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

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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 $^{39}\text{Ar}$
  • 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 Jigmeeddrorj – 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

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

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.

High acceptance after cuts

No events near ROI after cuts (including FV)

Limit set by DarkSide-50k:

$1.1 \times 10^{-44}$ cm$^2$ at 100 GeV/c$^2$

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.

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

DarkSide-50 set strong limits between 1.8 and 10 GeV.

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

X-rays after $^{37}$Ar decay

https://arxiv.org/abs/2107.08087

https://arxiv.org/abs/2209.01177

https://arxiv.org/abs/2207.11966

https://arxiv.org/abs/2107.08087

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 $^{39}$Ar with a specific activity of $0.964 \pm 0.001\text{stat} \pm 0.024\text{sys}$ Bq/kg

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

→ 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!

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

Calculate the prompt fraction after afterpulsing removal


Data at \sim 18 \text{ keV}_{ee}

Leakage probability of EM events

Nuclear recoil acceptance

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 its analysis by accounting for Effective Field Theory and Galactic Models.

\[ \frac{dR}{dE_R} = \frac{\rho_T}{m_T} \frac{\rho_X}{m_X} \varepsilon(E_R) \int_{\nu_{\text{min}}}^{\infty} v f^\oplus \left( \frac{d\sigma}{dE_R} d^3\vec{v} \right) \]

(Conventional limit)

\[ f(v) \text{ [km/s]}^{-1} \]

0 km/s 800 km/s

Sub: Gaia Sausage
Ref. Necib et al.

\[ \sigma_1 = 1_N 1_N \]
\[ \sigma_3 = i \vec{S}_N \cdot \left( \frac{\vec{q}}{m_N} \times \vec{v}_\perp \right) \]
\[ \sigma_5 = i \vec{S}_X \cdot \left( \frac{\vec{q}}{m_N} \times \vec{v}_\perp \right) \]
\[ \sigma_8 = \vec{S}_X \cdot \vec{v}_\perp \]
\[ \sigma_{11} = i \vec{S}_Y \cdot \frac{\vec{q}}{m_N} \]
\[ \sigma_{12} = \vec{v}_\perp \cdot (\vec{S}_X \times \vec{S}_N) \]
\[ \sigma_{15} = - \left( \vec{S}_X \cdot \frac{\vec{q}}{m_N} \right) \left( \vec{S}_N \times \vec{v}_\perp \right) \cdot \frac{\vec{q}}{m_N} \]


DEAP-3600 searched for Planck-scale dark matter

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

Simulation

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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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

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

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 $^{39}\text{Ar} DF = 10$ 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 $^{39}\text{Ar}$ signal and the black dots denote the simulated data.
Larger detectors will require 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 $^{210}\text{Pb}$ (22.3 yr half life)
- $^{210}\text{Po}$ (138 day half life) produces alphas that mimic WIMP signals.
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 ($\alpha$,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)**
21 m² in TPC; 5 m² 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: \( >40\% \text{ at } 77 \text{ K} \)
Dark count rate: \( <0.01 \text{ Hz/mm}^2 \text{ at } 77 \text{ K} \)
SNR: \( >8 \) for \( 10 \times 10 \text{ cm}^2 \text{ TPC PDU} \)

https://doi.org/10.1088/1748-0221/12/09/P09030
SNO-style motor & pulley for calibration deployment

Flexible shaft coupling

To the power supply & controller

Grooved drum (30 m rope)

Follower pulley on linear bearing geared to pitch of drum

Loadcell

Spring with rope in center to limit extent at ~20 N

Very low friction encoder pulley (encoder is mounted on rear side)

To the cryostat
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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ARGO: a multi-hundred tonne detector

3000 tonne year projection
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./(m²×s);
• calibration 100k p.e./(m²×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\textsuperscript{222} / Rn\textsuperscript{220} and their progeny on detector components

• Response of Pyrene-doped Polystyrene coatings to alpha scintillation.
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.
• 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.