The CYGNUS Galactic Directional Recoil Observatory

**Natural radioactivity recorded by the LIME detector at LNGS*

or else, how to surf the neutrino fog with directionality

GSSI

Elisabetta Baracchini

INFN
Istituto Nazionale di Fisica Nucleare

on behalf of the CYGNUS proto-collaboration

International Conference on High Energy Physics 2022
Bologna, 9th July 2022

European Research Council
Established by the European Commission

Outline

- **The need (now more than ever) for a directional DM detector at the ton scale**
- **The CYGNUS project for a Galactic Directional Recoil Observatory**
  - **Feasibility studies for WIMP searches through nuclear recoils (arXiv:2008.12587)**
  - **Solar neutrinos through electron recoils physics case**
- **TPCs projects in the world and R&Ds towards CYGNUS**

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

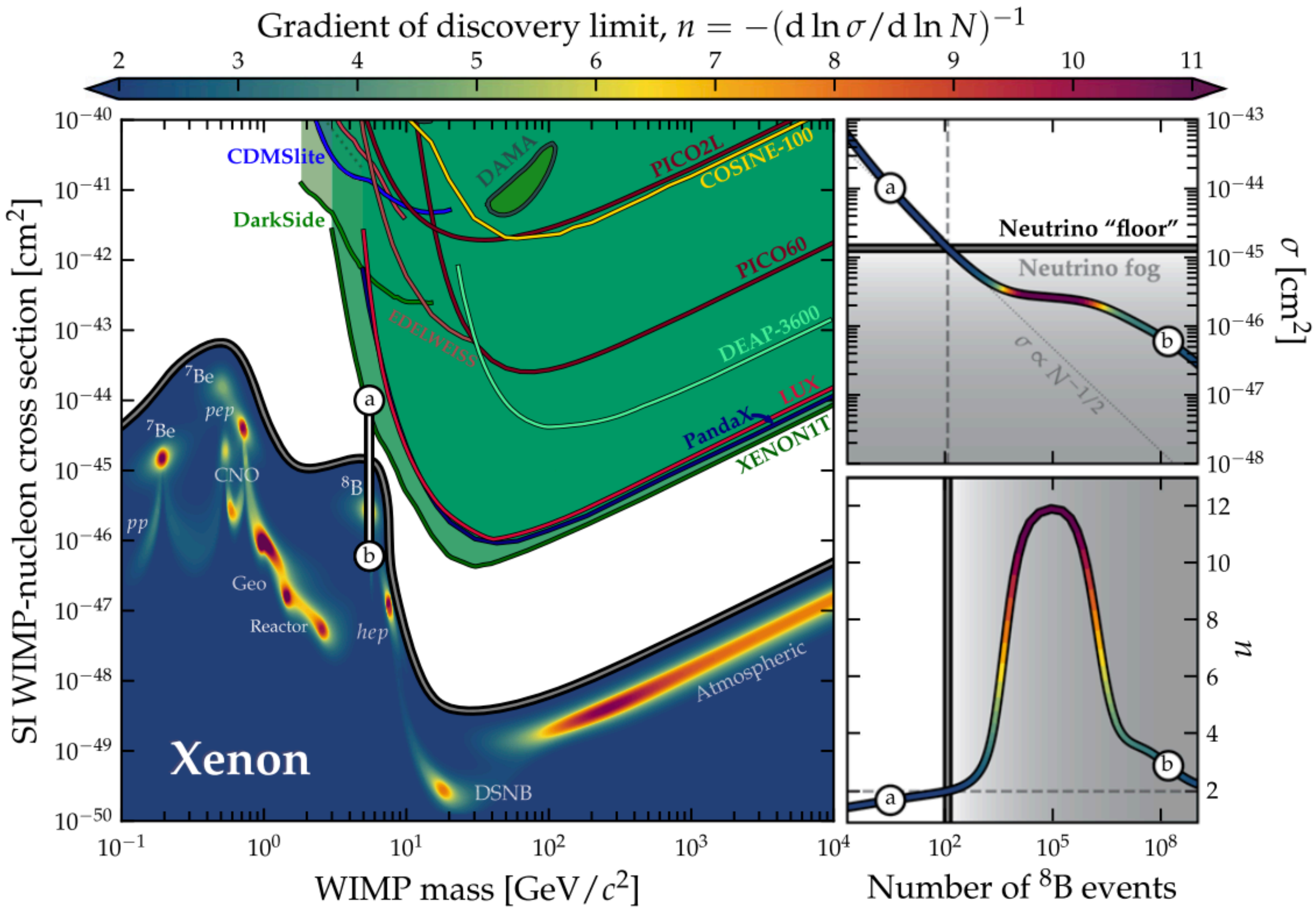
$$N\delta\Phi^2 \ll 1, \sigma \propto 1/\sqrt{N}$$

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

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

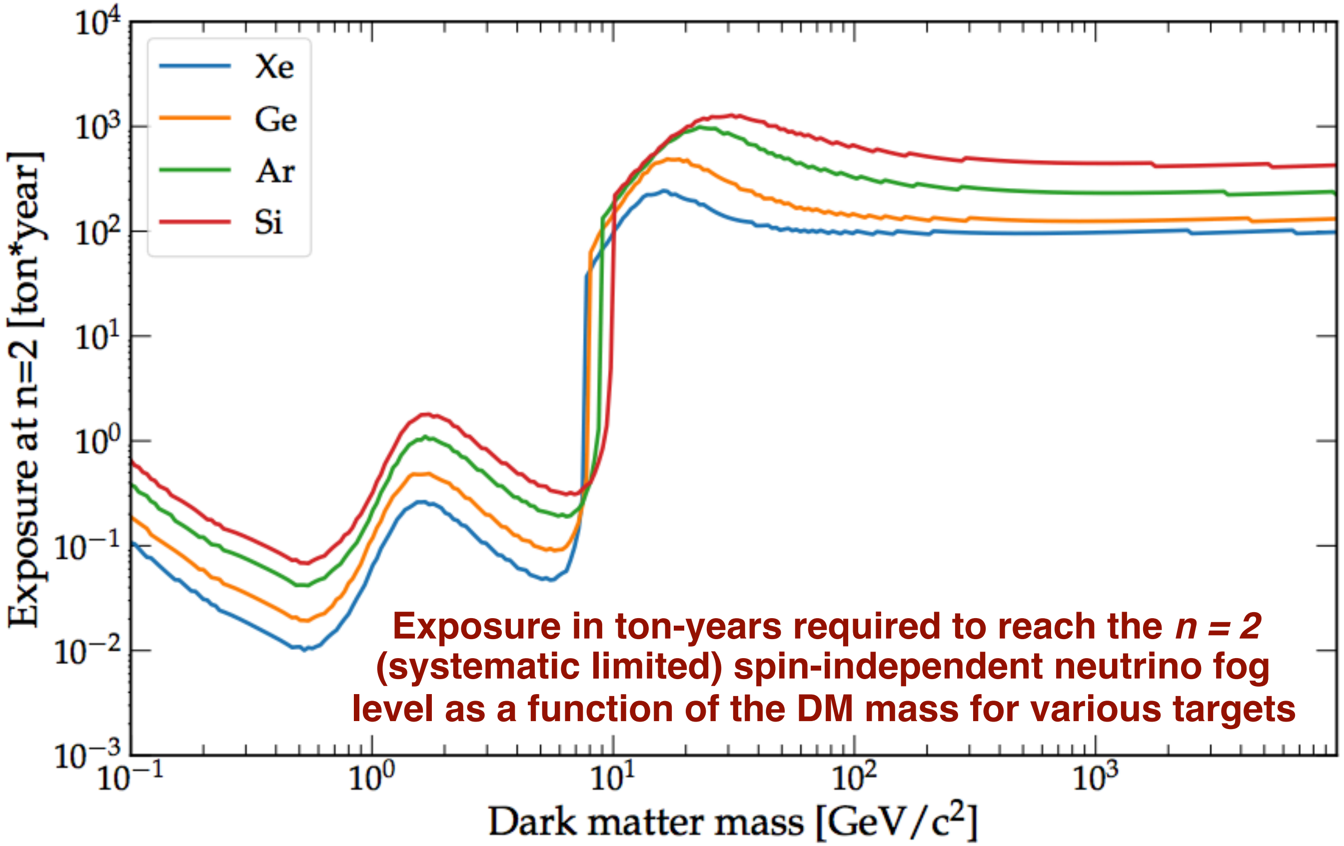
$$N\delta\Phi^2 \ll 1, \sigma \propto 1/\sqrt{N}$$

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.

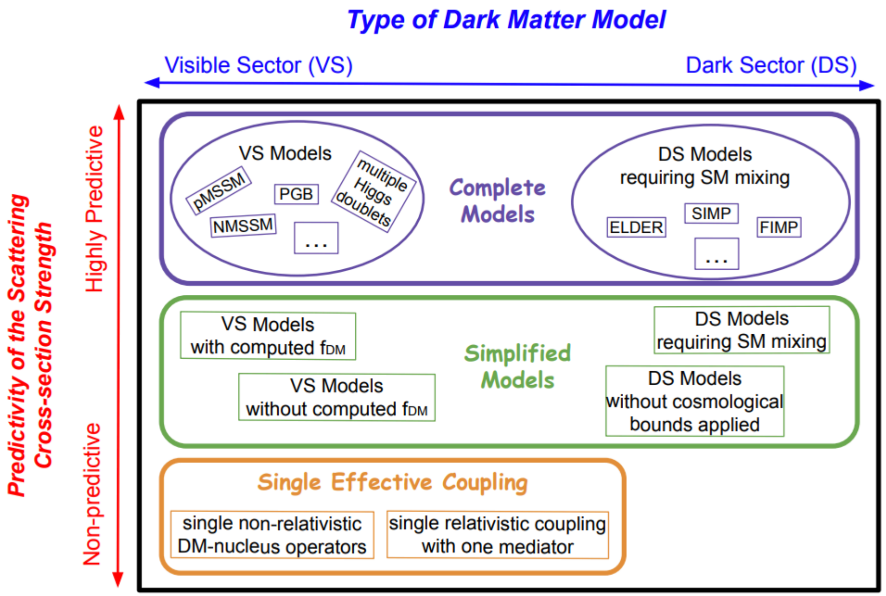
$$n = -\left(\frac{d \log \sigma}{d \log MT}\right)^{-1}$$

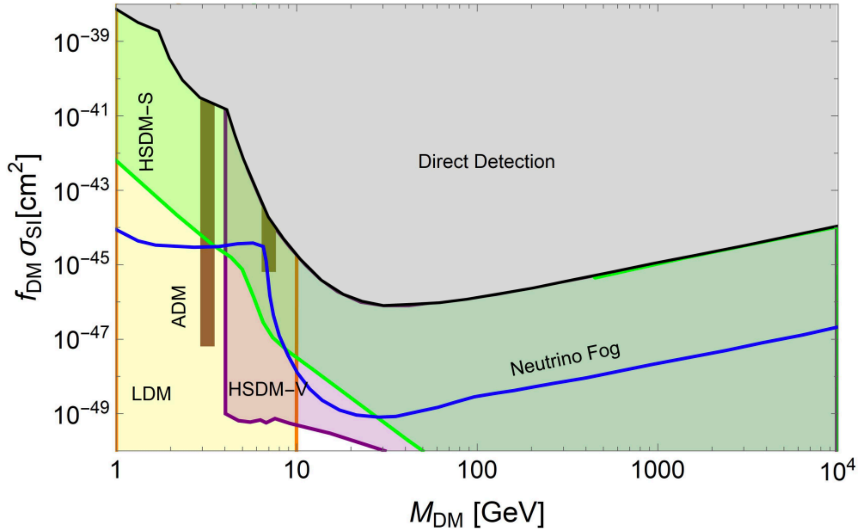


Exposure in ton-years required to reach the *n = 2* (systematic limited) spin-independent neutrino fog level as a function of the DM mass for various targets

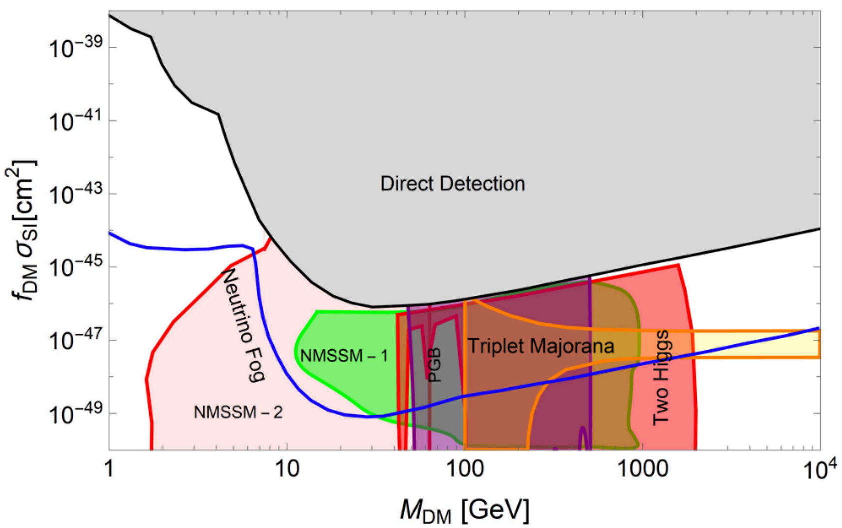
Reducing the sensivity of an experiment by a factor *x* requires an increas in the exposure by *at least x^n*

The need to penetrate the fog

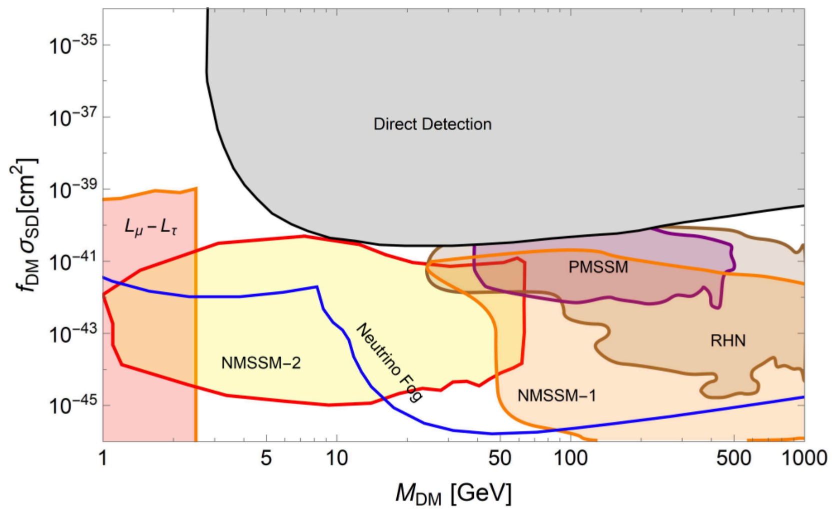




Dark sector models SI

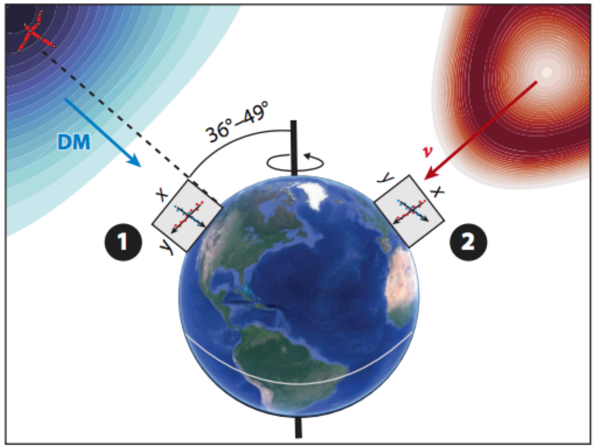


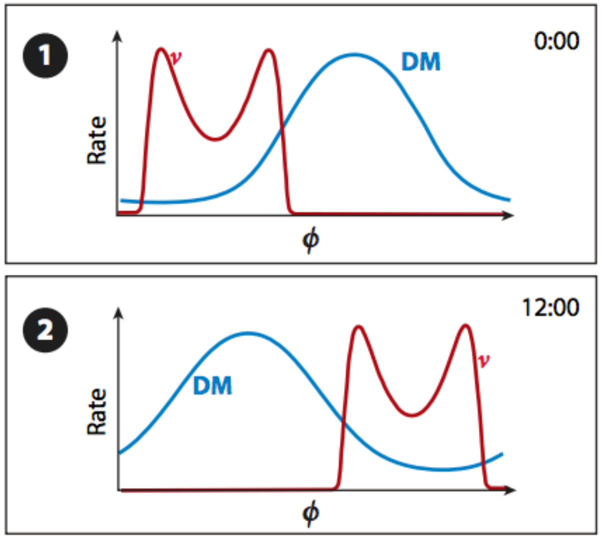
Visible sector models SI



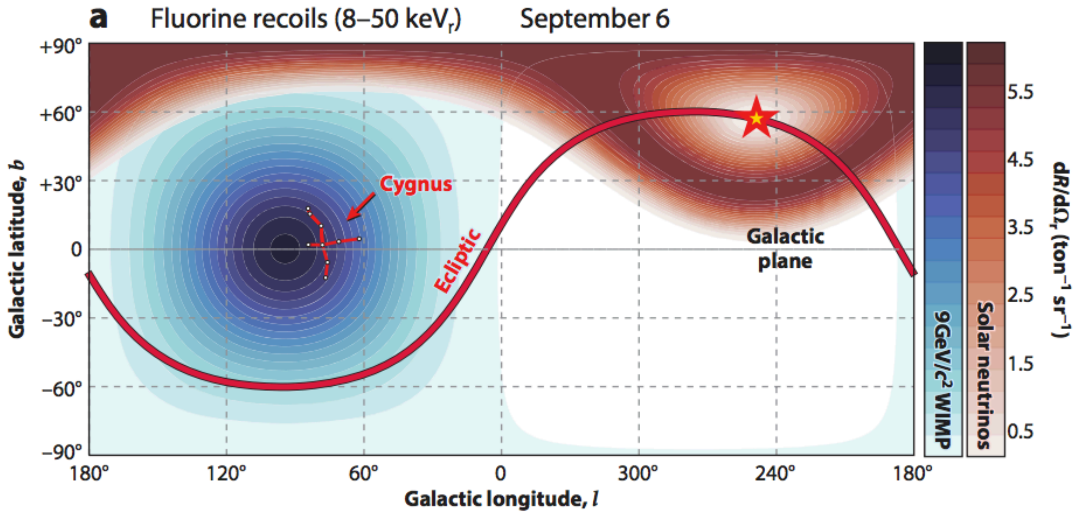
Visible sector models SD

How to see through the neutrino fog?

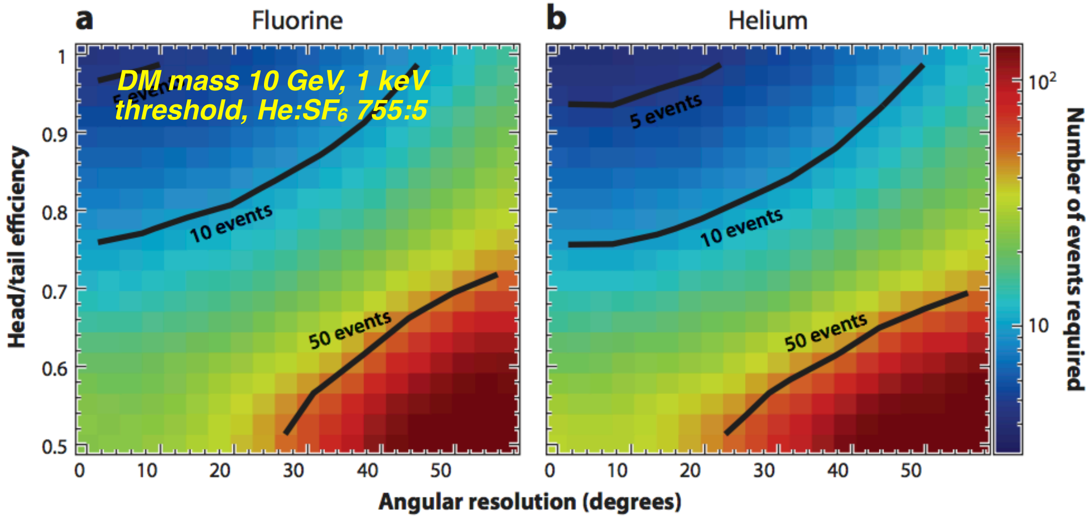




DM and solar neutrinos event rate as a function of some angle ϕ on a two-dimensional readout plane at 12 h time distance or 180° of longitude



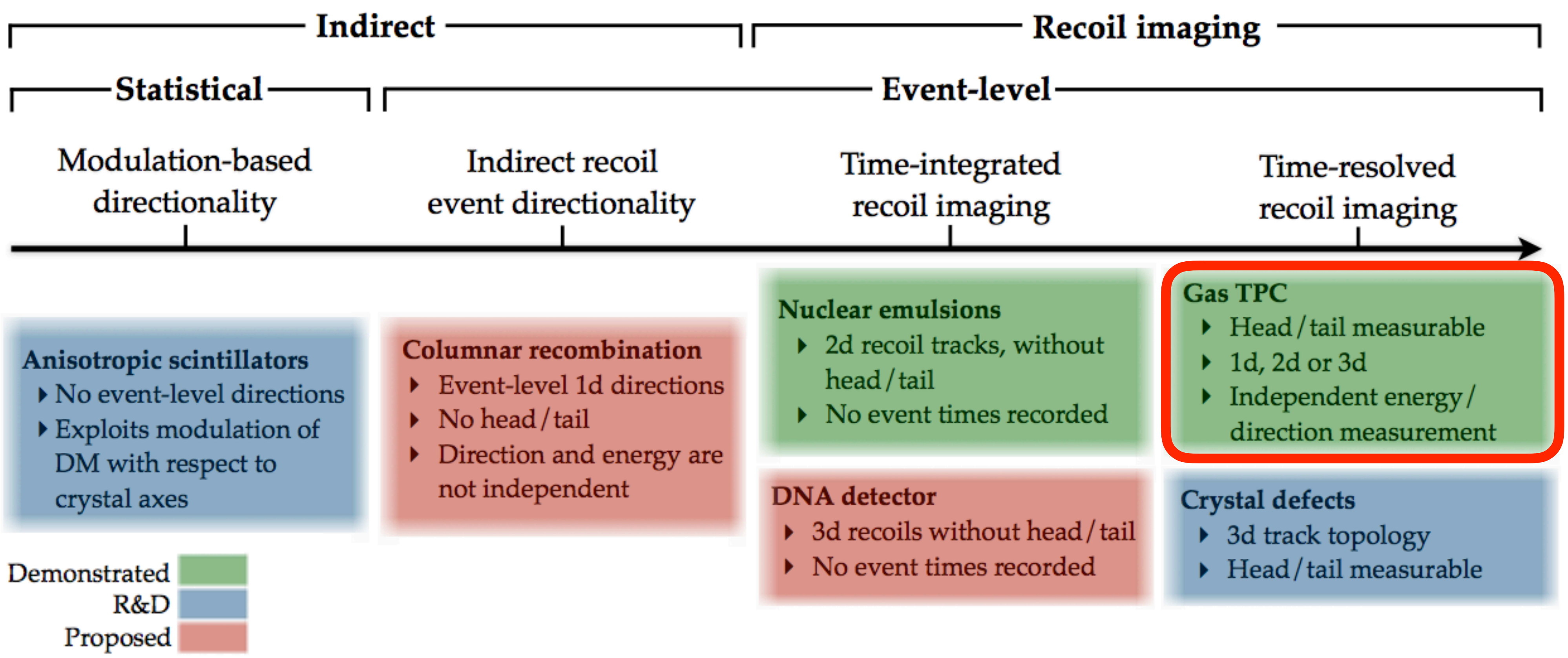
Required number of detected He and F recoils to exclude solar neutrinos at 90% C.L. vs angular resolution and head-tail efficiency



Take away message: head-tail is more important than angular resolution

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

Detector classes by directional information

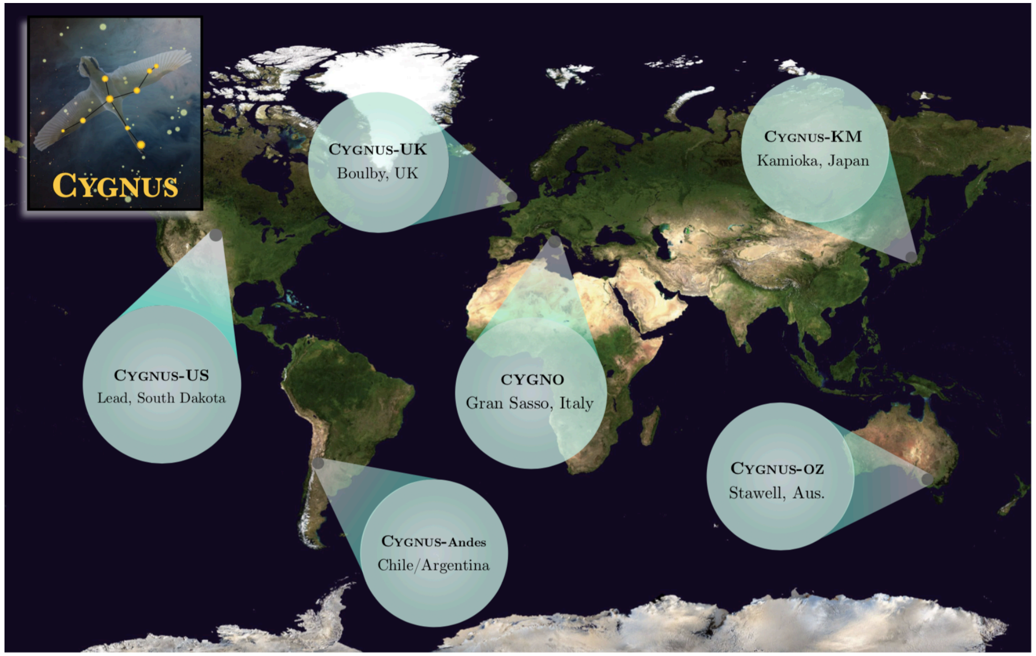


We believe gaseous TPC to be the best experimental approach because it can provide the best observables not only for DM searches but for multiple physics cases

The CYGNUS project

CYGNUS proto-collaboration

Since fall 2016



- 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)

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 <u>with directionality</u>

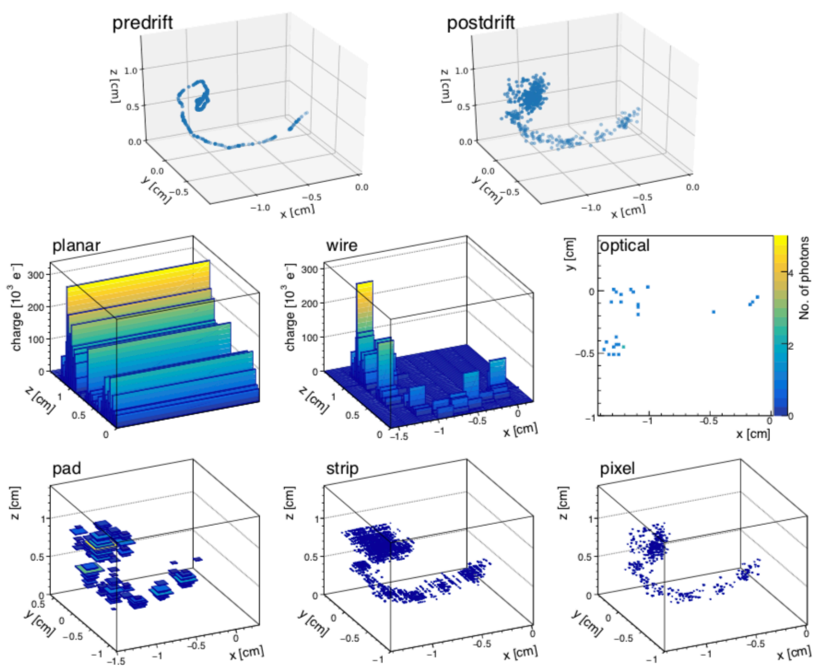
- **Helium/Fluorine gas mixtures at 1 bar**
  - **Sensitivity to O(GeV) WIMP for both SI & SD couplings**
  - **Possibility of switching between higher (search mode) and lower gas densities (improved directionality) for signal confirmation**
- **Reduced diffusion**
  - **Through negative ion drift or "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: Feasibility of a nuclear recoil observatory with directional sensitivity to dark matter and neutrinos

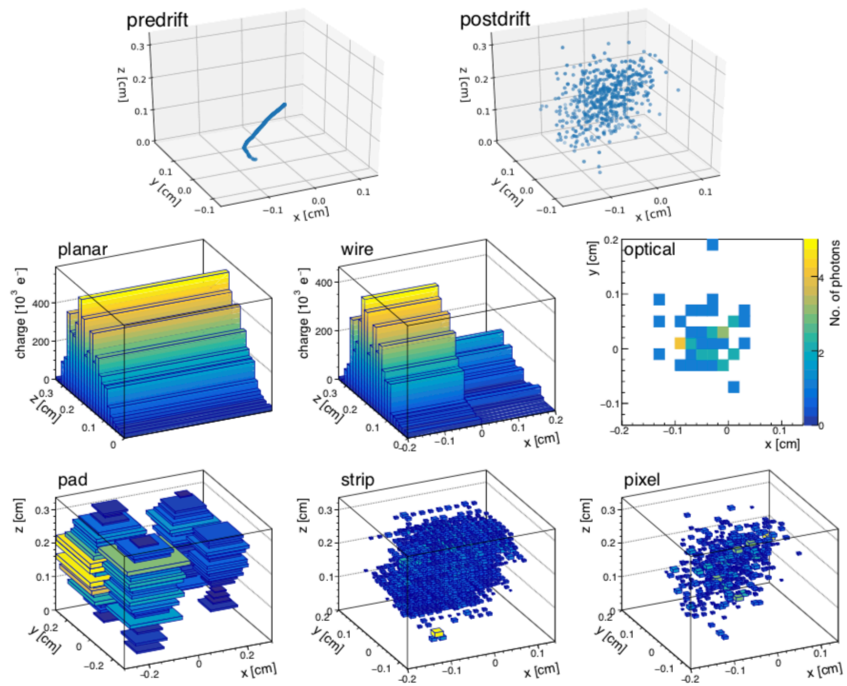
S. E. Vahsen,[1] C. A. J. O'Hare,[2] W. A. Lynch,[3] N. J. C. Spooner,[3] E. Baracchini,[4,5,6] P. Barbeau,[7] J. B. R. Battat,[8] B. Crow,[1] C. Deaconu,[9] C. Eldridge,[3] A. C. Ezeribe,[3] M. Ghrear,[1] D. Loomba,[10] K. J. Mack,[11] K. Miuchi,[12] F. M. Mouton,[3] N. S. Phan,[13] K. Scholberg,[7]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

- **Extensive concept paper on 1000 m³ gaseous NITPC detector focused on technical feasibility and WIMP searches through nuclear recoils**
- **Detailed simulation of seven readout options with negative ion drift in He:SF_6 at 1 atm with a cost/benefit FOM**
- **Background discrimination studies**
- **Detailed simulation and study of all internal and external backgrounds**
- **Engineering studies for a 1000 m³ detector**

20 keV$_{ee}$ electron recoil in He:SF_6 740:20 Torr



20 keV$_{nr}$ Helium nuclear recoil in He:SF_6 740:20 Torr

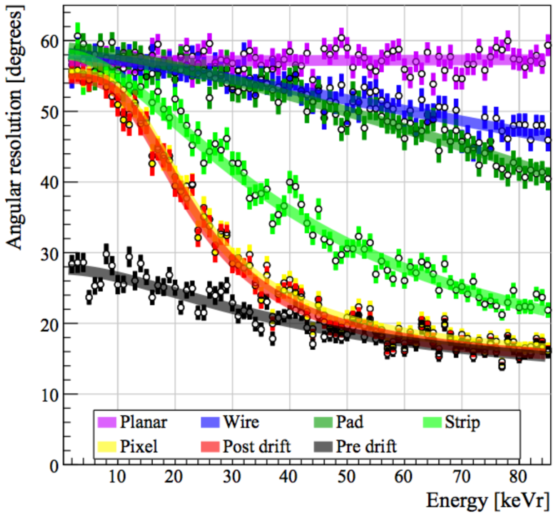


arXiv: 2008.12587

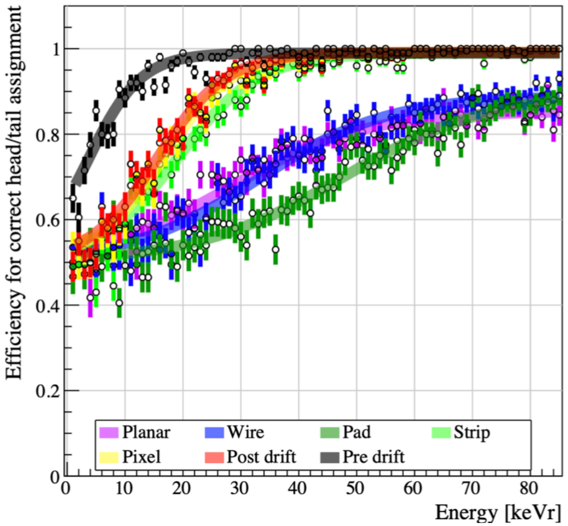
CYGNUS: Feasibility of a nuclear recoil observatory with directional sensitivity to dark matter and neutrinos

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]

Angular resolution



Sense recognition



Negative ion drift in He:SF_6 755:5 Torr

Pixels extract the entire directional information left after diffusion

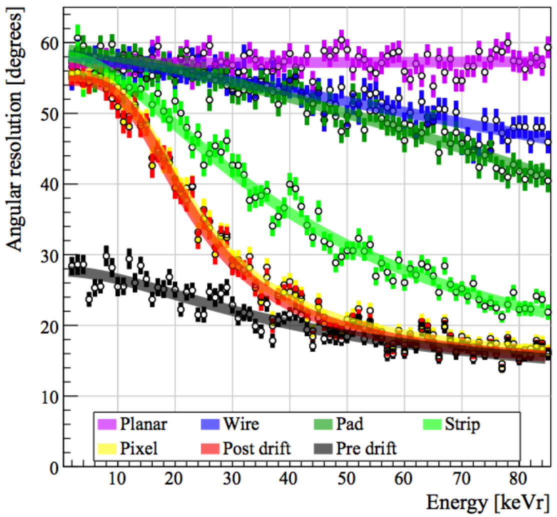
Strips readout perform almost as pixels, but at much lower costs

arXiv: 2008.12587

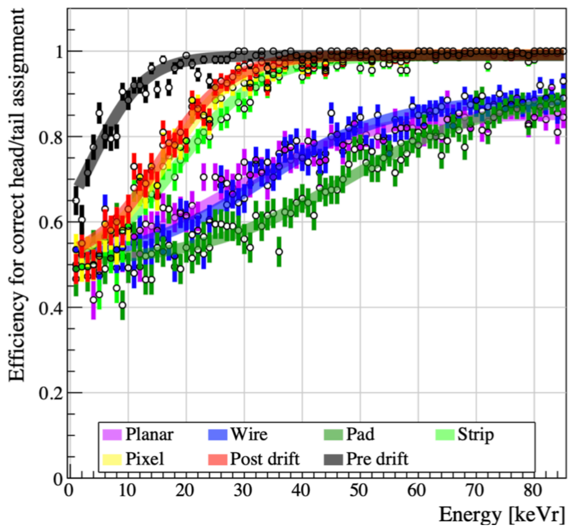
CYGNUS: Feasibility of a nuclear recoil observatory with directional sensitivity to dark matter and neutrinos

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]

Angular resolution



Sense recognition

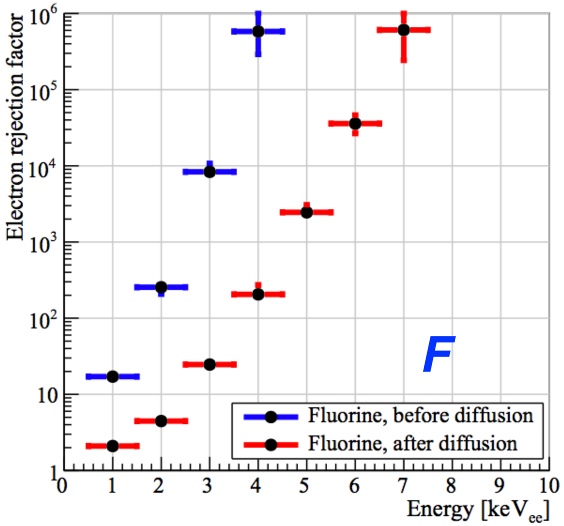


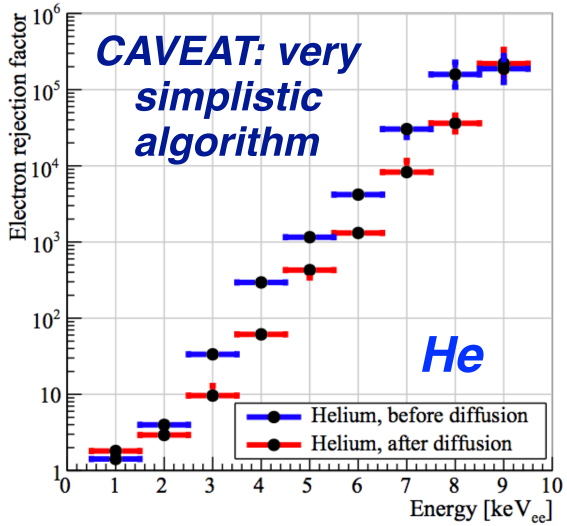
Negative ion drift in $He:SF_6$ 755:5 Torr

Pixels extract the entire directional information left after diffusion

Strips readout perform almost as pixels, but at much lower costs

Background rejection



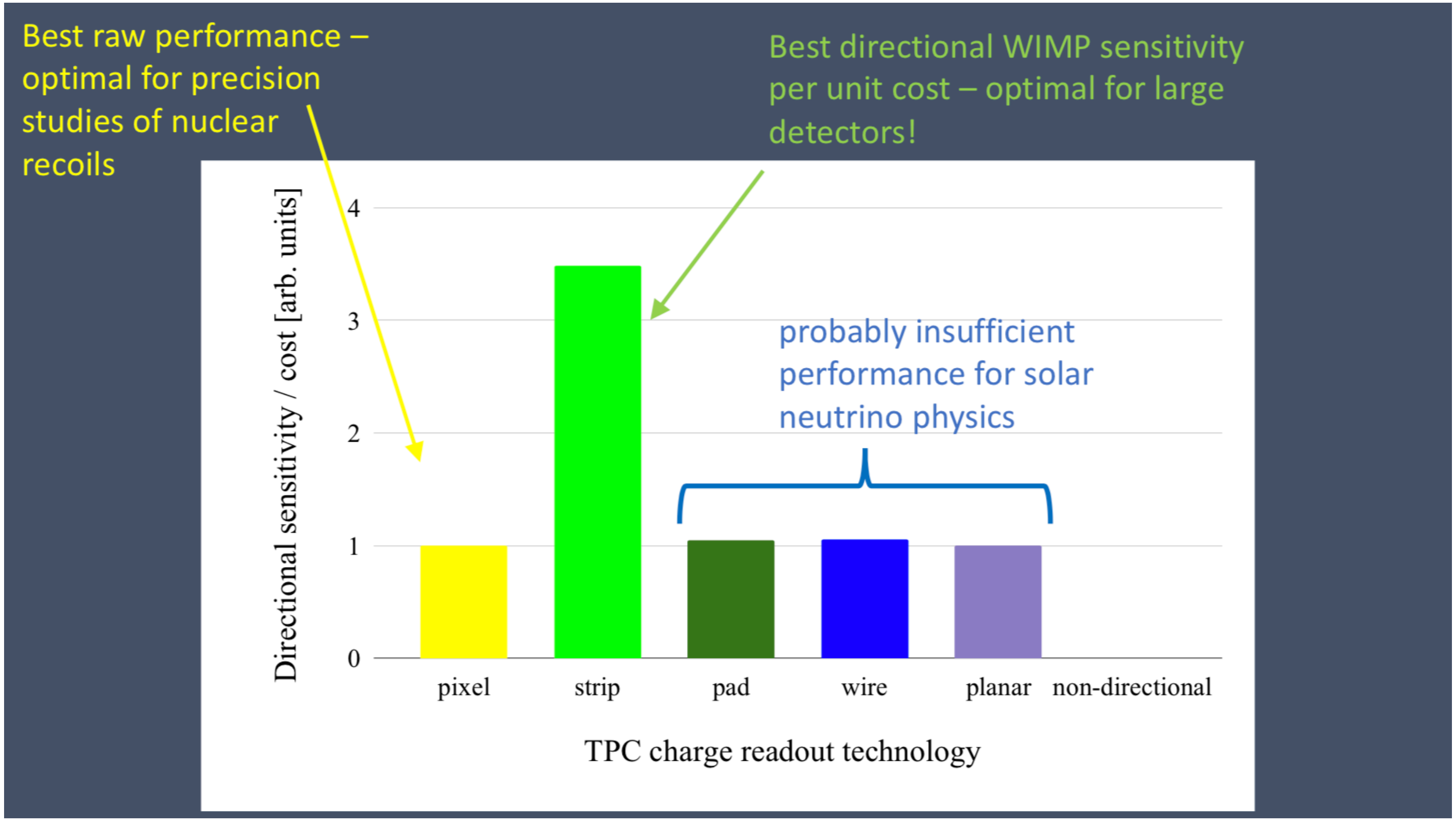


Rejection at O (keV_{nr}) possible, > 10^6 @ 10 keV_{nr}

Can be sigificantly improved by combination of more variables (x 100 with HD readout arXiv: 2012.13649) or machine learning approach (under development)

Cost vs benefit study result

arXiv: 2008.12587

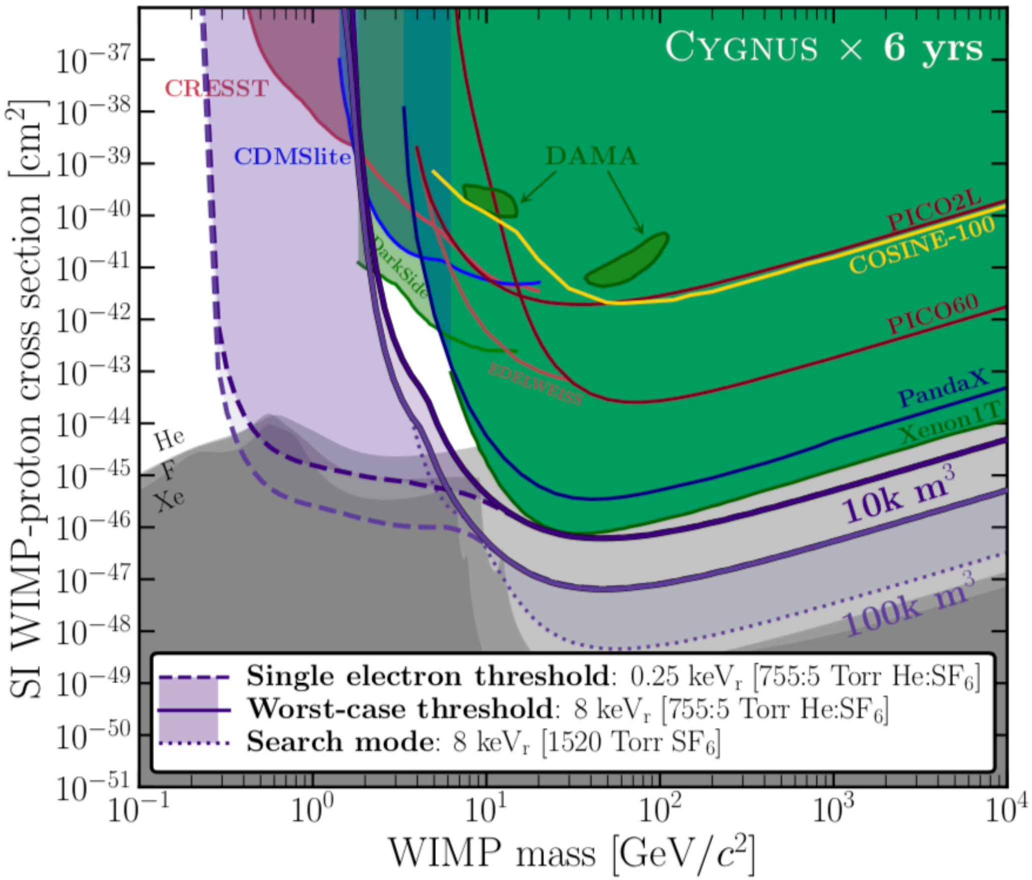


For He:SF$_6$ 755:5 with negative ion drift, strips results the best choice in terms of costs versus performances, radiation budget and engineering cosiderations

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

CYGNUS 1 ton WIMP searches expected sensitivity

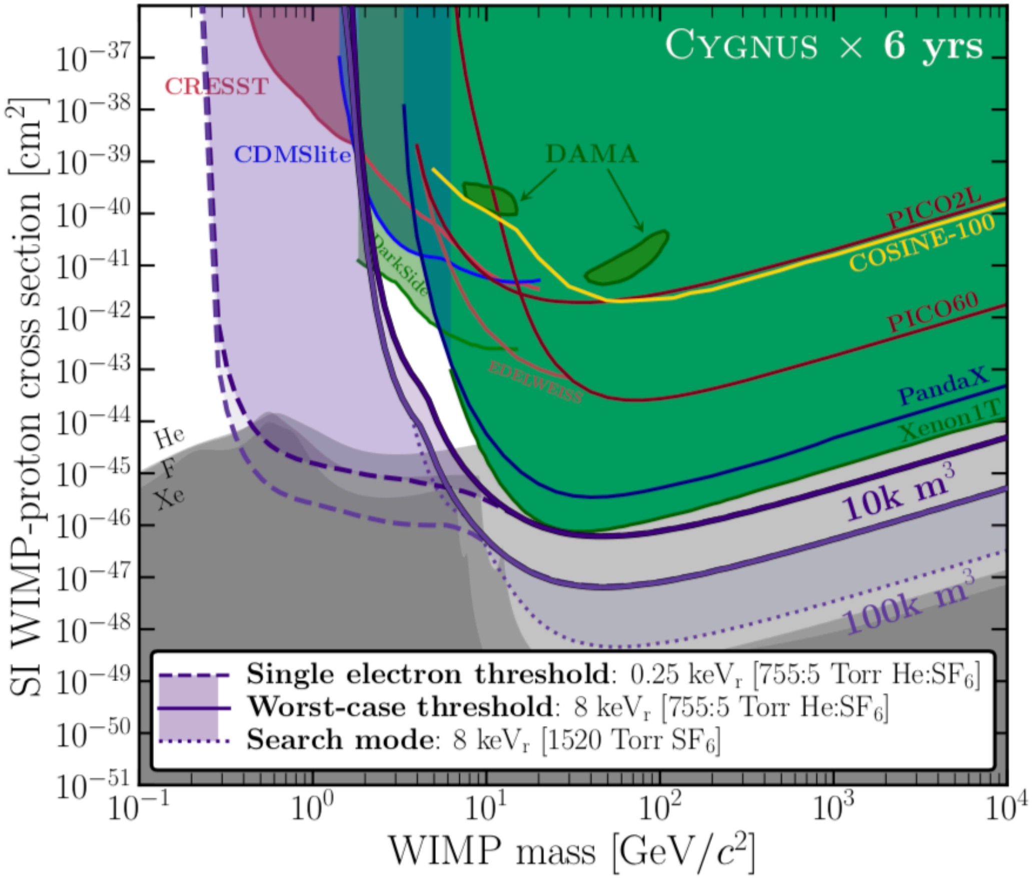
He:SF_6 755:5

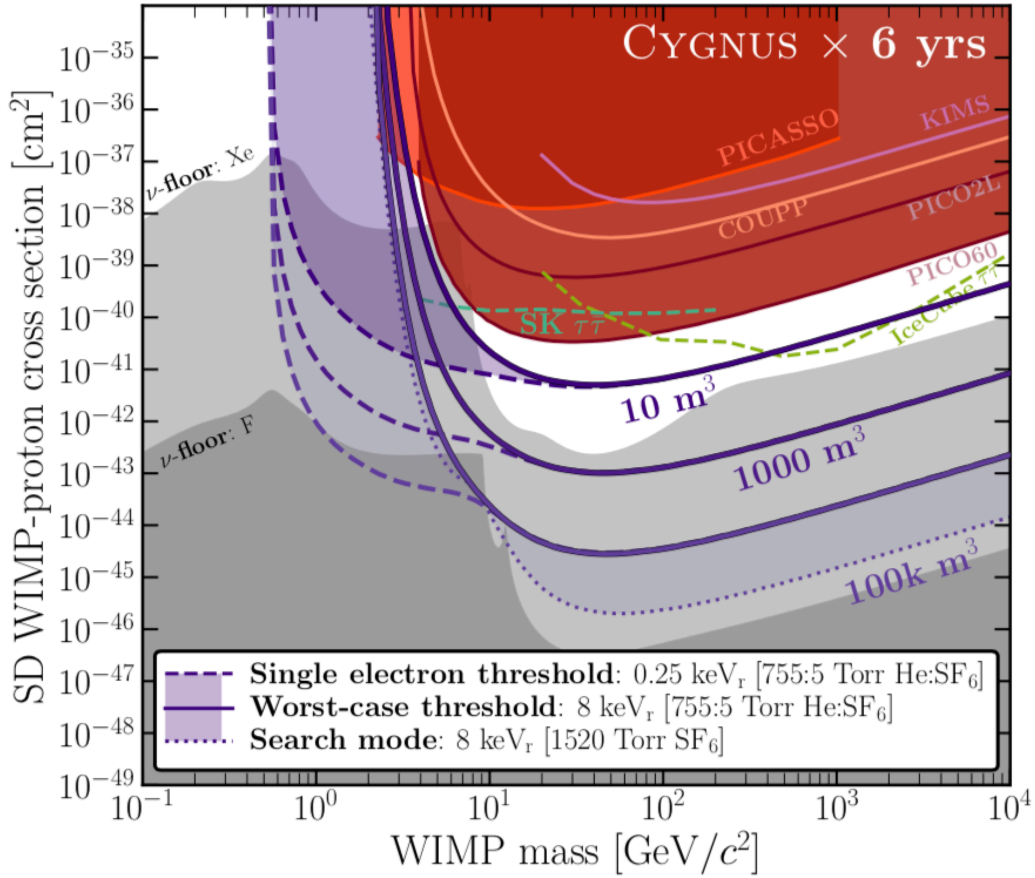


Significant improvement in SI in the low WIMP mass region, expect 10-50 IDENTIFIED neutrino nuclear recoil events

CYGNUS 1 ton WIMP searches expected sensitivity

He:SF_6 755:5





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

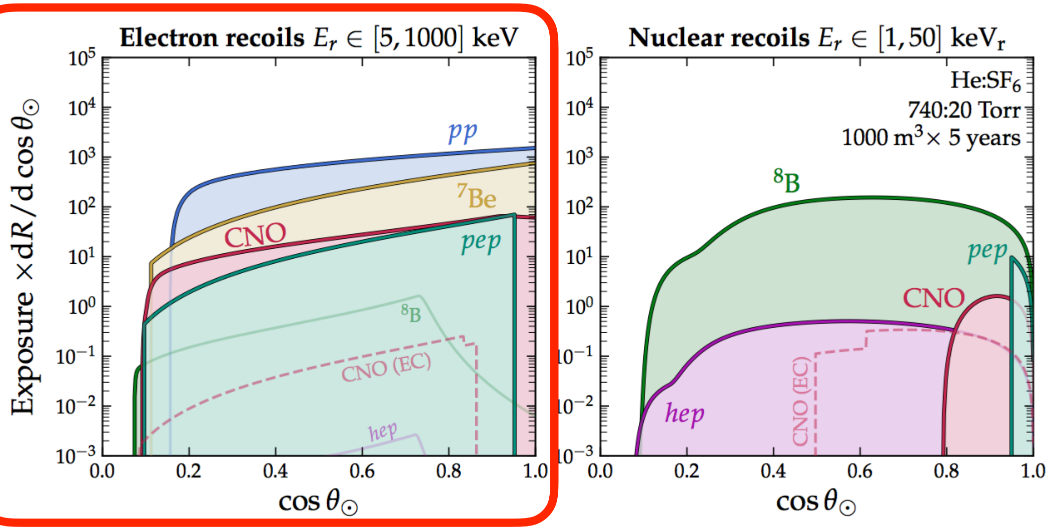
Significant improvement in SD reach over existing experiments for all WIMP masses, a 10 m³ detector can already breach the Xe neutrino floor

Neutrinos in CYGNUS: promoting background to signal

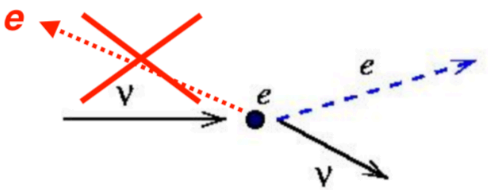
[C. A. J. O'Hare et al., 2022 Snowmass Summer Study, arXiv:2203.05914](arXiv:2203.05914)

INFN

Expected number of ER and NR events as a function of the cosine of the angle away from the Sun



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



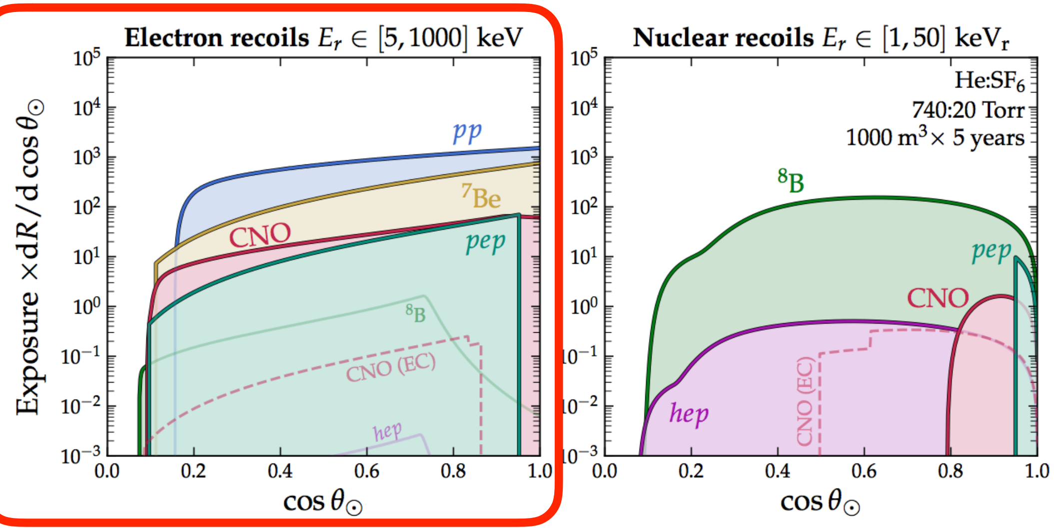
Differently from WIMPs, background can be measured on sidebands data

- ***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 + ^{7}Be fluxes through directionality**

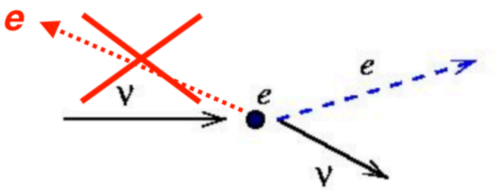
Neutrinos in CYGNUS: promoting background to signal

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

Expected number of ER and NR events as a function of the cosine of the angle away from the Sun

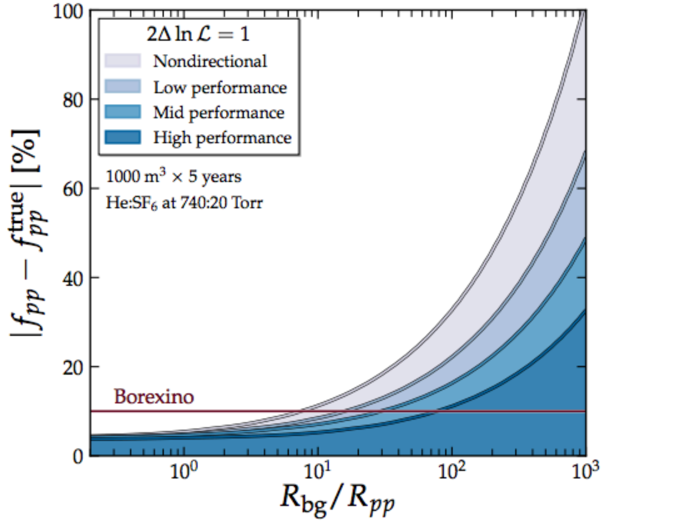


Given the Sun position, recoils in opposite direction are kinematically forbidden

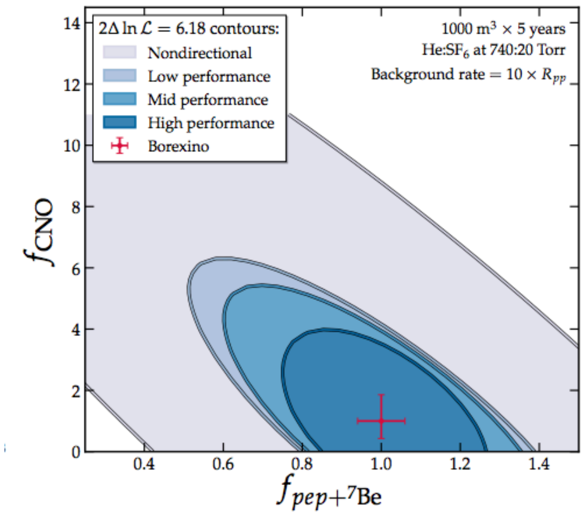


Differently from WIMPs, background can be measured on sidebands data

- *Electron recoils directionality in CYGNUS enables solar neutrino spectroscopy through neutrino-electron elastic scattering on an event-by-event basis*
  - An O(10) m^3 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 + ^{7}Be fluxes through directionality



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 + ^{7}Be pp fluxes, fixing the background rate to 10 times the pp electron recoil rate

ER multiple scattering revisited

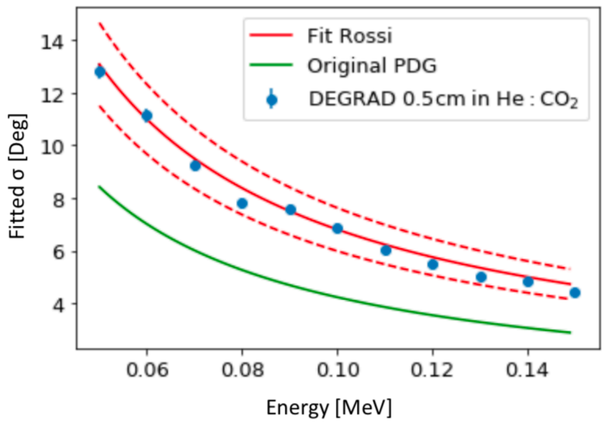
Found to be inadequate to describe MS for ER: we fit these two parameters to DEGRAD simulation of gas mixtures

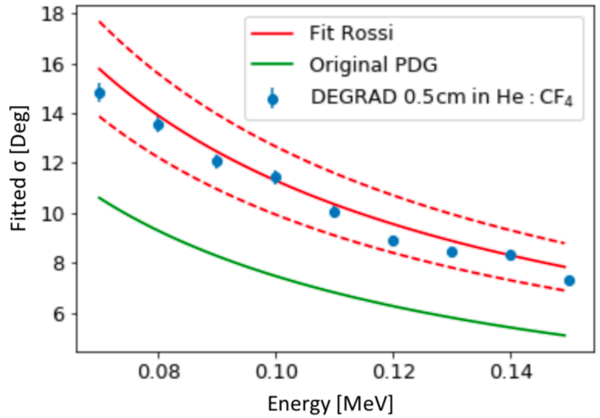
Gas Mixture	Pressure	Rad. Length
60% He 40% CF_4	760 torr	220 m
70% He 30% CO_2	760 torr	606 m

M. Ghrear & S. Vahsen, paper in preparation

$$\sigma_{\Psi_{\rm plane}} = \frac{1}{\sqrt{3}}\frac{13.6\,{\rm MeV}}{\beta c p}\sqrt{\frac{x}{X_o}}\left[1 + 0.038\ln\frac{x}{X_o\beta^2}\right]$$

Lynch and Dahl obtain these parameters by fitting to RMS values for nuclear recoils distributions with Geant. They fit to different values of x and Z (X_o), for **singly charged (z=1) heavy particles with beta = 1**.





ER multiple scattering revisited & optimal track length for directionality

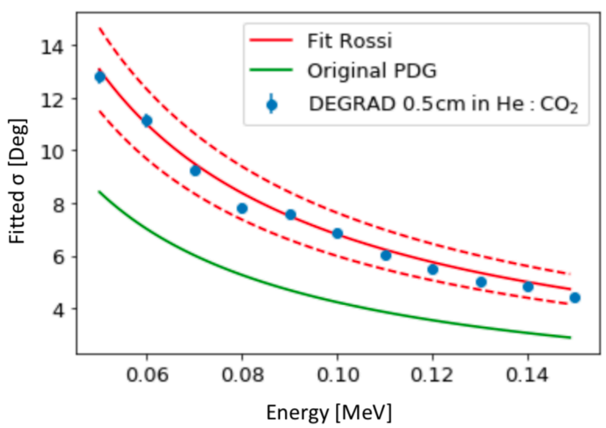
Found to be inadequate to describe MS for ER: we fit these two parameters to DEGRAD simulation of gas mixtures

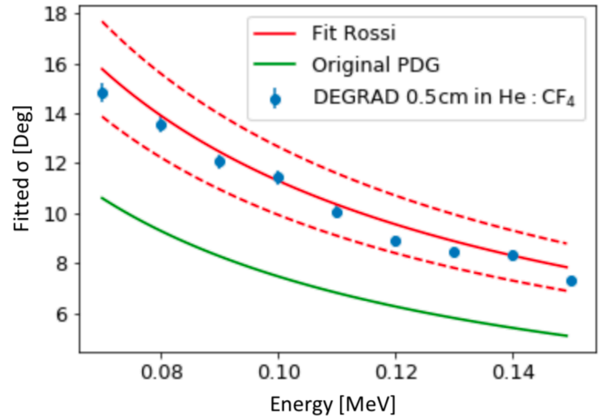
Gas Mixture	Pressure	Rad. Length
60% He 40% CF_4	760 torr	220 m
70% He 30% CO_2	760 torr	606 m

M. Ghrear & S. Vahsen, paper in preparation

$$\sigma_{\Psi_{\mathrm{plane}}} = \frac{1}{\sqrt{3}}\frac{13.6\mathrm{MeV}}{\beta c p}\sqrt{\frac{x}{X_o}}\left[1 + 0.038\ln\frac{x}{X_o\beta^2}\right]$$

Lynch and Dahl obtain these parameters by fitting to RMS values for nuclear recoils distributions with Geant. They fit to different values of x and Z (X_o), for **singly charged (z=1) heavy particles with beta = 1**.





PRELIMINARY

By combining the fitted multiple scattering with the point resolution as from S. E. Vahsen et al. NIM A 788 (2015) 95-105:

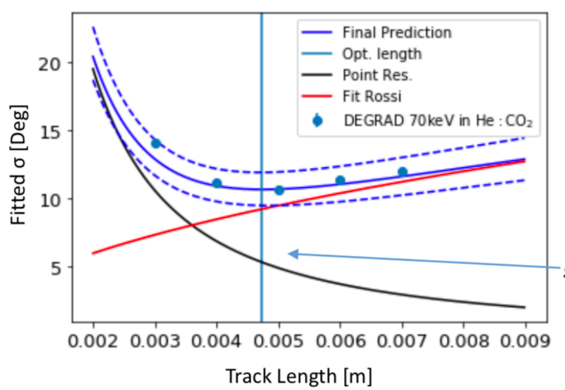
$$\sigma_\phi^{\mathrm{plane}} = \frac{\sqrt{12}\sigma_{x/y/z}}{L\sqrt{N}}$$

$$\sigma_\Psi^{\mathrm{plane}}(x) = \sqrt{a^2x + b^2x^{-3}}$$

$$a \equiv \frac{1}{\sqrt{3}}\frac{13.1\mathrm{MeV}}{\beta c p\sqrt{X_o}} \qquad b \equiv \sigma_{x/y/z}\sqrt{\frac{12W}{dE/dx}}$$

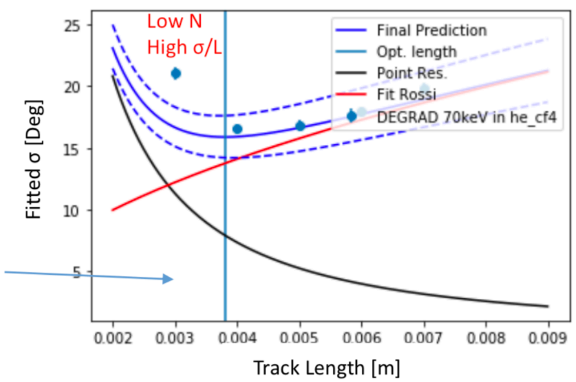
we can estimate the expected ER angular resolution from gas mixture properties and predict the optimal track length for angle evaluation (with simple SVD algorithm)

70 keV electron recoils in 70% He 30% CO_2



$x_o = 3^{\frac{1}{4}}\sqrt{b/a}$

70 keV electron recoils in 60% He 40% CF_4



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)

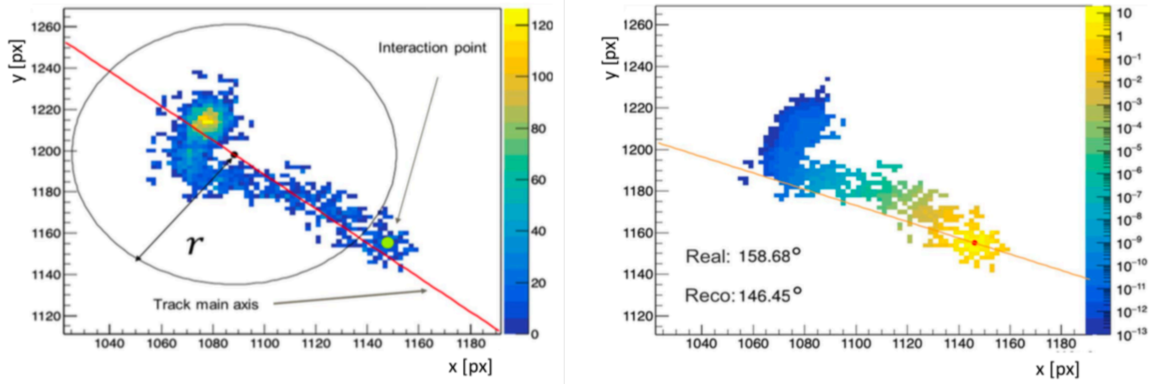
- Second part of the algorithm aims to find the direction:
  - Track point intensity rescalad with the distance from the interaction point: $W(d_{ip}) = exp(-d_{ip}/w)$
  - Direction taken as the the main axis of the rescaled track passing from the interaction Point
  - Orientation given following the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

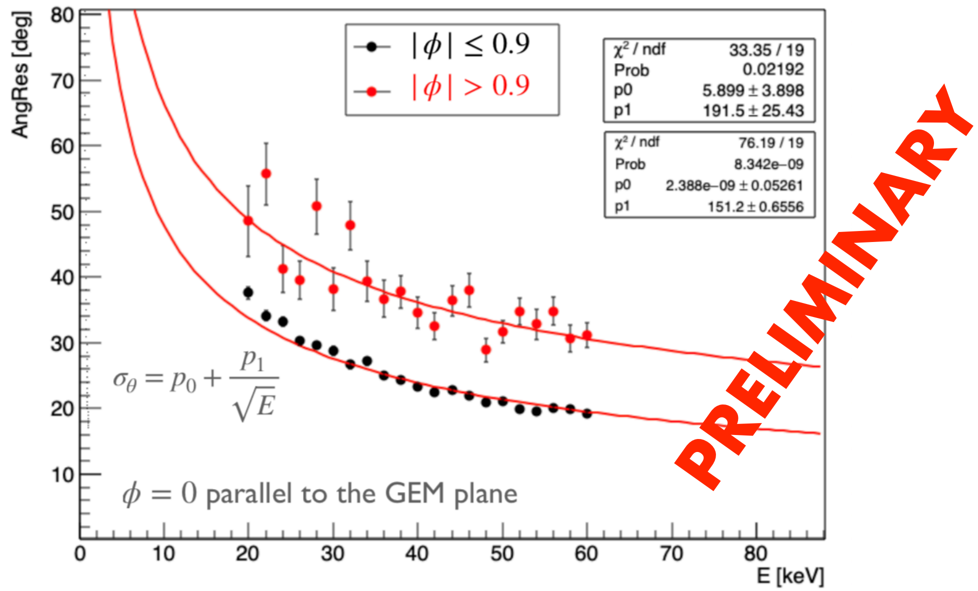
- Algorithm adapted from X-ray polarimetry:

"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





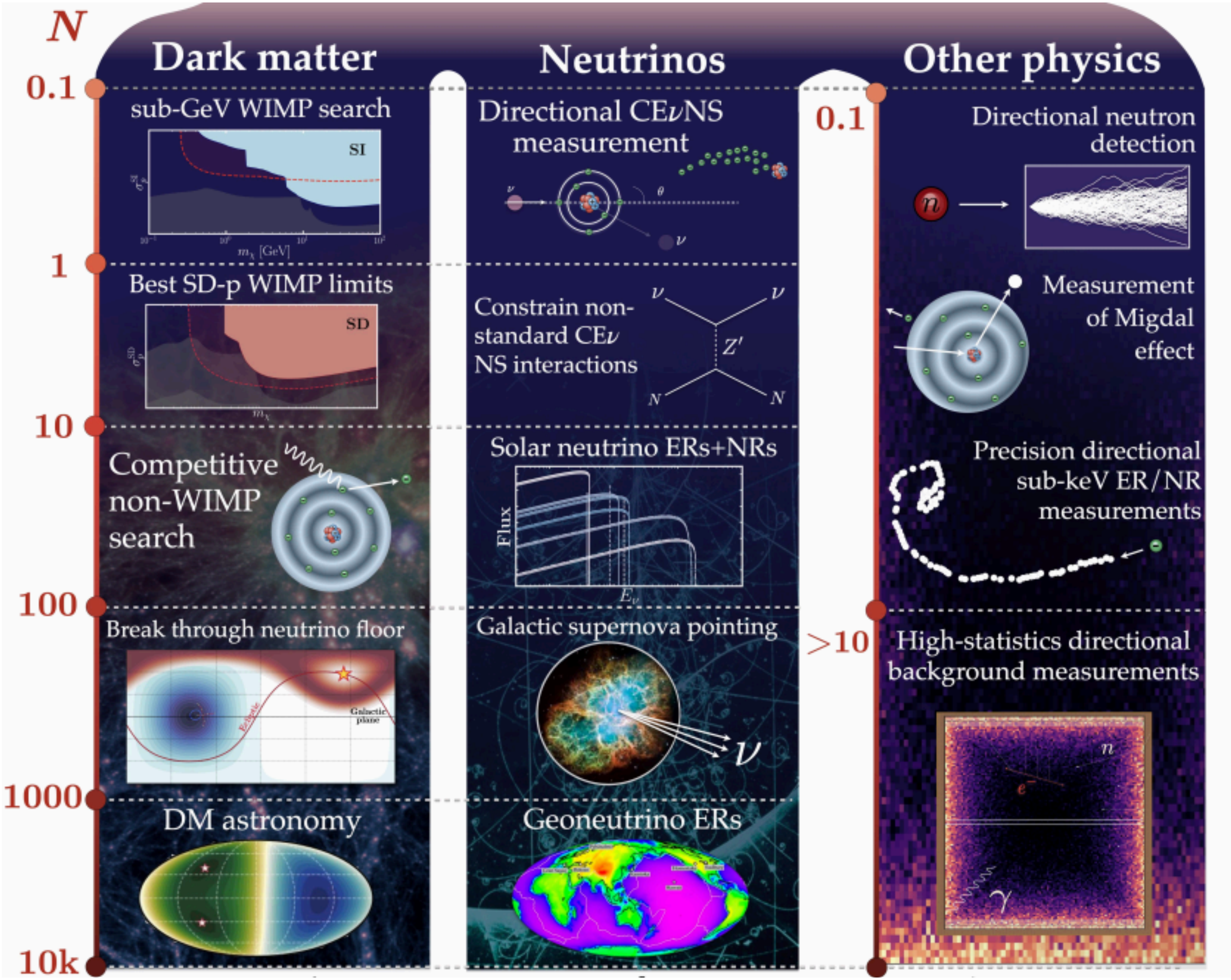
Fit expectation for 70 keV ER compatible with prediction from previous slide and in the "Mid-perfornance" range

Physics cases for directional TPCs as a function of exposure

N = volume in m³ assuming 1 atm operation

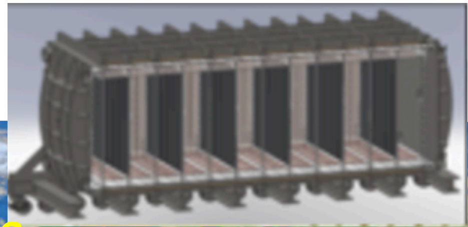
Many interesting physics opportunities already at relatively small scale

See also I. Katsisoulas talk on MIGDAL measurement today at 18.00 in the Dark Matter session

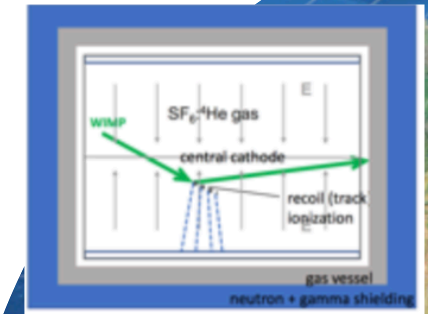


TPCs projects within CYGNUS

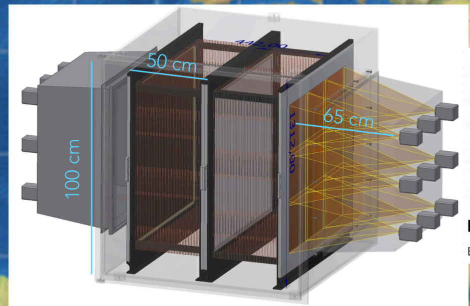
CYGNUS projects in the world



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



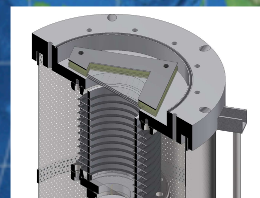
CYGNUS-HD10
Strip micromegas
$He{:}CF_4{:}X$
40 L + $1\ m^3$ R&D detectors under construction



European Research Council
Established by the European Commission

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

CYGNO/INITIUM
GEMs + sCMOS + PMT
$He{:}CF_4\ ({:}SF_6)$
LNGS, Italy
$1\ m^3$ demonstrator funded towards $30\ m^3$ experiment



ARC CENTRE OF EXCELLENCE FOR DARK MATTER

CYGNUS-OZ
Stawell, Australia
GEMs + CCDs for gas studies
Plans for $1\ m^3$ demonstrator

Gaseous TPC experimental scenery within CYGNUS

	Established readout & directionality	Established gas	R&D readout	R&D gas	Largest detector realised	Detector under development
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	40 L + 1 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)
CYGNUS-OZ			3 GEMs + PMT + charge	$He:CF_4:(SF_6)$ @ 0.05-0.1 bar		100 mL (funded)
CYGNUS			All of the above	Helium-Fluorine @ 1 bar		1000 m^3

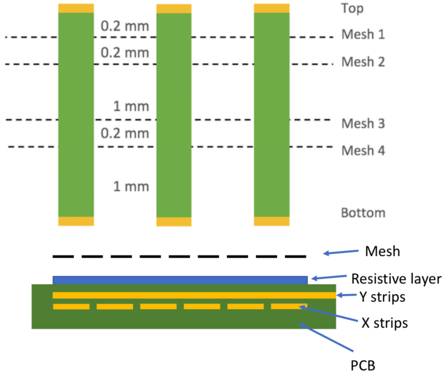
Electron drift ***Negative ion drift*** ***Charge readout*** ***Optical readout***

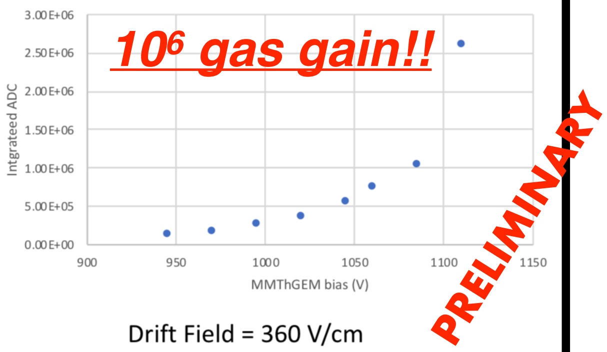
Some highlights from R&D towards CYGNUS

- Operation with SF_6
- Large vessels realisations & projects
- Simulation & analysis

Operation with SF_6

Hybrid THGEM-Micromegas at 40 Torr CF_4:SF_6 (DRIFT & Newage)



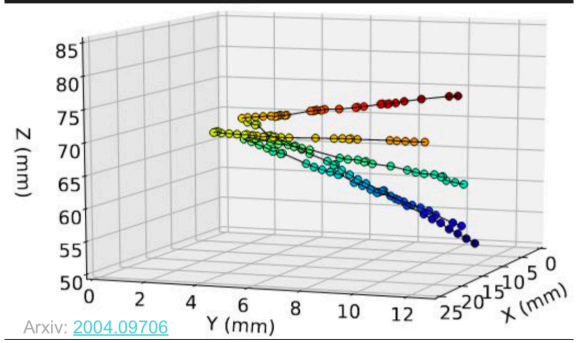


CF_4:SF_6 39.0:1.8 Torr

Drift Field = 360 V/cm

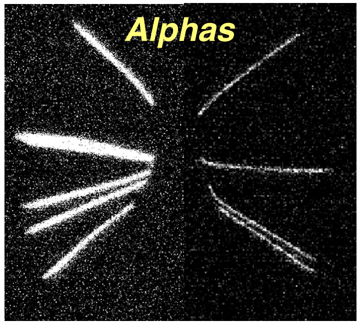
$V_{Micromegas}$= 515 V

Alphas 3D tracking with 130 um resolution in 20 Torr pure SF_6 (Newage)



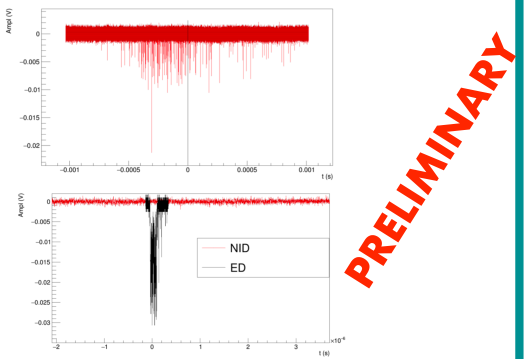
JINST 15 (2020) 07, P07015

He:CF_4:SF_6 operation at 880 Torr with sCMOS & PMT (CYGNO)



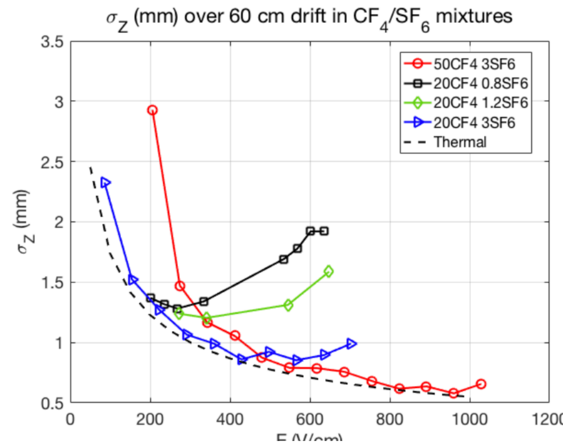
He:CF_4 60:40 (ED)

He:CF_4:SF_6 59:39.4:1.6 (NID)



Analysis of PMT signals returns mobility consistent with JINST 13 04 P04022

CF_4:SF_6 operation at 20-50 Torr with CCD (New Mexico)



R. Lafler, PhD Thesis, UNM, 2019

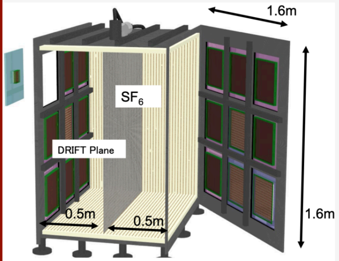
GSSI

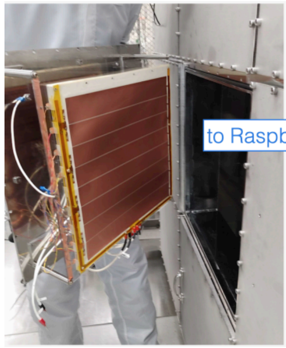
Large detectors realisation & projects

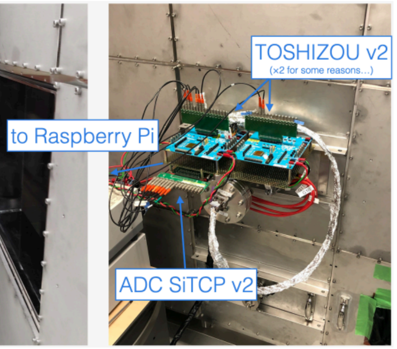
INFN

CYGNUS-KM / NEWAGE (C/N-1.0)

- 18 modules capable 1 m³ chamber
  - ➡ placed in Kobe University



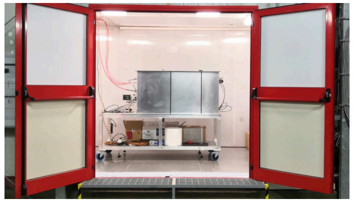


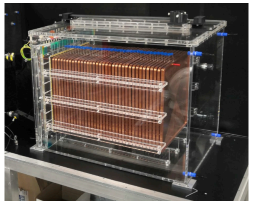


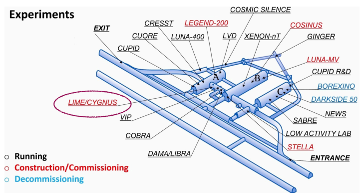
- ***A single 30 x 30 cm² module for 50 cm drift length commissioning the chamber at Kobe University***
  - ***Goal: detect SF_6^- and SF_5^- peaks***
- ***After commissioning, to be moved to underground Kamioka Mine***

LIME - CYGNO PHASE 0

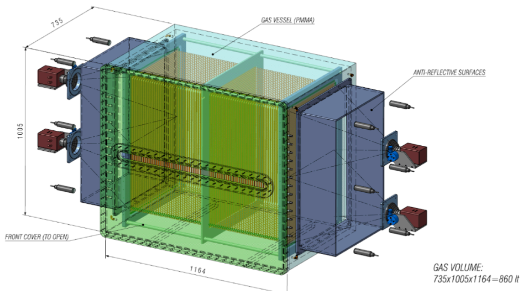
1 sCMOS + 4 PMT + 3 GEMs
33 x 33 cm² readout area
50 cm drift length







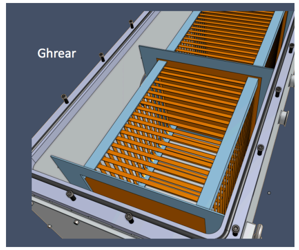
Base module design for PHASE 1 @ underground LNGS taking data



CYGNO PHASE 1 0.4 m³ detector & shielding TDR submitted to INFN

CYGNUS HD "Keiki"

CERN strip Micromegas + SRS
20 x 20 cm² readout area
50 cm drift length x 2 (double sided)



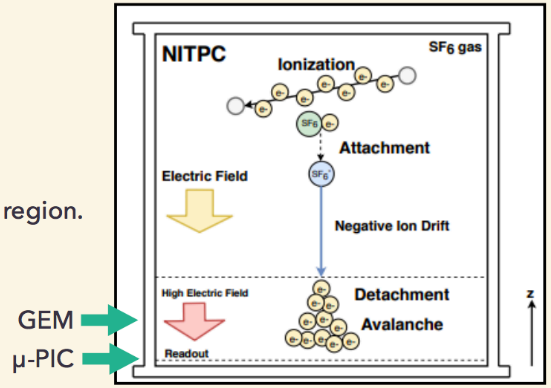
Under construction
Goal: evaluation of components for follow-on 1 m³ detector

1 m³ vessel design completed

Simulation & analysis

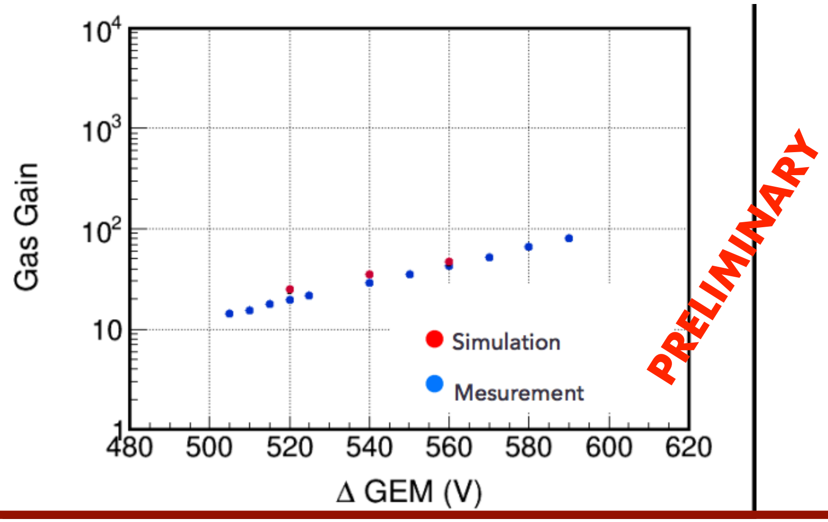
Garfield++ simulation of negative ion drift TPC (Newage)

1. Ionized electrons are produced.
2. Attachment.
3. Negative ion are produced.
4. Negative ion are drifted.
5. Detachment in high electric field region.
6. Avalanche amplification.



- Cross section model

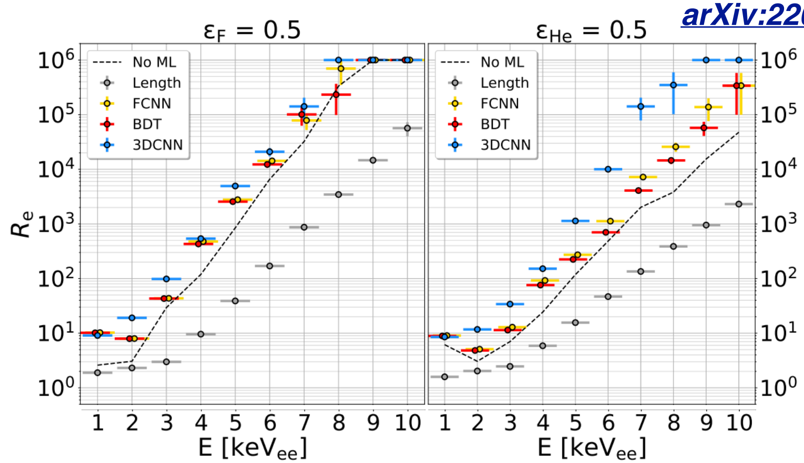
Detach with probability by calculating the mean free path from energy vs cross section.



Machine Learning in simulated high definition TPCs (CYGNUS-HD)

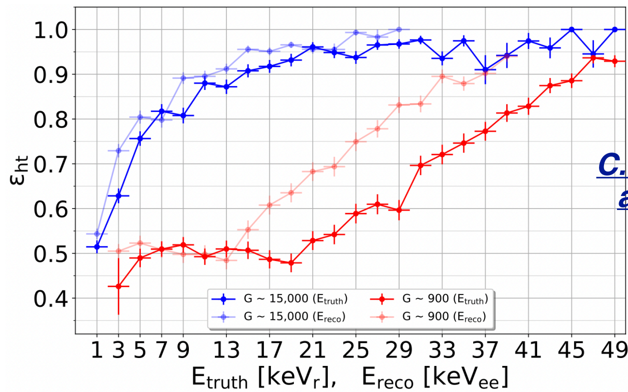
Diffusion & quantization included

J. Schuler et al, arXiv:2206.10822



O(10⁵) ER rejection below 10 keV achievable

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



Head-tail at 1 keV achievable

Conclusions & Outlook

- CYGNUS goal is to establish a Galactic Recoil Observatory to test the DM hypothesis inside the neutrino fog with directionality and perform solar neutrino measurements through both ER and NR recoils signals
  - Extensive concept paper on 1000 m^3 gaseous NITPC detector focused on technical feasibility and WIMP searches through nuclear recoils arXiv:2008:12587
  - Alternative physics cases, also involving electron recoils, under development
- CYGNUS will have installations in multiple underground sites, and will proceed through a staged expansion approach
  - Interesting physics opportunities at each stage of deveopment
- CYGNUS groups are working on a coordinated R&D to experimentally establish at the O(1) m^3 scale the performances of different readout and gas options
  - Several significant advancements in recent years for SF6 operation, large detectors realisation, simulation and analysis
- CYGNUS has recently received interest as part of the Snowmass Decal Planning Exercise in the US arXiv:2203.05914

Stay tuned for (a flock of) CYGNUS birth!

Backup slides

Comparison of “neutrino floors”

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

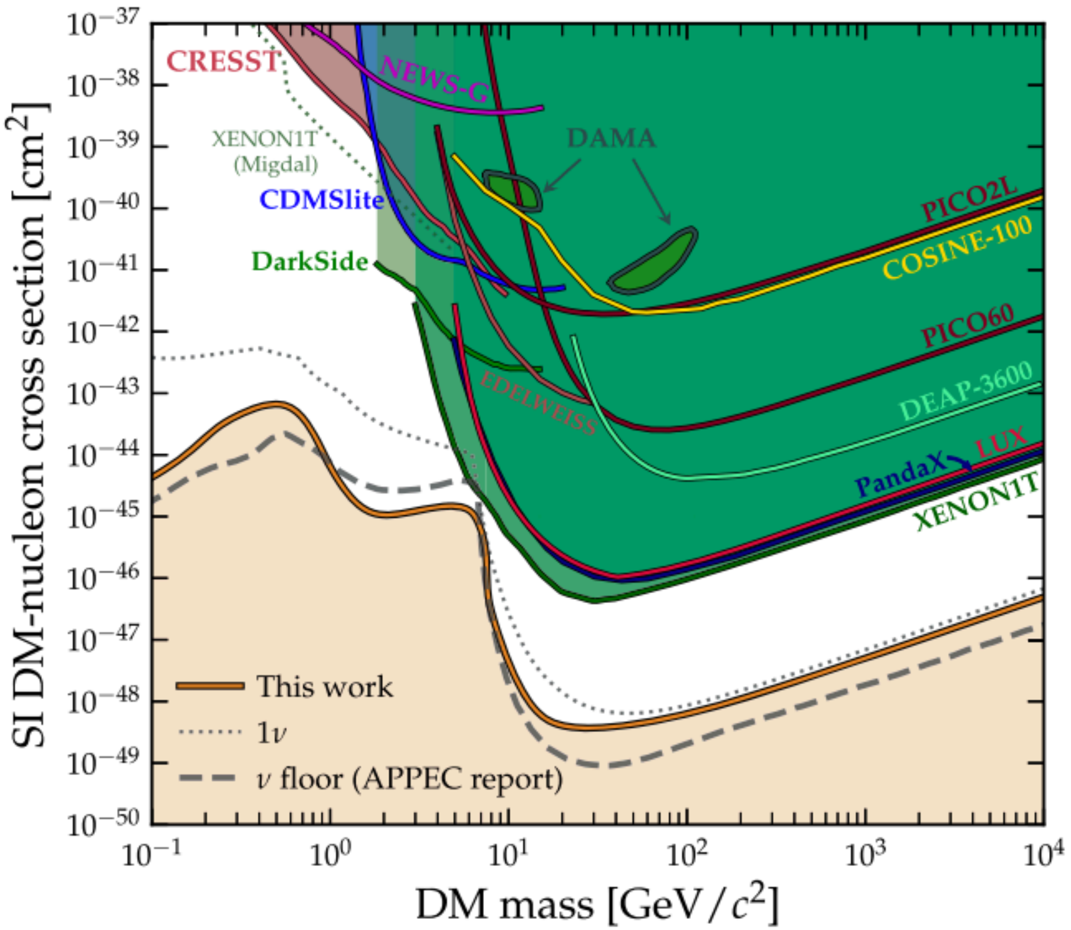
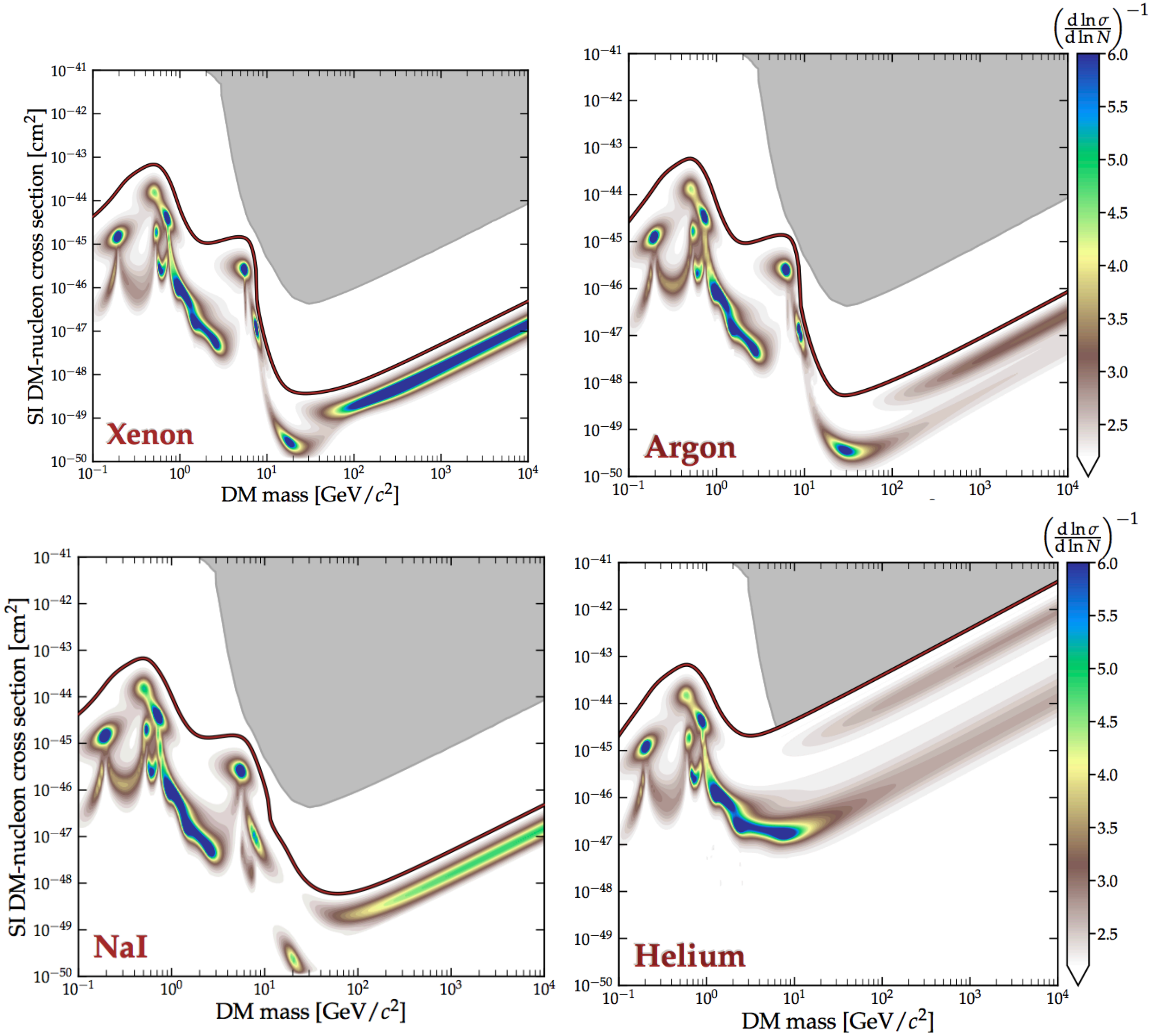
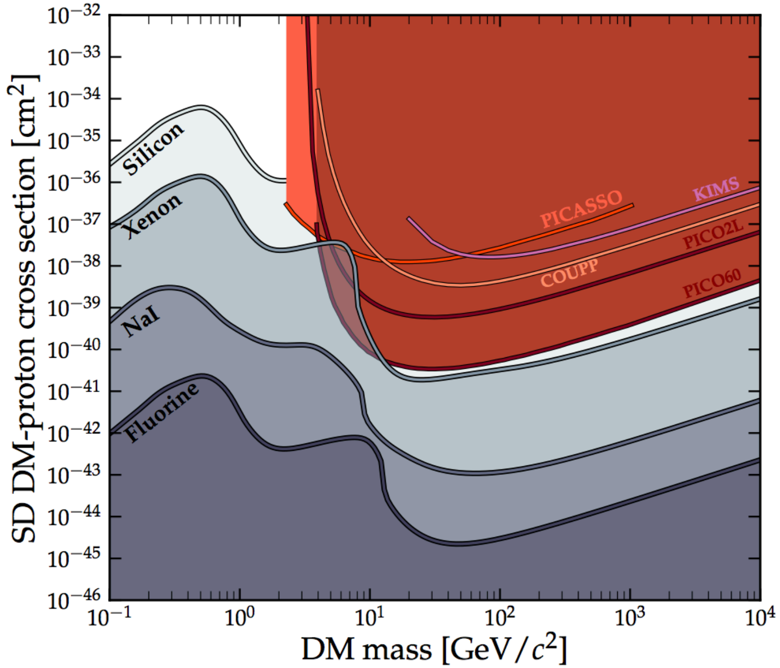


FIG. 1. Present exclusion limits on the spin-independent DM-nucleon cross section (assuming equal proton or neutron couplings) [7,58–71]. Beneath these limits we show three definitions of the neutrino floor for a xenon target. The previous discovery-limit-based neutrino floor calculation shown by the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

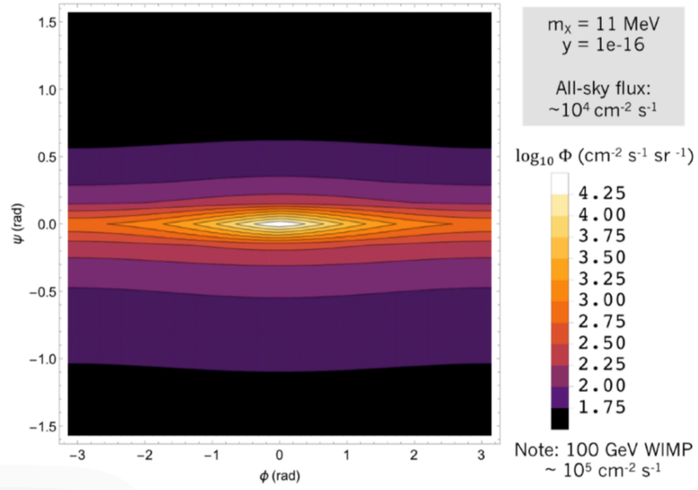
Nuetrino fog for various targets

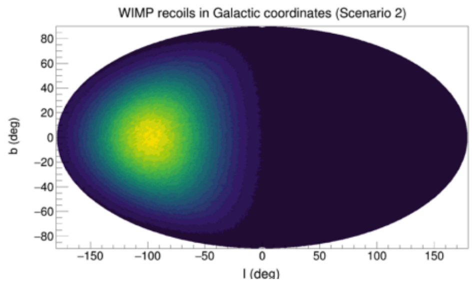
[C. A. J. O'Hare, Phys. Rev. Lett. 127 (2021) 25, 251802](#)

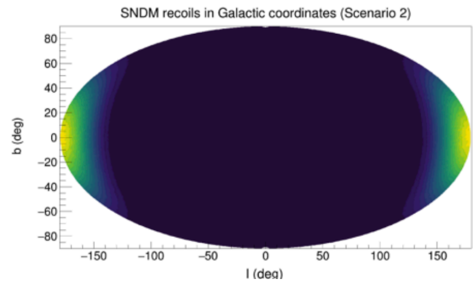


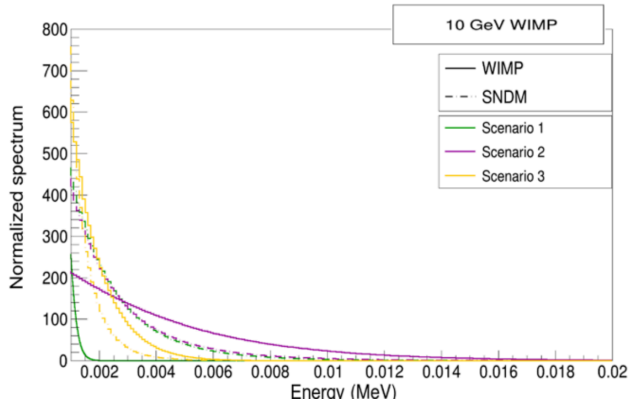


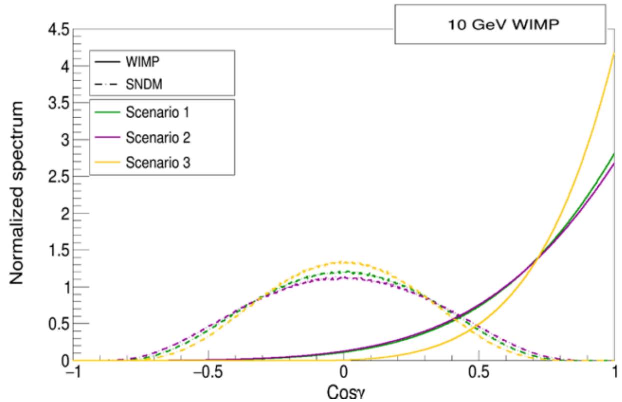
Not only WIMP Dark Matter: potentialities for discovery of MeV DM from SN with directionality

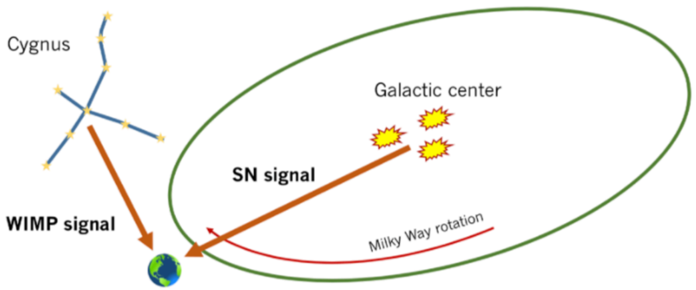


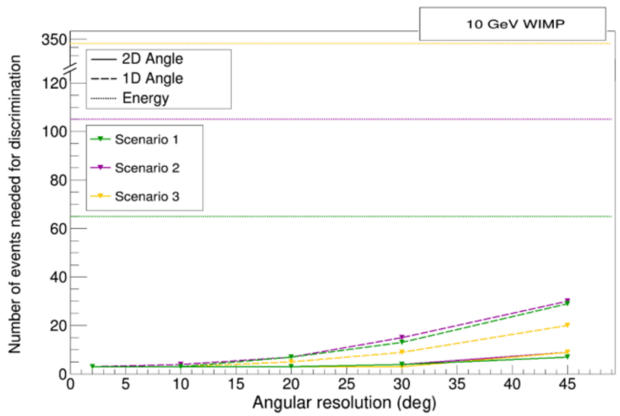


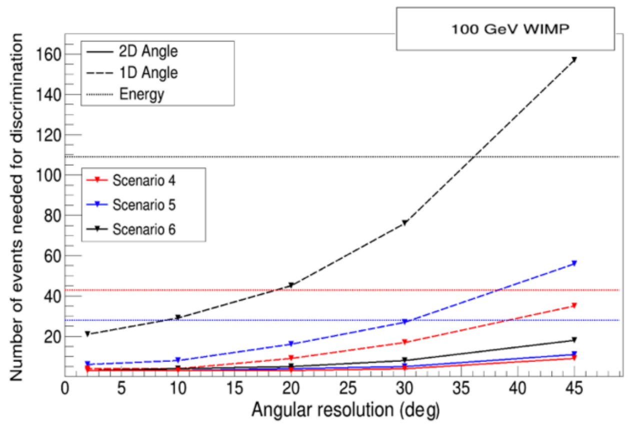












Solar neutrino spectroscopy with gaseous TPCs

1992 **He**

A HIGH RATE SOLAR NEUTRINO DETECTOR
WITH ENERGY DETERMINATION

J. Séguinot, T. Ypsilantis
Collège de France, IN2P3 - CNRS
et CERN, Genève, Suisse

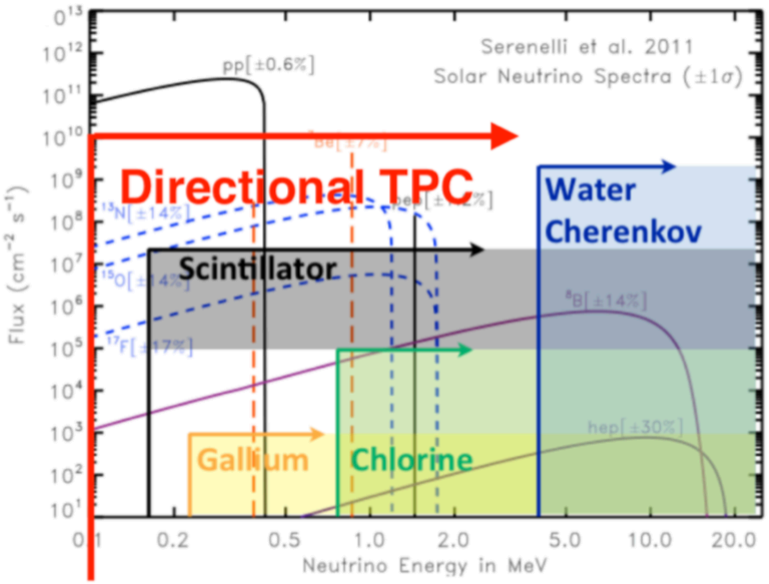
A. Zichichi
CERN, Genève, Suisse
et INFN-Laboratoire national du Gran Sasso, Italie

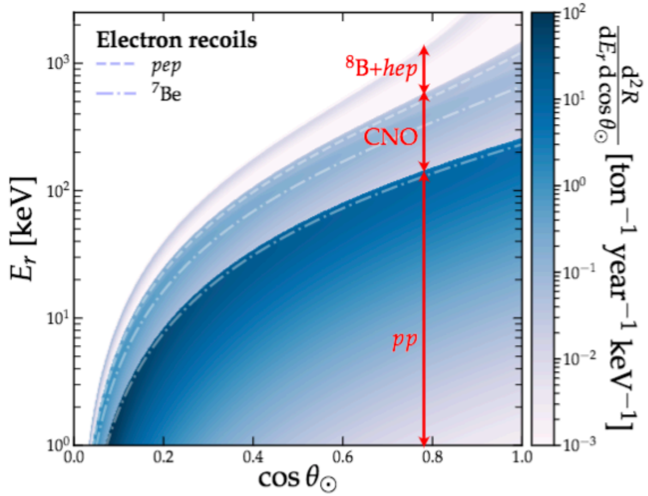
1996 **CF**

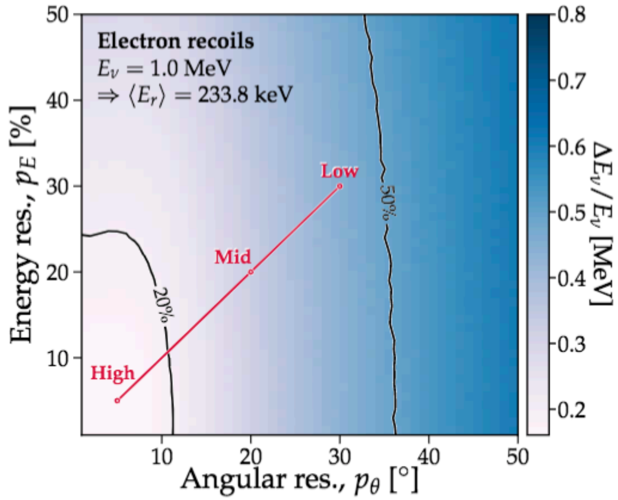
A possible gas for solar neutrino spectroscopy

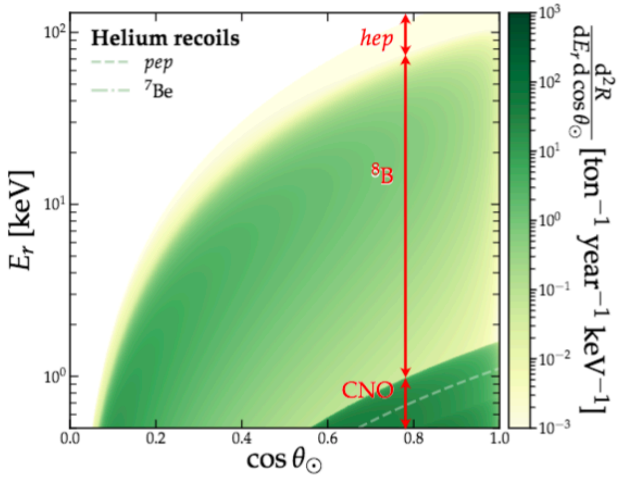
C. Arpesella[a], C. Broggini[b], C. Cattadori[c]
[a] I.N.F.N. Laboratori Nazionali del Gran Sasso, I-67010 Assergi (AQ), Italy
[b] I.N.F.N. Sezione di Padova, via Marzolo 8, I-35131 Padova, Italy
[c] I.N.F.N. Sezione di Milano, via Celoria 16, I-20133 Milano, Italy

Received 25 July 1995; revised 24 October 1995









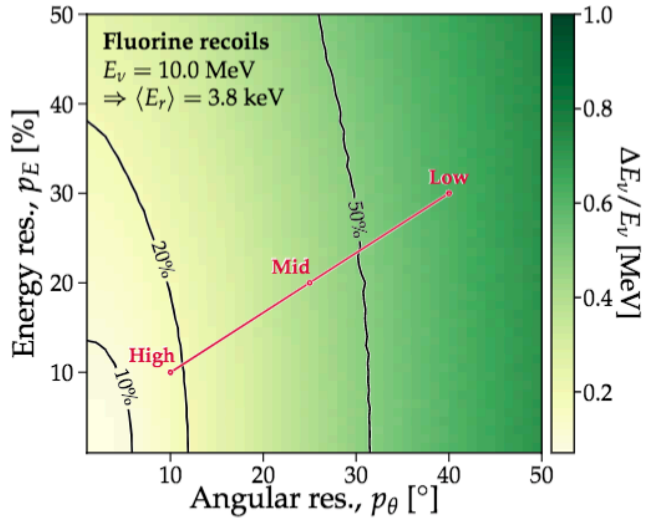


Table 1 Approximate expected numbers of neutrino-induced nuclear and electron recoils[a]

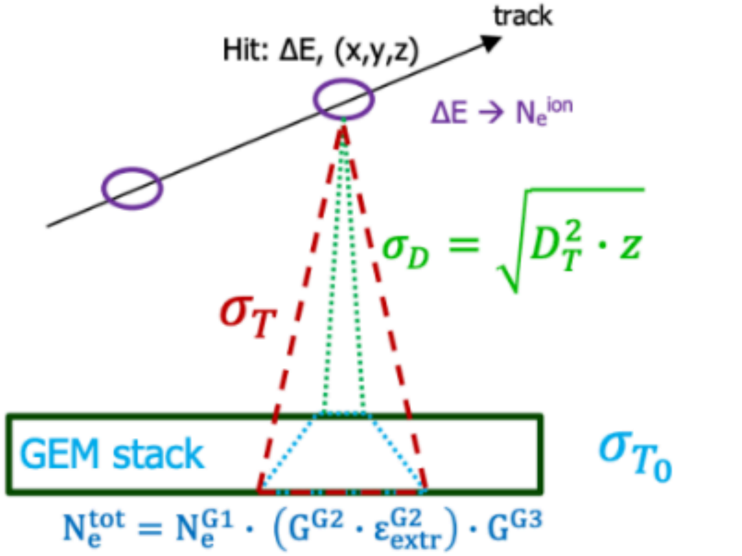
Nuclear recoils	SF_6			CF_4			He		
Threshold (keV_r)	1	5	10	1	5	10	1	5	10
Solar (mainly ^8B)	73	15	2	54	16	3	3	2	1
3-kpc supernova	25	18	12	18	13	10	0.6	0.5	0.5
Electron recoils	**SF_6**			**CF_4**			**He**		
Threshold (keV)	5	500	1,000	5	500	1,000	1	500	1,000
Solar (total)	537	42	4	438	34	3	102	8	0.8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

[a] Assuming a target volume of 1,000 m^3, 1 atmosphere pressure, and an exposure time of 1 year.

LIME sCMOS images MC simulation

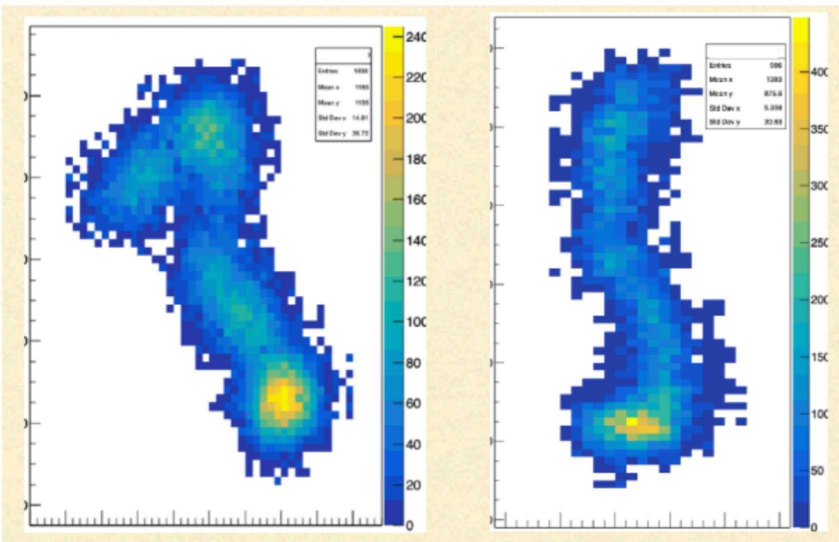
- **Electron tracks generated with GEANT4**
- **# of primary ionisation electrons extracted from a Poisson distribution with mean $N_e = \Delta E/W_i$ with $W_i = 46.2$ eV/pair**
- **Primary ionisation electron diffused longitudinally and transversally along drift following Gaussian distribution with $\sigma_T = \text{sqrt}(\sigma^2_0 + D^2_T\, z)$ with σ_0 & D_T from measurements**
- **Electron avalanche fluctuation taken into account for the first GEM foil**
  - **For each ionisation electron *k*, $N^{G1,k}_e$ multiplication electron at first foil extracted from exponential distribution with mean = G_{GEM}**
  - **Total # of multiplication electron from first foil $N^{G1}_e = \sum_k N^{G1,k}_e$**
  - **$G_{GEM} = 123$ from IEEE, Vol. 65, No.1, Jan 2018**
- **Total electron gain $N^{tot}_e = N^{G1}_e \cdot (G_{GEM})^2$**
- **Mean total number of photon N^{tot}_γ from Poisson distribution with mean $N^{mean}_\gamma = 0.07$ γ/e**
- **Number of photon hitting the sensor $N_\gamma = N^{tot}_\gamma \cdot \Omega$**
- **sCMOS sensor noise from real data**

$$\Omega = \frac{1}{(4(1/\delta + 1) \times a)^2} \qquad \delta = \frac{f}{d - f}$$



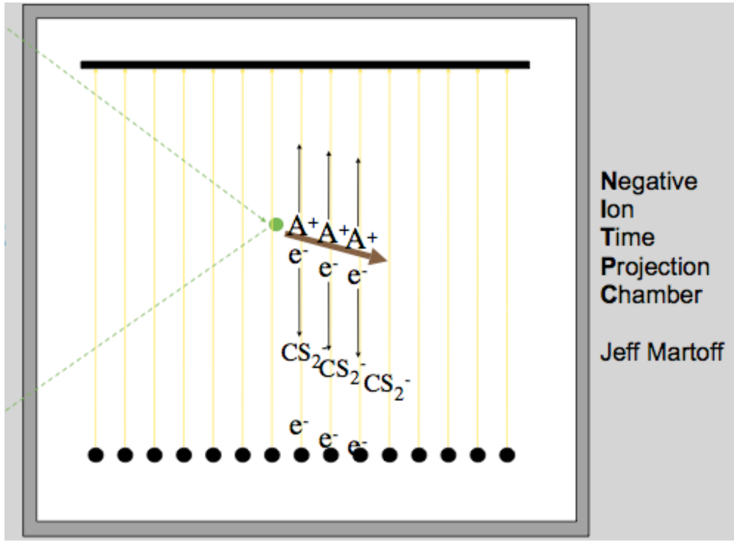
30 keV electron

PRELIMINARY



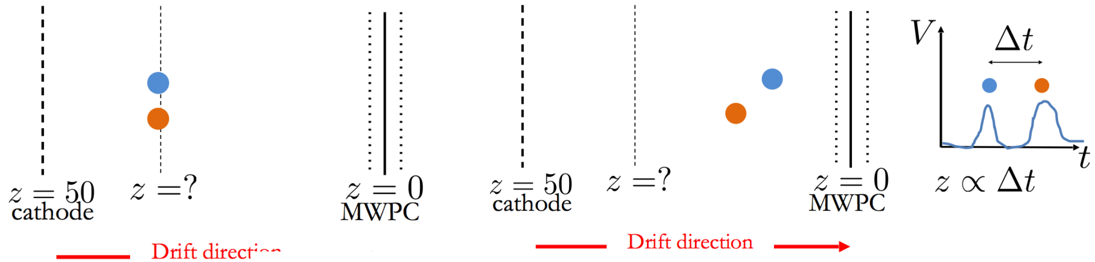
Simulation **Data**

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



Multiple charge carriers

start together *…but drift at different velocity*



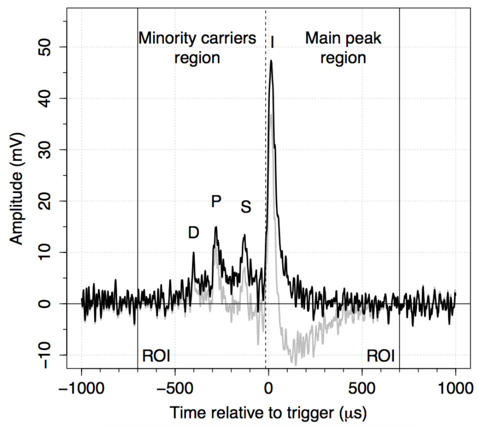
$$z = (t_m - t_p)\frac{v^m_{drift}v^p_{drift}}{v^m_{drift} - v^p_{drift}}$$

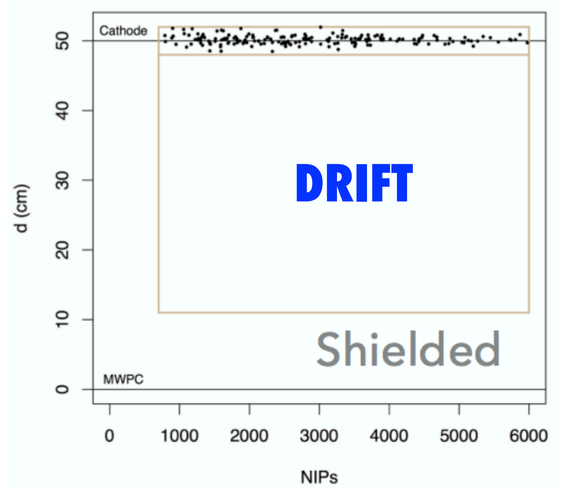
- Electronegative dopant in the gas mixture (CS_2, SF_6, CH_3NO_2, …)
- Primary ionization electrons captured by electronegative gas molecules at O(100) um
- Anions drift to the anode acting as the effective image carrier instead of the electrons and reducing both longitudinal and transverse diffusion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

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





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

Astroparticle Physics 91 (2017) 65–74

T. Ohnuki et al., NIM A 463

J. Martoff et al., NIM A 440 355