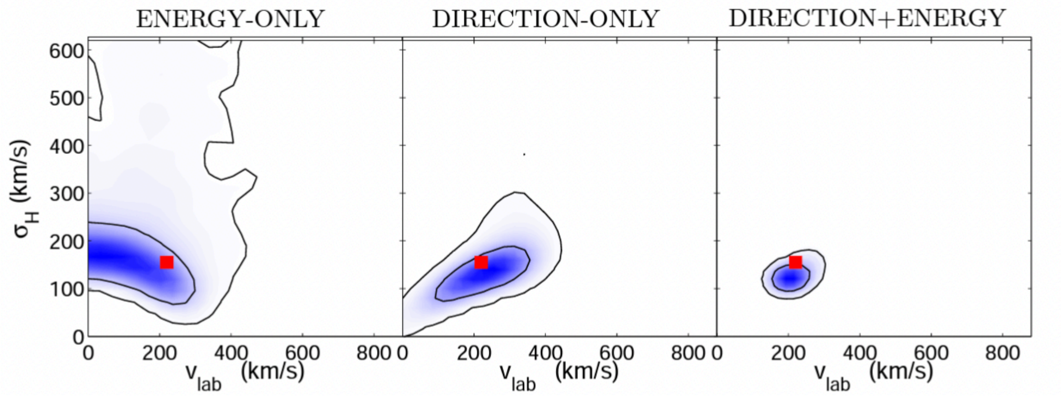
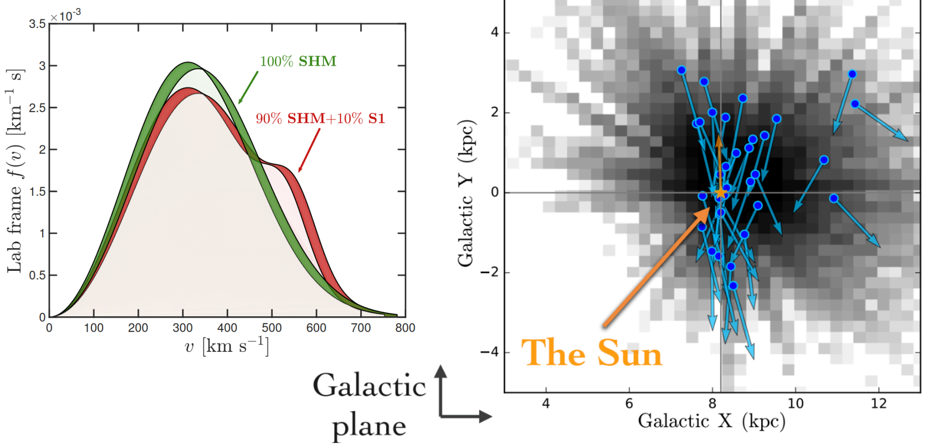
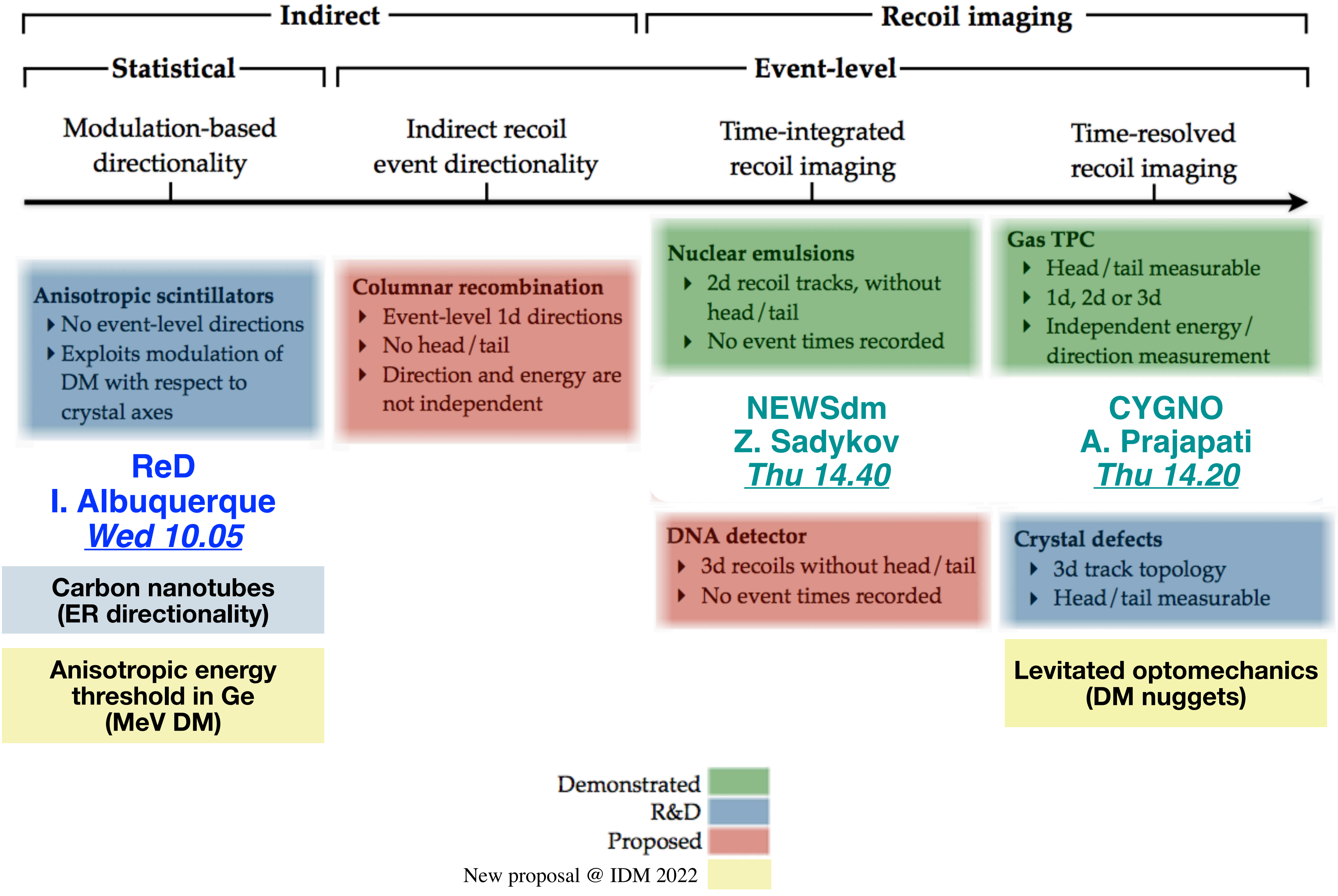


Phys.Rev.D 98 (2018) 10, 103006



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

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

ReD
I. Albuquerque
Wed 10.05

Carbon nanotubes (ER directionality)

Anisotropic energy threshold in Ge (MeV DM)

Indirect recoil event directionality

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

Time-integrated recoil imaging

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

NEWSdm
Z. Sadykov
Thu 14.40

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

Time-resolved recoil imaging

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

CYGNO
A. Prajapati
Thu 14.20

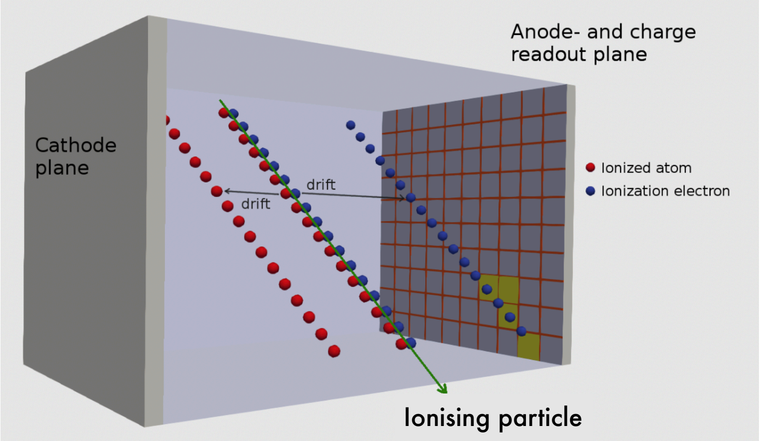
Crystal defects
- 3d track topology
- Head / tail measurable

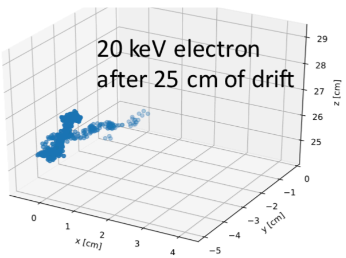
Levitated optomechanics (DM nuggets)

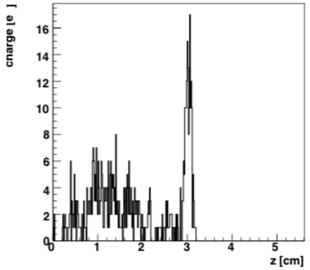
Demonstrated 🟩
R&D 🟦
Proposed 🟥
New proposal @ IDM 2022 🟨

Gaseous TPC experimental approach

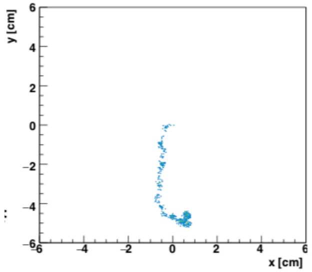
Depending on the anode segmentation (x-y) and time sampling (z), tracks can be reconstructed in 1D, 2D or 3D



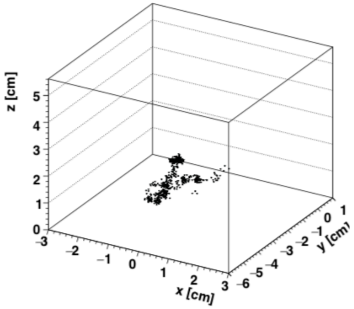




1D GEM



2D optical



3D pixels

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

Less event information → **More event information**

Improved background discrimination
More physics cases per exposure

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 (funded)

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***

The CYGNUS project

Since fall 2016

CYGNUS proto-collaboration vision

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


CYGNUS 2019 @Roma

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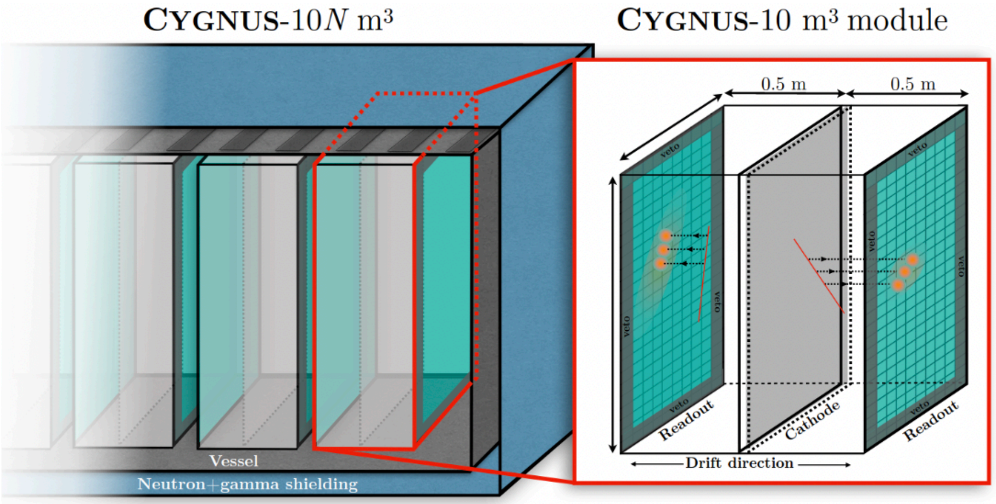
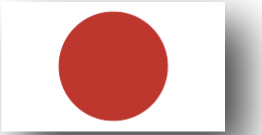


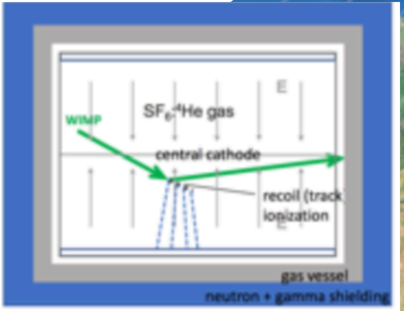
- About 70 members
- Steering group:
  - Elisabetta Baracchini (GSSI/INFN, Italy)
  - Greg Lane (Canberra, Australia)
  - Kentaro Miuchi (Kobe, Japan)
  - Neil Spooner (Sheffield, UK)
  - Sven Vahsen (Hawaii, USA)



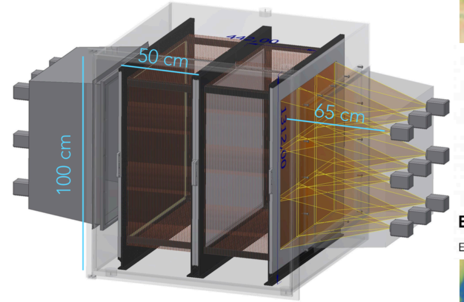

- **Helium/Fluorine gas mixtures at 1 bar**
  - **Sensitivity to O(GeV) WIMP for both SI & SD couplings**
- **Reduced diffusion**
  - **Through negative ion drift or "cold" gases (CF_4)**
- **3D fiducialization**
  - **Through minority carriers or fit to diffusion**
- **Directional threshold at O(keV)**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

CYGNUS projects in the world



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

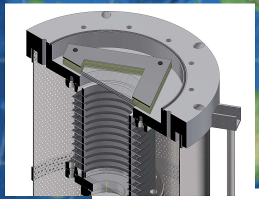
CYGNUS-10
10 m^3, GEMs + wires
He:SF_6
Boulby, UK
R&D ongoing on 1 m^3



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 funded towards 30 m^3 experiment

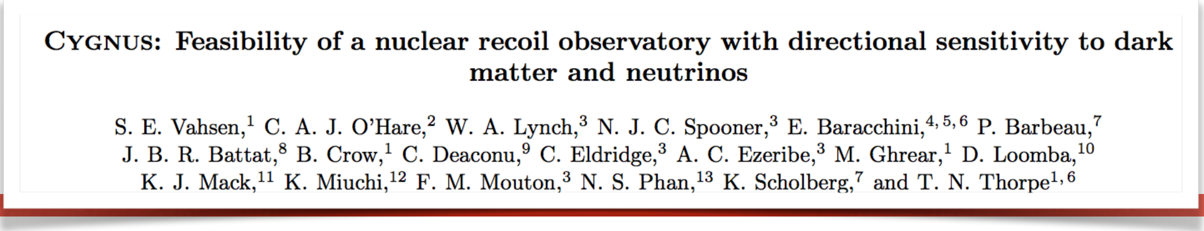
CYGNUS-KM
1 m^3, GEMs + 2D strips
SF_6/CF_4
Kamioka, Japan
R&D ongoing on 1 m^3



ARC CENTRE OF EXCELLENCE FOR DARK MATTER

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

arXiv:2008.12587

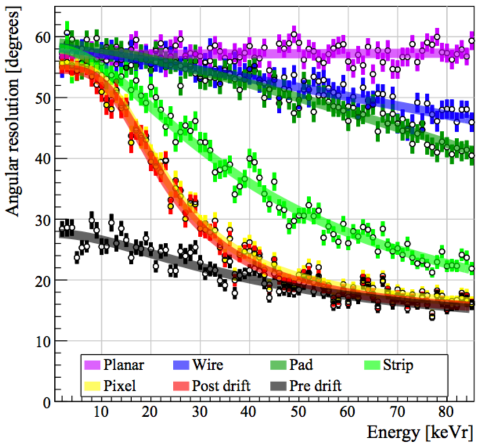

CYGNUS: Feasibility of a nuclear recoil observatory with directional sensitivity to dark matter and neutrinos

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]

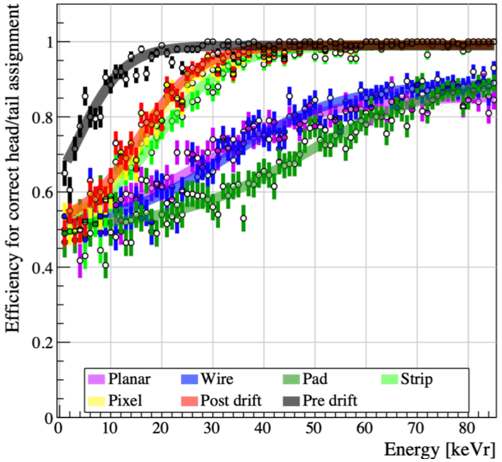
- **Extensive concept paper on 1000 m^3 gaseous NITPC detector focused on technical feasibility and WIMP searches through nuclear recoils**
- **Detailed simulation of seven readout options with with a cost/benefit FOM**
- **Background discrimination studies**
- **Detailed simulation and study of all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

Negative ion drift in He:SF_6 755:5 Torr

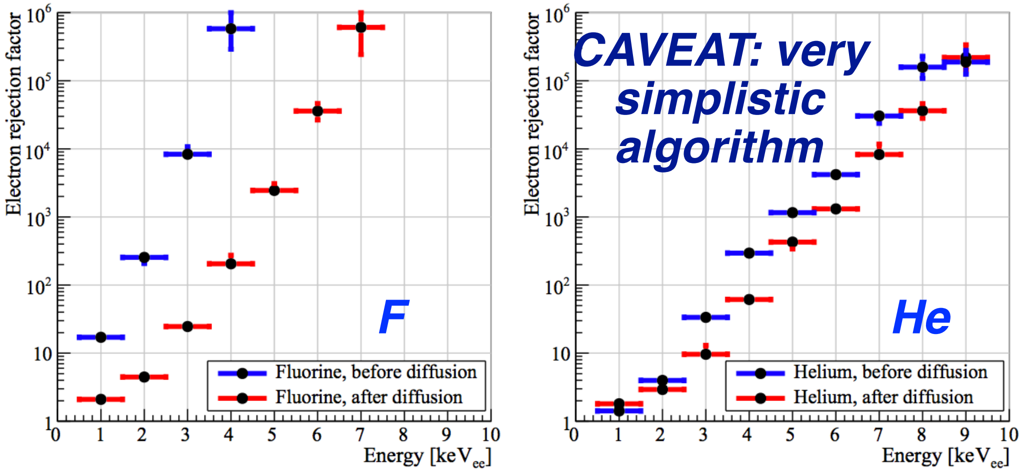
Angular resolution



Sense recognition



Electron recoil rejection

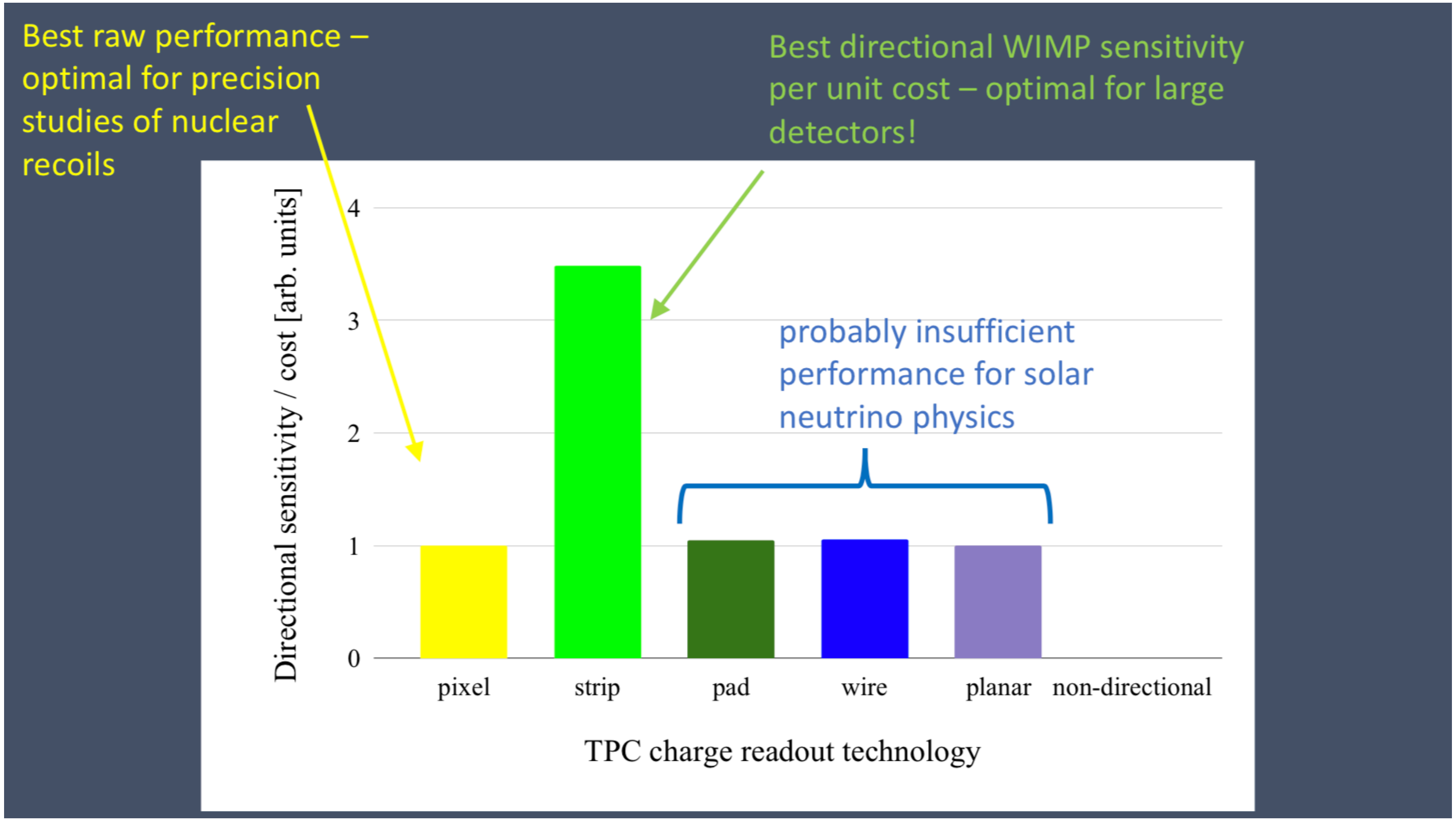


CAVEAT: very simplistic algorithm

- **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}**

arXiv:2008.12587

Cost vs benefit study result (for NID operation)



Best raw performance – optimal for precision studies of nuclear recoils

Best directional WIMP sensitivity per unit cost – optimal for large detectors!

probably insufficient performance for solar neutrino physics

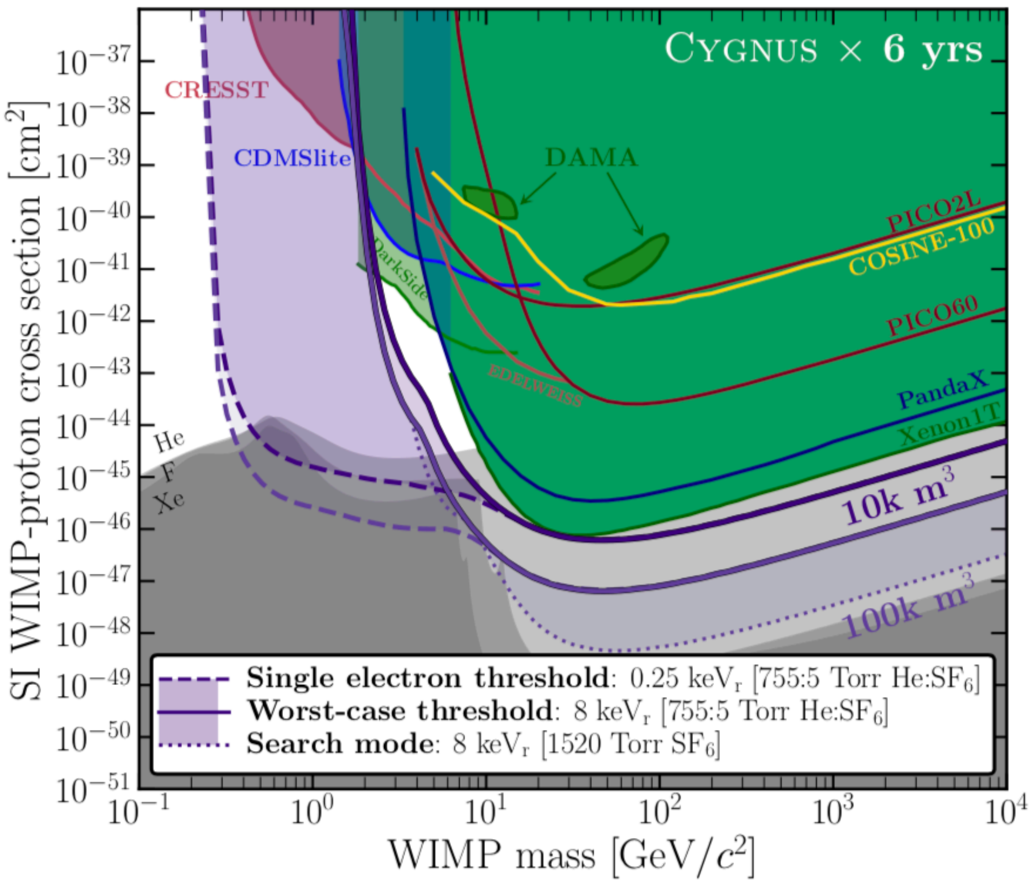
For He:SF$_6$ 755:5 with negative ion drift, strips results the best choice in terms of costs versus performances, radiation budget and engineering cosiderations

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

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

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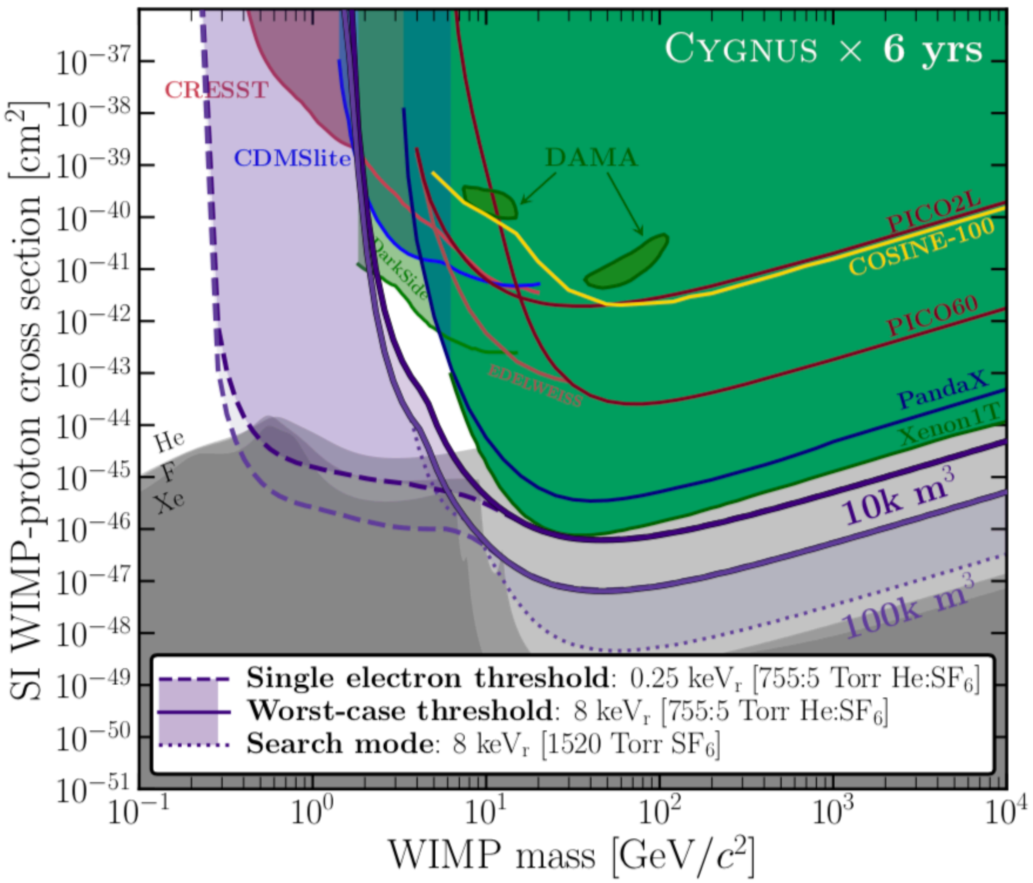
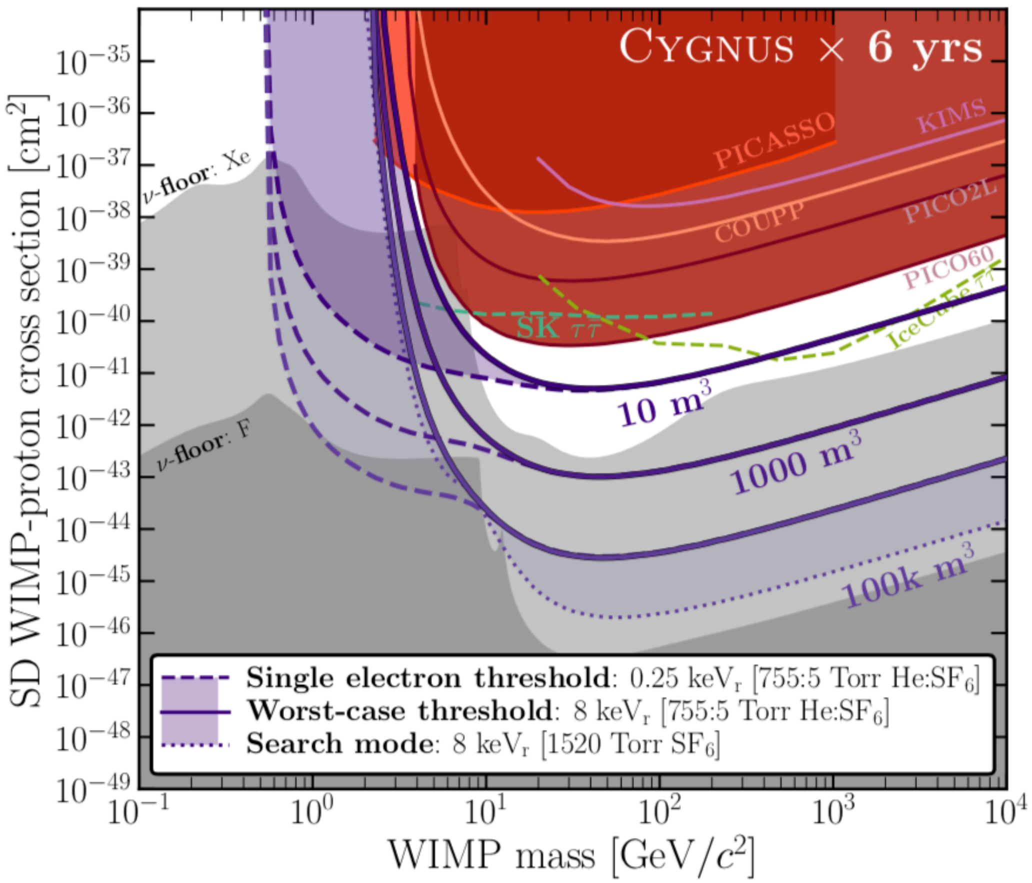




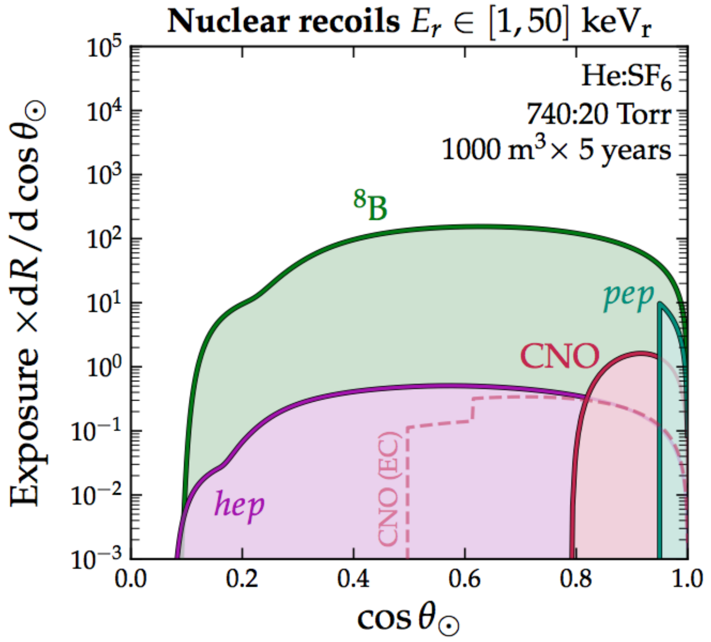
Significant improvement in SI in the low WIMP mass region, expect 10-50 IDENTIFIED neutrino nuclear recoil events

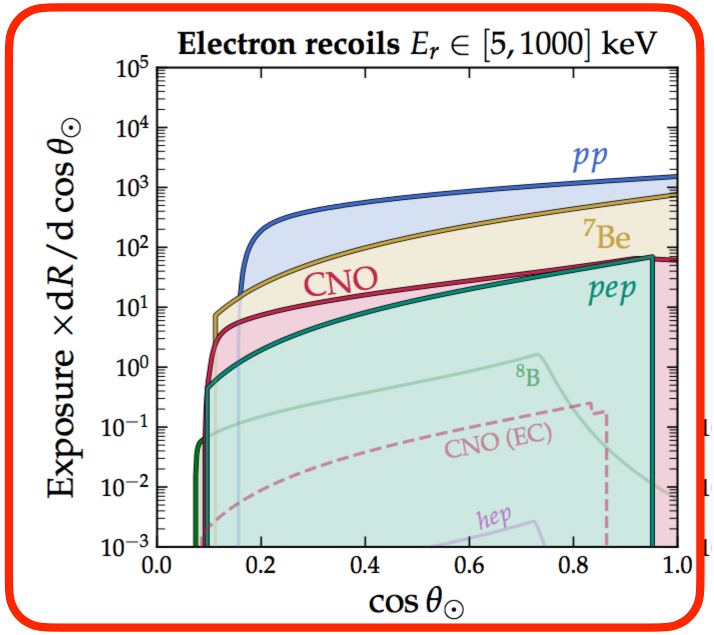
Significant improvement in SD reach over existing experiments for all WIMP masses, a 10 m^3 detector can already breach the Xe neutrino floor

Neutrinos in CYGNUS: promoting background to signal

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

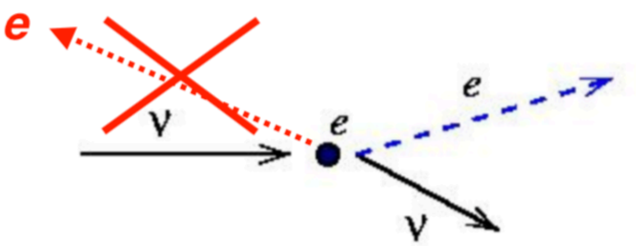
Expected number of recoil events as a function of the cosine of the angle away from the Sun





ER from elastic scattering of solar neutrinos features

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



*Differently from WIMPs, background can be **measured** on sidebands data*

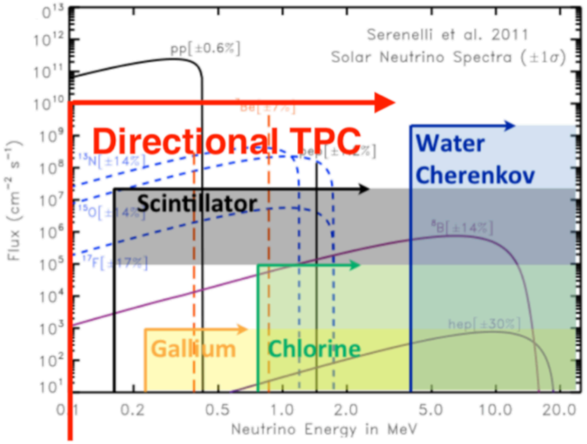
NOTE: among DM experiments, only a directional detector can distinguish ERs from solar neutrinos from ERs from any other background source….

NEW!

Original idea by Seguinot et al (1992)

Solar neutrino spectroscopy on an event-by-event basis

Dedicated CYGNUS paper in preparation



1000 m³, 1 atm, 1year

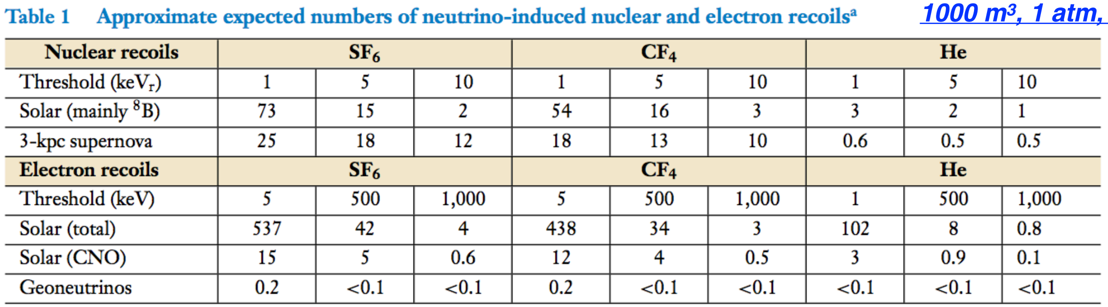


Table 1 Approximate expected numbers of neutrino-induced nuclear and electron recoils[a]

Nuclear recoils	**SF_6**			**CF_4**			**He**		
Threshold (keV_r)	1	5	10	1	5	10	1	5	10
Solar (mainly ^8B)	73	15	2	54	16	3	3	2	1
3-kpc supernova	25	18	12	18	13	10	0.6	0.5	0.5
Electron recoils	**SF_6**			**CF_4**			**He**		
Threshold (keV)	5	500	1,000	5	500	1,000	1	500	1,000
Solar (total)	537	42	4	438	34	3	102	8	0.8
Solar (CNO)	15	5	0.6	12	4	0.5	3	0.9	0.1
Geoneutrinos	0.2	<0.1	<0.1	0.2	<0.1	<0.1	<0.1	<0.1	<0.1

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

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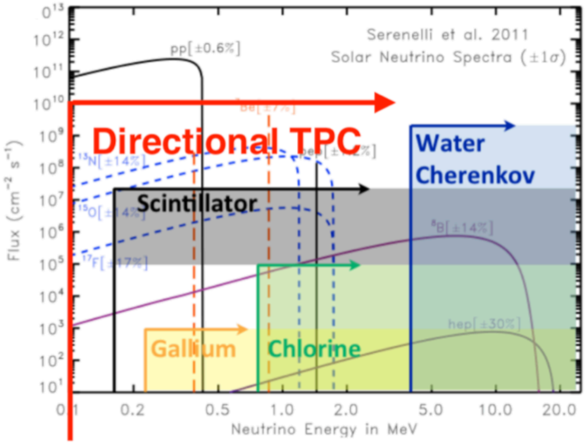

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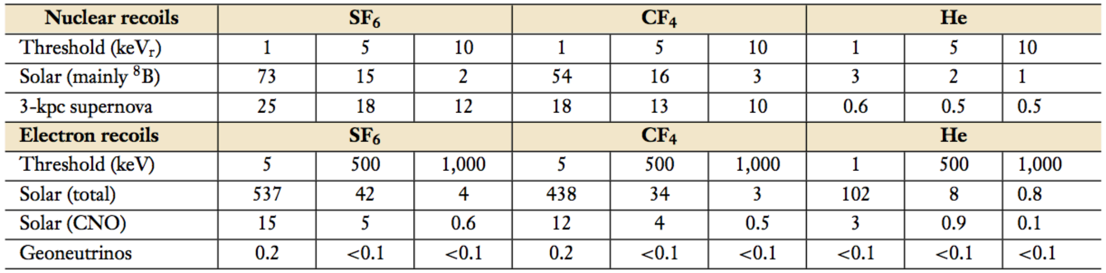

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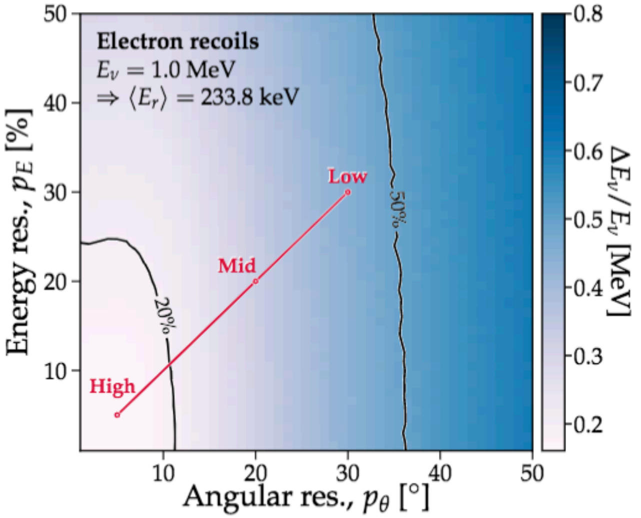
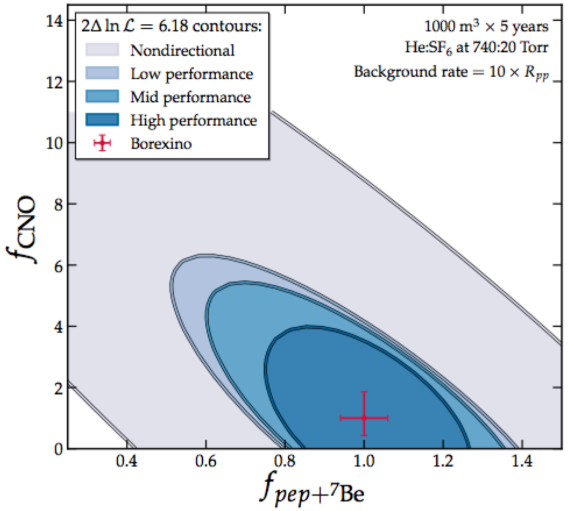
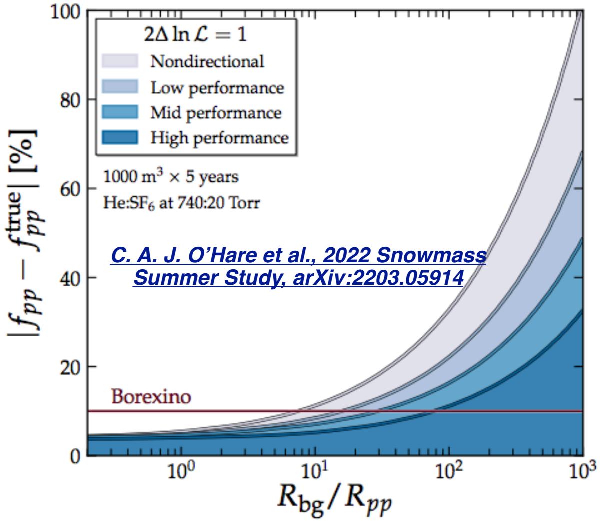


1 σ sensitivity to pp flux as a function of the total non-neutrino ER background



2 σ sensitivity to combined measurement of the CNO and pep + ⁷Be pp fluxes, fixing the background rate to 10 times the pp electron recoil rate

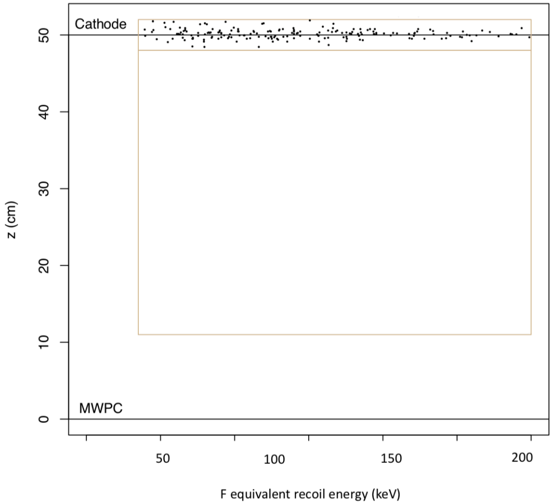


C. A. J. O'Hare et al., 2022 Snowmass Summer Study, arXiv:2203.05914

- ***Electron recoils directionality in CYGNUS enables solar neutrino spectroscopy through neutrino-electron elastic scattering on an event-by-event basis***
  - **An O(10) m³ ER directional detector could extend Borexino pp measurement to lower energy**
  - **CYGNUS 1 ton could measure the CNO cycle by breaking the degeneracy with pep + ⁷Be fluxes through directionality**

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)

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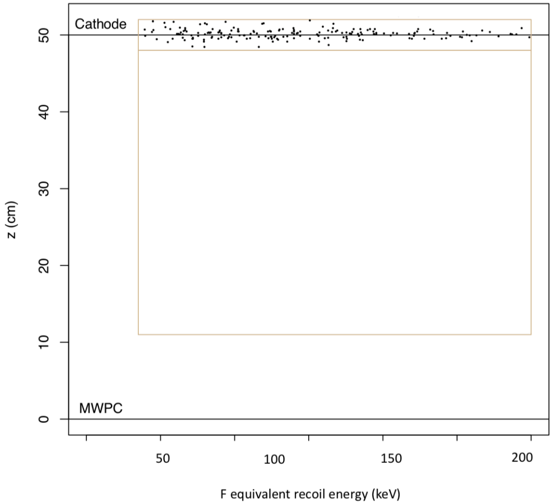

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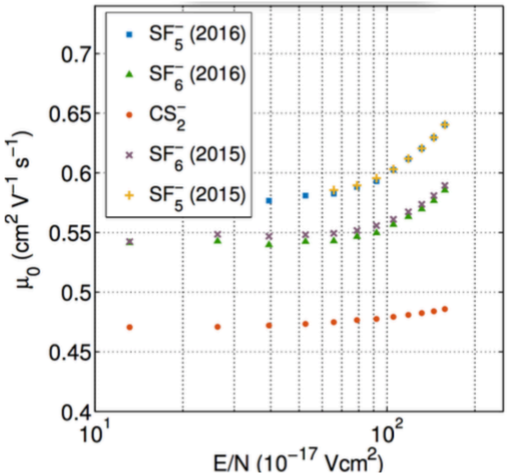
NID operation with SF_6 20-40 Torr, much safer and easier to handle than CS_2



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

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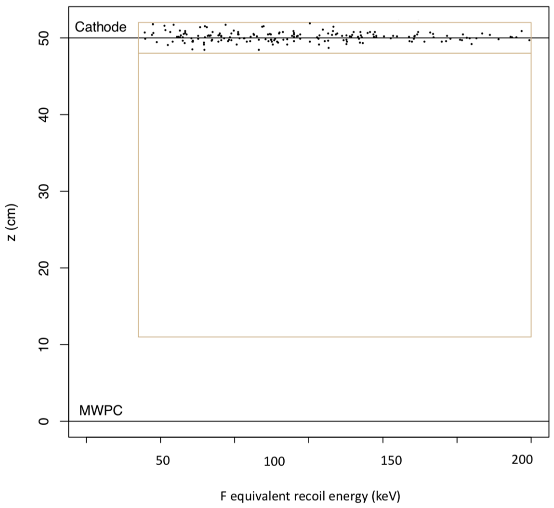

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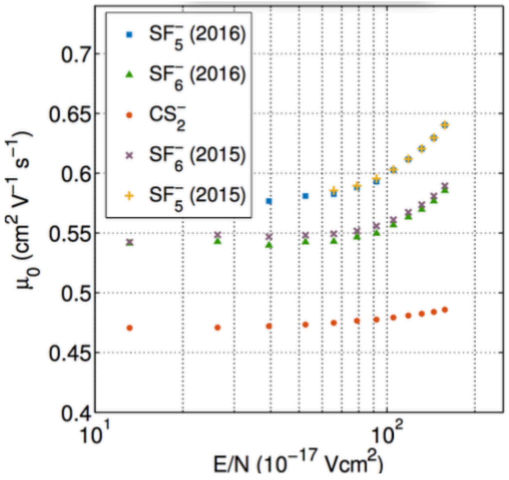

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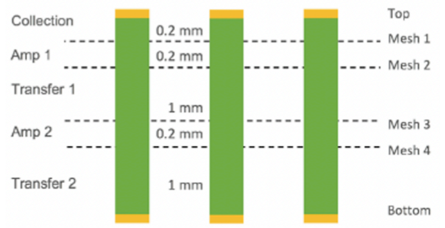
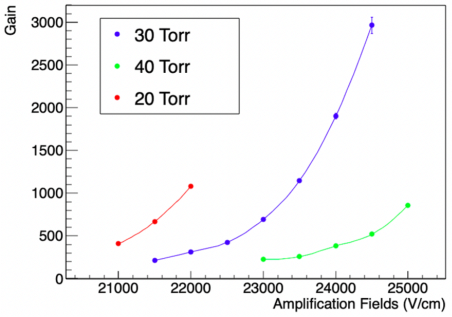
Dedicated amplification structure MMThickGEM 20-40 Torr





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

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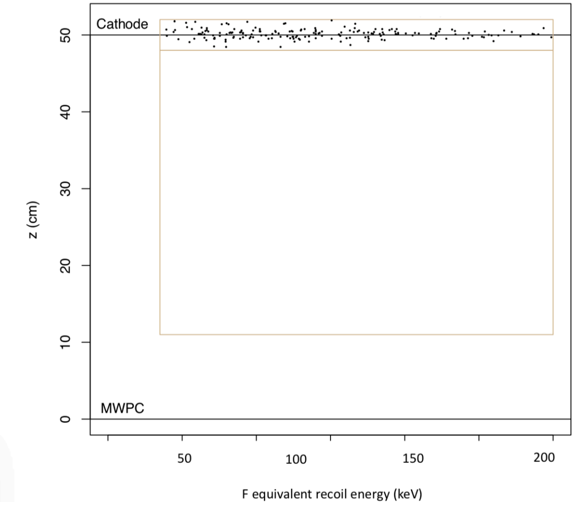

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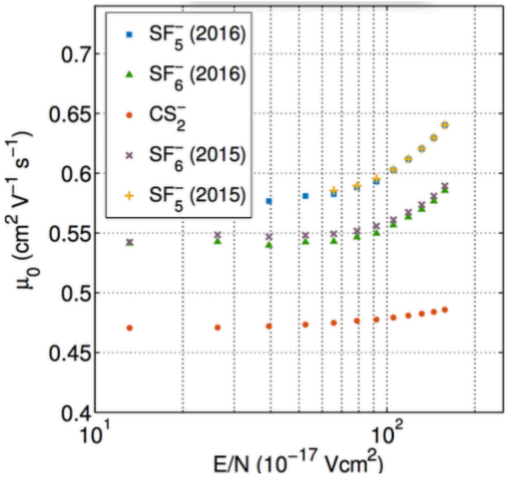

JINST 12 (2017) 02, P02012

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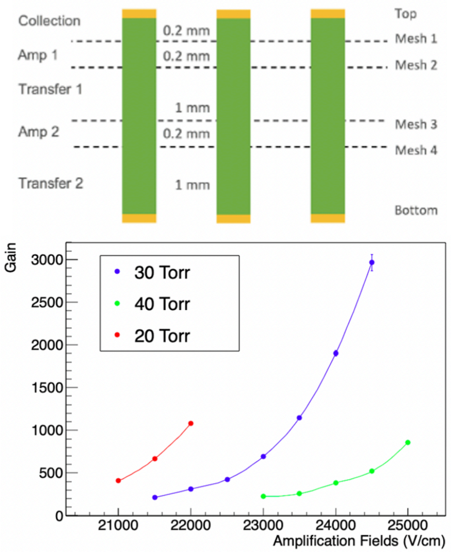
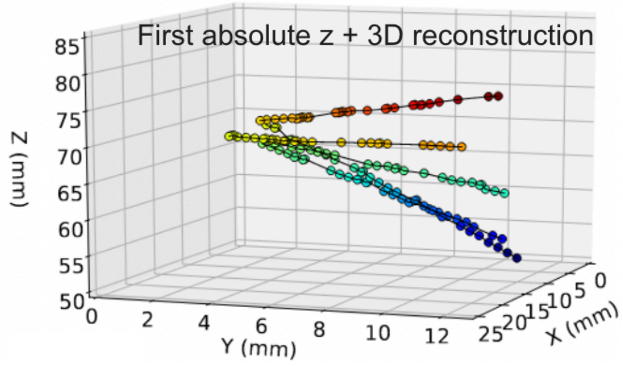


JINST 18 (2023) 08, P08021

Absolute Z + 3D tracking @ 20 Torr



JINST 15 (2020) 07, P07015

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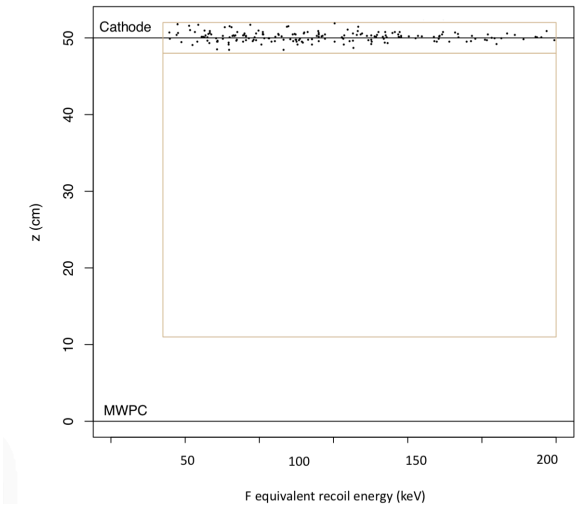

[Phys. Dark Univ. 9-10 (2015)](#)

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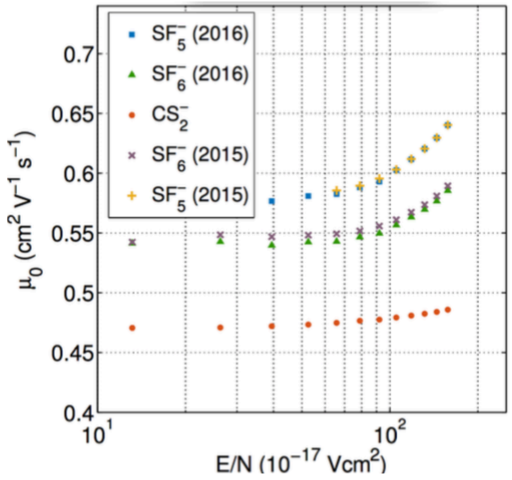

JINST 12 (2017) 02, P02012

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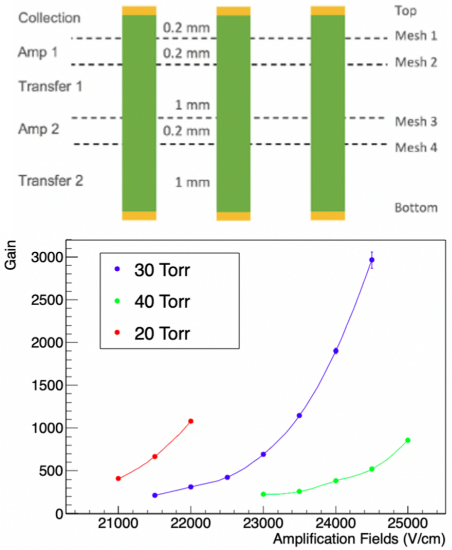

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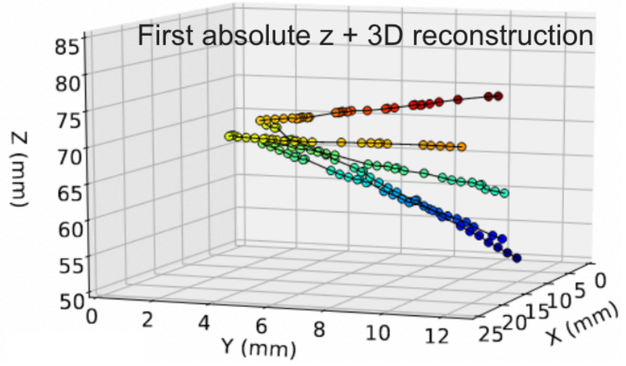
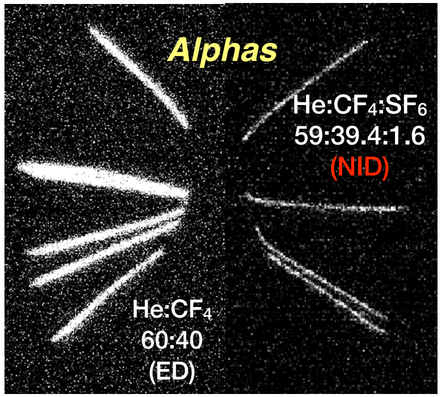
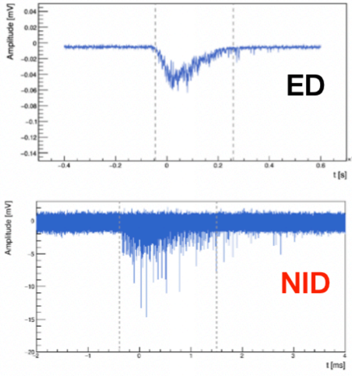
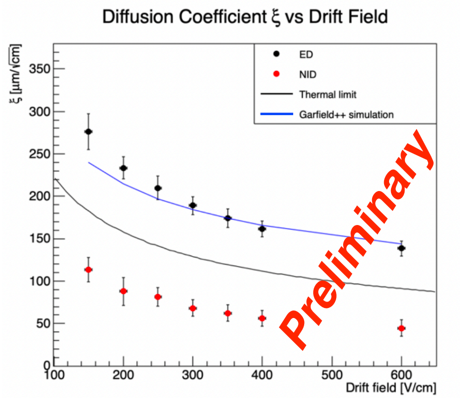


JINST 15 (2020) 07, P07015

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







Paper in preparation

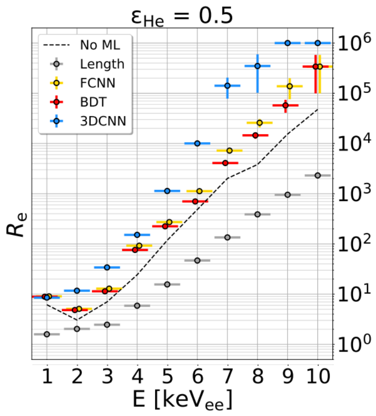
See A. Prajapati talk on CYGNO Thu 14.20

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



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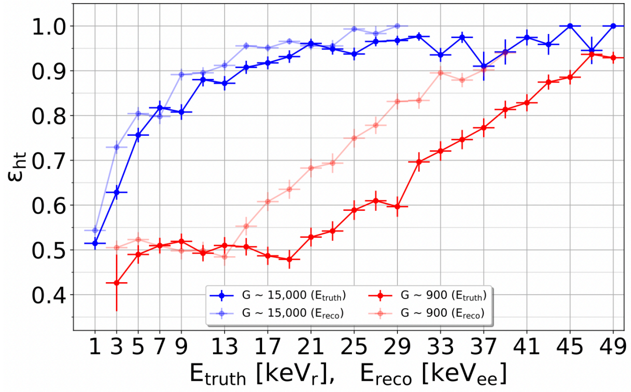
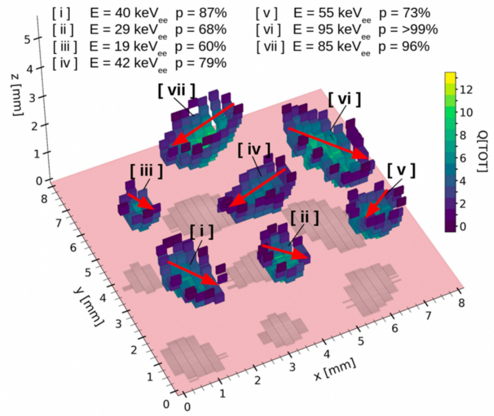


O(10^5) ER rejection on simulated data below 10 keV achievable @ 60 Torr

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



DETECTED He recoils at 1 atm with pixel readout

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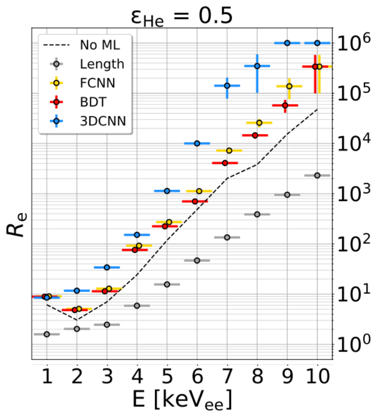

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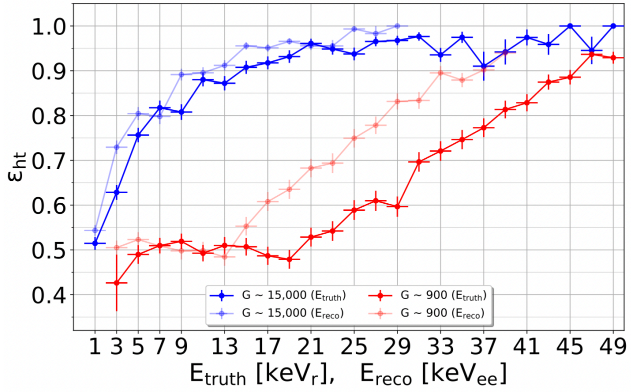

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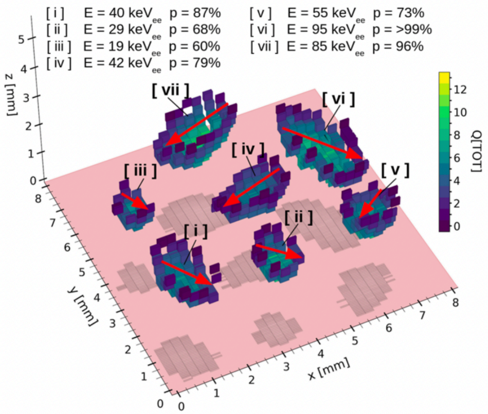

Machine Learning on simulated data with optical readout (CYGNO)

Full simulation of detector effects

Preliminary

Models	Signal Efficiency $[\epsilon^S]\%$	Bkg. Rej. Efficiency $[1-\epsilon^B]\%$
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

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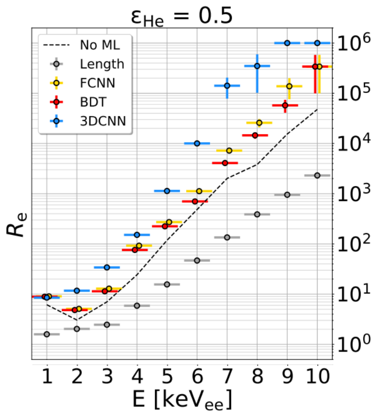
J. Schuler et al, arXiv:2206.10822



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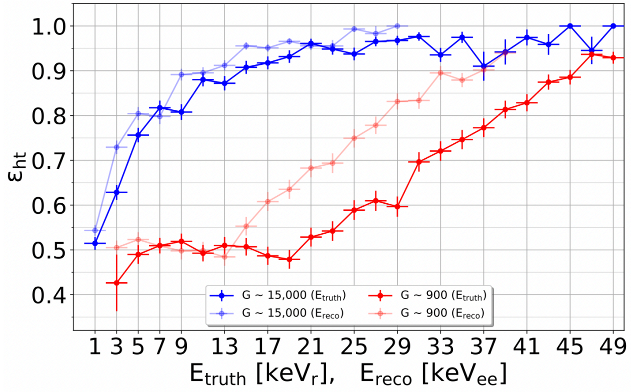

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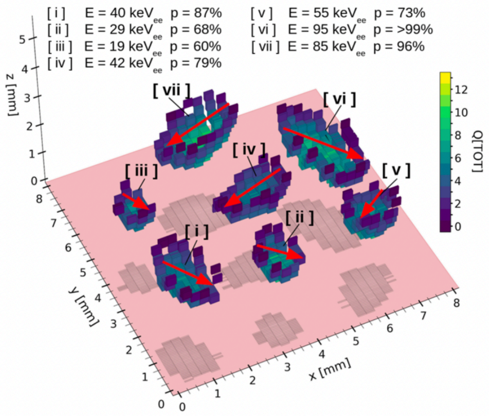

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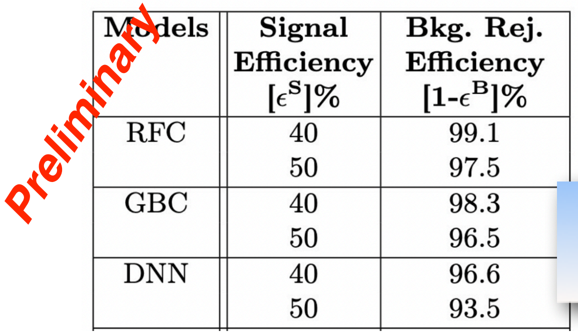

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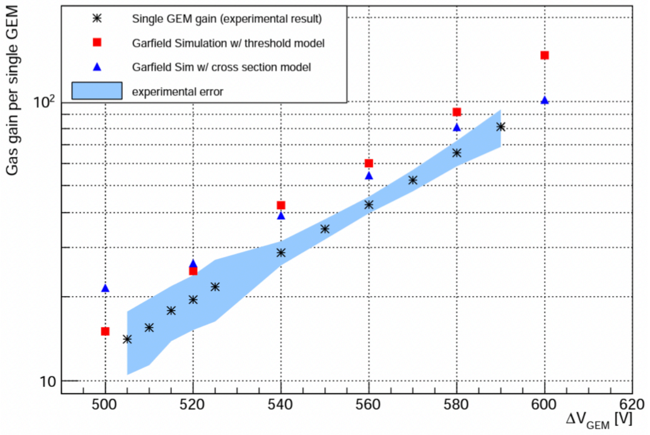
O(10^3) ER rejection in the 1-35 keV @ 1 atm

GEM SF_6 NID amplification Garfield++ simulation



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

CYGNUS R&D: detectors & prototypes

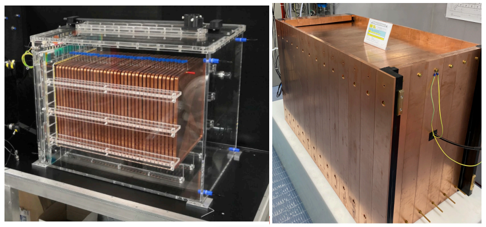
CYGNO

(Italy + UK + Portugal + Brasil)

GEMs + sCMOS + PMTs

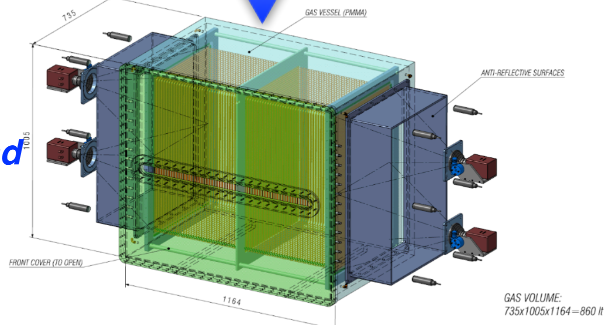
arXiv: 2305.06168

50 L underground



See A. Prajapati talk on Thu 14.20

0.4 m^3 underground FUNDED



CYGNUS-HD (US)

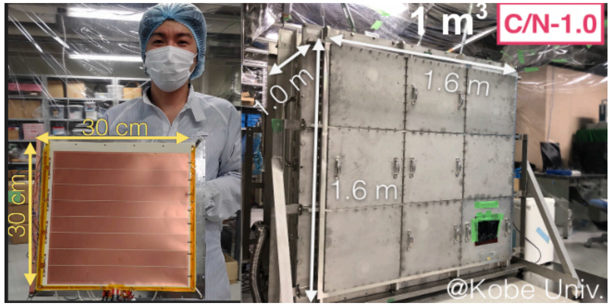
CERN strip Micromegas + SRS

40 L under construction

1 m^3 project

NEWAGE (Japan)

GEMs + muPIC



1 m^3 vessel, readout installation through staged approach

CYGNUS-OZ (Australia)

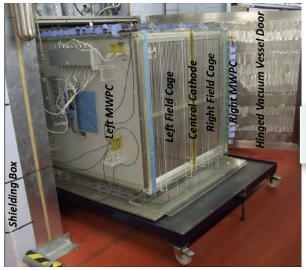
GEMs + (CCD) + PMTs

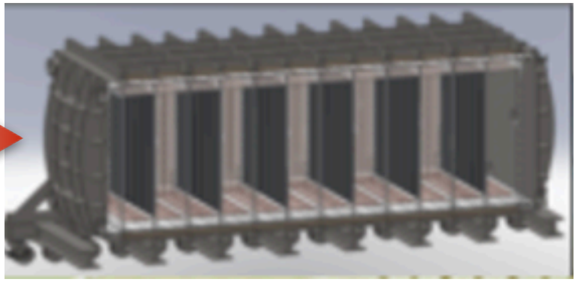
40 L prototype

DRIFT (UK)

MWPC —> MMThickGEM

1 m^3 experiment



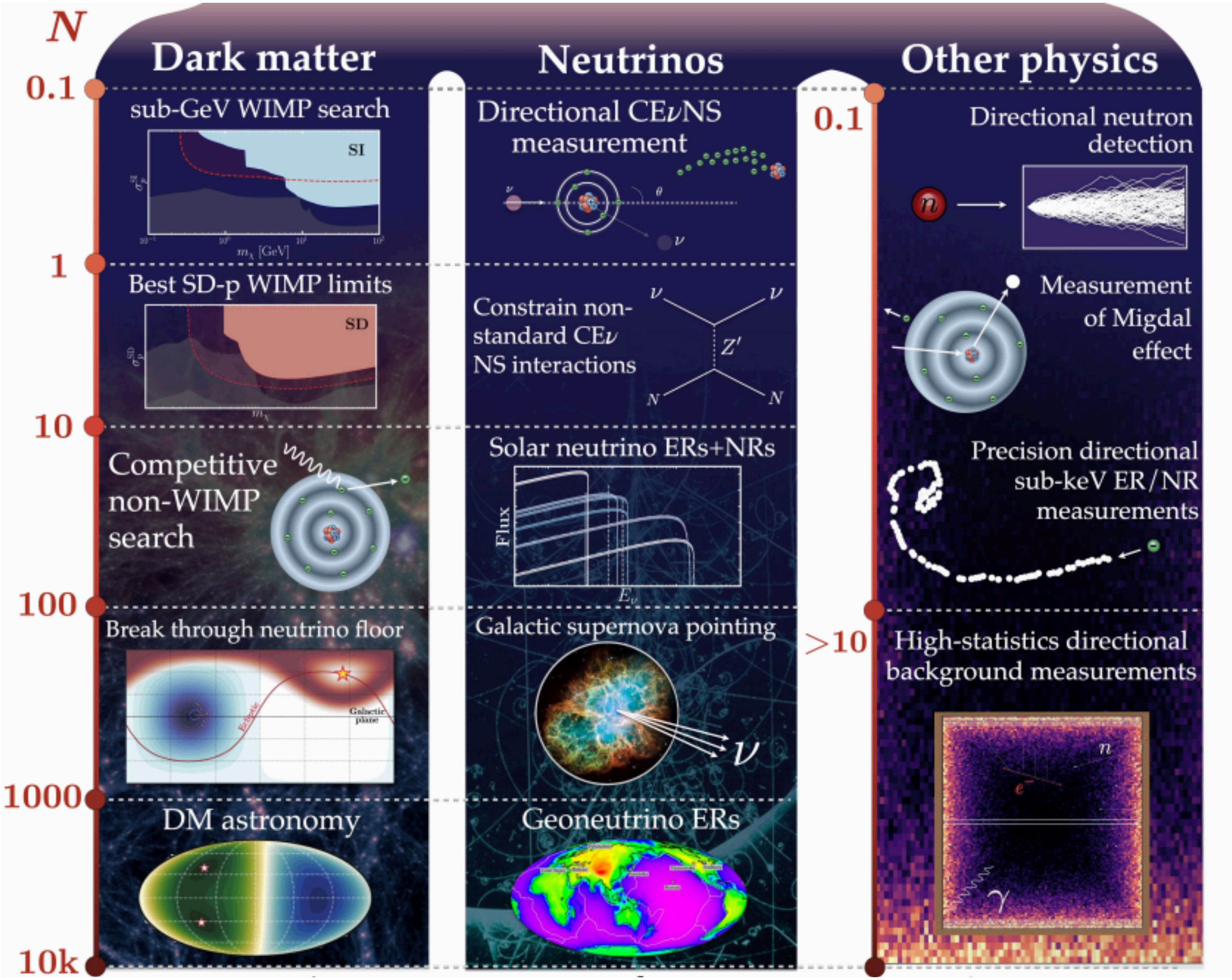


O(10) m^3 project

Physics cases for directional TPCs as a function of exposure

N = volume in m³ assuming 1 atm operation

Many interesting physics opportunities already at relatively small scale



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

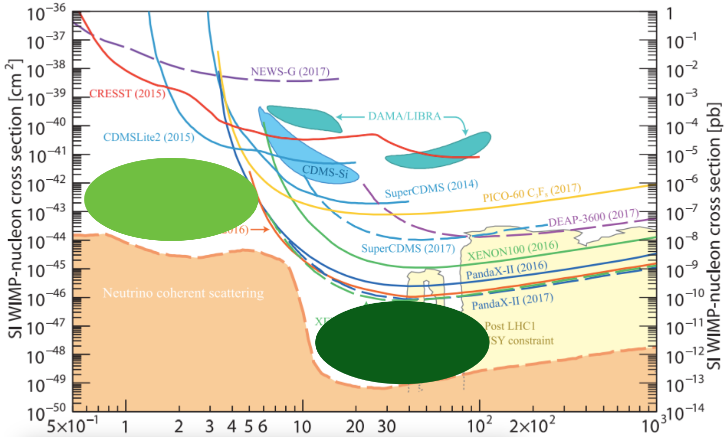
For example, X-ray polarimetry with 1 cm³ detector
i.e. IXPE experiment launched Dec 2021

- Nature **619**, 41–45 (2023)
- Nature **611**, 677–681 (2022)
- Nature **611**, 677–681 (2022)
- Nature Astronomy **4**, 547 (2020)
- Nature Astronomy (2023)

….and many more

Direct DM search future

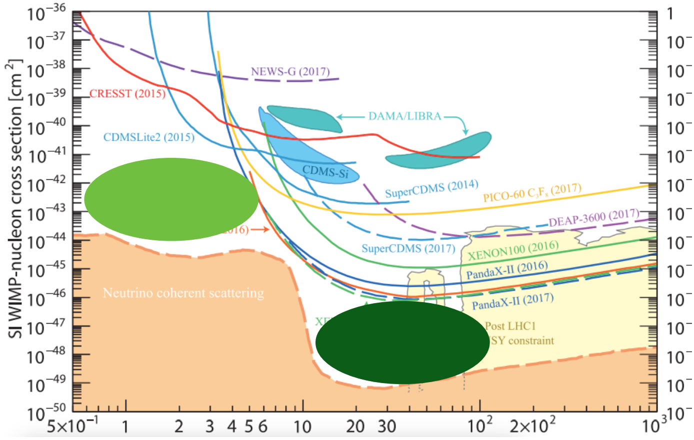
Old limits, only illustrative purpose



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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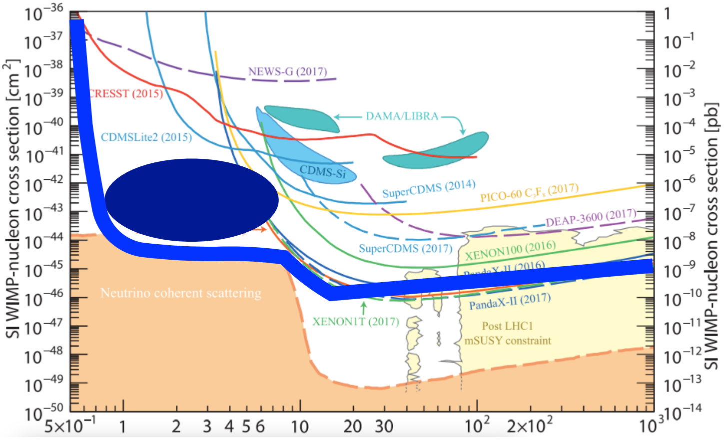
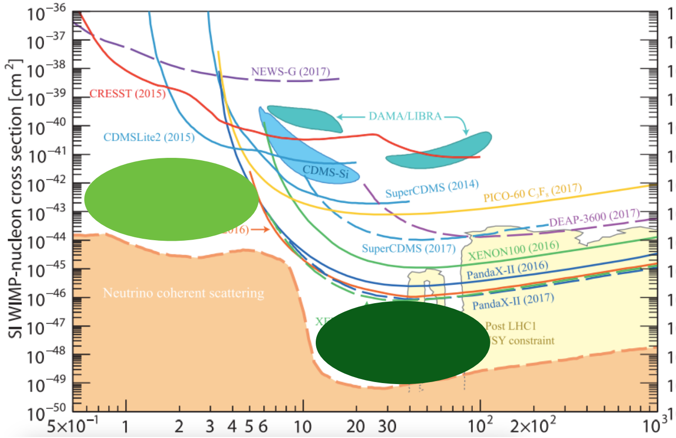
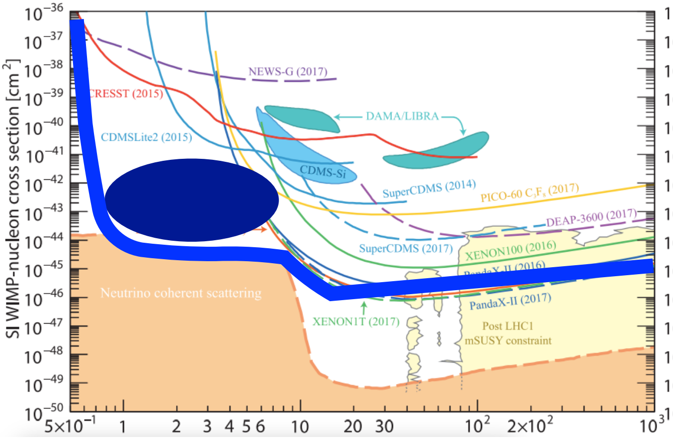


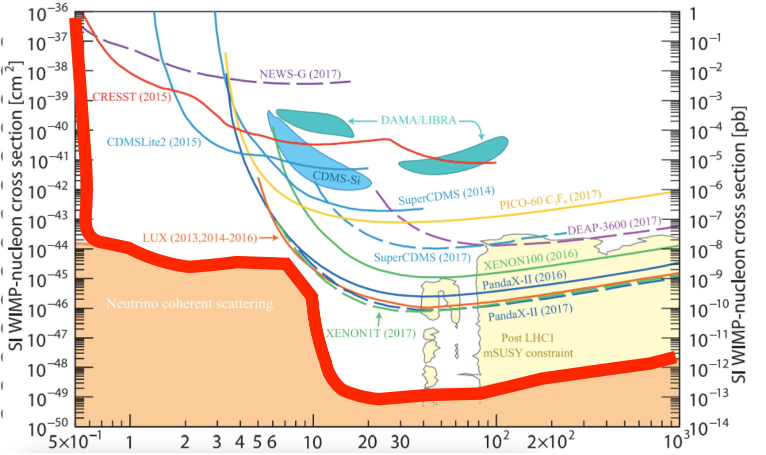
Incompatible results:
only a directional experiment can test the galactic origin of the observed signal

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

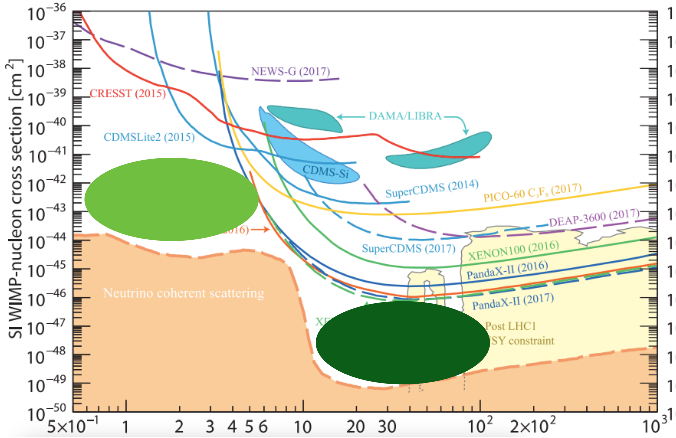
Incompatible results: only a directional experiment can test the galactic origin of the observed signal

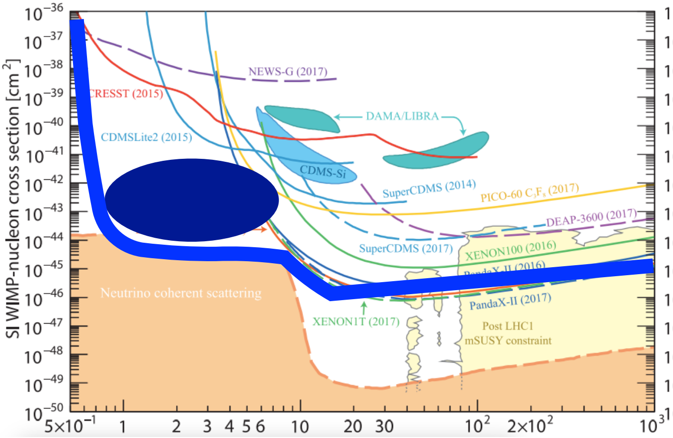
DM is excluded to the Neutrino Fog: only a directional experiment can continue DM searches and study neutrinos

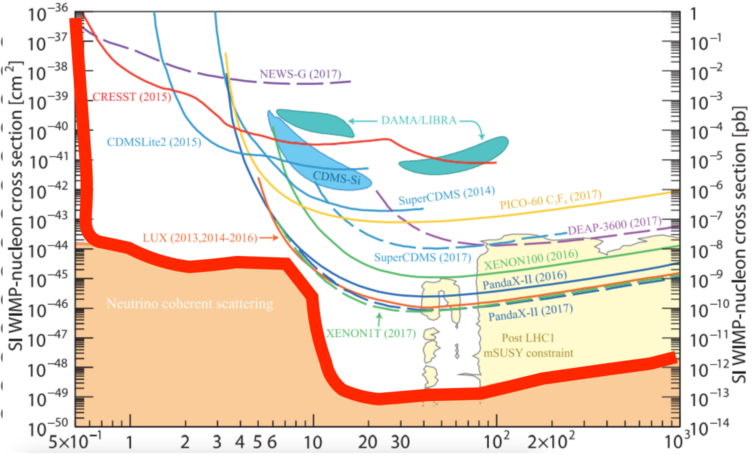
*Or we "hit" some new other irreducible background

Direct DM search future

Old limits, only illustrative purpose







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Directional DM community in CYGNUS ready for the challenge!

...and invites you to join the 8th CYGNUS workshop on Directional Recoil Detection in December 2023 in Sidney

8th CYGNUS Workshop on Directional Recoil Detection

Dec 11 – 15, 2023
Sydney Nanoscience Hub (SNH)
Australia/Sydney timezone

- Directional detection of dark matter
- Directional neutrino detection
- Directional neutron detection
- Gas TPCs and MPGDs
- Novel directional detection technologies
- Recoil simulation tools
- Detection of rare nuclear decays

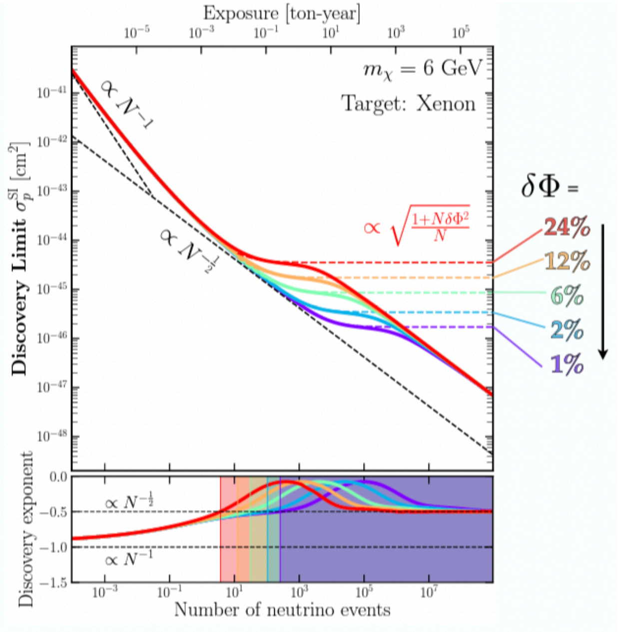
Free registration at
https://indico.cern.ch/event/1258644/

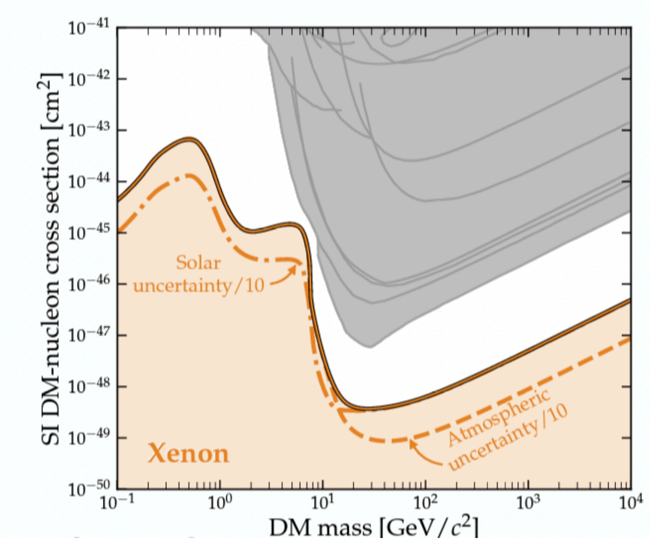
Backup slides

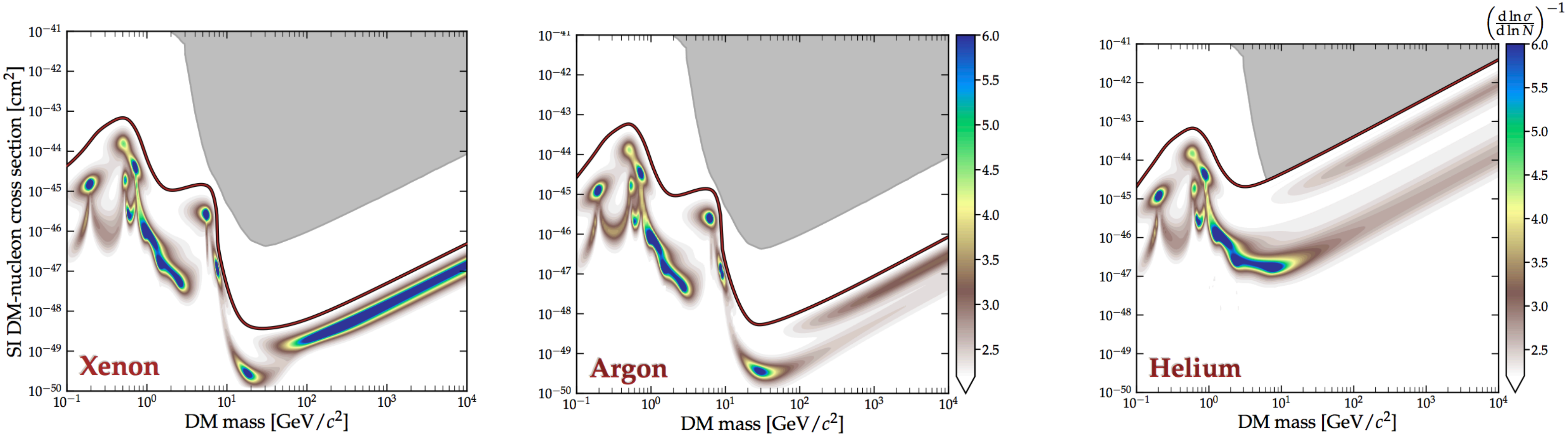
Neutrino fog: neutrino flux uncertainties & targets complementarity

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)

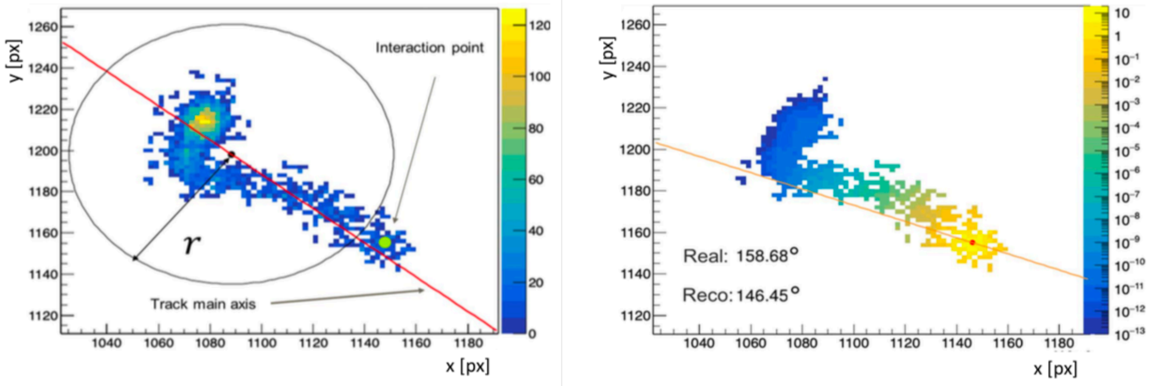
- Second part of the algorithm aims to find the direction:
  - Track point intensity rescalad with the distance from the interaction point: $W(d_{ip}) = exp(-d_{ip}/w)$
  - Direction taken as the the main axis of the rescaled track passing from the interaction Point
  - Orientation given following the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

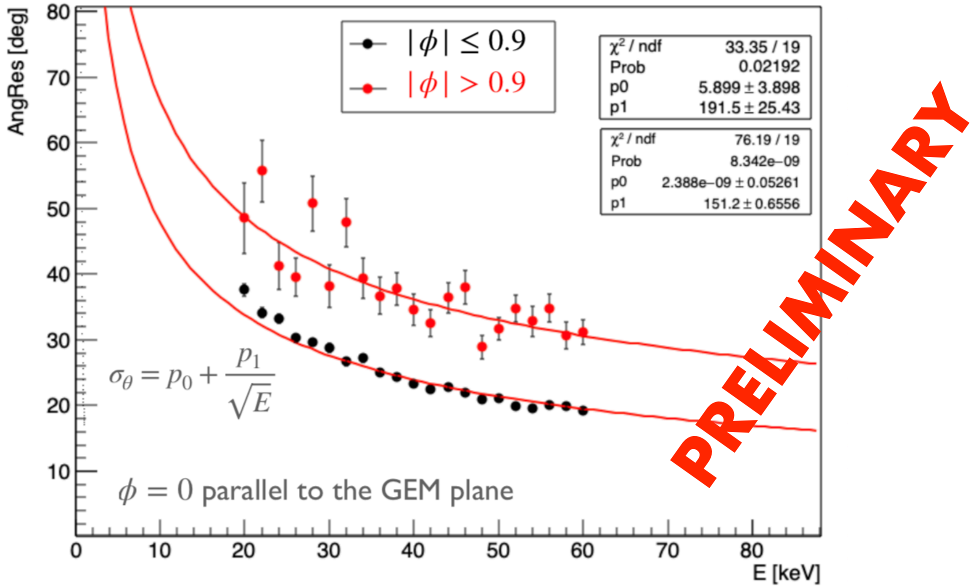
- Algorithm adapted from X-ray polarimetry:

"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

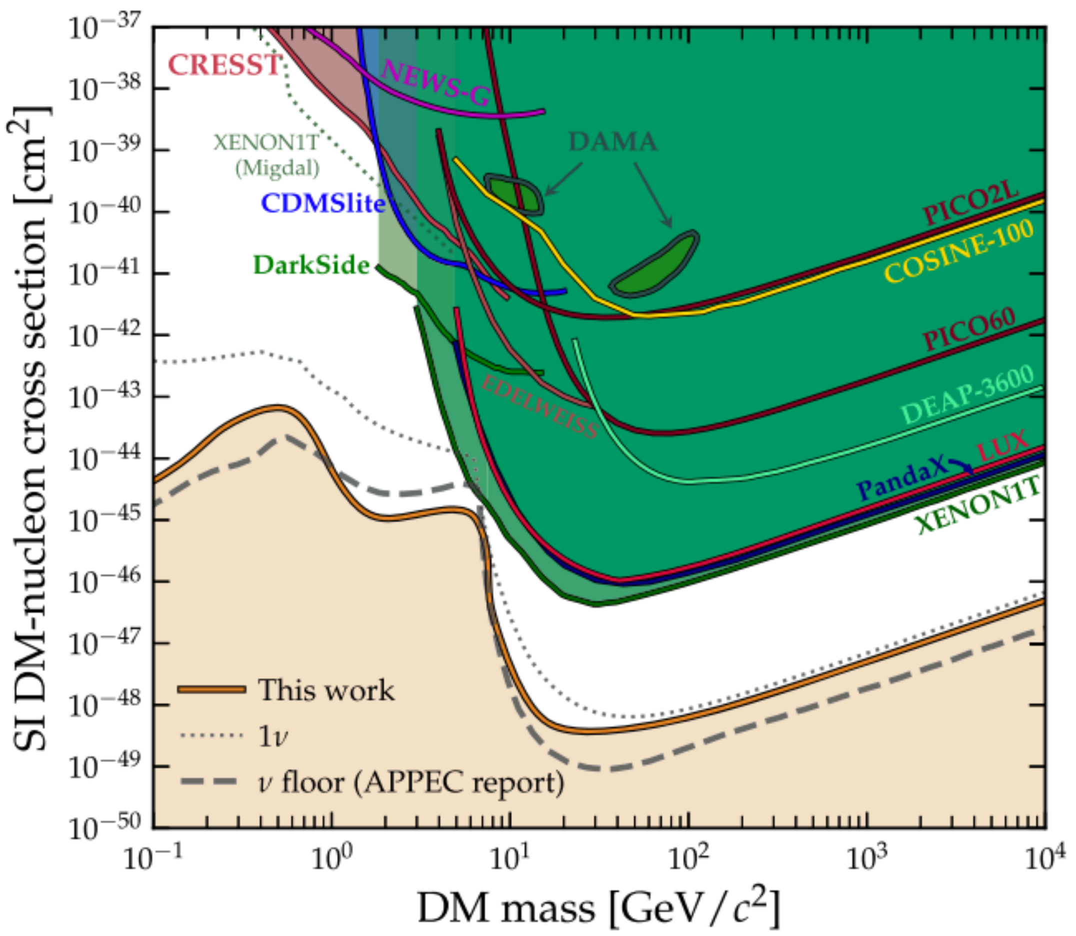
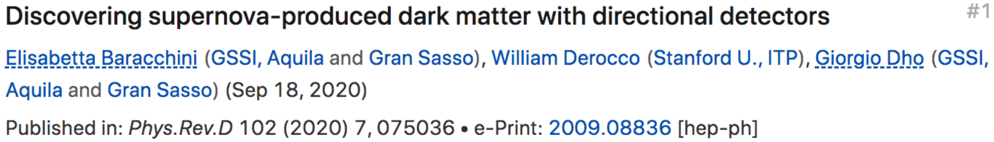


FIG. 1. Present exclusion limits on the spin-independent DM-nucleon cross section (assuming equal proton or neutron couplings) [7,58–71]. Beneath these limits we show three definitions of the neutrino floor for a xenon target. The previous discovery-limit-based neutrino floor calculation shown by the 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

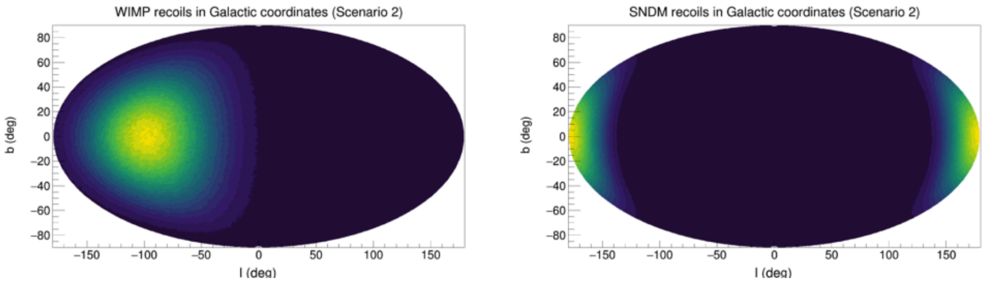


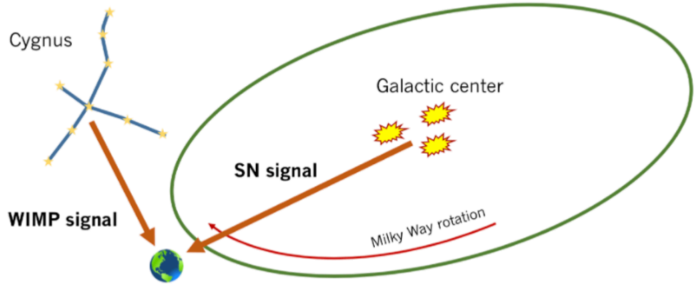
Discovering supernova-produced dark matter with directional detectors #1

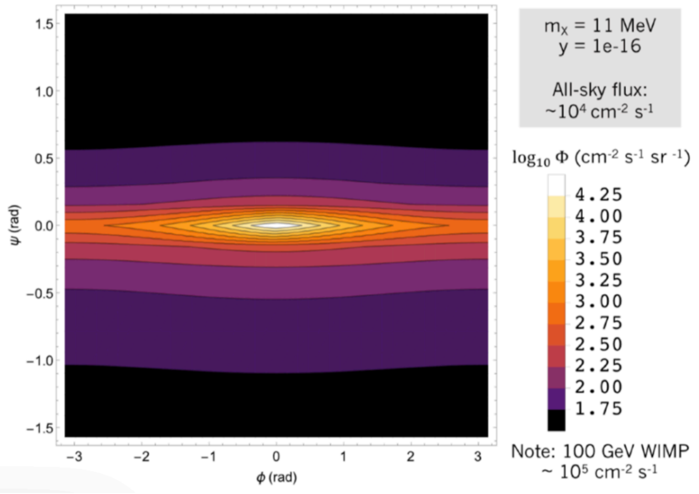
Elisabetta Baracchini (GSSI, Aquila and Gran Sasso), William Derocco (Stanford U., ITP), Giorgio Dho (GSSI, Aquila and Gran Sasso) (Sep 18, 2020)

Published in: *Phys.Rev.D* 102 (2020) 7, 075036 • e-Print: 2009.08836 [hep-ph]

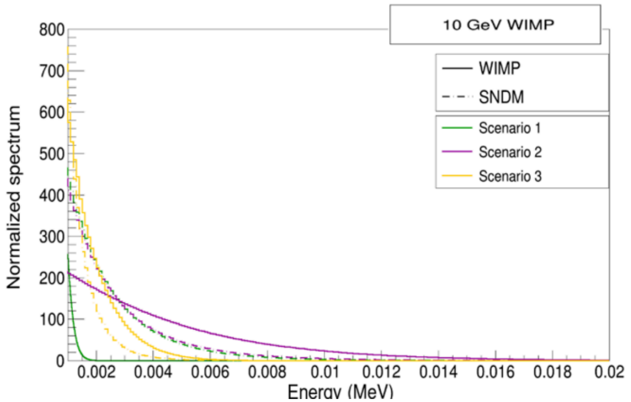
W. DeRocco, P. W. Graham, D. Kasen, G. Marques-Tavares, and S. Rajendran, Phys. Rev. D **100**, 075018 (2019).

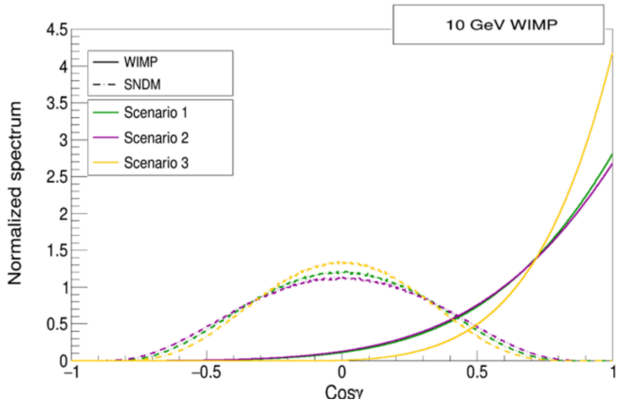


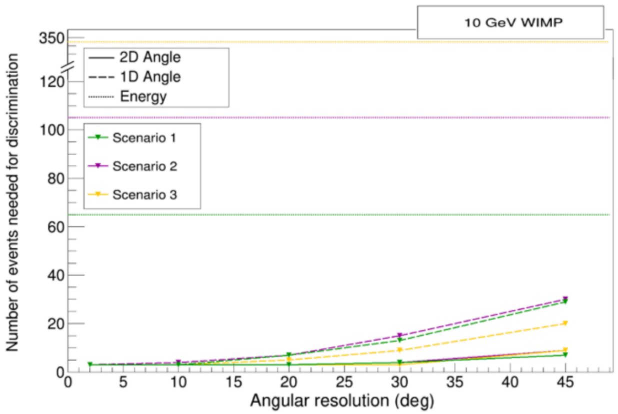


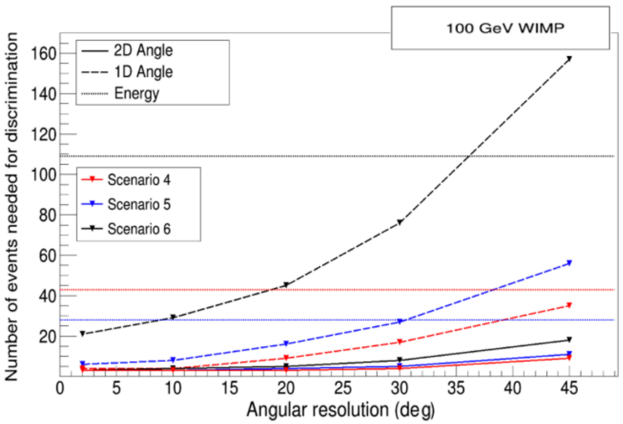


Note: 100 GeV WIMP ~ 10^5 cm^{-2} s^{-1}



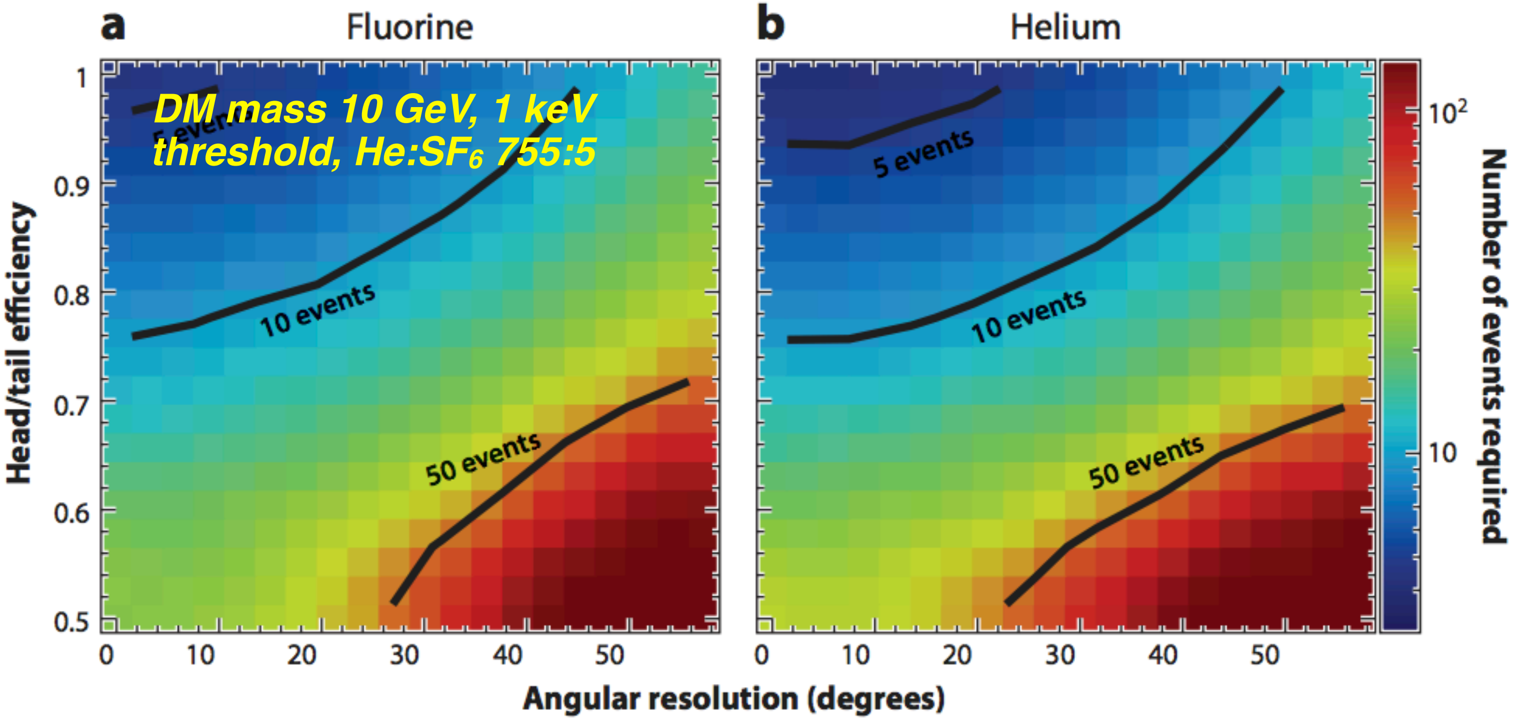






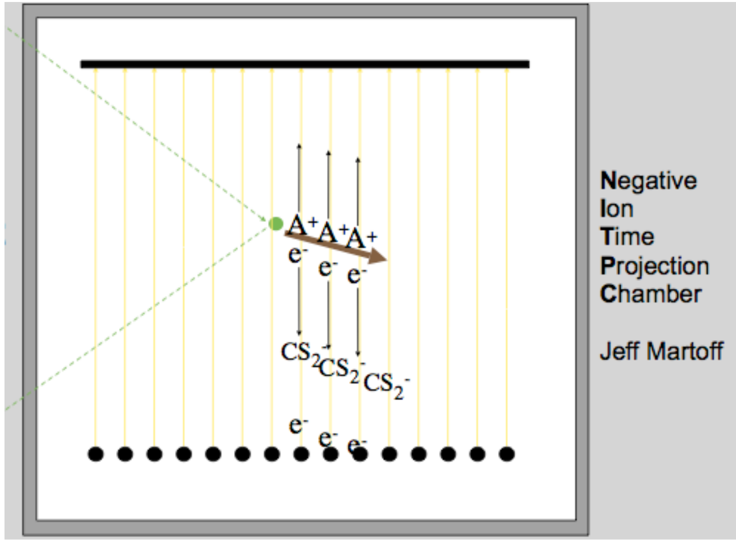
The importance of HT

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

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

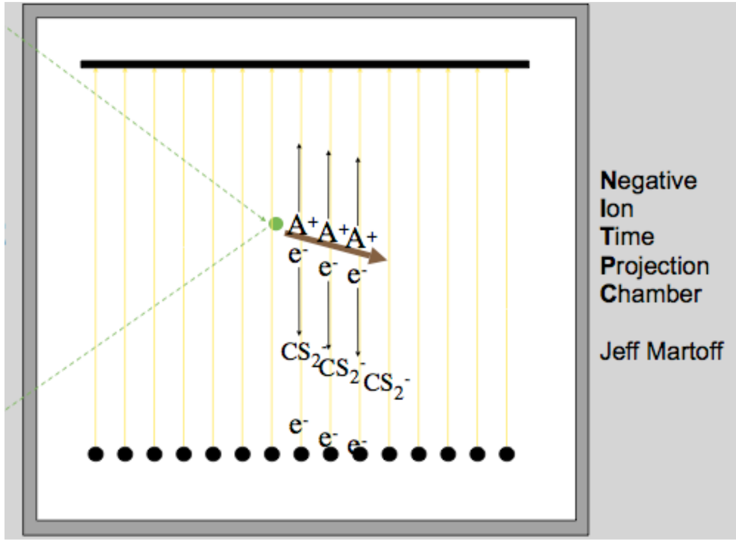
low diffusion increases active volume per readout area

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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low diffusion increases active volume per readout area

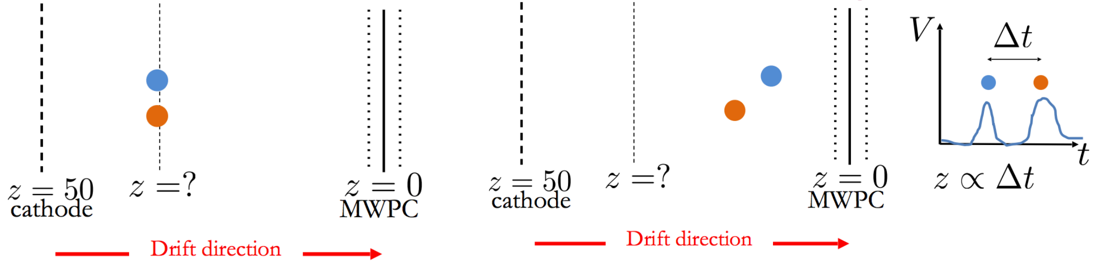
T. Ohnuki et al., NIM A 463

J. Martoff et al., NIM A 440 355

Multiple charge carriers = fiducialization!!

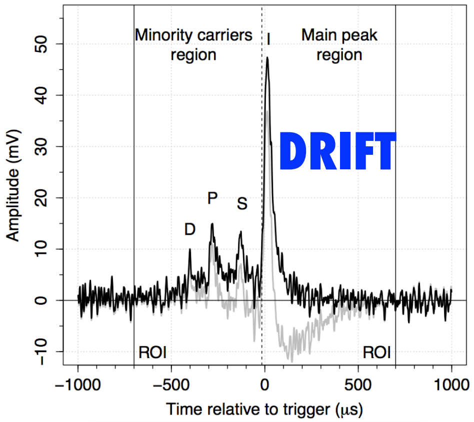
start together

...but drift at different velocity



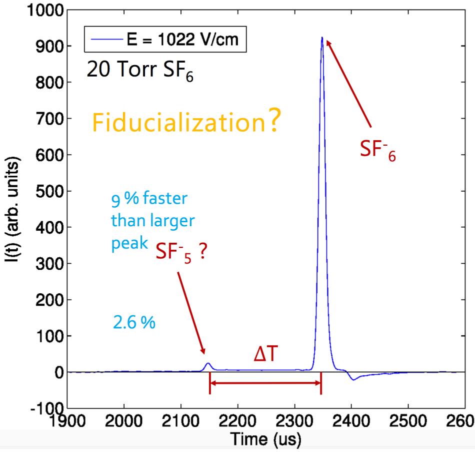
$$\boxed{z = (t_m - t_p)\frac{v^m_{drift}v^p_{drift}}{v^m_{drift}-v^p_{drift}}}$$

- 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