The Experimental Landscape of Dark Matter Direct Detection

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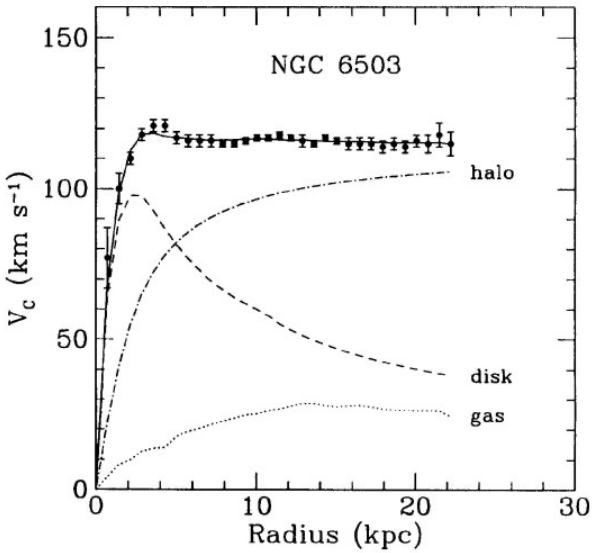
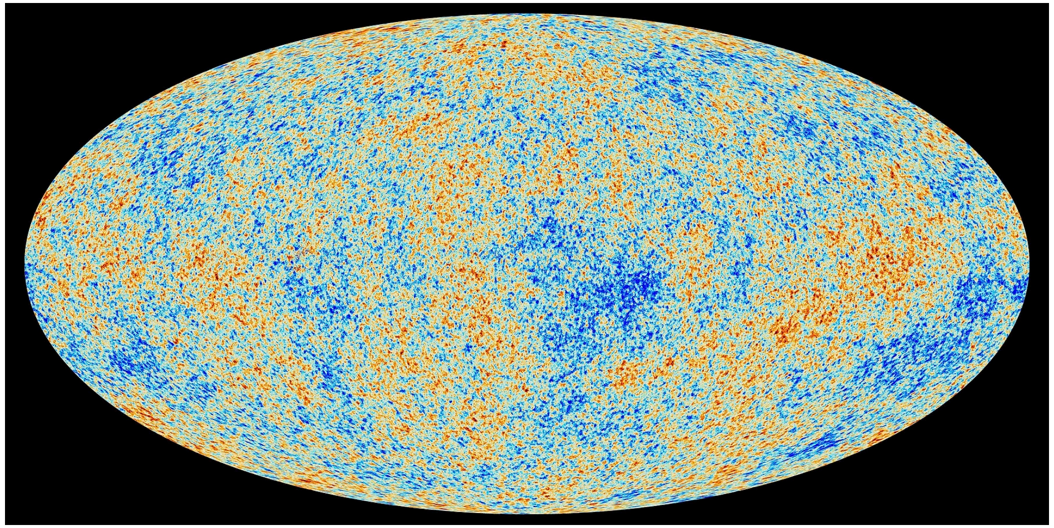
12th Workshop on Flavor Symmetries and Consequences in Accelerators and Cosmology (FLASY 2026)

August 21, 2026 Gyeongju, Korea

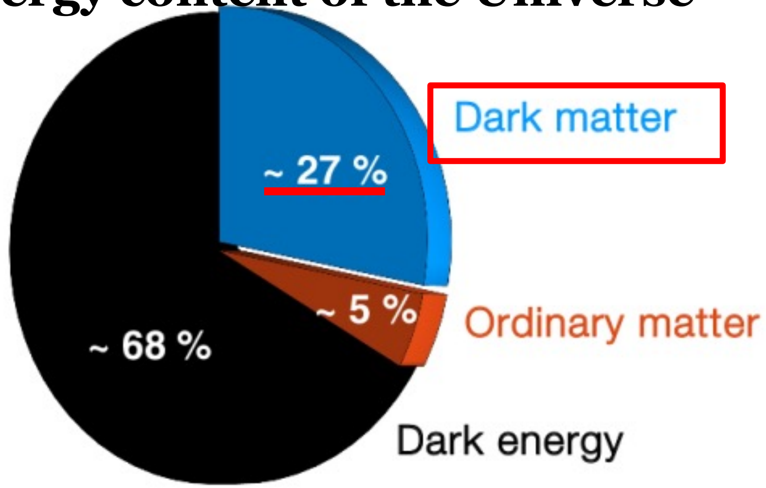
Dark Matter

Evidence of Dark Matter

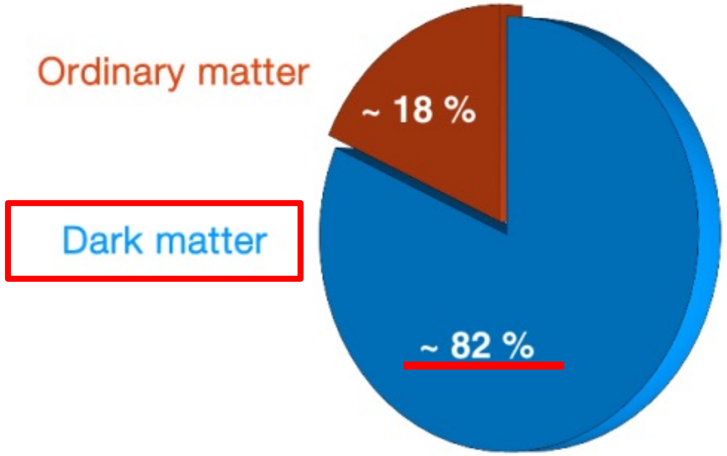




Energy content of the Universe



Matter content of the Universe



(Particle) Dark Matter Candidate

- Weakly Interacting Massive Particle (WIMP)

PHYSICAL REVIEW LETTERS

VOLUME 39 | 25 JULY 1977 | NUMBER 4

Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee[a]
Fermi National Accelerator Laboratory,[b] *Batavia, Illinois 60510*

and

Steven Weinberg[c]
Stanford University, Physics Department, Stanford, California 94305
(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.

PHYSICAL REVIEW D | VOLUME 31, NUMBER 12 | 15 JUNE 1985

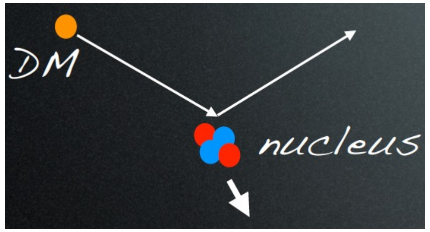
Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

Mass > 2 GeV

Direct Detection of DM



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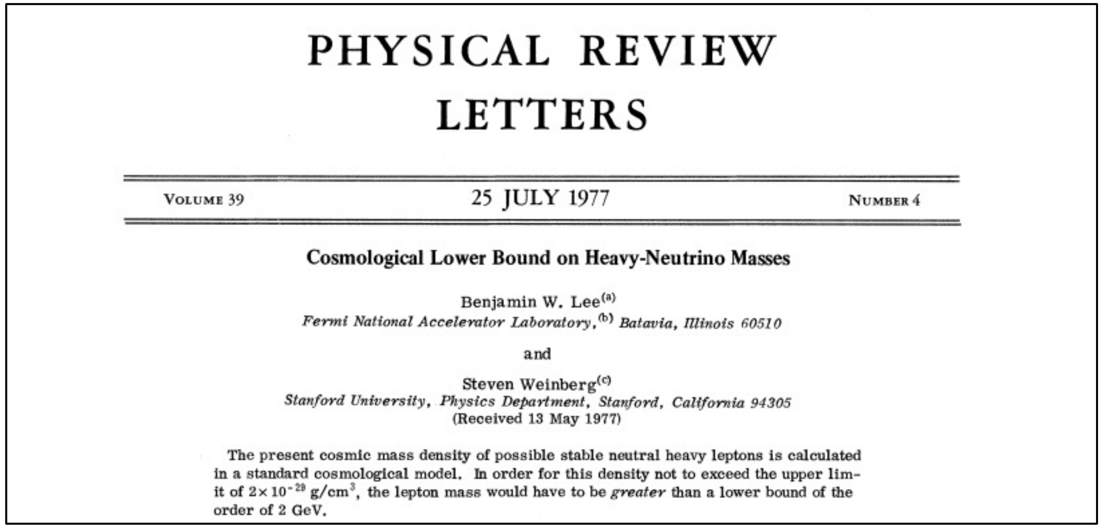

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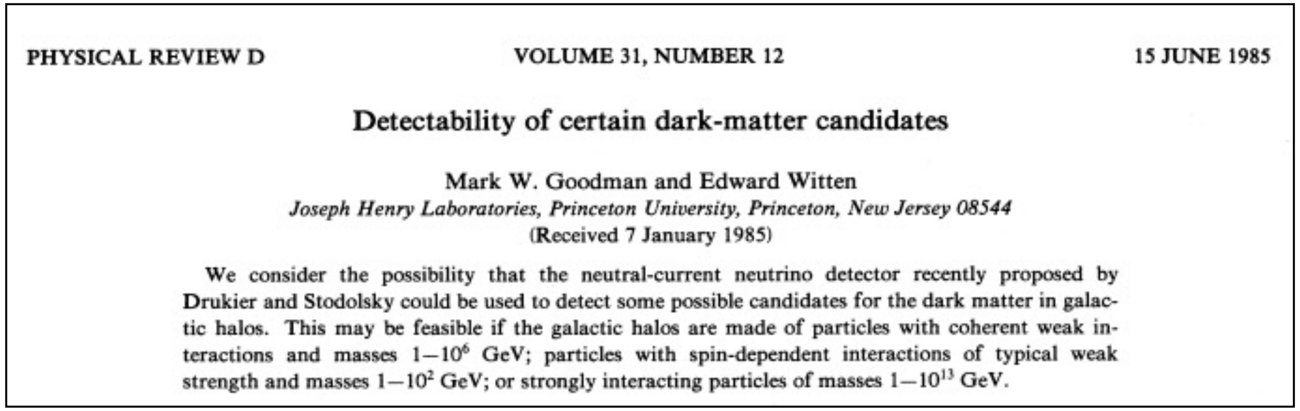

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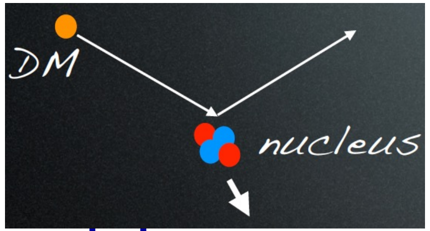
Mass > 2 GeV

- **Sub-GeV dark matter**

Direct Detection of DM



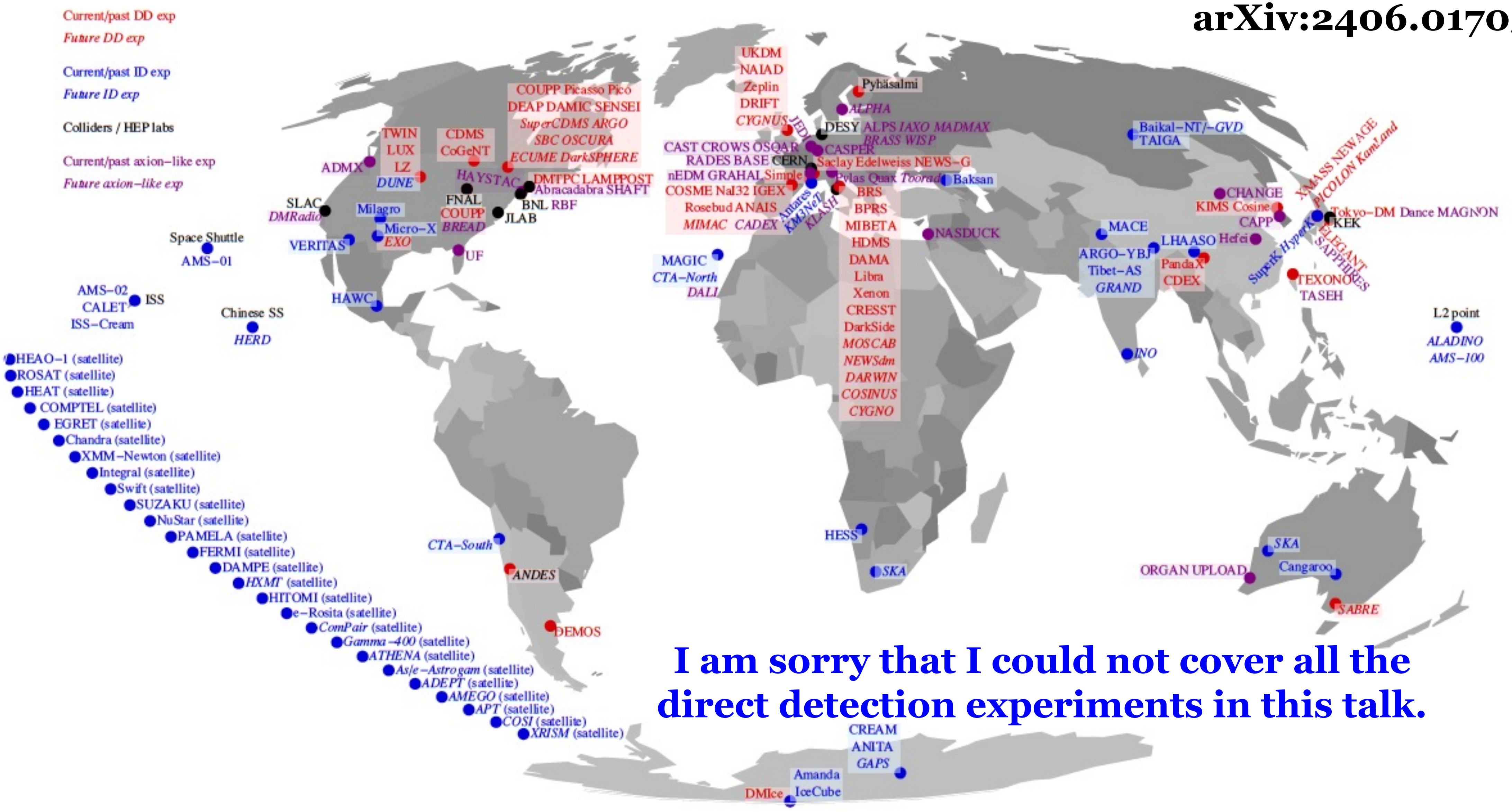
  - ❖ Well motivated by recently developed theoretical models
    - ❑ WIMPless DM, SIMP, Asymmetric DM, MeV (scalar) DM …
  - ❖ Low energy threshold
  - ❖ Low mass-number target
  - ❖ Electron recoil, Migdal Effect

Small energy & only a few events/year

Ultra-sensitive and ultra-clean detector required

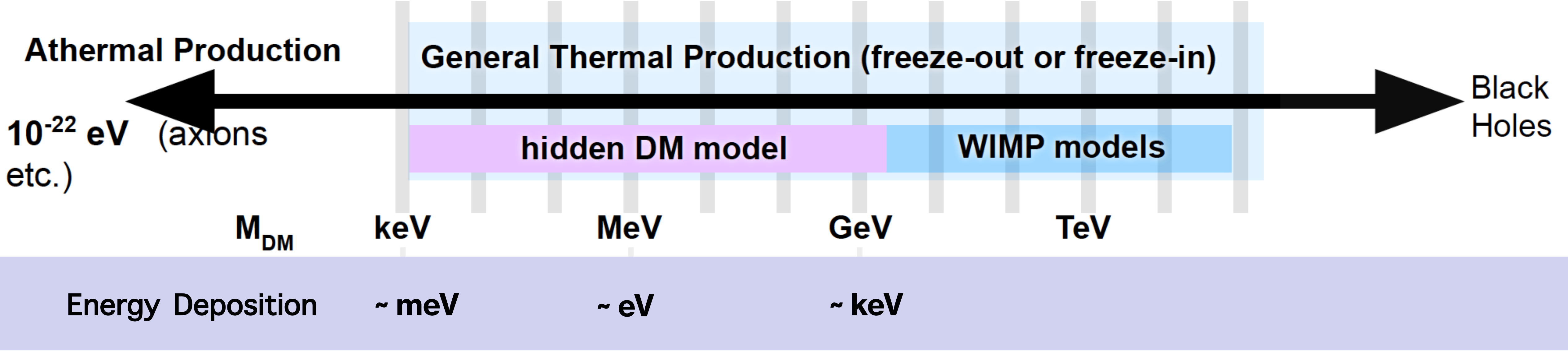
Dark Matter Detection Experiments

arXiv:2406.01705



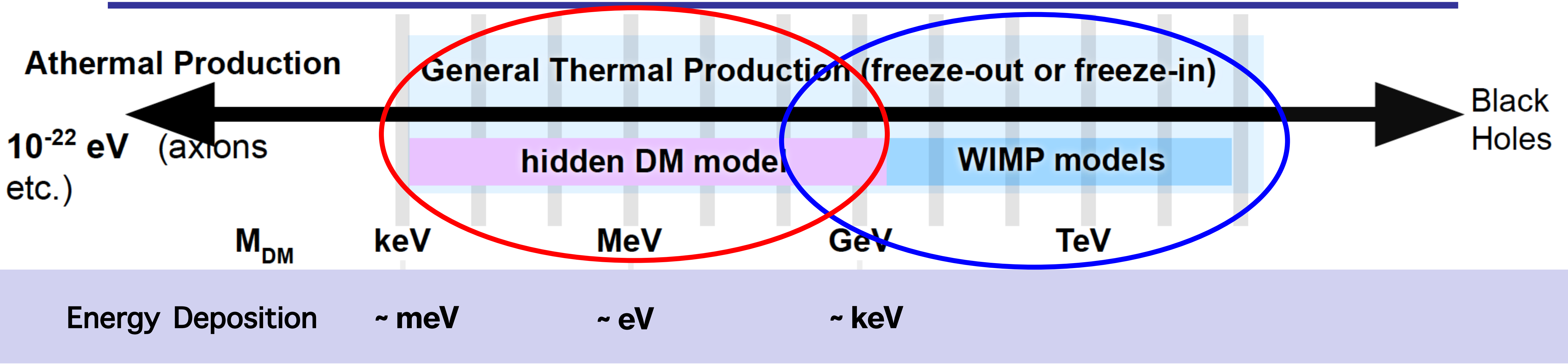
I am sorry that I could not cover all the direct detection experiments in this talk.

Landscape of Direct Detection



CENTER FOR UNDERGROUND PHYSICS ibs

Landscape of Direct Detection



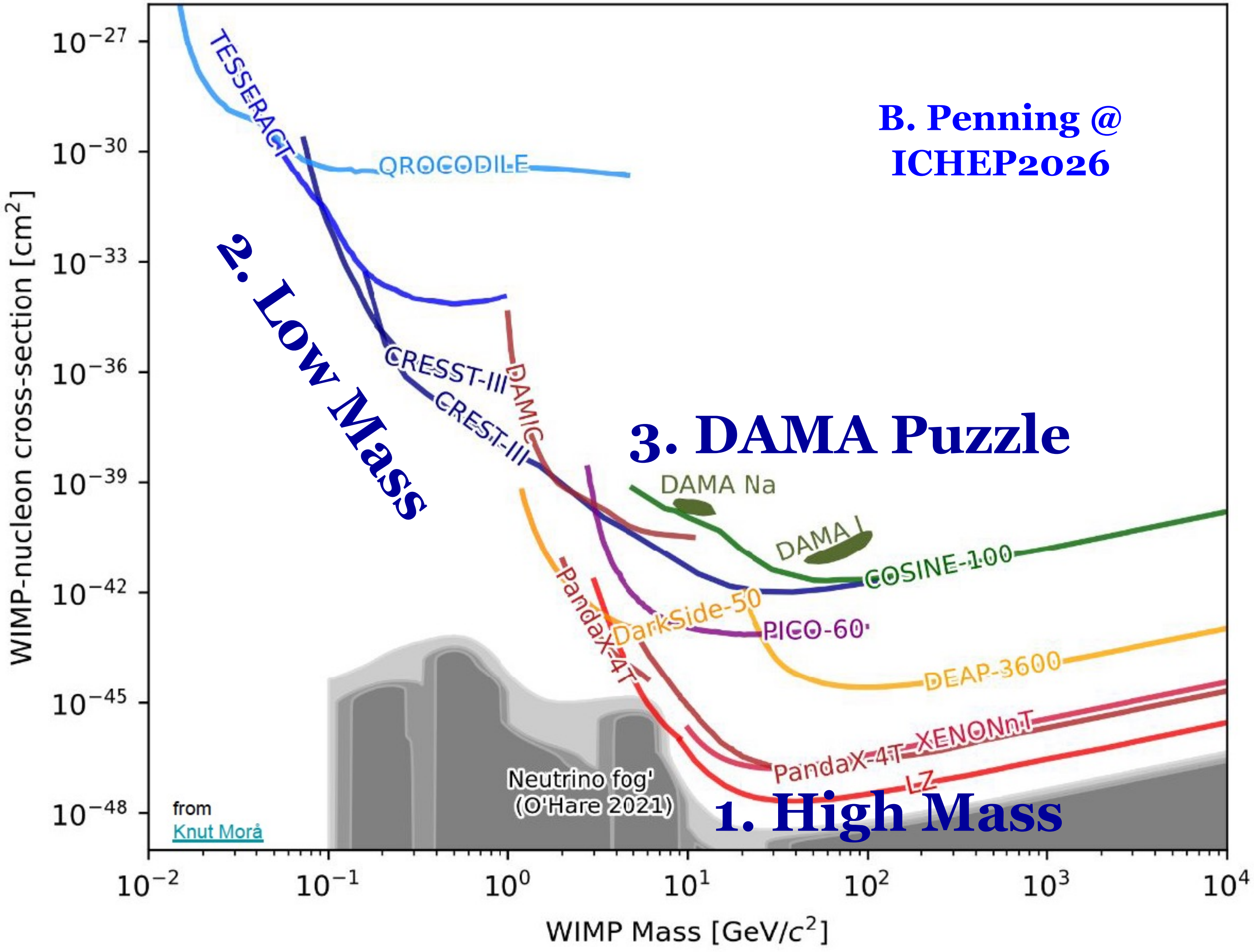
Low-Mass Dark Matter

- Signatures
  - ❖ Nuclear recoil (light target element)
    - ❑ Migdal (electron) signals
  - ❖ Electron scattering
- Low-threshold
- Quantum sensors

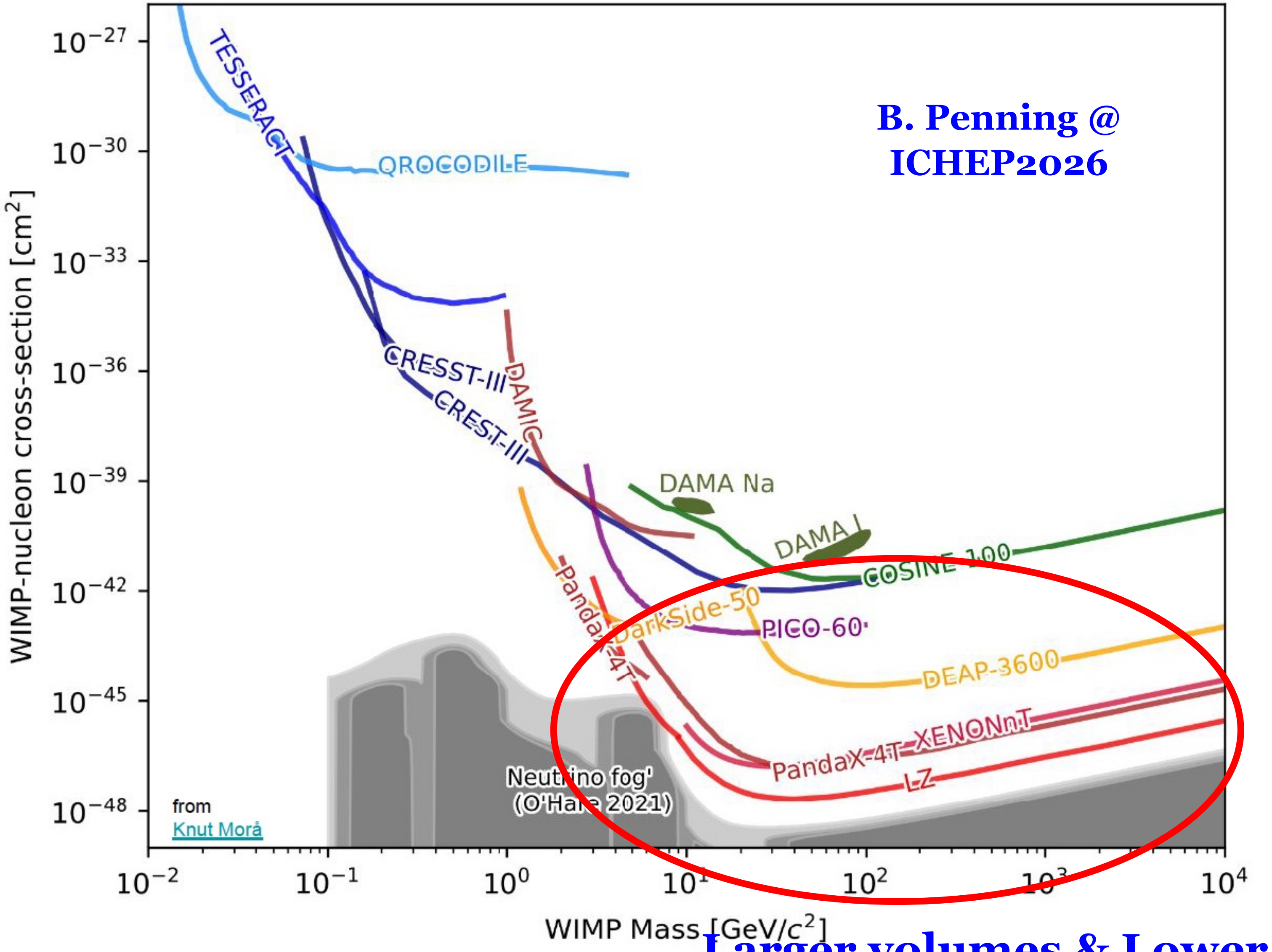
WIMP Dark Matter

- Signatures
  - ❖ Nuclear recoil
- Preparable high mass number target
  - ❖ $\sigma \sim A^2$
- Large volume & low-background

Status of Direct Detection

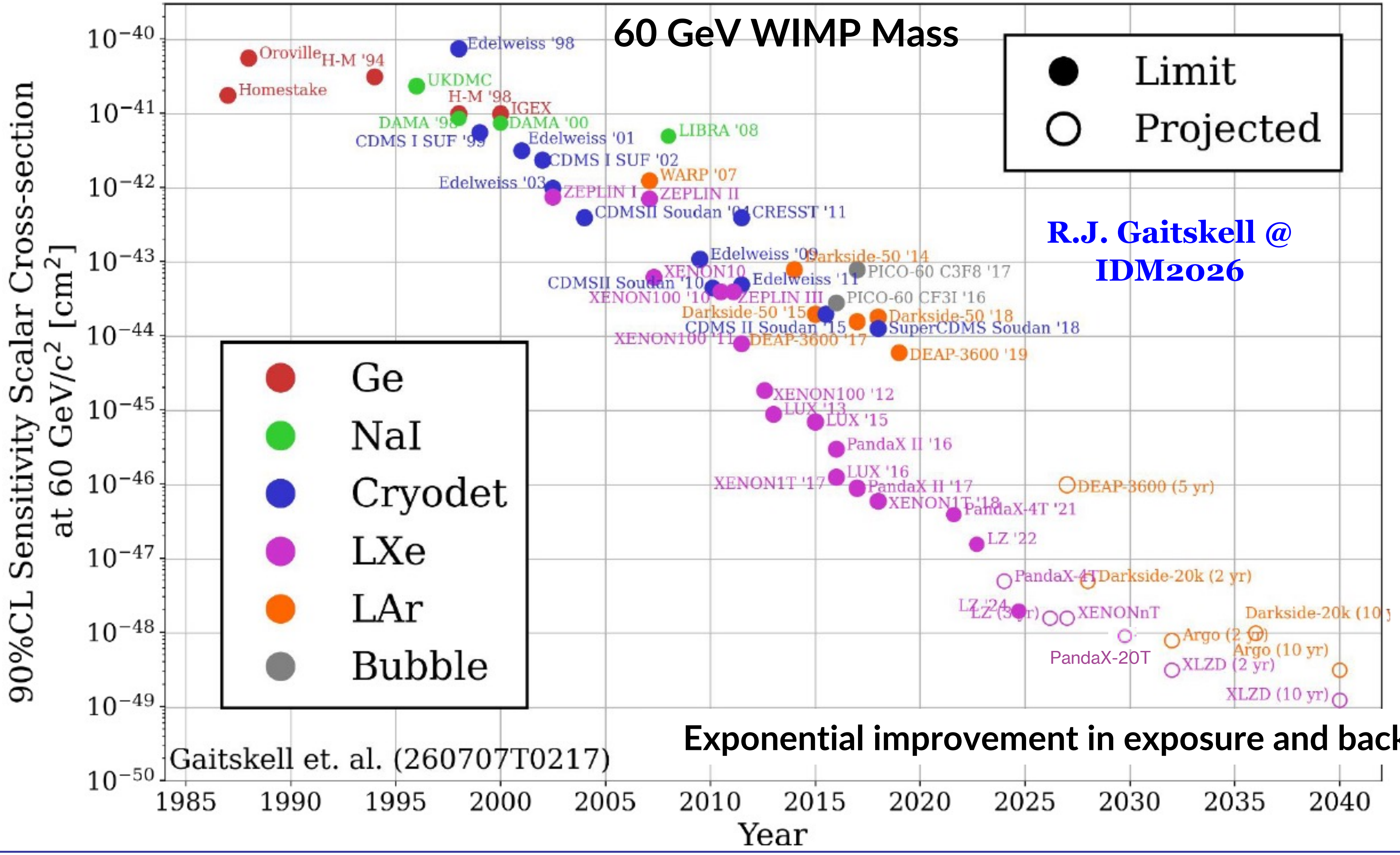


High-mass region



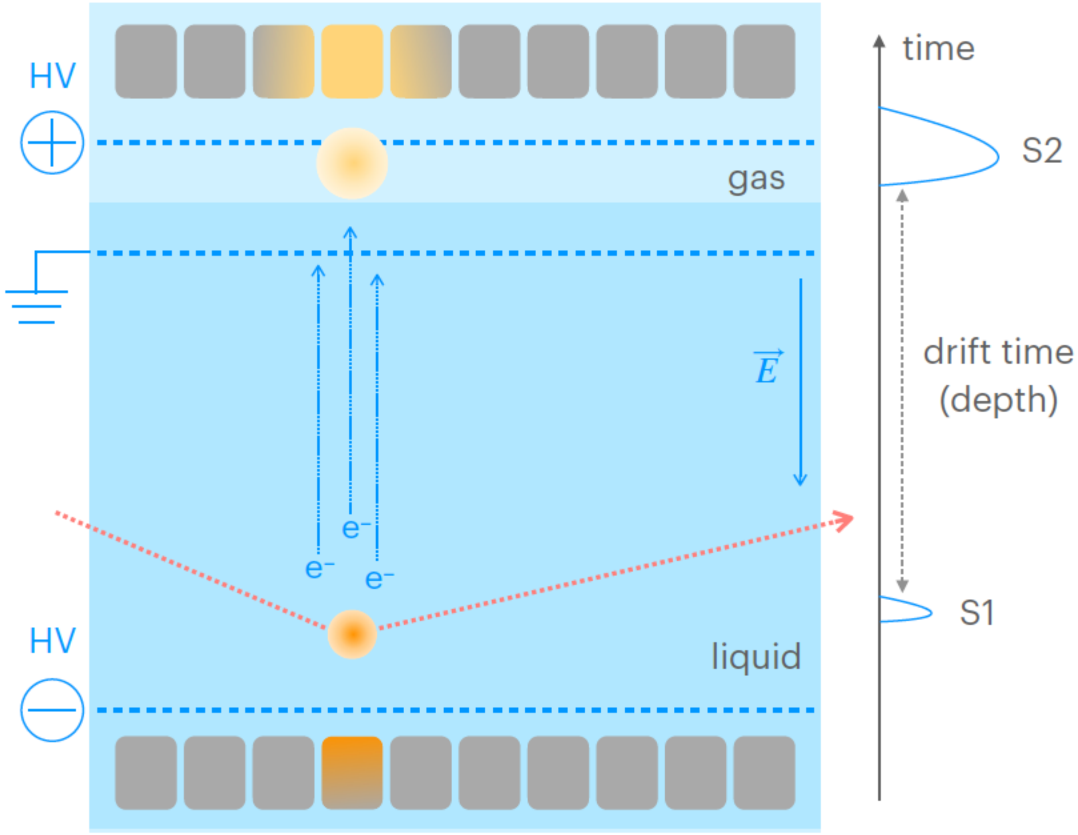
Larger volumes & Lower backgrounds

Decades of Progress in Direct Detection

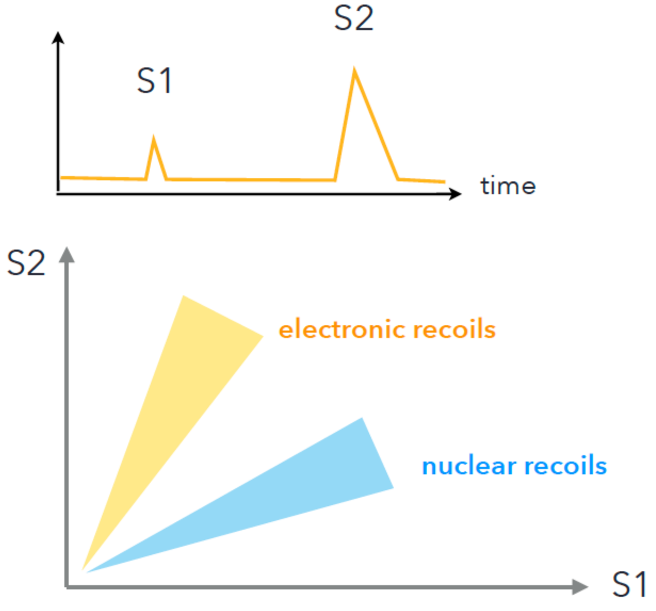


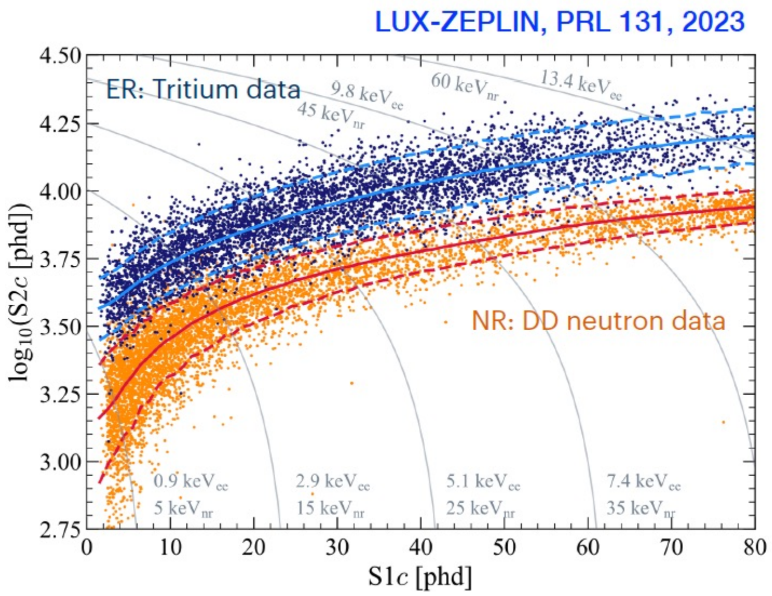
Exponential improvement in exposure and background

Two-phase liquid Xe



$$\lambda_{LXe} = 175 \text{ nm}$$





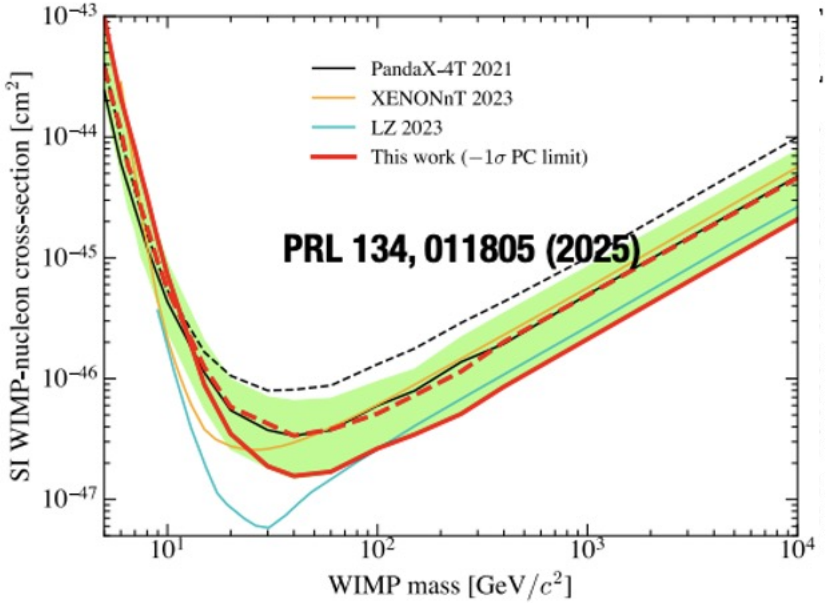
- Dual phase TPC
- Good particle identification
- Easy to scale up
- Background mitigation
  - ❖ Self-shielding with fiducial volume
  - ❖ In situ purification

Big three

LZ
7 (10) tonne
XENON
5.9 (8.6) tonne
PandaX
3.7 (5.6) tonne
Control room
LN storage room
LZ detector inside water tank
Xenon storage room
Canada
Ísland
Suomi
Sverige
United Kingdom
Беларусь
France
Україна
România
Россия
Казахстан
Монгол улс
O'zbekiston
Türkmenistan
España
Türkiye
Ελλάς
日本
Brasil
Paraguay

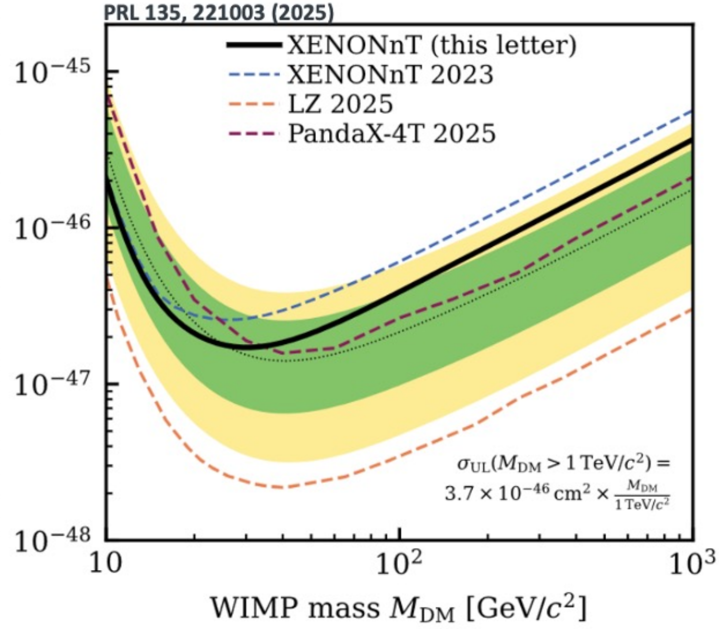
Recent results from liquid Xe detectors

PandaX-4T 1.5 tonne·yr



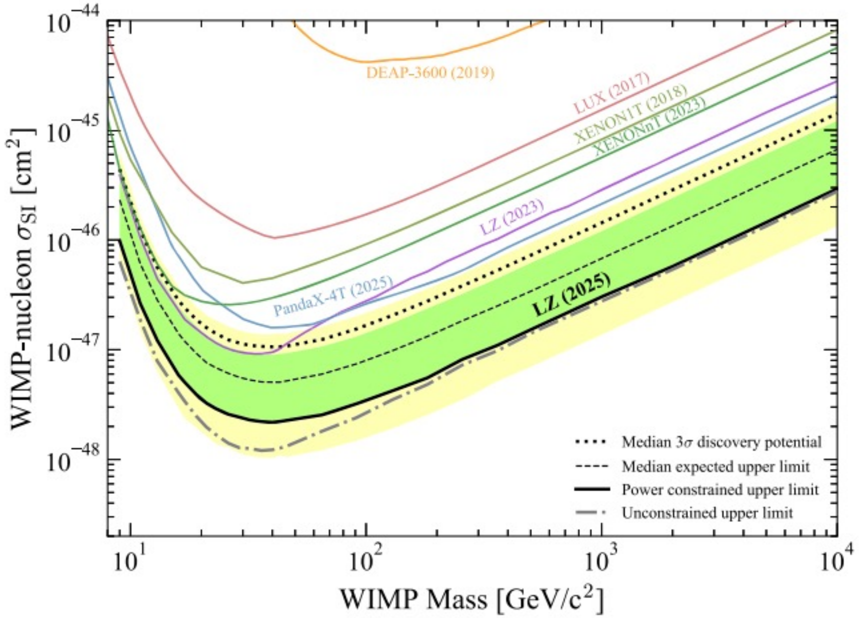
PRL 134, 011805 (2025)

XENONnT 3.1 tonne·yr

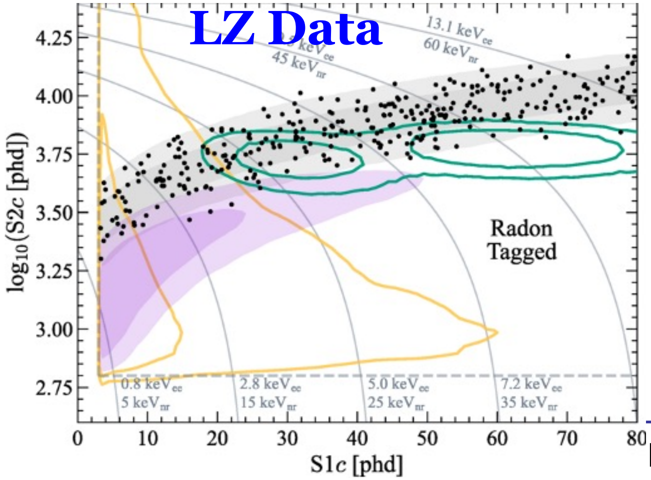


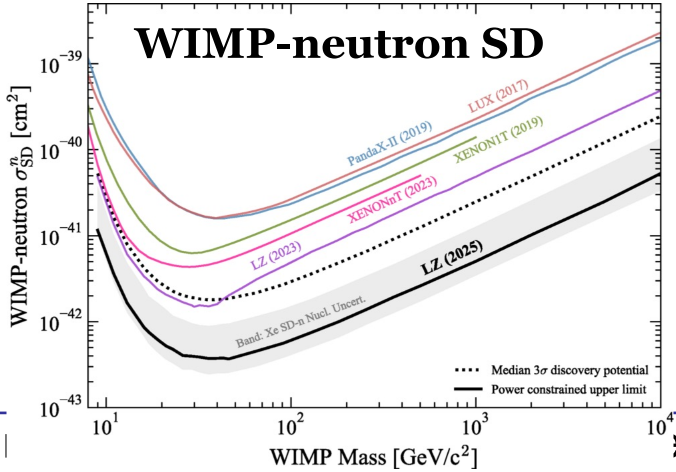
PRL 135, 221003 (2025)

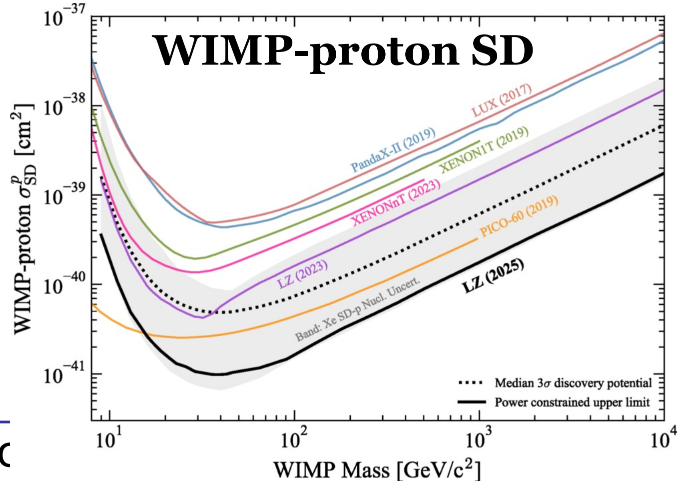
LZ 4.2 tonne·yr



PRL 135, 011802 (2025)

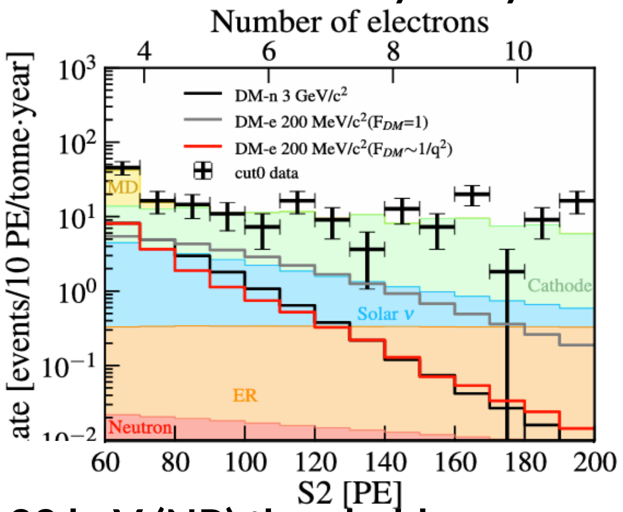






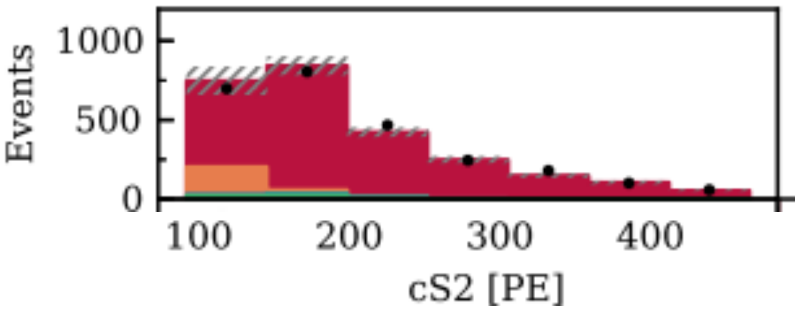
Low-mass searches with Xe

PandaX-4T S2-only analysis



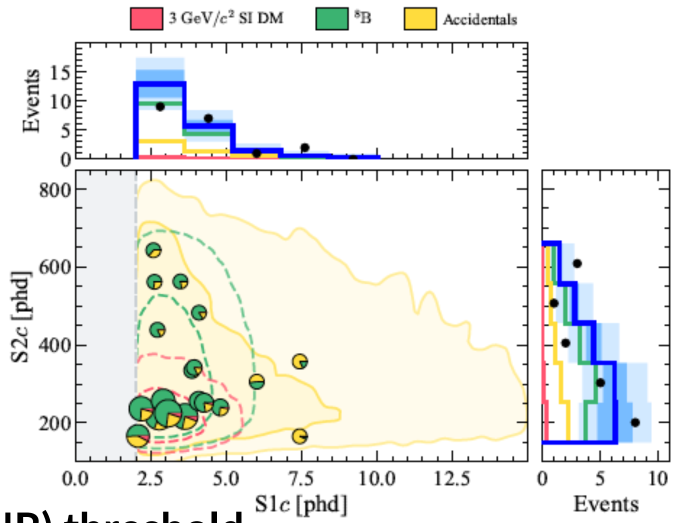
0.33 keV (NR) threshold

XENONnT S2-only analysis

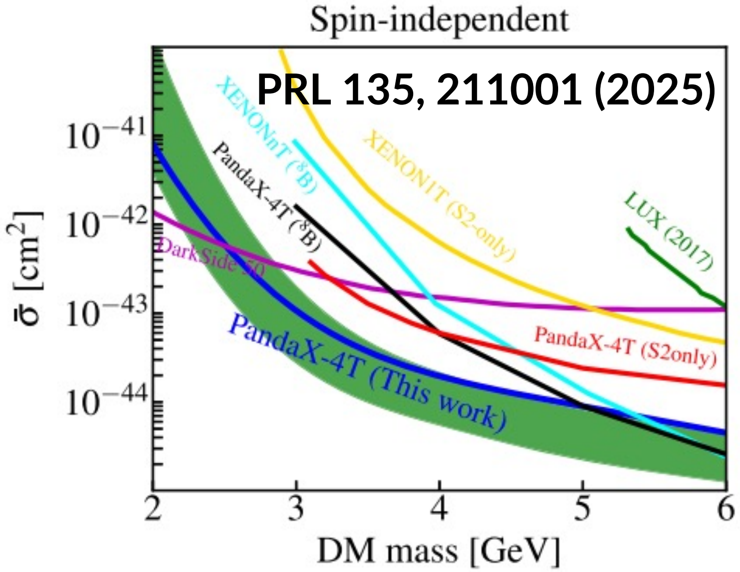


0.5 keV (NR) threshold

LZ 2025 analysis

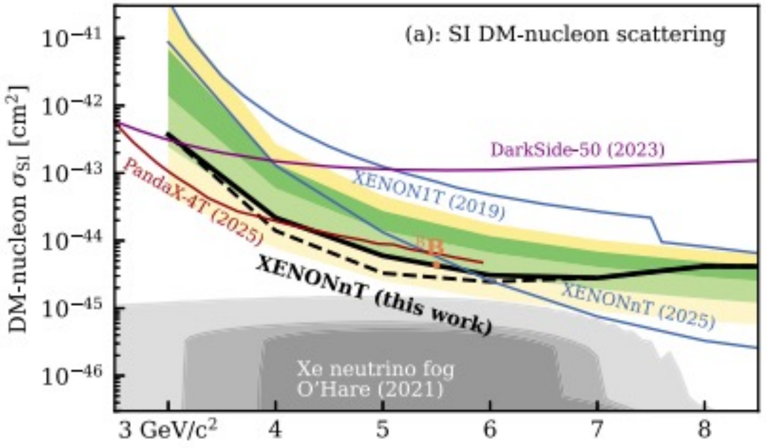


1 keV (NR) threshold

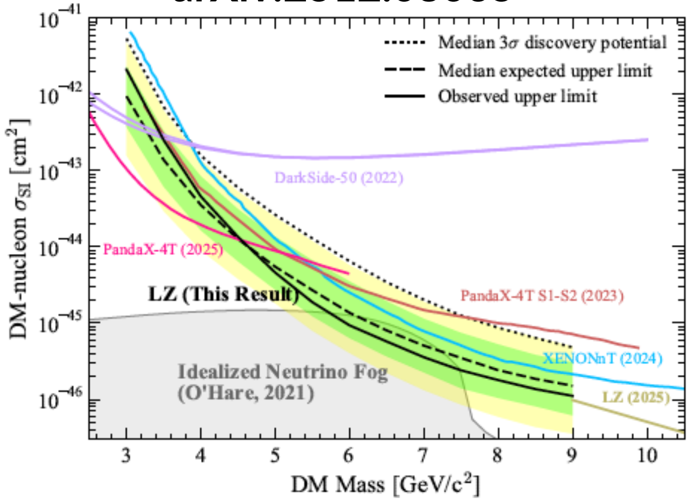


PRL 135, 211001 (2025)

PRL 137, 051003 (2025)

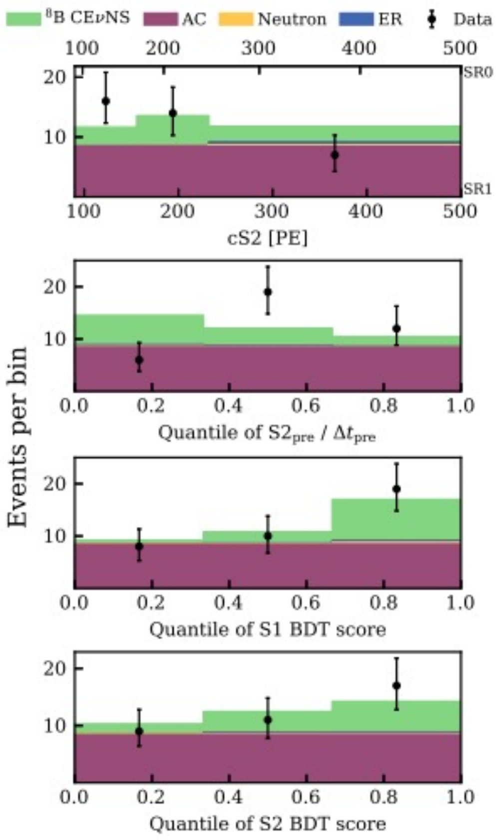


arXiv:2512.08065



^{8}B neutrino CEνNS

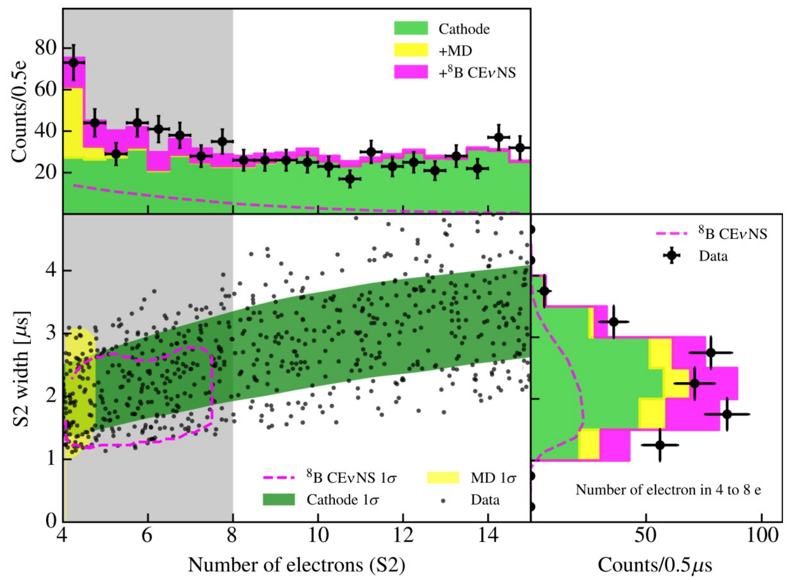
XENONnT



PRL 133, 191002 (2024)

2.73 σ

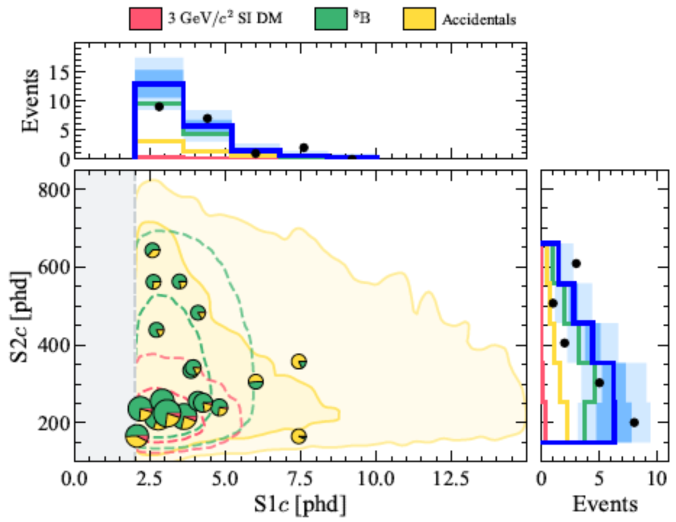
PandaX-4T



PRL 133, 191001 (2024)

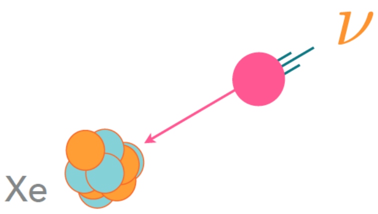
2.64 σ

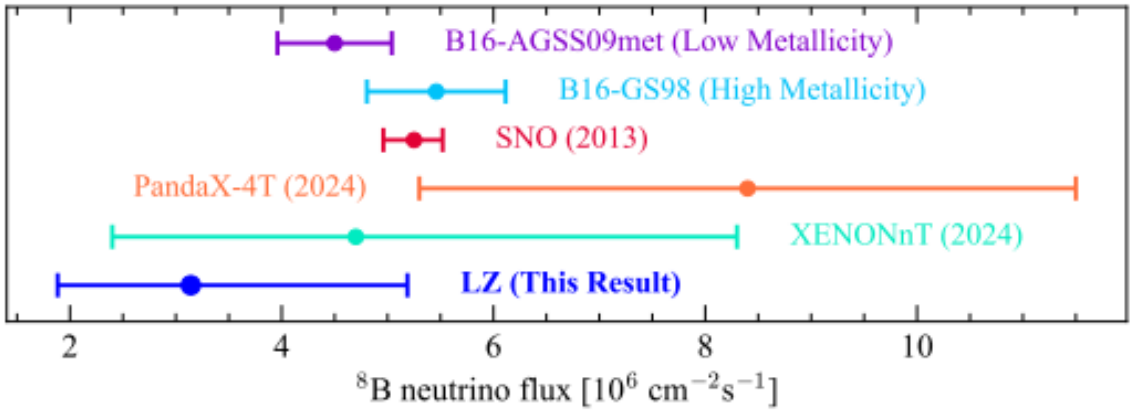
LZ 2025 analysis



arXiv:2512.08065

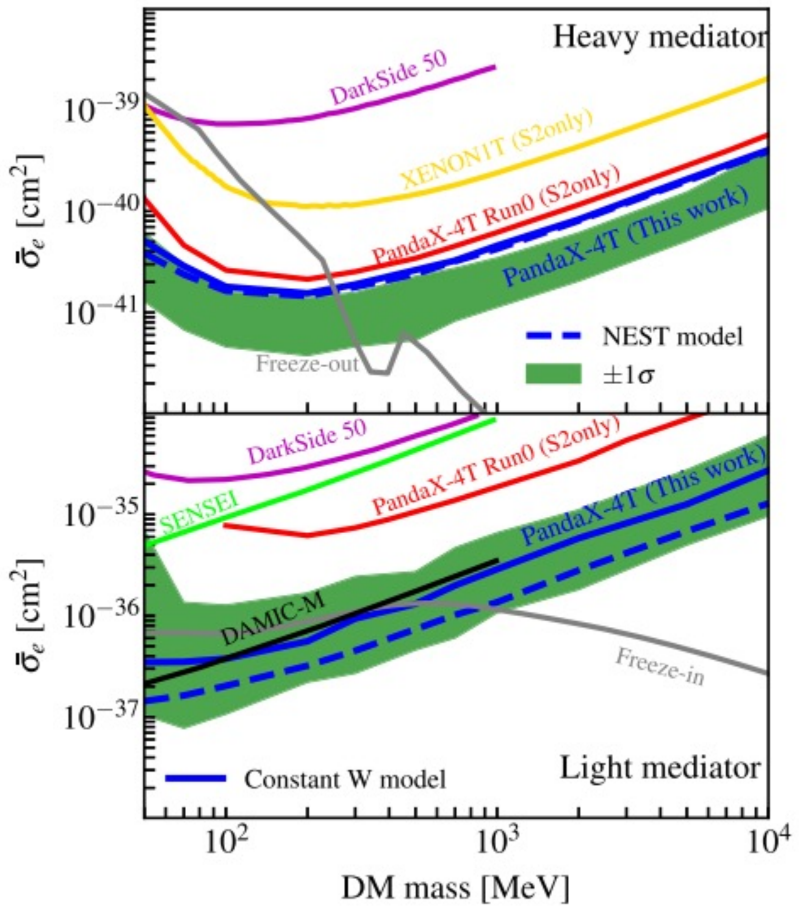
4.5 σ





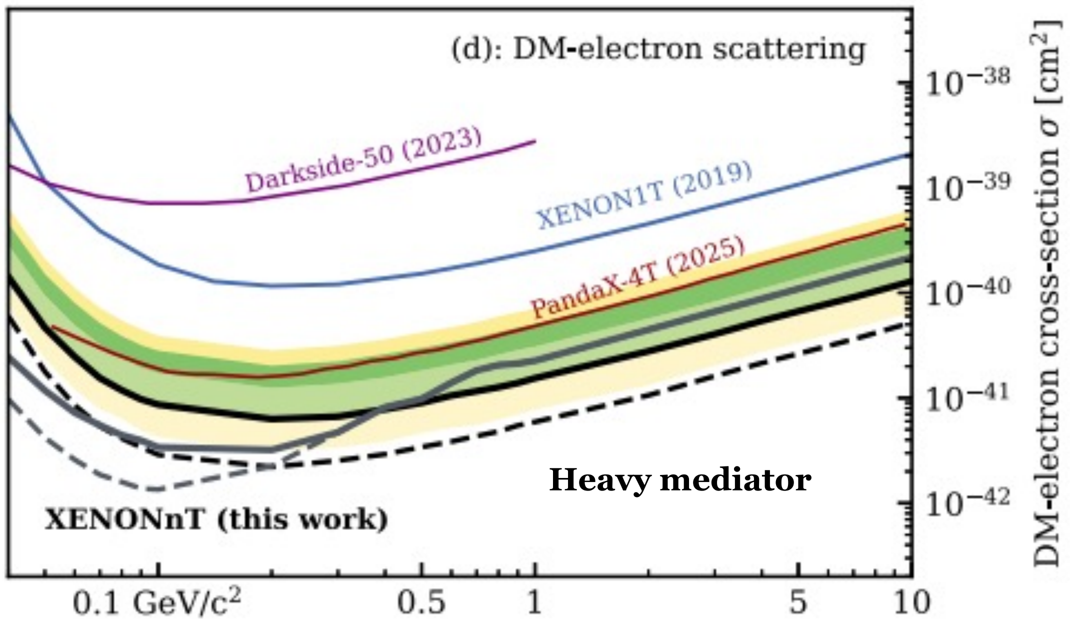
WIMP-electron scattering

PandaX-4T S2-only analysis



PRL 135, 211001 (2025)

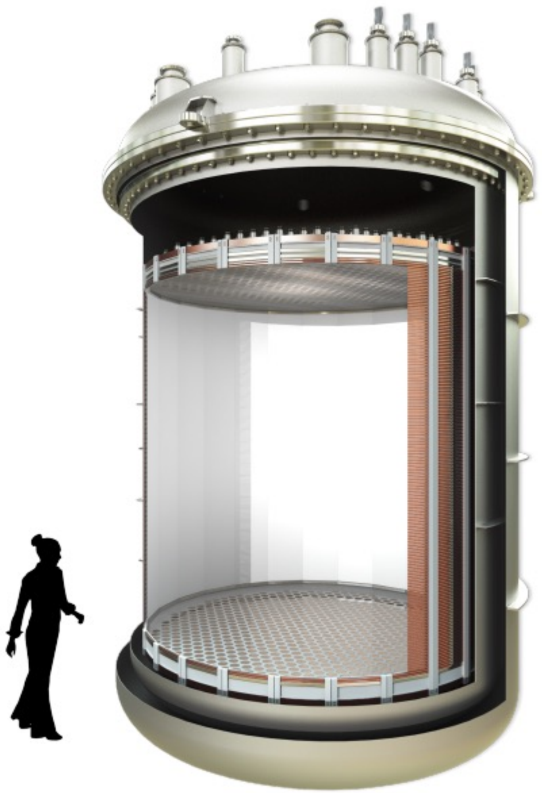
XENONnT S2-only analysis



PRL 137, 051003 (2025)

Future Liquid Xenon Detectors

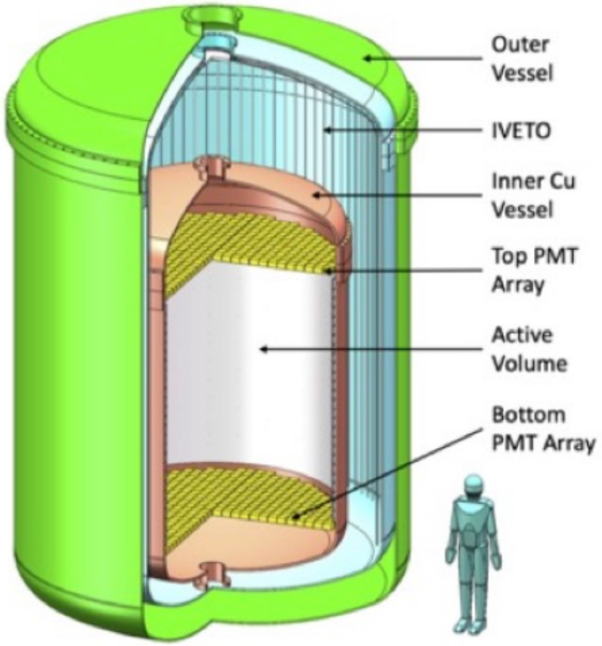
XLZD (XENON-LZ-DARWIN)



78 t LXe (60 t active target)

2 arrays of 3-inch PMTs

PandaX-xT

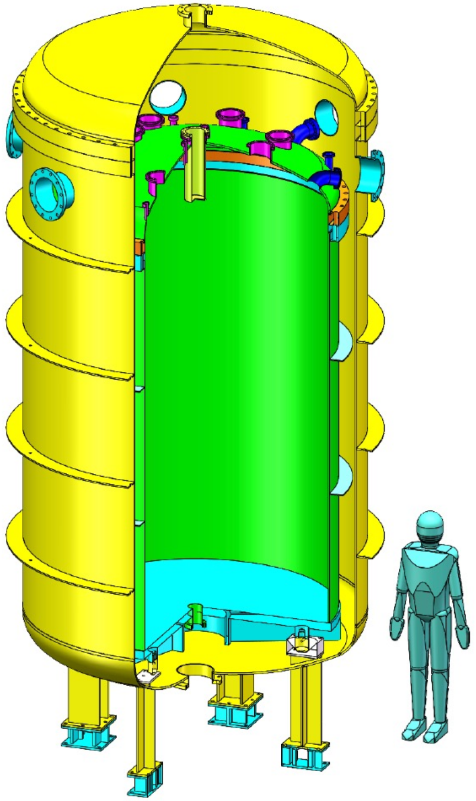


47 t LXe (43 t active target)

2 arrays of 2-inch PMTs

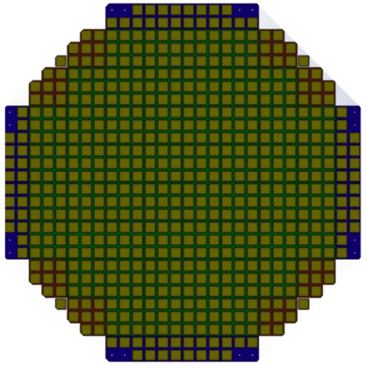
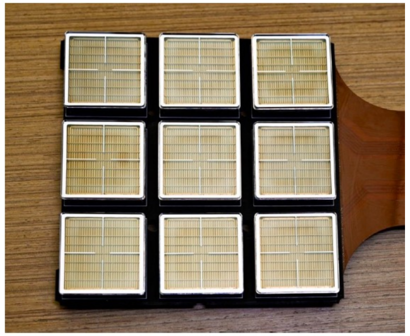
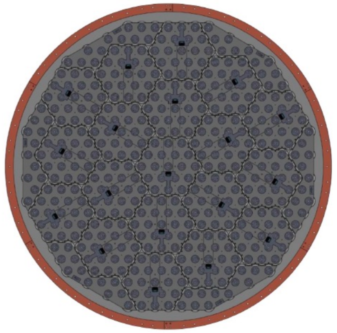
PandaX-20T

Inner vessel: In fabrication



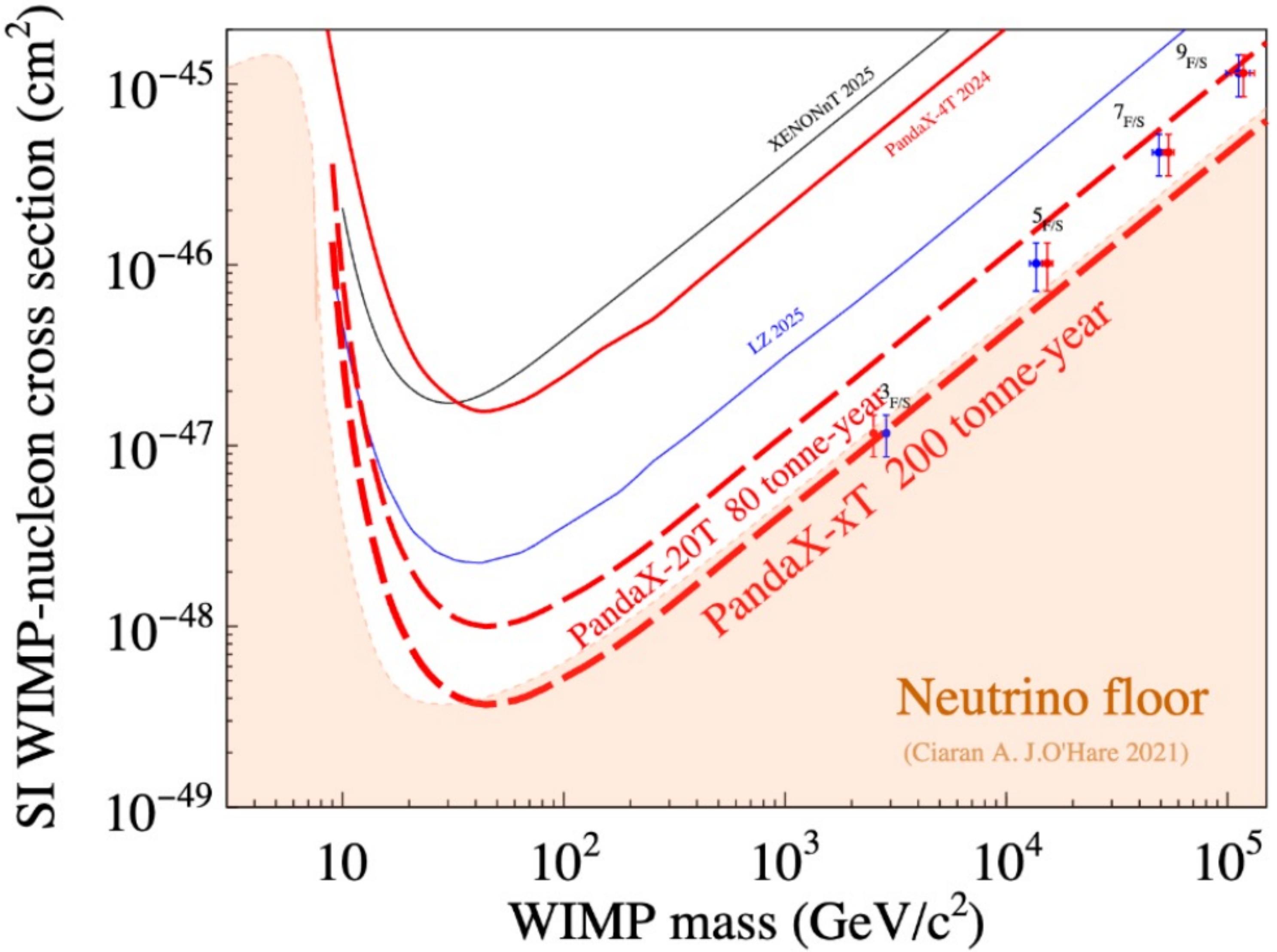
TPC Field Cage

PMT arrays

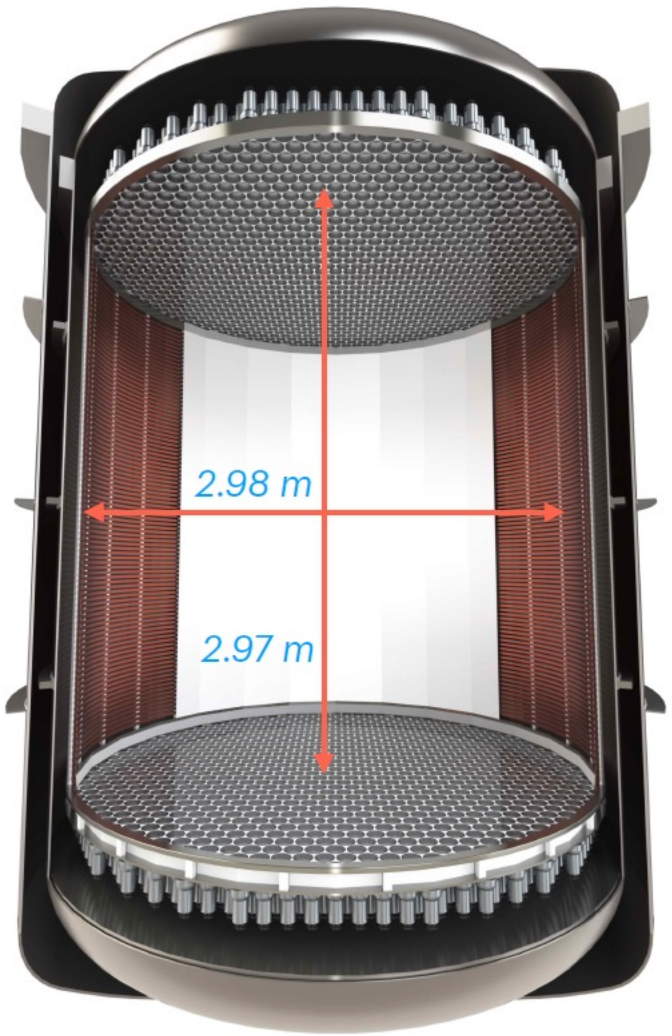

- 20T is fully funded (eventually moving to 47T)
- Goal: Physics run starts from 2028.1

PandaX-xT sensitivities



XLZD

XLZD TPC



TPC: 60 t LXe (78 t total), early science with 45 t LXe

Merged XENON/LZ/DARWIN effort

- 2021: MoU signed by 104 research group leaders from 16 countries
- 2024: full collaboration formed
- Design book: 2410.17137

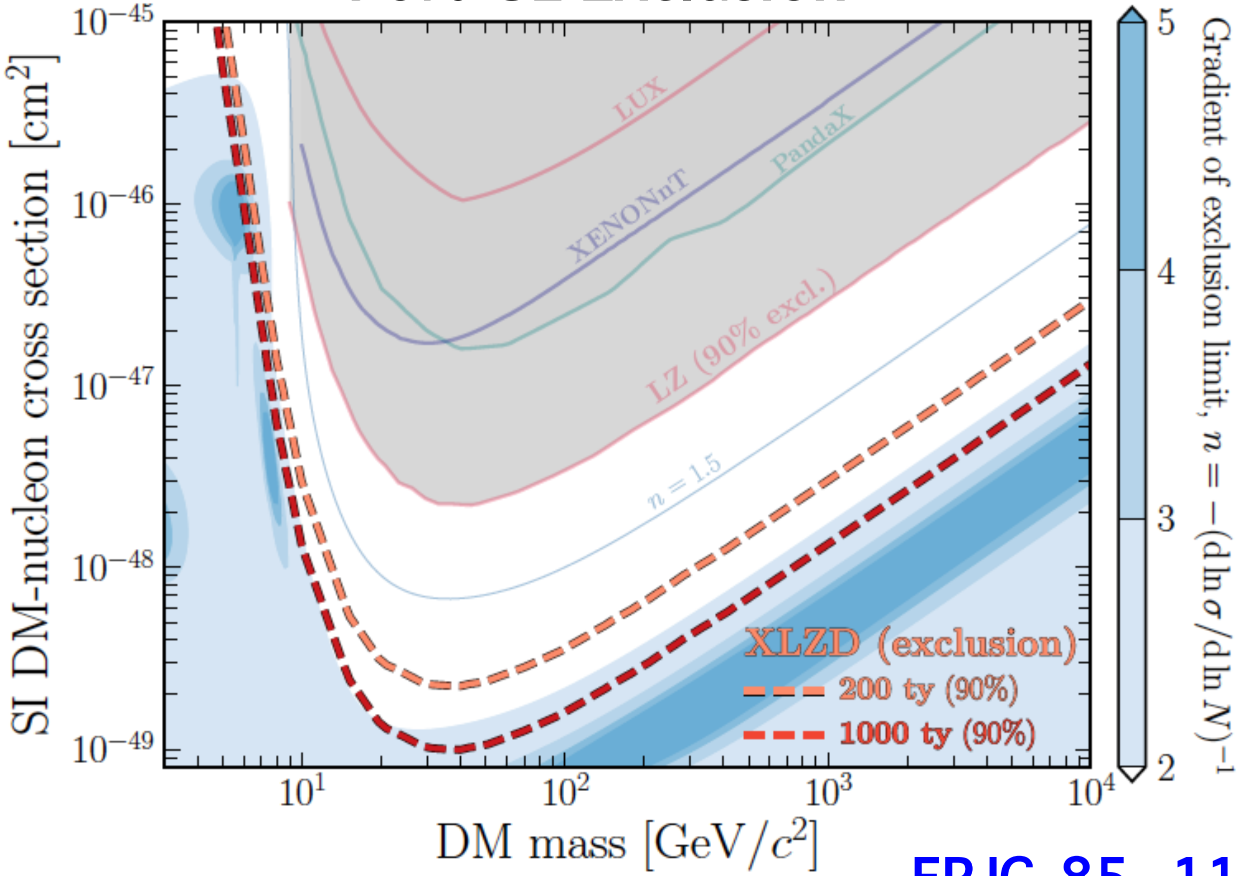
  EPJC 85, 1192 (2025)

- Possibility of a longer 80 t detector if funding allows
- Candidate sites
  - LNGS, SURF, Boulby, SNOLAB

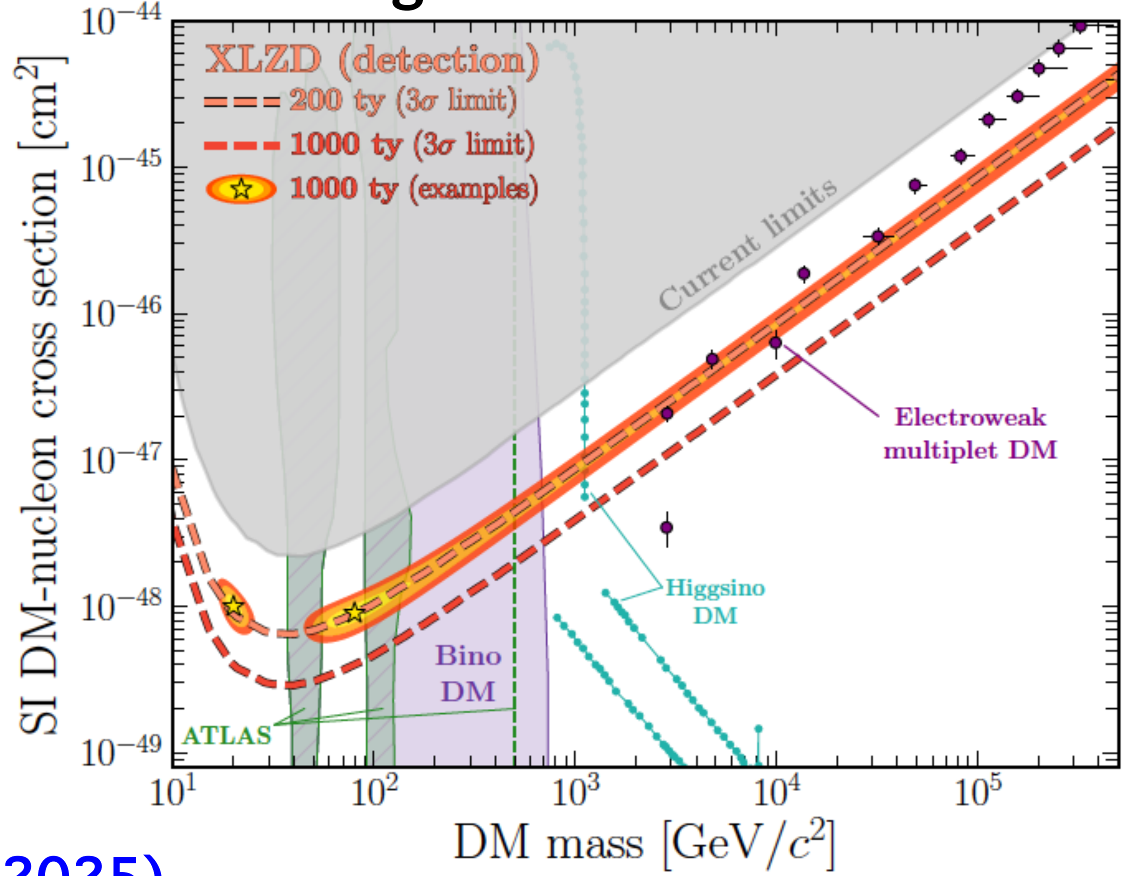
Physics run (2032??)

XLZD Sensitivities

90% CL Exclusion

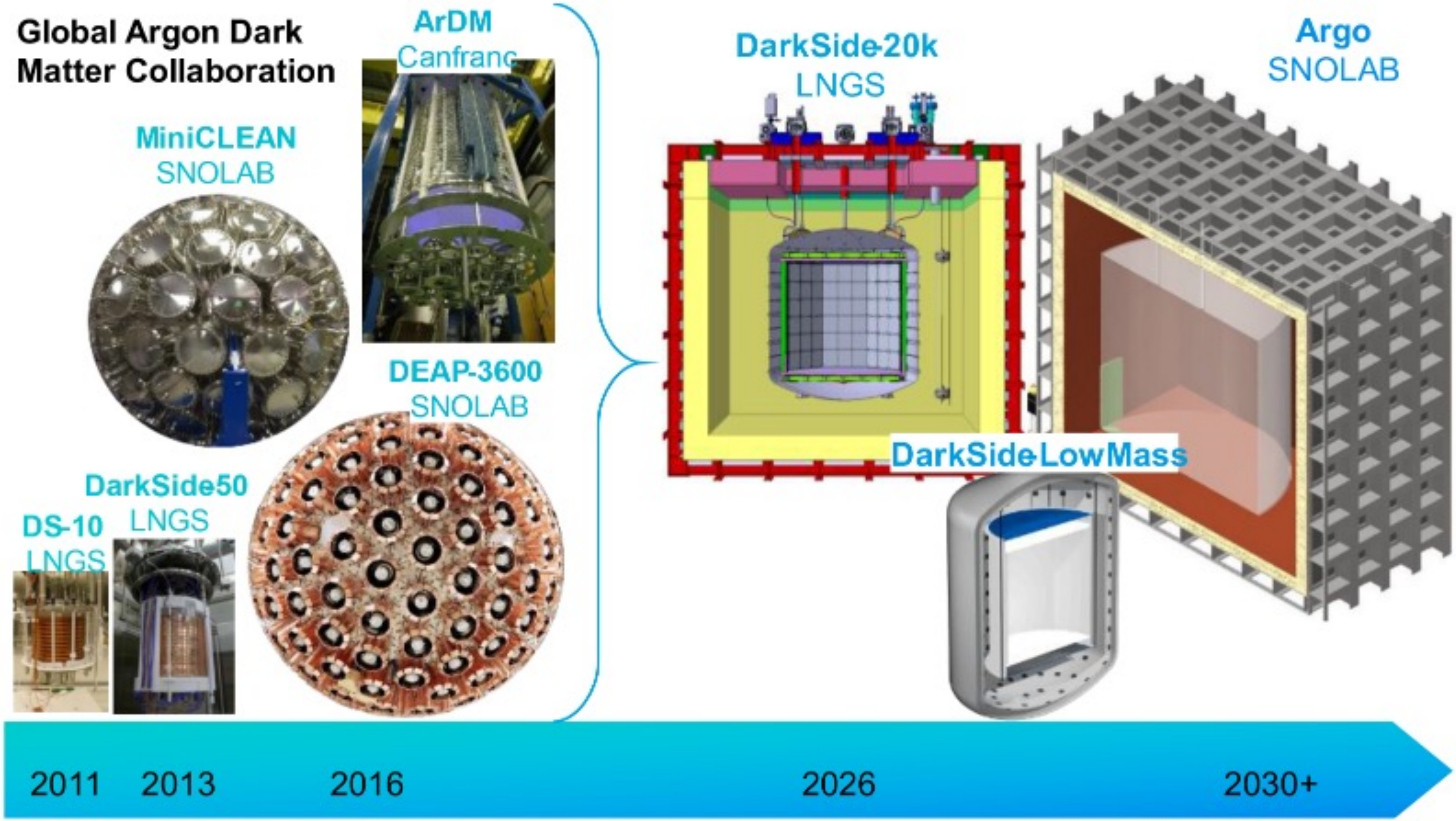


3 sigma observation



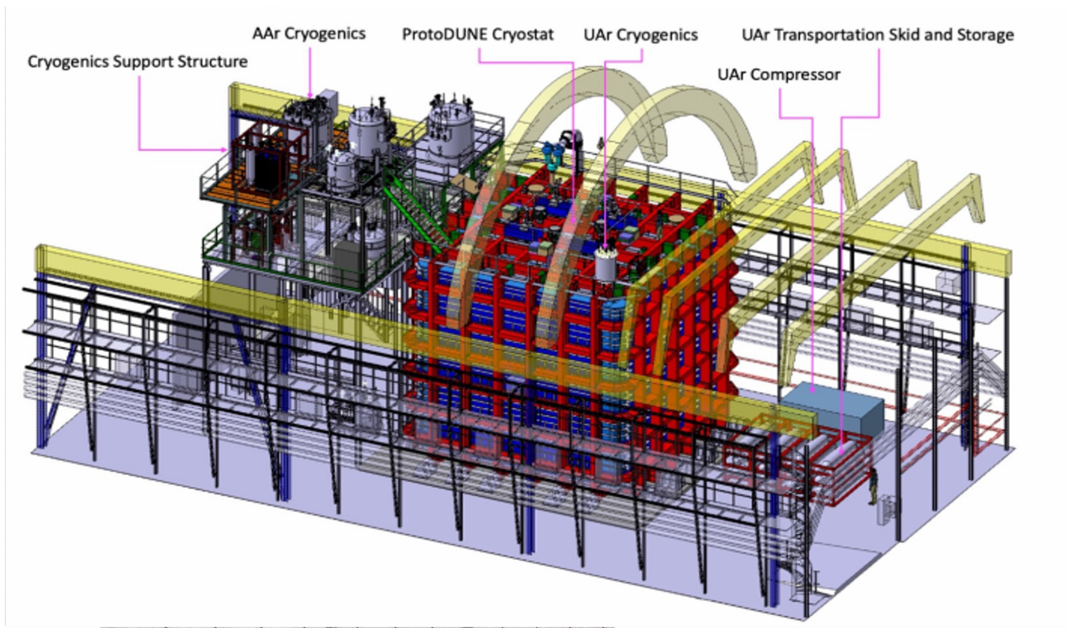
EPJC 85, 1192 (2025)

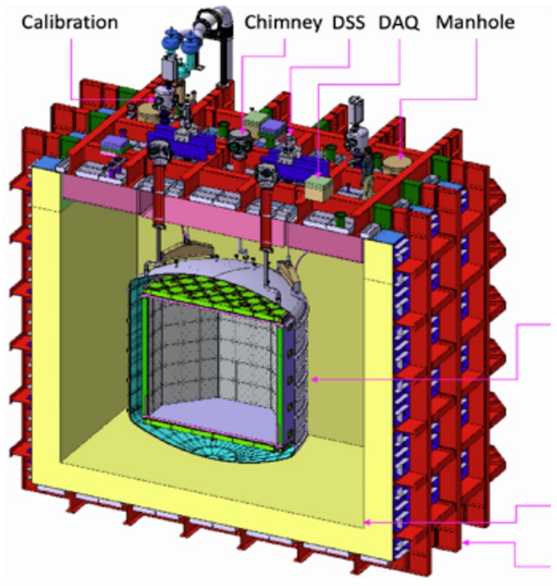
Liquid Ar Detectors

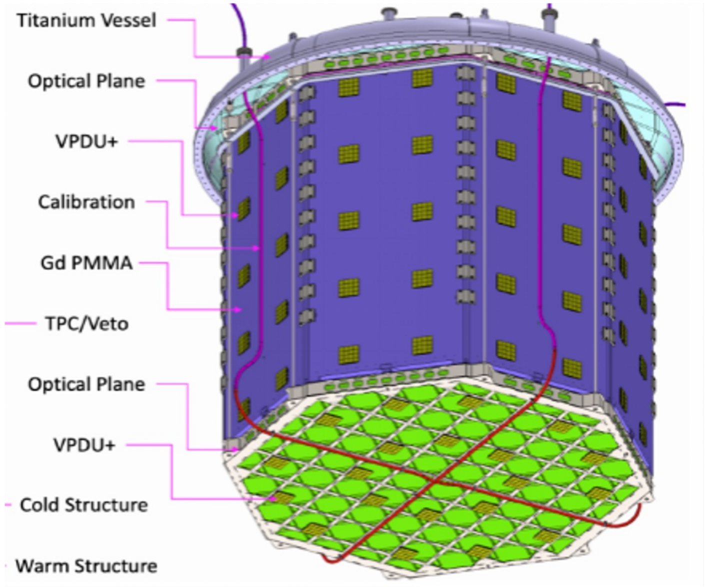


A.B. McDonald: "Dark matter detection with liquid argon", Nucl. Phys. B 1003 (2024) 116436

Darkside-20k

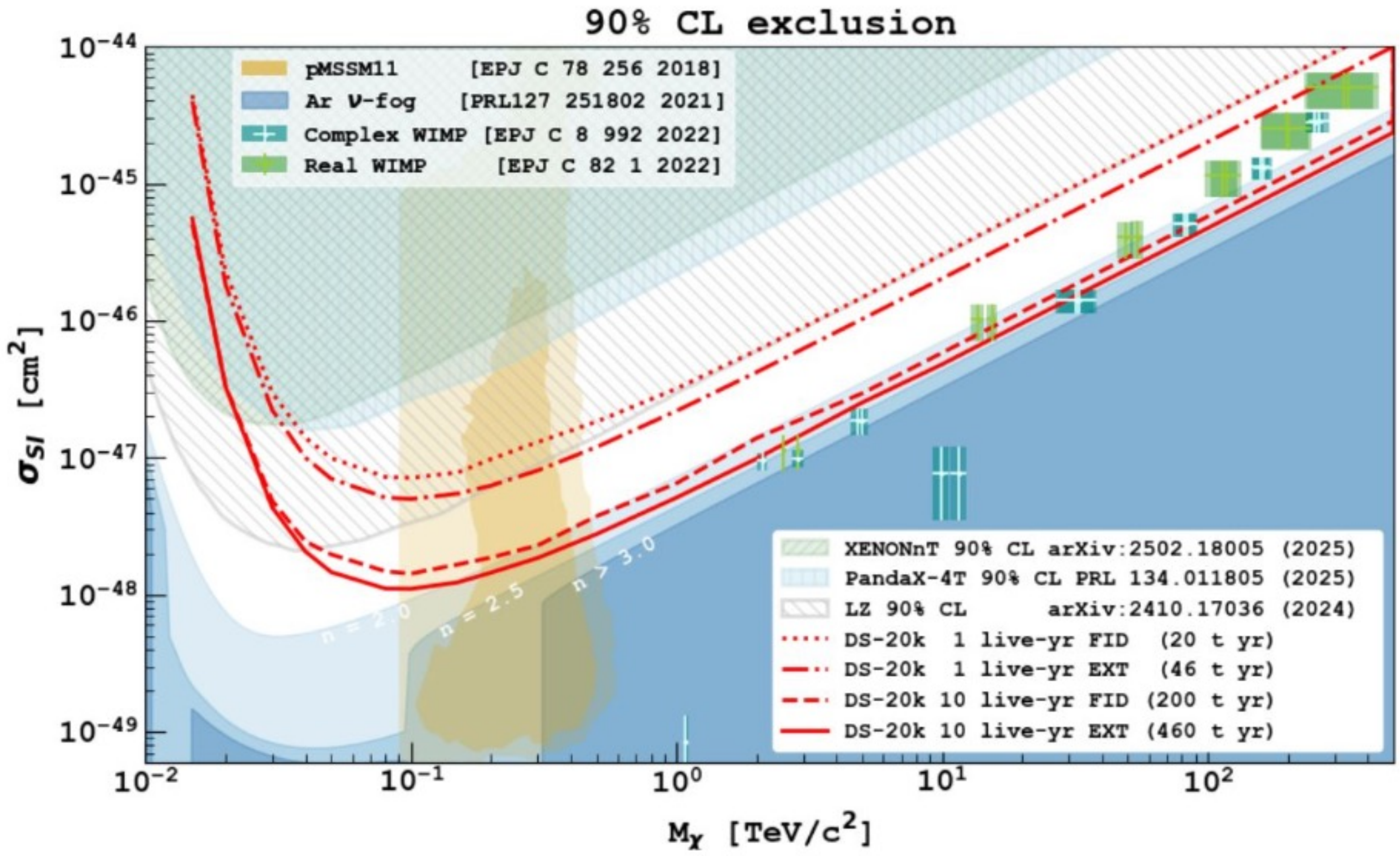






- 650 t of atm. Ar (ProtoDUNE-like cryostat) – veto detector
- 51 t of underground Ar (20 t fiducial)
  - ❖ Cosmogenic ^{39}Ar reduction (~ 3 orders)
  - ❖ Dual-phase Ar TPC, SiPM readout
- Target zero background in the signal region
- Detector operation starts ~2028

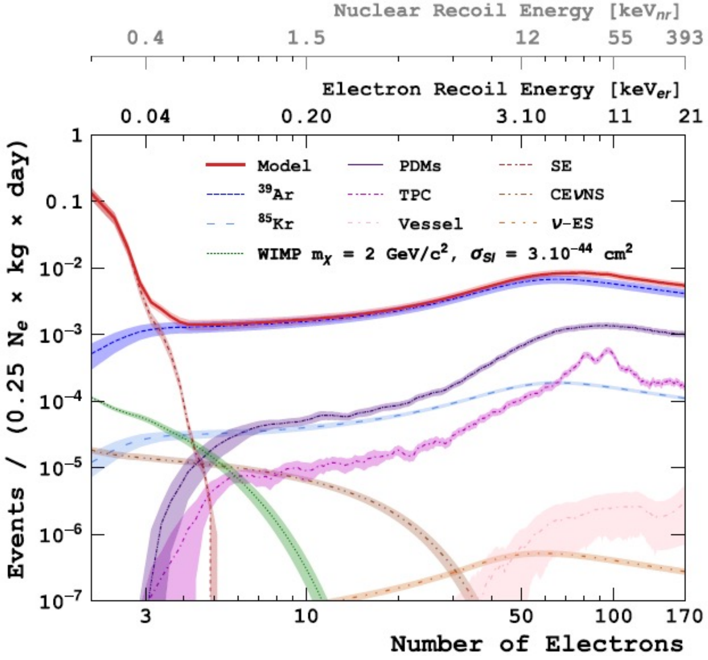
Darkside-20k sensitivities



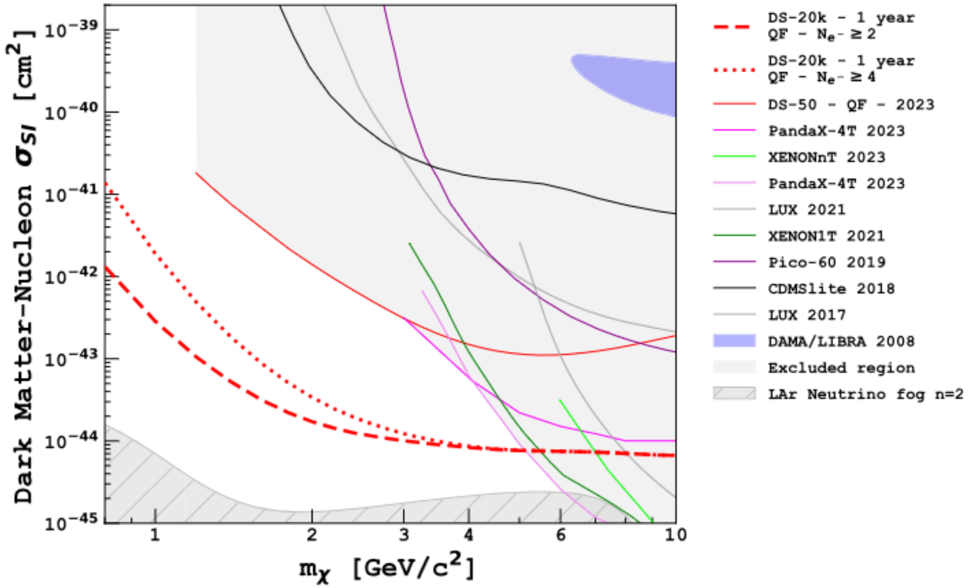
- Expected background rate <0.3 events in ROI (20-200 keV_{nr}) with 200 t-yr exposure

Darkside-20k “Low-mass” Dark Matter

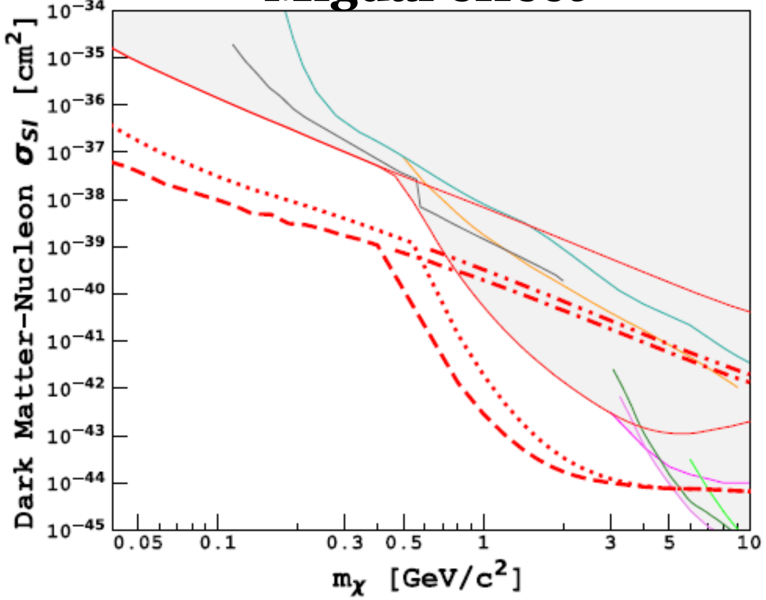
S2 only expected background



Expected sensitivities



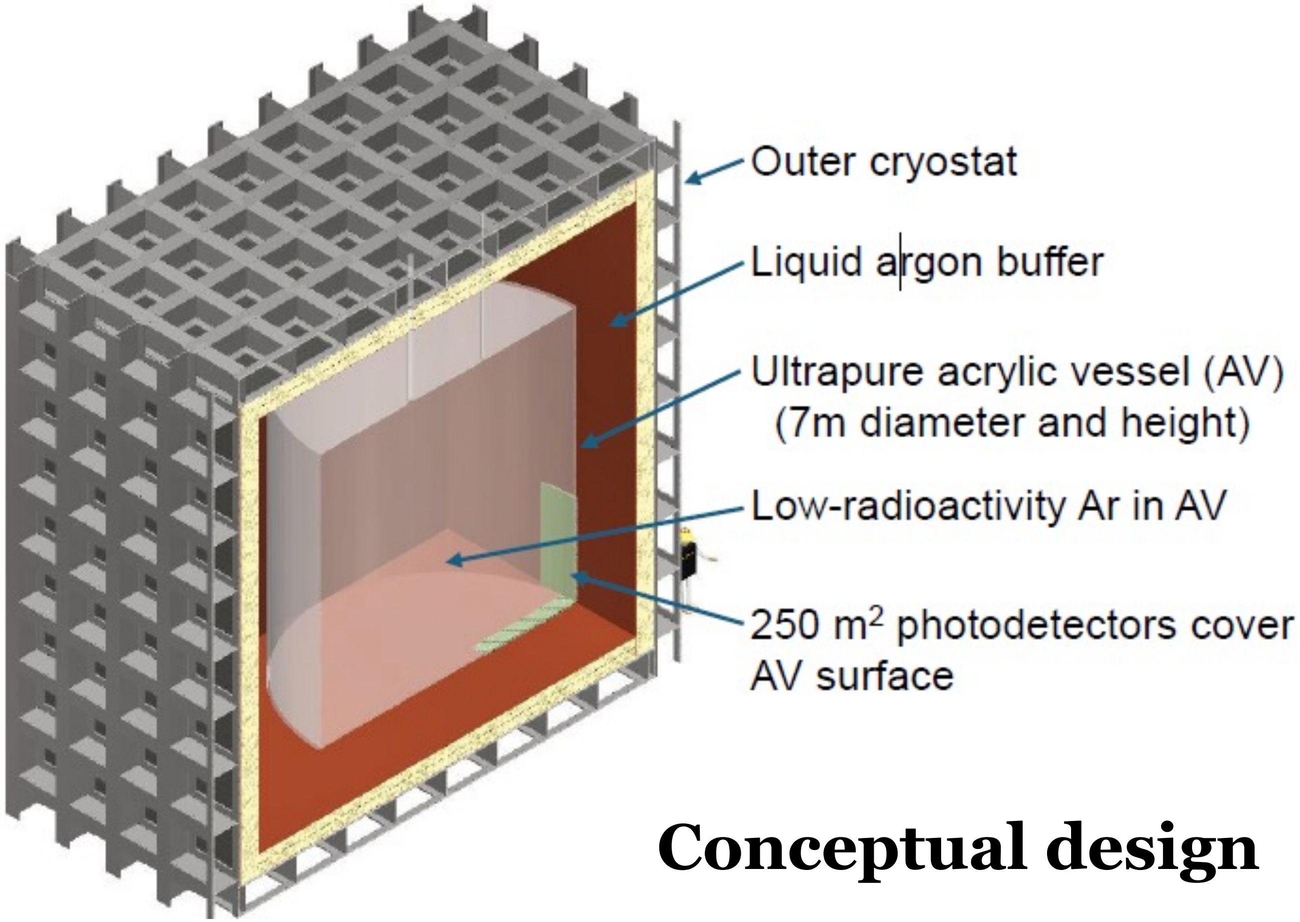
Expected sensitivities with Migdal effect



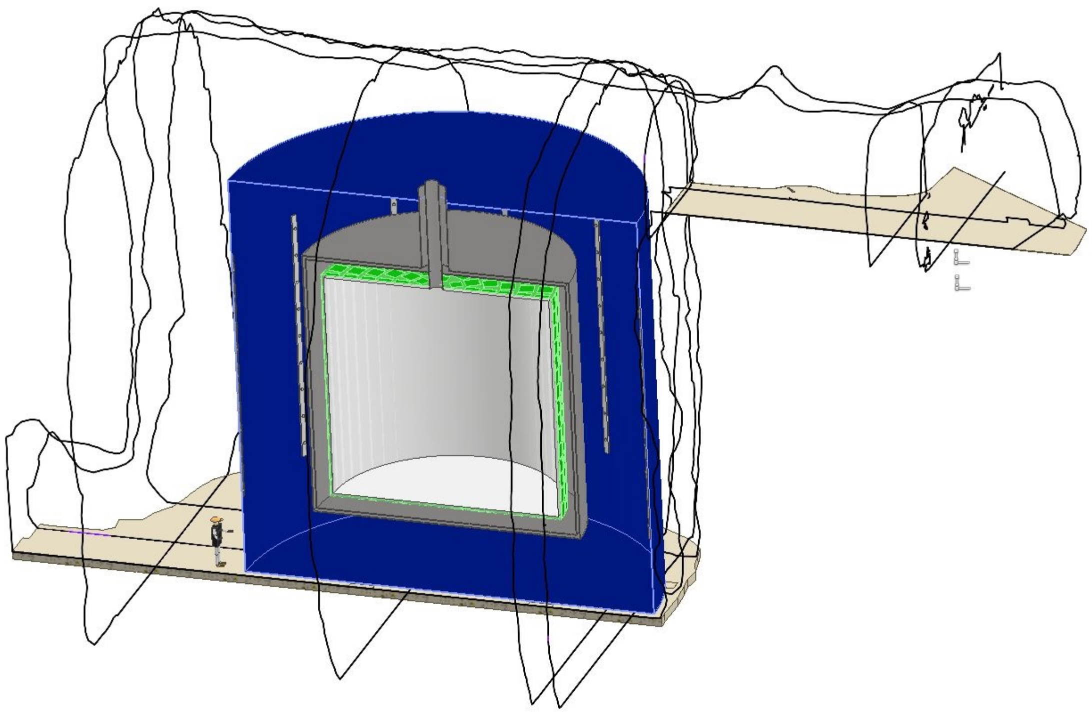
Commun Phys 7, 422 (2024)

- S2-only (drift electrons) analysis without collection of nuclear recoils (PSD)
- Background dominated by ^{39}Ar ($N_e \geq 4$) and single electrons ($N_e \leq 3$)
- Two scenarios of threshold N_e=4 and N_e=2

ARGO: next-generation liquid-argon detector



Conceptual design

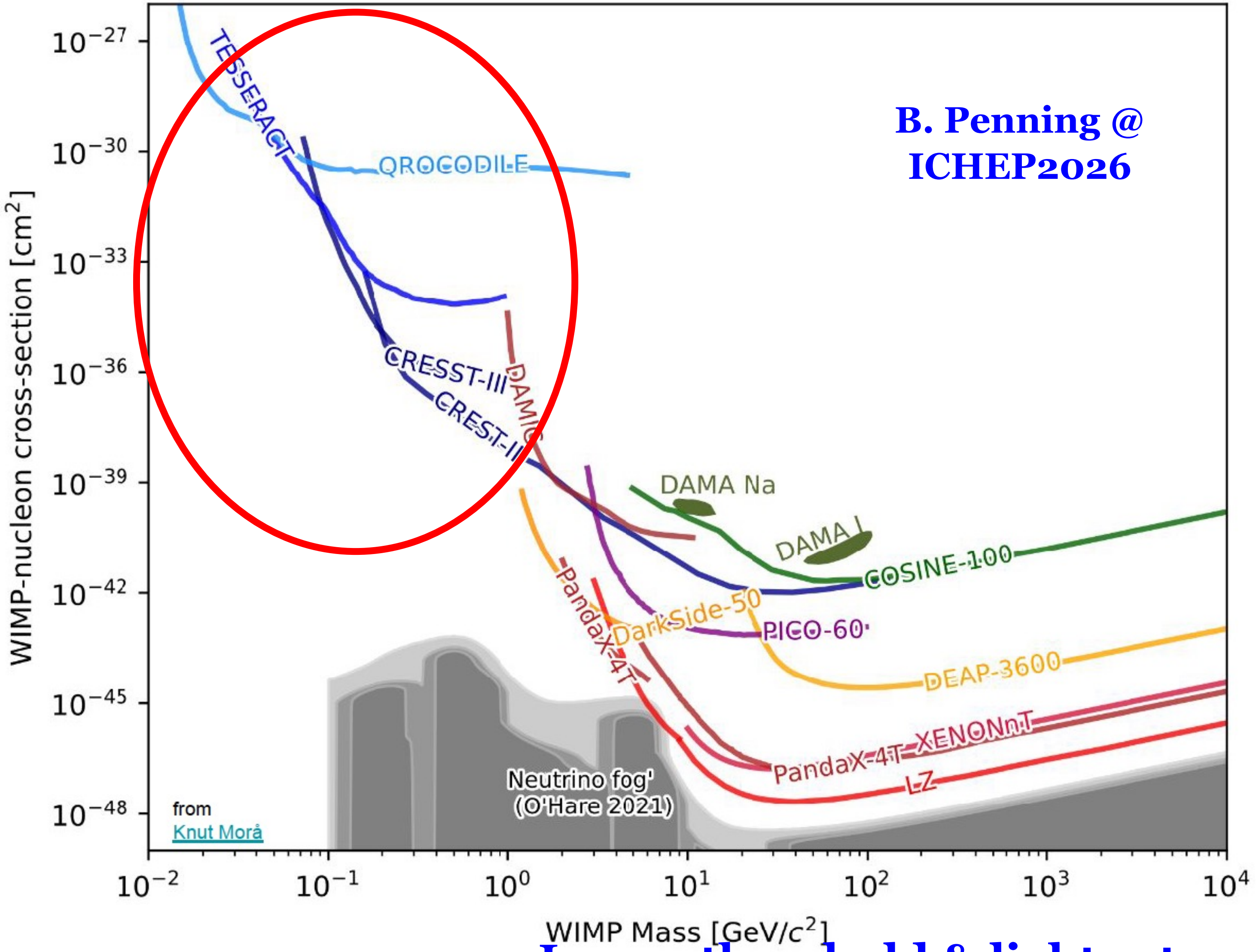


SNOLAB Cube Hall

- 400 tonnes of low-background argon; 300 tonnes fiducial mass
- Can we reach background-free in the WIMP ROI?

CENTER FOR UNDERGROUND PHYSICS ibs

Low-mass region



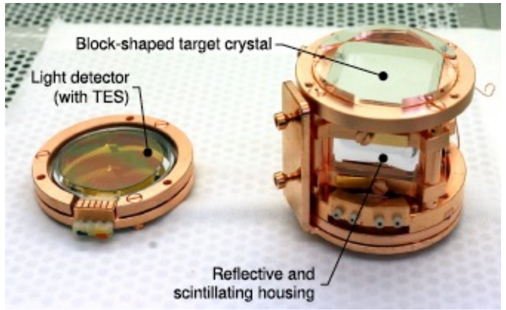
Lower threshold & lighter target element

CRESST

- Cryogenic bolometer measuring phonon (~meV quanta)

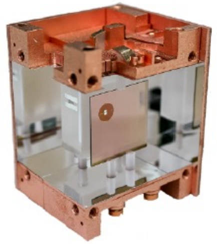
Signal: **phonons and light**

CRESST-II detector

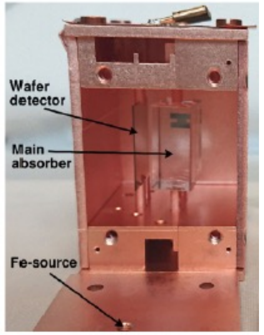


2009
$CaWO_4$
M ~ 300 g
E_{th} ~ 300 eV

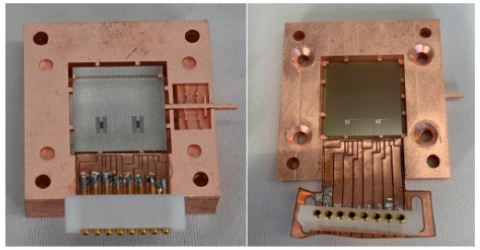
CRESST-III detector



2019
$CaWO_4$ (Det.A)
m = 24 g
E_{th} = 30.1 eV

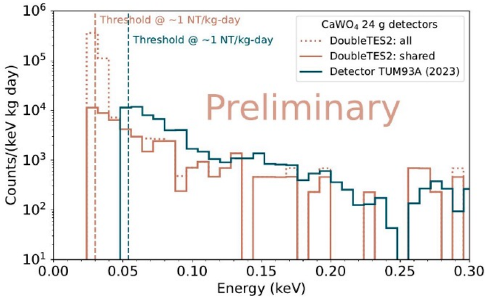


2024
SOS-wafer
m = 0.6 g
E_{th} = 6.7 eV
Silicon-on Sapphire (SOS)



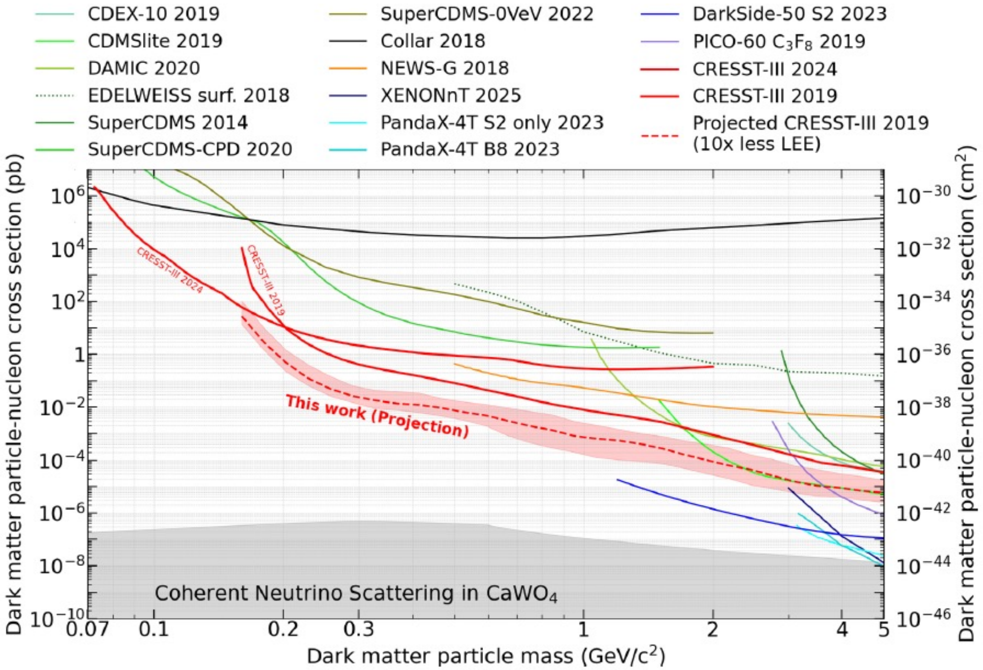
Upcoming
DoubleTES
m = 24 g / 0.6 g

$CaWO_4$
or SOS



5 $CaWO_4$ (24 g)
4 SOS (0.6 g)

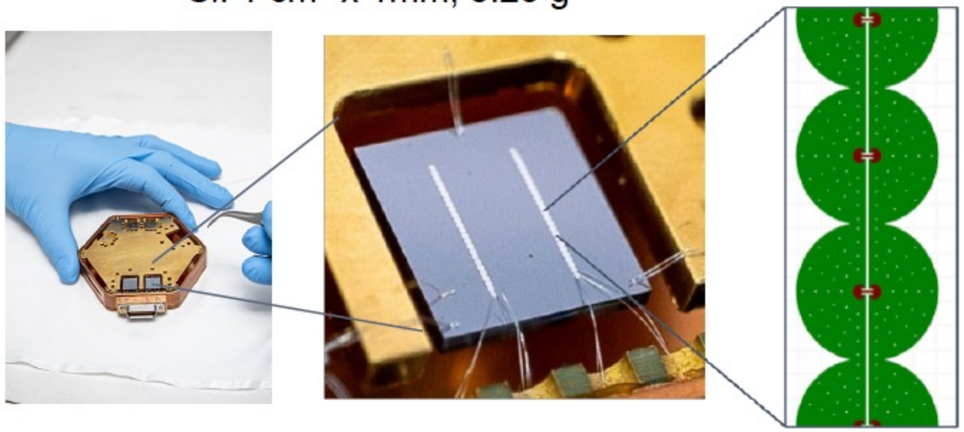
Sensitivity

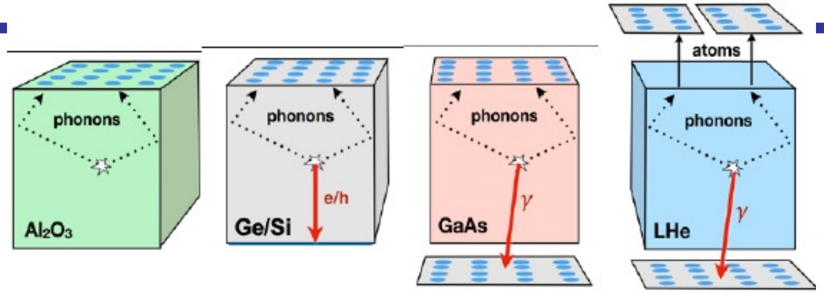


Commun Phys 9, 163 (2026)

TESSERACT

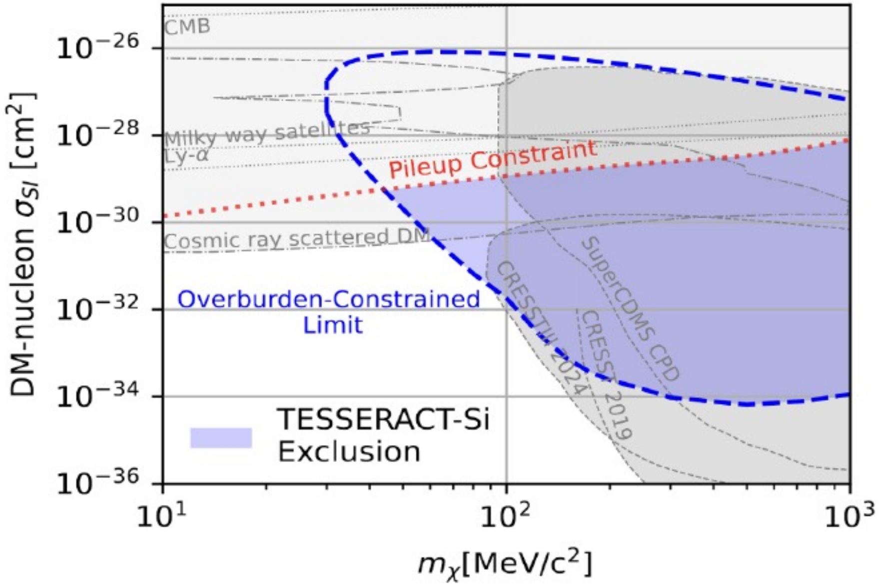
Si: 1 cm² x 1mm, 0.23 g



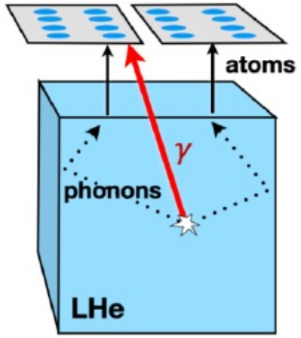


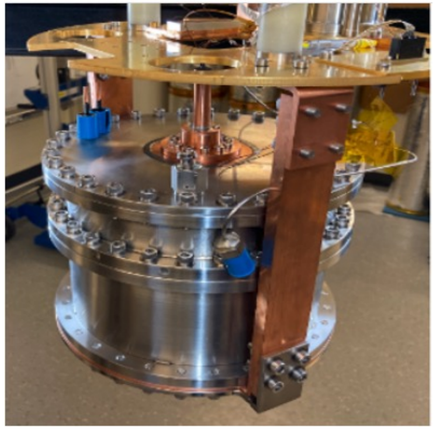
- Especially low energy threshold
  - ❖ 360 meV photon resolution (NTL Amplification)
- Same detector type will be used for the liquid helium detector

0.23 g × 12 hours at the surface laboratory



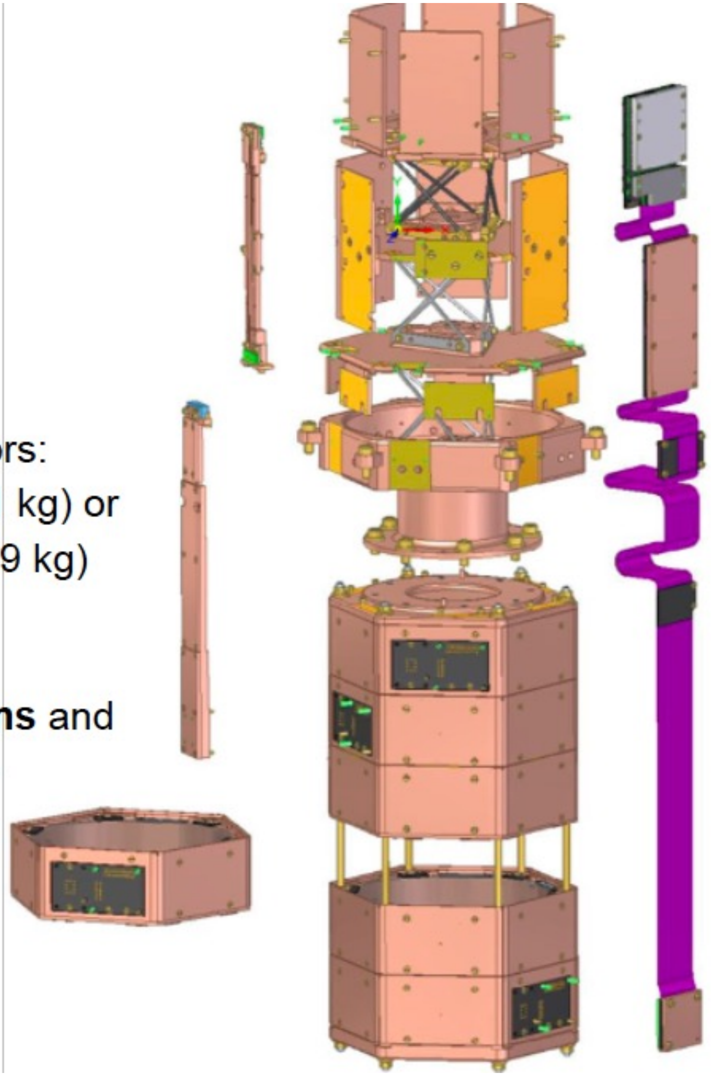
PRL 135, 161002 (2025)





- Project phase (FY2025 ~ FY2028)
- Operation phase (FY2029 ~ FY2031)
  - ❖ Moving to the Modane underground laboratory in 2028

SuperCDMS



HEMT: amplifier for iZIP charge channels (4K stage)

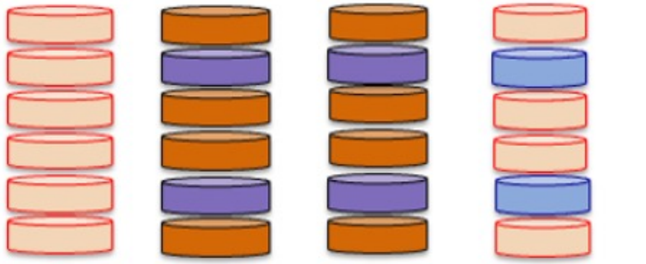
SQUID: **TES**-based (Transition Edge Sensor) readout (1K stage)

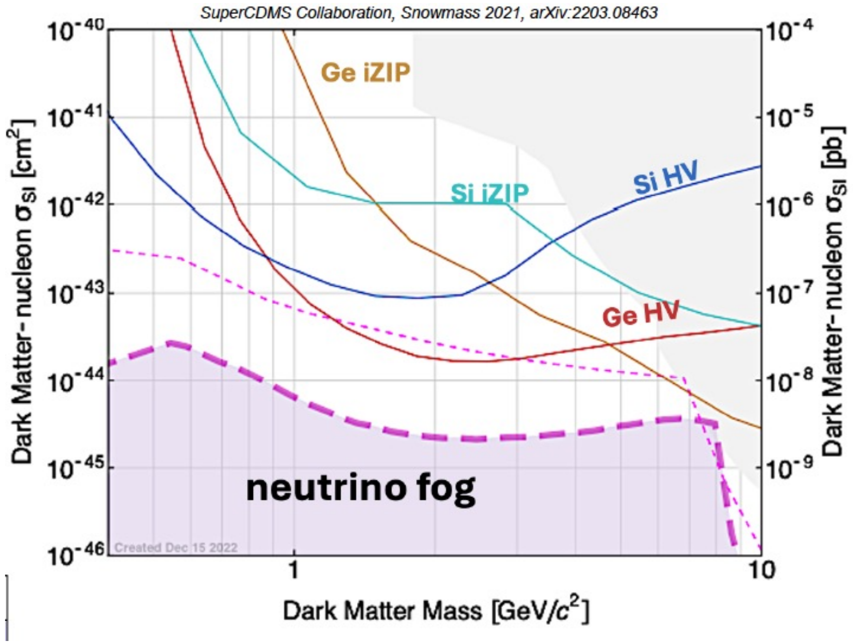
Detectors: **Si** (0.61 kg) or **Ge** (1.39 kg)

Signal: **phonons** and **charge**

Detectors are kept at the MC stage (base temperature **~15 mK**)

Initial SNOLAB payload

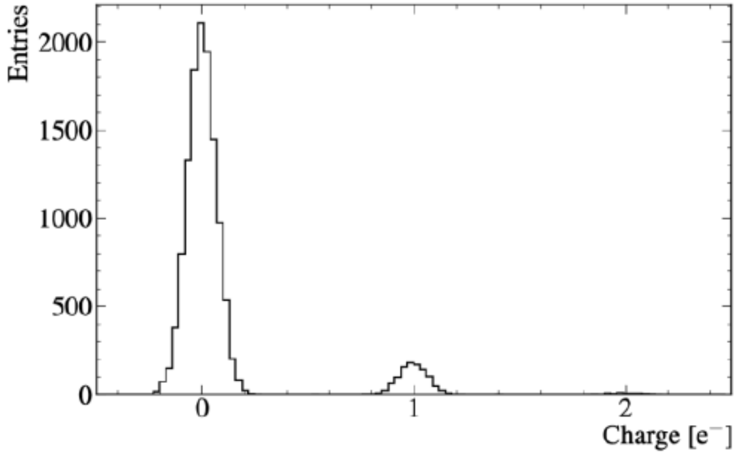


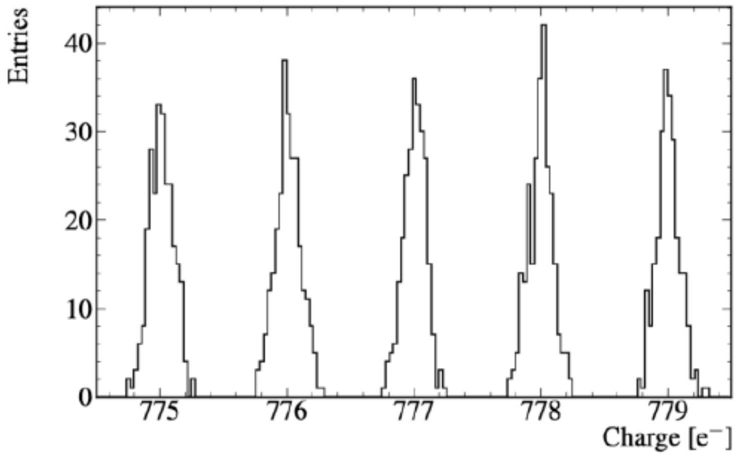


- Science run starting soon!!

WIMP-electron scattering with CCD

SENSEI (40g; 1-2e threshold)

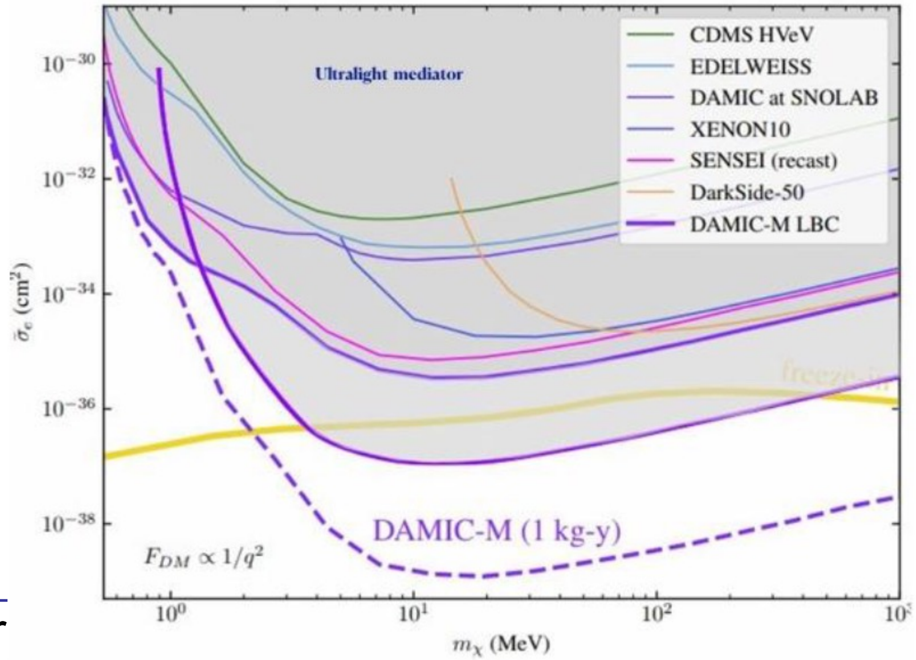




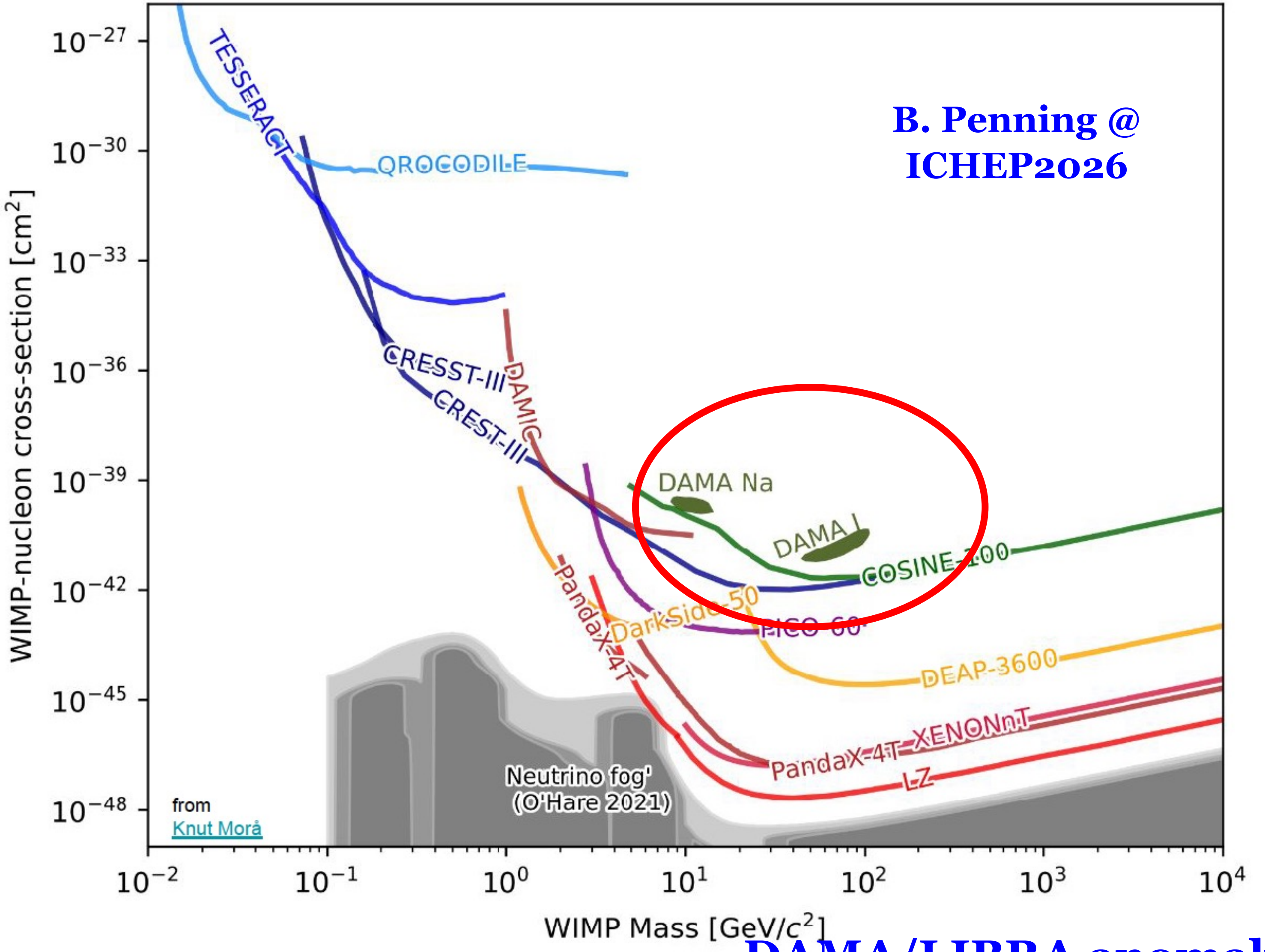
Single electron ~ 1.2 eV threshold

DAMIC-M (~250g; 1e threshold)

Installation this summer



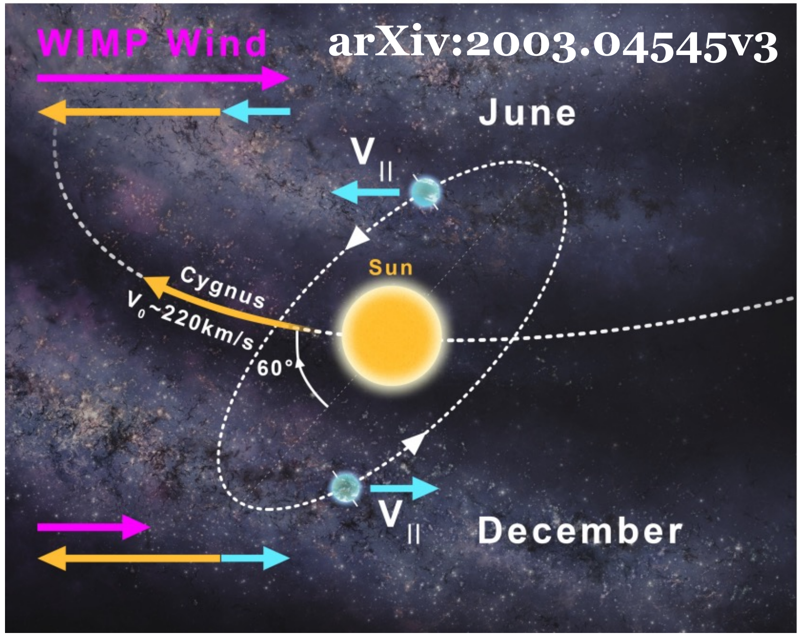
DAMA/LIBRA



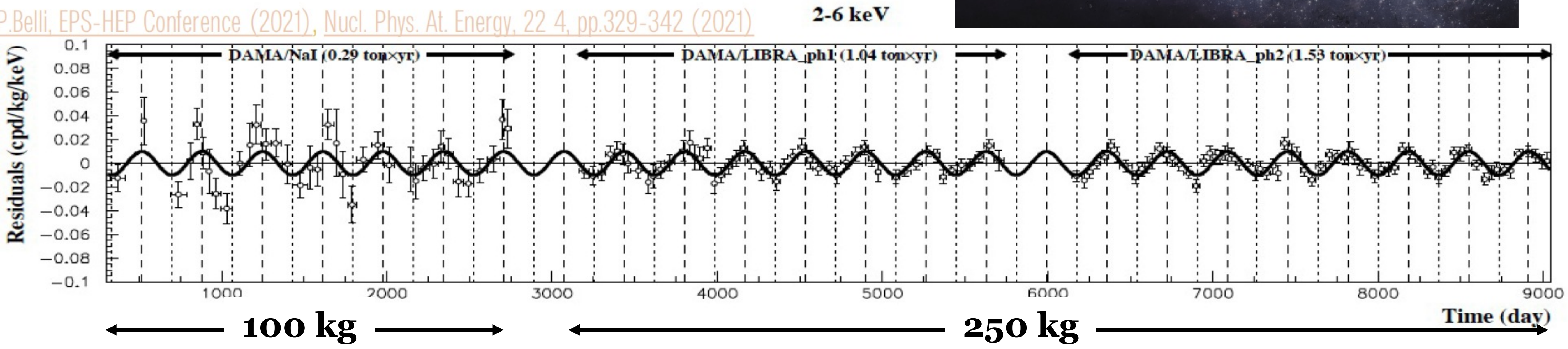
DAMA/LIBRA anomaly

DAMA/NaI and DAMA/LIBRA puzzle

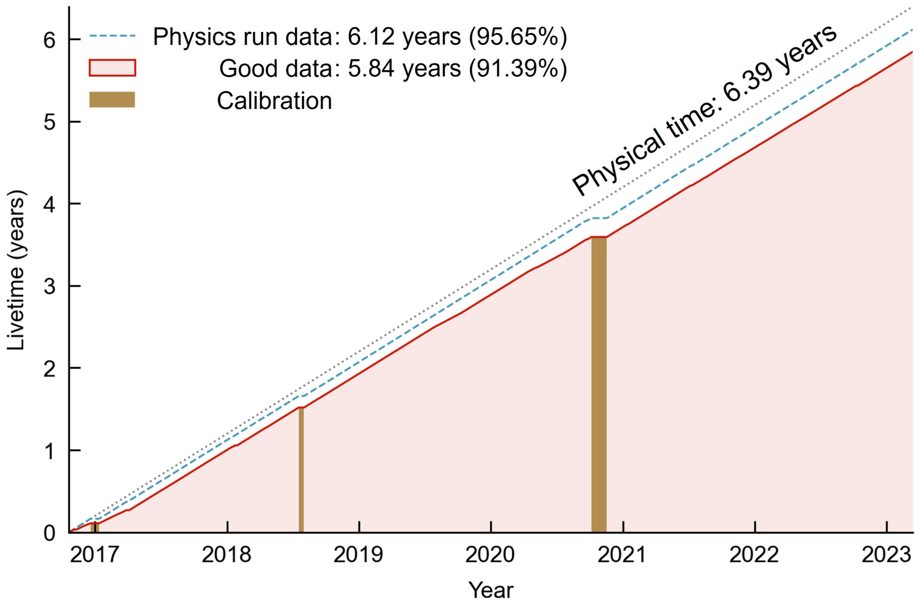
Observation of **annual modulation since 1998** using NaI(Tl) crystals

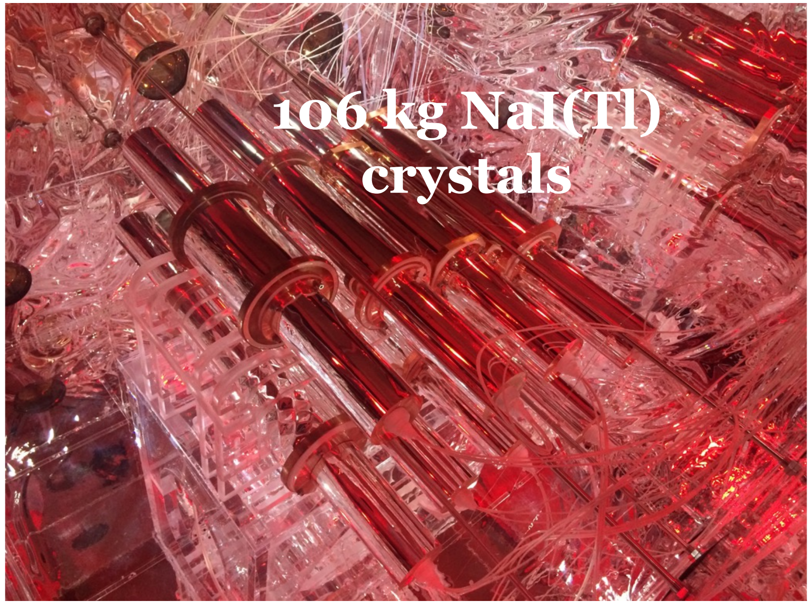


P.Belli, EPS-HEP Conference (2021), Nucl. Phys. At. Energy, 22 4, pp.329-342 (2021)



COSINE-100 experiment

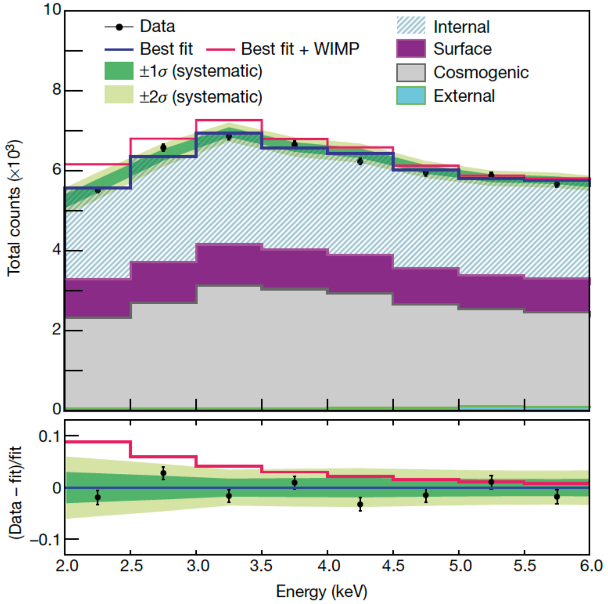


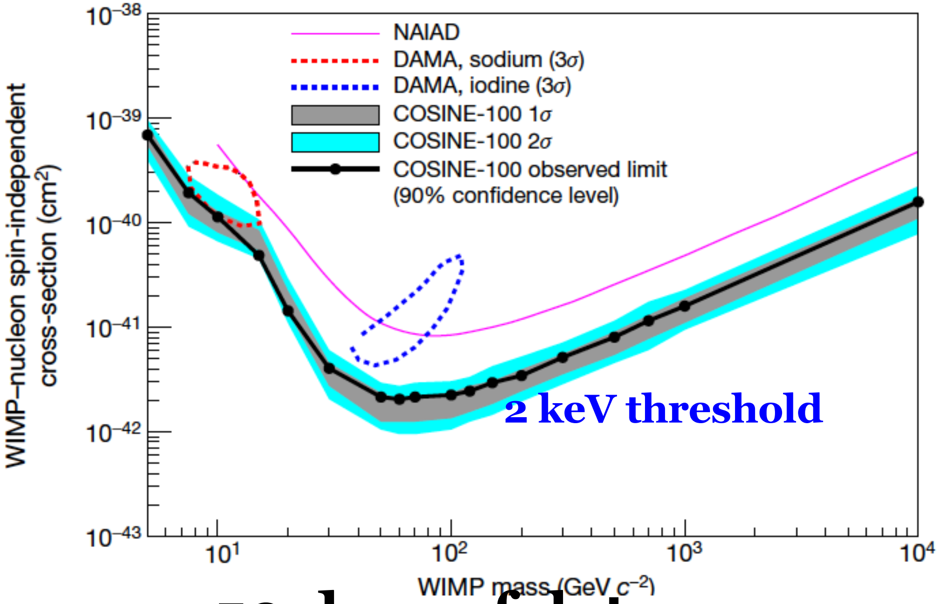


- Yangyang underground laboratory
  - **October/2016 ~ March/2023**
- Decommissioning
  - Moved to **Yemilab**
  - Upgrade of detector for **high light yield**

COSINE-100

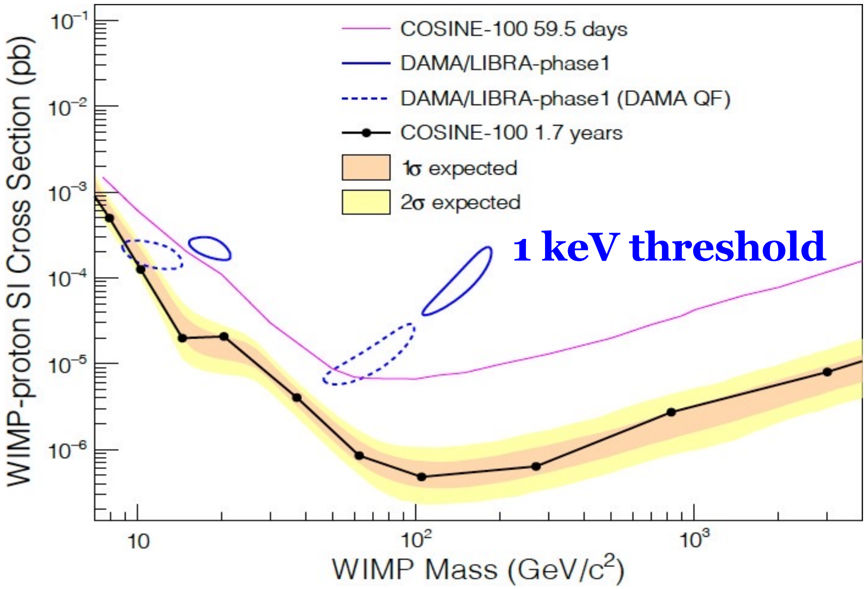
Nature 564, 83 (2018)





59 days of data

Sci. Adv. 7, eabk2699 (2021)



1.7 years of data

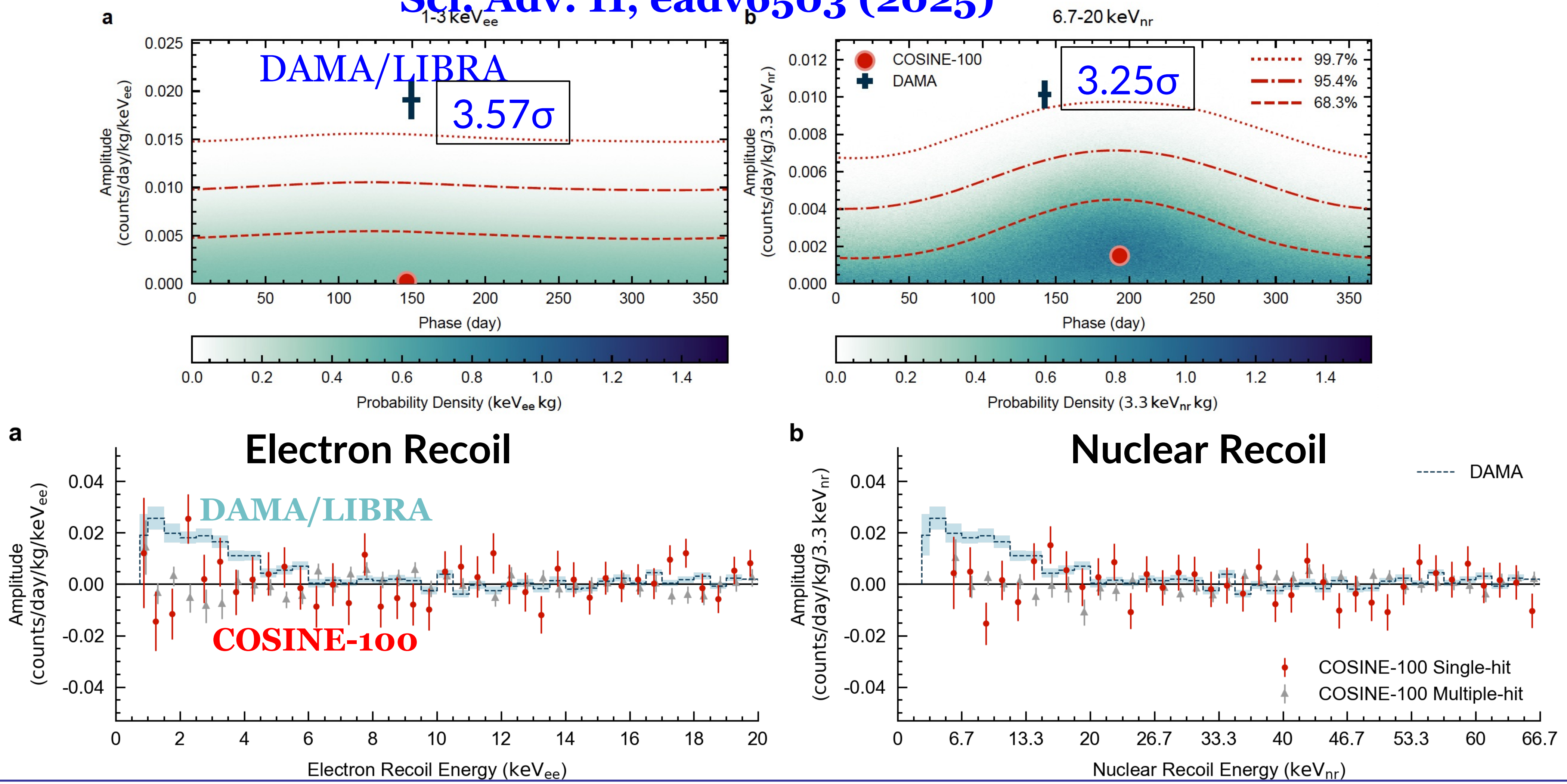
These are unique analyses in COSINE compared to other NaI-based experiments

Model-dependent test **ruled out DAMA/LIBRA** with the same NaI(Tl)

Annual modulation search – 6.4 years data

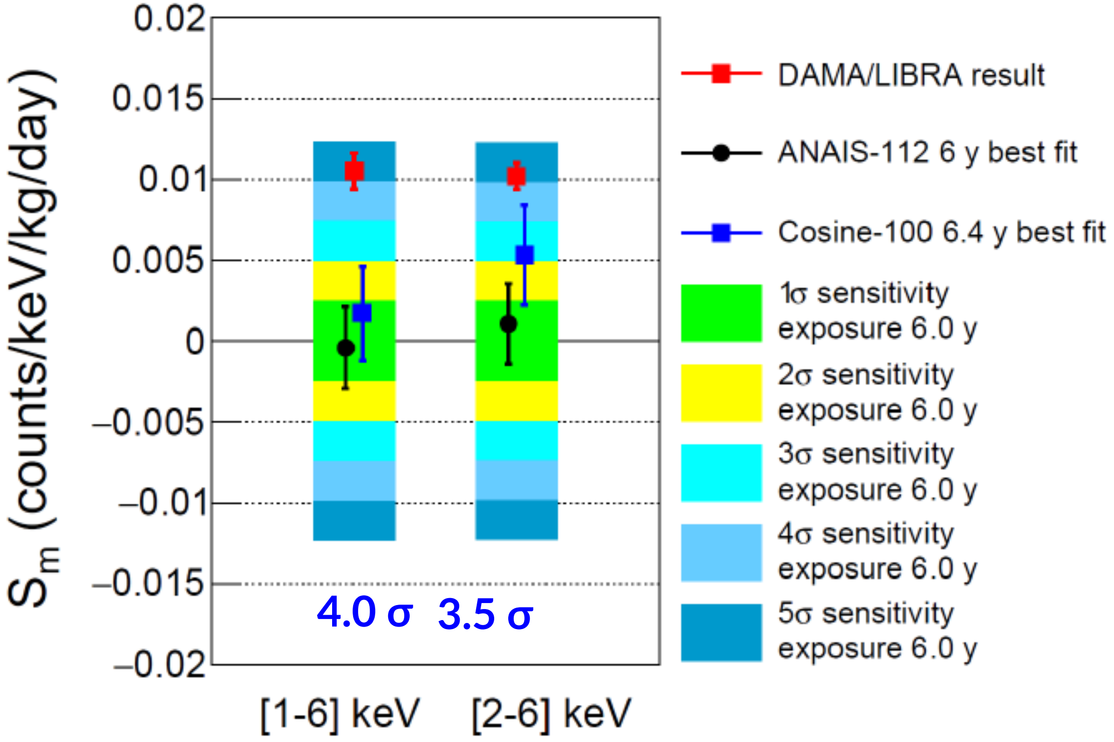
- DAMA/LIBRA's method on energy calibration; Alternative scenario of different nuclear recoil quenching factor; No modulation observed

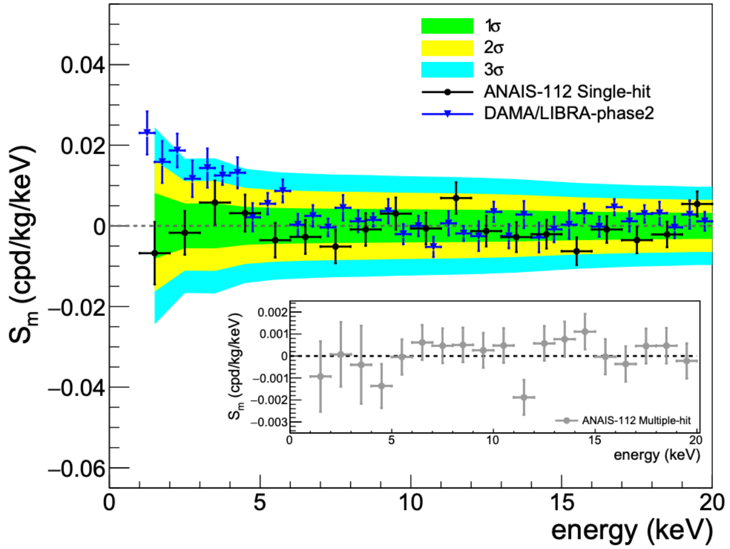
Sci. Adv. 11, eadv6503 (2025)



ANAIS-112

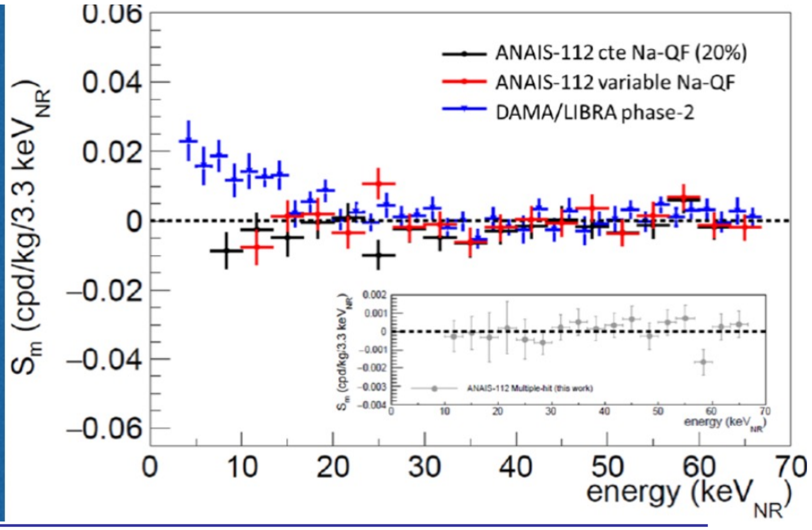
- 112 kg of NaI(Tl) crystals, 6 years of data analyzed





PRL 135, 051001 (2025)

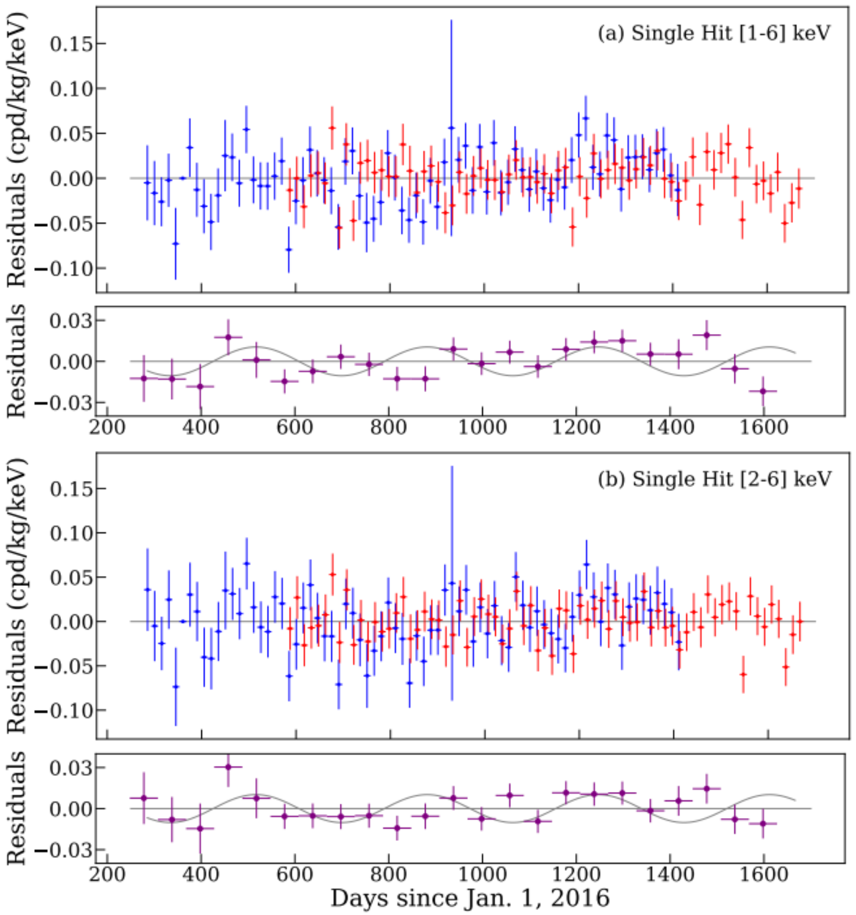
Effect of **different Quenching Factors** for DAMA/LIBRA and ANAIS?

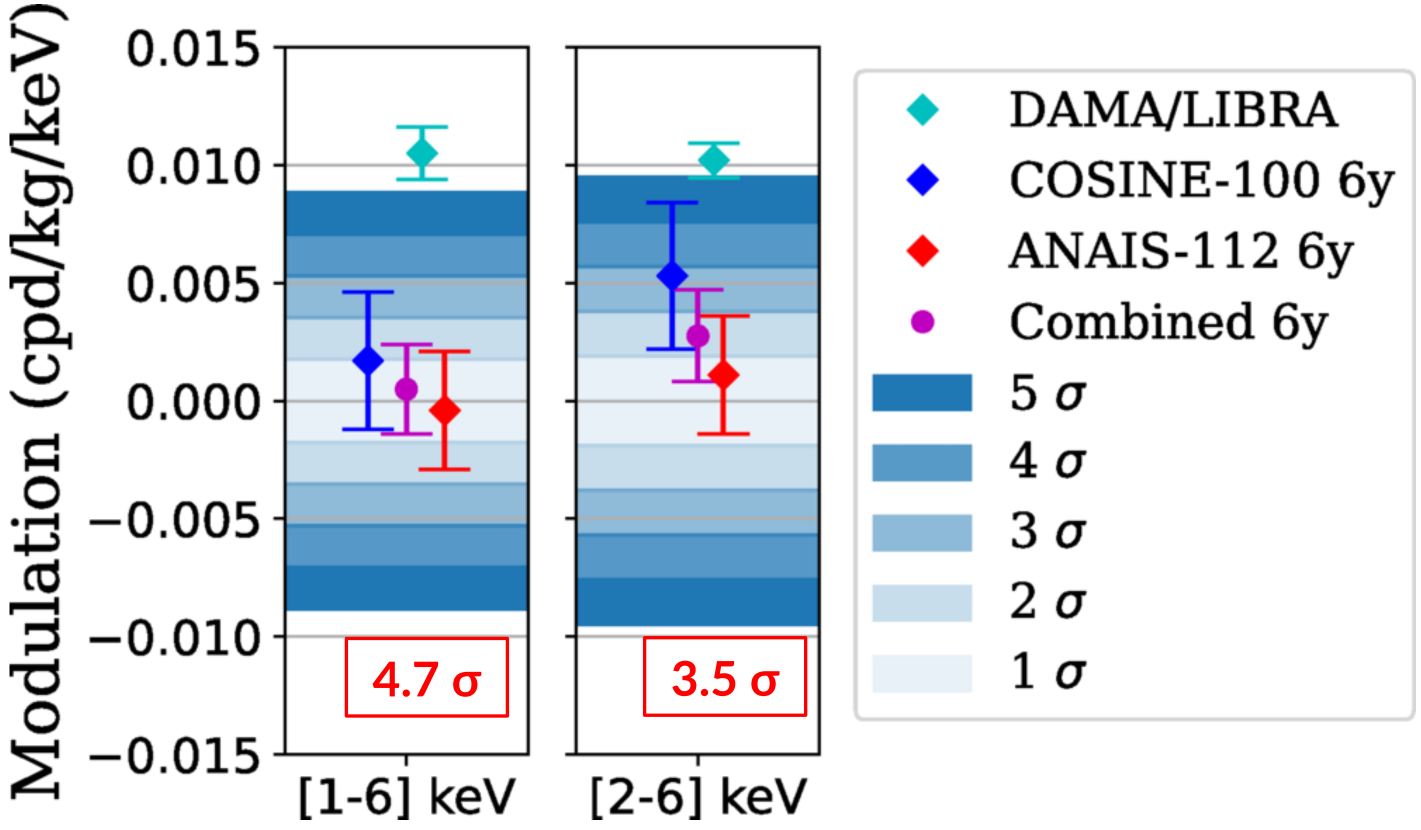


- No modulation observed

Combining ANAIS-112 & COSINE-100

Combined fit of two datasets





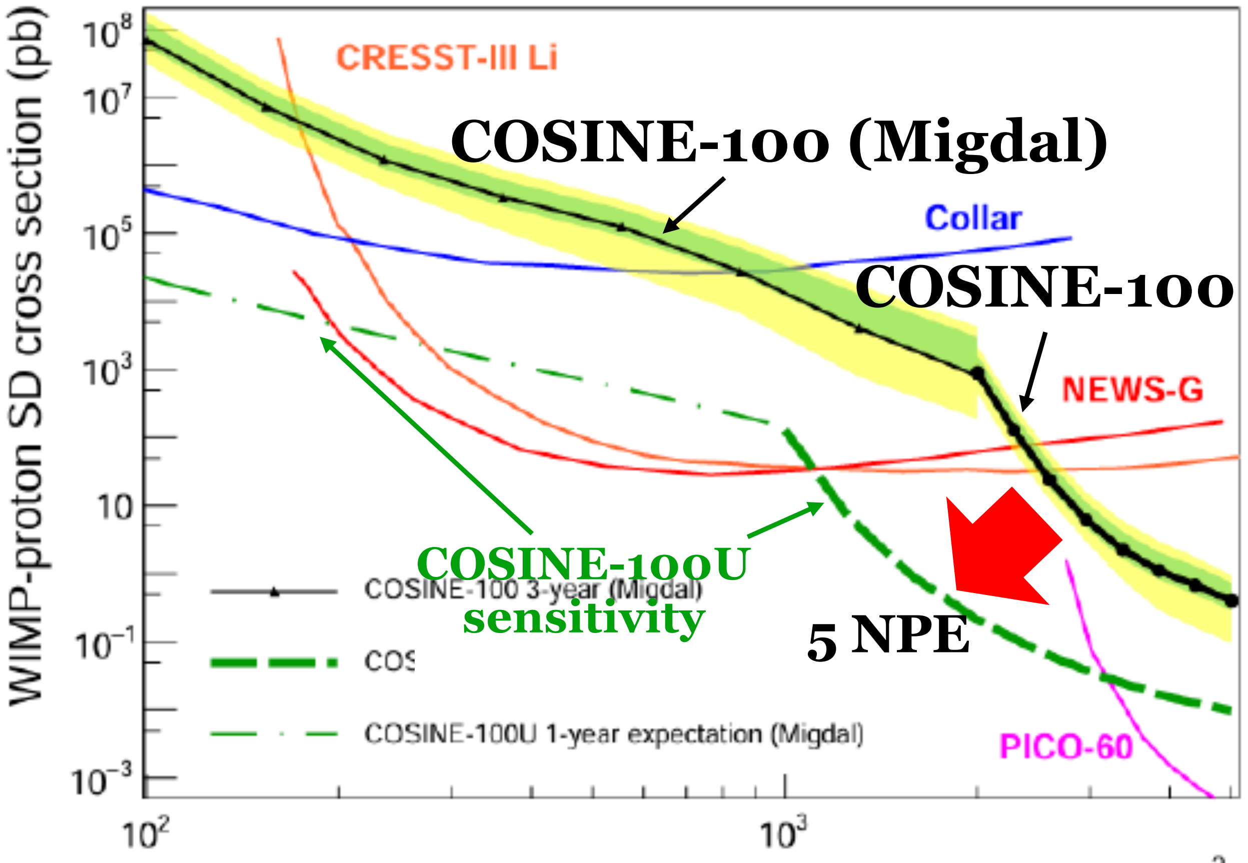
Phys. Rev. Lett. 135, 121002 (2025)

Model-independent test also **ruled out DAMA/LIBRA** with the same analysis method

Low-mass search with COSINE-100

- Na (Z = 11) and I (Z = 53)
  - ❖ Good for spin-dependent WIMP-proton interactions
  - ❖ Si (Z = 14), Ge (Z = 32), Ar (Z = 18), Xe (Z = 54)
  - ❖ Good for low-mass (sodium)
- Reduced threshold
  - ❖ Current threshold: **8 NPE** (0.7 keV)
  - ❖ **COSINE-100 goal: 5 NPE (0.5 keV)**
    - ❑ Ongoing analysis with full dataset
  - ❖ Higher light yield
    - ❑ Improved detector encapsulation

WIMP-proton spin-dependent interaction



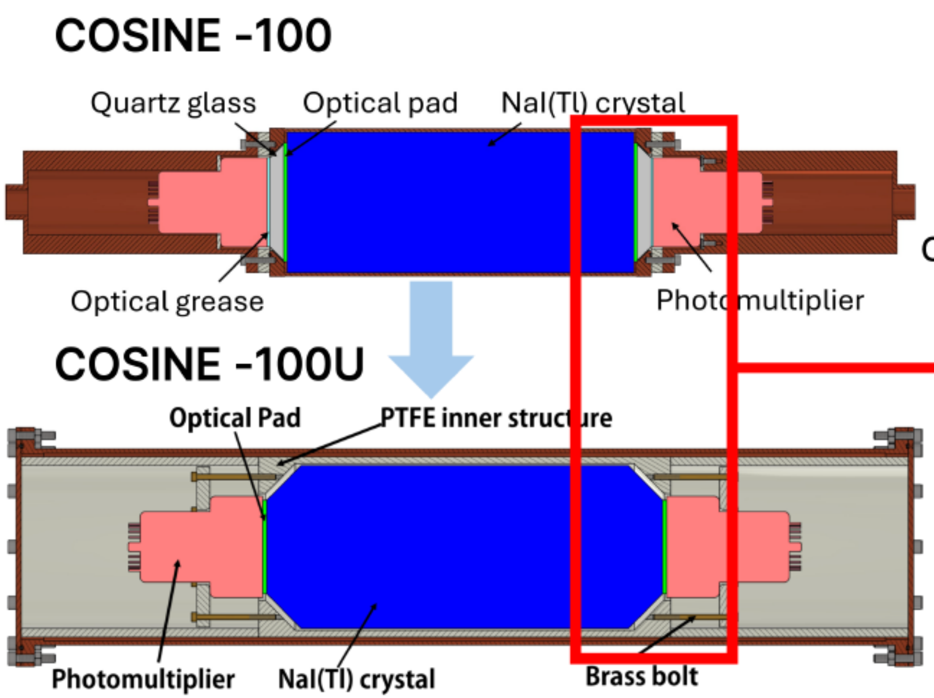
COSINE-100 3 years data

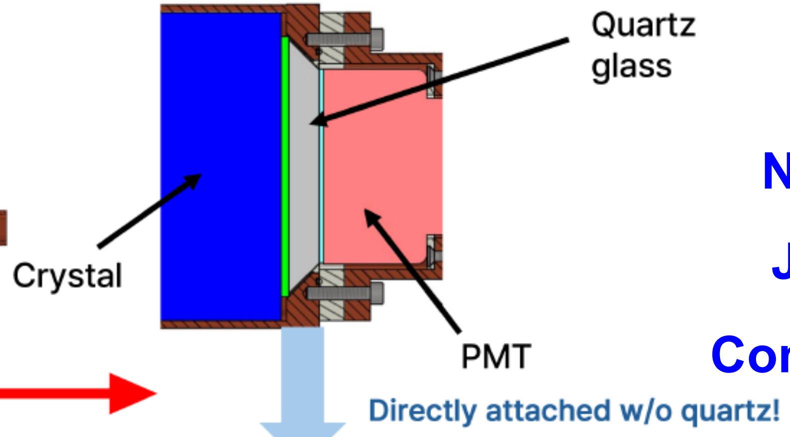
8 NPE threshold

Phys. Rev. Lett. 135, 231001 (2025)

Detector upgrade (COSINE-100U)

- Similar encapsulation to the NEON detector
- **Upgraded detector assembly for high light output**

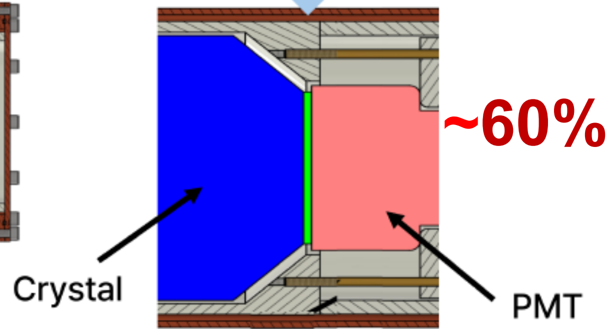




NIMA 981 (2020) 164556

JINST 19 (2024) P10020

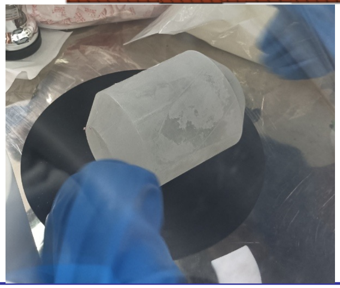
Commun. Phys. 8 (2025) 135



~60% increased light collection

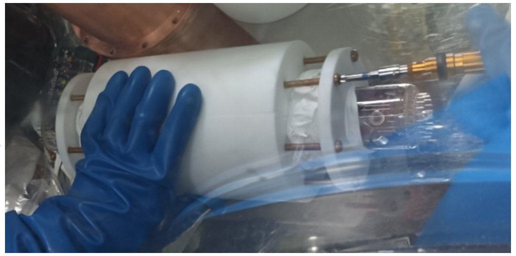
8.26 kg

7.19 kg



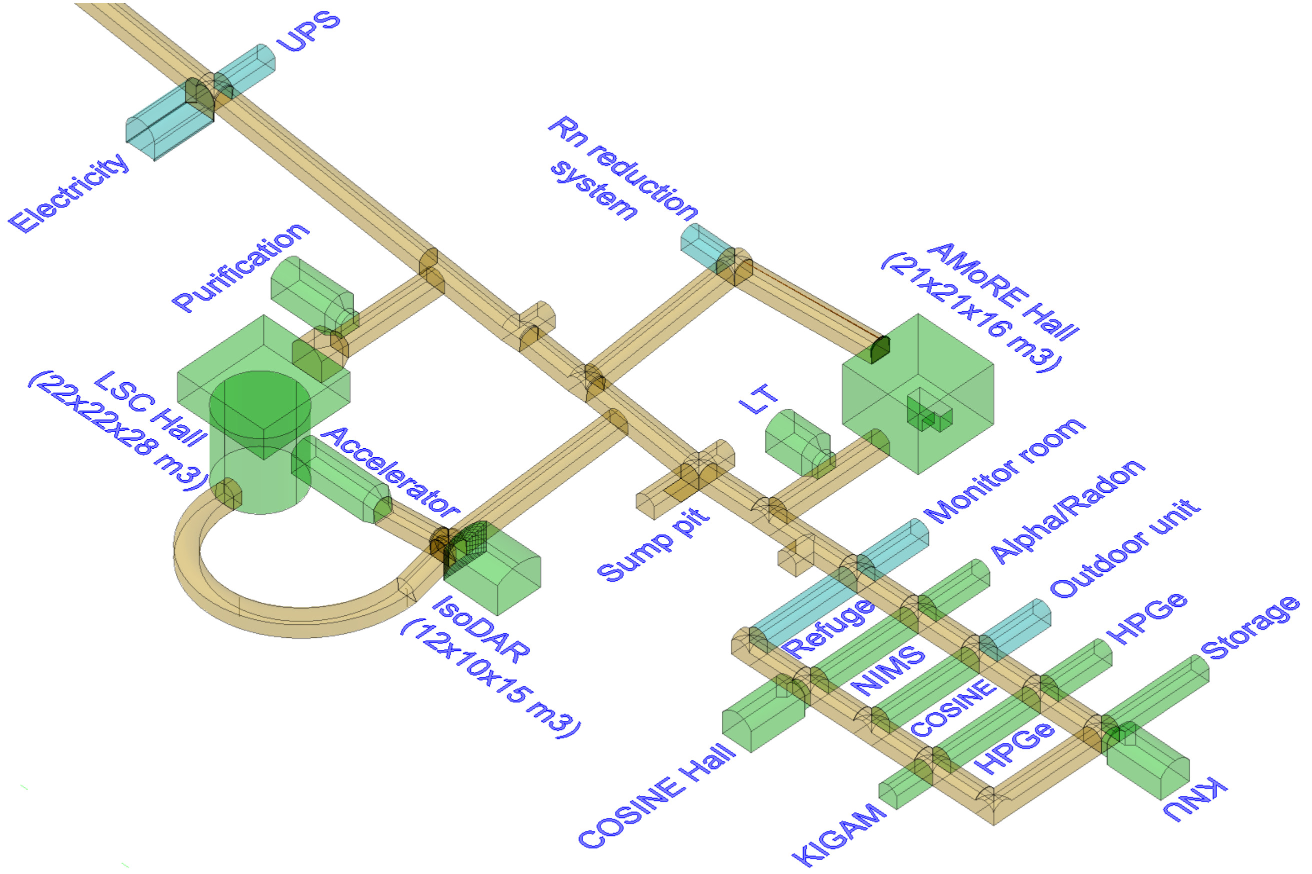
Polishing

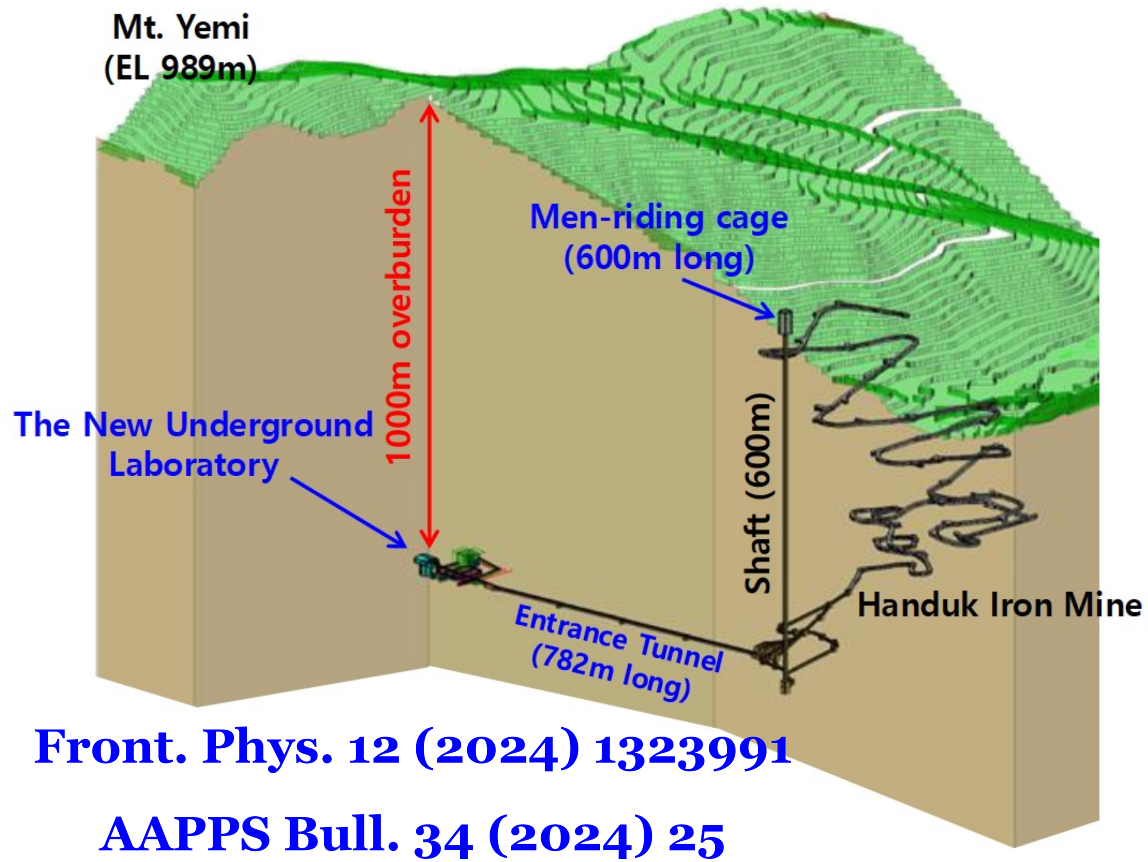
Assembly



Yemilab (Since 2022)

- **Dedicated underground laboratory for basic science**





Front. Phys. 12 (2024) 1323991

AAPPS Bull. 34 (2024) 25

- **Large experimental space (~3000 m^2)**
- Available space to host next-generation experiments

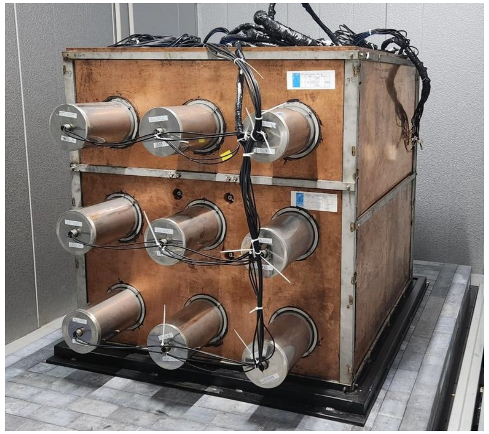
COSINE-100U @ Yemilab

Freeze room for -20^{o}C operation

Astropart. Phys. 141, 102709 (2022)

Detector upgrade for high light yield

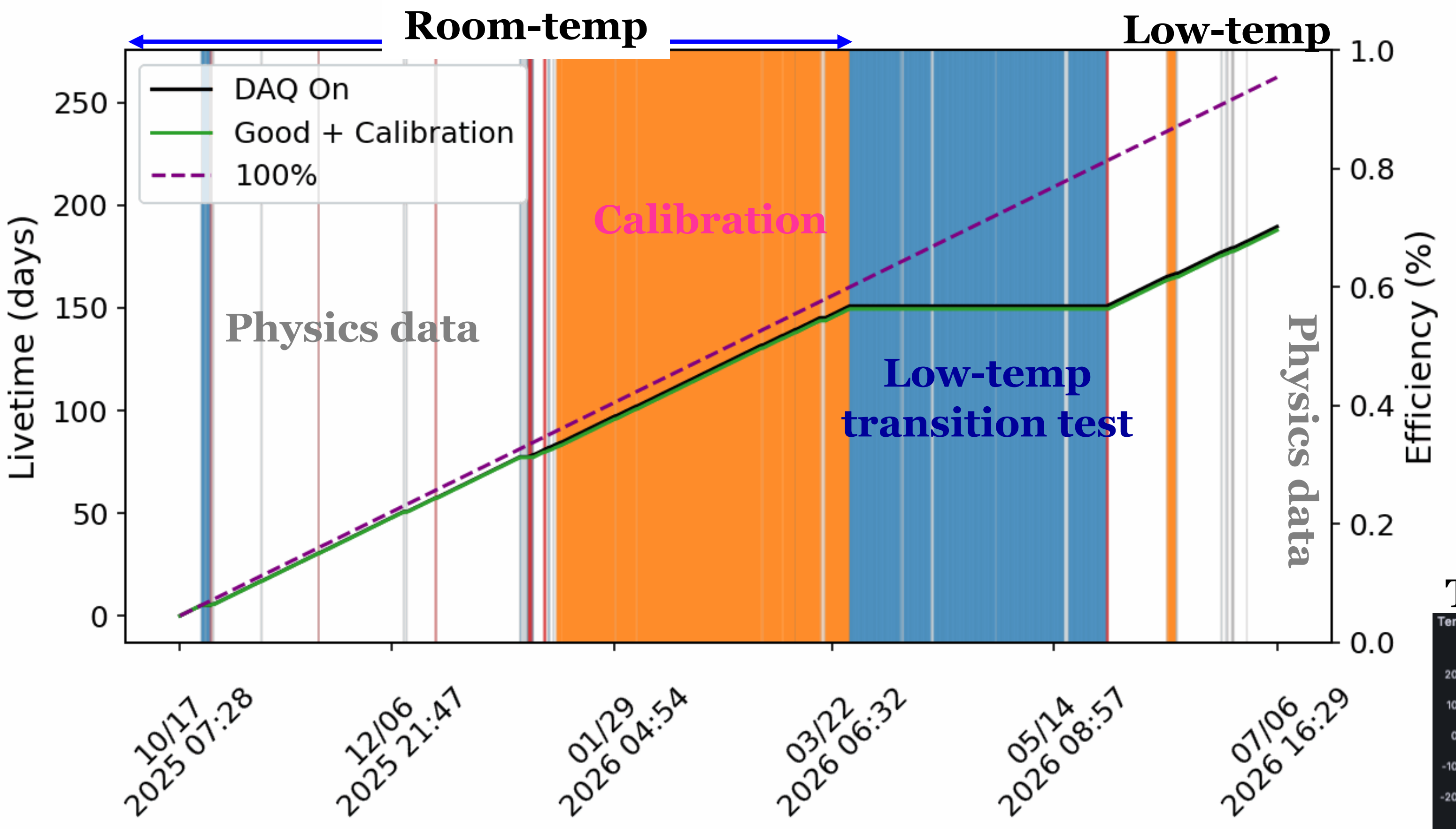
Liquid scintillator veto

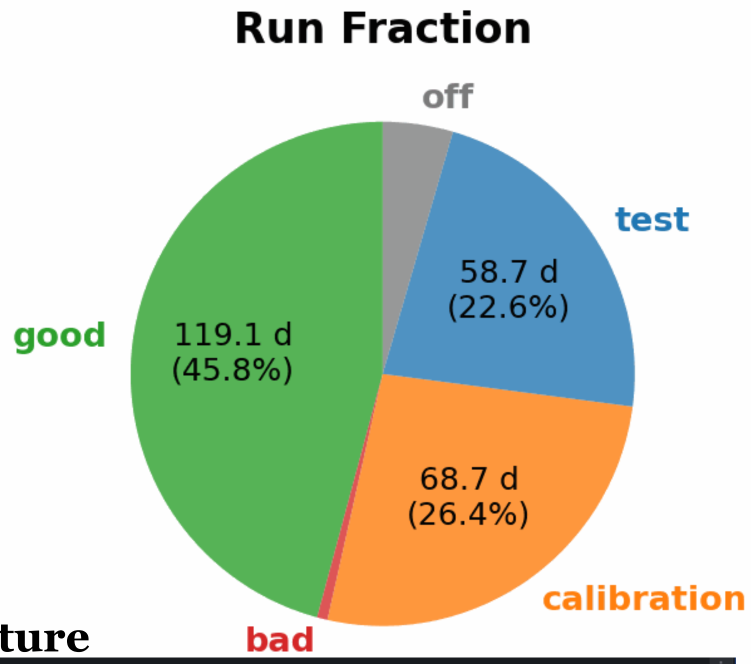


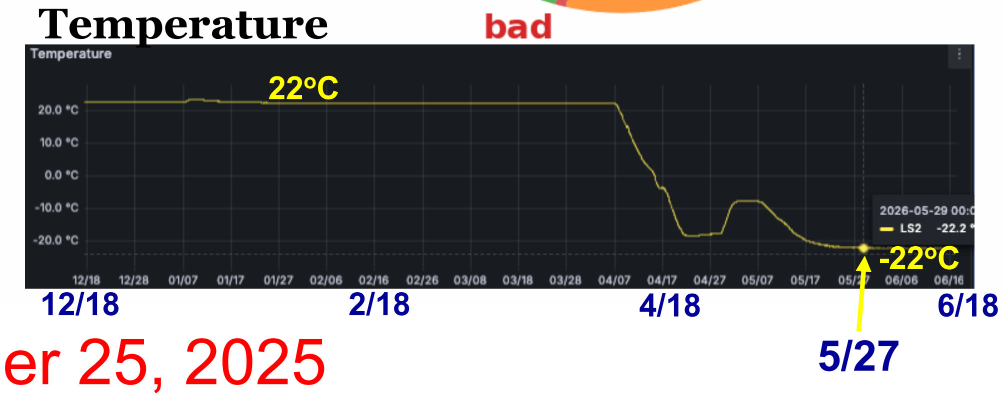
Crystal & LS install

Most shields and electronics were reused from COSINE-100 (Y2L) for COSINE-100U (Yemilab)

COSINE-100U operation



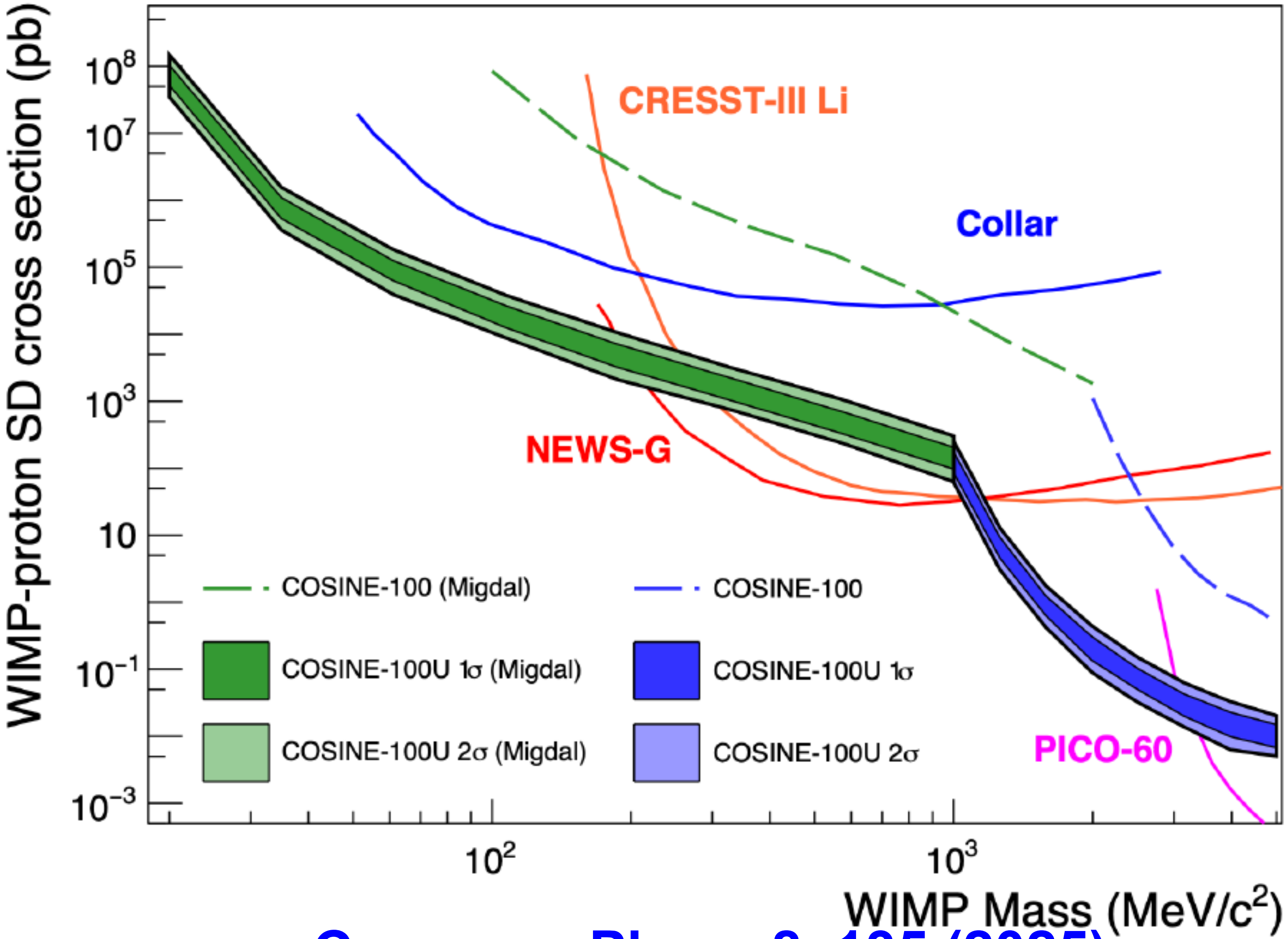




- Room-temp operation commenced on September 25, 2025
- With ~100 days of physics data and 67 days of ^{22}Na calibration data, we switched to low-temp (-22°C) operation, **starting the physics run on May 27, 2026**

COSINE-100U sensitivity

WIMP-Proton spin-dependent interaction



Commun. Phys. 8, 135 (2025)

Assumptions

- 20 NPE/keV light yield
- 8 Crystals, total 99.0 kg
- 1-year exposure
- 5 NPE threshold
- Same background as COSINE-100

- ~23 NPE/keV
- ~ 1 dru reduced background
- Low-temp operation

Conclusion

- Direct detection now spans a **broad landscape** — meV to keV, many targets & techniques

- **High-mass frontier**: liquid-Xe TPCs (XENONnT, LZ, PandaX-4T, PandaX-xT, XLZD) and liquid-Ar TPCs (DarkSide-20k, ARGO) set (or will set) the strongest SI/SD limits, closing in on the neutrino fog

- **Low-mass frontier**: Cryogenic bolometers (CRESST, SuperCDMS, TESSERACT) and skipper-CCDs (SENSEI, DAMIC-M) lead this frontier

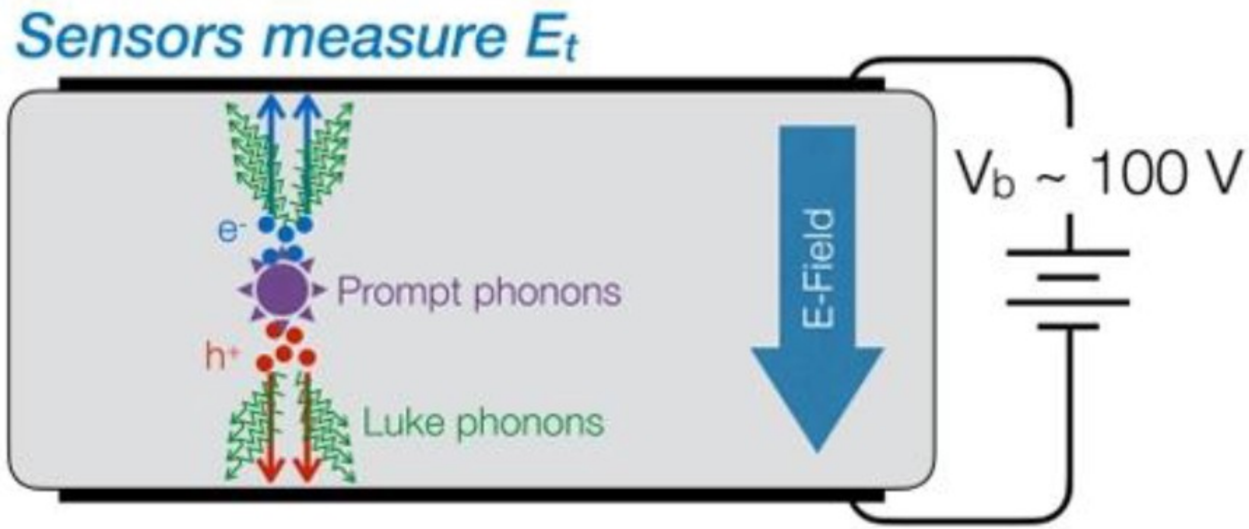
- **DAMA/LIBRA puzzle**: ANAIS-112 + COSINE-100 combined fit excludes modulation at **3.5–4.7σ**, model-independently

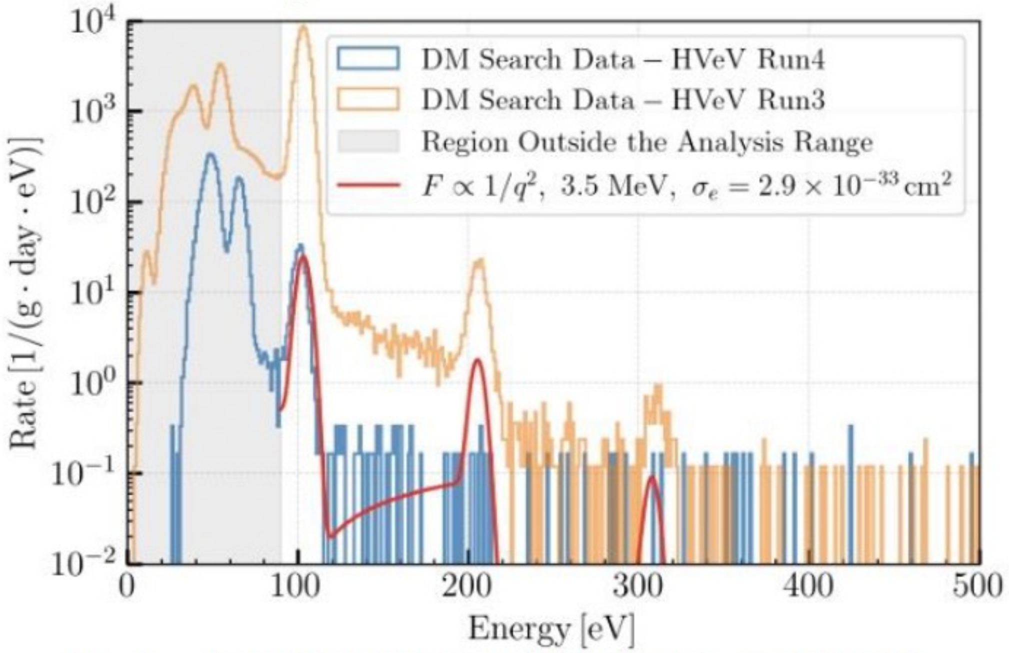
- **COSINE-100U @ Yemilab** (**~23 NPE/keV**): definitive NaI(Tl) test + new low-mass reach

Thank you very much

NTL-Amplification – Neganov-Trofimov-Luke Effect

Clever way to search for individual e-h pair creation with a phonon sensor!





$$E_{ph} = E_r + n_{eh} \cdot e \cdot V_{\text{bias}}$$

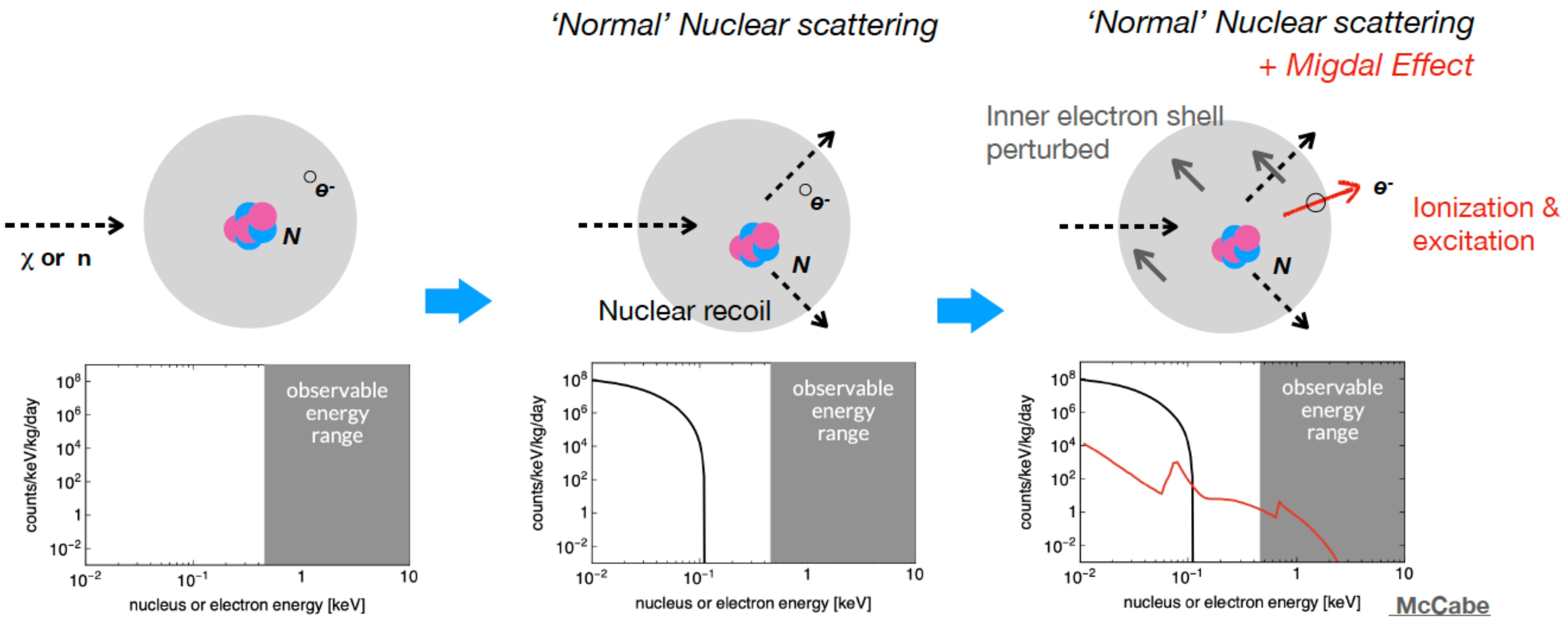
Albakry et al, PRD 113, 032001 (2026) [arXiv:2509.03608]

Pros: in-situ aggregate discrimination, target-agnostic*, timing, 1-10 dru backgrounds

Cons: large dark rates, limited position information, no event-by-event discrimination

see Mon. talk from Aditi Pradeep, Wed. talk from Aviv Simchony, and see Wed. plenary from Belina von Krosigk for more information on SuperCDMS

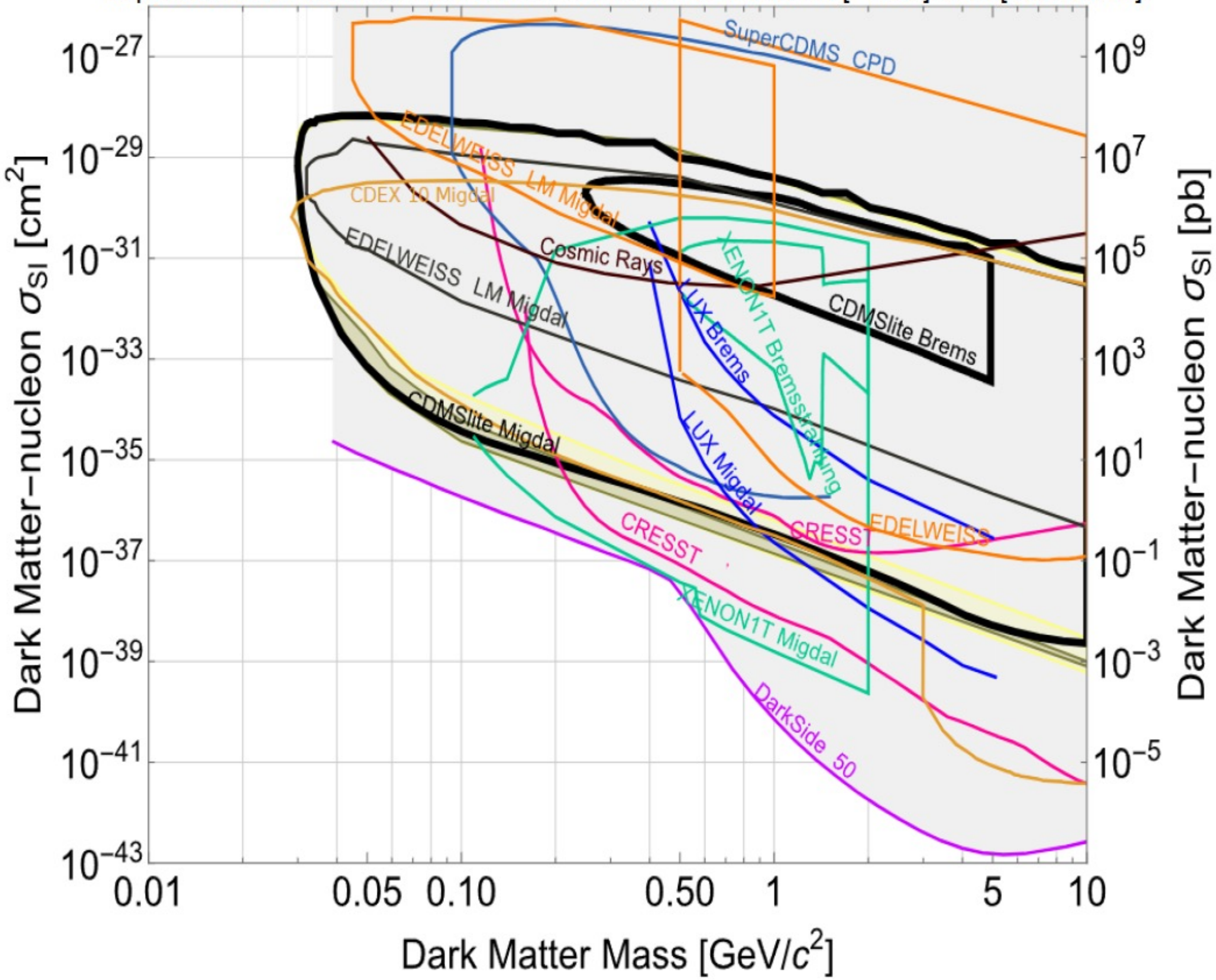
Migdal effect



- Deposited energy from Migdal events is higher than conventional elastic nuclear recoil make more detectable excitation

Sub-GeV DM Searches with Migdal effect

SuperCDMS Collaboration. Inelastic DM search with CDMSlite R3 [EB/OL]. 2025[2026-03-02].



Search for Light Dark Matter Interactions Enhanced by the Migdal Effect or Bremsstrahlung in XENON1T #1
XENON Collaboration • E. Aprile (Columbia U.) et al. (Jul 30, 2019)
Published in: Phys.Rev.Lett. 123 (2019) 24, 241803 • e-Print: 1907.12771 [hep-ex]
pdf DOI cite claim reference search 329 citations

Search for new physics in low-energy electron recoils from the first LZ exposure #1
LZ Collaboration • J. Aalbers (SLAC and Stanford U., Phys. Dept. and KIPAC, Menlo Park) et al. (Jul 28, 2023)
Published in: Phys.Rev.D 108 (2023) 7, 072006 • e-Print: 2307.15753 [hep-ex]
pdf links DOI cite datasets claim reference search 73 citations

Search for Dark-Matter–Nucleon Interactions with a Dark Mediator in PandaX-4T #1
PandaX Collaboration • Di Huang (Shanghai Jiao Tong U.) et al. (Aug 3, 2023)
Published in: Phys.Rev.Lett. 131 (2023) 19, 191002 • e-Print: 2308.01540 [hep-ex]
pdf DOI cite claim reference search 51 citations

Results of a Search for Sub-GeV Dark Matter Using 2013 LUX Data #1
LUX Collaboration • D.S. Akerib (Case Western Reserve U. and SLAC and KIPAC, Menlo Park) et al. (Nov 27, 2018)
Published in: Phys.Rev.Lett. 122 (2019) 13, 131301 • e-Print: 1811.11241 [astro-ph.CO]
pdf DOI cite claim reference search 213 citations

Search for Dark-Matter–Nucleon Interactions via Migdal Effect with DarkSide-50 #1
DarkSide Collaboration • P. Agnes (Royal Holloway, U. of London) et al. (Jul 25, 2022)
Published in: Phys.Rev.Lett. 130 (2023) 10, 10 • e-Print: 2207.11967 [hep-ex]
pdf links DOI cite claim reference search 107 citations

Search for low-mass dark matter via bremsstrahlung radiation and the Migdal effect in SuperCDMS #1
SuperCDMS Collaboration • M.F. Albakry (British Columbia U. and TRIUMF) et al. (Feb 17, 2023)
Published in: Phys.Rev.D 107 (2023) 11, 2023 • e-Print: 2302.09115 [hep-ex]
pdf links DOI cite claim reference search 43 citations

Search for sub-GeV dark matter via the Migdal effect with an EDELWEISS germanium detector with NbSi transition-edge sensors #2
EDELWEISS Collaboration • E. Armengaud (IRFU, Saclay) et al. (Mar 8, 2022)
Published in: Phys.Rev.D 106 (2022) 6, 062004 • e-Print: 2203.03993 [astro-ph.GA]
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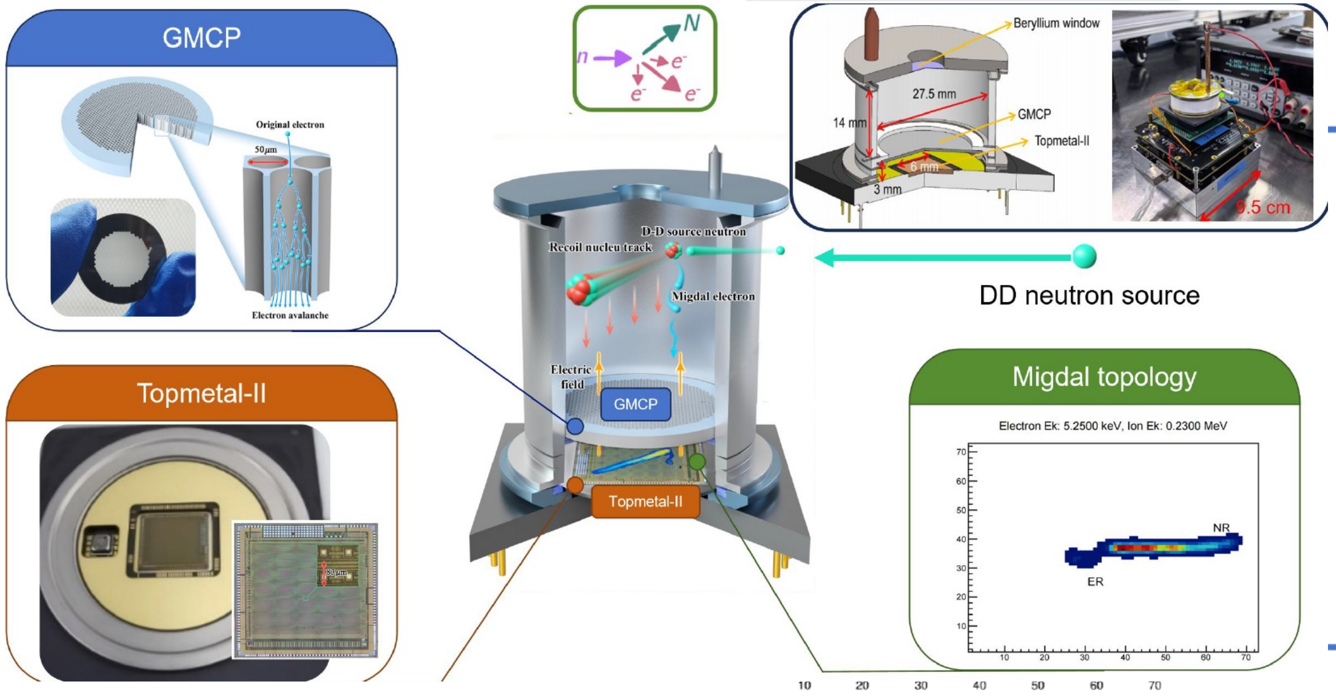
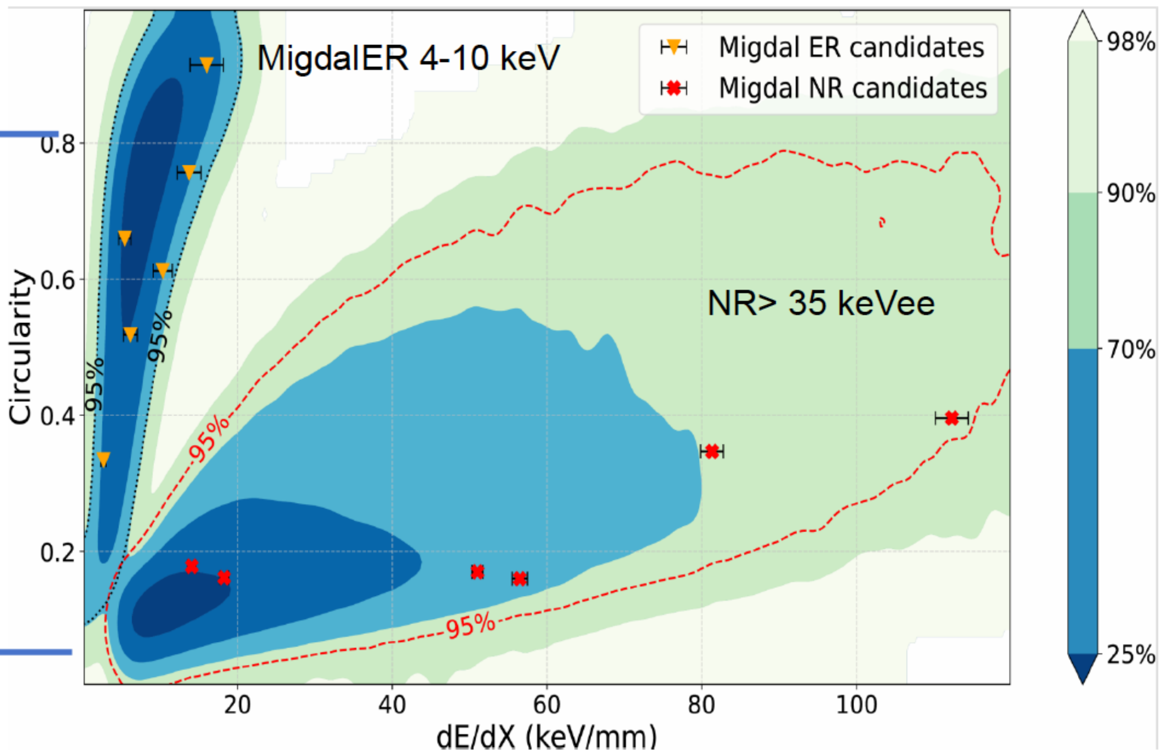
XENON/LZ/PandaX/CDEX/DarkSide-50/SuperCDMS/EDELWEISS/LUX…

Observation of Migdal Process

$5\ keV_{ee} < Ee < 10\ keV_{ee}, E_{nr} > 35keV_{ee}$





Six candidate events observed

[*Nature* 649, 580–583 (2026)](https://www.nature.com)

Background: $0.229 \pm 0.032(stat.) \pm 0.043(syst.)$

Migdal/Nuclear recoil ratio:

Result: $4.9^{+2.6}_{-1.9} \times 10^{-5}$

Theory: 3.9×10^{-5}

Worldwide efforts on NaI(Tl)