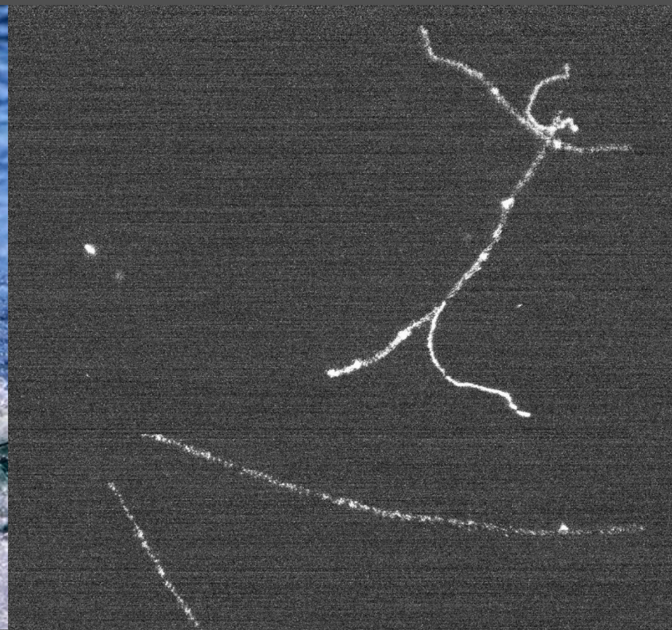
Update on the current status of (directional) Dark Matter searches

An Elisabetta surfing (for the first time)



Soft electrons in CYGNO prototype at LNGS

or else, why imaging TPC allow us to surf on other experiments at low WIMP masses

A personal and biased view by:

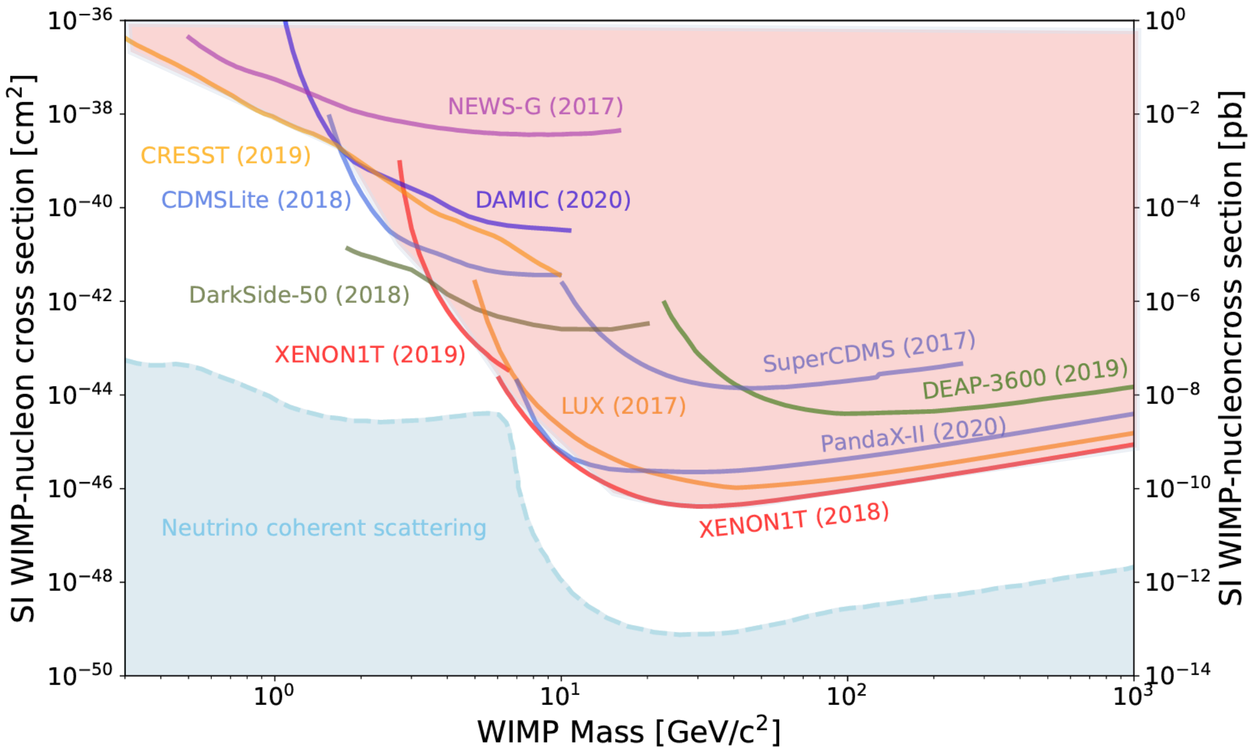
Elisabetta Baracchini

CYGNO Collaboration meeting 2023

Outline

- DM searches overview & contest
- Low mass dedicated experiments, i.e. bolometers
- Ton scale noble liquid experiments analysis for low mass
- Where CYGNO stands in this picture

Overview & Context



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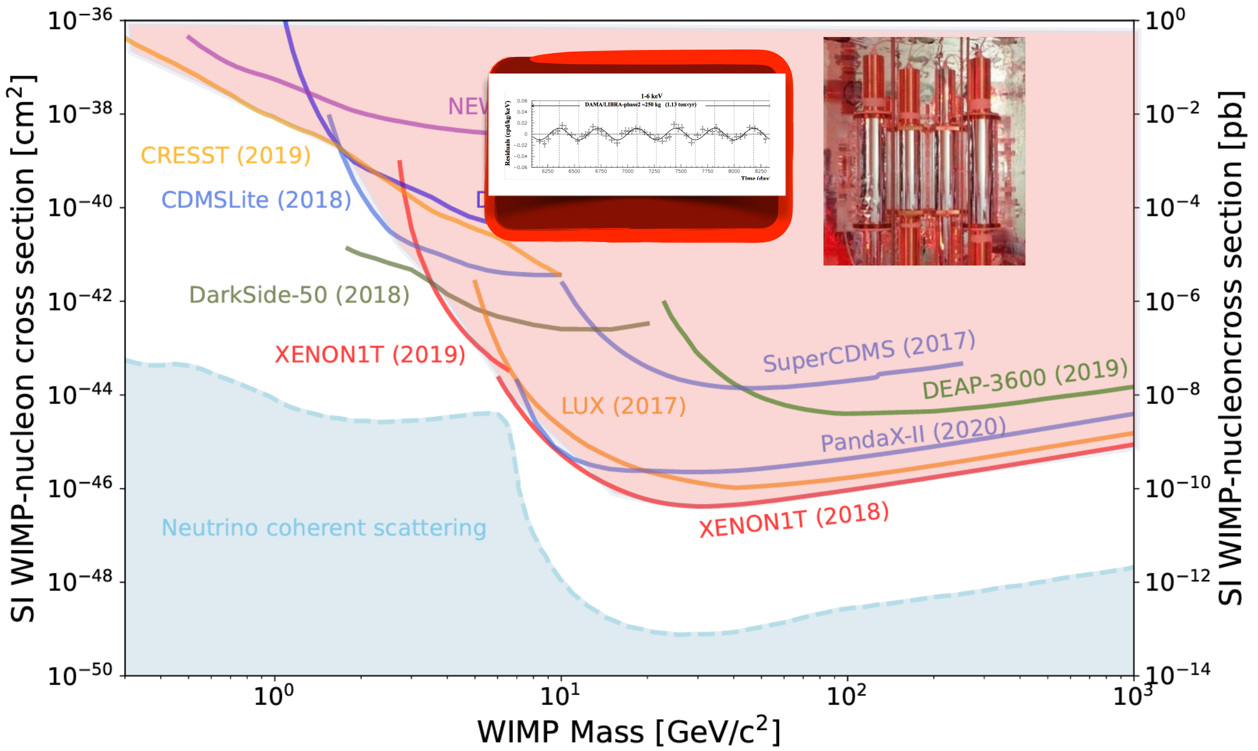

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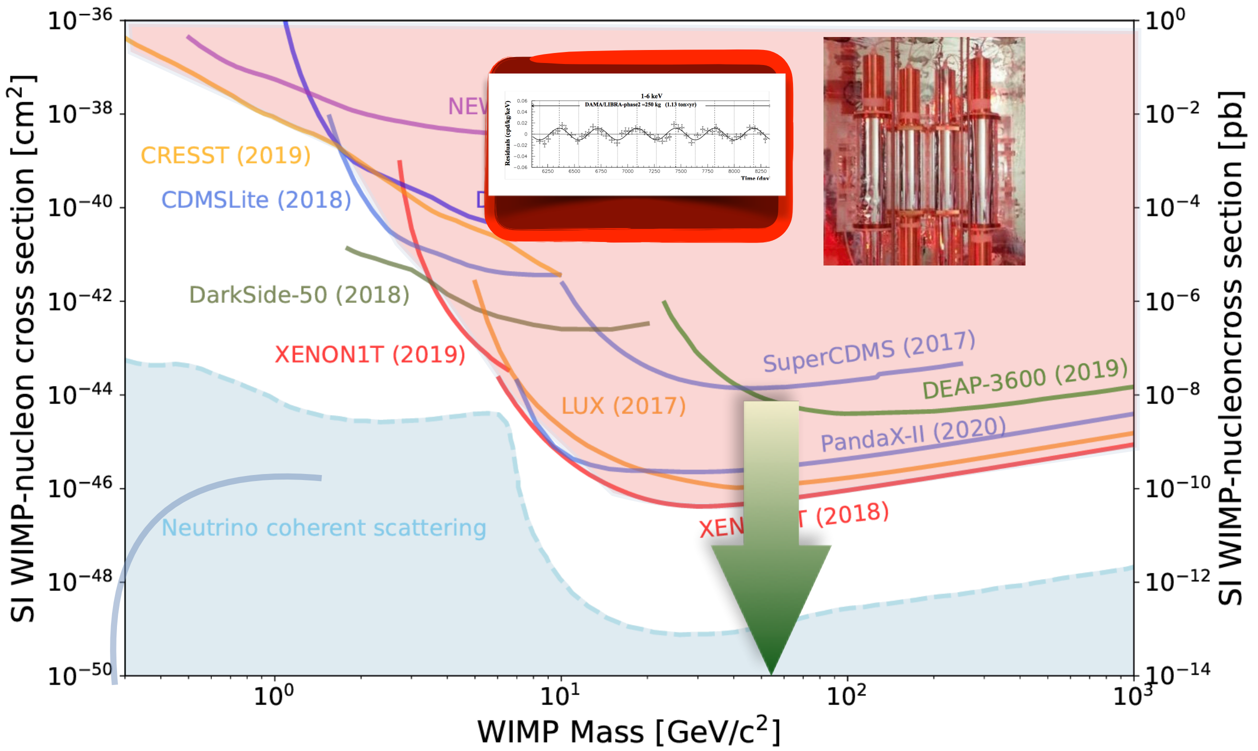
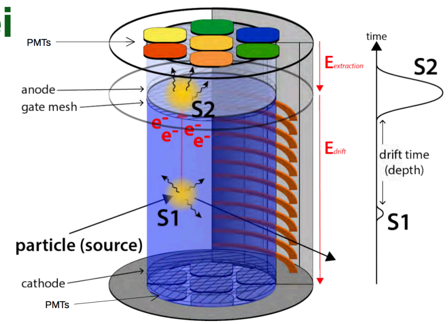


- **Ton scale detector with heavy nuclei**
- **10^3 (LXe) - $10^{7\text{-}10}$ (LAr) rejection**
- **Can go to M_{WIMP} <10 GeV only completely giving up background discrimination (S_2 only analyses)**
- **Eventually, will be dominated by neutral background also at high masses**



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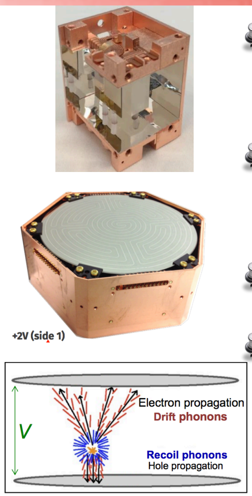
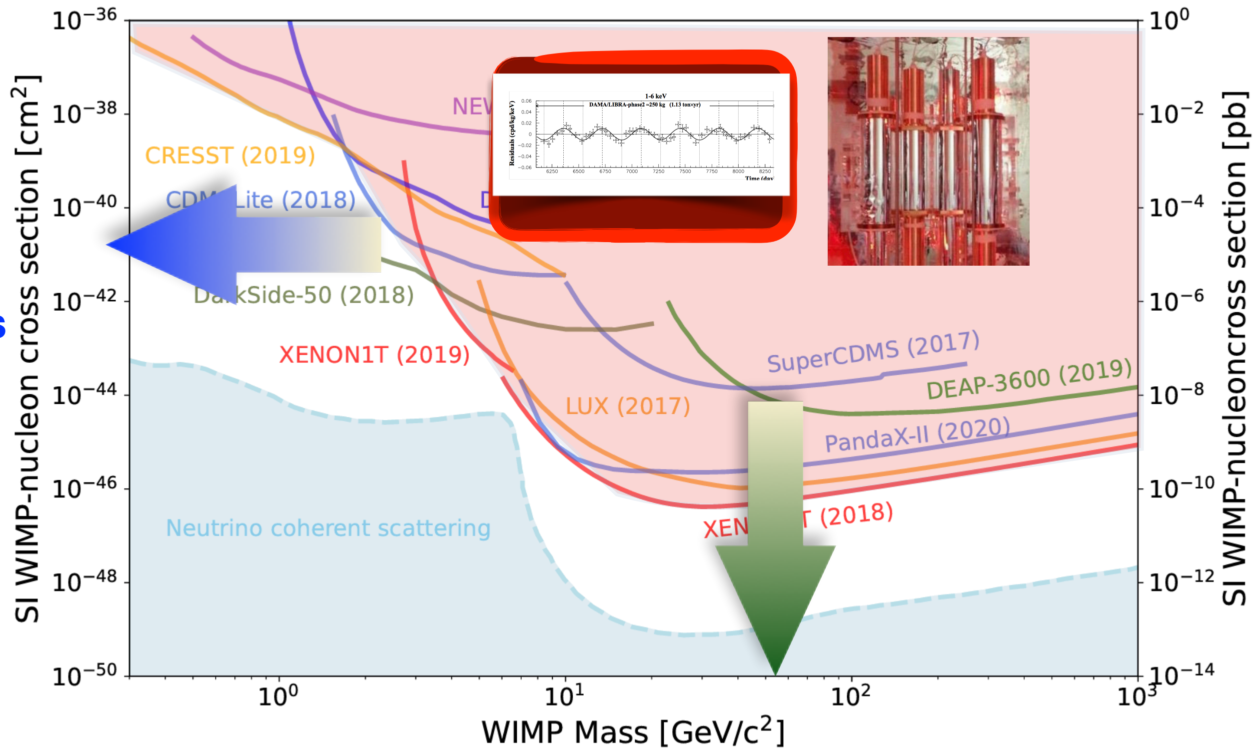


- **Small mass detectors with light nuclei**
- **0.1-1 kg enough to explore uncharted territories**
- **10^4-10^5 rejection @ 10 keV**
- **Trend to reduce module mass & background discrimination to reach lower threshold**



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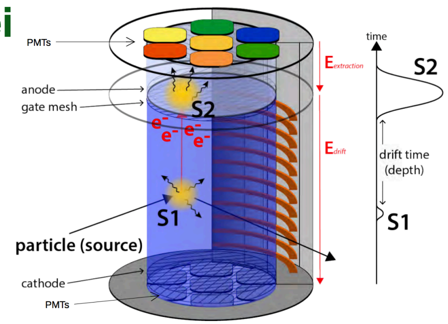

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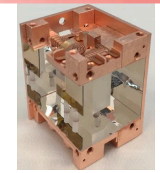

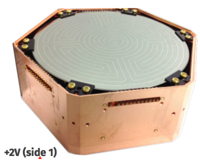

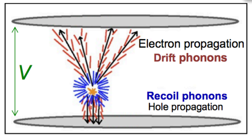

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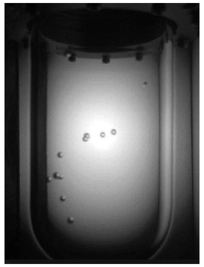
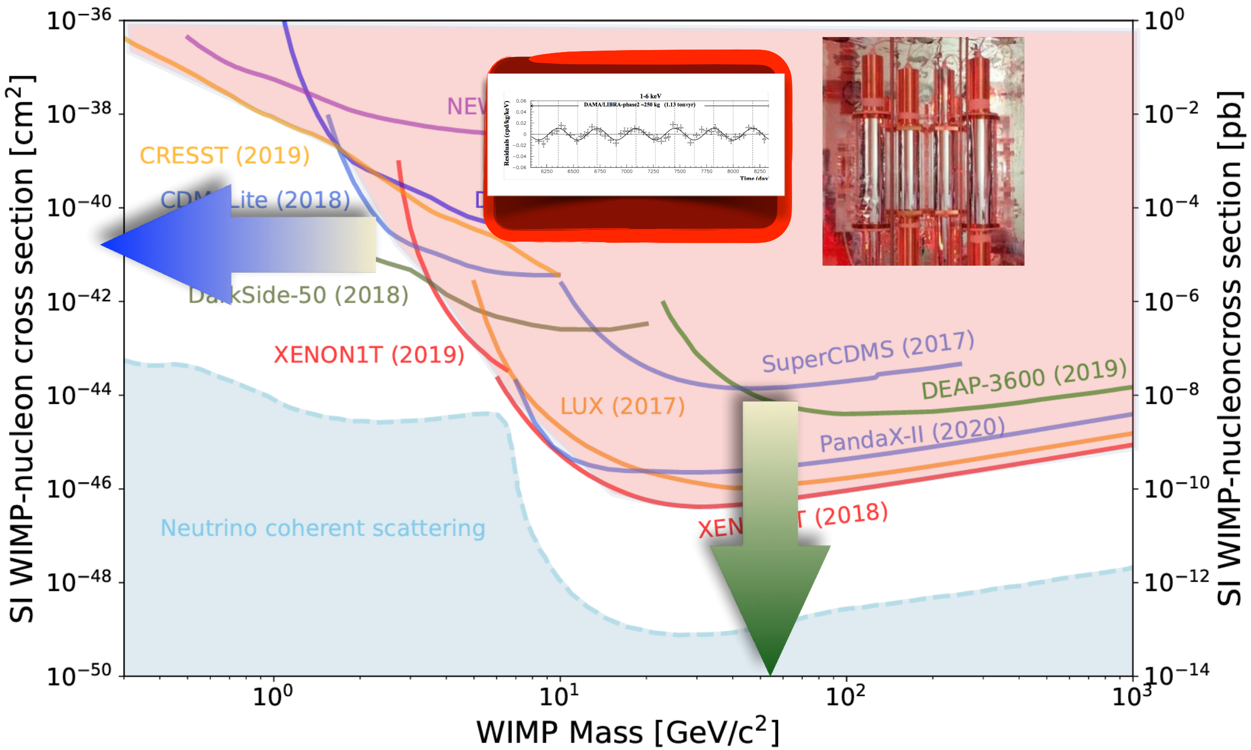


- PICO dominating SD searches
- Insensitive to e/γ by construction (10^{10} rejection @ 3 keV)



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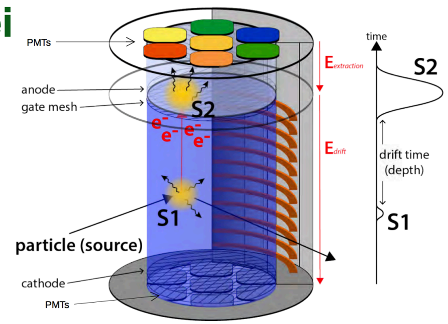

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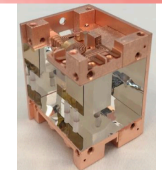

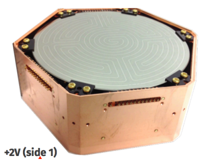

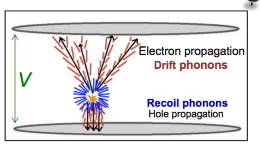

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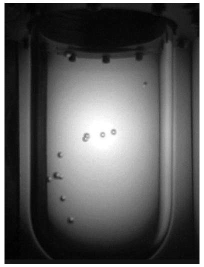

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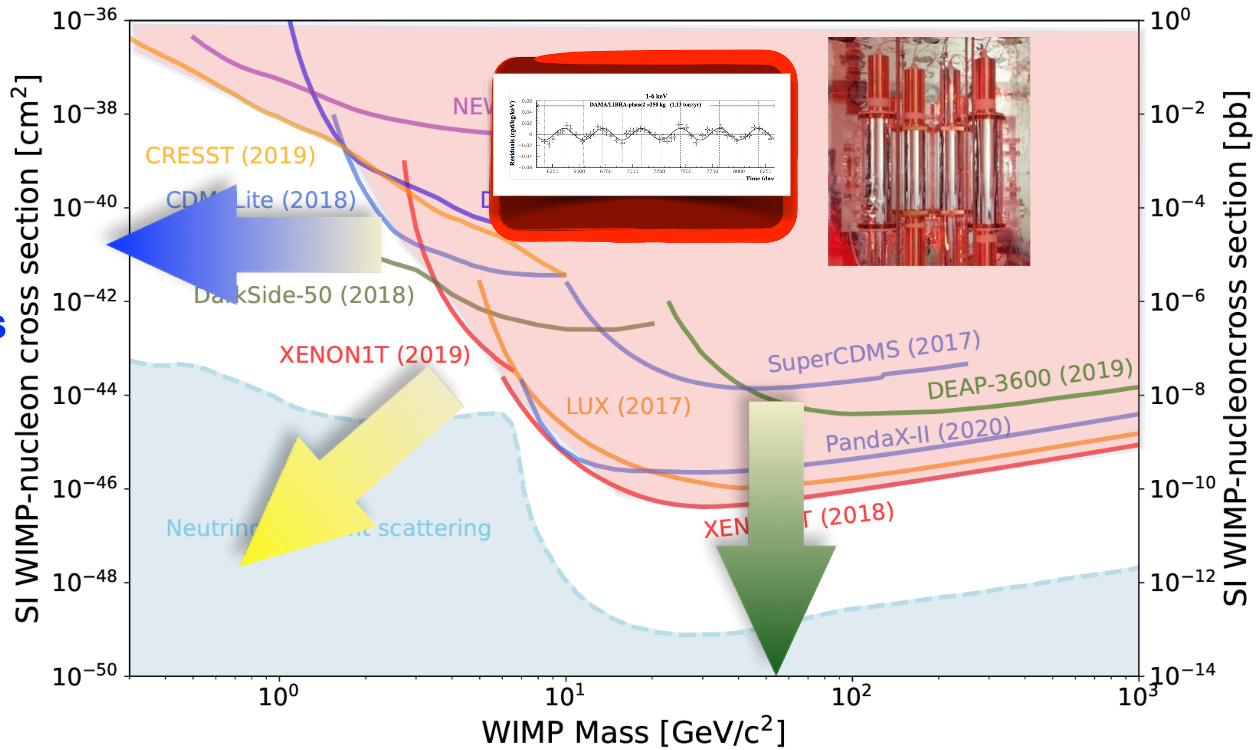
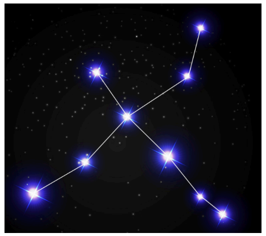
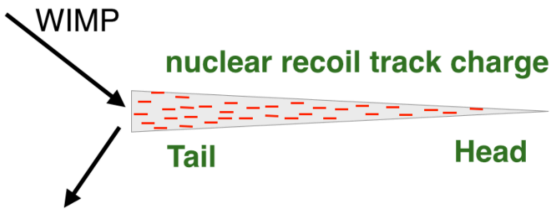


The "third way": directional tracking detectors for both SI and SD





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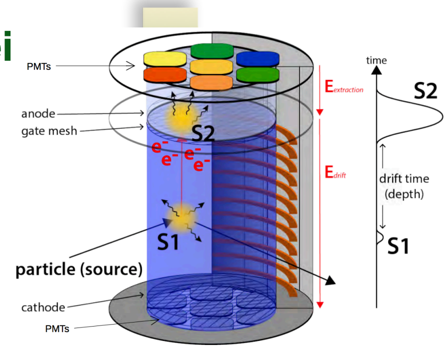

Low-mass dedicated experiments: bolometers

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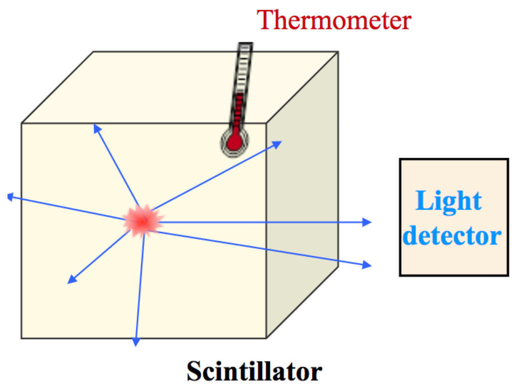
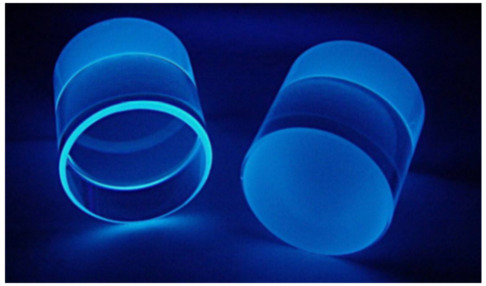
Heat + Scintillation

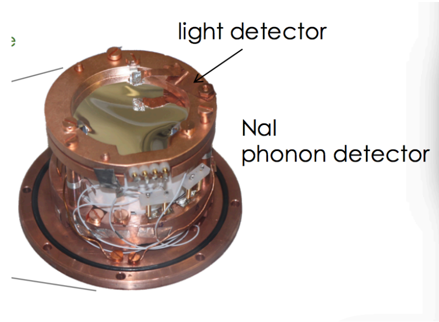


CRESST



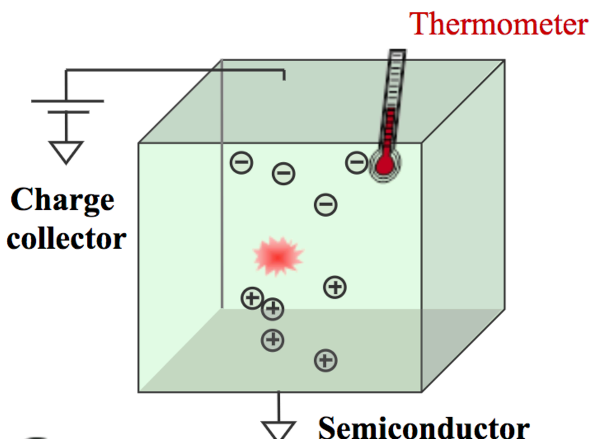
$CaWO_4$ crystals + TES

COSINUS

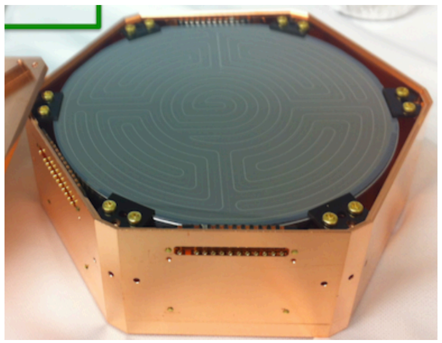


NaI crystals + TES

Heat + Ionisation

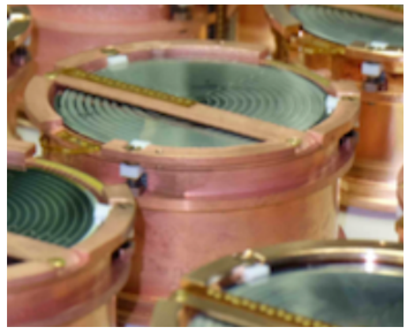


CDMS



Ge, Si semiconductor + TES

EDELWEISS



Ge semiconductor + NTD

more on this later (see LEE)

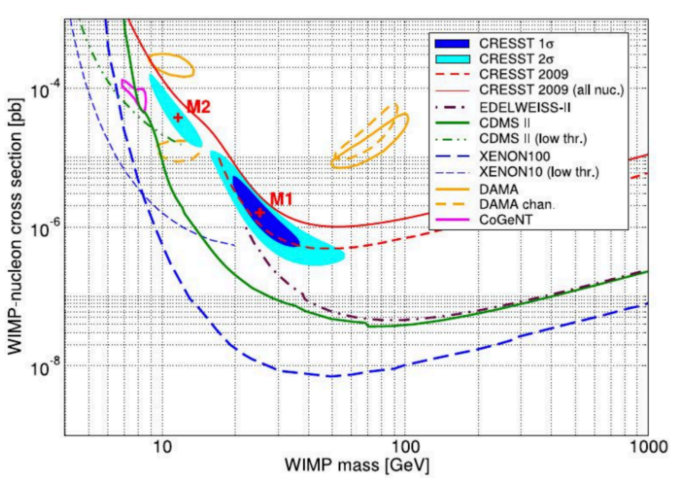
CRESST and the intrinsic background problem

CRESST-II

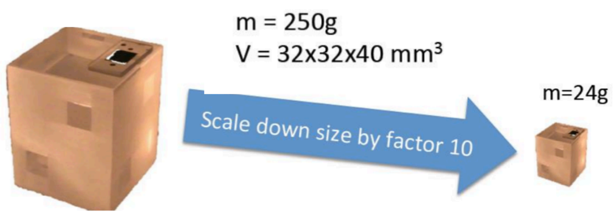
- Positive background signal
- Origin: Non-Scintillating bronze clamps

$$^{210}\text{Pb} \rightarrow {}^{206}\text{Pb}\ (103\text{keV}) + \alpha(5.3\text{MeV})$$

…but interpreted as real DM signal at that time, hence contours in the limit plot!



From CRESST-II to CRESST-III



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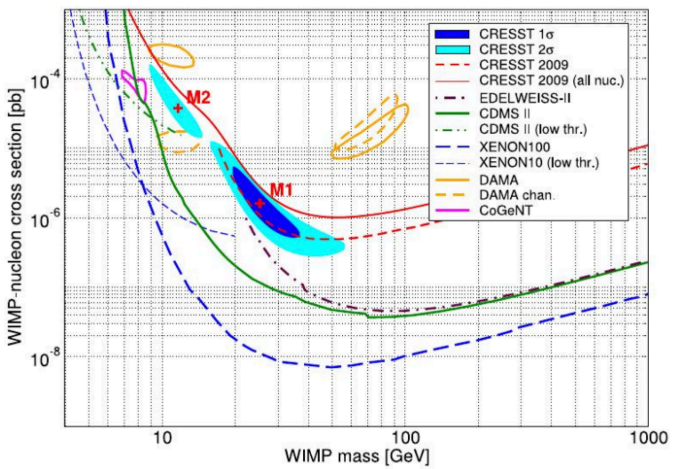

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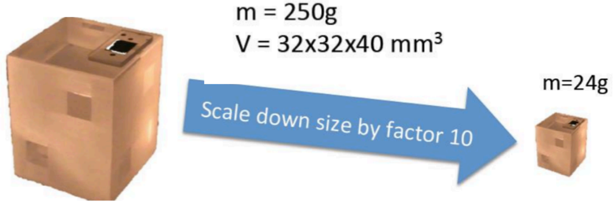
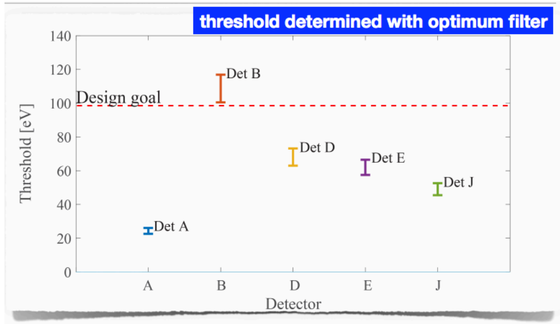
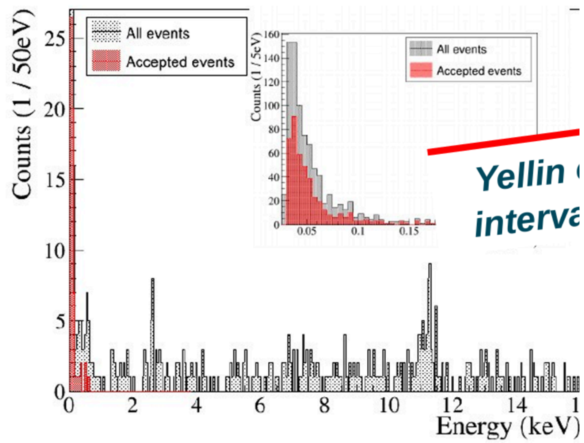


CRESST-III

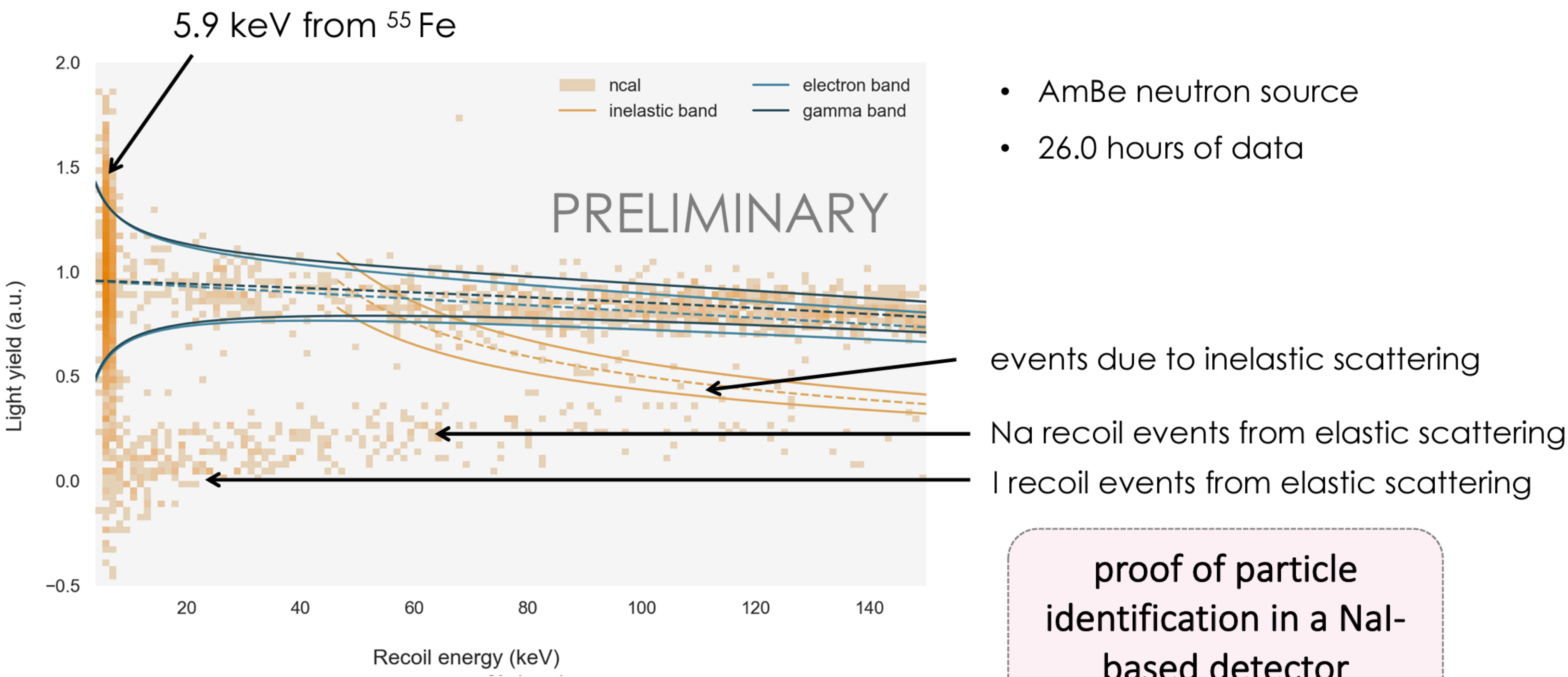


- 4 out of 5 detectors exceed design goal of 100 eV threshold

but 4 out of 5 detector exeeced also the expected background! Only detector A used for setting limit.....



COSINUS (not yet quantified) background discrimination



- AmBe neutron source
- 26.0 hours of data

proof of particle identification in a NaI-based detector

COSINUS WIMP mass goal are the DAMA regions, that are largely accessible to CYGNO-04! (see later)

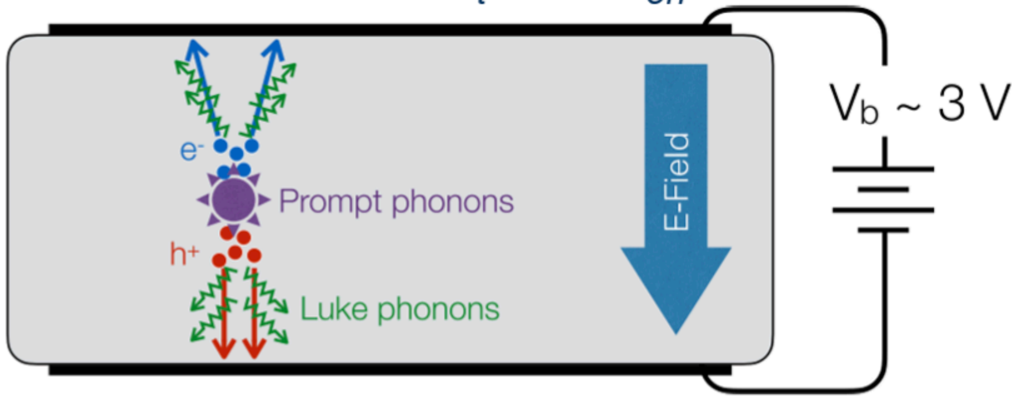
….but actual discrimination capabilities not quantified yet

SuperCDMS detectors concept

iZIP detector → low background

- **I**nterleaved **Z**-sensitive **I**onization and **P**honon detector
- Prompt phonon and ionization signals allow for NR/ER event discrimination

Sensors measure E_t and N_{eh}



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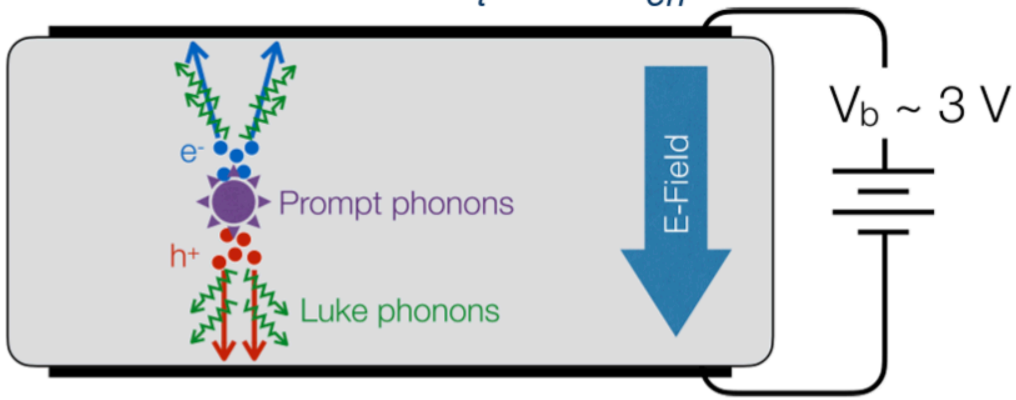
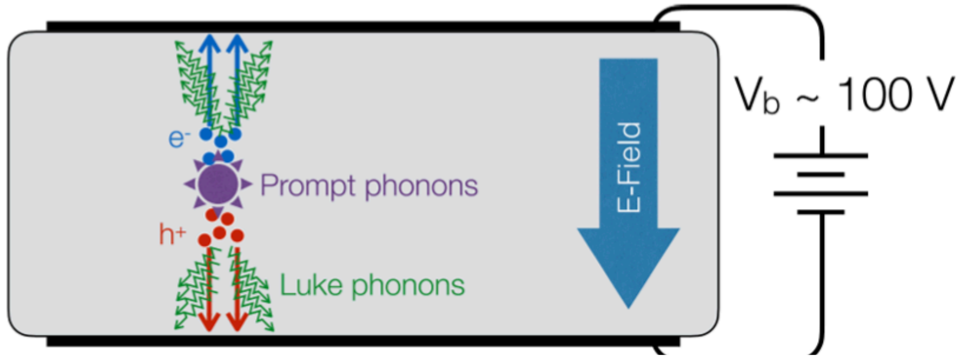


HV detector → low threshold

- Drifting charge carriers (e^-/h^+) across a potential (V_b) generates a large number of Luke phonons (NTL effect)
- Trade-off: no NR/ER discrimination

$$\underbrace{E_t}_{\text{total phonon energy}} = \underbrace{E_r}_{\text{primary recoil energy}} + \underbrace{(N_{eh} \cdot e \cdot V_b)}_{\text{Luke phonon energy}}$$

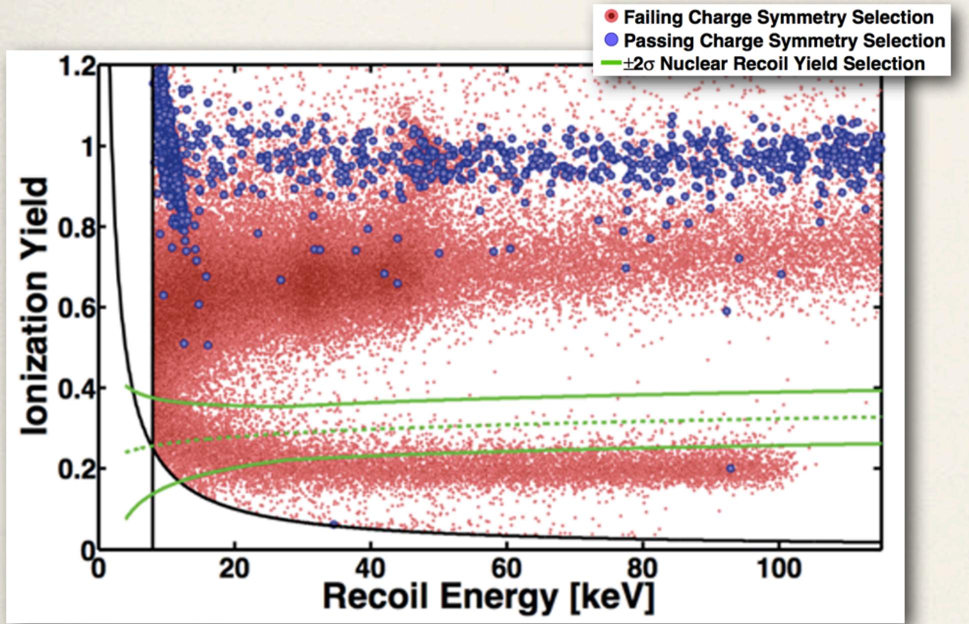
Sensors measure E_t

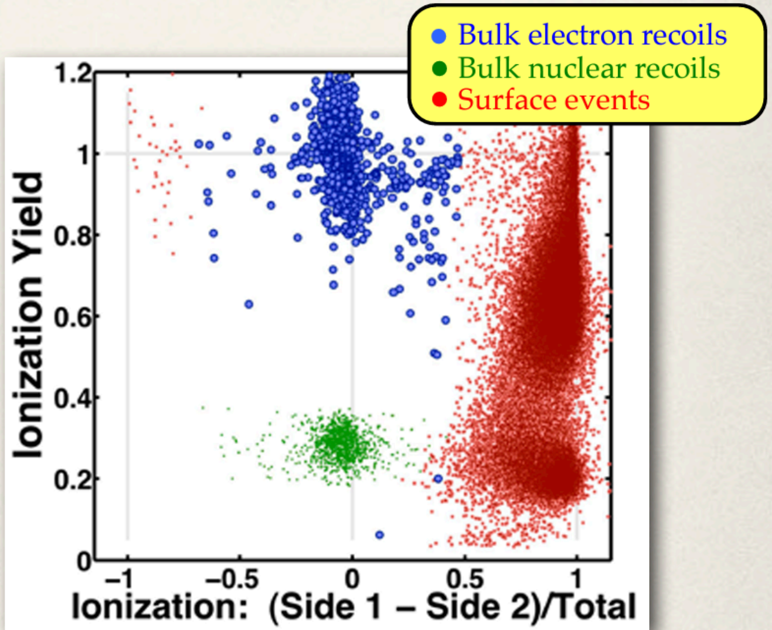


hence, HV detectors need to strongly rely on the intrinsic background minimisation

SuperCDMS iZIP background discrimination

2 x 10^{-5} @ 10 keV with 63% fiducial volume





- March - July 2012: ~65,000 electrons and ~15,000 ^{206}Pb recoil surface event collected from ^{210}Pb source.
- 0 events leaking into the signal region (< 2.5 x 10^{-5} @90% C.L. misID)
- 63% fiducial volume (8-100 keVnr)
- Good enough for a 200 kg experiment run for 4 years at SNOLAB!

Low Radioactivity Techniques 2013 - April 10-13, 2013 15 *Jodi Cooley - SMU*

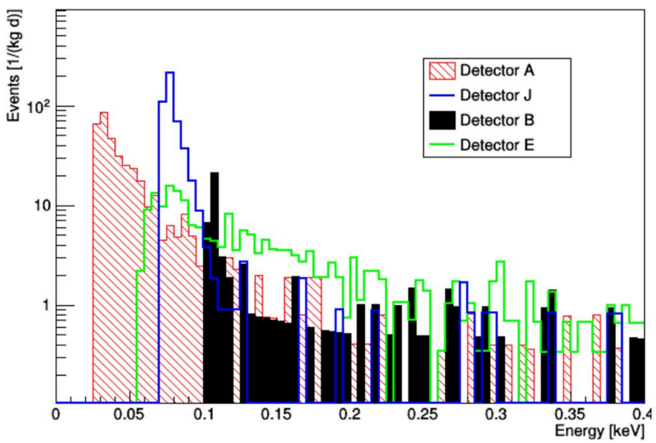
…but SuperCDMS adventure started <u>24 years ago</u>

…but, a new emerging feature common to many experiments

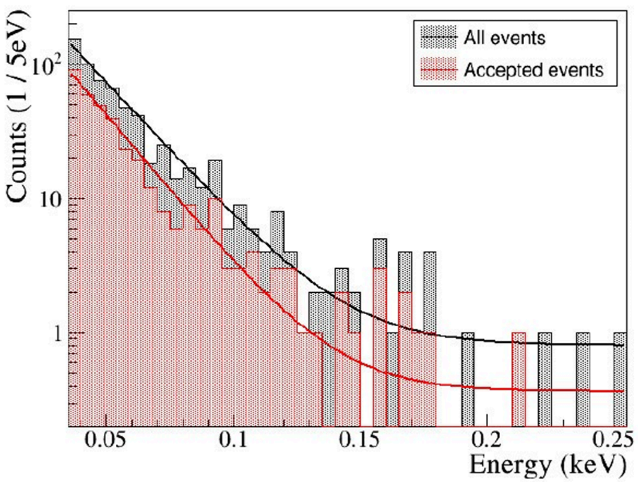
The low energy excess (LEE) *…here presented for CRESST only as example,*

First observations: 2016 – 2018

Overview of $CaWO_4$ Detectors



Detector A – Zoom

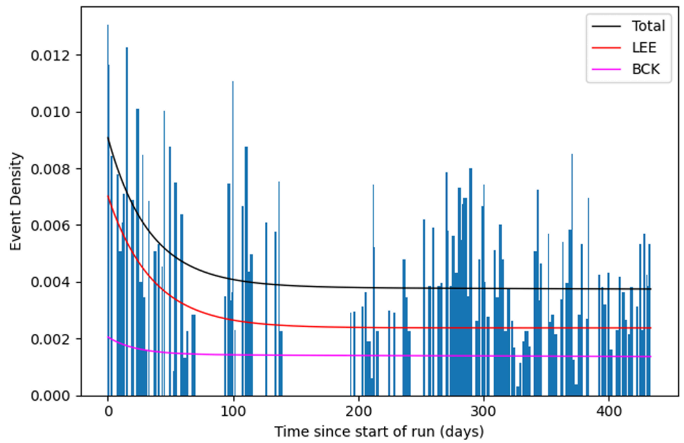


Unexplained event population at low energies

- high count rate
- steep rise in energy below ~200 eV
- different shape in different detectors

Detector	Threshold
Det-A	30.1 eV
Det-B	120 eV
Det-E	64.8 eV
Det-J	83.4 eV

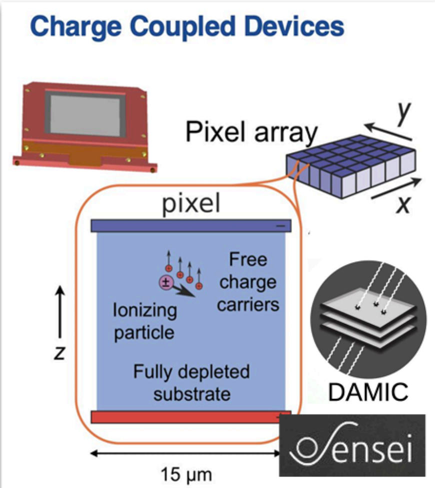
Rate over time for Detector A

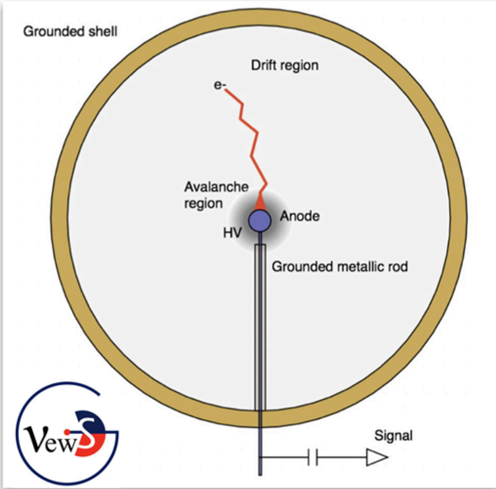


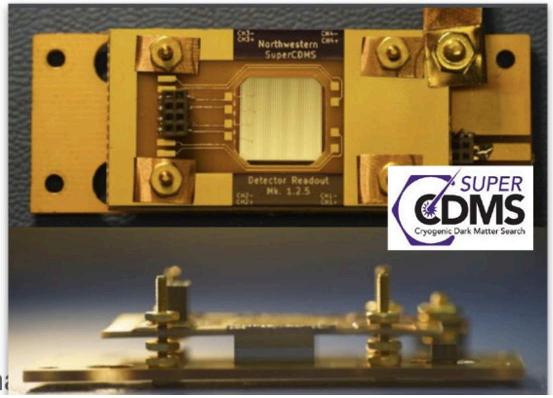
- count rate decreases over time

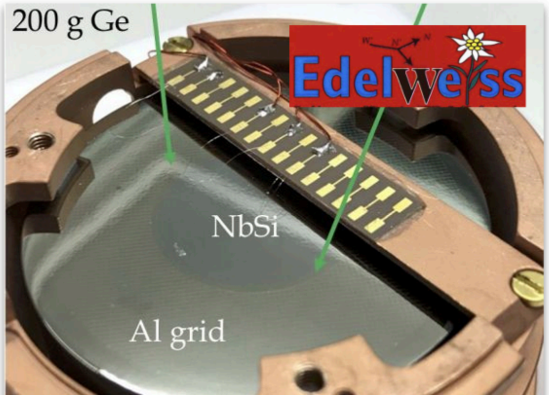
The EXCESS initiative in 2022

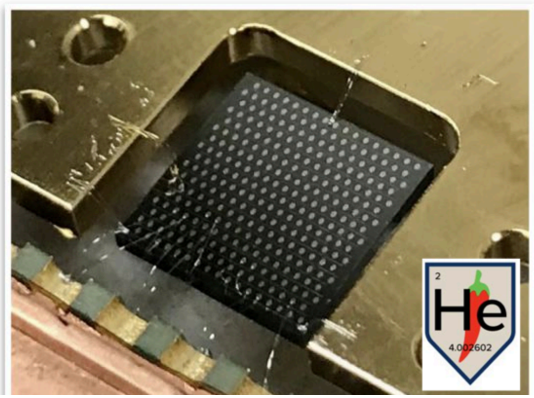
EXCESS22@IDM: Experiments







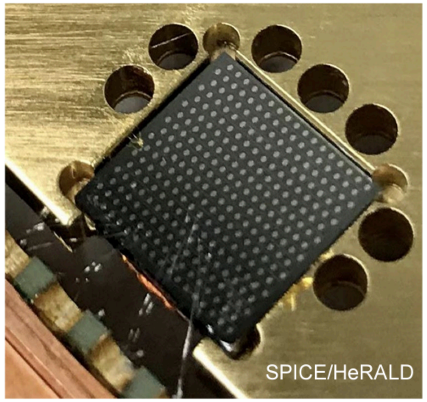




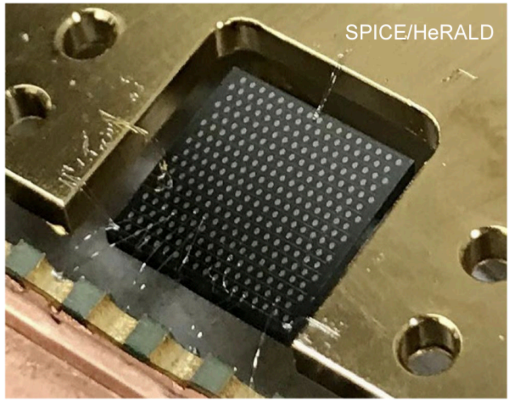
Belin

EXCESS preliminary findings

- **Excluded hypotheses on major contributions**
  - DM interactions
  - External and intrinsic radioactivity
  - Noise triggers and electronic artifacts
  - Scintillation light
- **Possible options under further investigation**
  - Intrinsic crystal effects
  - Sensor related effects
  - Holding induced stress



Glued down to copper substrate
=> **high stress**

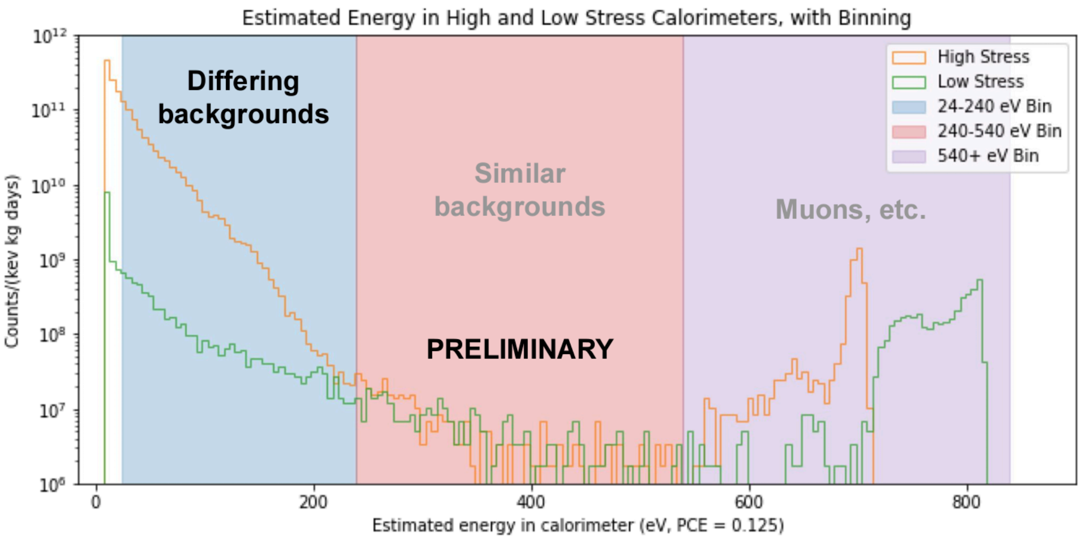


Suspended from wire bonds
=> **low stress**

..but not yet demonstrated nor suceeded……

- Low stress rate still ~200x SuperCDMS-CPD, ~10^5x CRESST
  - Hypothesis: fabrication-induced strain at TES interface varies greatly between detectors
- **Stress event rate decreases while cold**, may anneal out while warm too
- **Mitigation Plan: Fanatically minimize stress everywhere in the detectors**

Stress creates enormous low energy background!



EXCESS conclusive slide @ TAUP2023

Three unique types of excesses identified!

- Excesses in **cryo-detectors** (non-ionizing, decaying, …) have possibly one common origin! Hot suspect: interface and bulk stress. Currently focused research topic, transferable impact expected (qubits, …).
- Excesses in **CCDs** (single electron production) can be explained by dark current and detector effects, but further reduction is required or future experiments (e.g. OSCURA).
- The **DAMIC excess** remains a riddle.

The workshop continues as a platform for focussed discussions. We are currently scouting a location for the next iteration, planned for summer 2024.

- Contact us at excessworkshop@gmail.com

Reasons for optimism! Lot's of progress so far! We will figure this out!

Wish

Reality

symbolic image

Wish: map observations to phenomena as easy as a hitchhikers map (left).

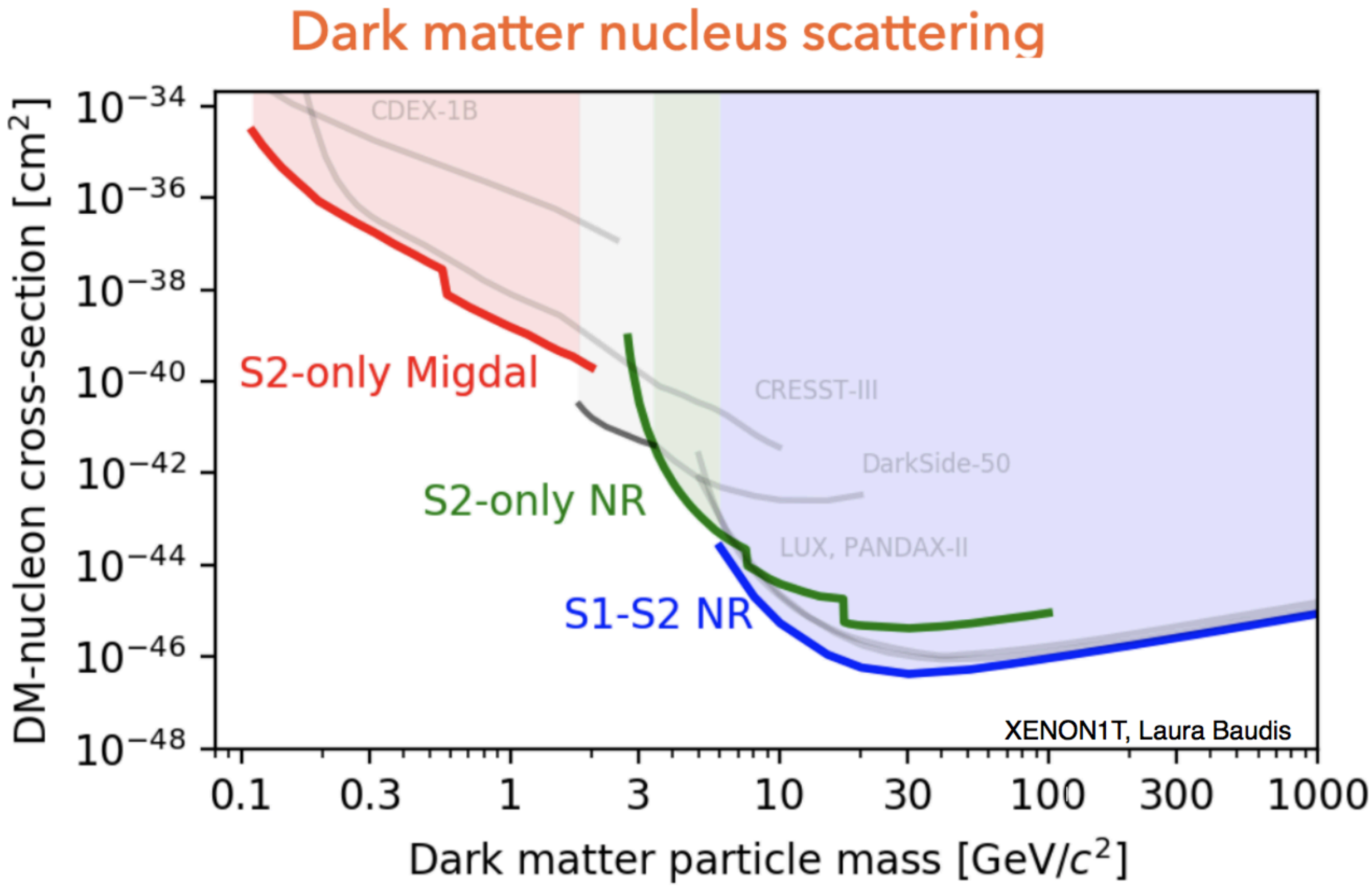
Reality: a lot is going on close to energy thresholds, with many paths leading apart and some leading back together (right).

GSSI

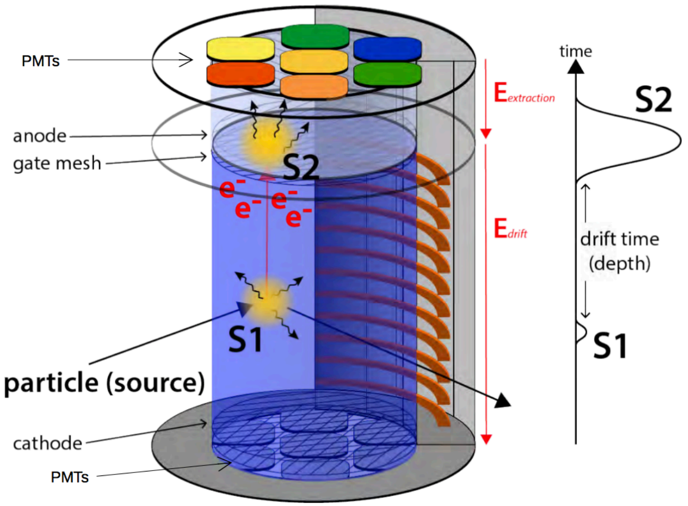
INFN
Istituto Nazionale di Fisica Nucleare

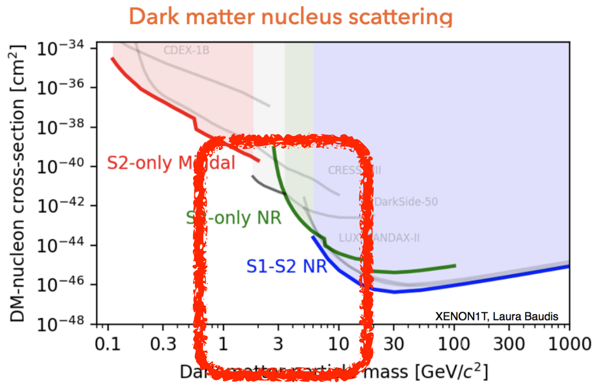
Take away message: if not solved, LEE could kill the bolometric approach at very low energies

Large noble liquid detector analysis for < 10 GeV WIMP masses



Large noble liquid detector analysis for < 10 GeV WIMP masses: S2 only analysis





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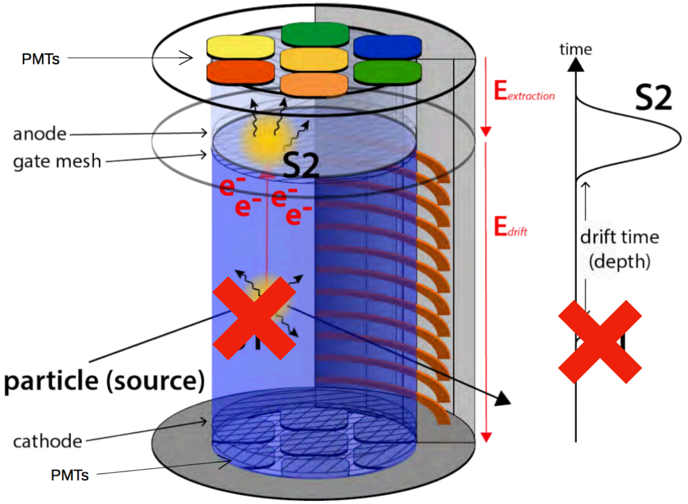
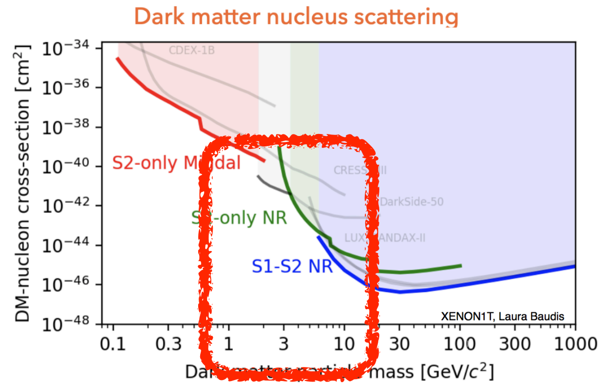
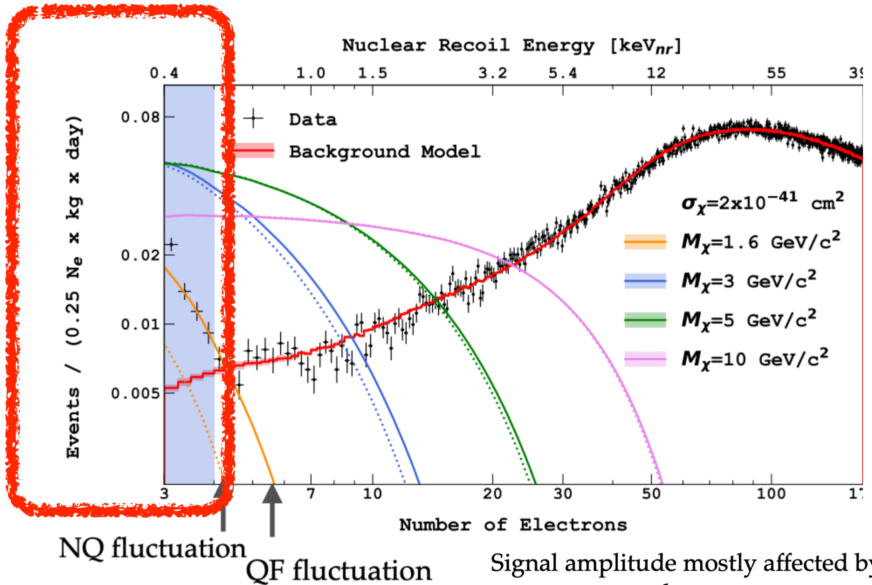


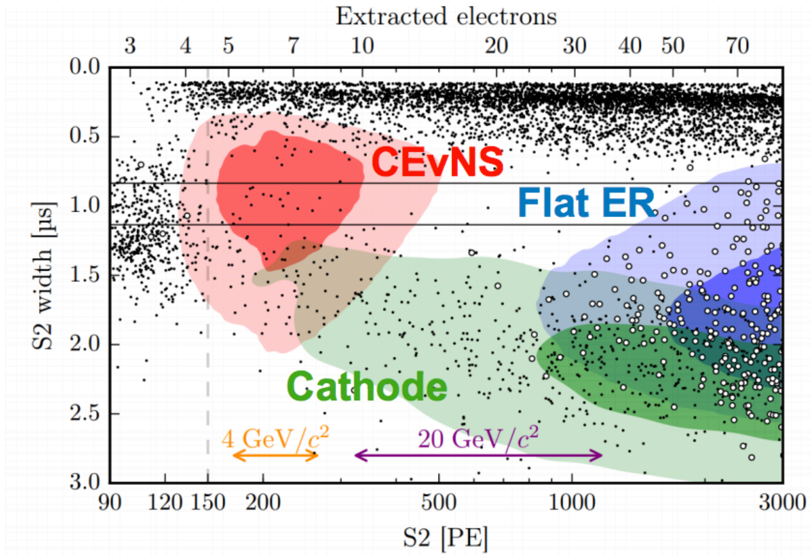
No Z coordinate
No PSD
No S_1/S_2
No vetoes
only X-Y





Signal amplitude mostly affected by uncertainty on the NR ionization response and fiducial volume.

X10 more stringent limit @ 3GeV/c2



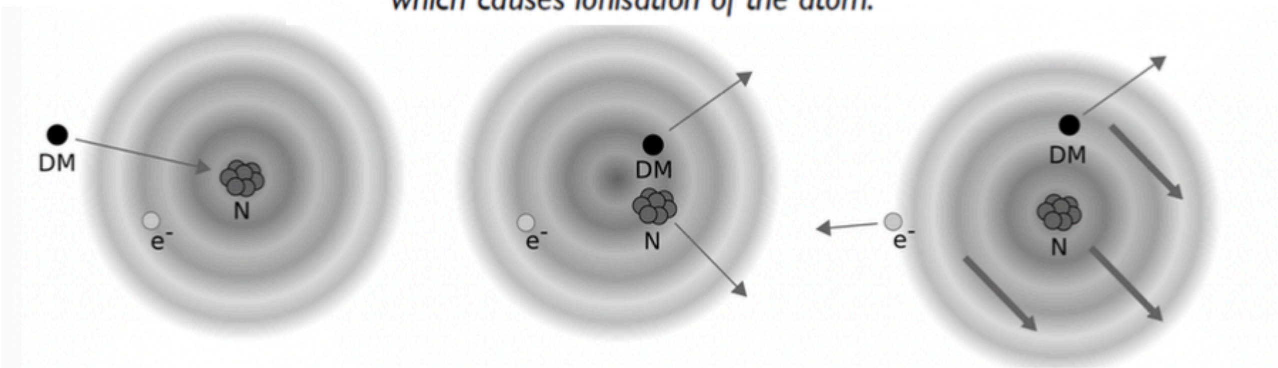
Cut on S_2 time width (related to diffusion, i.e. Z distance) rejects part of e.m. background from cathode wires

Take away message: S2 only analyses heavily raises the requirement for detector material radiopurity and for capability to precisely predict the expected background, further hampering the possibility to positively identify a DM signal with these

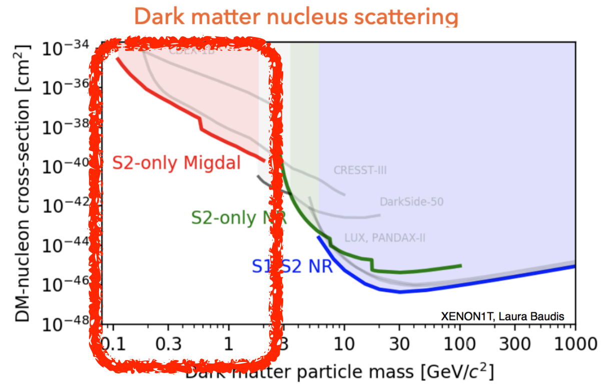
Large noble liquid detector analysis for < 10 GeV WIMP masses: S2 only Migdal analysis

How to "artificially" lower the WIMP mass reach of a DM experiment by exploiting the Migdal effect

"…it takes some time for the electrons to catch up, which causes ionisation of the atom."



Migdal Effect - nucleus moves relative to the electron cloud. Individual electron might be ejected leading to ionisation.



1) the DM interaction produces a simultaneous ER + NR from the same vertex;

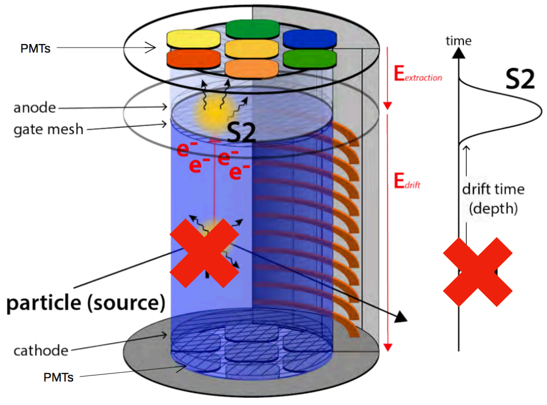
2) NR are quenched w.r.t. ER

3) Hence, for a given energy threshold the Migdal-induced ER might be above threshold while the Migdal-induced NR might be below

4) An isolated ER signature is interpreted as a Migdal induced ER + NR event where the NR was not detectable, effectively lowering the threshold on NR

5) Since ER is the signature, ER/NR discrimination is given up to further lower the threshold (i.e. S2-only analysis)

6) The limit on DM search is evaluated assuming the Migdal effect as calculated from theory (often with simplistic assumptions)

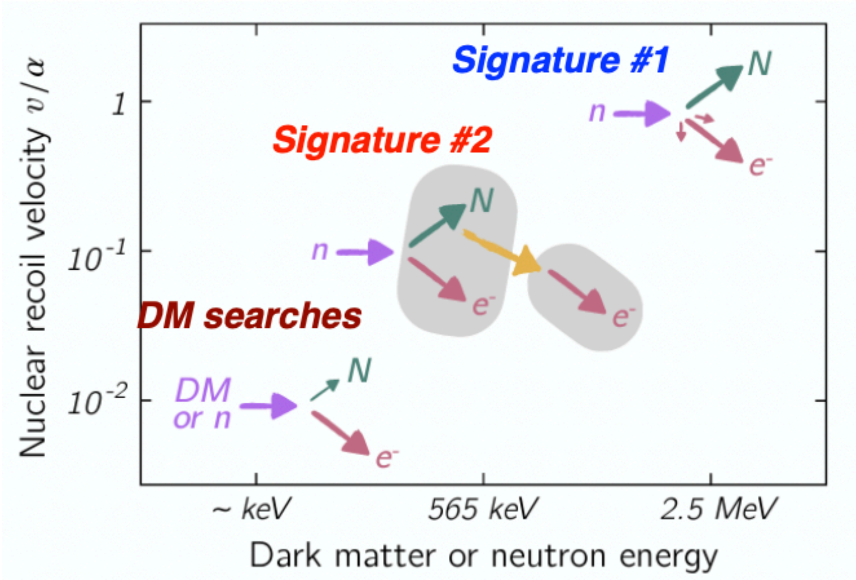


….but Migdal effect has never been experimentallly measured!

See M. D'Astolfo talk for details on our efforts towards this goal

Migdal effect measurement excursus

NOTE: Migdal effect is independent from DM existence: i.e. you can induce it with any neutral particle having elastic scatter with nuclei (i.e. fast neutrons)



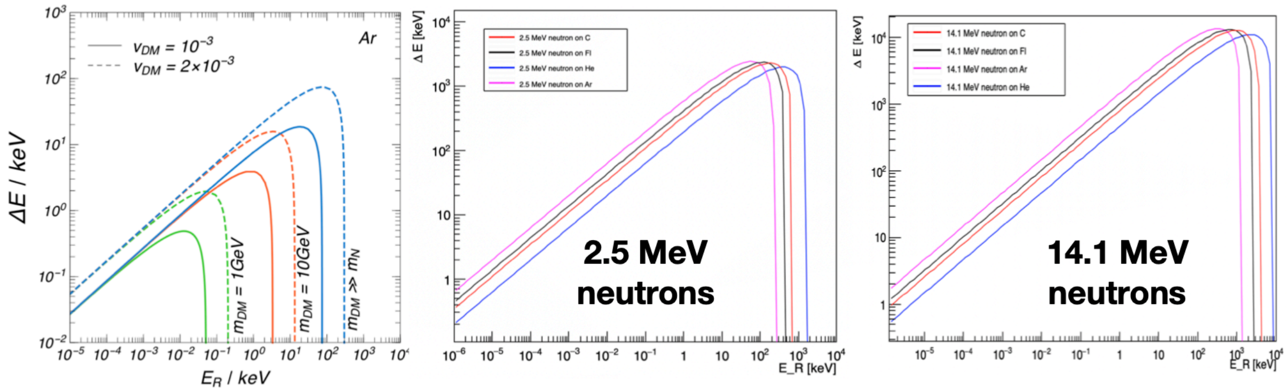
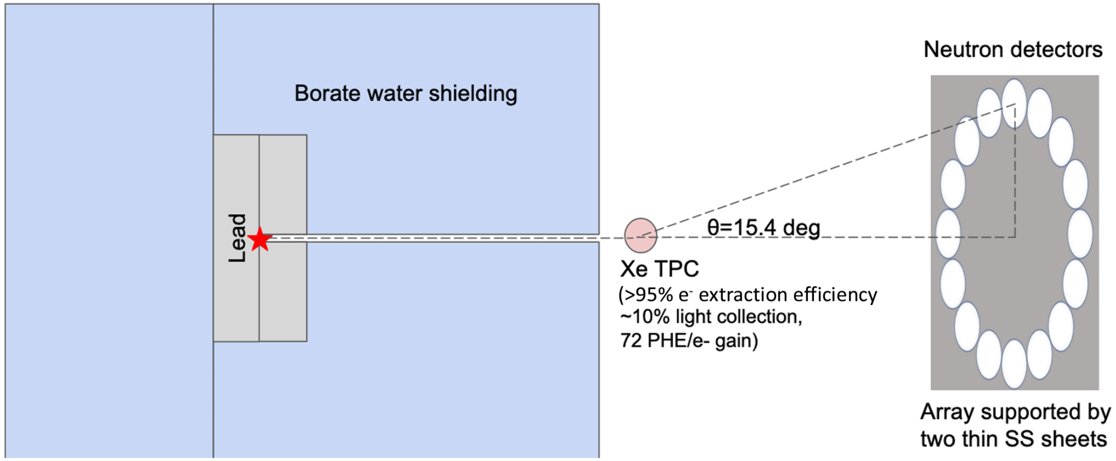


Fig. 2 Kinematically allowed region of E_R and ΔE for Ar atoms elastically scattered by WIMP with velocity v_{DM} of 1-2 x 10^{-3} on the left from [2] and for He (blue), Ar (pink), C (red), and F (black) atoms elastically scattered by neutrons of 2.5 MeV and 14.1 MeV energies on the center and right respectively.

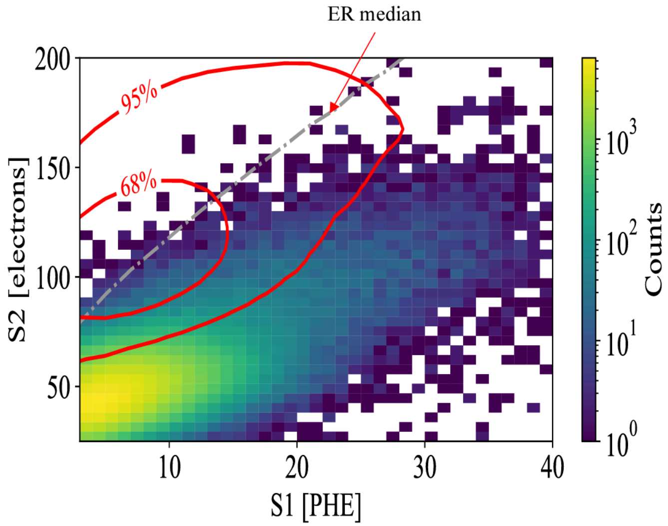
arXiv:2307.12952

Current status of Migdal searches: test with LXe

- **High energy neutrons (14.1 MeV):** enhance Migdal cross section, reduce neutron multi-scatter (NMS)
- **Tag scattered neutrons:** obtain interaction time, reduce background with neutron time of flight (TOF)
- **Quasi-mono-energetic NR:** reduce signal rate uncertainties from nuclear cross section and efficiency
- **Low scatter angle:** reduce NR energy, separate Migdal events from pure NRs



- ~300,000 NRs at 7+/-1.5keV
  - ~5 PHE for S1
  - ~45 e- for S2
- ~4000 Migdal events expected
  - ~200 M-shell interactions
  - 0—20 additional photons, or up to 2 extra PHE
  - ~50 additional electrons
- Electron recoil background is relatively small
- Backgrounds from NMS at high S1-S2 values



No signal observed at the expected rate.

arXiv:2307.12952

Current status of Migdal searches: test with LXe

- **High energy neutrons (14.1 MeV):** enhance Migdal cross section, reduce neutron multi-scatter (NMS)
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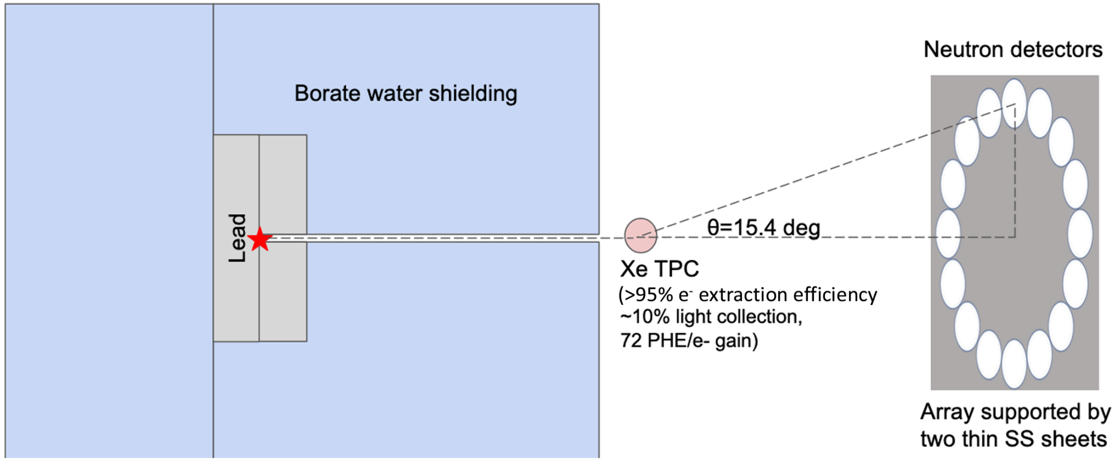
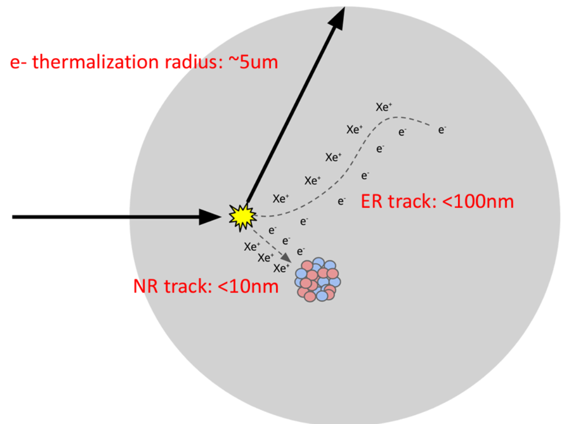


- Electrons and ions produced by the NR track and ER track overlap in space
- Recombination can be enhanced relative to that of NR or ER



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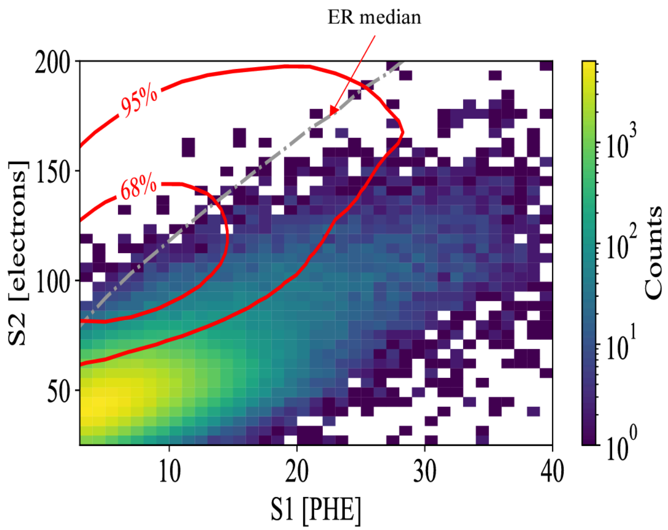
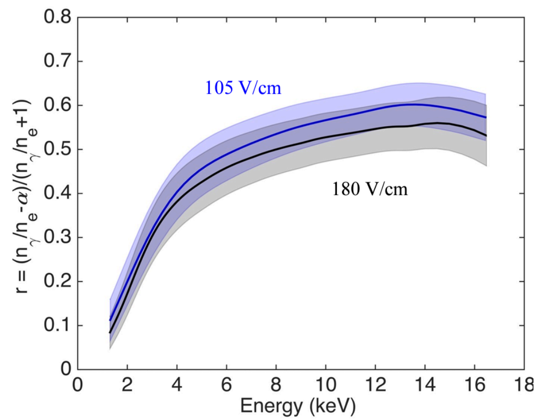


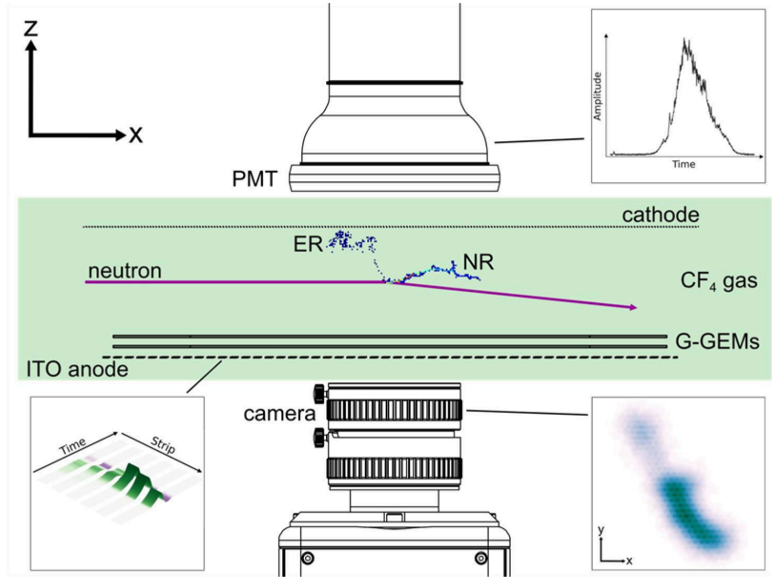


Recombination probability for low-energy 3H decay events in liquid xenon measured by LUX, PRD 93, 072009 (2016)

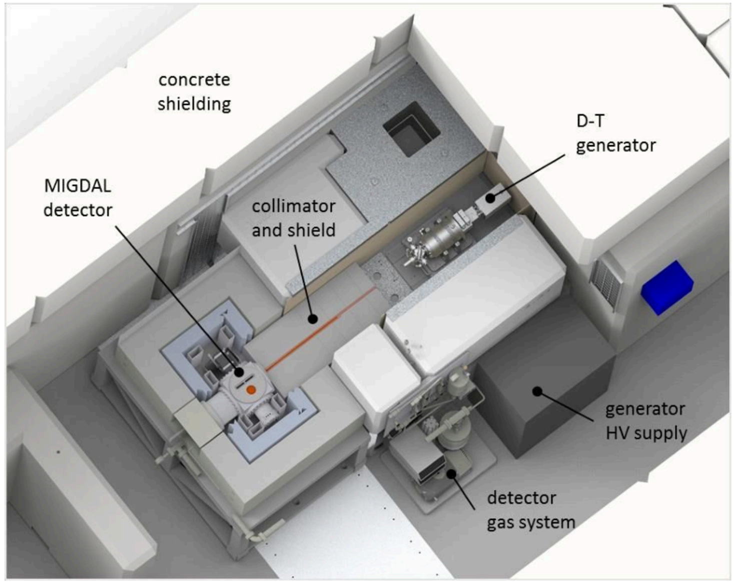
No signal observed at the expected rate: possible explanation from Xe physics

Current status of Migdal searches: the Migdal experiment

10 x 10 x 3 cm³
Orca Quest + PMT + ITO strips readout



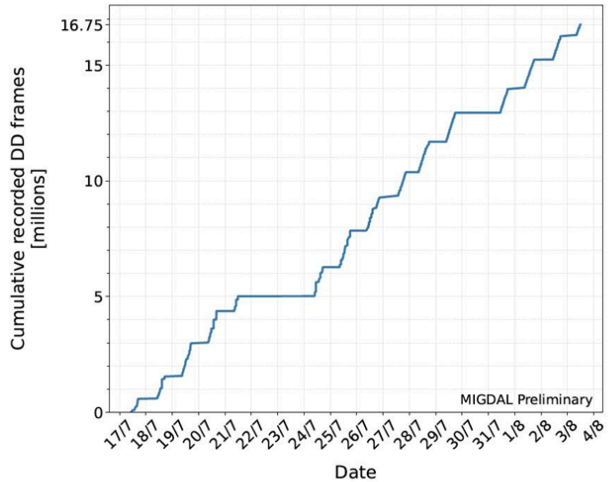
Dedicated D-D (10^9 n/s) and D-T (10^{10} n/s) neutron gun



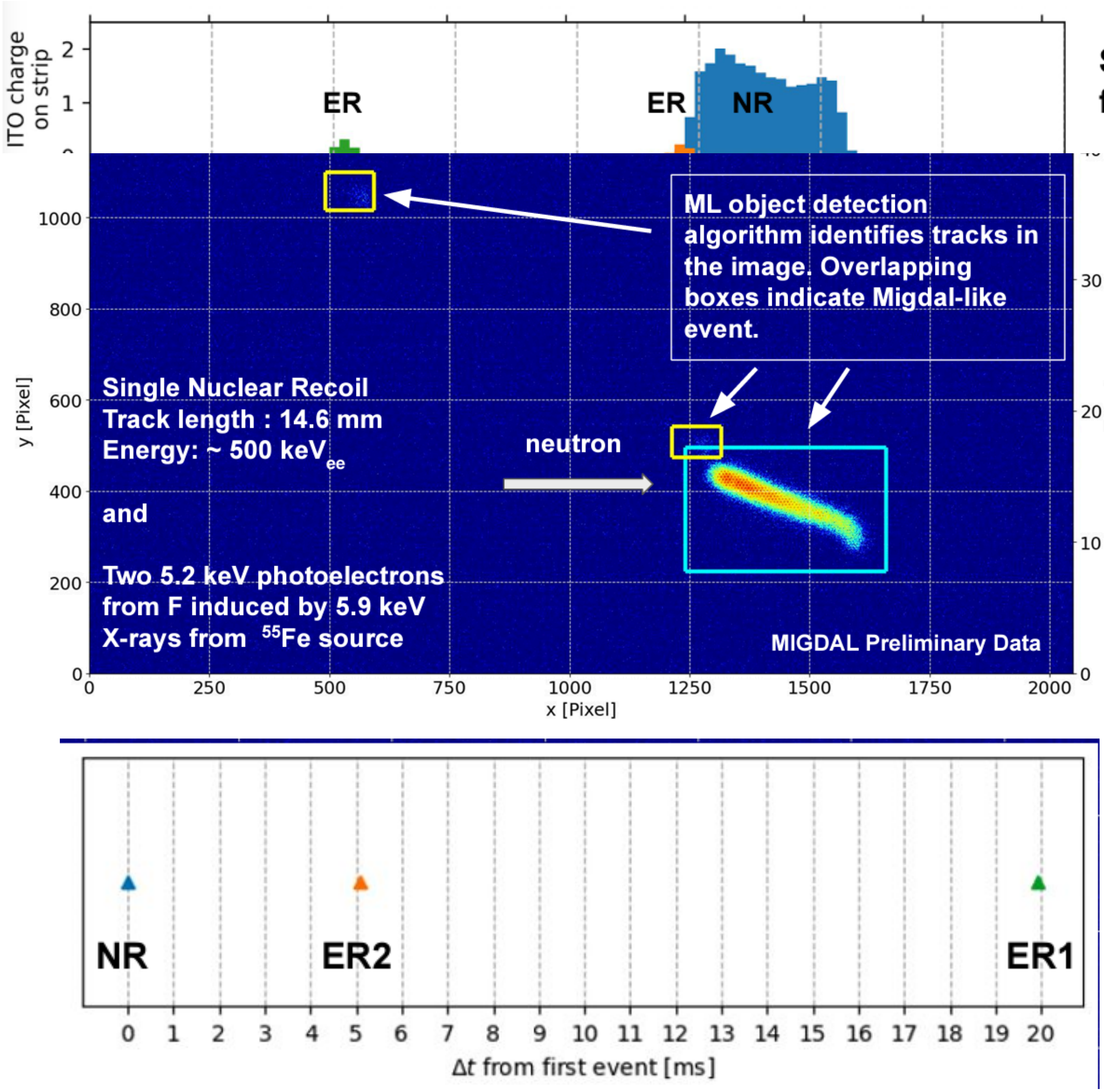
Experiment setup with D-T generator

- Low-pressure gas: 50 Torr of CF_4
  - Extended particle tracks
  - Avoid gamma interactions
  - Can stably work with fraction of Ar
- TPC Signal amplification
  - 2 x glass-GEMs (Cu + Ni cladded)
- Readout :
  - Optical : Camera + photomultiplier tube
  - Charge: GEMs + 120 ITO anode strips
- High-yield neutron generator
  - D-D: 2.47 MeV (10^9n/s)
  - D-T: 14.7 MeV (10^{10}n/s)
  - Defined beam, "clear" through TPC

- The First Science run took place from the 17th of July to the 3rd of August.
- Data taken using D-D neutron generator, with a lower NR rate than designed, is recorded continuously during 10 hour long shifts, and includes significant fraction of empty frames.
- Frames taken with 20 ms exposure time. Longer than planned due to problems with camera's Linux firmware.
- Half of the data is blinded.



A Migdal like event in the Migdal experiment



Synchronised signals from ITO strips.

Timing information from ITO strips separates all 3 tracks.

i.e. this is not Migdal, is accidental pile-up

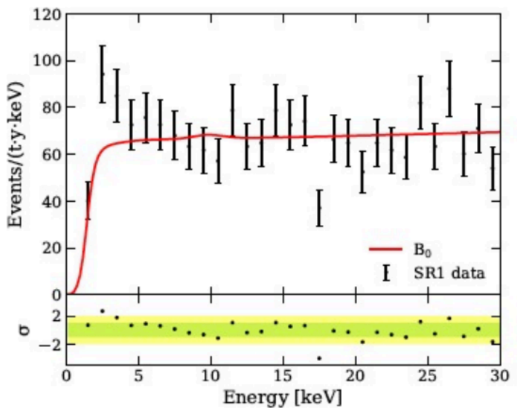
Extremely encouraging first science run (project exclusively dedicated to Migdal measurement)

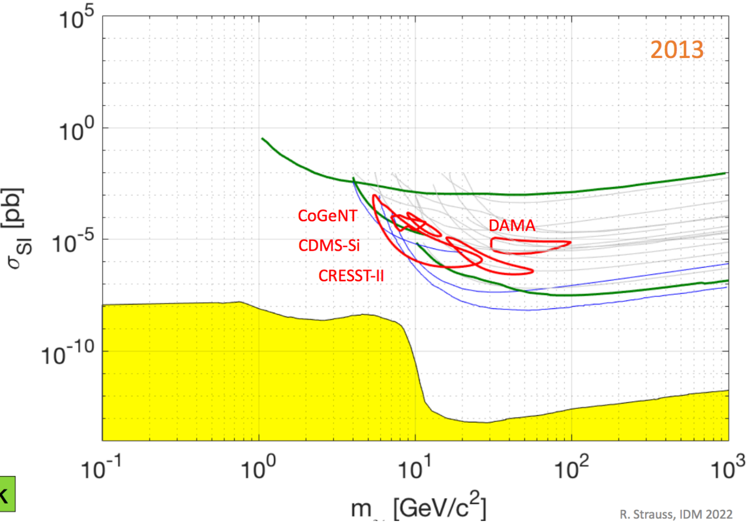
Take away message: until Migdal effect is effectively measured in the actual target material, limits exploiting Migdal effect **can not be trusted at 100%**

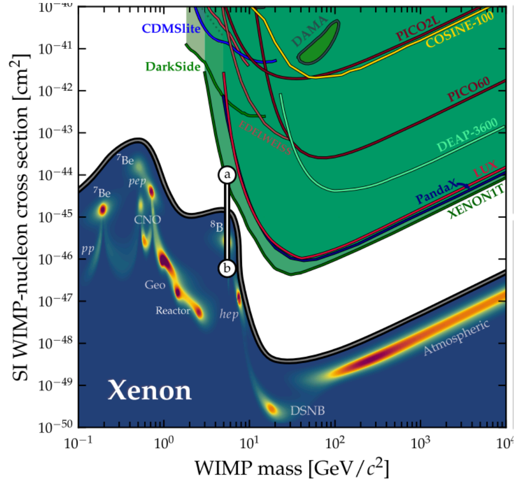
Looking for DM is a search hampered by many false promises both at high and low masses

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

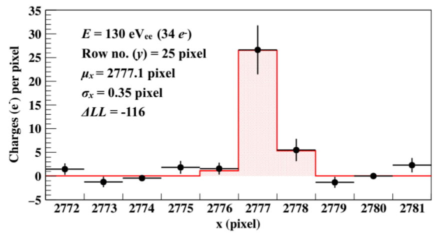
Direction is the only way

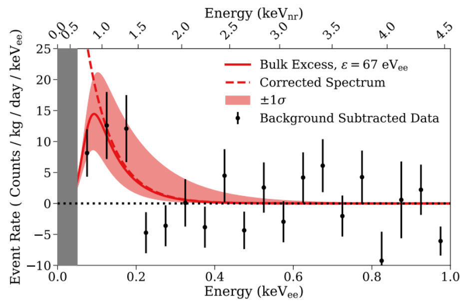




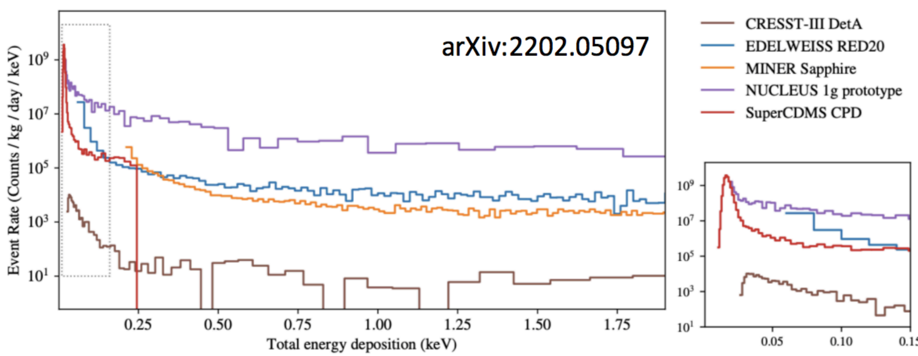


A. Chavarria's talk





Exponentially rising background towards lower energies



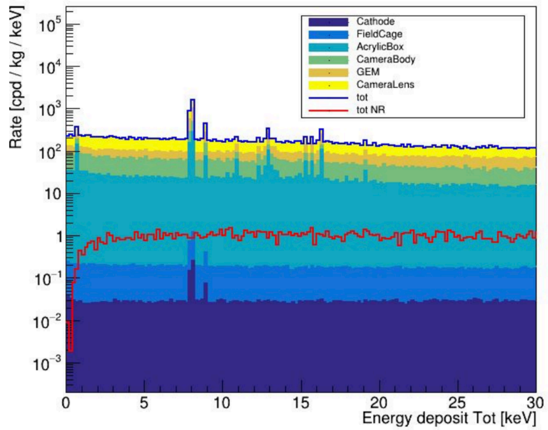
Currently limiting the sensitivity globally !
Origin still unknown, but a lot of R&D is going on ...

Where does CYGNO stand in this picture?

PHASE 1 back of the envelope final background estimation

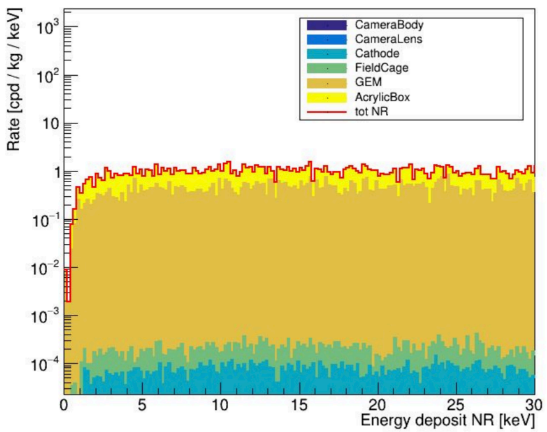
Preliminary CYGNO-04 background evaluation through scaling from CYGNO-1 full simulation

- CYGNO: ER rate [1-20] keV = 2.3x10^6 cts/yr
- CYGNO_04: ER rate [1-20] keV = 4.9x10^5 cts/yr

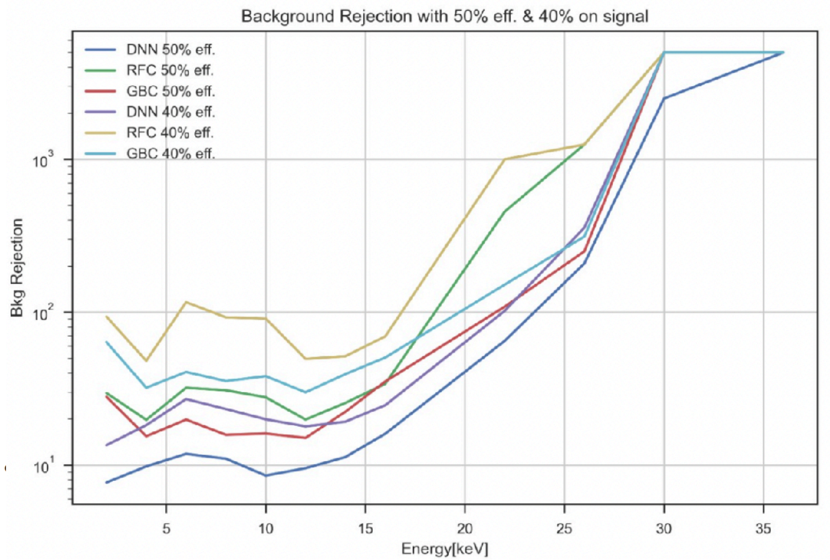


Internal ER background

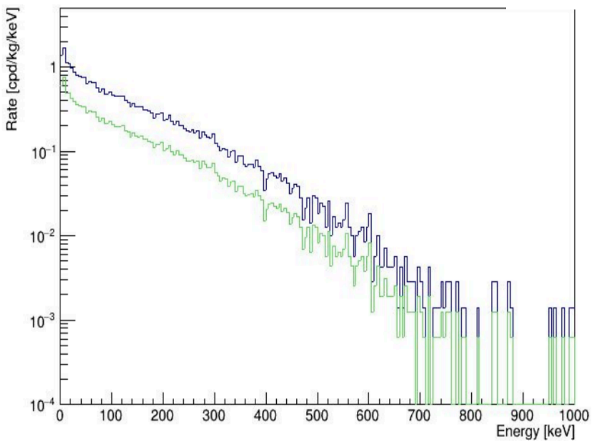
- CYGNO: NR rate [1-20] keV = 1.1x10^4 cts/yr
- CYGNO_04: NR rate [1-20] keV = 2.6x10^3 cts/yr



Internal NR background



- Rate [1-20] keV = 1.4x10^4 cts/yr (CYGNO)
- Rate [1-20] keV = 6.4x10^3 cts/yr (CYGNO_04)

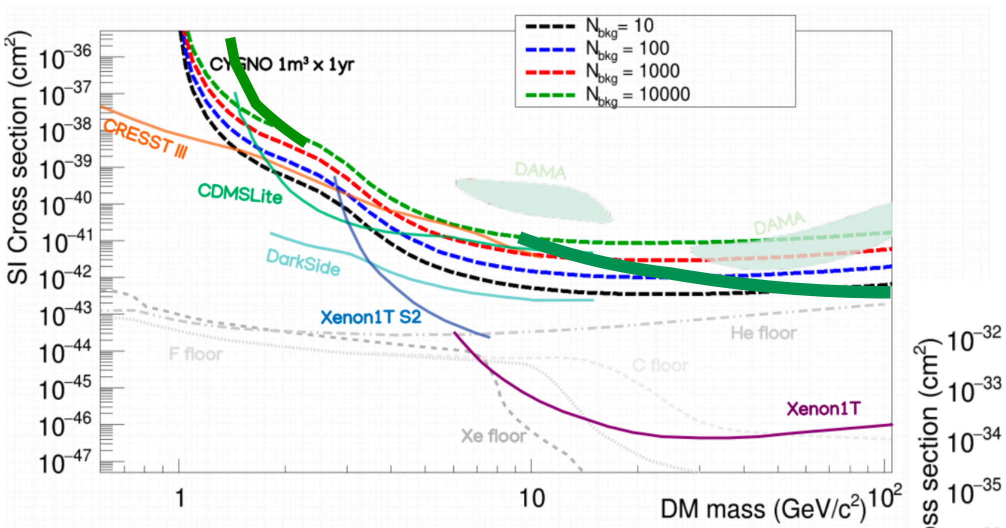


Total external background

- **Assume entire NR background rejected with fiducial cuts**
- **Assume ER rate in [20-30] 2.5 x 10^5 events/year**
- **Roughly evaluate the ER rate per keV and roughly apply RFC rejection from Atul studies**
- **±7000 background events/year in the full energy range (internal + external) after rejection**

CYGNO-04 physics reach

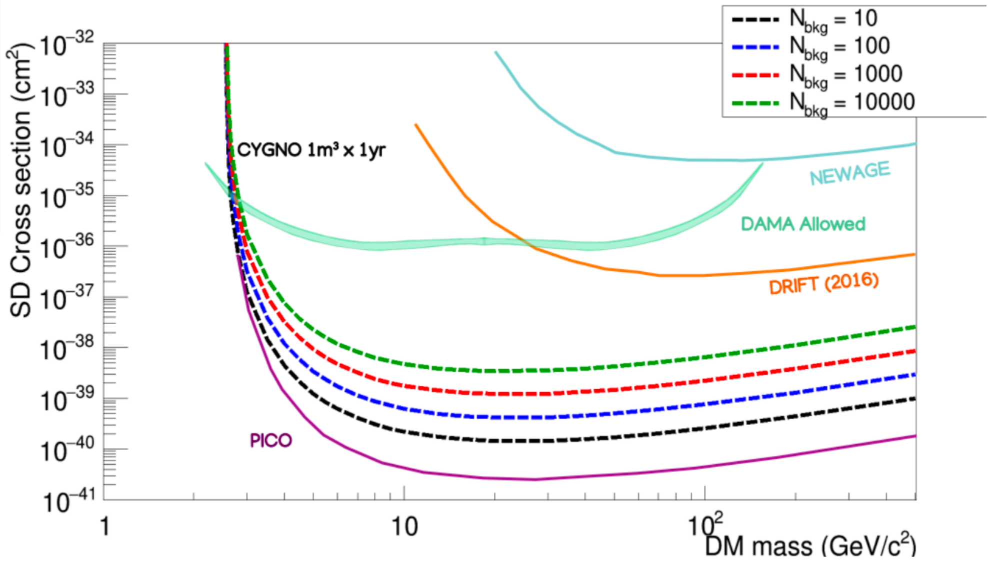
constant 30º angular resolution assumed with full head tail capability: optimistic at low energies/WIMP masses) pessimistic at high energy/WIMP masses



CYGNO-04 x 1 year is only a factor 2.5 less than limits in the plots, that results barely perceptible in a log-log plot

Rough evaluation of background after rejection consistent with our of our sensitivity evaluation hypothesis

[4-14]

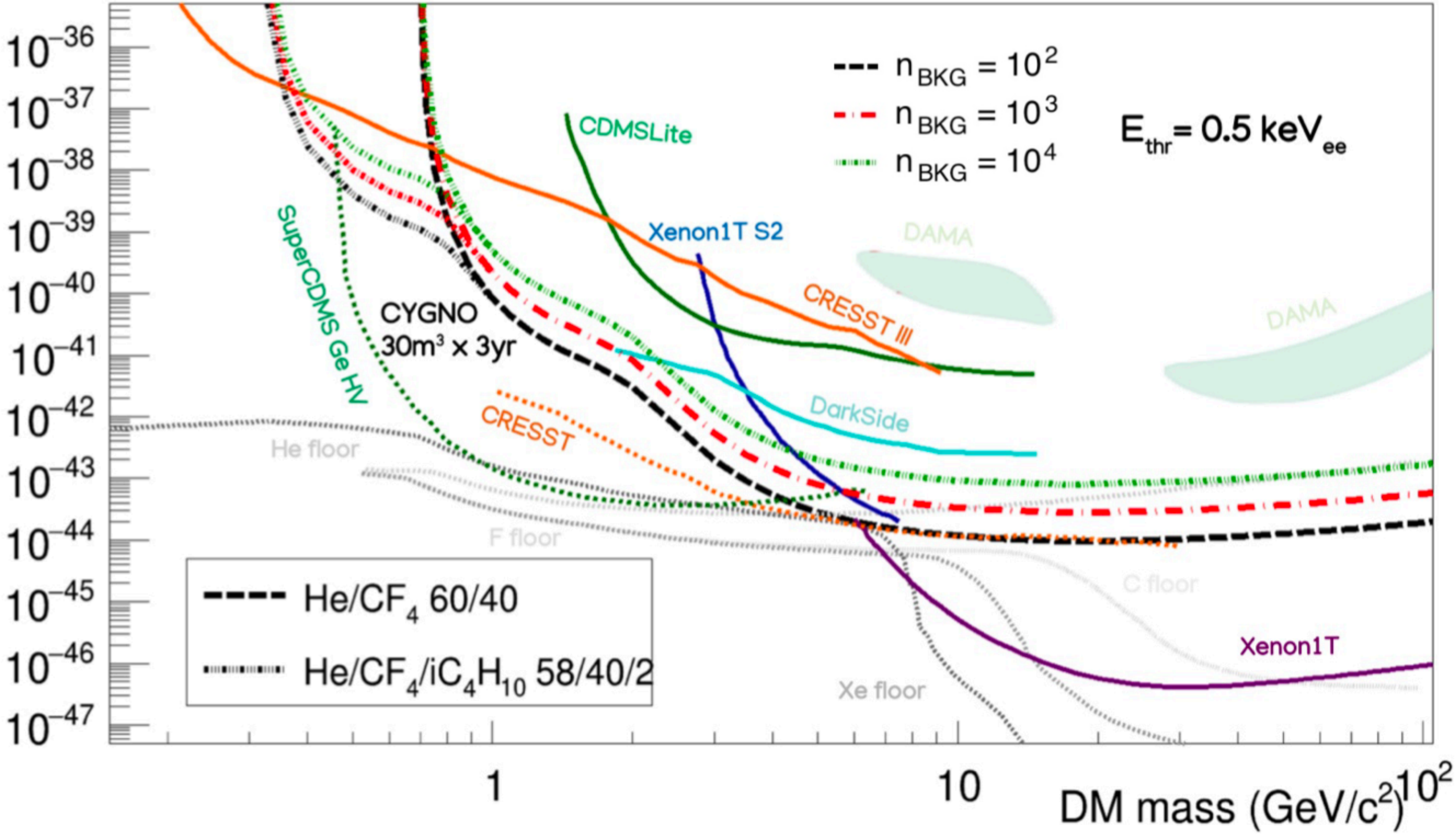


<u>THIS IS NOT</u> the goal of CYGNO-04, but as nice byproduct we have the potentialities of:

- ***put the best directional limit on SD improving on several order of magnitude w.r.t. other directional experiments***
- ***put the first directional limit on SI, probing the DAMA region (also for SD)***

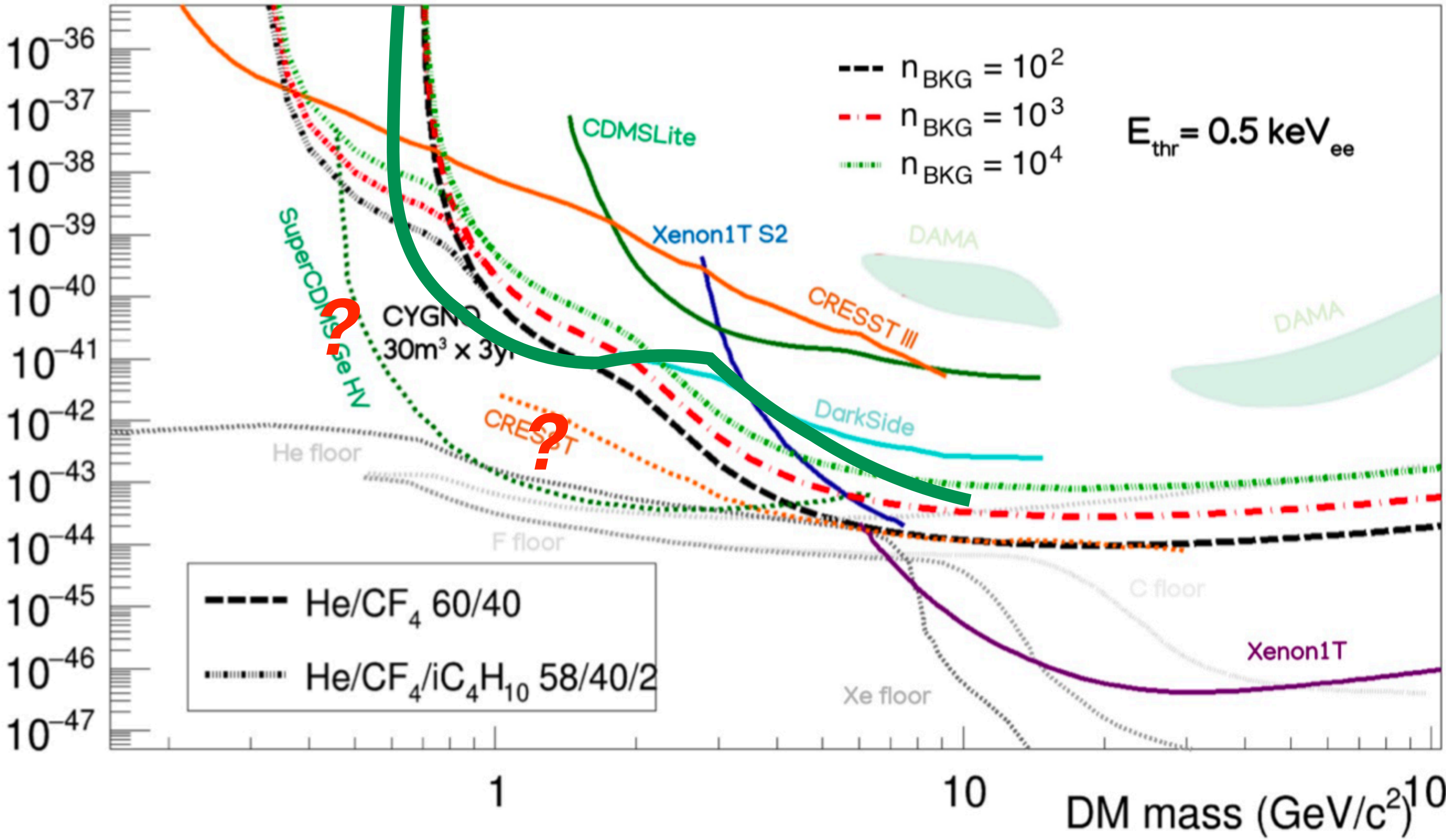
CYGNO-30 vs bolometers & S2 analyses

Note: in this case, rough evaluation of background after rejection consistent with our of our sensitivity evaluation hypothesis after assuming capability of reducing internal backgrounds of about a factor 50-100 w.r.t. CYGNO-04

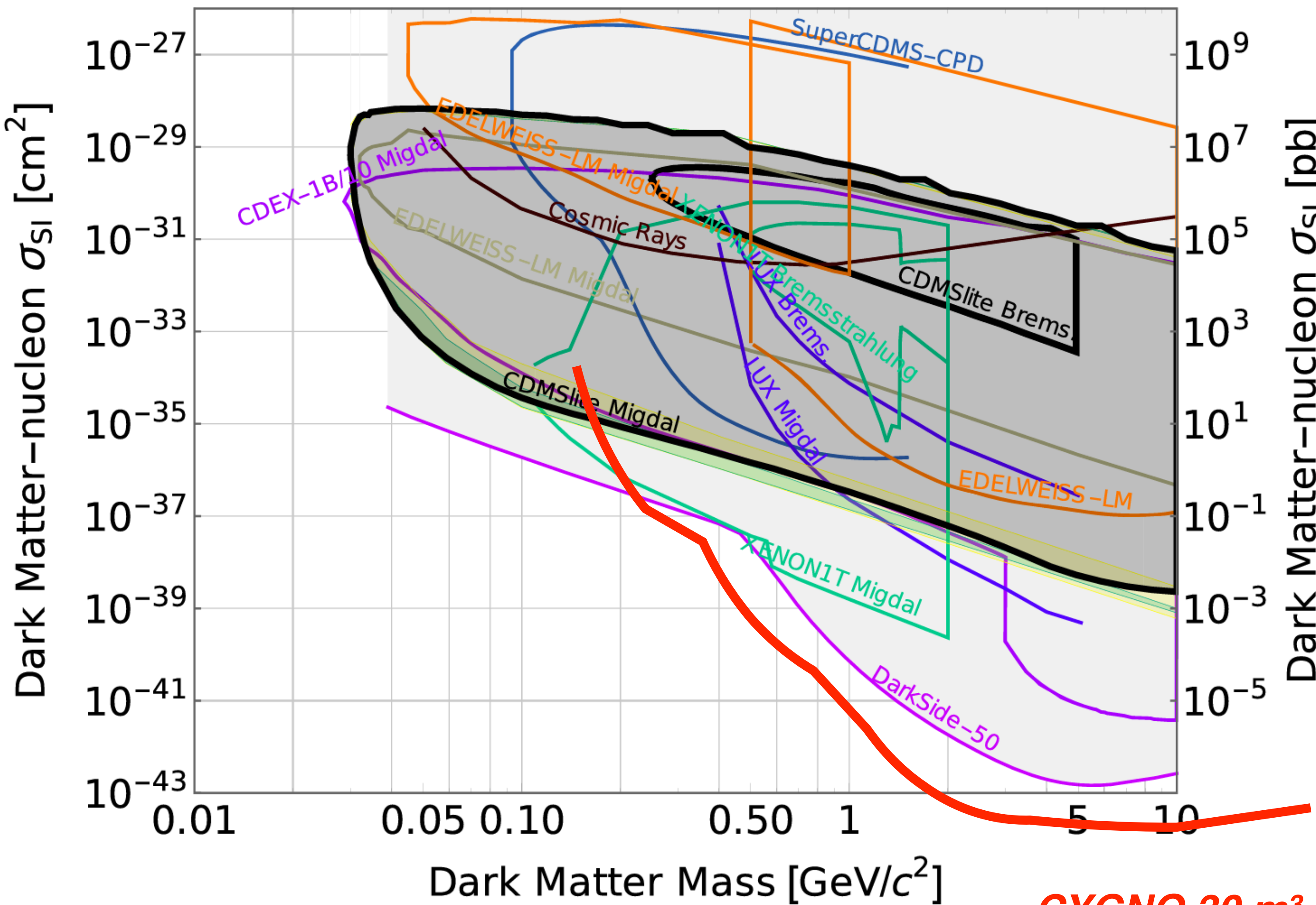


CYGNO-30 vs bolometers & S2 analyses

SuperCDMS Si iZip with 10^{-5} rejection @ 10 keV

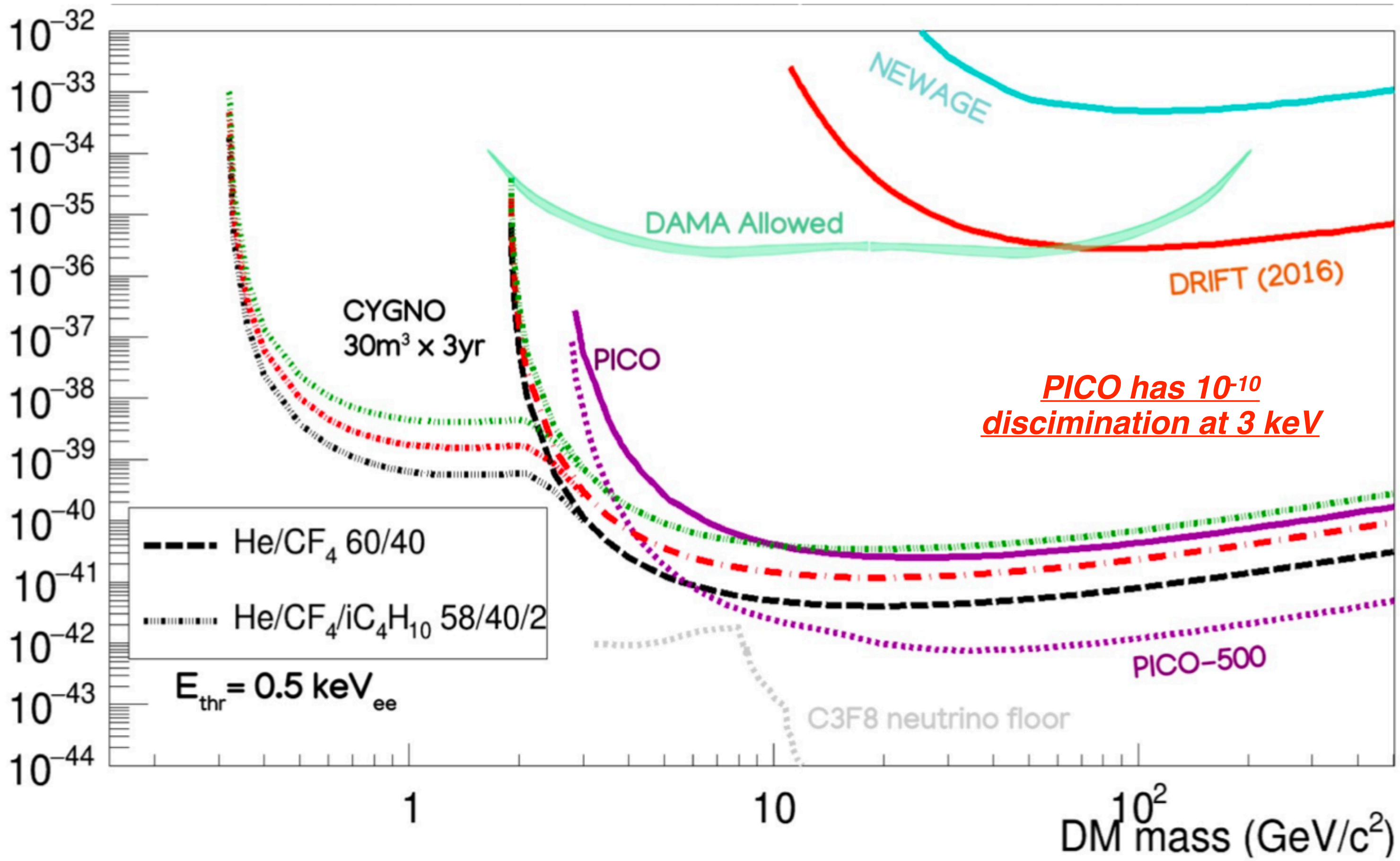


CYGNO-30 vs Migdal



CYGNO 30 m³ 3 year 10000 bkg events 0.5 keV threshold with He:CF_4:iC_4H_{10}

CYGNO-30 SD reach



- PICO is a threshold detector, i.e. no event energy measurement (only lower limit): if a DM-like signal event is observed, no possibility of constraining DM mass vs coupling
- Improvement of 6-7 order of magnitude with respect to current directional limits
- With Hydrogen doping, unique capability to extend sensitivity to a WIMP mass region not explored by any other experiment.

Many thanks to you all for your contribution to the success of the CYGNO project

I told you since the start it was biased ;)

Backup slides

Comparison of "neutrino floors"

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

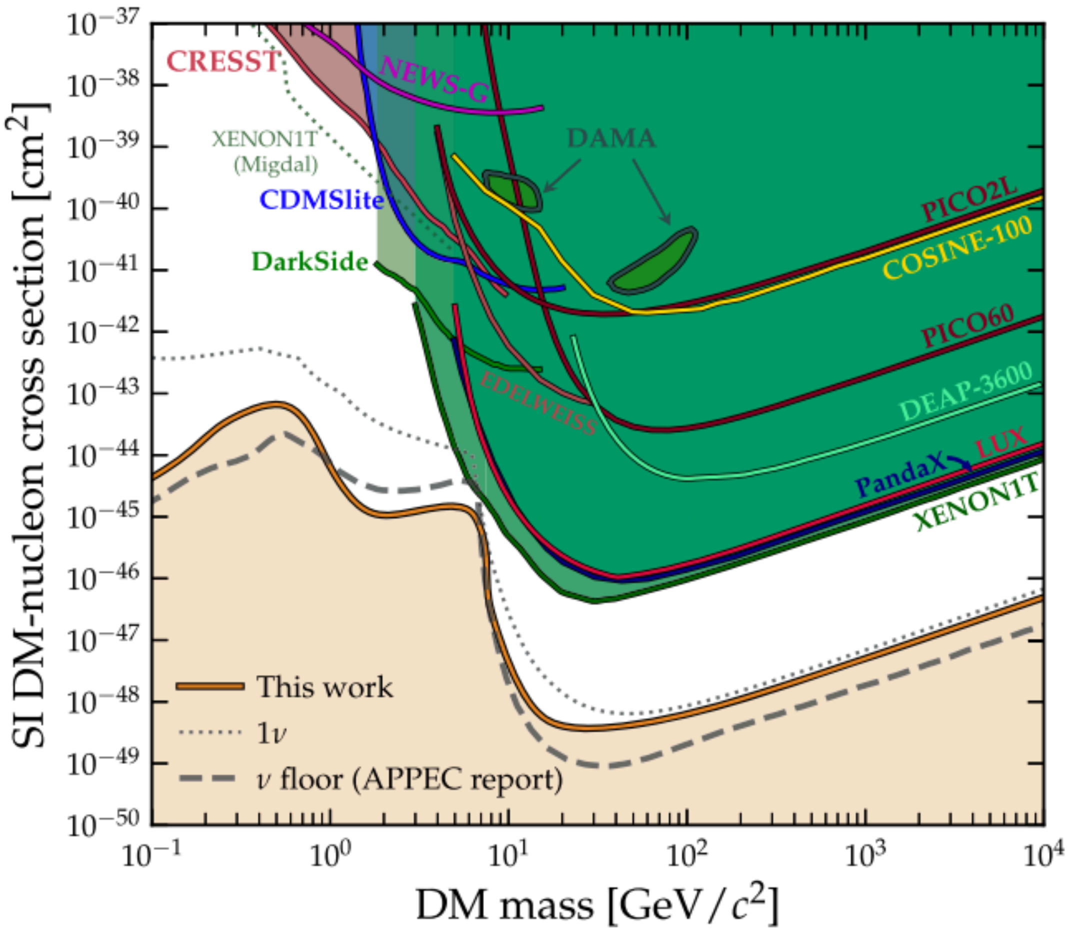
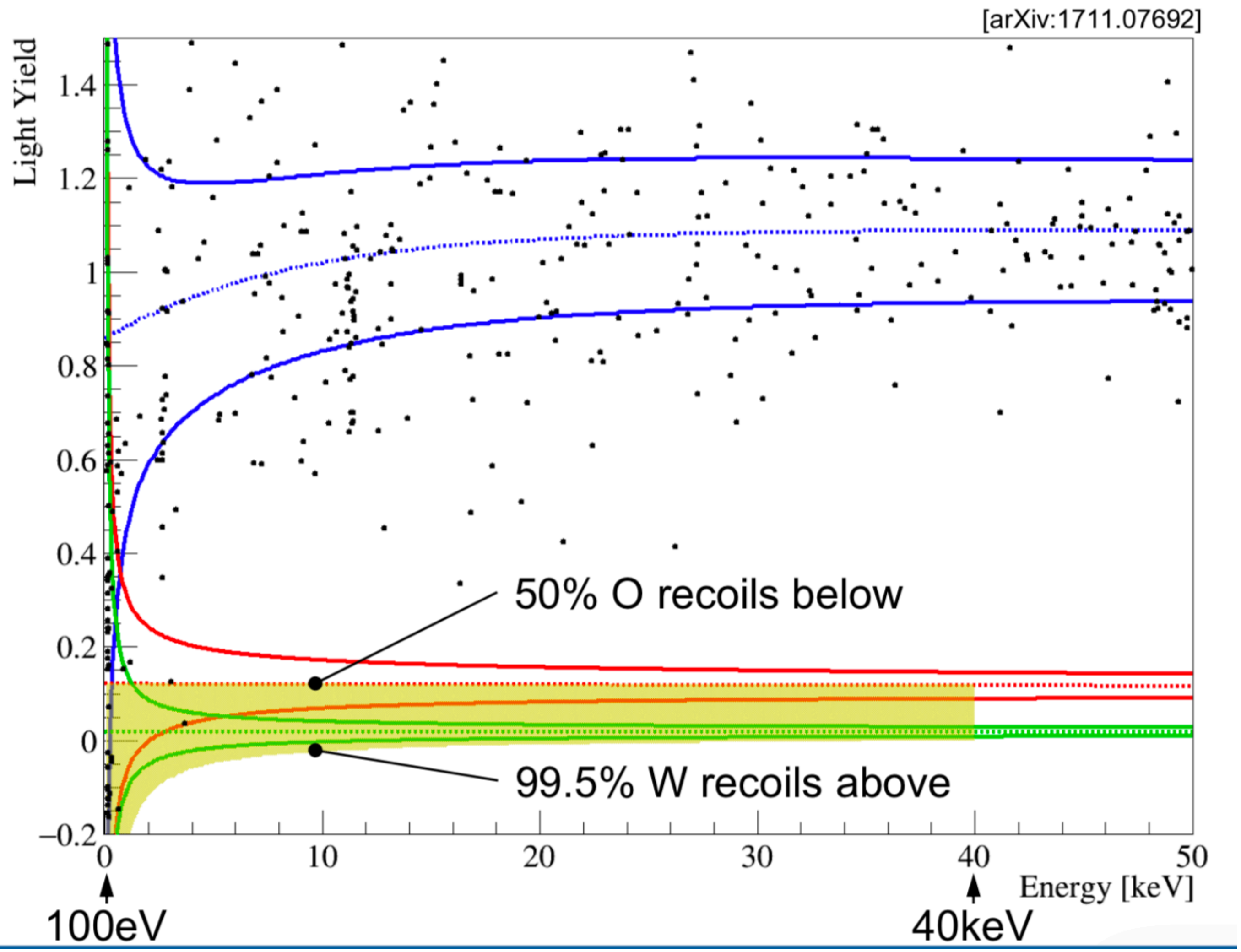


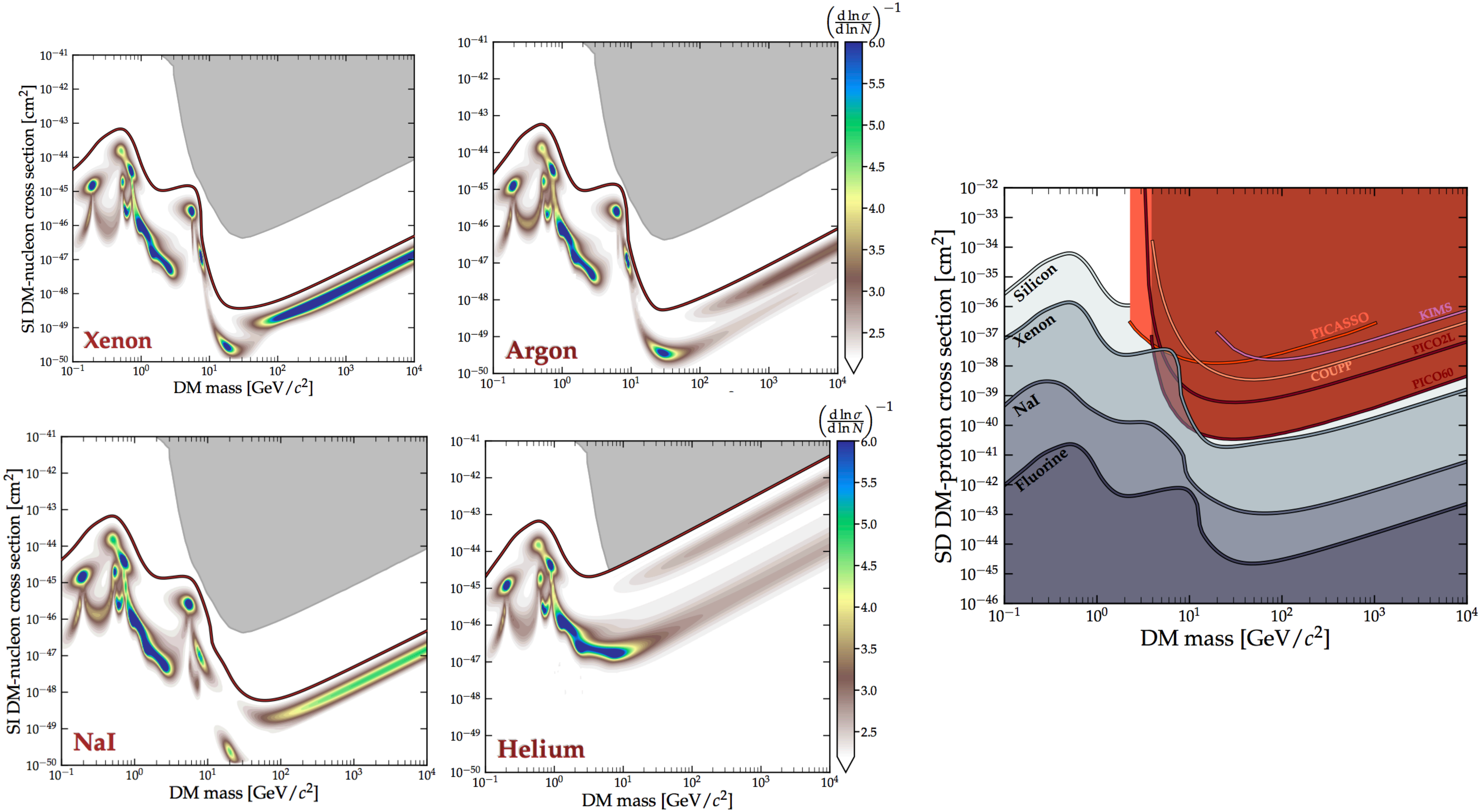
FIG. 1. Present exclusion limits on the spin-independent DM-nucleon cross section (assuming equal proton or neutron couplings) [7,58–71]. Beneath these limits we show three definitions of the neutrino floor for a xenon target. The previous discovery-limit-based neutrino floor calculation shown by the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

CRESST data from det A



Nuetrino fog for various targets

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



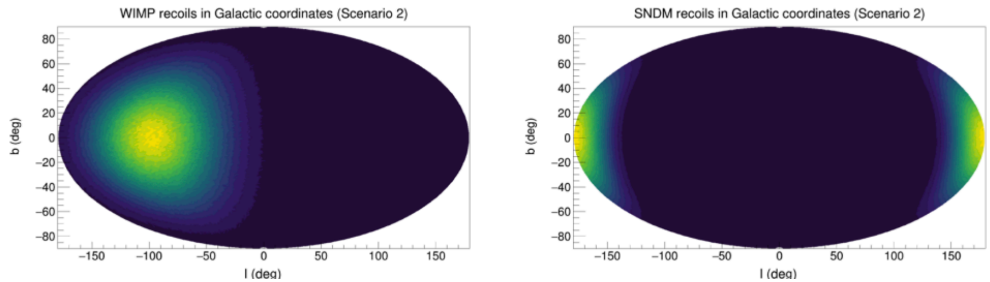
Not only WIMP Dark Matter: potentialities for discovery of MeV DM from SN with directionality

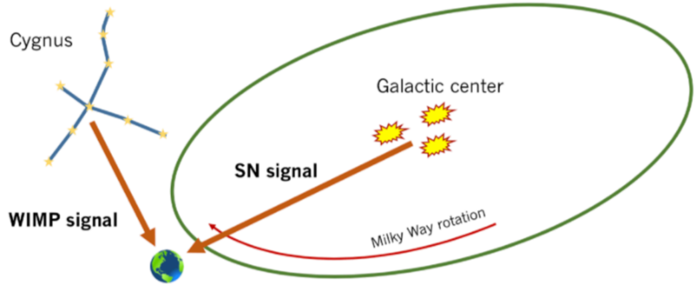
Discovering supernova-produced dark matter with directional detectors #1

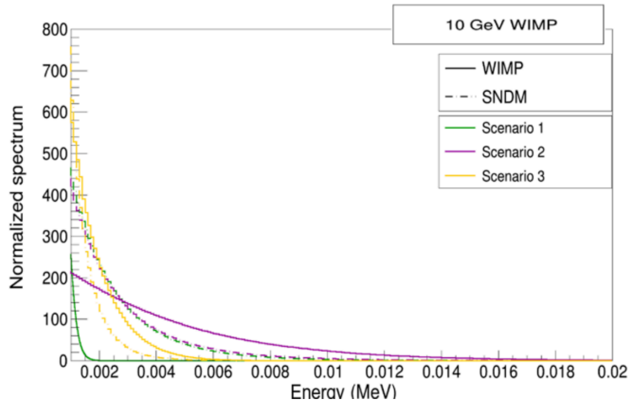
Elisabetta Baracchini (GSSI, Aquila and Gran Sasso), William Derocco (Stanford U., ITP), Giorgio Dho (GSSI, Aquila and Gran Sasso) (Sep 18, 2020)

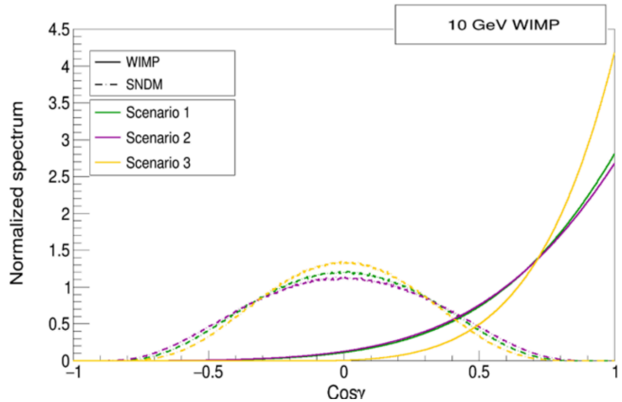
Published in: *Phys.Rev.D* 102 (2020) 7, 075036 • e-Print: 2009.08836 [hep-ph]

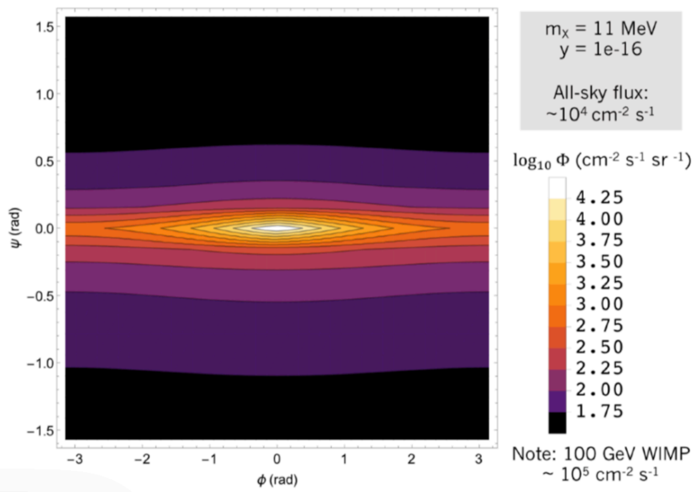
W. DeRocco, P. W. Graham, D. Kasen, G. Marques-Tavares, and S. Rajendran, Phys. Rev. D **100**, 075018 (2019).

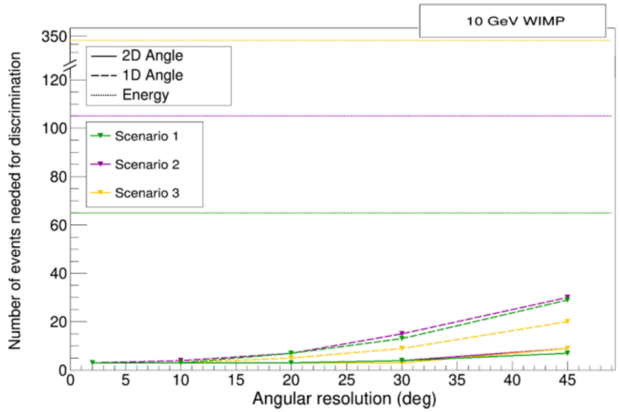


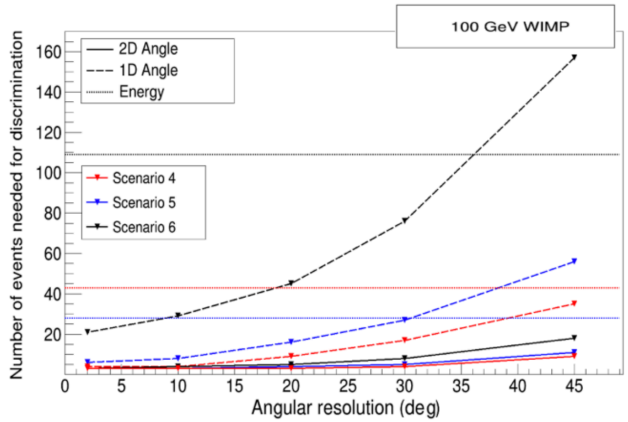






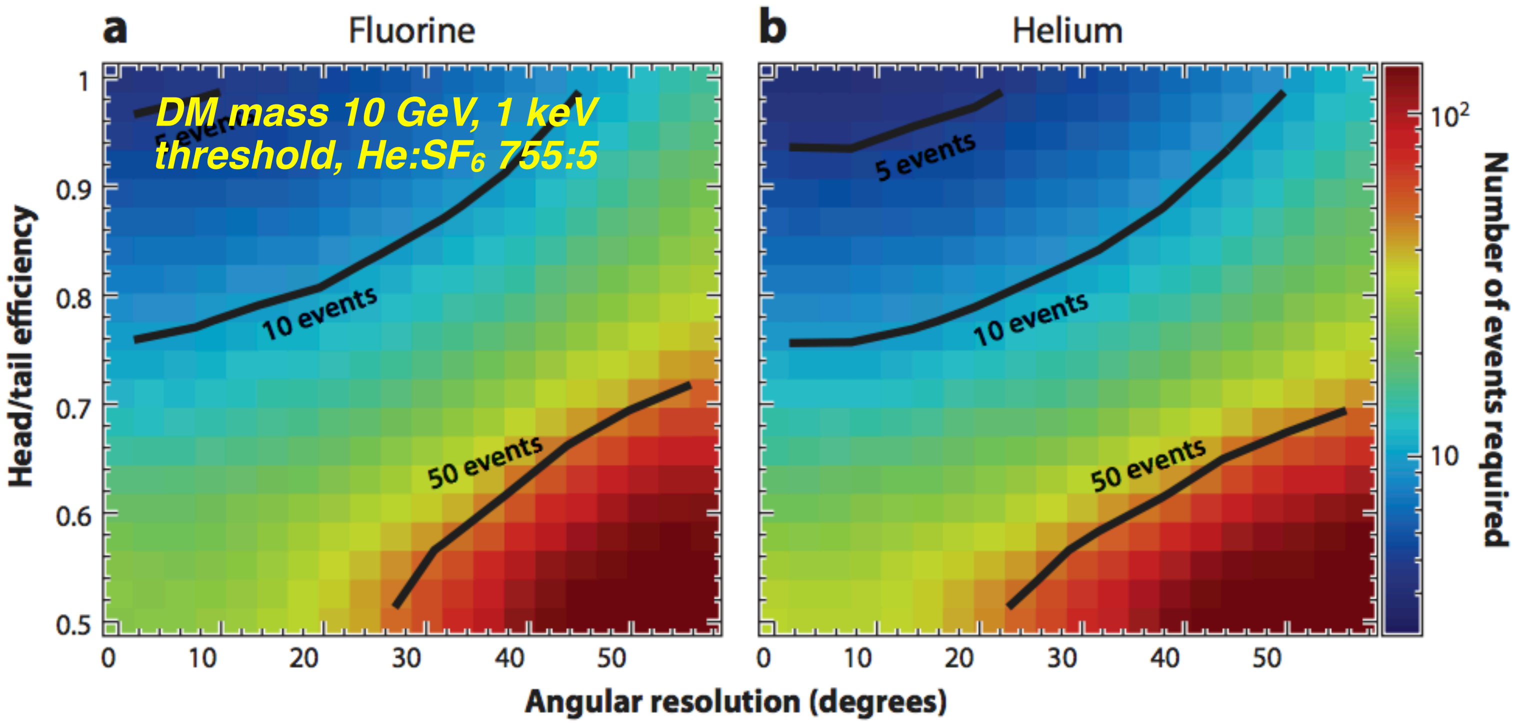






The importance of HT

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
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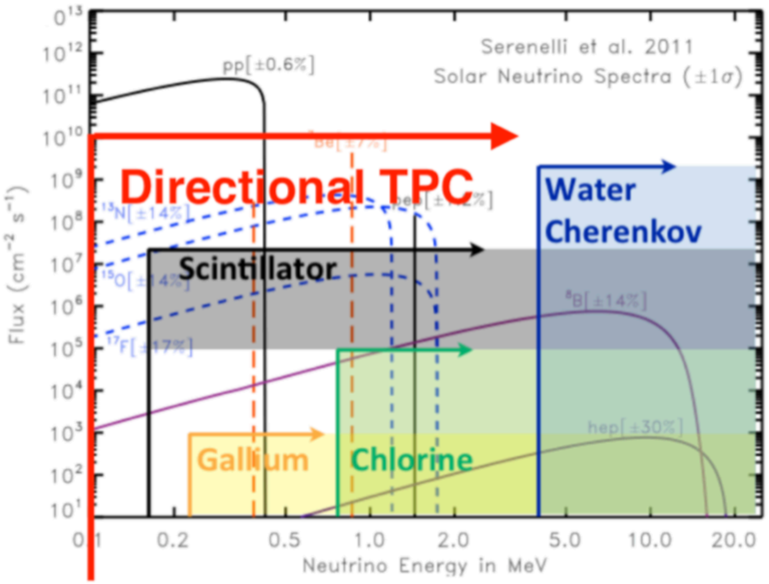
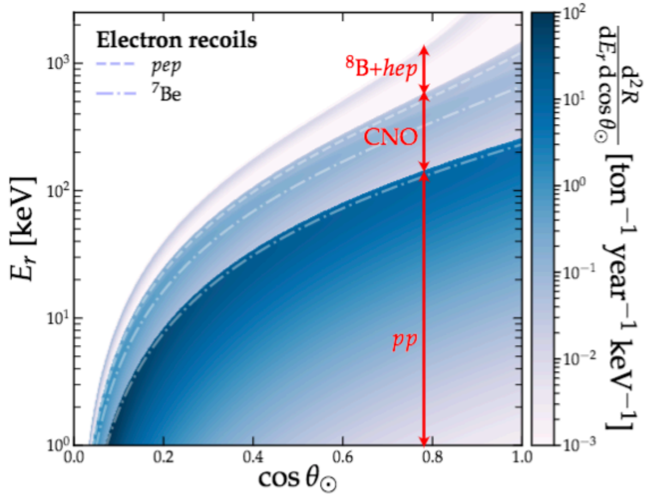
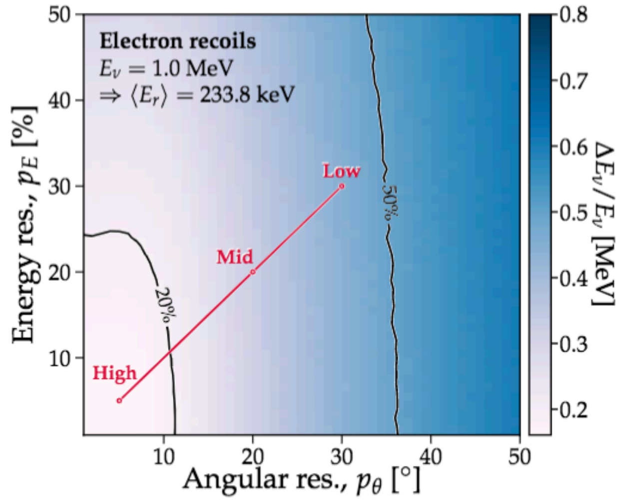
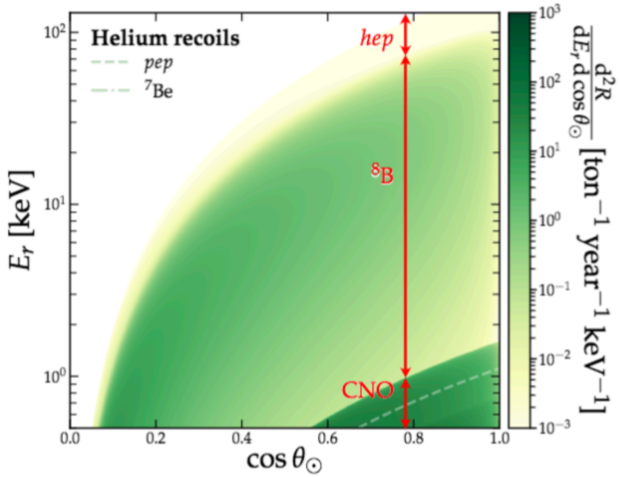
Received 25 July 1995; revised 24 October 1995









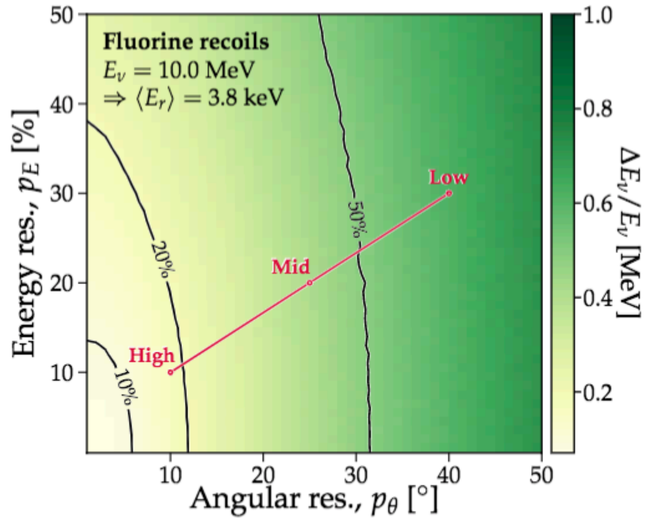


Table 1 Approximate expected numbers of neutrino-induced nuclear and electron recoils[a]

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.

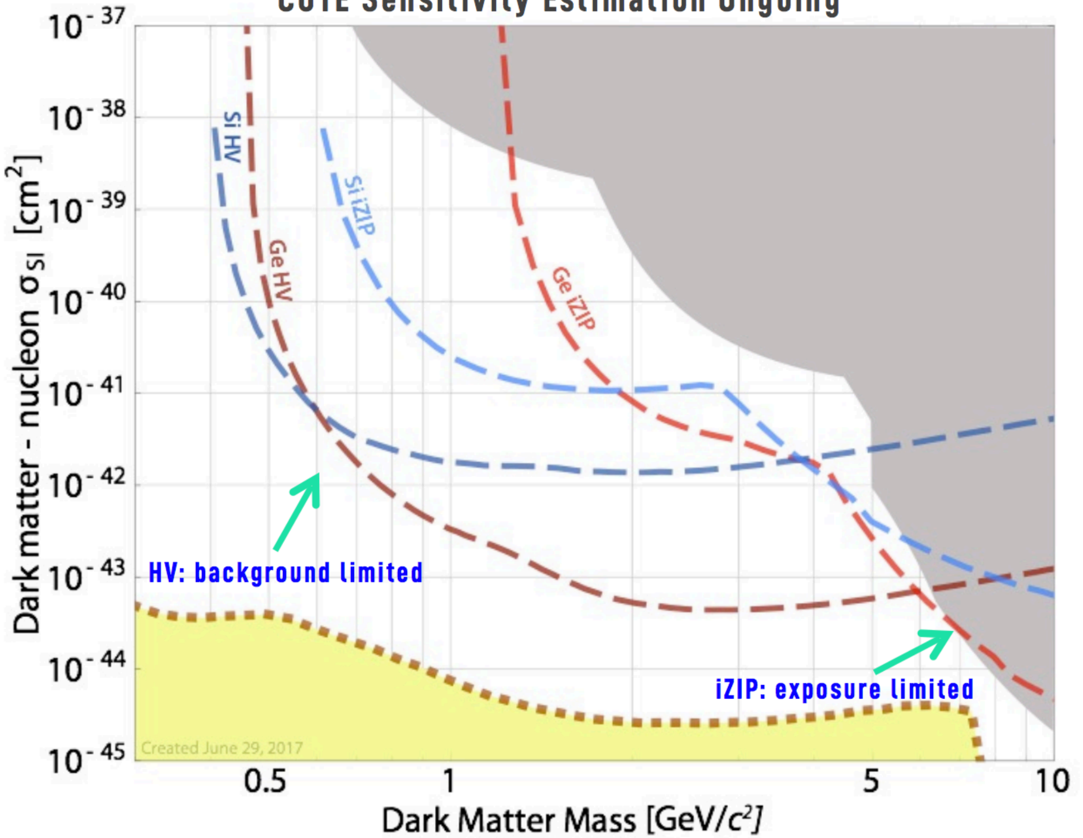
SuperCDMS expected sensitivity

	Soudan	SNOLAB
Phonon resolution, eVt	~250	10 HV, 50 iZIP
HV Bias Voltage, V	70	100
iZIP Charge resolution, eVee	~400	160
HV Threshold, eVnr	300	40

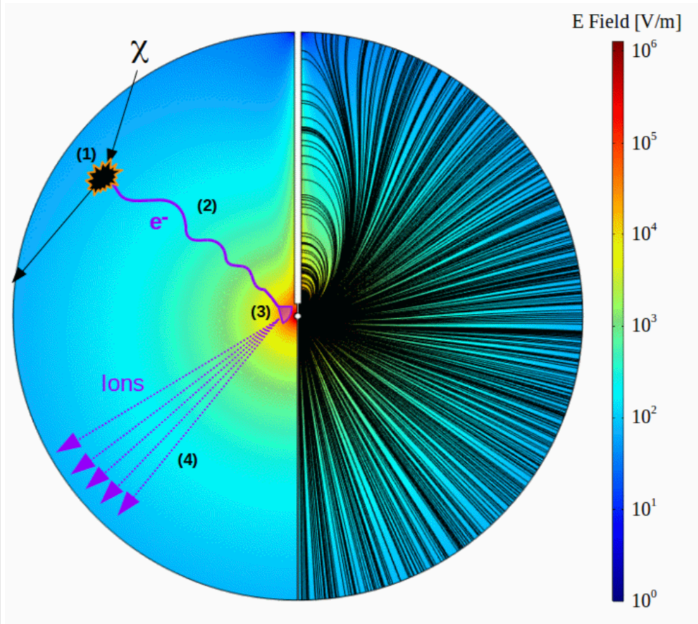
.....to my knowledge, not yet demonstrated

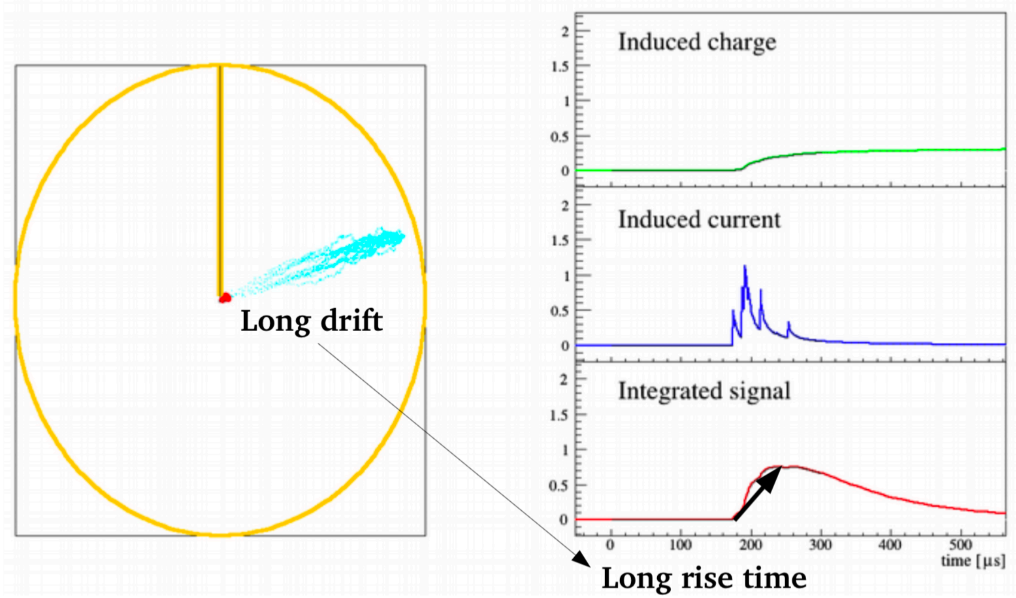
SUPERCDMS FULL OPERATION WILL START FROM ~~2021~~ *2022?*

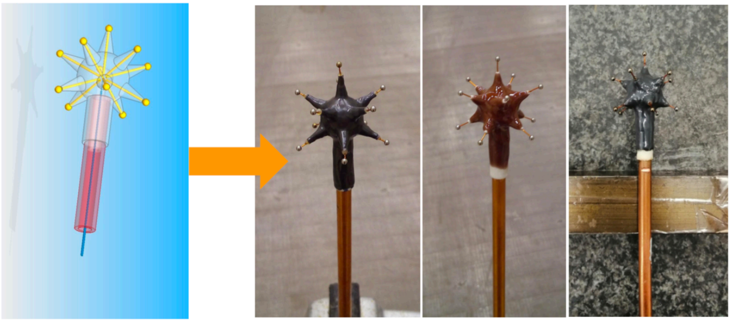
CUTE Sensitivity Estimation Ongoing



News-G





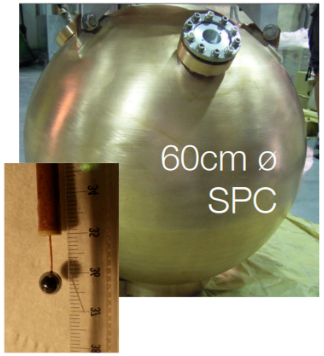


only surface event discrimination via diffusion, no ER/NR

…even with achinos, field lines on sphere north emisphere very weird

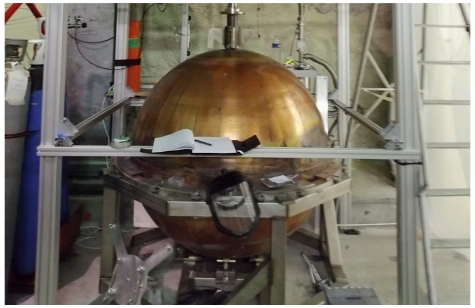
Aim at maximal radiopurity (…the bigger you go, the more radiocontaminants you discover…..)

News-G latest results

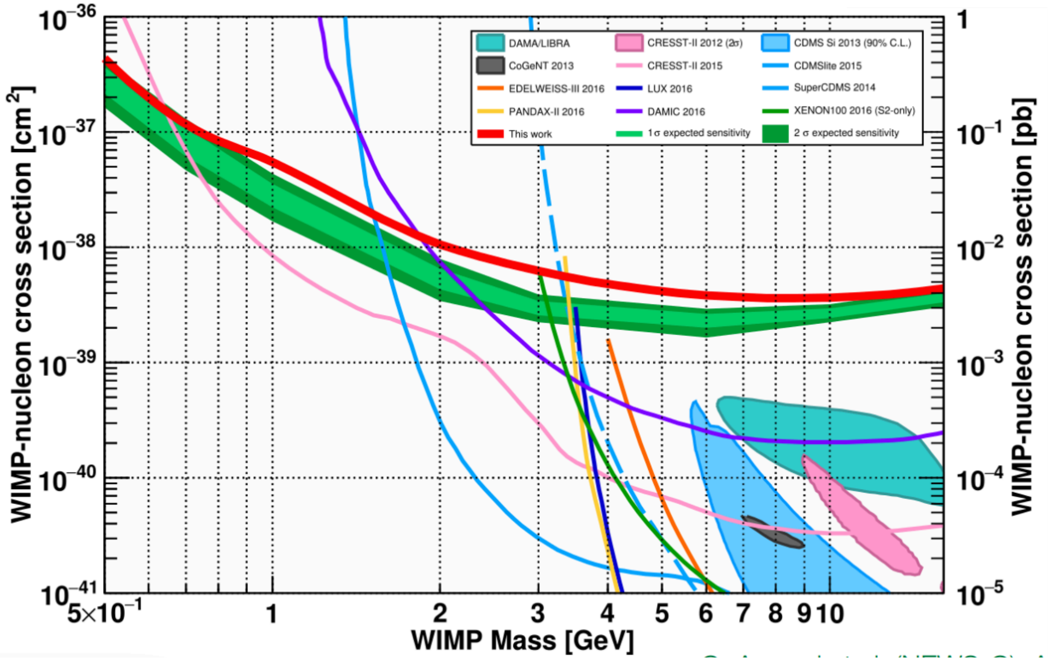


3.1 bars of Ne
+ 0.7% CH_4

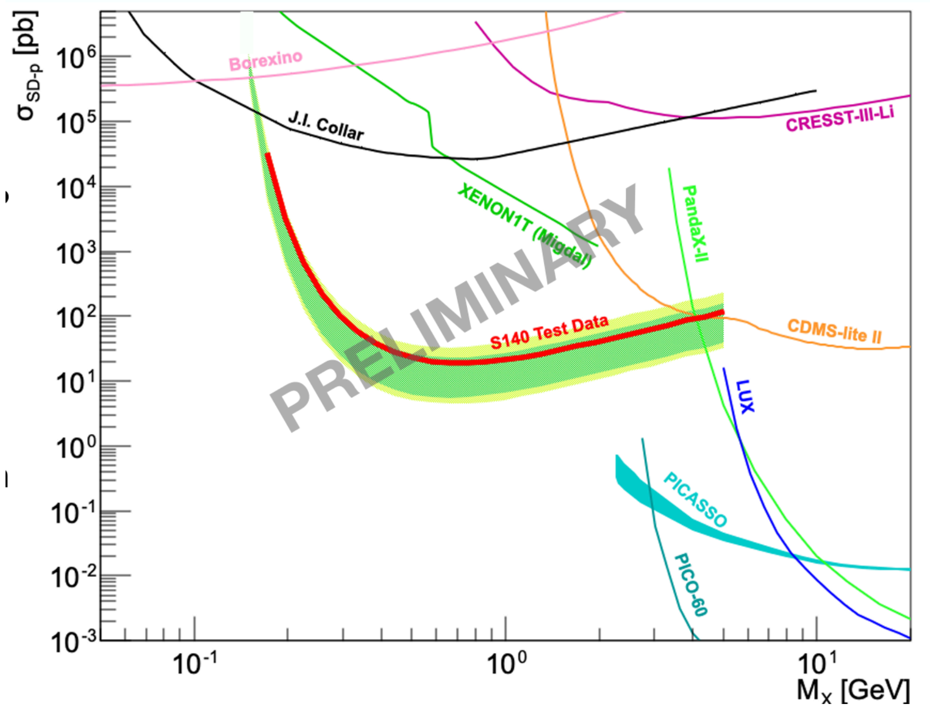
42 days of data



- Constructed and first operated in LSM
- Initial commissioning data taking in LSM
  - **UV Laser and ^{37}Ar calibration systems**
  - **Multi-anode sensor - ACHINOS**
- Temporary lead + water shielding installed end 201
- **~10 days of commissioning data taken**
  - **135 mbar of CH4 (~100g)**



Constraints on Spin-Dependent WIMP-protoncross-section



SNOGLOBE (140 cm diameter) now taking data at SNOLAB with Ne+CH_4

NOTE: pure CH_4 operation at >= 1 bar are dangerous…..

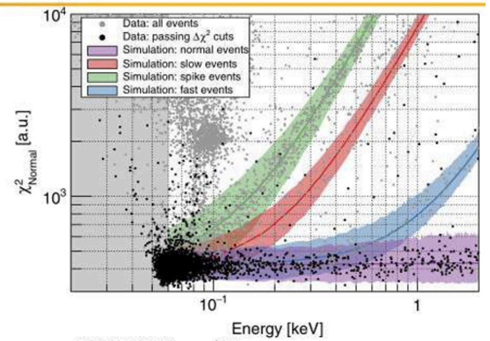
EXCESS studies

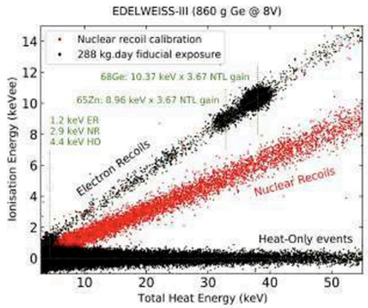
Review on Low-Energy Excess Signals Observed in Cryogenic Rare Event Search Experiments - J. Gascon

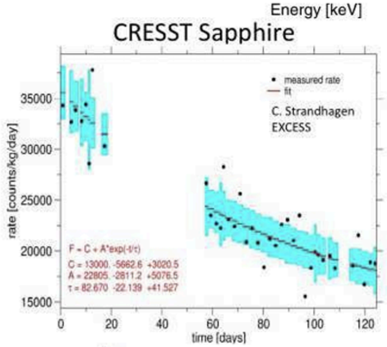
EXCESS

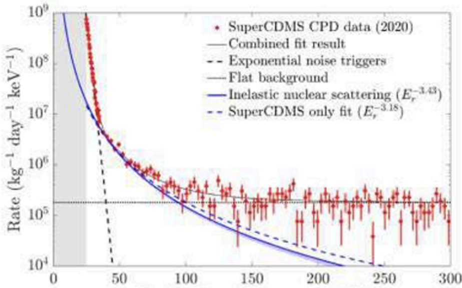
Key features to study and compare

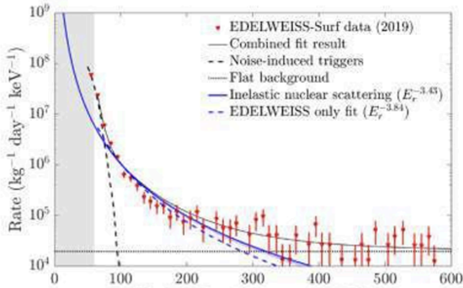
- Rise and decay times of event
  - Faster/slower pulse: indications of nature/location of event
- (Non-) ionizing nature of event
- Timing
  - Coincidence with external events?
  - Correlation between successive events?
- Variation of rate with time since cool-down
  - Consistent with known radioactive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











Belina von Krosigk | Margarita Kaznacheeva

IDM 2022

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 $\delta\Phi$ on neutrino fluxes**

Background free

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

Poissonian background subtraction

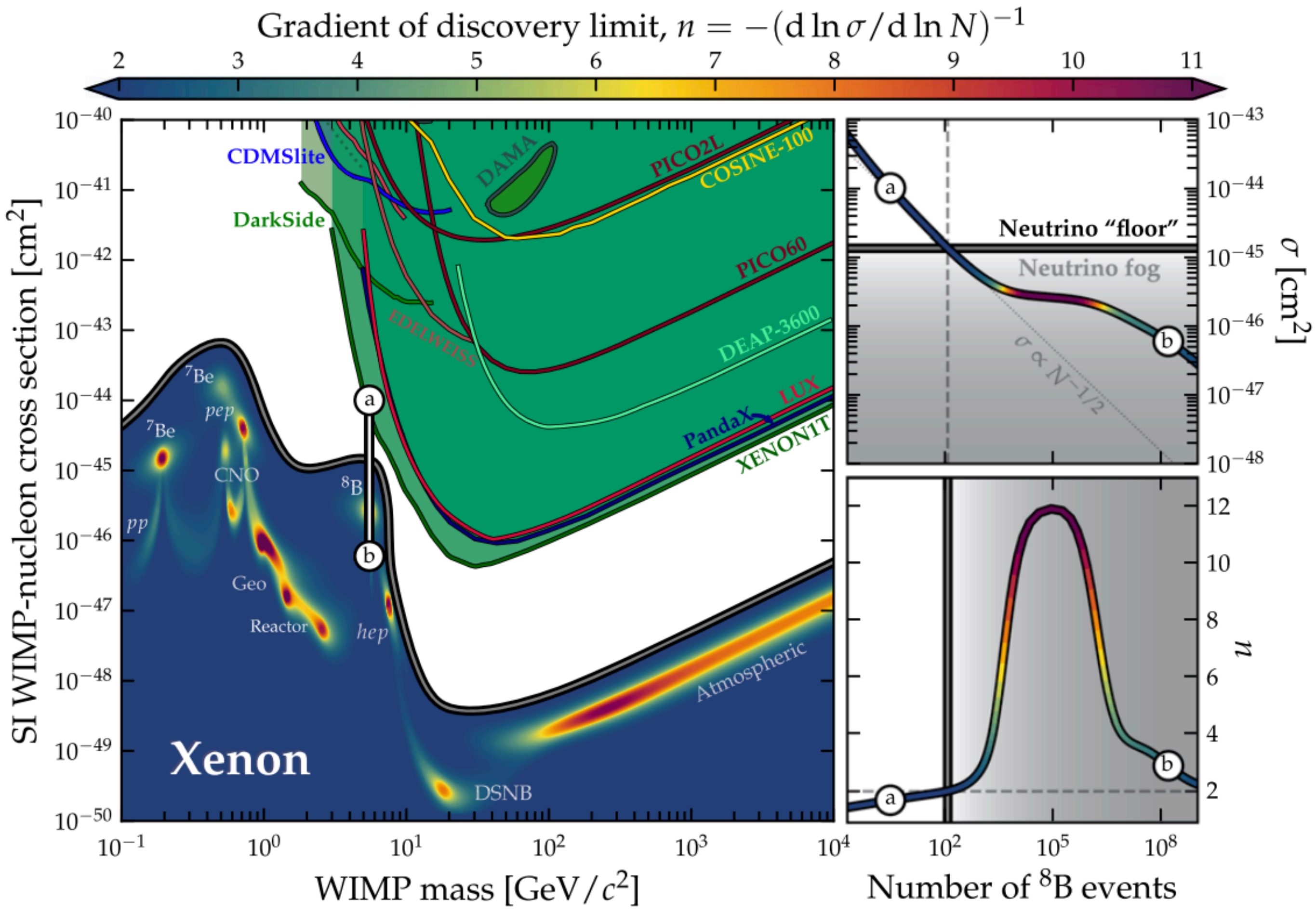
$$N\delta\Phi^2 \ll 1, \sigma \propto 1/\sqrt{N}$$

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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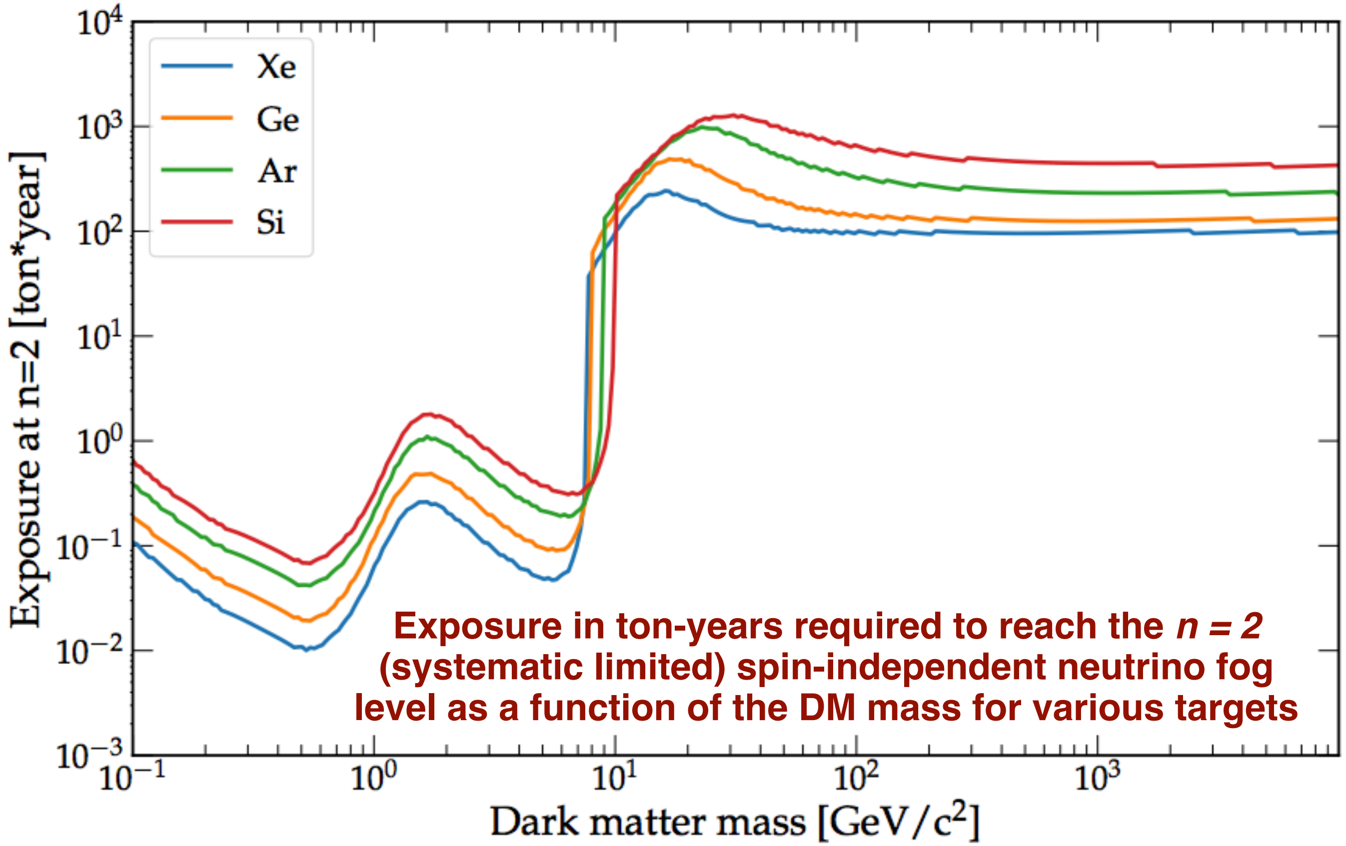
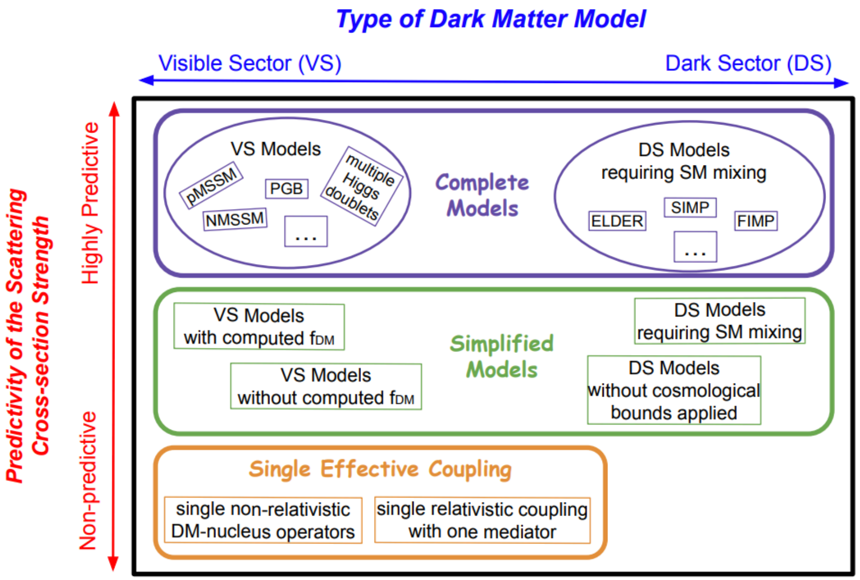
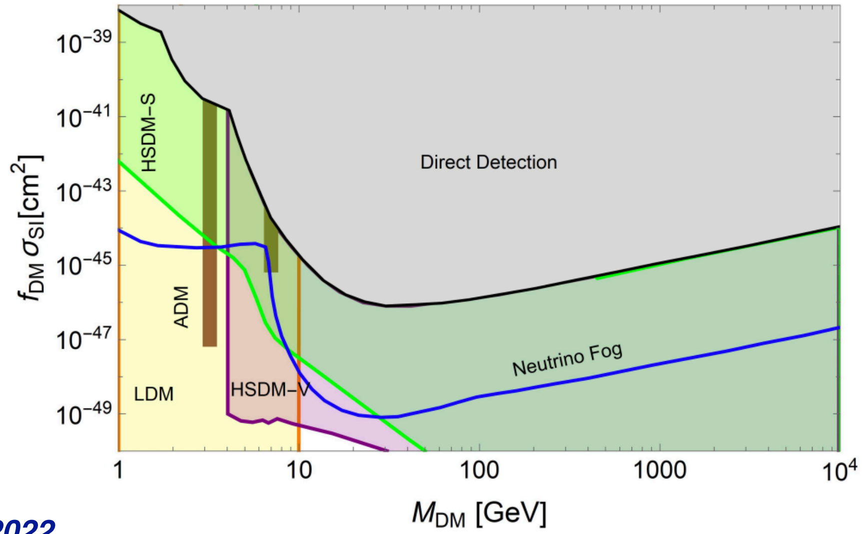


Exposure in ton-years required to reach the *n = 2* (systematic limited) spin-independent neutrino fog level as a function of the DM mass for various targets

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

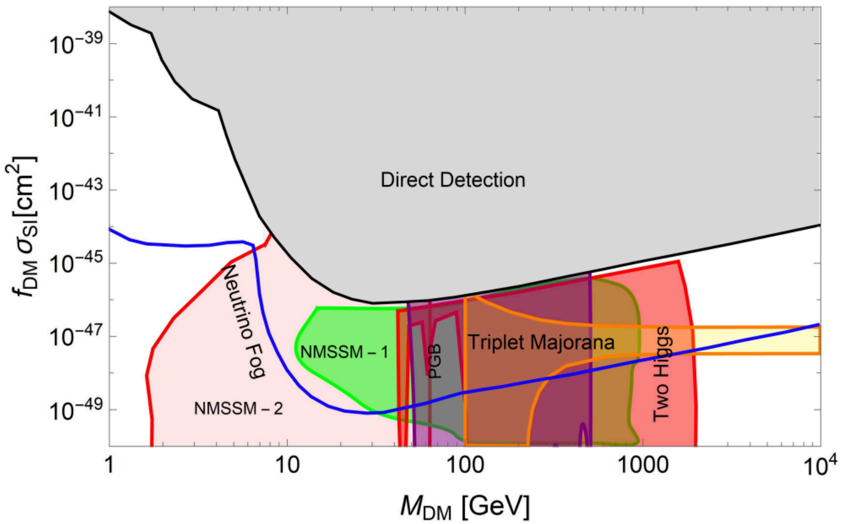
The need to penetrate the fog



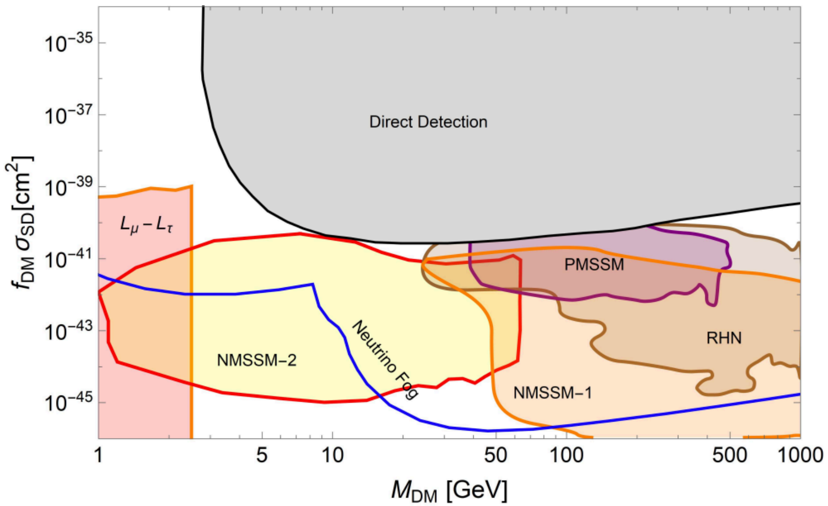


Dark sector models SI

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



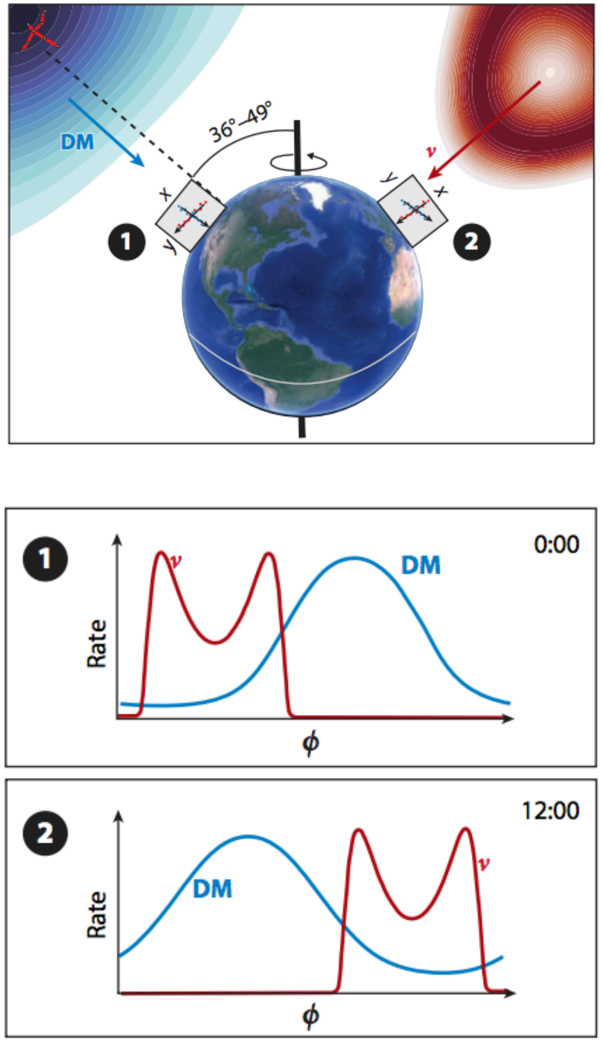
Visible sector models SI



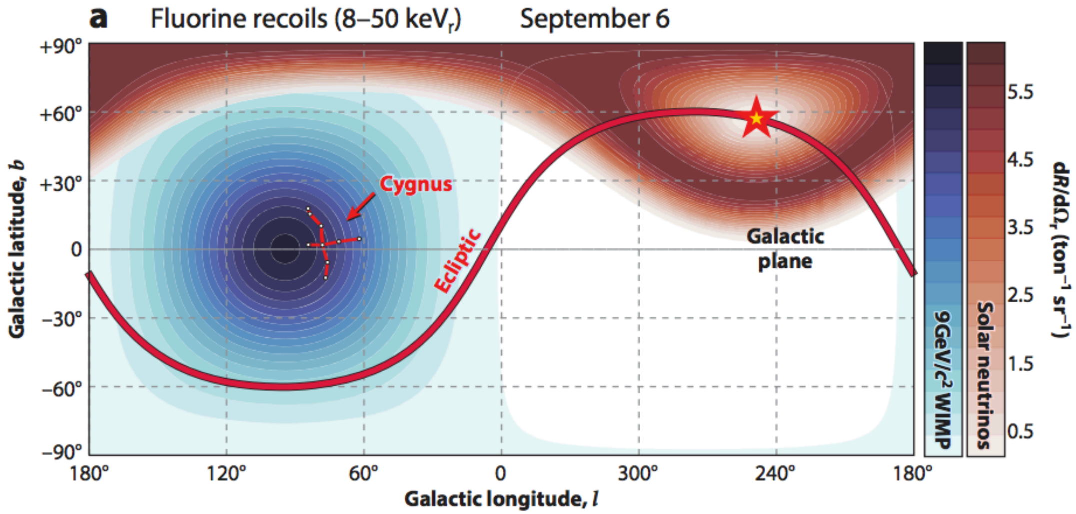
Visible sector models SD

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 180º 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"