Direct Detection of Dark Matter Using Liquid Argon

McDonald Institute Summer Particle Astrophysics Workshop (EIEIOO)
Queen's University, Kingston, ON

2024 May 13

Fred Schuckman II

Outline

Introduction

- A reminder of the big picture: What are we looking for?
- What is direct detection and why use a Liquid Argon (LAr) Target?
- Single-Phase and Dual-Phase Detectors
- LAr Physics Basics and Pulse Shape Discrimination

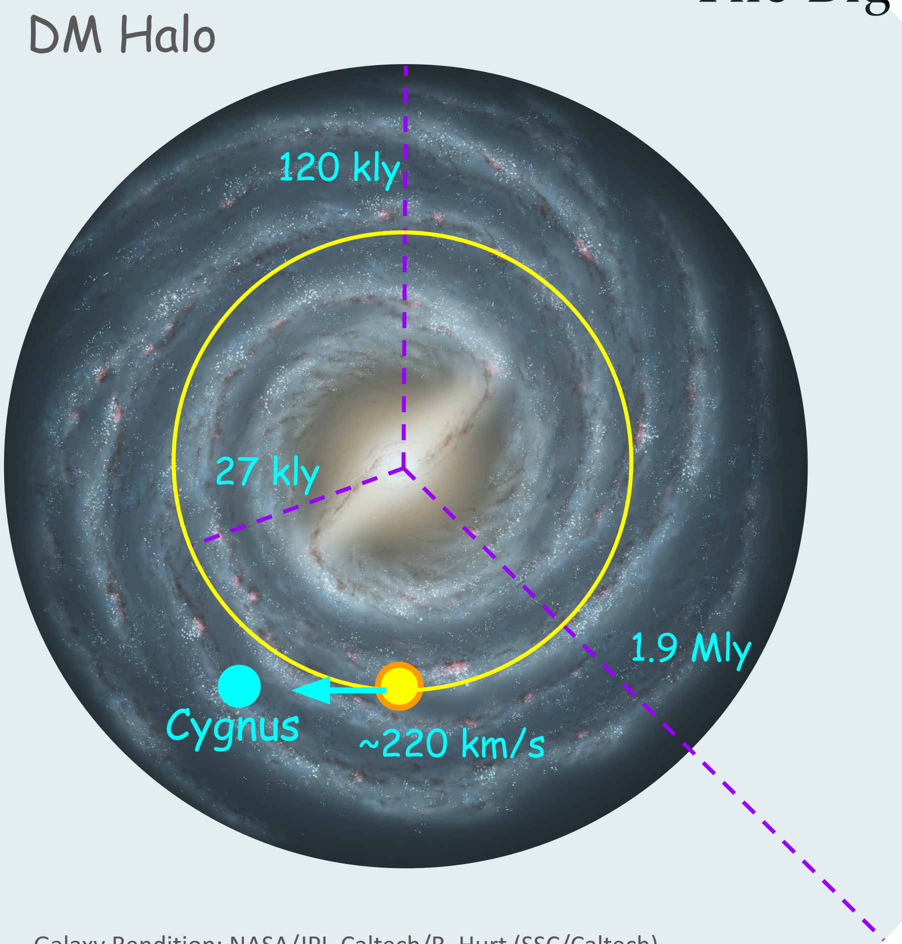
DEAP-3600

- The detector, status, and upgrades

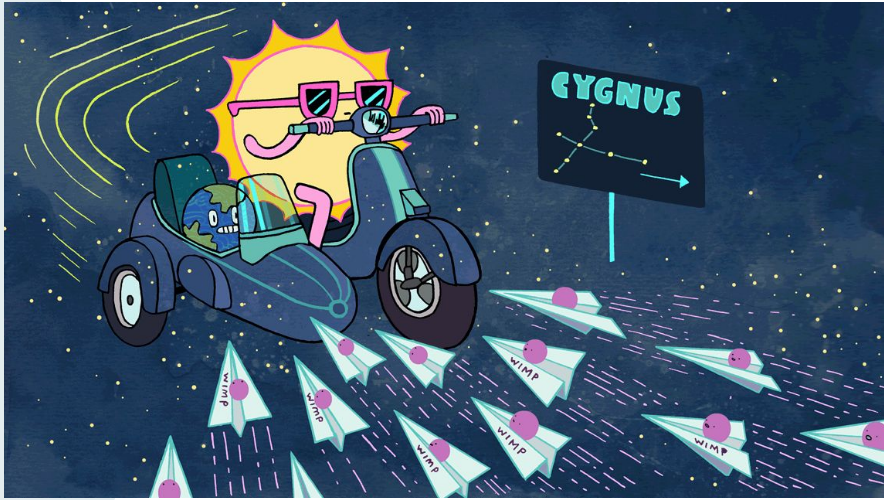
DarkSide-20k

- Introduction to the detector and data acquisition

The Big Picture

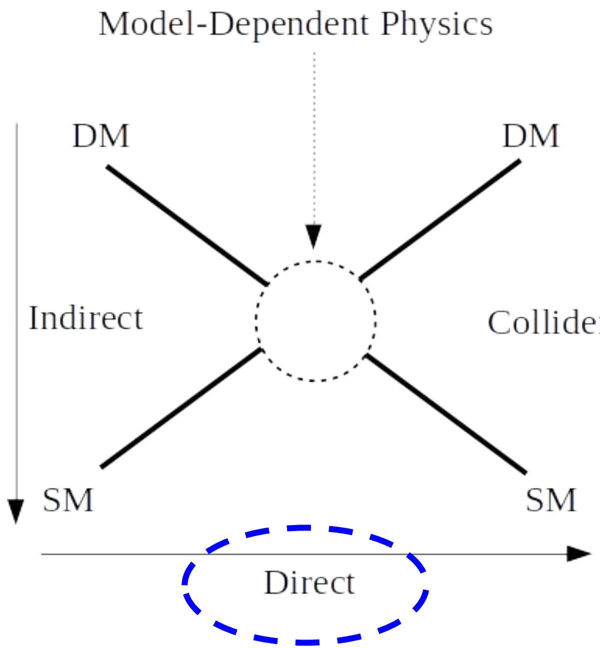


Galaxy Rendition: NASA/JPL-Caltech/R. Hurt (SSC/Caltech)



Symmetry Magazine, Artwork by Sandbox Studio, Chicago with Corinne Mucha

Direct Detection



The focus of this presentation is direct searches where energy is measured in the form of photons and ionization.

Liquid Argon Targets

- Good at scintillating and ionizing which are measurable ways to look for the energy deposited by particle interactions
- A liquid medium allows for a large target mass
- transparent to its own 128 nm scintillation light
- Atmospheric argon (AAr) is abundant and easy to purify
  - have ~1 Bq/kg of 39Ar beta decays, however, these can be excluded extremely well through Pulse Shape Discrimination (PSD)
  - DEAP uses AAr
- Deposits of underground argon (UAr) have been shown to have this activity suppressed by a factor of ~1400
  - DarkSide-20k will use UAr for its inner detector

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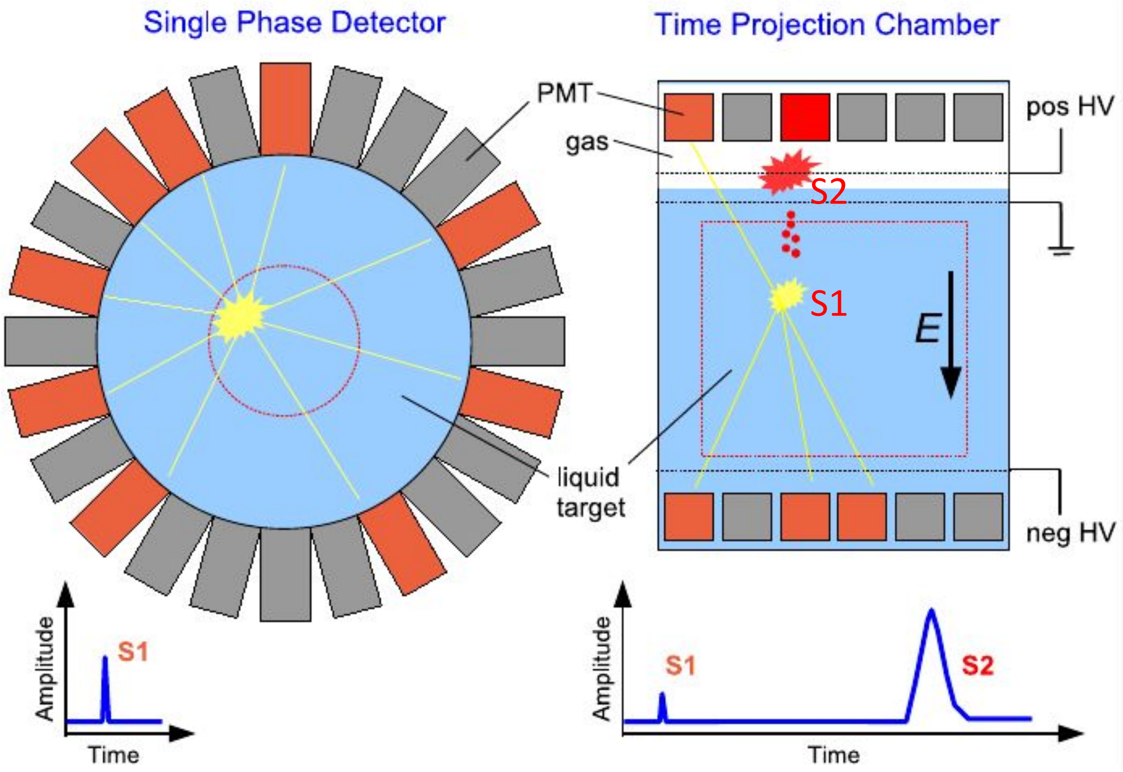
Single-Phase and Dual-Phase Detectors

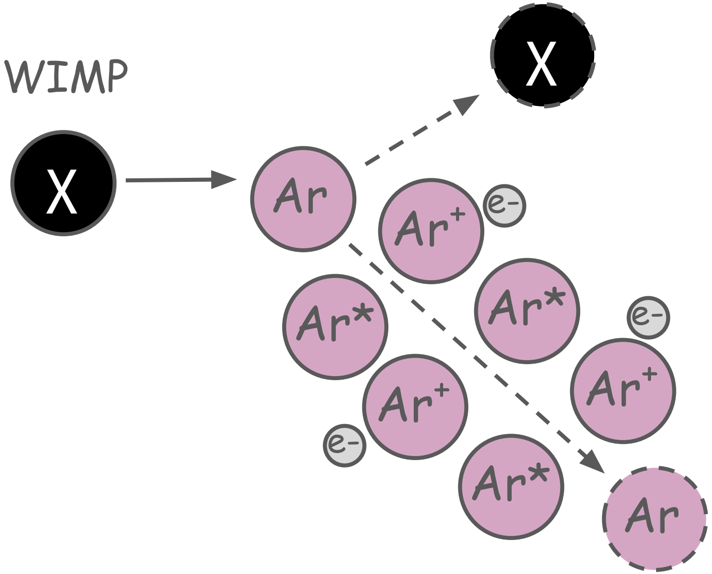
Position reconstructed from light distribution and timing across PMTs



- Horizontal position: S2 signal location on top sensor plane
- Vertical position: time difference between S1 and S2
- Electronic and nuclear recoils distribute their energy differently between S1 and S2

Marc Schumann, arXiv:1206.2169 [astro-ph.IM]

LAr Physics Basics

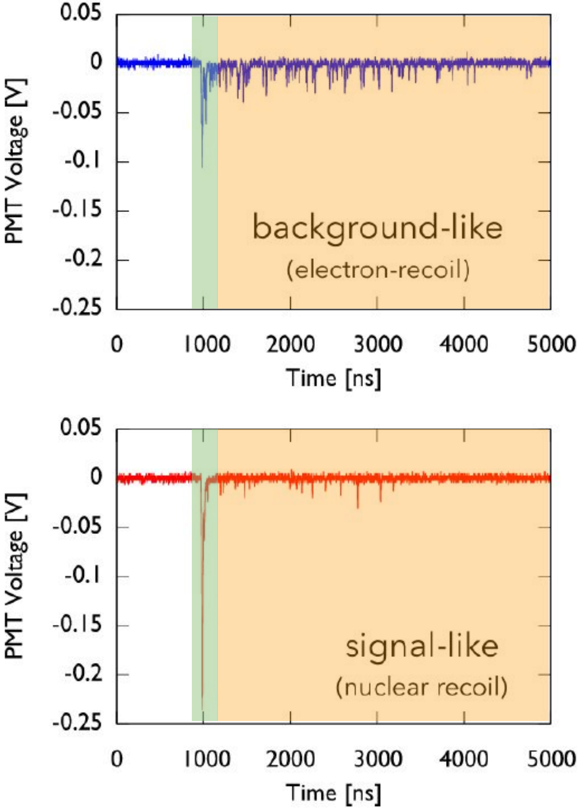


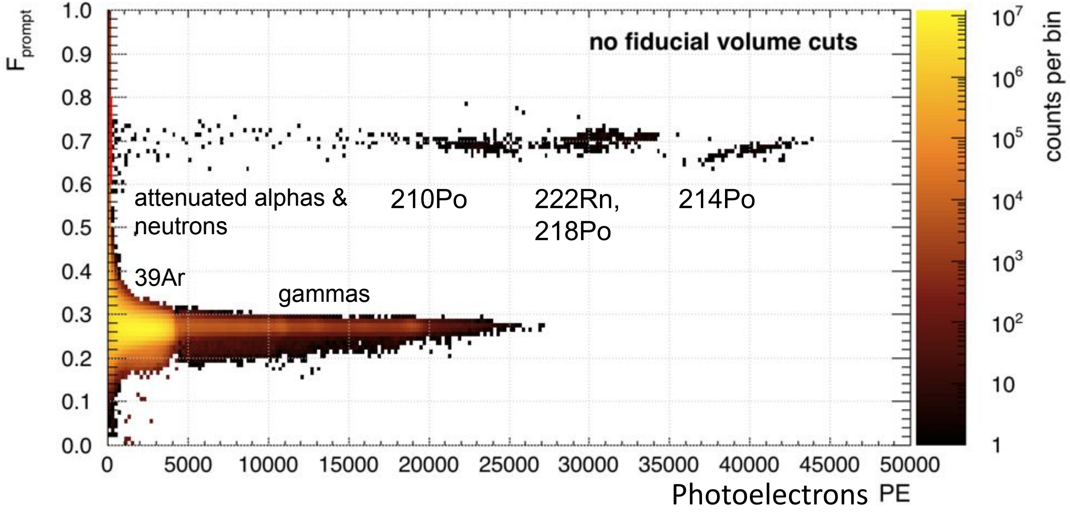
- Both Ar* and Ar^+ (through a chain of intermediate interactions) can lead to:
  - $Ar^* + Ar \rightarrow Ar_2^*$
  - $Ar_2^* \rightarrow 2Ar$ + 128 nm light
- The excited argon dimers (Ar_2^*) can be populated in two varieties:
  - **singlet state**: short lived (~7 ns), preferred by nuclear recoils (WIMPs, neutrons, alphas)
  - **triplet state**: long lived (~1.6 us), preferred by electronic recoils (betas, gammas)

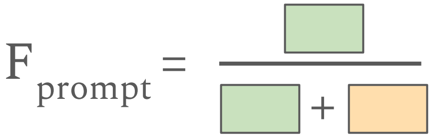
The main takeaway from this slide:

The signal produced by nuclear recoils is more prompt than for electronic recoils. This is known as Pulse Shape Discrimination (PSD).

Pulse Shape Discrimination (DEAP Data)







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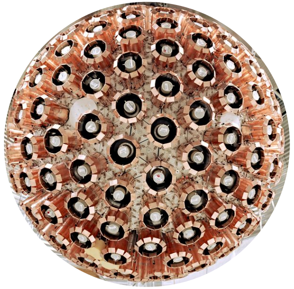
Global Argon Dark Matter Collaboration

MiniCLEAN

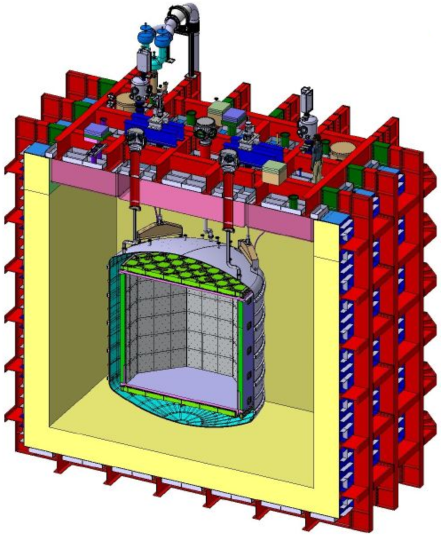
DEAP-3600
(< 1 tonne fiducial)



ArDM

DarkSide-50

DarkSide-20k
(20 tonne fiducial)



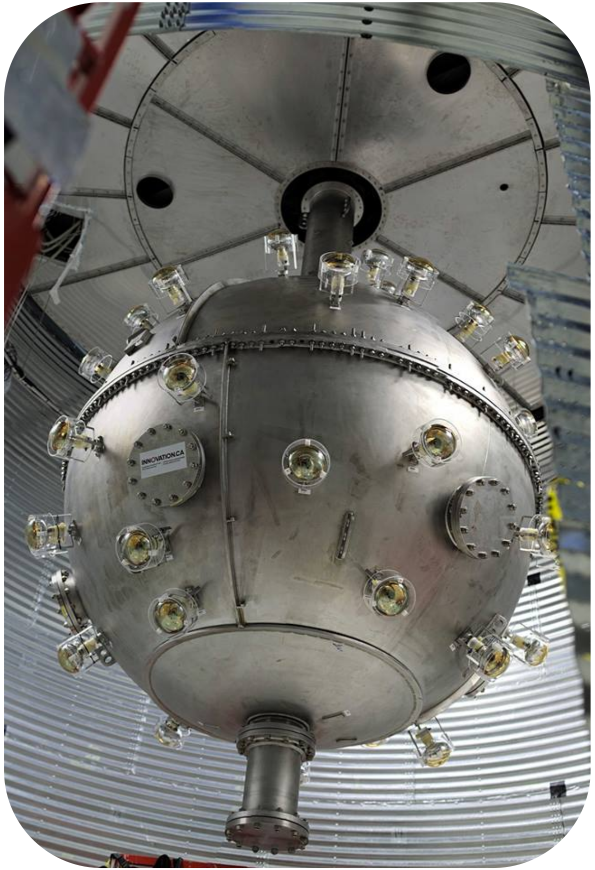
Under Construction
at LNGS

ARGO
(300 tonne fiducial)
Construction may begin
in 2030s

Dark matter **E**xperiment using **A**rgon **P**ulseshape discrimination

DEAP-3600

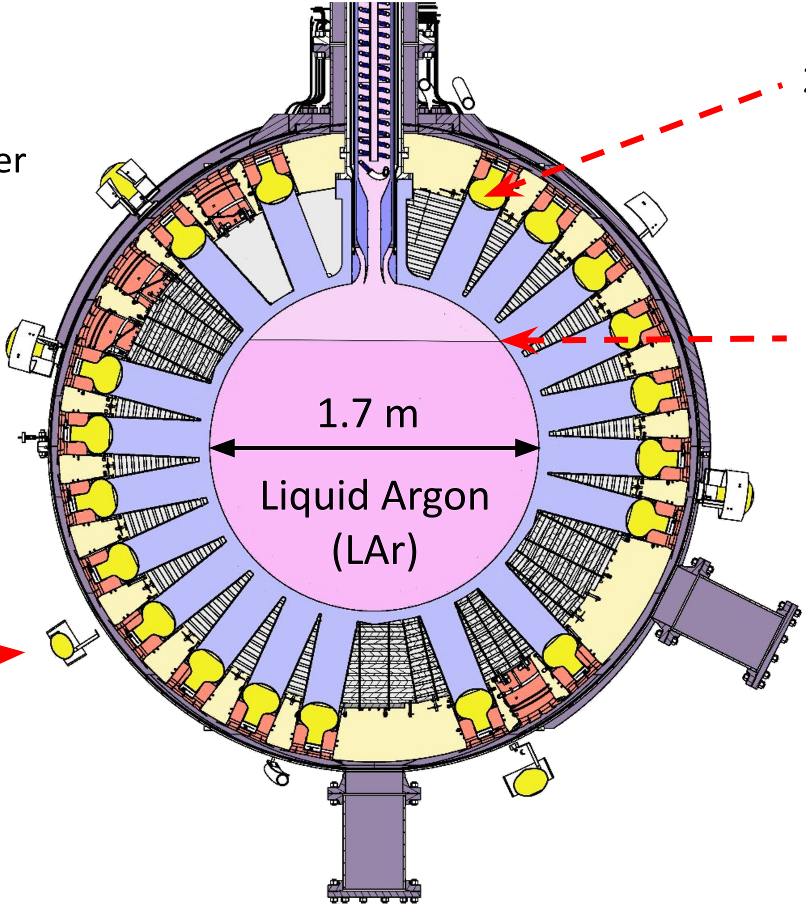
Sited 2 km underground at SNOLAB



DEAP-3600

Inner surface of spherical vessel coated with 3 um of tetraphenyl butadiene (TPB) wavelength shifter (128 nm to 420 nm)

255 inward-facing PMTs



3279 kg LAr for a fill level of 551 mm above center of Acrylic Vessel

Immersed in water shield (muon veto) with 48 outward-facing PMTs

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Status of DEAP

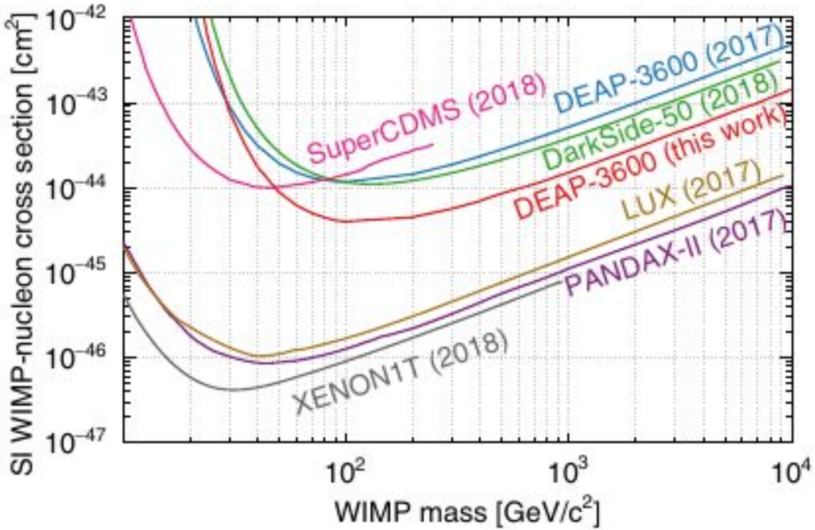
Have collected over 800 days of WIMP-search data with 388 days of that being open (the rest remains blinded)

DEAP has set the most sensitive limit to-date for spin-independent WIMP-nucleon scattering for a WIMP mass above ~30 GeV using LAr as a target

Detector is currently empty of LAr and undergoing a set of hardware upgrades that will further reduce backgrounds originating from degraded-energy alphas.

Nominally, the plan is to complete the third fill of the detector and be collecting data by December 2024.

Currently working on a WIMP search analysis using a profile likelihood approach, using our open data set, and extending both our ROI and fiducial volume.



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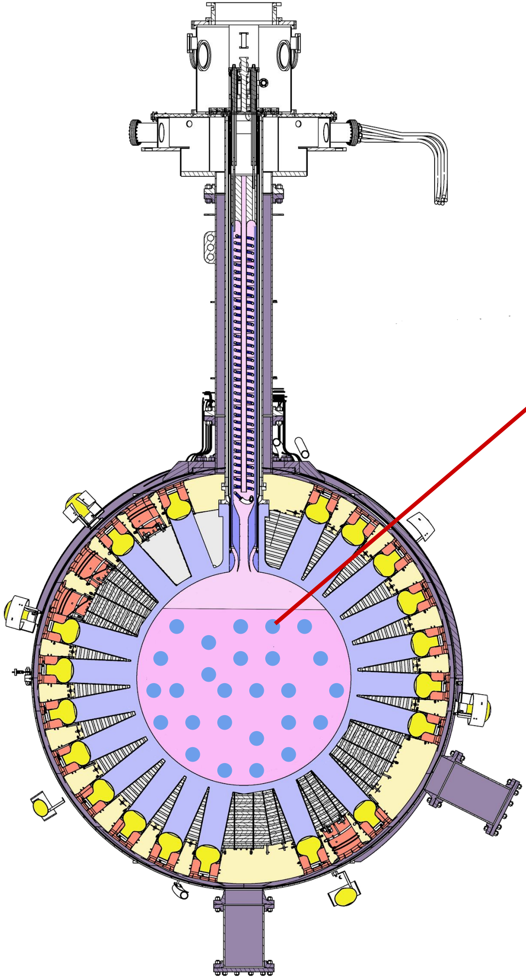
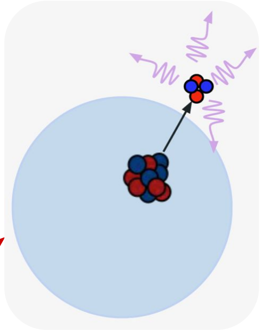
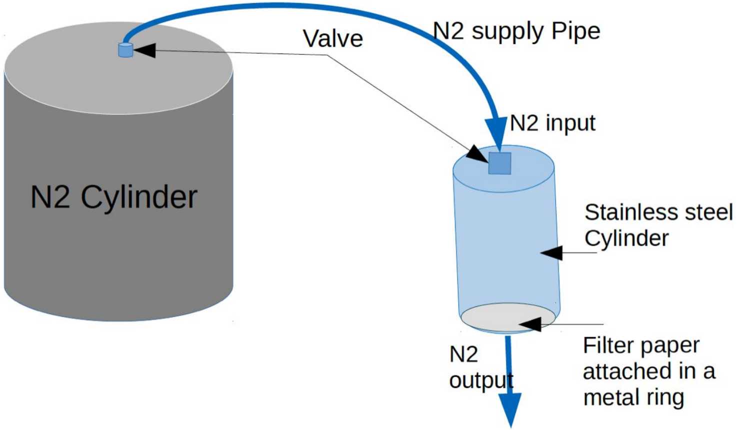
Dust Alphas

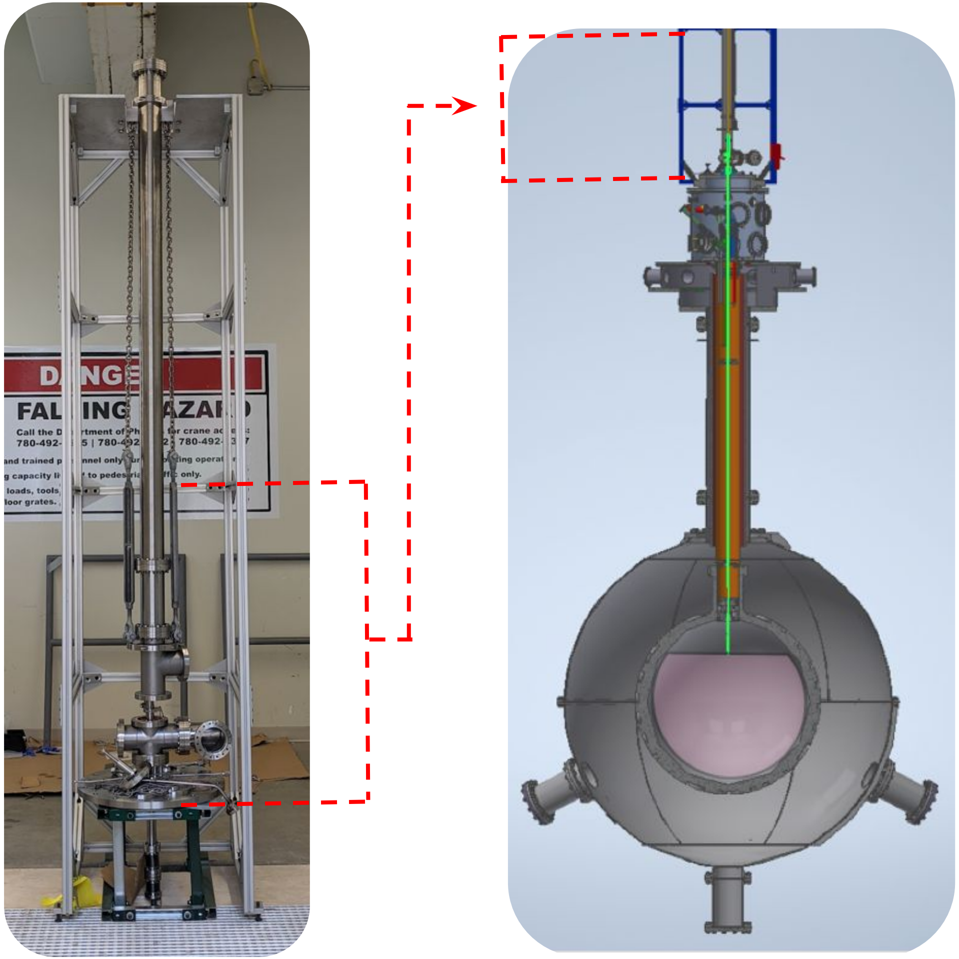




Alpha energy lost in the dust and by shadowing

- Dust particles distributed throughout the LAr with ^{210}Po contamination
- Where did the dust come from?
  - One theory motivated by ex situ measurement
    - Before LAr fill, 10 tonnes of N_2 gas used to flush the vessel
    - 50 um pore-size filter was used during the flush

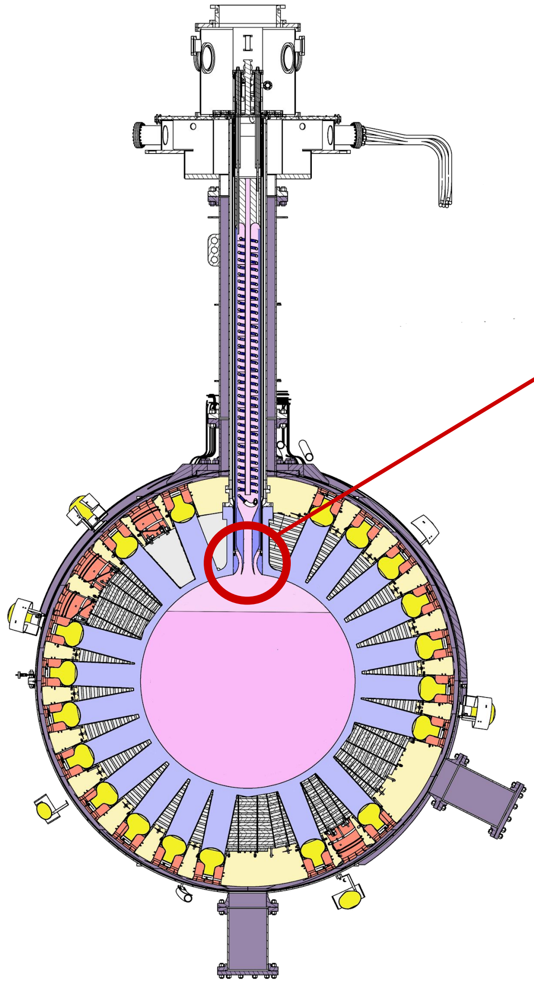


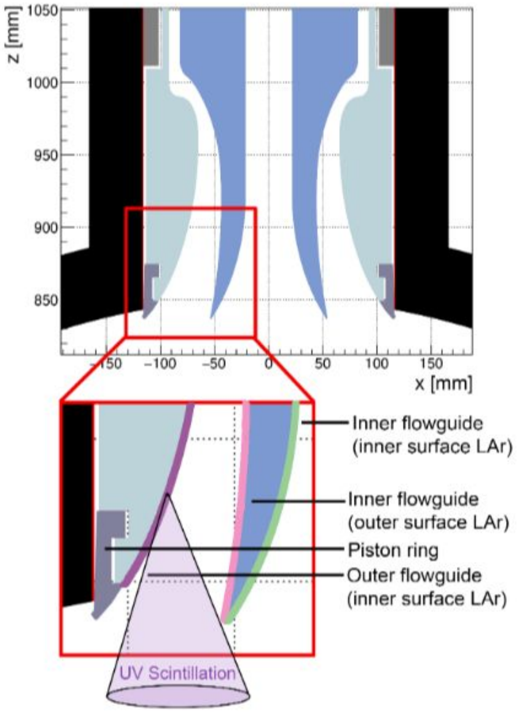


Hardware Upgrades

- Dust removal
  - A tube will be deployed to the bottom of the AV to pull LAr (and dust) out of the AV
  - A process is in place to preserve the dust so that it can be characterized
  - Detector will be filled through tube, a filter on the Ar purification system will prevent dust from getting into the AV

Shadowed Alphas



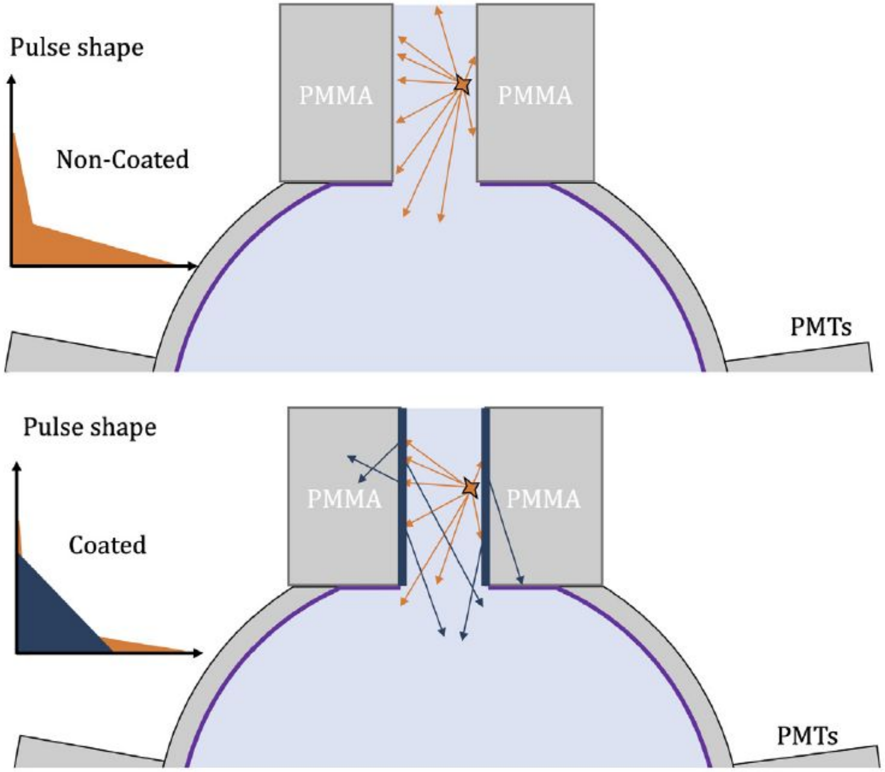


- ^{210}Po decays along flowguides in neck region
  - no TPB on flowguides
  - thin layer of LAr on flowguides
- The acrylic is UV absorbing and results in shadowing (and three distinct populations)
- Reconstruct within the fiducial volume of the detector

Mitigation:

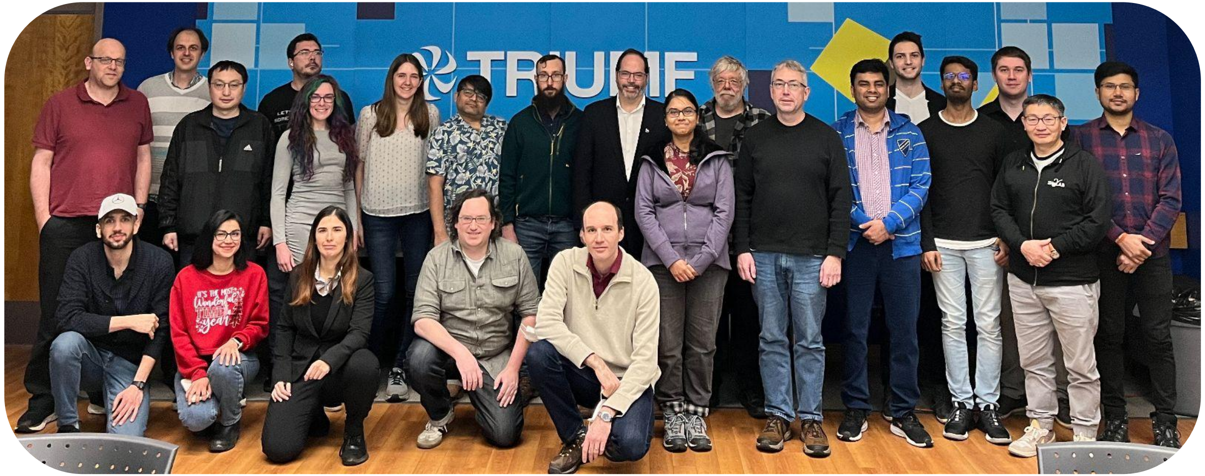
- Fraction of charge observed in top PMTs
- Early light in top PMTs
- Light in neck veto PMTs
- Deep and machine learning algorithms to tag them

Hardware Upgrades



- External cooling of the Ar (vs in the neck) will allow for a warmer neck to prevent LAr film from forming on the flowguides
- Pyrene (slow wavelength shifter) on flowguides
  - adjust the pulse shape of neck alpha events to make them distinguishable

Nucl. Instr. Meth. A 1034 (2022) 166683



January 2024
Collaboration Meeting
Vancouver, BC

University of Alberta
AstroCeNT – Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences
UC Riverside
Canadian Nuclear Laboratories / Laboratoires Nucléaires Canadiens
Carleton University
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"
Laurentian University / Université Laurentienne
IF – Instituto de Física
Princeton University
Queen's University
Royal Holloway University of London
Particle Physics – Rutherford Appleton Laboratory
SNOLAB
University of Sussex
Technical University of Munich – TUM
TRIUMF

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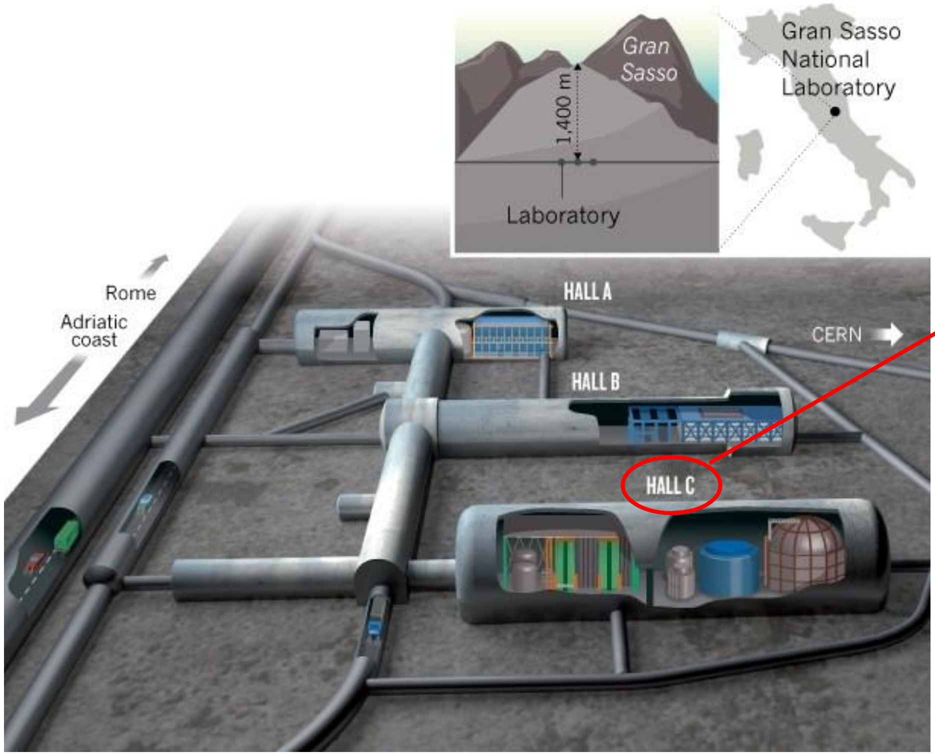
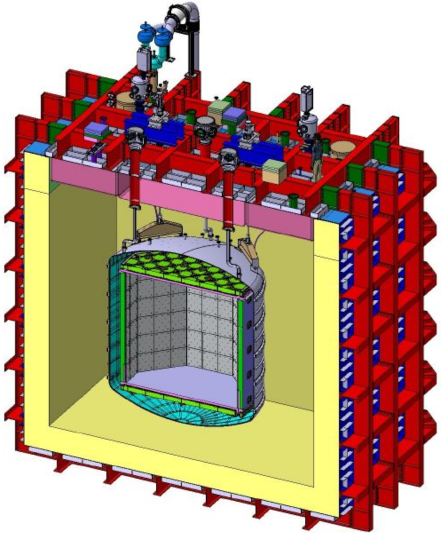
DarkSide-20k



Nosengo, N. Gran Sasso: Chamber of physics. *Nature* 485, 435–438 (2012)

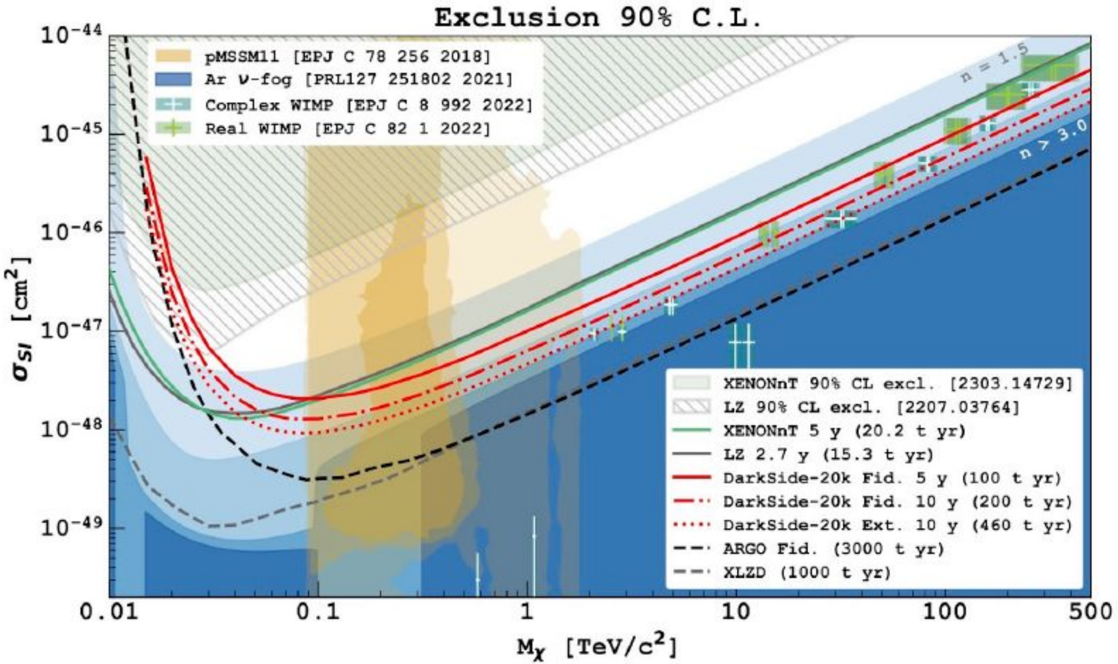
Under construction in Hall C



1400 m of rock overhead to shield cosmics

One accesses the lab via a 10 km long highway that runs beneath the mountain.

DarkSide-20k Goals

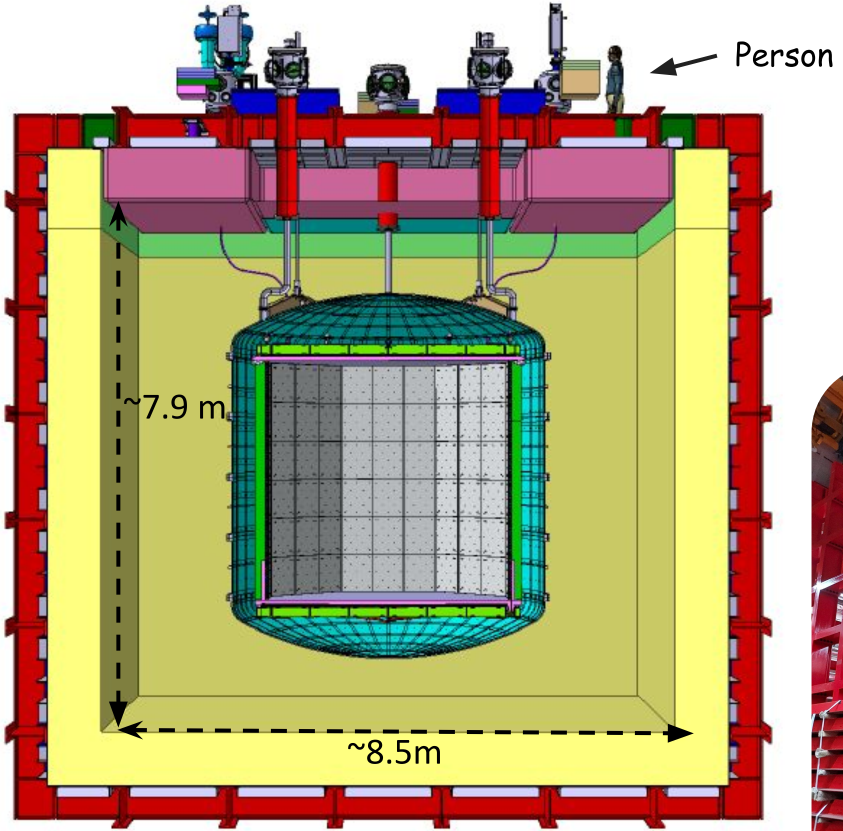


Target of < 0.1 neutron events in our ~30-200 keVnr ROI in 200 tonne-years (10 years of run time)

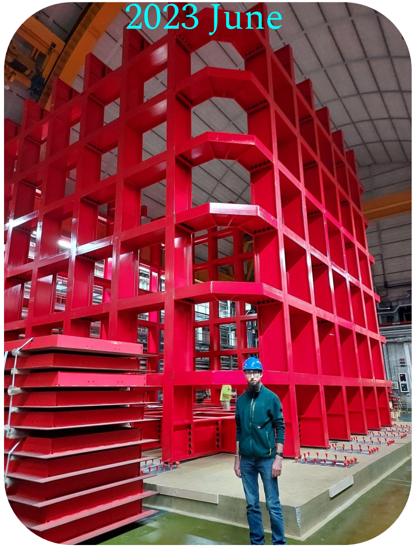
Projected sensitivity of 6.3E-48 cm^2 at 1 TeV 90% CL exclusion

Expect to see ~3 coherent-elastic neutrino-nucleus scatters

DarkSide-20k: Inner and Outer Vetos

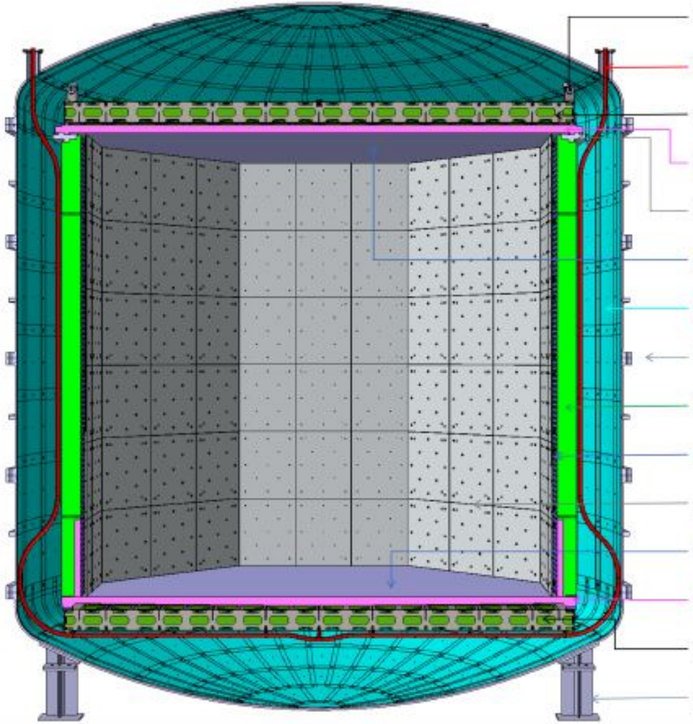


- **Inner Veto**
  - 32 tonnes of Underground Ar housed in stainless steel vessel
  - monitored by 480 photo detector channels
  - Look for coincident signals between this veto and the detector to tag, for instance, neutrons



- **Outer Veto**
  - Used to tag cosmogenics
  - Nominally, 128 photo detector channels
  - Cryostat based on design already demonstrated to work for ProtoDUNE
  - volume is approximately a cube of side length 8 m
  - 700 tonnes of Atmospheric Ar

DarkSide-20k: Inner Detector



- 49.7 tonne LAr (active mass), 20 tonne (fiducial)
- 348 cm drift length
- Electric Field
  - Anode, Cathode, and Field-Shaping rings made of coating of optically-transparent Clevios
  - 200 V/cm field strength corresponding to 3.7 ms max electron drift time
- Gas pocket at top of detector 7 mm thick!
  - Needs to be precise across the 350 cm diameter optical plane at the top
- Lateral Walls
  - The nominal design was to use Gd-loaded acrylic
  - Lined with reflective foil and coated with TPB wavelength shifter
- Top/Bottom Faces
  - TPB, Clevios, Acrylic, Plane of Silicon Photomultipliers (SiPMs)
- Target Resolution: ~1 cm (horizontal) and ~1 mm (vertical)

DarkSide-20k: TPC Photo Detection

SiPMs

- Can operate at cryogenic temperatures
- Radiopurity (PMT glass is a background source)
- Operate at relatively low voltage
- High photon detection efficiency of > 40% at 77 K (7 VoV)

- Dark count rate: < 0.01 Hz/mm^2 (Relatively large compared to PMTs)
- Signal-to-noise of more than 8
- However, these devices are quite small, so many need to be tiled and read out in tandem to instrument a large-scale detector

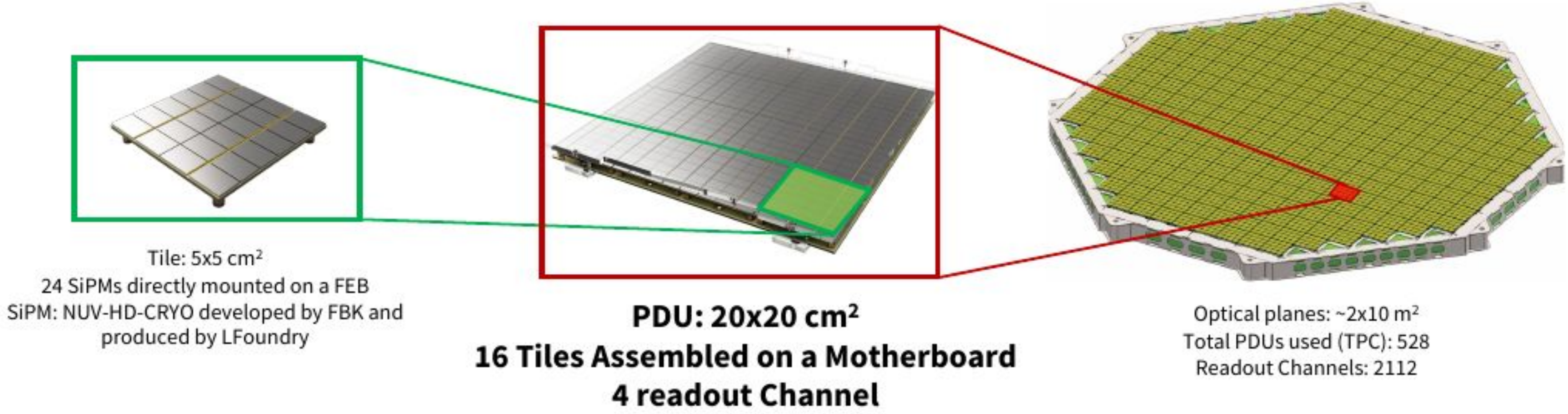
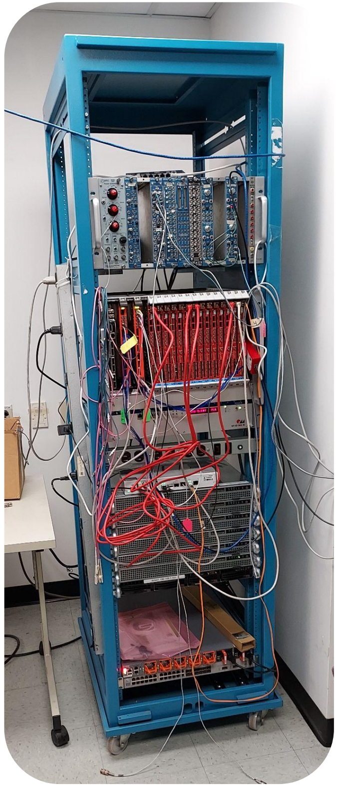
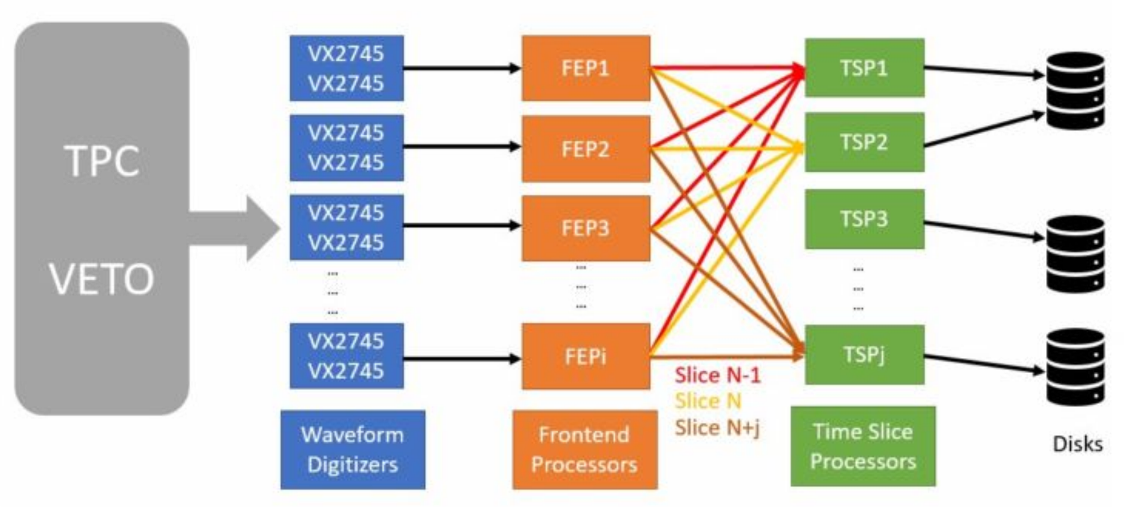


Figure: G. Matteucci, Light readout in DarkSide-20k with cryogenic SiPMs, TPC2023

DarkSide-20k: Data Acquisition



Initial testing of ¼ of the digitizers at TRIUMF (January 2024)



Digitize with CAEN VX2745 (125 Msps, 16-bit)

36 digitizers for 2112 TPC channels

12 digitizers for the vetos (480 inner + 128 outer)

Custom firmware used to isolate waveform segments with single photoelectron capability

Each **Front End Processor** (FEP) handles 2 digitizers (24 needed)

Algorithms applied at this stage for data reduction (waveforms to hits)

(Basically, “hit” means to identify each individual photoelectron pulse within a larger waveform)

Each **Time Slice Processor** (TSP) receives data from all FEPs over a 1-second slice of real time and assembles that data into a time slice which then gets saved to disk

Flow diagram: from previous presentations by A. Capra

June 2023 Collaboration Meeting
Assergi, Italy

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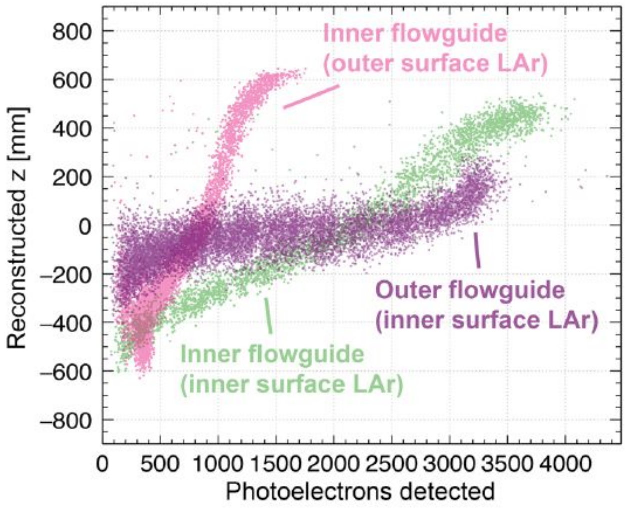
Extra

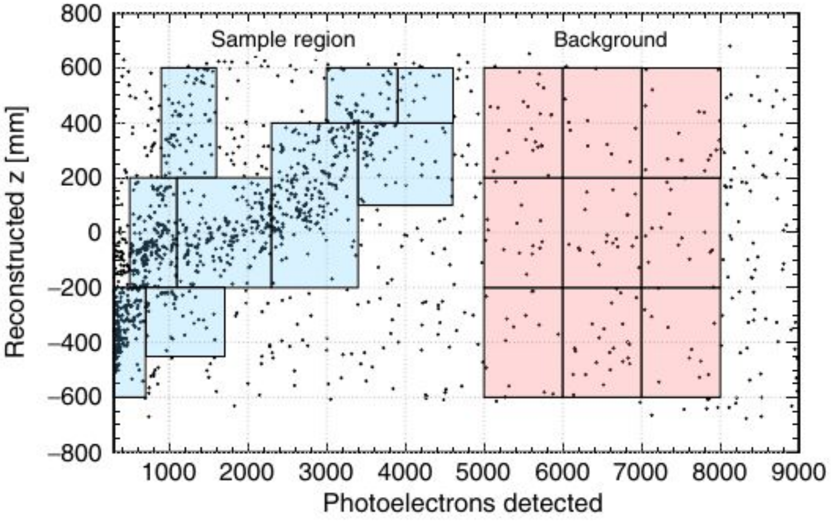
Shadowed Alphas

Full vertical length of detector

Simulation



Data



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DarkSide-20k: Brief overview of work at Queen's

We are part of a group that is developing the format for how data will be saved to disk. If one has a model for how an event will be structured on disk, one can estimate the output data rate of the detector based on simulation, which needs to fall within a certain budget. We use simulations to understand what waveforms will look like for the 2112 TPC channels, and what the sums of those waveforms look like across the top and bottom planes.

Goals toward online-monitoring:

- Understand algorithms that are already present to perform data reduction on the waveforms that are output from digitizers
- Develop algorithms that can be applied at the TSP-level
  - Work on summed waveforms and classify signals as S1 or S2
  - Can we come up with a fast algorithm to pair S1 and S2 events online?
- We want to be able to monitor the "health" of the detector by watching how the data we collect evolves with time.
  - example at FEP-level: What is the rate at which we are seeing waveforms for each of the 2112 TPC channels. It is of interest to know if a group of these are stable over many days and then the rate on a channel changes significantly the next day.
- Develop graphical user interfaces to be able to view events in real time, review past events, look at stability plots for each of the variables we measure, save the monitoring data to disk and be able to relate it to the physics data collected for the same period of real time
- Develop algorithms to identify anomalies and make a shifter aware