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Dark matter detection with liquid argon

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ABSTRACT

Liquid argon has very desirable timing characteristics for the detection of interactions of Weakly Interacting Massive Particles (WIMPs) as Dark Matter candidates. Nuclear recoil interactions emit light with time constants of the order of nanoseconds, whereas gammas and betas have time constants of the order of microseconds, enabling discrimination of such backgrounds by factors greater than 10^8. The global community using liquid argon for the detection of WIMPs includes a series of experiments ranging from Dark-Side-50, ArDM, DEAP-3600, DarkSide-20k and in the future ARGO and a detector studying low-mass WIMPs. Characteristics and status of this series of detectors are presented.

1. Introduction

The Global Argon Dark Matter Collaboration (GADMC) was formed in 2017 and now includes over 400 scientists from 90 institutions in 14 countries working on liquid argon detectors in Europe and Canada. These include single-phase (light detection) and double-phase (light detection from the liquid argon in a Time Projection Chamber (TPC) and electroluminescence in a high voltage gaseous region at the end of the TPC drift region). Extreme care has been exercised in the creation of very low-radioactivity conditions in the detector fiducial volumes and in the detector materials.

This has resulted in a succession of papers with increasing sensitivity for WIMP interactions with argon nuclei. DarkSide-50 [1] at the Laboratoire Nationale Gran Sasso (LNGS) in Italy was a TPC using 50 kilograms (fiducial) of liquid argon obtained from an underground source in Colorado with a reduced content of ^{39}Ar, a beta-decaying isotope produced by cosmic rays in the atmosphere. The DEAP-3600 experiment [2] at SNOLAB in Canada used 3 tonnes of argon from atmospheric sources and single-phase light detection. The DarkSide-20k [3] experiment now under construction at LNGS will use 100 tonnes of underground argon in a TPC with 20 tonnes of projected fiducial volume. Future projects under development include the ARGO project with 400 tonnes of underground argon (UAr) and DarkSide-Low Mass [4] with about 1 tonne of underground argon with further isotopic purification at a cryogenic distillation facility called ARIA in Sardinia. Verification of the content of ^{39}Ar will be performed using a rejuvenated ArDM detector forming the DART detector [5] in the CanFranc laboratory in Spain. Fig. 1 shows this series of detectors with an approximate timeline.

2. Properties of liquid argon for the detection of WIMP interactions with Argon

When liquid argon is exposed to ionizing radiation, dimers are excited and occur in singlet and triplet states with very different lifetimes, about 6 ns and about 1.5 microseconds, respectively. The linear energy transfer (LET) determines the relative population of these states, and fewer triplet states are produced at high LET, such as occurs for nuclear recoils following interactions with WIMPS. Since the singlet state has a much shorter lifetime, it is possible to discriminate very effectively between WIMP interactions and interactions with low LET, such as low energy electrons or gammas, by digitizing pulses and comparing the light emission in the first tens of nanoseconds compared to the full pulse duration. [6].

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This is particularly effective for discrimination against the 565 KeV beta decays of ^{39}Ar that occur at a rate of 1 Bq/kg in argon obtained from atmospheric sources. Discrimination factors in excess of 10^8 have been demonstrated in the DEAP-3600 detector with atmospheric argon. In addition, a source of argon depleted in ^{39}Ar by more than a factor of 1400 has been identified from an underground stream of carbon dioxide near Cortez, Colorado, USA. About 100 kg of underground argon was used in the DarkSide-50 detector. [7], and the depletion factor was measured. A greatly upgraded extraction facility is about to be installed at the Colorado site that will be capable of providing up to 90 tonnes/day of underground argon for the DarkSide-20k detector and other future experiments.

A small, low-radioactivity TPC, DART, [5] is being installed within the ArDM detector in the CanFranc laboratory that will be capable of determining ^{39}Ar depletion at factors greater than 1400. It will be used for quality control on underground argon for DarkSide-20k in future.

3. DarkSide-50

The DarkSide-50 detector [1] in Hall C of LNGS was a two-phase (liquid-gas) time projection chamber filled with 100 kg of underground argon from the Colorado source. The TPC is illustrated in Fig. 2. The central volume is viewed by two sets of 19 3-inch Hamamatsu R11065 Photomultipliers (PMTs) at the top and bottom. They view the cylindrical central volume through fused silica windows coated with indium tin oxide, creating a conductive coating for the anode and cathode surfaces of the TPC. The inner surfaces are coated with tetraphenyl butadiene (TPB) that shifts the 128 nm light from the argon to 420 nm for detection by the photomultipliers. Electrons from ionizing events are drifted by a 200 volt/cm field to a grid at the top, where a 2.8 kV / cm field accelerates them into the gas region, where they create further light. Scintillation photons from events in the liquid argon are observed as an initial signal (S1) exhibiting the variation of decay time characteristic of argon, followed by the photons from the gas (S2). The signals from the PMTs are digitized. Pulse Shape discrimination on S1 is used for background rejection, the drift time between S1 and S2 is used for localization in the vertical direction and the light pattern on the PMTs is used for localization in the horizontal direction.

The TPC is mounted at the center of a liquid scintillator veto (LSV) instrumented with 110 PMTs and filled with 30 t of boron-loaded liquid scintillator. Surrounding the LSV is a 1 kt water Cerenkov veto (WCV) instrumented with 80 PMTs. Signals from the LSV and WCV are used to reject events in the LAr TPC caused by cosmic-ray muons, cosmogenic (muon-induced) neutrons or radiogenic neutrons and γ rays from radioactive contamination in the detector components.

The DarkSide-50 detector was operated for 532.4 days [7] with a fiducial volume of 46.4 kg of underground argon. It set a depletion limit of more than 1400 for ^{39}Ar in the underground argon. It also set limits on WIMP interactions with argon that are illustrated in Fig. 3 for the region above about 10 GeV/c^2 using both S1 and S2 signals.

An independent analysis using only the S2 signal was able to attain a much lower threshold and thereby look for WIMP-argon interactions below 10 GeV/c^2, setting the best limits in this region, as described in reference 8.

4. DEAP-3600

The DEAP-3600 detector [2] illustrated in Fig. 4, is located 2 km underground in the SNOLAB laboratory near Sudbury, Canada. It is a single-phase detector, using the light emitted from events in the 3322 kg of atmospheric liquid argon with pulse shape discrimination

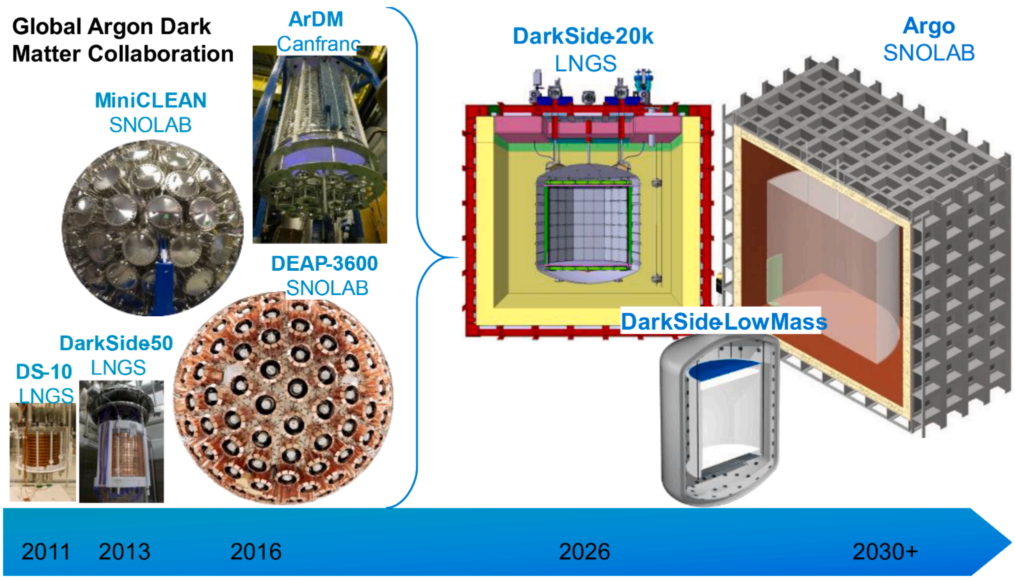

Fig. 1. Progression of liquid argon experiments for the detection of WIMP interactions with argon nuclei.

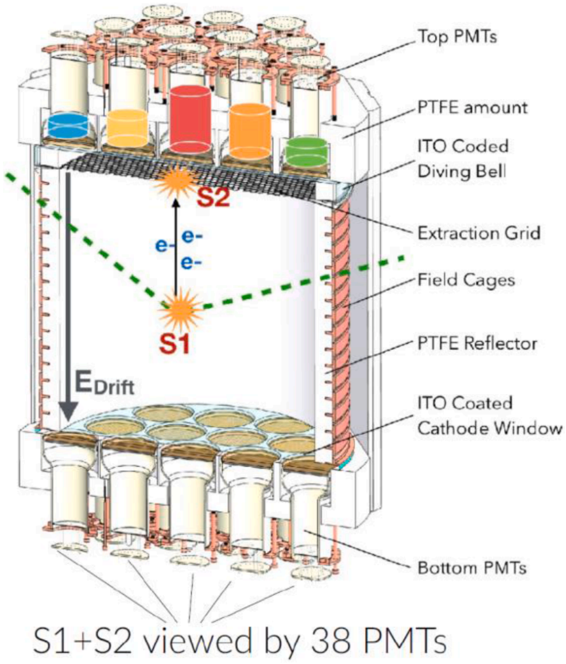

Fig. 2. Diagram illustrating principal components of the DarkSide-50 Time Projection Chamber.

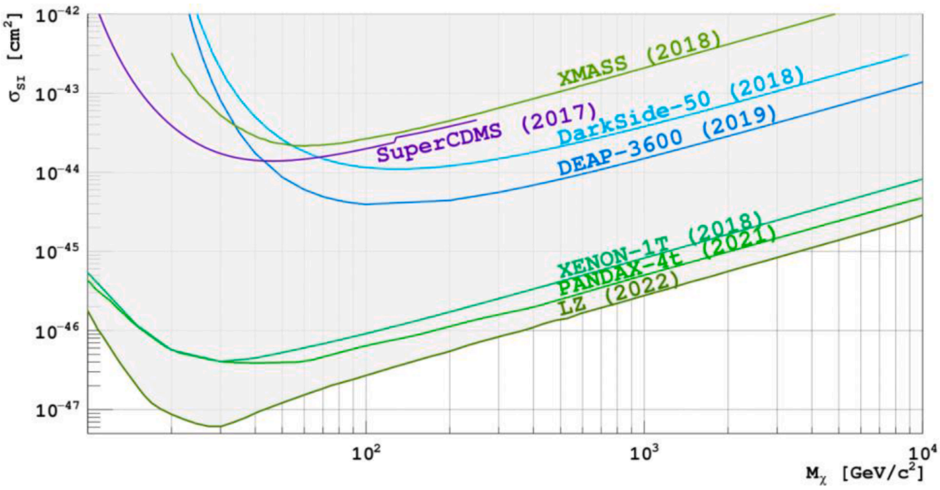

Fig. 3. Limits on the cross-section for WIMP-argon interactions as a function of WIMP mass for the DarkSide-50 and DEAP-3600 experiments and recent measurements by other experiments.

(PSD) to reduce the background from ^{39}Ar beta decay events by a factor of greater than 10^8. The argon is contained in a cylindrical acrylic vessel, 1.7 m in diameter and 5 cm thick, coated on the inside with TPB for wavelength shifting. The light is observed through 45 cm-long acrylic light guides by 255 Hamamatsu R5912-HQE PMTs, 20 cm in diameter. The space between the PMTs is filled with high-density polyethylene to provide a full spherical shield of thermalizing material for neutrons originating in the PMTs or other external sources. All signals are digitized to enable PSD, and the timing and distribution of the signals reaching the PMTs are used for event position reconstruction.

As is the case for all the detectors described herein, extreme care was taken in the choice of materials used in detector construction. The final inner surface of the acrylic was sanded to remove radon daughters, using rotating disks on a device that could be inserted through the neck of the vessel prior to the deposition of TPB. The PMTs and acrylic vessel were contained in a stainless-steel shell, and a 7.8-meter diameter cylindrical external water shield instrumented with 48 Hamamatsu R1408 PMTs serves as a muon veto.

The results of a 231-day exposure with the DEAP-3600 detector [8] are shown in Fig. 3. The detector is undergoing an upgrade to reduce backgrounds from alpha events in the neck region that mimic WIMP events after multiple scatters within the neck. A slower

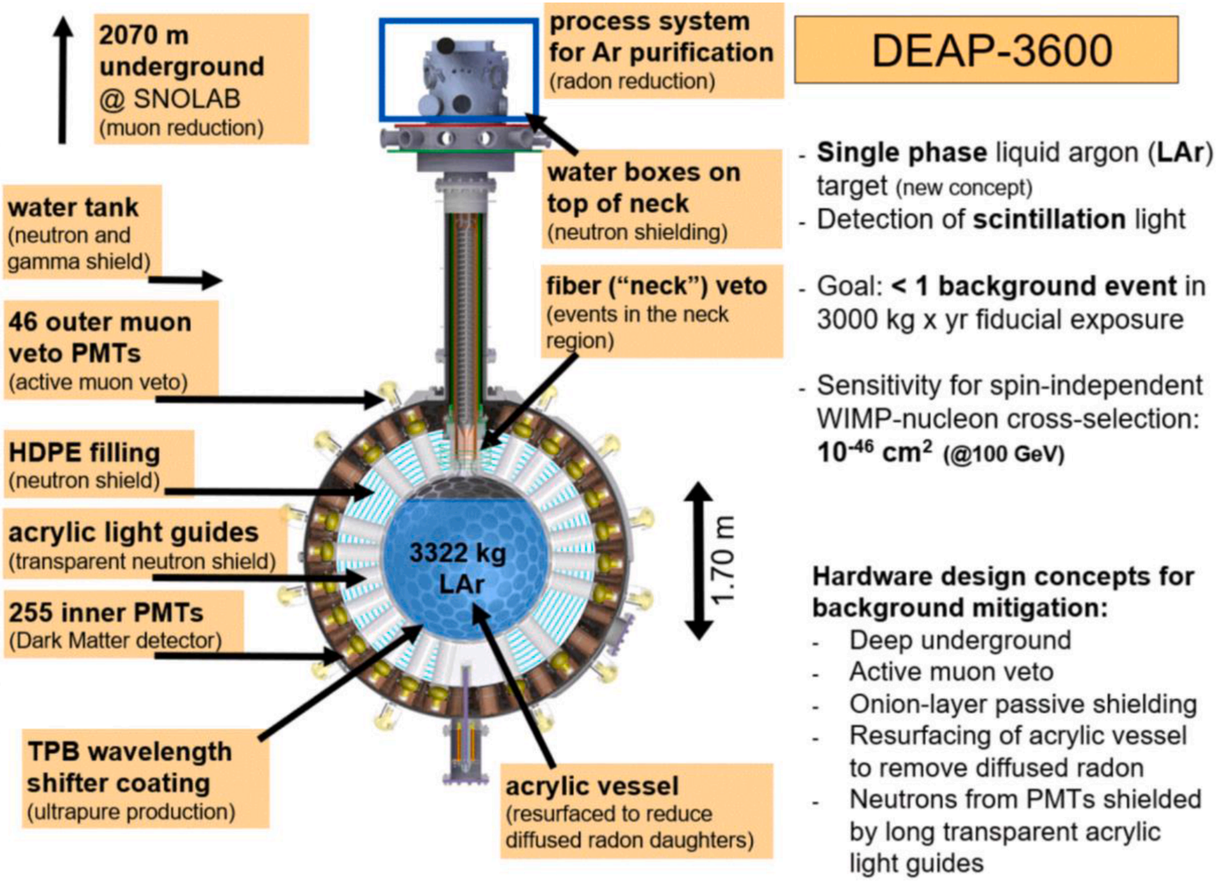

Fig. 4. The DEAP-3600 detector.

wavelength shifter has been deposited on the inner surfaces of the neck region to enable these events to be discriminated. A leaking seal in the neck will be corrected to remove the restrictions in the liquid level, and a recirculation and filtration system will be employed to remove events from trace amounts of radioactivity on dust particles in the argon.

5. DarkSide-20k

The DarkSide-20k experiment [3] is being constructed in Hall C at LNGS. A central TPC will contain about 100 tonnes of liquid argon from the underground source in Cortez, Colorado and this inner detector will be housed within an outer cryostat modelled on the Proto-DUNE cryostat at CERN [9], which will be filled with about 700 tonnes of atmospheric argon. The detector is illustrated in Fig. 5, and more details of the inner TPC are provided in Fig. 6.

The TPC anode and cathode windows will be constructed from ultra-pure acrylic, coated on the top and bottom windows with Clevios, an electrically conducting organic coating that is transparent in small thicknesses. The barrel-shaped sides of the TPC will be constructed from acrylic loaded with about 1 % Gadolinium as part of a neutron veto system. Rings machined in the barrel panels will also be coated with Clevios and connected to a resistor chain and electrical supply to provide a uniform field gradient between the cathode and anode regions. The inner surfaces of the barrel and the inner surface of the stainless-steel vessel housing the TPC will be lined with panels made of Enhanced Specular Reflector (ESR) film. The inner reflecting panels and the anode and cathode will be coated with a TPB wavelength shifter. The outer ones will use Polyethylene Napthalate (PEN) film as a wavelength shifter.

The field gradient within the liquid argon will be 2.8 kV/cm. At the top of the detector, a 7.0 mm gas pocket will be maintained with a voltage gradient of 4.2 kV/cm. Optical planes of silicon photomultipliers (SiPMs) will provide light detection at the top and bottom for the observation of S1 and S2 signals. Additional SiPMs will be attached to the outer surface of the Gd-loaded barrel pieces and the inner surface of the stainless-steel vessel to provide signals from the liquid argon veto region. A further set of SiPMs will be used to obtain muon veto signals from the 700-tonne atmospheric argon outer cryostat.

The photoelectronics for the optical planes and veto detectors are described in Fig. 7.

The UAr will be produced at the URANIA facility at the Kinder-Morgan site near Cortez, Colorado, using an extraction system built by the Polaris company. The system will be capable of extracting 90 tonnes per day of argon from the main carbon dioxide stream. The argon will be shipped in cryogenic containers to the ARIA facility in Sardinia, where it will be purified chemically in cryogenic

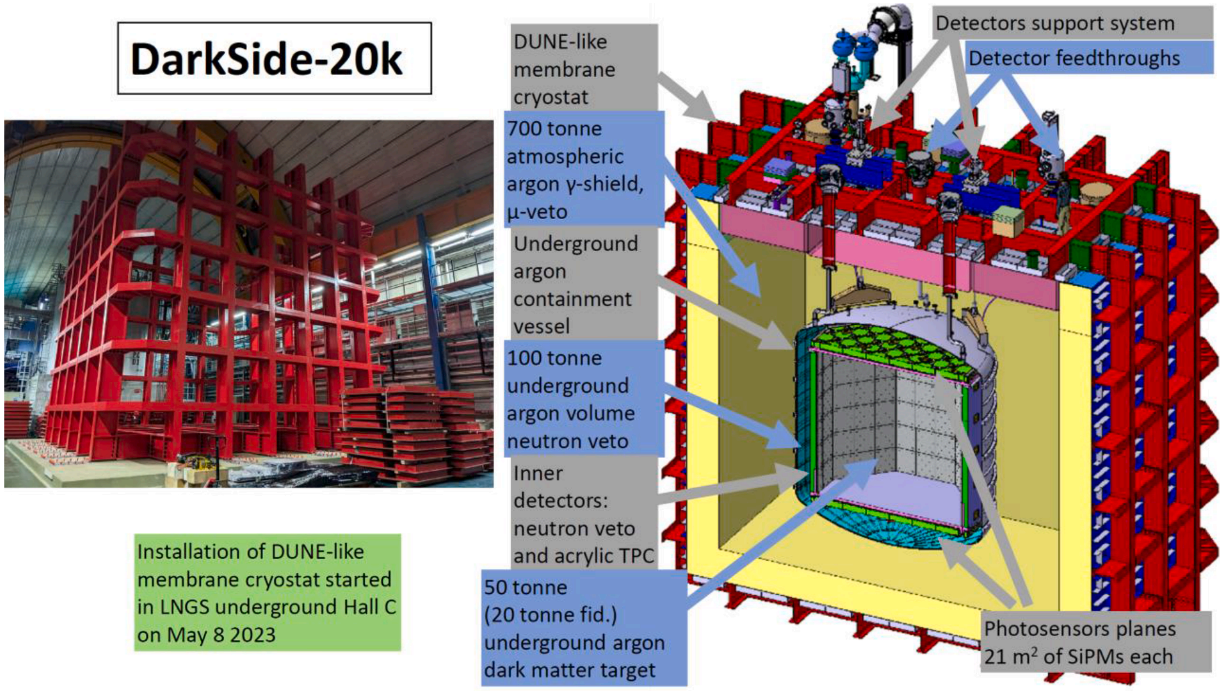

Fig. 5. The DarkSide-20k detector.

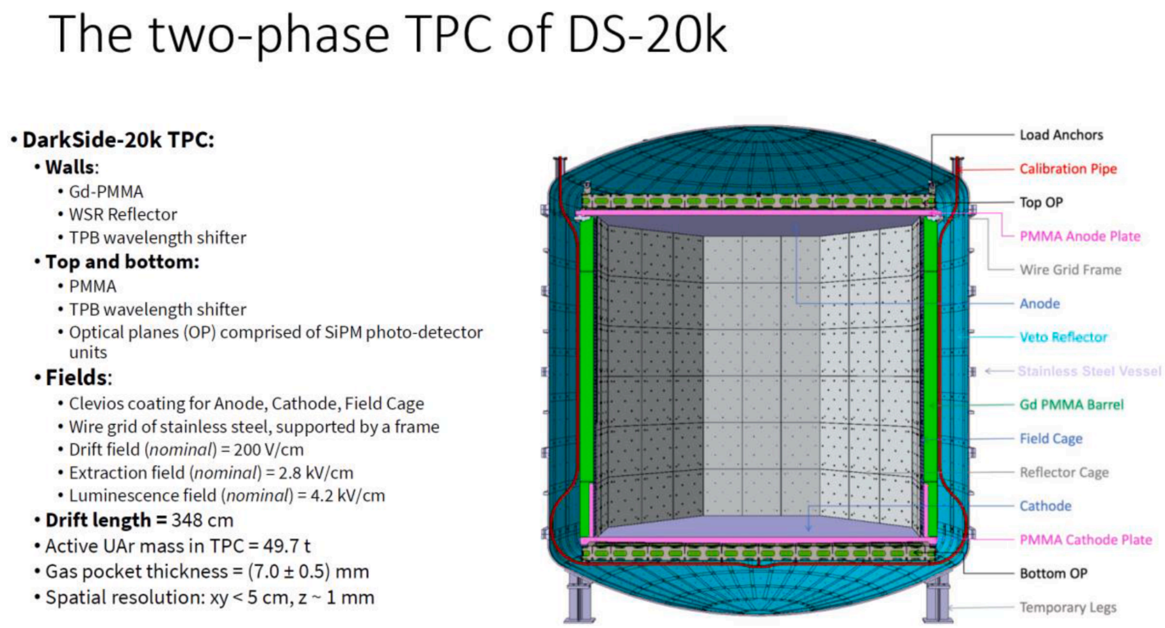

Fig. 6. Details of the inner TPC for DarkSide-20k.

distillation columns at a rate of 1 tonne per day. The 350-meter high ARIA system [10] is being installed in a former coal mine and will also be capable of isotopic removal of ^{39}Ar by a factor of 10 if run at a rate of ~3 kg/day.

Samples of the UAr for quality control will be measured at the DART detector [5] within the former ArDM detector situated at the CANFRANC laboratory in Spain.

Simulations of the DarkSide-20k detector indicate that a 20-tonne central fiducial volume can achieve an ultra-low background rate down to the level of a few events per year dominated by the atmospheric neutrino flux. Fig. 8 shows the projected exclusion sensitivity for various exposures, as well as published results and projections for the LZ [11] and Xenon NTonne [12] detectors.

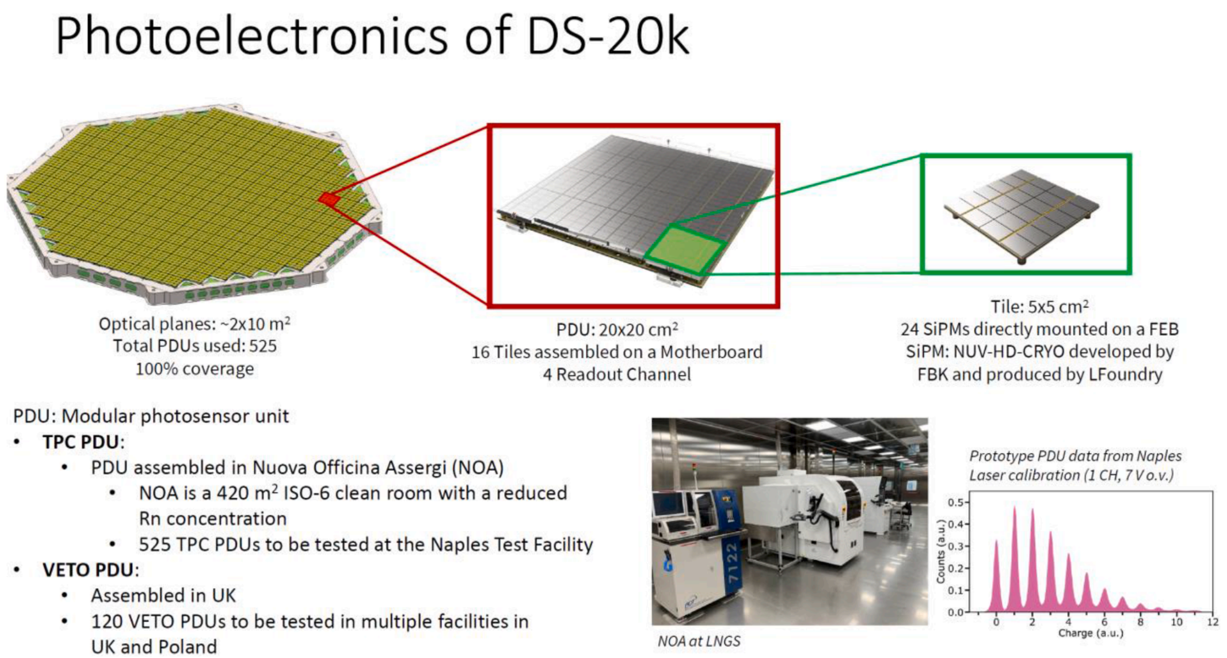

Fig. 7. Photoelectronics for DarkSide-20k.

Projections for DarkSide-20k are provided for the 20-tonne fiducial volume and for an assumption that the full volume within the TPC can be analyzed for a ten year exposure. The so-called neutrino floor for argon is extracted from reference 13.

6. ARGO

Early design work is in progress for a larger-scale liquid argon detector called ARGO, with 400 tonnes of UAr and a fiducial volume of 300 tonnes. Fig. 9 shows projections of exclusion projections for 90 % confidence limits, assuming that background from other than neutrinos can be suppressed to an insignificant level.

Discussion in reference 13 indicates that background rates at various WIMP mass regions for solar and atmospheric neutrinos will be different for Xenon and Argon, adding to the need for such larger-scale detectors for both liquid argon and xenon in order to remove any ambiguity in the event of a finite observation.

7. DarkSide low mass

The success of the DarkSide-50 detector for defining limits for WIMP masses as low as 1 GeV/c^2 has inspired design work on a detector [4] with an inner TPC somewhat similar to DarkSide-20k but using UAr that has been purified further at slower rates in the ARIA facility, reducing the ^{39}Ar content by a factor of ten. This would reduce the background contribution from ^{39}Ar to be similar to gamma rays from detector components and external sources.

Fig. 9 shows a conceptual design for such a detector. The sensitivity for this detector would be obtained primarily from the S2 signal.

Fig. 10 shows projected sensitivities for such a detector, along with other previous results and a representation of the neutrino fog from reference 13.

8. Dark matter with Planck-scale mass

A search has been made for Dark Matter with Planck-scale mass by studying multiple scatters in the DEAP-3600 detector. [17]. Constraints were obtained for dark matter masses between 8.3×10^6 and 1.2×10^{19} GeV/c^2, and ^{40}Ar-scattering cross sections between 1.0×10^{-23} and 2.4×10^{-18} cm^2.

9. Conclusions

Liquid argon provides an excellent medium for the search for WIMPS interacting with nuclei over a broad range of WIMP masses above 0.3 GeV/c^2. Above 20 Gev/c^2 the pulse shape discrimination capability of the initial light emission provides excellent discrimination against gamma and beta sources of background. Below that mass, the gaseous electroluminescence in a TPC design

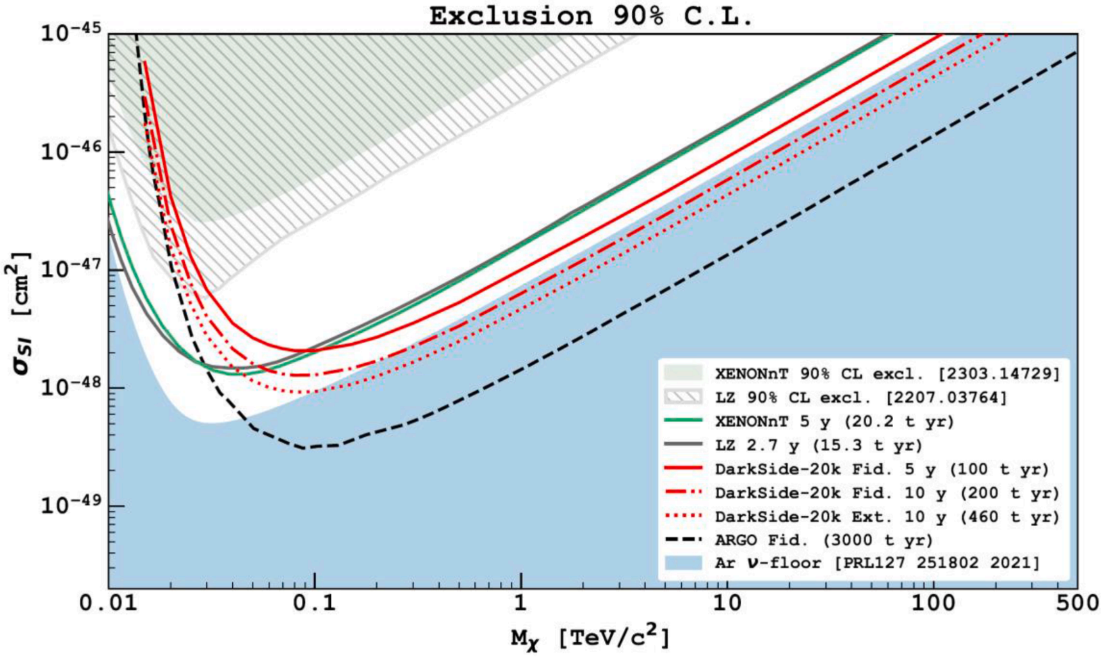

Fig. 8. Projections of sensitivity for Exclusion of WIMPS at 90% confidence level for DarkSide-20k and other future experiments.

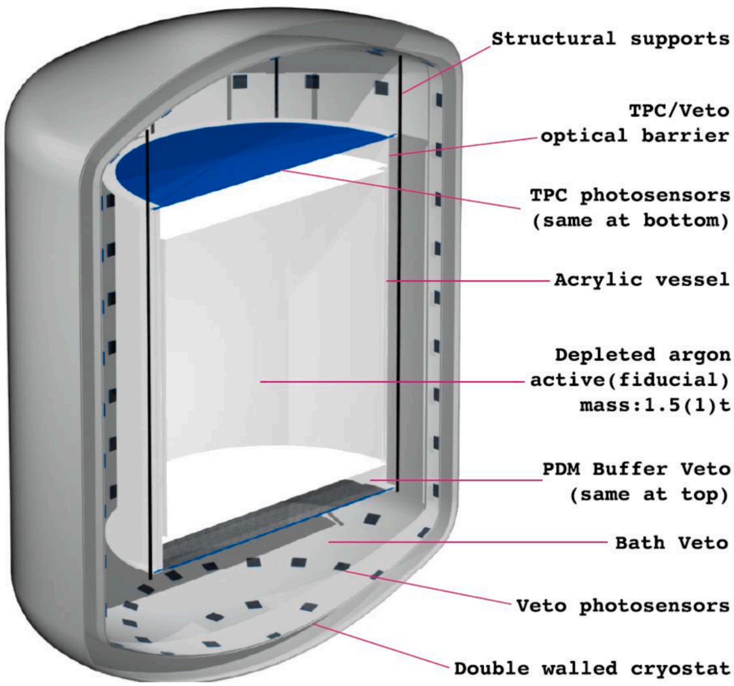

Fig. 9. Conceptual design for the DarkSide Low Mass detector.

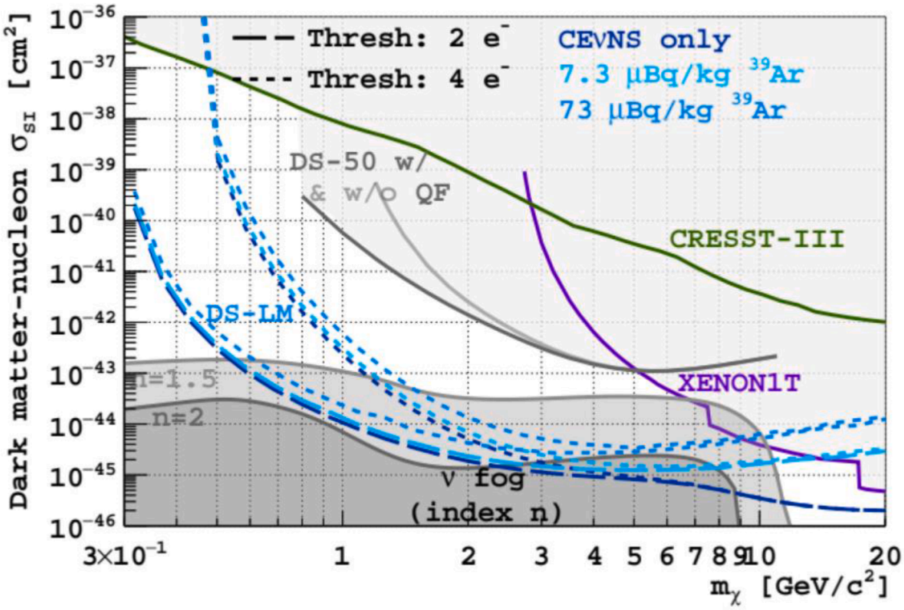

Fig. 10. Projected exclusion plots for 90% confidence level for DarkSide-Low-Mass for 1 tonne-year exposure. The two background levels for ^{39}Ar correspond to before and after a factor of ten reduction by the ARIA facility. Also shown are reported limits from DS-50 [14], CRESST [15] and XENON 1T [16] and a representation of the neutrino fog in this WIMP mass region from reference 13.

provides a low threshold for WIMP observation, but the background suppression is more challenging. An underground source of argon is being developed that can provide large quantities of argon with ^{39}Ar reduced by factors of 1400 and more by a combination of the inherent source quality and the use of massive cryogenic distillation.

The application of progressively larger and more specific detector technology for liquid argon will enable the sensitivity to be improved to the point where the limiting background will be neutrinos from atmospheric and solar sources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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