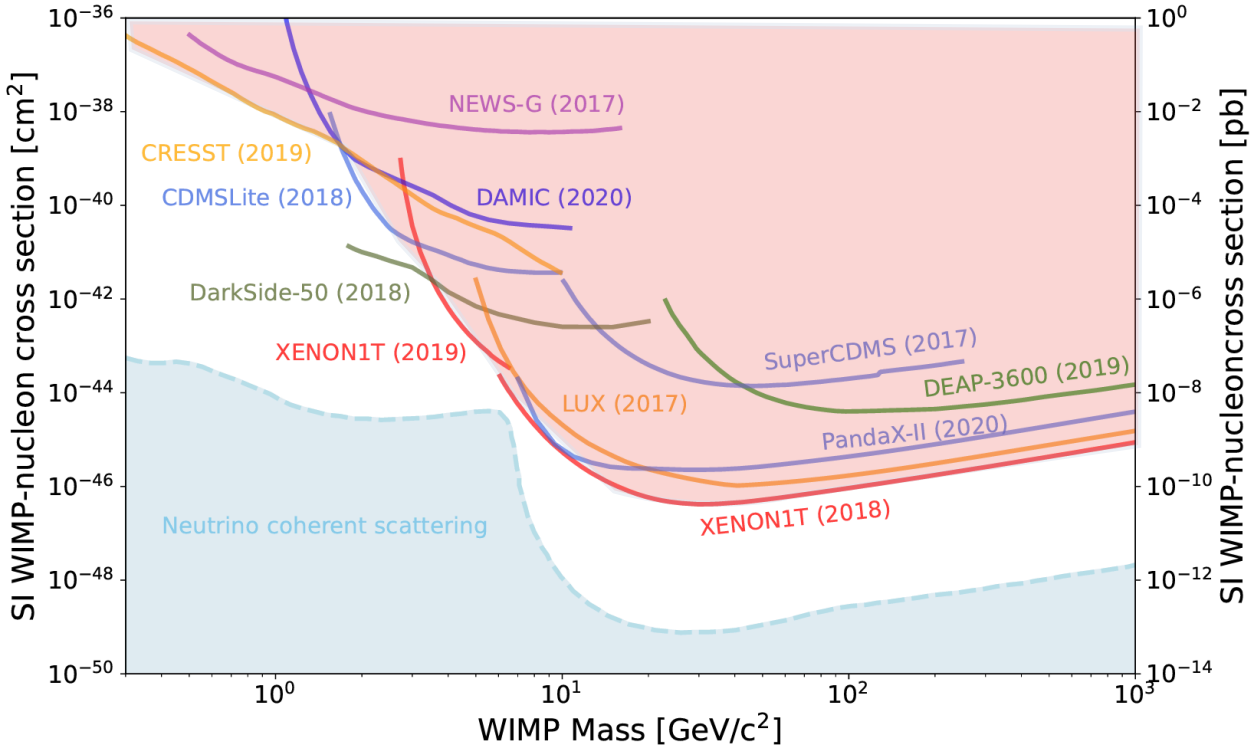
Update on the current status of direct Dark Matter searches

A personal and biased view by:

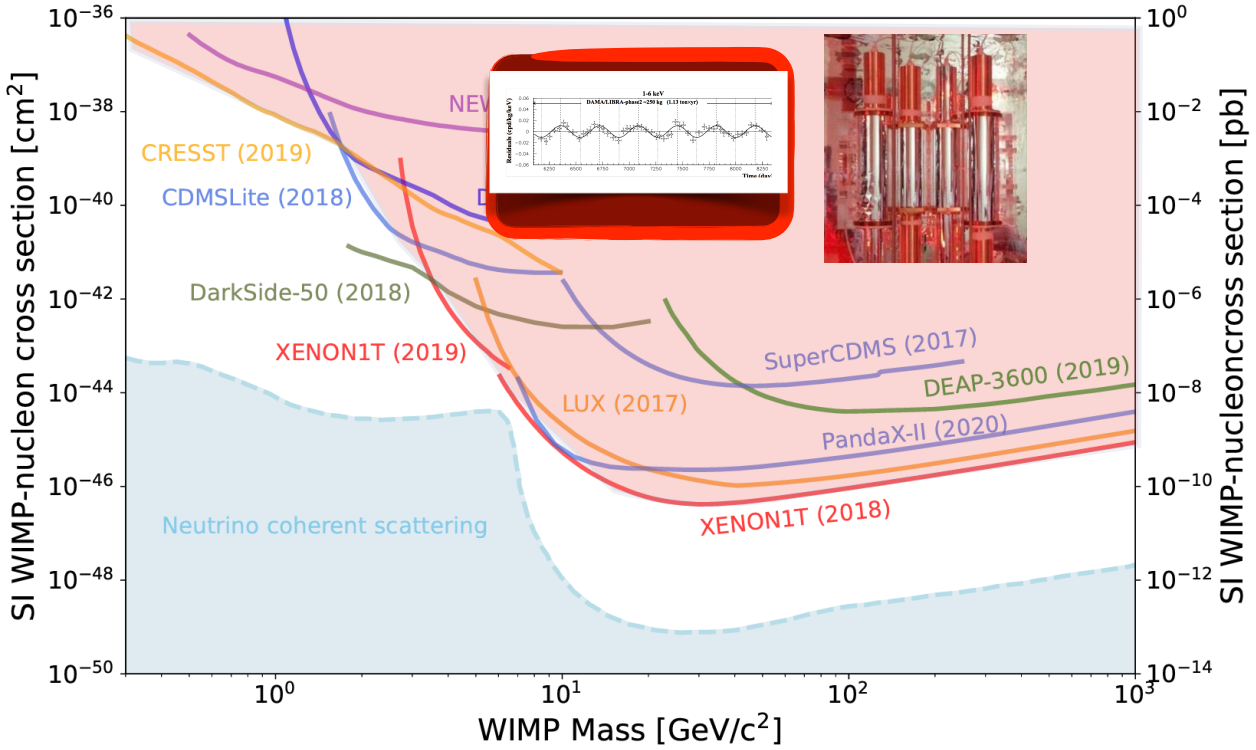
Elisabetta Baracchini

CYGNO Collaboration meeting 2024

DM searches overview & context

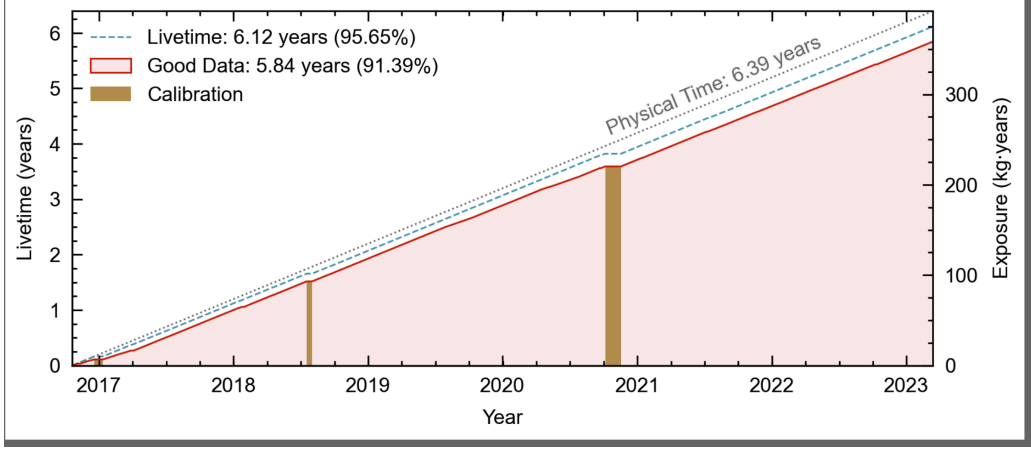


DM searches overview & context



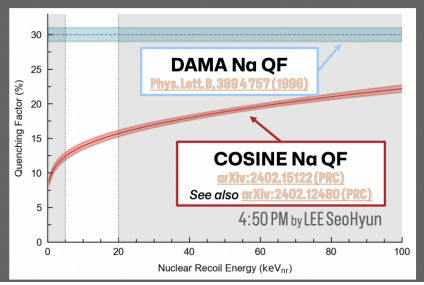
NaI based experiments to test DAMA claim: COSINE-100

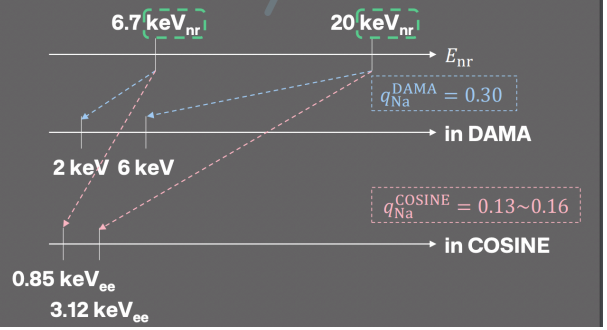
6 Years 4 Months 22 Days Later...



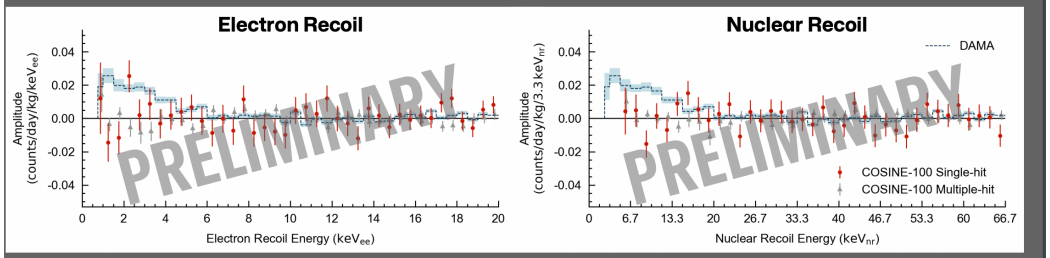
Calibration for Testing DAMA's Claim

1. Linear calibration: keV_{ee}
2. Quenching factor corrected: keV_{nr}





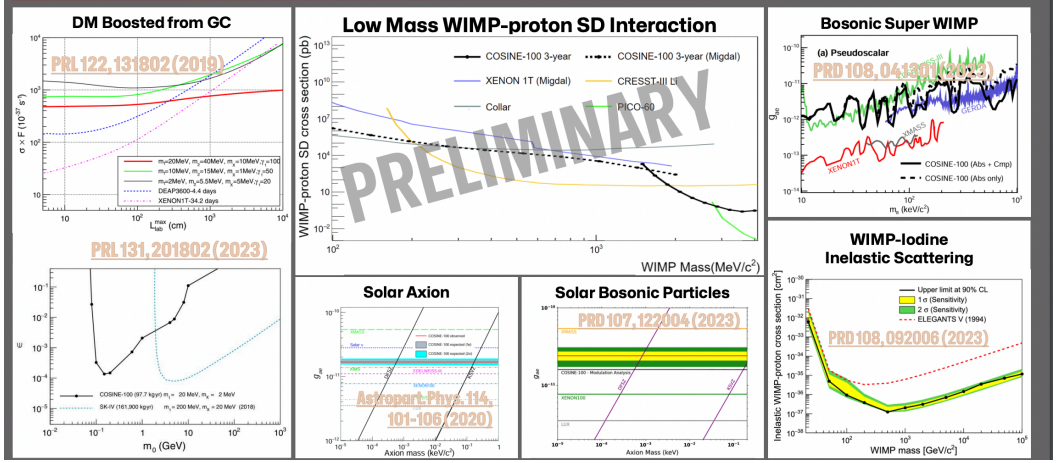
No Modulation Detected



E (keV$_{ee}$)	A (counts/day/kg/keV$_{ee}$)	
	COSINE-100	DAMA/LIBRA
1~3	0.0004 ± 0.0050	0.0191 ± 0.0020
1~6	0.0017 ± 0.0029	0.01048 ± 0.00090
2~6	0.0053 ± 0.0031	0.00996 ± 0.00074

E (keV$_{nr}$)	A (counts/day/kg/3.3 keV$_{nr}$)	
	COSINE-100	DAMA/LIBRA
6.7~20	0.0013 ± 0.0027	0.00996 ± 0.00074

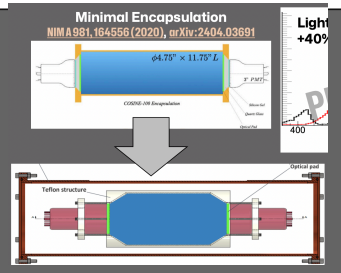
No Dark Matter in NaI(Tl) Data

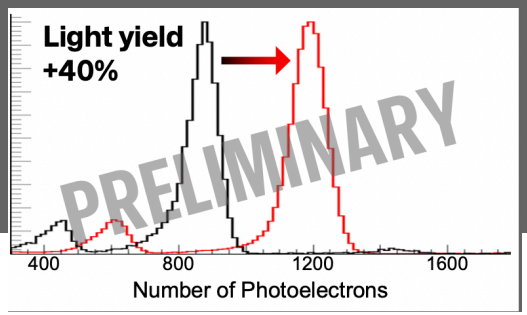


NaI based experiments to test DAMA claim: COSINE-100

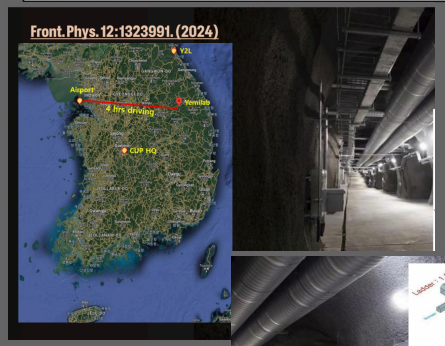
COSINE-100Upgrade

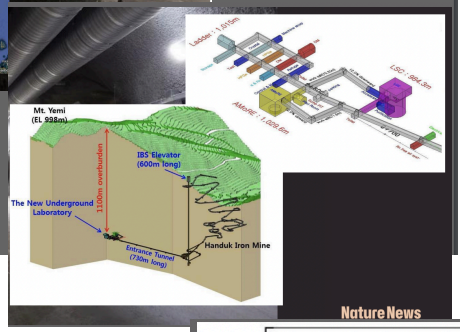
Lower Threshold





New Deeper Site

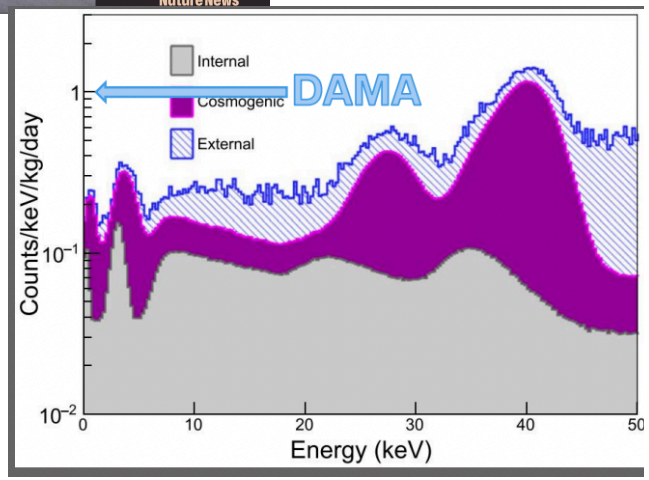




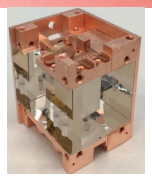
Ultra-pure NaI(Tl) Development for COSINE-200

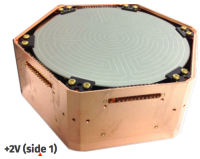
- 400 kg of ultra-pure NaI powder is ready.
  - J. Rad. Nucl. Chem. 317, 1329 (2018), JINST 15, C07031 (2020)
  - EPJC 80, 814 (2020), Front. Phys. 11, 1142849 (2023)
- We grew 0.7 kg of crystal with 0.2 counts/day/kg/keV.
- Further R&D to grow large crystals within the safety regulation is ongoing.

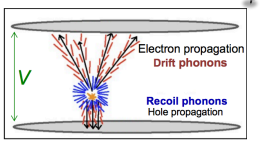
(ppb)	K	Pb	U	Th
Initial	248	19.0	<0.01	<0.01
Purified	<16	0.4	<0.01	<0.01



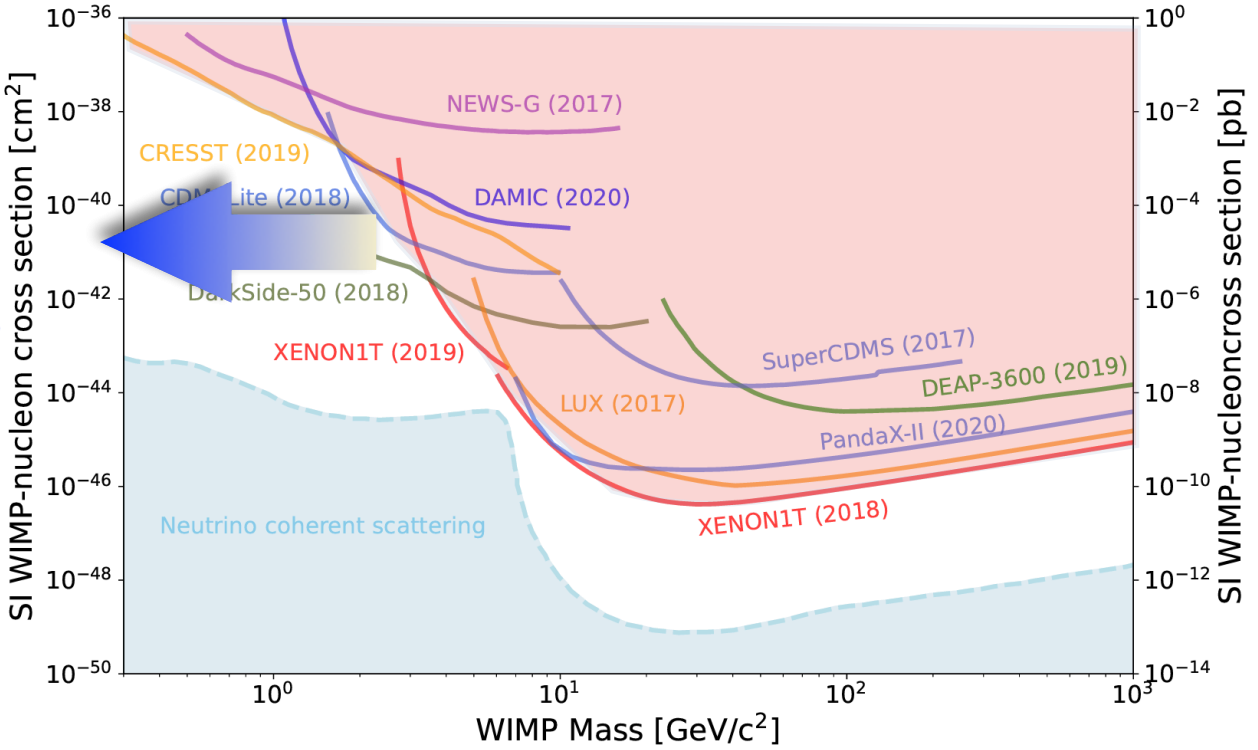
DM searches overview & context







- **Small mass detectors with light nuclei**
- **0.1-1 kg enough to explore uncharted territories**
- **10^4-10^5 rejection @ 10 keV**
- **Trend to reduce module mass & background discrimination to reach lower threshold**



Low-mass dedicated experiments: bolometers

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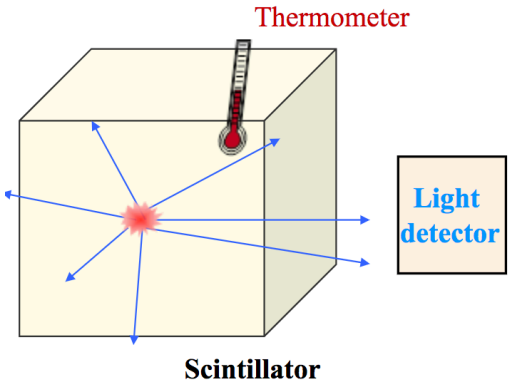
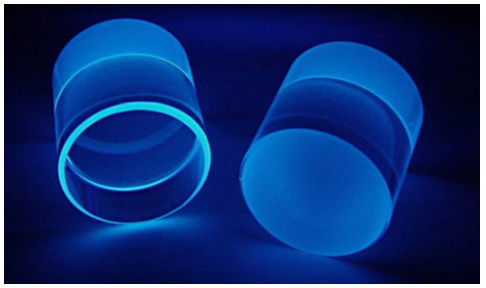
Heat + Scintillation

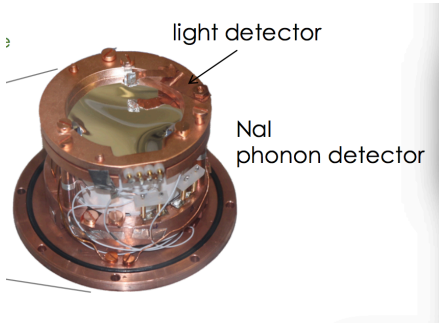


CRESST



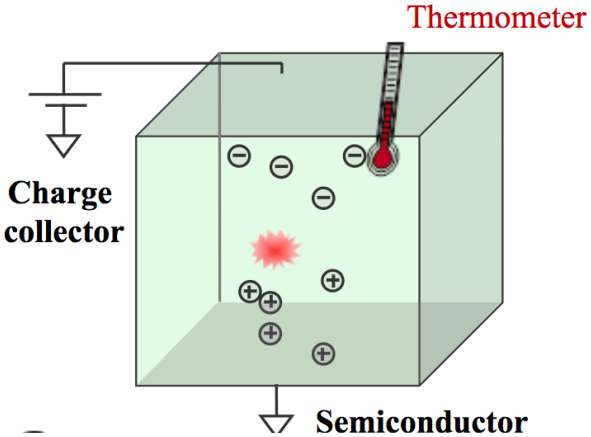
$CaWO_4$ crystals + TES

COSINUS

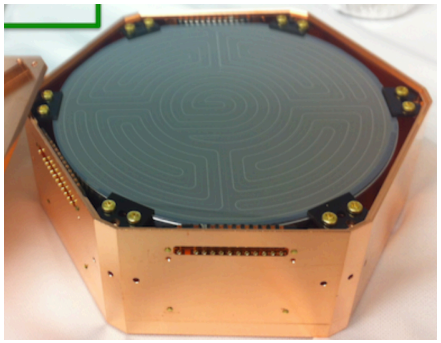


NaI crystals + TES

Heat + Ionisation

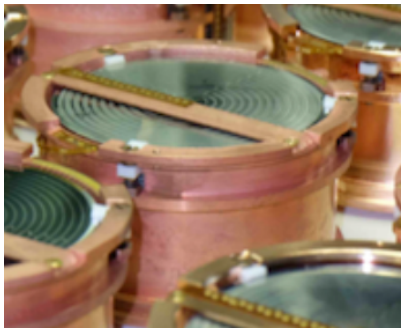


CDMS



Ge, Si semiconductor + TES

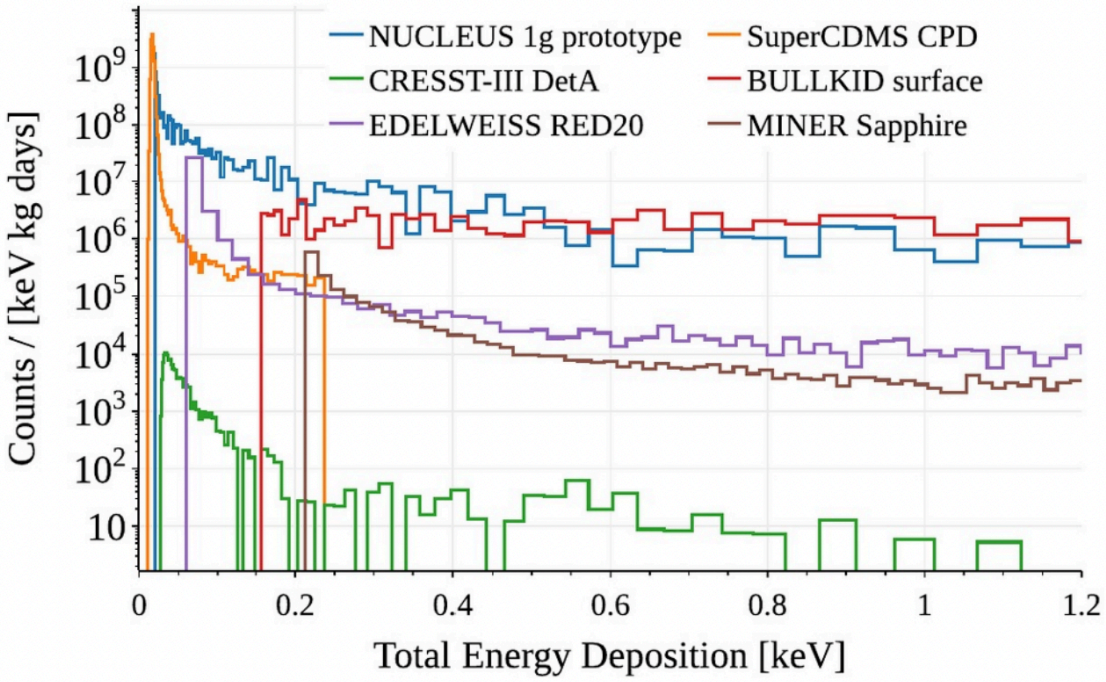
EDELWEISS



Ge semiconductor + NTD

The Low Energy Excess (LEE) since 2022

The LEE, if not experimentally solved, could kill the bolometric approach



- 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

The Low Energy Excess (LEE) as of today

C. Strandhagen | IDM `24

Ideas about the origin of the LEE

- lack of ionization and time behavior strongly **disfavors particle origin**
- favored explanation by the community – energy release through relaxation processes

Three main categories:

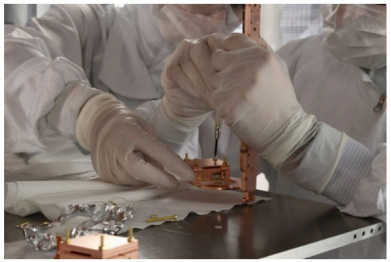
- Stress induced by the **holding structure**
- **Intrinsic stress** from the bulk material
- Stress in the **sensors** or the **interface to the sensors**

As of today, not univocal explanation yet

C. Strandhagen | IDM `24

What's next ?

- many experiments have started or are preparing new measurements at undeground laboratories
  - new CRESST campaign at LNGS started in April
  - SuperCDMS HVeV taking data in CUTE at SNOLAB
  - SuperCDMS SNOLAB is in installation phase



New campaing measurements planned

Low-mass dedicated experiments: SPC

News-G experiment

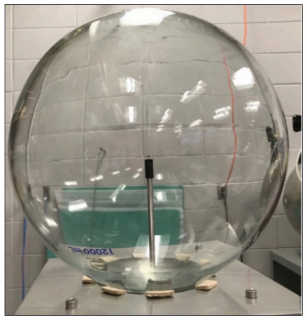
The Spherical Proportional Counter

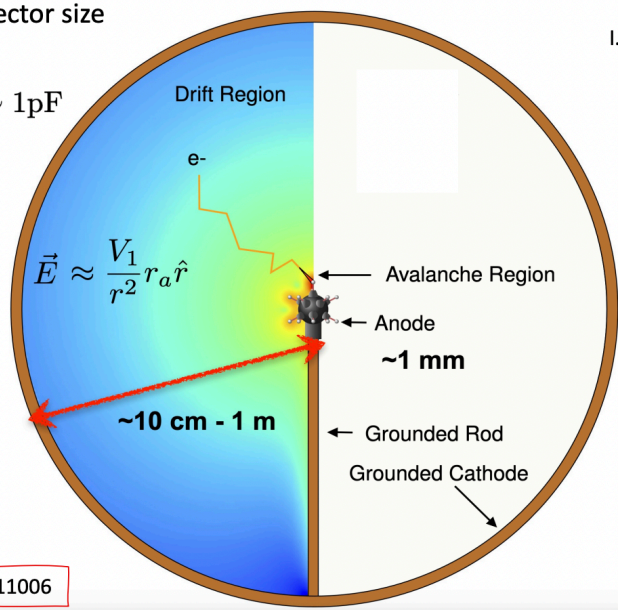
Electric field scales as $1/r^2$
- Divided into "drift" and "amplification" regions

Capacitance independent of detector size
- Low electronic noise

$$C = 4\pi\varepsilon_0 \frac{r_c r_a}{r_c - r_a} \approx 4\pi\varepsilon_0 r_a \sim 1\text{pF}$$

r_c = cathode radius
r_a = anode radius



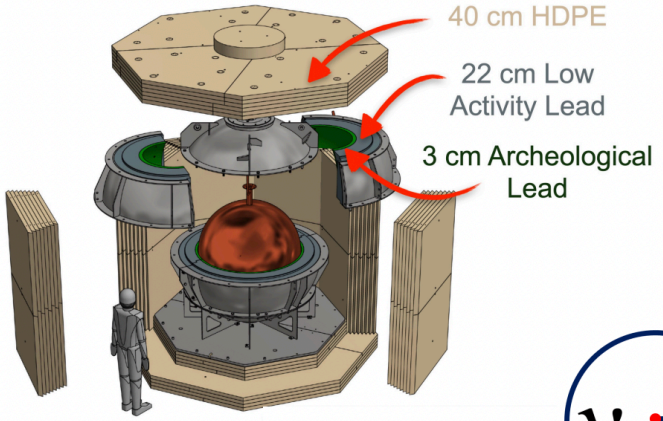


JINST 3 (2008) P09007, JINST 13 (2018) P11006

Light Dark Matter Searches with the SPC in SNOLAB

- ⌀**140 cm SPC** 4N (99.99% pure) Aurubis copper
  - Electroplated internal layer
  - Low radioactivity shielding material
- Constructed and tested in LSM, France
- Commissioning data analysis finalising
- **First physics run in SNOLAB** in 2023

✓ **~20 kg·days exposure** with Ne:CH_4

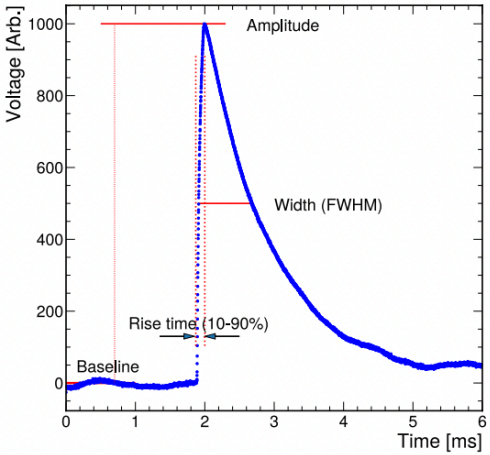


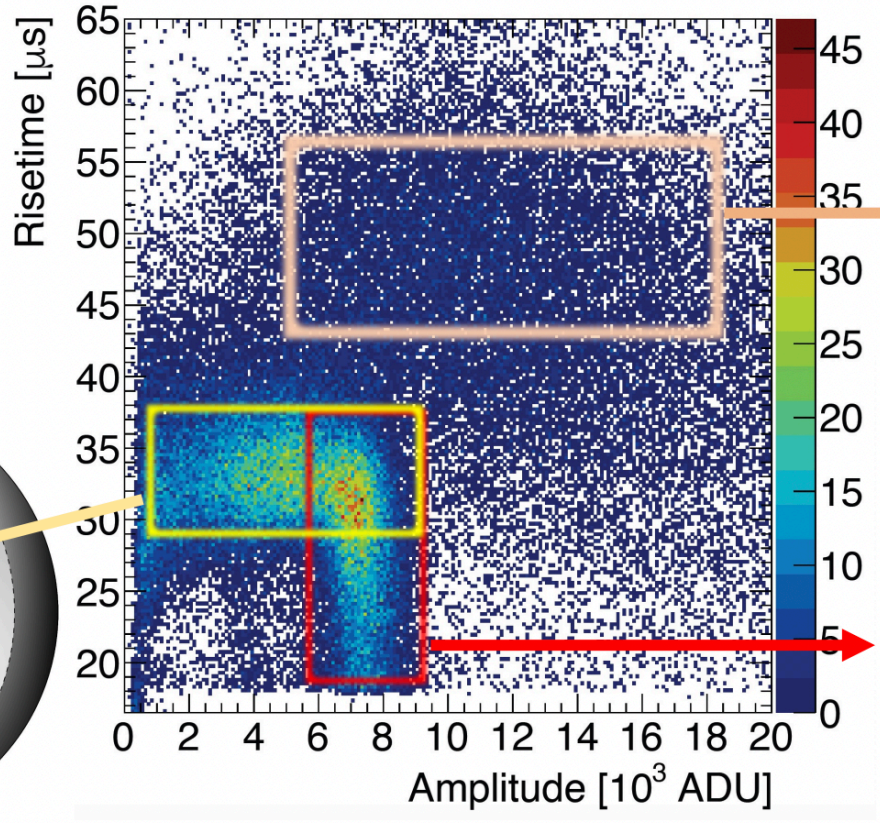
JINST 18 (2023) 02, T02005

ER/NR discrimination in News-G

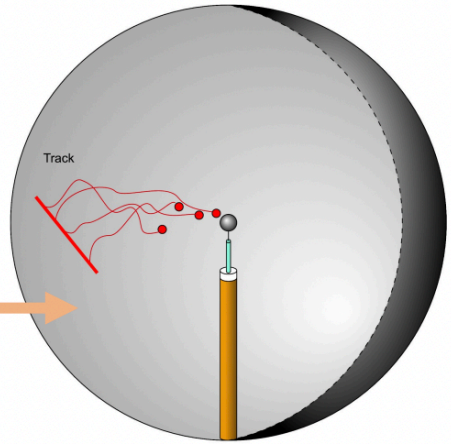
Pulse Shape Discrimination

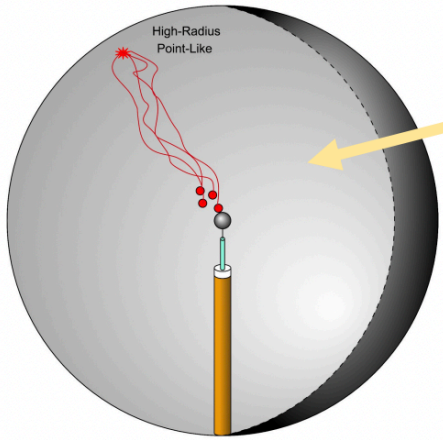
Use pulse shape parameters to differentiate events

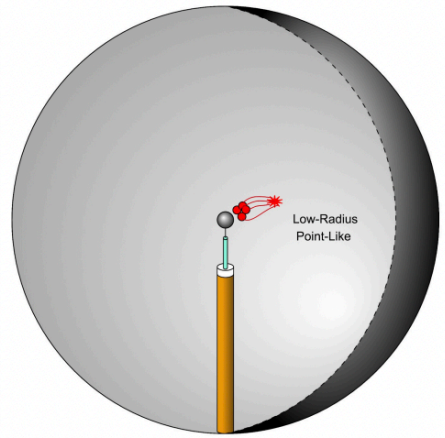




'muon'-like events





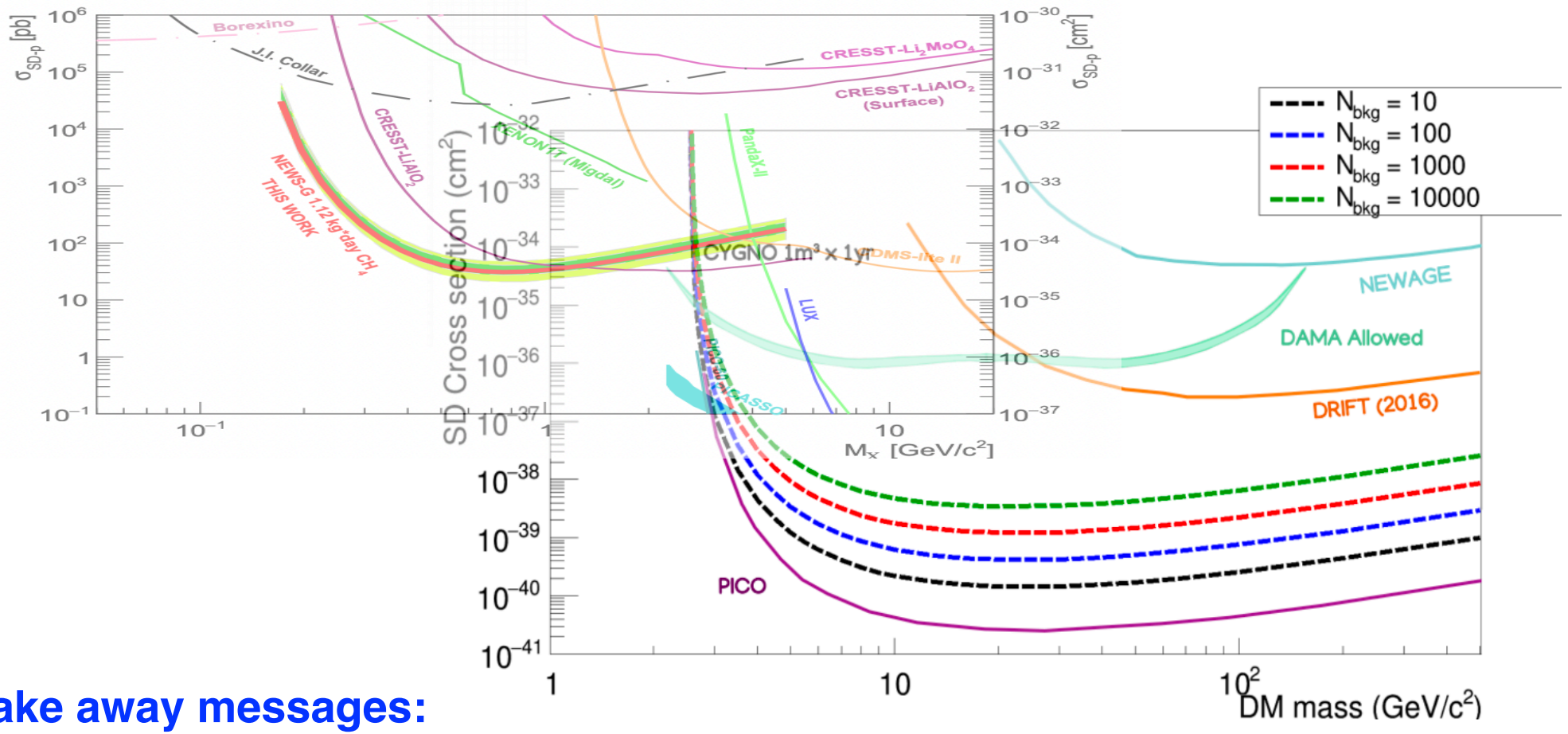


News-G SD proton SD latest result vs CYGNO-04 last year back-of-the-envelope sensitivity

Search for light dark matter with NEWS-G at the LSM using a methane target #1

NEWS-G Collaboration • M.M. Arora (Queen's U., Kingston) et al. (Jul 17, 2024)

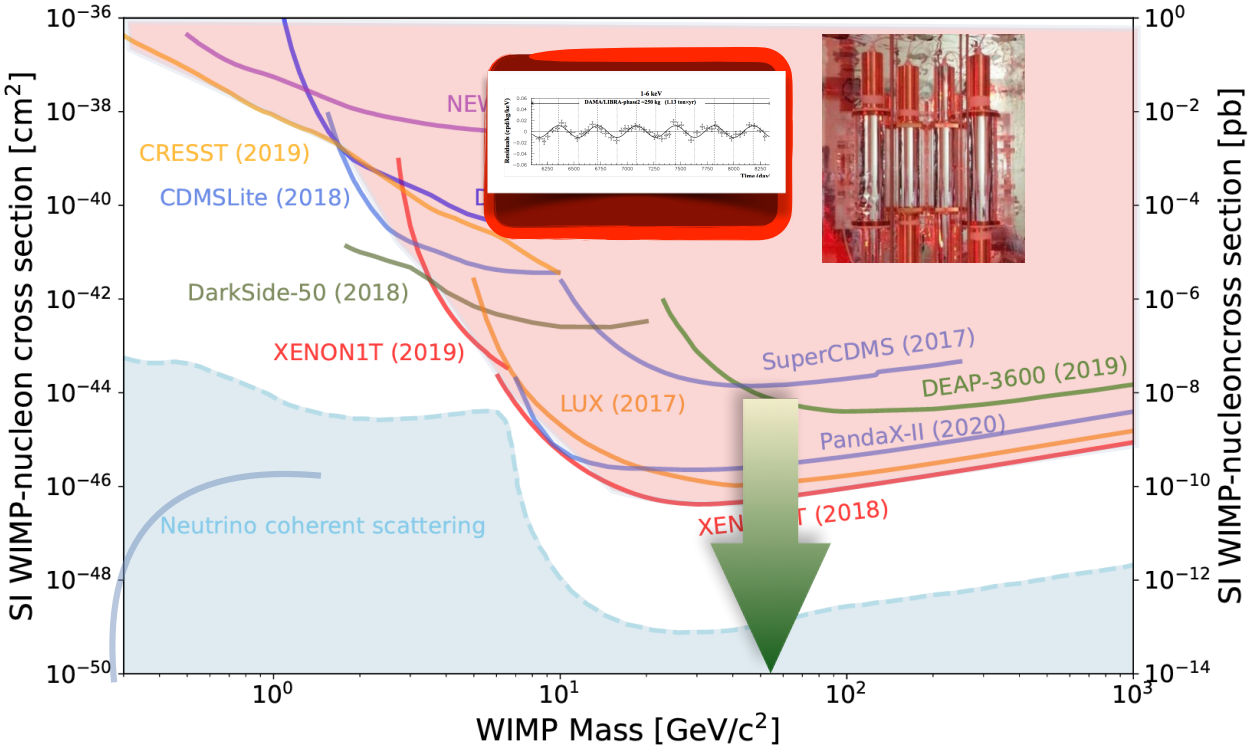
e-Print: 2407.12769 [hep-ex]



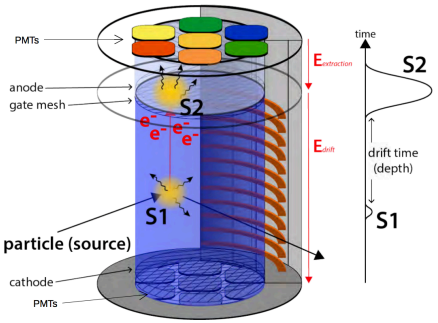
Take away messages:

- **News-G and CYGNO explore two different WIMP masse ROIs**
- **News-G is not directional and has limited ER/NR discrimination**
- **Hence, News-G and CYGNO are not competitors**

DM searches overview & context



- **Ton scale detector with heavy nuclei**
- **10^3 (LXe) - $10^{7\text{-}10}$ (LAr) rejection**
- **Eventually, will be dominated by neutral backgrounds from CEvNS, aka the Neutrino Fog**
  - **From solar neutrinos (mainly ^{8}B) at <10 GeV**
  - **From DSN & atmospheric neutrinos fat >10 GeV**



The Neutrino Fog: a recap

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

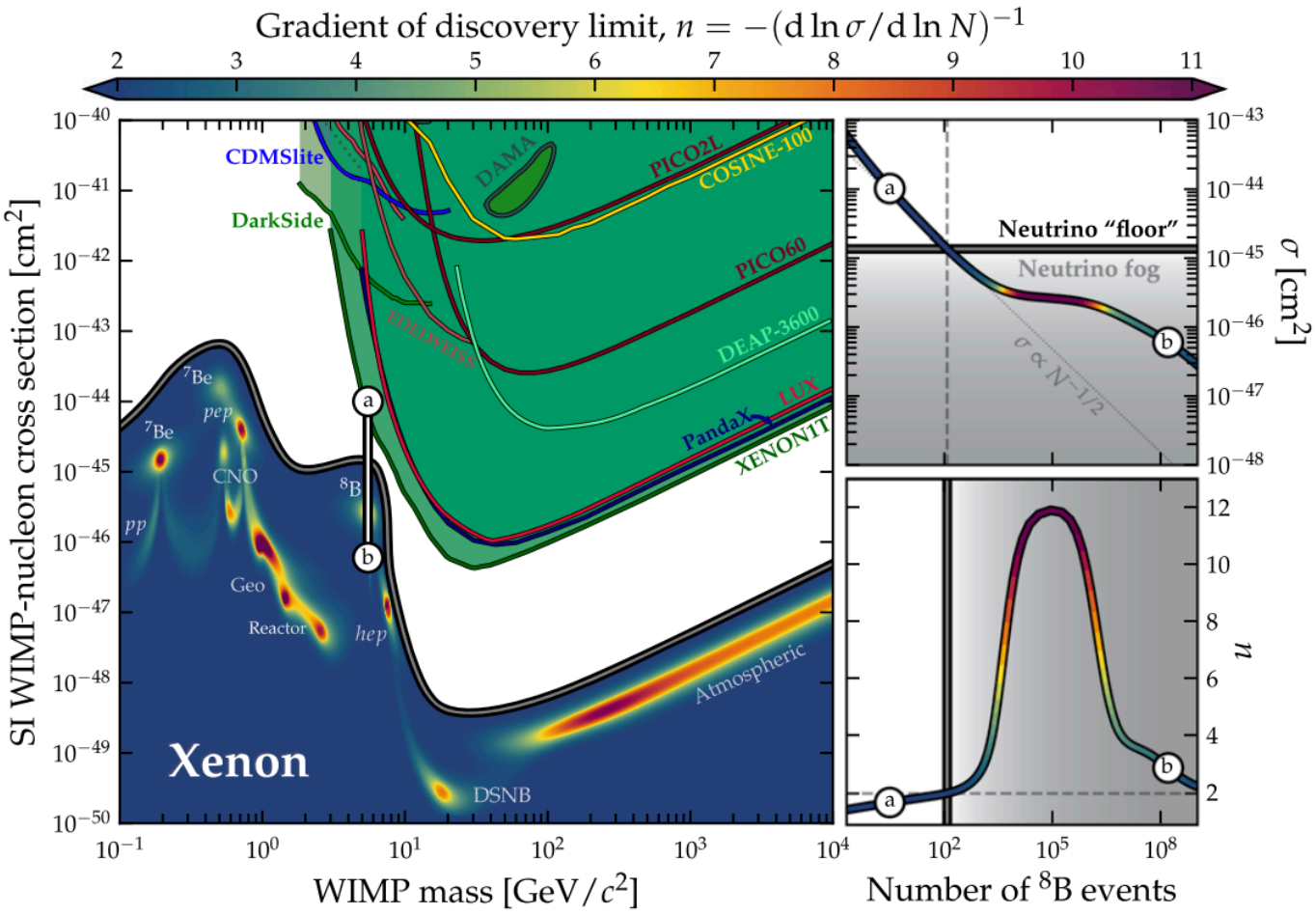
$$N\delta\Phi^2 \ll 1, \sigma \propto 1/\sqrt{N}$$

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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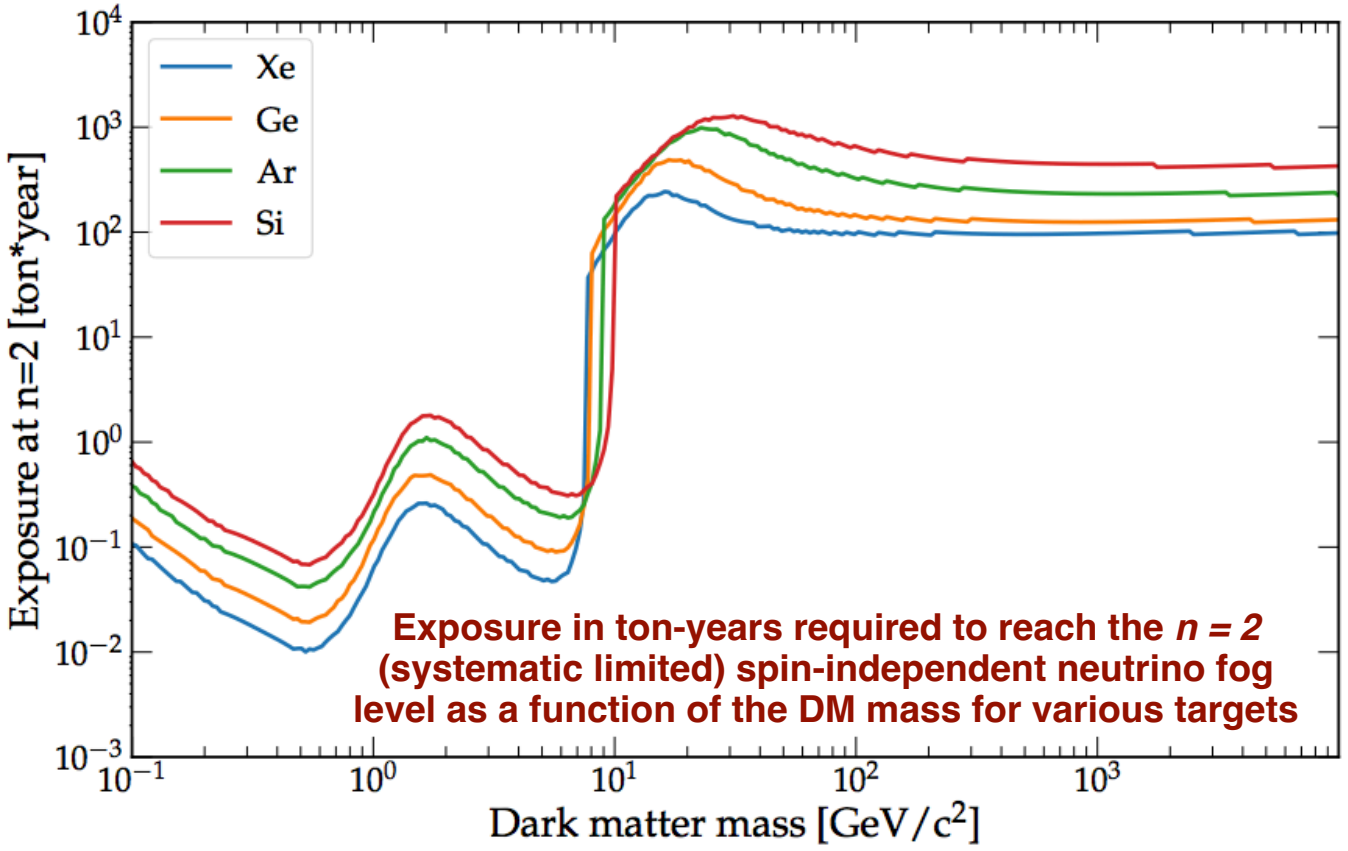


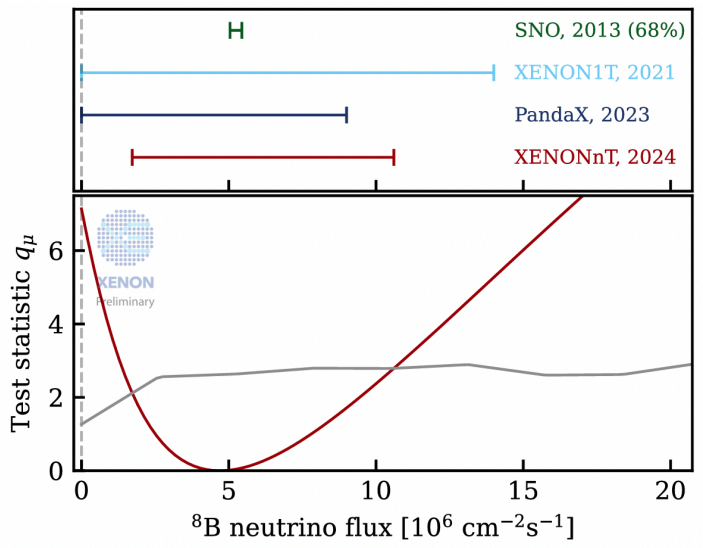
Exposure in ton-years required to reach the *n = 2* (systematic limited) spin-independent neutrino fog level as a function of the DM mass for various targets

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

The Neutrino Fog: here we are

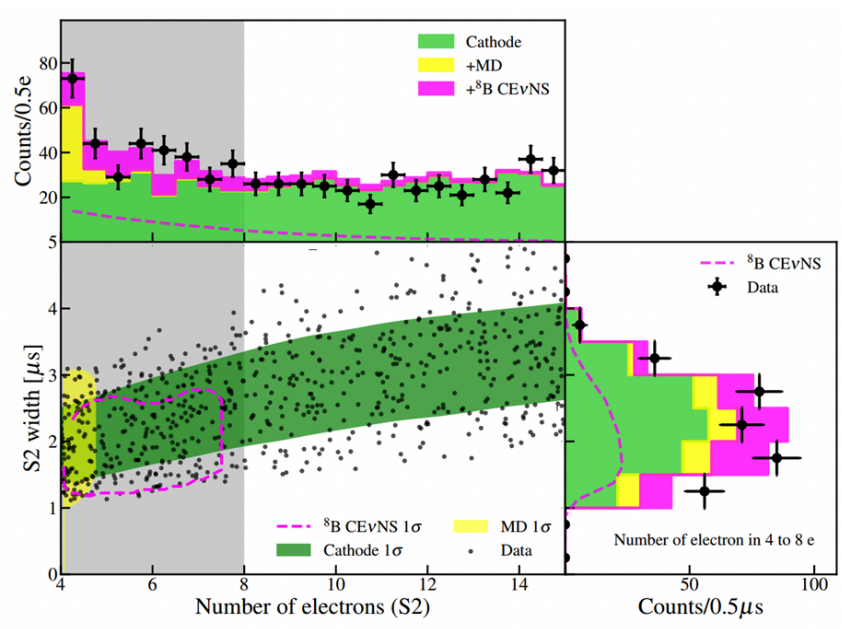
XenonNT arXiv:2408.02877

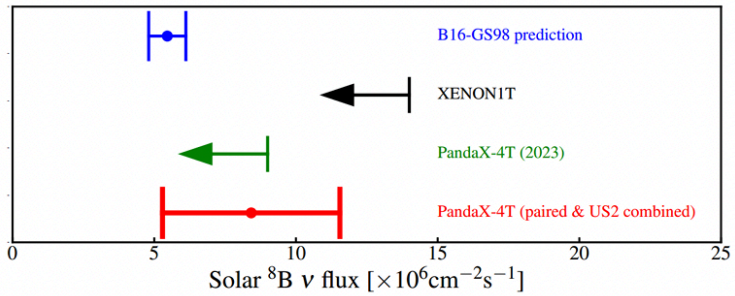


Component	Background only fit	Background + ^{8}B fit	Nominal Expectation
AC - SR0	7.55	7.36	7.48 ± 0.52
AC - SR1	18.26	17.90	17.77 ± 1.23
ER	0.74	0.54	0.68 ± 0.68
NR	0.50	0.45	0.47 ± 0.32
Total Background	27.05	26.24	26.4 ± 1.5
^{8}B	-	10.71	11.9 ± 3.1
Observed		37	

The background-only hypothesis is disfavored at 2.73σ

Panda-X arXiv:2407.10892

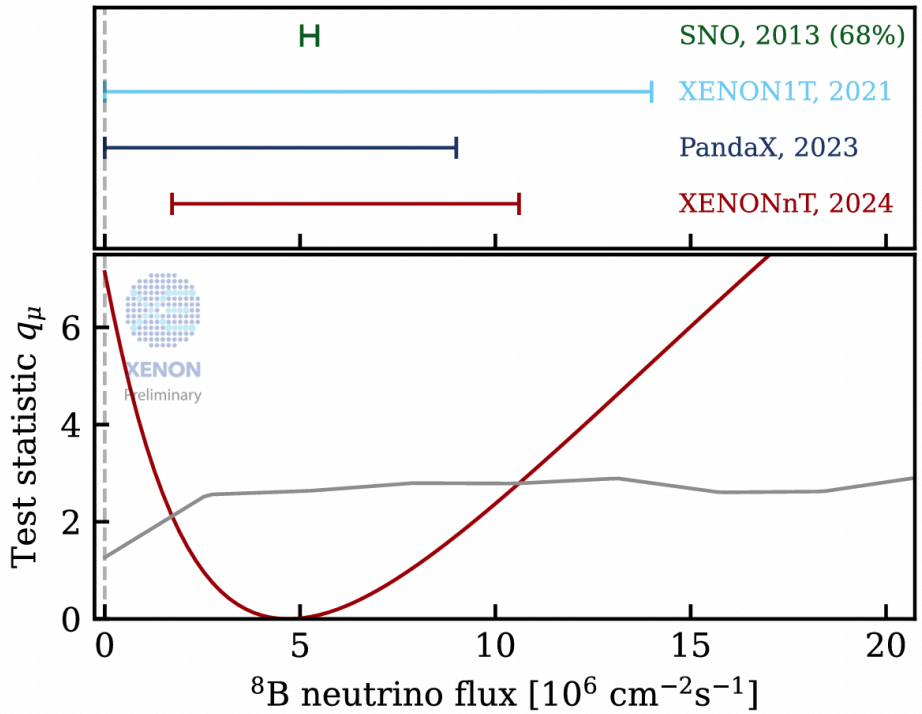




- Reject bkg-only hypothesis with significance of 2.64σ, with best-fit B8 events is 75±28 (US2) and 3.5±1.3 (paired);

A provocative question:

(that neither XenonNT nor PandaX speakers at 2 conferences were able to answer…)



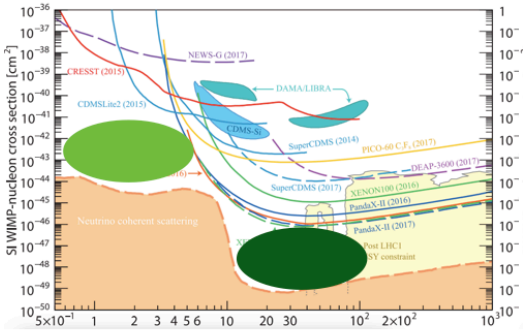
where is the positive proof that these are not 6 GeV WIMPs?

....a provocative answer....

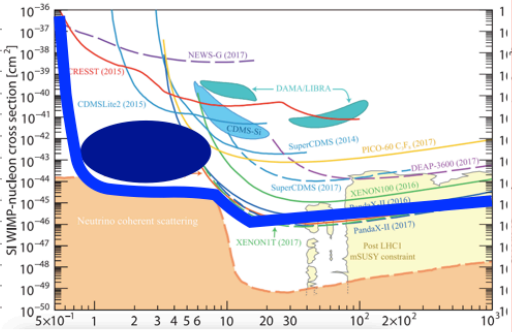
...self-citing my usual old closing slide..

Direct DM search ~~future~~ present!

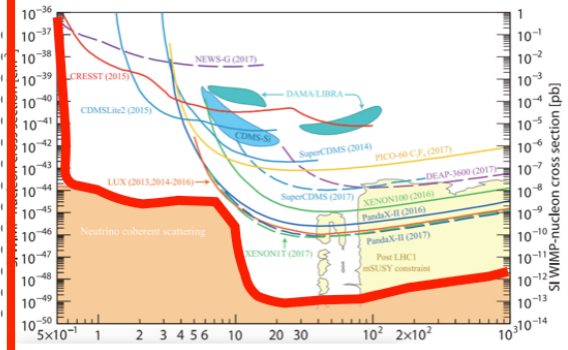
**Old limits, only illustrative purpose*



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

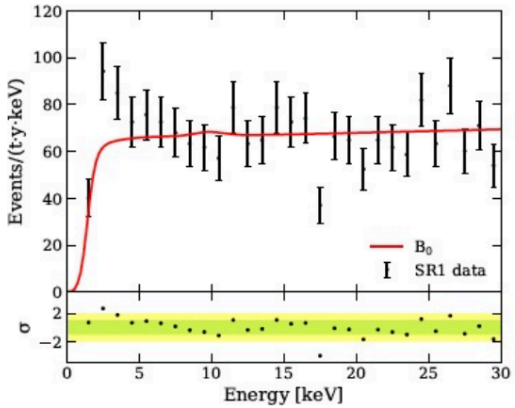


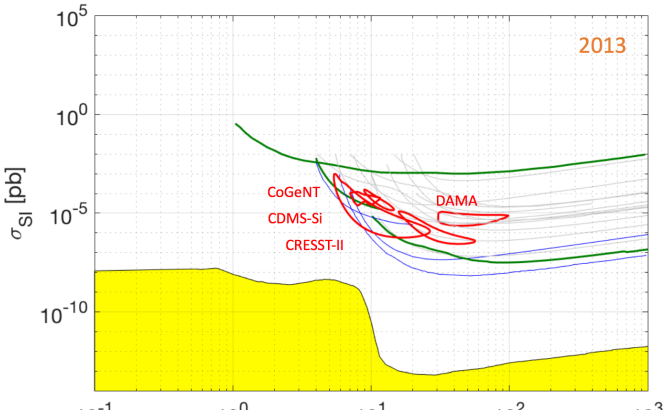
DM is excluded to the Neutrino Fog:
only a directional experiment can continue DM searches and study neutrinos

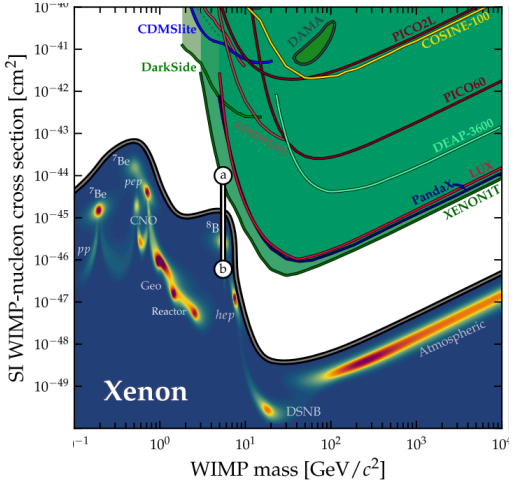
***Or we "hit" some new other irreducible background**

Looking for DM is a search hampered by many false promises both at high and low masses

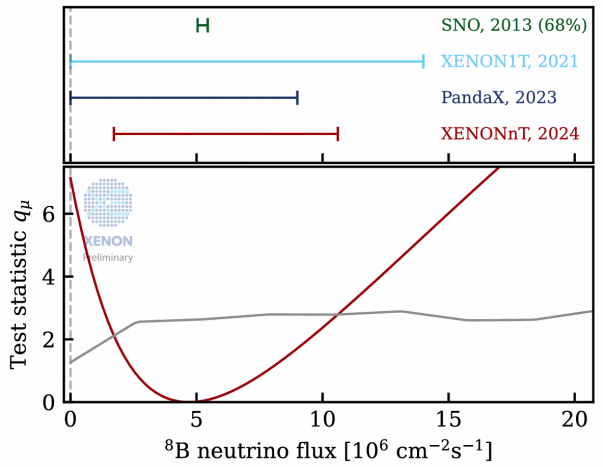
i.e. many things can look like a signal if you don't know where they are coming from



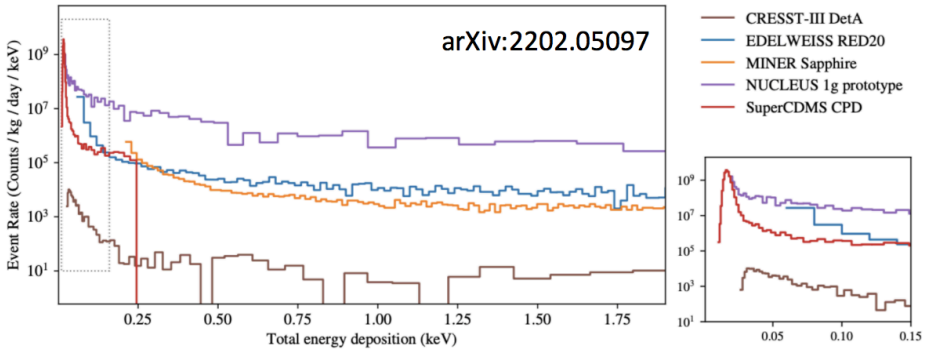




Direction is the only way



…er energies



Currently limiting the sensitivity globally !

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

Where does the CYGNO/ INITIUM project stand in this picture within the context of directional DM searches?

Directional DM search experiments: exposure comparison

DRIFT and NEWAGE data reported for the latest and most sensitive limits published, no MIMAC undeground limit exists

	Exposure	Exposure for SD searches	Energy threshold	Reference
DRIFT II-d	3.5 kg days	0.96 kg days	20 keV_{ee}	Astropart. Phys. 91 (2017) 65-74
NEWAGE 3b	3.2 kg days	3.2 kg days	50 keV_{ee}	PTEP 2023 (2023), 10 113F01
LIME Run4	2.6 kg days	2.0 kg days	1 keV_{ee}	My rough back-of-the-envelope evaluation
CYGNO-04 (1 year)	203 kg days	190 kg days	1-0.5 keV_{ee}	My rough back-of-the-envelope evaluation

LIME status *Stefano Piacentini*

Salone degli Stemmi, Palazzo Pubblico 14:35 - 14:55

Early LIME DM limit *Rita Antonietti*

Salone degli Stemmi, Palazzo Pubblico 14:55 - 15:15

will show us how LIME data taking campaign, while not aimed originally at setting any DM limit, can actually be competitive with other directional DM experiments limits

Directional DM search experiment: NID operation panorama

Charge Readout

Low pressure

- Concept demonstratred in 2000 at 40 Torr CS_2 with MWPC [1]
- Pioneered in a actual experiment by DRIFT with CS_2:CF_4:O_2 at 40 Torr with MWPC [2]
- 20-40 Torr pure SF_6 in 2017 with THGEM [3]
- 20 Torr pure SF_6 with THGEM-multiwire [4] and muPIC in 2020 [5] *See also S. Hishino talk @ 12.30*

(nearly) Atm pressure

- Demonstrated in 2010's in He:CS_2[6] and CO_2:Ne:CH_3NO_2[7] with GEMs and MWPC
- In 2017 at 610 Torr of He:CF_4:SF_6 with GEMs and TimePix2 [8]
- In 2021 in Ar:iC_4H_{10}:CS_2 with GridPix (Ingrid + Timepix3) [9] *See also J. Kaminsky talk on Tue*

Optical Readout

- 50-150 Torr CF_4:CS_2 with glass GEM and CMOS [D. Loomba, talk at RD51 June 2022 meeting]

INTIUM

European Research Council
Established by the European Commission

[1] C. J. Martoff et al. NIM A 440 335
[2] G. J. Alner et al., NIM A 535
[3] N. S. Phan et al, *JINST* 12 (2017) 02, 02
[4] A. C. Ezeribe NIM A 987
[5] T. Ikeda et al, *JINST* 15 07, P07015
[6] C. J. Martoff et al, NIM A 555
[7] C. J. Martoff et al, NIM A 598
[8] E. Baracchini et al, *JINST* 13 04, P04022
[9]C. Ligtenberg et al, NIM A 1014 165706

Negative Ion Drift update — *Elisabetta Baracchini*

Salone degli Stemmi, Palazzo Pubblico — 15:40 - 16:10

will provide experimental evidences of potentialities for improved directionality with NID operation beyond expectations

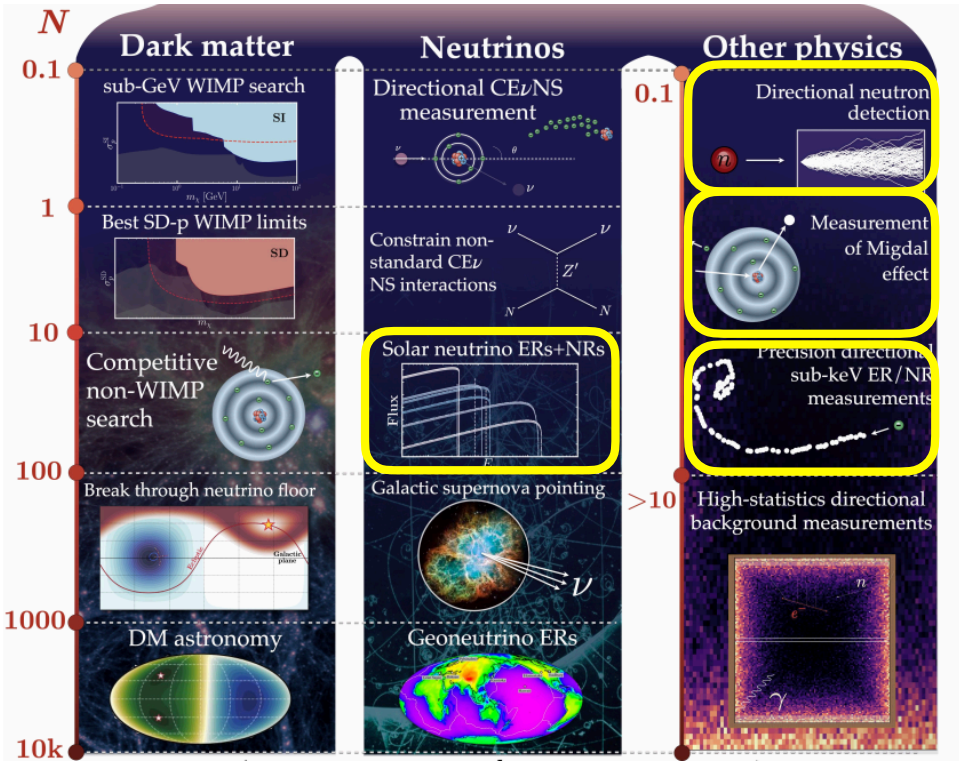
Where does the CYGNO/ INITIUM project stand in the wider context of rare events search experiments?

One, no one, one hundred thousand ;) physics cases for CYGNO/INITUM!

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

CYGNO/INTIUM synergic projects

MIUR PRIN 2017

LIME Run5

FARE RICERCA IN ITALIA

"FINEM: Full Imaging of Nuclear recoil for Experimental Migdal measurement"

PRIN 2020

"HypeX: High Yield Polarimentry Experiment in X-rays"

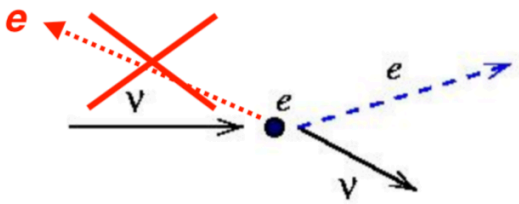
Solar neutrinos spectroscopy through elastic scattering on electrons in CYGNUS: promoting background to signal

Original idea by Seguinot et al (1992)

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

C. Lisotti, …, E. Baracchini, … S. Torelli, Eur. Phys. J. C 84 (2024) 10, 1021

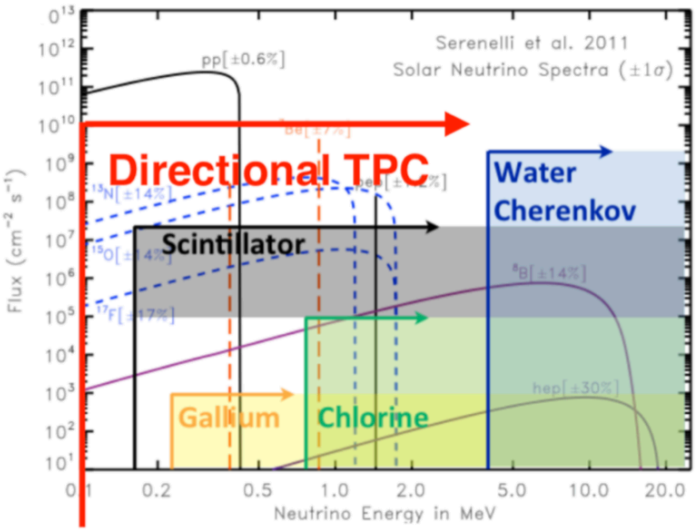
Given the Sun position, recoils in opposite direction are kinematically forbidden



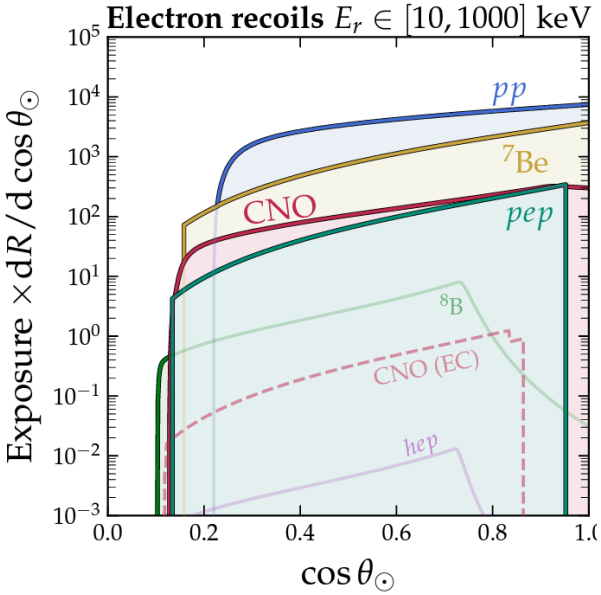
Differently from WIMPs, background can be measured on sidebands data

CYGNO approach used as benchmark also for CYGNUS

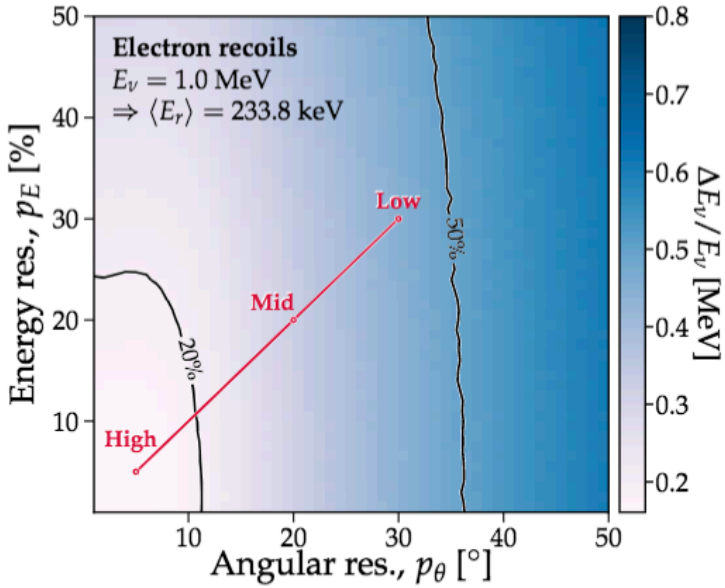
See S. Torelli talk



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:CF_4 60:40 1000 m³)



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

Finally, a realistic feasibility study for CYGNO-30

GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

Doctoral Thesis Research Proposal

Feasibility of a directional solar neutrino measurement with the CYGNO/INITIUM experiment

---

PhD Program in Particle and Astroparticle Physics:
XXXV cycle

Author: Samuele Torelli

Thesis Advisor: Prof. ssa Elisabetta Baracchini

Neutrino physics case — *Samuele Torelli*

Salone degli Stemmi, Palazzo Pubblico — 15:15 - 15:40

will show us how CYGNO-30 could provide the first directional solar neutrino spectroscopy measurement, testing the neutrino pp energy spectrum down to 55 keV for the first time ever (N.B. Borexino threshold 300 keV)

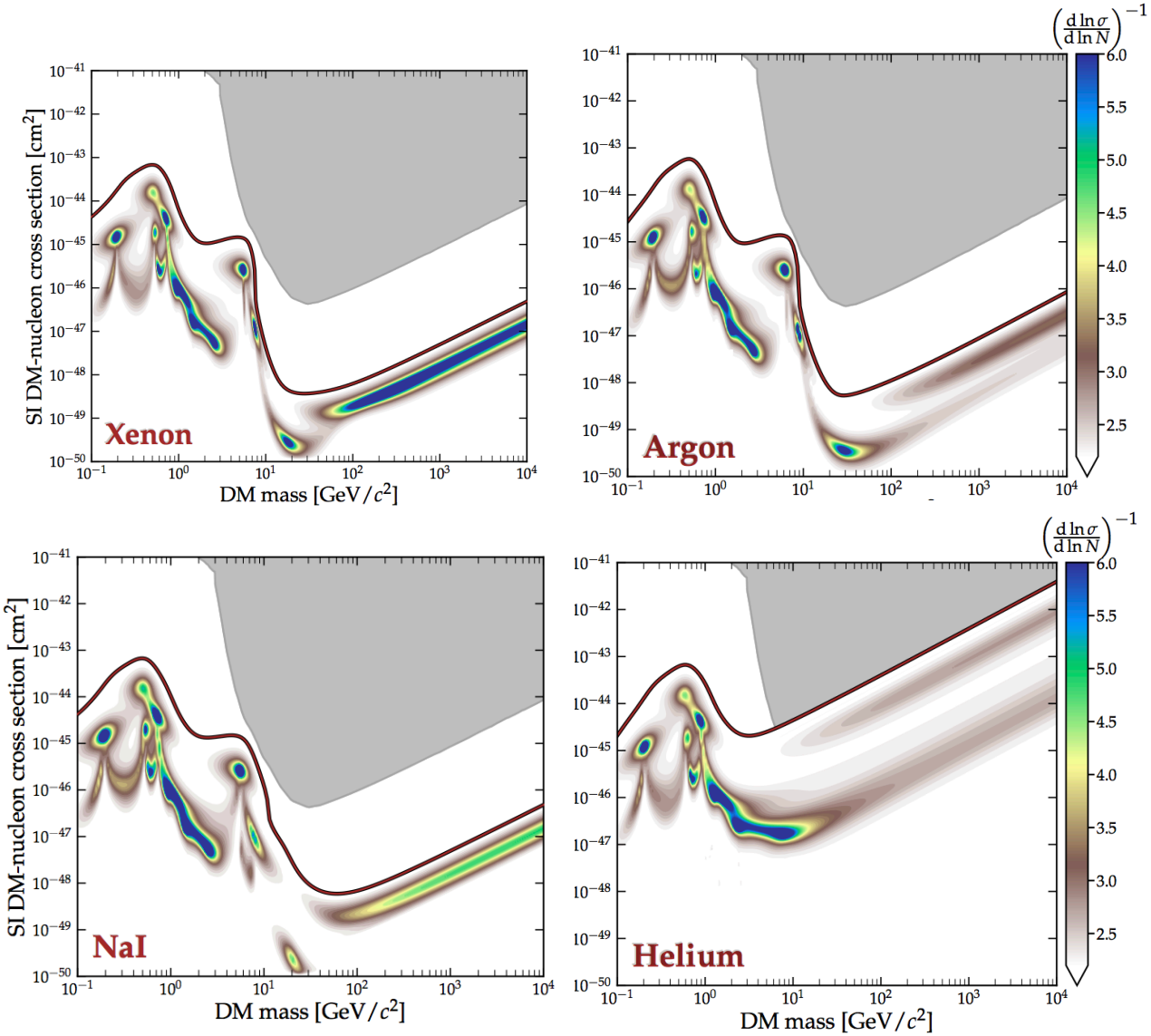
..effectively opening the doors for a CYGNUS-1000 solar neutrino experiment that might be able to precisely measure all solar neutrinos components up to the CNO cycle through electron elastic and CvNeS scattering simultaneously

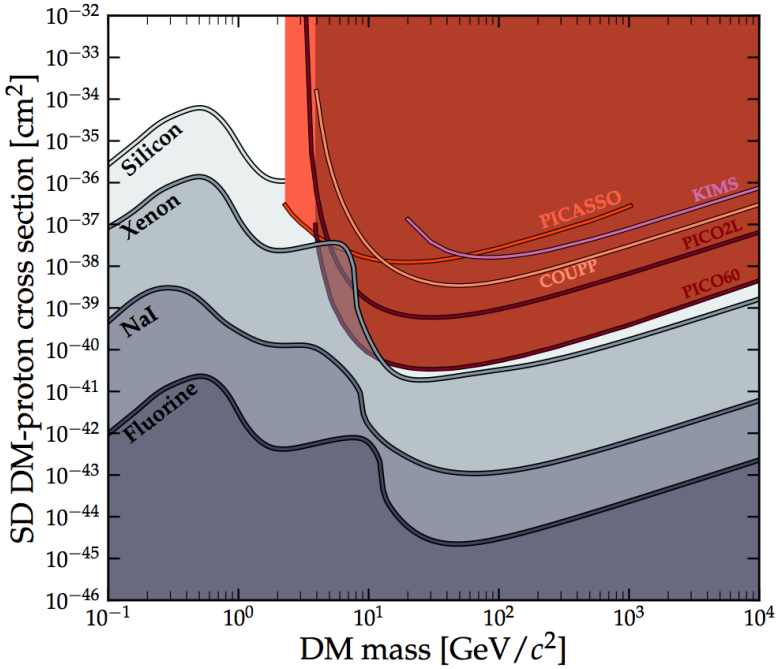
Many thanks to you all for your contribution to the success of the CYGNO/INITIUM and all its synergic projects!

Backup slides

Nuetrino fog for various targets

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





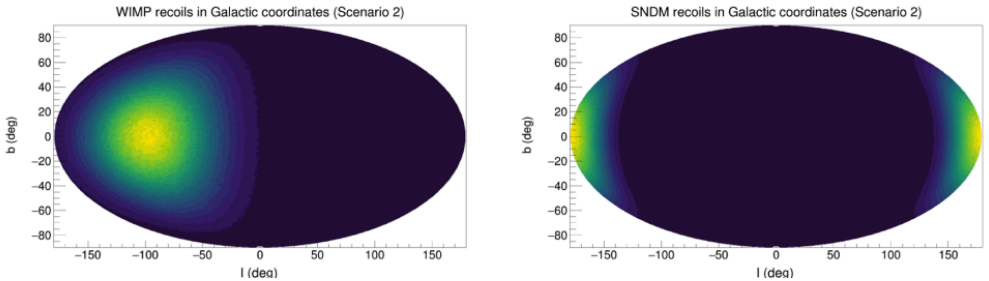
Not only WIMP Dark Matter: potentialities for discovery of MeV DM from SN with directionality

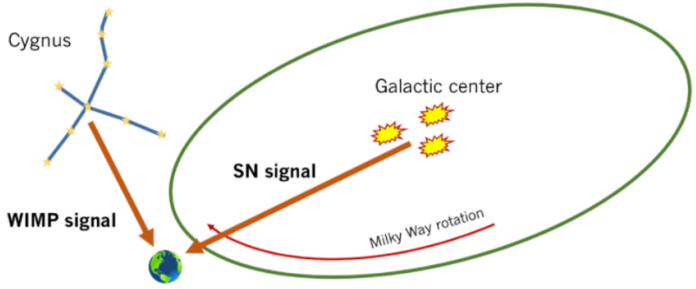
Discovering supernova-produced dark matter with directional detectors #1

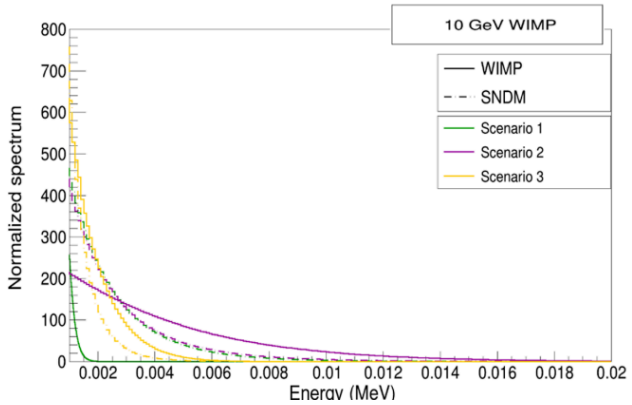
Elisabetta Baracchini (GSSI, Aquila and Gran Sasso), William Derocco (Stanford U., ITP), Giorgio Dho (GSSI, Aquila and Gran Sasso) (Sep 18, 2020)

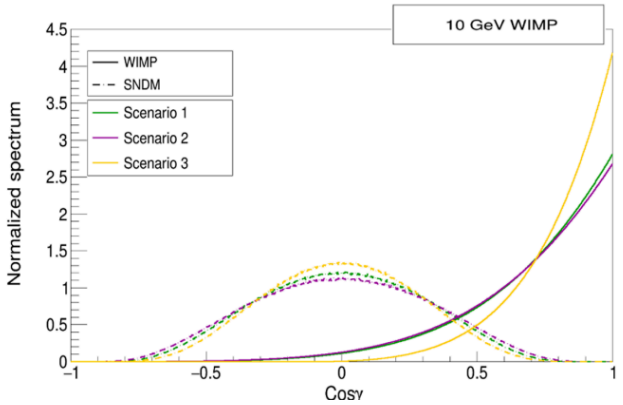
Published in: *Phys.Rev.D* 102 (2020) 7, 075036 • e-Print: 2009.08836 [hep-ph]

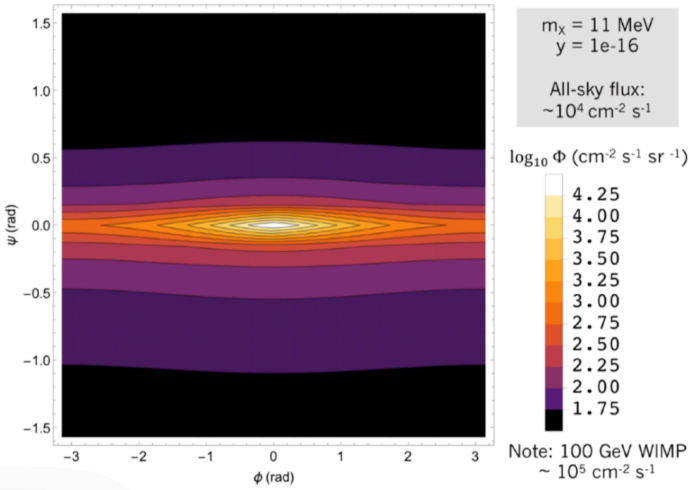
W. DeRocco, P. W. Graham, D. Kasen, G. Marques-Tavares, and S. Rajendran, Phys. Rev. D **100**, 075018 (2019).

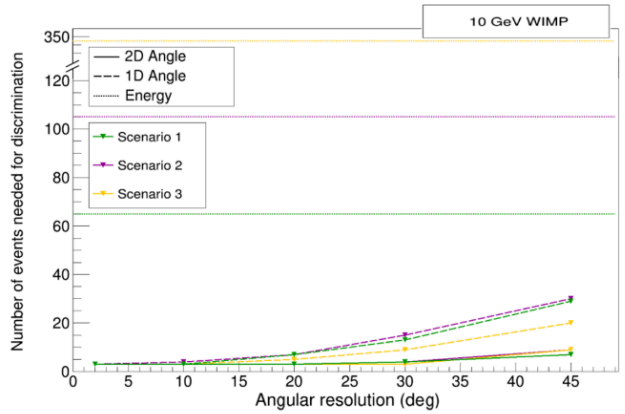


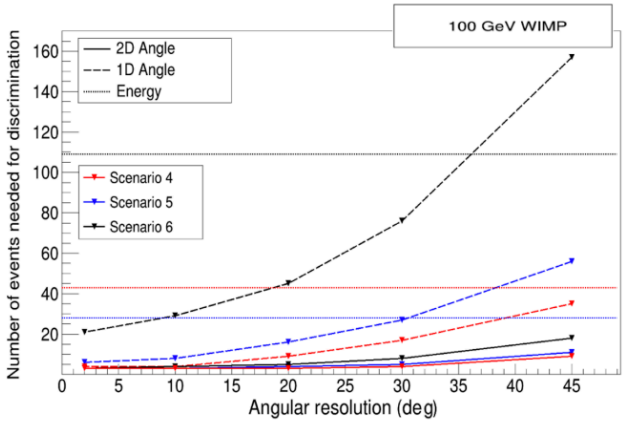






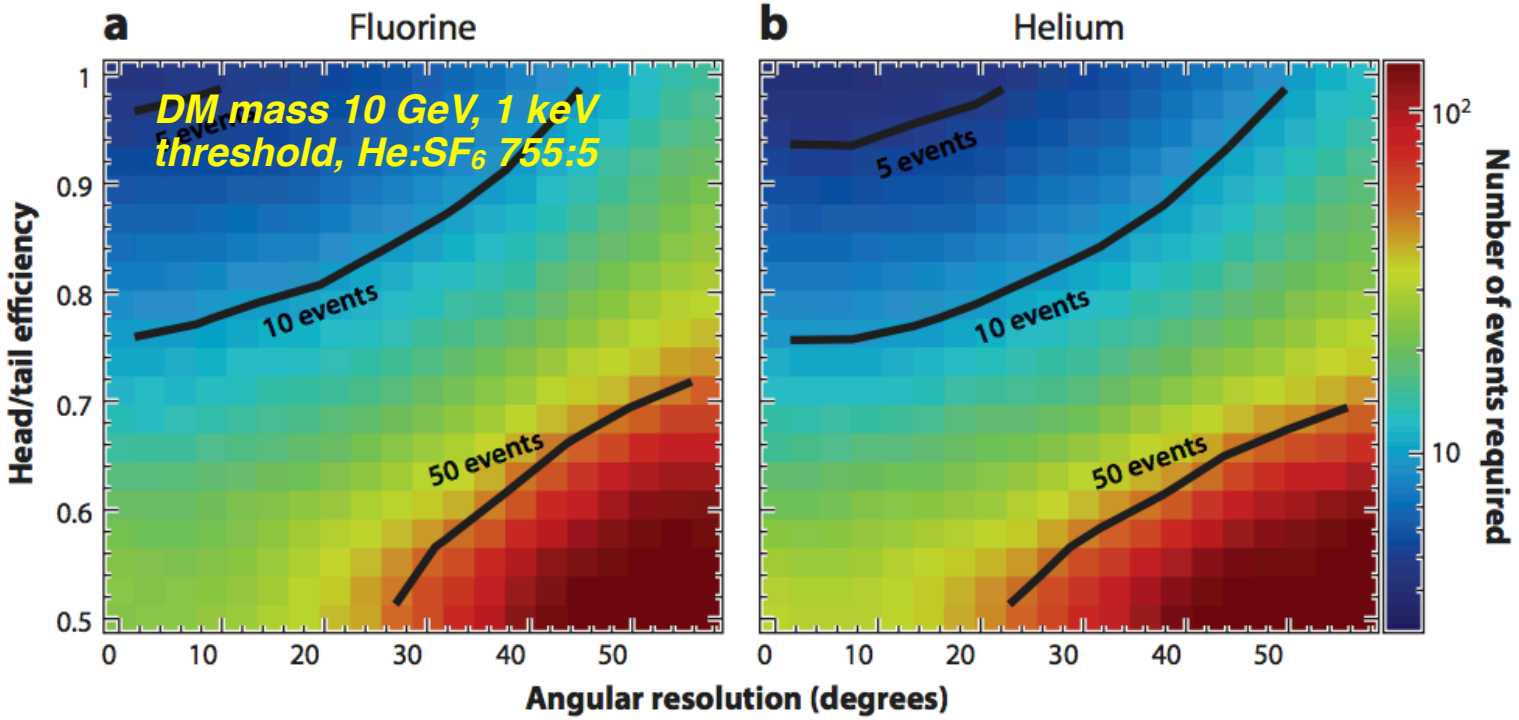






The importance of HT

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



Solar neutrino spectroscopy with gaseous TPCs

A HIGH RATE SOLAR NEUTRINO DETECTOR WITH ENERGY DETERMINATION

1992 **He**

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

A possible gas for solar neutrino spectroscopy

1996 **CF**

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

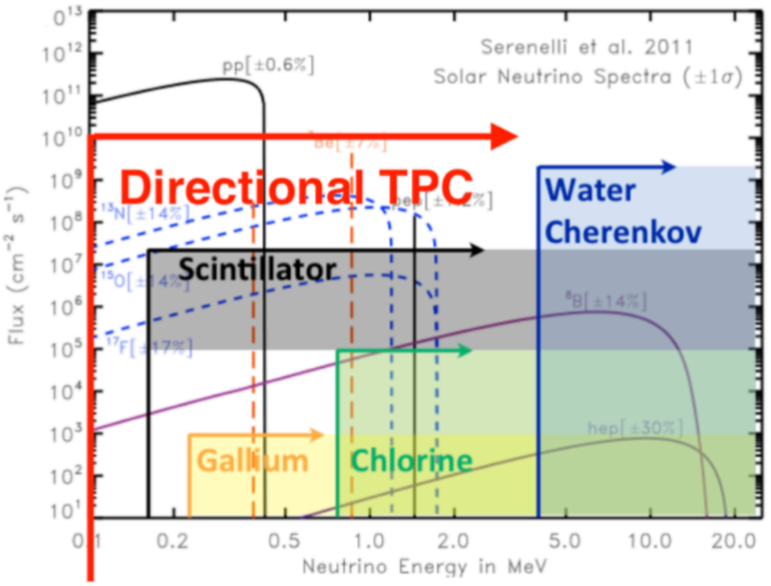
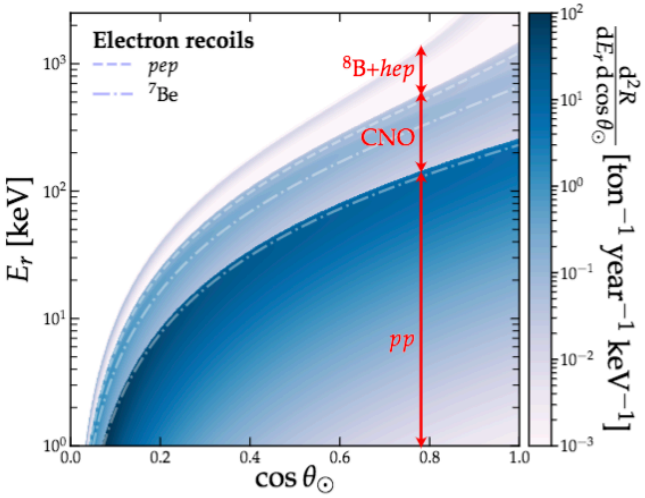
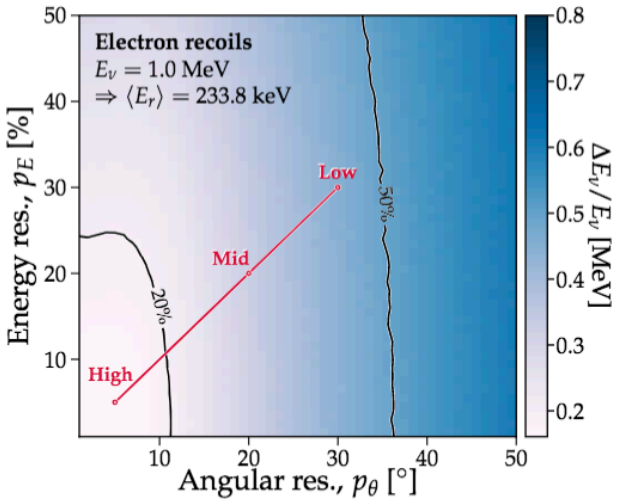


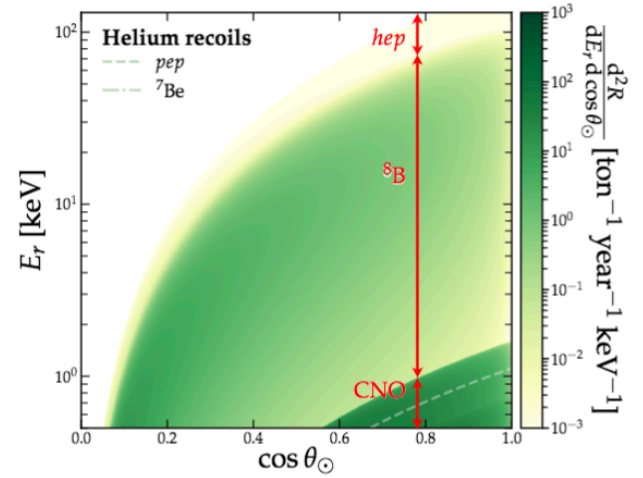
Table 1 Approximate expected numbers of neutrino-induced nuclear and electron recoils[a]

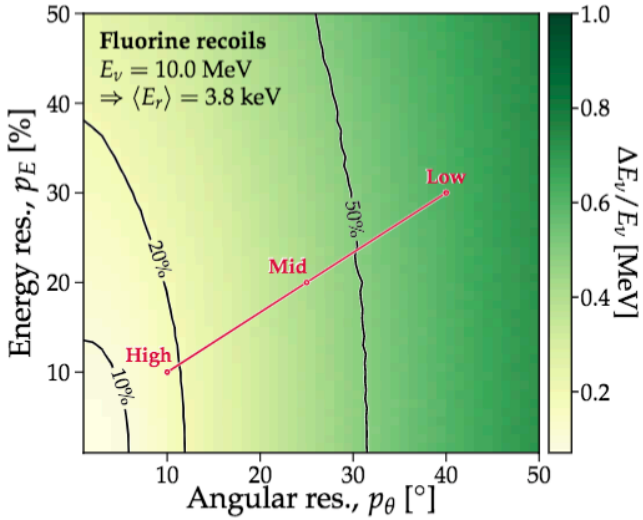
Nuclear recoils	SF_6			CF_4			He		
Threshold (keV$_r$)	1	5	10	1	5	10	1	5	10
Solar (mainly ^{8}B)	73	15	2	54	16	3	3	2	1
3-kpc supernova	25	18	12	18	13	10	0.6	0.5	0.5
Electron recoils	**SF_6**			**CF_4**			**He**		
Threshold (keV)	5	500	1,000	5	500	1,000	1	500	1,000
Solar (total)	537	42	4	438	34	3	102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







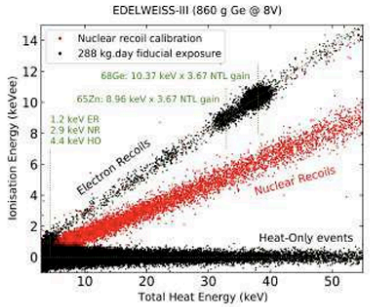


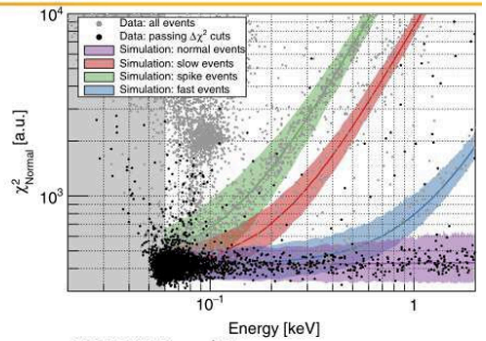
EXCESS studies

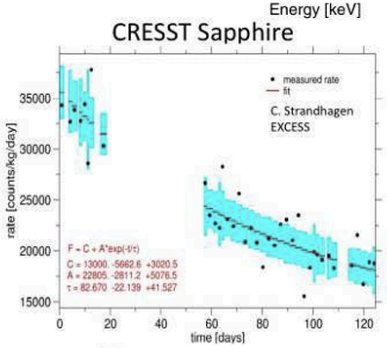
Review on Low-Energy Excess Signals Observed in Cryogenic Rare Event Search Experiments - J. Gascon

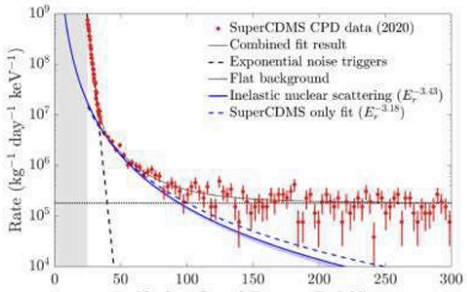
Key features to study and compare

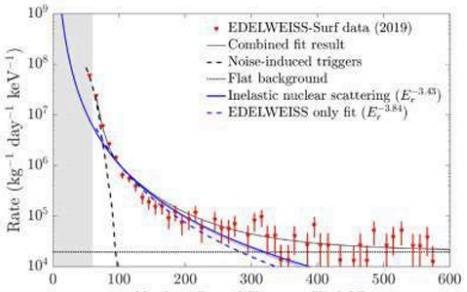
- Rise and decay times of event
  - Faster/slower pulse: indications of nature/location of event
- (Non-) ionizing nature of event
- Timing
  - Coincidence with external events?
  - Correlation between successive events?
- Variation of rate with time since cool-down
  - Consistent with known radioactive backgrounds?
  - Accumulated stress as potential source?
- Energy
  - Range
  - Shape / steepness of rise





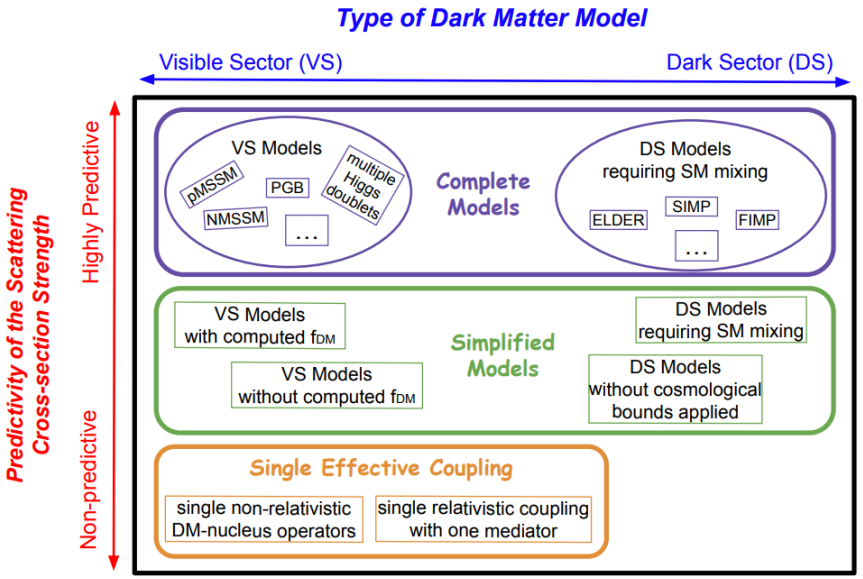


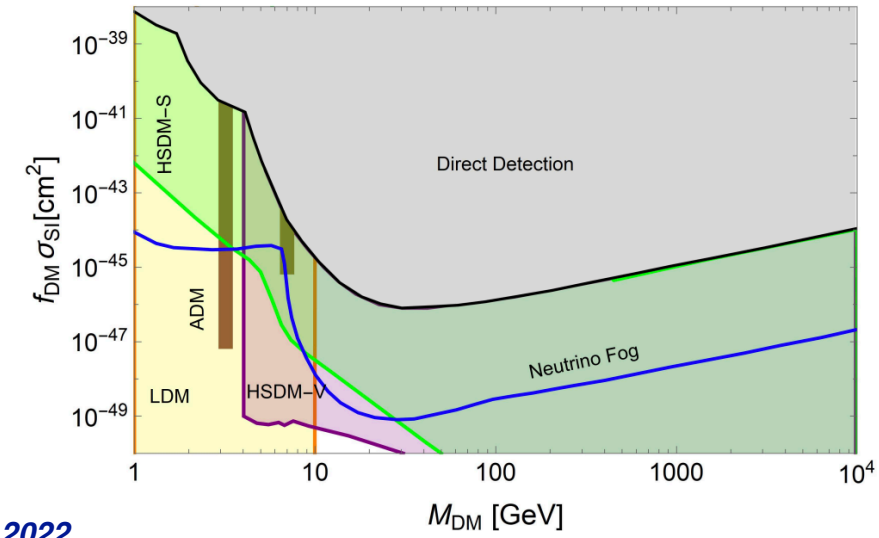




Belina von Krosigk | Margarita Kaznacheeva IDM 2022

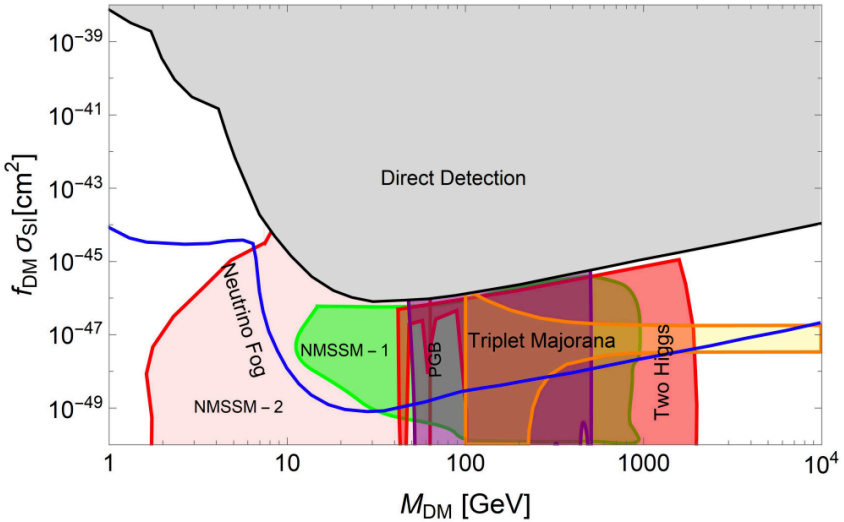
The need to penetrate the fog



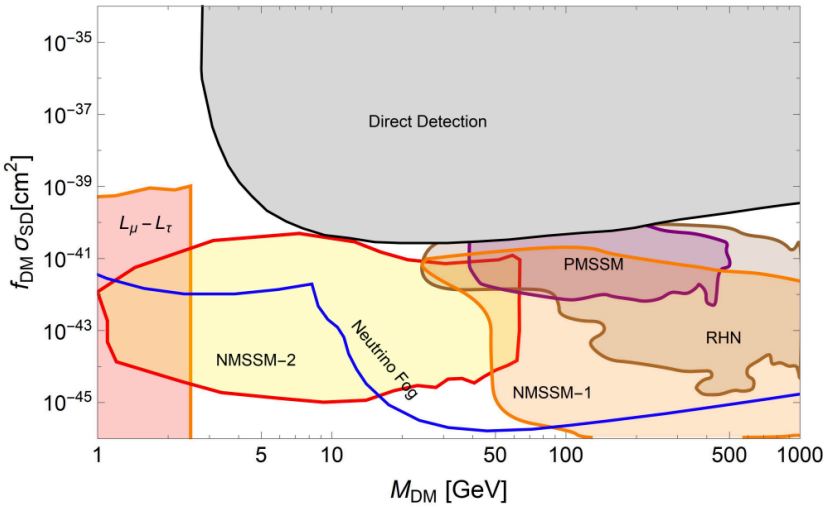


[D. S. Akerib et al., 2022 Snowmass Summer Study, arXiv:2203.08084]

Dark sector models SI



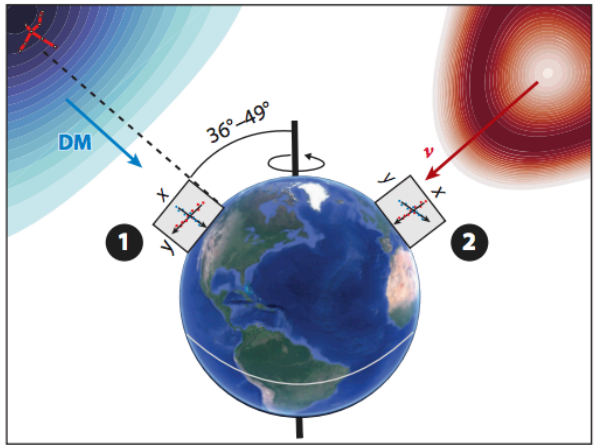
Visible sector models SI

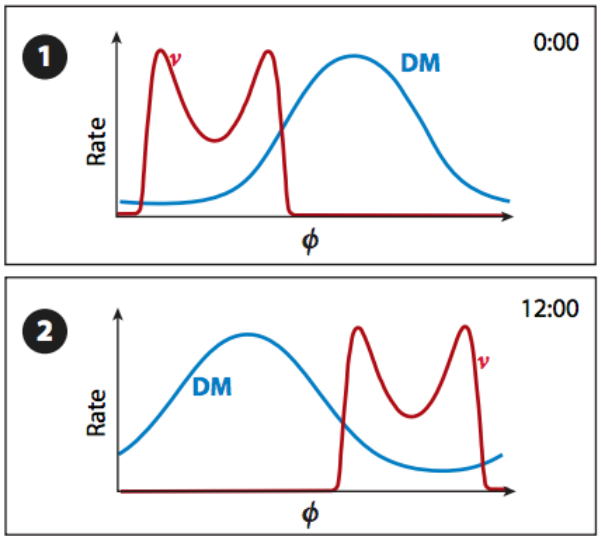


Visible sector models SD

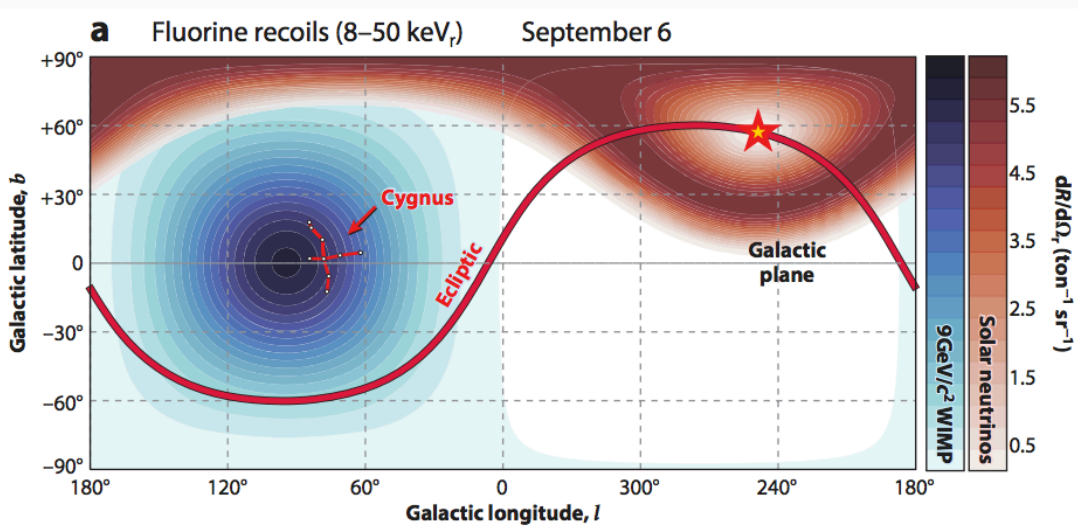
S. Vahsen et al., Ann. Rev. Nucl. Part. Sci. 71 (2021) 189-224

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



What is required to clear the neutrino fog?

(see our review [2102.04596] and Snowmass WP [2203.05914] for reasoning)

- 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

Can this be done? Maybe, but the way to go seems to be "recoil imaging"