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# The DarkSide Experiment: Present Status and Future

G. Zuzel[40], P. Agnes[1], I. F. M. Albuquerque[2], T. Alexander[3,4,5], A. K. Alton[6], D. M. Asner[5], H. O. Back[5], B. Baldin[4], K. Biery[4], V. Bocci[7], G. Bonfini[8], W. Bonivento[9], M. Bossa[10,8], B. Bottino[11,12], A. Brigatti[13], J. Brodsky[14], F. Budano[15,16], S. Bussino[15,16], M. Cadeddu[17,9], L. Cadonati[3], M. Cadoni[17,9], F. Calaprice[14], N. Canci[19,8], A. Candela[8], M. Caravati[17,9], M. Cariello[12], M. Carlini[8], S. Catalanotti[20,21], P. Cavalcante[8], A. Chepurnov[22], C. Cicalò[9], A. G. Cocco[21], G. Covone[20,21], D. D'Angelo[42,13], M. D'Incecco[8], S. Davini[10,8,12], S. De Cecco[23], M. De Deo[8], M. De Vincenzi[15,16], A. Derbin[24], A. Devoto[17,9], F. Di Eusanio[14], G. Di Pietro[8,13], C. Dionisi[7,25], E. Edkins[26], A. Empl[19], A. Fan[27], G. Fiorillo[20,21], K. Fomenko[28], G. Forster[3,4], D. Franco[1], F. Gabriele[8], C. Galbiati[14,13], S. Giagu[7,25], C. Giganti[23], G. K. Giovanetti[14], A. M. Goretti[8], F. Granato[29], L. Grandi[30], M. Gromov[22], M. Guan[31], Y. Guardincerri[4], B. R. Hackett[26], K. Herner[4], D. Hughes[14], P. Humble[5], E. V. Hungerford[19], Al. Ianni[32,8], An. Ianni[14,8], I. James[15,16], T. N. Johnson[33], C. Jollet[34], K. Keeter[35], C. L. Kendziora[4], G. Koh[14], D. Korablev[28], G. Korga[19,8], A. Kubankin[36], X. Li[14], M. Lissia[9], B. Loer[5], P. Lombardi[13], G. Longo[20,21], Y. Ma[31], I. N. Machulin[18,37], A. Mandarano[10,8], S. M. Mari[15,16], J. Maricic[26], L. Marini[11,12], C. J. Martoff[29], A. Meregaglia[34], P. D. Meyers[14], R. Milincic[26], J. D. Miller[19], D. Montanari[4], A. Monte[3], B. J. Mount[35], V. N. Muratova[24], P. Musico[12], J. Napolitano[29], A. Navrer Agasson[23], S. Odrowski[8], M. Orsini[8], F. Ortica[38,39], L. Pagani[11,12], M. Pallavicini[11,12], E. Pantic[33], S. Parmeggiano[13], K. Pelczar[40], N. Pelliccia[38,39], A. Pocar[3,14], S. Pordes[4], D. A. Pugachev[18,37], H. Qian[14], K. Randle[14], G. Ranucci[13], M. Razeti[9], A. Razeto[8,14], B. Reinhold[26], A. L. Renshaw[19,27], M. Rescigno[7], Q. Riffard[1], A. Romani[38,39], B. Rossi[21,14], N. Rossi[8], D. Rountree[41], D. Sablone[8], P. Saggese[13], R. Saldanha[30], W. Sands[14], C. Savarese[10,8], B. Schlitzer[33], E. Segreto[43], D. A. Semenov[24], E. Shields[14], P. N. Singh[19], M. D. Skorokhvatov[18,37], O. Smirnov[28], A. Sotnikov[28], C. Stanford[14], Y. Suvorov[27,8,18], R. Tartaglia[8], J. Tatarowicz[29], G. Testera[12], A. Tonazzo[1], P. Trinchese[20], E. V. Unzhakov[24], M. Verducci[7,25], A. Vishneva[28], B. Vogelaar[41], M. Wada[14], S. Walker[20,21], H. Wang[27], Y. Wang[31,27], A. W. Watson[29], S. Westerdale[14], J. Wilhelmi[29], M. M. Wojcik[40], Xi. Xiang[14], X. Xiao[27], J. Xu[14], C. Yang[31], A. Zec[3], W. Zhong[31], C. Zhu[14]

E-mail: grzegorz.zuzel@uj.edu.pl (correspopnding author)

[1] APC, Université Paris Diderot, CNRS/IN2P3, CEA/Irfu, Obs. de Paris, Sorbonne Paris Cité, Paris 75205, France
[2] Instituto de Física, Universidade de São Paulo, São Paulo 05508-090, Brazil
[3] Amherst Center for Fundamental Interactions and Dept. of Physics, University of Massachusetts, Amherst, MA 01003, USA
[4] Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
[5] Pacific Northwest National Laboratory, Richland, WA 99354, USA
[6] Department of Physics, Augustana University, Sioux Falls, SD 57197, USA
[7] Istituto Nazionale di Fisica Nucleare Sezione di Roma, Roma 00185, Italy
[8] Laboratori Nazionali del Gran Sasso, Assergi AQ 67010, Italy
[9] Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, Cagliari 09042, Italy
[10] Gran Sasso Science Institute, L'Aquila AQ 67100, Italy
[11] Department of Physics, Università degli Studi, Genova 16146, Italy
[12] Istituto Nazionale di Fisica Nucleare, Sezione di Genova, Genova 16146, Italy
[13] Istituto Nazionale di Fisica Nucleare, Sezione di Milano, Milano 20133, Italy
[14] Department of Physics, Princeton University, Princeton, NJ 08544, USA
[15] Istituto Nazionale di Fisica Nucleare, Sezione di Roma Tre, Roma 00146, Italy
[16] Department of Physics and Mathematics, Università degli Studi Roma Tre, Roma 00146, Italy
[17] Department of Physics, Università degli Studi, Cagliari 09042, Italy
[18] National Research Centre Kurchatov Institute, Moscow 123182, Russia
[19] Department of Physics, University of Houston, Houston, TX 77204, USA
[20] Department of Physics, Università degli Studi Federico II, Napoli 80126, Italy
[21] Istituto Nazionale di Fisica Nucleare, Sezione di Napoli, Napoli 80126, Italy
[22] Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow 119991, Russia
[23] LPNHE Paris, Université Pierre et Marie Curie, Université Paris Diderot, CNRS/IN2P3, Paris 75252, France
[24] St. Petersburg Nuclear Physics Institute NRC Kurchatov Institute, Gatchina 188350, Russia
[25] Physics Department, Sapienza Universita' di Roma, Roma 00185, Italy
[26] Department of Physics and Astronomy, University of Hawai'i, Honolulu, HI 96822, USA
[27] Department of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA
[28] Joint Institute for Nuclear Research, Dubna 141980, Russia
[29] Department of Physics, Temple University, Philadelphia, PA 19122, USA
[30] Kavli Institute, Enrico Fermi Institute, and Dept. of Physics, University of Chicago, Chicago, IL 60637, USA
[31] Institute of High Energy Physics, Beijing 100049, China
[32] Laboratorio Subterráneo de Canfranc, Canfranc Estación 22880, Spain
[33] Department of Physics, University of California, Davis, CA 95616, USA
[34] IPHC, Université de Strasbourg, CNRS/IN2P3, Strasbourg 67037, France
[35] School of Natural Sciences, Black Hills State University, Spearfish, SD 57799, USA
[36] Radiation Physics Laboratory, Belgorod National Research University, Belgorod 308007, Russia
[37] National Research Nuclear University MEPhI, Moscow 115409, Russia
[38] Department of Chemistry, Biology and Biotechnology, Università degli Studi, Perugia 06123, Italy
[39] Istituto Nazionale di Fisica Nucleare, Sezione di Perugia, Perugia 06123, Italy
[40] Smoluchowski Institute of Physics, Jagiellonian University, Krakow 30348, Poland
[41] Department of Physics, Virginia Tech, Blacksburg, VA 24061, USA
[42] Department of Physics, Università degli Studi, Milano 20133, Italy
[43] Institute of Physics Gleb Wataghin, Universidade Estadual de Campinas, São Paulo 13083-859, Brazil

**Abstract.** DarkSide is a multi-stage program devoted to direct searches of Dark Matter particles with detectors based on double phase liquid Argon Time Projection Chamber. The DarkSide-50 setup is running underground at the Laboratori Nazionali del Gran Sasso. First it was operated with Atmospheric Argon and during that run (1422 ± 67) kg×d of truly background-free exposure has been accumulated. Obtained data made it possible to set a 90% C.L. upper limit on the WIMP-nucleon cross section of $6.1 \times 10^{-44}$ cm$^2$ (for a WIMP mass of 100 GeV/c$^2$). Presently the detector is filled with Underground Argon, which is depleted in $^{39}$Ar by a factor of (1.4 ± 0.2)×10$^3$ with respect to Atmospheric Argon. Acquired so far (2616 ± 43) kg×d (71 live days) in combination with the data from the Atmospheric Argon run give us the 90% C.L. upper limit on the WIMP-nucleon spin-independent cross section of $2.0 \times 10^{-44}$ cm$^2$ for a WIMP mass of 100 GeV/c$^2$. Up to date this is the best limit obtained with an argon target.

## 1. Introduction

Our knowledge about the composition of the Universe is derived only by indirect observations. We know that the baryonic matter (luminous matter) accounts only for about 5%, while Dark Energy and Dark Matter (DM) are estimated to provide the larger contributions, which account for 68% and 27%, respectively (according to the recent results of the Planck experiment).

A leading candidate explanation is that DM is composed of Weakly Interacting Massive Particles (WIMPs) formed in the early Universe and gravitationally clustered together with the standard baryonic matter. WIMPs could have been thermally produced in the very early Universe and their expected masses are between ~1 GeV/c$^2$ and ~10 TeV/c$^2$. In order to convincingly detect a WIMP signal, a specific signature from a particle populating our galactic halo is important i.e. the Earth's motion through the galaxy induces a seasonal variation of the total event rate. The observation of a recoil spectrum with at least two different targets should provide complementary information on the WIMP properties, such as the WIMP mass. Once a WIMP signal is detected, isotopic separation in odd and even nuclei can further distinguish between spin-dependent and spin-independent interactions, using the same detector.

Non-accelerator experimental searches for WIMP candidates have been already conducted for many years. These efforts can be divided into two broad classes: direct detection [1], in which the Dark Matter particles are observed in a detector through elastic scattering of the nucleus of ordinary matter, and indirect detection [2], where one looks for the products of Dark Matter annihilations in their high density regions or in space. There are also attempts to combine data from both types of experiments in order to extract the DM parameters [3].

WIMPs appearing in terrestrial detectors would primarily be those gravitationally bound to our galaxy. Since the escape velocity is a few hundred km/s [4] one can easily estimate that the maximum energy transfer from a WIMP to an electron initially at rest is at most in the eV range, while the energy transfer to an atomic nucleus would typically be in the range of some tens of keV$_r$. Therefore direct detection experiments typically search for nuclear recoils. The cross section for WIMP-nucleon interaction calculated using minimal super-symmetric models (popular extensions of the Standard Model) spans many orders of magnitude. Typical values for the spin-independent cross section are between $10^{-44}$ cm$^2$ and $10^{-46}$ cm$^2$ [5, 6]. Such small values imply that large target masses and long measurement times are required. At the lower end of the cross section range typical interaction rates are a few events per ton and per year. These low expected rates pose a major challenge considering that typical background rates from environmental radioactivity and cosmic radiation are much higher.

## 2. The DarkSide program

The ultimate goal of the DarkSide (DS) project is to develop and deploy a background-free multi-ton liquid argon (LAr) detector that has best sensitivity for direct registration of WIMP interactions. LAr is a promising medium for WIMP detection due to its efficient conversion of energy from WIMP-induced nuclear recoils into both scintillation and ionization signals. In a dual-phase Time Projection Chamber (TPC), scintillation (causing the so-called S1 signal) and ionization (S2) can be independently detected and spatially resolved through large volumes of liquid. The relative size and time dependence of these signals permit discrimination of nuclear recoils from background events (mostly gammas and electrons). LAr allows also for very effective pulse shape discrimination between different types of radiation, thus also opens up possibilities for powerful background reduction.

In order to accomplish the ambitious goals, the DarkSide collaboration is proceeding through a staged approach. The first prototype (DarkSide-10), built in Princeton and run in the underground laboratory of the Laboratori Nazionali del Gran Sasso (LNGS Italy, overburden by 3400 m w.e. of rock working as a shield from cosmic rays) until 2013, proved the stability of the detector and showed possibilities to achieve a record light yield of 8.9 p.e./$keV_{ee}$[1] [7].

In the next step the DarkSide-50 detector with the active mass of about 47 kg has been completed (total LAr mass of 153 kg) and operated first with Atmospheric Argon and presently with Underground Argon. Its construction is based on several innovative features that allow for truly background-free operations, which results in a significant science result in spite of relatively small size of the detector. Development of the innovations described below is an important goal in its own right as they are very important part of the background reduction strategy followed by the DarkSide collaboration. DS-50 serves also as a prototype for a future multi-ton detector. The very unique features of DarkSide-50 (to be also implemented in the next stages of the DarkSide program) are:

- Application of Underground Argon (UAr) depleted in radioactive $^{39}$Ar. Atmospheric abundance of $^{39}$Ar in Ar ($\sim$1 Bq/kg) limits the size of a DM TPC detector filled with LAr to some hundreds of kilograms. In order to overcome this problem the DarkSide collaboration is using Ar extracted from an underground source ($^{39}$Ar is produced in the atmosphere by cosmic ray interactions such as $^{40}$Ar(n,2n)$^{39}$Ar) at the Kinder Morgan Doe Canyon $CO_2$ complex located in Cortez, Colorado, USA. A plant for the separation of argon at this site has been deployed. It is fed with $CO_2$ gas coming from underground wells and containing argon at a concentration of $\sim$400 ppm, and produces a crude argon mixture containing argon with a typical concentration of $\sim$3% (with the balance $N_2$ and He). Separation of the argon from the accompanying Nitrogen and Helium is accomplished by cryogenic distillation. A system operated at Fermilab delivered 99.9999%-purity argon. In total 156 kg of UAr have been produced for DS-50 and 153 kg were filled into the detector in 2015.
  Figure 1 shows the normalized spectra obtained for the Atmospheric Argon (AAr) run [14] and the Underground Argon run [15]. A simultaneous Monte Carlo fit to the S1 spectrum is used to determine the $^{39}$Ar and $^{85}$Kr specific activities in UAr to be (0.73 $\pm$ 0.11) mBq/kg and (2.05 $\pm$ 0.13) mBq/kg, respectively. The measured $^{39}$Ar activity is a factor 1400 lower compared to AAr going far beyond the limit measured earlier [8]. The source of $^{85}$Kr in UAr is not yet understood but its presence is not critical since it can be removed during Ar distillation planned to be performed within the Aria project (see later).
- Application of a compact high efficiency Liquid Scintillator Veto (LSV) for neutrons [9]. DarkSide-50 is the first (and to date the only) experiment with the Dark Matter detector operated inside an active neutron veto (see figure 4). It is made by a 4 m diameter sphere, filled with 30 t of organic liquid scintillator and equipped with 110 8" PMTs.

[1] $keV_{ee}$: electron recoil equivalent

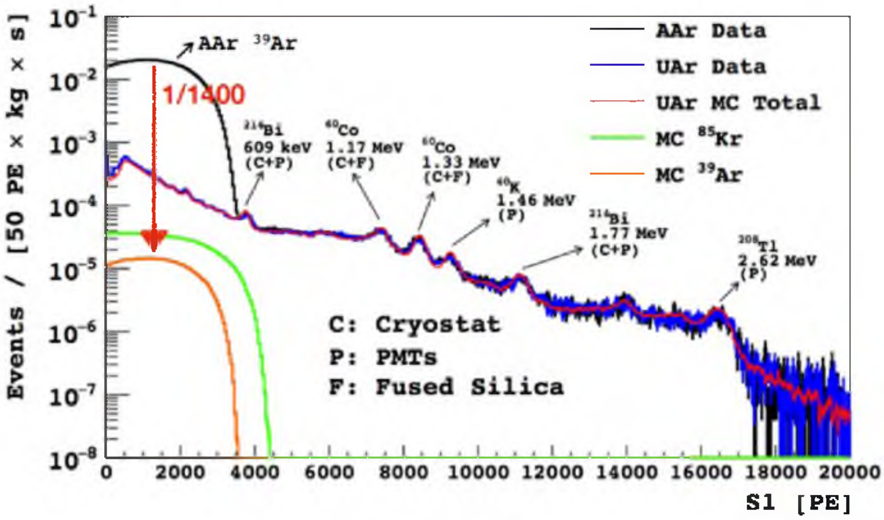


**Figure 1.** Comparison of the measured and normalized to exposure S1 spectra for UAr (blue) and AAr (black). In red the MC fit to the UAr data is shown. Deduced from the fit $^{85}$Kr and $^{39}$Ar contributions are displayed in green and orange, respectively. Indicated are also contributions from other background sources, as well as their origin.

The solution is made by Pseudocumene (PC) and TriMetylButadiene (TMB), the latter being a molecule, loaded with Boron, with a very high neutron capture cross section. With the TMB concentration of 5% the radiogenic neutrons are tagged with $\geq$99.1% efficiency (according to MC simulations and calibrations with AmBe).

- Assembly of the DarkSide detectors in $^{222}$Rn-free clean rooms. The first $^{222}$Rn suppressed clean-room ($C_{Rn}$ ~1 Bq/m$^3$ in the air inside) in the world was built at the Princeton University in 1998 - 1999 for the construction of the Borexino nylon vessels, achieving surface activities of <10 $\alpha$/(m$^2$×d) [10, 11]. The DarkSide collaboration has built two practically radon-free clean rooms in Hall C of LNGS, the so-called Hanoi Cleaning Room (CRH) and Cleaning Room 1 (CR1). These rooms receive all their make-up air from a dedicated radon abatement system and are almost completely lined with stainless steel panels to limit radon emanation from the walls. The clean room CRH is located on top of the water tank and gives direct access into the muon and neutron vetoes through their top flanges. CR1 contains the equipment used for the cleaning and preparation of the DarkSide LAr-TPC parts [12]. Both clean rooms are sized to allow for preparation, assembly, and deployment of a multi-ton TPC detector. A dedicated $^{222}$Rn system has been developed to monitor on-line the $^{222}$Rn content in the air assayed directly from the abatement system and from the clean-rooms. The measured values were at the level of 2 - 20 mBq/m$^3$ [13], what makes the clean rooms the best world-wide. For comparison, measurements of hall C air give about 20 - 50 Bq/m$^3$. Handling of parts and assembly of the DarkSide TPCs (as it happened for the DarkSide-50 TPC) in a $^{222}$Rn-free environment is a part of the DarkSide background reduction strategy (preventing deposition of radioactive $^{222}$Rn-daughters on the detector's surfaces).
  Figure 2 shows results of $^{222}$Rn monitoring (measurements taken every 6 h) in CRH over a weekend. The average $^{222}$Rn concentration was about 4.5 mBq/m$^3$ with two significantly higher values registered when a person entered the clean room.
- Due to the long triplet life time of the excited argon (some $\mu$s) for the LAr-based detectors it is possible to perform Pulse Shape Analysis (PSA). In case of DarkSide we define the

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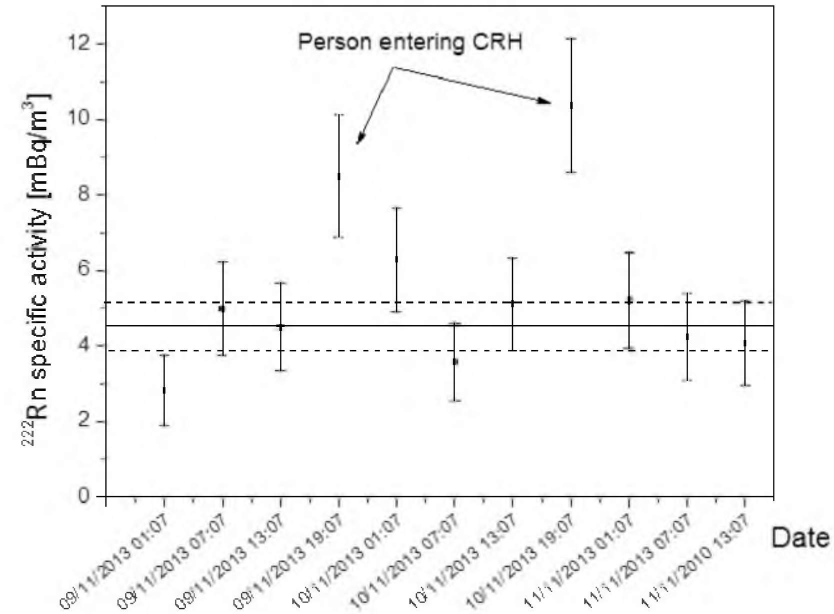


**Figure 2.** $^{222}$Rn concentration in CRH measured over a weekend (no activities inside). The two higher values were registered when a person entered the clean room.

so-called f90 parameter, which is a measure of the S1 signal fraction occurring in the first 90 ns after the trigger. By analyzing the data from the AAr run we have shown [14] that the applied PSA method has very high efficiency ($\geq 10^7$) and allowed for truly background-free operation of the detector.

The core of the DarkSide-50 experiment is the double phase TPC, 36 cm diameter and 36 cm height, and filled with ~46.7 kg of LAr. Two arrays of 19 photo-multipliers view the active volume from the top and from the bottom surfaces. On the top of the liquid volume, a 1 cm height gas region is created by heating the LAr. A uniform electric field (200 V/cm) is maintained along the vertical axis of the cylinder and a stronger electric field is present in the gas region (2800 V/cm) for the extraction of ionization electrons. All the internal surfaces of the TPC are reflective and coated with TPB (ThetraPhenylButadiene), a wavelength-shifter required in order to convert the 128 nm LAr scintillation light in visible one, to match the photocathode sensitivity. Figure 3 shows schematically the DarkSide-50 TPC.

The cryostat (hosting the TPC) is placed inside the neutron detector and the latter one inside a tank containing ~1 kt of high-purity water instrumented with 80 8" PMTs installed on the side and on the bottom. The water tank is acting as a Cherenkov detector (CD) for the surviving cosmic muons at the depth of the Laboratories. A sketch of the three nested detectors is shown in figure 4.

## 3. WIMP searches with AAr and UAr

The DarkSide-50 detector was filled first with Atmospheric Argon and the presented analysis concerns data acquired between November 2013 and May 2014 [14]. The usable live-time, defined as all runs taken in Dark Matter search mode with a drift field of 200 V/cm and with all three detectors (TPC, LSV, CD) included, was (53.8 ± 0.2) d. Taking into account the applied cuts,

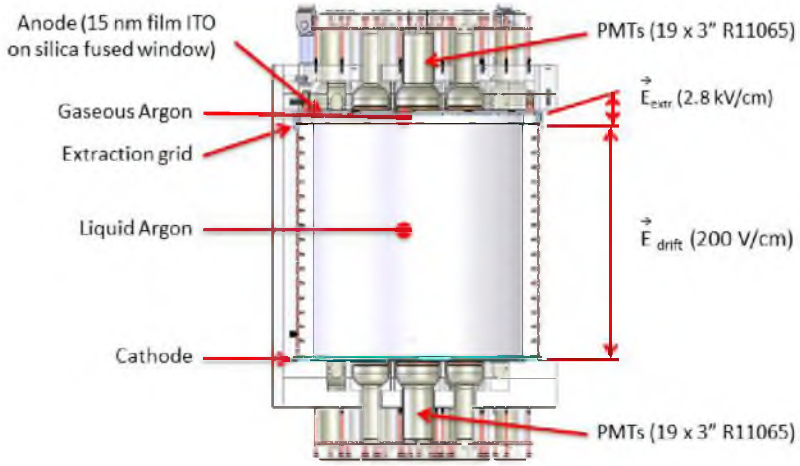


**Figure 3.** Schematic view of the DarkSide-50 Time Projection Chamber.

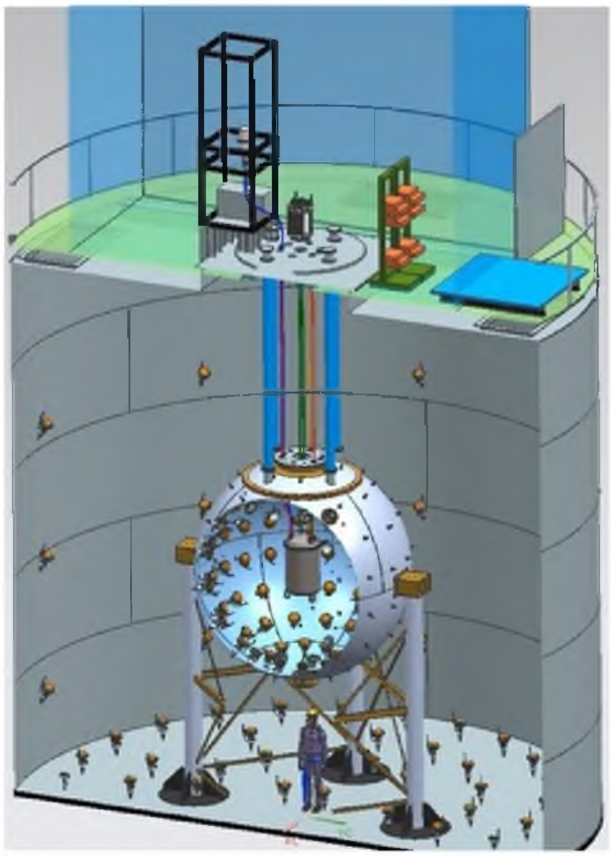

**Figure 4.** The nested detector system of DarkSide-50. The outermost is the water Cherenkov detector, the sphere is the neutron detector and the gray cylinder at the center of the sphere is the LAr TPC cryostat.

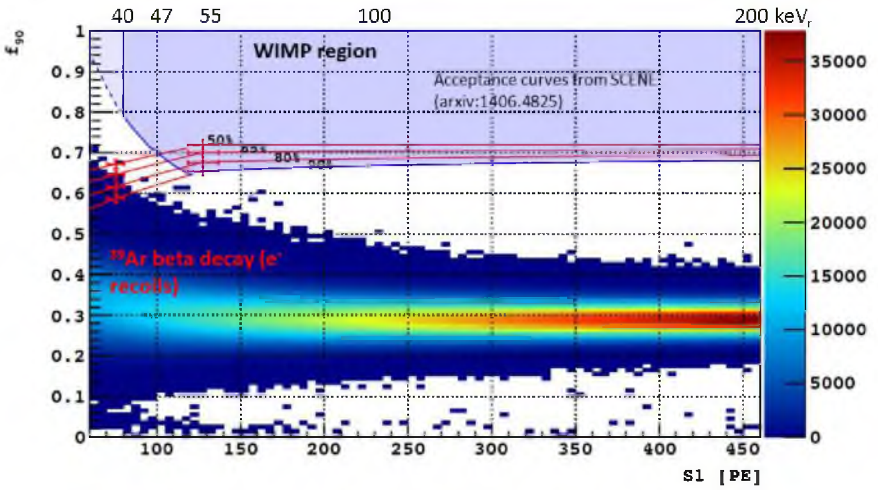


**Figure 5.** Distribution of the events in the scatter plot of f90 vs. S1 for the AAr run. Percentages label the f90 acceptance contours (DM box) for nuclear recoils drawn connecting points was determined from the SCENE measurements.

reducing the live-time to (47.1 ± 0.2) d, the fiducial volume of the detector ((36.9 ± 0.6) kg) and the overall acceptance ($0.82^{+0.01}_{-0.04}$) the total exposure was (1422 ± 67) kg×d.

The main calibration of the detector has been realized by introducing $^{85}$Kr inside the Argon circulation loop. $^{85}$Kr is a source of two low energy gammas (for a total deposit of 41.5 keV) and has a mean life time of 1.8 h. The position of the 41.5 keV peak over the $^{39}$Ar $\beta$-spectrum allowed to measure the light yield of the detector to be (7.9 ± 0.4) p.e./keV$_{ee}$ without the electric field and about 7.0 p.e./keV$_{ee}$ at 200 V/cm. Measurements with neutron (AmBe) and various gamma sources ($^{57}$Co, $^{133}$Ba and $^{137}$Cs) deployed in the neutron detector were also performed.

The WIMP acceptance region on the f90 PSD parameter vs. S1 energy plane was determined by scaling the results from the SCENE experiment [16] and it is shown in figure 5. Is was obtained by intersecting the 90% nuclear recoil acceptance line from SCENE with the curve corresponding to a leakage of $^{39}$Ar events of 0.01 events/(5-p.e. bin).

The background-free operation of the DS-50 detector filled with AA allowed to set a 90% C.L. upper limit on the WIMP-nucleon cross section of $6.1 \times 10^{-44}$ cm$^2$ for a WIMP mass of 100 GeV/c$^2$.

In 2015 in the DarkSide-50 detector AAr was replaced by UAr. For the 70.1 live days (after all cuts) [15] acquired between April 8 and July 31 2015 no background events have been observed in the DM window shown on the scatter plot in figure 6. The WIMP window in the f90 vs. S1 space was defined assuming 90% nuclear recoil acceptance contour derived from SCENE [16], and a leakage curve corresponding to a total predicted leakage of $\leq$0.1 events during the entire exposure of (2616 ± 43) kg×d. The combined analysis with the AAr data gives an upper limit on the WIMP-nucleon cross section of $2.0 \times 10^{-44}$ cm$^2$ for WIMP masses of 100 GeV/c$^2$. The standard 90% C.L. exclusion curves for the AAr and UAr (including also results of other experiments) are shown in figure 7.

## 4. DarkSide Future

The data taking with UAr will continue for another few years. Simultaneously preparation for construction of the next generation detector are already ongoing. DarkSide-20k will be based on 23 t (active mass, 20 t fiducial) of Depleted Ar (DAr) filled into an octagonal TPC. As light

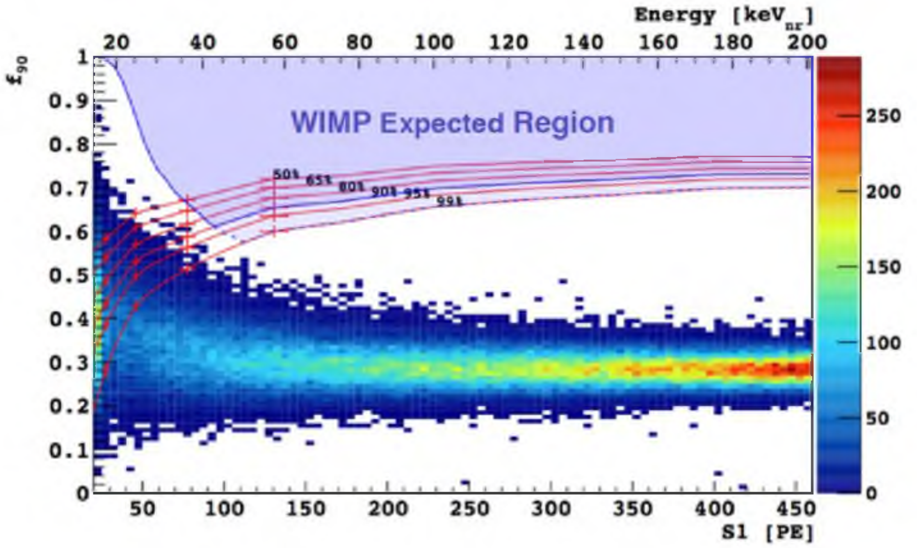


**Figure 6.** Distribution of the events in the scatter plot of f90 vs. S1 for the UAr run.

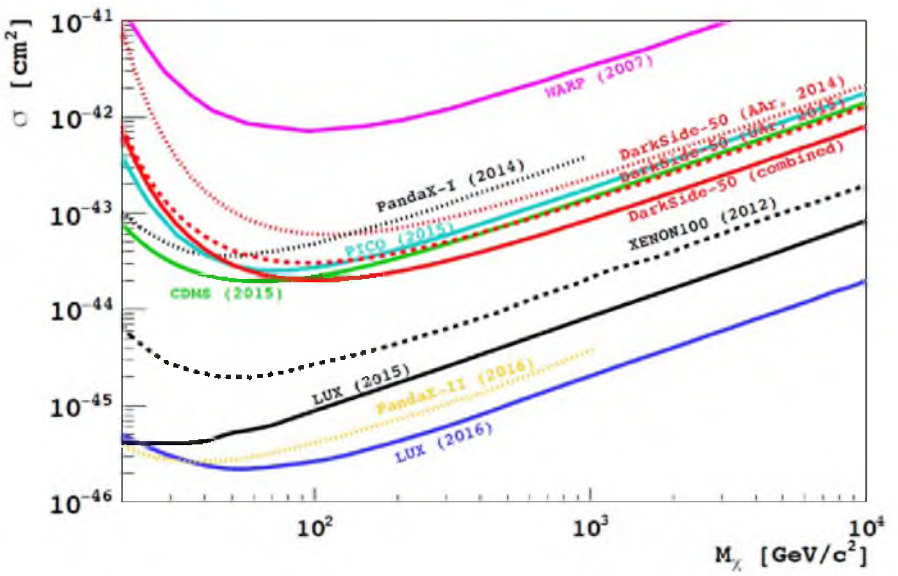


**Figure 7.** Spin-independent WIMP-nucleon cross section as a function of a WIMP mass. Exclusion curves for the DarkSide-50 experiment in comparison with results from other projects are shown.

detectors a large array (~15 m$^2$) of silicon photomultipliers (SiPMs) will be used. Radiopurity is their main advantage with respect to classical PMTs. To get the required amount of DAr the argon extraction plant at Cortez, Colorado will be enlarged (project Urania) to achieve production rate of about 100 kg/d of UAr. UAr will be next further depleted in $^{39}$Ar by another factor 10 in a dedicated 350-m tall distillation column (project Aria, 150 kg/d throughput). The column will be installed in a deep shaft of a mine located in Sardinia, Italy. The Urania and Aria project received funding and are being realized.

DarkSide-20k aims for a 100 t×y background-free exposure (starting operation in 2020) to give a projected sensitivity of $9\times10^{-48}$ cm$^2$ for a WIMP mass of 1 TeV/c$^2$. Ultimately, a detector with 200 t of active DAr mass (Argo) could be built. After collecting 1000 t×y of data it expected that the projected sensitivity for WIMP-nucleon cross section will reach the so-called neutrino floor (cross section for coherent neutrino-nucleus scattering) for WIMP masses above 1 TeV/$c^2$.

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