

Dark Matter Searches with Liquid Argon in DEAP-3600 and DarkSide-20k

*On behalf of the **DEAP** and **DarkSide** collaborations.*

By Daniel Huff (University of Houston) 
CIPANP 2025



Overview

- Detecting Dark Matter with Liquid Argon
- An Introduction to [DEAP-3600](#)
- Results from [DEAP-3600](#)
- An Introduction to [DarkSide-20k](#)
- The Future of Liquid Argon in Dark Matter Searches

Dark Matter plush from particlezoo.net



SNOLAB in Canada

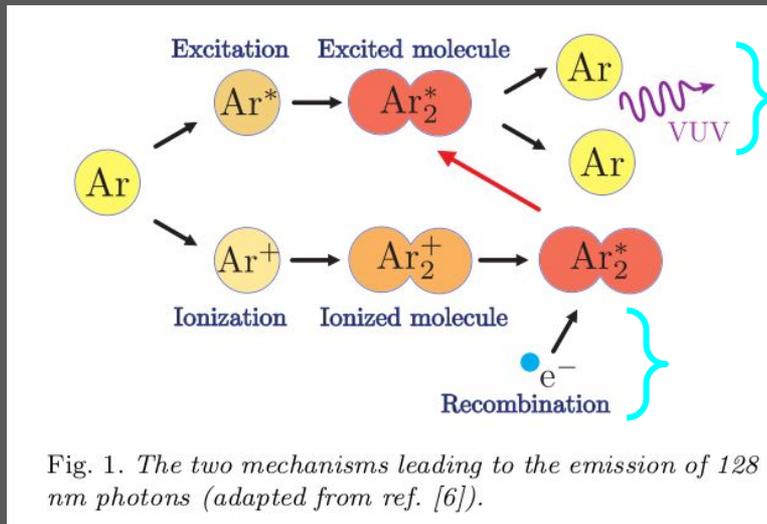


LNGS in Italy

Detecting Dark Matter with Liquid Argon

Noble Liquid Scintillation

- Noble liquids can be excited via a weak interaction with a projectile
- This forms a dimer
- The output light is a proxy for an interaction



Detected with a PMT (photomultiplier tube)

Not all of these will be reabsorbed- this is used in DarkSide-20k

Fig. 1. The two mechanisms leading to the emission of 128 nm photons (adapted from ref. [6]).

Fig. 1 from [1]

The dimers can decay in two different timescales, from either the singlet or triplet state.
The ratio of the production of the two decay states depends on the type of projectile. [1]

Singlet = 6ns decay

Triplet = 1.5 μ s decay

Advantages of Argon

- Better (30x) pulse shape discrimination (PSD) [2]
 - The ratio of the production of the two decay states depends on the type of projectile [1]
 - This can be determined by measuring if more light is produced earlier or later in the signal

Singlet = 6ns decay

Triplet = 1.5 μ s decay

$$f_{\text{prompt}} = f_{90} = \frac{\text{Light in first 90ns}}{\text{Total light}}$$

Higher f_{prompt} = more singlet production = nuclear recoil (NR)

Lower f_{prompt} = more triplet production = electronic recoil (ER)

- Highly pure underground sources (UAr)
- Colder liquid temperature
- More readily available

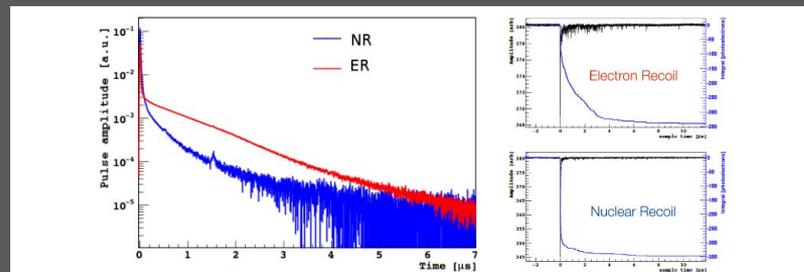
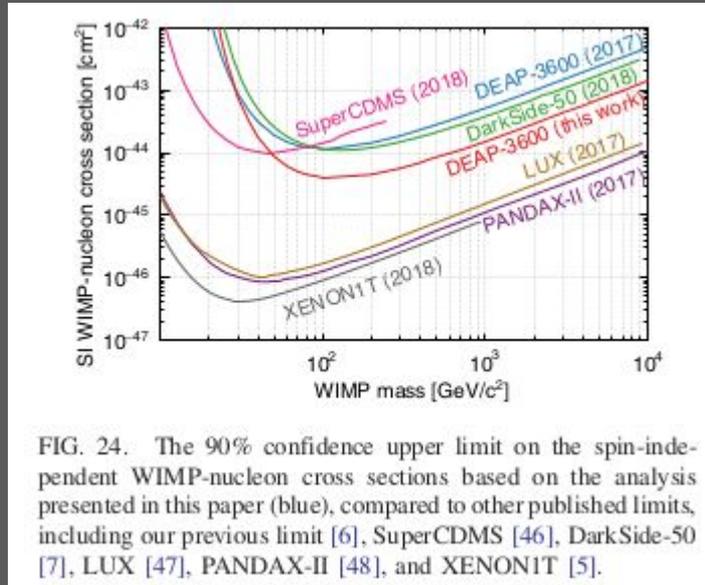


Figure 1: (Left) Amplitude of an S1 signal for an ER and an NR. (Right) Waveforms of an electron and a nuclear recoil, superimposed with integrated charge.

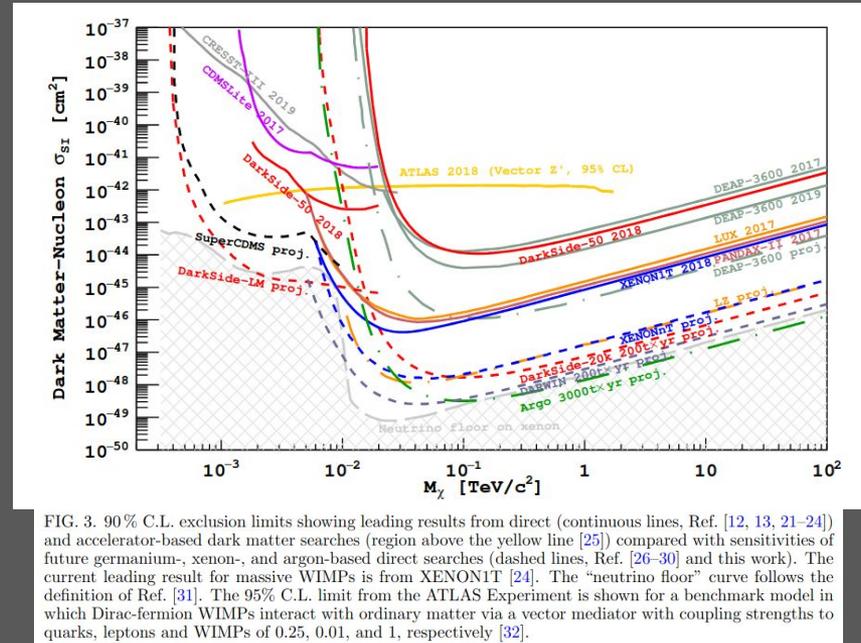
Fig. 1 from [10]

The Field of WIMP Searches

- Both **DEAP** and **DarkSide** look for WIMPs (weakly interacting massive particles), a dark matter candidate that has not yet been detected



From [3], 2019



From [4], 2021

An Introduction to DEAP-3600

What, Where, and When



- Spherical LAr detector with a 3300kg target (atmospheric ^{40}Ar)
- 2km underground at SNOLAB in Sudbury, Ontario (Canada)
- Construction completed in 2016



Photograph of the detector taken inside the muon veto tank during construction.



DEAP-3600 Components

LAr target volume

Acrylic vessel

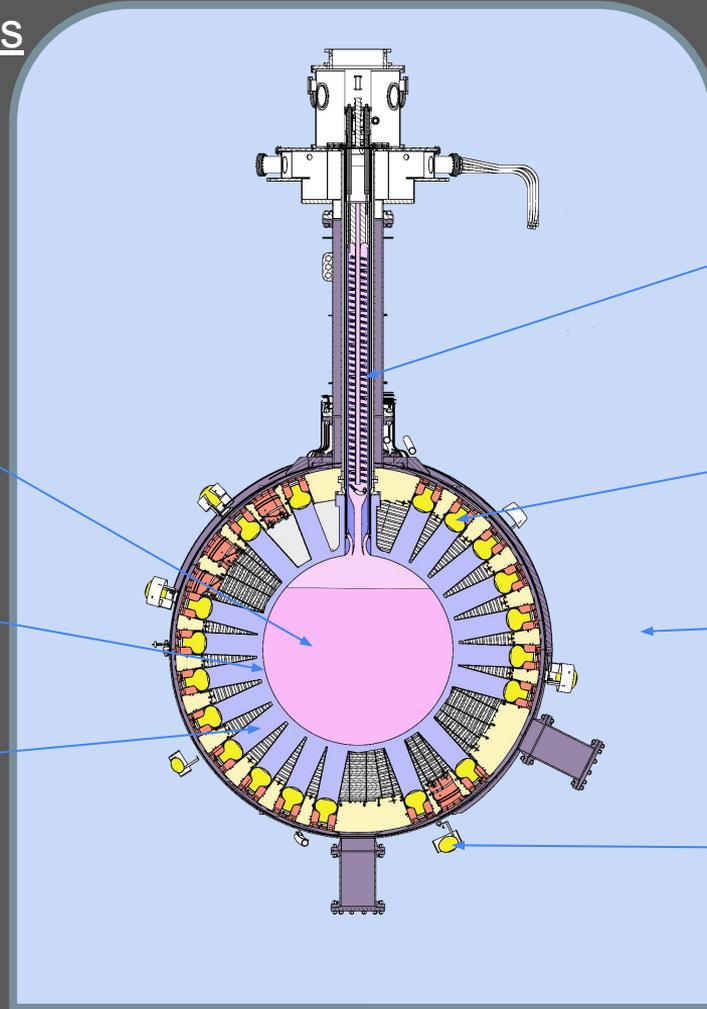
Acrylic light guide
(fused to vessel)

Neck

Interior
PMT

Ultra-pure
water

Exterior
(or veto) PMT



Results from DEAP-3600

The 231-Day WIMP Search [3]

- 758 tonne-day exposure over 231 days of livetime
- No signal events
- Set a leading limit on the WIMP-nucleon spin-independent cross section on an LAr target

$$3.9 \times 10^{-45} \text{ cm}^2 \quad (100 \text{ GeV}/c^2 \text{ WIMP})$$

$$1.5 \times 10^{-44} \text{ cm}^2 \quad (1 \text{ TeV}/c^2 \text{ WIMP})$$

- Cherenkov light in acrylic
- Radiogenic neutrons
- Cosmogenic neutrons
- α -decays from the acrylic

$N_{\text{bkg}}^{\text{ROI}} =$	0.62	$+0.31$ -0.28	events
$N_{\text{obs}}^{\text{ROI}} =$	0		events

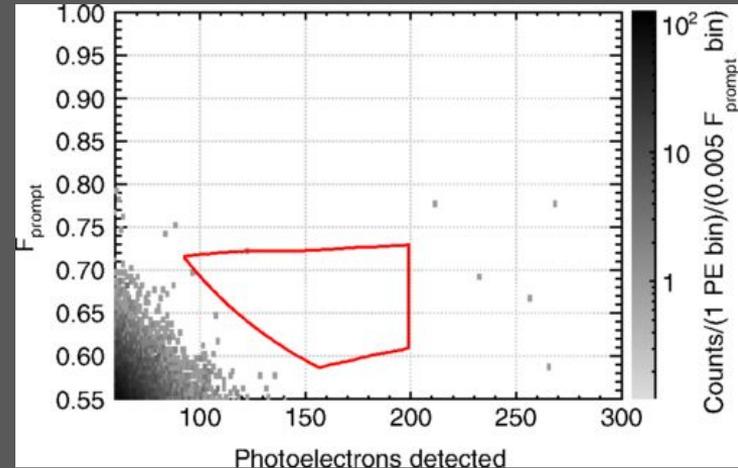


Fig. 22 from [3]: Observed F_{prompt} vs PE distribution after all cuts. The region of interest is shown in red.

(PE is the number of photoelectrons)

90% CL

Results from DEAP-3600

The 231-Day WIMP Search [3]

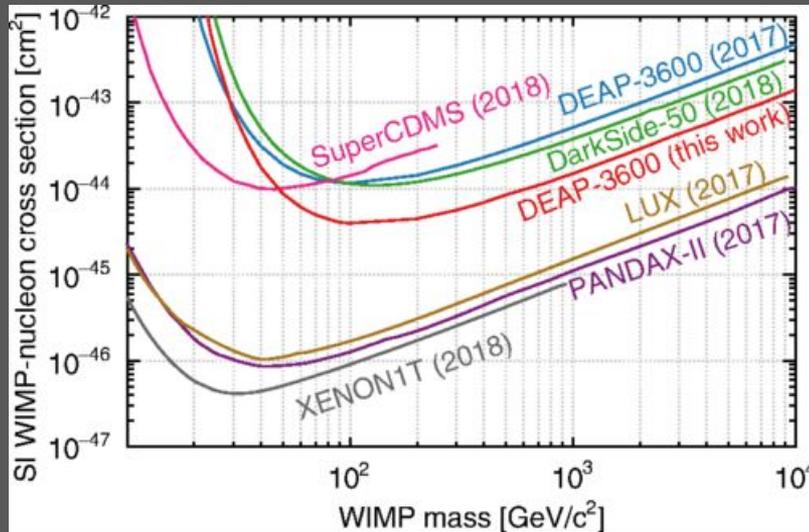


Fig. 24 from [3] (see slide 5).

$3.9 \times 10^{-45} \text{ cm}^2$ (100 GeV/c² WIMP)

$1.5 \times 10^{-44} \text{ cm}^2$ (1 TeV/c² WIMP)

- Cherenkov light in acrylic
- Radiogenic neutrons
- Cosmogenic neutrons
- α -decays from the acrylic

$N_{\text{bkg}}^{\text{ROI}}$ =	0.62 ^{+0.31} _{-0.28}	events
$N_{\text{obs}}^{\text{ROI}}$ =	0	events

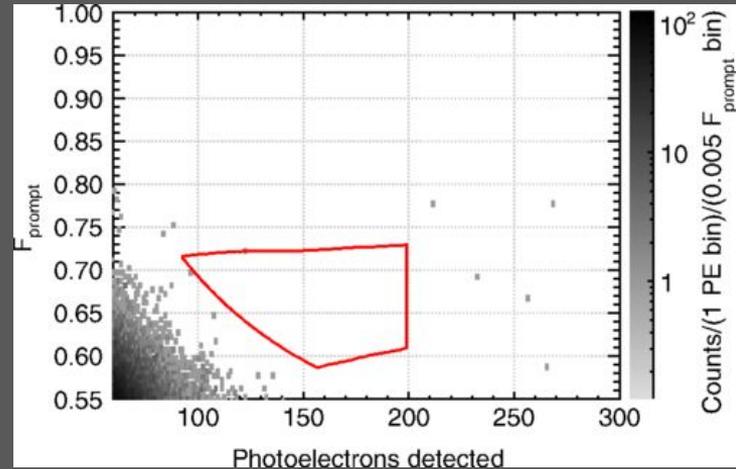
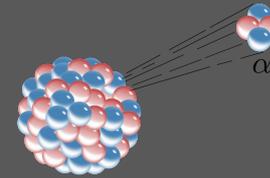


Fig. 22 from [3]: Observed F_{prompt} vs PE distribution after all cuts. The region of interest is shown in red.

(PE is the number of photoelectrons)

α -Particle Scintillation Quenching [5]



- Low backgrounds essential for DM searches
- α -decays are “the most challenging”
- Need to understand light produced vs energy, quantified with the **quenching factor (QF)**

$$QF = \frac{E_{\text{scintillation photons}}}{E_{\text{total deposited}}}$$

$$QF = \frac{PE_{\alpha}}{Y \times E_{\alpha}}$$

PE is number of photoelectrons produced, Y is light yield, and E is the particle's energy

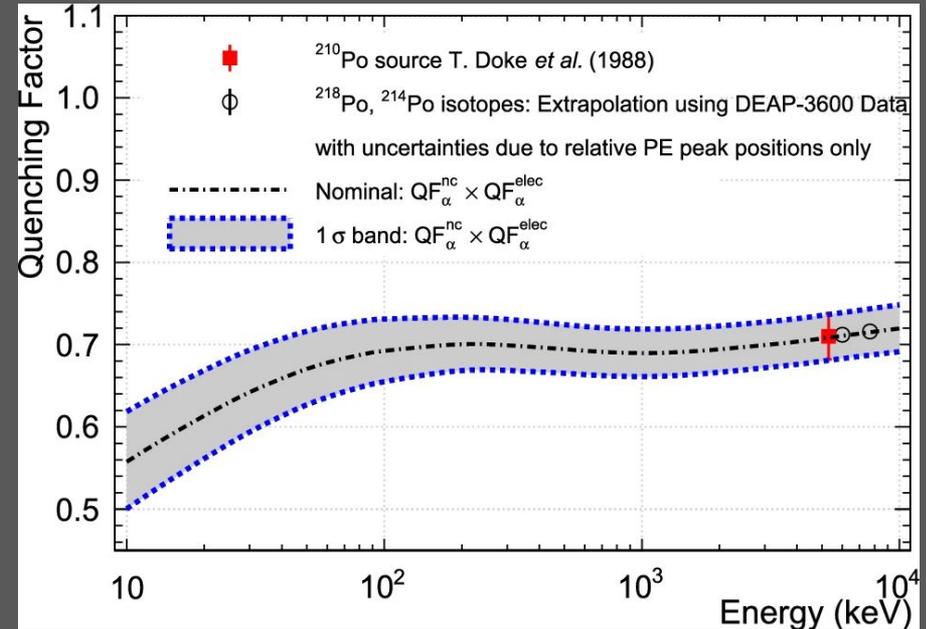
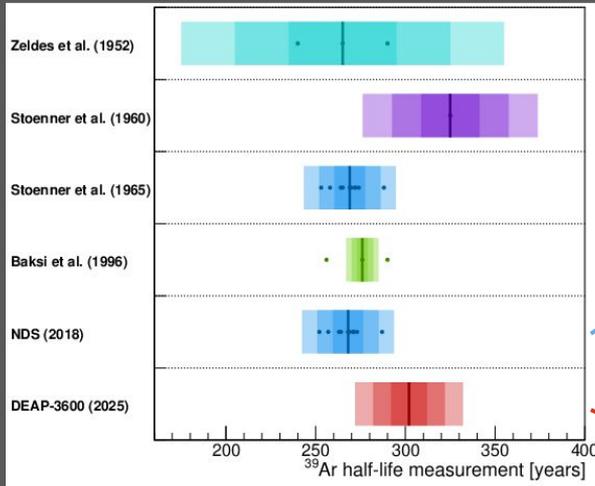


Fig. 6 from [5]: Energy-dependent scintillation QF curve for α -particles within LAr, as a function of their energy on a logarithmic scale. The nominal and $\pm 1\sigma$ QF curves are the product of the electronic QF (see Fig. 5) with the nuclear QF from TRIM (see Fig. 2).

Argon-39 Half Life Measurement [6]

- ^{39}Ar is an isotope used in “radioisotope dating, radiochemistry, radiometry, geochronology” and its decay is the dominant trigger source in DEAP-3600
- Decay rate can be *directly* measured in DEAP-3600 through changes in event rate



268 \pm 8 years, commonly used NDS number. The DEAP result rejects this with a p-value of 0.008

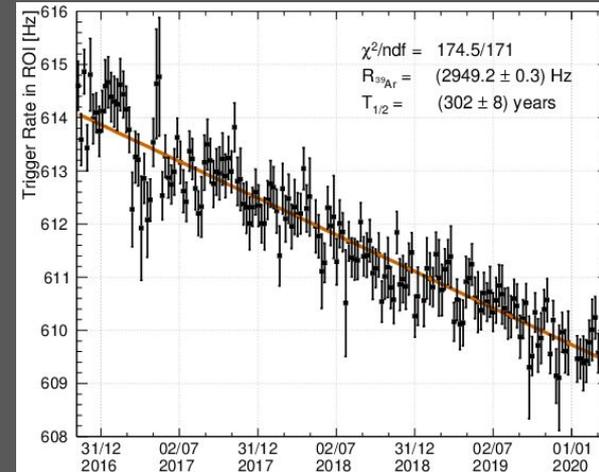


Fig. 7 from [6]: The trigger rate fit for the full dataset. Each point here represents the rates averaged over a one week period. The best-fit values of $R_{^{39}\text{Ar}}$ and $T_{1/2}$ are shown with statistical uncertainties only.

Fig. 1 from [6]: A comparison of existing ^{39}Ar half-life measurements with this work. The points shown for Zeldes (1952), Stoenner (1960), Stoenner (1965), Baksi (1996), and NDS (2018) denote the individual measurements which were reported. The vertical line represents either the average value or the single reported value. The shaded boxes indicate the 1σ , 2σ , and 3σ error bands.

302 ($+8_{\text{stat}}$ $+6_{\text{sys}}$) year half-life

The Next Steps

- Third fill happening now!
- Detector upgrades added!
- More physics to come



Don't miss a talk on

The DEAP-3600 dark matter search and charged-current ^8B neutrino measurements in liquid argon

By Abhijit Garai
(Tomorrow during "Dark Matter: Parallel 9: Joint DM/Neutrinos")

In addition, DEAP members have joined forces with the DarkSide, ArDM, and MiniCLEAN collaborations to work on the next generation of LAr DM detectors.

This leads us to...

An Introduction to DarkSide-20k



What, Where, and When [7] (or “DS-20k”)

- The next step up from DEAP-3600, DarkSide-50, and ArDM
- *Dual-phase* LAr detector with a 50,000kg active target (20,000kg fiducial vol.) of *underground* ^{40}Ar (UAr)
- Under a mountain (3800 m.w.e) at LNGS in Gran Sasso, Italy



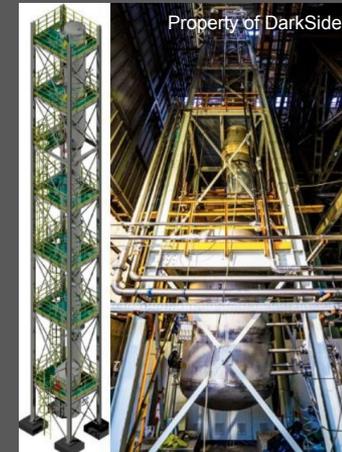
Photograph of the outside of the cryostat taken inside Hall C



Underground Argon?

- Argon is available in the atmosphere, mostly in the isotope needed for detectors, ^{40}Ar
 - * however *
- atmospheric argon also contains radioactive ^{39}Ar
- A source without as much ^{39}Ar would be an improvement: we can get that underground!

Gran Sasso, Italy
LNGS



Sardinia, Italy
Aria: refine UAr
99.999% purity

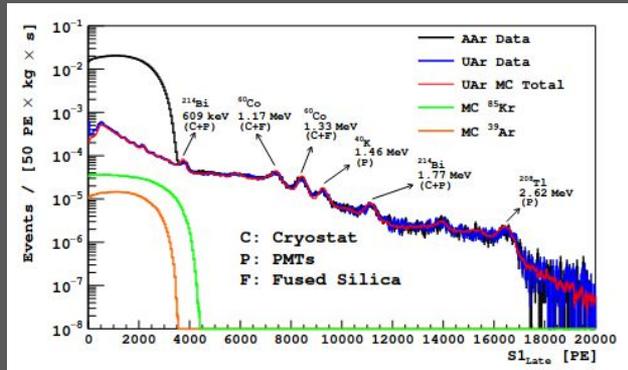
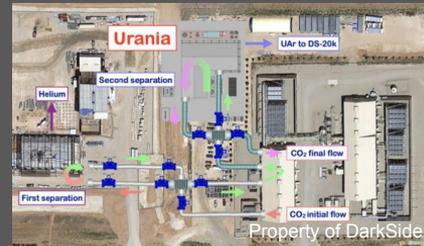


Fig. 6 from [11]: Comparison of the measured field off spectra for the UAr (blue) and AAr (black) targets, normalized to exposure. Also shown are the MC fit to the UAr data (red) and individual components of ^{85}Kr (green) and ^{39}Ar (orange) extracted from the fit.



Cortez, Colorado, USA
Urania: extract UAr
99.99% purity



Dual Phase?

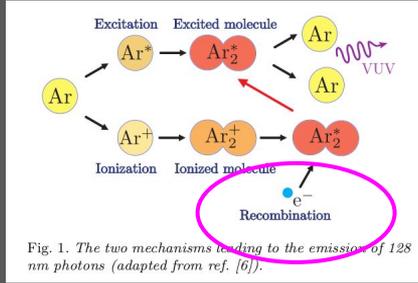
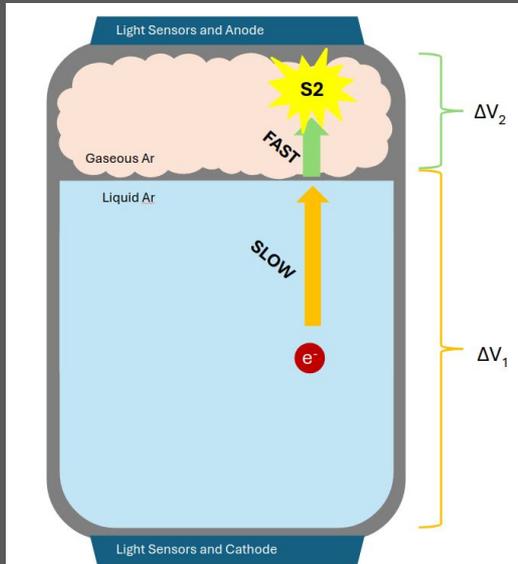
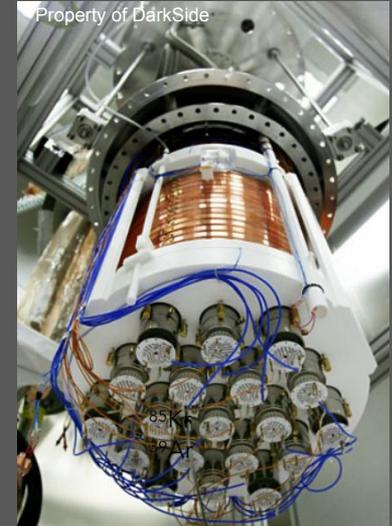


Fig. 1 from [1]



- Remember those electrons?
- These can be carefully removed from the LAr, then used to cause a second collision in gaseous argon (GAR)
- Liquid + gas = dual-phase detector
- Advantages of dual-phase:
 - Amplified signal
 - S2-only analysis
 - Simplified position reconstruction



DarkSide-50, which was used to validate the dual-phase concept in LAr

Improvements in Detection [8]

- The combination of new technology and a bigger detector greatly increases the projected sensitivity to:

$$6.3 \times 10^{-48} \text{ cm}^2 \quad (1 \text{ TeV}/c^2 \text{ WIMP})$$

(this is the 90% CL over the expected 200 tonne-year exposure)

- The design sensitivity for DEAP was:

$$1.5 \times 10^{-46} \text{ cm}^2 \quad (1 \text{ TeV}/c^2 \text{ WIMP})$$

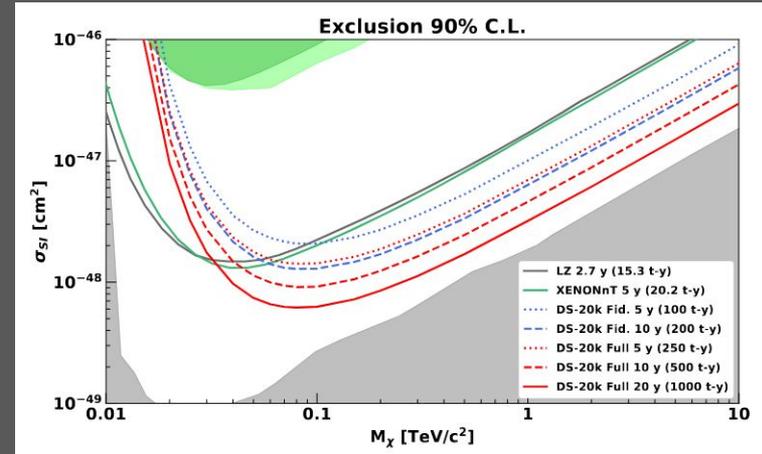


Fig. 2.6 (top) from [12]: DarkSide-20k exclusion limit for different running times (5 years dotted lines, 10 years dashed lines and 20 years full line) and different search volume considerations (fiducialised volume ('Fid.' curves, blue) or not ('Full' curves, red)). The limits are compared with the neutrino floor (grey shaded area), the result of PANDA-X (light green shaded) and XENON1T (dark green shaded) and the projection of LZ (grey) and XENONnT (green) experiments. Sensitivity computed in terms of exclusion power at 90 % Confidence Level.

- DS-20k will also operate at a background rate < 1 event per tonne-year

Current Status

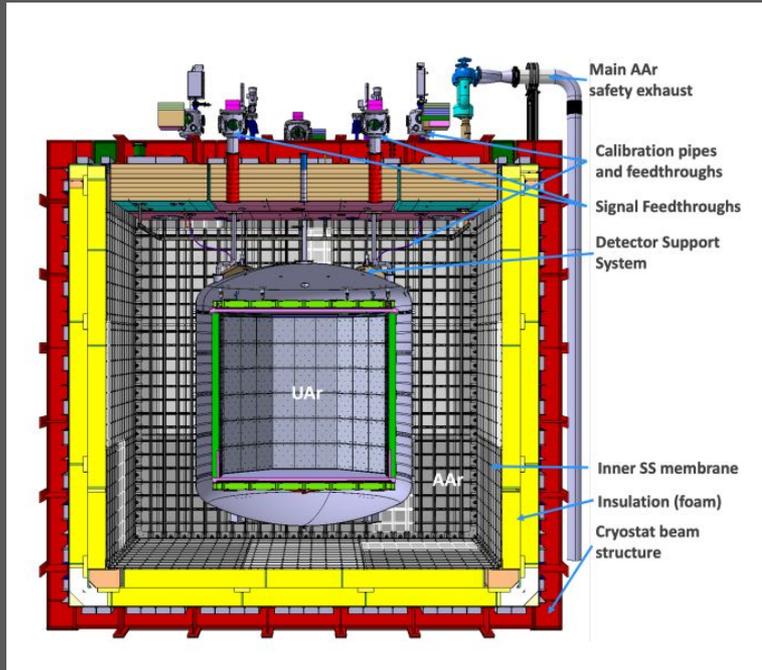


Fig. 1 (right) from [8]: detector hanging on the roof of the AAr cryostat, along with installed feedthroughs for support and signal extraction

The whole collaboration is working hard to finish the detector!

Prototypes Proto-0 and Mockup have provided the desired tests and insights.



Several infrastructure components are ready.

Current goal to begin taking data in 2028.

Conclusions & Future Goals

DEAP-3600



- Set a novel upper limit on spin-independent WIMP-nucleon cross section for LAr
- Results beyond WIMPs
 - α -particle scintillation quenching factor
 - ^{39}Ar half-life measurement
 - ^8B solar neutrino charged current search
 - Ultra-heavy DM constraints
 - Position reconstruction analysis
 - ^{39}Ar specific activity paper

arXiv [2108.09405]
arXiv [2503.10383]
arXiv [2302.14639]

DarkSide-20k



- Even better limits on spin-independent WIMP-nucleon cross section for LAr
- Will test dual-phase concept and UAr processing pipeline for use in the future
- Low-mass DM sensitivity projected to $1 \times 10^{-42} \text{ cm}^2$ for masses above 800 MeV/c^2 [13]

arXiv [2407.05813]

Conclusions & Future Goals

DEAP-3600



DarkSide-20k



ARGO



Concept for the future of Ar-based DM detectors

- 400 tonne active volume (300 tonne fiducial vol.)
- Total exposure of 3000 tonne-years
- Sensitive to cross sections into the neutrino fog
- Neutrino physics capabilities

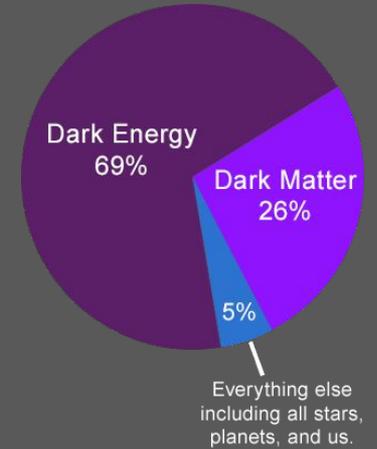
Thank you!

- [1] C. Amsler et al. “Luminescence quenching of the triplet excimer state by air traces in gaseous argon”. In: JINST 3 (2007).
- [2] Abe et al. “A measure of the scintillation decay time constant of nuclear recoils in liquid xenon with the XMASS-I detector”. In: JINST 13 (2018).
- [3] R. Ajaj et al. “Search for dark matter with a 231-day exposure of liquid argon using DEAP-3600 at SNOLAB”. In: Phys. Rev. D 100 (2019).
- [4] The DarkSide-20k collaboration. “DarkSide-20k Technical Design Report: DARKSIDE-CSN2-TDR-2112– v3.0”. Gran Sasso, Italy, 2021.
- [5] P. Adhikari et al. “Relative measurement and extrapolation of the scintillation quenching factor of α -particles in liquid argon using DEAP-3600 data”. In: Eur. Phys. J. C. 85 (2025)
- [6] P. Adhikari et al. “Direct Measurement of the ^{39}Ar Half-life from 3.4 Years of Data with the DEAP-3600 Detector”. In: Eur. Phys. J. C. Preprint (2025).
- [7] C. E. Aalseth et al. “DarkSide-20k: A 20 Tonne Two-Phase LAr TPC for Direct Dark Matter Detection at LNGS”. In: The European Physical Journal Plus 133 (2018).
- [8] A. Zani on behalf of the DarkSide-20k collaboration. “The DarkSide-20k Experiment”. Milano, Italy, 2024.
- [9] Nasim Fatemighomi for the DEAP-3600 collaboration. “DEAP-3600 Dark Matter Experiment”. In: Physics in Collision. University of Warwick. 2015.
- [10] Charles Jeff Martoff. “DarkSide Status and Prospects”. In: The European Physical Society Conference on High Energy Physics. 2017.
- [11] P. Agnes et al. “Results from the first use of low radioactivity argon in a dark matter search”. In: Phys. Rev. D 93 (2016).
- [12] Marie van Uffelen. “Direct search for dark matter with the DarkSide-20k experiment”. PhD thesis. Aix-Marseille University, 2024.
- [13] F. Acerbi et al. “DarkSide-20k sensitivity to light dark matter particles”. In: Communication Physics 7, 422 (2024).

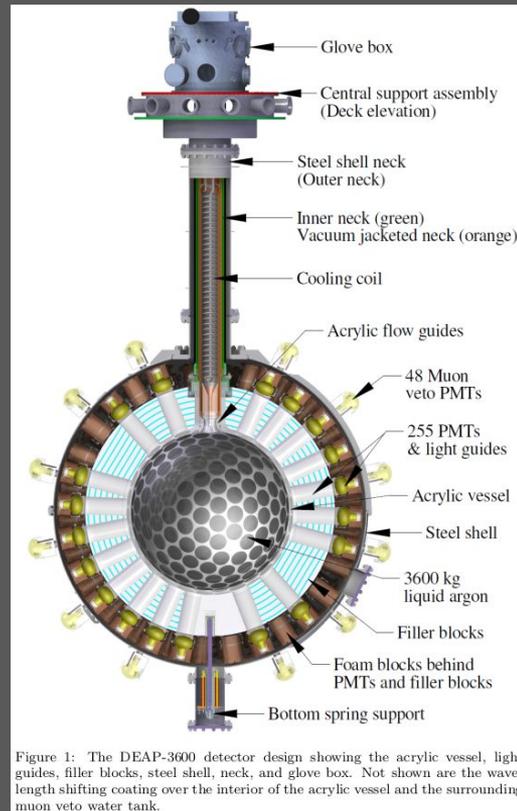
Backup 1: Dark Matter

Properties of Dark Matter (DM) [griest]

- Neutral / dark → Does not interact with light
 - Massive → Interacts gravitationally
 - Weakly interacting → Interacts via the weak nuclear force
-
- A kind of particle known as a WIMP (Weakly Interacting Massive Particle) fits these parameters. WIMPs have not yet been detected. [griest]
 - A common choice for direct DM detection is a *noble liquid scintillator*.

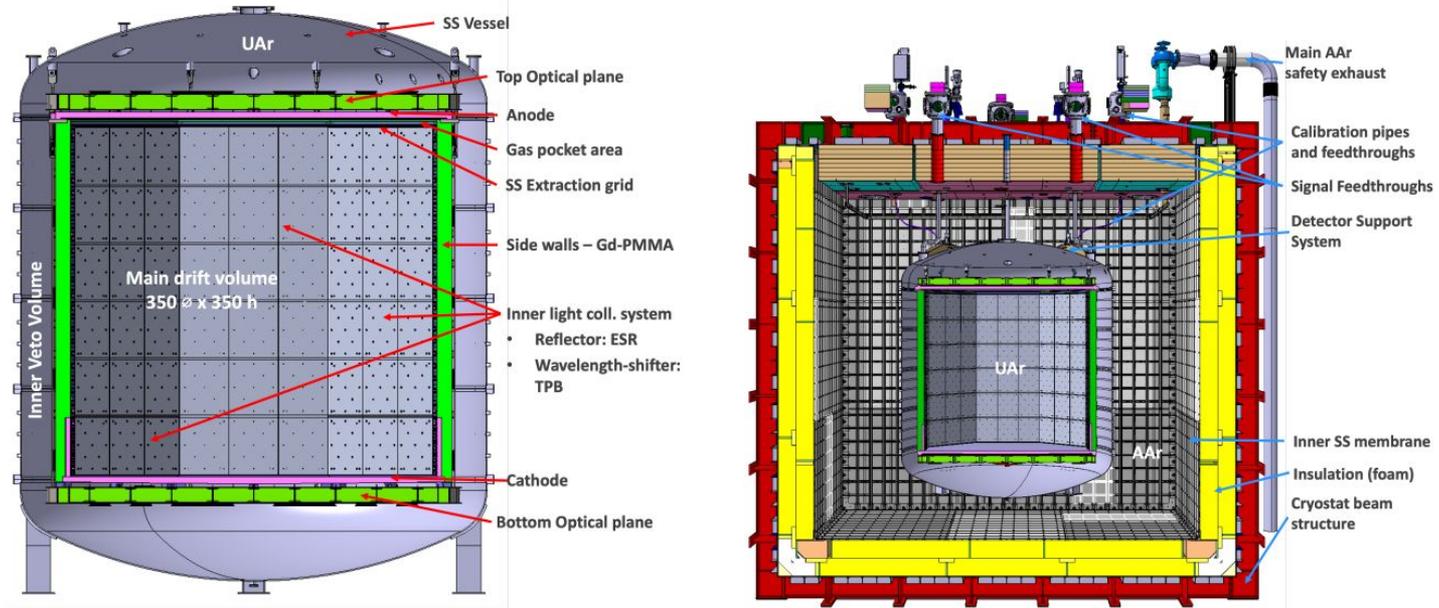


Backup 2: Full DEAP Diagram



From [9]

Backup 3: Full DS Diagram



From [8]

Figure 1. Current design of the DarkSide-20k detector, shown in section views. Left, Inner Detector and Inner Veto, hosted in their SS vessel. Right, detector hanging on the roof of the AAr cryostat, along with installed feedthroughs for support and signal extraction. See text for details.