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# DarkSide new results and prospects

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**Summary.** — New results on the scattering cross-section between dark matter particles and nuclei and electrons are presented. They are obtained using a live-days exposure of 532.4 days from the DarkSide-50 experiment, which is a dual-phase liquid-argon time projection chamber (LAr TPC) installed at Laboratori Nazionali del Gran Sasso (LNGS). In this paper, the DarkSide-20k experiment, a LAr TPC with an active (fiducial) mass of 23 t (20 t) to be built at LNGS, is also reviewed. Thanks to its exceptionally low instrumental background, DarkSide-20k will be able to exclude cross sections between weakly interacting massive particles (WIMPs) and nuclei at 90% confidence level down to $2.8\times10^{-48}\,\mathrm{cm}^2$ ($1.2\times10^{-47}\,\mathrm{cm}^2$) for a WIMP mass of $100\,\mathrm{GeV}/c^2$ ($1\,\mathrm{TeV}/c^2$).

## 1. – Introduction

The existence of dark matter (DM) in the Universe is one of the most fascinating problems that modern physics needs to solve. Since its proposal by Jan Oort and Fritz Zwicky in the 1930s, it has nowadays been accepted by the physics community in order to explain many otherwise puzzling astrophysical and cosmological anomalies. Dark matter properties can be inferred from the observation of several phenomena and it is commonly believed that roughly 25% of the mass-energy content of the universe is in some non-baryonic form that does not interact electromagnetically nor via the strong force. The most promising candidate for dark matter is a yet to be discovered *weakly interacting massive particle* (WIMP). Those particles, that cannot be found within the Standard Model (SM), must interact weakly enough to survive a myriad of bounds set by precision astrophysical and cosmological tests and heavy enough to have been in non-relativistic motion when they decoupled from the hot particle plasma in the early stages of the expansion of the Universe. Many theories that predict the existence of phenomena not included in the SM provide a valuable WIMP candidate that could be experimentally observed thanks to its possible interactions with SM particles.

The *golden method* to observe DM is represented by so-called direct searches that aim to measure the effects produced by a possible interaction between a DM candidate with the target material of the detector. Different technologies have been developed in order to provided different approaches to direct DM searches. At the time of writing, dual-phase noble liquid Time Projection Chambers (TPCs) represent the leading technology in the direct detection of WIMP particles with masses larger than a few $\mathrm{GeV}/c^2$. Due to the fact that noble elements do not react chemically and are excellent scintillators and good ionizers in response to the passage of radiation, they are perfect to build this kind of detectors. They allow to obtain large, homogeneous, low-background, and self-shielding detectors. In particular, the usage of liquid argon (LAr) guarantees an excellent discrimination power ($> 10^8$) in the scintillation pulse shape between nuclear and electron recoils. However, a disadvantage of natural argon is that it contains cosmogenic $^{39}$Ar contamination. This problem can be overcome by extracting LAr from deep underground, where $^{39}$Ar is suppressed by more than 3 orders of magnitude. Underground Ar is exploited by the DarkSide-50 experiment, which main goal is to measure nuclear recoils (NR) after scattering with WIMPs, with masses of a few tens of $\mathrm{GeV}/c^2$, in a basically background-free regime. In this way, a positive claim can be made with as few events as possible. Relaxing the background-free requirement, DarkSide-50 has also the potentialities to explore lower energies and hence lower WIMP mass ranges, below and above the GeV/$c^2$ scale. Those regimes are usually referred to as the low-mass and high-mass range, respectively.

In these proceedings, the new results from the high- and low-mass DM searches obtained exploiting the data collected by the DarkSide-50 experiment are presented. The data is accumulated in 532.4 live-days, from August 2, 2015 to October 4, 2017. At the end, the potentialities of a new generation DM experiment, called DarkSide-20k, capable of collecting an exposure of 100 tonne year are investigated. DarkSide-20k, a dual-phase LAr TPC of 20 tonne active mass, is expected to keep the number of instrumental background interactions to less than 0.1 events in the nominal exposure, apart from background events induced by Coherent Elastic neutrino-Nucleus Scattering (CEnNS).

## 2. – The DarkSide-50 detector

The basic principle of the the DarkSide-50 TPC is that argon recoils, possibly due to a DM interaction, produce a scintillation signal, referred to as S1. In this process ionisation electrons are also produced, which thanks to an applied electric field of 200 V/cm drift to a gas phase, producing an electroluminescence signal referred to as S2. Two arrays of PMTs at the top and the bottom of the TPC, as shown in fig. 1 (left), collect the light. The maximum drift time, corresponding to the height of the TPC (35.6 cm), is $\sim 375\,\mu$s. From the time delay between S1 and S2 is possible to infer the $z$-position of the particle interaction. The TPC is surrounded by the so-called Liquid Scintillator Veto (LSV) [1], a 4.0 m-diameter stainless steel sphere equipped with an array of PMTs and filled with borated scintillator. The LSV allows to shield the detector from radiogenic and cosmogenic neutrons, gammas and cosmic muons events (see fig. 1). In particular, requirements on the anti-coincidence between LSV and TPC are very powerful in rejecting neutrons, originating in the detector materials, interacting in the LAr target, and escaping the TPC. Single scattering neutrons represent one of the most dangerous source of background, being able to perfectly mimic the WIMP signal. The LSV allows

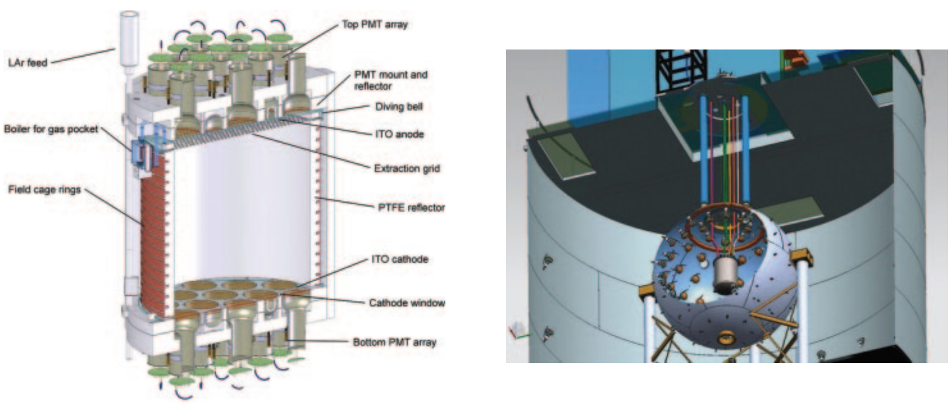


Fig. 1. – (Left) Profile of the DarkSide-50 Liquid Argon Time Projection Chamber. (Right) Scale sketch of the three DarkSide detectors (details in the text).

to detect and reject about ∼98% of neutrons that produce a single scattering in LAr, thanks to the neutron-capture reaction $^{10}$B(n,$\alpha$)$^7$Li. The LSV is in turn surrounded by the Water Cherenkov Detector (WCD), a 11 m-diameter, 10 m-high cylindrical tank filled with high purity water, serving as shielding and as anti-coincidence for cosmic muons thanks to an array of 80 PMTs, mounted on the side and bottom of the water tank, that detects Cherenkov photons produced by muons or other relativistic particles traversing the water.

## 3. – Detector calibration and energy threshold

The TPC response calibration is performed exploiting neutron and gamma sources and with gaseous $^{83m}$Kr injected into the target volume [2]. Morevoer, additional calibration is achieved thanks to cosmogenic $^{37}$Ar and $^{39}$Ar isotopes, that are naturally present in LAr. The S1 scintillation efficiency of nuclear recoils is measured with test beam experiments, namely SCENE [3] and ARIS [4], and cross-calibrated with DarkSide-50 measurements using AmBe and AmC neutron sources [5]. The S1 electron recoil (ER) photoelectron (pe) yield at the TPC center is measured at $7.0 \pm 0.3$ pe/keV [6] with 200 V/cm drift field and at the $^{83m}$Kr peak energy of 41.5 keV. The amplification factor for the ionization signal is equal to $23 \pm 1$ photoelectrons per electron extracted in the gas phase [5] with a resolution of about 20%.

As it will be clear in the next section, in the high-mass analysis both the S1 and S2 pulses are exploited. While from the S1 pulse shape one gets information on the event energy and nature, the S2 allows to determine the position and to reject multiple scatter events. The so-called f90 parameter, which corresponds to the fraction of S1 photons in the first 90 ns is used as a powerful Pulse Shape Discrimination (PSD) estimator. Due to the acceptance of f90 the threshold of nuclear recoils is set at 13 keV$_{nr}$. In this energy range, the background is dominated by $\gamma$'s from natural radioactivity in the detector materials and by two internal $\beta$ sources, $^{39}$Ar and $^{85}$Kr, with activities of ∼0.7 and ∼2 mBq/kg, respectively.

In the low-mass analysis, an energy threshold of less than 0.1 keV$_{ee}$ is achieved using S2 as a particle energy estimator. More precisely, the threshold is set to 4 electrons, which corresponds to ∼ 0.6 keV$_{nr}$ (the mean ionization energy in LAr is ∼23.6 eV), taking into account NR quenching. The disadvantage of this strategy is that due to the fact that S1 cannot be used, the PSD and fiducialization along the $z$-axis are more difficult to achieve. A key ingredient of the low-mass analysis is thus an accurate modelling of the ER background, obtained thanks to Monte Carlo simulations and measurements from detector material screening. Energy calibration of S2 is performed by looking at the 0.27 keV $L$-shell and the 2.82 keV $K$-shell radiation that happens after electron capture in $^{37}$Ar (fig. 2 left), and on NRs induced by AmBe and AmC neutron sources.

## 4. – Analysis in the high-mass range

The analysis of the DarkSide data in the high-mass range is performed in blind-mode. The strategy used is that sections of the blinded data outside of the WIMP search region, in the (S1, f90) parameter space, are opened subsequently as the analysis develops but a last, blind region that was opened only when all analysis criteria have been fixed. This scheme was defined to improve background predictions before the final box opening, as shown in fig. 2 (right). The expected background components can be classified into three categories: surface events, neutrons (cosmogenic and radiogenic), and ERs. The

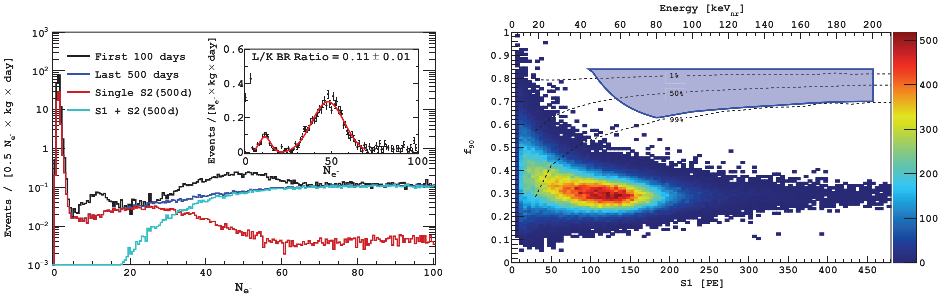


Fig. 2. – (Left) Underground Ar data sets corresponding to the first 100 days (black) and the following 500 days (blue) of exposure. The visible difference is due to the presence of cosmogenic $^{37}$Ar. (Right) WIMP search box in the (S1, f90) parameter space, after the data unblinding.

first are mostly rejected thanks to the fiducialization of the active volume, neutrons are efficiently suppressed with the LSV, and electron recoils are mostly removed by PSD. The LSV, whose efficiency is estimated to be $0.9964 \pm 0.0004$, identified 4 neutron candidates. After this cut, the dominant component is due to ERs $(0.08 \pm 0.04)$ [7]. The acceptance after all cuts is 60.9% and the fiducial mass corresponds to $36.9 \pm 0.6$ kg. The number of events expected using the entire statistics and after all the background rejection is $0.09 \pm 0.04$. After the data unblinding, no events were observed in the defined WIMP search region, as shown in fig. 2 (right). The lack of events observed is consistent with up to 2.3 WIMP-nucleon scatters expected at 90% CL, which sets an upper limit on the spin-independent scattering cross-section corresponding to $1.14 \times 10^{-44}$ cm$^2$ ($3.79 \times 10^{-44}$ cm$^2$, $1.10 \times 10^{-44}$ cm$^2$) for a WIMP mass of 100 GeV/$c^2$ (1 TeV/$c^2$, 126 GeV/$c^2$), as shown in fig. 4(a). This limit is obtained assuming a standard isothermal WIMP halo model, with $v_{\text{escape}} = 544$ km/s, $v_0 = 220$ km/s, $v_{\text{Earth}} = 232$ km/s, and $\rho_{\text{DM}} = 0.3$ GeV/($c^2$ cm$^3$).

## 5. – Analysis in the low-mass range

There are many challenges related to a low mass analysis that one has to face, from the energy determination to the fiducialization.

In order to overcome the problem of low detection efficiencies at very low energies, the energy is estimated from the S2 signal. Indeed in DarkSide-50 the hardware event trigger occurs when 2 or more PMT signals exceed a threshold of 0.6 pe within a 100 ns window. The efficiency of the software pulse finding algorithm is essentially 100% for S2 signals larger than 30 pe, which corresponds, in average, to 1.3 ionization electrons ($N_{e^-}$), well below the analysis threshold of 4 $N_{e^-}$. The detector acceptance is $0.43 \pm 0.01$ above 30 pe with the dominant acceptance loss due to the restricted fiducial region.

Since the S1 pulsed produced are usually not detectable, fiducialization can not rely on a drift time cut, and neither on the reconstruction of the $xy$ position, which does not work at low recoil energy due to low photoelectron statistics. Thus, a $xy$ fiducial region is designed selecting only events where the S2 signal peaks in one of the seven central top-array PMTs. Events detected in the single-electron regime, with low energy, are observed to be correlated in space and time with preceding events with large ionization. The probability to observe this kind of correlated events is larger when the getter is off, $(3.5 \pm 0.3) \times 10^5 e^-/e$, while it becomes $(0.5 \pm .1) \times 10^5 e^-/e$ when the getter is active, normalized in both cases to the total yield of ionization electrons. This observation

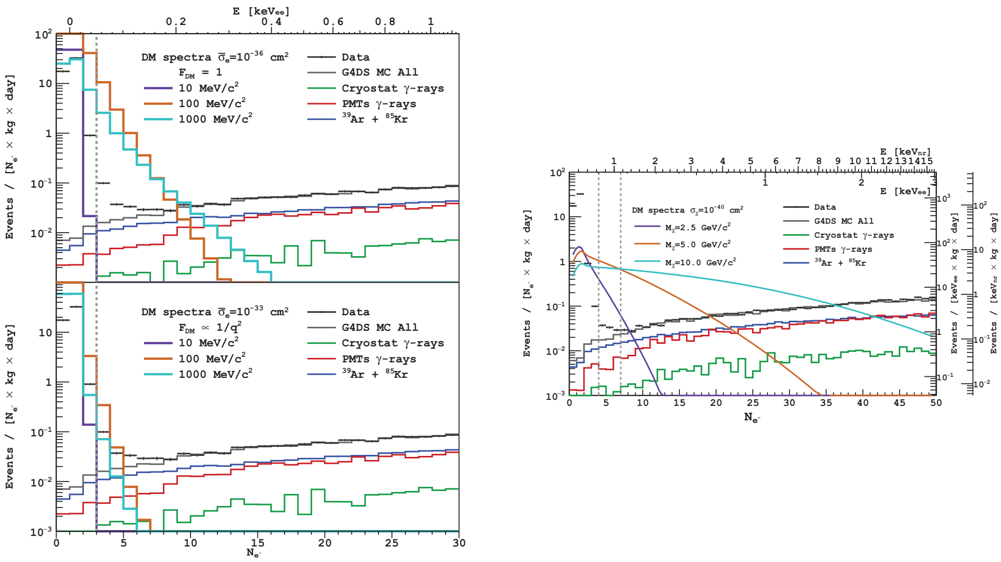


Fig. 3. – (Left) The $N_{e^-}$ data from the analysis of the last 500 days of exposure compared with a simulation of the background components from known radioactive contaminants. Also shown are calculated DM-electron scattering spectra for different DM particles masses and cross sections. The vertical dashed line indicates the $N_{e^-} = 3$ analysis threshold. (Right) The same $N_{e^-}$ data superimposed with the expected rates for recoils induced by DM particles of different masses.

corroborate the hypothesis that these events originate from electrons captured by, and subsequently released from, trace impurities in the argon. For this reason, data collected when the getter is off is ignored in this analysis. Moreover, a requirements on a time separation of 2.5 ms from a preceding trigger reduces spurious events from these delayed electrons, with a sacrifice of only 1% of exposure.

As shown in fig. 3, above 7 $N_{e^-}$ the background obtained from Monte Carlo (MC) simulations reproduces the data very well. A small excess of data in the region between 4 and 7 $N_{e^-}$, whose origin is unknown, is conservatively attributed to DM particle interactions in the determination of the exclusion limit. The observed DarkSide-50 rate is ~1.5 events/(keV$_{ee}$ kg d) in the range from 0.1 keV$_{ee}$ to 10 keV$_{ee}$. Data are analysed assuming two models: WIMP interactions with argon nuclei and with electrons. In the former analysis, the data set is divided into two signal regions. The first one is obtained using a threshold of 4 $N_{e^-}$ to remove trapped electron background, the second one uses a threshold of 7 $N_{e^-}$, where, as already stated, the background is well described by MC. The analysis of the first region results in weaker bounds on the DM-nucleon cross-section. The uncertainty on the expected WIMP signal near the analysis threshold is dominated by the average ionization yield, as extracted from calibrations, and its intrinsic fluctuations, modelled by applying binomial statistics to the ionization yield and the recombination processes. However, due to the lack of models for the NR quenching fluctuations, two extreme cases are considered: no fluctuations, which is equivalent to an analysis threshold of 0.59 keV$_{nr}$, and a binomial distribution. In fig. 4(b) the 90% CL exclusion curves for the binomial fluctuation model and the model with zero fluctuation are shown using red dotted and dashed lines, respectively. The limit is considered valid only for masses above

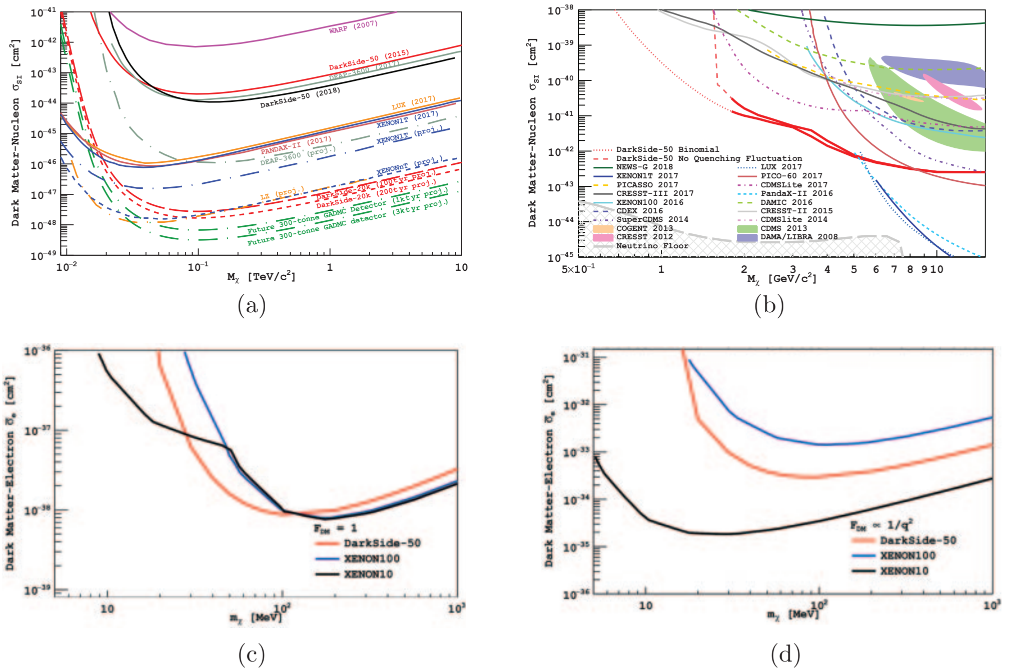


Fig. 4. – Exclusion limits from high- (top/left) and low- (top/right) mass WIMP-nucleus analyses, and from DM-electron interactions assuming heavy- (bottom/left) and light- (bottom/right) mediators.

$1.8\,\mathrm{GeV}/c^2$, where it is nearly insensitive to the chosen model. This result extends the exclusion region for DM below previous limits in the range 1.8–6 $\mathrm{GeV}/c^2$, assuming the same cosmological parameters of the high-mass analysis.

Sub-GeV DM particles can interact through a mediator with couplings smaller than the weak-scale. This interaction can directly ionize electrons and create a S2 signal. The interaction induces an ER signal, whose response is therefore not subjected to the quenching uncertainty of the ionization signal induced by WIMP-nucleus interactions. To search for this kind of DM-electron interactions the same data selection described above is used but with a threshold set to 3 $N_{e^-}$, equivalent to $0.05\,\mathrm{keV}_{ee}$. The resulting 90% CL limits are shown in fig. 4, assuming two different DM form-factors, corresponding to two extreme cases of heavy (c) and light mediators (d). In the case of a heavy mediator, this analysis improves the existing exclusion limits in the range from $30\,\mathrm{MeV}/c^2$ to $70\,\mathrm{MeV}/c^2$ DM masses.

## 6. – DarkSide-20k

Since no clear observation of DM has been so far performed, there are strong motivations to construct a new generation of experiments. Detectors with tens of tonnes of active target mass are now mandatory to improve current sensitivity levels by a few orders of magnitude. At this level of precision, controlling the background coming from neutrino-electron scattering would be of utmost importance for a possible discovery of DM. Thanks to their outstanding $\beta/\gamma$ background rejection, argon detectors represent a promising technology to operate in a background-free regime. For this reason DarkSide-20k, a two-phase LAr TPC of 20 tonnes active mass to be built at LNGS, capable of collecting an exposure of 100 tonnes year, has been proposed by the DarkSide Collaboration. Thanks to its extraordinary capability in distinguishing nuclear from electron recoils, DarkSide-20k will be able to keep the instrumental background content to less than 0.1 events for a total exposure of 100 tonnes year.

However, it will be affected by CEnNS, that induce nuclear recoils almost indistinguishable from those potentially induced by WIMPs. The number of expected CEnNS candidates has been estimated to be $1.33 \pm 0.26$, considering an exposure of 100 tonne year and after the inclusion of the experimental DarkSide-20k nuclear recoil acceptance. It has been understood that the atmospheric neutrinos contribution is the dominant one, being the diffuse supernova neutrinos contribution negligible. The uncertainty on the number of predicted CEnNS candidates is dominated by the uncertainty on the atmospheric neutrino fluxes.

Taking into account the impact of this background, that for DarkSide-20k will be the dominant one, the WIMP-nucleon sensitivity at 90% CL has been determined. Namely, DarkSide-20k will be able to exclude WIMP-nucleon cross section down to $2.8 \times 10^{-48}\,\text{cm}^2$ ($1.2 \times 10^{-47}\,\text{cm}^2$) for a WIMP mass of $100\,\text{GeV}/c^2$ ($1\,\text{TeV}/c^2$) (see fig. 4(b)).

## 7. – Conclusions

In this paper the results obtained from the analysis of 532.4 days of data collected with the DarkSide-50 detector have been presented. In the high-mass range, DarkSide-50 has demonstrated to be capable to achieve a zero-background regime with margins for further suppression. The results obtained are extremely promising and set the basis for a future detector, called DarkSide-20k, which will house a multi-tonne argon target mass capable of collecting an exposure of 100 tonne year. Finally, exclusion limits at low DM masses have been presented for DM interactions with nuclei and electrons.

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