Direct detection searches for dark matter with liquid argon

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Light Dark World

July 30, 2026

Carleton University

Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

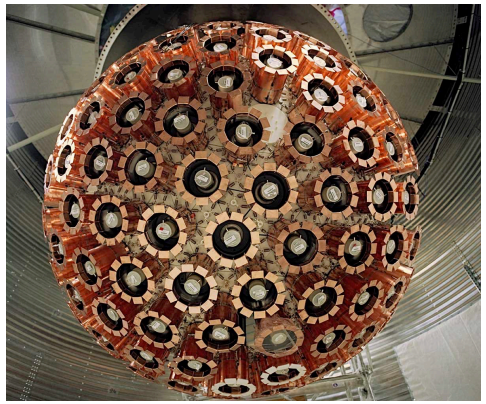
“Looking for dark matter” according to ChatGPT

Query by Michael Perry

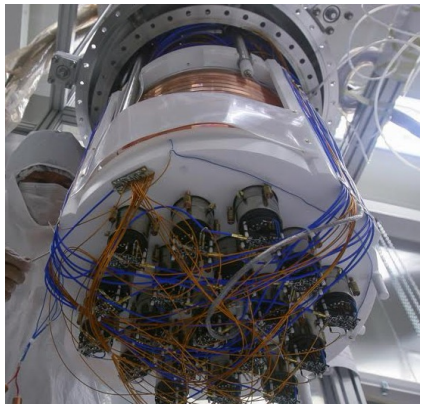
Global Argon Dark Matter Collaboration

More than 400 researchers, at more than 100 institutions, in 14 countries

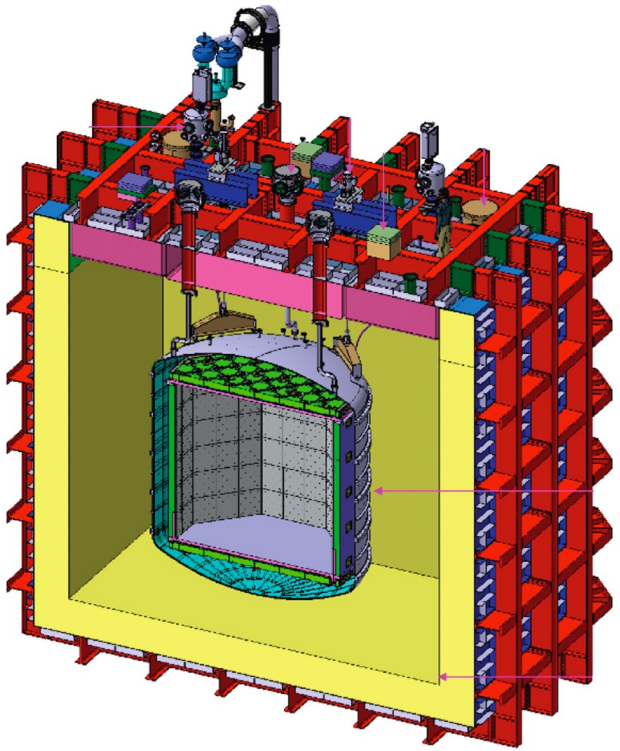
DEAP-3600



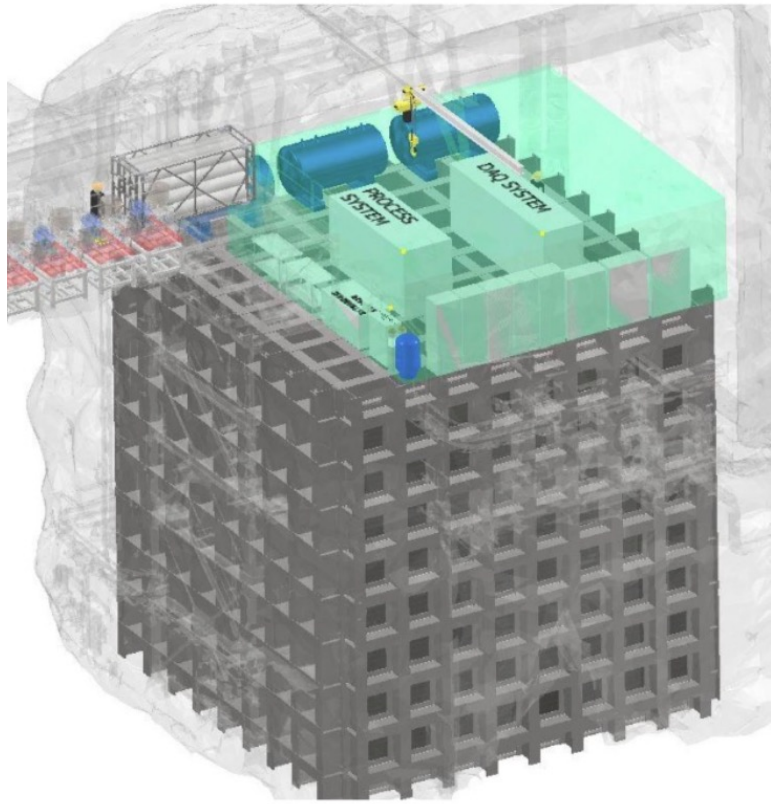
DarkSide-50



DarkSide-20k



ARGO



… and multiple related liquid argon detectors; R&D and QA infrastructure

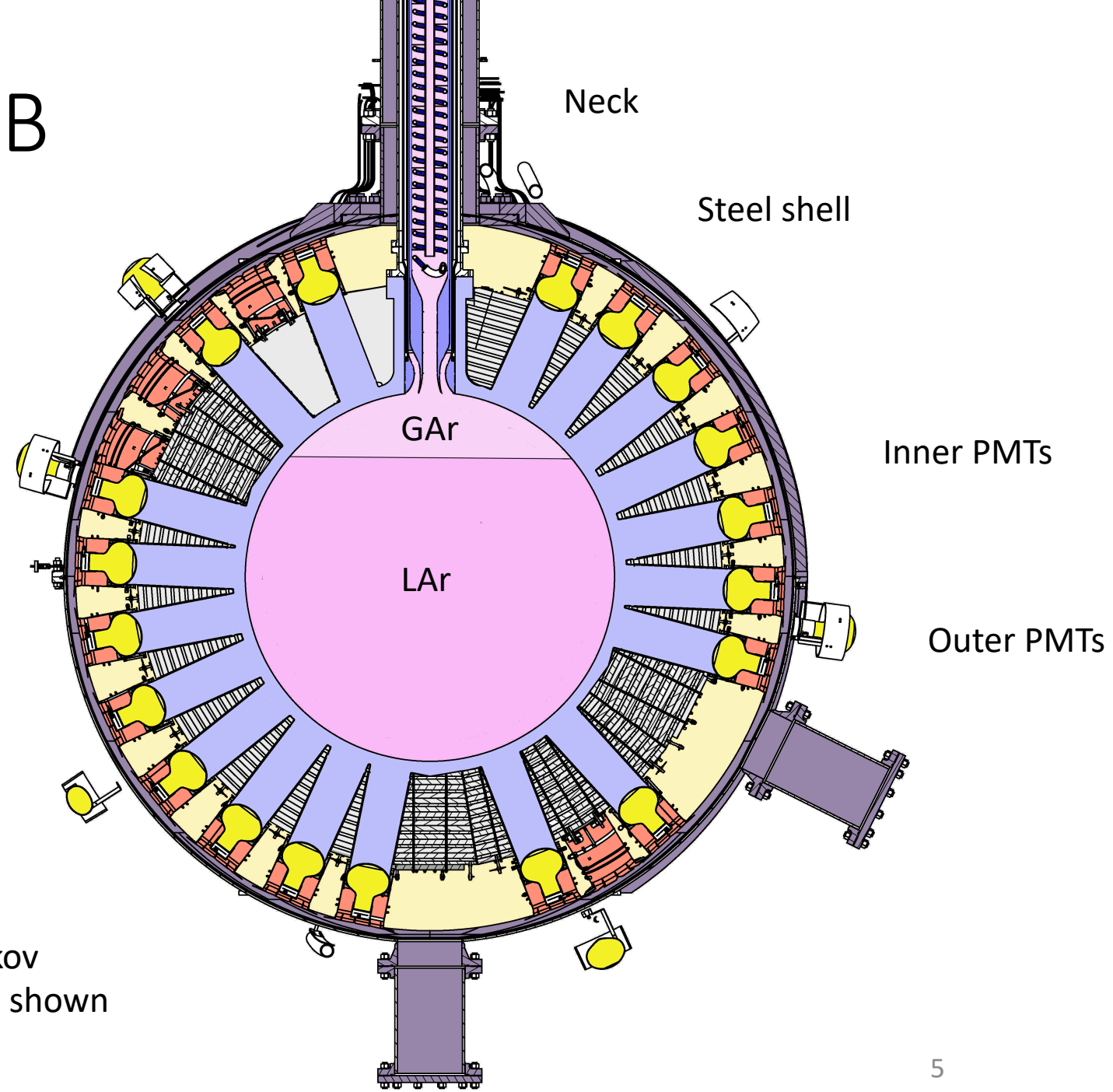
Outline

- Latest results from **DEAP-3600** at SNOLAB
  - Physics analyses with second-fill dataset: WIMP search, solar neutrinos!
  - Now taking data with detector in the upgraded configuration
- **DarkSide-50** searches for low-mass dark matter
- **DarkSide-20k** under construction at LNGS, Italy
  - Key Canadian contributions
  - Expected sensitivity to WIMPs including at low mass from 1 GeV/c^2
- **ARGO** design and expected performance
- Detectors dedicated to low-mass dark matter searches
  - **Scintillating Bubble Chamber**
  - **AURORA** proposal

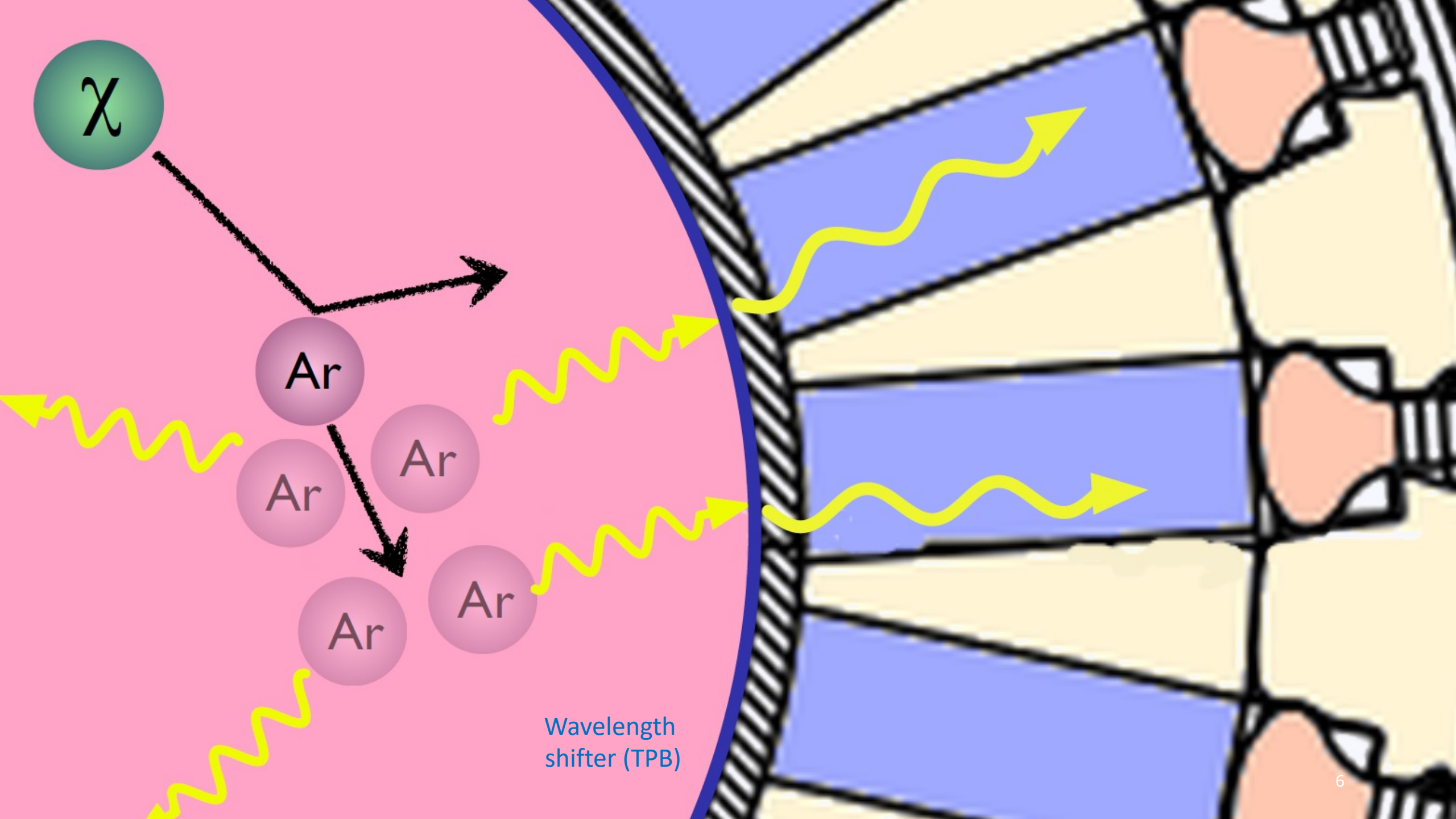
DEAP-3600 @ SNOLAB

Located in Cube Hall, 2 km underground

Detector design and construction:
DEAP Collaboration (2019)
Astropart. Phys. 108, 1-23



Water Cherenkov
muon veto not shown


χ
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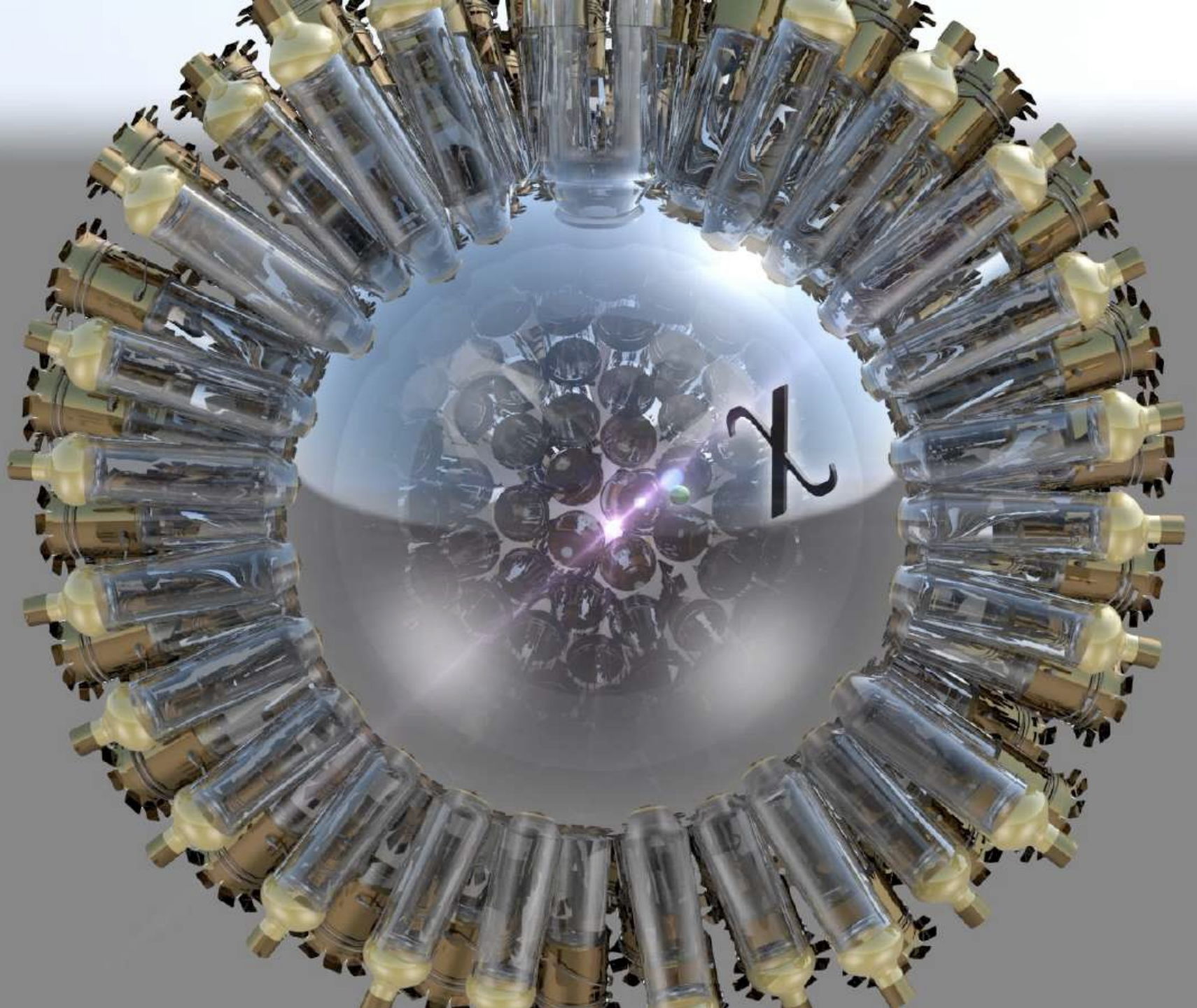
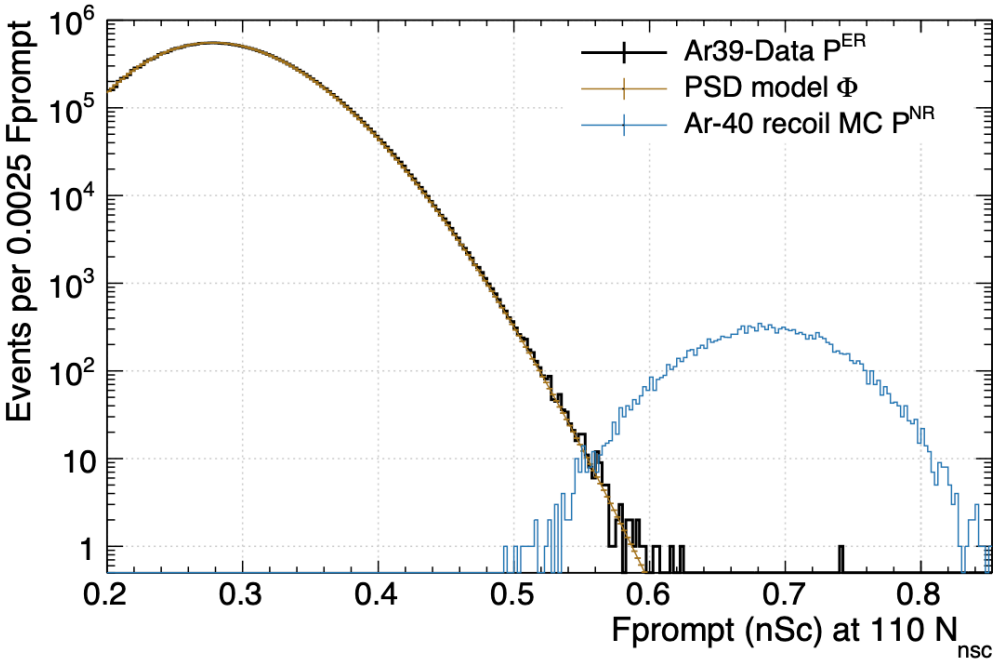
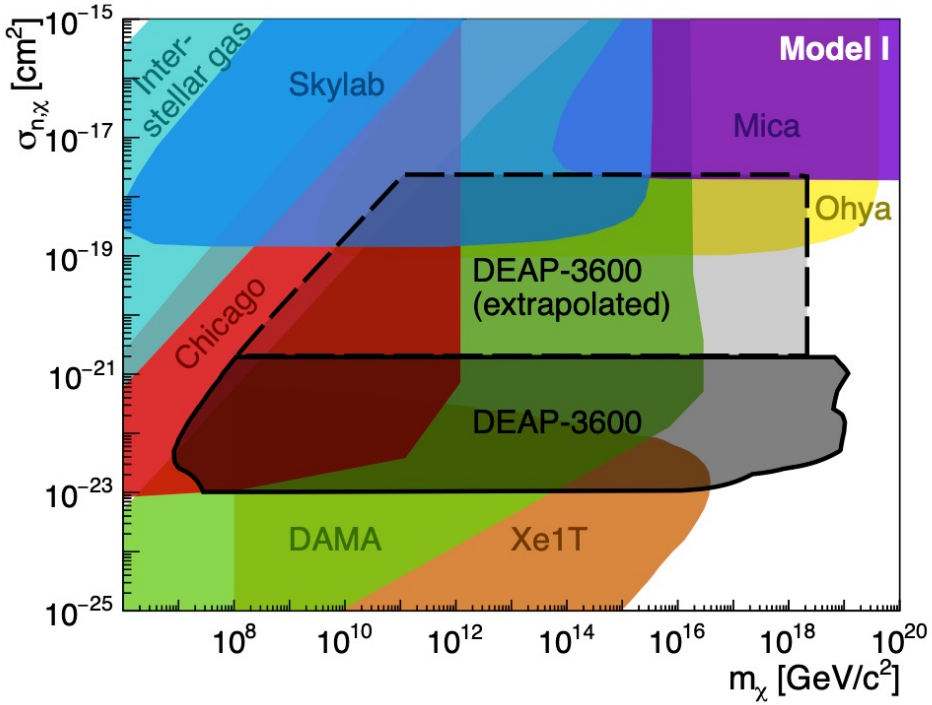
Wavelength
shifter (TPB)



DEAP-3600 @ SNOLAB

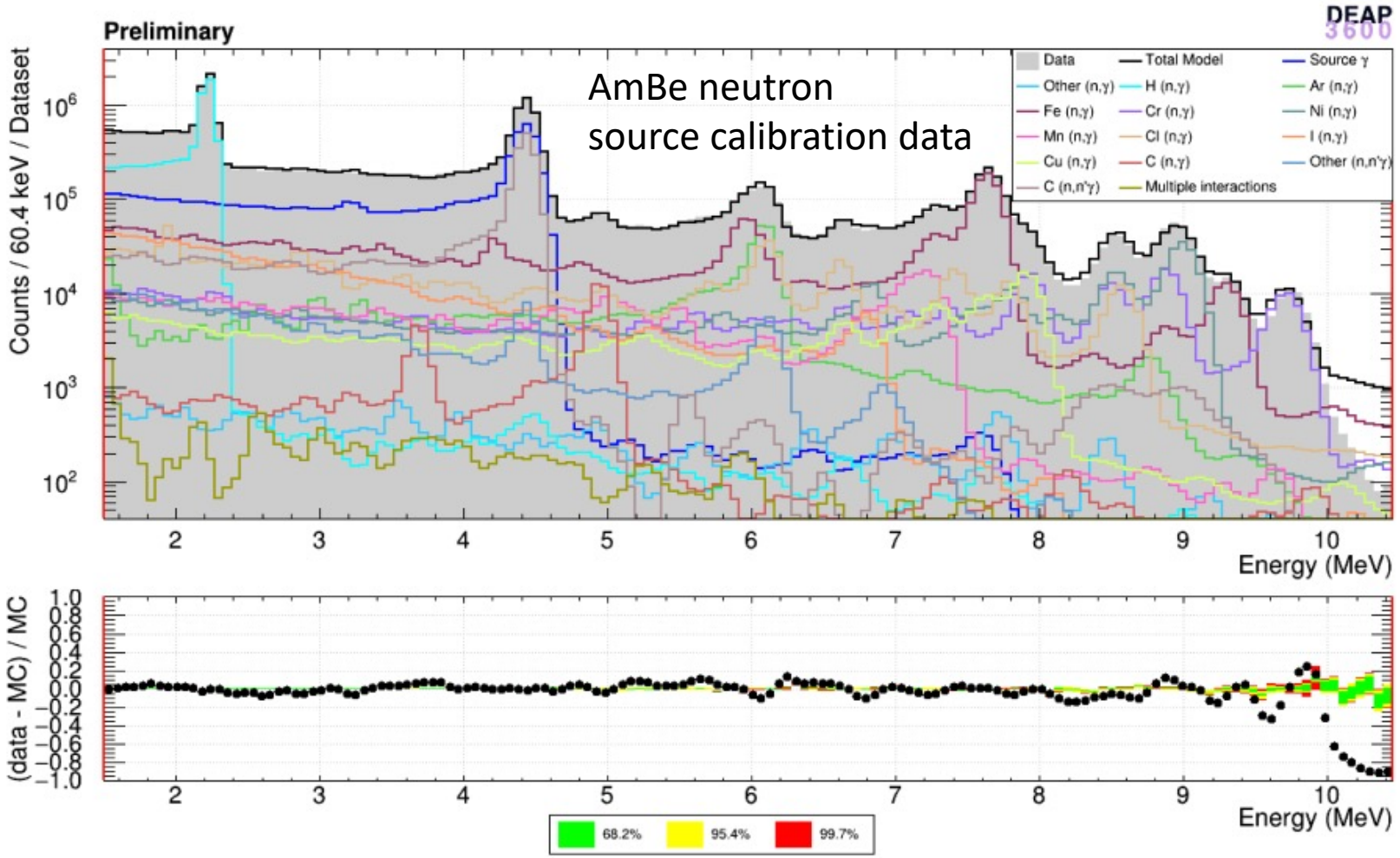
- Data collected in 2016-2020 with 3269 kg of liquid argon
- Reject electronic recoil backgrounds using **pulseshape discrimination** (PSD)
  - Demonstrated 10^{-10} leakage fraction at 50% nuclear recoil acceptance
  - DEAP Collaboration (2020) EPJC 80, 303
  - DEAP Collaboration (2021) EPJC 81, 823
- Best limits on DM interactions with argon
  - DEAP Collaboration (2019) PRD 100, 022004
  - DEAP Collaboration (2020) PRD 102, 082001
  - DEAP Collaboration (2022) PRL 128, 011801
  - DEAP Collaboration (2026) arXiv:2603.13965





DEAP-3600 @ SNOLAB

- Search for 5.5 MeV solar axions (as a light dark matter candidate)



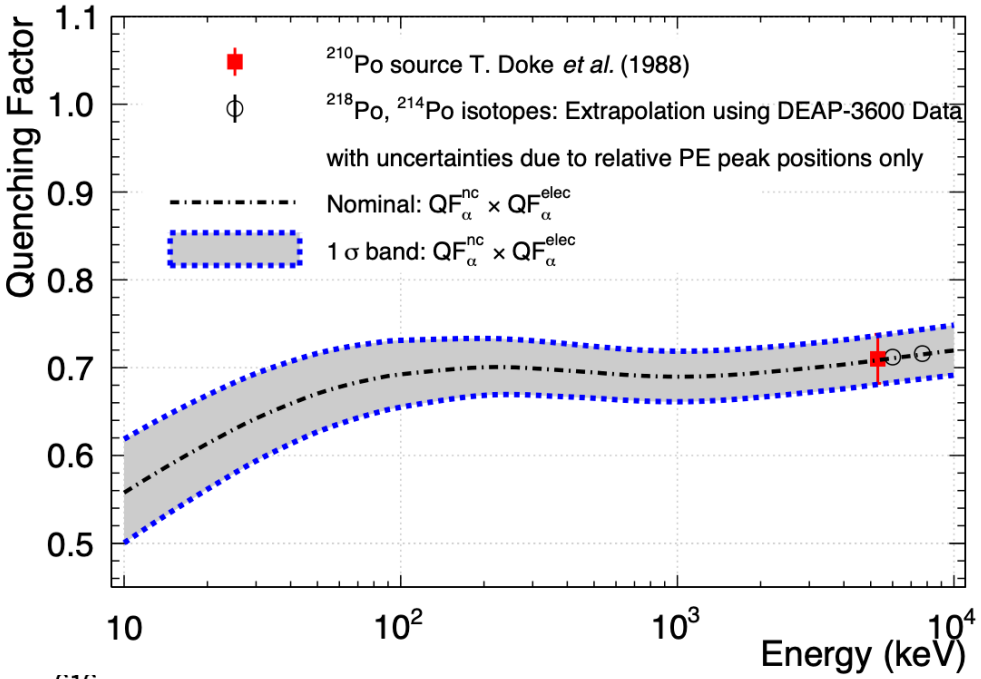
p + d → ^{3}***He + a***
with *α* instead of *γ*

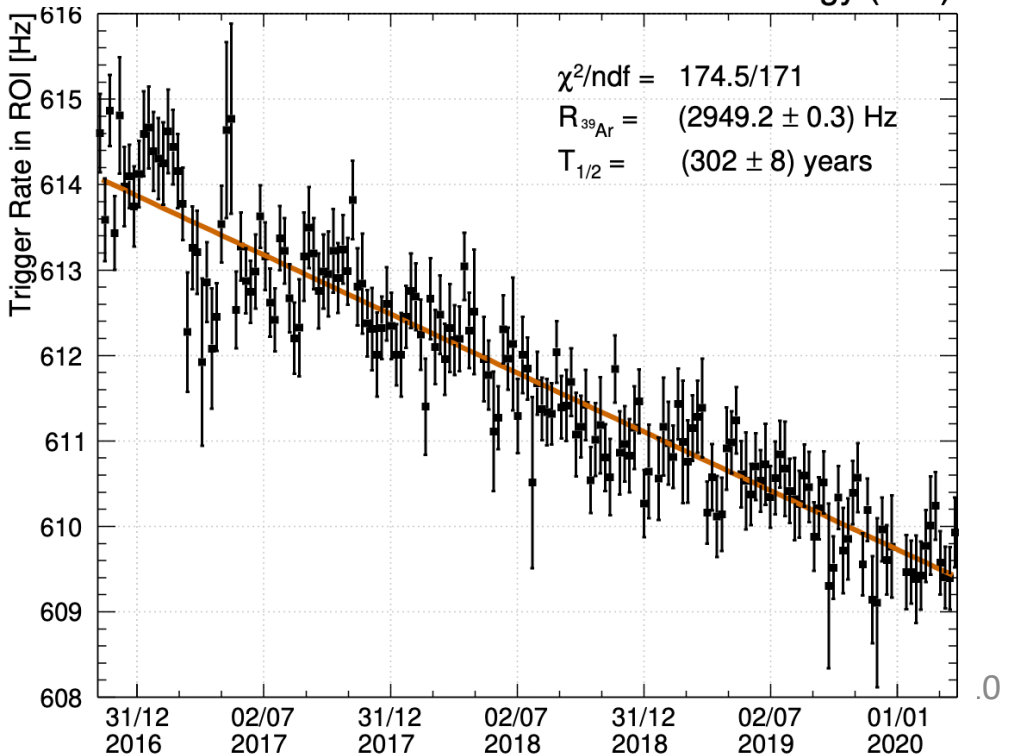
Very challenging fit to sources of gamma backgrounds

For more details, please see PhD thesis by Carl Rethmeier (2021)

DEAP-3600 @ SNOLAB

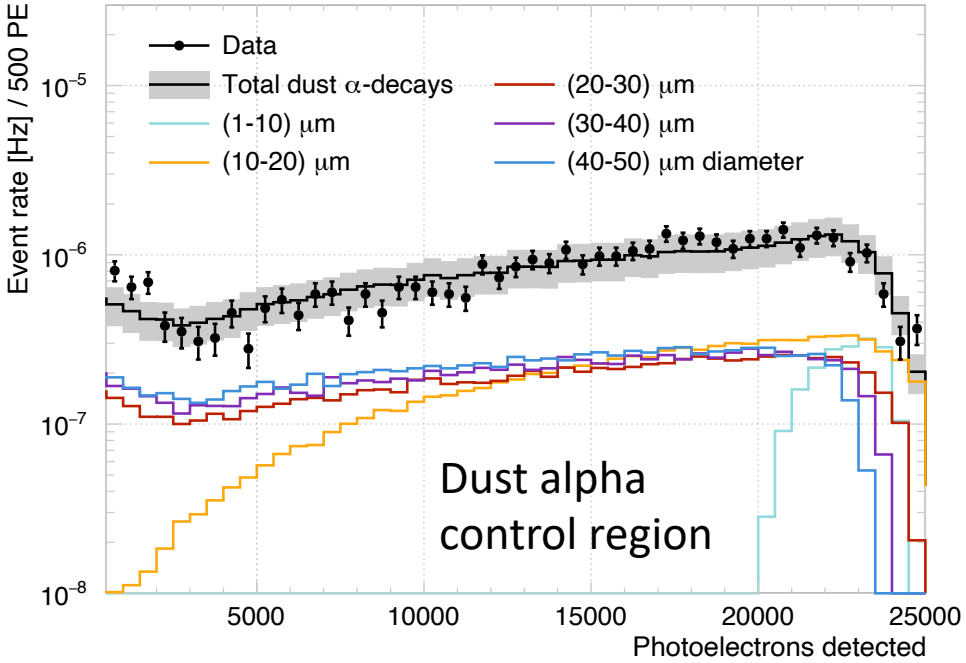
- Relative measurement and extrapolation of the scintillation **quenching factor** of alpha-particles in liquid argon
  - DEAP Collaboration (2025) EPJC 85, 87
- Measurement of the **^{39}Ar specific activity** in atmospheric argon
  - 0.964 ± 0.001 [stat] ± 0.024 [sys] Bq/kg$_{atmAr}$
  - DEAP Collaboration (2023) EPJC 83, 642
- Direct measurement of the **^{39}Ar half-life**
  - 302 ± 8 [stat] ± 6 [sys] years
  - DEAP Collaboration (2025) EPJC 85, 728
- Position reconstruction in DEAP-3600
  - **Neural network** against shadowed alpha decays from neck
  - DEAP Collaboration (2025) JINST 20, P07012

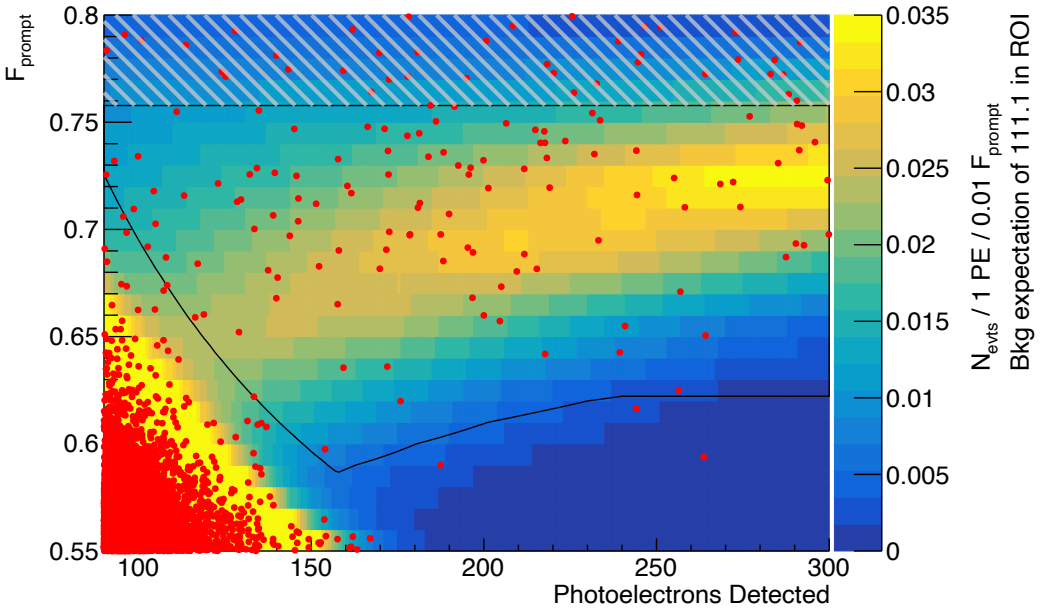




DEAP-3600: WIMP search

- WIMP dark matter search using the **profile likelihood analysis** method
  - Updated event selection, with overall 5x increase in **signal acceptance** while accepting background in the region-of-interest
  - **Control regions** to constrain main backgrounds
  - 3D fit in number of photoelectrons detected, PSD observable, and reconstructed position
  - Sensitivity limited by trace amount of **dust**, a source of attenuated alpha-decay events
    - Upon unblinding the data, observed an excess of events, attributed to background

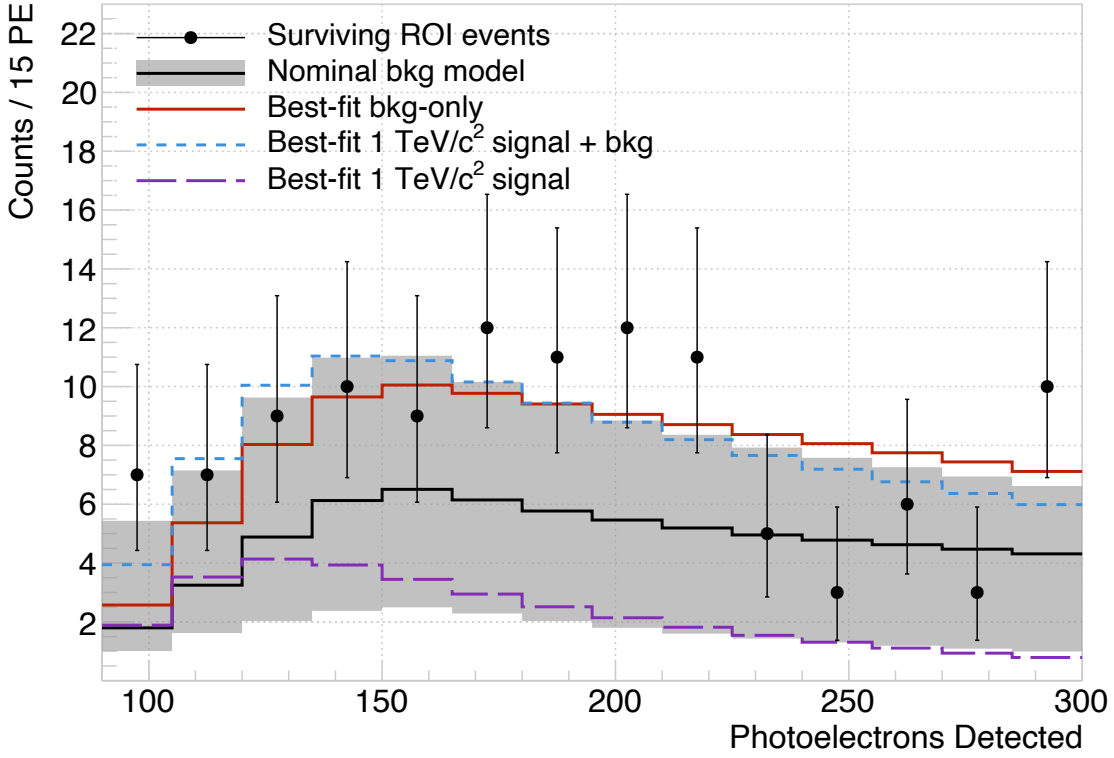


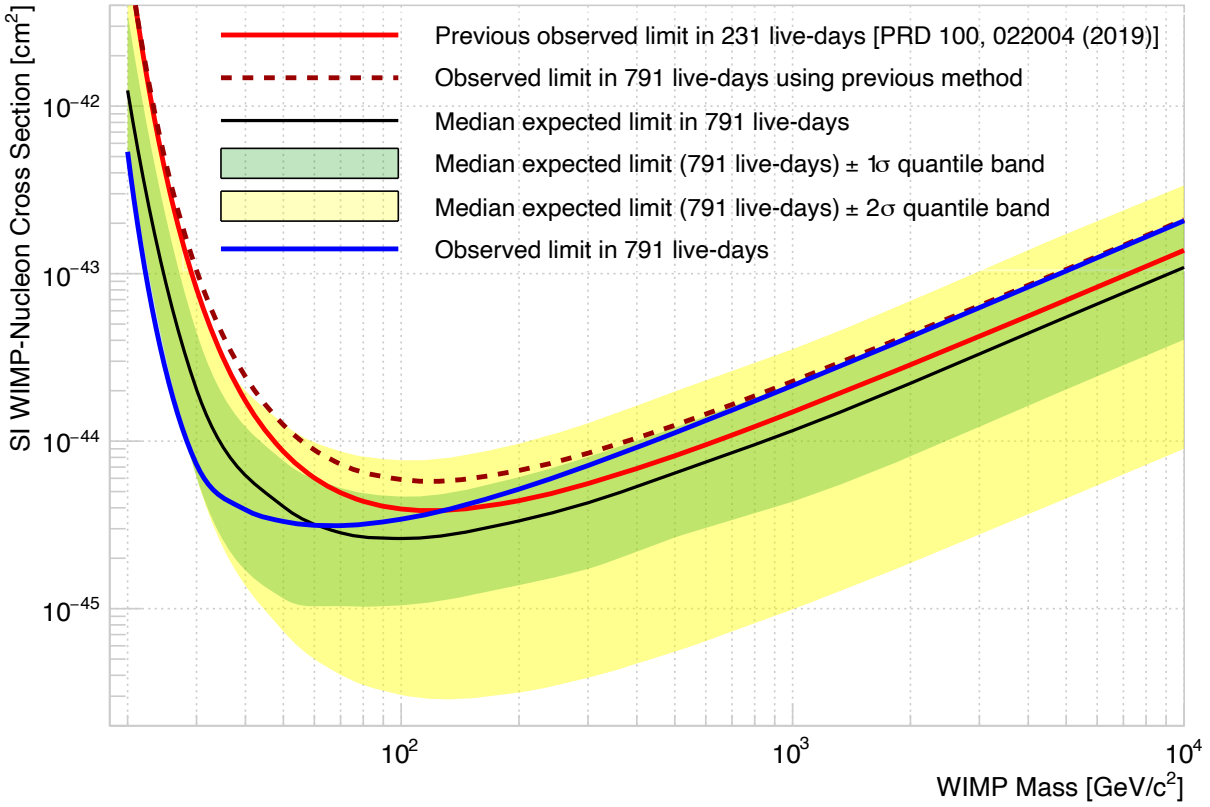


DEAP Collaboration (2026) arXiv:2603.13965

DEAP-3600: WIMP search

- The excess is compatible with bkg-only and bkg+signal hypotheses
  - New data taking with **upgraded detector** to mitigate backgrounds (2025 – present)

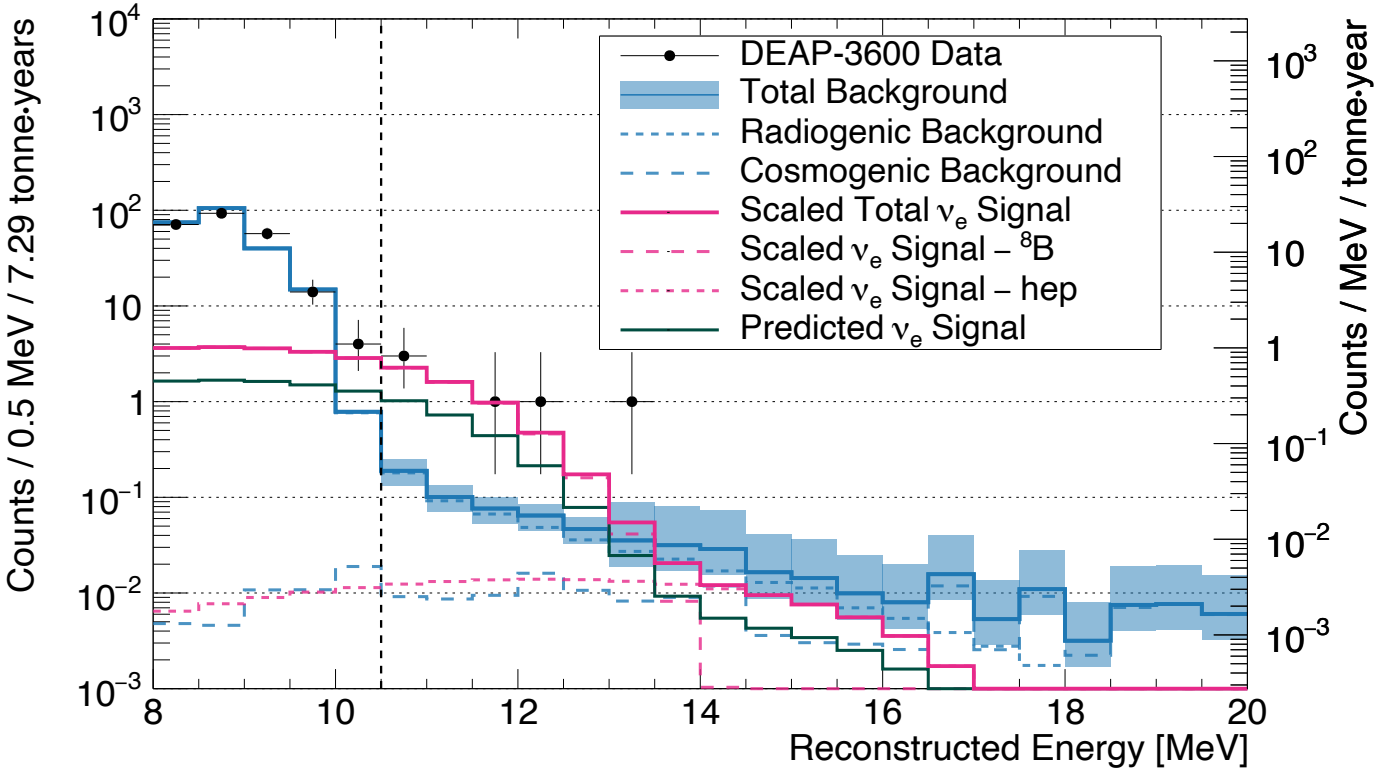




DEAP Collaboration (2026) arXiv:2603.13965

DEAP-3600: Solar neutrinos

- First evidence of **neutrino absorption on argon** using ^{8}B solar neutrinos



$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$

Using ^{8}B ν_e signals above 10.5 MeV

Observed 6 events (4σ significance)

Background expectation: $0.48^{+0.16}_{-0.15}$

E-average cross section $2.4^{+1.3}_{-1.0}\times$ higher than *Bhattacharya et al. (2009)* prediction

Reject background-only hypothesis at 4σ

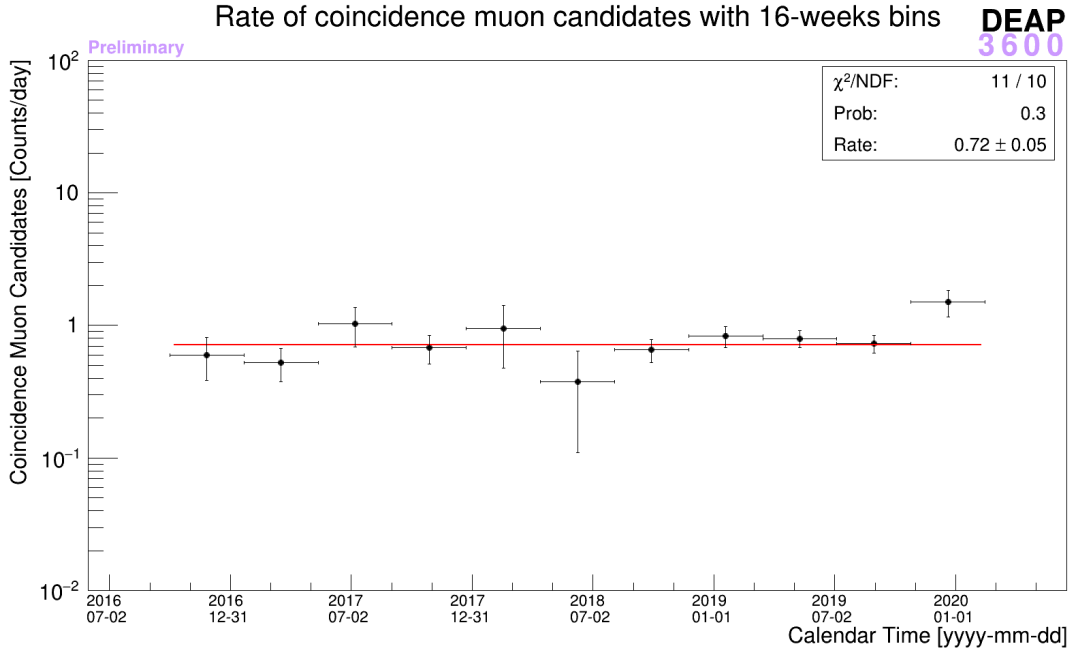
DEAP Collaboration (2026) arXiv:2605.12769

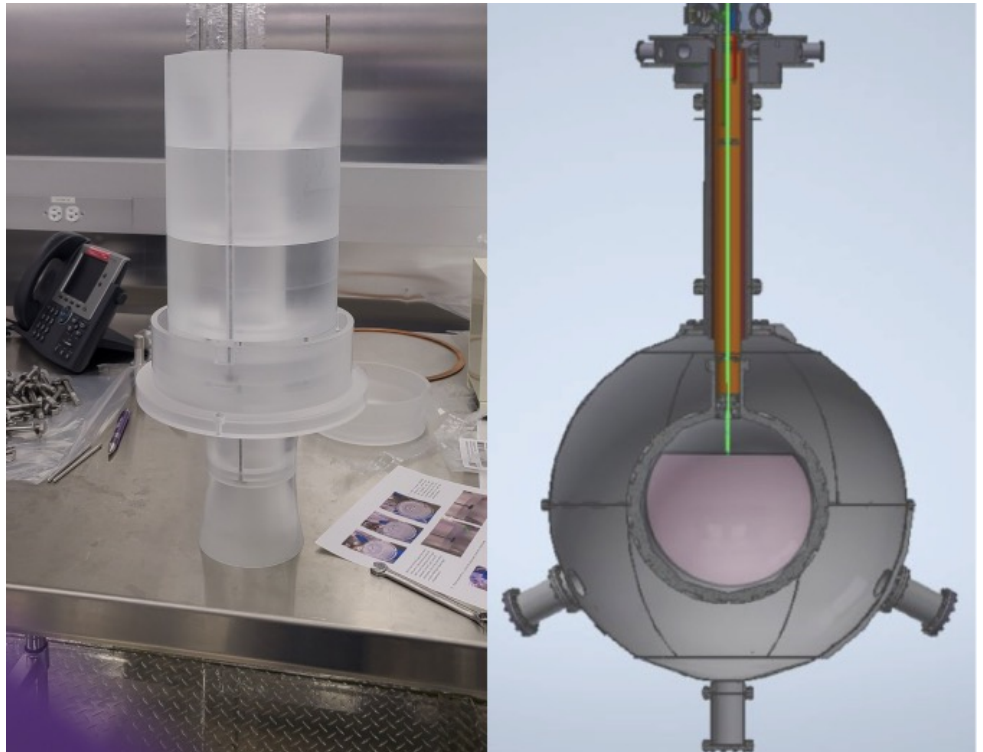
DEAP-3600: Coming up

- **Muon flux** measurement

- Search for **neutrinos** in coincidence with gravitational wave signals

- Results from data collected in the **upgraded detector** configuration
  - Pyrene-coated neck flow guides
  - Dust removal using a custom pipe
  - Cryogenic system maintenance

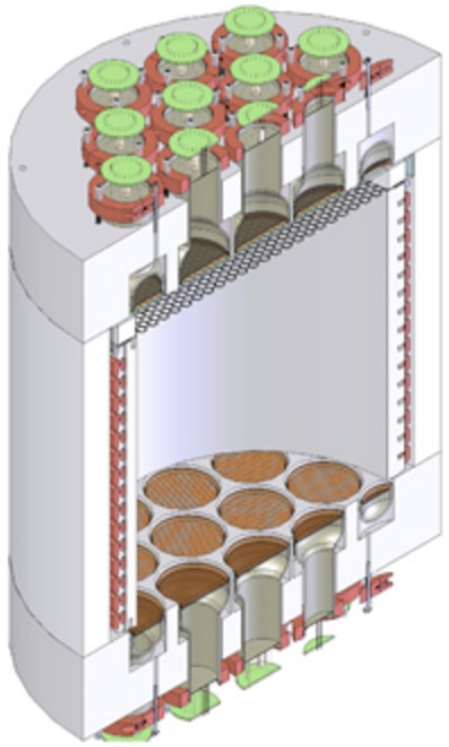


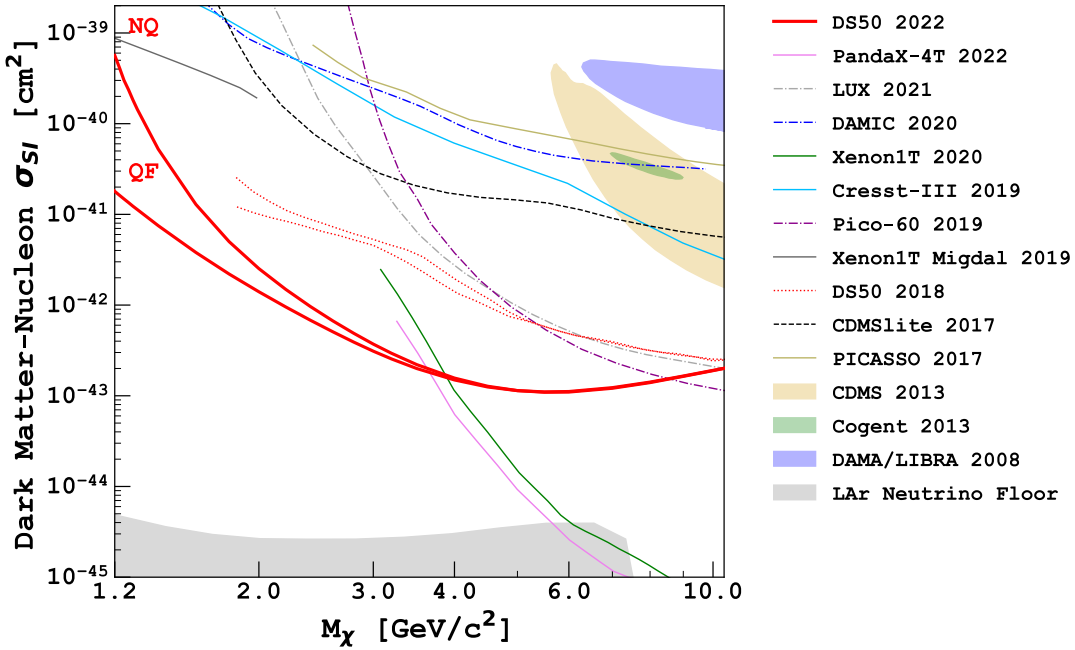


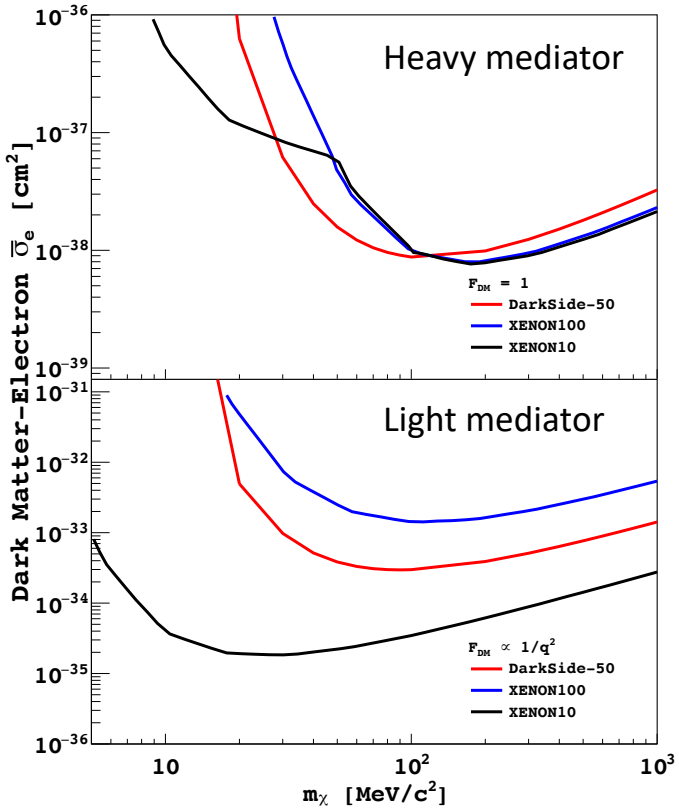
DarkSide-50 @ LNGS

Limits set on:
- Regular WIMPs
- Low-mass WIMPs
- WIMP-electron interactions

- Dual-phase time projection chamber (TPC) with 50 kg underground argon
  - Collected a 653 live-day exposure in 2015-2018





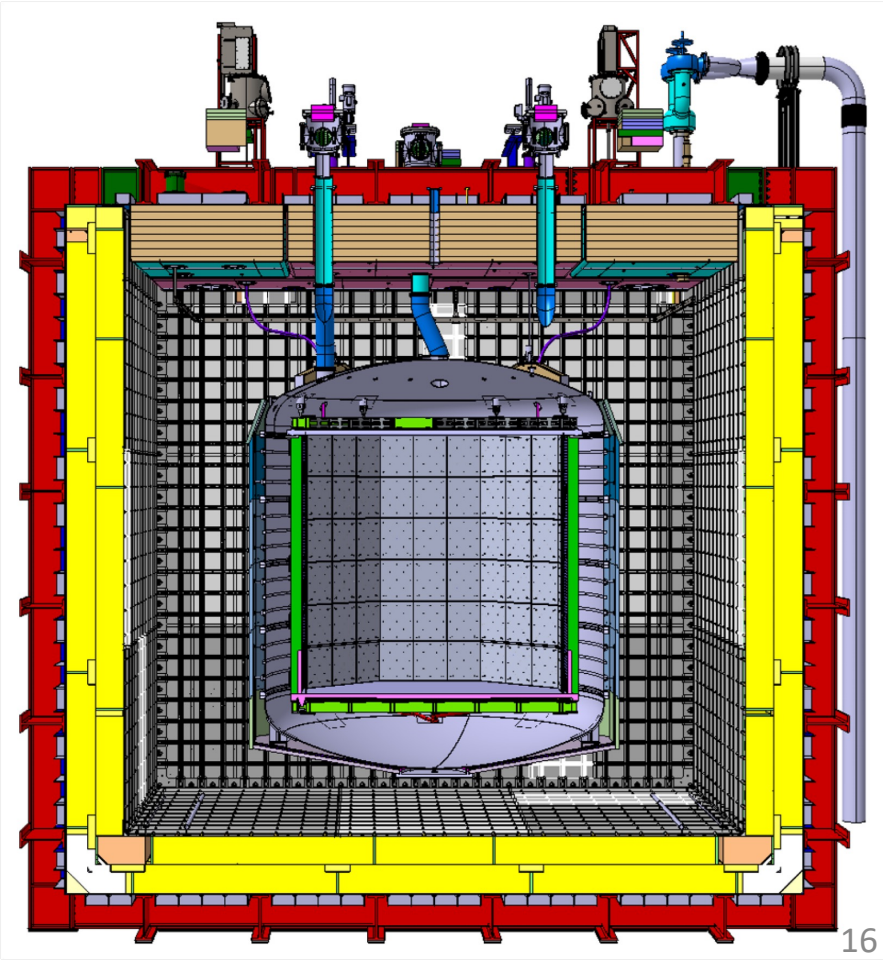


DarkSide-50 Collaboration (2018) PRL 121, 111303
DarkSide-50 Collaboration (2018) PRD 98, 102006
DarkSide-50 Collaboration (2021) PRD 104, 082005
DarkSide-50 Collaboration (2023) PRD 107, 063001

DarkSide-20k @ LNGS

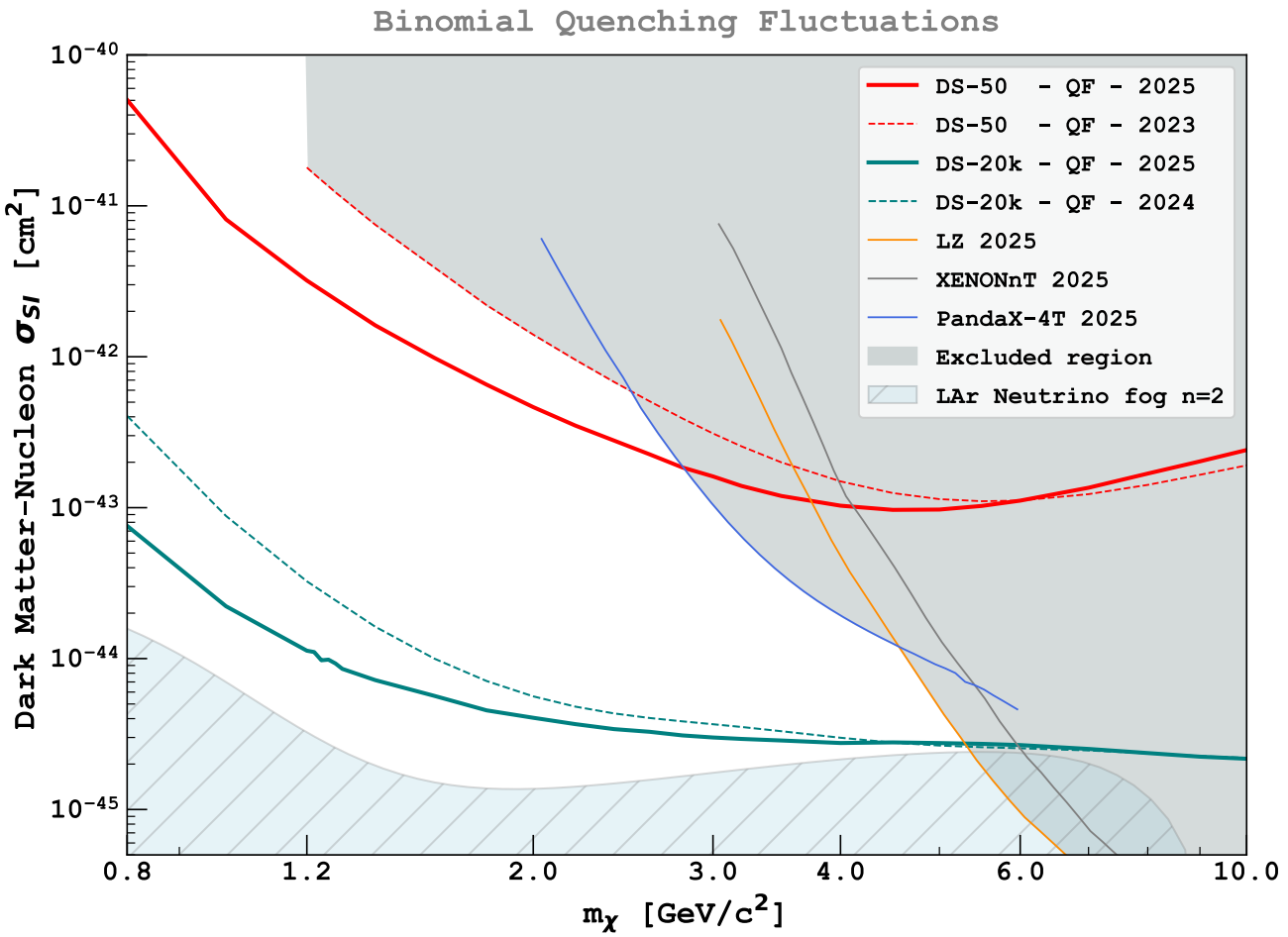
- Dual-phase TPC with **50 tonnes underground argon** (UAr), 20 tonnes fiducial

- Expected sensitivity to dark matter interactions
  - ^{40}Ar NR: DS-20k Collaboration (2018) EPJ Plus 133, 131
  - e^-: DS-20k Collaboration (2024) Nature Comm. Phys. 7, 422
- Supernova neutrinos
  - DS-20k Collaboration (2021) JCAP 2021, 03, 043
- **Key Canadian contributions:**
  - Construction of the time projection chamber
  - Material assay and quality control for radiopurity
  - Surface coatings
  - Data acquisition system
  - Calibration systems
  - Underground argon extraction with URANIA



DarkSide-20k: Sensitivity to low-mass WIMPs

- **Re-analysis** using latest results from ReD, ARIS, SCENE to improve modeling of the ionization response of LAr to nuclear recoils
  - No quenching fluctuations (conservative) vs. binomial quenching fluctuations
  - New and improved observed limits from DarkSide-50
  - **Updated expected sensitivity** from DarkSide-20k



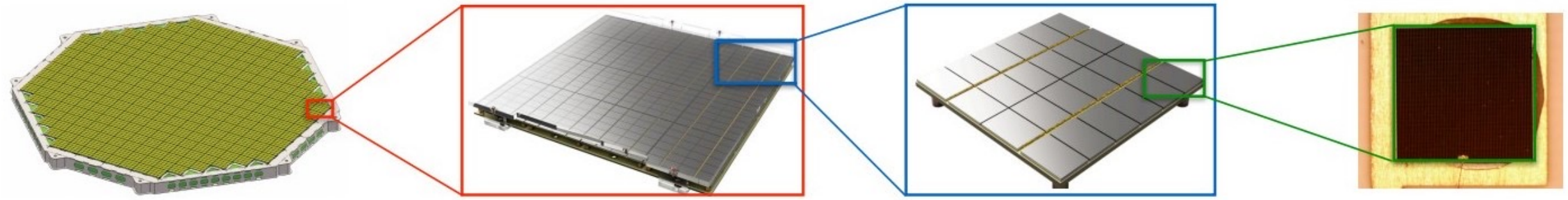
DarkSide-50 and DarkSide-20k Collaborations (2026) PRD 113, 123045

DarkSide-20k photodetector system

- Photo-detection units each 400 cm^2
  - **SiPMs by FBK**, model NUV-HD-Cryo
    - Technology transferred to **LFoundry**
  - Device meets or exceeds all requirements
    - A. Gola et al. (2019) Sensors 2019, 19(2), 308
  - Fabrication in progress!
    - Quality assurance and quality control papers (2025): EPJC 85, 534, EPJC 85, 1334

- Photodetection efficiency > 40% at 420 nm
- Low noise at LAr temperature and 9 V overvoltage:
  DCR < 0.1 Hz/mm^2, AP < 0.1 in 5 µs
- Radiopurity: expected tile contribution to neutron background << 0.1 event / 200 t-y

SPADs (900 µm^2)

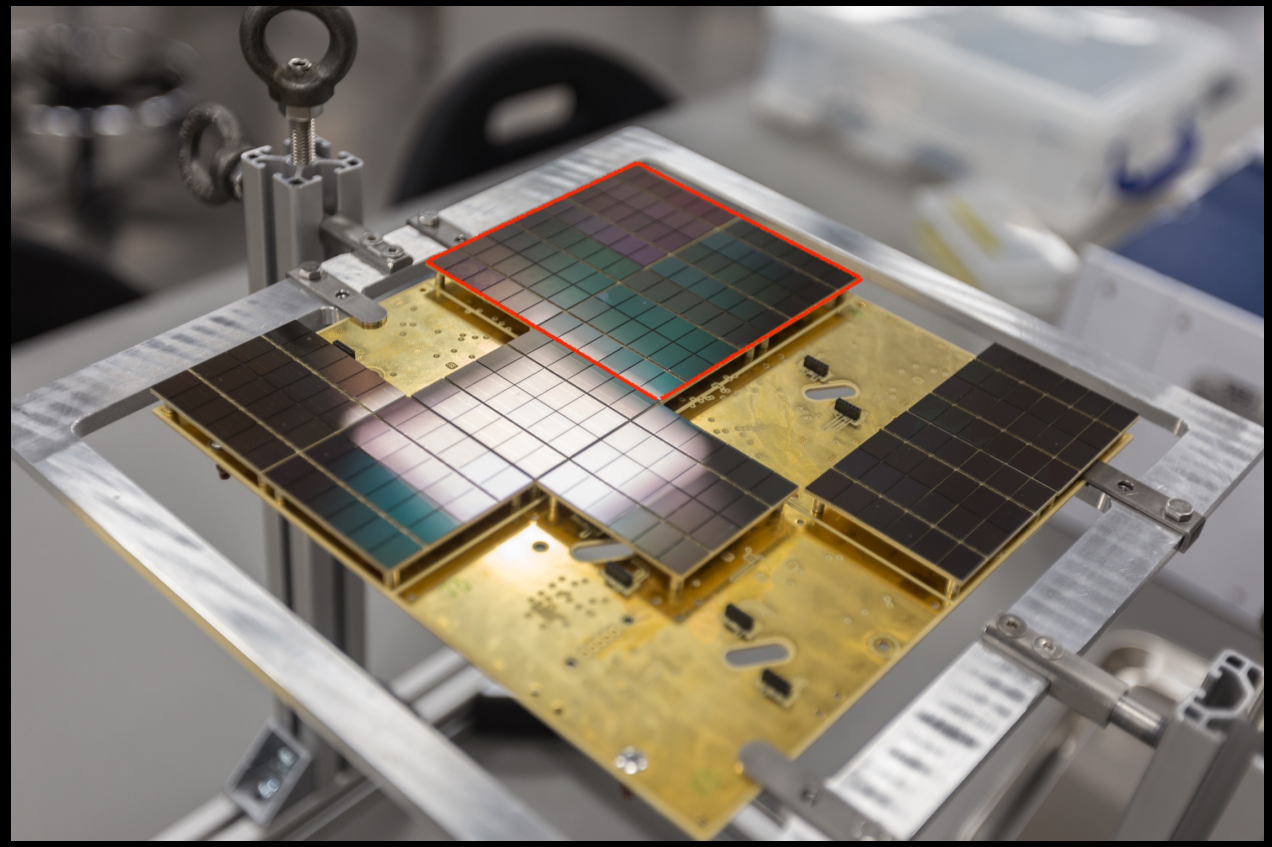


TPC optical plane (~ 21 m^2)
680 PDUs: 528 in TPC, 128 in Veto

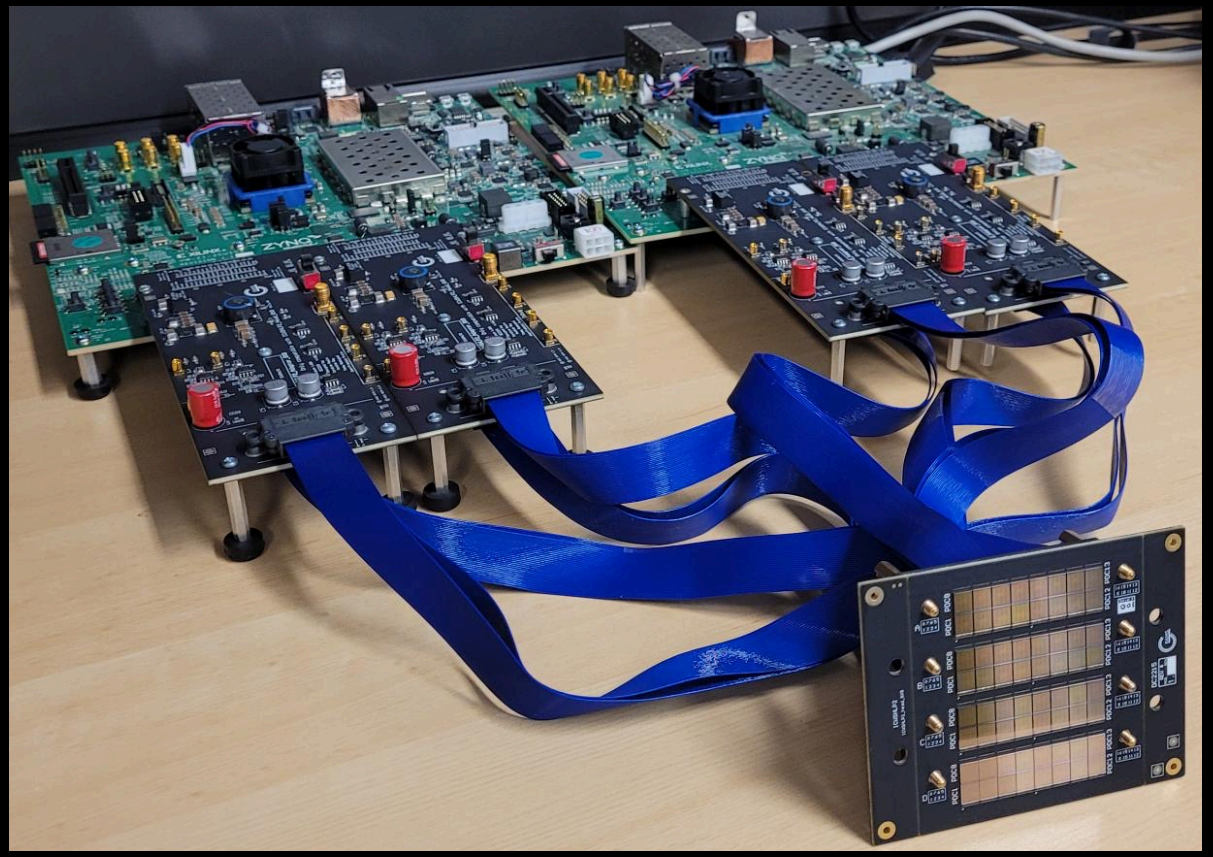
Photo-detection unit
16 tiles arranged into 4 channels

Tile / photo-detector module
24 SiPMs + signal amplifier

SiPM (~ 1 cm^2)



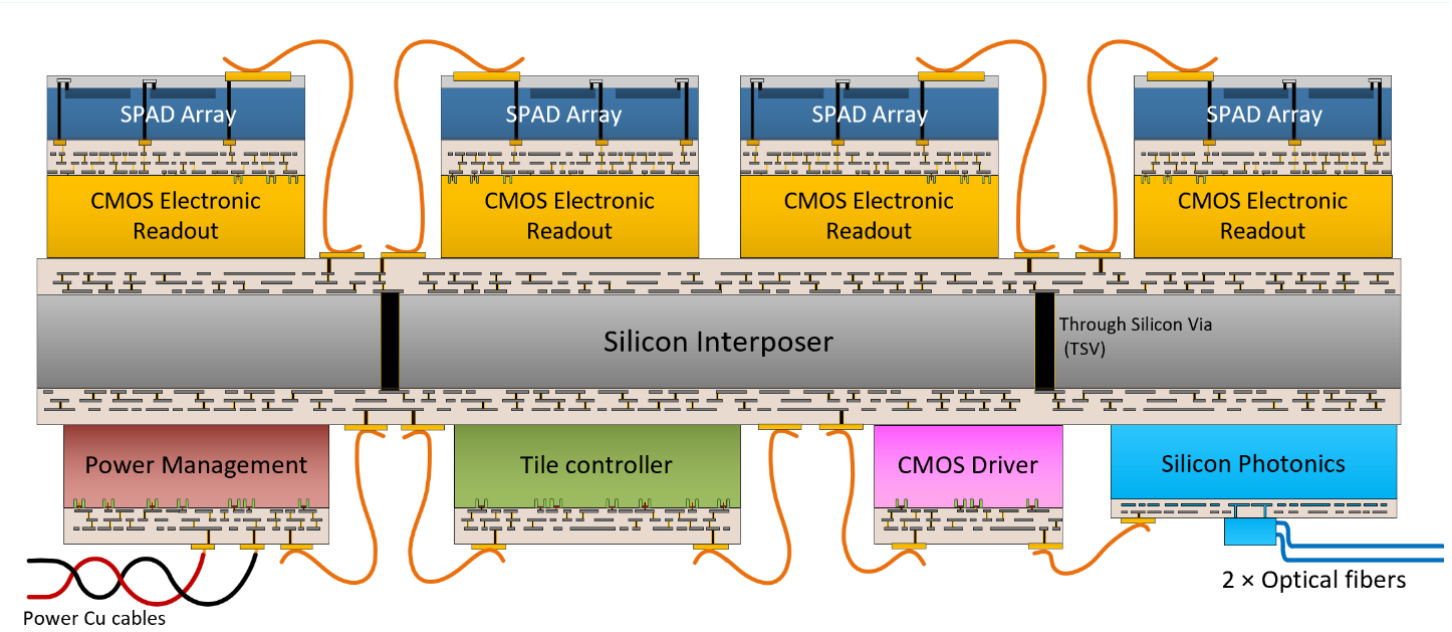
The present: **Analog SiPMs**
DarkSide photodetector unit (PDU) assembled at Nuova Officina Assergi, INFN LNGS

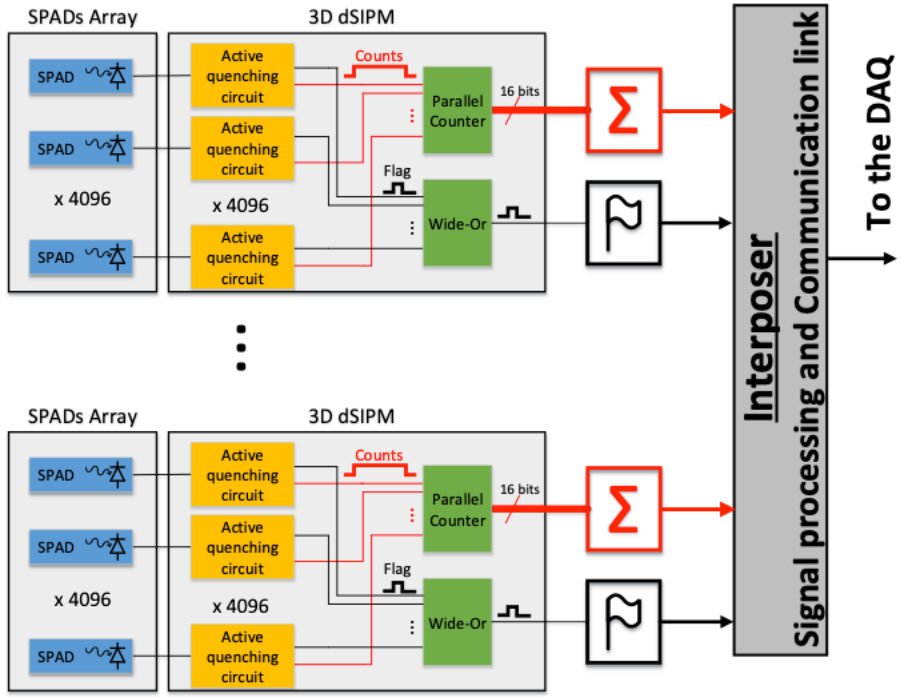


The future: **Digital SiPMs**
Photon-to-digital converter (PDC) tile from U. Sherbrooke with Teledyne-DALSA

Photon-to-digital converters (PDCs)

- Also known as **3D digital SiPMs**
  - Analog front-end electronics replaced by digital active quenching circuit for each SPAD
  - Reduced power dissipation
  - Noise reduction from enhanced capability and flexibility of *configurable digital readout electronics*

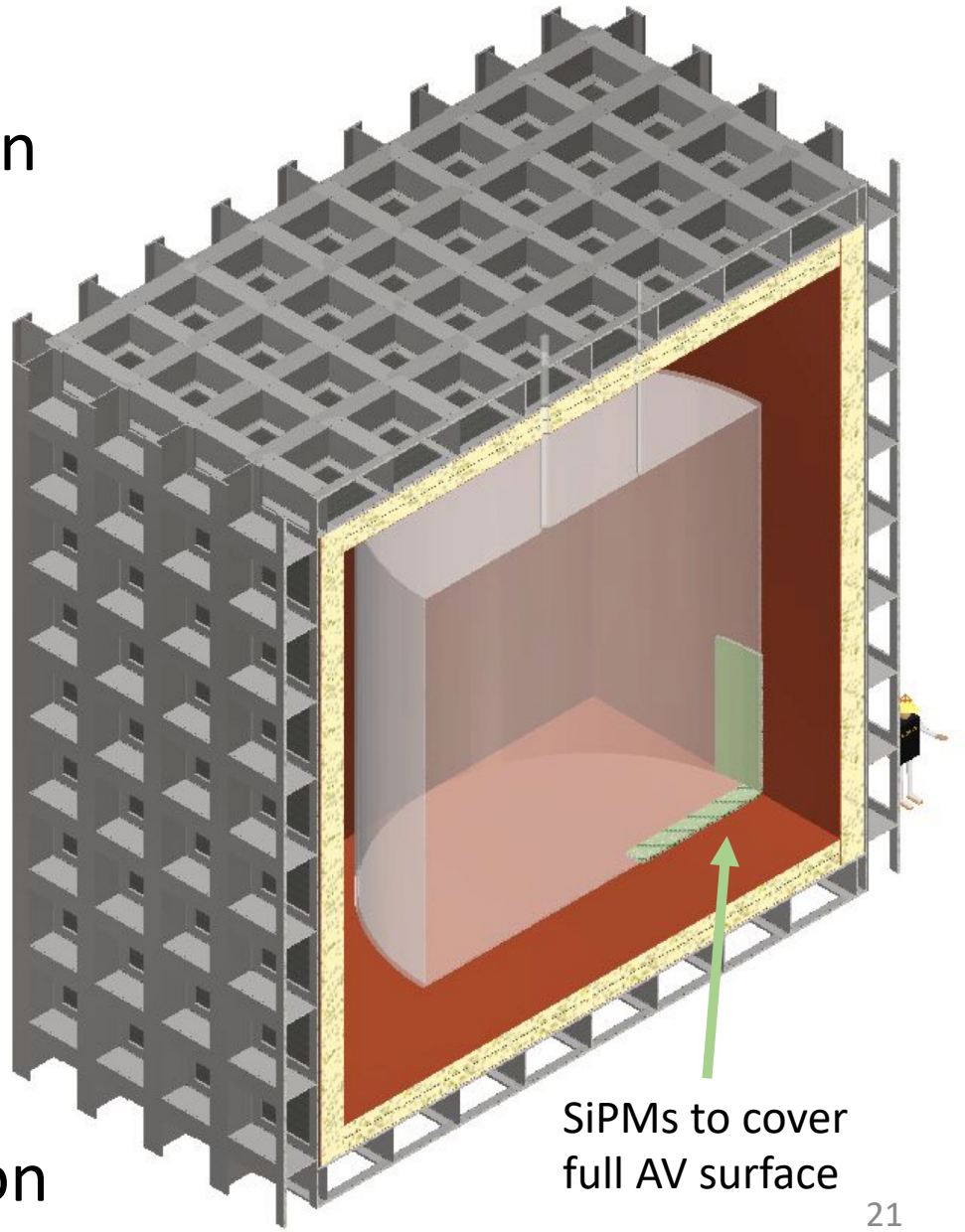




J.-F. Pratte et al. (2021) Sensors 2021, 21(2), 598
T. Rossignol et al. (2024) JINST 19, P09017

ARGO @ SNOLAB

- Ultimate direct detection experiment with argon
  - 400 tonnes underground argon
  - **250 m^2 of digital SiPMs** for full coverage
  - Smart DAQ system
- Designing single-phase option for Cube Hall
  - Minimize neutron backgrounds
  - Position reconstruction against surface alphas
  - Photodetector system design and simulation
    - Detector layout optimization
    - Quantify impact of external cross-talk
    - Performance requirements
- Part of collaboration works on dual-phase option



ARGO: Ultra-low background requirements

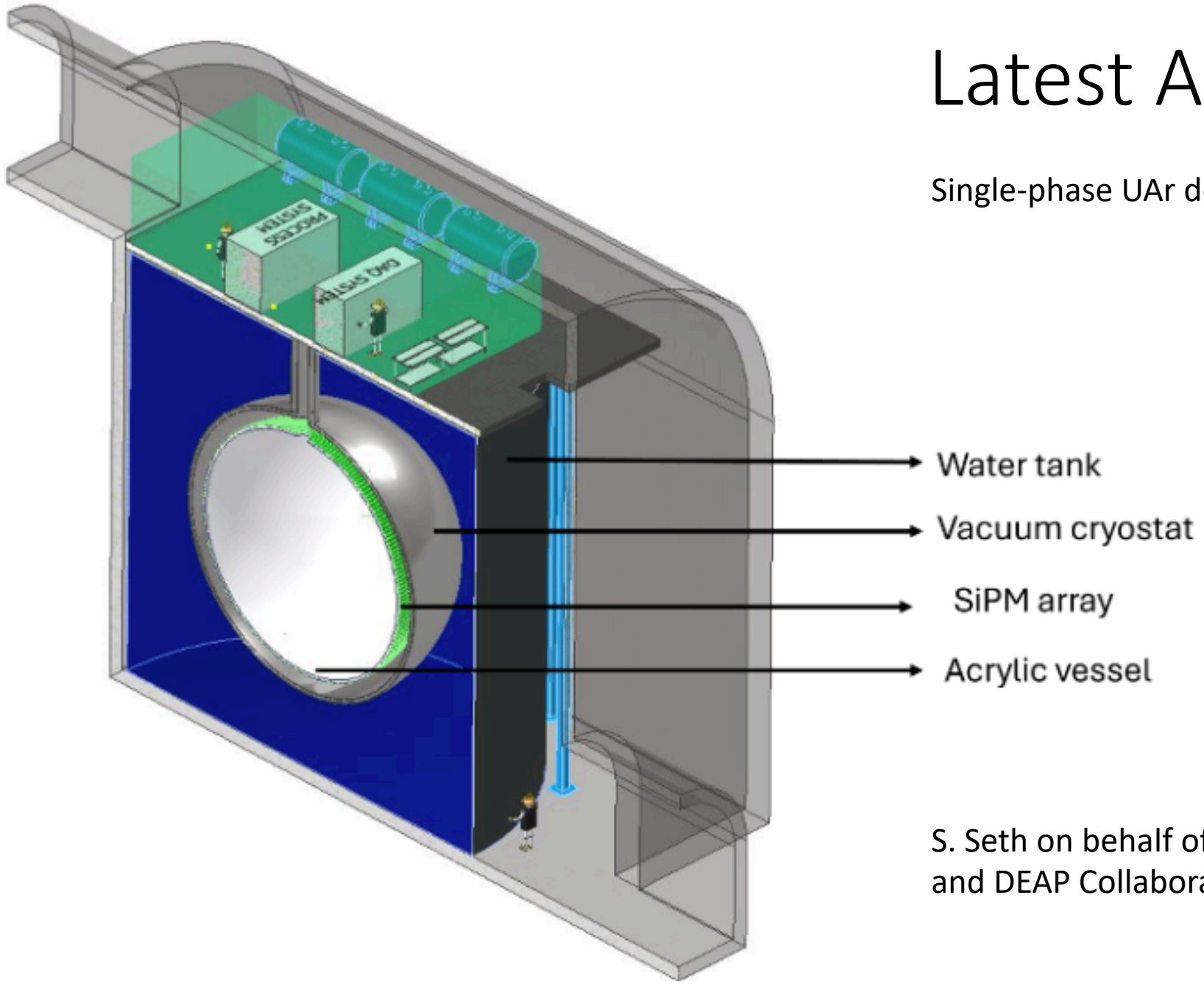
- Every order of magnitude in sensitivity comes with the corresponding reduction in backgrounds

- At the scale of ARGO, with a **fiducial volume of 300 tonnes**:
  - Underground argon: Reducing the ^{39}Ar event rate by 3 orders of magnitude
  - PSD performance: Reducing ER backgrounds by a factor $\mathbf{10^{-9}}$
    - Already demonstrated by DEAP-3600
  - Position reconstruction: Reducing surface alpha backgrounds by a factor $\mathbf{10^{-5}}$
    - Likelihood-based and machine-learning algorithms
    - Pattern of detected scintillation light, time of arrival
  - Neutron mitigation to only 1.5 event in 3000 tonne-years
    - New design: custom-made vacuum cryostat, 2 m water shield, 1 m LAr veto, 10 cm acrylic vessel

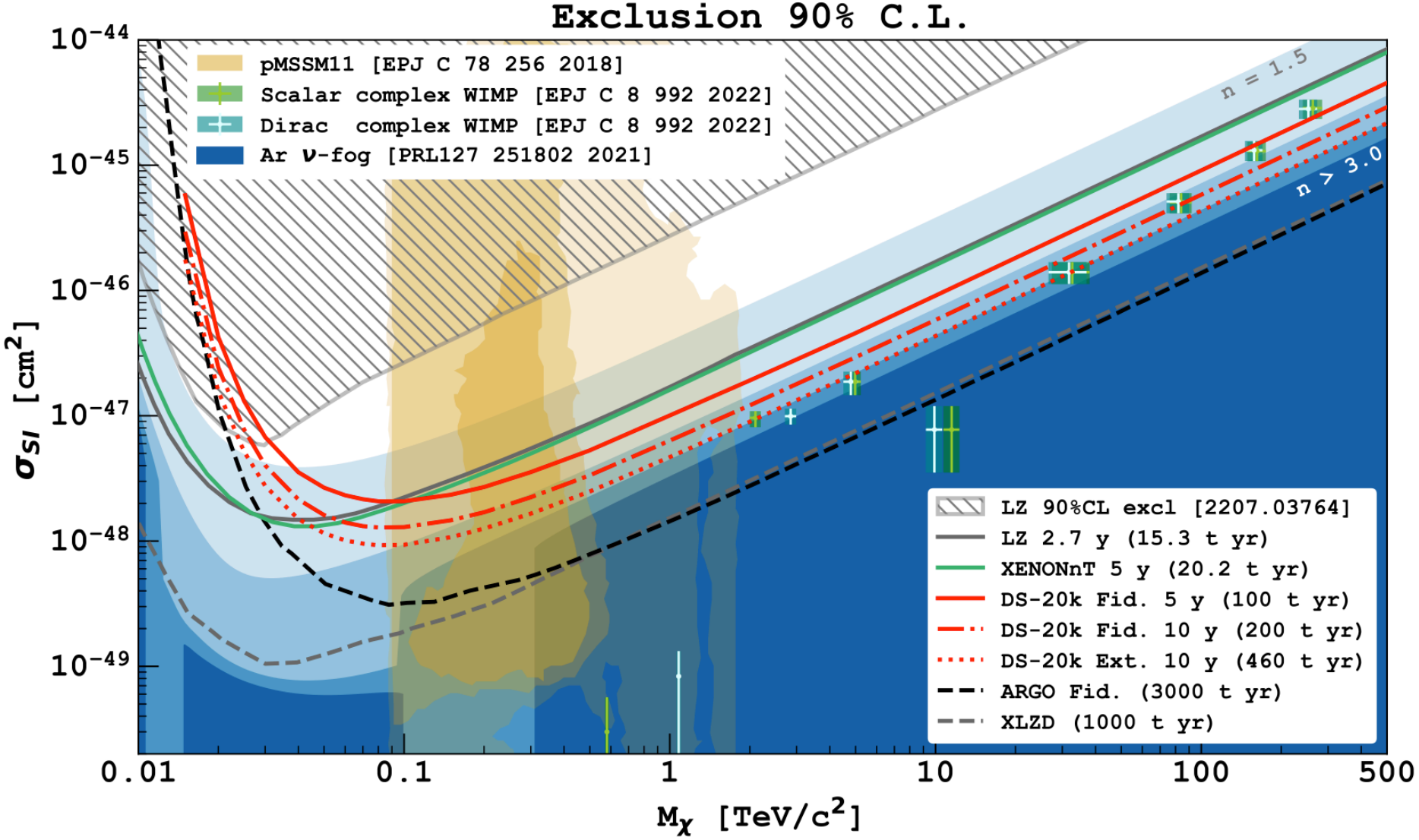
Source: ARGO talks at CAP 2026

Latest ARGO design

Single-phase UAr detector with a spherical geometry



S. Seth on behalf of the Global Argon Dark Matter and DEAP Collaborations (2026) JINST 21, C04054



World-leading expected sensitivity to WIMP dark matter, all the way into the neutrino fog

+ **Neutrino physics** with ARGO:

Sensitivity to supernova neutrinos all the way to the Large Magellanic Cloud

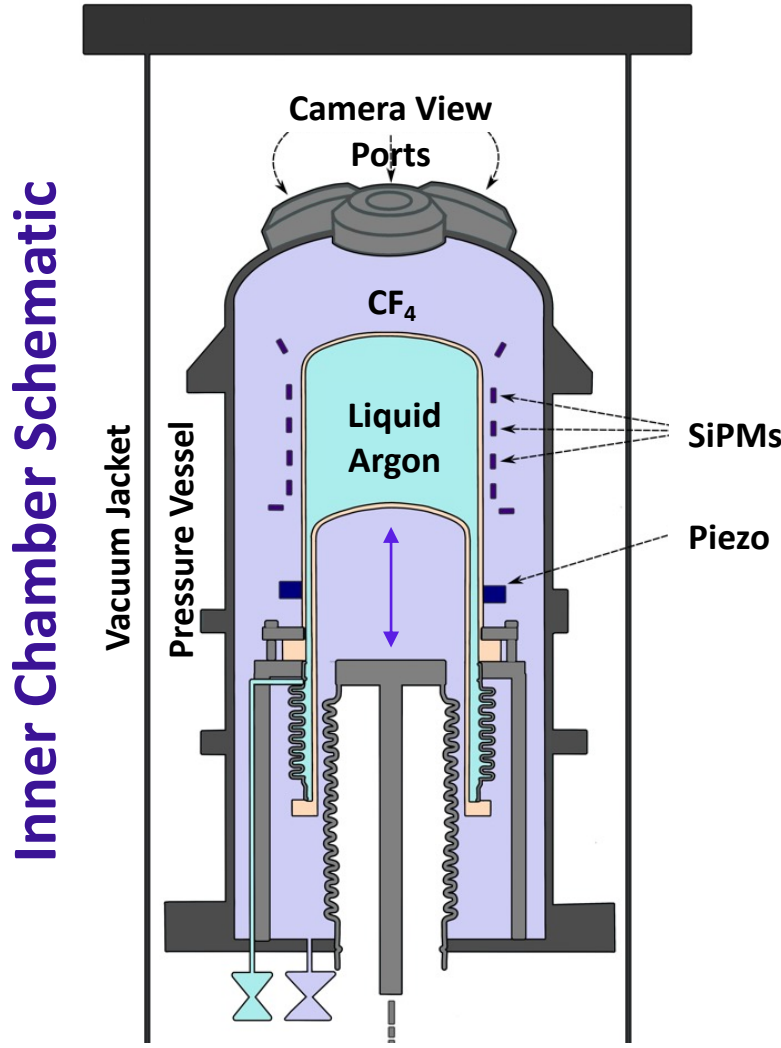
Measurement of intermediate-energy neutrinos with enough statistics to resolve the solar metallicity problem

How to lower thresholds?

Exploring sensitivity to WIMP dark matter with masses down to O(10^{-1} GeV/c^2)

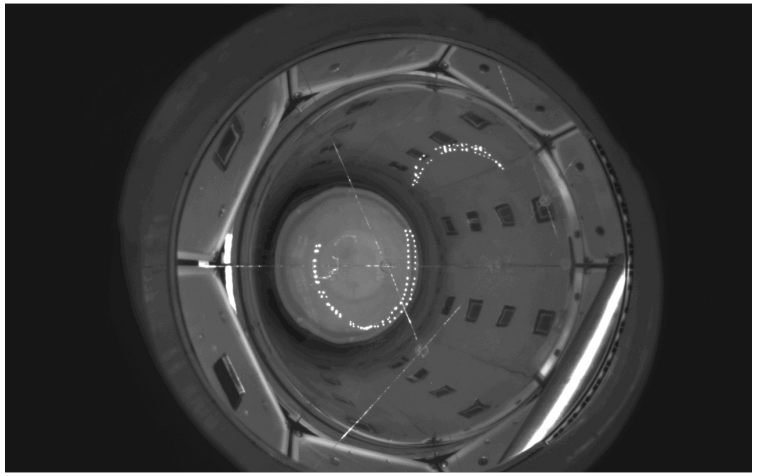
Scintillating Bubble Chamber (SBC)

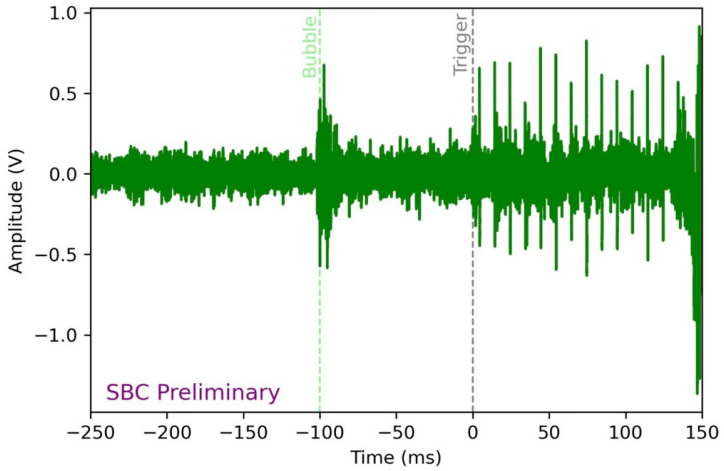
- **Noble liquid bubble chamber**
  - Sensitive to nuclear recoils from dark matter and CEvNS
  - Insensitive to electronic recoil backgrounds, as these don't create bubbles
- "SBC-LAr10" with 10 kg LAr doped with 10 ppm Xe
  - Twin units at Fermilab and SNOLAB
  - Objective: scale up technology to reach 1 t-y exposure
- Three key sensory components
  - **Cameras** detect bubbles, provide visual trigger
  - **Piezoelectric transducers** detect acoustic bubble data
  - **UV-sensitive SiPMs** detect scintillation light
  - Radiopurity is key

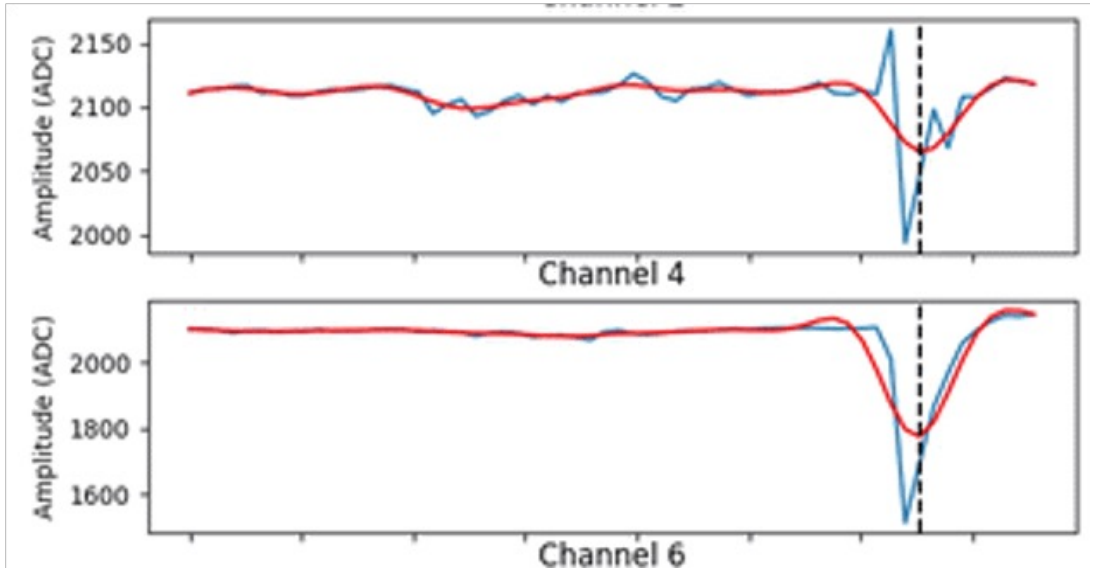


SBC Collaboration (2023) Universe 2023, 9(8), 346
SBC Collaboration (2025) PRD 111, 032002

Scintillating Bubble Chamber (SBC)

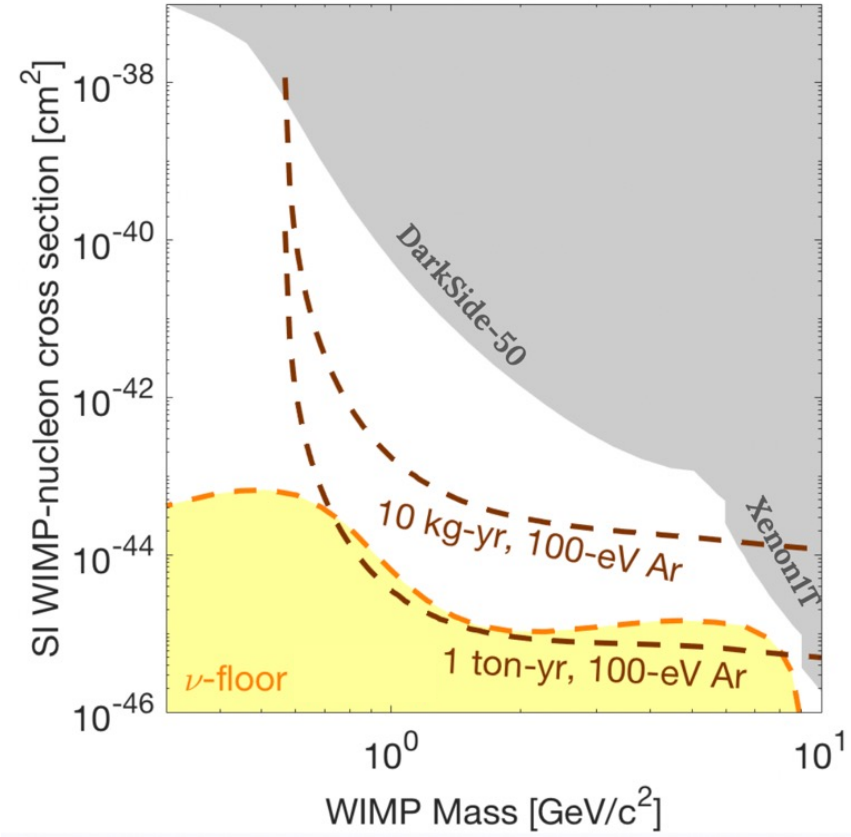






Example signals from **SBC-LAr10**:

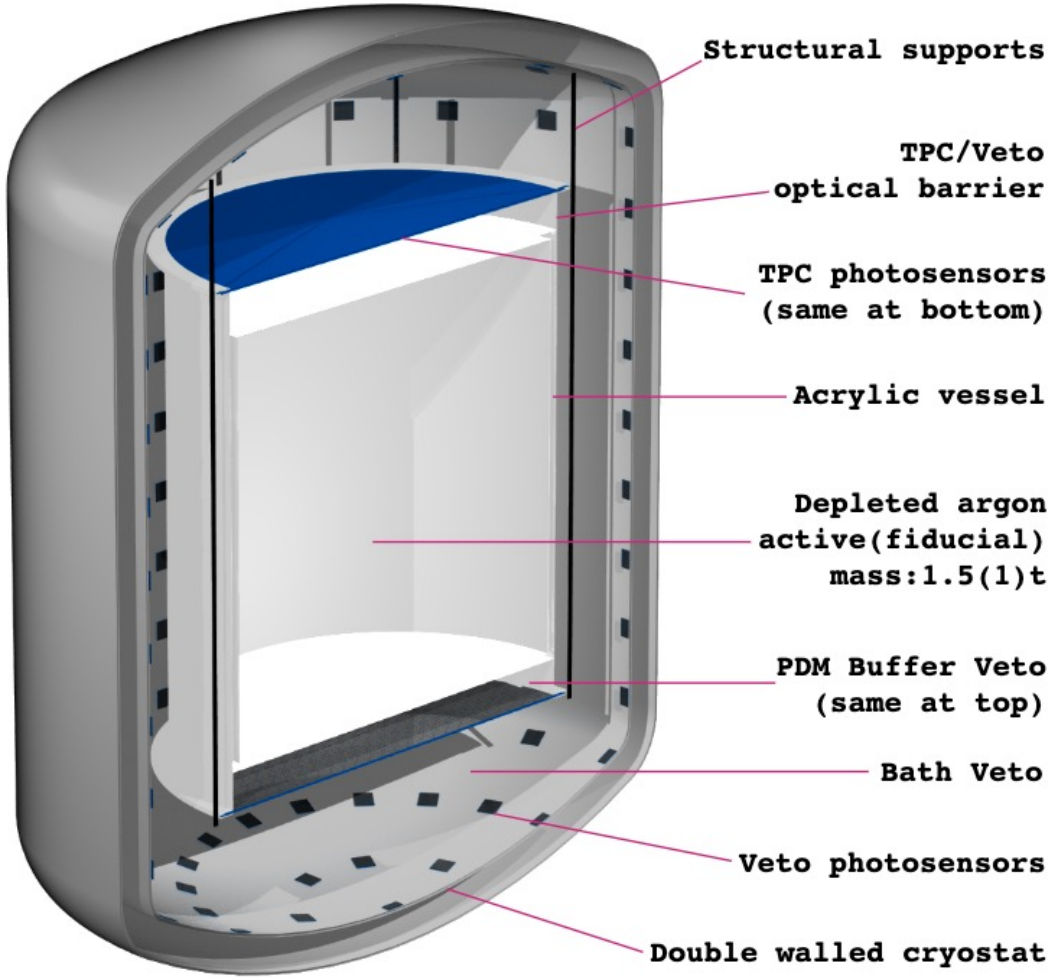
- Camera
- Piezo
- SiPM



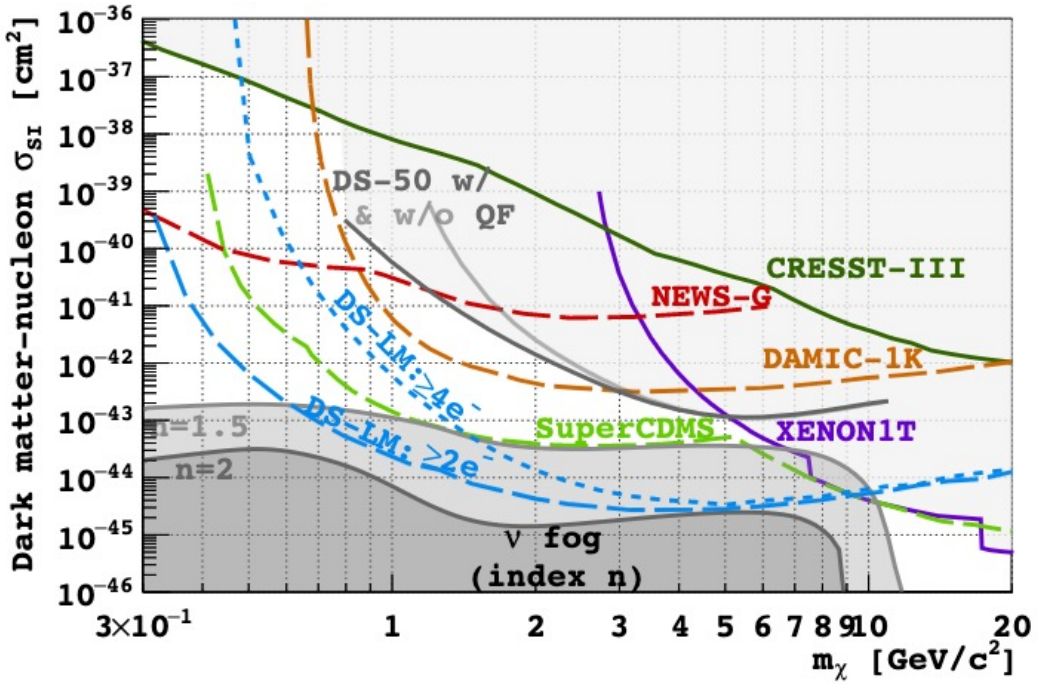
Expected sensitivity of **SBC-SNOLAB** with a 100 eV threshold

SBC Collaboration (2023) Universe 2023, 9(8), 346
SBC Collaboration (2025) PRD 111, 032002

AURORA [previously known as DarkSide-LowMass]



- Dual-phase UAr TPC (1.5 tonnes) optimized for low-mass dark matter search in **ionization-only channel** (S2)
  - Argon doping R&D
  - Sensitivity all the way into neutrino fog



Global Argon Dark Matter Collaboration (2023) PRD 107, 112006

Summary

- **Liquid argon detectors** have excellent sensitivity to dark matter
- New results from 2026
  - DEAP-3600: WIMP search, Solar neutrinos
  - DarkSide-50: Updated low-mass WIMP limits
  - DarkSide-20k expected sensitivity
  - ARGO design optimization
- New data collection in progress with upgraded DEAP-3600 at SNOLAB
- DarkSide-20k is under construction at LNGS
- Vibrant R&D program
  - Scintillating Bubble Chamber and AURORA
  - New ideas