The Search for Dark Matter with Liquid Argon: DEAP, DarkSide, and ARGO

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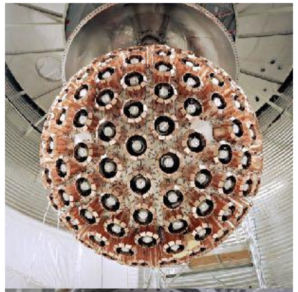
SNOLAB/Laurentian University

on behalf of the **Global Argon Dark Matter Collaboration**

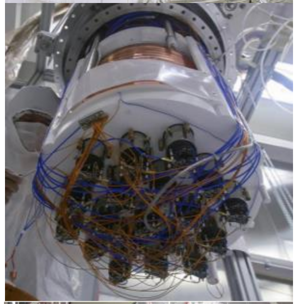
Overview

- The Past and Present
  - Some highlights from DarkSide-50
  - DEAP-3600
- Needs of larger detectors
  - Underground argon – low in ^{39}Ar
  - Better control of surface backgrounds – coatings
  - Lower radioactivity light collection – from PMTs to SiPMs
- DarkSide-20k
- ARGO
- Getting there – the Canadian group's medium-term plans

The Global Argon Dark Matter Collaboration



DEAP



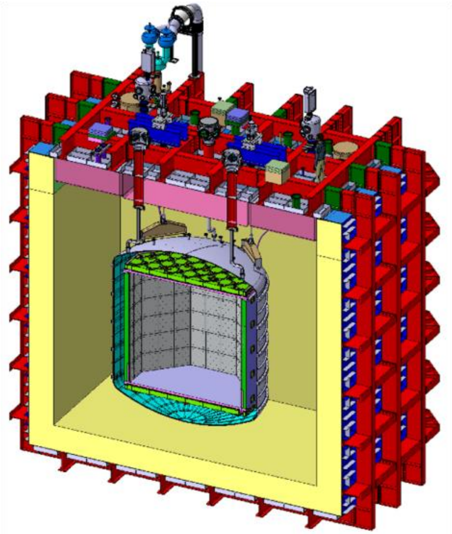
DarkSide-50

MiniCLEAN

ArDM

The GADMC

First priority: DarkSide-20k under construction at LNGS

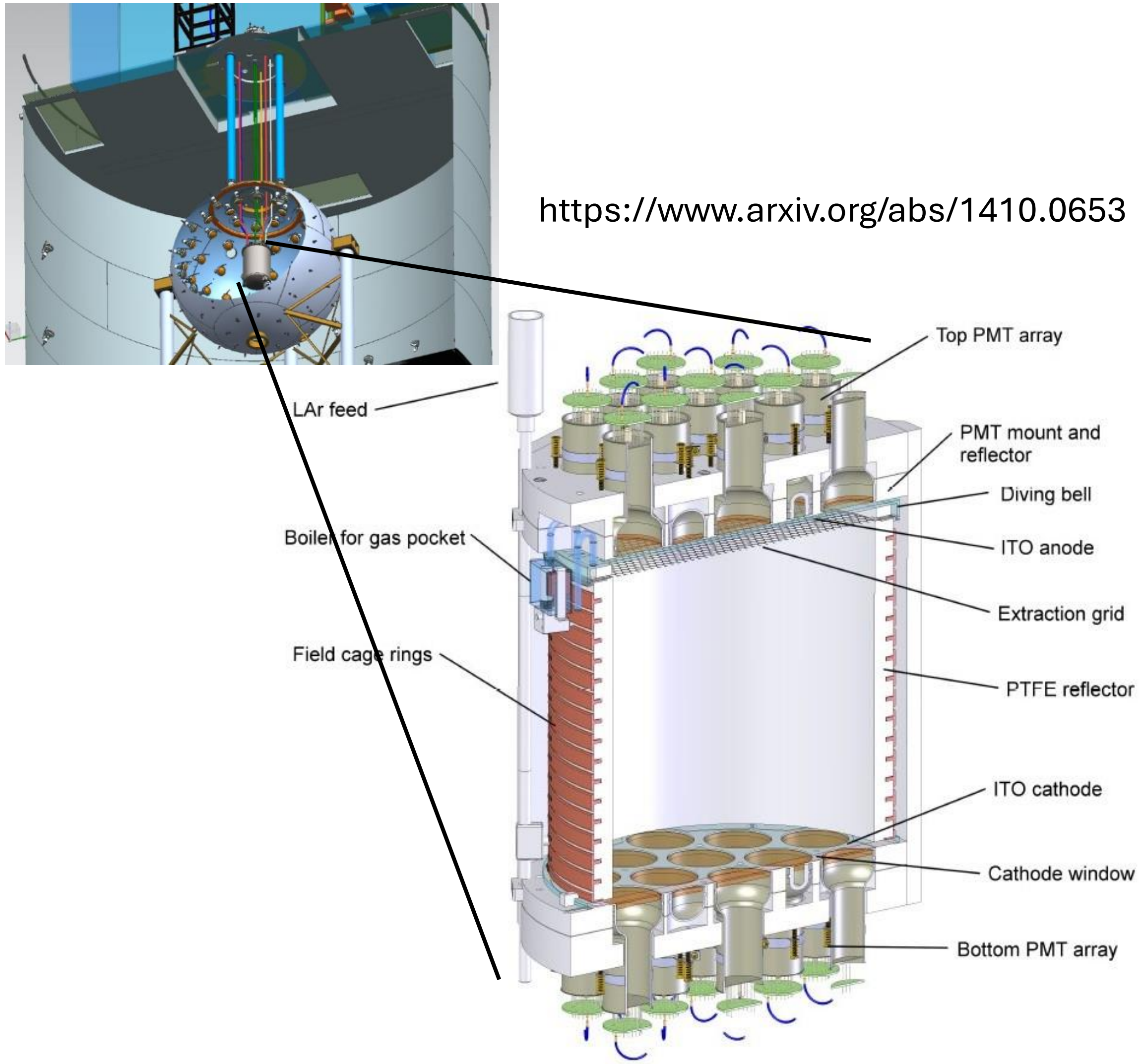


Next: ARGO

At this meeting … (Monday and Tuesday)

- Emma Ellingwood - Searching for neutrino absorption in 40Ar using the DEAP-3600 dark matter detector
- Nicholas Swidinsky - Fluorescence measurements of Clevios for use in particle detectors
- Badamsambuu Jigmeddorj – Precise High-Energy Gamma Calibration for DEAP-3600 and Position Reconstruction for ARGO (Poster)

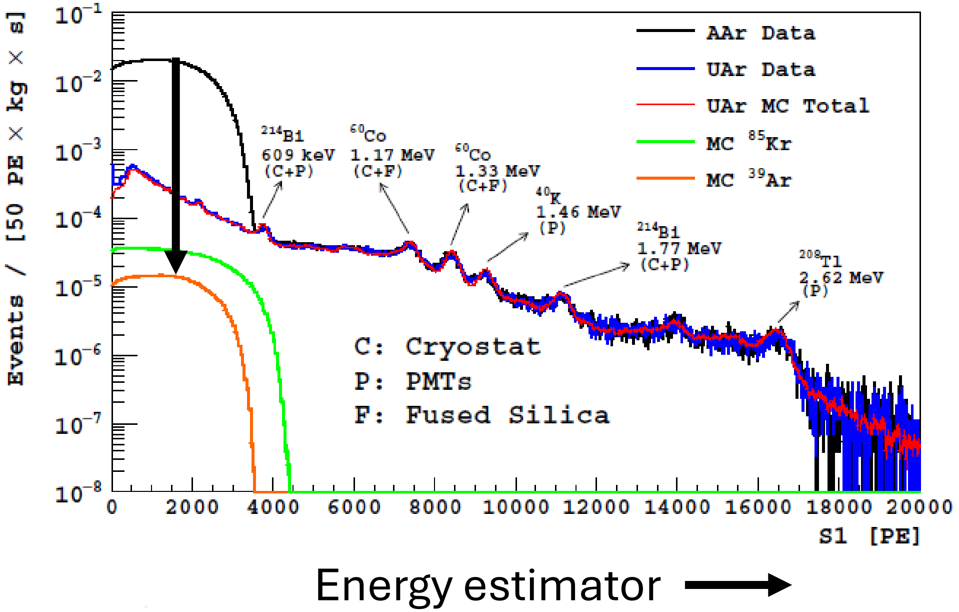
DarkSide-50 had a successful run with atmospheric, then underground, Argon



https://www.arxiv.org/abs/1410.0653

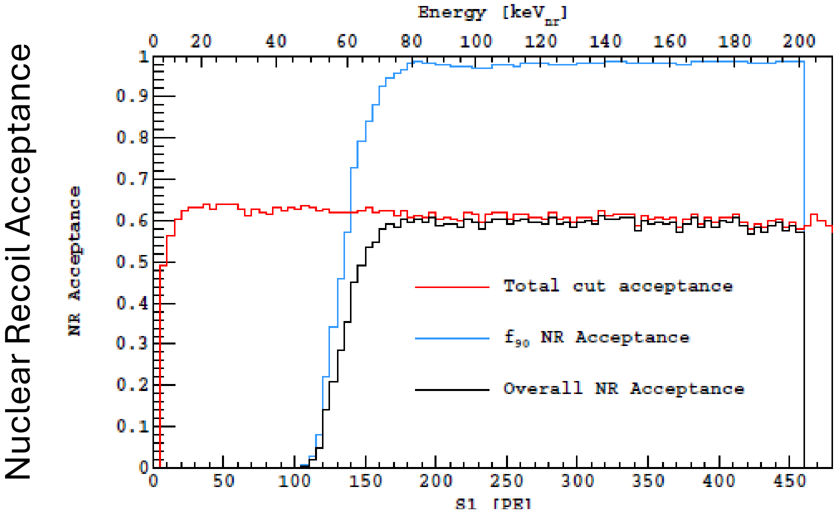
- Excellent fit to a detailed EM background model.
- Underground Ar depleted in Ar-39 w.r.t. surface Ar by a factor of at least 1400.

https://arxiv.org/abs/1510.00702

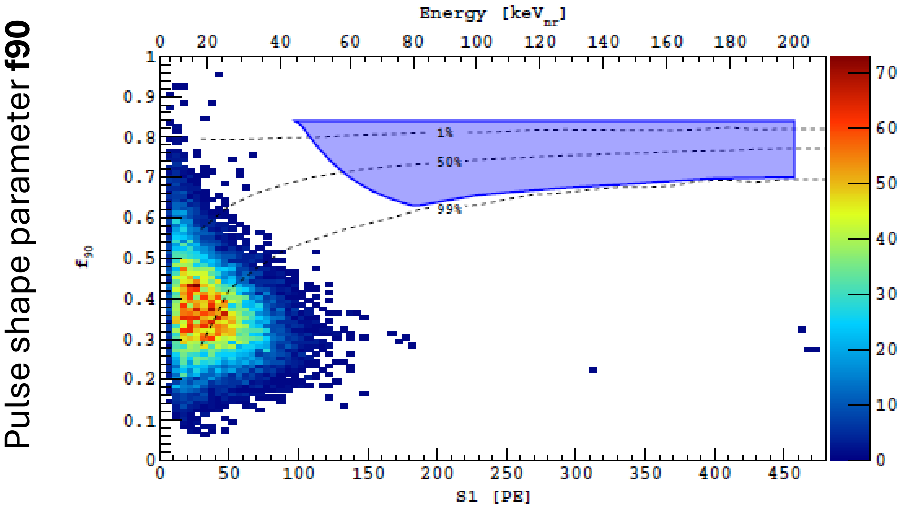


The DarkSide-50 532-day run had no events in the ROI and set stringent limits on WIMP-nucleon couplings

https://arxiv.org/abs/1802.07198



High acceptance after cuts



0 **Energy** 200 keV NR

No events near ROI after cuts (including FV)

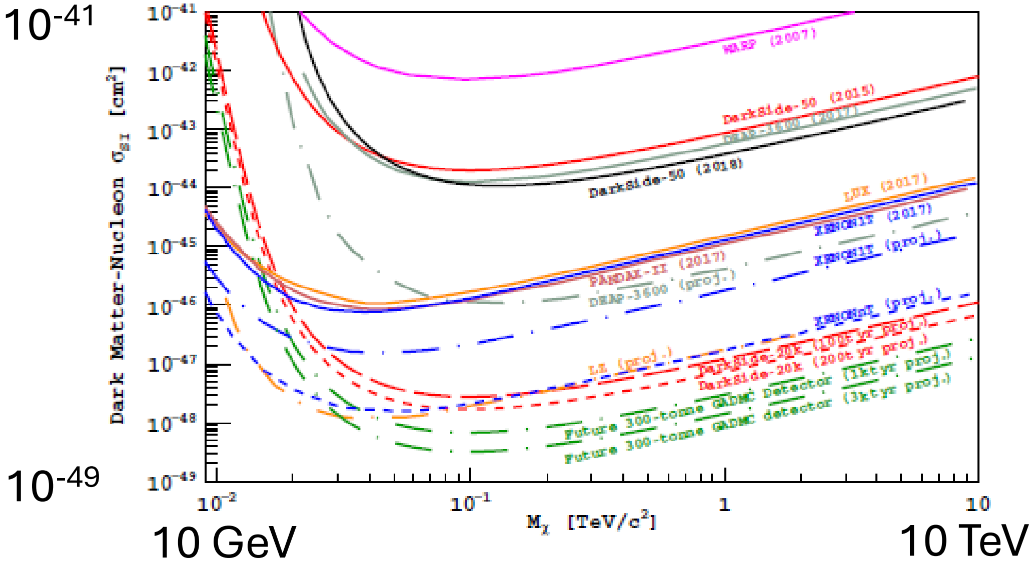


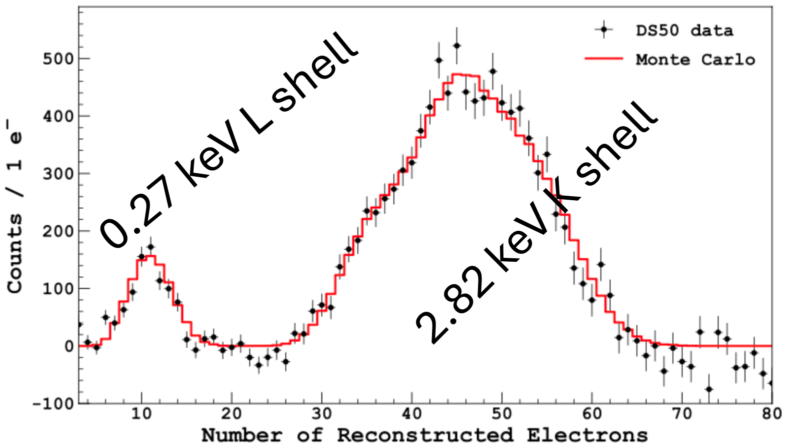
FIG. 10. Spin-independent DM-nucleon cross section 90 % C.L. exclusion limits from the analysis detailed in this paper (in black), compared with selected results and projections.

Limit set by DarkSide-50k:

1.1×10^{-44} cm^2 at 100 GeV/c^2

Liquid Argon is an excellent choice for a low mass WIMP search

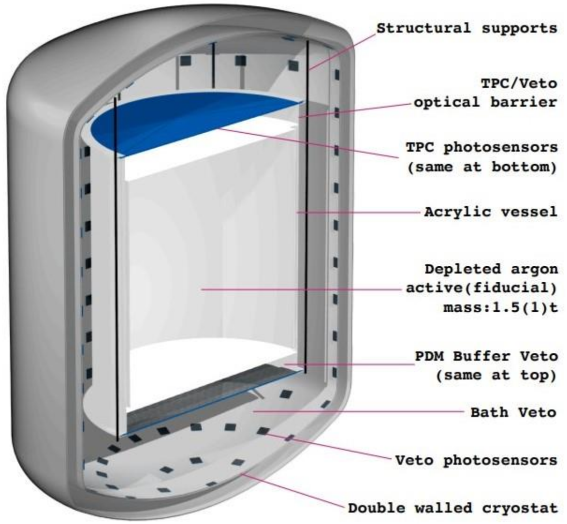
DarkSide-50 set strong limits between 1.8 and 10 GeV

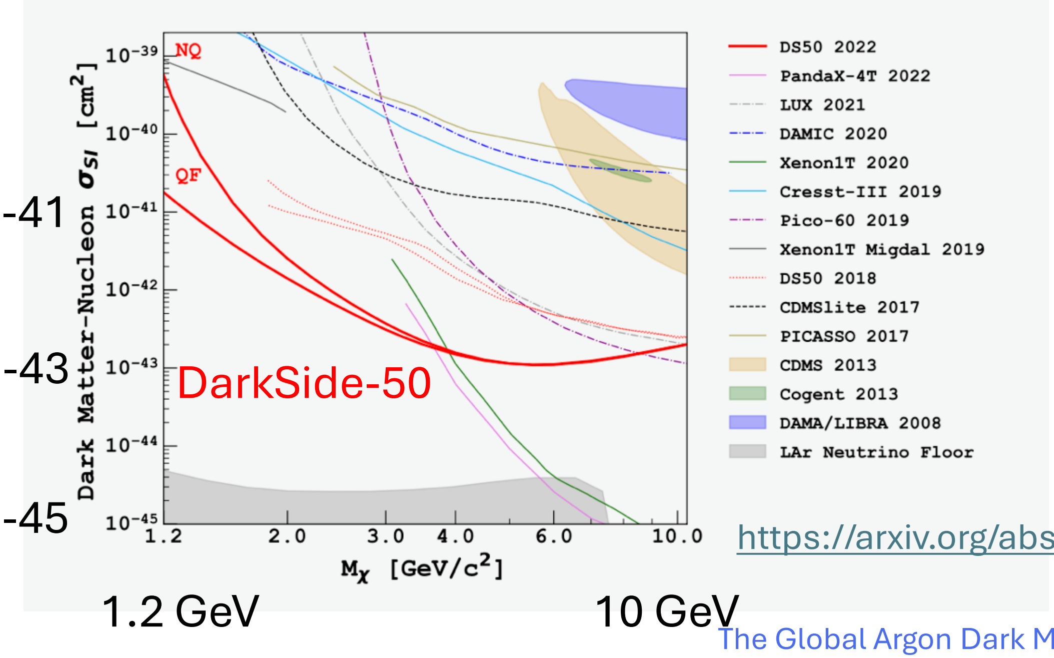


X-rays after ^{37}Ar decay

https://arxiv.org/abs/2107.08087

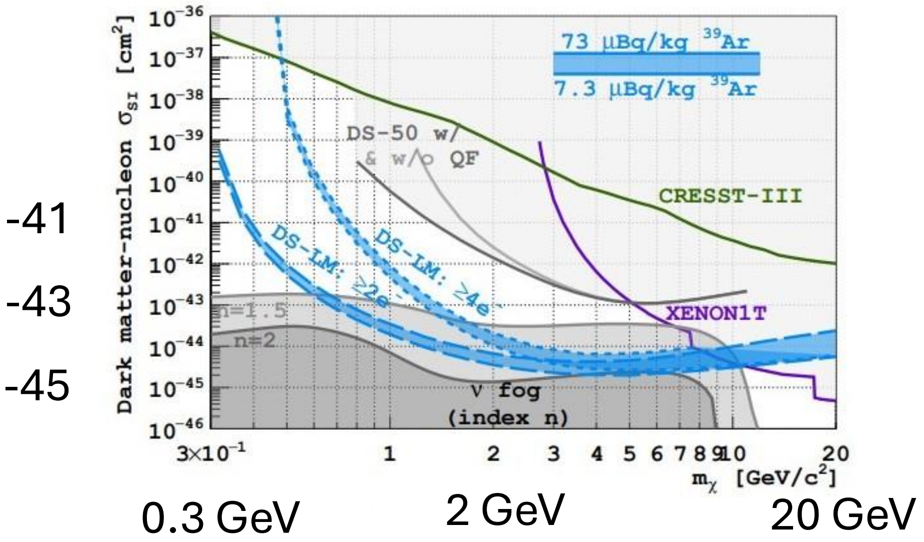
A series of studies was carried out for a detector with 1.5 tonnes UAr optimized for low-mass WIMPS.





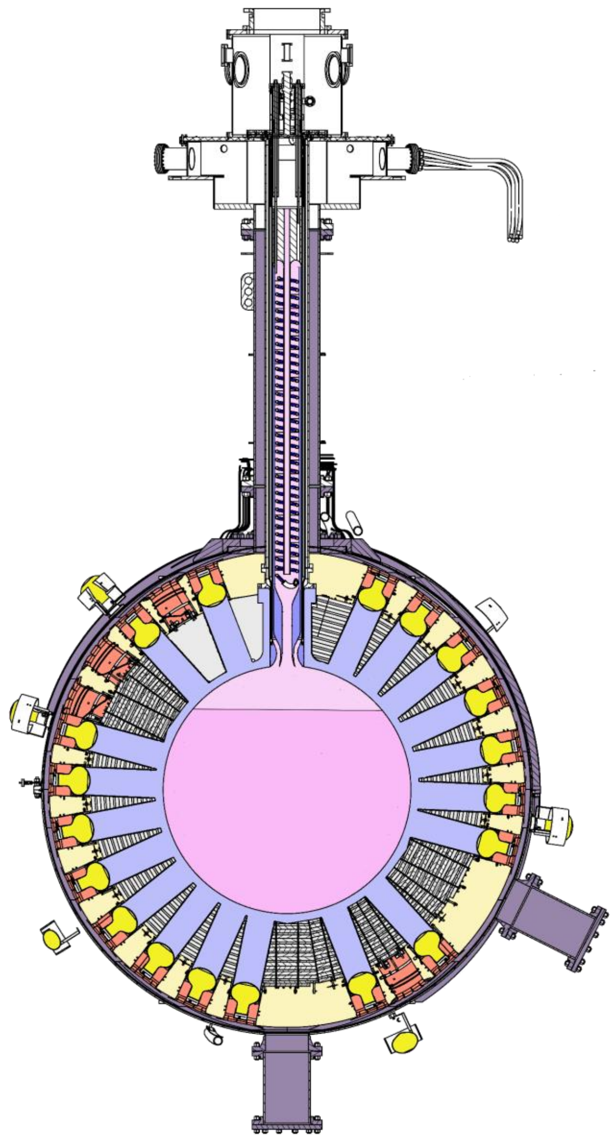
https://arxiv.org/abs/2207.11966

https://arxiv.org/abs/2209.01177

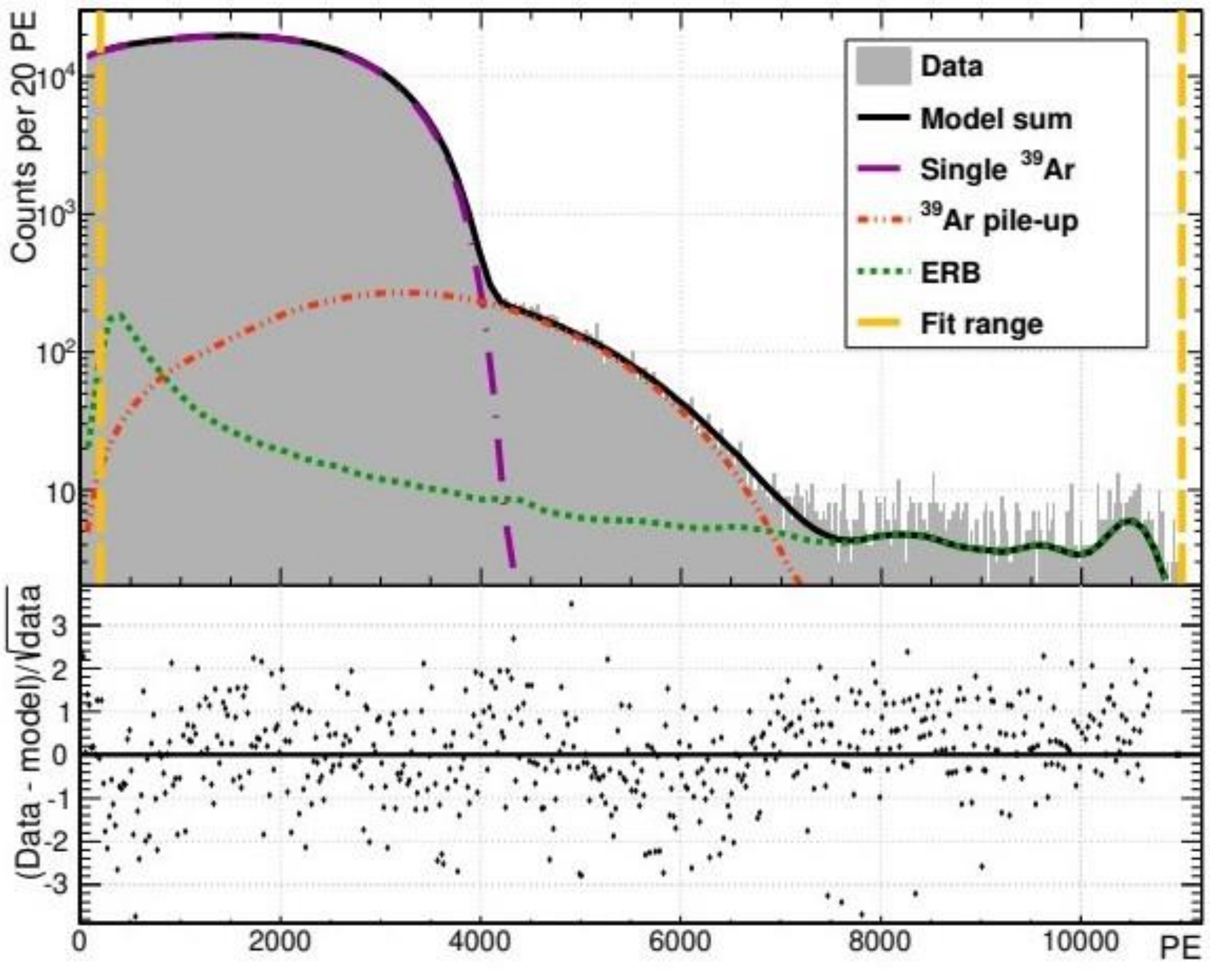


DEAP-3600 ran successfully for 3 + years at SNOLAB and we are currently finalizing hardware upgrades

- 3300kg of atmospheric argon in a high radio-purity acrylic vessel.
- TPB wavelength shifter to convert VUV argon scintillation light into the optical
- Detected with 255 PMTs
- Outward looking PMTs in a water tank make the muon veto



Atmospheric Argon contains 39Ar with a specific activity of 0.964 ± 0.001stat ± 0.024sys Bq/kg



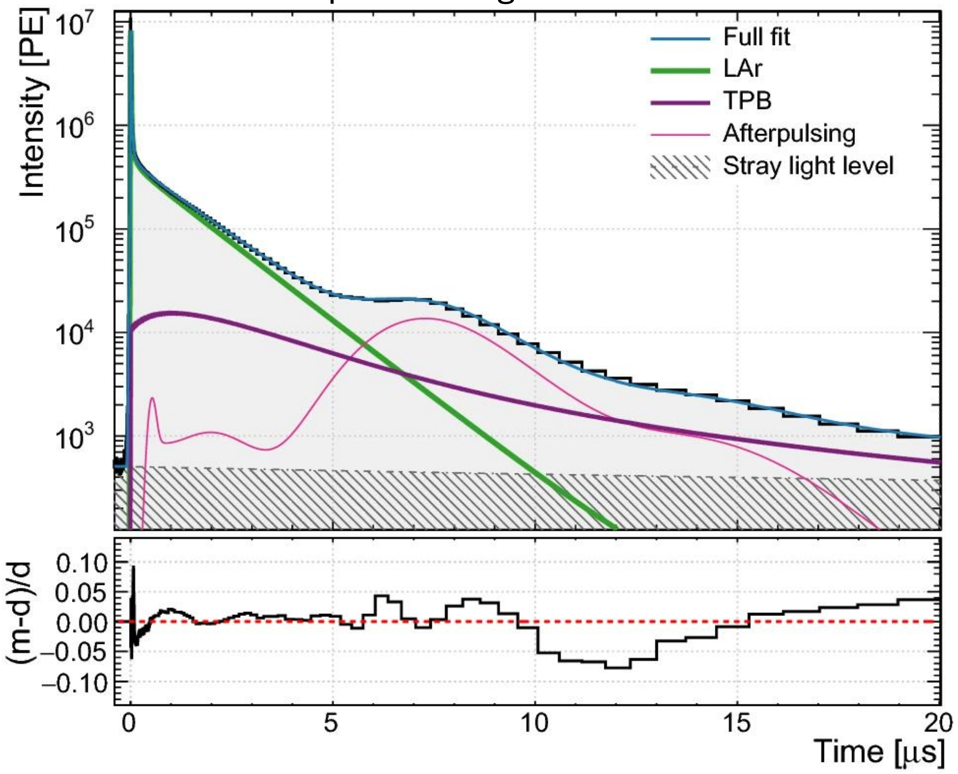
- ^{39}Ar is created in the atmosphere from ^{40}Ar(n,2n)
- Half life of 268y
- Endpoint 565 ± 5 keV

→ Find argon in underground gas, extract it, purify it and store underground for use.

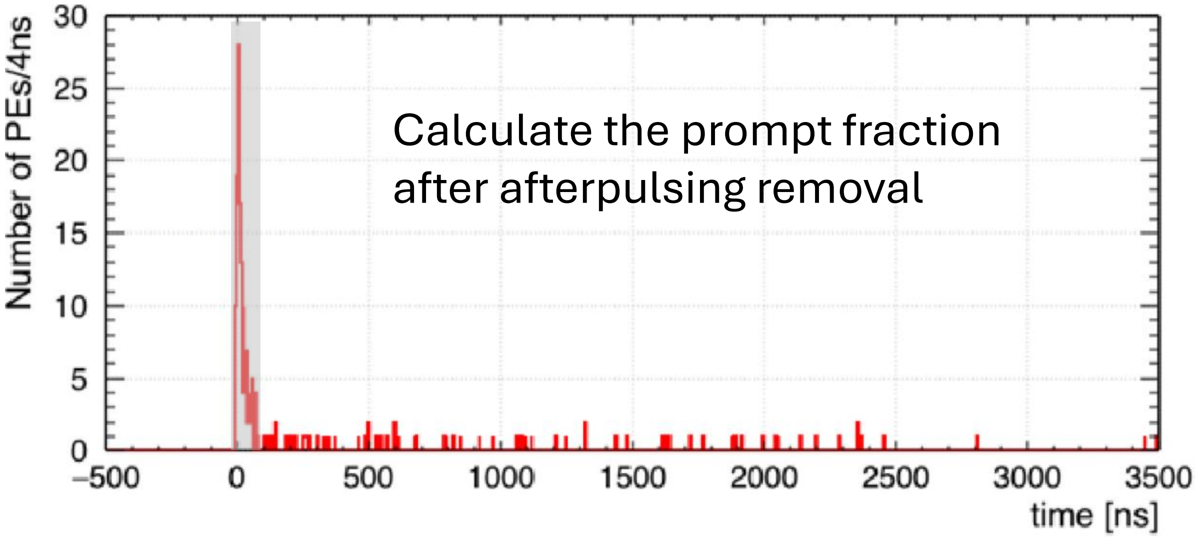
https://arxiv.org/abs/2302.14639

Pulse-Shape Discrimination in Liquid Argon Works!

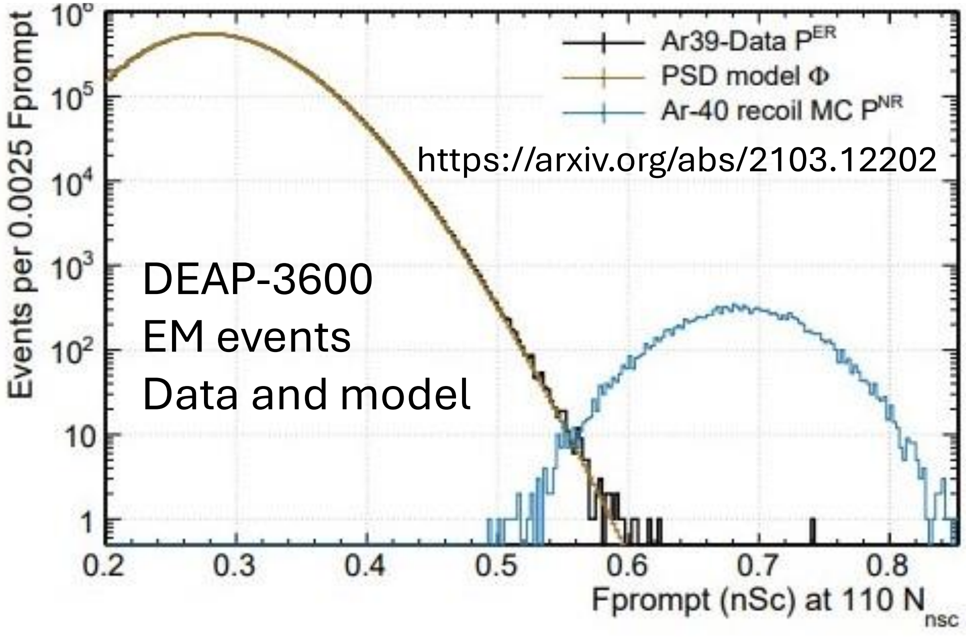
http://arxiv.org/abs/2001.09855



Liquid argon pulse shapes, including instrumental effects such as PMT afterpulsing and stray light are well understood.



Calculate the prompt fraction after afterpulsing removal



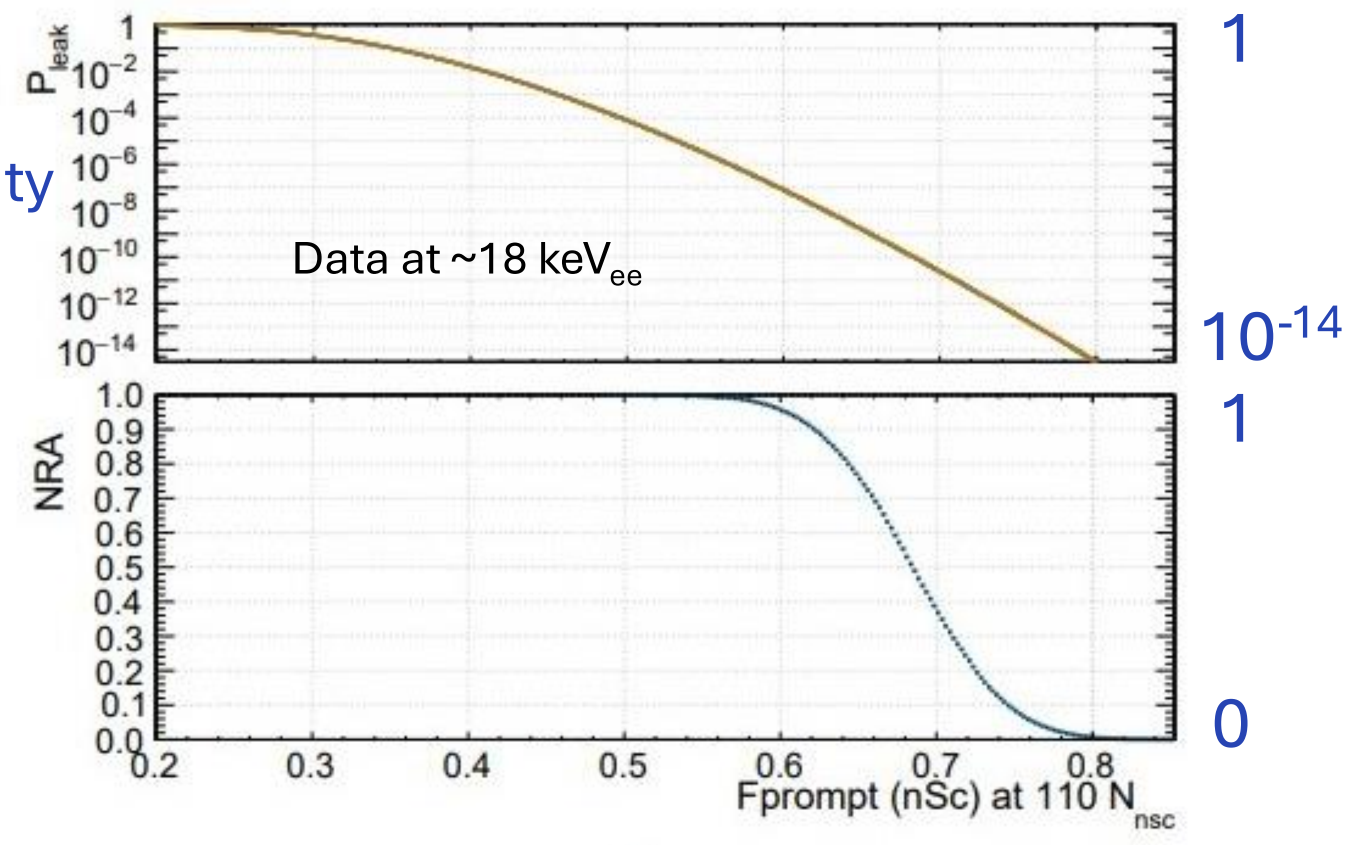
https://arxiv.org/abs/2103.12202

DEAP-3600
EM events
Data and model

Data at ~18 keV_{ee}

Leakage probability of EM events

Nuclear recoil acceptance

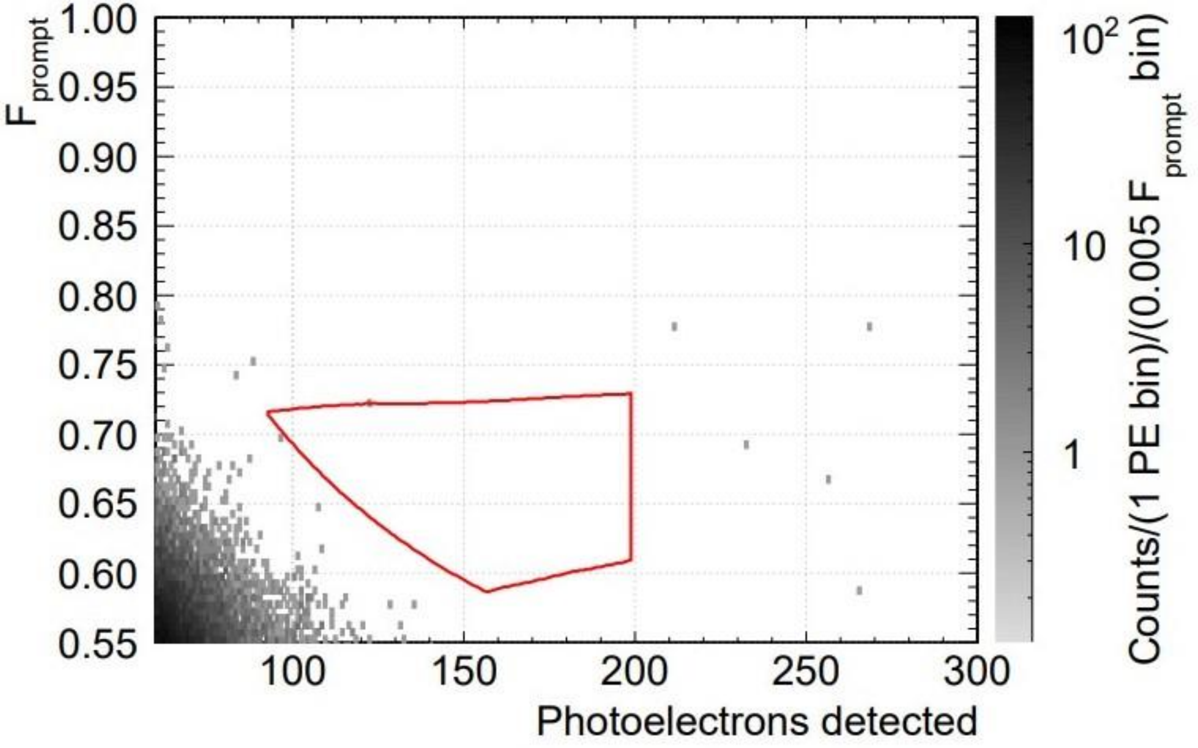


(b)

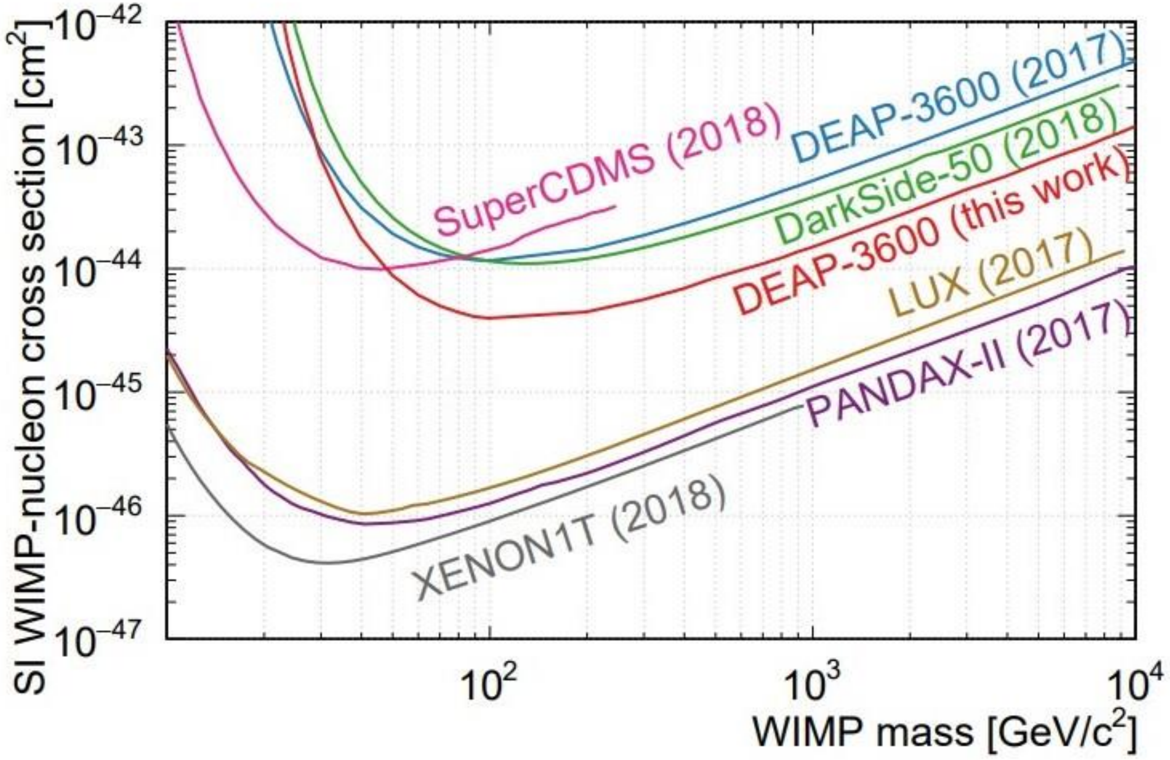
The PSD demonstrated in DEAP-3600 is sufficient for ARGO

DEAP-3600 set the most stringent limit on WIMP-nucleon coupling using Argon

Zero events in ROI (with two near misses)



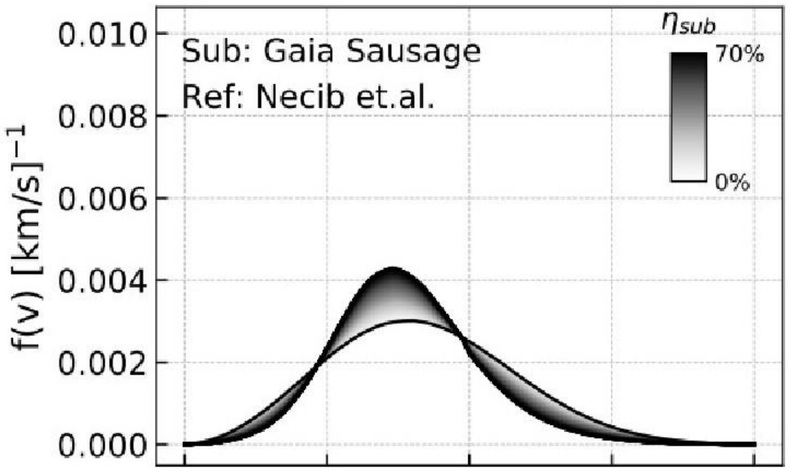
https://arxiv.org/abs/1902.04048



DEAP-3600 expanded that analysis taking into account Effective Field Theory and Galactic Models

http://arxiv.org/abs/2005.14667

$$\frac{dR}{dE_R} = \frac{\rho_T}{m_T}\frac{\rho_\chi}{m_\chi}\varepsilon(E_R)\int_{v_{\rm min}}^{\infty} v f_\chi^{\oplus}(\vec{v})\frac{d\sigma}{dE_R}d^3\vec{v}$$



0 km/s — 800 km/s

(one of 16 velocity distributions considered)

$\mathcal{O}_1 = 1_\chi 1_N$

$\mathcal{O}_3 = i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}_\perp)$

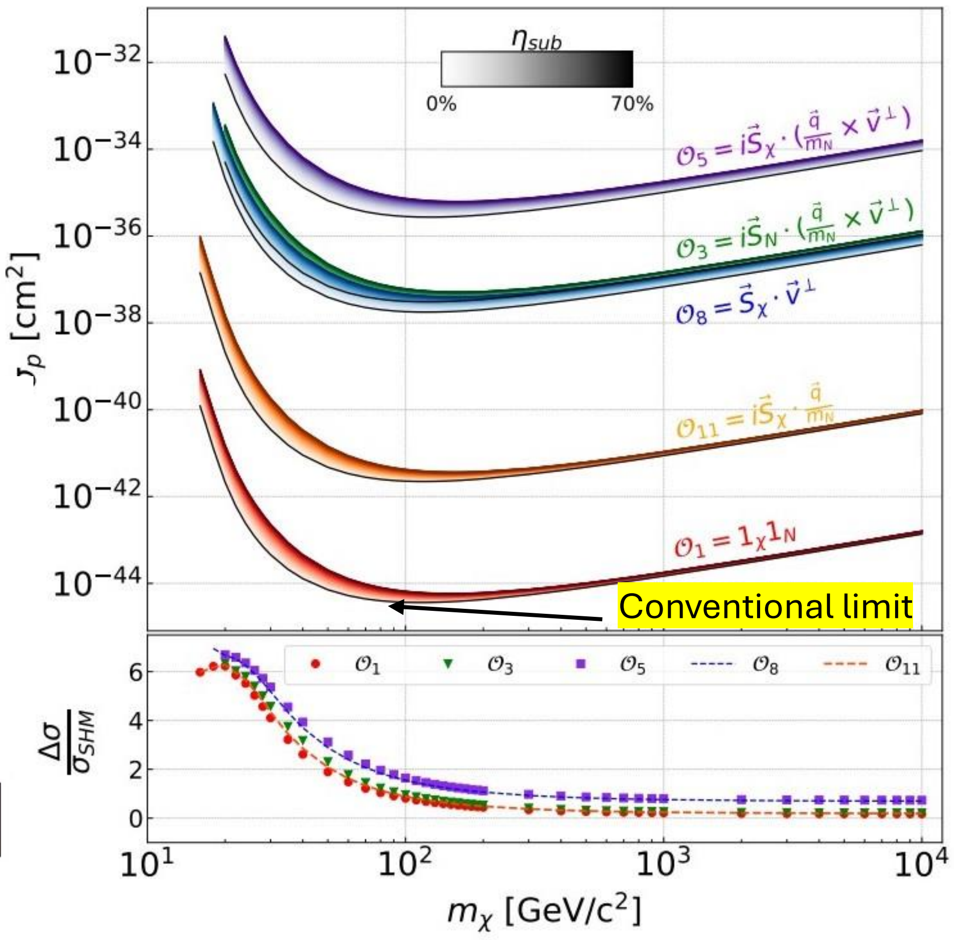
$\mathcal{O}_5 = i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}_\perp)$

$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}_\perp$

$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$

$\mathcal{O}_{12} = \vec{v}_\perp \cdot (\vec{S}_\chi \times \vec{S}_N)$

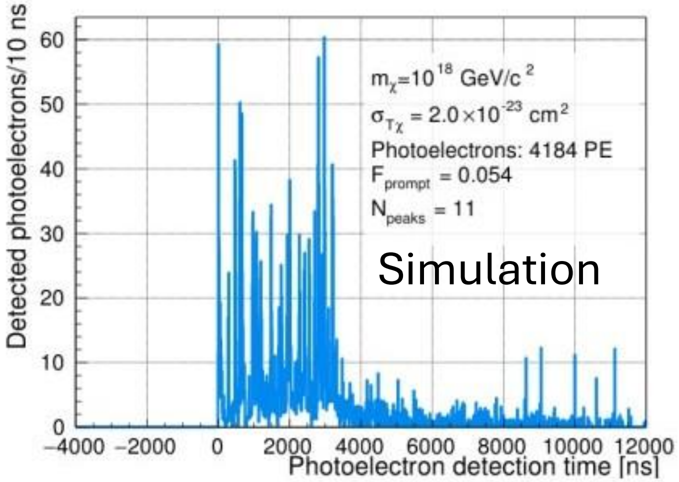
$\mathcal{O}_{15} = -\left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left[\left(\vec{S}_N \times \vec{v}_\perp\right) \cdot \frac{\vec{q}}{m_N}\right]$

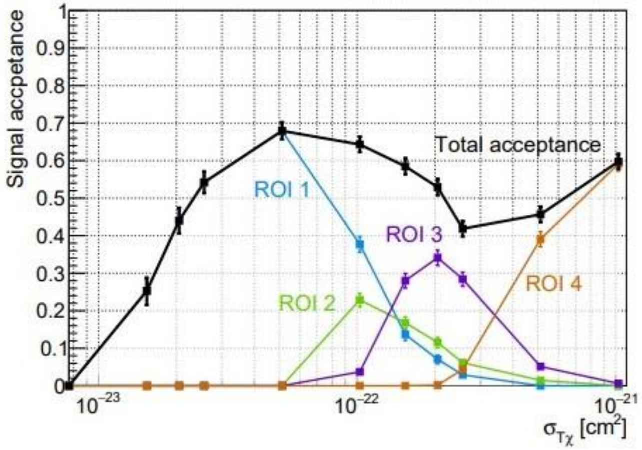


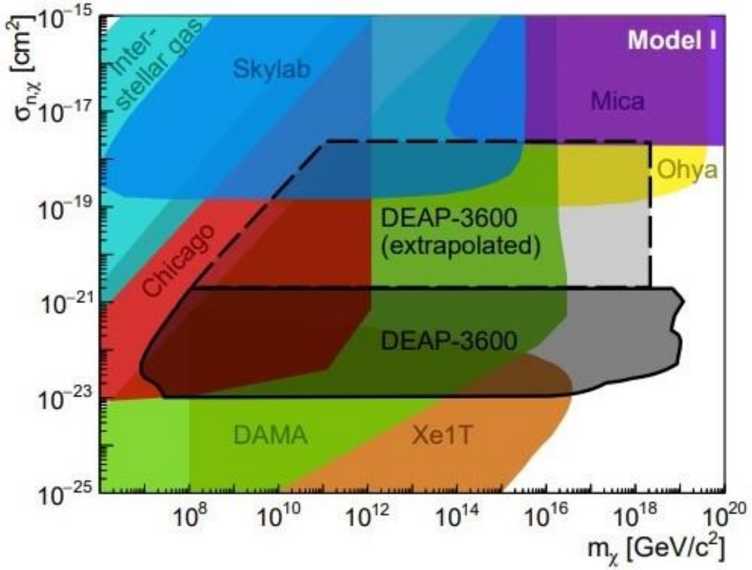
(a) *Gaia* Sausage (Necib *et al.*) [60]

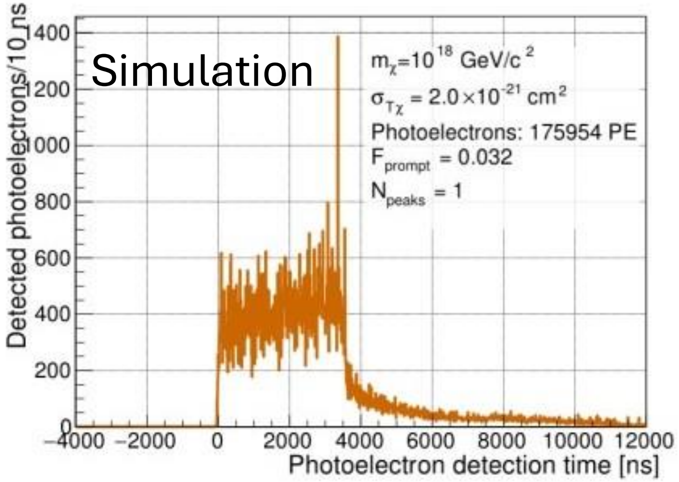
DEAP-3600 searched for Planck-scale dark matter

These interact many times traversing the detector and give large and unique signals.



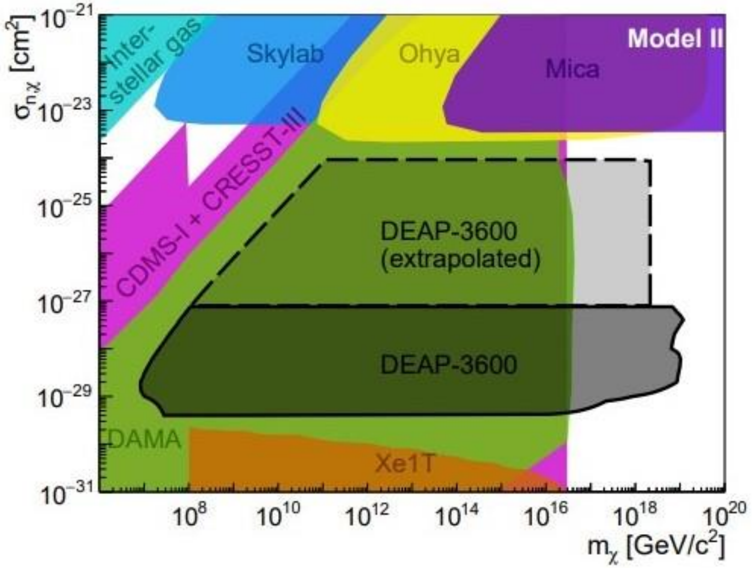






DEAP produced world-leading limits

https://arxiv.org/abs/2108.09405

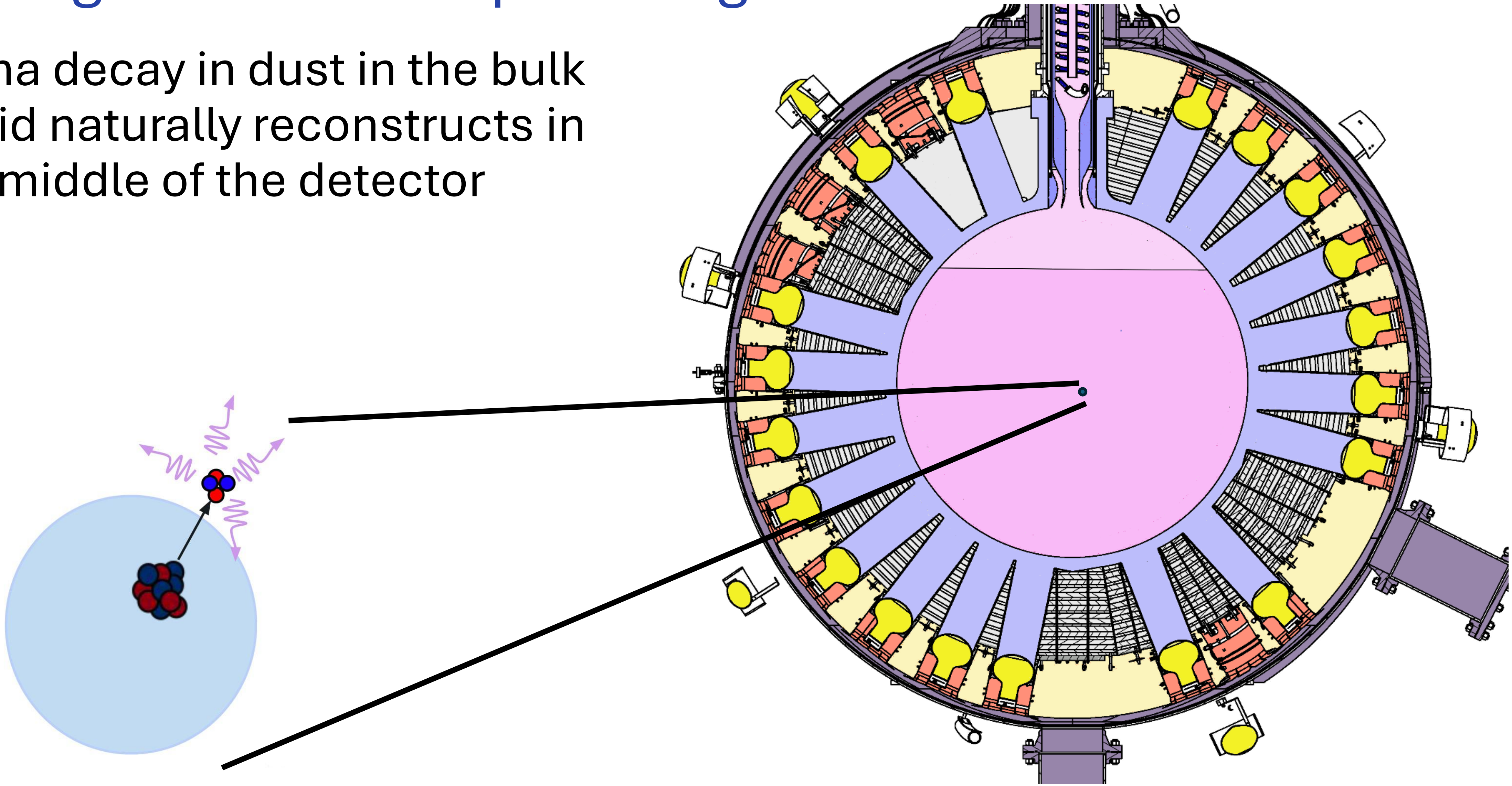


Six analyses to complete this year

- A Profile-Likelihood Ratio dark matter search using the entire second-fill data set.
- A measurement of the lifetime of Argon-39.
- A search for Boron-8 solar neutrinos.
- A search for a 5.5 MeV solar axion.
- A muon-flux measurement.
- A measurement of alpha-particle quenching in liquid argon.

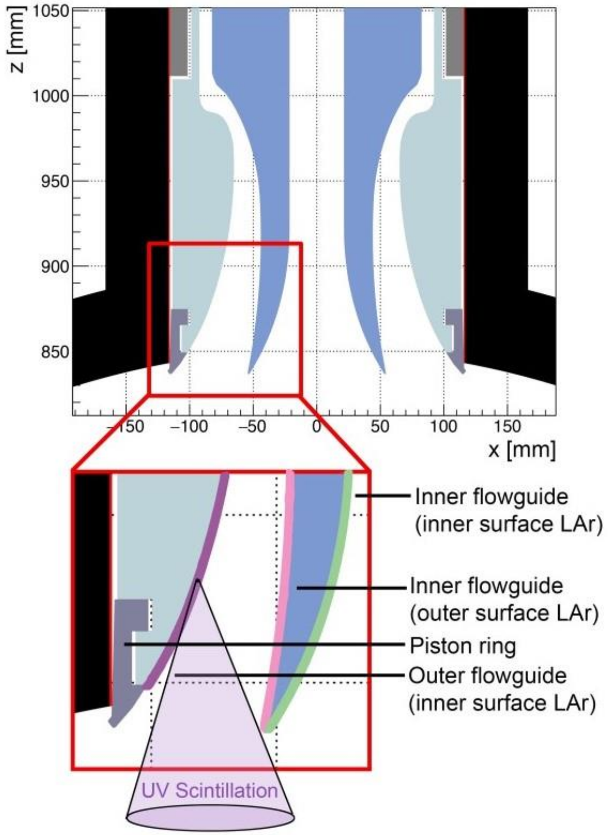
DEAP-3600 background model contains two alpha backgrounds that require mitigation

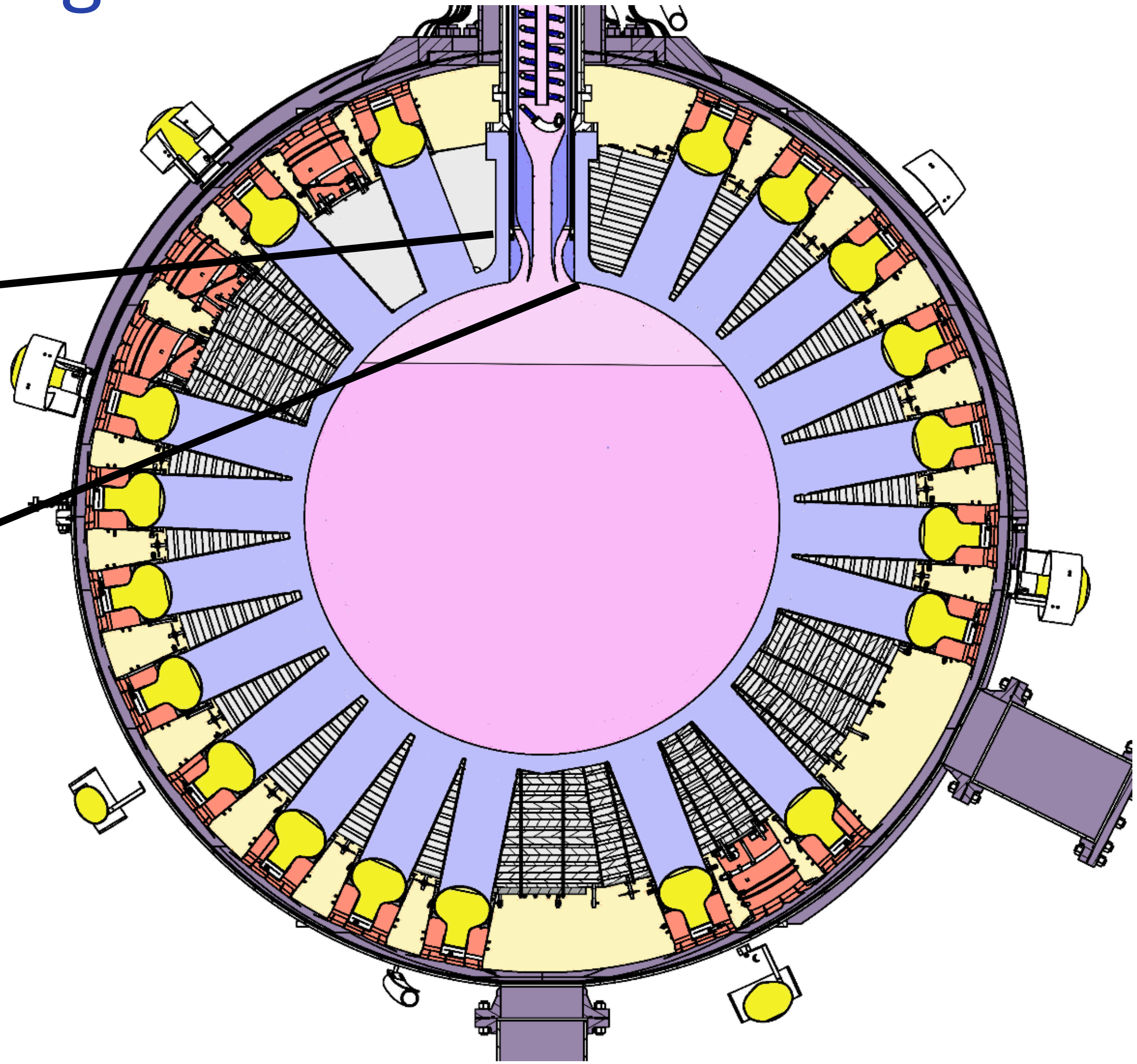
Alpha decay in dust in the bulk liquid naturally reconstructs in the middle of the detector



DEAP-3600 background model contains two alpha backgrounds that require mitigation

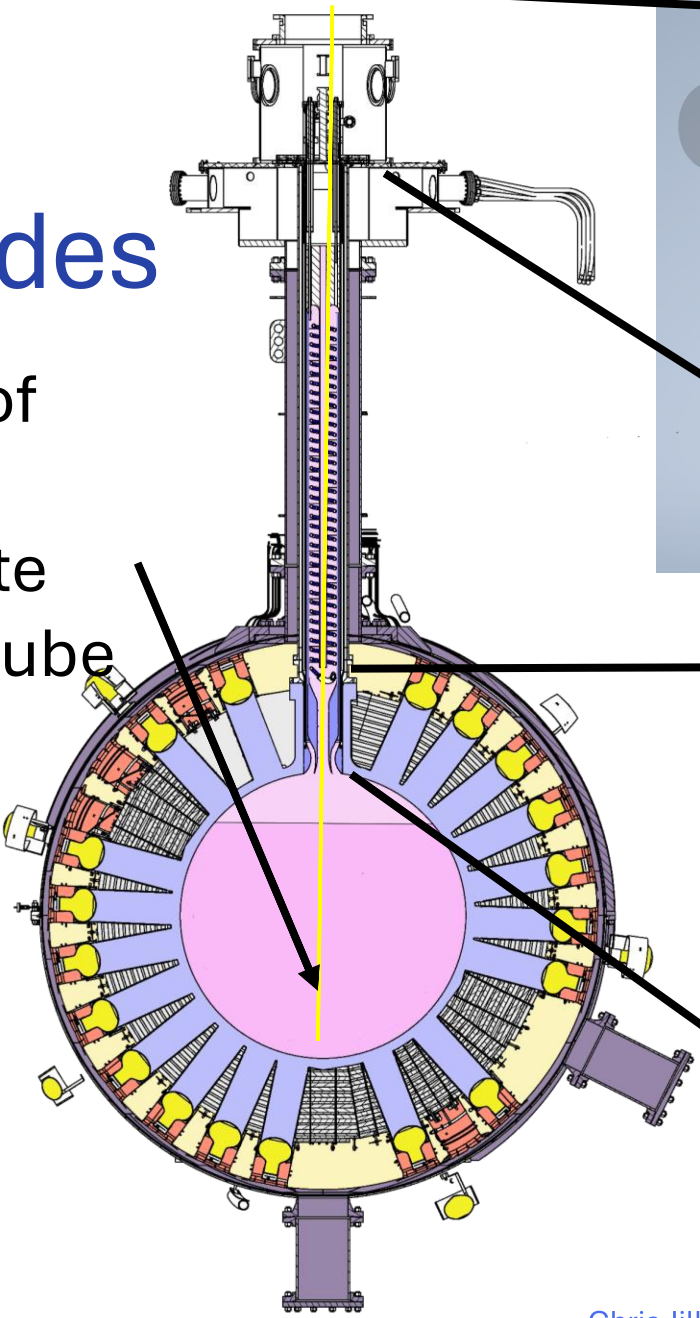
Alpha decay in the neck allows for a small fraction of light to enter the main detector

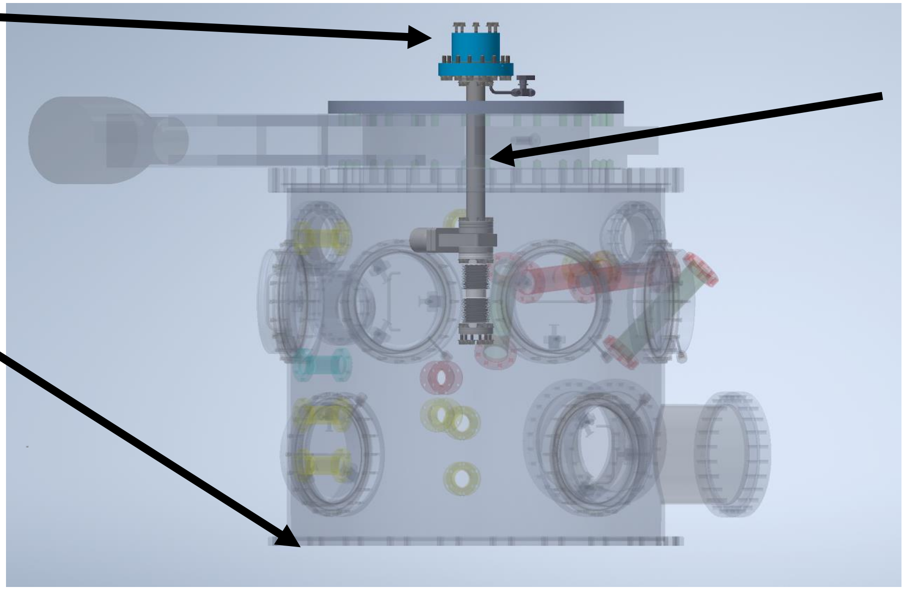




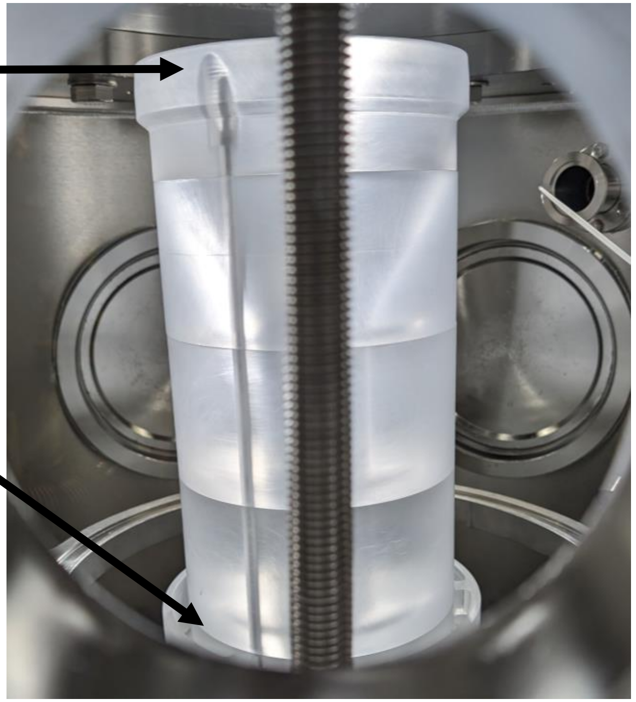
Upgrades

Position of deployed particulate removal tube





New radon-tight deployment system for particulate removal/external cooling



Replacement acrylic flowguide assembly made in Rn-clean room and coated with pyrene-doped polystyrene

The hardware upgrades will allow us to reach DEAP-3600 design sensitivity, allow us to verify the DEAP background model, and allow us to have a “zero background” data set.

1. Dust removal
    1. Liquid recirculation from detector
    2. Improved filtration on process systems
2. Elimination of neck events
    1. Scintillating coatings to tag neck alphas with PSD
    2. Possible external cooling to allow neck to stay warm
3. Replace faulty VETO PMTs
4. Many maintenance/process improvements

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- Needs of larger detectors
  - Underground argon – low in ^{39}Ar
  - Better control of surface backgrounds – coatings
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- ARGO
- Getting there – the Canadian group's medium-term plans

DEAP-3600 the largest detector you can make with atmospheric argon

Argon signal is about 10 microseconds long

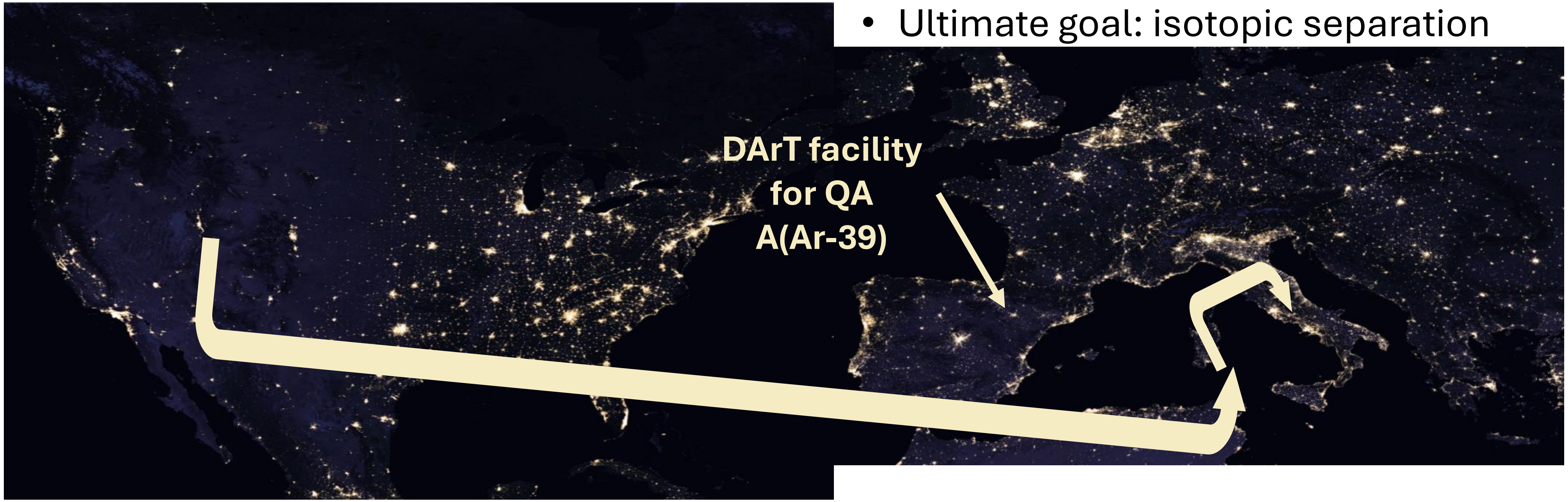
At 1 Bq/kg and 3300kg in DEAP-3600,

~3.3% of events contain random Ar-39 pile-up

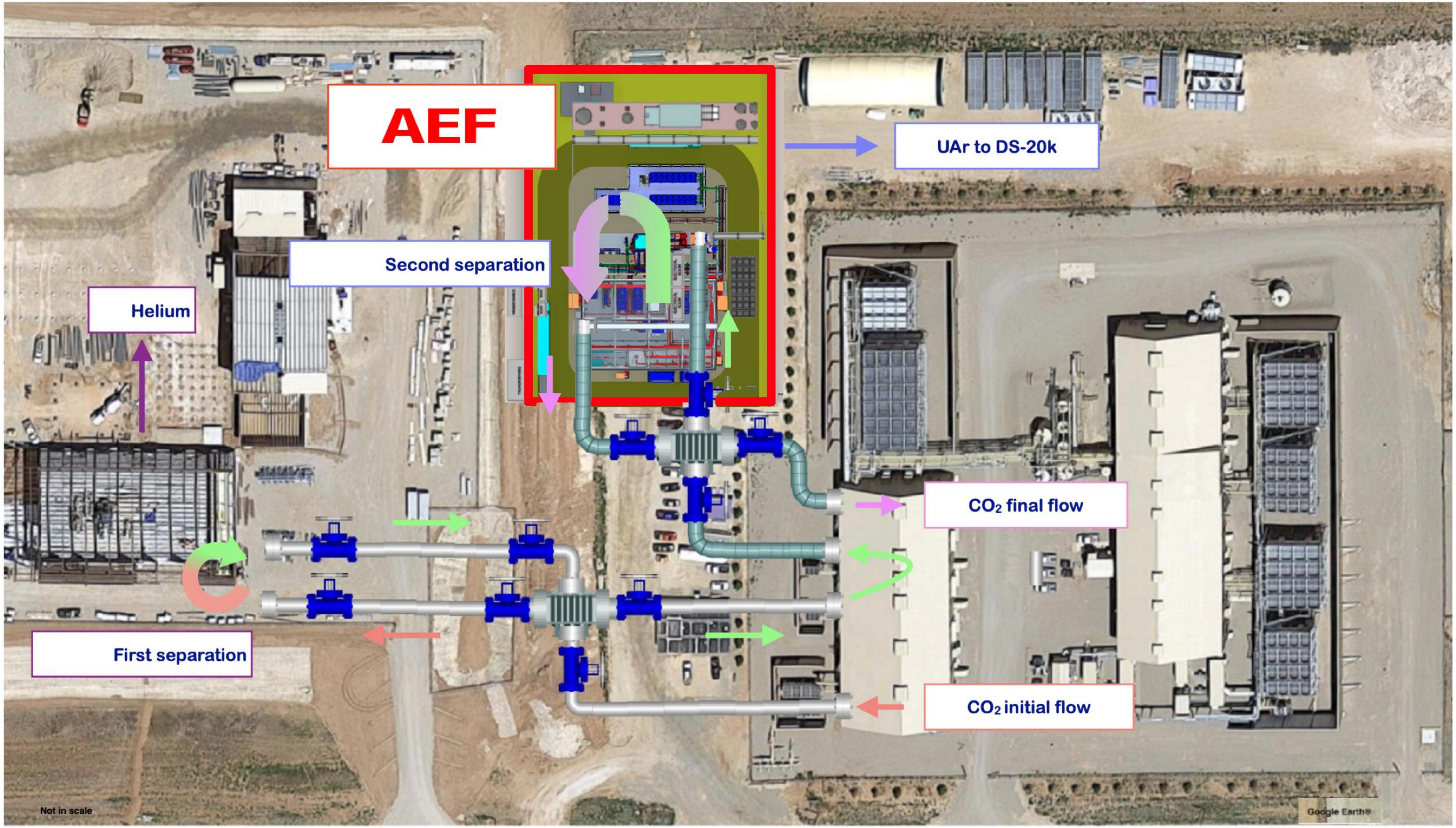
Industrial Scale Underground Argon Production

- **Production: Urania**
- **Cortez, CO**
- Industrial scale extraction plant
- Extraction rate: 250-330 kg/day
- Production capability ≈ 120 t over two years
- UAr purity: three-four nines

- **Production: Aria**
- **Sardinia, Italy**
- Industrial scale extraction plant
- 350 m cryogenic distillation column
- O(1 tonne)/day capability
- UAr purity: > six nines
- Ultimate goal: isotopic separation



The Urania Plant at Kinder Morgan



The ARIA Prototype runs were successful

- The prototype tower is 26m tall
- Isotopic separation of Ar-36, Ar-38, and Ar-40 has been demonstrated.

https://doi.org/10.1140/epjc/s10052-021-09121-9

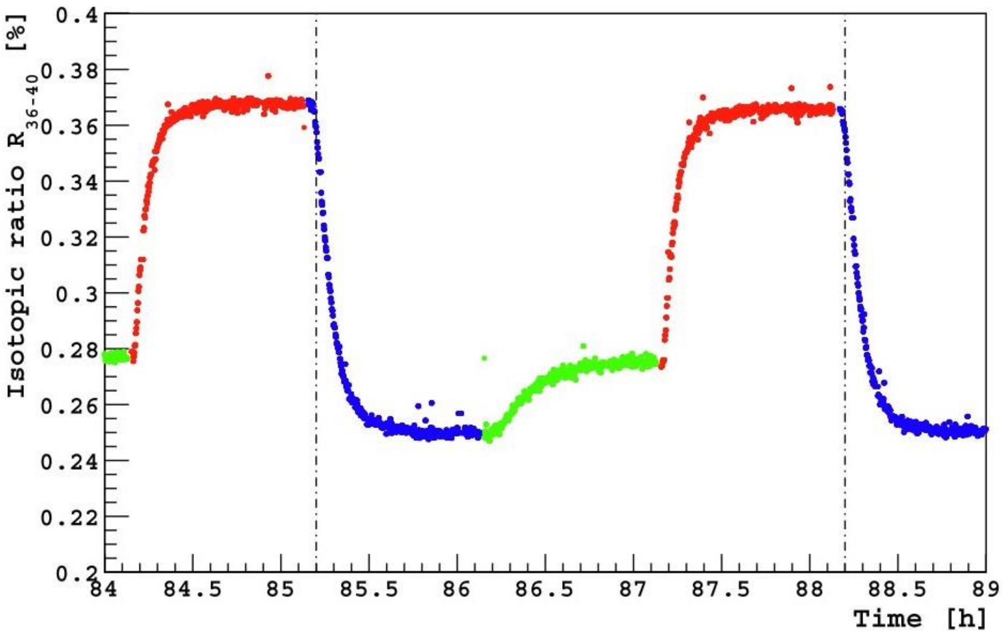
https://doi.org/10.1140/epjc/s10052-023-11430-0

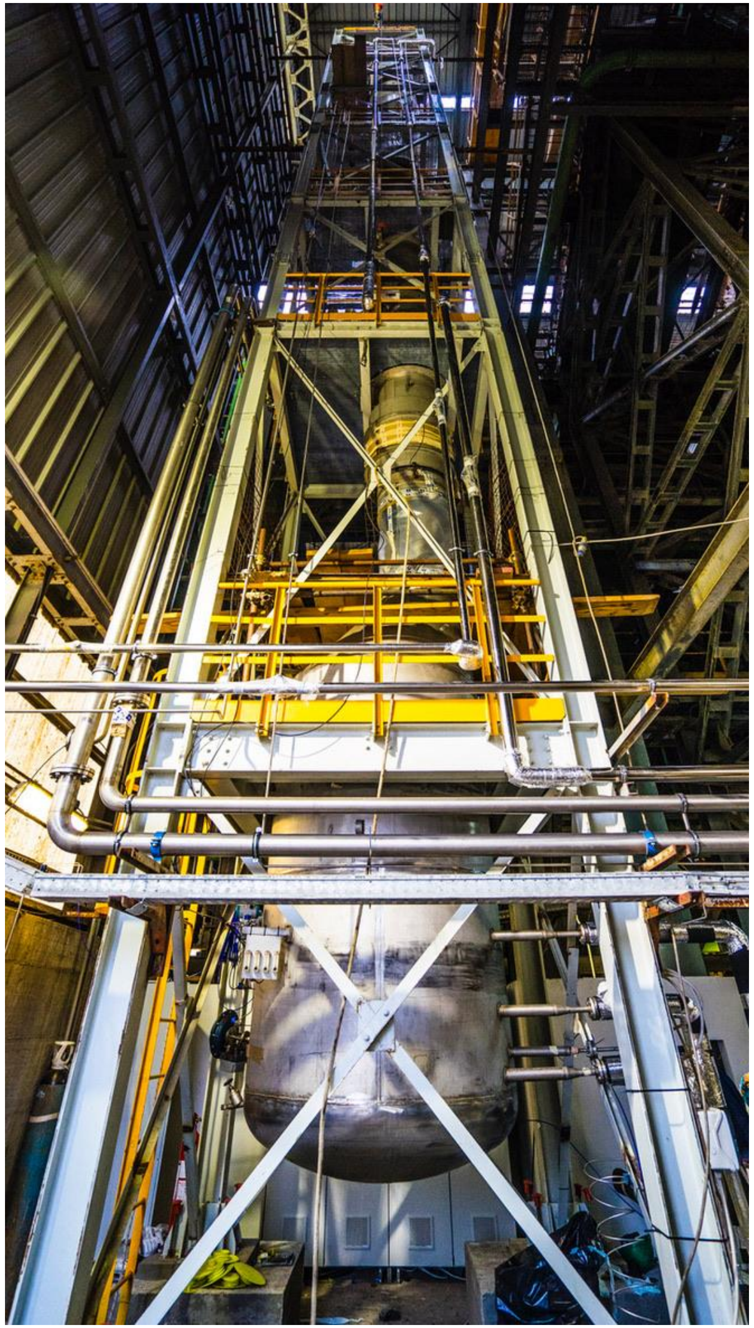
0.36% top of tower

Ratio Ar-36/Ar-40

0.28% feed

0.25% bottom





The DArT in ArDM QA detector measures A(Ar-39) in ~ kg samples in 1 week

DOI 10.1088/1748-0221/15/02/P02024

ArDM acts as Compton suppression and veto detector.

Use atmospheric argon to calibrate the signal shape.

1400x depletion measured with 7% statistical error.

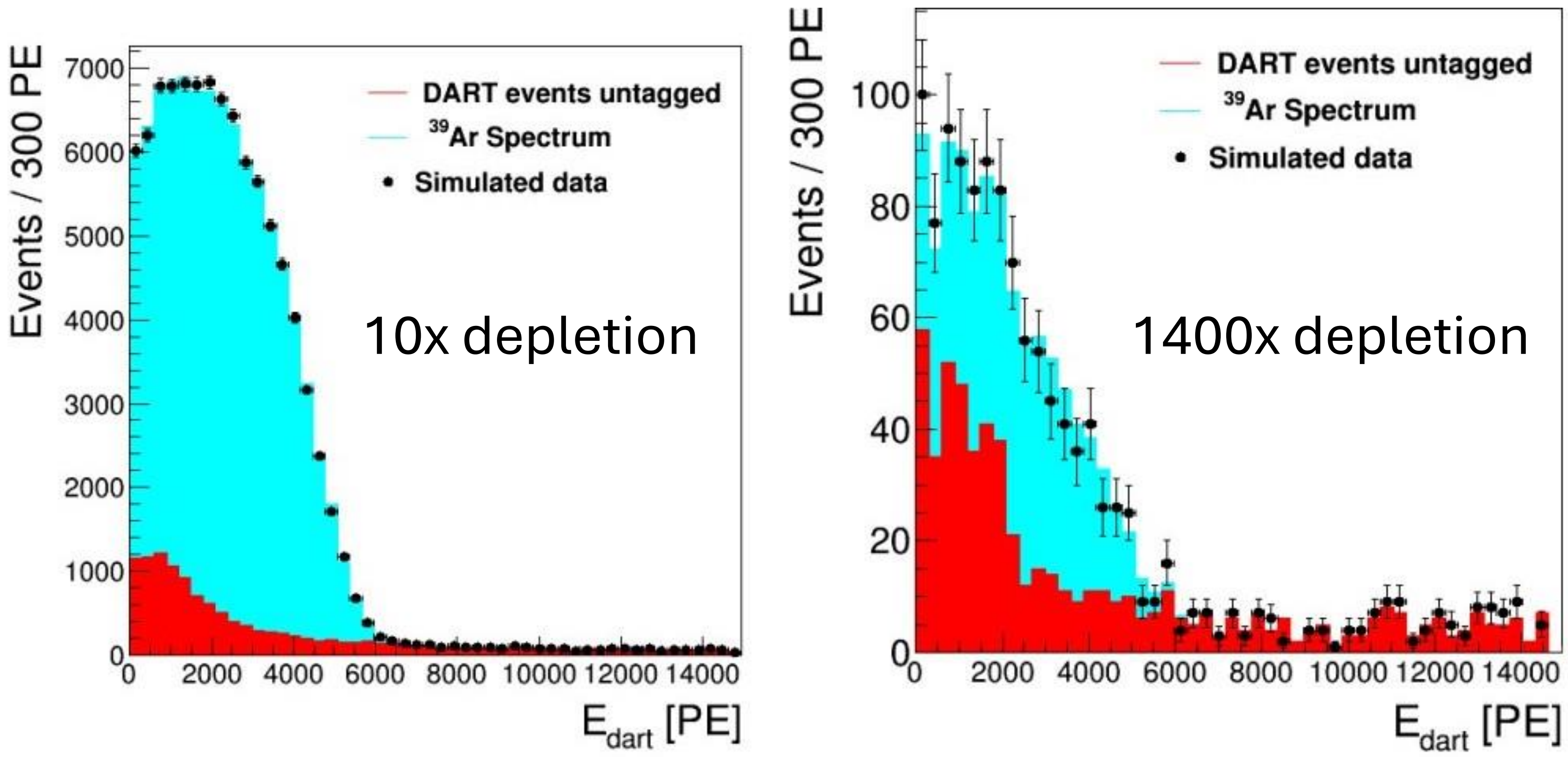
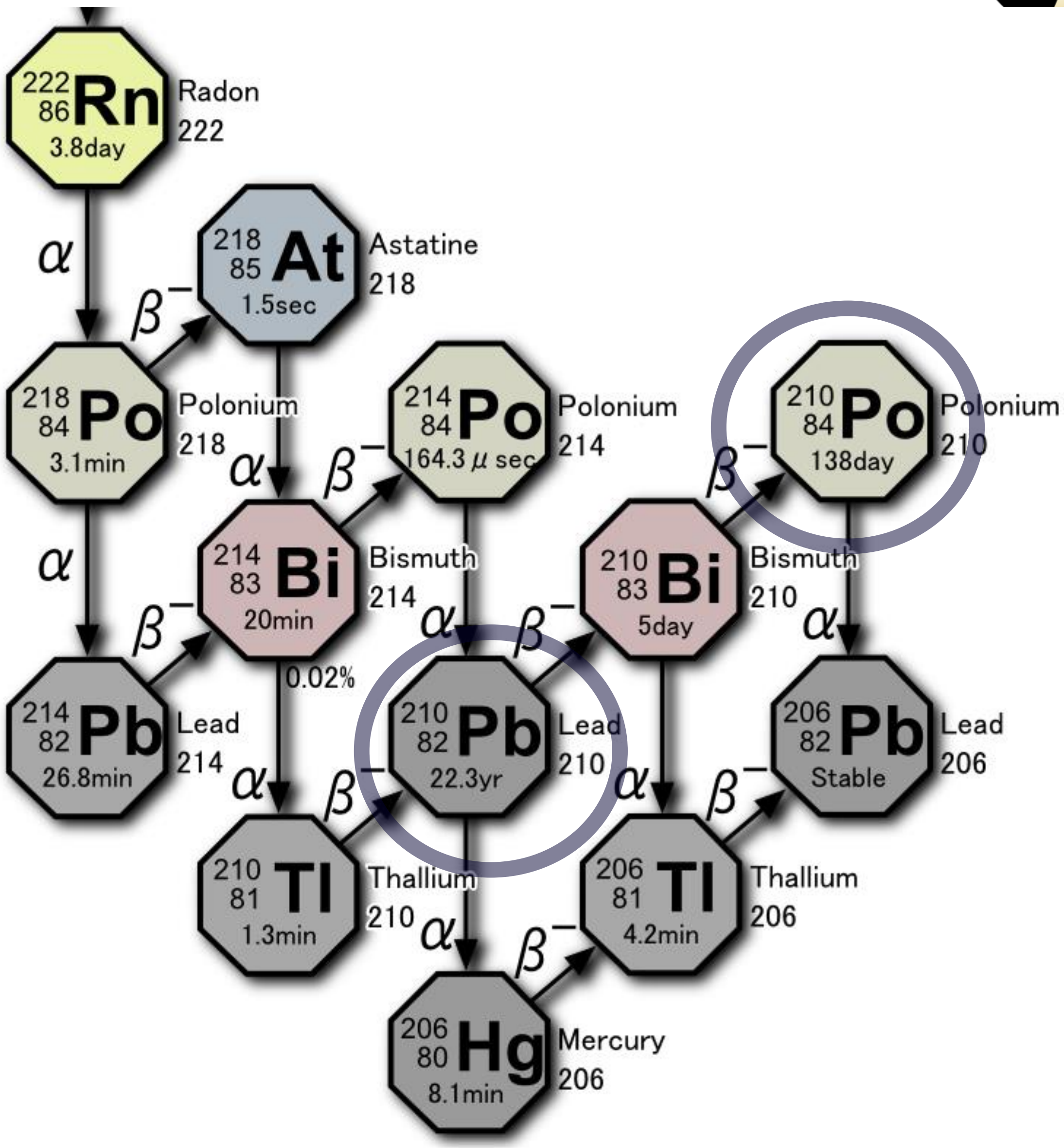


Figure 8. Photo-electron spectra corresponding to one week of data taking, (left) for an ^{39}Ar *DF* = 10 without lead shield and (right) for *DF* = 1400 with lead shield. The red (dark) histogram represents the background spectrum, the blue (light) histogram is the ^{39}Ar signal and the black dots denote the simulated data.

Larger detectors will requite improved control of backgrounds from surfaces

- Detectors are built with large volumes and we use position reconstruction to suppress events from surfaces.
- Exposure of surface to Rn builds up ^{210}Pb (22.3 yr half life)
- ^{210}Po (138 day half life) produces alphas that mimic WIMP signals.



Coat the Surfaces with Scintillating Materials

Pyrene doped polystyrene is excited by VUV light from argon scintillation.

The pyrene has a scintillation time of ~280 ns and results in a pulse shape different from WIMP interactions in argon.

Need to develop large-area coatings that allow suppression of alpha decays from surfaces in generation 3 experiments.

https://arxiv.org/abs/2109.06819

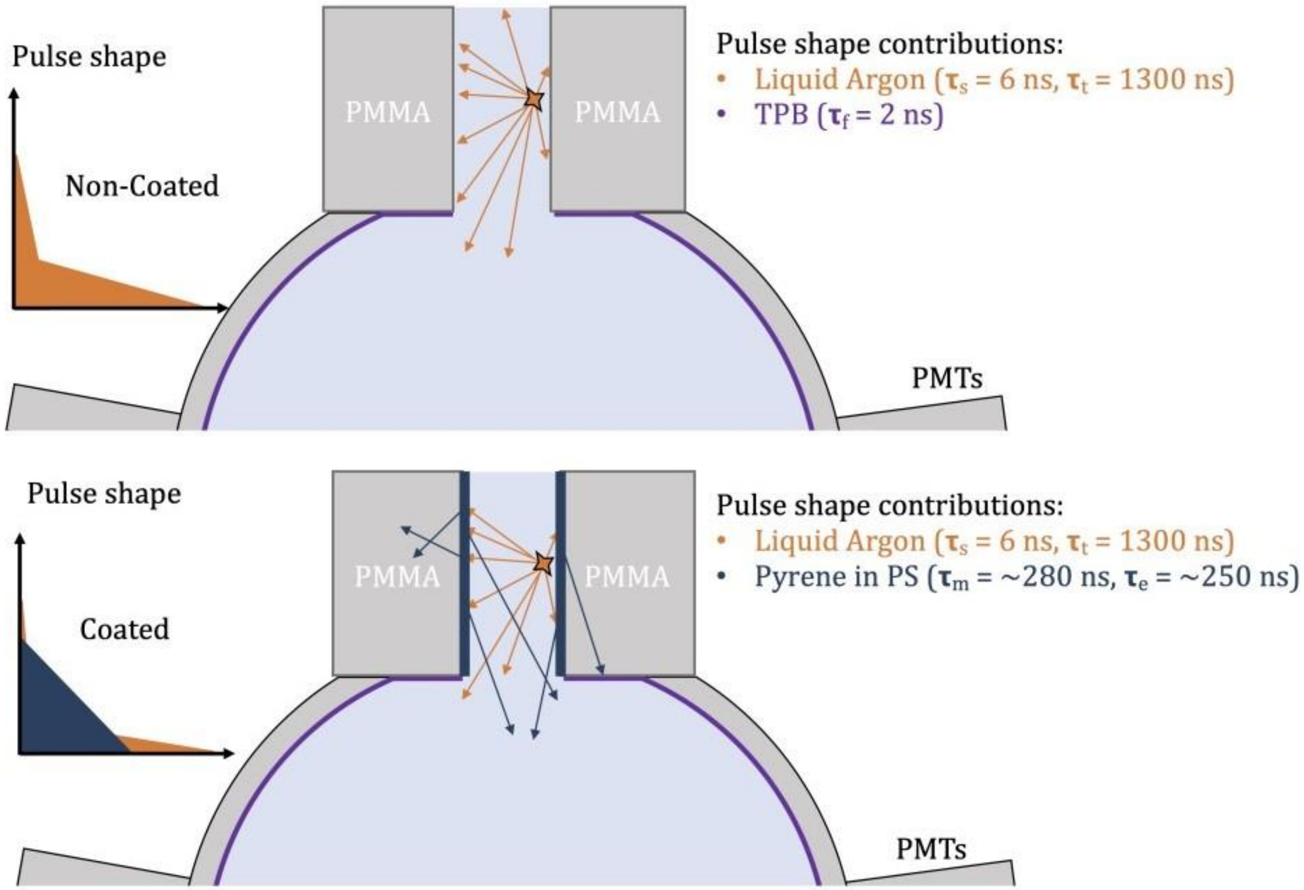


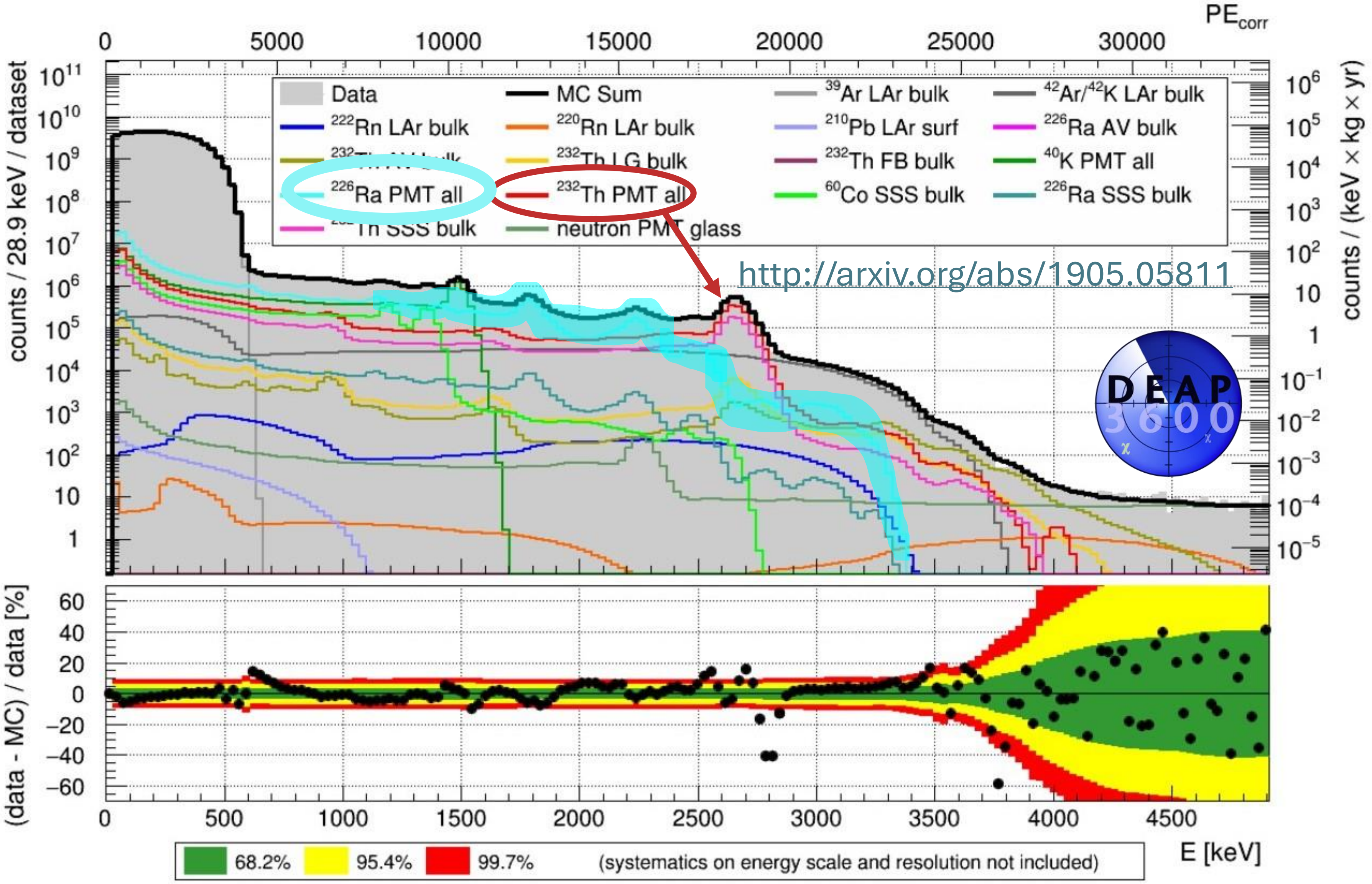
Figure 1: Top: α scintillation event occurs in the neck of the DEAP-3600 detector, VUV scintillation light is absorbed by the acrylic of the neck and produces a shadowed low energy, highly prompt, event that mimics a potential dark matter signal. Bottom: VUV light from α scintillation in argon is absorbed by the pyrene + PS film coating and is shifted to visible and delayed by the time constant of the film. This produces events with a strong "intermediate" component that can be tagged efficiently using PSD, as illustrated by the inlaid pulse shapes.

DarkSide-20k and ARGO Require Improved Photon Detection

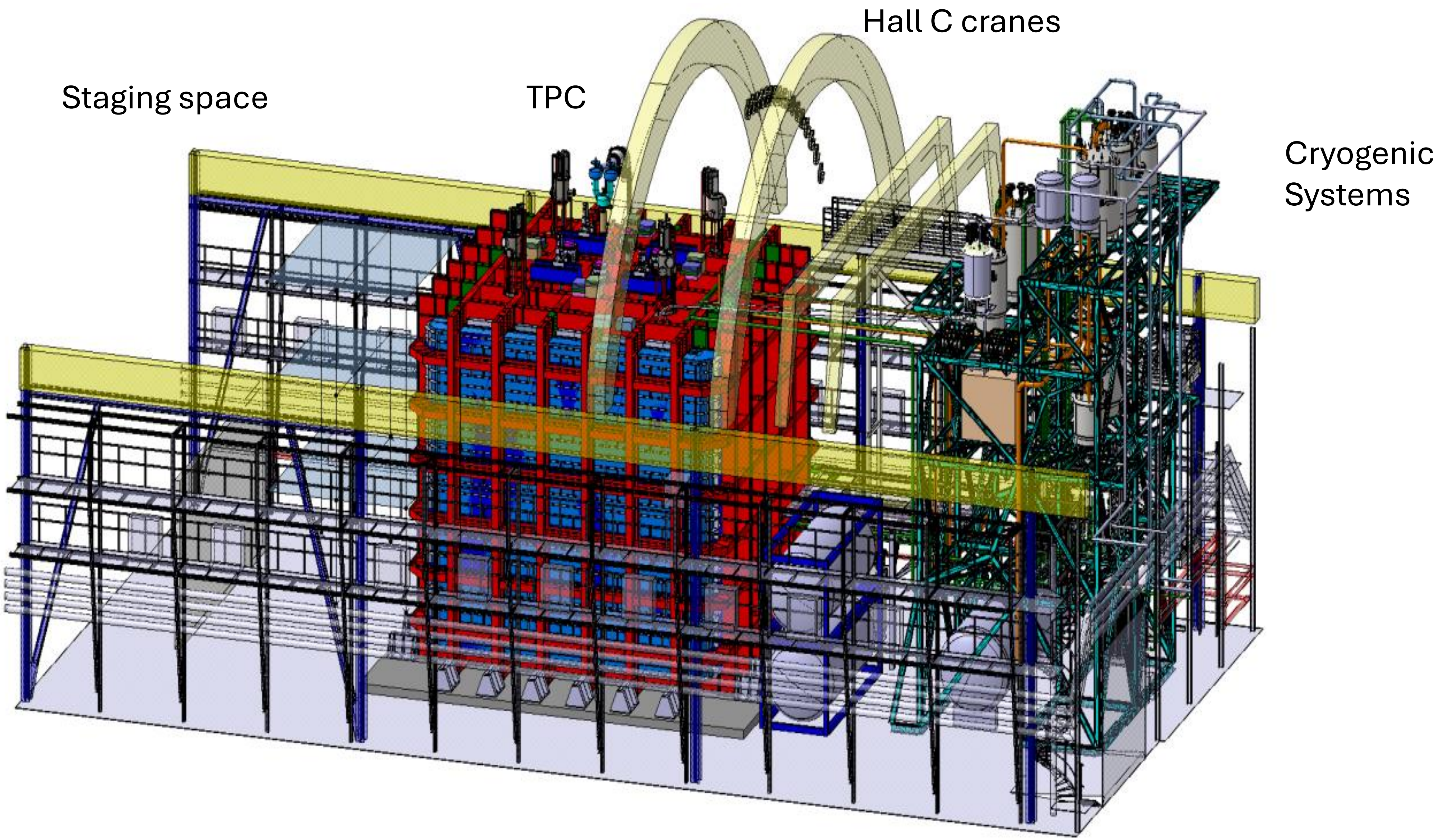
Conventional photomultiplier tubes are great, but:

1: They are made of glass, which is radioactive by our standards

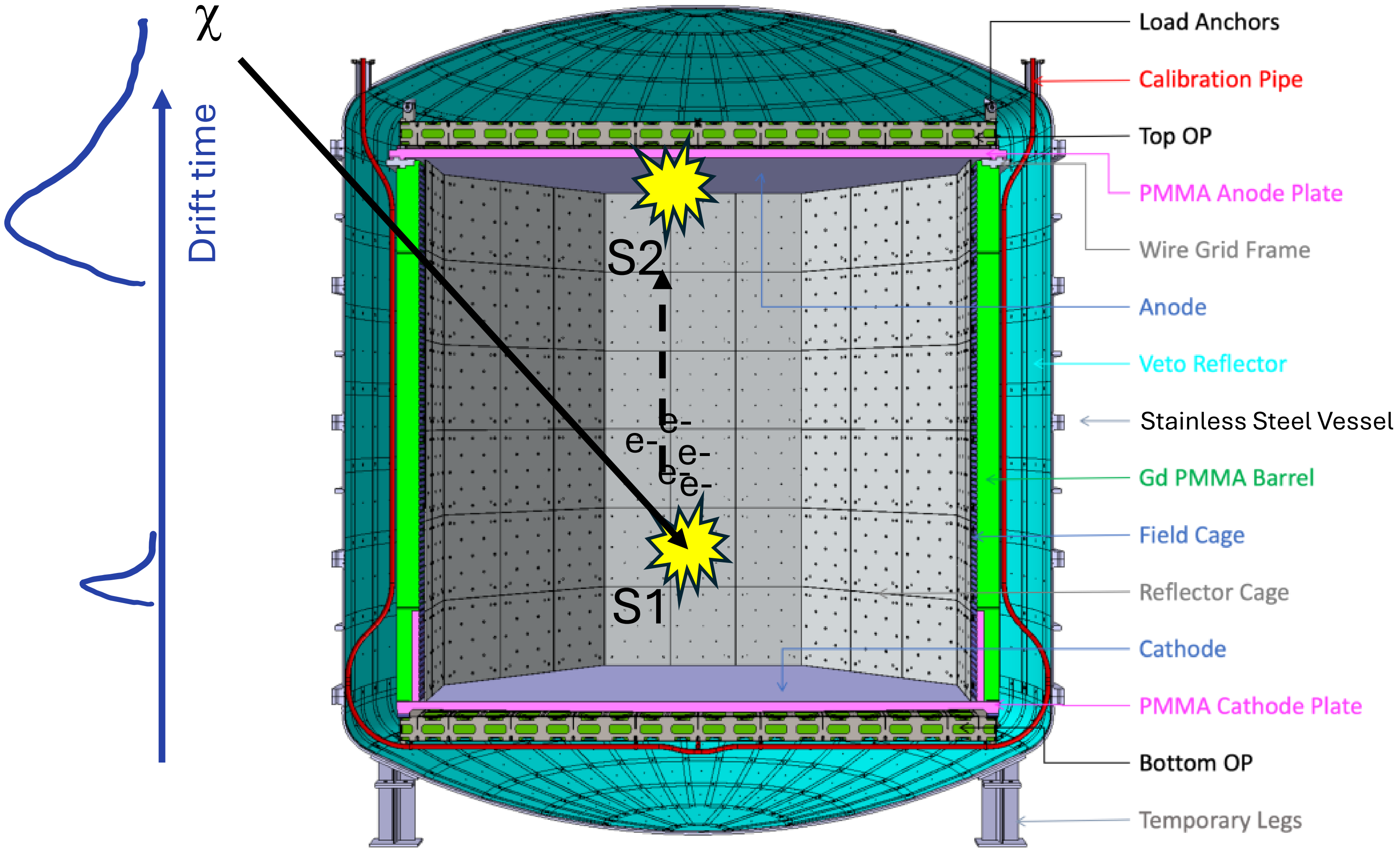
2: The glass contains Boron (Borosilicate glass) which has a high (α,n) cross section



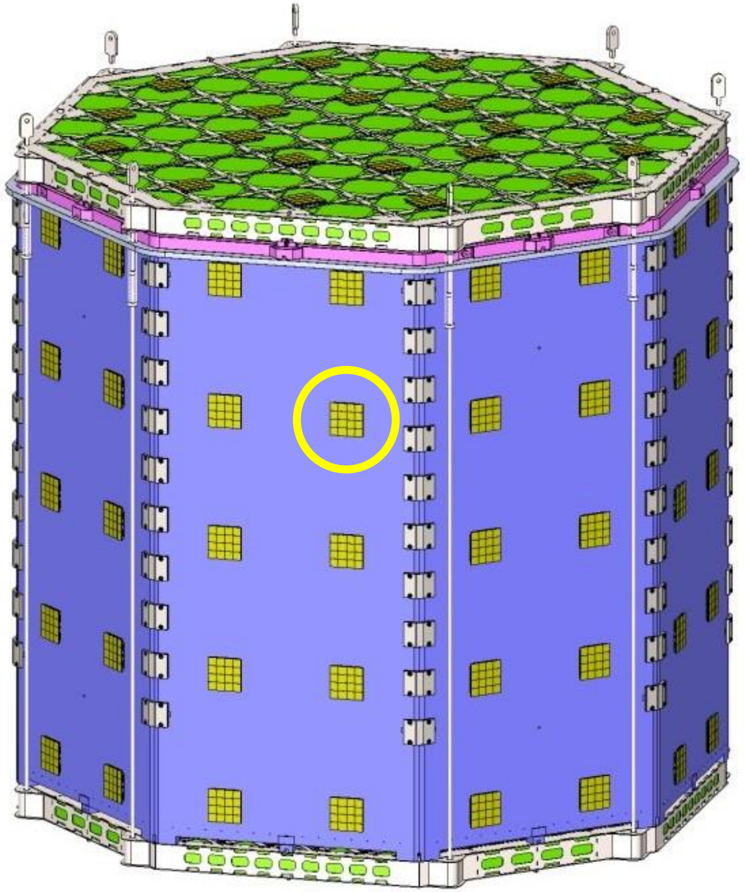
DarkSide-20k is under construction at LNGS



DarkSide-20k is a two-phase Underground Argon TPC with 20t fiducial volume

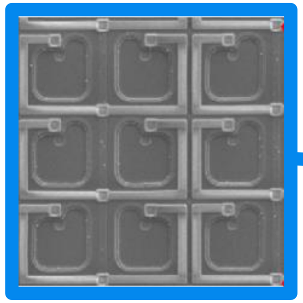


... surrounded by an instrumented LAr veto

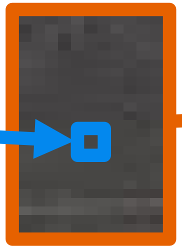


Low-radioactivity, Low-noise, High Efficiency SiPM Arrays

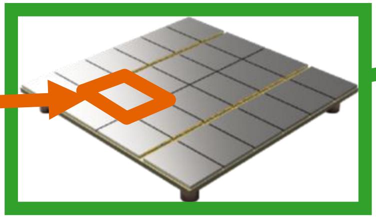
SPAD
30 x 30 μm²



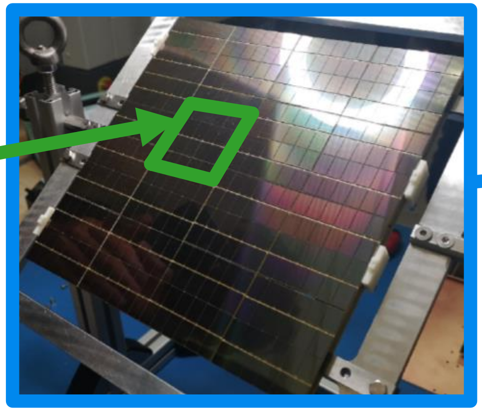
SiPM
8 x 12 mm²



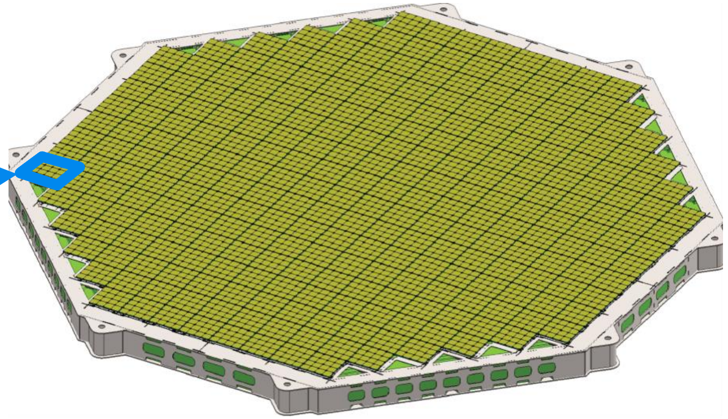
Tile (24 SiPM)
5 x 5 cm²



PDU
20 x 20 cm²



Optical Plane (264 PDUs)
21m² in TPC; 5m² in veto



PDU packaging and assembly at Nuova Officina Assergi (NOA) at LNGS

Low-Mass Analog SiPM Tiles are ready for deployment in DarkSide-20k

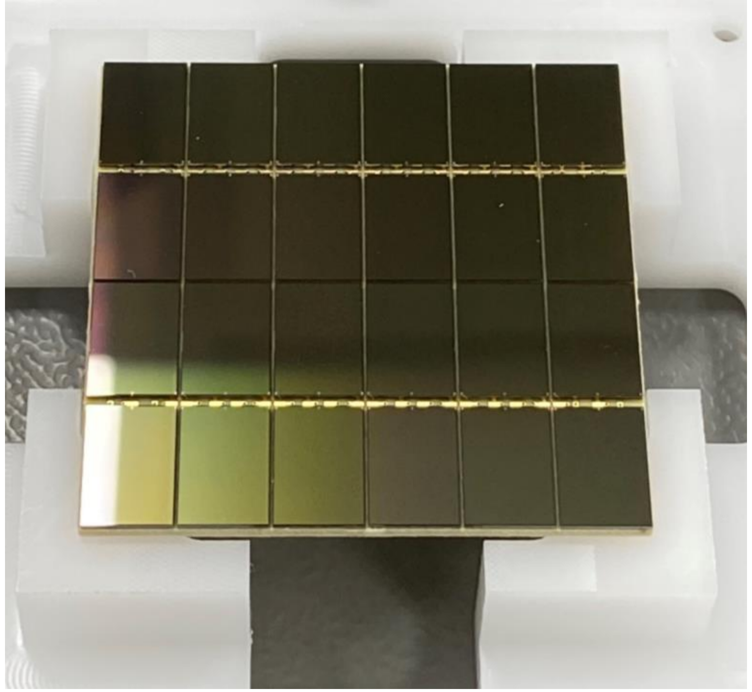
A DarkSide Tile is shown with a low-mass circuit board. Has one signal amplifier.

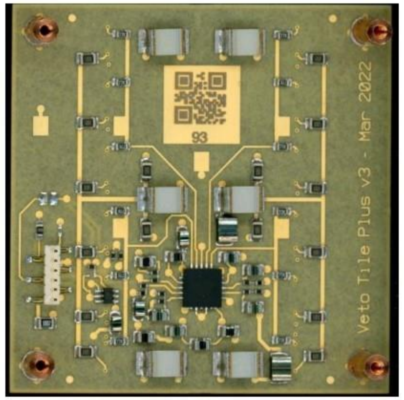
Silicon photomultipliers by Fondazione Bruno Kessler, model NUV-HD-CRYO meet all requirements on photodetection efficiency, low noise at liquid argon temp.

All individual components and whole assemblies pass radiopurity requirements for DarkSide-20k

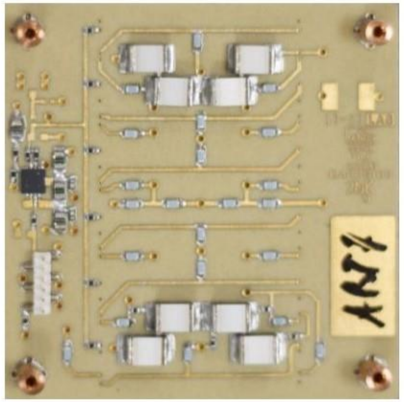
Photon detection efficiency: **>40%** at 77 K
Dark count rate: **<0.01 Hz/mm²** at 77 K
SNR: **>8** for 10×10 cm² TPC PDU)

https://doi.org/10.1088/1748-0221/12/09/P09030



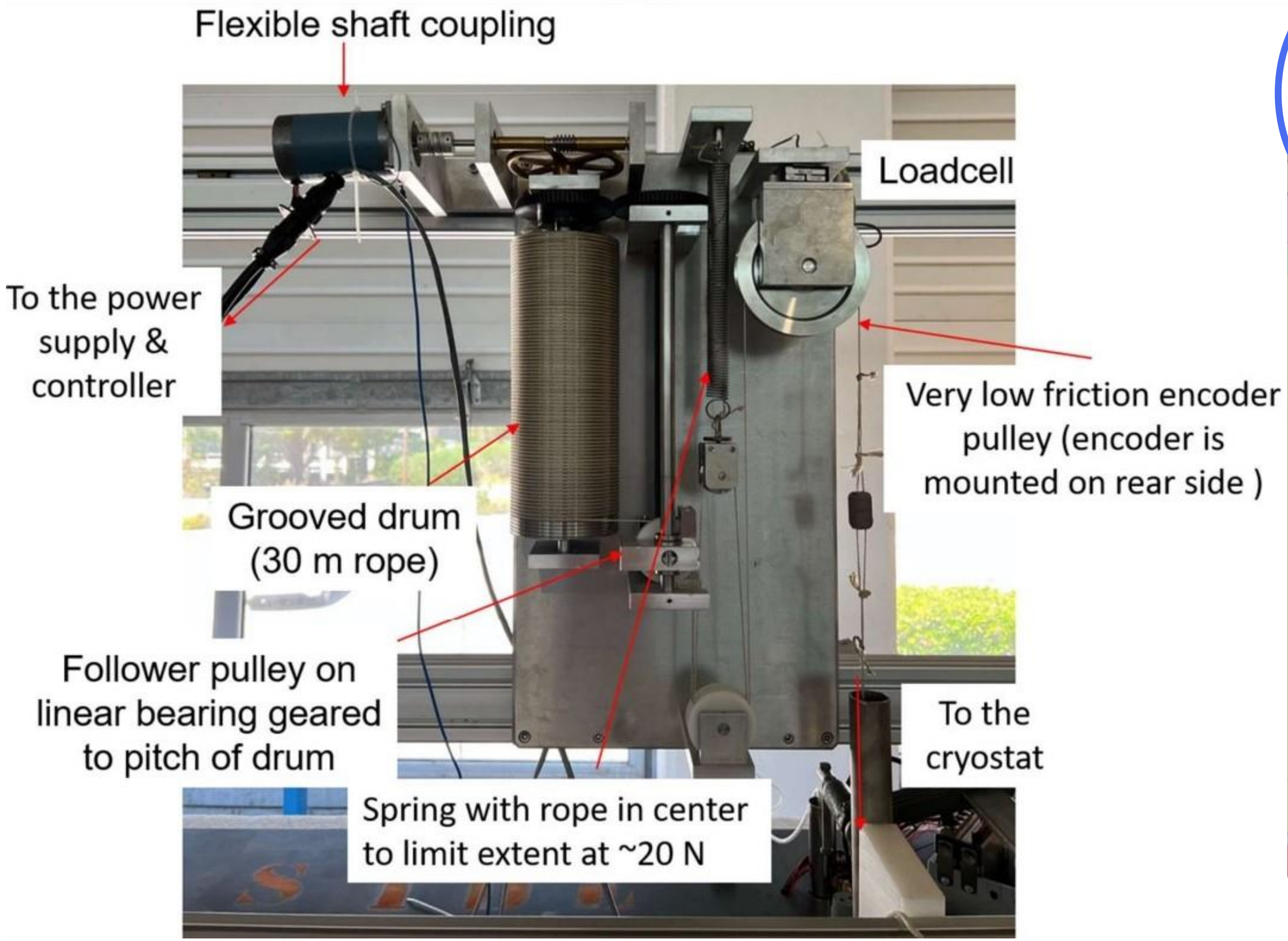


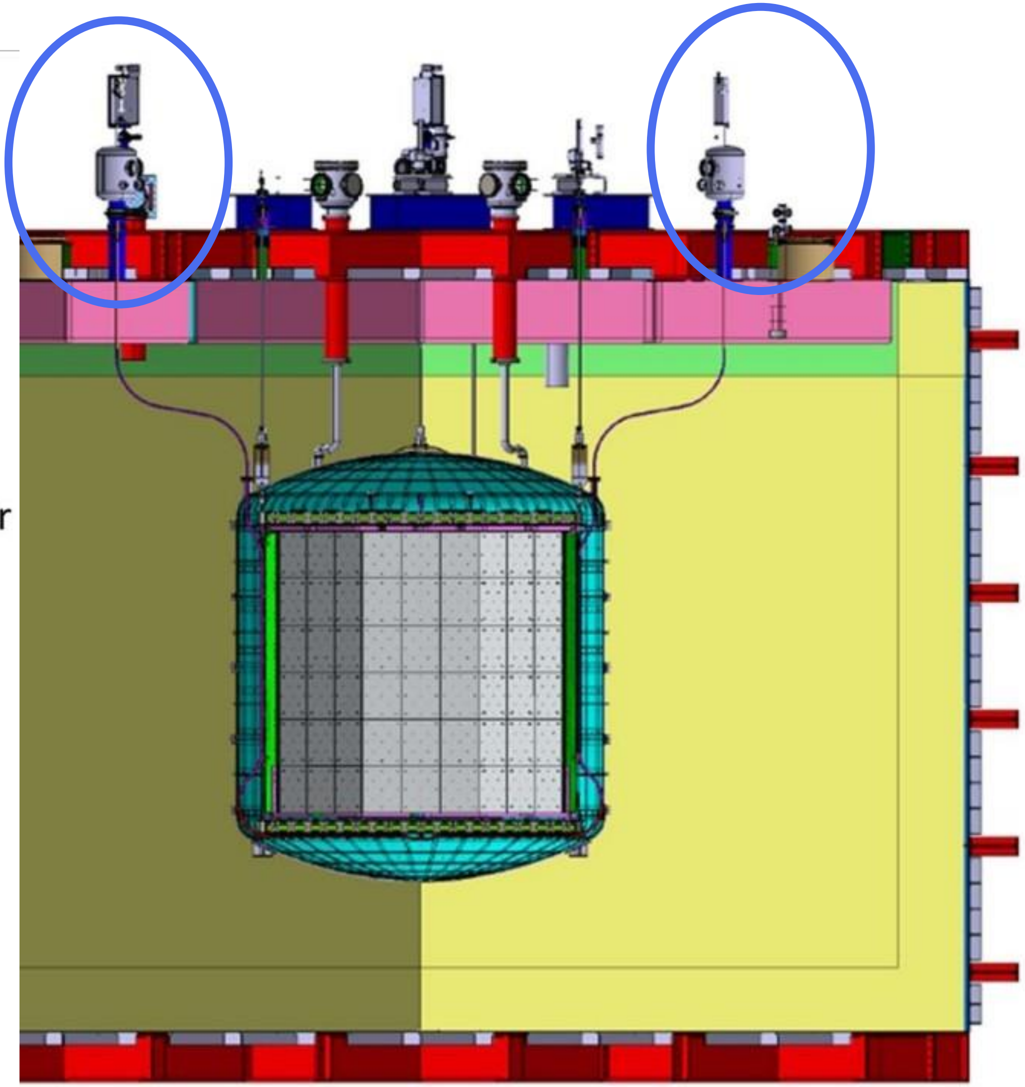
vTile backside



TPC Tile backside

SNO-style motor & pulley for calibration deployment

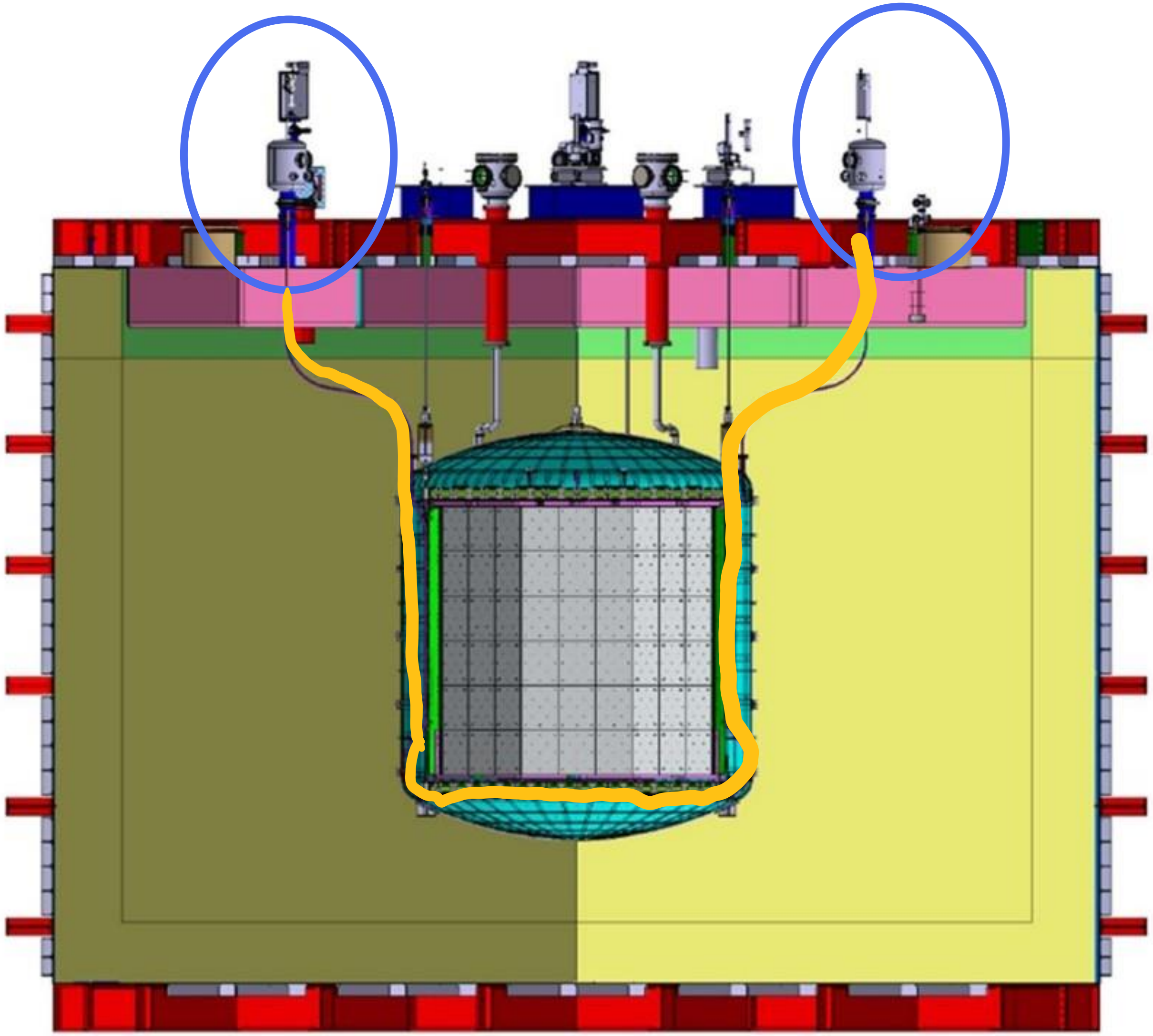




SNO-style motor & pulley for calibration deployment

Control code expanded to work in mode of keeping two ends of a rope in tension. Friction modeled. (Source deployed in tube highlighted yellow.)

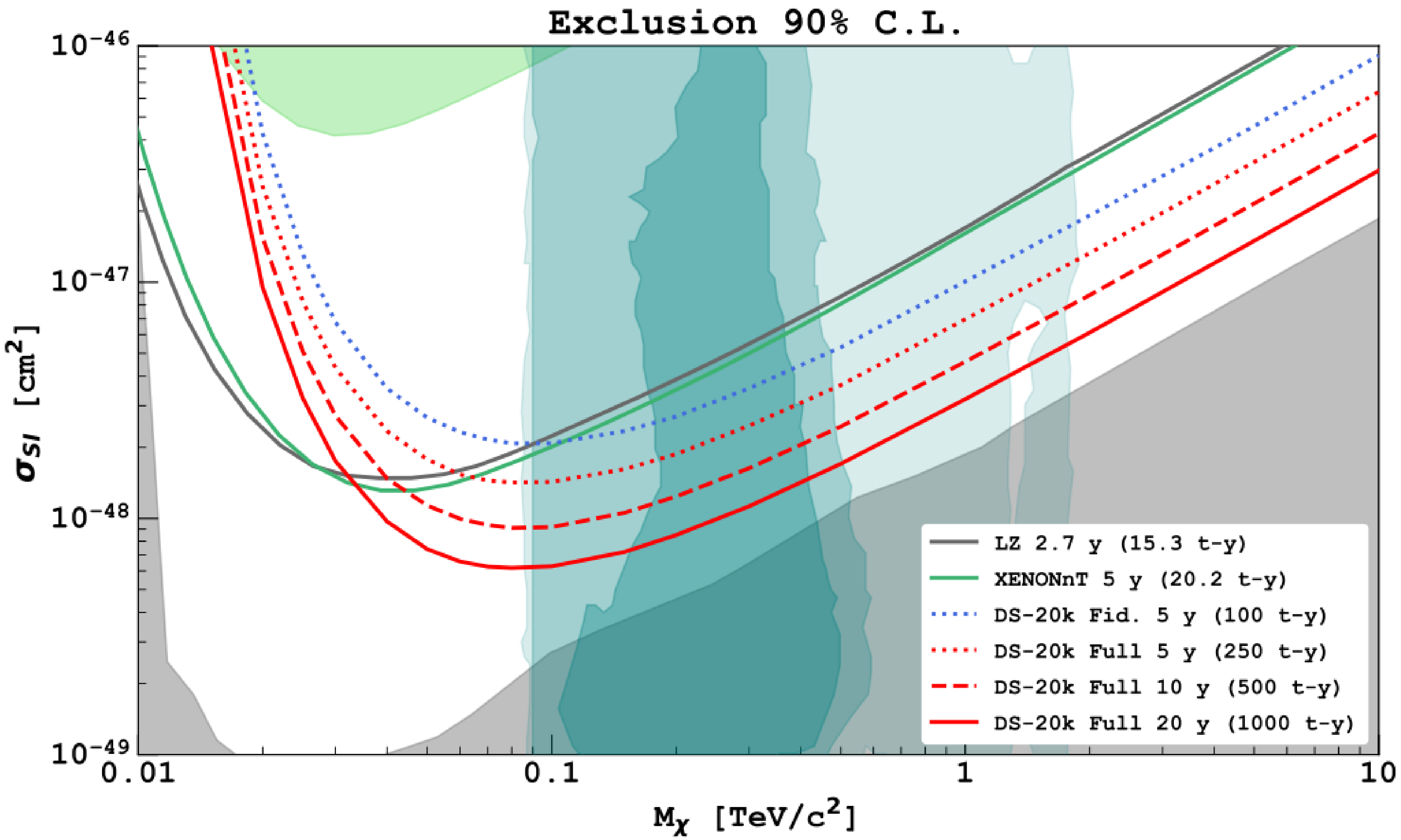
Cryo-tests passed.



Projected Sensitivity of DarkSide-20k

Expect 3 events in 200 ton x year from neutrino coherent scattering

Underground Argon target, excellent PSD, and neutron veto allow zero instrumental background



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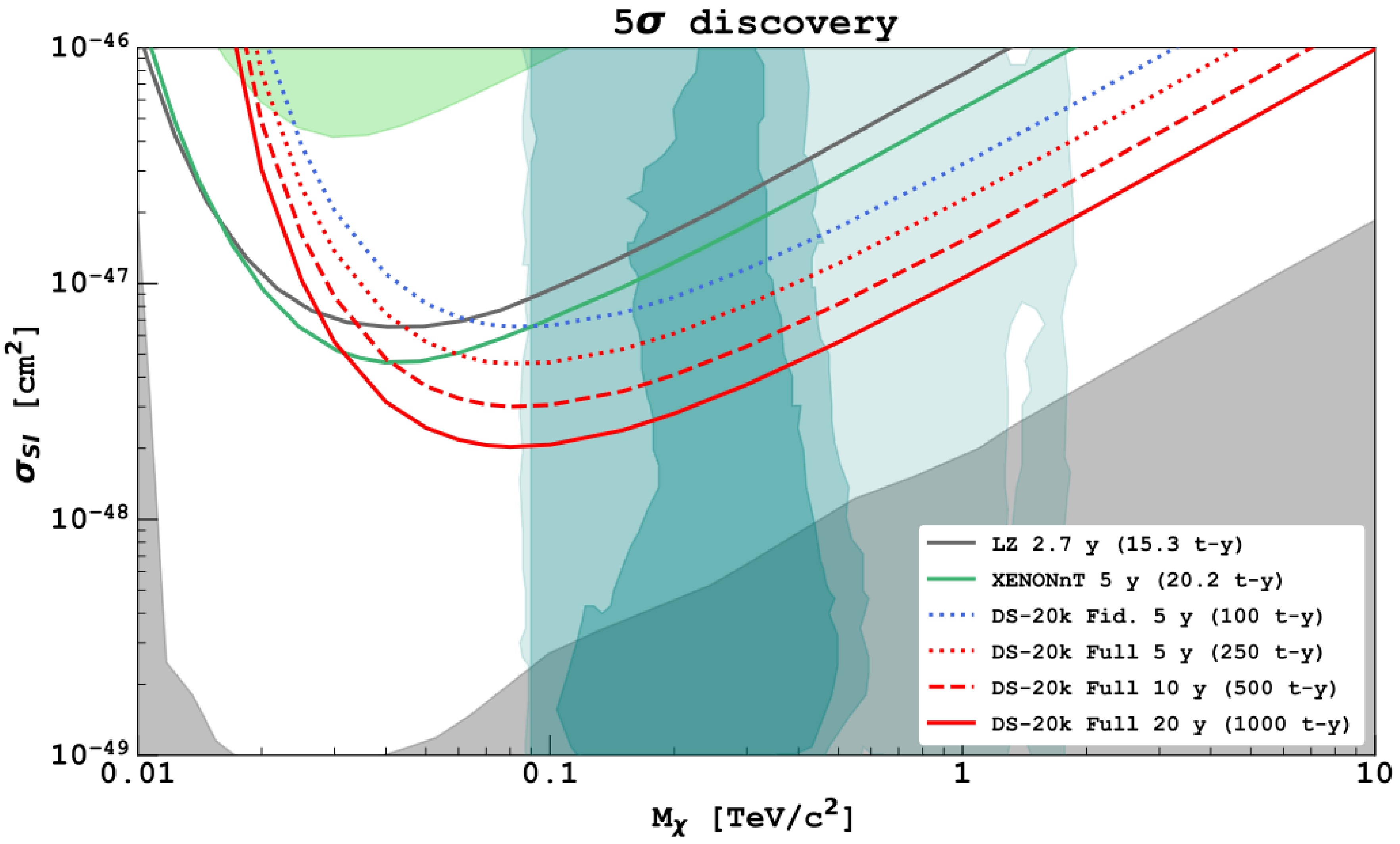
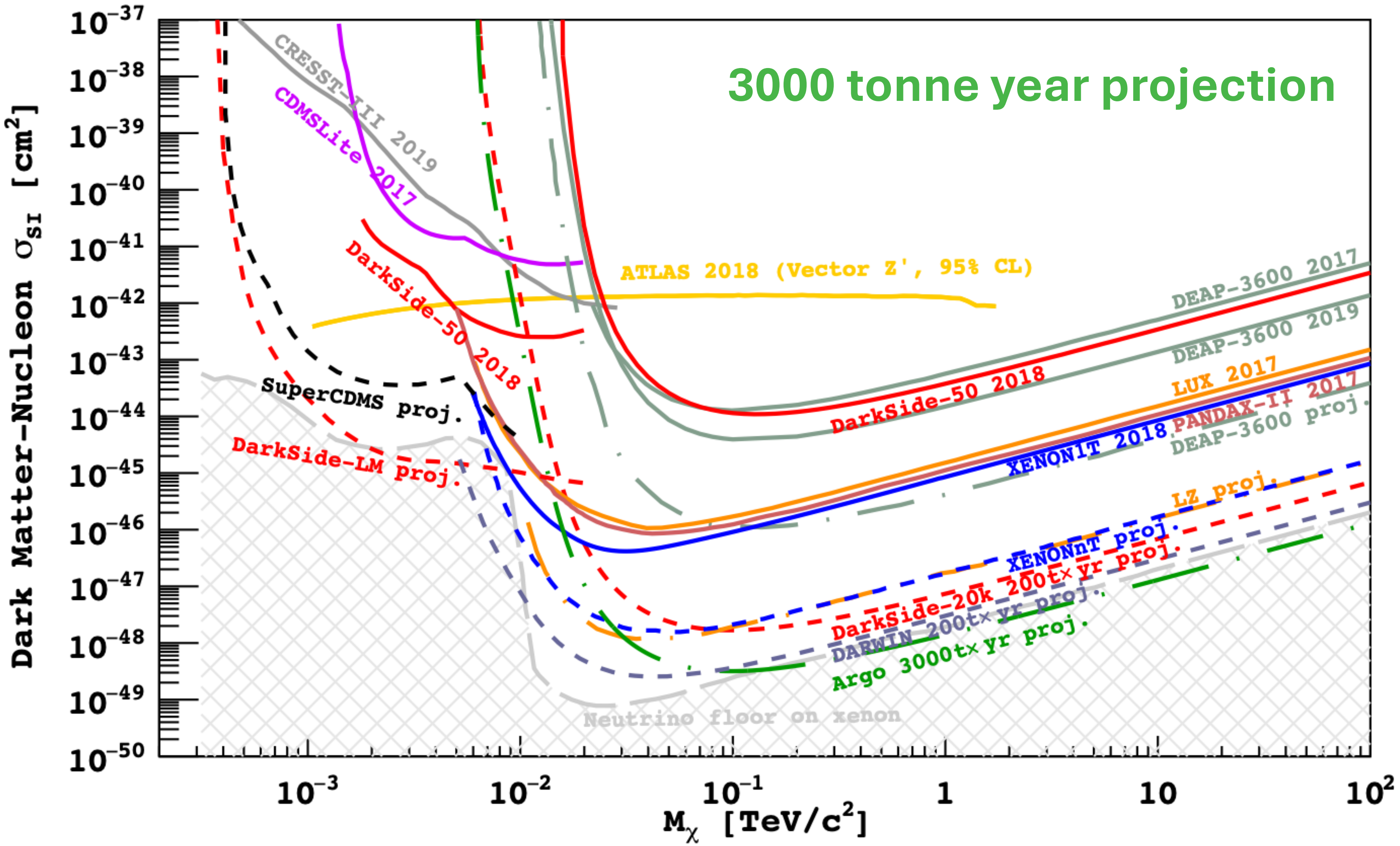


Overview

- The Past and Present
  - Some highlights from DarkSide-50
  - DEAP-3600
- Needs of larger detectors
  - Underground argon – low in ^{39}Ar
  - Better control of surface backgrounds – coatings
  - Lower radioactivity light collection – from PMTs to SiPMs
- DarkSide-20k
- ARGO
- Getting there – the Canadian group's medium-term plans

ARGO: a multi-hundred tonne detector



A Large Two-Phase TPC and a Single-Phase Detector are Being Considered

- The first choice of site is SNOLAB
- The second choice of site is SURF

The D.O.E. in its DOE Perspectives on the P5 Report as part of the HEPAP process, stated support for proposals

DOE response and actions : https://science.osti.gov/hep/hepap/Meetings/202405

- At the present time, based on the Snowmass Community Summer Study, there have been two proposals for G3 Dark Matter detectors : XLZD and ARGO
- Each concept has explored potential sites both within the US and off-shore.
- At the present time, DOE is supportive of the development of the off-shore concepts.
- DOE will entertain proposals by U.S. groups for pre-project R&D consistent with experiment deployment at an off-shore site.

ARGO Design Essentials

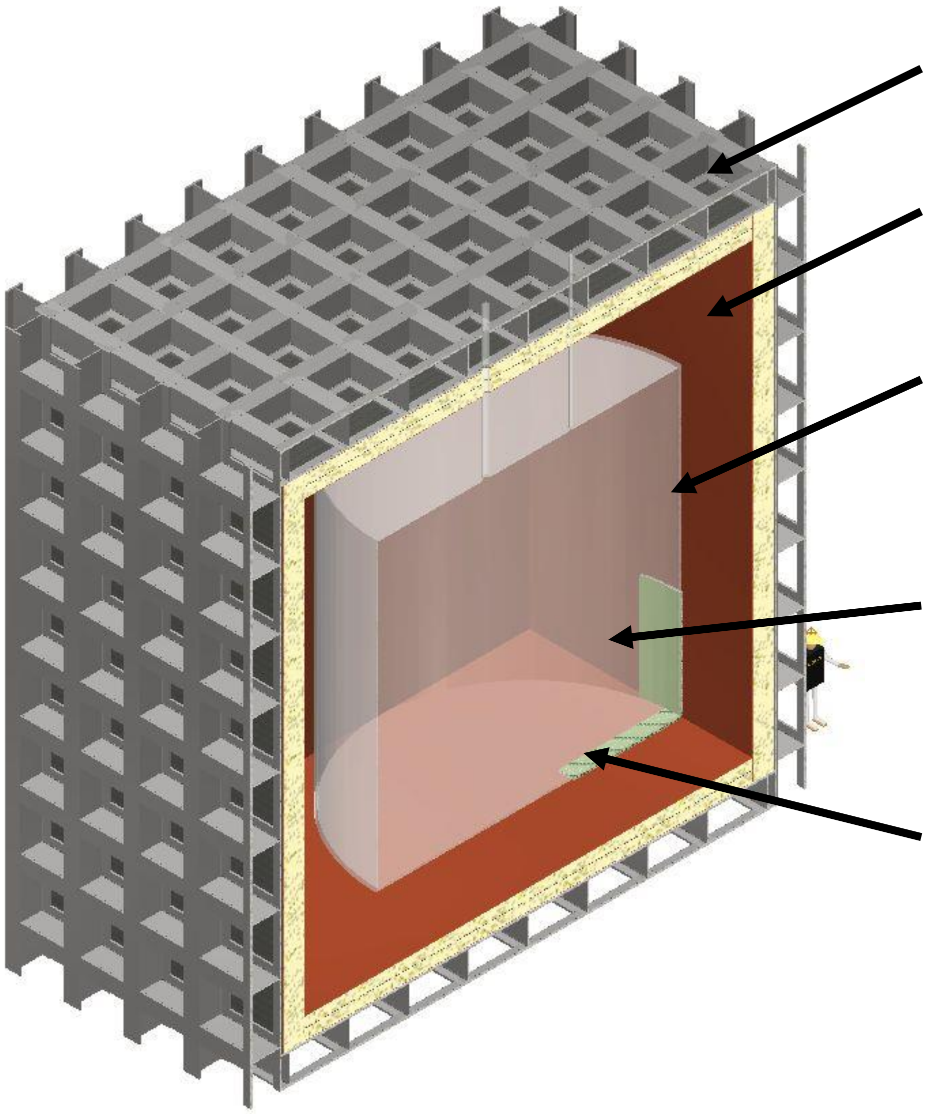
UAr Mass:

- total 400 tonnes;
- fiducial 300 tonnes.

SiPMs assemblies arranged as photon-to-digital converters (PDCs).

Data rates:

- operation 5k p.e./(m^2×s);
- calibration 100k p.e./(m^2×s).



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Preparing for ARGO – Canadian Context

- The Canadians in the GADMC are based at TRIUMF, The University of Alberta, SNOLAB, Laurentian University, Queen's University at Kingston, Carleton University, and the Université de Sherbrooke.
- We are working on a single-phase design and have laid out several tasks.
  - Development of Photon-to-Digital converters
  - Development of an AI-based DAQ to tease signal from noise and keep data rates manageable
  - Background estimation and creation of a background budget
  - Development of surface coatings to suppress backgrounds
  - Engineering of the detector and estimation of utility needs
  - Development of the ARgon UnderGround Storage (ARGUS)

Photon-to-Digital Converters

Low power

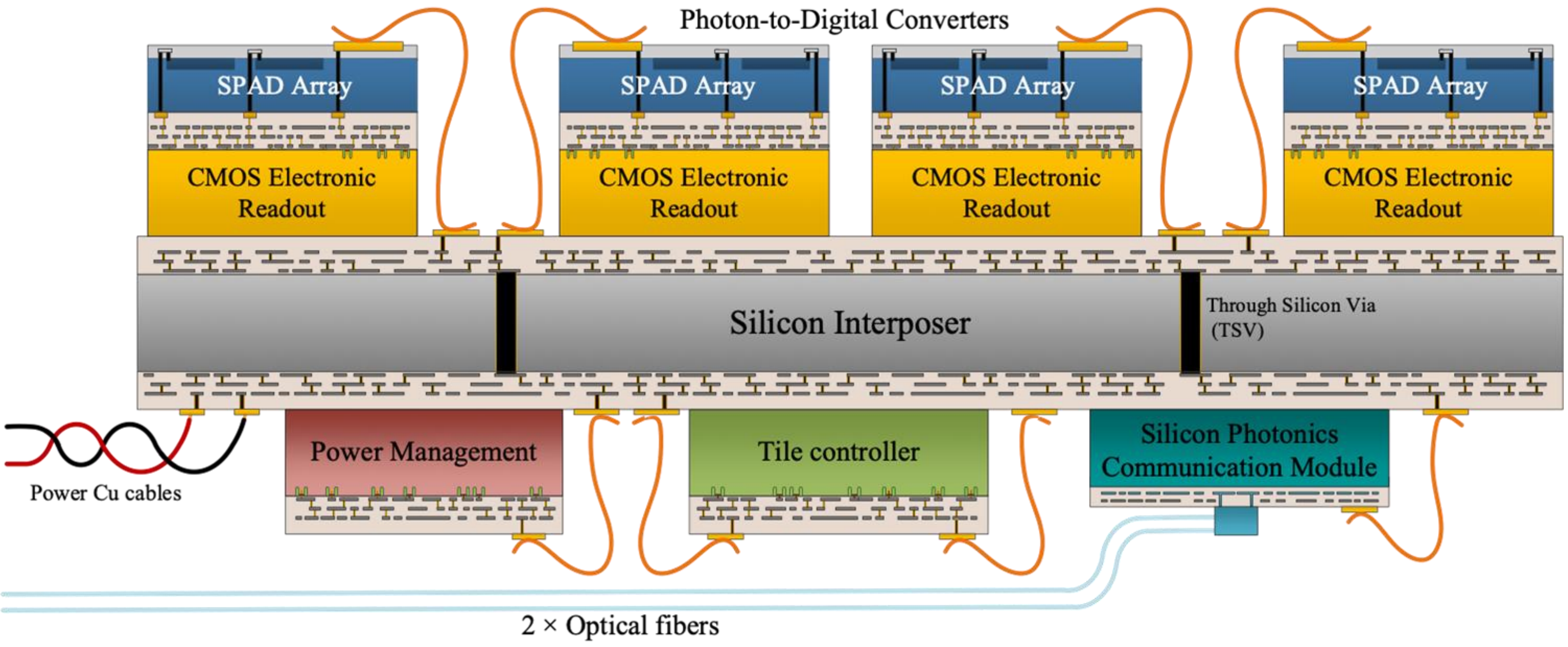
Electronics immediately behind the SPAD arrays

Digital output over fibre

Ability to control individual SPADs

Led by U Sherbrooke

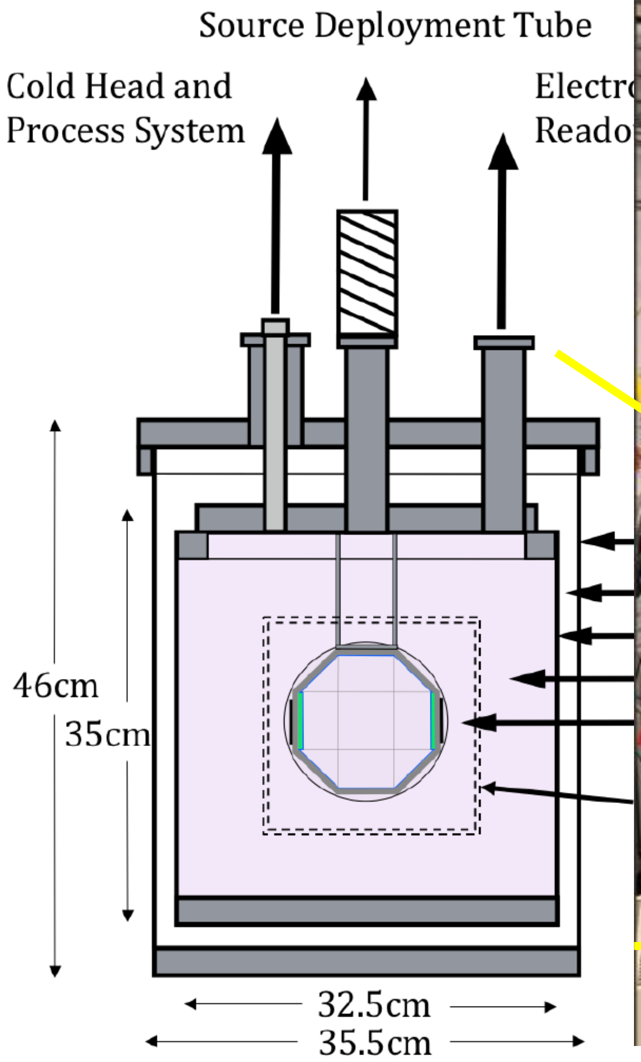
This work as received CFI IF support in 2017, 2020, and 2023

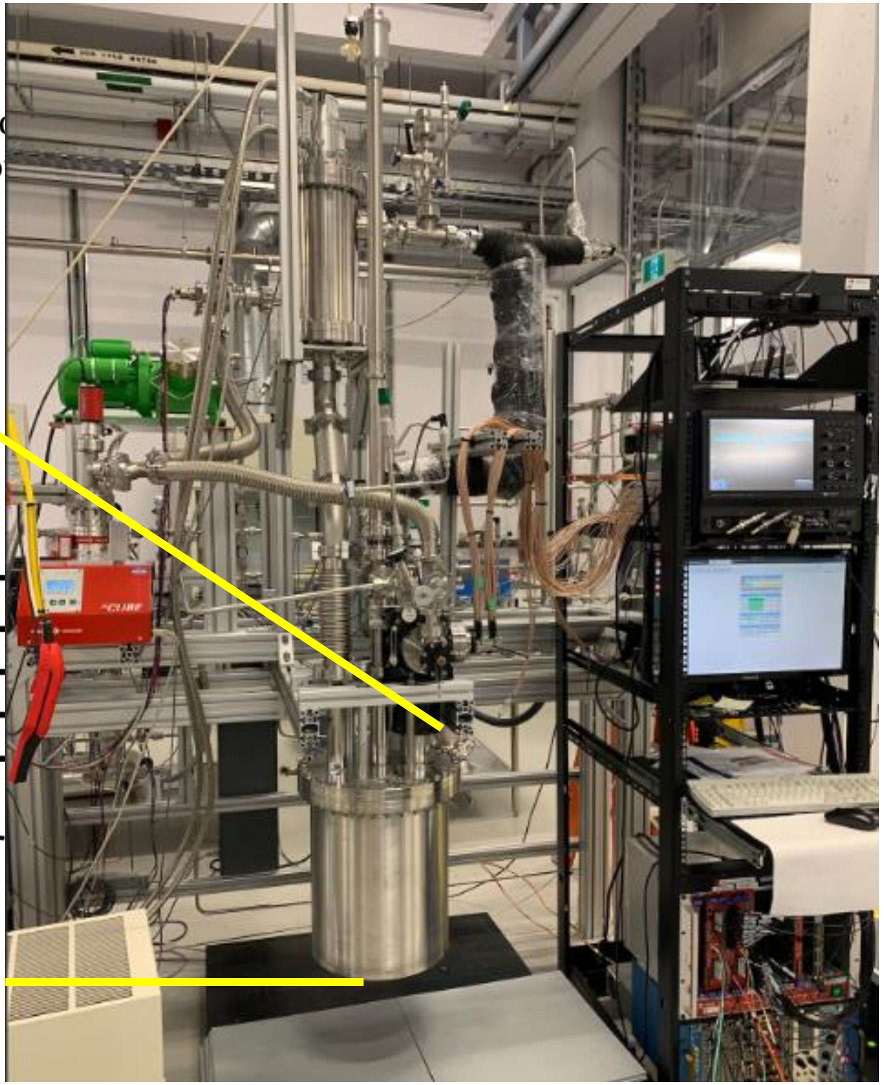


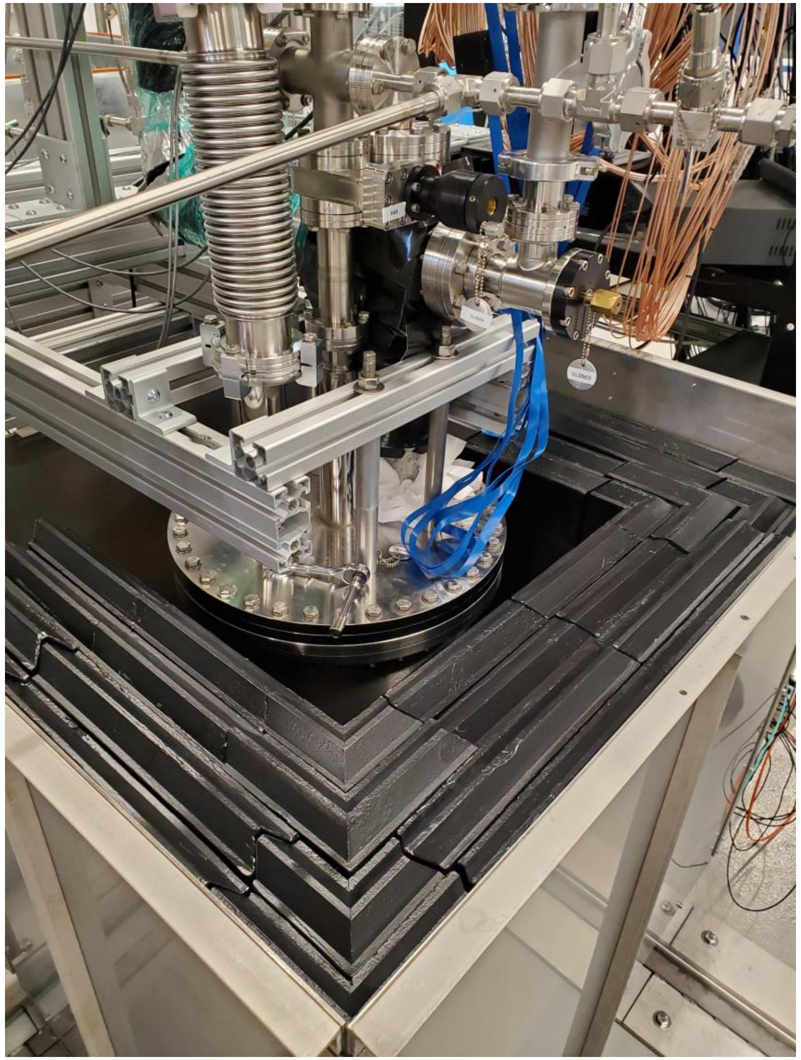
Smart DAQ and Edge Computing

- Audrey Corbeil Therrien (Canada Research Chair) in Electrical Engineering at U. Sherbrooke brings this expertise to the group and is co-leader of the Canadian group.
- Data rates are high: 1.2 M pe/s in normal physics data taking.
- Need an efficient and smart DAQ system.

Argon-1 Test Detector at Carleton: 35kg LAr







Argon-1 Measurements

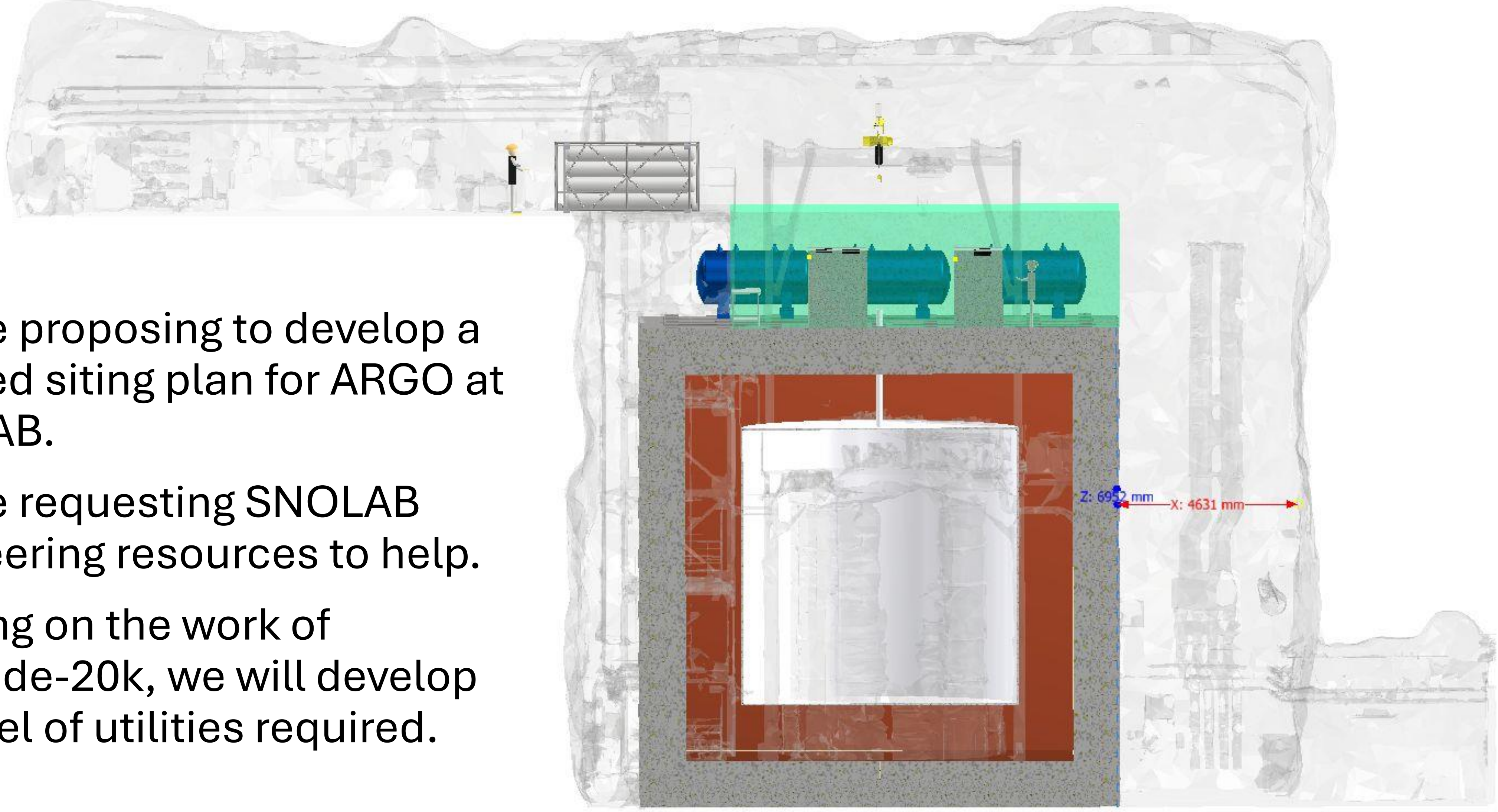
- Studies of alpha scintillation quenching in liquid argon via deployment of alpha sources directly into the detector (cold source deployments and data taking recently completed, analysis ongoing)
- Pulseshape discrimination capabilities of SiPMs for future liquid argon based detectors using tagged gamma source (this summer)
- Further measurements of effects of Rn^{222}/ Rn^{220} and their progeny on detector components
- Response of Pyrene-doped Polystyrene coatings to alpha scintillation.

Proto-typing the Future

- The Canadian group is proposing a prototyping station to be built at SNOLAB using existing services for DEAP-3600 (ie cooling, power, Ar purification, compressed air).
- We foresee two detectors in ~identical cryostats
  - A two-phase TPC
  - A single-phase detector into which different components can be inserted.
- Each would have approximately 1 tonne of Argon.
- They could be deployed (one at a time) into the existing DEAP shielding tank in the Cube Hall after the next DEAP data run is complete.

Siting the Future:
ARGO Fits in the SNOLAB Cube Hall

- We are proposing to develop a detailed siting plan for ARGO at SNOLAB.
- We are requesting SNOLAB engineering resources to help.
- Building on the work of DarkSide-20k, we will develop a model of utilities required.



Summary

- Liquid Argon is a powerful technology for discovery of WIMPs masses above ~50 GeV/c2 and between about ~ 1 and 10GeV well into the neutrino fog.
- The Global Argon Dark Matter Collaboration has a phased approach to probe this critically important part of parameter space.
- Completing the DEAP-3600 run plan and then transitioning to DarkSide-20k will allow us to verify detailed alpha background models and then have world-leading sensitivity to WIMP dark matter.
- Many interesting exotic phenomena are studied well with liquid argon
- A multi-hundred tonne liquid argon detector, ARGO, proposed for SNOLAB, will allow us to be sensitive well into the neutrino floor.
- Canadian groups are involved in all phases of this project.