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DarkSide-50 Results and the Future Liquid Argon Dark Matter Program

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DarkSide uses a dual-phase Liquid Argon Time Projection Chamber (TPC) to search for WIMP dark matter. The paper will present the latest result on the search for low mass ($M_{WIMP} < 20\,Gev/c^2$) and high mass ($M_{WIMP} > 100\,Gev/c^2$) WIMPs from the current experiment, DarkSide-50, running since mid 2015 a 50-kg-active-mass TPC, filled with argon from an underground source. The next stage of the DarkSide program will be a new generation experiment involving a global collaboration from all the current Argon based experiments. DarkSide-20k, is designed as a 20-tonne fiducial mass TPC with SiPM based photosensors, expected to be free of any background for an exposure of >100 ton x years. Like its predecessor DarkSide-20k will be housed at the Gran Sasso (LNGS) underground laboratory, and it is expected to attain a WIMP-nucleon cross section exclusion sensitivity of $10^{-47}\,cm^2$ for a WIMP mass of $1\,TeV/c^2$ in a 5 yr run. A subsequent objective, towards the end of the next decade, will be the construction of the ultimate detector, ARGO, with a 300 t fiducial mass to push the sensitivity to the neutrino floor region for high mass WIMPs. The combination of the three experiments, part of a single family, will cover completely the WIMP hypothesis from $1\,GeV/c^2$ to several hundreds of TeV/c^2 masses.

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1. Introduction

Despite much evidence from astronomy for dark matter (DM), years of laboratory and indirect searches have yielded no experimental evidence for DM that is not contradicted by other experiments. Weakly interacting massive particles (WIMPs) remain a promising candidate for DM, but direct searches are being pushed to probe lower WIMP-nuclear interaction cross sections and to lower ($< 10\,GeV/c^2$) and higher ($> 1\,TeV/c^2$) DM masses. Probing lower cross sections requires higher sensitivity and, hence, larger exposures (target mass and run time) and also, as importantly, more efficient background suppression. This issue is especially acute for spin-independent scattering for DM masses above $10\,GeV/c^2$, where current limits on the WIMP-nucleon cross section are $< 10^{-44}\,cm^2$, reaching as low as $4.1 \cdot 10^{-47}\,cm^2$ at $30\,GeV/c^2$ [1] in LXe TPC. Liquid argon time projection chambers (LAr TPCs) share the scalability and three-dimensional position reconstruction of liquid xenon TPCs. Moreover, LAr TPCs have powerful pulse shape discrimination (PSD) in the scintillation channel that separates the nuclear recoils (NR) expected from WIMP scattering from the electron recoil (ER) events from the dominant β- and γ-induced backgrounds. Exploiting this PSD, the single-phase DEAP- 3600 LAr scintillation detector has recently reported the best available DM-nucleon cross-section limit using an Ar target, $1.2 \cdot 10^{-44}\,cm^2$ at a DM mass of $100\,GeV/c^2$, from an initial 9.87 ton-day exposure.

2. DarkSide-50 results

2.1 The detector

The core of DarkSide-50 is a dual phase TPC filled with low radioactivity liquid argon (LAr) extracted from underground sources. The basic principle is that argon recoils, possibly due to a DM interaction, produce a scintillation signal, referred to as S1. The interaction in LAr produces

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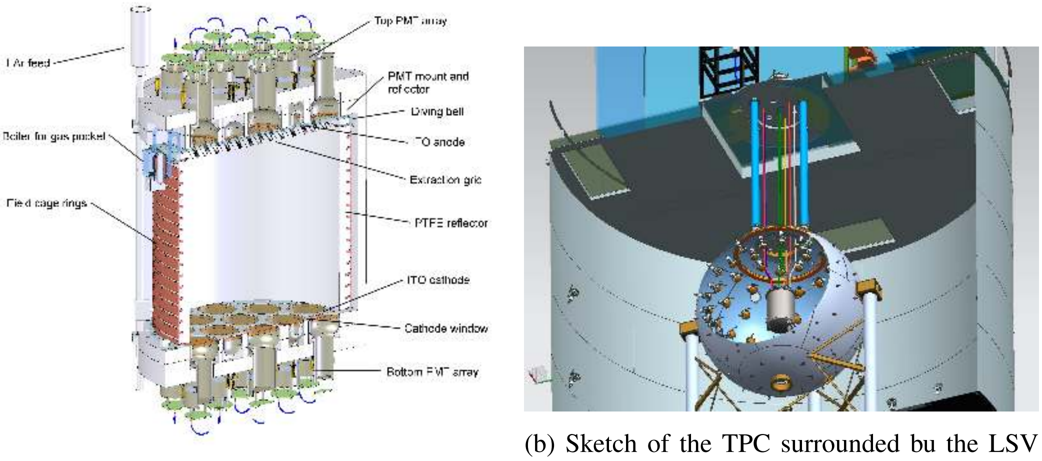

(a) Detailed sketch of the TPC.

(b) Sketch of the TPC surrounded bu the LSV placed inside the WCD.

Figure 1: Sketch of the DarkSide-50 experiment at LNGS. Picture from [2].

2.2 Results of DarkSide-50

2.2.1 High-mass analysis

The analysis of the 532 days of DarkSide-50 data is performed in blind-mode. Details of the analysis can be found here [3]. The analysis is optimized keeping blind the region in the (S1, f90) space where WIMP interactions are expected. The TPC PSD parameter f90 is defined as the fraction of S1 light detected in the first 90 ns of a pulse. This parameter allows very strong pulse shape discrimination between NR and ER. The aforementioned search box has been opened only when all analysis criteria had been fixed. This scheme was defined to improve background predictions before the final box opening. The background sources can be classified into surface events, neutron-induced background (both cosmogenic and radiogenic) and electron recoils (ERs). It was possible to get rid of surface background via fiducialization of the active volume, neutron-induced events were removed by LSV (4 neutron candidates, efficiency 0.9964 ± 0.0004) and ERs via pulse shape discrimination. ERs remain the dominant source of background 0.08 ± 0.04. Consequently the expected background in the full dataset is 0.09 ± 0.04 while the acceptance after all cuts is 60.9% and the fiducial mass corresponds to 36.0 ± 0.6 kg.

After the unblinding no events were present in the WIMP search. This result is consistent with up to 2.3 WIMP-nucleon scatters expected at 90% CL, wich can be interpreted as an upper limit on the spin-independent scattering cross section (a standard isothermal WIMP halo model is assumed $v_{escape} = 544\,km/s$, $v_0 = 220\,km/s$, $v_{Earth} = 232\,km/s$, $\rho_{DM} = 0.3/(c^2 cm^3)$). The result is shown if figure 2 and the limit on the cross section is $1.14 \cdot 10^{-44}\,cm^2$ for a WIMP mass of $100\,GeV/c^2$, $3.79 \cdot 10^{-44}\,cm^2$ for a WIMP mass of $1\,TeV/c^2$, and $1.10 \cdot 10^{-44}\,cm^2$ for a WIMP mass of $126\,GeV/c^2$.

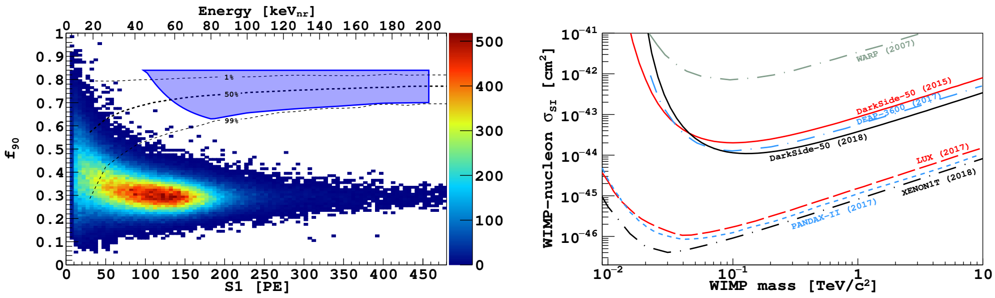

Figure 2: Left: WIMP search box in the (S1, f90) parameter space obtained after unblinding. Right: Exclusion limits for DM-nucleon interaction for DarkSide. Plot from [3].

2.2.2 Low-mass analysis

A low mass analysis has been performed, whose details can be found here [4, 5] . In order to lower the trigger threshold, S2 only signals were accepted. The DarkSide-50 hardware generates a trigger when at least 2 PMTs signals exceed a 0.6 photoelectrons threshold within $100\,ns$. From the analysis point of view, the efficiency of pulse finding software is close to 100% for S2 signals larger than 30 photoelectrons, which in average corresponds to 1.3 ionization electrons (N_{e^-}), that is safely below the analysis threshold that is set to 4 N_{e^-}.

The energy range of this analysis is not large enough to allow to detectable S1, consequently fiducialization cannot rely on drift time. Nor, given the low photoelectron statistics, allow to use standard xy reconstruction algorithms. Consequently, a xy fiducial region is designed selecting only events where the S2 signal peaks in one of the seven central top-array PMTs, implying a detector acceptance of 0.42 ± 0.01 above 30 photoelectrons.

The analysis is performed comparing the acquired energy spectra with simulations. The model implemented in our simulaiton code reproduces data very well above 7 N_{e^-}. A small excess of data is present in the region between 4 N_{e^-} and 7 N_{e^-}. The origin of the excess is unknown and it is conservatively attributed to dark matter particle interactions when the exclusion limit is determined. In the region $(0.1, 10)\,keV_{ee}$ the observed rate is about $1.5\,events/(keV_{ee}\,kg\,d)$. Data are analized assuming WIMP interaction with argon nuclei [4] and with argon electrons [5].

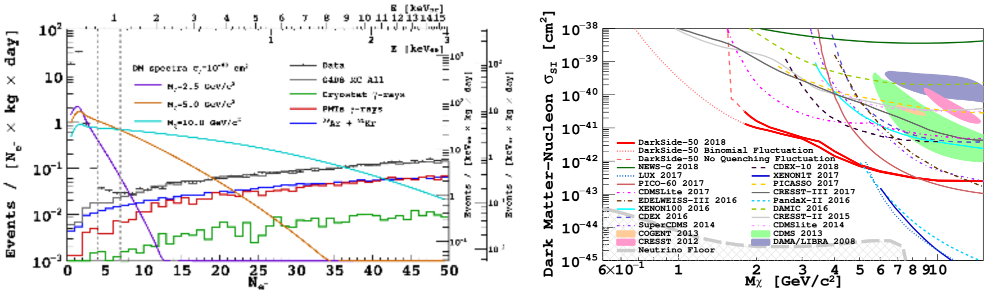

Figure 3: Left: data from the last 500 days of data taking compared to the model of the background components. The expected signal for different DM-nucleus interactions are superimposed. Right: Exclusion limits for WIMP-nucleus interactions in case of low mass analysis assuming binomial (dotted line) and zero (dashed line) fluctuation. Plots from [4].

The analysis takes into account two regions: one has a threshold of 4 N_{e^-} to remove events due to trapped electrons, i. e. electrons captured by, and subsequently released from, trace impurities in the argon. The second analysis uses an analysis threshold of 7 N_{e^-} where the background is well described by MC. The first region results in weaker bounds on the DM-nucleon cross-section. The main uncertainty in implementing the WIMP signal near the analysis threshold is the effect due to the average ionization yield, as extracted from calibrations, and its intrinsic fluctuations that can be modelled by applying binomial statistics to the ionization yield and the recombination process. Since there is not an established model for the NR quenching fluctuations, two extreme cases are evaluated: one allowing for fluctuations in energy quenching, ionization yield, and recombination processes obtained with binomial distributions and another where the fluctuations in energy quenching are set to zero, equivalent to imposing an analysis threshold of 0.59 keV_{NR}. Figure 3 shows the exclusion limits (90% CL) obtained using models allowing binomial fluctuation (dotted line) and zero fluctuation (dashed line). Limits above 1.8 GeV/c^2 are nearly insensitive to the chosen model.

The same dataset has been analyzed also looking for a mediator with couplings smaller than the weak-scale. The interaction can ionize electrons thus creating a S2 signal. Since it is an electron recoil signal, it is not affected by quenching uncertainties mentioned above. This analysis threshold is set to 3 N_{e^-} (0.05 keV_{ee}). Figure 4 shows the data collected and the shape of the relevant background and the signal expected in case of heavy and light mediators. The right part of the same figure shows the 90% CL limits of the search. At the moment of the conference the analysis was leading the search in the range between 30 MeV/c^2 and 70 MeV/c^2 DM masses. It is worth to note that recently the Xenon collaboration improved our results in this search [6].

3. DarkSide-20k

DarkSide-20k (DS-20k) will be located in Hall C of the Laboratori Nazionali del Gran Sassso (LNGS) of INFN. It consists of two detectors: the inner detector and the veto detector, both hosted in a ProtoDUNE-like cryostat [7]. The inner detector is a Liquid Argon Time Projection Chamber (LAr TPC) filled with liquid argon depleted from ^{39}Ar coming from underground wells (UAr). The

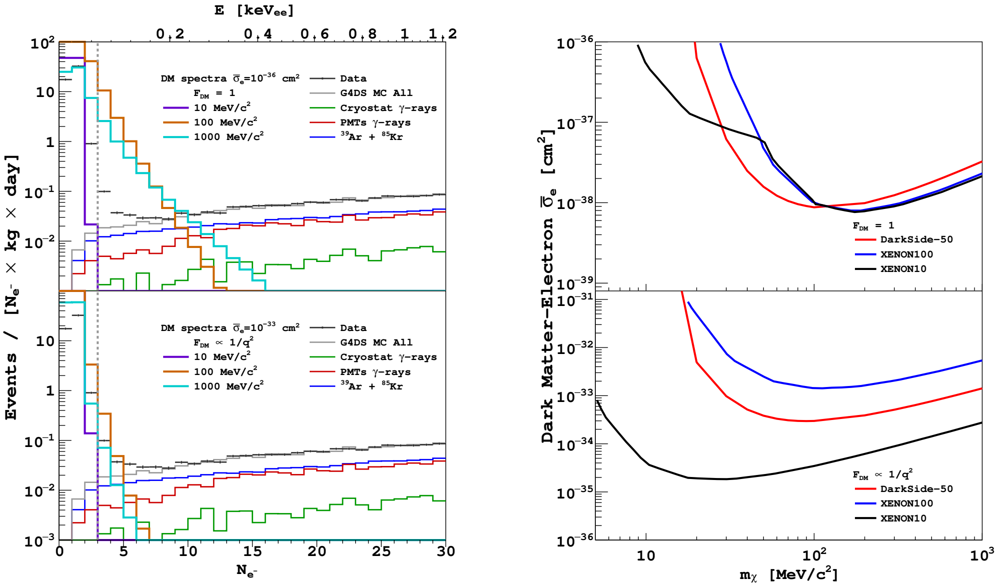

Figure 4: Left: data from the last 500 days of data taking compared to the model of the background components. The expected signal for different DM-electron interactions are superimposed assuming heavy (top) or light (bottom) mediator. Right: Exclusion limits for DM-electron interactions in case of assuming heavy (top) or light (bottom) mediator. Plots from [5].

veto detector is made of a plastic shell, loaded with Gd, surrounding the inner detector, sandwiched between two active atmospheric argon (AAr) layers. Figure 5 shows a 3D schematic, with the inner detector placed at the middle position of the veto detector. Operating the TPC directly in the ProtoDUNE-like cryostat eliminate the need for a stainless steel (SS) cryostat immediately surrounding the TPC, the leading contribution to the residual background. A new design for the TPC, in which the fully sealed vessel is built from the same ultra-pure plastic and it is filled with UAr have been developed. This UAr-filled vessel would be immersed in the bath of liquefied AAr held at the same temperature and pressure. The outer walls of the TPC will sit approximately 2 m away from inner wall of the much larger ProtoDUNE-like cryostat. This large AAr-filled cryostat will be surrounded by layers of plastic for moderation of cosmogenic and radiogenic neutrons from the rocks surrounding Hall C.

DarkSide-20k will exploit several innovative technologies in order to push further the sensitivity of the experiment: standard PMTs will be replaced by about 12000 SiPM tiles operating at LAr temperature; ultra-pure poly(methyl methacrylate) loaded with Gd compounds will be the key element for tagging efficiently neutron-induced events and depleted argon will be the active target of the TPC.

A broad strategy has been developed to increase the production of UAr to procure the target required for DarkSide-20k. The Urania project will extract and purify the UAr from the CO_2 wells in Cortez, CO. However, it will be necessary to make a final chemical purification of the UAr before deployment into the LAr TPC. This will happen using a cryogenic distillation column called Seruci-I in Sardinia, Italy, before inserting the argon inside the TPC. Additionally, it would

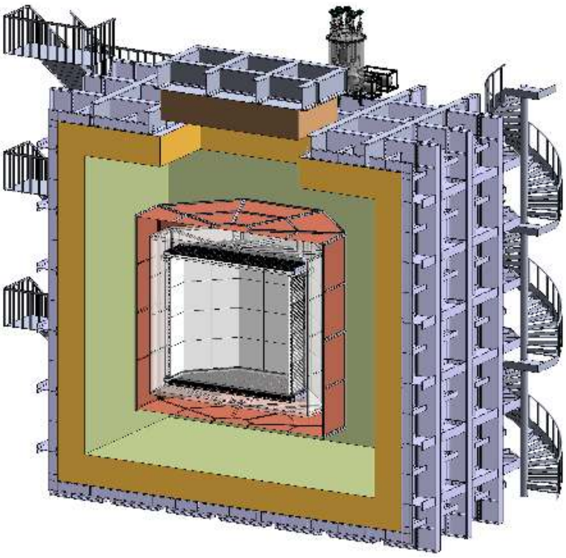

Figure 5: Sketch of DarkSide-20k detectors inside the cryostat.

be beneficial to further deplete the UAr of ^{39}Ar, giving extended sensitivity to DarkSide-20k.

Thanks to an accurate material selection and an extraordinary capability in distinguish 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. Taking into account also Coherent Elastic Neutrino Nucleus Scattering (CEnNS), DarkSide-20k will be able to exclude WIMP-nucleon cross section down to $\approx 10^{-48}\,cm^2$ cross section.

The collaboration is planning a phased approach towards reaching the neutrino floor. After DarkSide-20k, the collaboration plans to mount the Argo detector for an ultimate dark matter search with an exposure of 3000 ton yr. Although the detailed design for such a detector is not in place, a detector with a fiducial mass of approximately 300 tons is foreseen. 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.

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