Future Dark Matter Searches with Low-Radioactivity Argon

The Global Argon Dark Matter Collaboration

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I. SCIENCE MOTIVATION

There is strong evidence from astronomical measurements for the existence of Dark Matter in our Universe. A potential candidate that matches the observations is Weakly Interacting Massive Particles (WIMPs) that were produced in the early Universe but which are so massive and weak that they have not yet been observed in experiments here on Earth. The observation of these particles is a major objective of the experimental program at the High Luminosity Large Hadron Collider at WIMP masses up to about 1 TeV/c^2. Future high energy colliders like FCC-*hh* (Future Circular Collider) will be able to extend these searches up to the 10 TeV/c^2 mass range [1]. Many direct and indirect detection techniques will allow a comprehensive search program for Dark Matter extending in many ways the future collider reach. Direct detection of dark matter, via elastic scattering of galactic WIMPs in a liquid argon target, is a technique making excellent progress towards probing the energies above the reach of the LHC.

The detection properties of liquid argon (LAr) are particularly favorable for the rejection of radioactive background that produces Electron Recoils (ERs) because these interactions produce light output with time constants of microseconds compared to nanoseconds for Nuclear Recoil (NR) events. The DEAP-3600 experiment, with 3200 kg of LAr, has demonstrated an exceptional pulse shape discrimination (PSD) against such background, projected to be in excess of 10^9 [2]. The DarkSide-50 experiment has demonstrated a two-phase detection technique measuring direct light output together with electroluminescence from a gaseous region above the liquid from the acceleration of electrons into this region, which provides excellent positional resolution for efficient fiducialization [3, 4]. With the discrimination available in this experiment, zero background has been obtained in a run period in excess of two years [5], with the data analyzed in a rigorous blind-analysis scheme. Thus, LAr provides excellent sensitivity in the region of WIMP masses above 30 GeV/c^2 using single or two phase detection with direct light observation for the rejection of ER events. The two phase method also enables sensitivity for lower WIMP masses through the use of the electroluminescence signal alone: a leading sensitivity below 10 GeV/c^2 has been obtained by DarkSide-50 [6, 7]. With careful control of ER background from local radioactivity and reduction of ^{39}Ar background, a 1 t LAr detector has the potential to reach the "neutrino floor" due to solar neutrinos in this low mass region.

Given the strong potential for the LAr technology to push the sensitivity for WIMP detection several orders of magnitude beyond current levels, scientists from all the major groups currently working with this technology (ArDM, DarkSide-50, DEAP-3600, and MiniCLEAN) have joined the Global Argon Dark Matter Collaboration (GADMC) to pursue a sequence of future experiments to follow this potential.

The enabling technologies of the GADMC program are: the argon target obtained from the high-throughput extraction of low-radioactivity argon naturally depleted in ^{39}Ar from underground sources (UAr) via the Urania plant; the target high-throughput purification and active isotopic separation via the Aria cryogenic distillation column; light detection via large-area cryogenic photodetector modules (PDMs) made of custom-designed silicon photomultipliers (SiPMs) assembled in a custom-built factory; operation of the WIMP detector within an active veto with liquefied atmospheric argon (AAr) as scintillator, hosted inside a membrane cryostat built with the technology developed at CERN for ProtoDUNE.

The immediate objective is the DarkSide-20k two-phase LAr detector, currently under construction at the Gran Sasso laboratory (LNGS). DarkSide-20k will have ultra-low backgrounds, with the ability to measure its backgrounds *in situ*, and sensitivity to WIMP-nucleon cross sections of 1.2×10^{-47} cm^2 (1.1×10^{-46} cm^2) for WIMPs of 1 TeV/c^2 (10 TeV/c^2) mass, to be achieved during 5 yr run with exposure of 100 t yr. This projected sensitivity is a factor of >50 better than currently-published results above 1 TeV/c^2, and covers a large fraction of the parameter space currently preferred by supersymmetric models. With 100 t yr exposure 1.6 NR events are expected from the coherent scattering of atmospheric neutrinos, making DarkSide-20k the first ever direct dark matter detection experiment to reach this crucial milestone. The sensitivity would further improve to 7.4×10^{-48} cm^2 (6.9×10^{-47} cm^2) for WIMPs of 1 TeV/c^2 (10 TeV/c^2) mass for a decade run with exposure of 200 t yr, see Fig. 1. DarkSide-20k is foreseen to operate from 2022 and will either detect WIMP dark matter or exclude a large fraction of the favored parameter space. As shown in Fig. 2, DarkSide-20k will reach a conclusive 5σ-observation for cross sections much below that probed by the LZ and Xenon-nT experiment, and for dark matter mass above the reach of the LHC. In case of the observation of a WIMP signal, it would be valuable to have in operation detectors with both LAr and LXe targets such as to cross check each other.

In parallel to DarkSide-20k, a second and important element for this program will be a detector of the order of 1 t in mass: DarkSide-LowMass (DS-LM), which we will propose to install at LNGS and specifically optimized for the observation of the electroluminescence signal below 10 GeV/c^2 with strong restriction of ER background through careful detector design. Based on demonstrated ultra-low threshold and world-leading sensitivity achieved with DarkSide-50, and coupled to additional ^{39}Ar reduction by distillation in Aria and the use of a massive AAr veto, this dedicated search would have an excellent discovery capability, reaching through the so-called "neutrino floor" in the low-mass search region, see Fig. 1.

The crowning objective, towards the end of the next decade, will be the construction of the ultimate Argo detector with a 300 t fiducial mass to push the sensitivity to the region where neutrino background will be a limitation in detectors without directional capability. The WIMP detection sensitivity will only be limited by systematic uncertainties in NR background from Coherent Neutrino Scattering of Atmospheric neutrinos. The strong ER rejection will eliminate background from solar neutrinos and some residual internal backgrounds such as radon. This unique property of argon extends the sensitivity with respect to technologies with more limited ER discrimination. The throughput of the Urania argon extraction system would enable 400 t of UAr to be extracted and purified in the Aria facility over a period of about 6 yr. SNOLAB would be strong potential site for this detector motivated by the dark matter search, but also possibly enabling the observation of ultra-rare solar neutrino sources (CNO, *hep*) [20]. A Letter of Intent has been sent to SNOLAB and funding is being sought for this to be a long term underground storage location for the extracted UAr to prevent activating.

Thus, the GADMC program will completely cover the WIMP hypothesis from 1 GeV/c^2 to several hundreds of TeV/c^2 masses in the search for spin-independent coupling.

The GADMC collaboration submits this input to the European Strategy because there is a strong scientific correspondence and important technology synergy with the capabilities at CERN. The ProtoDUNE cryostat design is being adopted as the basis for the DarkSide-20k and the DarkSide-LowMass detectors, as well as being considered for Argo, which is still being designed. It is hoped that the cooperation that has developed with CERN to date may be continued and extended for these future programs as the CERN scientific interest and technical capabilities are very well matched to the objectives of the GADMC program for dark matter detection. This would be naturally aligned with the strong support for dark matter research of the

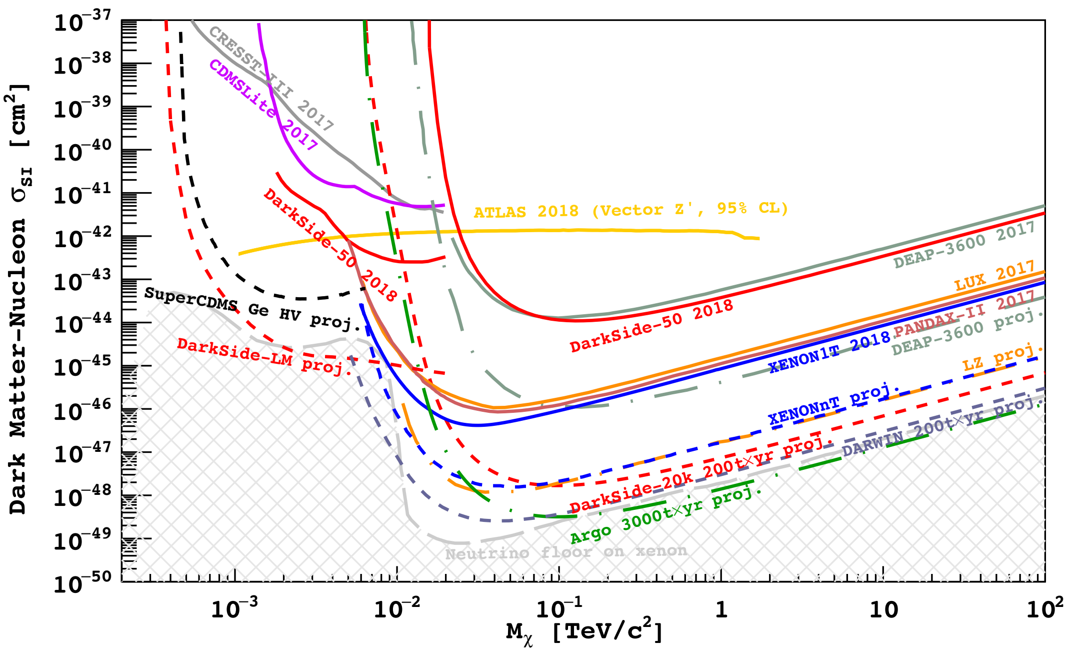

FIG. 1. 90 % C.L. exclusion limits, showing leading results from direct (continuous lines, Ref. [5, 6, 8–11]) and accelerator-based dark matter searches (region above the yellow line, [12]) compared with sensitivities of future germanium-, xenon-, and argon-based direct searches (dashed lines, Ref. [13–17] and this work). The "neutrino floor" curve follows the definition of Ref. [18]. The 95% C.L. limit from the ATLAS Experiment is shown for a benchmark model in which Dirac-fermion WIMPs interact with ordinary matter via a vector mediator[19] with coupling strengths to quarks, leptons and WIMPs of 0.25, 0.01 and 1, respectively.

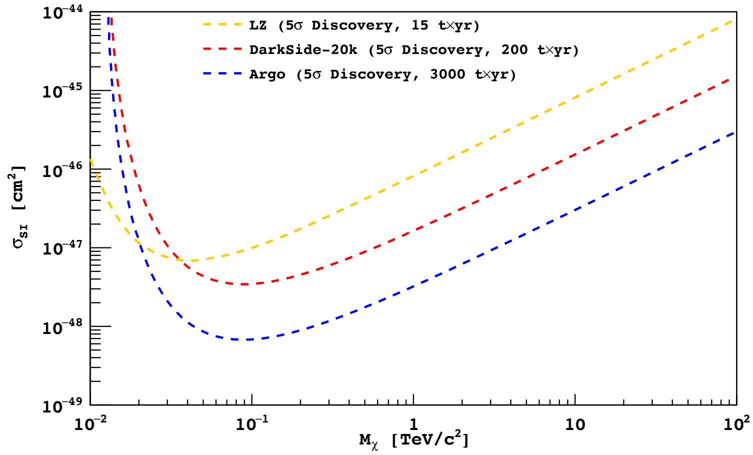

FIG. 2. 5σ discovery potential of the leading future noble liquid dark matter searches. See Tab. I for details and sources.

Experiment	Target	Threshold [keVr]	Exposure [t yr]	Source
LZ	LXe	4	15	[28]
DarkSide-20k	LAr	30	200	This work
DARWIN	LXe	7	200	[29]
Argo	LAr	30	3000	This work

TABLE I. Comparison of characteristics and expected performance of future LXe and liquid argon LAr direct detection dark matter experiments.

European underground laboratories expressed in the recent ApPEC strategy document [21], as well as its explicit recommendation to build two ultimate dark matter detectors, one based on xenon and one based on argon.

II. COMPARISON WITH XENON-BASED EXPERIMENTS AND THE "NEUTRINO FLOOR"

Next generation dark matter experiments will have sensitivity to several sources of neutrinos, via $\nu - e$ elastic scattering creating ER and coherent elastic neutrino scattering (CEνNS) on nuclei creating NR. CEνNS represents an irreducible nuclear recoil background for dark matter searches, mostly for high-exposure detectors, that can be expressed as a limit in the Weakly Interacting Massive Particles parameters plane. The CEνNS process, recently observed by the COHERENT experiment [22], appears in line with the Standard Model prediction [23–27].

As neutrinos will be the main background for huge experiments, it is important to take into account their effect in sensitivity studies. Atmospheric and diffuse supernovae neutrinos affect most significantly high-mass argon dark matter searches above $30\,\mathrm{GeV}/c^2$. Because of their high energies, they can produce NRs of energy in excess of $20\,\mathrm{keV_{nr}}$. Low-energy solar neutrinos are instead responsible for the CEνNS background in low-mass searches, below $10\,\mathrm{GeV}/c^2$.

From the experimental point of view, the energy released by a coherently scattered neutrino in a liquid noble detector is almost indistinguishable from a WIMP-nucleus scattering signal. In particular, in order to claim a dark matter detection, the fundamental ingredients to distinguish neutrinos from dark matter are the number of events expected in the detector and their spectra. However, neutrinos can scatter also off electrons bound into the atoms. For LAr, through the pulse shape discrimination, the electron recoils are suppressed by a factor 10^9 with respect to NRs, making this channel negligible. Liquid xenon (LXe) detectors, with their limited rejection power, must also deal with non-negligible residual ER background, which represents a significant challenge.

When calculating the sensitivity of large-scale dark matter searches, it is fundamental to fully account for the presence of neutrino-induced background through a statistical method. We note that the position of the

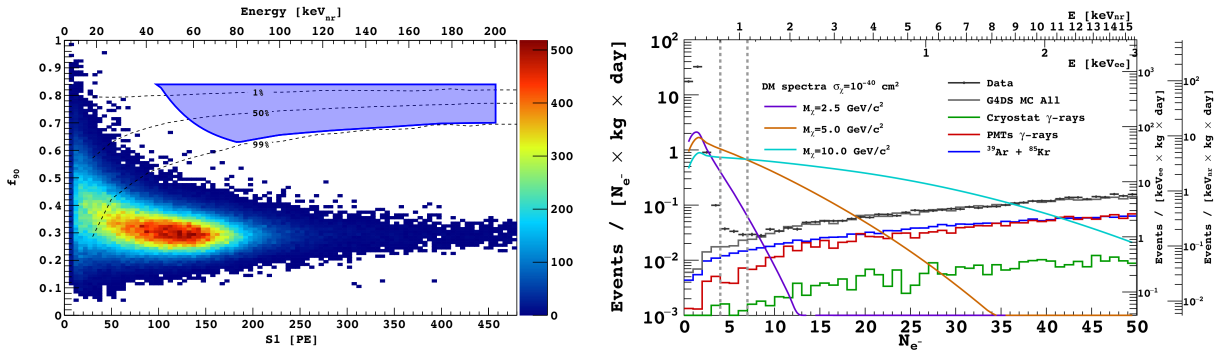

FIG. 3. **Left:** DarkSide-50 532.4 live-days high-mass WIMP search [5]. Observed events in the f_{90} vs. S1 plane surviving all cuts in the energy region of interest. The solid blue outline indicates the dark matter search region. The 1 %, 50 %, and 99 % f_{90} acceptance contours for nuclear recoils, as derived from fits to our ^{241}AmBe calibration data, are shown as the dashed lines. **Right:** the DarkSide-50 N_{e^-} spectra at low recoil energy from the analysis of the last 500 days of exposure compared with a G4DS simulation of the background components from known radioactive contaminants [6]. Also shown are the spectra expected for recoils induced by dark matter particles of masses 2.5, 5, and 10 GeV/c^2 for a 10^{-40} cm^2 cross section. The y-axis scales at right hand side are approximate event rates normalized at $N_{e^-} = 10\,e^-$.

"neutrino floor", initially conceived as indicative of the maximum sensitivity attainable by an experiment in the presence of CEνNS background, is critically dependent on the target, experimental technique, statistical analysis, neutrino flux uncertainty and theoretical cross section uncertainty. We therefore include the detailed accounting of the CEνNS and elastic scattering off electron backgrounds in the sensitivity and discovery potential curves shown here, in Fig. 1 and Fig. 2.

We conservatively estimate a total 20 % uncertainty on the neutrino background for high-mass (30 GeV/c^2) searches with Argo: this accounts for a 15 % uncertainty on the atmospheric neutrino flux at mid-latitude locations such as SNOLAB or LNGS, based on the latest data-driven models of cosmic primaries [30] as well as models of solar cycle, seasonal, geographic and geomagnetic dependence of the neutrino flux [31, 32]; for a 5 % theoretical uncertainty on the Standard Model interaction cross-section, driven by the nuclear form factor uncertainties; and for the constraint on non-Standard Model contributions stemming from measurements planned by the COHERENT collaboration with a LAr target [33], driven by their current 10 % uncertainty on neutrino flux [22]; and for a 6 % uncertainty on the LAr response as measured by SCENE [34, 35] and ARIS [36]. The planned improvements of COHERENT, including a sharper characterization of the neutrino flux and a measurement with a LAr target, should reduce the uncertainty on the neutrino background below 10 %, and this would strongly benefit the GADMC program.

Within this framework we calculate the 5σ discovery potential for DarkSide-20k and Argo, and compare it with that of future LXe experiments such as LZ [28] (we could not find a corresponding curve for DARWIN [29]): as seen from Fig. 2, DarkSide-20k has a stronger discovery potential than that of LZ.

III. ACCOMPLISHMENTS

In early 2018 the DarkSide Collaboration reached the milestone of its DS-50 program by publishing results from a 532.4 live-days campaign with a two-phase LAr time projection chamber (LAr TPC) in operation since 2013 in the underground Laboratori Nazionali del Gran Sasso (LNGS) [5–7].

The outcome of the high-mass WIMP dark matter search is a null result (see Fig. 3), delivering on the promise of zero-background and producing the best limit with an argon target (see Fig. 1).

The extremely low background, high stability, and low 100 eV$_{\rm ee}$ (600 eV$_{\rm nr}$) analysis threshold of DarkSide-50, enabled a study of very-low energy events, characterized by the presence of the sole ionization signal (see Fig. 3), which resulted in the world-best limit for low-mass dark matter searches in the mass range 1.8 GeV/c^2 to 6.0 GeV/c^2 [6] (see Fig. 1). The same analysis stream also produced very competitive limits for the scattering of dark matter off electrons [7].

DS-50 provided a powerful assessment of the performance of the pulse shape discrimination of the scintillation pulses in LAr: operating with a fill of atmospheric argon (AAr), we demonstrated that the pulse shape discrimination (PSD) of the primary scintillation signal guarantees a rejection factor better than one part in

1.5×10^7 [3]. (Note: the rejection factor is limited by the available statistics, and supported by independent measurements with DEAP-1 and DEAP-3600 [2, 37]; a supplementary analysis of Monte Carlo simulated data predicts an ultimate rejection factor $>3 \times 10^9$ [38].)

DS-50 also demonstrated the viability of an underground argon (UAr) target, which can be obtained with an ^{39}Ar content that is suppressed by a factor of more than 1400 with respect to AAr, drastically reducing the expected number of electron recoil (ER) events to be discriminated [4, 5, 39].

DS-50, finally, demonstrated the use of a comprehensive anti-coincidence veto scheme, based on a water Cherenkov and on an organic liquid scintillator, which suppressed the residual background from γ-rays and neutrons [40].

In parallel, the single-phase approach pursued by the DEAP-3600 Collaboration has achieved a number of milestones. The largest to date low-background dark matter detector, with a total mass of 3200 kg of argon, has been developed and built. It is collecting data since 2016 and released the first results in 2017 [2] and expects to release results with leading sensitivity for an argon-based DM search in 2018; its design sensitivity is $2 \times 10^{-46}\,\mathrm{cm}^2$ for a $100\,\mathrm{GeV}/c^2$ mass WIMP.

The DEAP Collaboration pioneered the use of PSD in liquid argon for electron background suppression and demonstrated unprecenteded PSD, projected to 10^9 at threshold with the lowest-ever achieved ER-limited threshold in argon.

In DEAP-3600 several novel and cutting-edge technological solutions were successfuly developed and implemented. The collaboration developed and qualified ultrapure acrylic for use as a cryogenic vacuum vessel, controlled the acrylic radioactivity during production, developed a large-scale "resurfacer" device to produce radiopure surface and maintained radon-free conditions after resurfacing, and developed a large-area in-situ deposition system for wavelength shifter, depositing $10\,\mathrm{m}^2$ of tetraphenylbutadiene (TPB) wavelength shifter over the surface area of the DEAP-3600 vessel. The lowest radon backgrounds in a dark matter search has been achieved, with 200 nBq/kg of ^{222}Rn [2].

With the very low rate of cosmogenic muon-induced neutrons at SNOLAB, and the DEAP-3600 design which includes substantial passive neutron shielding for external-source neutrons, DEAP-3600 has achieved the lowest rate of neutron-induced nuclear recoils of any dark matter experiment. DEAP-3600 has also demonstrated for the first time excellent position reconstruction in a large single-phase argon dark matter experiment, with a resolution better than 10 mm for external-source low-energy events.

DEAP-3600 has also set a limit on neutrinoless double EC decay of ^{36}Ar with unique sensitivity to all three available detection channels, and performed precision measurements of ^{36}Ar and ^{42}Ar activity in AAr.

IV. NEW TECHNOLOGIES

The following four key technologies will enable the next generation of experiments.

Low-Radioactive underground argon with Urania: Although the depletion factor of ^{39}Ar in the UAr is established by DS-50, in order to scale up the experiment, a large amount of UAr has to be procured in a timely fashion. This will be accomplished by Urania, an underground argon extraction and purification plant capable of extracting 250 kg per day of UAr. The Urania plant is being designed and will be installed in Colorado. It is projected to collect approximately 50 tonnes of argon for use in DS-20k by 2022 and will continue to produce underground argon for the 300 tonne detector.

Active depletion with Aria: For the DS-20k experiment the level of depletion of 1400 present in the UAr is sufficient to run the experiment with zero background. However, for the DarkSide-LowMass experiment the level of depletion impacts directly on the sensitivity and therefore further depletion would be advisable. To this purpose, the Aria plant, which consists of a 350 m tall cryogenic distillation column, capable of separating isotopes, is under construction in Sardinia, Italy. The plant is estimated to be able to process UAr at a rate of 10 kg/d, obtaining a ^{39}Ar depletion factor of 10 per pass. The Aria plant could potentially exceed significantly the design criterion of a factor of 10 depletion per pass, with multiple passes. At much larger rate this plant will perform chemical purification of the UAr for DS-20k to make it detector grade.

SiPM-based cryogenic photosensors: SiPMs are one of the key enabling technologies for large-scale LAr-based dark matter experiments. SiPMs may also play an important role in the next generation of LAr-based neutrino detectors, such as DUNE, and liquid xenon based detectors for neutrinoless double beta decay, such as nEXO. SiPMs have a number of performance advantages over traditional PMTs, including higher photo-detection efficiency and much better single-photon resolution, all while operating at much a

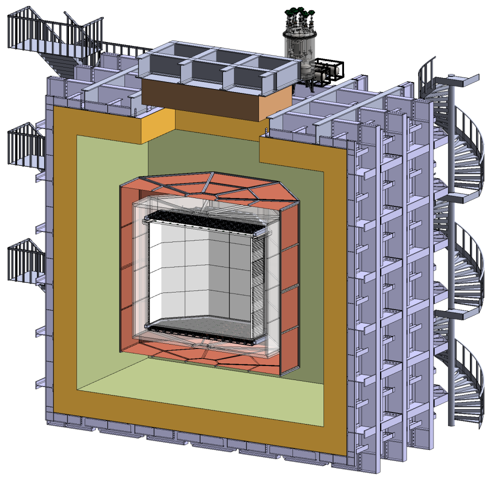

FIG. 4. 3D schematics of the DarkSide-20k experiment. The drawing shows the PPMA TPC filled with UAr, surrounded by the VETO detector made of Gd-loaded PMMA shell sandwiched between two AAr active layers (the inner one, named IAB and the outer one, named OAB in the text), all contained in the ProtoDUNE-like cryostat. The OAB is optically separated by the AAr in contact with the cryostat wall by a membrane, whose characteristics are yet to be defined.

lower bias voltage. SiPMs can also be efficiently integrated into tiles that cover large areas and feature better radiopurity up to an order of magnitude than PMTs.

Utilization of ProtoDUNE cryostat: The decision to abandon an organic liquid scintillator veto and to host DS-20k within a ProtoDUNE-like cryostat was originally motivated by the need of minimizing the environmental impact on underground LNGS operations but carries significant performance advantages. Indeed, operating the TPC directly in the ProtoDUNE-like cryostat allows eliminating the stainless steel cryostat and placing SiPMs modules outside the TPC, thus keeping most radioactive components further away from the active volume. Also, the scalability to even larger experiment is higher with this design.

V. DARKSIDE-20K

DS-20k will be located in the Hall-C of the Gran Sasso National Laboratory (LNGS) in Italy. It consists of two detectors: the inner detector and the veto detector, both hosted in a ProtoDUNE-like cryostat [41, 42]. The inner detector is a Liquid Argon Time Projection Chamber (LAr TPC) filled with UAr contained in an acrylic vessel made from the same ultra-pure poly(methyl methacrylate) (PMMA) developed for the DEAP-3600 experiment. The active volume is defined by octagonal reflector panels and top & bottom windows of the acrylic vessel. All the surface touching the active volume is coated with TPB wavelength shifter to convert LAr scintillation light to detectable light to SiPMs. The top and bottom SiPM-based PDM arrays, 4140 PDMs each, are located outside the acrylic vessel viewing the active volume through the acrylic windows. The height of the TPC is 2.63 m. With this design, the total mass of LAr in the active volume is 38.6 t.

The veto detector is made of a passive Gd-loaded PMMA shell, surrounding the inner detector, sandwiched between two active AAr layers. The Gd-loaded PMMA shell moderates neutrons emitted from materials of the LAr TPC and enhances neutron capture on Gd, resulting in the emission of multiple γ-rays. The γ-rays are detected by use of scintillation light emitted by the AAr layers. The ProtoDUNE-like cryostat will be surrounded by layers of plastic for moderation of cosmogenic and radiogenic neutrons from the rocks surrounding the LNGS Hall C.

Fig. 4 shows a 3D schematic, with the TPC placed inside the Veto detector. DS-20k is expected to be operated in a zero-background mode, i.e., suppressing background from instrumental sources to < 0.1 events in a 100 t yr exposure.

VI. LOW MASS SEARCH PROGRAM

In a complete synergy with DS-20k, DarkSide-LowMass will utilize the DarkSide-Proto detector in construction at CERN to support tests of the DS-20k elements, and in particular of the PDMs [43, 44]. Thanks to the use of the low-background SiPM-based PDMs, of a low-background cryostat, and of an ultra-low background argon target purified by the Aria cryogenic distillation column, DS-LM will perform a competitive and compelling exploration of the low-mass discovery region, reaching into the neutrino floor.

The world-leading low-mass results of DS-50 were enabled by the study of the (sole) ionization signal from very low energy events. The analysis threshold is of $100\,\mathrm{eV_{ee}}$ ($600\,\mathrm{eV_{nr}}$), corresponding to $4\,e^-$ extracted from the liquid target, with each electron producing in average, by electroluminescence, 23 PE. The residual background above $7\,e^-$ ($1.2\,\mathrm{keV_{nr}}$) in DS-50 is completely characterized and accounted for by known sources: the dominant components are the residual target contaminations in ^{39}Ar and ^{85}Kr and radioactive contamination of the PMTs.

The DS-LM TPC will be a scaled-down version of that of DS-20k, can be operated in a low-radioactivity copper container, and within a AAr active veto. Thanks to the Aria cryogenic distillation column, we are able to project the complete removal of ^{85}Kr and the reduction of ^{39}Ar, for small, tonne-size batches, to the level of 1 µBq/kg. The limiting low-energy background from PDMs can be reduced by the use of ultra-pure light guides and by planned abatements of the radioactivity of the PDMs components.

Detailed studies show the background limiting the analysis threshold to $4\,e^-$ in DS-50 is related to the impurity and radioactivity levels in the active volume. Thus, we plan on a strong reduction of both impurity and radioactivity levels by using novel noise and contamination techniques [45–47], advanced paths for purification of the region at the boundary between the two phases, reinforcement of the overall purification rate of the bulk liquid, and use of advanced fiducialization techniques, such as to achieve a very strong reduction of background and to lower the analysis threshold to $2\,e^-$, opening the way to reach the sensitivity shown in Fig. 1.

An improved knowledge of the ionization distribution of nuclear recoils is needed to reduce the uncertainties in the expected signal yield above the analysis threshold and thus improve the sensitivity at the lowest masses. As part of the GADMC program, we plan to study low energy nuclear recoils performing direct measurements of scintillation and ionization yield using a neutron-beam in the ReD experiment, and we plan to perform dedicated studies in the energy range of interest for low mass DM detection ($<1\,\mathrm{keV_{nr}}$), with the specific goal of a first direct measurement of the ionization yield in liquid argon and, possibly, of establishing a realistic and detailed model for fluctuations of ionization of nuclear recoils.

VII. ARGO

The GADMC is planning a phased approach towards reaching the neutrino floor. DS-20k, with a planned total exposure of 200 t yr, will reach a sensitivity approximately 60 times beyond that of DEAP-3600, which has a design exposure of 3 t yr. After DS-20k, the collaboration plans to mount the Argo detector for an ultimate dark matter search with an exposure of 3000 t yr, again representing a factor of 15 increase in sensitivity. Although the detailed design for such a detector is not in place, we anticipate a detector with a fiducial mass of approximately 300 t, with the experiment starting around 2028. Argo will thus allow an increase in sensitivity of 1000 beyond the current generation of experiments with a strong potential for discovery, and in the event that dark matter interactions are observed with cross-sections above the neutrino floor, the potential for elucidating the nature of the dark matter particle, namely its mass and interaction cross-section. Argo would allow other important measurements beyond the dark matter search. Control of electron backgrounds in the argon could allow measurement of medium-energy solar neutrinos, including CNO [20]. Such a large detector would also have excellent sensitivity to neutrino bursts associated with supernovae and provide the possibility of a flavour-blind measurement, complementing measurements made with other detectors, such as Super-KamiokaNDE, see Sec. VIII B.

As described in the previous sections, both DEAP-3600 and DS-50 have demonstrated the strong rejection of electronic backgrounds possible with argon using pulse-shape discrimination. Coupling this strong rejection power with the depleted argon from Urania and Aria plants, the rate of ^{39}Ar decays will not be a limiting factor of the experimental sensitivity even for the scale of DS-20k and Argo. To prevent activating ^{39}Ar in the argon due to cosmic rays and thus to maintain this depletion level, the collaboration has recently submitted a letter of intent to SNOLAB to explore underground storage of argon for Argo, and we intend to collect and store the underground argon over a five year period.

Once electronic recoil backgrounds have been mitigated and the inner argon sufficiently radiopure, the other relevant backgrounds for the dark matter search are from neutron-induced nuclear recoils, from other events occurring near the detector surfaces and ultimately from coherent scattering of neutrinos from argon nuclei. For a sensitive dark matter search, the first two classes of events, which both occur near the detector surfaces, need to be suppressed. The collaboration has so far employed two techniques. A two-phase time projection chamber (DS-50 and DS-20k) allows for precise position reconstruction and rejection of external-source events. Detection of the primary scintillation signal only (DEAP-3600) also allows precise reconstruction of event positions, with rejection capability expected to increase for larger detectors, in the same way as time-of-flight is used to achieve excellent position resolution in large solar neutrino detectors. DS-50 also employed an active neutron veto to reduce the rate of these events, where DEAP-3600 uses a large radiopure acrylic shield to reduce the total rate of neutron interactions to an acceptable level. Two techniques developed in our collaboration will be combined to mitigate these backgrounds in the design of Argo aiming at a factor of 1000 increase in sensitivity beyond the current generation of experiments, with a goal of a 2028 start date.

In summary, we are defining a program towards realizing Argo that will allow a full exploration of the high WIMP-mass region of parameter space to the neutrino floor, an increase of sensitivity of a factor of 1000 over current experimental results, significantly extending the reach in the search for dark matter and opening the door for discovery and possibly first measurements of dark matter particle properties. Such a program would also enable a rich set of physics measurements in addition to the dark matter search.

VIII. OTHER WORLD-LEADING PHYSICS GOALS

A. Solar Neutrinos

Measurement of CNO neutrino flux from the Sun has a broad impact in astrophysics, leading to improved models for star formation and supernova explosions, and with the potential to solve the long-standing "Solar Metallicity Problem", the stark disagreement between predicted and observed sound speed profiles. The discrepancy between predicted CNO neutrino fluxes from the two leading metallicity models, high [48] and low [49] (up to 38 %), makes the CNO neutrino flux the optimal candle to solve the problem. The rate of expected CNO neutrino interactions above 565 keV (the ^{39}Ar Q-value), via neutrino-electron elastic scattering, in a 1500 t yr exposure for Argo, is about 3500 (5000) CNO neutrinos, assuming the low (high) solar metallicity model, in addition to 6000 *pep* and 16 000 ^{7}Be neutrinos in the same energy range [20].

The advantages of using the LAr technology are several, especially when compared to Borexino, which provided the strongest constraint to CNO flux with an organic liquid scintillator technology. LAr is a more powerful scintillator, four to five times brighter than organic scintillators, and more radio-pure. Other advantages are the excellent fiducialization with rejection of surface activities, ease of purification of ^{210}Pb and ^{210}Bi, and possibility to discriminate multiple-scatter events. These advantages allow not only to suppress γ-ray backgrounds but also to determine radioactivities in the detector by looking at the full absorption peaks. The *in situ* activation of cosmogenic isotopes, another important source of background in Borexino, does not represent an issue in Argo thanks to the SNOLAB depth, which limits its rate to about two orders of magnitude lower than the expected signal. The presence of pre-activated, long-life isotopes, like ^{37}Ar, ^{39}Ar, and ^{42}Ar, is disfavored by the use of LAr extracted from deep underground, and hence naturally shielded against cosmic rays.

Argo will profit from excellent energy and position resolutions, sharp fiducialization, multiple scatter event rejection, and exceptional radiopurity provided by the LAr technology. These, in association with the cosmic-rays suppression at SNOLAB, guarantee a unique potential in detecting, for the first time, CNO neutrinos and in solving the Solar Metallicity Problem.

B. Supernova Neutrinos

Galactic supernova is a rare process which provides a means for multi-messenger astronomy to unlock key secrets in the understanding of stellar evolution and death, as well as remaining questions within particle physics. In the 400 t of LAr of Argo, there would be the potential to observe more than 2000 CEνNS events coming from a supernova burst at a distance of 10 kpc from Earth, and at the time of expected operation the largest number of CEνNS events. In comparison, this is only ∼1000 fewer interactions compared to the charged current scattering events that would be observed in the 40 kt DUNE experiment, and about 25 % of the number of expected inverse-beta and elastic scattering events from the 50 kt SuperKamiokande detector. Because the CEνNS channel is flavor insensitive, this observation would give a statistically significant measurement of the total neutrino flux coming from the supernova with the keV scale threshold, which is not accessible to other water Cherenkov and scintillator detectors. The triggerless design of DarkSide-20k/Argo data acquisition will allow to explore CEνNS events down to a single ionization electron (∼23 eV). The background affecting this region will be precisely constrained from data acquired before and after supernova events. If the veto detector of the Argo experiment can also be used to make a detection of ν_e flavor neutrinos, the Argo experiment would be capable of measuring the neutrino mass hierarchy.

The GADMC will be joining into the SuperNova Early Warning System (SNEWS) network. The operation of DarkSide-20k and Argo would represent a strong addition to SNEWS, in support of the network attempt to point any possible astronomy instrumentation towards the direction of the supernova and wait for the signal to come, to fully exploit the supernova signal towards the understanding of its explosion process and neutronization burst, and its implications on neutrino masses and oscillations [50, 51].

IX. DISCUSSION OF TECHNOLOGICAL COMMONALITY WITH NEUTRINO PLATFORM AT CERN

In addition to the strong overlap between the CERN scientific program for Dark Matter production and observation and the program for direct galactic Dark Matter detection with argon detectors, there is a strong overlap in the technology. Liquid noble gases are used as detector media due to the intrinsic properties of ionization and scintillation when charged energetic particles traverse the medium. Both ionization and scintillation are measurable in a wide range of energy deposition. In particular in liquid argon, the measurements of these ionization and scintillation signals and the characterization of these signals enables the detection of very low energy rare events down to keV such as dark matter detection and up to multi GeV events for long baseline neutrino studies or high energy cosmic rays (Neutrino Platform, NP).

The technological requirements for liquid argon detectors for dark matter and neutrino physics have large overlap. To utilize the measurement of the ionization and the scintillation in liquid argon, the common set of basic requirements include: 1. a cryogenics system handling the large detector mass; 2. a purification system to filter the argon such that it reaches the cleanliness level that both scintillation light and ionization charge can be measured; 3. development of large area photo-sensors operational in liquid argon environment; 4. TPC design and optimization, for either dual-phase (DS, NP02) or single-phase (NP04) operation; 5. high voltage system development for delivering the needed potential for TPC operation; 6. low noise cold readout electronics for the photon sensors (DarkSide, NP02, NP04) or the charge sensors (NP02 & NP04); and, 7. DAQ and data handling with zero dead-time signal processing. Beyond shared technological challenges, there is also a large overlap of the communities working in liquid argon dark matter and neutrino detection in Europe.

The current DarkSide-20k scale is already comparable in target mass to the neutrino platform ProtoDUNE system, and many of the items stated above share the same technological solutions. Towards the Argo scale, we wish to highlight the relevance of readout technique development towards fully digital silicon sensors, which have prospects for application in future DUNE modules. Beyond readout, another area of important shared development could be the reduction of ^{39}Ar backgrounds, which impact the reach of DUNE for low-energy solar and supernova neutrino physics. DarkSide has reduced the ^{39}Ar background level by mining argon from underground sources by a factor of more than 1400 and the achievement proved the feasibility of establishing a production level for DarkSide-20k at about 250 kg/d. The amount of underground argon available in the CO_2 stream is much higher, which could lead to the possibility of scaling up to produce underground argon for use in the Neutrino Platform and beyond.

We emphasize the importance of the infrastructure and expertise of CERN in underpinning the European research program in both dark matter and neutrino physics using liquid argon. Synergy with the Neutrino Platform cryostat developments has led to a significant design evolution of the DarkSide-20k detector. We encourage the European Strategy to recognize the importance of these shared technological developments and the role of CERN as an extraordinary catalyzing factor of discovery and feedback concerning the future directions to follow in the Argo program.

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