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Sensitivity to low-mass WIMPs with an improved liquid argon ionization response model within the DarkSide program / Acerbi, F., Adhikari, P., Agnes, P., Ahmad, I., Albergo, S., Albuquerque, I.f., Alexander, T., Alton, A.k., Amaudruz, P., Angiolilli, M., Aprile, E., Atzori Corona, M., Auty, D.j., Ave, M., Avetisov, I.c., Azzolini, O., Back, H.o., Balmforth, Z., Barrado Olmedo, A.i., Barrillon, P., et al.. - In: PHYSICAL REVIEW D. - ISSN 2470-0010. - ELETTRONICO. - 113:12(2026), pp. 1-10. [10.1103/x3vt-q676]

Availability:

This version is available at: 11583/3015020 since: 2026-08-31T13:32:49Z

Publisher:

American Physical Society

Published

DOI:10.1103/x3vt-q676

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Sensitivity to low-mass WIMPs with an improved liquid argon ionization response model within the DarkSide program

F. Acerbi,¹ P. Adhikari,² P. Agnes,^{3,4} I. Ahmad,⁵ S. Albergo,^{6,7} I. F. Albuquerque,⁸ T. Alexander,⁹ A. K. Alton,¹⁰ P. Amaudruz,¹¹ M. Angiolilli,^{3,4} E. Aprile,¹² M. Atzori Corona,^{13,14} D. J. Auty,¹⁵ M. Ave,³ I. C. Avetisov,¹⁶ O. Azzolini,¹⁷ H. O. Back,⁹ Z. Balmforth,¹⁸ A. I. Barrado Olmedo,¹⁹ P. Barrillon,²⁰ G. Batignani,^{21,22} S. Bharat,²³ P. Bhowmick,²⁴ S. Blua,^{25,26} V. Bocci,²⁷ W. Bonivento,¹³ B. Bottino,^{28,29} M. G. Boulay,² T. Braun,²⁴ A. Buchowicz,³⁰ S. Bussino,^{31,32} J. Busto,²⁰ M. Cadeddu,¹³ R. Calabrese,^{33,34} V. Camillo,³⁵ A. Caminata,²⁹ N. Canci,³⁴ M. Caravati,^{3,4,13} M. Cárdenas-Montes,¹⁹ N. Cargioli,^{13,14} M. Carlini,⁴ P. Cavalcante,⁴ S. Cebrian,²³ S. Chashin,³⁶ A. Chepurnov,³⁶ S. Choudhary,⁵ L. Cifarelli,^{37,38} B. Cleveland,^{39,40} Y. Coadou,²⁰ I. Coarasa,²³ V. Cocco,¹³ E. Conde Vilda,¹⁹ L. Consiglio,⁴ A. F. V. Cortez,⁵ B. S. Costa,⁸ M. Czubak,⁴¹ S. D'Auria,^{42,43} M. D. Da Rocha Rolo,²⁵ A. Dainty,⁴⁴ G. Darbo,²⁹ S. Davini,²⁹ R. de Asmundis,³⁴ S. De Cecco,^{45,27} M. De Napoli,⁶ G. Dellacasa,²⁵ A. V. Derbin,⁴⁶ L. Di Noto,^{28,29} P. Di Stefano,⁴⁷ L. K. Dias,⁸ D. Díaz Mairena,¹⁹ C. Dionisi,^{45,27} G. Dolganov,^{48,49} F. Dordei,¹³ V. Dronik,⁵⁰ A. Elersich,⁵¹ T. Erjavec,⁵¹ N. Fearon,²⁴ M. Fernández Díaz,¹⁹ L. Ferro,^{14,13} A. Ficorella,¹ G. Fiorillo,^{33,34} D. Fleming,⁵¹ P. Franchini,²⁴ D. Franco,⁵² H. Frandini Gatti,⁵³ E. Frolov,⁵⁴ F. Gabriele,¹³ D. Gahan,^{13,14} C. Galbiati,⁵⁵ G. Galiński,³⁰ G. Gallina,⁵⁵ M. Garbini,^{56,38} P. Garcia Abia,¹⁹ A. Gawdzik,⁵⁷ G. K. Giovanetti,⁵⁸ V. Goicoechea Casanueva,⁵⁹ A. Gola,¹ L. Grandi,⁶⁰ G. Grauso,³⁴ G. Grilli di Cortona,⁴ A. Grobov,⁴⁸ M. Gromov,³⁶ J. Guerrero Cánovas,¹⁹ M. Gulino,^{61,62} B. R. Hackett,⁹ A. L. Hallin,¹⁵ M. Haranczyk,⁴¹ B. Harrop,⁵⁵ T. Hessel,⁵² C. Hidalgo,³ J. Hollingham,⁴⁴ S. Horikawa,⁵⁹ J. Hu,¹⁵ F. Hubaut,²⁰ D. Huff,⁶³ T. Hugues,⁴⁷ E. V. Hungerford,⁶³ An. Ianni,⁵⁵ V. Ippolito,²⁷ A. Jamil,⁵⁵ C. Jillings,^{39,40} R. Keloth,³⁵ N. Kemmerich,⁸ A. Kemp,⁶⁴ M. Kimura,⁵ A. Klenin,⁵⁰ K. Kondo,^{4,65} G. Korga,⁶⁶ L. Kotsiopolou,⁶⁷ S. Koulosousas,⁶⁶ A. Kubankin,⁵⁰ P. Kunzé,^{3,4} M. Kuss,²² M. Kuźniak,⁵ M. Kuzwa,⁵ M. La Commara,^{68,34} M. Lai,⁶⁹ E. Le Guirriec,²⁰ E. Leason,²⁴ A. Leoni,^{4,65} L. Lidey,⁹ J. Lipp,⁴⁴ M. Lissia,¹³ L. Luzzi,⁵¹ O. Lychagina,⁷⁰ O. Macfadyen,⁶⁶ I. Machts,⁵² I. N. Machulin,^{48,49} S. Manecki,^{39,40} I. Manthos,¹⁸ L. Mapelli,⁵⁵ A. Marasciulli,⁴ S. M. Mari,^{31,32} C. Mariani,³⁵ J. Maricic,⁵⁹ M. Martinez,²³ C. J. Martoff,^{71,9} G. Matteucci,^{33,34} K. Mavrokoridis,⁵³ A. B. McDonald,⁴⁷ S. Merzi,¹ A. Messina,^{45,27} R. Milincic,⁵⁹ S. Minutoli,²⁹ A. Mitra,⁷² J. Monroe,²⁴ M. Morrocchi,^{21,22} A. Morsy,⁷³ V. N. Muratova,⁴⁶ M. Murra,¹² P. Musico,²⁹ R. Nania,³⁸ M. Nessi,⁷⁴ G. Nieradka,⁵ K. Nikolopoulos,¹⁸ E. Nikoloudaki,⁵² I. Nikulin,⁵⁰ J. Nowak,⁷⁵ K. Olchanski,¹¹ A. Oleinik,⁵⁰ V. Oleynikov,⁵⁴ P. Organtini,^{4,55} A. Ortiz de Solórzano,²³ A. Padmanabhan,⁴⁷ M. Pallavicini,^{28,29} L. Pandola,⁶¹ E. Pantic,⁵¹ E. Paoloni,^{21,22} D. Papi,¹⁵ B. Park,¹⁵ G. Pastuszek,³⁰ G. Paternoster,¹ R. Pavarani,^{14,13} A. Peck,⁶⁹ K. Pelczar,⁴¹ R. Perez,⁸ V. Pesudo,¹⁹ S. Piacentini,^{3,4} N. Pino,⁶¹ G. Plante,¹² A. Pocar,⁷³ S. Pordes,³⁵ P. Pralavorio,²⁰ E. Preosti,⁵⁵ D. Price,⁵⁷ M. Pronesti,²⁰ S. Puglia,^{6,7} M. Queiroga Bazetto,⁵³ F. Raffaelli,²² F. Ragusa,^{42,43} Y. Ramachers,⁷² A. Ramirez,⁶³ S. Ravinthiran,⁵³ M. Razeti,¹³ A. L. Renshaw,⁶³ A. Repond,⁶⁹ M. Rescigno,²⁷ S. Resconi,⁴³ F. Retiere,¹¹ L. P. Rignanese,³⁸ A. Ritchie-Yates,⁵⁷ A. Rivetti,²⁵ A. Roberts,⁵³ C. Roberts,⁵⁷ G. Rogers,⁷⁶ L. Romero,¹⁹ M. Rossi,²⁹ D. Rudik,^{33,34,49} J. Runge,⁷³ M. A. Sabia,^{45,27,5} D. Sablone,⁷¹ P. Salomone,^{4,5} O. Samoylov,⁷⁰ S. Sanfilippo,⁶¹ D. Santone,²⁴ R. Santorelli,¹⁹ E. M. Santos,⁸ I. Sargeant,⁶⁴ M. L. Sarsa,²³ C. Savarese,⁷⁷ E. Scapparone,³⁸ F. G. Schuckman,⁴⁷ D. A. Semenov,⁴⁶ C. Seoane,²³ M. Sestu,^{14,13} V. Shalamova,⁶⁹ S. Sharma Poudel,⁶³ A. Sheshukov,⁷⁰ M. Simeone,^{78,34} P. Skensved,⁴⁷ M. D. Skorokhvatov,^{48,49} O. Smirnov,⁷⁰ T. Smirnova,⁶⁹ B. Smith,¹¹ F. Spadoni,⁹ M. Spangenberg,⁷² A. Steri,^{13,79} V. Stornelli,^{4,65} S. Stracka,²² A. Sung,⁵⁵ C. Sunny,⁵ Y. Suvorov,^{33,34,48} A. M. Szelc,⁶⁷ O. Taborda,^{3,4} R. Tartaglia,⁴ A. Taylor,⁵³ J. Taylor,⁵³ G. Testera,²⁹ K. Thiemé,⁵⁹ A. Thompson,⁶⁶ S. Torres-Lara,⁶³ A. Tricomi,^{6,7} S. Tullio,^{14,13} E. V. Unzhakov,⁴⁶ M. Van Uffelen,²⁴ P. Ventura,⁸ G. Vera Díaz,¹⁹ S. Viel,² A. Vishneva,⁷⁰ R. B. Vogelaar,³⁵ J. Vossebeld,⁵³ B. Vyas,² M. Wada,⁵ M. Walczak,^{3,4} Y. Wang,^{80,81} S. Westerdale,⁶⁹ L. Williams,⁸² M. M. Wojcik,⁴¹ M. Wojcik,⁸³ C. Yang,^{80,81} J. Yin,^{80,81} A. Zabihi,⁵ P. Zakhary,^{6,7} A. Zani,⁴³ Y. Zhang,⁸⁰ T. Zhu,⁵¹ A. Zichichi,^{37,38} G. Zuzel,⁴¹ and M. P. Zykova¹⁶

(DarkSide-50 and DarkSide-20k Collaboration)

¹Fondazione Bruno Kessler, Povo 38123, Italy

²Department of Physics, Carleton University, Ottawa, ON K1S 5B6, Canada

³Gran Sasso Science Institute, L'Aquila 67100, Italy

⁴INFN Laboratori Nazionali del Gran Sasso, Assergi (AQ) 67100, Italy

⁵AstroCeNT, Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences, 00-614 Warsaw, Poland

⁶Università di Catania, Catania 95124, Italy

⁷INFN Catania, Catania 95121, Italy

⁸Instituto de Física, Universidade de São Paulo, São Paulo 05508-090, Brazil

- ⁹Pacific Northwest National Laboratory, Richland, Washington 99352, USA
- ¹⁰Physics Department, Augustana University, Sioux Falls, South Dakota 57197, USA
- ¹¹TRIUMF, 4004 Wesbrook Mall, Vancouver, BC V6T2A3, Canada
- ¹²Physics Department, Columbia University, New York, New York 10027, USA
- ¹³INFN Cagliari, Cagliari 09042, Italy
- ¹⁴Physics Department, Università degli Studi di Cagliari, Cagliari 09042, Italy
- ¹⁵Department of Physics, University of Alberta, Edmonton, AB T6G 2R3, Canada
- ¹⁶Mendelev University of Chemical Technology, Moscow 125047, Russia
- ¹⁷INFN Laboratori Nazionali di Legnaro, Legnaro (Padova) 35020, Italy
- ¹⁸Institute of Experimental Physics, University of Hamburg, Luruper Chaussee 149, 22761, Hamburg, Germany
- ¹⁹CIEMAT, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Madrid 28040, Spain
- ²⁰Centre de Physique des Particules de Marseille, Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France
- ²¹Physics Department, Università degli Studi di Pisa, Pisa 56127, Italy
- ²²INFN Pisa, Pisa 56127, Italy
- ²³Centro de Astropartículas y Física de Altas Energías, Universidad de Zaragoza, Zaragoza 50009, Spain
- ²⁴University of Oxford, Oxford OX1 2JD, United Kingdom
- ²⁵INFN Torino, Torino 10125, Italy
- ²⁶Department of Electronics and Communications, Politecnico di Torino, Torino 10129, Italy
- ²⁷INFN Sezione di Roma, Roma 00185, Italy
- ²⁸Physics Department, Università degli Studi di Genova, Genova 16146, Italy
- ²⁹INFN Genova, Genova 16146, Italy
- ³⁰Institute of Radioelectronics and Multimedia Technology, Faculty of Electronics and Information Technology, Warsaw University of Technology, 00-661 Warsaw, Poland
- ³¹INFN Roma Tre, Roma 00146, Italy
- ³²Mathematics and Physics Department, Università degli Studi Roma Tre, Roma 00146, Italy
- ³³Physics Department, Università degli Studi “Federico II” di Napoli, Napoli 80126, Italy
- ³⁴INFN Napoli, Napoli 80126, Italy
- ³⁵Virginia Tech, Blacksburg, Virginia 24061, USA
- ³⁶Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow 119234, Russia
- ³⁷Physics Department, Università degli Studi di Bologna, Bologna 40126, Italy
- ³⁸INFN Bologna, Bologna 40126, Italy
- ³⁹Department of Physics and Astronomy, Laurentian University, Sudbury, ON P3E 2C6, Canada
- ⁴⁰SNOLAB, Lively, ON P3Y 1N2, Canada
- ⁴¹M. Smoluchowski Institute of Physics, Jagiellonian University, 30-348 Krakow, Poland
- ⁴²Physics Department, Università degli Studi di Milano, Milano 20133, Italy
- ⁴³INFN Milano, Milano 20133, Italy
- ⁴⁴Science and Technology Facilities Council (STFC), Rutherford Appleton Laboratory, Technology, Harwell Oxford, Didcot OX11 0QX, United Kingdom
- ⁴⁵Physics Department, Sapienza Università di Roma, Roma 00185, Italy
- ⁴⁶Saint Petersburg Nuclear Physics Institute, Gatchina 188350, Russia
- ⁴⁷Department of Physics, Engineering Physics and Astronomy, Queen’s University, Kingston, ON K7L 3N6, Canada
- ⁴⁸National Research Centre Kurchatov Institute, Moscow 123182, Russia
- ⁴⁹National Research Nuclear University MEPhI, Moscow 115409, Russia
- ⁵⁰Radiation Physics Laboratory, Belgorod National Research University, Belgorod 308007, Russia
- ⁵¹Department of Physics, University of California, Davis, California 95616, USA
- ⁵²APC, Université de Paris Cité, CNRS, Astroparticule et Cosmologie, Paris F-75013, France
- ⁵³Department of Physics, University of Liverpool, The Oliver Lodge Laboratory, Liverpool L69 7ZE, United Kingdom
- ⁵⁴Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia
- ⁵⁵Physics Department, Princeton University, Princeton, New Jersey 08544, USA
- ⁵⁶Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi, Roma 00184, Italy
- ⁵⁷The University of Manchester, Manchester M13 9PL, United Kingdom
- ⁵⁸Williams College, Department of Physics and Astronomy, Williamstown, Massachusetts 01267, USA
- ⁵⁹Department of Physics and Astronomy, University of Hawai’i, Honolulu, Hawai’i 96822, USA
- ⁶⁰Department of Physics and Kavli Institute for Cosmological Physics, University of Chicago, Chicago, Illinois 60637, USA

- ⁶¹*INFN Laboratori Nazionali del Sud, Catania 95123, Italy*
⁶²*Engineering and Architecture Faculty, Università di Enna Kore, Enna 94100, Italy*
⁶³*Department of Physics, University of Houston, Houston, Texas 77204, USA*
⁶⁴*Science and Technology Facilities Council (STFC), Rutherford Appleton Laboratory, Particle Physics Department, Harwell Oxford, Didcot OX11 0QX, United Kingdom*
⁶⁵*Università degli Studi dell'Aquila, L'Aquila 67100, Italy*
⁶⁶*Department of Physics, Royal Holloway University of London, Egham TW20 0EX, United Kingdom*
⁶⁷*School of Physics and Astronomy, University of Edinburgh, Edinburgh EH9 3FD, United Kingdom*
⁶⁸*Pharmacy Department, Università degli Studi "Federico II" di Napoli, Napoli 80131, Italy*
⁶⁹*Department of Physics and Astronomy, University of California, Riverside, California 92507, USA*
⁷⁰*Joint Institute for Nuclear Research, Dubna 141980, Russia*
⁷¹*Physics Department, Temple University, Philadelphia, Pennsylvania 19122, USA*
⁷²*University of Warwick, Department of Physics, Coventry CV47AL, United Kingdom*
⁷³*Amherst Center for Fundamental Interactions and Physics Department, University of Massachusetts, Amherst, Massachusetts 01003, USA*
⁷⁴*Istituto Nazionale di Fisica Nucleare, Roma 00186, Italia*
⁷⁵*Physics Department, Lancaster University, Lancaster LA1 4YB, United Kingdom*
⁷⁶*School of Physics and Astronomy, University of Birmingham, Edgbaston, B15 2TT, Birmingham, United Kingdom*
⁷⁷*Center for Experimental Nuclear Physics and Astrophysics, and Department of Physics, University of Washington, Seattle, Washington 98195, USA*
⁷⁸*Chemical, Materials, and Industrial Production Engineering Department, Università degli Studi "Federico II" di Napoli, Napoli 80126, Italy*
⁷⁹*Department of Mechanical, Chemical, and Materials Engineering, Università degli Studi, Cagliari 09042, Italy*
⁸⁰*Institute of High Energy Physics, Beijing 100049, China*
⁸¹*University of Chinese Academy of Sciences, Beijing 100049, China*
⁸²*Department of Physics and Engineering, Fort Lewis College, Durango, Colorado 81301, USA*
⁸³*Institute of Applied Radiation Chemistry, Lodz University of Technology, 93-590 Lodz, Poland*



(Received 18 November 2025; revised 27 January 2026; accepted 13 May 2026; published 17 June 2026)

Dark matter detection experiments using liquid argon rely on a precise characterization of the ionization response to nuclear recoils, especially in the keV energy range relevant for light dark matter interactions. In this work, we present a comprehensive analysis that combines new measurements from the ReD setup, part of the DarkSide experimental program, with calibration data from DarkSide-50, as well as results from the ARIS and SCENE experiments. These combined datasets enable improved constraints on atomic screening effects in the modeling of the ionization response of liquid argon to nuclear recoils. The analysis is performed within the Thomas-Imel recombination framework adopted in previous DarkSide studies, and is here further constrained by the inclusion of ReD data, which allow the screening function to be determined from calibration measurements. By including the updated ionization model into the DarkSide-50 analysis framework, we obtain stronger exclusion limits on low-mass weakly interacting massive particle (WIMP) interactions, setting new world-leading constraints in the 1–3 GeV/c² WIMP mass range. Finally, we recast the sensitivity projections for the upcoming DarkSide-20k detector, demonstrating a significantly enhanced discovery potential for low-mass dark matter candidates.

DOI: [10.1103/x3vt-q676](https://doi.org/10.1103/x3vt-q676)

I. INTRODUCTION

The search for dark matter remains one of the most pressing challenges in astroparticle physics and cosmology.

Among the various experimental strategies, liquid argon dual-phase time projection chambers (LAr TPCs) have proven to be highly effective detectors for weakly interacting massive particles (WIMPs) scattering off nuclei. In dual-phase TPCs, particle interactions in the liquid argon produce both scintillation light and ionization electrons. The electrons are drifted upward by a uniform electric field and extracted into the gas phase, where they generate a secondary scintillation signal via electroluminescence. Both light signals are detected by photosensors located

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at the top and bottom of the TPC, allowing for precise vertex reconstruction and effective particle identification.

In recent years, the potential of this detection technique has been extended to the low-mass regime (in the GeV/c^2 scale) by exploiting the ionization channel alone, as the ability to detect single-electron signals enables sensitivity to keV-scale nuclear recoils. A key ingredient for achieving this sensitivity is the accurate modeling of the ionization yield (Q_y) from nuclear recoils, which hinges on a detailed description of the atomic collision processes between the recoiling nucleus and the surrounding argon atoms. As a nucleus propagates through liquid argon, its interactions with neighboring atoms are not governed by bare Coulomb forces but are instead modified by electron screening. The electron clouds surrounding each nucleus alter the effective interaction potential, which is described by screening functions (SFs). These functions determine the energy transferred during atomic collisions and, in turn, directly affect the Q_y observed in the detector.

The present work builds upon this framework, modeling the ion-electron recombination probability with the Thomas-Imel box model [1]. We provide a unified treatment of all available low-energy LAr Q_y measurements, enabling a meaningful discrimination among screening models and a direct impact on the resulting experimental limits and projections.

II. THE IONIZATION YIELD MODEL

In a previous study [2], we attempted to constrain these screening models by combining nuclear recoil data from DarkSide-50, starting at energies of about 0.4 keV, with measurements from ARIS [3] and SCENE [4], two small-scale liquid argon setups that provided monoenergetic nuclear recoils down to 7 keV. While further dedicated sub-keV nuclear recoil calibrations would be valuable, the existing *in situ* AmC data already provide direct constraints on the ionization response in the low-energy region relevant for this analysis. However, the experimental sensitivity was insufficient to discriminate between alternative theoretical descriptions, namely the SFs proposed by Ziegler *et al.* [5] (hereafter ZBL), Molière [6], and Lenz-Jensen [7,8].

These functions, while similar in their general approach to modeling electron cloud effects, differ in their mathematical formulation and underlying assumptions. The ZBL screening function is largely empirical and is widely used in ion implantation simulations. Both the Molière and Lenz-Jensen screening functions are based on the statistical Thomas-Fermi model. The Molière function provides a three-term exponential approximation to the Thomas-Fermi potential, while the Lenz-Jensen function offers a simpler, single-term analytic form derived from the same theoretical framework. However, it is important to note that in our previous DarkSide-50 analysis [2], as well as in Bezrukov *et al.* [9], the Molière potential was implemented using the

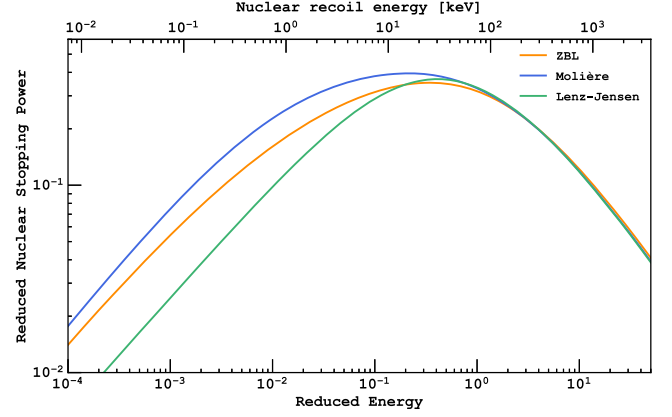


FIG. 1. Reduced nuclear stopping power $s_n(\epsilon)$ as a function of the reduced energy ϵ for the three screening models considered in this work: ZBL, Molière, and Lenz-Jensen [13]. The corresponding nuclear recoil energy scale, shown on the top axis, is computed for liquid argon.

approximate form compiled by Winterbon [10], with numerical coefficients incorrectly transcribed in the widely used tabulation by Sigmund [11]. We also note that, unlike the case of the Lenz-Jensen potential, the Winterbon approximation deviates significantly from the true Molière stopping power [10], even when the correct coefficients are used. To address this, we adopt an improved parametrization by Wilson *et al.* [12], providing a percent-level agreement with the original Molière screening function. The three screening models, illustrated in Fig. 1, show noticeable differences at low reduced energies, corresponding to nuclear recoil energies in liquid argon below ~ 50 keV.

The limited ability to discriminate between screening models has led to sizeable differences in predictions for Q_y from nuclear recoils, particularly below 5 keV, the energies most relevant for light WIMP detection. This, in turn, has impacted the interpretation of experimental data and constrained the sensitivity of dark matter searches using liquid argon detectors. In our previous studies, we therefore adopted the ZBL SF, which yields the lowest ionization response among the models considered, namely Lenz-Jensen and Molière, as defined in Ref. [9], resulting in the most conservative sensitivity to WIMP interactions for both DarkSide-50 [14] and DarkSide-20k [15] in the GeV/c^2 mass range.

The ionization yield model, $Q_y^{\text{TI}}(E_{nr})$, describes the number of electrons escaping recombination with ions per unit of recoil energy (E_{nr}) as [2]

$$Q_y^{\text{TI}}(E_{nr}) = \frac{(1-r)N_i}{E_{nr}}, \quad (1)$$

where N_i is the number of initially produced electron-ion pairs and r is the recombination probability. In the

low-energy regime (few keV) we model r with the Thomas-Imel box formalism [1], which describes geminate recombination of electrons and ions initially distributed within a small volume (“box”) and accounts for the competition between Coulomb attraction, diffusion, and electron escape under the applied drift field. In this limit

$$r = 1 - \frac{1}{\gamma N_i} \ln(1 + \gamma N_i), \quad (2)$$

where $\gamma = C_{\text{box}}/F$ is the recombination parameter, with F the drift field and C_{box} a phenomenological parameter that effectively sets the “box” scale.

The initial number of ionization pairs, N_i , is estimated assuming a constant excitation-to-ionization ratio, and is modeled as

$$N_i = \beta \kappa(\epsilon) = \beta \frac{\epsilon s_e(\epsilon)}{s_n(\epsilon) + s_e(\epsilon)}, \quad (3)$$

where β is a normalization constant. The function κ quantifies the energy fraction going into electronic excitations, while s_e and s_n are the electronic and nuclear stopping powers, respectively. Both s_e and s_n depend on the dimensionless variable ϵ ($\sim 0.0135 E_{nr}/\text{keV}$ in LAr), which in turn depends on the recoil energy E_{nr} , the atomic number, and the Thomas-Fermi screening length, as discussed in [9].

It is worth noting that the ionization response model of Eq. (1) depends on the nuclear stopping power through $s_n(\epsilon)$, which in turn depends on the choice of atomic screening potential, as well as on two free parameters: the recombination constant C_{box} and the normalization constant β .

The model $Q_y^{\text{II}}(E_{nr})$ from Eq. (1) was previously constrained by a simultaneous fit to ARIS, SCENE, and DarkSide-50 (Ref. [2]). Here we repeat that fit including the new ReD measurement, which provides direct sensitivity in the few-keV region and tightens constraints on the atomic screening models.

III. THE RED EXPERIMENTAL SETUP

In the recent campaign of the ReD experiment [16], the setup was exposed to neutrons from a ^{252}Cf fission source. ReD is a small-scale dual-phase LAr TPC specifically designed to study the ionization response to nuclear recoils. The chamber has an active volume of $5 \times 5 \times 6 \text{ cm}^3$, with a 7 mm-thick gas pocket above the liquid. An electric field of 200 V/cm, established between two Indium Tin Oxide-coated acrylic windows acting as an anode and a cathode, allows a maximum electron drift time of 54 μs . Light signals from both scintillation (S1) in the liquid and electroluminescence (S2) in the gas pocket, induced by drifted ionization electrons, are collected by cryogenic silicon photomultipliers arranged in two $5 \times 5 \text{ cm}^2$ tiles

placed above and below the active volume. The nuclear recoil energy estimator S2 is converted into the number of ionization electrons by normalizing it to $g_2 = 18.6 \pm 0.7 \text{ pe/e}^-$ [17]. Here g_2 is defined as the average number of photoelectrons detected per free electron extracted into the gas phase. Effects that reduce the number of electrons surviving drift and extraction in the gas phase are included in the detector response implemented in Monte Carlo. A more detailed description of the ReD detector is provided in [18].

To perform the neutron time-of-flight (ToF) measurements, the setup includes two fast BaF_2 scintillators coupled to photomultiplier tubes, which were placed symmetrically around the ^{252}Cf source to detect prompt fission radiation and define the start time. The stop signal is provided by a neutron spectrometer located approximately 1 m from the TPC and 2 m from the source. It consists of two 3×3 arrays of 1-inch EJ-276 plastic scintillators, allowing for position reconstruction and neutron/ γ discrimination via pulse shape analysis. The arrays are placed symmetrically above and below the beam axis, covering a range of scattering angles of 12° to 17° , which enables exploration of the LAr response to nuclear recoil energies in the [2, 8] keV range. This is made possible by the broad energy spectrum of neutrons from ^{252}Cf , which extends to over 10 MeV, with an average energy of approximately 2 MeV.

The overall ToF resolution, measured using prompt γ s from ^{252}Cf , is 0.7 ns, allowing the neutron energy to be reconstructed with an uncertainty of 1–2%. The resulting Q_y is in excellent agreement with that measured by the ARIS experiment [3] at 7.1 keV, as reported in [17], which also provides details of the ReD measurement.

The Q_y measured by ReD, and shown in Fig. 2 (gray points), exhibits an overall uncertainty of 5.7% at 2.4 keV, decreasing to 4.3% at 7.5 keV. The dominant sources of systematic uncertainty stem from the calibration of g_2 and from a potential vertical shift (Δz) of the TPC. The latter refers to an offset between the TPC and the center of the cryostat, which is aligned using a laser with the axis defined by the ^{252}Cf source and the center of the neutron spectrometer. The presence of nonzero Δz was investigated using calibration data from a ^{241}Am source placed at the vertical center of the cryostat surface. The distribution along the z -axis of 59.5 keV γ -rays from ^{241}Am , reconstructed in the TPC via the electron drift time, was compared to Monte Carlo simulations. This study yielded an estimated offset of $0.23 \pm 0.96 \text{ cm}$.

The systematic uncertainty on g_2 impacts Q_y uniformly across the energy range, introducing a 3.8% scaling uncertainty in a consistent direction. In contrast, nonzero Δz affects the reconstructed scattering angle and, consequently, the inferred recoil energy of each event, leading to an uncertainty on the mean energy that varies between 0.7% and 2.4%. Although this uncertainty is small, a nonzero offset introduces a visible bias in Q_y , with opposite

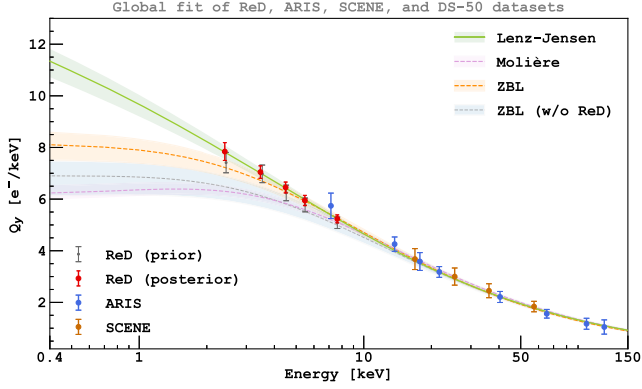


FIG. 2. Simultaneous fit to the ReD, ARIS, SCENE, and DarkSide-50 datasets assuming the Lenz-Jensen screening function (green solid line). ReD data points are shown with both prior (gray) and posterior (red) uncertainties. The gray line and its corresponding uncertainty band represent the previous ionization model, based on the ZBL screening function and fitted without ReD data [2]. For comparison, the global fit including the ReD dataset was also performed using the screening functions of ZBL (orange dashed line) and Molière (purple dashed line).

trends for nuclear recoils detected by the top and bottom plastic scintillator arrays.

IV. THE GLOBAL FIT

The fit of $Q_y^{\text{TI}}(E_{\text{nr}})$ follows the approach developed in Ref. [2], where a simultaneous fit to data from the ARIS, SCENE, and DarkSide-50 calibrations was performed, providing coverage over the full range from about three to more than 200 extracted electrons. The fit minimizes a global χ^2 , obtained by summing the χ^2 contributions from each dataset after marginalizing over the corresponding g_2 values.

The DarkSide-50 dataset consists of a continuous nuclear recoil spectrum from 0.4 to 200 keV, produced using a neutron source based on the $^{12}\text{C}(\alpha, n)^{15}\text{O}$ reaction, initiated by alpha particles emitted in the decay of ^{241}Am (AmC source). The SCENE and ARIS datasets provide monoenergetic nuclear recoil lines in the ranges 17–60 keV and 7–120 keV, respectively. In the ARIS detector, which did not include a gas pocket, only the prompt scintillation light (S1) was observed. ARIS data, acquired at 200 V/cm, are rescaled to the DarkSide-50 response by comparing the field-off S1 light yields of the two detectors. This mapping allows each ARIS recoil energy to be associated with the corresponding S1 value at 200 V/cm in DarkSide-50. Further details can be found in Ref. [2].

In this framework, the low-energy ionization response down to sub-keV nuclear recoils is constrained by *in situ* DarkSide-50 calibration data, as demonstrated in previous analyses [2,14]. In this work, we extend this approach by including the ReD Q_y measurements, which provide direct

constraints in the 2–10 keV range, an energy region highly sensitive to the choice of screening potential.

The fit is performed by minimizing a global χ^2 map, numerically constructed as the sum of the individual χ^2 contributions from each dataset. The free parameters C_{box} and β are varied, while the drift field is fixed at 200 V/cm, common to all datasets. The ReD nuisance parameters, g_2 and the TPC vertical offset, are included in the fit with Gaussian penalty terms based on their respective uncertainties. To account for the systematic uncertainty on Δz , the ReD data are split into two subsamples corresponding to events tagged by the top and bottom scintillator arrays, which are required to yield consistent Q_y values. Each subsample is independently divided into five energy intervals, and in each interval an unbinned likelihood fit is performed using a Gaussian signal over a constant background. The stability of the extracted Q_y values was verified by varying the energy intervals.

The resulting 2×5 Q_y points are fitted with the $Q_y^{\text{TI}}(E_{\text{nr}})$ model. For a given screening function model, the fit is performed by scanning the (C_{box}, β) parameter space. At each point, the nuisance parameters g_2 and Δz are marginalized to compute the corresponding χ^2 , which contributes to the global χ^2 map.

The posterior distributions are derived from a Bayesian analysis based on the χ^2 maps obtained in the global fit. The likelihood function is constructed as $\mathcal{L} \propto \exp(-\chi^2/2)$ over a uniform prior in the (C_{box}, β) parameter space. Posterior means and confidence regions are estimated via numerical marginalization.

To quantify the preference among the three screening models, we compute the Bayes factor (BF), which compares the marginal likelihoods (or evidences) integrated over the parameter space. This approach is well suited for non-nested models, where standard $\Delta\chi^2$ tests do not apply. Assuming equal prior belief in two models, a $\log_{10}\text{BF} > 2$ implies that the data make one model at least 100 times more likely than the other, a level considered decisive [19,20]. The results indicate a decisive preference for Lenz-Jensen over ZBL, with $\log_{10}\text{BF} = 3.8$, and an even stronger preference over Molière, with $\log_{10}\text{BF} = 7.2$.

We verify that the posterior mean values are in excellent agreement with the best-fit points (Table I) obtained from the χ^2 minimization, indicating that the likelihood surfaces are well behaved and that the fit is not biased by asymmetric parameter degeneracies. This consistency check provides additional confidence in the robustness of the model selection.

A simultaneous fit of all datasets was performed separately for each of the three screening functions. The results are shown in Fig. 2, where the ReD Q_y measurements are displayed assuming both the prior and the posterior nuisance parameters, the latter obtained from the fit using the Lenz-Jensen SF. For visualization purposes, the ReD

TABLE I. Best-fit values of the free parameters C_{box} and β from the global fit to all datasets, for each of the tested screening functions.

Parameter	ZBL	Lenz-Jensen	Molière
C_{box} [V/cm]	$8.1^{+0.1}_{-0.2}$	$7.9^{+0.2}_{-0.2}$	$8.6^{+0.3}_{-0.2}$
β [$\times 10^3$]	$7.0^{+0.3}_{-0.2}$	$6.5^{+0.1}_{-0.3}$	$8.8^{+0.4}_{-0.5}$
Δz [cm]	$-0.53^{+0.19}_{-0.10}$	$-0.58^{+0.05}_{-0.14}$	$-0.39^{+0.05}_{-0.24}$
g_2 [pe/ e^-]	$18.2^{+0.4}_{-0.4}$	18.8 ± 0.4	$17.6^{+0.4}_{-0.4}$

Q_y points shown in the figures correspond to the combined top and bottom array subsamples.

This fit yields nuisance parameters $g_2 = 18.8 \pm 0.4$ pe/ e^- and $\Delta z = -0.58^{+0.05}_{-0.14}$ cm, which are consistent within 1σ with the priors and with the posteriors obtained using the other two SFs. This demonstrates that the nuisance parameters are stable and largely independent of the specific choice of SF.

With the posterior nuisance parameters, the uncertainty on the ReD Q_y measurement is reduced to 4.5% at 2.4 keV and 3.0% at 7.6 keV. This behavior reflects the fact that variations of the nuisance parameters Δz and g_2 affect the reconstructed recoil energy and electron yield, respectively, and therefore propagate to both the mean value and the uncertainty of the extracted Q_y points.

The global fit using the Lenz-Jensen SF shows excellent agreement with the data. In contrast, both the ZBL-based model [2] and the Molière one underestimate Q_y with respect to ReD data below 5 keV.

For the Lenz-Jensen model, the posterior mean and standard deviation are $C_{\text{box}} = 7.9$ V/cm with $\sigma_{C_{\text{box}}} = 0.3$ V/cm and $\beta = 6.6 \times 10^3$ with $\sigma_{\beta} = 0.3 \times 10^3$, with a correlation coefficient of 0.24. These values characterize the Q_y model favored by the global fit.

The contours representing the 1σ , 2σ , and 3σ confidence levels in the (C_{box}, β) plane are shown in Figs. 3–5 for the

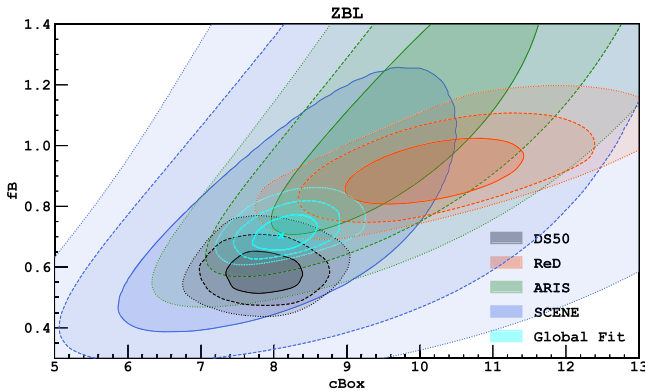


FIG. 3. Global fit under the ZBL screening model. The 1σ (solid line), 2σ (dashed), and 3σ (dotted) confidence contours are shown for each dataset, along with the global fit result (cyan).

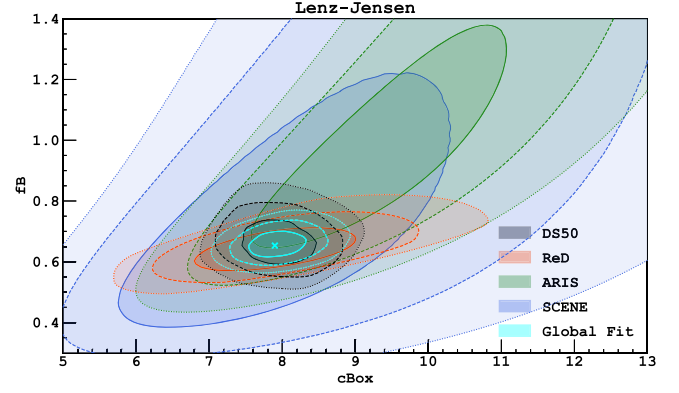


FIG. 4. Same as above, for the Lenz-Jensen model. The confidence contours exhibit excellent agreement among all datasets in the (C_{box}, β) plane.

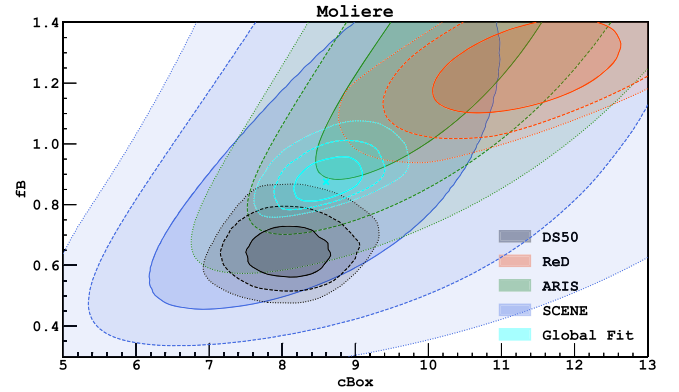


FIG. 5. Same as above, for the Molière screening model. Note the strong tension between ReD and DarkSide-50 datasets.

ZBL, Lenz-Jensen, and Molière screening functions, respectively. Each dataset is shown separately, together with the global fit result. The Lenz-Jensen model yields a remarkable agreement across all datasets, with overlapping confidence regions and a significantly higher marginal likelihood compared to the other screening models. In contrast, the ZBL potential exhibits clear tension, while the Molière potential shows even more pronounced inconsistencies, in particular between the DarkSide-50 and ReD datasets.

V. IMPACT ON THE WIMP SENSITIVITY

The impact of the fitted Lenz-Jensen SF-based response $Q_y^{\text{TI}}(E_{nr})$, compared to the previous model based on the ZBL SF, on the resulting WIMP spectra is illustrated in Fig. 6, for various WIMP masses and assuming the DarkSide-50 detector resolution [14]. Due to the absence of a stochastic model for the energy quenching process in nuclear recoils, two scenarios are considered: one assuming no fluctuations (NQ), and one incorporating

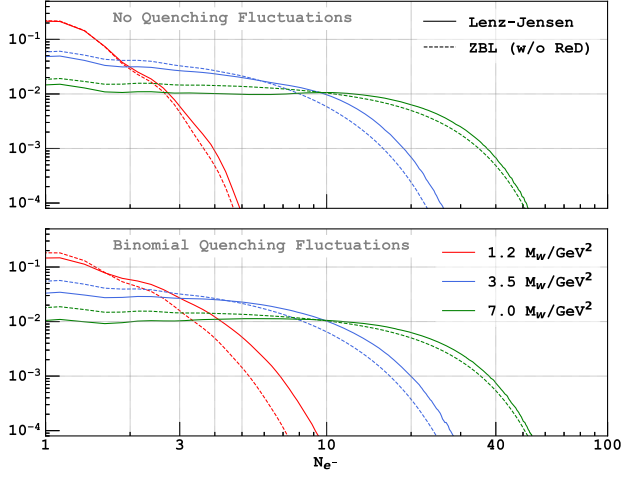


FIG. 6. Probability density functions of the expected WIMP-induced ionization spectra in DarkSide-50 for WIMP masses of 1.2, 3.5, and 7.0 GeV/c^2 , shown for three different SF models. The $Q_y^\pi(E_{nr})$ response based on the ZBL SF corresponds to the previous fit without ReD data [2], while the Molière SF-based $Q_y^\pi(E_{nr})$ curve is from this work. In the top panel, no fluctuations are assumed in the nuclear recoil quenching process (NQ), whereas in the bottom panel, quenching fluctuations are modeled with a binomial distribution (QF).

binomial fluctuations between detectable and undetectable quanta (QF).

The Lenz-Jensen SF predicts a higher ionization yield at low energies compared to the ZBL SF, thereby increasing the probability of detecting signals above analysis thresholds. This results in improved predicted sensitivity, especially for WIMPs with masses in the order of $\mathcal{O}(1 \text{ GeV}/c^2)$, which produce nuclear recoils close to the DarkSide experiment thresholds. We then recalculate both the DarkSide-50 observed and the DarkSide-20k expected exclusion limits, adopting the Lenz-Jensen screening function in place of the ZBL one, given its improved agreement with the overall calibration data.

The 90% C.L. exclusion limits are derived from a binned profile likelihood fit, following the same procedure and inputs (namely, statistical and systematic uncertainties, background models, and detector resolutions), as in the previous limit calculations for DarkSide-50 [14] and DarkSide-20k [15]. For DarkSide-50, the analysis threshold is set at $4 e^-$, with a dataset corresponding to an effective exposure of approximately 12 ton/day after selection cuts. For DarkSide-20k, the simulated dataset assumes 10 years of data taking, yielding an effective exposure of 342 ton/year and a $2 e^-$ analysis threshold. The DarkSide-20k background model includes spurious electrons, which dominate the event rate in the few e^- range. Although their origin is not yet fully understood, they are observed to correlate with impurity concentrations in LAr. See Refs. [14,15,21] for additional details.

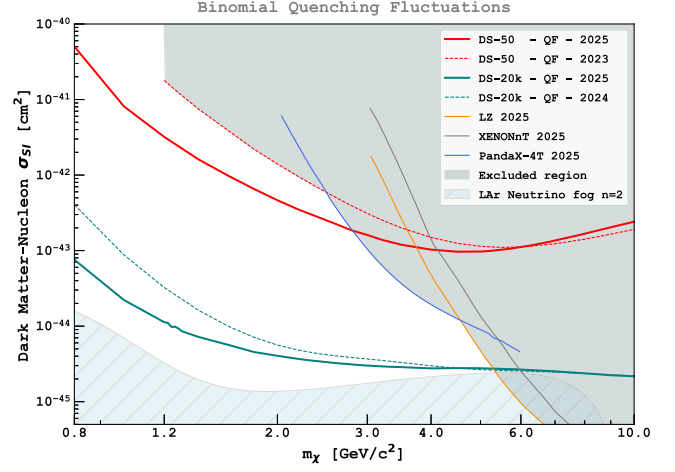


FIG. 7. DarkSide-50 (red) exclusion limits with a $4 e^-$ analysis threshold and DarkSide-20k (teal) expected sensitivity assuming the binomial quenching fluctuation model (QF), 10 years of exposure, and $2 e^-$ threshold. The updated limits are derived using the Lenz-Jensen screening function in the LAr ionization response model and are compared to previous results obtained with the ZBL screening function. Most recent limits from XENONnT [22], LZ [23], and PandaX-4T [24] are also presented. The neutrino fog in LAr with index $n = 2$ [25] is also shown.

The DarkSide-50 and DarkSide-20k limits are shown in Figs. 7 and 8 for the QF and NQ scenarios, respectively. Owing to the improved ionization response model in LAr, the DarkSide-50 limit improves by a factor of 5 (2.5) at $1.2 \text{ GeV}/c^2$ assuming QF (NQ) fluctuations, setting the world's most stringent limits in the $[0.8, 3.5] \text{ GeV}/c^2$ ($[1.0, 3.3] \text{ GeV}/c^2$) mass range. Similarly, for DarkSide-20k, the 90% C.L. exclusion sensitivity improves by a factor of 3 (10) at $1.2 \text{ GeV}/c^2$ for the QF (NQ) model.

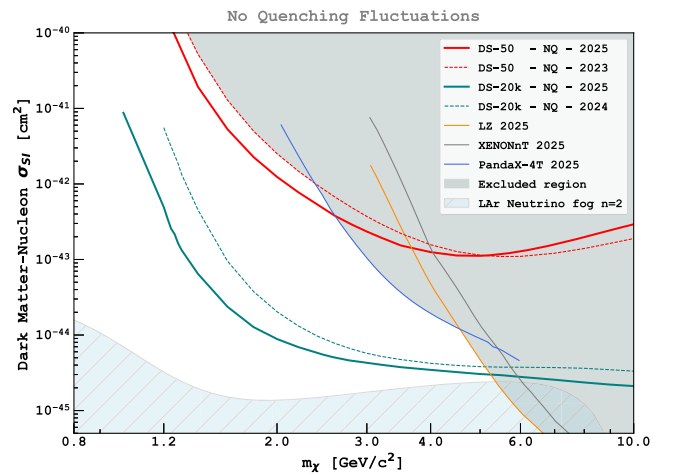


FIG. 8. DarkSide-50 exclusion limits (red) and DarkSide-20k projected sensitivity (teal) under the NQ assumption. For color scheme and references, see the caption of Fig. 8.

VI. CONCLUSIONS

The combined ReD, ARIS, SCENE, and DarkSide-50 datasets yield a significantly improved description of the LAr ionization response at low energies, which translates into stronger WIMP exclusion limits and enhanced projected sensitivity for DarkSide-20k. The analysis is performed within the Thomas-Imel recombination framework previously adopted in DarkSide studies. The addition of ReD measurements tightens the constraints on the model parameters and enables a data-driven selection of the preferred atomic screening function. Thanks to its high-accuracy event-by-event energy reconstruction, ReD also has the potential to resolve the ambiguity between the two quenching-fluctuation scenarios. A dedicated campaign within the new ReD+ project, employing a ^{252}Cf source and a deuterium-deuterium neutron generator, is planned to further pursue this investigation.

ACKNOWLEDGMENTS

This work was supported by the U.S. National Science Foundation (NSF) under Grants No. PHY-0919363, No. PHY-1004072, No. PHY-1004054, No. PHY-1242585, No. PHY-1314483, No. PHY-1314507, No. PHY-1352795, No. PHY-1455351, No. PHY-1606912, No. PHY-1622337, No. PHY-1622415, No. PHY-1812482, No. PHY-1812547, No. PHY-2310091, and No. PHY-2310046, as well as the Major Research Instrumentation Grant No. MRI-1429544 and collaborative NSF grants No. PHY-1211308, No. PHY-1314501, and No. PHY-1455351. Additional support was provided by the U.S. Department of Energy (DOE), Office of Science, under Contracts No. DE-FG02-91ER40671, No. DE-AC02-07CH11359, and No. DE-AC05-76RL01830. We acknowledge the Pacific Northwest National Laboratory (PNNL), operated by Battelle for the DOE under Contract No. DE-AC05-76RL01830, and the Fermi National Accelerator Laboratory (Fermilab), a DOE Office of Science HEP User Facility managed by Fermi Research Alliance, LLC, under Contract No. DE-AC02-07CH11359. Support in Italy was provided by the Istituto Nazionale di Fisica Nucleare (INFN) through grants from the Ministero dell'Istruzione, dell'Università e della Ricerca (MIUR)—Progetto Premiale 2013 and Commissione Scientifica Nazionale II. This work also received funding from the Ministero dell'Università e della Ricerca (MUR) through the PRIN2020 project (Grant No. PRIN 20208XN9TZ) and the PRIN2022 project (Grant No. 2022JCYC9E, CUP I53D23000690006), issued under the National Recovery and Resilience Plan (NRRP), Mission 4, Component 2, Investment 1.1, funded by the European Union—NextGenerationEU. This work received support from the French Institut National de Physique Nucléaire et de Physique des Particules (IN2P3) and from

IN2P3—COPIN (Grant No. 20-152). Funding was also provided by the Agence Nationale de la Recherche (ANR) under Grants ANR-22-CE31-0021 (X-ArT) and ANR-23-CE31-0015 (FIDAR). Support was provided by the Natural Sciences and Engineering Research Council of Canada (NSERC), SNOLAB, and the Arthur B. McDonald Canadian Astroparticle Physics Research Institute. The work was also supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy—EXC 2121: Quantum Universe (Grant No. 390833306). We acknowledge support from the Spanish Ministry of Science and Innovation (MICINN) through Grants No. PID2022-138357NB-C22 and No. PID2022-138357NB-C21, and the Atracción de Talento Grant No. 2018-T2/TIC-10494; from the Polish National Science Centre (NCN) under Grants No. UMO-2022/47/B/ST2/02015, No. UMO-2023/51/B/ST2/02099, and No. 2021/42/E/ST2/00331; from the Polish Ministry of Science and Higher Education (MNiSW) under Grant No. 6811/IA/SP/2018, and from the Foundation for Polish Science (FNP) through the International Research Agenda Programme AstroCeNT (MAB/2018/7) funded by the European Regional Development Fund. Additional support was provided by the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 952480 (DarkWave). This work was supported by the São Paulo Research Foundation (FAPESP) under Grants No. 2017/26238-4 and No. 2021/11489-7, and by the National Council for Scientific and Technological Development (CNPq). We also acknowledge support from the Chinese Academy of Sciences (Grant No. 113111KYSB20210030) and the National Natural Science Foundation of China (Grant No. 12020101004), from the Interdisciplinary Scientific and Educational School of Moscow University "Fundamental and Applied Space Research," and from the Ministry of Education and Science of the Russian Federation under Project No. FZWG-2020-0032 (2019-1569). Support from the Science and Technology Facilities Council (STFC), part of UK Research and Innovation, and from The Royal Society (United Kingdom) is also acknowledged. Finally, we gratefully acknowledge the invaluable technical and logistical support of the staff at the Laboratori Nazionali del Gran Sasso (LNGS), and the assistance of the Fermilab Particle Physics, Scientific, and Core Computing Divisions during the construction and operation of the DarkSide-50 detector.

DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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