Status of DEAP-3600, Darkside-20k and ARGO: the Global Argon Program

Outline:

- Status and Plans for DEAP-3600
- Recent results
- Hardware upgrades
- Status and Plans for Darkside-20k
- Development of ARGO

Carleton University

Mark Boulay
August 9, 2023 Canadian APP community meeting

Global Argon Dark Matter Program formed in 2017

Over 400 researchers from

- DarkSide
- DEAP
- ArDM
- MiniCLEAN

- GADMC includes over 400 researchers from 100 institutions in 14 countries
- Completion of current science program with DEAP.
- Joint collaboration on DS-20k at LNGS (200 tonne-years). 2027 start.
  DS-20k: 200 tonne-year argon exposure with TPC.
- Joint collaboration on ARGO detector to reach neutrino floor. 2030's
  ARGO: 3000 tonne-year argon exposure, conceptual design in progress

The DEAP Collaboration

- **D**ark matter **E**xperiment using **A**rgon **P**ulseshape discrimination
- Direct detection of dark matter experiment utilizes single phase liquid argon detector.
- Operating in SNOLAB underground facility in Sudbury, Canada.
- DEAP-3600 experiment collected data from November, 2016 – March, 2020, now undergoing upgrades.

Particle Physics
Rutherford Appleton Laboratory

SNOLAB

University of Sussex

Technical University of Munich

TRIUMF

Instituto de Física

PRINCETON UNIVERSITY

Queen's University

ROYAL HOLLOWAY UNIVERSITY OF LONDON

UNIVERSITY OF ALBERTA

ASTROCENT
NICOLAUS COPERNICUS ASTRONOMICAL CENTER OF THE POLISH ACADEMY OF SCIENCES

Canadian Nuclear Laboratories
Laboratoires Nucléaires Canadiens

Carleton UNIVERSITY

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

INFN
Istituto Nazionale di Fisica Nucleare

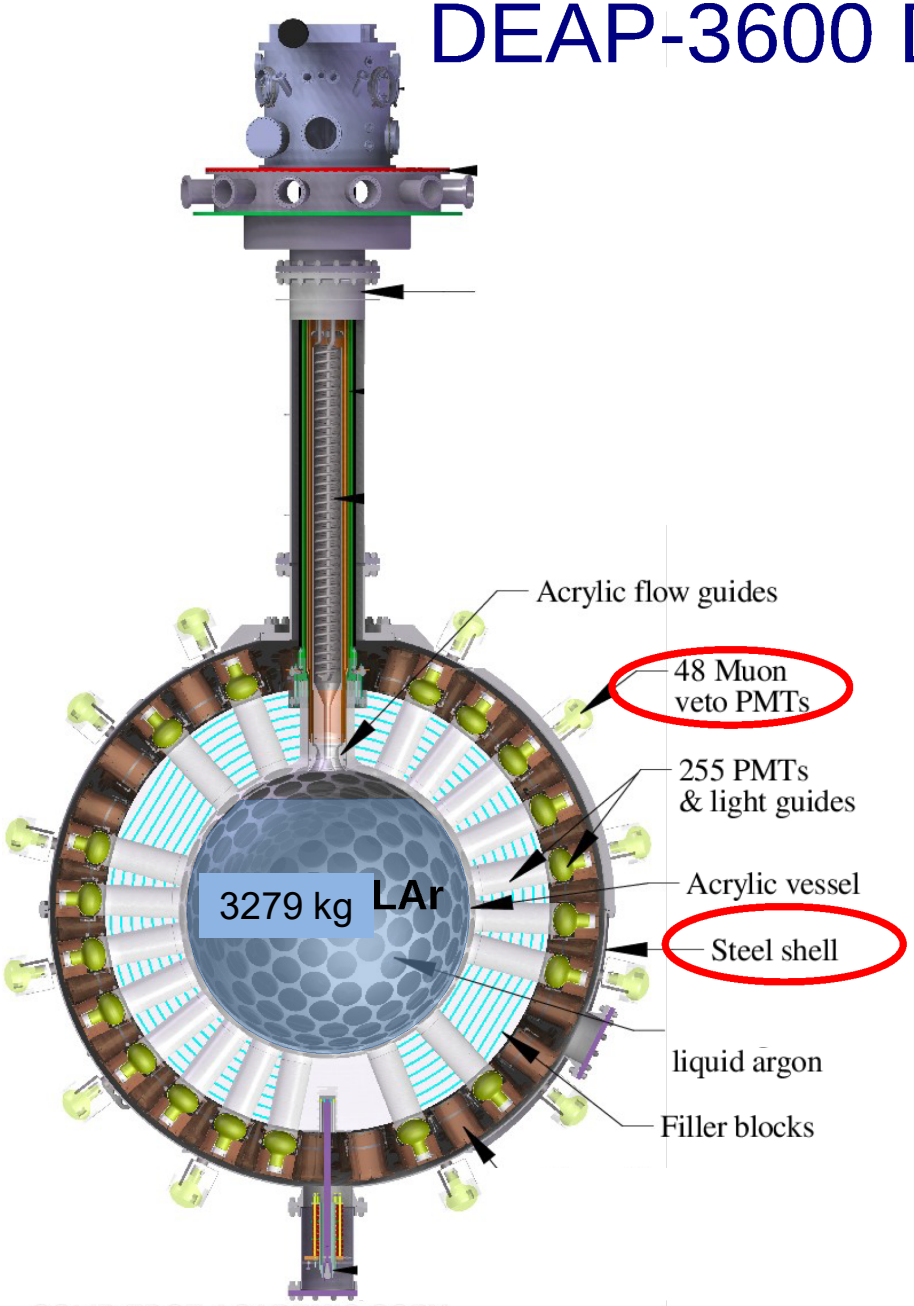
JOHANNES GUTENBERG UNIVERSITÄT MAINZ
JG|U

NATIONAL RESEARCH CENTER "KURCHATOV INSTITUTE"

LaurentianUniversity
UniversitéLaurentienne

~95 researchers from 9 countries: Canada, Germany, Italy, Mexico, Poland, Russia, Spain, UK, USA

DEAP-3600 Dark Matter Search



- **Single phase liquid argon** approach: simple, scalable, inexpensive
- 3.3 tonne target (1000 kg fiducial) in sealed ultraclean Acrylic Vessel
- Vessel is “resurfaced” in-situ to remove deposited Rn daughters after construction
- In-situ vacuum evaporated TPB wavelength shifter (~10 m^2 surface)
- Bonded 50 cm long light guides + polyethylene shielding against neutrons
- 255 Hamamatsu R5912 HQE PMTs 8-inch (32% QE, 75% coverage)
- Detector immersed in 8 m water shield, instrumented with PMTs to veto muons
- Located 2 km underground at SNOLAB

Some comments

	Source	N^{CR}	N^{ROI}
β/γ's	ERs	2.44×10^9	0.03 ± 0.01
	Cherenkov	$< 3.3 \times 10^5$	< 0.14
n's	Radiogenic	6 ± 4	$0.10^{+0.10}_{-0.09}$
	Cosmogenic	<0.2	<0.11
α's	AV surface	<3600	< 0.08
	Neck FG	28^{+13}_{-10}	$0.49^{+0.27}_{-0.26}$
	Total	N/A	$0.62^{+0.31}_{-0.28}$

Background rate is **LOW!**

0.07 ± 0.03 ev/t.y/keV$_{ee}$

(NR bkg in WIMP search ROI)

231 live-days with 824 kg fiducial mass

v. Low backgrounds; ^{222}Rn 0.2 microBq/kg

First physics publications:

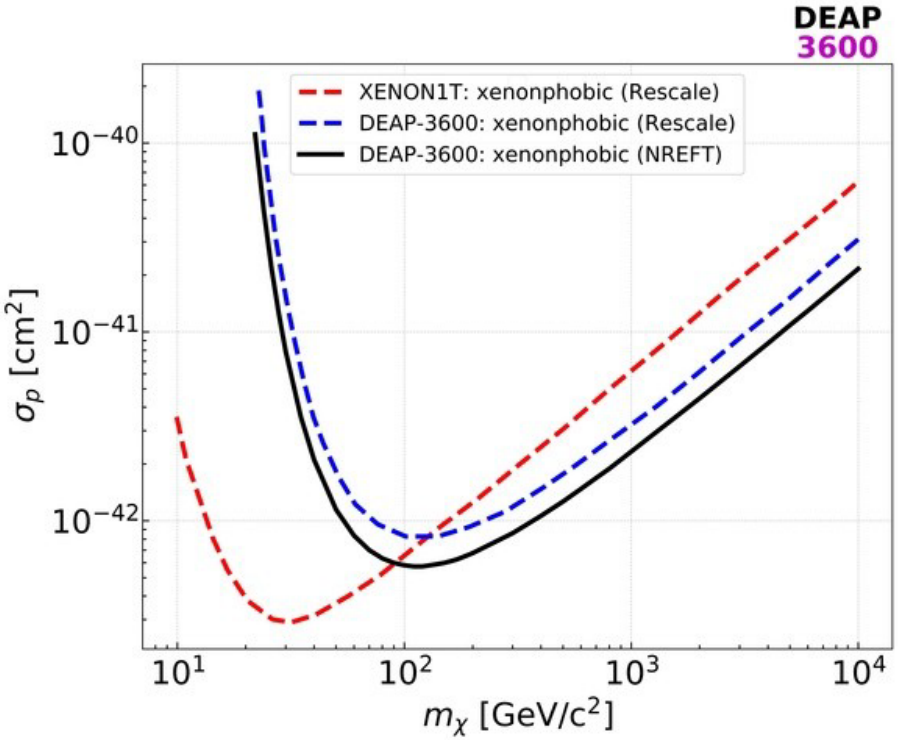
PRL 121 071801 (2018)
PRD 100 022004 (2019)

Dominant source: shadowed α decays from ^{210}Po on neck flowguides

Further Constraints from DEAP

- 231 live-days results were reinterpreted with a more general Non-Relativistic Effective Field Theory framework (NREFT) --- can explore isospin-violating couplings.

- Provides world leading sensitivity for isospin-violating xenonphobic dark matter at high mass.

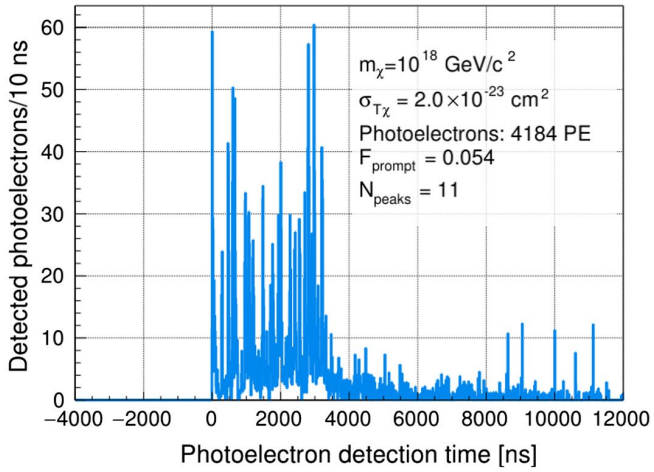


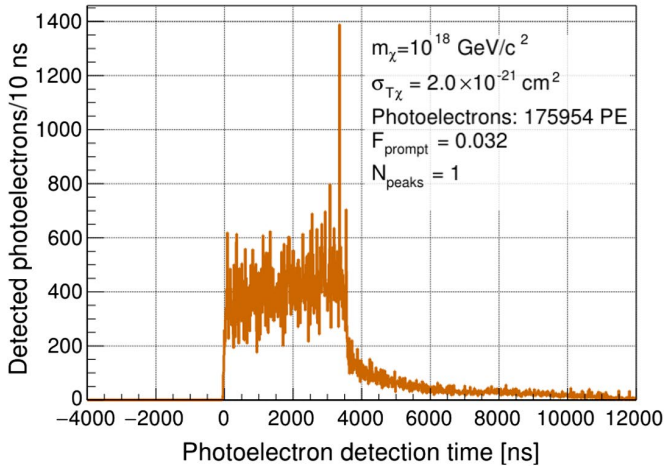
PRD 102 082001 (2020)

Constraints on Planck-Scale Mass Multi-scattering Dark Matter

DM candidates with $\sigma_{\chi-n} \cong 10^{-25}$ cm^2 and mass $\gtrsim 10^{12}$ GeV/c^2 lose a negligible amount of energy in the scatterings with the Earth nuclei and can reach underground detectors.

- Event signature:
  - Contains multiple nuclear recoil scatters: produces multiple peaks in the signal
  - low F_{prompt}



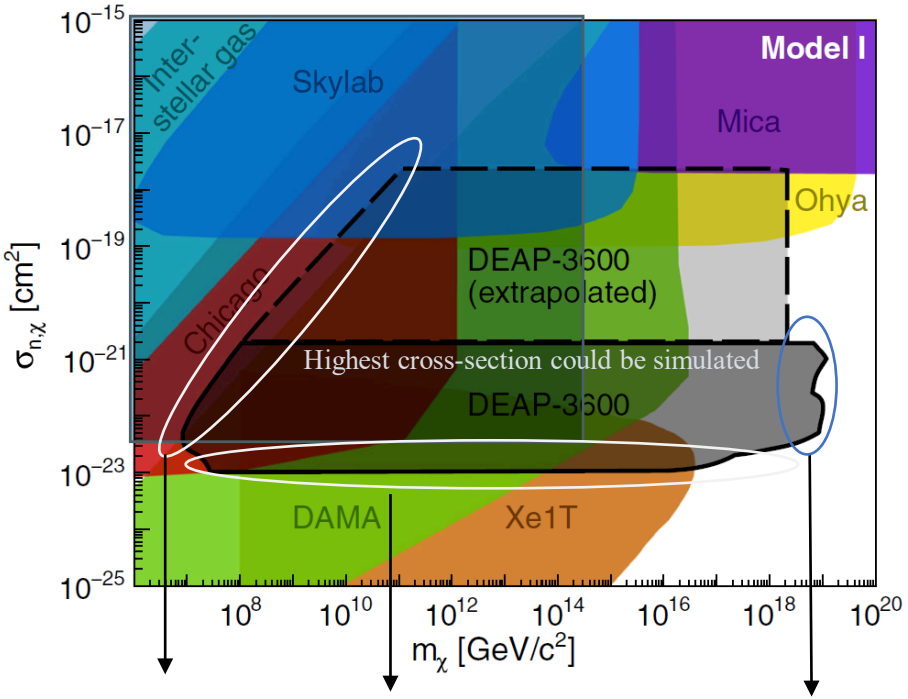


Simulated photoelectron time distribution

As cross-section increases, F_{prompt} decreases and number of dominant peaks starts to merge.

PRL 128 011801 (2022)

DEAP is the first experiment to reach Planck-scale sensitivity (2022)



Affected by the Earth's overburden ⟹ attenuation of energy of DM

Lowest cross-section can be excluded by null results

Above this mass, number density of DM is too low compared to the surface area ⟹No DM expected to pass through the detector within livetime

- Analyzed 813 live-days data (November, 2016 – March 8, 2020) : No events were observed.
- Constrain the DM masses between (8.3×10^6-1.2×10^{19}) GeV/c^2 and ^{40}Ar-scattering cross-sections between 1×10^{-23} and 2.4×10^{-18} cm^2.

Phys. Rev. Lett. 128 011801 (2022)

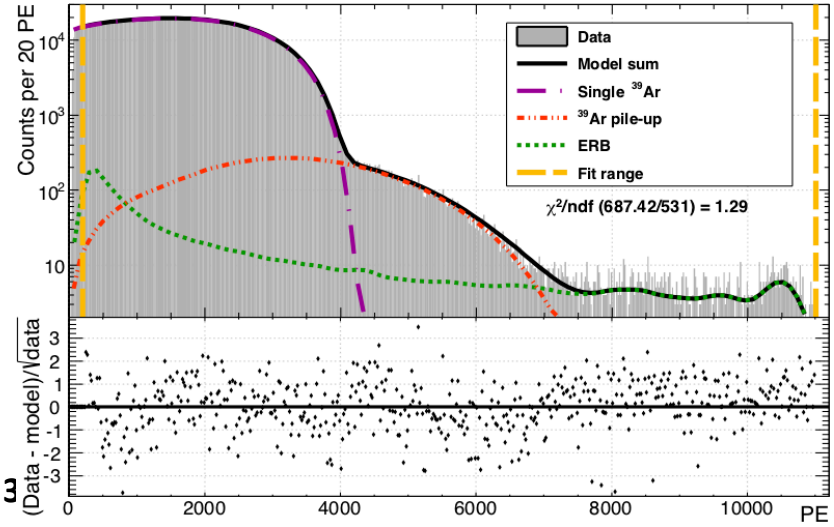
DEAP-3600 physics programme (slides from Simon Viel)

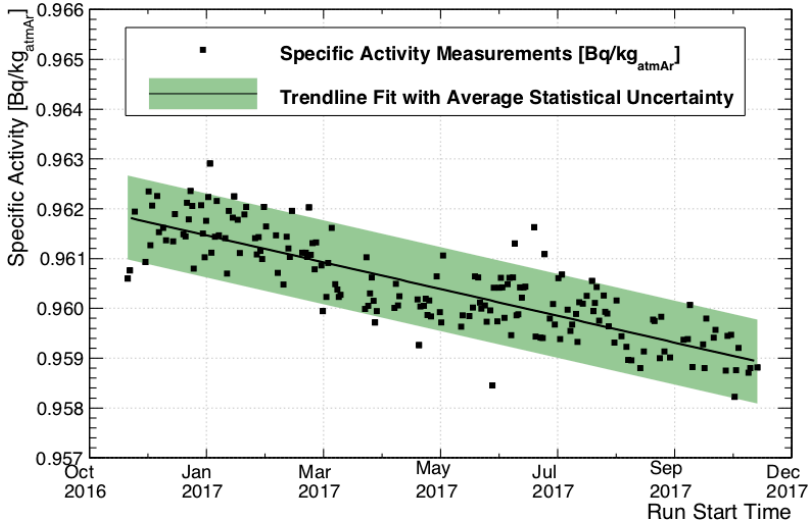
Published!
Final review
Analysis priorities
Coming up next

- Dark matter searches
  - Super-heavy multiply-interacting massive particles
  - **WIMP search** on open dataset with profile likelihood ratio method
  - WIMP search with full 2016-2020 dataset
  - Boosted dark matter
  - 10-100 keV-scale hidden photons and axion-like particles
  - Low-mass WIMP search via annular modulation
  - Low-mass WIMP search using low-threshold data
  - Sterile neutrinos
- Other searches
  - 5.5 MeV solar axions
  - ^{8}B neutrino absorption (inverse beta decay)
  - ^{36}Ar 0vECEC
  - Short-lived cosmogenic isotope production in LAr
- Measurements
  - **^{39}Ar specific activity**
  - ^{39}Ar half-life
  - Muon flux (with muon veto instrumentation)
  - ^{39}Ar decay spectrum and nuclear parameters
  - Alpha scintillation in LAr
- Pulse-shape discrimination
  - PSD performance: likelihood vs. prompt fraction
  - Wavelength shifter long time constants
- Detector papers
  - Muon veto instrumentation (with muon flux meas.)
  - Position reconstruction
  - PMT non-linearity and digitizer clipping corrections
  - LAr optical model
  - GAr pulse shapes and lifetimes

^{39}Ar measurements

- **^{39}Ar specific activity** measurement in atmospheric argon
  - EPJC 83 7 642 July 2023
  - Result: 0.964 ± 0.024 Bq/kg$_{atmAr}$ with updated LAr mass 3269 ± 24 kg





- Complete fit model includes ^{39}Ar pileup events with ^{39}Ar, Cherenkov, ER backgrounds
- Detailed estimates of the time-dependence of systematic uncertainties are necessary

WIMP search

- Focusing our efforts on completing the profile-likelihood ratio (PLR) analysis on open data (388 live-days) taken in 2016-2020

  - Improvements in sensitivity with respect to published results expected due to live-time, expanded region of interest (ROI), and less stringent cuts to increase acceptance

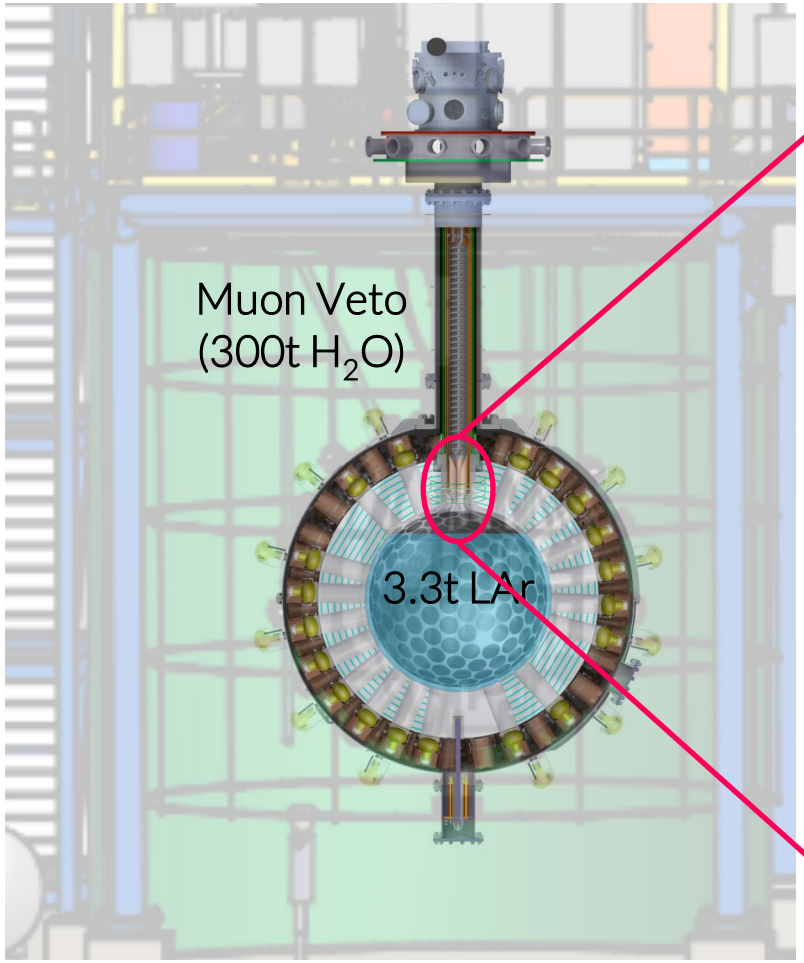
  - PLR fit in photoelectrons detected (PE), Fprompt, and reconstructed radius

  - Event selection re-optimization, including machine-learning algorithms, towards analysis of full dataset including runs where WIMP ROI is blinded (total of 813 live-days)

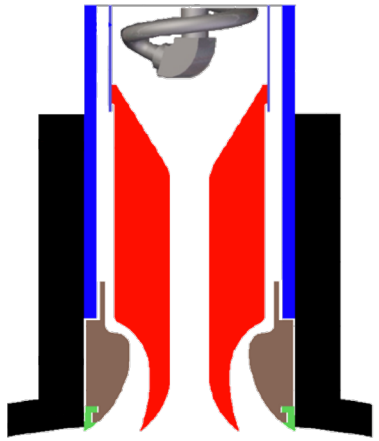
  - Stay tuned.

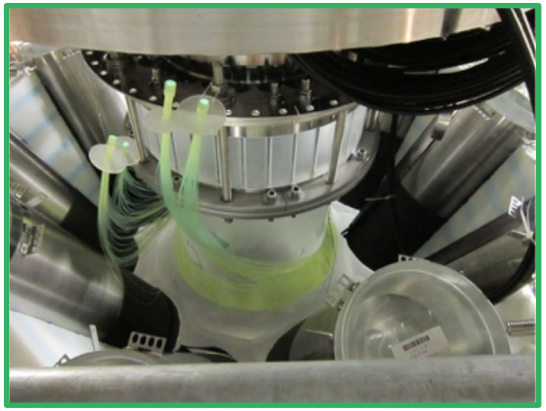
DEAP backgrounds

"shadowed" alphas (in our case, from the neck) and degraded alphas from dust in argon. Expect these will be problematic for many experiments at the ~1 event per tonne-year level…



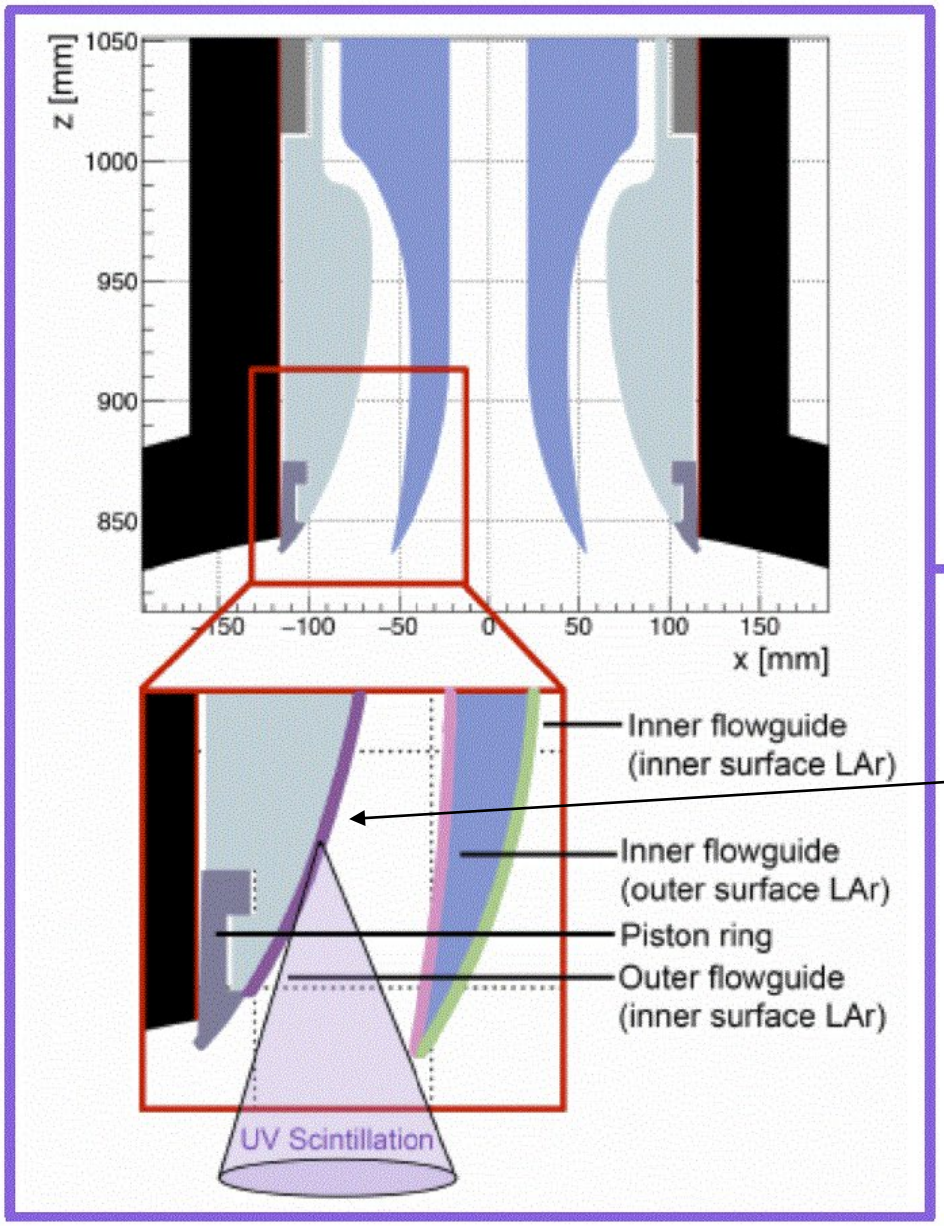
Flow guides





Neck Veto

Backgrounds – Shadowed alphas



Shadowed α decays from liquid argon in neck region lead to low-energy backgrounds

^{210}Po

DEAP Upgrades

Upgrades are specially designed to remove neck alpha and dust alpha backgrounds

Dust Filtration:

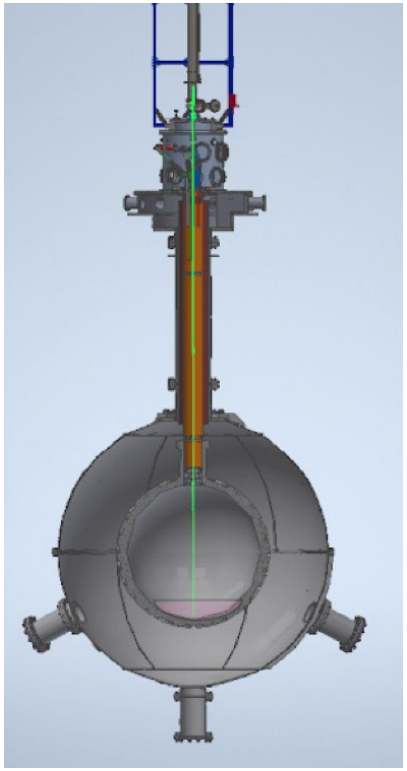
- Deployment of vacuum jacketed stainless steel pipe through the neck of the detector ---- to remove liquid argon and allow filtration to remove dust and refill the detector with clean liquid argon.

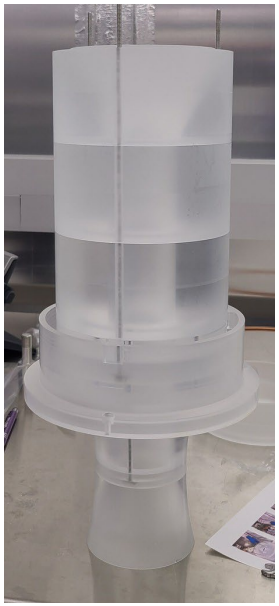
Removal of Neck alpha events:

- Allow warming of the neck region --- to remove possibility of formation of liquid film or droplets.

Flowguide Coating:

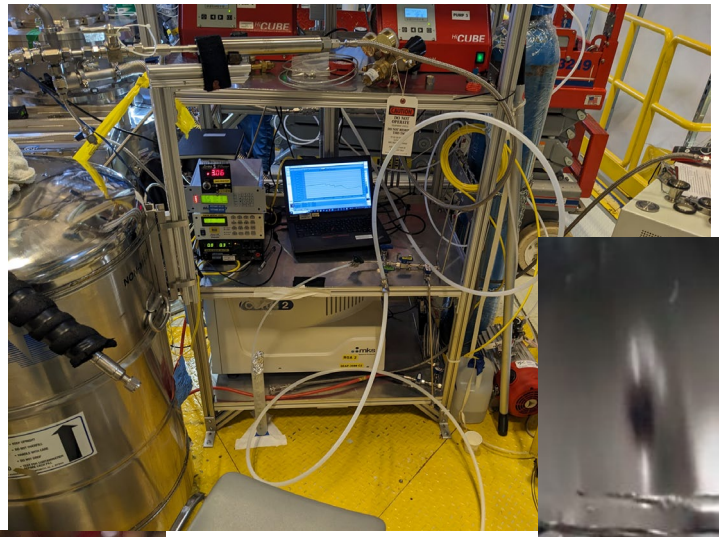
- Coat the flow guide surfaces with a "slow" wavelength shifter – custom pyrene/polymer film.
- Pyrene has a long decay time : neck alpha events will have lower $F_{prompt.}$





Will complete upgrades and start collecting new data in 2024. Target sensitivity at level of current Xe experiments, with essentially zero backgrounds.

DEAP neck and flowguides removed July 24, 2023



New pyrene slow WLS on neck flowguides

Developed pyrene/polystyrene custom WLS coating, “slow” WLS ~ 150 ns
Shifts surface alphas from NR band to low-Fprompt band ; strong PSD suppression
R&D and construction completed – flowguides on site ready for installation

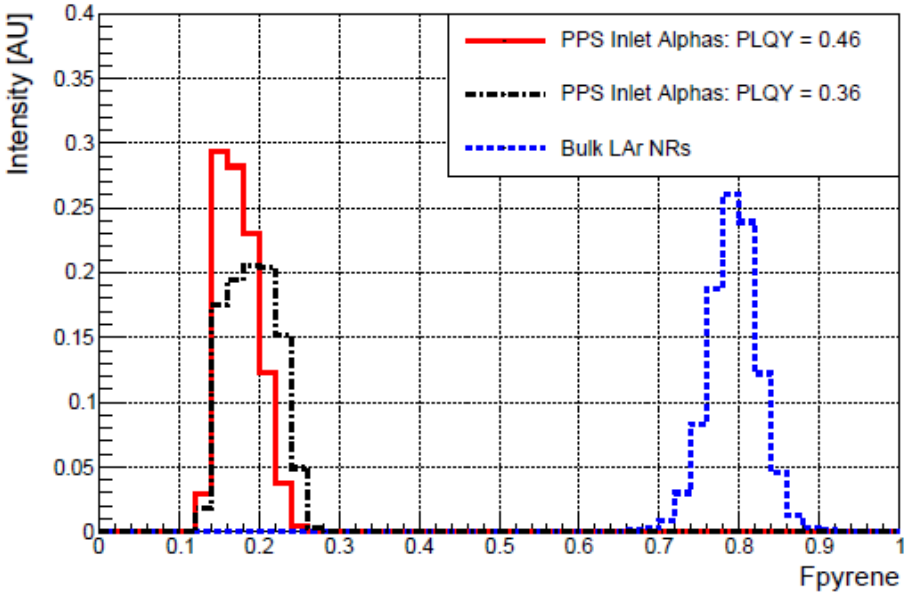
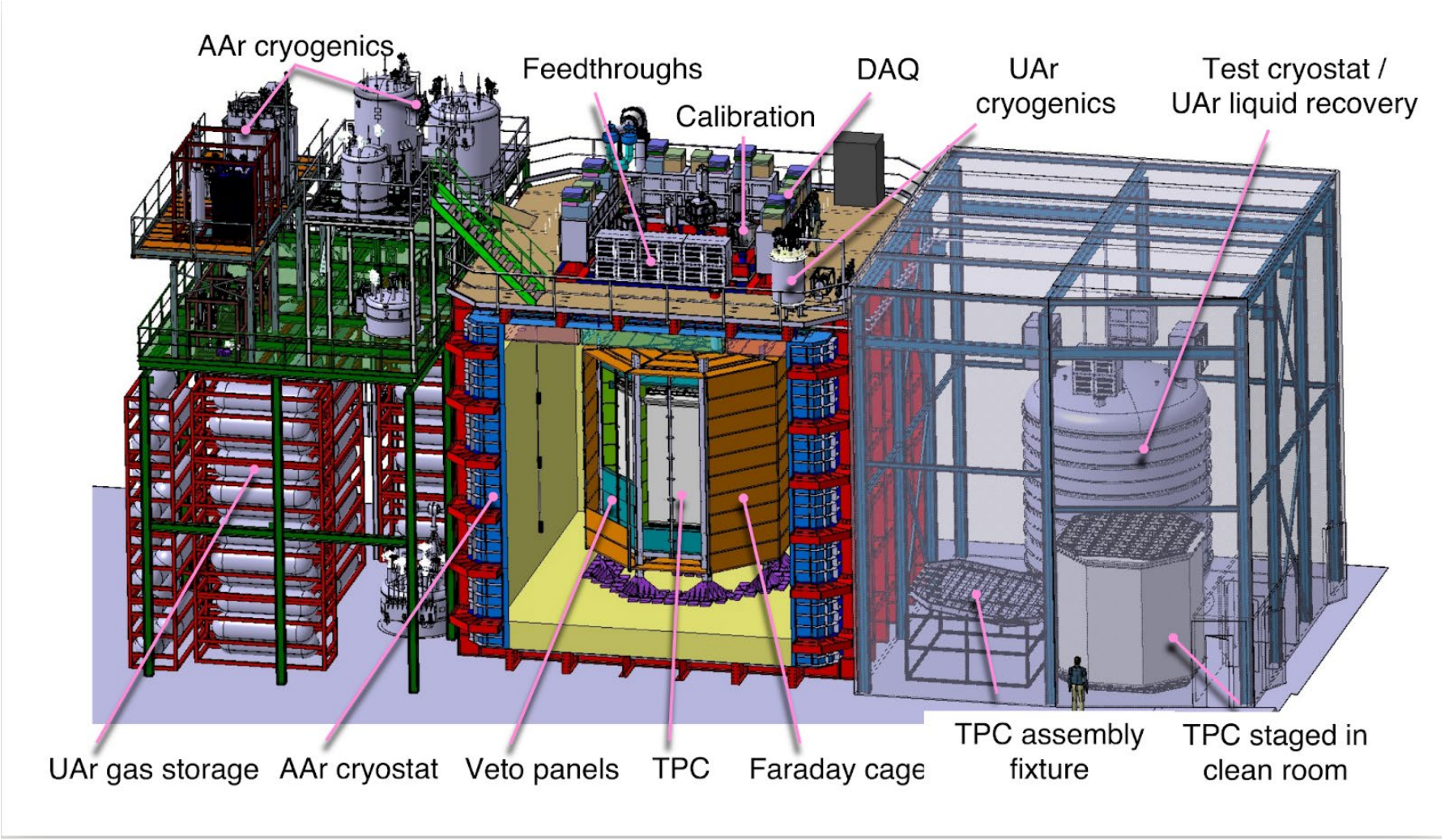


Figure 8: Fpyrene distributions for pure LAr NR-like signals and low-energy shadowed PPS coated inlet α's. Both nominal PLQY and lower bound for inlet α's are shown, with lower bound from ILTSR, all distributions are normalized to unit integral

NIM A 1034 166683 (2022) coating development for DEAP
also see NIMA 968 163631 (2020) surface PSD technique
JINST 16 P12029 (2021) coating characterization

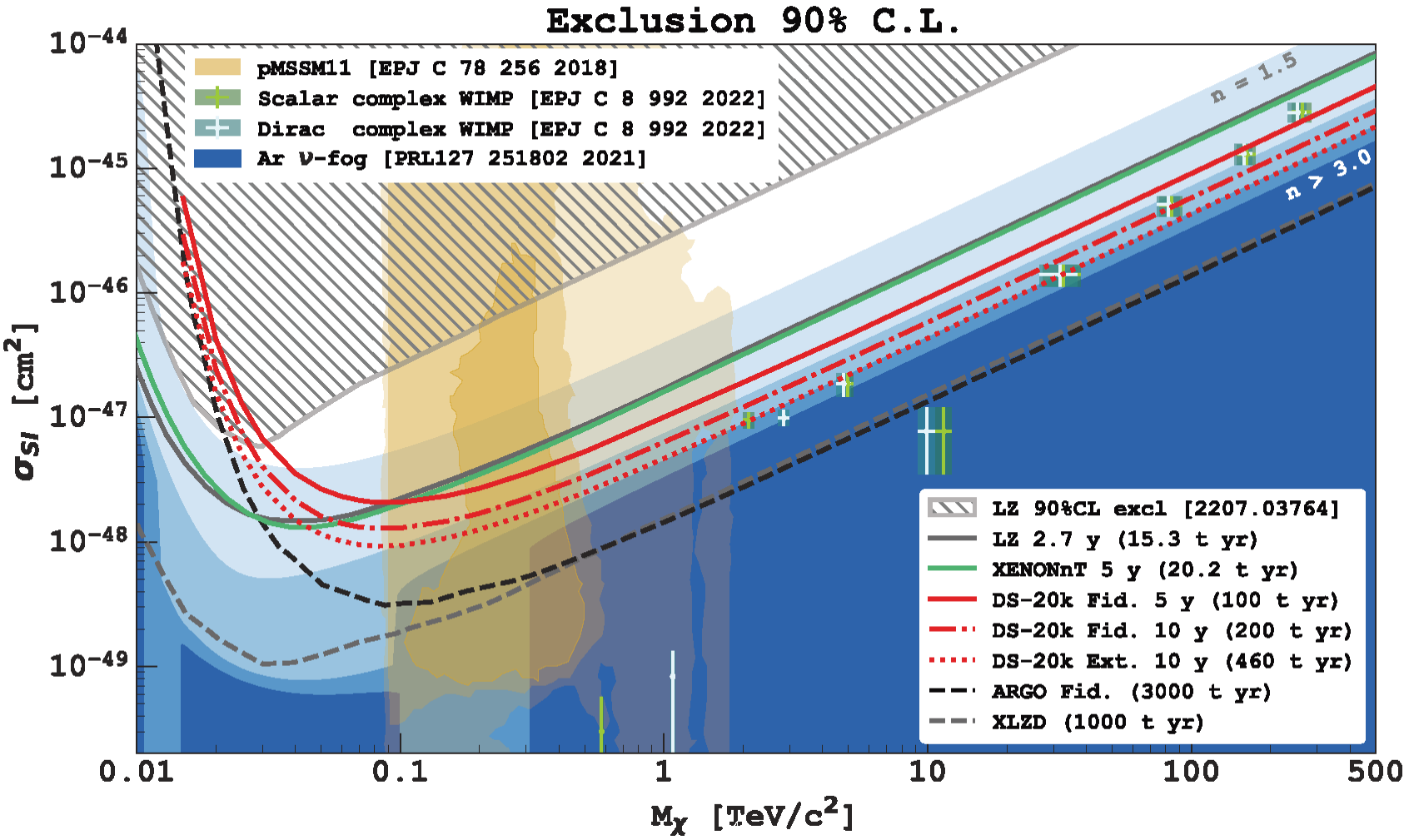
Characterization by Di Stefano’s group (Queen’s)

Darkside-20k

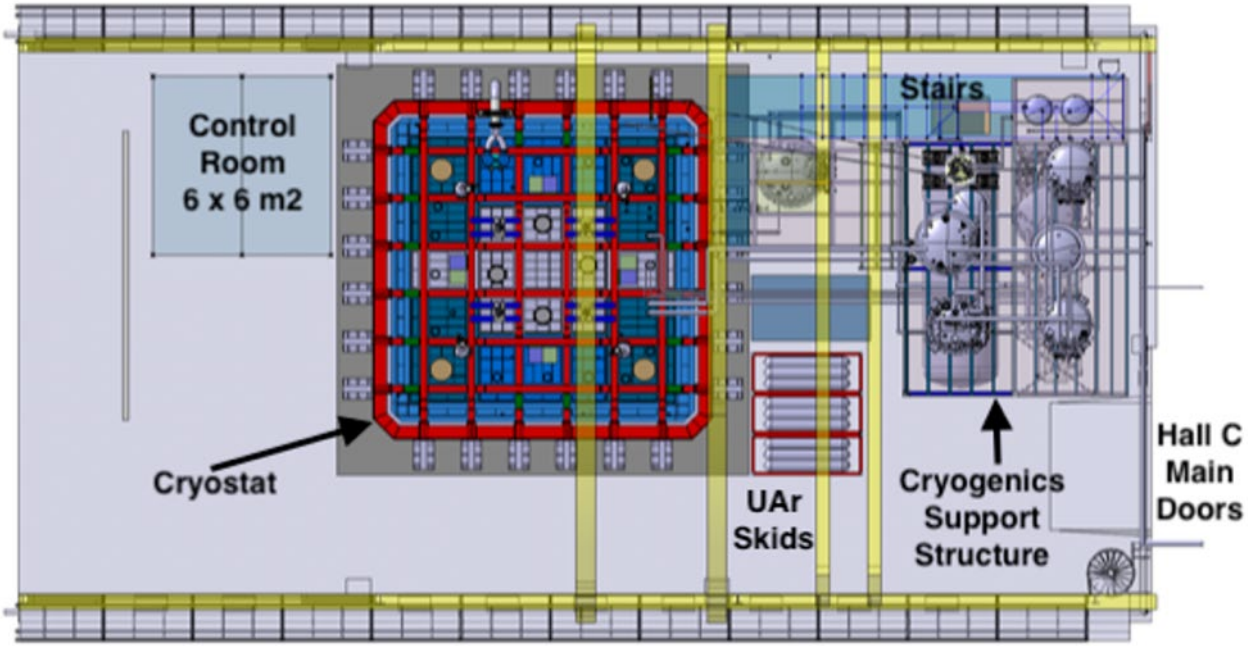


TPC contains 100 tonnes of low-activity UAr underground argon (low in 39Ar)

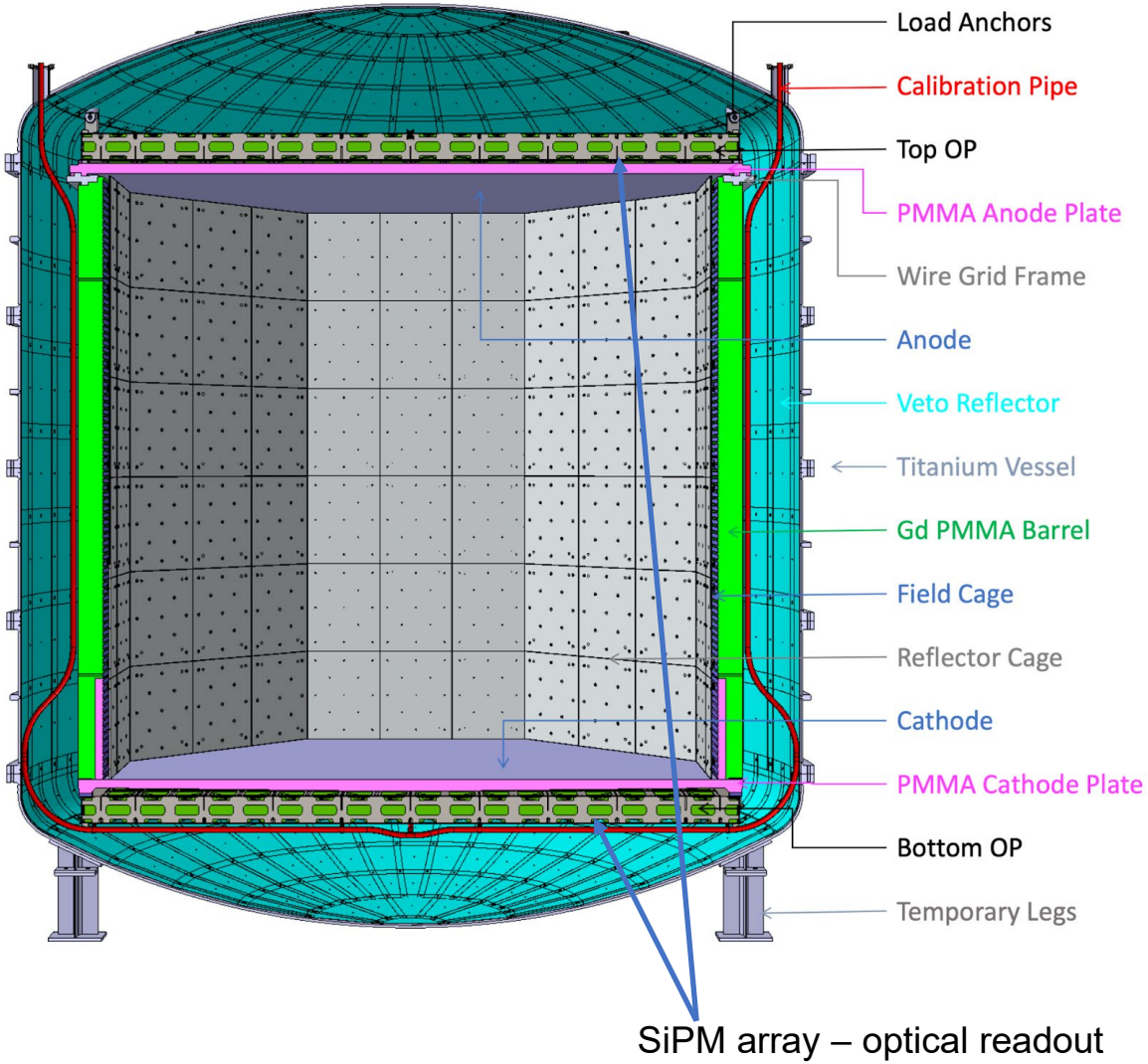
First experiment to use large-scale Uar
Novel large-area SiPM array for light detection


Exclusion 90% C.L.
pMSSM11 [EPJ C 78 256 2018]
Scalar complex WIMP [EPJ C 8 992 2022]
Dirac complex WIMP [EPJ C 8 992 2022]
Ar ν-fog [PRL127 251802 2021]
n = 1.5
n > 3.0
LZ 90%CL excl [2207.03764]
LZ 2.7 y (15.3 t yr)
XENONnT 5 y (20.2 t yr)
DS-20k Fid. 5 y (100 t yr)
DS-20k Fid. 10 y (200 t yr)
DS-20k Ext. 10 y (460 t yr)
ARGO Fid. (3000 t yr)
XLZD (1000 t yr)
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
σ_{SI} [cm^2]
0.01
0.1
1
10
100
500
M_χ [TeV/c^2]

DS-20K layout



Darkside-20k TPC



Canadian responsibilities on DS-20k

Canadian groups have several high-profile and critical responsibilities:

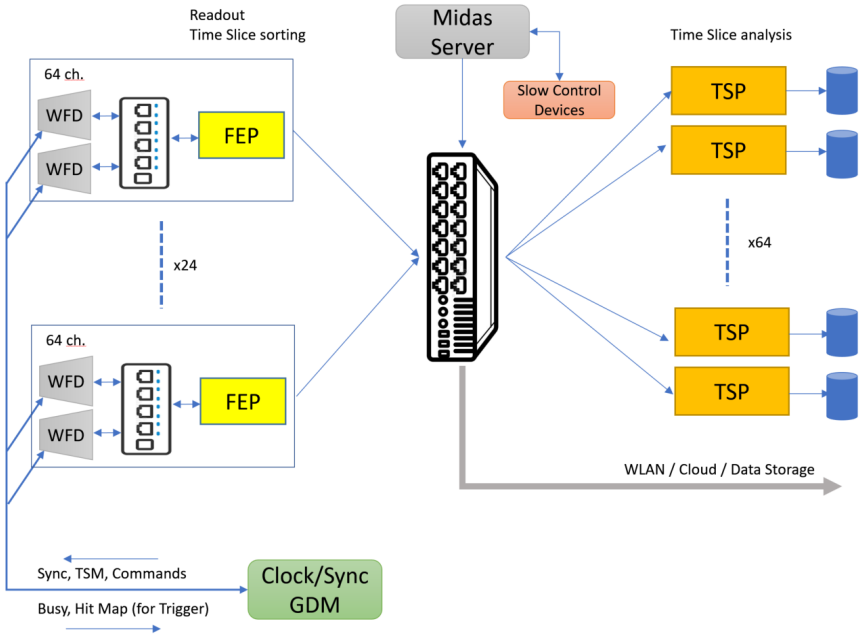
Data acquisition system (hardware and software): TRIUMF and Queen's

Acrylic TPC vessel (Alberta)

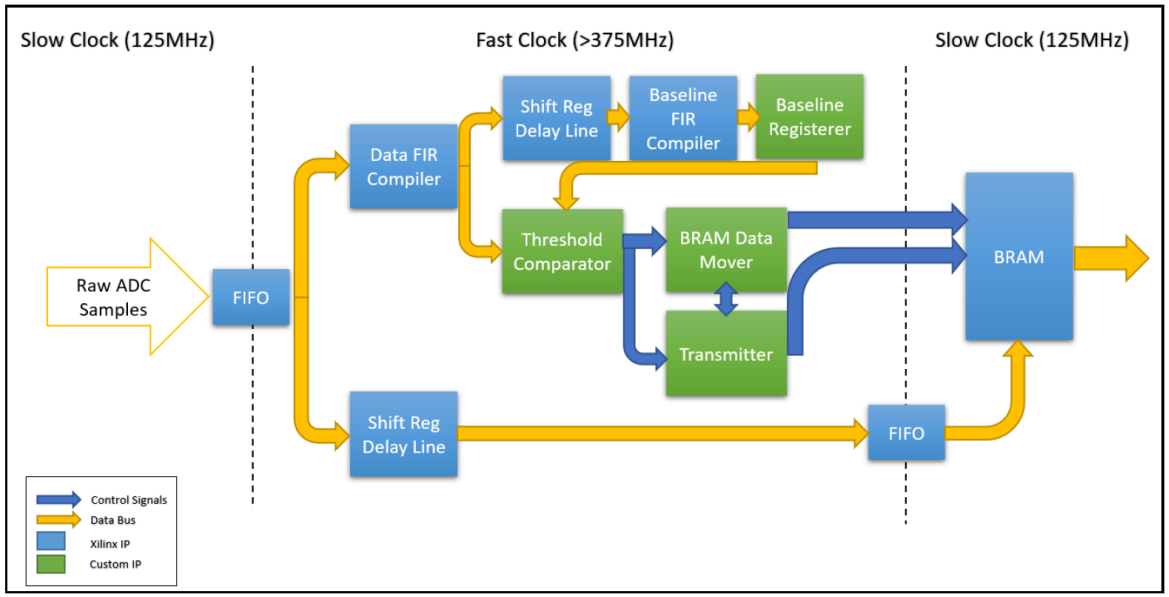
Low-background coatings (conductive polymer and TPB wavelength shifter): Carleton

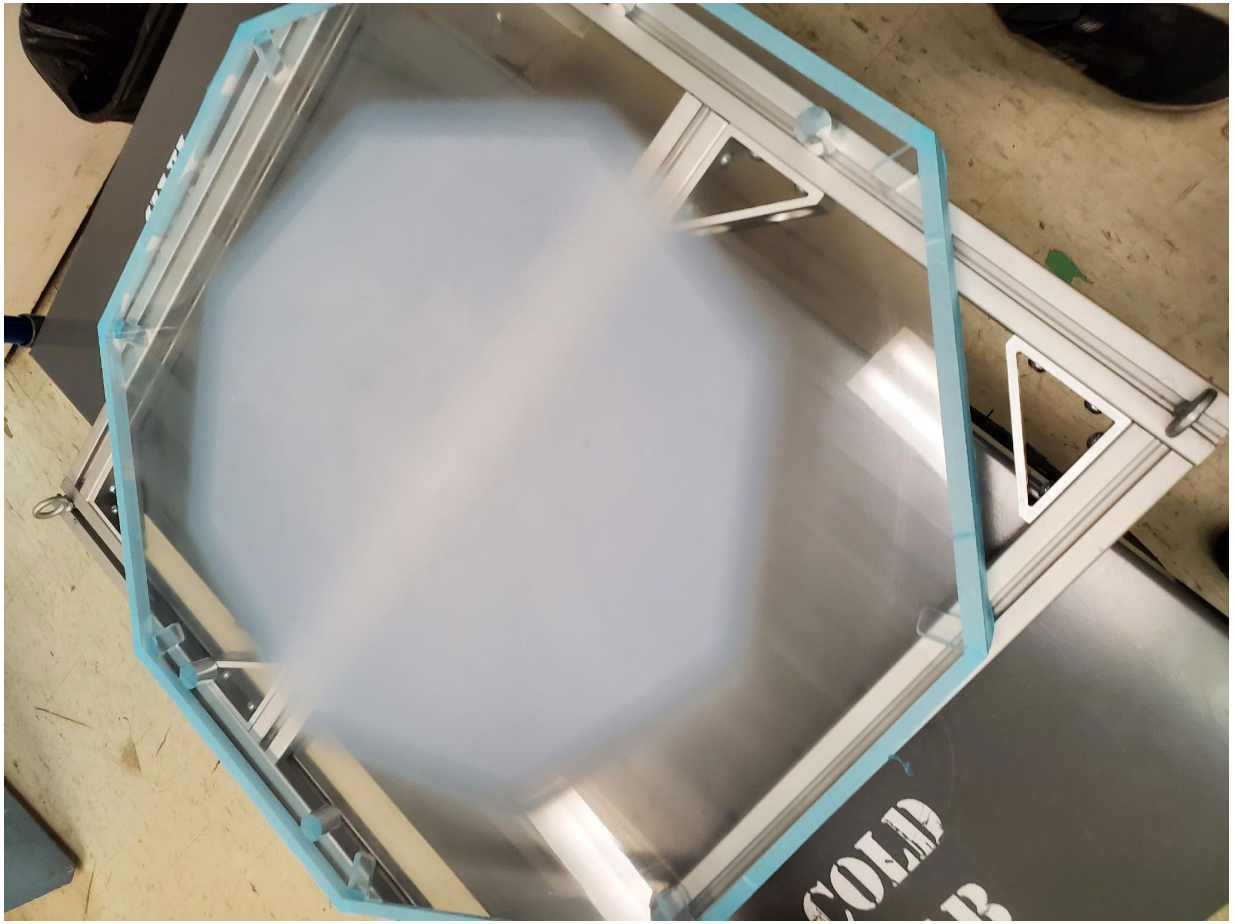
Underground argon (Queen's and Carleton)

Data Acquisition System for Darkside-20k



TRIUMF and Queen's groups



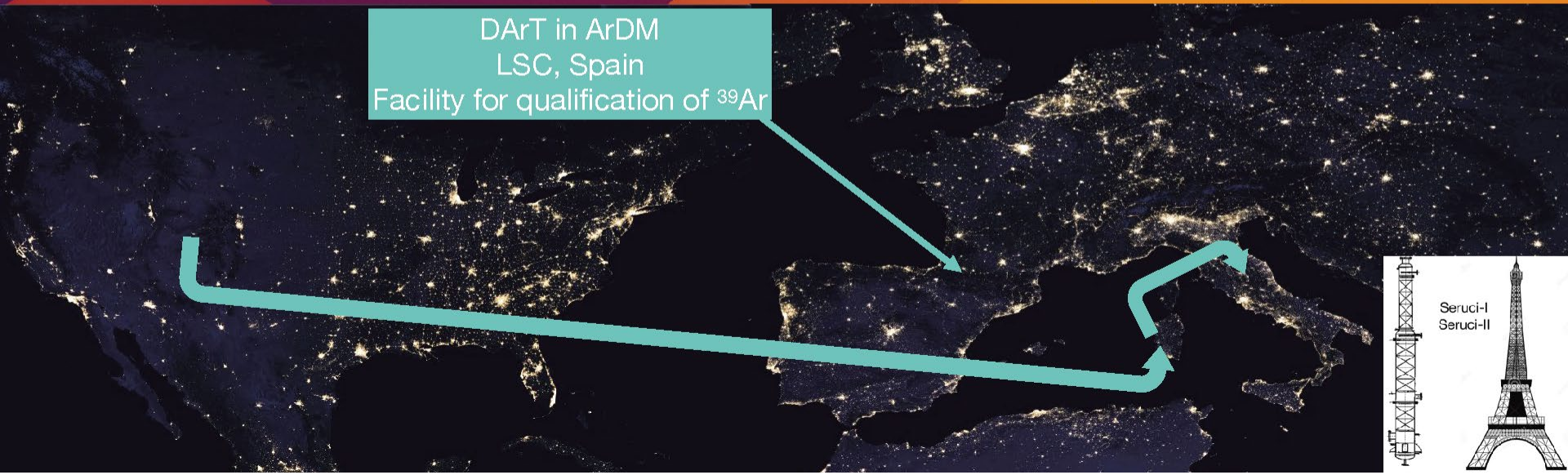


Acrylic TPC anode plane (mockup prototype) fabricated at Alberta and coated at Carleton

Industrial Scale Underground Argon (UAr) 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



Will extract 120 tonnes UAr for Darkside-20k

400 tonnes for ARGO, planning to store at SNOLAB (ARGUS = ARGon Underground Storage)

ARGO: Key Elements of Conceptual Design

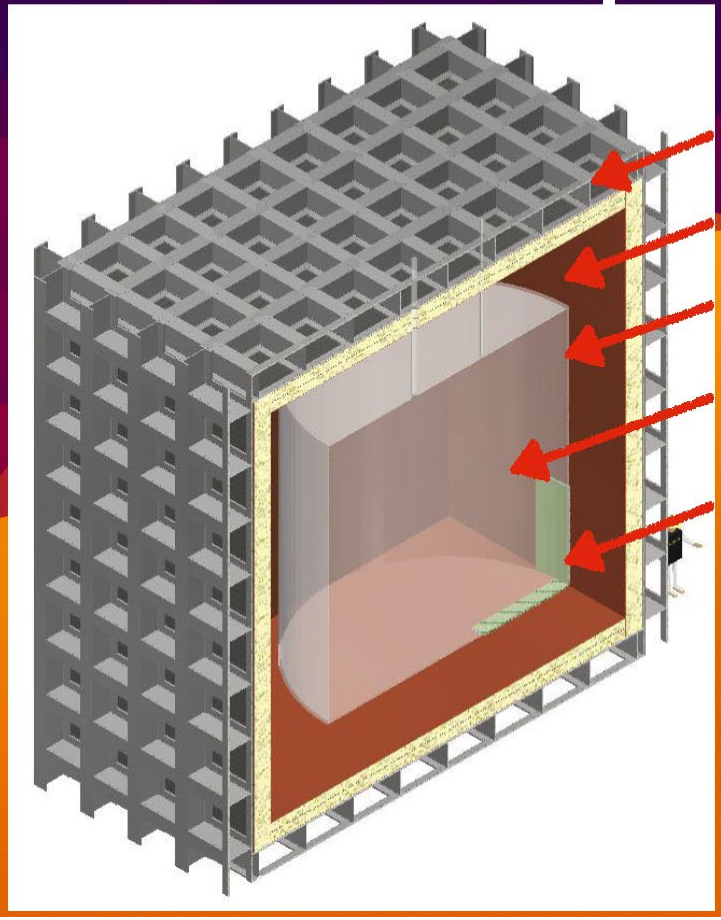
UAr Mass:

- 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).



ARGO and R&D activities

Working on conceptual design and definition of physics sensitivity + required R&D program (simulations)

Development of all-digital SiPM system (photon to digital converter) - Sherbrooke, TRIUMF, Carleton, Alberta). Development of “SMART” trigger system for data reduction (Sherbrooke). Goal of working prototype/demonstrator in LAr “mid-2020’s”

Develop additional assay sensitivity

- ^{39}Ar assay (Ar2D2) complements GADMC facilities (scintillation counter)
- Want surface alpha assay to ~10 microBq/m^2
- Further extend ^{210}Pb sensitivity to <10^{-20} g/g
- Study particulate deposition requirement and desorption/cleaning efficiency
- Study diffusion of ^{210}Pb in polymers to D=10^{-14} cm^2/sec

15 faculty in Canada on NSERC SAP grant combining DEAP, DS-20k and ARGO activities 2023-2025.

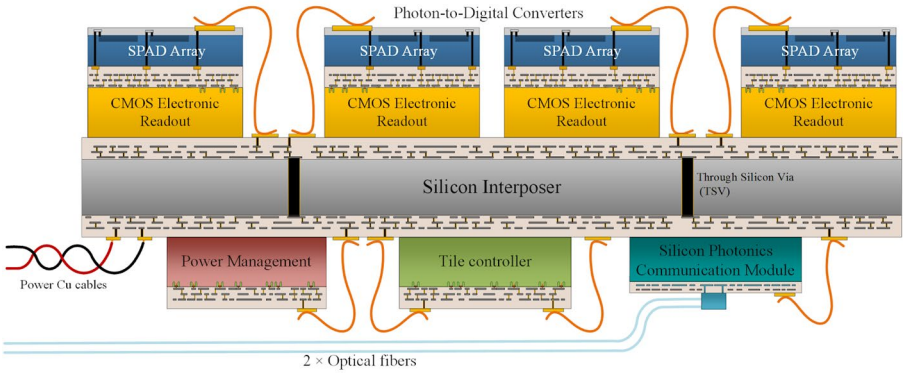
Timeline:

- now – 2026: simulations and enhance capabilities
- 2027 – engineering start
- 2028-2032 – UAr collection
- 2030-ish – start of construction activities

Digital SiPMs:

- Signal processing at sensor level allows much simpler implementation
- All-digital system not affected by electronic noise encountered in analog
- Ability to disable noisy Single Photon Analog Diodes (SPAD)
- Active quenching suppresses essentially all after-pulsing
- Lower power consumption
  - no event no power for digitizing
- Excellent potential for time resolution
  - ~100ps

Going further to enable large scale detectors:
A fully digital photodetector module



To reduce wire count and mass:

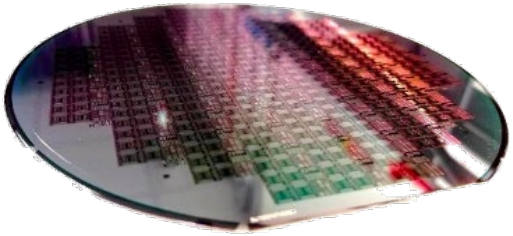
- On tile power management
- Bidirectional digital optical communication

Low background and cryogenic operation:

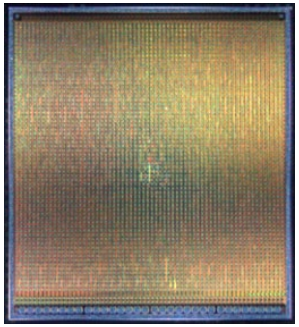
- silicon based tile substrate - low background
- CTE matched to silicon - PDCs and ASICs

Leverages past CFI and NSERC funding:

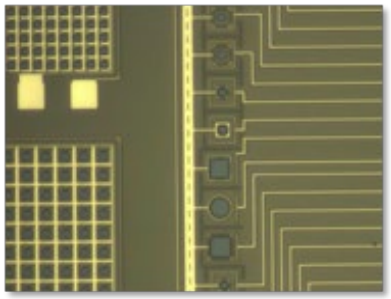
Wafer level development (SPAD)



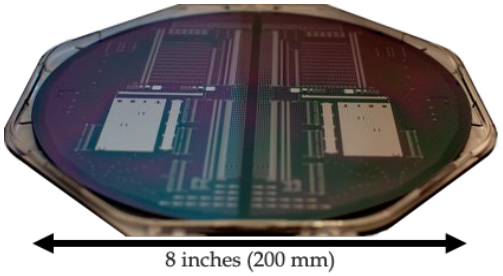
CMOS readout
(2 revisions)



Sensitivity enhancement
for direct detection

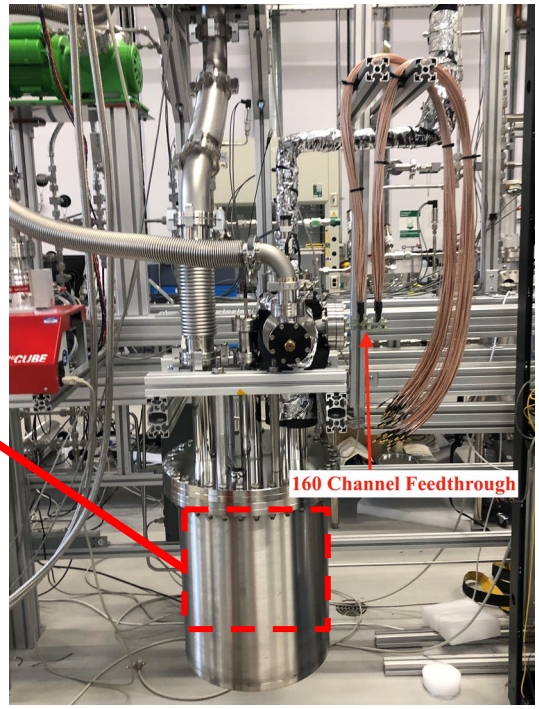


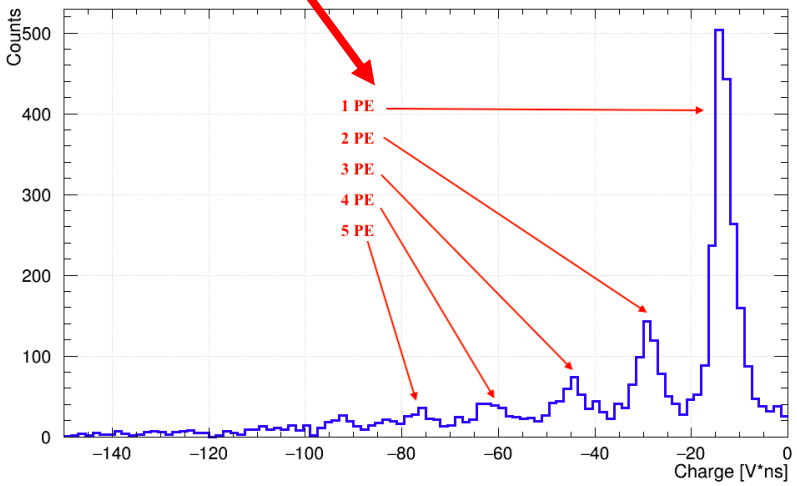
Silicon interposer development



Carleton Facility and upcoming digital test

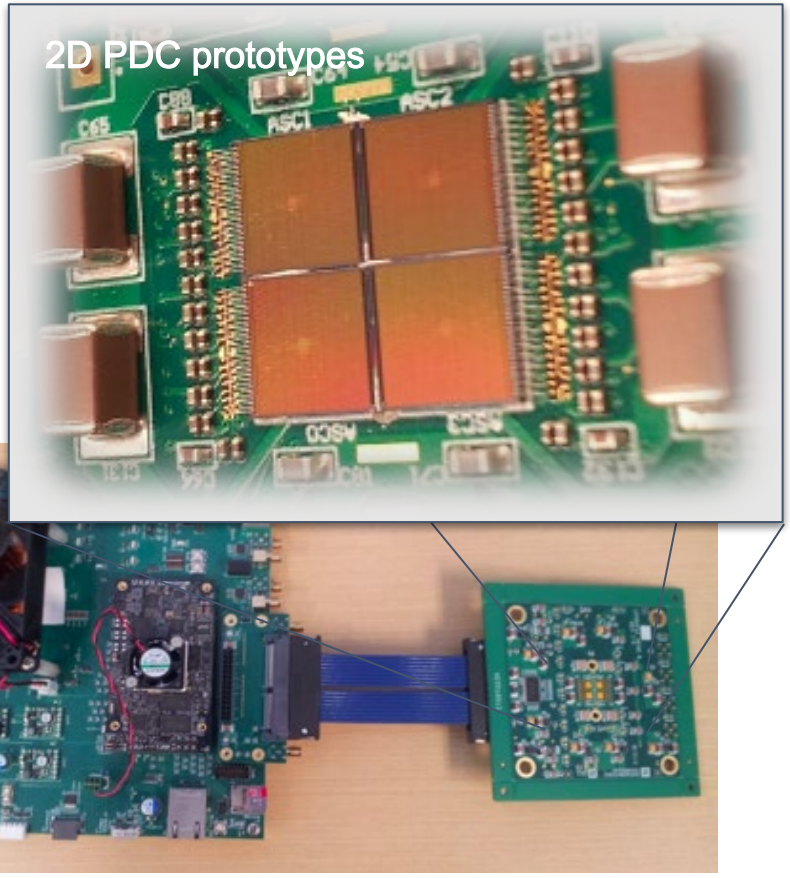
30 kg LAr Argon-1 @ Carleton with analog SiPMs



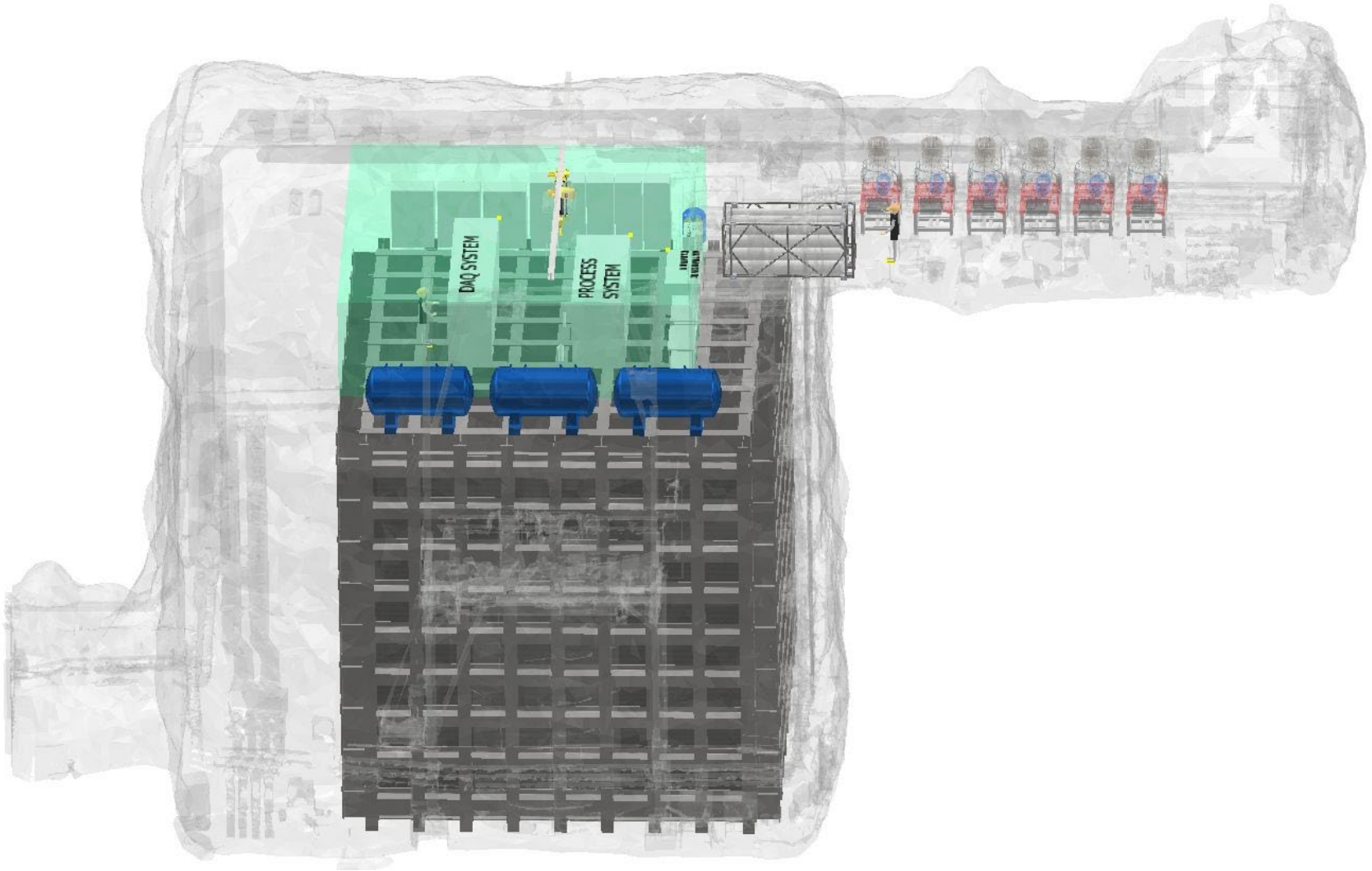


Getting ready for first LAr testing of Digital SiPMs from Sherbrooke

- coding FPGA
- adapting the board size and connectors to the setup



ARGO concept in SNOLAB Cube Hall



Summary

Long-term program for DM with argon defined with strong collaboration.

DEAP-3600 demonstrated single-phase technique for DM, most sensitive search with argon and some world-leading results. So far cut-and-count analysis, to be extended to multivariate analysis. Upgrading detector for background reduction to restart in 2024. Rich physics program ongoing with updated results soon.

DEAP HW upgrades tackle the dominant background sources, critical to understand these for the next gen experiments.

ER backgrounds are handled by PSD up to ARGO scale, using underground argon.

DS-20k will use a novel large-area SiPM array and the first large-scale use of underground argon for unprecedented sensitivity. Starts 2027 at LNGS in Italy.

Exciting technical development of digital SiPMs a potential game-changer. Working on ARGO concept for SNOLAB; continued R&D for ~2030's experiment; pushing on low-background techniques.

END