PROCEEDINGS OF SCIENCE

Recent searches for light dark matter with DarkSide-50

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DarkSide-50 has been an experiment for direct dark matter detection operated at Laboratori Nazionali del Gran Sasso. It uses a dual-phase time projection chamber filled with low-radioactivity argon extracted from underground. Thanks to single electron sensitivity and with an analysis based only on the ionization signal, Darkside-50 set the most stringent exclusion limit on WIMPs with a mass of few GeV/c^2. A recent analysis improves by 10 times the existing exclusion limits for spin-independent WIMP-nucleon interactions in the [1.2, 3.6] GeV/c^2 mass range. Thanks to the inclusion of the Migdal effect, the exclusion limits are extended down to 40 MeV/c^2 dark matter mass. Furthermore, new constraints are set to the interactions of dark matter particles with electron final state, namely low-mass WIMPs interacting with electrons, galactic axions, dark photons, and sterile neutrinos.

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1. The DarkSide-50 experiment

The DarkSide-50 experiment employed a dual-phase liquid argon (LAr) time projection chamber (TPC) to search for spin-independent interactions between nucleons and high-mass WIMPs (>10 GeV/c^2). The TPC was operated inside a double wall cryostat, placed inside a 4 m diameter sphere filled with borated liquid scintillator, acting as anti-coincidence neutron veto. The two detectors were in turn inserted in a 1 kt water tank acting as cosmic muon veto. The first data-taking campaign ran from November 2013 to April 2015 with an atmospheric argon (AAr) target [1]. The atmospheric argon target was then replaced with low-radioactivity argon extracted from deep underground (UAr), where the concentration of cosmogenically activated isotopes is strongly suppressed [2]. Data was acquired with an UAr fill from April 2015 to February 2018.

The TPC is made of a 36 cm tall PTFE cylinder, with two fused silica windows, coated with transparent ITO electrodes, as top and bottom surfaces. The active mass of the TPC is 46.4 ± 0.7 kg. Two arrays of 19 three-inch photomultiplier tubes (PMTs) observe the active volume from top and bottom. The liquid is immersed in a uniform electric field (200 V/cm nominal). A ~ 1 cm thick layer of gas is created on top of the liquid. A stronger extraction electric field is applied in the gaseous region. Particle interactions in the bulk induce ionization and excitation of the liquid argon. Excited dimers de-excite emitting 128 nm photons within few μs from the interaction time. The ionisation electrons which escape recombination are drifted by means of the electric field up to the gas layer, extracted from the liquid and accelerated. This causes a secondary light emission, once again at 128 nm, a mechanism known as electroluminescence. The maximum drift time at the nominal field is 376 μs.

All the inner surfaces of the TPC are coated with tetraphenyl butadiene (TPB), a wavelength shifter that absorbs 128 nm photons and re-emits in the visible (peak at 420 nm). Prompt scintilllation pulses are called S1, while delayed electroluminesce pulses are called S2. Thanks to the time difference between S2s and S1s, and to the distribution of the S2 signals on the top array of PMTs, DarkSide-50 can reconstruct interaction vertexes with mm precision along the vertical direction and cm precision in the horizontal plane.

The light collection efficiency is such that the S1 light yield is 8.1 ± 0.1 photoelectrons per deposited keV (PE/keV) at null field. The multiplication factor in the gas (g_2) measured at the center of the detector is g_2 = 23.1 PE per extracted electron.

The discovery potential of LAr detectors in searching for high-mass (>10 GeV/c^2) WIMPs relies on their extraordinary background rejection capability, thanks to pulse shape discrimination technique. This was proven by the DEAP-3600 experiment, where 2.9×10^9 electronic recoils from ^{39}Ar decays in the WIMP search region (16 to 33 keV$_{NR}$) were successfully rejected [3]. Furthermore, the UAr campaign of DarkSide-50 demonstrated how the dual-phase technology can be effectively implemented to perform a background-free WIMP search. No event was observed in the WIMP ROI in a 532 live-days dataset [4].

In 2018, DarkSide-50 extended the physics case to lighter dark matter candidates [5, 6] by lowering the energy threshold from tens of keV$_{NR}$ (nuclear recoil equivalent) to few hundreds of eV$_{NR}$. This was achieved by using to construct an energy estimator only the ionization signal (S2, which benefits from the multiplication in the gas) as opposed to prompt scintillation signals. While the ~ 16% detection efficiency of S1 photons induces a detection threshold at the level of

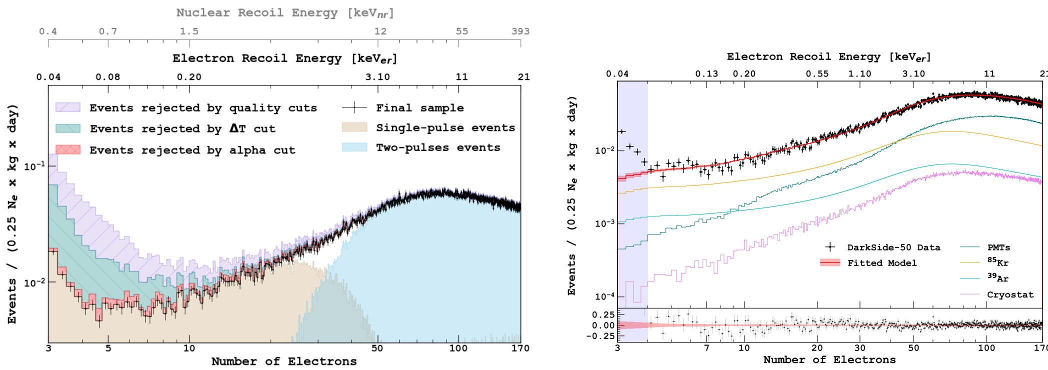

Figure 1: Left: the impact of quality and physics cuts on the initial dataset. Right: result of the background only fit, showing the individual background components. The excess below 4 Ne is attributed to the spurious electron background.

$\sim$ 10 keV$_{NR}$, single electrons are detected with nearly 100% efficiency. This enables to significantly lower the energy threshold and explore the sub-keV$_{NR}$ energy range.

The drawback of not requiring a valid S1 pulse for the event reconstruction is the reduced background discrimination power and volume fiducialization along the vertical direction. Nevertheless, this analysis technique, applied for the first time to a liquid argon experiment, led in 2018 to the improvement of existing limits on WIMP-nucleon and WIMP- electron interactions in the few GeV/c^2 and sub-GeV/c^2 mass ranges, respectively.

This paper describes the latest development of this analysis and describes updated results. Improvements were introduced at several levels in the analysis chain. First, the dataset size was increased by almost a factor of two using 653.1 live-days of data collected from December 12, 2015, to February 24, 2018. Second, the new analysis uses improved data selection criteria and a more accurate background model. Third, an improved calibration of the LAr ionization response to nuclear (NR) and electronic (ER) recoils, down to the sub-keV range, was introduced in 2021 [7]. This was achieved using the ^{37}Ar and ^{39}Ar decays naturally present in the early LAr dataset and can be extrapolated to 3 ionization electrons with the Thomas-Imel box model. The calibration of the NR energy scale down to $\sim$ 0.5 keV$_{NR}$, measured *in-situ* with a neutron source and using constraints from neutron beam experiments [8, 9], is the lowest ever achieved in liquid argon. Finally, the new analysis incorporates a more robust treatment of the systematic uncertainties in the statistical approach.

2. Search for sub-GeV dark matter candidates

For this search, the dark matter interaction signature is a single ionisation pulse resulting in $\lesssim$ 200 Ne (number od electrons) extracted in the gaseous phase. A set of quality and physics selection criteria is applied to the dataset to remove pathological events and to suppress backgrounds respectively. Quality cuts typically have $\sim$ 99% acceptance and use the ionisation signal (S2) time profile to identify and reject, for instance, pileup events and unresolved S1-S2 events occurring very close to the liquid surface. Physics cuts aim at rejecting backgrounds induced by natural radioactivity and by spurious electrons. Multi-sited events, resulting in multiple ionization signals in a single acquisition window, due to gamma-rays are removed from the dataset. The light pattern on the top array of PMTs is used to reconstruct the position of single sited events. Those reconstructed in the outermost ~5 cm of the TPC, and mainly due to X-rays form the detector materials, are discarded. This signal acceptance after the radial fiducialisation is 41.9%. Degraded alphas from the lateral surfaces may loose their ionization signal due to field effects near the TPC walls. However, the prompt scintillation may induce photo-ionization of the cathode, resulting in a low-Ne ionization signal following a NR-like S1-only pulse. While the combination of the two signals resembles a legit single-sited event from the bulk, the anomalous S2/S1 ratio compared to the one expected for NRs can be used to reject this class of events. Finally, spurious electron signals due to the trapping and delayed emission of electrons on electronegative impurities in the liquid or at the liquid surfaces generate S2only signals of few Ne. These sort of events correlate in space and time to preceding ionization signals. A 20 ms veto after each DAQ trigger is applied in order to suppress their rate. This cut induces a 3% signal acceptance loss.

The impact of each step of the data selection is shown in Figure 1 (left). The final dataset corresponds to an exposure of (12,306 ±184) kg d. It contains about 300,000 events in [4,170] Ne, the region of interest (RoI) for this analysis, equivalent to [0.06, 21] keVer or [0.64, 288] keV$_{NR}$. The analysis lower threshold is set at 4 Ne to minimize the spurious electron background. The overall signal acceptance is > 38% (including fiducialization).

The background model includes internal and external sources of ERs. The internal components are the unique first-forbidden beta decays of ^{39}Ar and ^{85}Kr. Their respective rates are measured by means of a spectral fit using both S1 and S2 signals and extending the energy RoI up to high energies. The activity of ^{85}Kr is further constrained by the result of a different analysis, searching for a β-γ decay channel occurring with a 0.43% branching ratio. The activities in the RoI and in the fiducial volume are estimated to be $(6.5 \pm 0.9) \times 10^{-4}$ Bq and $(1.7 \pm 0.1) \times 10^{-3}$ Bq, respectively. The external components are due to X- and γ-rays from the detector components. High-statistics simulations of decays and decay chains performed with G4DS, the DarkSide simulation tool [10], are used to determine the energy spectrum of single sited events in the fiducial volume. A detector response model is applied to convert energy to the Ne observable, including location dependent non-uniformities, the electron lifetime and the PMT response resolution. The 18 individually simulated components (decays or decay chains) are grouped according to their source location, either the stainless steel cryostat or the PMTs. The normalisation is constrained by the results of the material screening campaign undertaken before the detector construction.

Data are analyzed with a binned Profile Likelihood Ratio approach, which accounts for systematics by means of 11 nuisance parameters. The nuisance parameters act either on the normalization of the background components or on their shape, accounting for spectral distortions from the ionization response and from uncertainties on ^{39}Ar and ^{85}Kr β-decay spectral shapes due to uncertainties on Q-value and atomic exchange and screening corrections [11]. The data fit with the background-only model is shown in Figure 1 (right).

3. Results and conclusions

Using only the ionization signal, enabling a lower analysis threshold compared to a traditional scintillation+ionization search, allows to search for ~GeV dark matter candidates interacting with

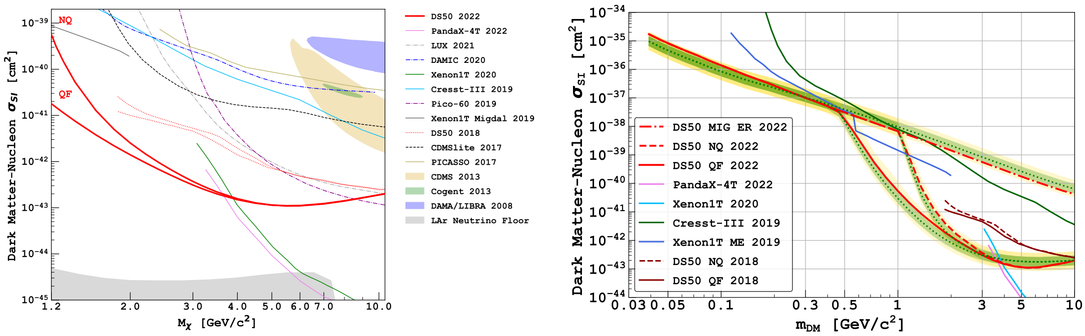

Figure 2: Left: Exclusion limits at 90%C.L. for spin-independent dark matter interaction with nuclei. Right: The same limit including the Migdal effect. In both plots, the two curves represent the uncertainty on the process governing the quenching fluctuations. The green and yellow shaded areas represent the $\pm 1\sigma$ and $\pm 2\sigma$ bands on the expected limits.

nuclei. The expected NR signal, computed under the assumption of a standard halo model, is simulated using the same detector response model employed for the background components. The NR response induces a systematic uncertainty on the shape of the signal, accounted for in the statistical approach. The exclusion for dark matter nucleon interactions and dark matter mass above 1.2 GeV/c^2 are shown in Figure 2 (left). The two presented curves reflect the uncertainty on the fluctuations of the quenching process affecting NR energy deposits. While no quenching fluctuations are considered for the curve labelled NQ, the curve labelled QF assumes a binomial process governing the energy partition between visible (ionization electrons and excitons) and invisible (phonons) quanta. Assuming NQ fluctuations, the most conservative model, DarkSide-50 establishes the current best 90% C.L. limits for dark matter with mass in the range [1.2, 3.6] GeV/c^2 and improves by a factor of ~10 at 3 GeV/c^2 over previous results [5, 12].

The inclusion of the hypothesized Migdal effect to the calculation of the NR signal model enables to explore dark matter candidates down to 40 MeV/c^2. The Migdal effect consists in atomic ionization following sudden acceleration by a nucleus struck by a dark matter particle. The energy of the prompt ionization and the subsequent atomic re-organization is released in the ER channel, not suppressed by the quenching process. The combination of NR and ER, treated as two independent energy deposits in this analysis, boosts the predicted signal above threshold. The exclusion curves including the Migdal effect are shown in Figure 2 (right) [13].

Finally, signal models predicting electrons in the final state were also investigated. Figure 3 shows the 90% C.L. exclusion limits on dark matter-electron scattering , in the limits of heavy (top left) and light (top right) mediators. The extracted exclusions improved over existing constraints in the [16, 56] MeV/c^2 mass range and above 80 MeV/c^2 respectively. The bottom row of Figure 3 reports exclusions limits for absorption of axion-like particles (ALPs) and dark photons, producing mono-energetic energy deposits in the fiducial volume at the particle's rest mass. Finally, DarkSide-50 is the first direct dark matter direct-detection experiment to set limits on the sterile neutrino mixing angle [14].

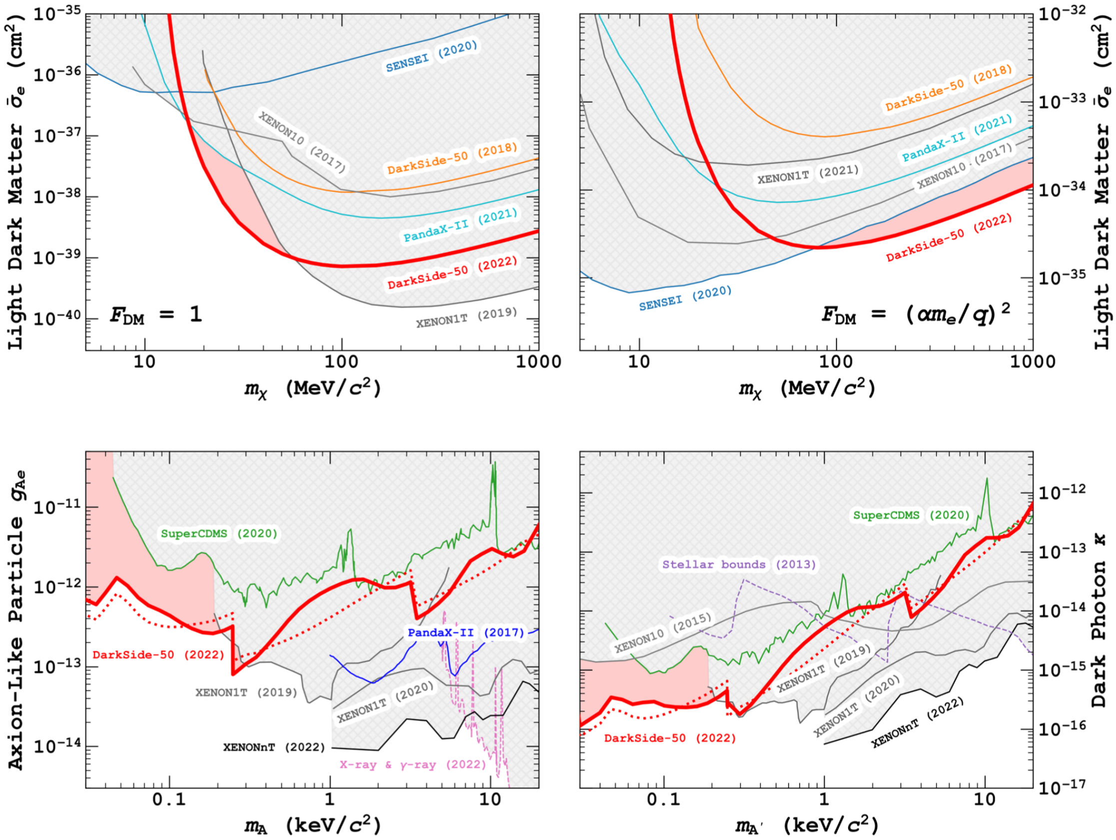

Figure 3: Exclusion limits at 90%C.L. on several dark matter interaction models with electron final states (solid lines). The dotted lines show the -1σ expected limits.

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