Searching in the dark:

in the hunt for WIMPs

COSMO 22
Rio de Janeiro, Brasil, 22-26 August 2022

Isabel Lopes
LIP & Universidade de Coimbra, Portugal

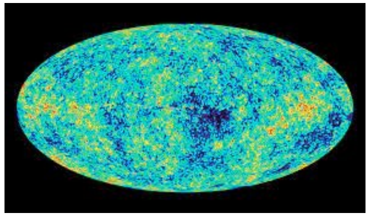
Credits: NASA, ESA, CSA, and STScI

The case for dark matter (DM)

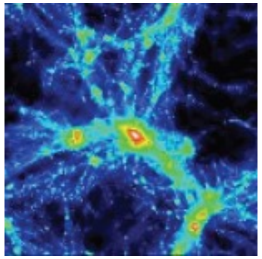
Plenty of (gravitational) evidence for dark matter at all scales

Size

Cosmological observations

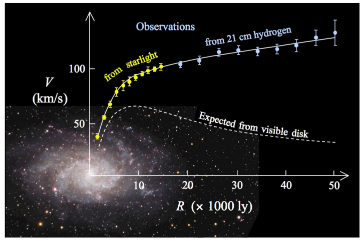


Cosmic Background Radiation



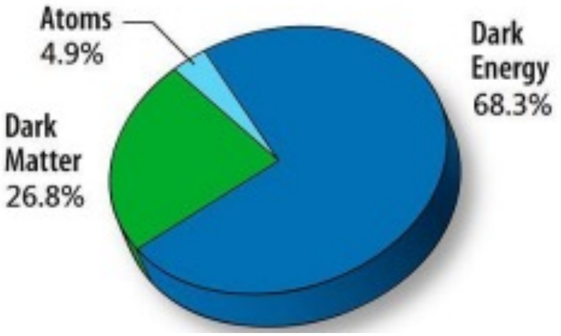
Clusters of galaxies

Galaxy mergers



Rotation curves

Gravitational interaction



For reviews on the dark matter evidences, see e.g.:
GB, Hooper & Silk, hep-ph/0404175. Bergstrom, hep-ph/0002126

Dark matter candidates

Adapted from GB, Tait, Nature (2018)1810.01668

Weakly **I**nteracting **M**assive **P**articles (WIMPs)

- If dark matter was in **thermal equilibrium** in a **radiation-dominated** universe:
  1) The dark matter particle must be heavier than a few MeV (to be compatible with the predictions of BBN)
  2) The dark matter particle must be lighter than ~100 TeV (not to exceed the measured dark matter abundance)
- To **freeze-out** with the measured abundance, DM particle must annihilate via an interaction comparable to the weak force

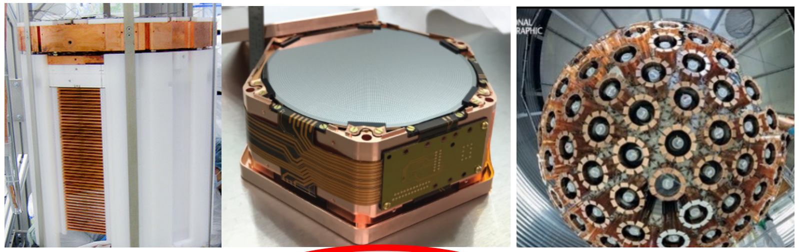
Dark matter candidates with roughly weak-scale masses and interactions –WIMPs – are well motivated

Weakly **I**nteracting **M**assive **P**articles (WIMPs)

A general class of particles that :

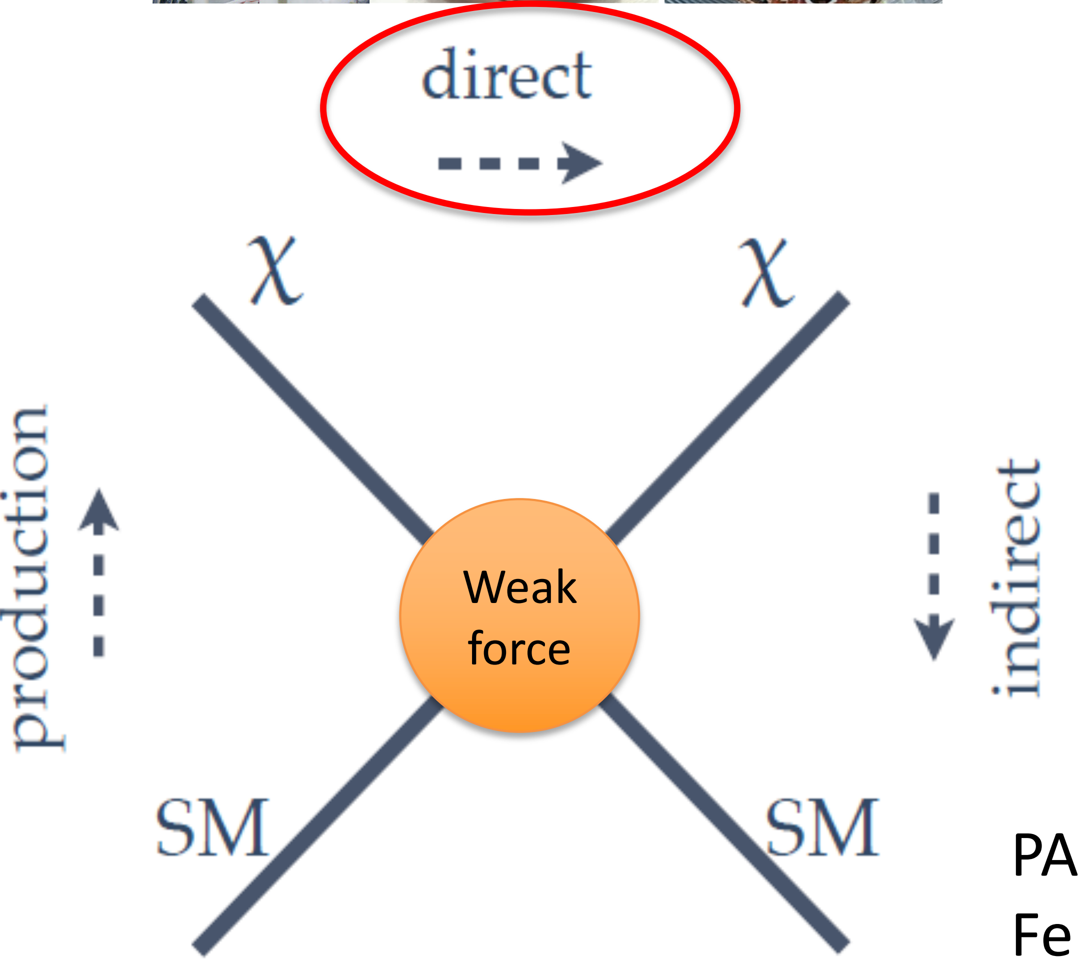
- Are "cold" (not-relativistic)
  - to be compatible with the large scale structure of the universe
- Are stable
  - half-life at least comparable to the age of the universe
- Are non-baryonic
- Do not interact via electromagnetic or strong interactions
- Have mass between ~1 GeV and ~ 100 TeV
  - Thermal production fails to explain DM abundance beyond this range (~MeV if EW gauge bosons are not involved)

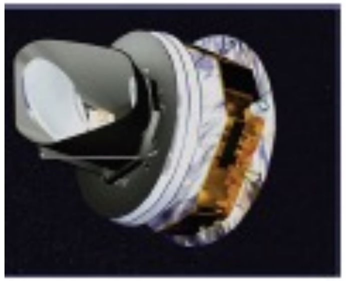
WIMP Searches



Accelerator searches (DM production)

LHC

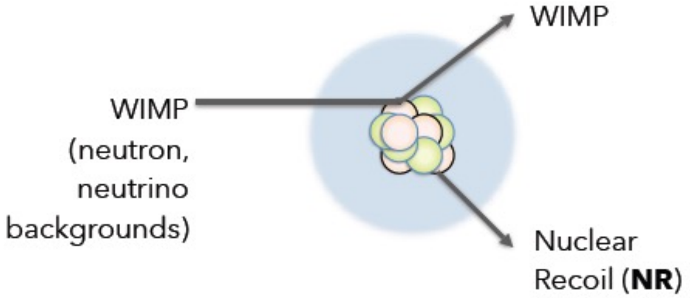


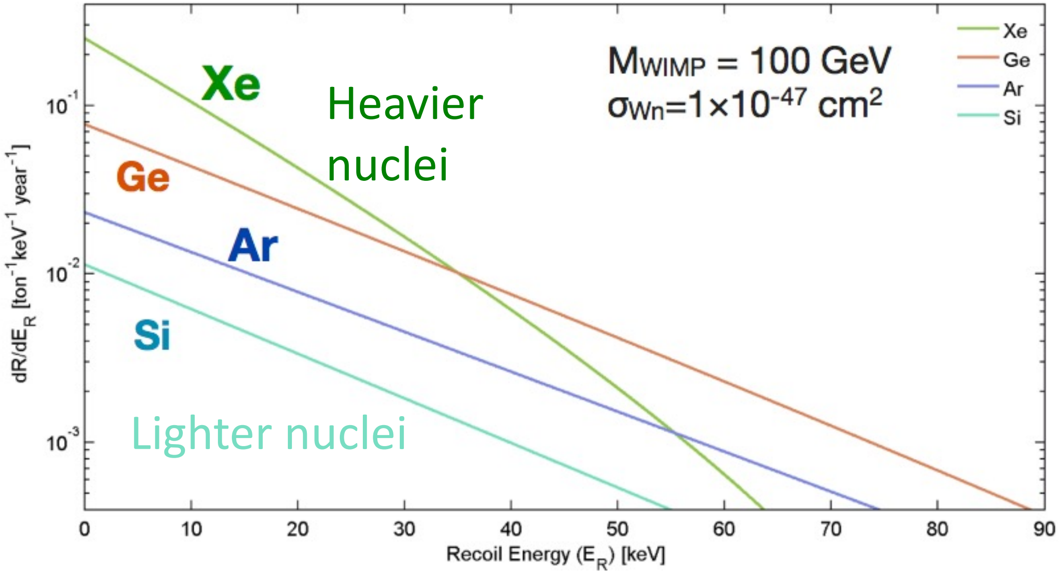


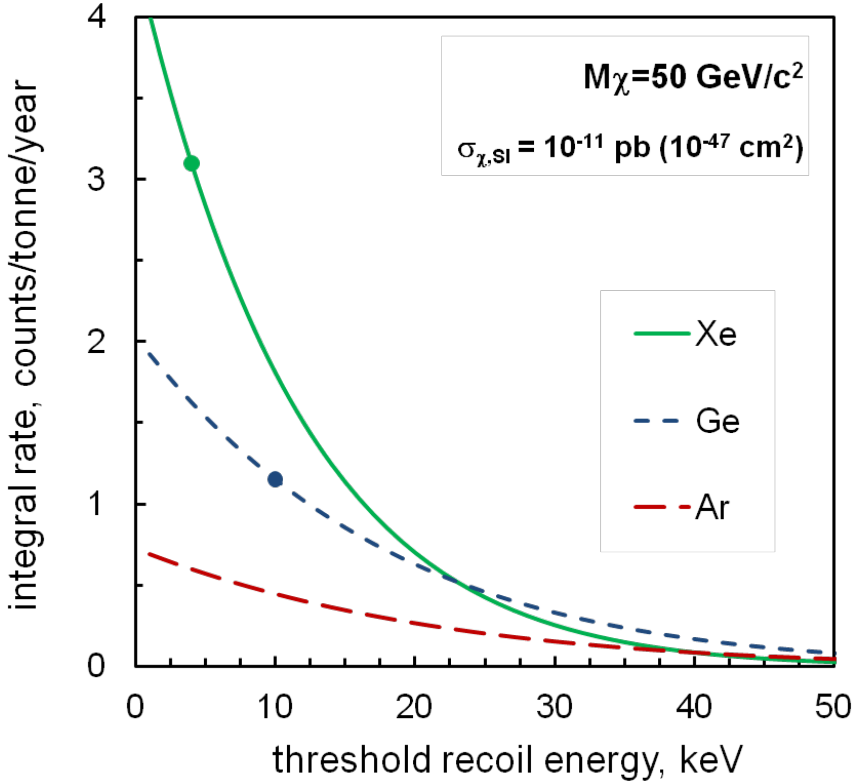
Indirect detection (DM annihilation)

PAMELA, ANTARES,
Fermi, IceCube, AMS
MAGIC, CTA, HESS

WIMP direct detection







For a threshold of the order of a few keV, total expected interaction rate for M_{WIMP}=50 GeV/c²

~ 1 event/tonne/year

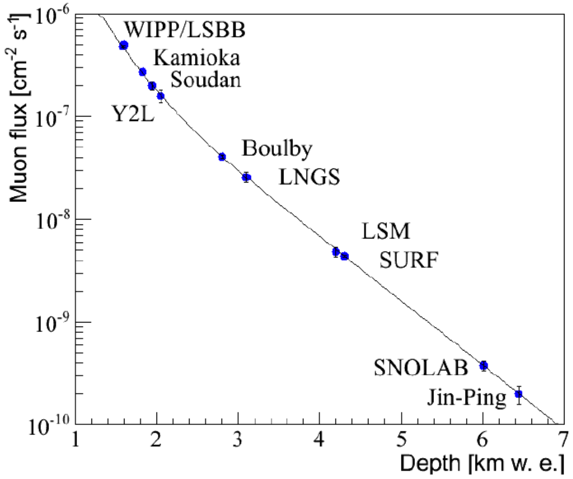
- Nearly exponential, featureless spectrum
- The detector energy threshold must be as low as possible
- **E_R typically < a few tens keV**

Isabel Lopes, COSMO 22

WIMP direct detection: backgrounds

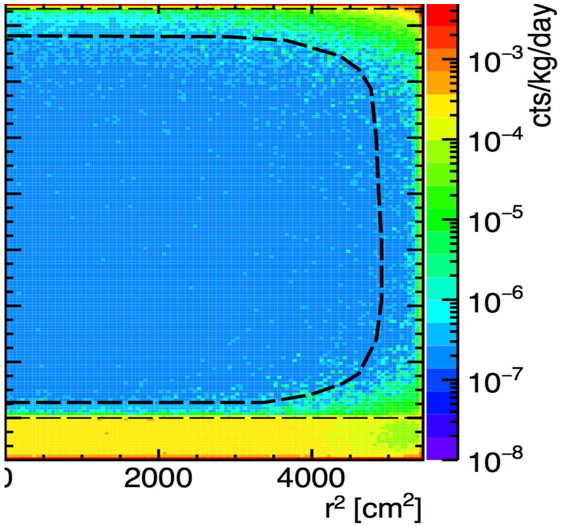
Main sources:

- Cosmic rays & cosmic activation of detector materials: μ, n, γ, α
- Natural (^{238}U, ^{232}Th, ^{40}K, **radon**) & anthropogenic (^{85}Kr, ^{42}Ar, ^{137}Cs) radioactivity: γ, e^-, n, α
- Ultimately: neutrino-nucleus scattering



How to cope with them:

- Operation deep underground
- Select ultra low radioactivity materials
- Use of passive and active veto detectors (e.g. muon Cerenkov in water, neutron capture on Gd)
- Fiducialization
  (use only the central part of the detector)
- Discrimination ER/NR at the detector level

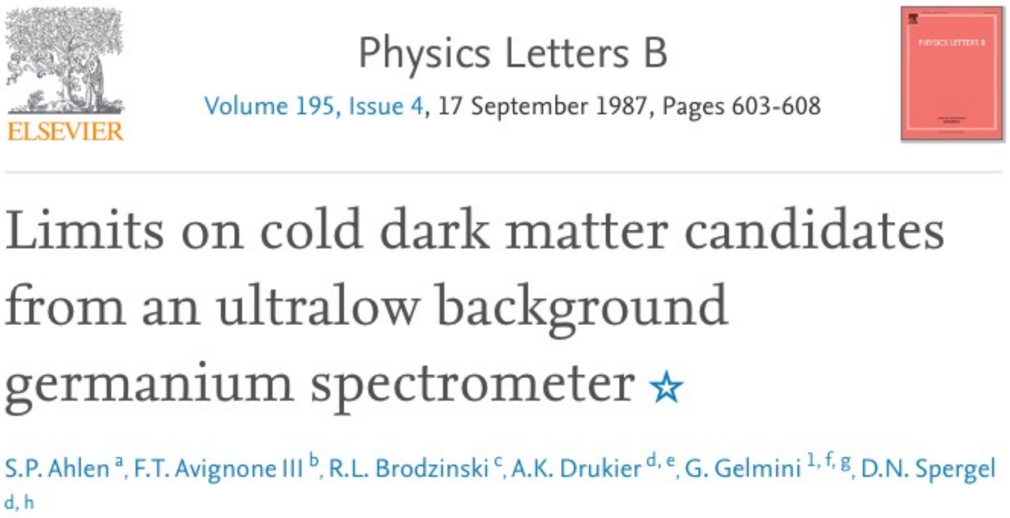


WIMP direct detection: detector requirements

- Large mass
- Low energy threshold (E_R)
- Very good 3D position resolution
- Low NR background (~0 in ROI)
- NR/ER (nuclear recoils gammas) discrimination

First dark matter direct detection attempt

Dark matter direct detection attempts date back to 1987 operating a 0.8 kg Ge ionization detector at Homestake Mine, SD (where presently SURF is located)



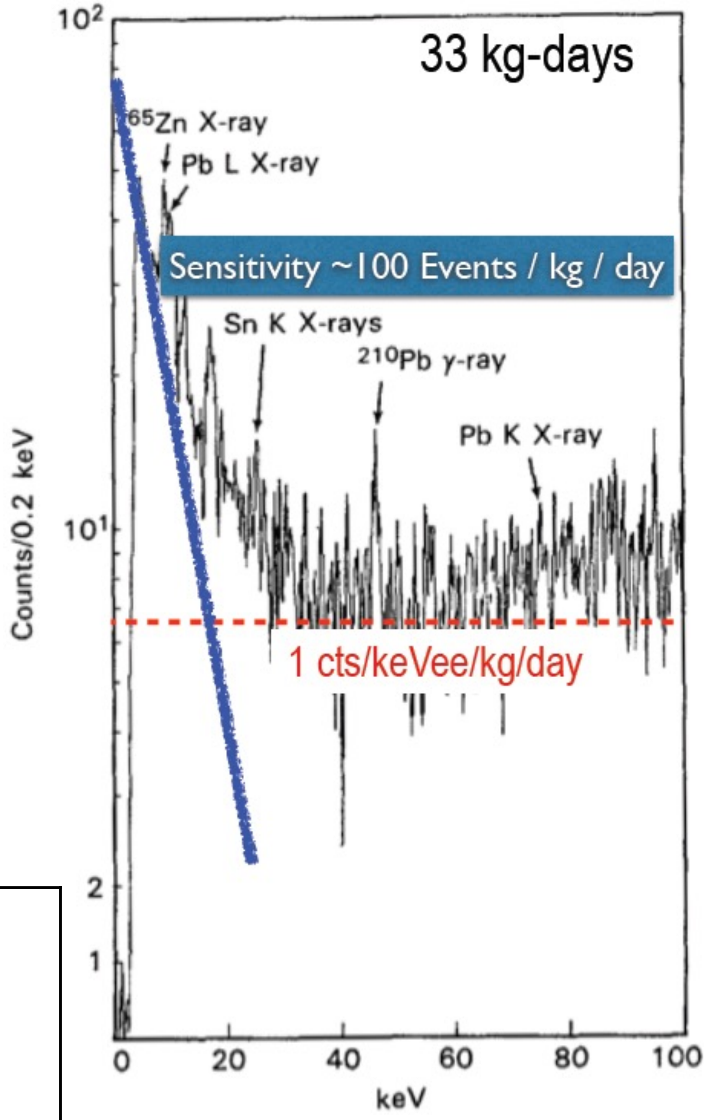
Physics Letters B

Volume 195, Issue 4, 17 September 1987, Pages 603-608

Limits on cold dark matter candidates from an ultralow background germanium spectrometer ☆

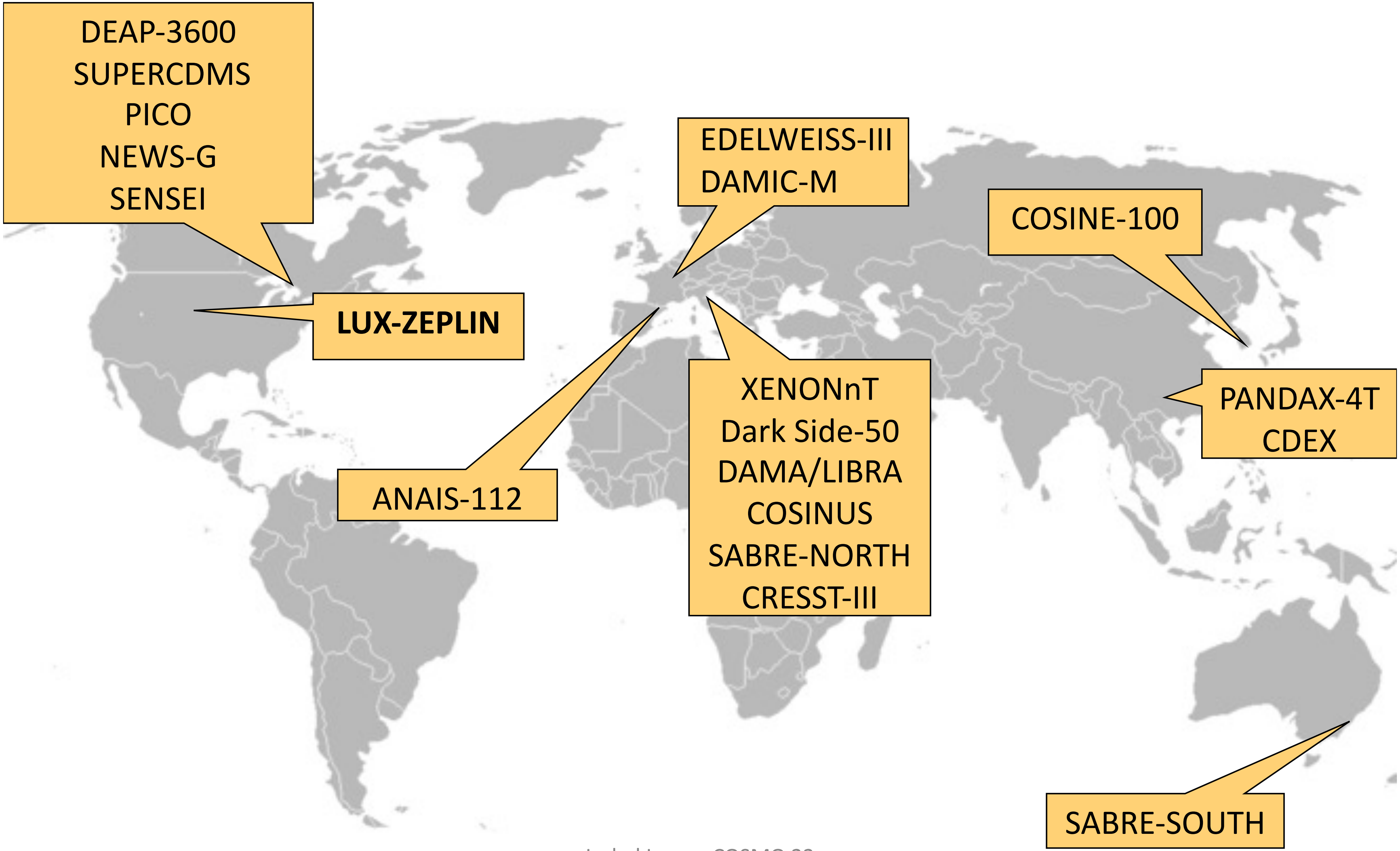
S.P. Ahlen [a], F.T. Avignone III [b], R.L. Brodzinski [c], A.K. Drukier [d, e], G. Gelmini [1, f, g], D.N. Spergel [d, h]

	Sensitivity	Background
1987	~100 events/kg/day	1 cts/keV/kg/day
2022	1 event/50 ton/day	ER: < 10^{-4} cts/keV/kg/day NR: < 10^{-8} cts/keV/kg/day



Adapted from
R. Gaitskell @ IDM2022

Direct Detection Dark Matter Experiments



DEAP-3600
SUPERCDMS
PICO
NEWS-G
SENSEI

LUX-ZEPLIN

ANAIS-112

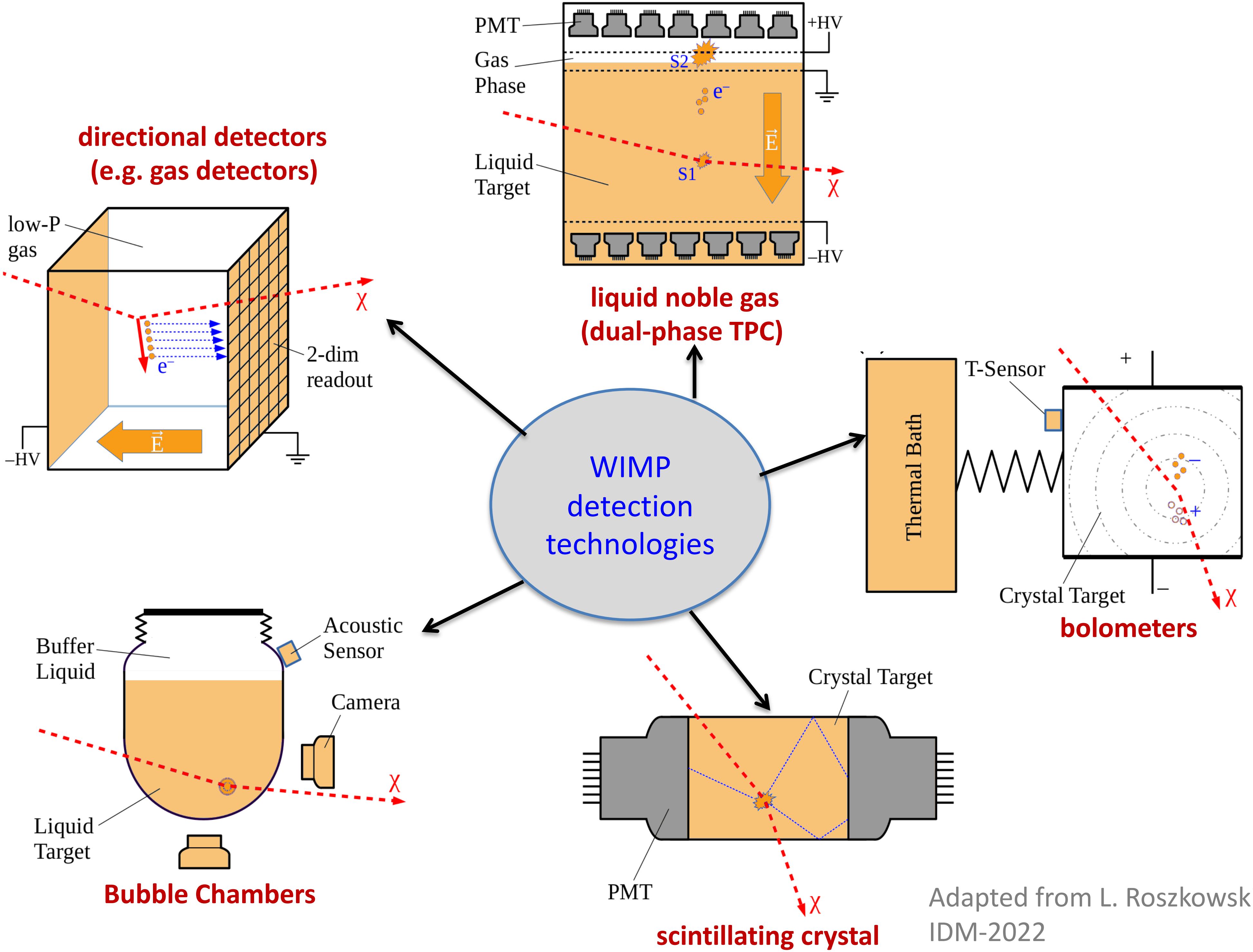
EDELWEISS-III
DAMIC-M

XENONnT
Dark Side-50
DAMA/LIBRA
COSINUS
SABRE-NORTH
CRESST-III

COSINE-100

PANDAX-4T
CDEX

SABRE-SOUTH



WIMP detection technologies

directional detectors (e.g. gas detectors)

liquid noble gas (dual-phase TPC)

bolometers

scintillating crystal

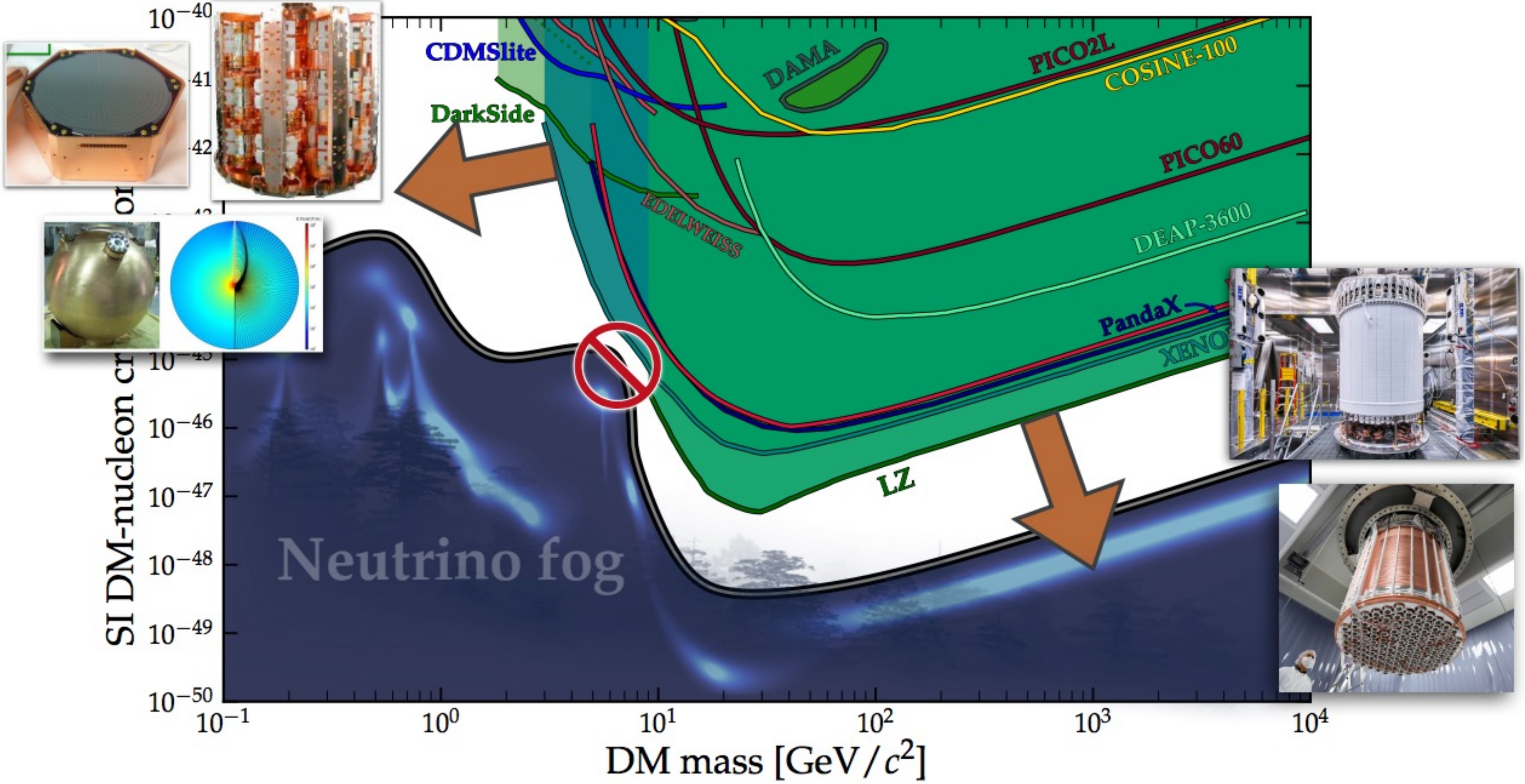
Bubble Chambers

Adapted from L. Roszkowski, IDM-2022

WIMP Direct detection: present status

Spin-independent WIMP-nucleon interactions

O'Hare@IDM2022

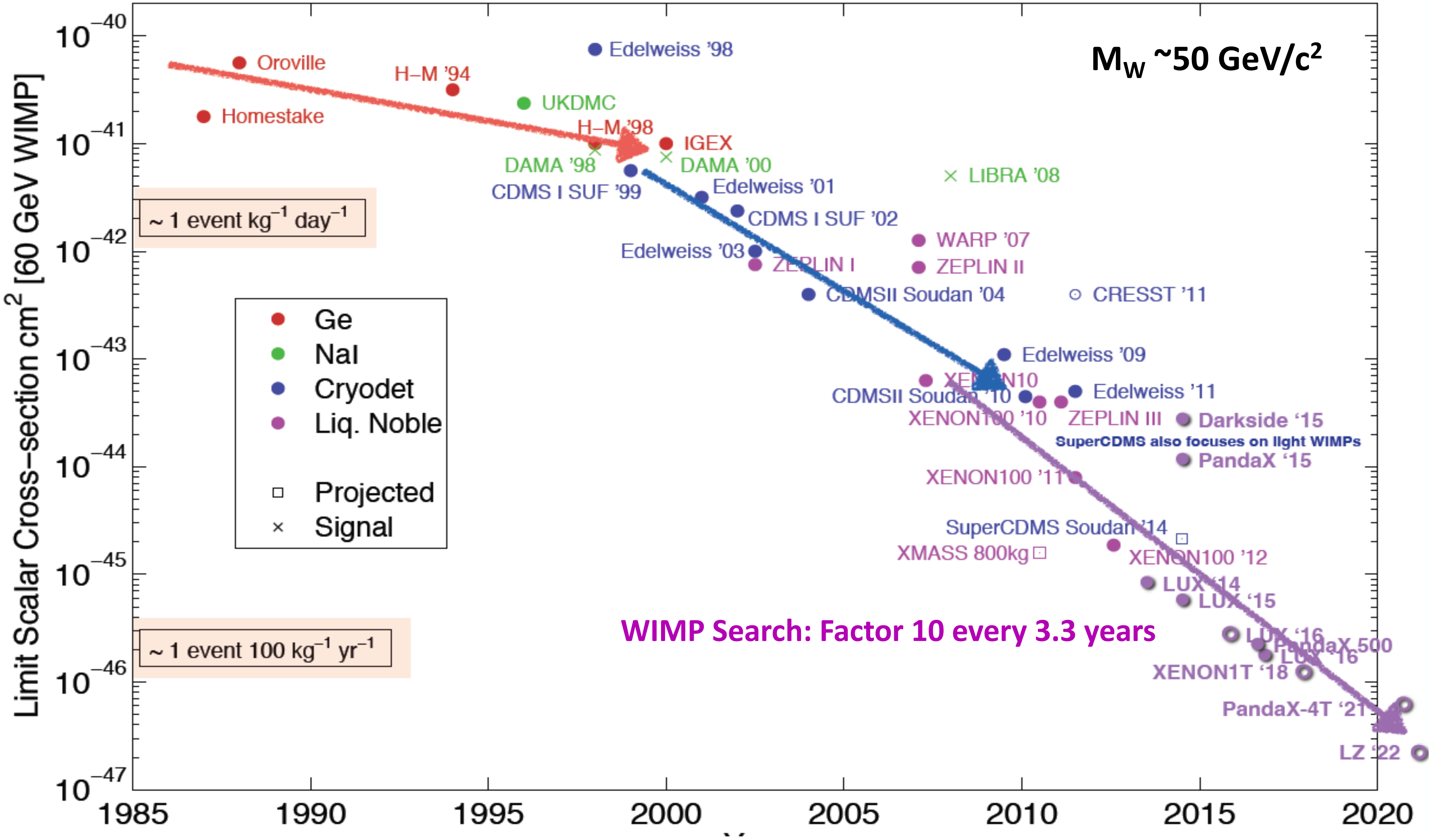


For intermediate masses, the bolometers(@tens mK) are the most sensitive because of the lower threshold

Liquid xenon TPCs are the most sensitive for WIMP masses >5 GeV/c^2 due to larger exposures

Progress in WIMP search

Exclusion limit for WIMP-nucleus SI interaction



From R. Gaitskell@IDM2022

Direct Detection Dark Matter Experiments

Experiment	Lab	Target	Mass [kg]	Ch	Sensitivity [cm^2@ GeV/c^2]	Exposure [t× year]	Timescale
Cryogenic bolometers (Section 4.6.1)							
EDELWEISS-subGeV	LSM	Ge	20	SI	10^{-43} @ 2	0.14	in prep.
SuperCDMS	SNOLAB	Ge, Si	24	SI	4×10^{-44} @ 2	0.11	constr.
CRESST-III	LNGS	$CaWO_4$+	2.5	SI	6×10^{-43} @ 1	3×10^{-3}	running
LXe detectors (Section 4.6.2)							
LZ	SURF	LXe	7.0 t	SI	1.5×10^{-48} @ 40	15.3	comm.
PandaX-4T	CJPL	LXe	4.0 t	SI	6×10^{-48} @ 40	5.6	constr.
XENONnT	LNGS	LXe	5.9 t	SI	1.4×10^{-48} @ 50	20	comm.
DARWIN	LNGS*	LXe	40 t	SI	2×10^{-49} @ 40	200	~2026
LAr detectors (Section 4.6.3)							
DarkSide-50	LNGS	LAr	46.4	SI	1×10^{-44} @ 100	0.05	running
DEAP-3600	SNOLAB	LAr	3.6 t	SI	1×10^{-46} @ 100	3	running
DarkSide-20k	LNGS	LAr	40 t	SI	2×10^{-48} @ 100	200	2023
ARGO	SNOLAB	LAr	400 t	SI	3×10^{-49} @ 100	3000	TBD
NaI(Tl) scintillators (Section 4.6.4.1)							
DAMA/LIBRA	LNGS	NaI	250	AM		2.46	running
COSINE-100	Y2L	NaI	106	AM	3×10^{-42} @ 30	0.212	running
ANAIS-112	LSC	NaI	112	AM	1.6×10^{-42} @ 40	0.560	running
SABRE	LNGS	NaI	50	AM	2×10^{-42} @ 40	0.150	in prep.
COSINUS-1π	LNGS	NaI	~1	AM	1×10^{-43} @ 40	3×10^{-4}	2022
Ionisation detectors (Section 4.6.4.2)							
DAMIC	SNOLAB	Si	0.04	SI	2×10^{-41} @ 3-10	4×10^{-5}	running
DAMIC-M	LSM	Si	~0.7	SI	3×10^{-43} @ 3	0.001	2023
CDEX	CJPL	Ge	10	SI	2×10^{-43} @ 5	0.01	running
NEWS-G	SNOLAB	Ne,He		SI			comm.
TREX-DM	LSC	Ne	0.16	SI	2×10^{-39} @ 0.7	0.01	comm.
Bubble chambers (Section 4.6.4.3)							
PICO-40L	SNOLAB	C_3F_8	59	SD	5×10^{-42} @ 25	0.044	running
PICO-500	SNOLAB	C_3F_8	1 t	SD	$\sim 1 \times 10^{-42}$ @ 50		in prep.
Directional detectors (Section 4.6.5)							
CYGNUS	Several	He:SF_6	10^3 m^3	SD	3×10^{-43} @ 45	6 y	R&D
NEWSdm	LNGS	Ag,Br,C,...		SI	8×10^{-43} @ 200	0.1	R&D

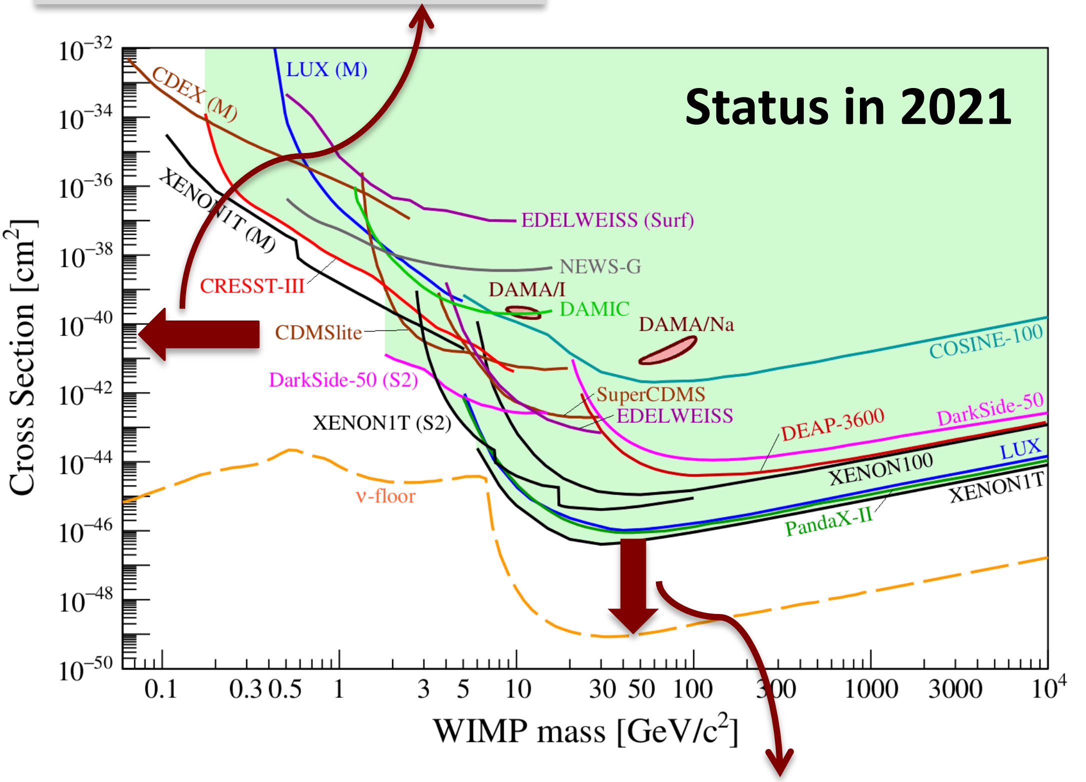
Table 1: Current, upcoming and proposed experiments for the direct detection of WIMPs. Mass is given in kg unless explicitly specified. The experiments' main detection channel (Ch) is abbreviated as: SI (spin independent WIMP-nucleon interactions), SD (spin dependent), AM (annual modulation). The sensitivity is reported for this channel, assuming the quoted exposure. Note that many projects have several detection channels. comm. = experiment under commissioning.

*No decision yet. A CDR for LNGS is being prepared.

Search for "light DM"

reduce threshold

reduce backgrounds



Status in 2021

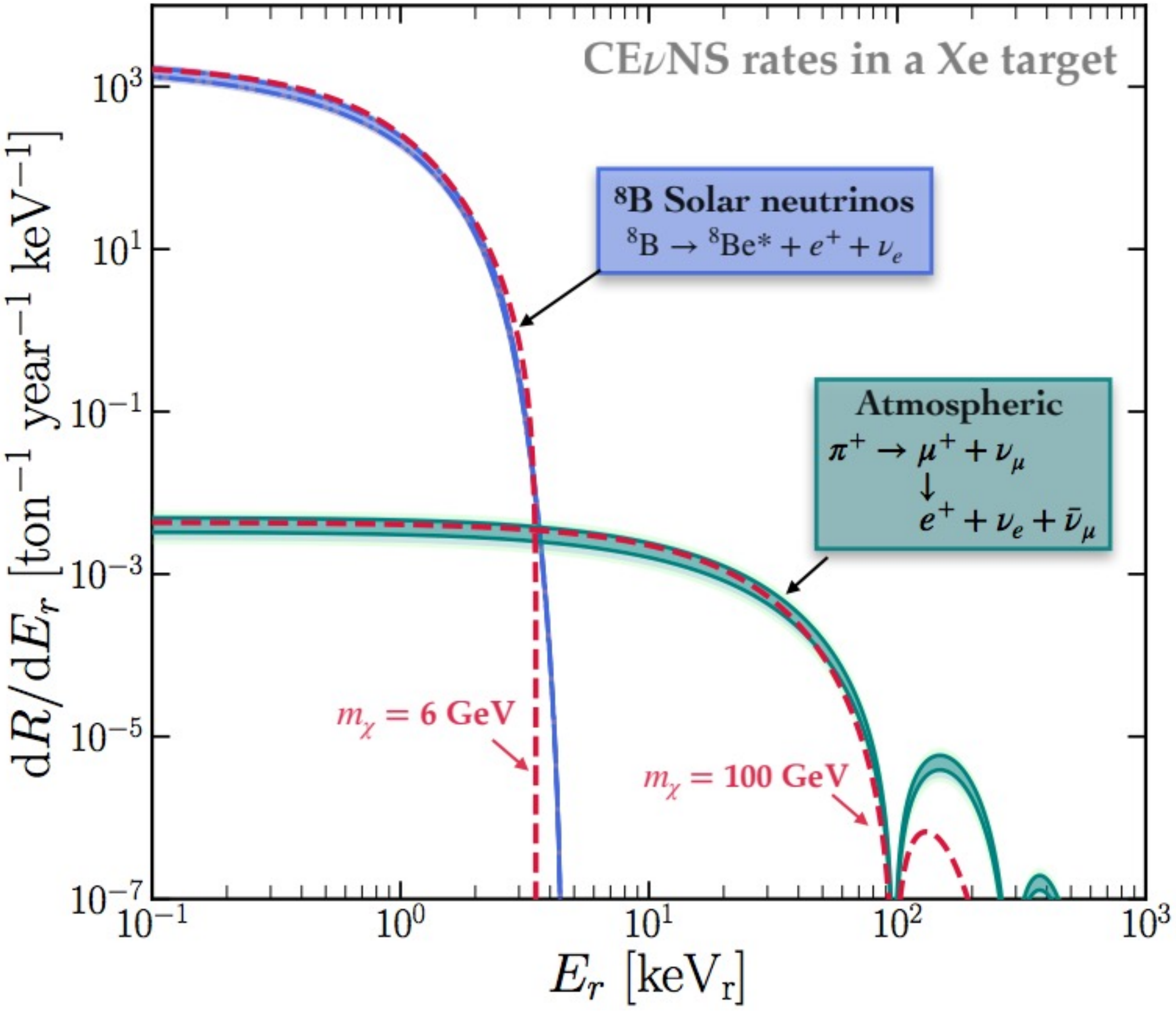
Search for "standard WIMPs"

increase exposure

reduce backgrounds

APPEC Committee Report
arXiv:2104.07634v1

CEνNS & WIMP nuclear recoil energy spectra



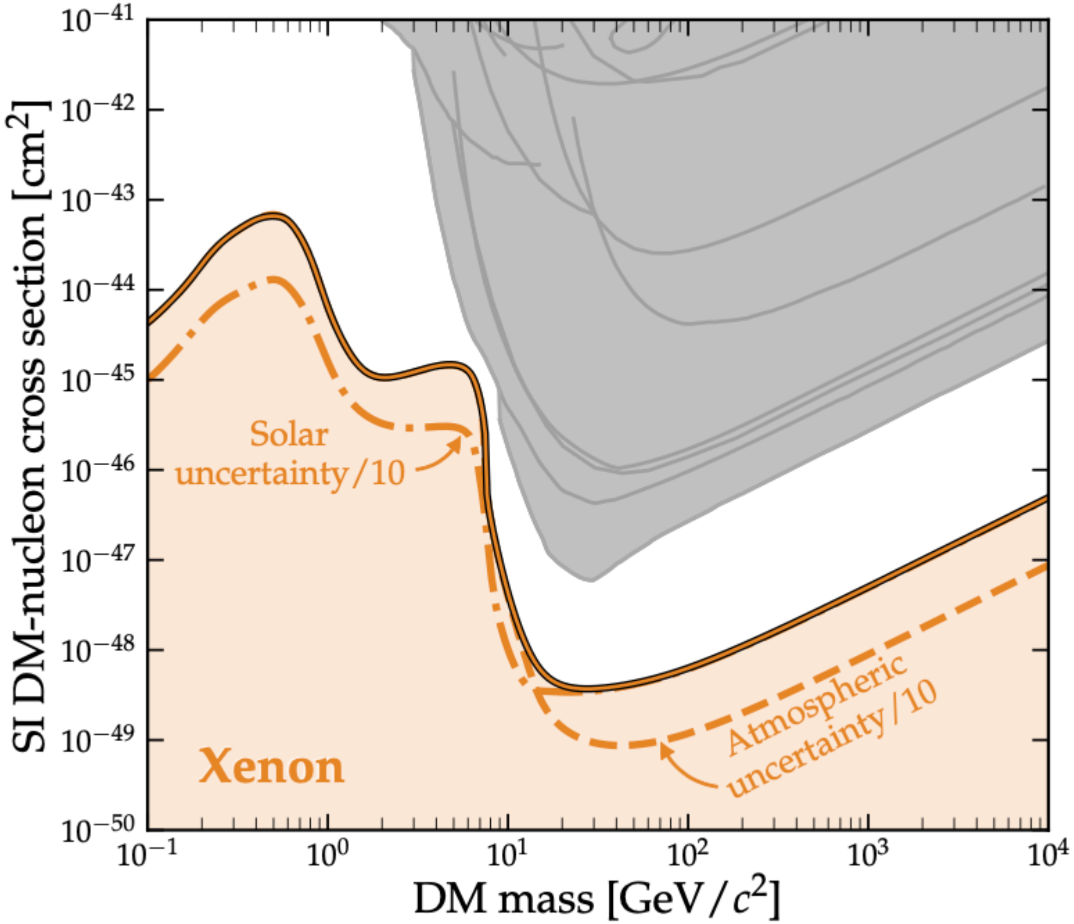
From C. O'Hare @ IDM2022

CEvNS will be observed in DM experiments very soon!

The **recoil signatures** of DM and neutrinos look remarkably alike.

The **nuclear recoil energy spectra** of CEνNS events closely resembles that of the WIMPs.

Effect of neutrino flux uncertainties



G. O'Hare, ArXiv 210903116

Smaller neutrino flux uncertainties push the boundary of the neutrino fog to lower cross sections

Present status and future plans of some of the main WIMP direct detection experiments

Two-phase liquid xenon TPCs landscape

LUX-ZEPLIN

M_T= 7 ton

M_{fid}= 5.5 ton

first results arxiv:2207.03764
at 30 GeV/c^2 excluding above
5.9x10^{-48} cm^2 (90%CL)

XENONnT

M_T= 5.9 ton

M_{fid}= 4 ton

first results coming soon

PANDAX-4T

M_T= 3.7 ton

M_{fid}=2.7 ton

first results PRL (2021)
at 40 GeV/c^2 excluding above
3.8x10^{-47} cm^2 (90%CL)

Dual phase TPC detection principle

- Particles interacting in the liquid create:
    - Primary scintillation (S1)
    - Secondary scintillation (S2) in the gas (ionization electrons drift and extracted into the gas)
- Excellent 3D position reconstruction
    - Z from S1 – S2 timing
    - X-Y from light pattern in PMT array(s)

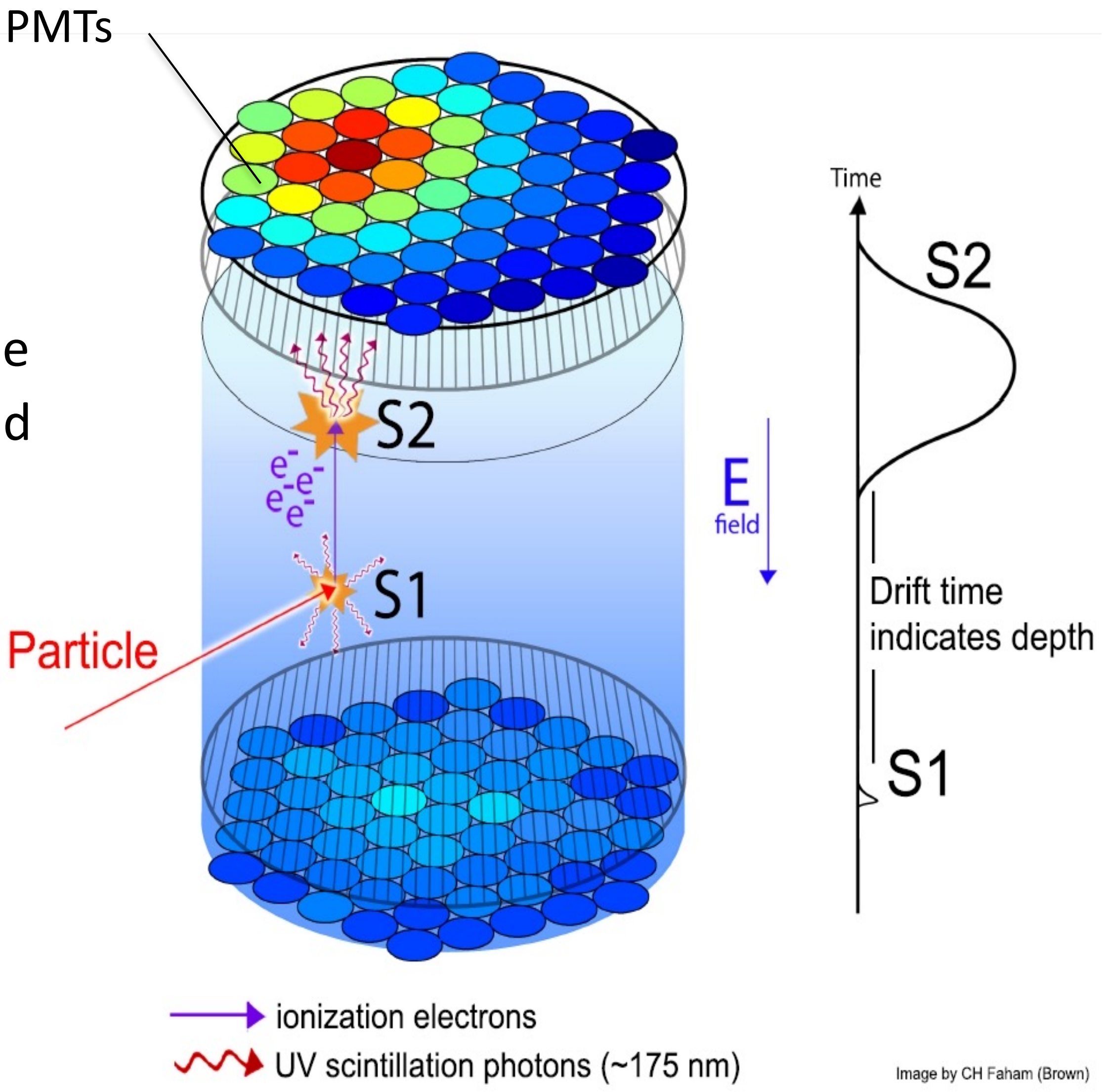
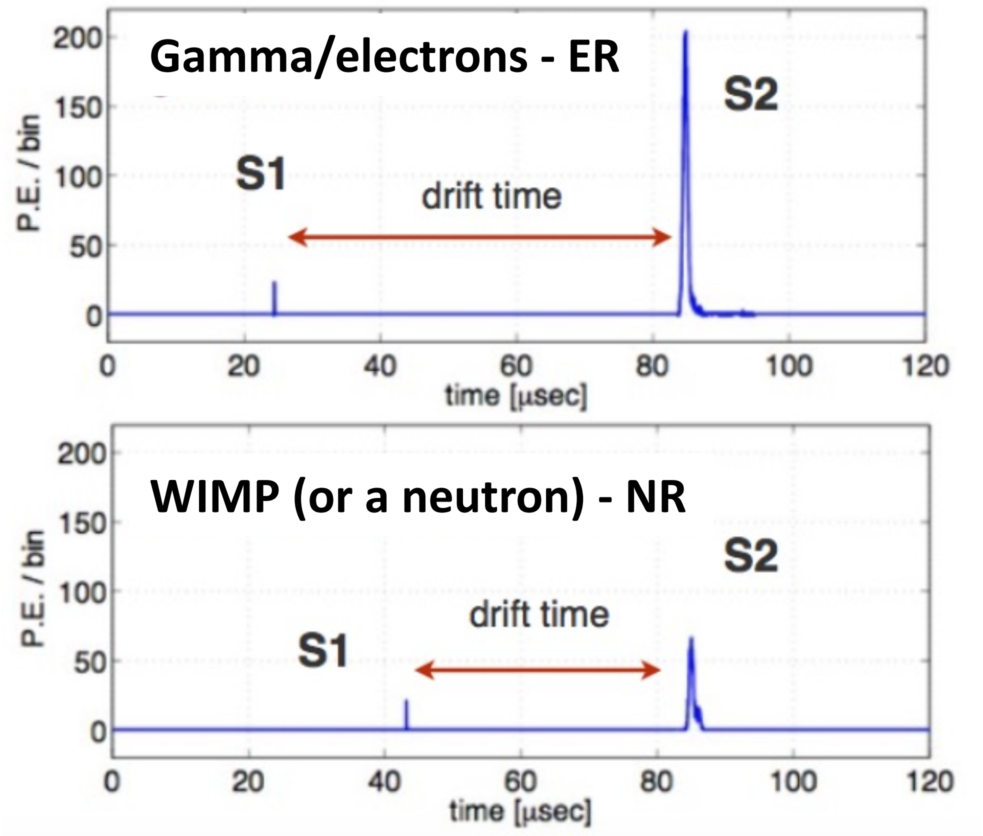


Image by CH Faham (Brown)

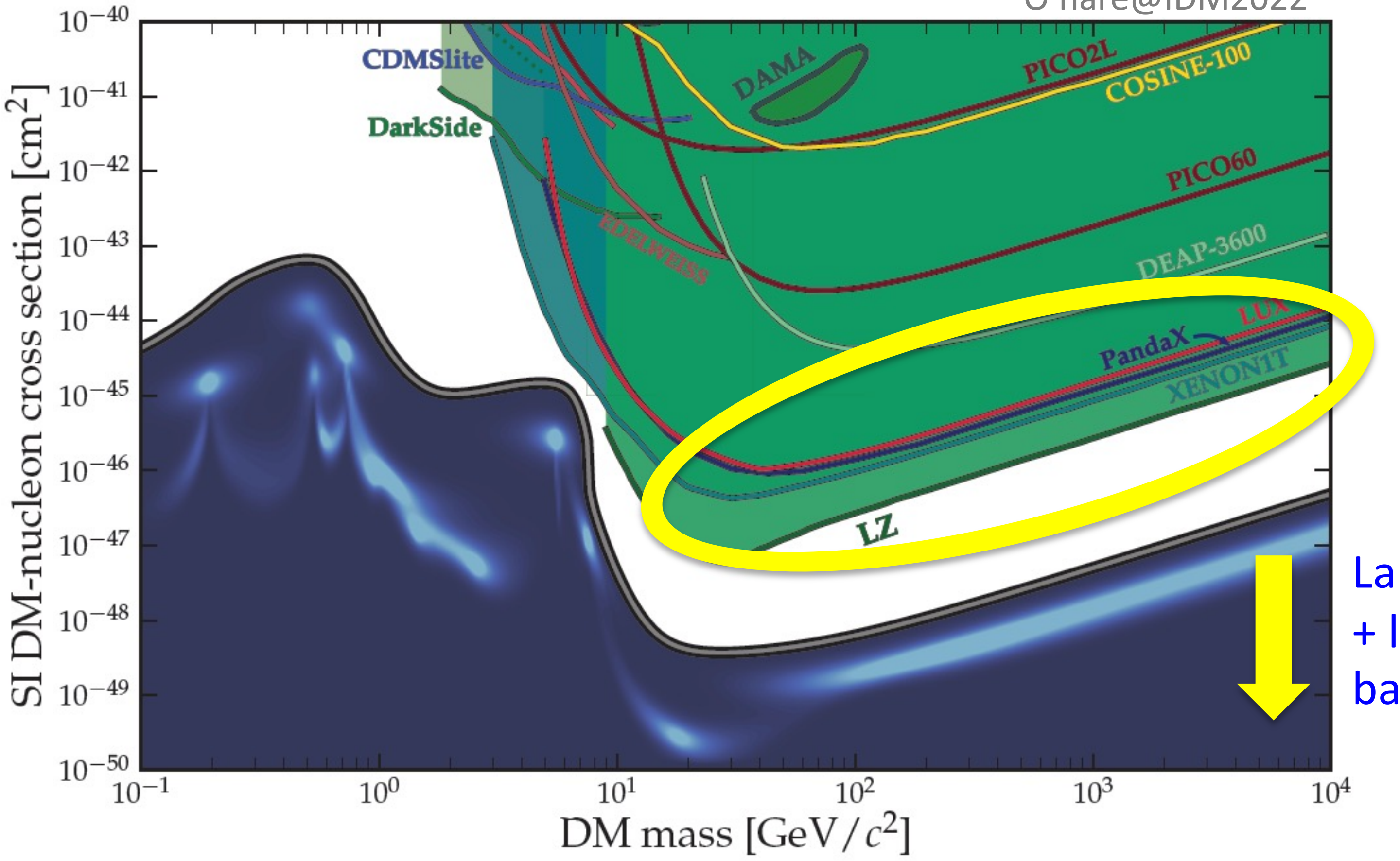
Discrimination in Dual Phase TPC



For the same energy, S2/S1 is much larger for gammas/electrons (ER) than for WIMPs or neutrons (NR)

- Distinguish between single scatters and multiple scatters
- S2/S1 ratio: discriminates electronic recoils (ER) due to background from potential WIMP nuclear recoils (NR)
- Energy reconstruction from S1 and S2

Liquid xenon TPCs



O'hare@IDM2022

Larger exposure + lower background

Liquid xenon time projection chambers are the most sensitive for WIMP masses >5 GeV, due to the combination of:

- very large target mass
- ultra-low background (due to fiducialization and radiopurification)
- excellent ER/NR discrimination (based on S2/S1)

LUX-ZEPLIN(LZ) experiment

LZ detector design:
NIM A, 163047 (2019)

7 tonne dual-phase Xe ultra-low background TPC designed for dark matter searches ① observed by 2 arrays of 253 (top) and 241 PMTs (bottom).

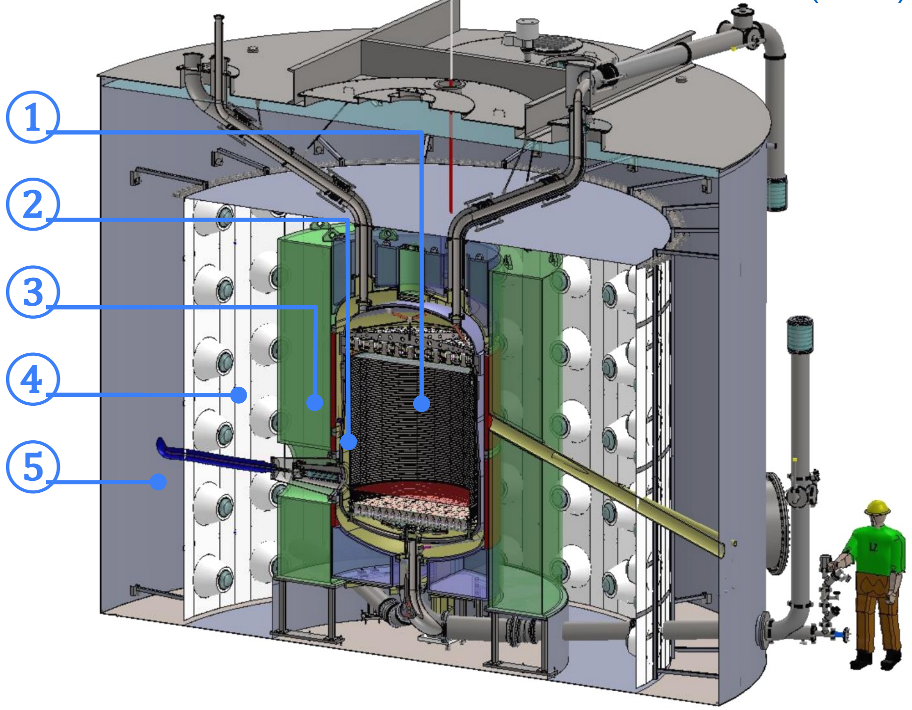
Two additional detectors for background modelling and mitigation:

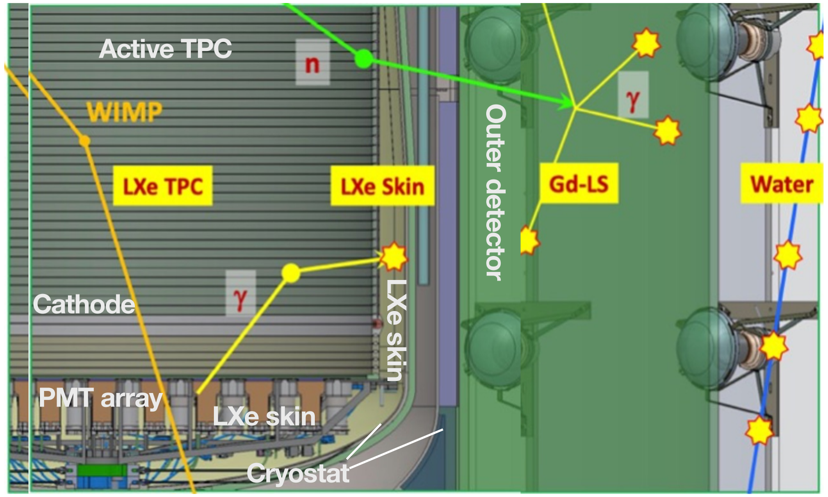
- ★ 2 t Xe “Skin” detector surrounding the TPC with a 131 PMT readout ②
- ★ 17.3 t Gd-loaded liquid scintillator Outer Detector ③ with a 120 PMT readout ④

All instrumented volumes submerged in a 228 t water shield ⑤ also working as a muon veto.

Veto efficiency (Water Cherenkov + Skin + OD):

- ● 88.5% for neutrons (measured)
- ● > 70% for gamma rays (projected)
- ➢ Maximize fiducial volume!





LZ first results

Science Run 1 -

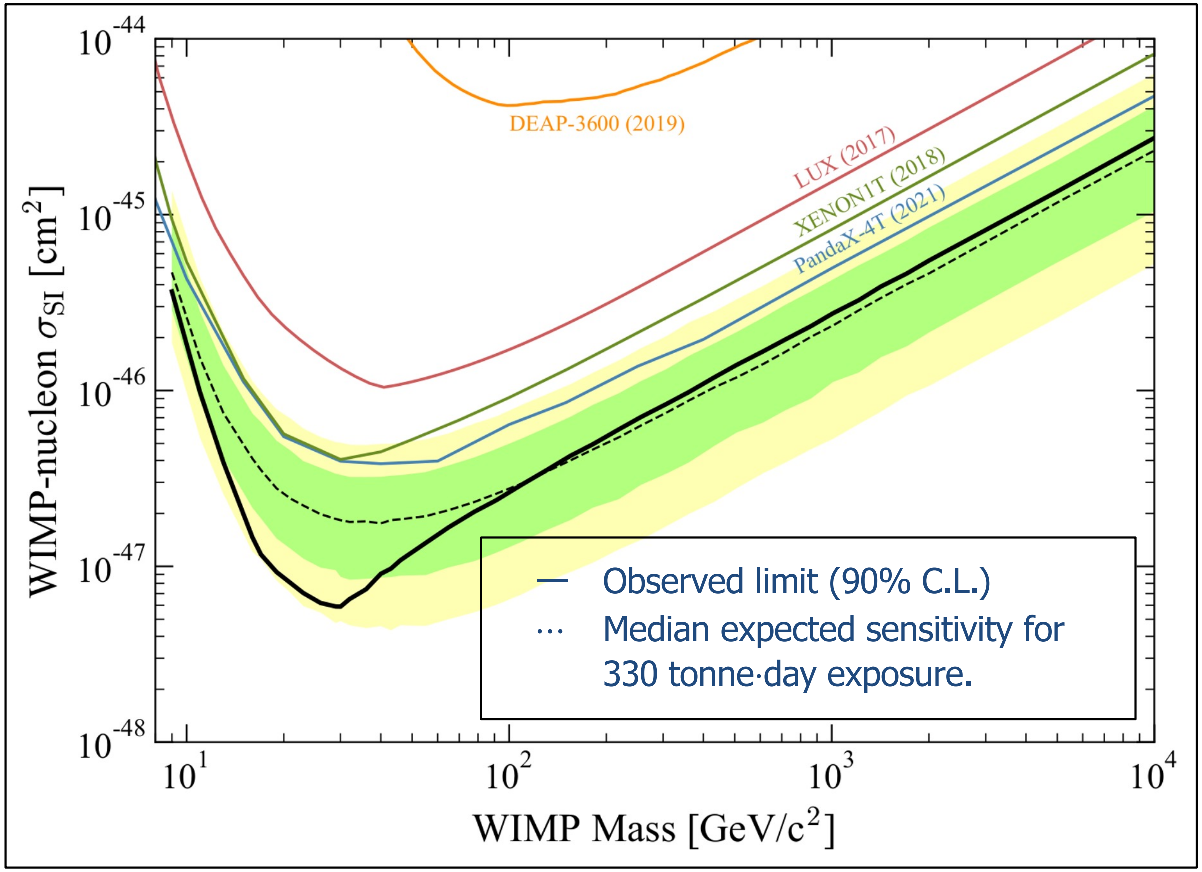
- ~3.5 month run, **exposure is 60 live days x 5.5 tonnes fiducial**
- **No evidence of WIMPs at any mass**

- Minimum exclusion on WIMP-nucleon cross-section (SI) of **5.9×10^{-48} cm^2 at 30 GeV.**

- Comparing to existing strongest upper limit:

X 6.7 improvement at 30 GeV

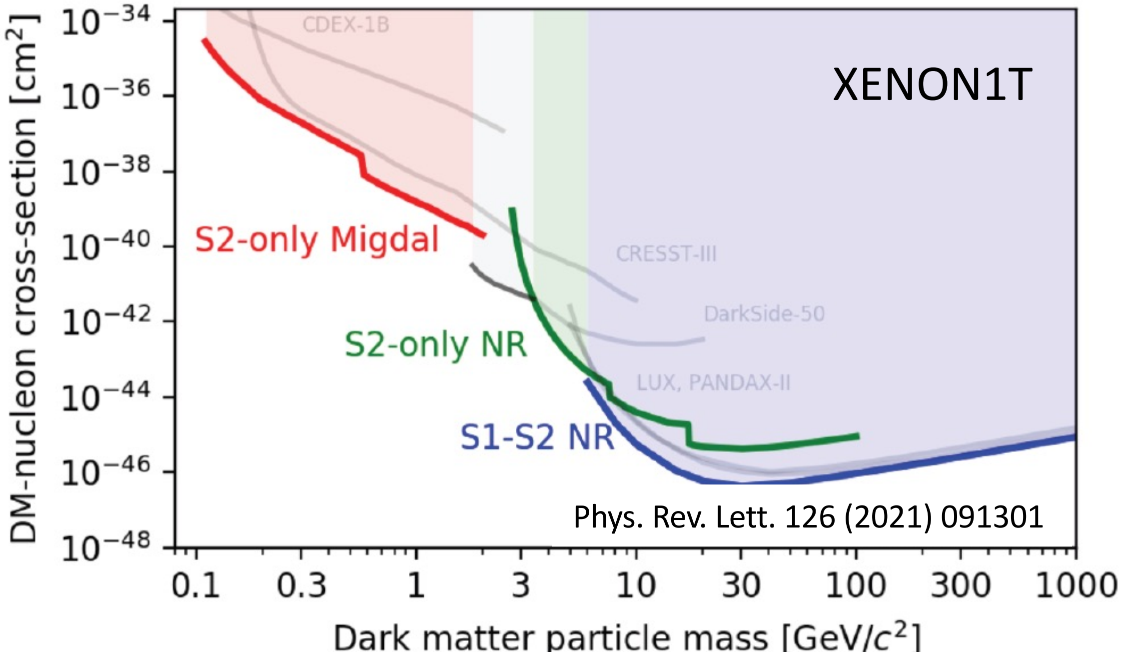
X 1.7 improvement above 1 TeV



arXiv:2207.03764

LZ will soon start the 2nd run. It aims to reach 1000 live days exposure

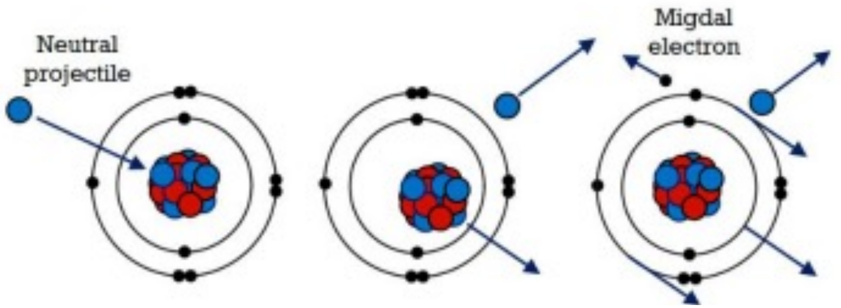
Lowering the threshold



Phys. Rev. Lett. 126 (2021) 091301

Threshold dominated by 3-fold PMT coincidence (XENON)

- lower it to 2
- Drop the S1: ionization (S2)-only - limit setting
- Look for the Migdal effect



Migdal event topology involves a nuclear recoil and electron recoil originating from the same vertex

But Migdal effect was never confirmed experimentally in scattering events

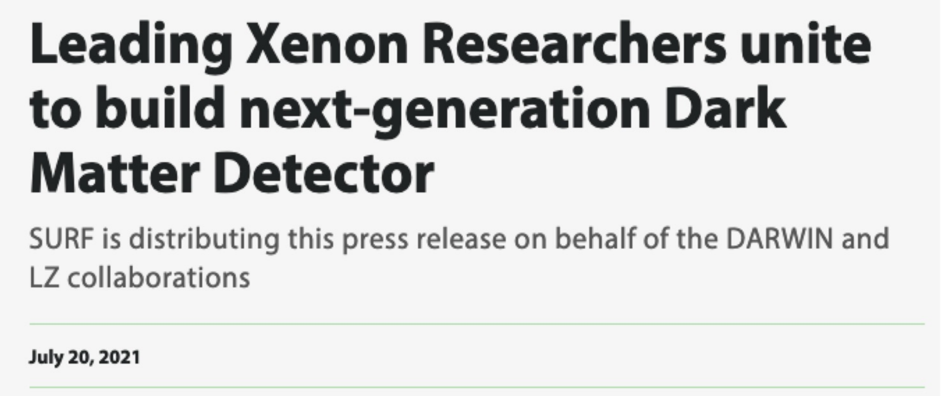
MIGDAL
Migdal In Galactic Dark mAtter expLoration

Aim: The *unambiguous* observation of the Migdal effect using an optical TPC with low-pressure CF_4 and other gases

https://migdal.pp.rl.ac.uk/

XLZD Consortium

XLZD - XENON LUX ZEPLIN DARWIN

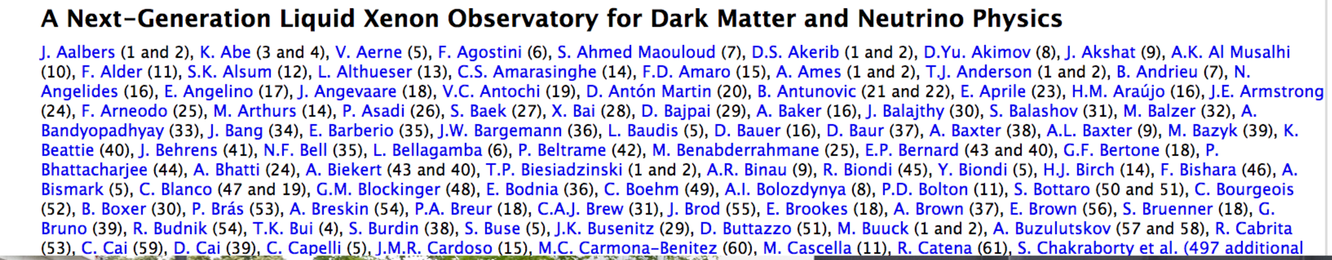


Leading Xenon Researchers unite to build next-generation Dark Matter Detector

SURF is distributing this press release on behalf of the DARWIN and LZ collaborations

July 20, 2021

- MOU between LUX-ZEPLIN, DARWIN and XENON
- Successful joint XLZD meeting June 27-29 at KIT
- https://xlzd.org/
- White paper (2203.02309)



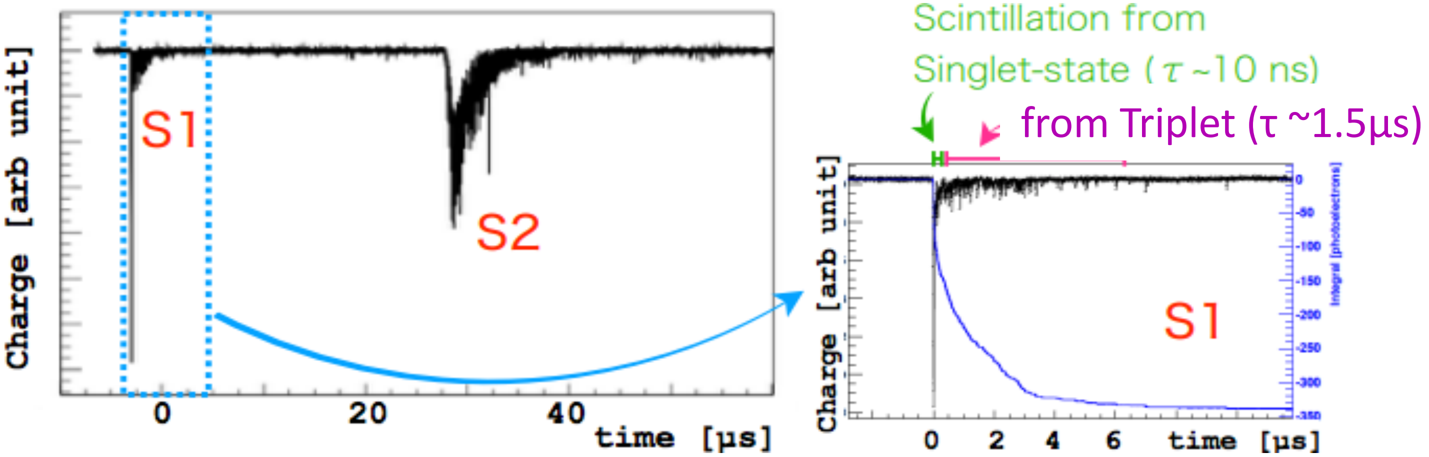
A Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics

J. Aalbers (1 and 2), K. Abe (3 and 4), V. Aerne (5), F. Agostini (6), S. Ahmed Maouloud (7), D.S. Akerib (1 and 2), D.Yu. Akimov (8), J. Akshat (9), A.K. Al Musalhi (10), F. Alder (11), S.K. Alsum (12), L. Althueser (13), C.S. Amarasinghe (14), F.D. Amaro (15), A. Ames (1 and 2), T.J. Anderson (1 and 2), B. Andrieu (7), N. Angelides (16), E. Angelino (17), J. Angevaare (18), V.C. Antochi (19), D. Antón Martin (20), B. Antunovic (21 and 22), E. Aprile (23), H.M. Araújo (16), J.E. Armstrong (24), F. Arneodo (25), M. Arthurs (14), P. Asadi (26), S. Baek (27), X. Bai (28), D. Bajpai (29), A. Baker (16), J. Balajthy (30), S. Balashov (31), M. Balzer (32), A. Bandyopadhyay (33), J. Bang (34), E. Barberio (35), J.W. Bargemann (36), L. Baudis (5), D. Bauer (16), D. Baur (37), A. Baxter (38), A.L. Baxter (9), M. Bazyk (39), K. Beattie (40), J. Behrens (41), N.F. Bell (35), L. Bellagamba (6), P. Beltrame (42), M. Benabderrahmane (25), E.P. Bernard (43 and 40), G.F. Bertone (18), P. Bhattacharjee (44), A. Bhatti (24), A. Biekert (43 and 40), T.P. Biesiadzinski (1 and 2), A.R. Binau (9), R. Biondi (45), Y. Biondi (5), H.J. Birch (14), F. Bishara (46), A. Bismark (5), C. Blanco (47 and 19), G.M. Blockinger (48), E. Bodnia (36), C. Boehm (49), A.I. Bolozdynya (8), P.D. Bolton (11), S. Bottaro (50 and 51), C. Bourgeois (52), B. Boxer (30), P. Brás (53), A. Breskin (54), P.A. Breur (18), C.A.J. Brew (31), J. Brod (55), E. Brookes (18), A. Brown (37), E. Brown (56), S. Bruenner (18), G. Bruno (39), R. Budnik (54), T.K. Bui (4), S. Burdin (38), S. Buse (5), J.K. Busenitz (29), D. Buttazzo (51), M. Buuck (1 and 2), A. Buzulutskov (57 and 58), R. Cabrita (53), C. Cai (59), D. Cai (39), C. Capelli (5), J.M.R. Cardoso (15), M.C. Carmona-Benitez (60), M. Cascella (11), R. Catena (61), S. Chakraborty et al. (497 additional

Liquid Argon detectors: PSD

Liquid Argon:

Strengths: pulse shape discrimination (PSD), radon reduction, purification

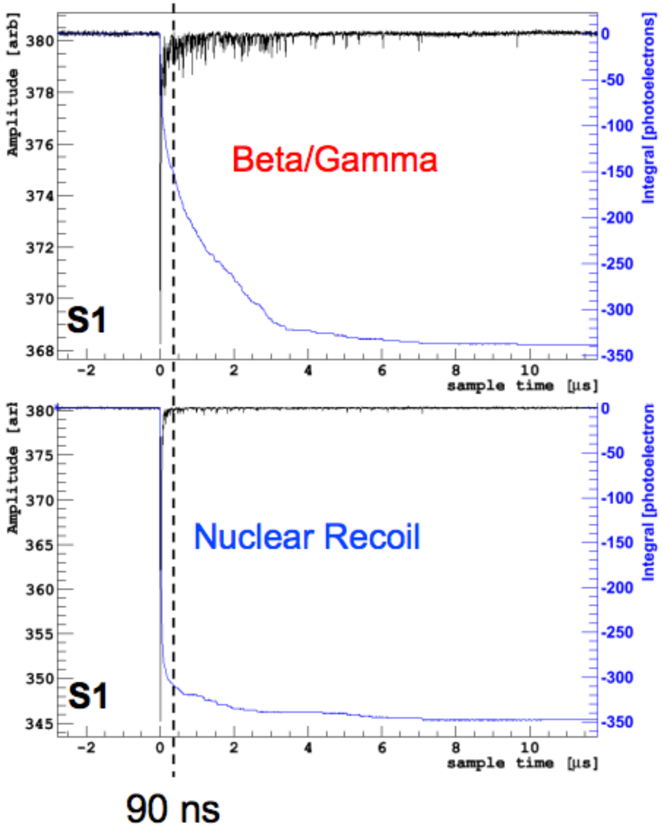


- Pulse shape discrimination (via f_{90}= S1 light fraction in first 90 ns):

  $f_{90} \approx 0.3$ for electron recoils (ER)

  $f_{90} \approx 0.75$ for nuclear recoils (NR)

  ER rejection power ~ 10^{-9}



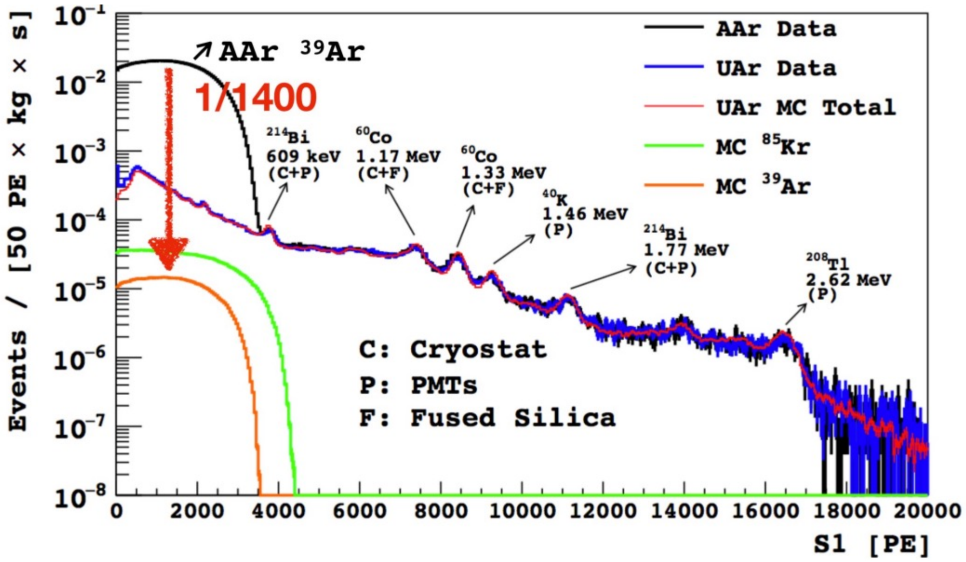
Liquid Argon detector: DarkSide-50

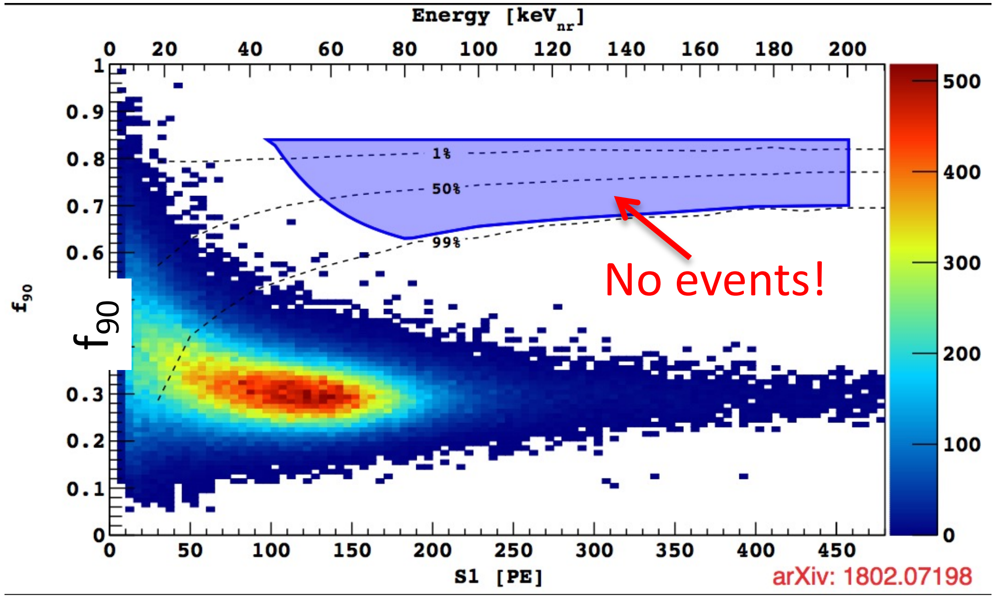
Challenge: ^{39}Ar

^{40}Ar(n,2n)^{39}Ar

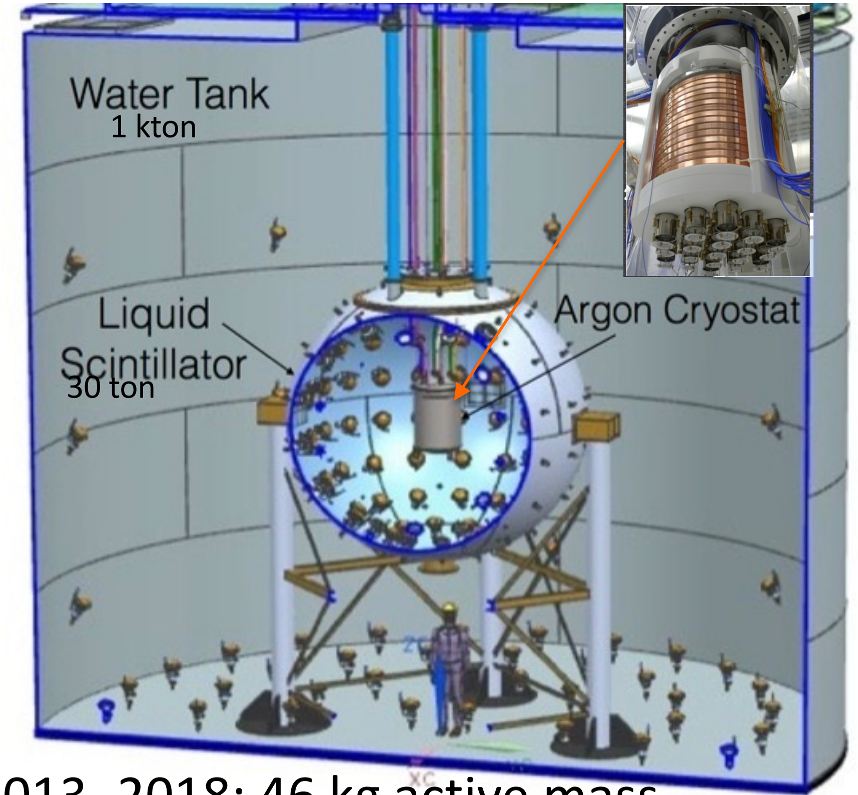
→ β^- with Q=565keV;
$\tau_{1/2}$ = 269 yr

- Use **underground Argon with 0.73 ± 0.11 mBq/kg of ^{39}Ar activity**)





arXiv: 1802.07198



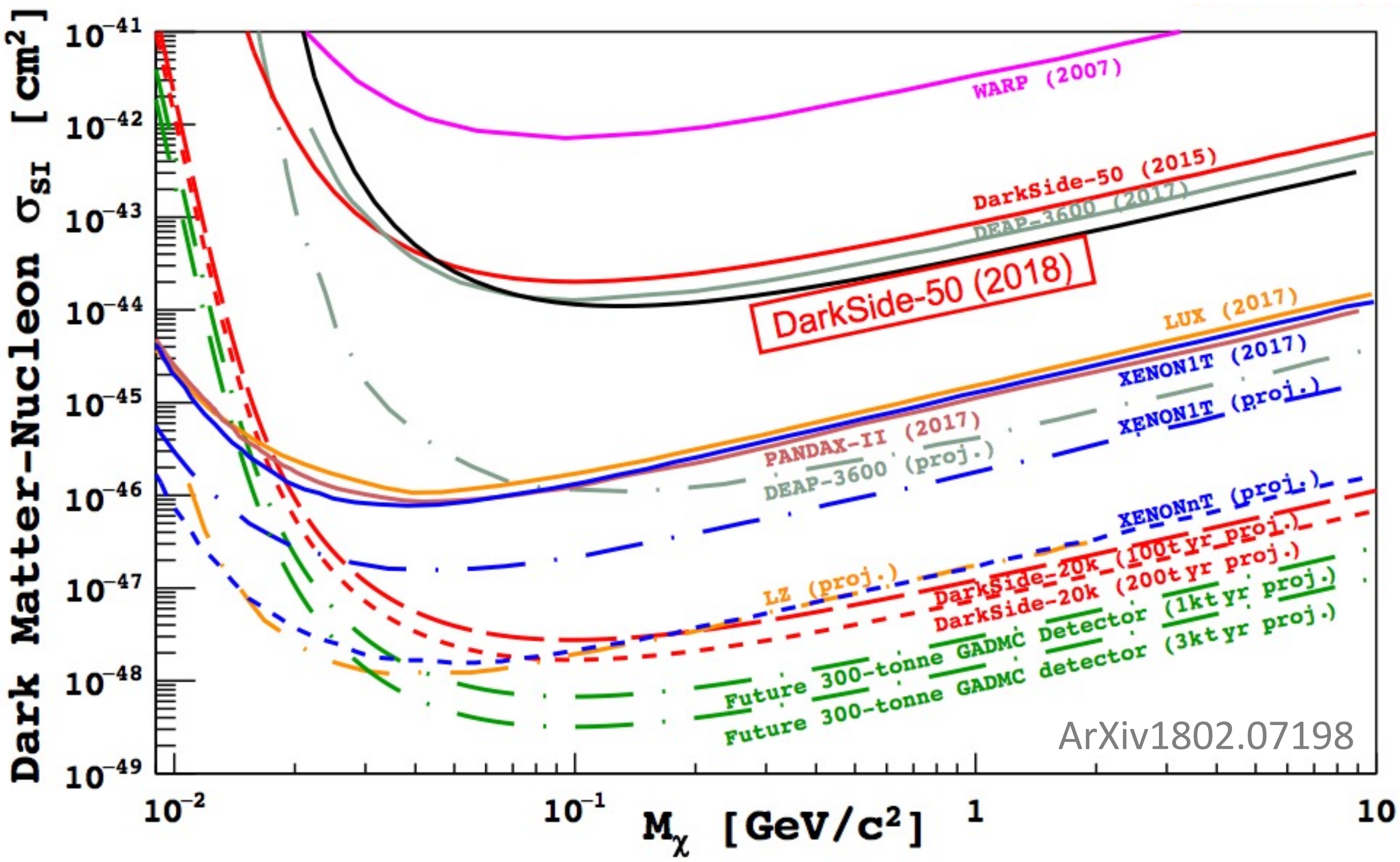
2013–2018; 46 kg active mass

Data from 19.6 ton.day exposure

Dark Side: present and future

DarkSide-20k
a **20-tonnes**
fiducial LAr two-phase TPC →
100 tonne×year
background-free

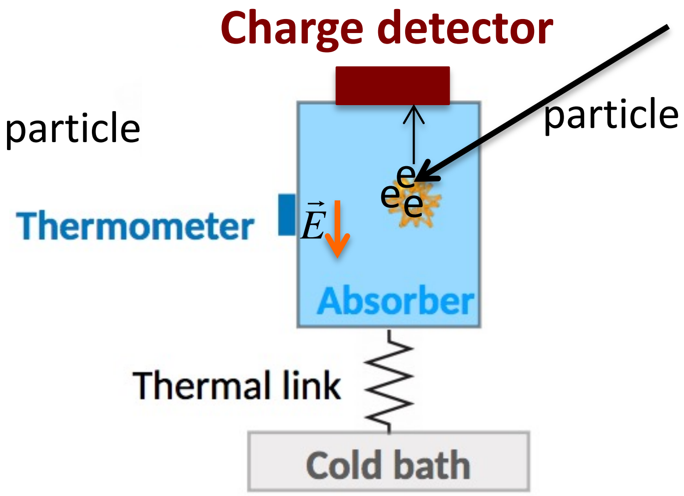
GADMC detector
a **300-tonnes**
depleted argon
detector
1,000 tonne×year
background-free



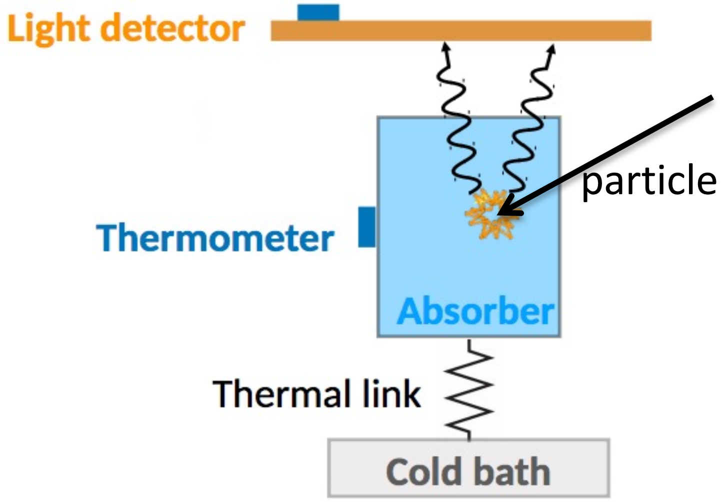
ArXiv1802.07198

- Upgrade of production of depleted argon to many tons
- PMTs replaced by SiPM arrays

Cryogenic Bolometers



CDMS, Edelweiss – absorber: **Si, Ge**



CRESST – absorber: **$CaWO_4$**

- Absorber at cryogenic temperatures (10-50 mK)
- Temperature rise: $\Delta T = E/C(T)$

Order of magnitude of ΔT:
E.g. at 10 mK, for **E=1 keV** in a 100 mg Ge detector

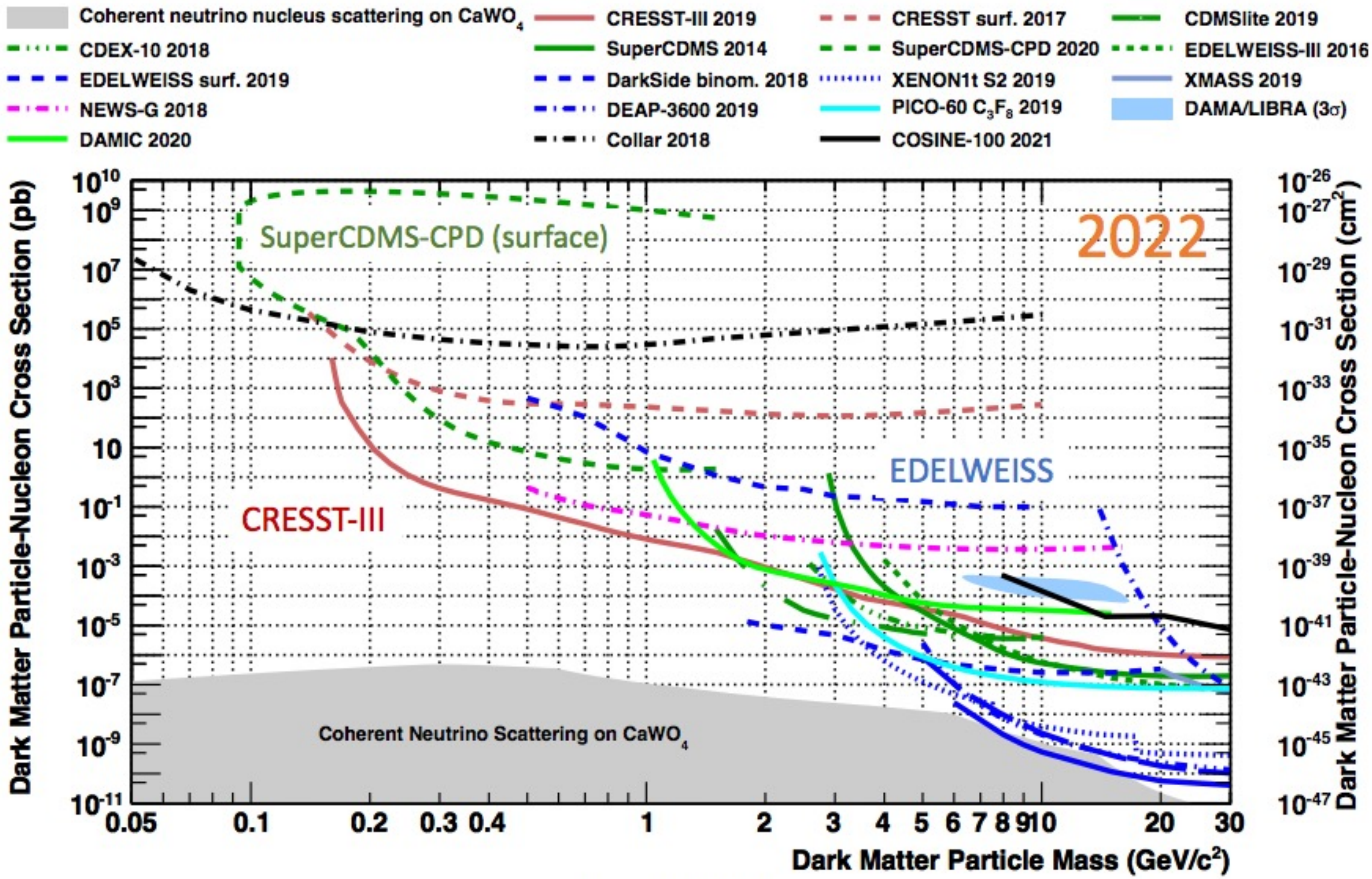
$$\Delta T \approx 1 \mu K$$

Challenging but possible to measure.

Mass of a single detector is limited to the kg-scale to keep the heat capacity small

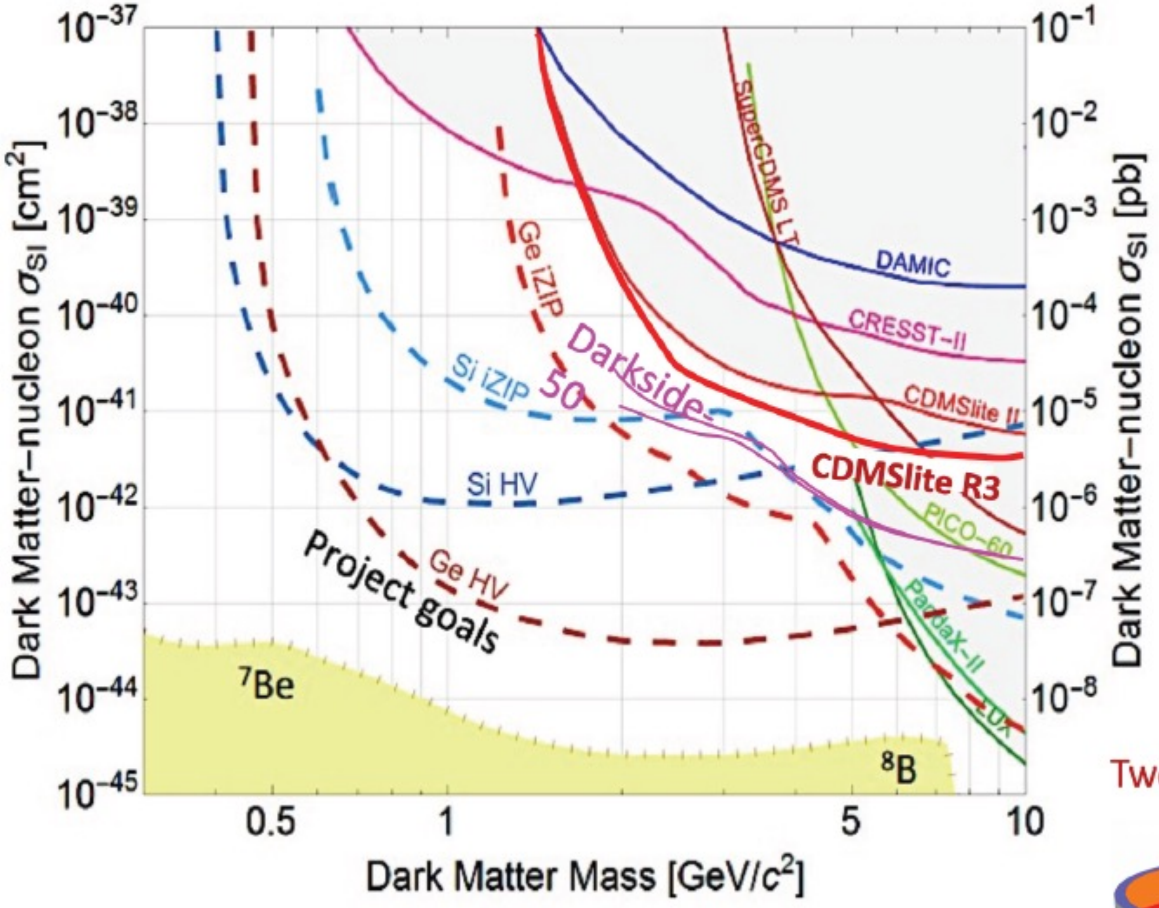
- ΔT allows to measure the total deposited energy with **low threshold** (~ hundreds or tens eV)
- Ratio light (or charge) to phonon signal amplitudes allows excellent **ER/NR** separation
- Background has been difficult to reduce to the desired levels

Present few GeV and sub-GeV landscape



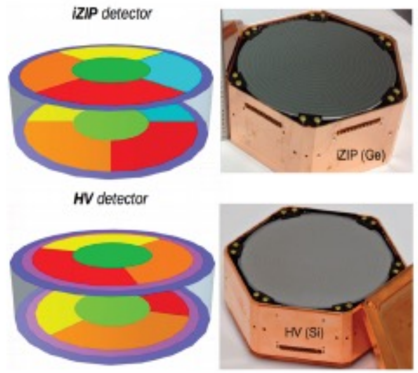
R. Strauss, IDM 2022

SuperCDMS@SNOLAB

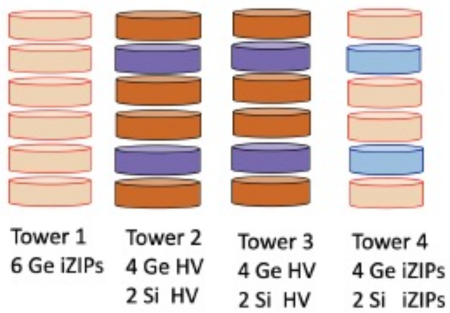


- New Cryogenic infrastructure being installed at SNOLab in order to allow 4-tower (and larger) payloads
  - **reduced background by a factor of 200**
  - start operation @Snolab in 2023

Two Types of Detectors

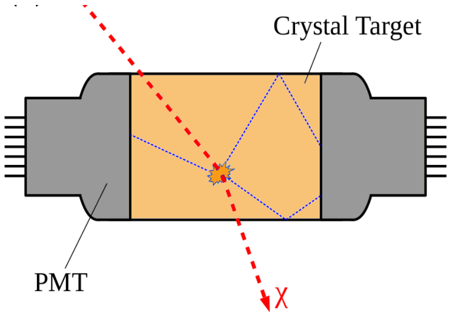


Initial 4-tower payload

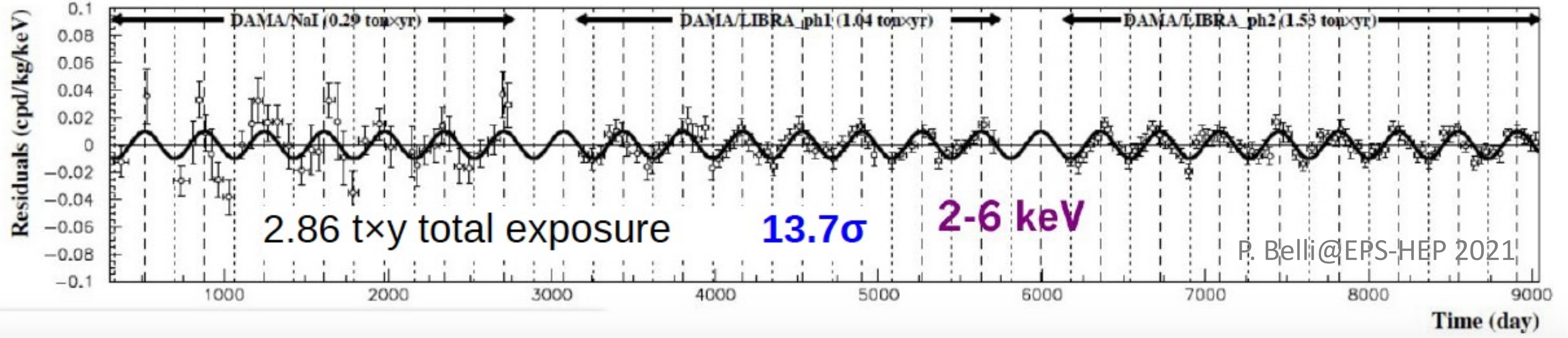


Total of 18 Ge and 6 Si detectors, each having respectively 1.39 and 0.61 kg

Annual Modulation and the DAMA/LIBRA case



242.5 kg NaI(Tl) New data: 2 more annual cycles



2.86 t×y total exposure **13.7σ** **2-6 keV**

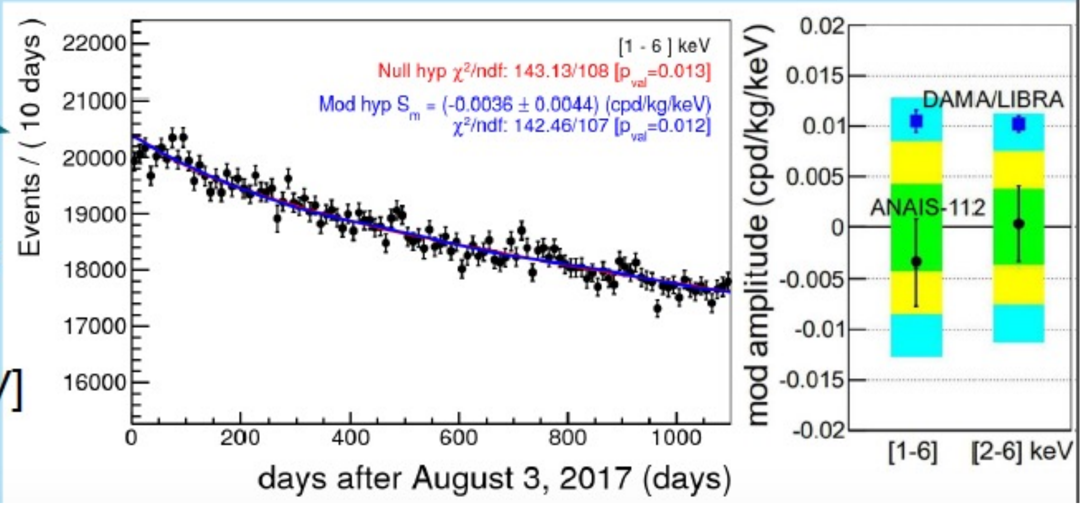
P. Belli@EPS-HEP 2021

First „model-independent“ test of DAMA/Libra with the same target and experimental approach

ANAIS (NaI)

PRD 103, 102005 (2021)

- 3 year data: 0.31 t x y exposure
  same threshold but ~3x higher background
- data consistent with no modulation;
  incompatible with DAMA at 3.3σ [1-6 keV]



Directional Detector: MIMAC

Measuring the direction of the nuclear recoil

⇒ Unambiguous WIMP identification

due to anisotropy of WIMP flux on Earth;

⇒ Allows to overpass the neutrino floor

- Properties

⦿ Gas mixture: i-C_4H_{10} + 50% CHF_3 at 30 mbar

⦿ Based on a Micromegas with a pixelated anode

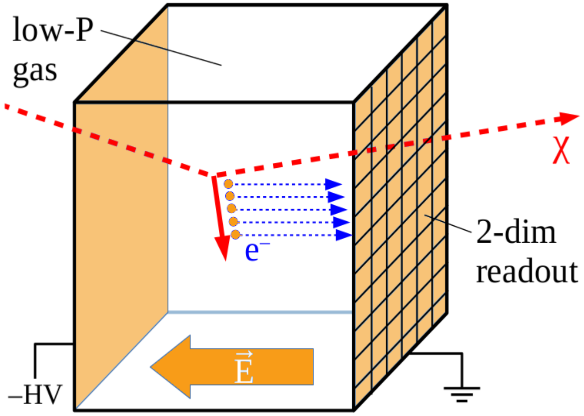
- Results

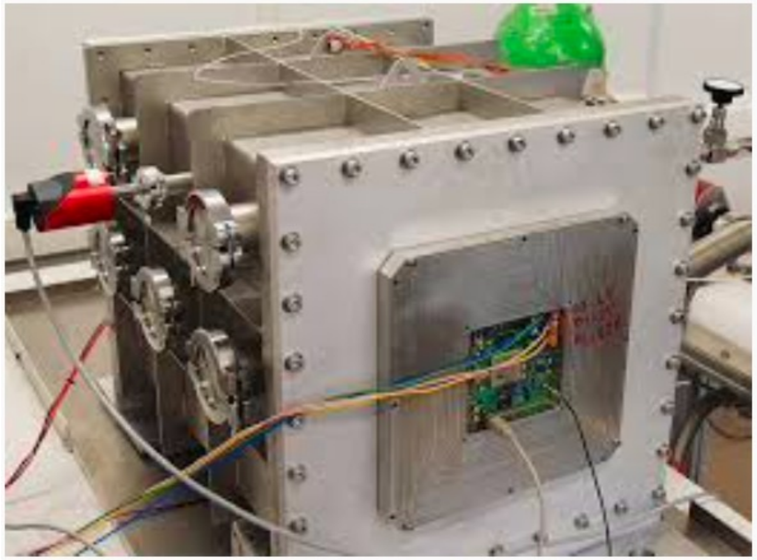
⦿ Demonstrate that directionality is accessible in the keV-range => probing WIMPs down to GeV

⦿ Developed a method to give access to head-tail recognition

⦿ Directional detection threshold : 1 keV

⦿ Measured angular resolution in the keV-range : 15°





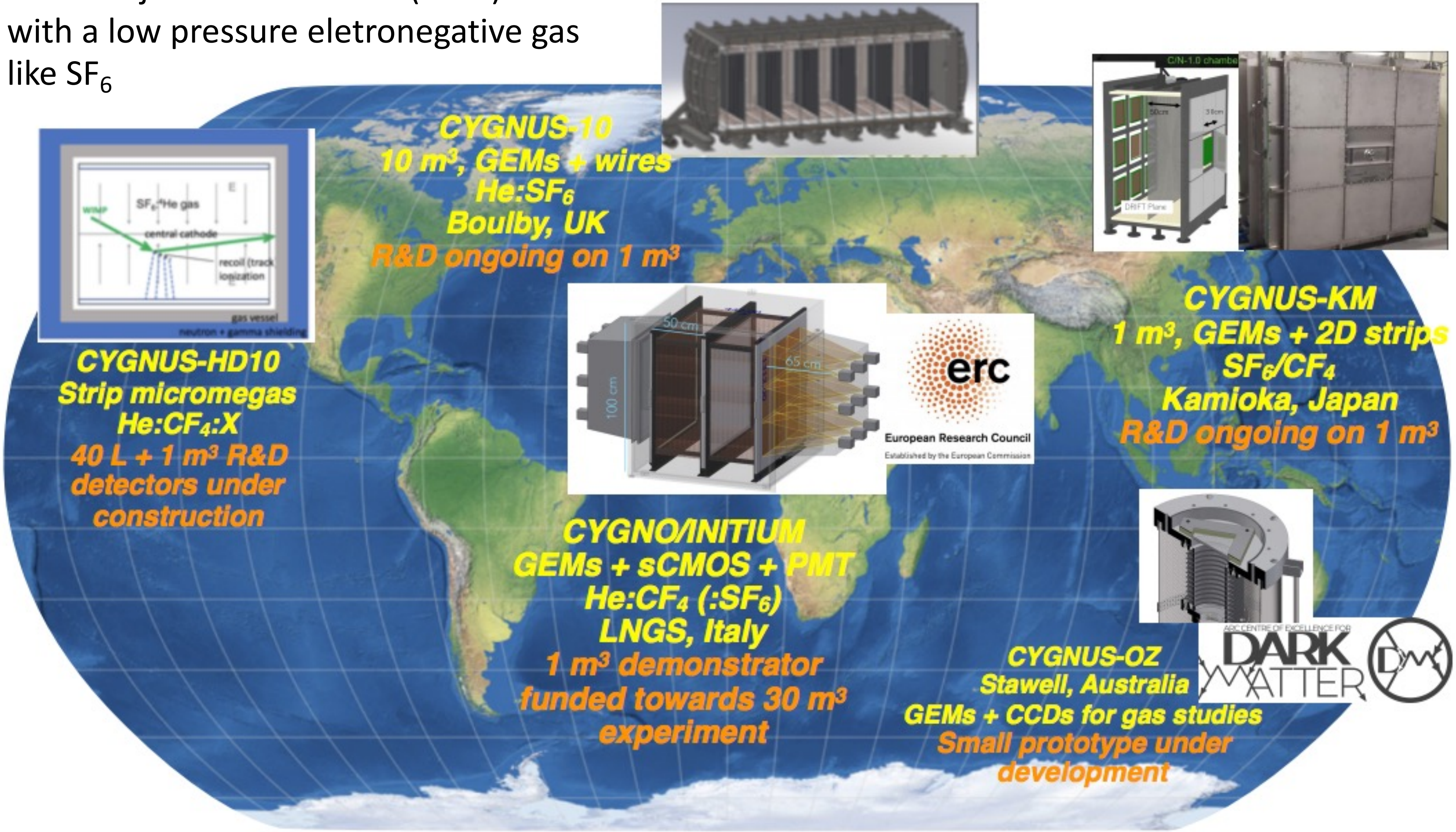
Other directional DM projects under R&D:

- NEWAGE (CF4 @0.1 bar; GEM)
- NEWSdm (nuclear emulsion)
- CYGNUS (He:SF_6/CF_4 TPC)

ArXiv2112.12469 C. Beaufort, IDM2022

CYGNUS project/network

Time Projection Chambers (TPCs) filled with a low pressure eletronegative gas like SF_6



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

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

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

E. Baracchini @IDM 2022

concept paper on 1000 m3 CYGNUS detector:
arXiv: 2008.12587

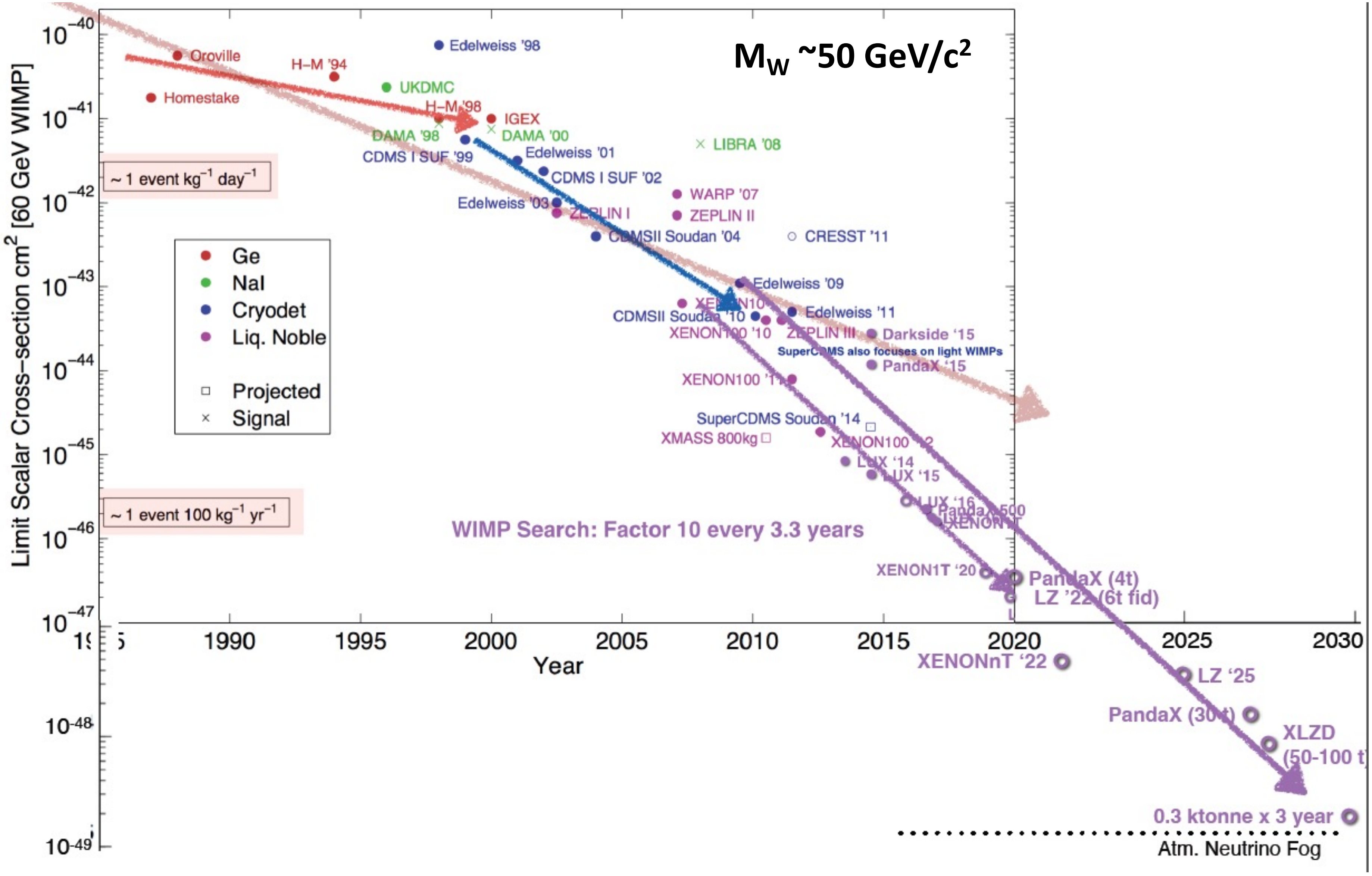
Conclusions & Outlook

- Gravitational mass is "missing" at all scales, including in our own galaxy
- Several well motivated candidates exist, the most popular are (still) thermal relics with weak interactions, i.e. WIMPs
- A large variety of technologies is used for their detection
- Very active field and tremendous progress with a large improvement of sensitivity:
    - ➢ **LXe dual TPCs** are the most sensitive for WIMP masses > 5 GeV
    - ➢ Below ~ 5 GeV **cryogenic bolometers** have best sensitivities
- Many new detection technologies in R&D stage for exploring the sub-Gev parameter space region down to 1 MeV
- Intense activity on **directional detectors** to get unambiguous identification of galactic DM particles even within the neutrino fog.
- **Goal**: probe the parameter space down to (and within, if possible) the neutrino fog.

Spares

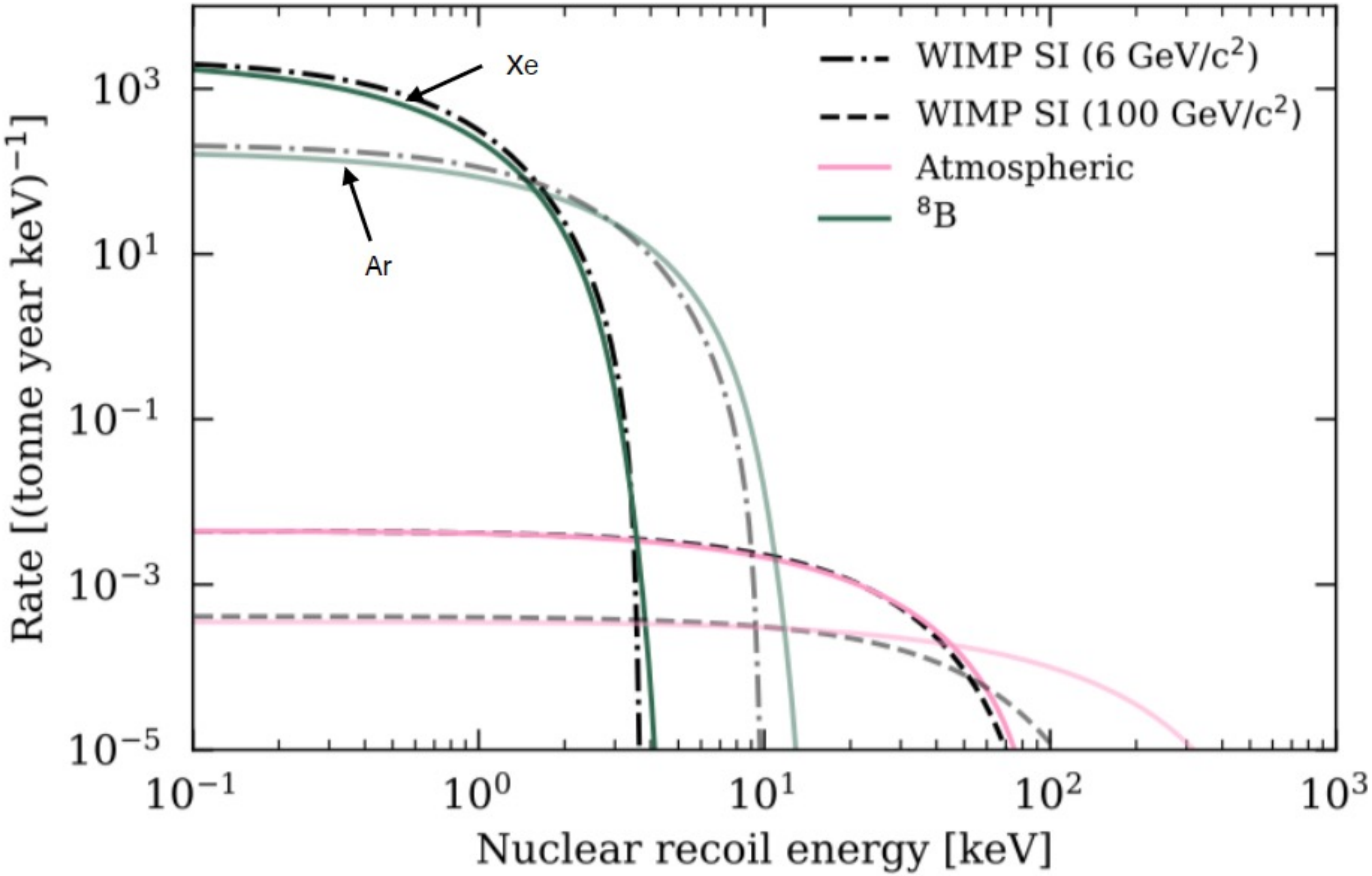
Progress in WIMP search

Moore's law: factor of 10 every 5 years



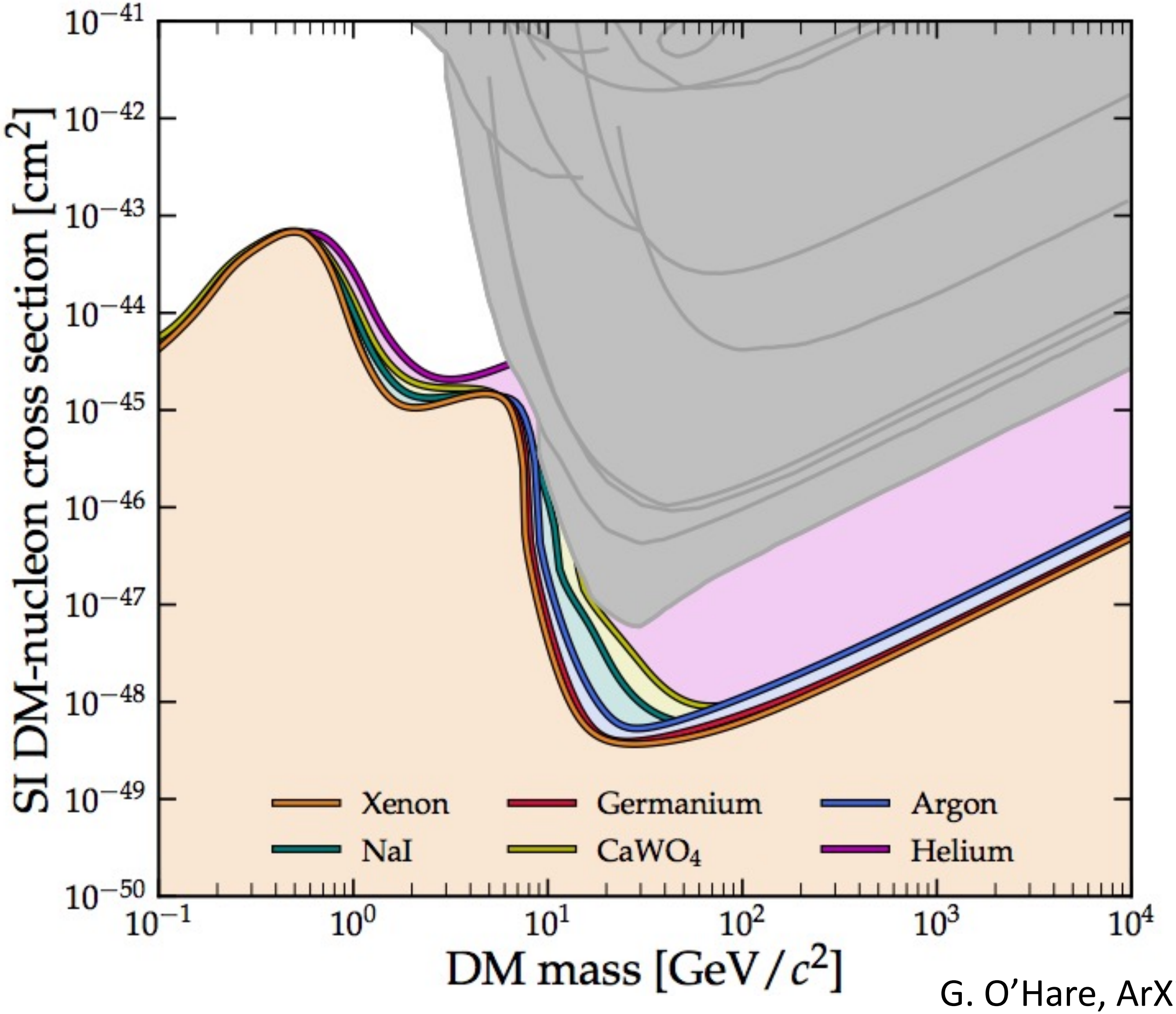
Adapted from R. Gaitskell@IDM2022

CEνNS & WIMP nuclear recoil energy spectra



From CF1 WP1 arXiv:2203.08084

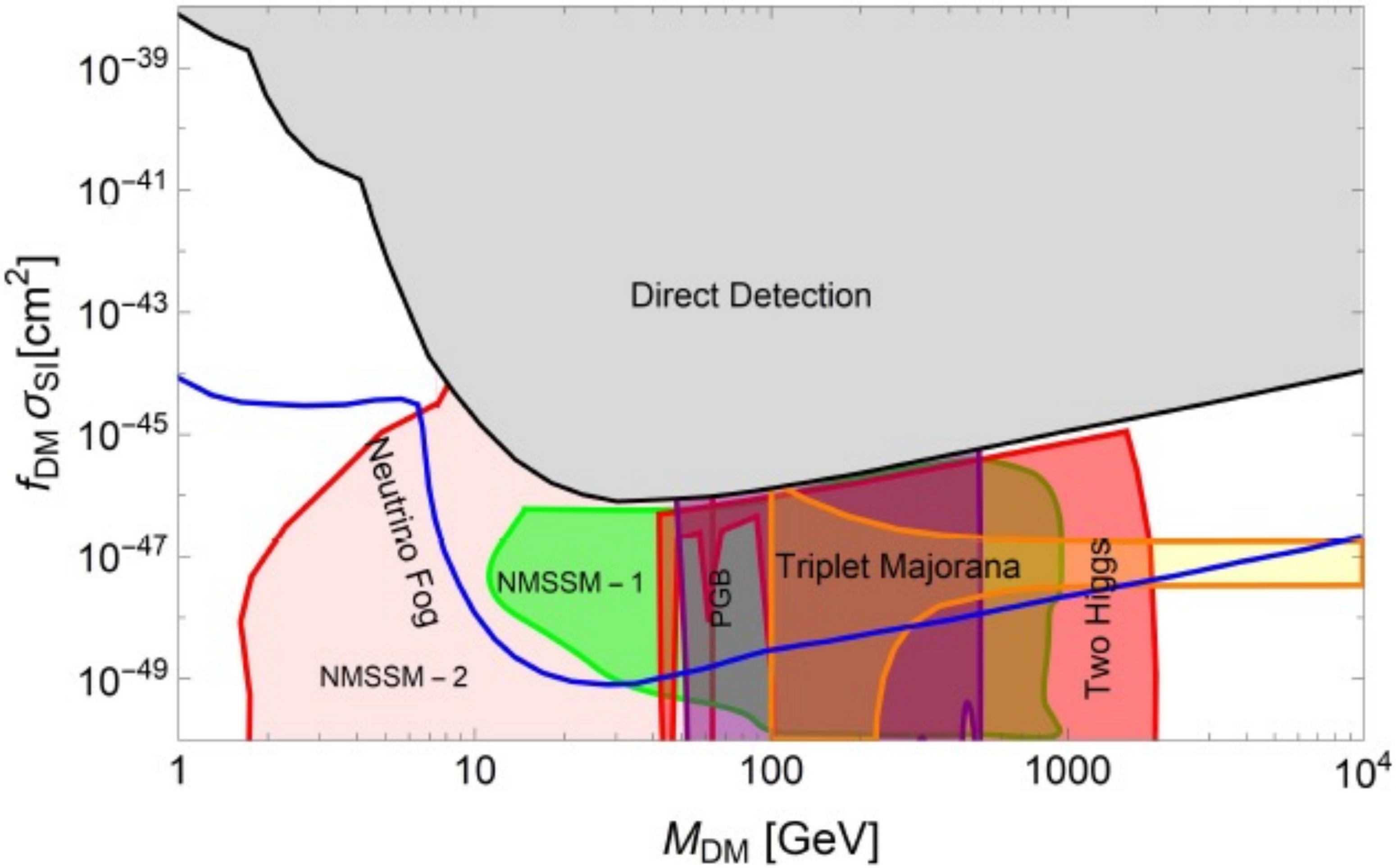
Neutrino fog dependence on the target



G. O'Hare, ArXiv 210903116

WIMP Candidates down to and well into the neutrino fog

CF1 WP1 arXiv:2203.08084



Predictions for SI scattering cross sections (in plots of dark matter-proton cross section times DM fraction versus dark matter mass) for some visible sector models

Why Liquid Xenon

Kinematically favors GeV to TeV DM masses

- **Scalability** to large (multi-ton) detector masses
- Manageable cryogenics: 170 K (LXe), 87 K (LAr)
- **Purification** in stages or continuously (both for radiopurity and electronegative impurities)
- High scintillation yield and transparent to its own light
- Can be easily ionized
- High atomic number and high density (particularly LXe) gives stopping power, self-shielding.
- Intrinsic radioactivity: Xe has long-lived ^{136}Xe and ^{124}Xe; ^{85}Kr can be removed.

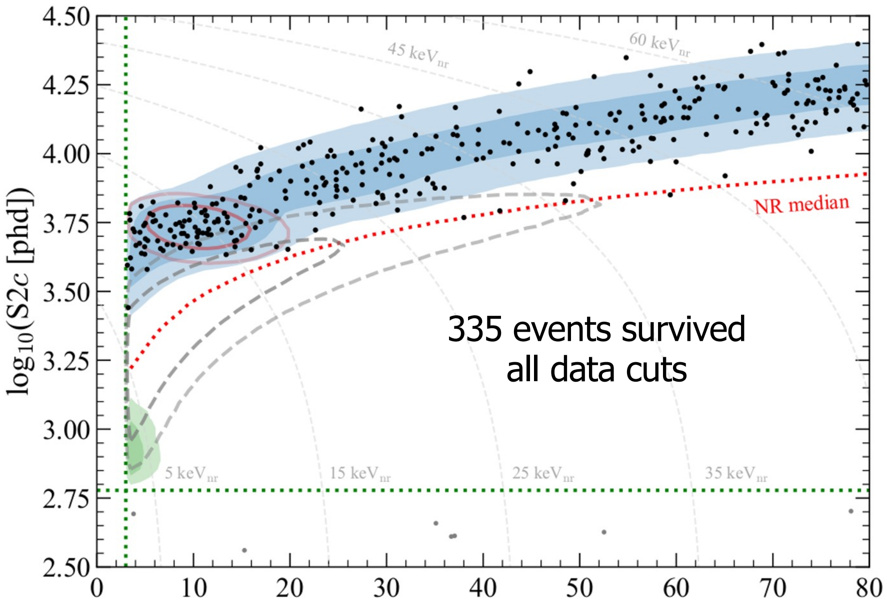
Science Run 1 Data

Data collected from 23 Dec 2021 to 11 May 2022 under stable detector conditions.

- ➔ 60 live-days of exposure for SR1.
- ➔ 32% dead time mostly due to hold-off after large S2 pulses.

Fiducial volume of 5.5 tonnes:

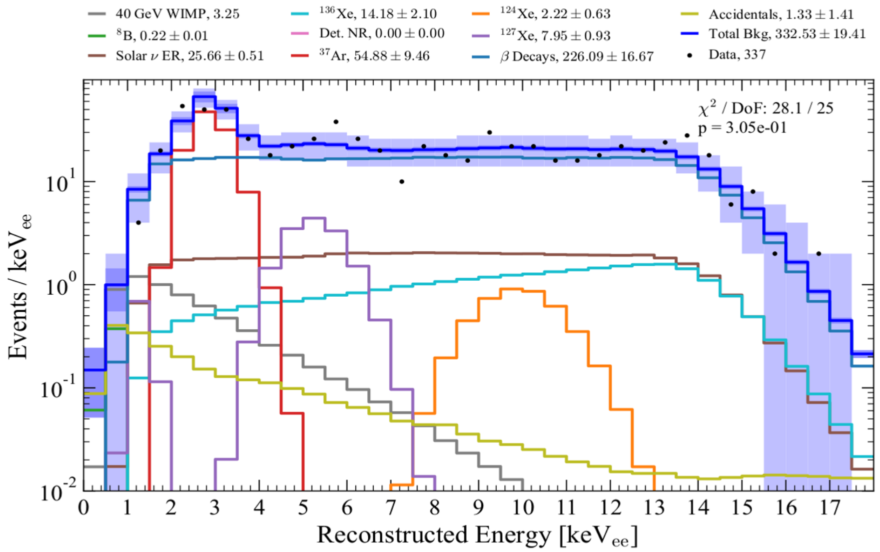
- ➔ **Total SR1 exposure of 330 tonne·days.**



335 events survived all data cuts

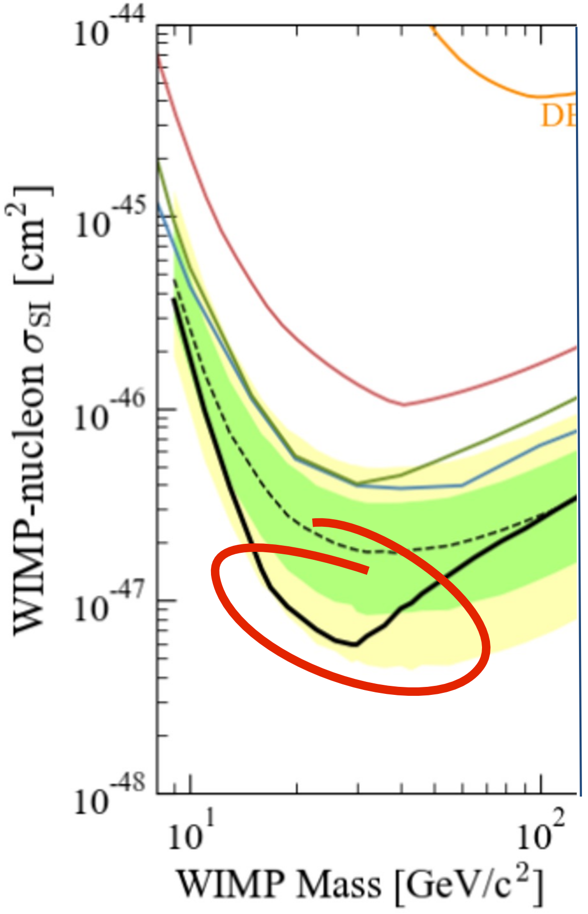
All backgrounds are within expectation:

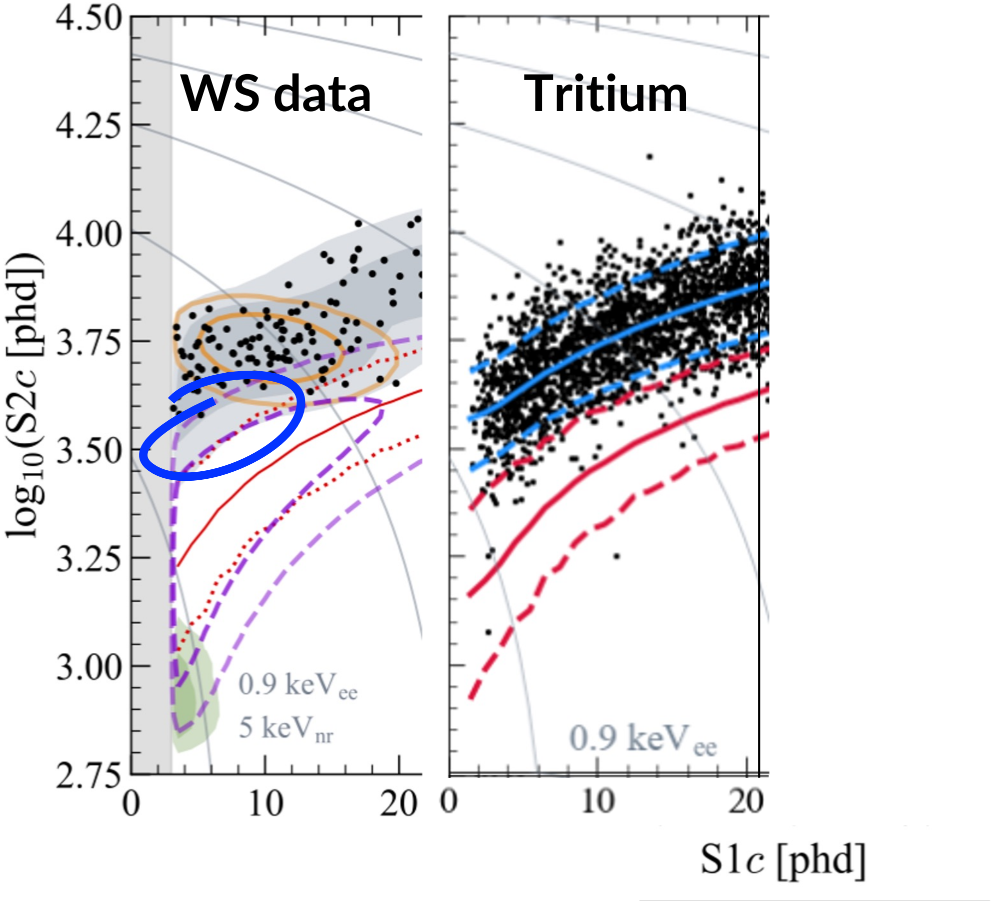
- ★ Data agrees with the background-only model (p-value of 0.96).
- ★ ^{37}Ar excess observed at 2.7 keV consistent with projected rate.



Electronic-equivalent energy spectrum for WIMP-search ROI

Underfluctuation

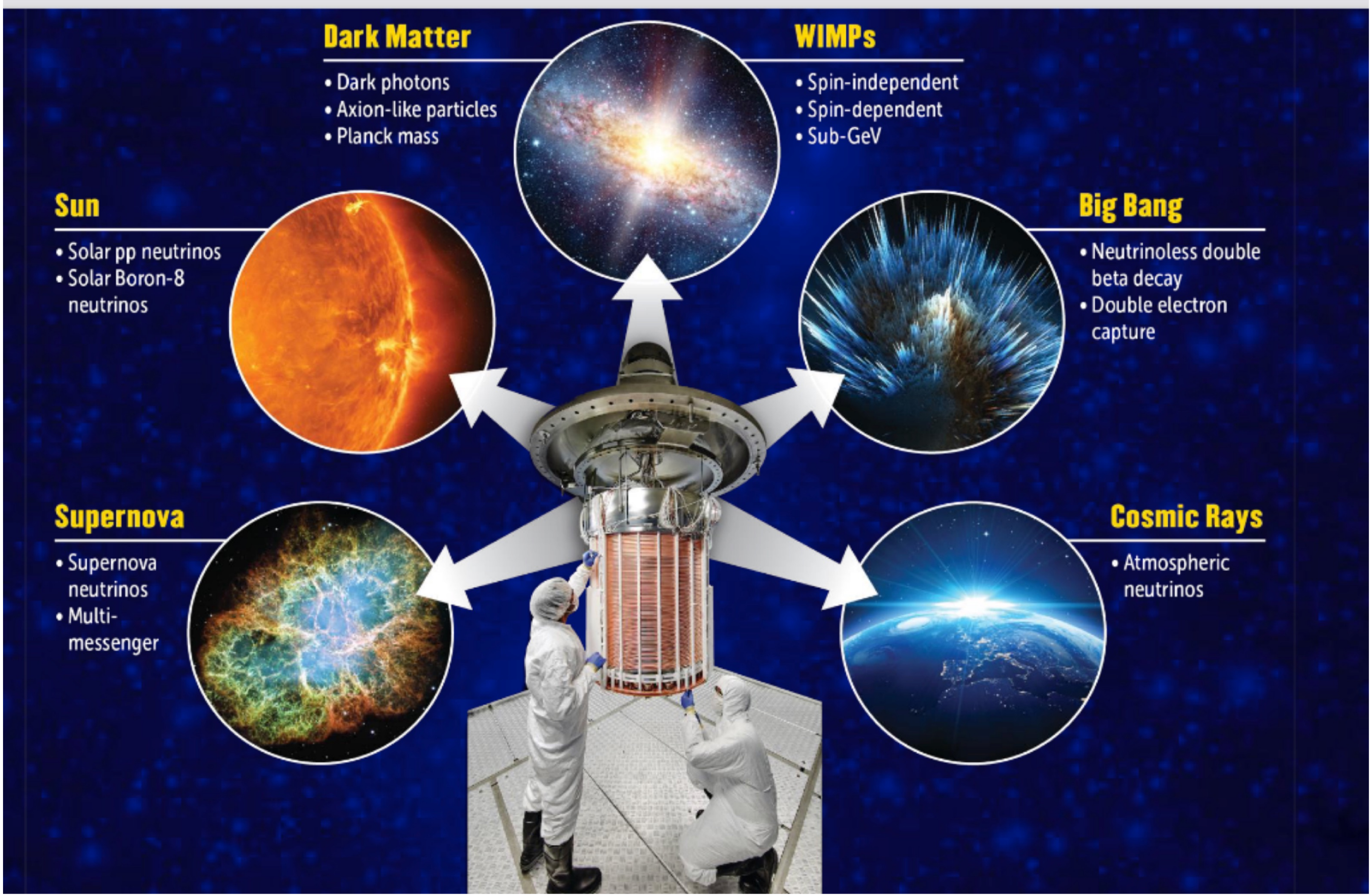




1. Downward fluctuation in the observed upper limit near 30 GeV/c^2 is a result of the deficit of events under the ^{37}Ar population.
   Due to background under-fluctuation or unaccounted for signal inefficiency? Probe the latter.

2. **Tritium** data analyzed identically to WS data. Deficit region is well-covered.

The Next Generation Liquid Xenon Observatory



Dark Matter
- Dark photons
- Axion-like particles
- Planck mass

WIMPs
- Spin-independent
- Spin-dependent
- Sub-GeV

Sun
- Solar pp neutrinos
- Solar Boron-8 neutrinos

Big Bang
- Neutrinoless double beta decay
- Double electron capture

Supernova
- Supernova neutrinos
- Multi-messenger

Cosmic Rays
- Atmospheric neutrinos