The global search for weakly-interacting dark matter using liquid argon

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CAP Congress at the University of Saskatchewan

June 12, 2025

Carleton University

Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

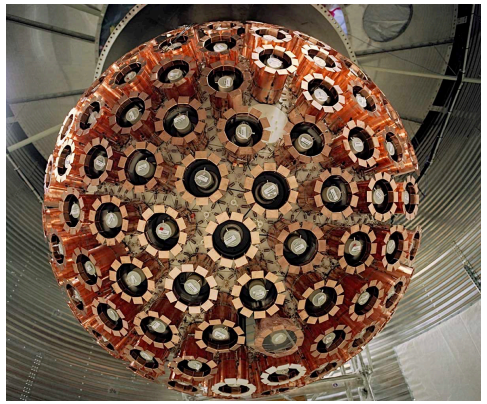
“Looking for dark matter” according to ChatGPT

Query by Michael Perry

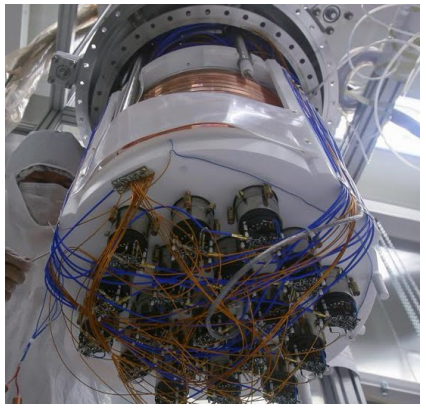
Global Argon Dark Matter Collaboration

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

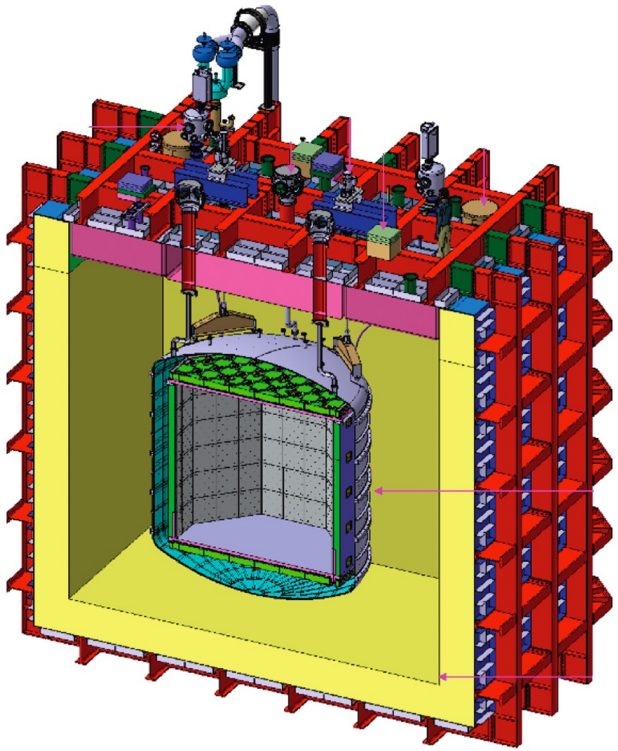
DEAP-3600



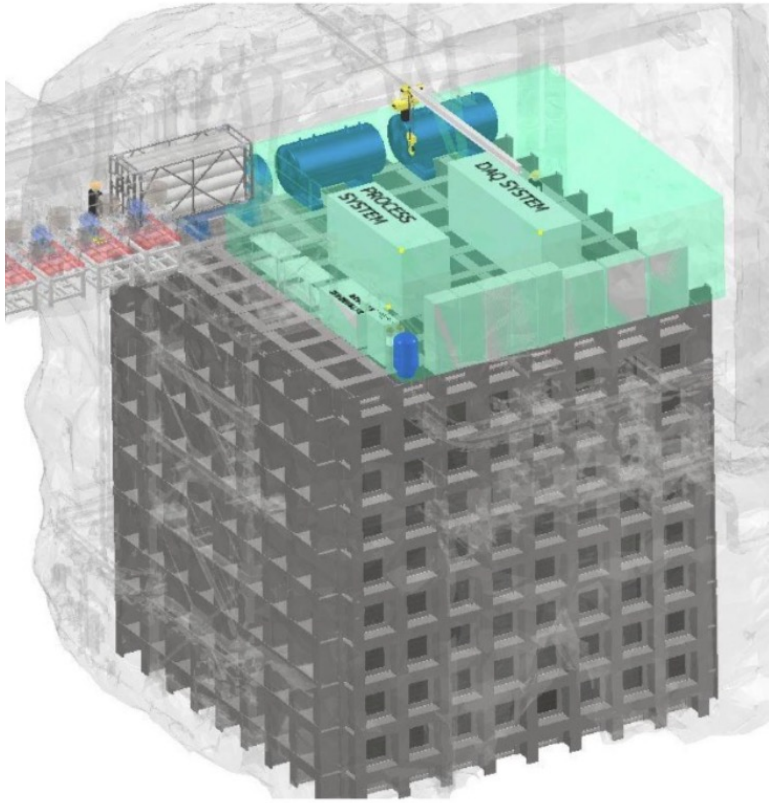
DarkSide-50



DarkSide-20k



ARGO



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

Related presentations at CAP 2025

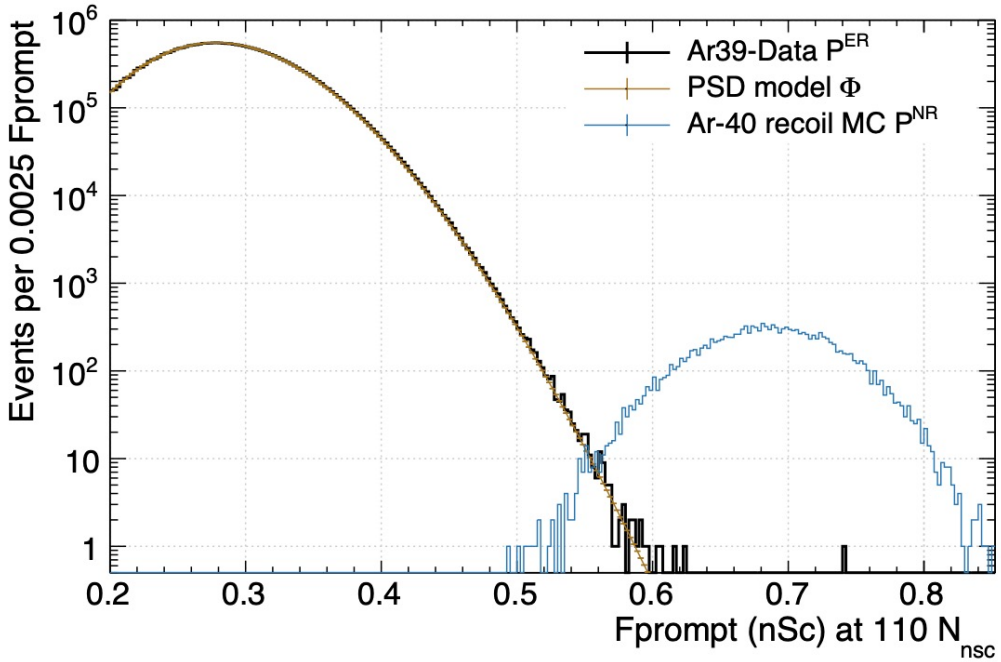
- Asish Moharana (Carleton)
  - SiPM Optical Modeling and Optical Crosstalk Simulation for ARGO
- Austin Murray (Queen's)
  - DEAP-3600 Hardware Upgrades and Third Fill
- Serge Charlebois (Sherbrooke)
  - Development of Photon-to-Digital Converters – A 3D Integrated Digital Single-Photon Detector for Large Scale Photodetection Systems
- Mark Boulay (Carleton)
  - Searching for Dark Matter within the Global Argon Dark Matter Program: DEAP-3600, DarkSide-20k and ARGO

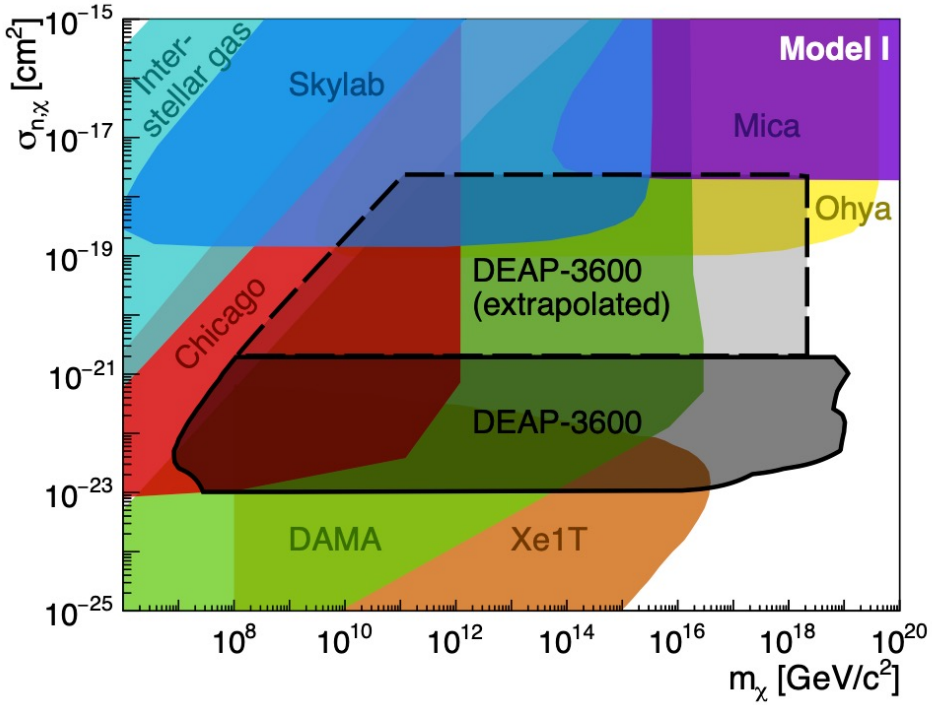
Outline

- Latest results from **DEAP-3600** at SNOLAB
  - Physics analyses with second-fill dataset
  - Hardware upgrades complete! Third-fill underway
- **DarkSide-20k** under construction at LNGS, Italy
  - Key Canadian contributions
- The Future
  - Photon-to-digital converters (PDC)
  - ARGOlite demonstrator → DarkSide-LowMass
  - **ARGO**

DEAP-3600 @ SNOLAB

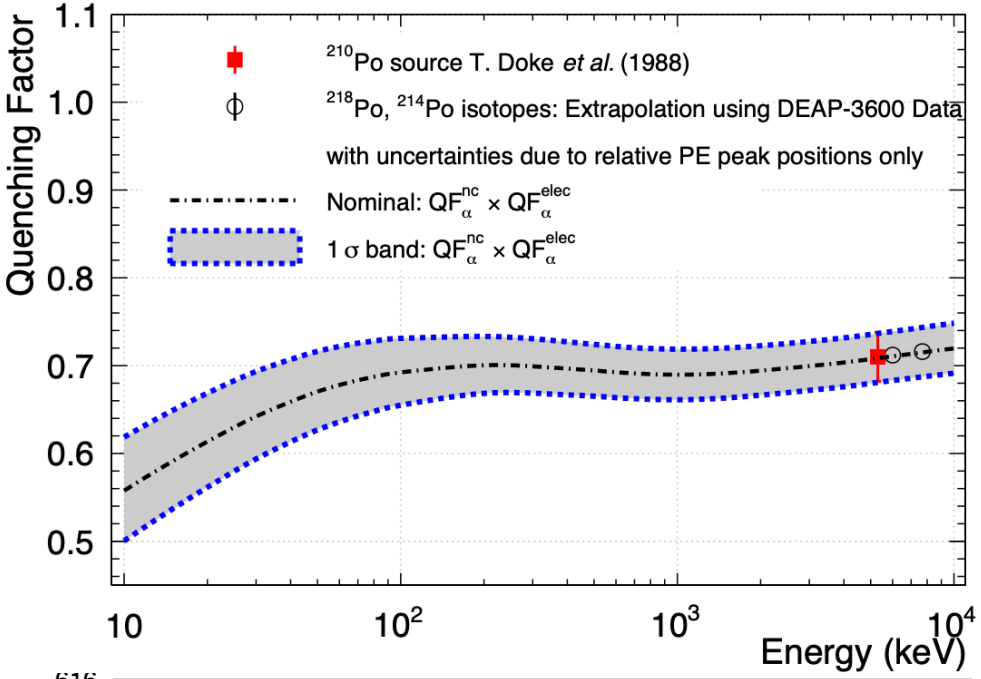
- Data collected in 2016-2020 with 3269 kg of liquid argon
- Reject electronic recoil backgrounds using **pulseshape discrimination** (PSD)
  - Demonstrated 10^{-10} leakage fraction at 50% nuclear recoil acceptance
  - DEAP Collaboration (2020) EPJC 80, 303
  - DEAP Collaboration (2021) EPJC 81, 823
- 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

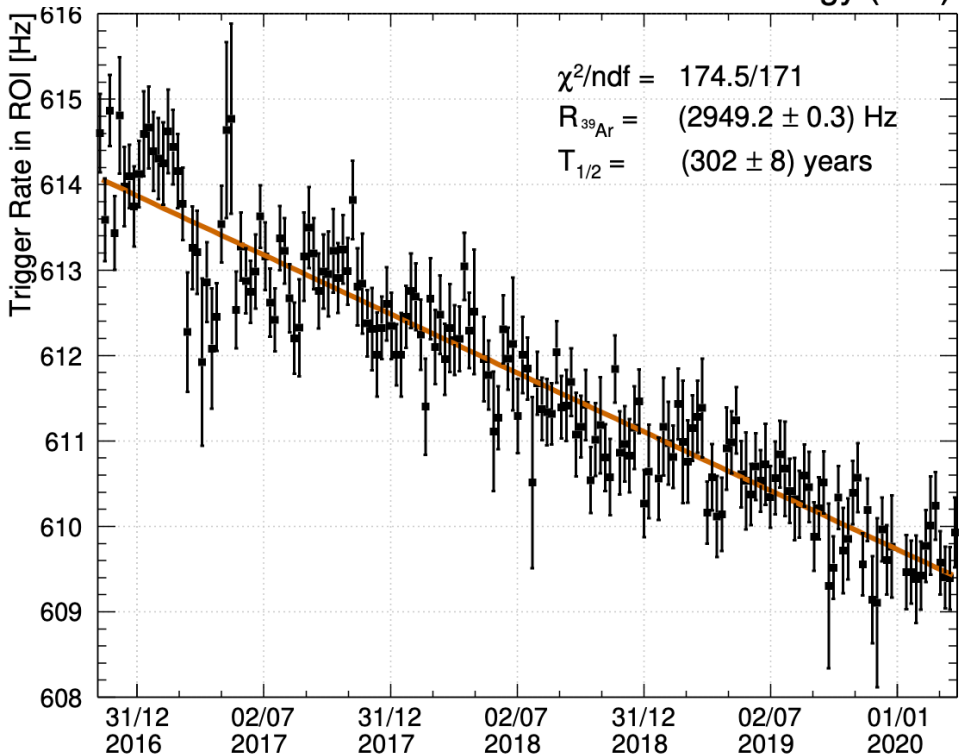




DEAP-3600: Latest results

- 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
  - Accepted by EPJC, arXiv:2501.13196
- Position reconstruction in DEAP-3600
  - **Neural network** against shadowed alpha decays from neck
  - Accepted by JINST, arXiv:2503.10383



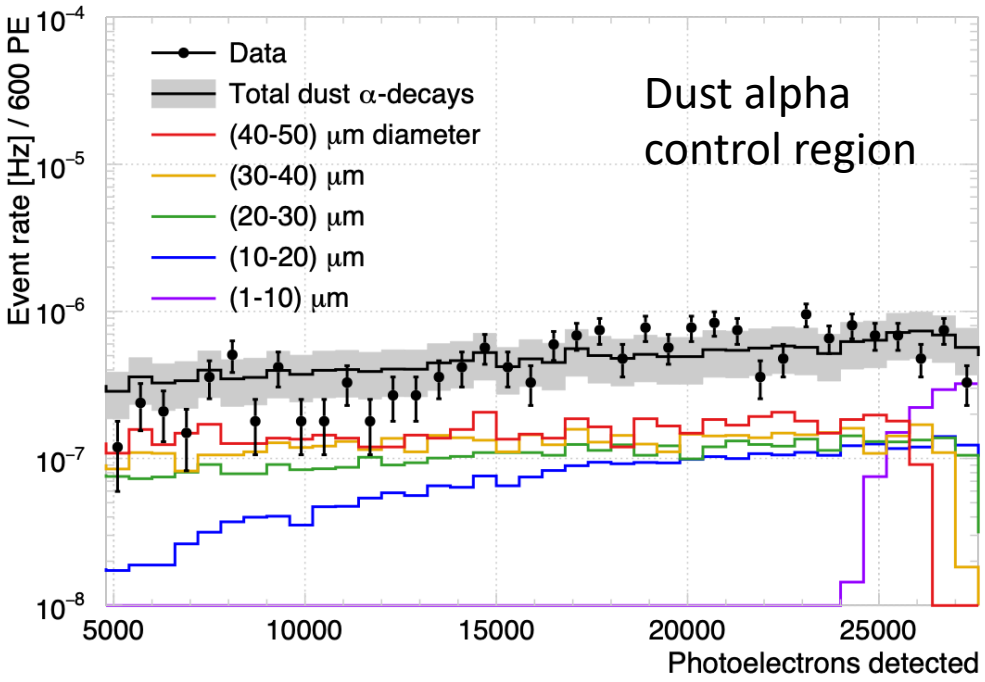


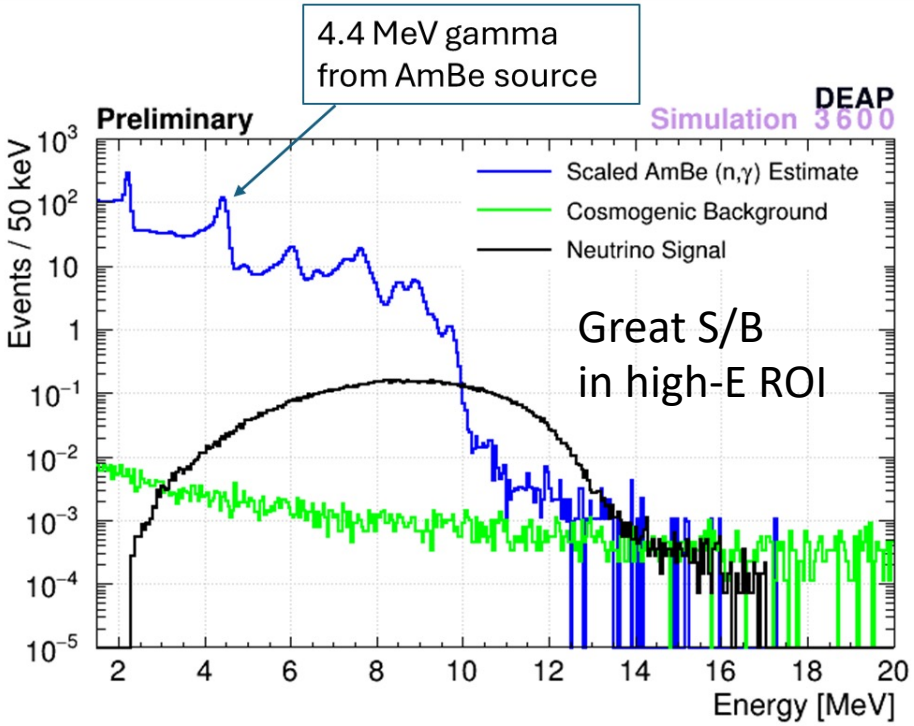
DEAP-3600: Coming up

- **WIMP dark matter search** using the profile likelihood analysis method in the full second-fill dataset

- ^{8}B solar **neutrino absorption**
- 5.5 MeV solar axion search
- Muon flux measurement

- Results from **third-fill data** to be collected in the upgraded detector configuration





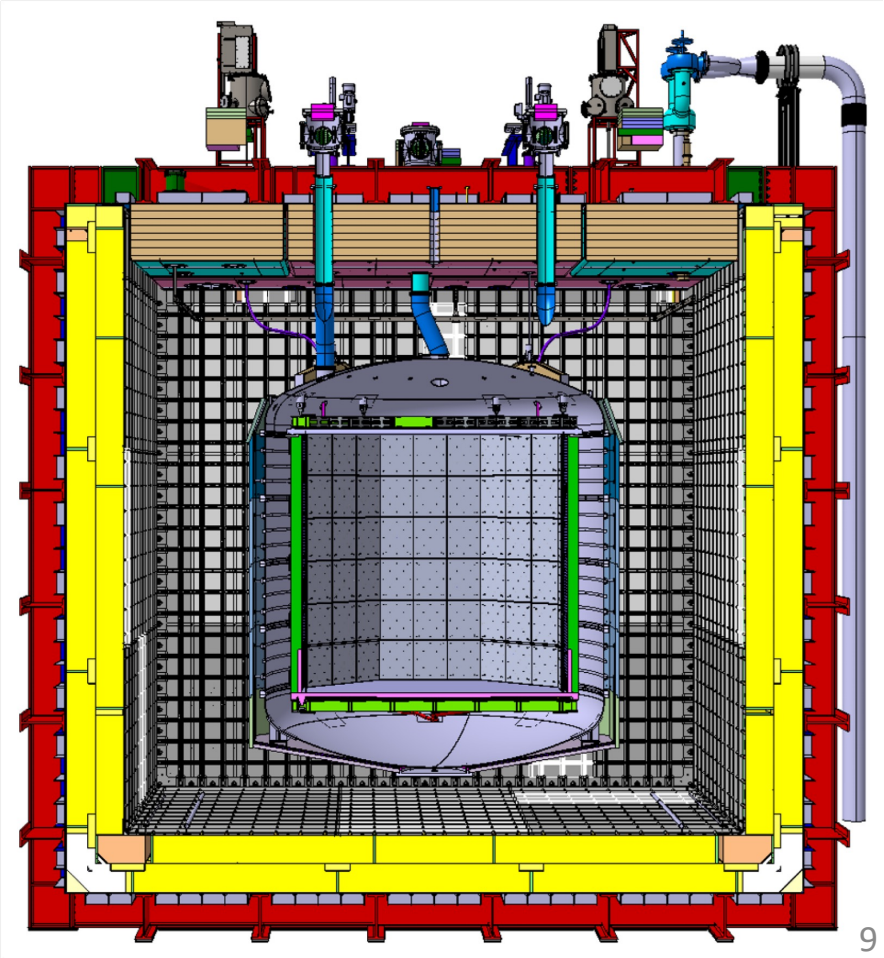
DarkSide-20k @ LNGS

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

- 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

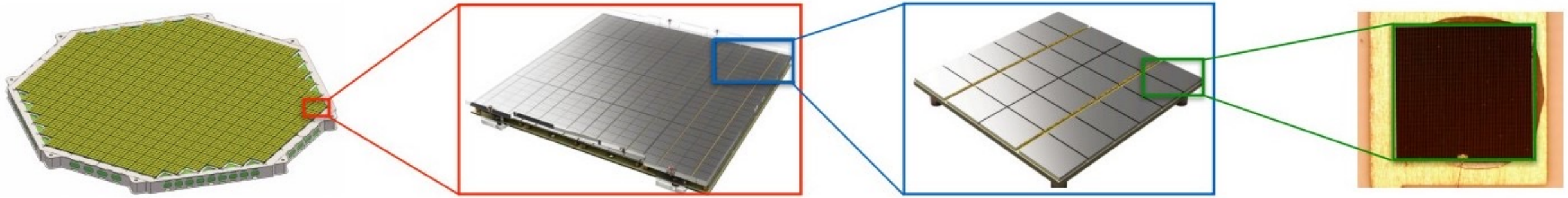


DarkSide-20k photodetector system

- 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 paper: DS-20k Collaboration (2025) EPJC 85, 534

- 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)

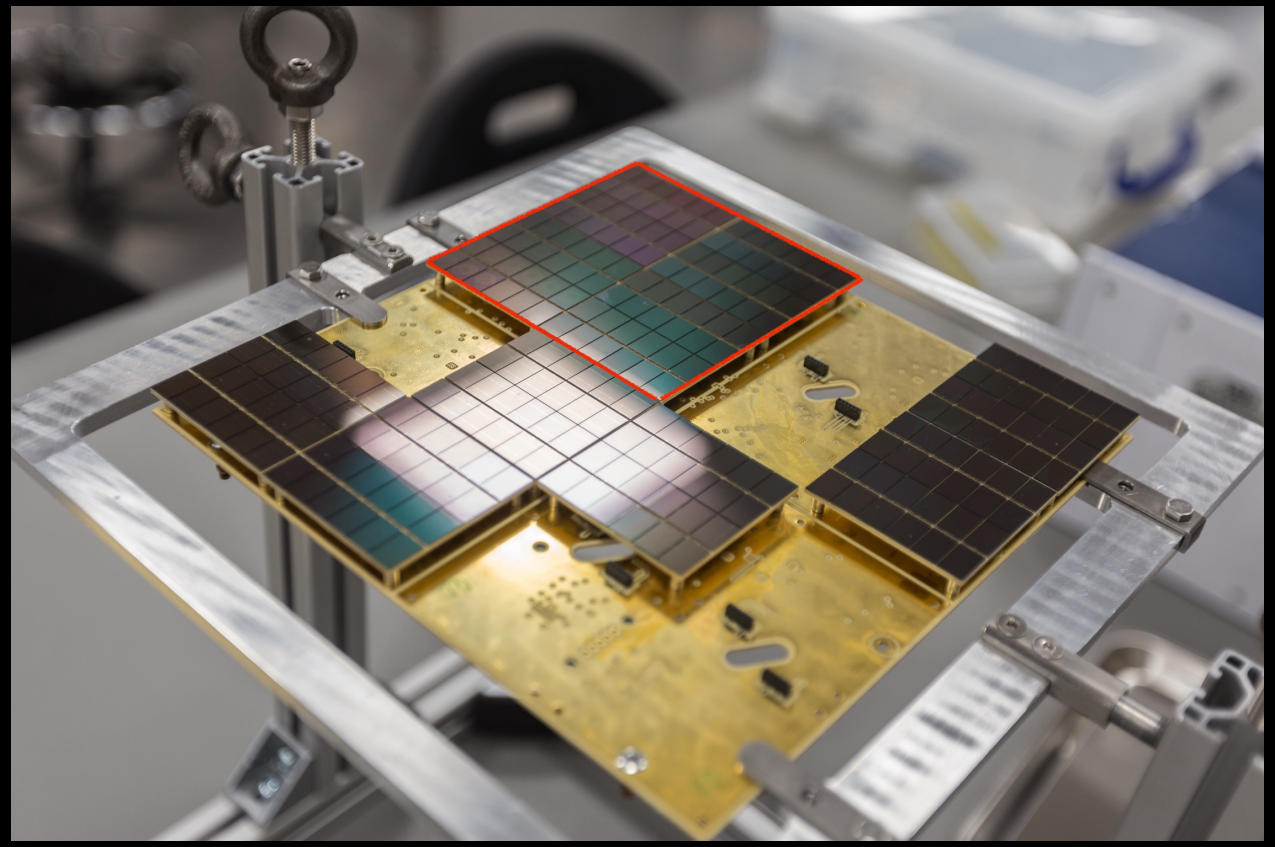


TPC optical plane (~ 21 m^2)
680 PDUs: 528 in TPC, 128 in Veto

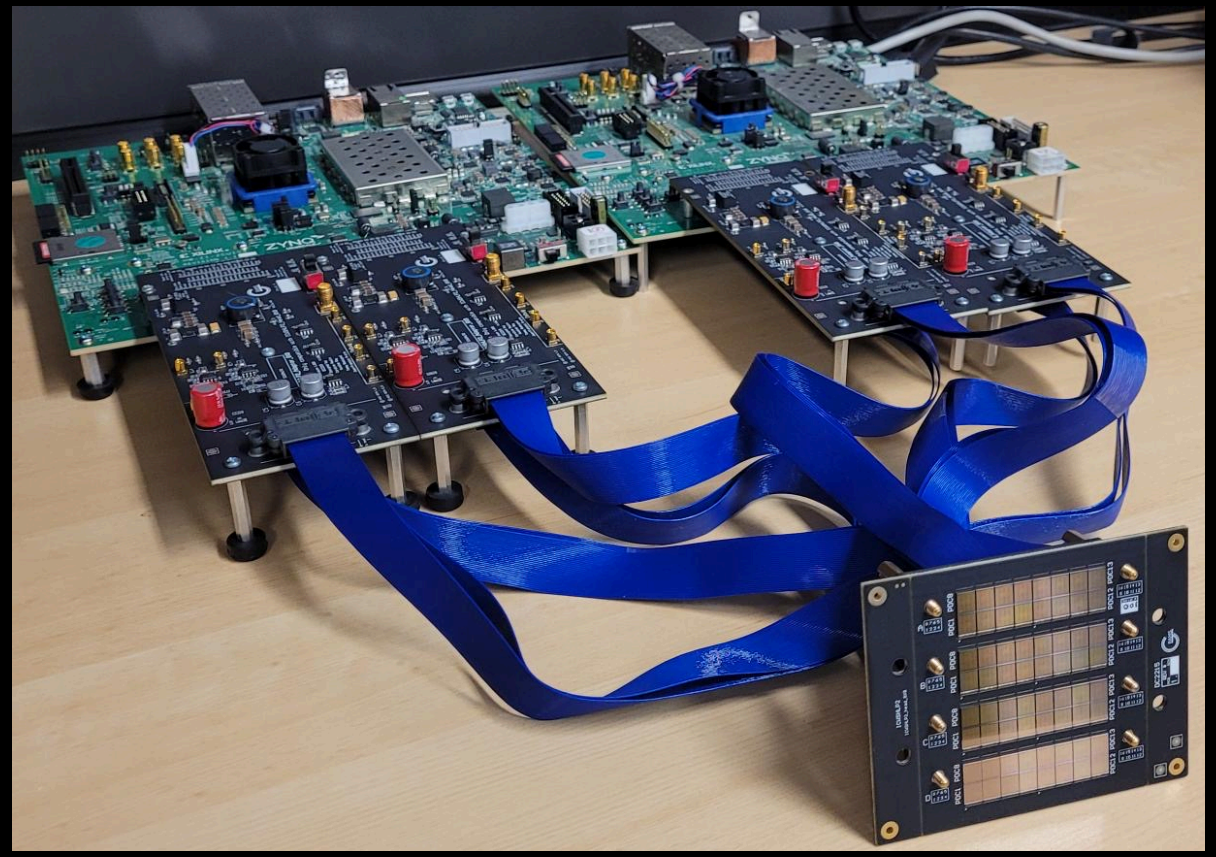
Photo-detection unit
16 tiles arranged into 4 channels

Tile / photo-detector module
24 SiPMs + signal amplifier

SiPM (~ 1 cm^2)



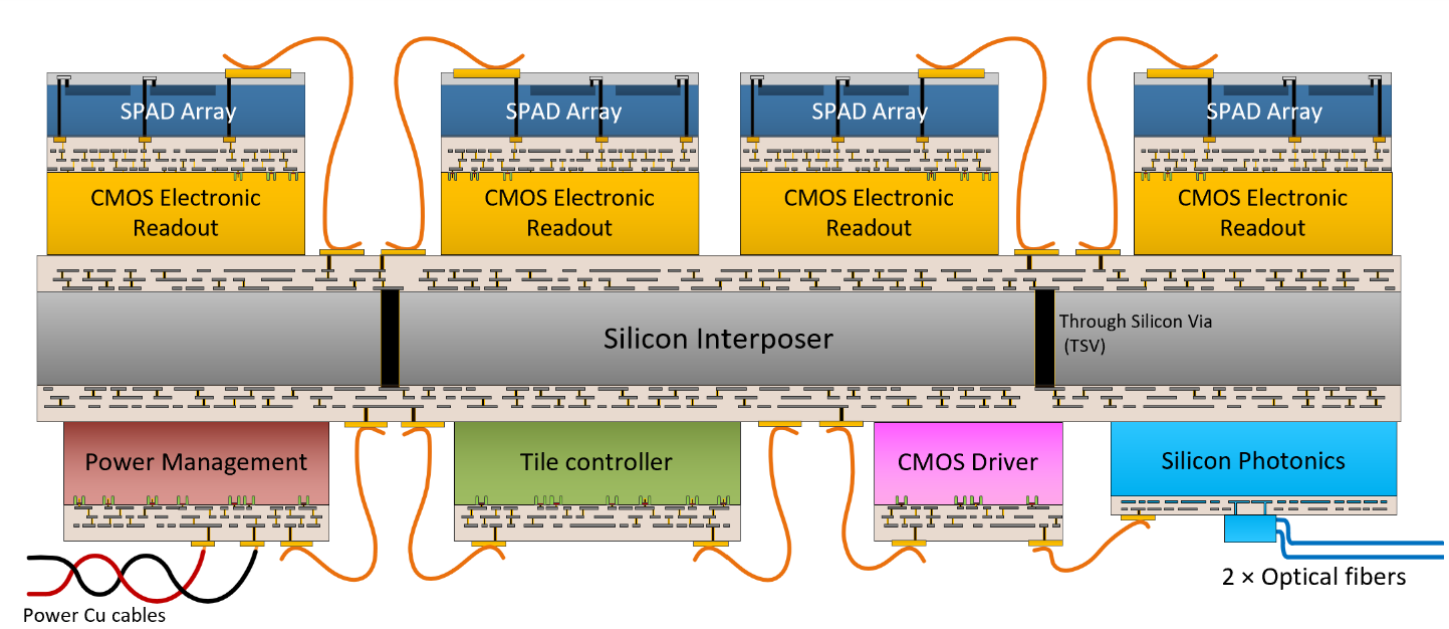
The present: **Analog SiPMs**
DarkSide photodetector unit (PDU) assembled at Nuova Officina Assergi, INFN LNGS

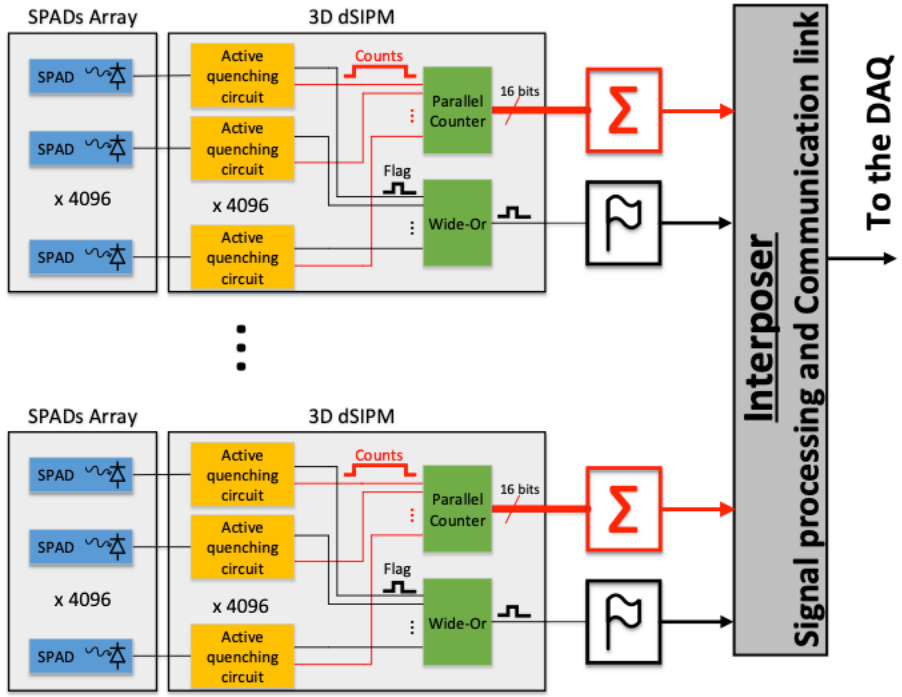


The future: **Digital SiPMs**
Photon-to-digital converter (PDC) tile from U. Sherbrooke with Teledyne-DALSA

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*



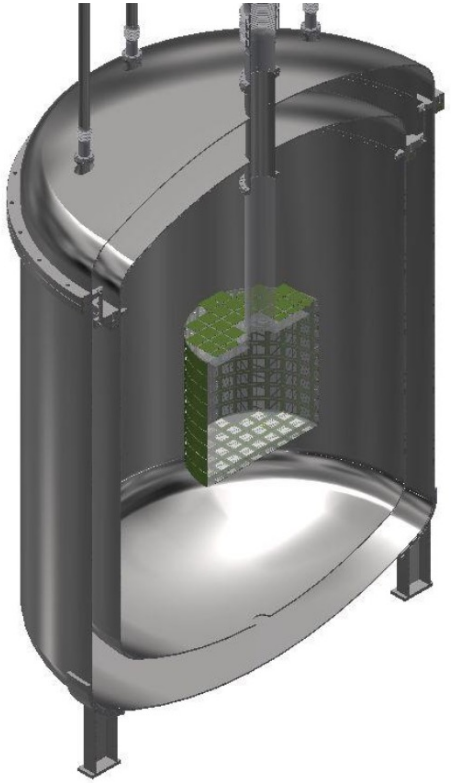


J.-F. Pratte et al. (2021) Sensors 2021, 21(2), 598
T. Rossignol et al. (2024) JINST 19, P09017

ARGOlite: technology demonstrator for ARGO

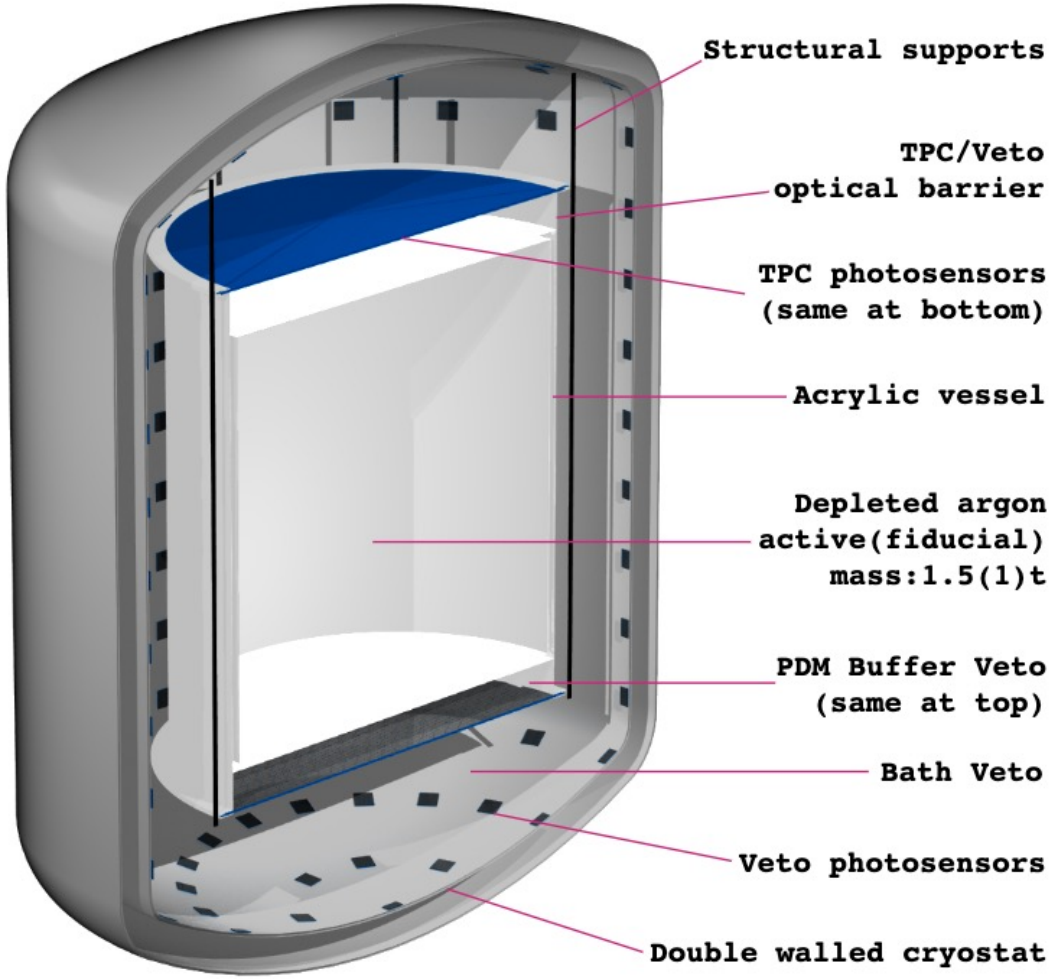
- **Single-phase** detector with 200 kg UAr
  - Fully instrumented with digital SiPMs (either 3D PDCs or “2.5D” ATARI devices or both)
  - **Smart DAQ**: machine-learning algorithms for event identification and reconstruction

ARGOlite preliminary design with SiPM tiles

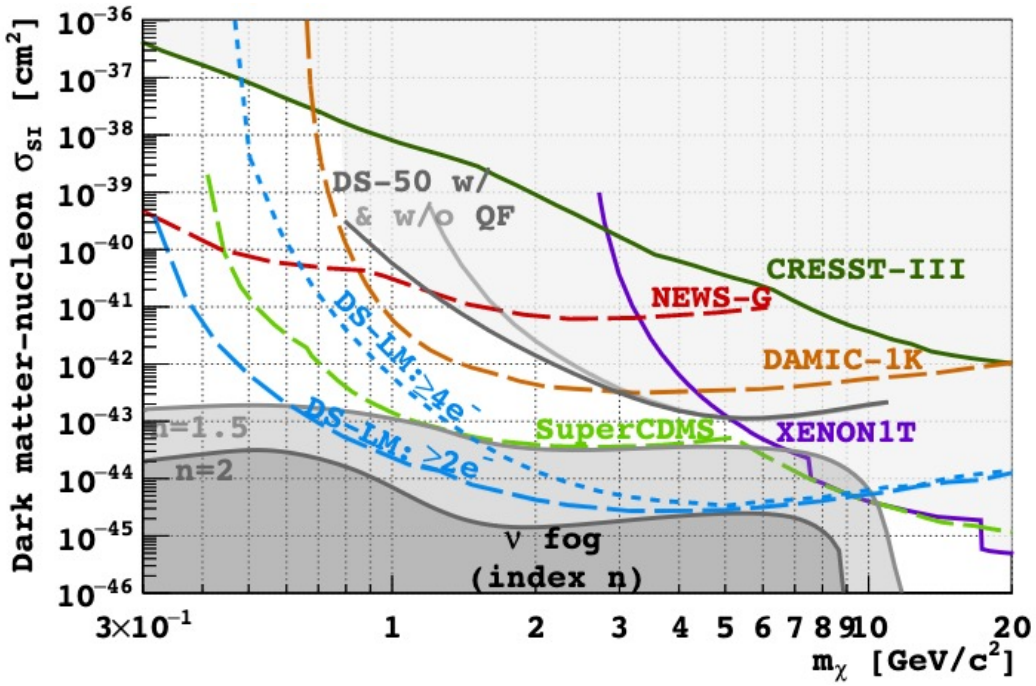


ARGOlite design in the DEAP-3600 water tank in Cube Hall at SNOLAB

DarkSide-LowMass



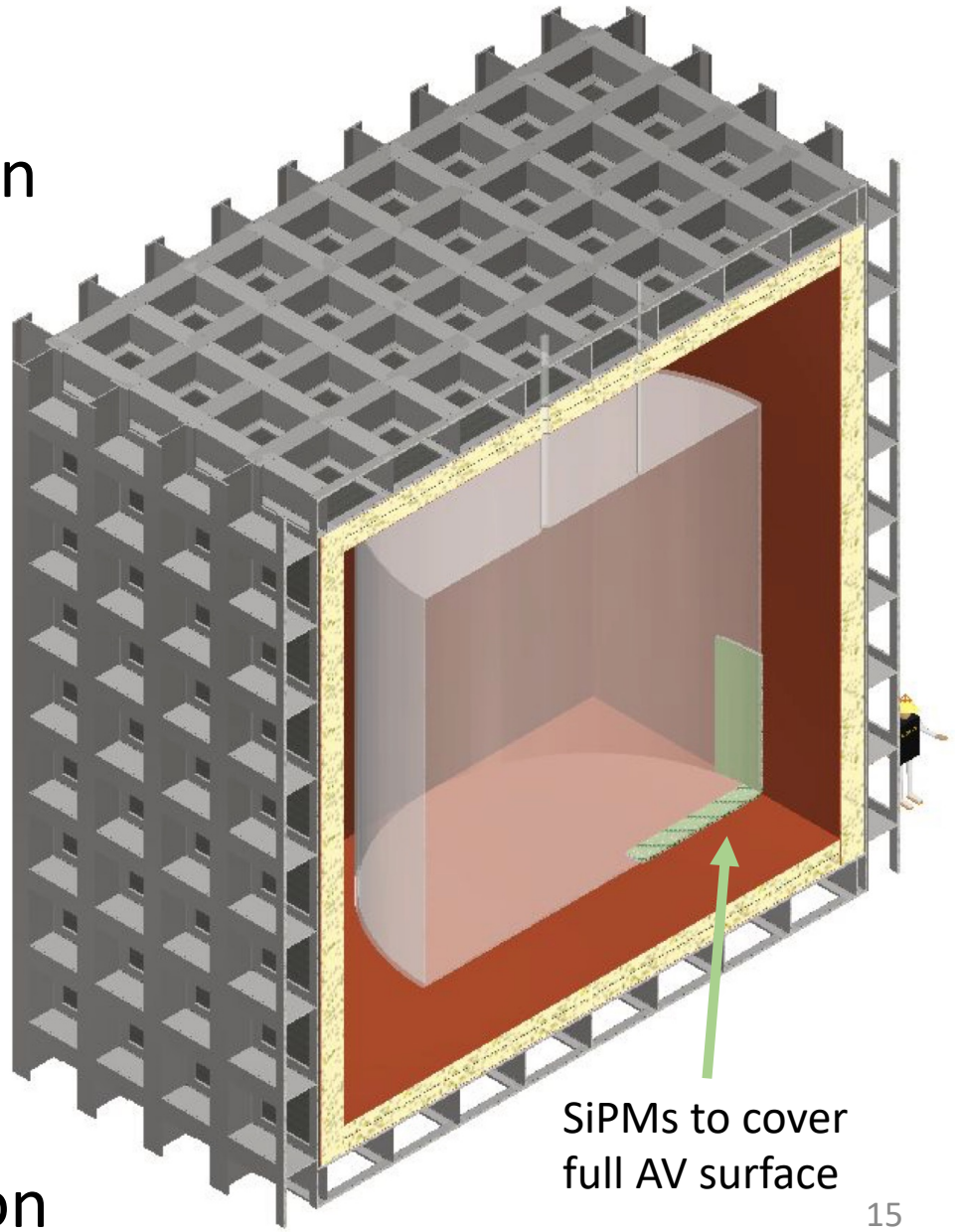
- Dual-phase UAr TPC (1.5 tonnes) optimized for low-mass dark matter search in **ionization-only channel** (S2)
  - Could be located in Cube Hall
  - Sensitivity all the way into neutrino fog

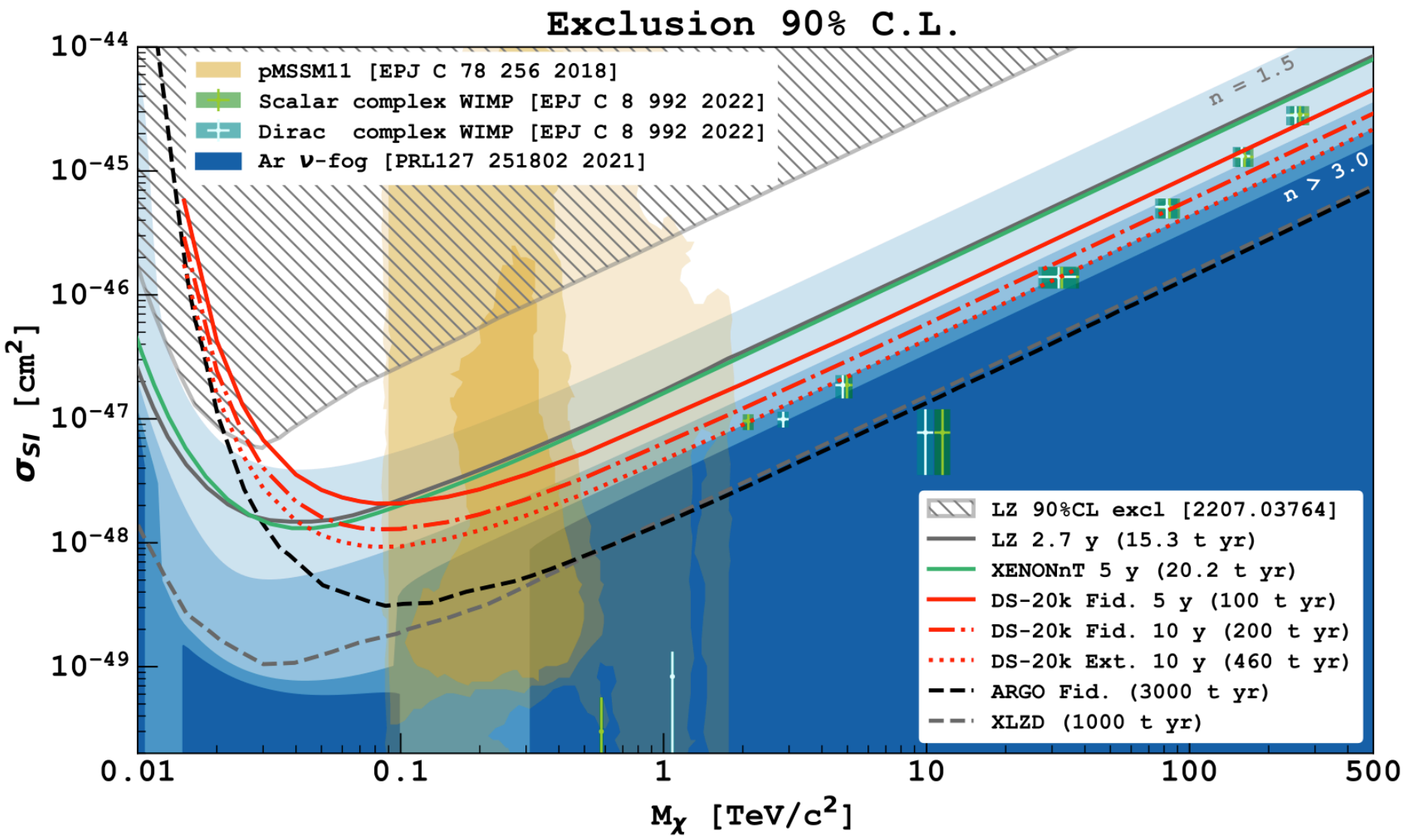


Global Argon Dark Matter Collaboration (2023) PRD 107, 112006

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





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

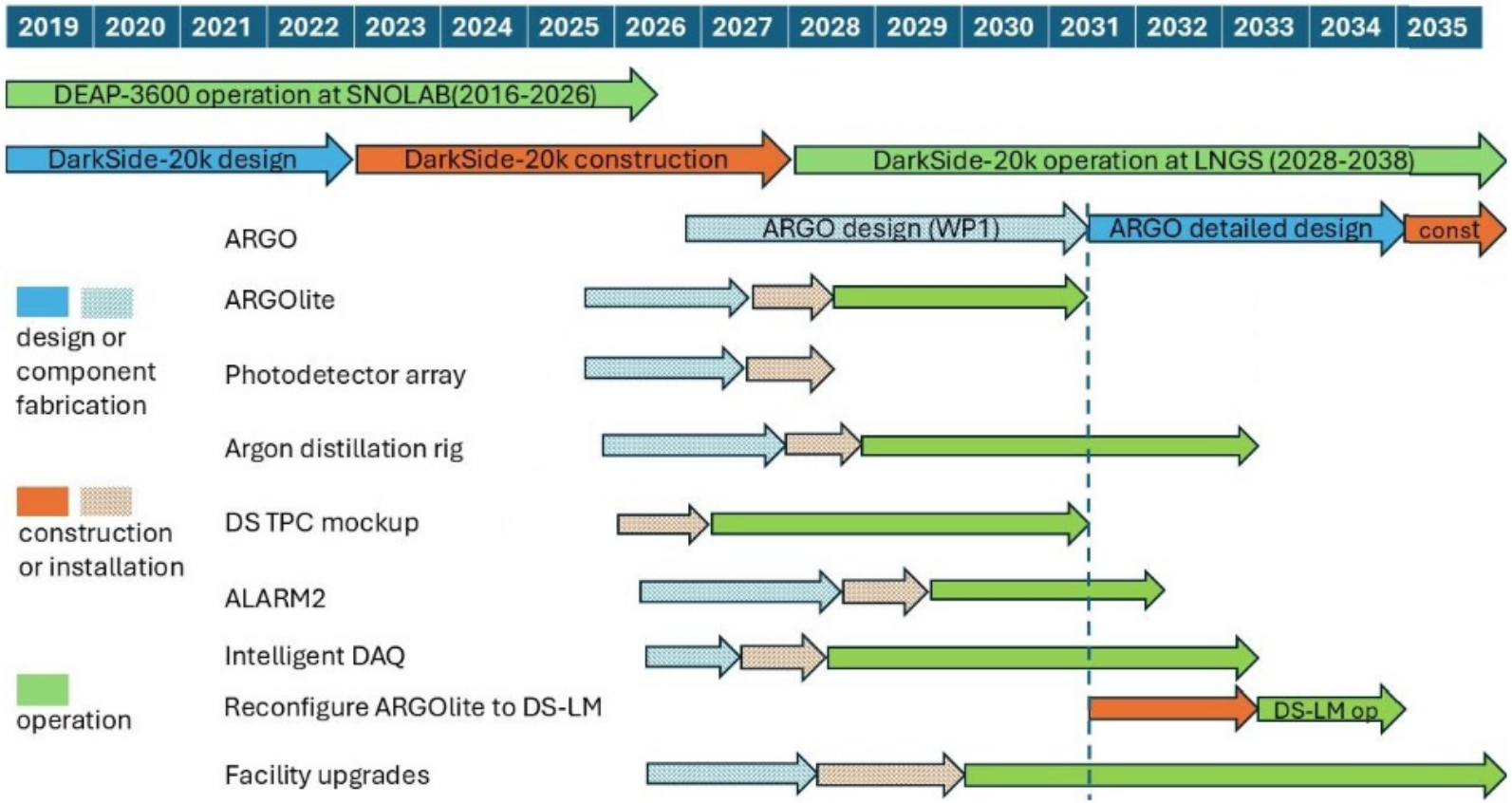
+ **Neutrino physics** with ARGO:

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

Summary

- **Liquid argon detectors** have potential to reach world-leading sensitivity for the direct detection of dark matter
  - Global Argon Dark Matter Collaboration has a research plan for the next decades



New collaborators are very welcome!