

Search for New Physics via Low-Energy Electron Recoils with a 4.2 Tonne-Year Exposure from the LZ Experiment

D. S. Akerib,^{1,2} A. K. Al Musalhi,³ F. Alder,³ J. Almquist,⁴ C. S. Amarasinghe,⁵ A. Ames,^{1,2} T. J. Anderson,^{1,2} N. Angelides,⁶ H. M. Araújo,⁶ J. E. Armstrong,⁷ M. Arthurs,^{1,2} A. Baker,^{6,8} S. Balashov,⁹ J. Bang,⁴ J. W. Bargemann,⁵ E. E. Barillier,^{10,11} K. Beattie,¹² T. Benson,¹³ A. Bhatti,⁷ T. P. Biesiadzinski,^{1,2} H. J. Birch,^{10,11} E. Bishop,¹⁴ G. M. Blockinger,¹⁵ B. Boxer,¹⁶ C. A. J. Brew,⁹ P. Brás,¹⁷ S. Burdin,¹⁸ M. C. Carmona-Benitez,¹⁹ M. Carter,¹⁸ A. Chawla,²⁰ H. Chen,¹² Y. T. Chin,¹⁹ N. I. Chott,²¹ S. Contreras,²² M. V. Converse,²³ R. Coronel,^{1,2} A. Cottle,³ G. Cox,²⁴ D. Curran,²⁴ C. E. Dahl,^{25,26} I. Darlington,³ S. Dave,³ A. David,³ J. Delgaudio,²⁴ S. Dey,²⁷ L. de Viveiros,¹⁹ L. Di Felice,⁶ C. Ding,⁴ J. E. Y. Dobson,⁸ E. Druszkiewicz,²³ S. Dubey,⁴ C. L. Dunbar,²⁴ S. R. Eriksen,²⁸ A. Fan,^{1,2} N. M. Fearon,²⁷ N. Fieldhouse,²⁷ S. Fiorucci,¹² H. Flaecher,²⁸ E. D. Fraser,¹⁸ T. M. A. Fruth,²⁹ R. J. Gaitskell,⁴ A. Geffre,²⁴ J. Genovesi,^{19,21} C. Ghag,³ A. Ghosh,¹⁵ R. Gibbons,^{12,30} S. Gokhale,³¹ J. Green,²⁷ M. G. D. van der Grinten,⁹ J. J. Haistson,²¹ C. R. Hall,⁷ T. Hall,¹⁸ E. Hartigan-O'Connor,⁴ S. J. Haselschwardt,¹⁰ M. A. Hernandez,^{10,11} S. A. Hertel,³² G. J. Homenides,³³ M. Horn,²⁴ D. Q. Huang,²² D. Hunt,^{27,34} E. Jacquet,⁶ R. S. James,³ K. Jenkins,¹⁷ A. C. Kaboth,²⁰ A. C. Kamaha,²² M. K. Kannichankandy,¹⁵ D. Khaitan,²³ A. Khazov,⁹ J. Kim,⁵ Y. D. Kim,³⁵ J. Kingston,¹⁶ D. Kodroff,¹² E. V. Korolkova,³⁶ H. Kraus,²⁷ S. Kravitz,³⁴ L. Kreczko,²⁸ V. A. Kudryavtsev,³⁶ C. Lawes,⁸ D. S. Leonard,³⁵ K. T. Lesko,¹² C. Levy,¹⁵ J. Lin,^{12,30} A. Lindote,¹⁷ W. H. Lippincott,⁵ J. Long,²⁵ M. I. Lopes,¹⁷ W. Lorenzon,¹⁰ C. Lu,⁴ S. Luitz,^{1,2} P. A. Majewski,⁹ A. Manalaysay,¹² R. L. Mannino,³⁷ C. Maupin,²⁴ M. E. McCarthy,²³ G. McDowell,¹⁰ D. N. McKinsey,^{12,30} J. McLaughlin,²⁵ J. B. McLaughlin,³ R. McMonigle,¹⁵ B. Mitra,²⁵ E. Mizrachi,^{7,37} M. E. Monzani,^{1,2,38} E. Morrison,²¹ B. J. Mount,³⁹ M. Murdy,³² A. St. J. Murphy,¹⁴ H. N. Nelson,⁵ F. Neves,¹⁷ A. Nguyen,¹⁴ C. L. O'Brien,³⁴ I. Olcina,^{12,30} K. C. Oliver-Mallory,⁶ J. Orpwood,³⁶ K. Y. Oyulmaz,^{14,*} K. J. Palladino,²⁷ N. J. Pannifer,²⁸ N. Parveen,¹⁵ S. J. Patton,¹² B. Penning,^{10,11} G. Pereira,¹⁷ E. Perry,¹² T. Pershing,³⁷ A. Piepke,³³ S. S. Poudel,²¹ Y. Qie,²³ J. Reichenbacher,²¹ C. A. Rhyne,⁴ G. R. C. Rischbieter,^{10,11} E. Ritchey,⁷ H. S. Riyat,^{12,†} R. Rosero,³¹ T. Rushton,³⁶ D. Rynders,²⁴ S. Saltão,¹⁷ D. Santone,^{20,27} A. B. M. R. Sazzad,^{33,37} R. W. Schnee,²¹ G. Sehr,³⁴ B. Shafer,⁷ S. Shaw,¹⁴ K. Shi,¹⁰ T. Shutt,^{1,2} C. Silva,¹⁷ G. Sinev,²¹ J. Siniscalco,³ A. M. Slivar,³³ R. Smith,^{12,30} V. N. Solovov,¹⁷ P. Sorensen,¹² J. Soria,^{12,30} A. Stevens,^{3,6} T. J. Sumner,⁶ A. Swain,²⁷ M. Szydagis,¹⁵ D. R. Tiedt,²⁴ M. Timalisina,¹² Z. Tong,⁶ D. R. Tovey,³⁶ J. Tranter,³⁶ M. Trask,⁵ K. Trengove,¹⁵ M. Tripathi,¹⁶ A. Usón,¹⁴ A. C. Vaitkus,⁴ O. Valentino,⁶ V. Velan,¹² A. Wang,^{1,2} J. J. Wang,³³ Y. Wang,^{12,30} L. Weeldreyer,⁵ T. J. Whitis,⁵ M. Williams,¹² K. Wild,¹⁹ L. Wolf,²⁰ F. L. H. Wolfs,²³ S. Woodford,¹⁸ D. Woodward,¹² C. J. Wright,²⁸ Q. Xia,¹² J. Xu,³⁷ Y. Xu,^{22,‡,§} M. Yeh,³¹ D. Yeum,⁷ W. Zha,¹⁹ H. Zhang,¹⁴ and T. Zhang¹²

(The LZ Collaboration)

¹SLAC National Accelerator Laboratory, Menlo Park, California 94025-7015, USA

²Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, California 94305-4085, USA

³University College London (UCL), Department of Physics and Astronomy, London WC1E 6BT, United Kingdom

⁴Brown University, Department of Physics, Providence, Rhode Island 02912-9037, USA

⁵University of California, Santa Barbara, Department of Physics, Santa Barbara, California 93106-9530, USA

⁶Imperial College London, Physics Department, Blackett Laboratory, London SW7 2AZ, United Kingdom

⁷University of Maryland, Department of Physics, College Park, Maryland 20742-4111, USA

⁸King's College London, Department of Physics, London WC2R 2LS, United Kingdom

⁹STFC Rutherford Appleton Laboratory (RAL), Didcot, OX11 0QX, United Kingdom

¹⁰University of Michigan, Randall Laboratory of Physics, Ann Arbor, Michigan 48109-1040, USA

¹¹University of Zurich, Department of Physics, 8057 Zurich, Switzerland

¹²Lawrence Berkeley National Laboratory (LBNL), Berkeley, California 94720-8099, USA

¹³University of Wisconsin-Madison, Department of Physics, Madison, Wisconsin 53706-1390, USA

¹⁴University of Edinburgh, SUPA, School of Physics and Astronomy, Edinburgh EH9 3FD, United Kingdom

¹⁵University at Albany (SUNY), Department of Physics, Albany, New York 12222-0100, USA

¹⁶University of California, Davis, Department of Physics, Davis, California 95616-5270, USA

¹⁷Laboratório de Instrumentação e Física Experimental de Partículas (LIP), University of Coimbra, P-3004 516 Coimbra, Portugal

¹⁸University of Liverpool, Department of Physics, Liverpool L69 7ZE, United Kingdom

¹⁹Pennsylvania State University, Department of Physics, University Park, Pennsylvania 16802-6300, USA

²⁰Royal Holloway, University of London, Department of Physics, Egham, TW20 0EX, United Kingdom

²¹South Dakota School of Mines and Technology, Rapid City, South Dakota 57701-3901, USA

²²*University of California, Los Angeles, Department of Physics and Astronomy, Los Angeles, California 90095-1547, USA*

²³*University of Rochester, Department of Physics and Astronomy, Rochester, New York 14627-0171, USA*

²⁴*South Dakota Science and Technology Authority (SDSTA), Sanford Underground Research Facility, Lead, South Dakota 57754-1700, USA*

²⁵*Northwestern University, Department of Physics & Astronomy, Evanston, Illinois 60208-3112, USA*

²⁶*Fermi National Accelerator Laboratory (FNAL), Batavia, Illinois 60510-5011, USA*

²⁷*University of Oxford, Department of Physics, Oxford OX1 3RH, United Kingdom*

²⁸*University of Bristol, H.H. Wills Physics Laboratory, Bristol, BS8 1TL, United Kingdom*

²⁹*The University of Sydney, School of Physics, Physics Road, Camperdown, Sydney, NSW 2006, Australia*

³⁰*University of California, Berkeley, Department of Physics, Berkeley, California 94720-7300, USA*

³¹*Brookhaven National Laboratory (BNL), Upton, New York 11973-5000, USA*

³²*University of Massachusetts, Department of Physics, Amherst, Massachusetts 01003-9337, USA*

³³*University of Alabama, Department of Physics and Astronomy, Tuscaloosa, Alabama 35487-0324, USA*

³⁴*University of Texas at Austin, Department of Physics, Austin, Texas 78712-1192, USA*

³⁵*IBS Center for Underground Physics (CUP), Yuseong-gu, Daejeon, Korea*

³⁶*University of Sheffield, Department of Physics and Astronomy, Sheffield S3 7RH, United Kingdom*

³⁷*Lawrence Livermore National Laboratory (LLNL), Livermore, California 94550-9698, USA*

³⁸*Vatican Observatory, Castel Gandolfo, V-00120, Vatican City State*

³⁹*Black Hills State University, School of Natural Sciences, Spearfish, South Dakota 57799-0002, USA*



(Received 21 November 2025; revised 28 May 2026; accepted 5 August 2026; published 2 September 2026)

We report results from searches for new physics models through electron recoils using data collected by the LUX-ZEPLIN experiment during its first two science runs, with a total exposure of 4.2 tonne-years. The observed data are consistent with a background-only hypothesis. Constraints are derived for electromagnetic interactions of solar neutrinos, solar axionlike particles (ALPs), mirror dark matter, and the absorption of bosonic dark matter candidates. The inverse Primakoff process for ^{57}Fe deexcitation solar ALPs is considered for the first time. These results represent the most stringent constraints to date on keV-scale Primakoff and ^{57}Fe solar ALPs, bosonic dark matter, mirror dark matter, and neutrino millicharge, while remaining competitive for the other signal models investigated.

DOI: [10.1103/wnxl-yf95](https://doi.org/10.1103/wnxl-yf95)

Dual-phase xenon time projection chambers (TPCs), combining a low energy threshold, scalability to large volumes, and ultralow background rates [1], have become a cornerstone technology for experimental searches for rare processes, particularly for the detection of weakly interacting massive particles (WIMPs) [2–4], a well-motivated dark matter (DM) candidate. While these detectors have traditionally focused on nuclear recoil (NR) signals expected from dark matter interactions [2–11], they also provide excellent sensitivity to electronic recoil (ER) signals [12–15]. This opens avenues to a broad spectrum of new physics searches other than conventional WIMPs. In this Letter, we report on searches for new physics scenarios

that produce ER signals, using data collected by the LUX-ZEPLIN (LZ) experiment. This analysis probes additional new physics models compared with previous LZ ER studies [12] and is the first to apply the radon tagging technique and to adopt a signal-dependent analysis and statistical treatment for low-energy electron-recoil searches.

Axions are pseudoscalar Nambu-Goldstone bosons arising from the Peccei-Quinn mechanism introduced to solve the strong charge-parity (CP) problem [16]. Axionlike particles (ALPs) share similar couplings to standard model (SM) particles but do not in general satisfy the mass-coupling relation characteristic of QCD axions [17,18]. With effective tree-level couplings to photons, electrons, or nucleons, ALPs can be produced in the hot solar-core plasma through thermally driven processes, with characteristic energies set by the keV-scale solar temperature. We consider solar ALPs produced in the Primakoff conversion induced by the photon coupling $g_{\gamma\gamma}$ with dimension GeV^{-1} [19,20], ABC processes (atomic recombination and deexcitation, bremsstrahlung, and Compton scattering) resulting from the dimensionless electron coupling g_{ae} [21–29], and ^{57}Fe nuclear deexcitation through the dimensionless effective nucleon coupling g_{aN}^{eff} , enabled by its low-lying 14.4 keV excited state that can be thermally populated in

*Contact author: kaan.oyulmaz@ed.ac.uk

†Contact author: harkiratriyat@gmail.com

‡Contact author: xuyongheng@physics.ucla.edu

§Also at Fysisk Institutt, The University of Oslo, Oslo, Norway.

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International](https://creativecommons.org/licenses/by/4.0/) license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP³.

the solar core [30–32]. For Primakoff ALPs, we use the mass-dependent solar flux of Ref. [33] and the inverse Primakoff scattering cross section from the relativistic Hartree-Fock treatment of Ref. [34]. Unlike previous experimental studies, this search retains the mass dependence in both the flux and the cross section model. For ^{57}Fe ALPs, we use the mass-dependent event rate from Refs. [14,35,36], which is phase-space suppressed as m_a approaches the excited state energy and vanishes above it. The deposited-energy spectrum of ^{57}Fe ALPs is modeled as a monoenergetic line at 14.4 keV. We consider both axioelectric and inverse Primakoff interactions in xenon, the latter being explored experimentally here for the first time for solar ^{57}Fe ALPs. For more details of the solar ALP modeling, please see Sec. I of Supplemental Material [37].

We search for bosonic halo dark matter in the keV/ c^2 mass range [23]. Bosonic dark matter may be produced as pseudoscalars (e.g., ALPs produced via the early-universe misalignment mechanism [42,43]) or as vectors [hidden photons (HP) [44,45]], generated through similar dynamics [46]. In such cases, bosonic DM may get absorbed by atoms in the liquid xenon (LXe) bulk, producing ER-like monoenergetic line signals via processes analogous to the photoelectric effect [14,23,47]. For both cases, the absorption rate on electrons is evaluated using calculations in Refs. [23,48], assuming a local dark-matter density of $0.3 \text{ GeV}/\text{cm}^3$ [49]. We note that the results depend on the assumed local density and leave detailed discussion of the modeling in Sec. II of Supplemental Material [37].

We study the mirror dark matter (MDM) model, which represents a theoretically motivated framework for plasma dark matter [50] by postulating an entire dark sector isomorphic to the SM [51]. In this model, the dark sector interacts with SM matter via gravity and photon-mirror photon mixing [52], which will lead to mirror electrons scattering with electrons in LXe [50,53]. In this search, the signal is modeled following Ref. [54], with the local mirror-helium density taken to be $5.8 \times 10^{-11} \text{ cm}^{-3}$, consistent with Ref. [53]. We also include the small time-averaged annual and diurnal modulation of the mirror-electron event rate predicted in this model. When averaged over the live time, this changes the expected event rate by about 2%. For more details of MDM, refer to Sec. III of Supplemental Material [37].

The last search in this analysis is the electromagnetic interaction of solar neutrinos. Neutrinos do not couple to photons at tree level. In the minimally extended SM, with loop-level correction applied, the Dirac magnetic moment is only of order $10^{-20} \mu_B$ for $\mathcal{O}(0.1) \text{ eV}$ neutrino masses, while the neutrino millicharge remains zero [55,56]. Such contributions are far below current detection sensitivity, so any observable neutrino electromagnetic signal would imply new physics, with a magnetic-moment interpretation additionally bearing on the Dirac-Majorana nature of the neutrino [57,58]. For such interactions from solar neutrinos, we use the flux from the standard solar model [59] and

the cross section from Ref. [60] with corrections from the random-phase approximation [61] applied. More details are provided in Sec. IV of Supplemental Material [37].

The data used in this search were collected during the first two science runs of the LZ experiment: WIMP search 2022 (WS2022) [5] and WIMP search 2024 (WS2024) [2], lasting from 2021 to 2024. The LZ experiment is located 4850 feet underground at the Sanford Underground Research Facility (SURF) in Lead, South Dakota, USA. At the center of the experiment is a dual-phase xenon TPC containing 7 tonnes of active xenon [62] as the target medium. To suppress radioactive backgrounds, the TPC is surrounded by a 2-tonne LXe skin detector and a 17.3-tonne gadolinium-loaded liquid scintillator outer detector for γ and neutron tagging, all within a 238-tonne ultrapure water shield [62].

Particle interactions in the TPC produce prompt scintillation (S1) and ionization electrons; electrons drifting to the liquid-gas interface under an electric field are extracted into the gas phase and generate secondary electroluminescence (S2) [5]. The S1-S2 time difference and S2 light pattern provide three-dimensional (3D) position reconstruction, while the S2/S1 ratio enables discrimination between ER and NR events [63]. Spatial and temporal variations in S1 and S2 are mapped with periodically injected monoenergetic ER sources, including $^{131\text{m}}\text{Xe}$ and $^{83\text{m}}\text{Kr}$ [64], defining corrected observables S1c and S2c; both are expressed in detected photons (phd), accounting for double-photoelectron emission [65,66].

Calibration campaigns are performed to study the detector's response to energy deposits from particle interactions. Specifically, the detector's response to ER events is calibrated using β decays of tritiated methane (CH_3T), ^{14}C [2,5], and ^{220}Rn [67]. The scintillation (g_1) and ionization (g_2) gains are obtained by tuning simulations generated with the Noble Element Simulation Technique (NEST) [68] to match calibration data, with additional constraints from monoenergetic peaks. The best-fit results are $g_1 = 0.114 \pm 0.002 \text{ phd/photon}$ and $g_2 = 47.1 \pm 1.1 \text{ phd/electron}$ for WS2022 [5] and $g_1 = 0.112 \pm 0.002 \text{ phd/photon}$ and $g_2 = 34.0 \pm 0.9 \text{ phd/electron}$ for WS2024 [2]. The different g_2 values mainly reflect the different operating conditions of WS2022 and WS2024, especially the extraction field. As ER sensitivity depends weakly on ER/NR discrimination, this configuration change does not significantly impact LZ's ER sensitivity.

The dominant contributor to the ER backgrounds in both LZ science runs is the β decay of ^{214}Pb with no coincident γ emissions. This isotope originates from ^{222}Rn , which emanates from detector materials and is dispersed into the liquid xenon bulk, resulting in a measured fiducial volume activity of $3.9 \pm 0.4 \mu\text{Bq/kg}$ [2]. To mitigate this background, a novel radon-tagging technique was developed to identify events with a high likelihood of being a ^{214}Pb β decay and applied to the WS2024 dataset [69,70]. This is achieved by creating a slow and laminar xenon flow

pattern in the central region of the TPC by adjusting the liquid xenon circulation rate, cooling power, and temperature gradients. Then the liquid velocity is mapped using coincident ^{222}Rn - ^{218}Po α decay pairs, enabling tracking of the movement of daughter atoms following the ^{218}Po alpha decay. In practice, a tag volume comoving with the ^{218}Po daughter is defined and lasts for three times the ^{214}Pb half-life (27 minutes), in which it is probable to find a ^{214}Pb β decay. Single scatter (SS) events that occur within this volume and time window contribute to a ^{214}Pb -rich dataset, containing 15% of the WS2024 exposure and approximately $60 \pm 4\%$ of the total ^{214}Pb activity [2]. The rest of the data, not being tagged as ^{214}Pb , form a dataset with a lower effective ^{214}Pb activity of $1.8 \pm 0.3 \mu\text{Bq/kg}$. As part of the likelihood, the radon-tagged events are also included in the final statistical analysis as a sideband dataset to improve the ability to constrain the tagging efficiency and other background contributions. The tagging efficiency is left to float as a nuisance parameter that scales the event rates in both the ^{214}Pb -rich and ^{214}Pb -poor datasets. Since ^{214}Pb is the dominant ER background, this subdivision gives the likelihood additional leverage to constrain the leading background component and thereby improves the sensitivity to ER signals.

Xenon electron capture (EC) and double electron capture (DEC) decays also contribute to the ER background with a smaller S2/S1 ratio than β decays because their higher ionization density enhances recombination. Measurements with neutron-activated ^{127}Xe and ^{125}Xe give the ratio between charge yields of L-shell decay and tritium β decay, $Q_y^L/Q_y^\beta = 0.87 \pm 0.03$ [71], confirming suppressed charge yield in EC. This suppression is incorporated in the background model. For ^{124}Xe DEC, LM captures involving one L-shell and one M-shell electron (LM captures; 5.98 keV) use a fixed factor of 0.87, while captures involving two L-shell electrons (LL captures; 10.00 keV) are described by a Thomas-Imel-motivated parameter floated in the fit [2,71–73]. Other ER backgrounds include dissolved β emitters in the LXe bulk, detector-material γ Compton scatters, solar neutrino-electron scatters, cosmogenic ^{37}Ar with a 35-day half-life at the beginning of WS2022, and residual CH_3T and ^{14}C from calibrations in WS2024 [1,74]. Additional subdominant backgrounds from solar and atmospheric $\text{CE}\nu\text{NS}$, detector NRs, and accidental coincidences are modeled as in Refs. [2,5] and have negligible impact on the final result, especially for one-dimensional (1D) absorptionlike analyses.

This analysis uses 280 live days of data, with a total exposure of 4.2 ± 0.1 tonne-years, of which 0.9 tonne-years are from WS2022 and the other 3.3 tonne-years are from WS2024. A fiducial volume is defined for each science run to suppress external backgrounds, and the fiducial mass for both runs is 5.5 ± 0.2 tonnes [2,5]. The drift field was reduced from 193 V/cm in WS2022 to 97 V/cm in WS2024 to mitigate light emission in the skin detector. Data selection criteria and acceptances are determined for

each run using a combination of calibration datasets and simulations. For this work, we retain the same data selection strategy as in Refs. [2,5], except for the region of interest (ROI).

To reflect the characteristics of different signal models, two ROI definitions are considered in this Letter. For all signal models, events are required to satisfy $\text{S1c} > 3$ phd in both science runs. The lower bound on uncorrected S2 size is 600 phd for WS2022 and 645 phd for WS2024, corresponding to 10 and 14.5 extracted electrons, respectively. The solar neutrino electromagnetic interaction and mirror dark matter scattering are expected to create pure β -like recoils in LXe due to their scattering nature, similar to solar neutrino weak interactions with electrons in LXe [12,75]. The recoil energy spectra of those events scale as $d\Gamma/dE_r \sim 1/E_r$ or $1/E_r^2$ because of the massless mediator, with most of the events concentrated near the energy threshold. As those signals are

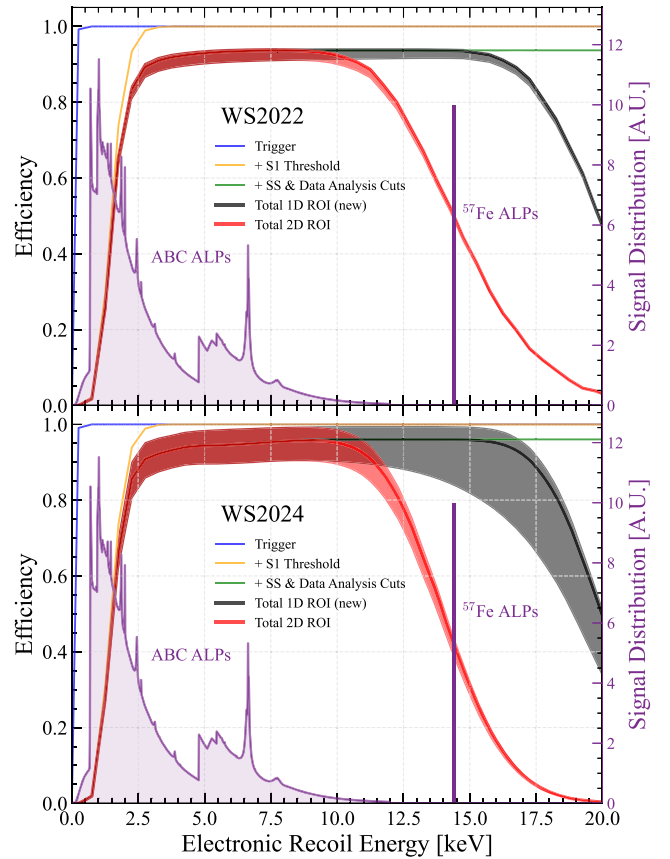


FIG. 1. Total data selection efficiencies of the 1D ROI (black) and 2D ROI (red), with uncertainties (shaded), in WS2022 and WS2024 data. The 1D ROI is introduced in this Letter. The trigger (blue), threefold coincidence and >3 phd on S1c (yellow), single-scatter reconstruction and data analysis cuts (green) efficiencies are also shown. The 1D ROI exhibits a slower efficiency drop at higher energies, which can be attributed to replacing the upper S1c bound of 80 phd with a requirement of $E_{\text{rec}} < 20$ keV. The true recoil energy distributions of solar ABC ALP and ^{57}Fe ALP events are also shown for comparison.

nearly fully contained in the ROI of both the WS2022 and WS2024 analyses, and the detector response to β -like recoils is well understood through CH_3T calibrations, we follow Refs. [2,5] and set the ROI upper bound as $\text{S1c} < 80$ phd, and we perform the analysis in the two-dimensional (2D) (S1c , S2c) observable space for maximal consistency. We refer to this ROI as the 2D ROI henceforth.

For solar ALPs and bosonic DM, detection in LXe relies either on absorption of an exotic particle analogous to the photoelectric effect [23] or the photoelectric effect of the inverse Primakoff photon. Previous studies found that photoelectric absorptions, albeit conserving total energy, display a different partition between light and charge yields [68]. As there is no pure photon calibration available below 20 keV, it is difficult to construct a reliable signal model for such processes in the traditional (S1c , S2c) space. Given this limitation, we model signal and background and conduct statistical inference in the reconstructed energy E_{rec} space, following the treatment in earlier experimental studies [13,14]. The ^{57}Fe signals are at 14.4 keV, at which energy the WIMP analysis selection efficiency has begun to roll off due to the $\text{S1c} < 80$ phd bound of the 2D ROI. To increase signal efficiency for ^{57}Fe and heavy bosonic DM signals, we replace the S1c upper bound with an

$E_{\text{rec}} < 20$ keV boundary. In practice, this is implemented through requiring $W_q[(\text{S1c}/g_1) + (\text{S2c}/g_2)] < 20$ keV, where $W_q = 13.5$ eV [63,76,77] is the work function of xenon. Hereafter, we refer to this as the 1D ROI.

The trigger efficiency, SS reconstruction efficiency, and analysis-cut acceptances are evaluated using calibration data together with simulations validated against those data. The impact of the ROI definitions, particularly the high-energy roll-off, is modeled using the same tuned simulations. Figure 1 illustrates the cumulative impact of different data selection stages on the ER signal efficiency as a function of true energy in both ROI settings, for WS2022 and WS2024, respectively. The uncertainty is evaluated from the statistical uncertainty and the difference between datasets, as in Refs. [2,5]. The true energy spectra for each physics signal and background component, except for accidentals, are passed through the LZ parametric simulation chain [78] based on NEST-2.4.0 [68] to create simulation datasets. The data selection efficiencies are applied to simulations to create probability distribution functions (PDFs) in the desired observable space as inputs for statistical inference.

To mitigate analyzer bias, LZ injected synthetic “salt” events at random times into the dataset during data taking.

TABLE I. Background-only fit results for the WS2022 (top) and WS2024 (bottom) datasets, for both the 1D and 2D ROIs. The WS2024 ER backgrounds are grouped according to how their rates are affected by radon tagging. In the 1D ROI introduced in this Letter, the detector NR and neutrino CE ν NS backgrounds are not included due to negligible rates and lack of discrimination.

Source		1D ROI (new)		2D ROI	
		Expectation	Fit result	Expectation	Fit result
WS2022	β decays + Detector γ s	305 ± 50	336 ± 20	215 ± 36	222 ± 16
	Solar ν ER	38.0 ± 2.3	38.1 ± 2.3	27.1 ± 1.6	27.2 ± 1.6
	^{136}Xe $2\nu\beta\beta$	27.2 ± 4.4	27.8 ± 4.3	15.1 ± 2.4	15.2 ± 2.4
	$^{127}\text{Xe} + ^{125}\text{Xe}$ EC	9.2 ± 0.8	9.3 ± 0.8	9.2 ± 0.8	9.3 ± 0.8
	^{124}Xe DEC	5.0 ± 1.4	5.0 ± 1.4	5.0 ± 1.4	5.2 ± 1.4
	^{37}Ar	[0, 288]	47.6 ± 9.4	[0, 288]	52.7 ± 9.4
	Accidental coincidences	1.2 ± 0.3	1.2 ± 0.3	1.2 ± 0.3	1.2 ± 0.3
	Det NR	...	...	...	$0.07^{+0.20}_{-0.07}$
	Solar ^8B NR	...	...	0.14 ± 0.01	0.14 ± 0.01
	Total	...	464 ± 23	...	333 ± 19
WS2024	^{214}Pb β	1099 ± 130	1096 ± 46	743 ± 88	733 ± 34
	$^{85}\text{Kr} + ^{39}\text{Ar} + \beta$ s + Detector γ s	237 ± 33	236 ± 31	162 ± 22	161 ± 21
	Solar ν ER	151 ± 9.0	151 ± 9.0	102 ± 6.1	102 ± 6.1
	^{136}Xe $2\nu\beta\beta$	107 ± 16	108 ± 16	55.6 ± 8.4	55.8 ± 8.2
	$^{218}\text{Po} + ^{212}\text{Pb}$ β s	92.1 ± 11.0	93.1 ± 10.9	62.7 ± 7.5	63.6 ± 7.4
	$^3\text{H} + ^{14}\text{C}$	61.2 ± 3.4	62.9 ± 3.4	58.3 ± 3.3	59.7 ± 3.3
	^{124}Xe DEC	20.0 ± 4.0	19.8 ± 4.0	19.4 ± 3.9	21.4 ± 3.6
	$^{127}\text{Xe} + ^{125}\text{Xe}$ EC	3.2 ± 0.7	2.8 ± 0.6	3.2 ± 0.7	2.7 ± 0.6
	Atmospheric ν NR	...	...	0.12 ± 0.02	0.12 ± 0.03
	Solar $^8\text{B} + \text{hep } \nu$ NR	...	...	0.06 ± 0.01	0.06 ± 0.01
	Det NR	...	...	...	$0.0^{+0.2}$
	Rn β tagging efficiency	0.60 ± 0.04	0.62 ± 0.02	0.60 ± 0.04	0.62 ± 0.02
	Total	1773 ± 136	1754 ± 60	1210 ± 91	1202 ± 42

All of the salt events in these runs were designed for WIMP searches, hence NR-like; no salt was introduced specifically for this ER search. While the region corresponding to the 2D ROI had already been unsalted for the analysis presented in Ref. [2], the energy-only 1D ROI used here extends outside that previously unsalted region and could therefore still contain higher-energy NR-like salt. The region between 1D and 2D ROI bounds was kept salted during the development of this work and was unsalted only after all analysis choices were frozen. No additional salt events were found.

Both the 1D and 2D background-only fits show good agreement between the postunsalting data and the background model, with goodness-of-fit p values of 0.80 and 0.24, respectively. The 2D analysis incorporates detector neutron and neutrino CE ν NS backgrounds, which in the 1D case can be effectively absorbed into the ER background sources due to their small event rates. The yield parameter for LL captures is allowed to vary in the 2D fits but is fixed in the 1D case since charge suppression has little impact on the 1D analysis. The pre and postfit event rates of different background components considered in the 1D and 2D fits are given in Table I.

As the background-only fits show good compatibility with observation, we follow conventions set in Ref. [79] to set upper limits for the signal models using a two-sided profile likelihood ratio (PLR) approach. The dataset after unsalting and best fit to the background-only model are shown in Fig. 2. The PLR test statistics [80] are evaluated using energy-only 1D PDFs for the solar ALPs and bosonic dark matter absorptions, while 2D PDFs (S1c, S2c) are used for the mirror DM and solar neutrino electromagnetic interactions. The sensitivity and power-constrained observed upper limits of the models tested are shown in Figs. 3 and 4.

This analysis sets stringent constraints across multiple physics searches. We obtain an upper limit of $g_{ae} < 1.8 \times 10^{-12}$ for the dimensionless ALP-electron coupling, which is a 15% improvement over leading terrestrial constraints [13,14]. The limit on ALP-photon coupling is $g_{a\gamma\gamma} < 3.5 \times 10^{-10} \text{ GeV}^{-1}$, providing the most stringent constraints to date for ALPs with masses of $\sim 1 \text{ eV}/c^2$ and above and improving upon previous leading constraints by 30% [13,14]. Our sensitivity extends above $m_a = 1 \text{ keV}/c^2$ due to the newly introduced mass-dependent Primakoff flux [33] and cross section [34]. The upper limit on the ^{57}Fe deexcitation ALP event rate in LXe is 14 events $\text{tonne}^{-1} \text{ year}^{-1}$, 30% improvement over previous constraints on $g_{ae}g_{aN}^{\text{eff}}$ [13,14]. This leads to the most stringent constraints on $g_{ae}g_{aN}^{\text{eff}}$ and the first experimental constraints on $g_{a\gamma\gamma}g_{aN}^{\text{eff}}$.

For solar neutrino electromagnetic interactions, we set the magnetic moment constraint on $\mu_\nu < 8.3 \times 10^{-12} \mu_B$, a

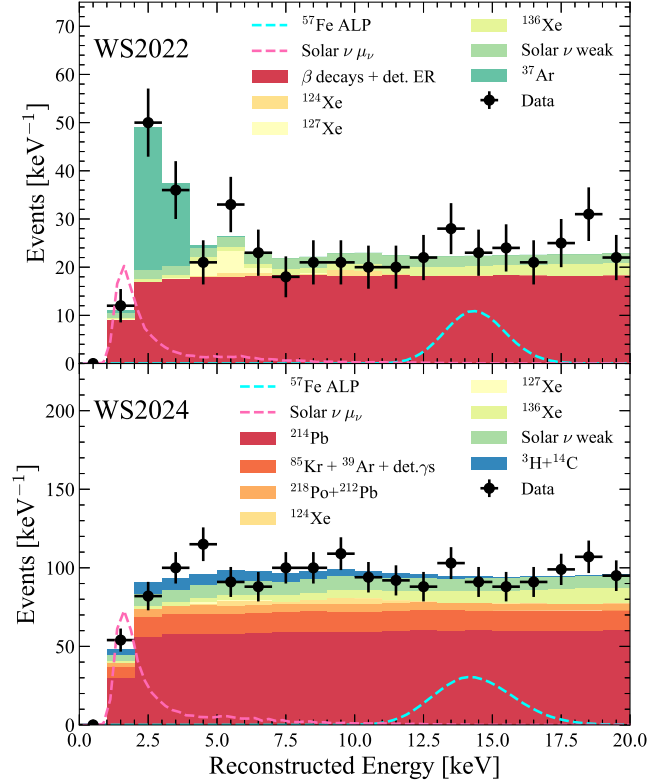


FIG. 2. LZ WS2022 + 2024 data (black dots) and best-fit background-only model (colored histogram) using the 1D likelihood. The region above 15 keV is reported publicly for the first time in this Letter. Simulated spectra for two representative signals, solar neutrino magnetic moment with $\mu_\nu = 2.8 \times 10^{-11} \mu_B$ (magenta) and ^{57}Fe solar ALPs with $m_a = 1 \text{ meV}/c^2$ and $g_{ae}g_{aN}^{\text{eff}} = 6.1 \times 10^{-18}$ (cyan), are overlaid for comparison. A fit in the WIMP search 2D ROI gives a very similar background-only description and is presented in Ref. [2].

factor of two stronger than our WS2022 result [12]. This improvement is driven primarily by the larger combined exposure of the WS2022 + WS2024 dataset and introduction of the radon-tagging technique. We also set the current leading limit on the neutrino millicharge, $\delta_Q < 1.6 \times 10^{-13} e_0$. The mirror dark matter temperature above $T_{\text{DM}} = 0.29 \text{ keV}$ is excluded; in terms of kinetic mixing, we set $\epsilon < 4 \times 10^{-12}$ for the photon-mirror-photon kinetic-mixing parameter at $T_{\text{DM}} = 0.5 \text{ keV}$, which surpasses the previous best [53] by 10%. Finally, our bosonic DM absorption limits are comparable with the leading constraints reported in Ref. [13], complementary to the astrophysical constraints on ALP-electron coupling derived from x-ray and γ -ray observations [84] and the constraints on the mixing strength between hidden photons and photons from stellar bounds [85].

Overall, the sensitivity of this analysis is slightly stronger than those of XENONnT and PandaX-4T [13,14]. While

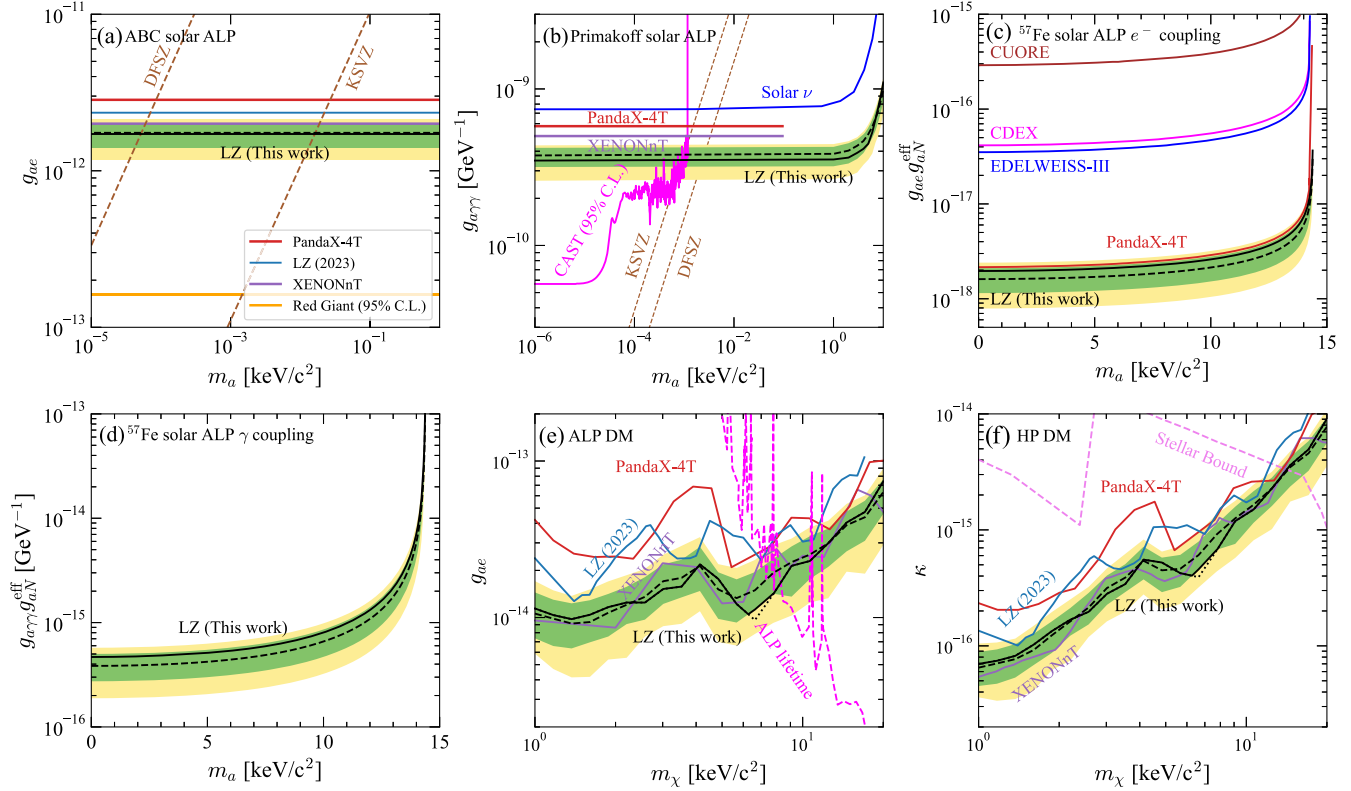


FIG. 3. Sensitivities and power-constrained 90% C.L. limits on new physics models tested using 1D statistical inference: (a) ABC solar ALP, (b) Primakoff solar ALP, (c) ^{57}Fe solar ALP electron coupling, (d) ^{57}Fe solar ALP photon coupling, (e) ALP DM, and (f) hidden photon (HP) DM. For the LZ results, the solid black curves show the reported observed power-constrained 90% C.L. limits upper limits, the dashed black curves show the median expected sensitivities, and the dotted black curves in panels (e) and (f) show the upper limits obtained without applying the power constraint. The green (yellow) bands indicate the central 68% (95%) ranges of the expected sensitivities under the background-only hypothesis. Selected constraints from terrestrial experiments [12–14,35,81–83] and astrophysical observations [84–87], together with the regions allowed by two benchmark QCD axion realizations, KSVZ [88] and DFSZ [89], are also shown for comparison.

this search benefits from a larger total exposure and radon tagging, the higher overall ER background rate than XENONnT partially offsets these advantages. The relative strength of the observed limits does not follow a uniform pattern across models, but instead depends on the signal’s spectral shape and, consequently, on fluctuations in the local data in the relevant energy region.

The introduction of radon tagging has improved LZ’s sensitivity to ER signals. Fits to toy datasets indicate that incorporating radon tagging reduces the median upper limits on signal events by approximately 10%–25% and the median sensitivities to a similar extent. The improvement is smaller than the tagging efficiency because the tagging efficiency carries a systematic uncertainty, originating mainly from the ^{214}Pb branching ratio [70]. As a result, the upper limits derived from observed data typically improve by about 5%–10%, with the exact gain depending on the signal’s spectral shape and underlying physics, particularly the exponent with which the reported model parameter enters the expected signal rate. The only exception is the ^{57}Fe solar ALPs, for which the observed upper limit with radon tagging is slightly weaker. This is

consistent with a modest local upward fluctuation in the reconstructed-energy spectrum around 14.4 keV, visible in Fig. 2 as the data lie slightly above the background-only model in the region where the ^{57}Fe signal template peaks.

More importantly, this work demonstrates that xenon TPCs are powerful probes of new physics in the ER channel. With the development of radon background control techniques [70,96] and the scaling up of exposure, their reach for keV-scale electron-coupling new physics will continue to improve. Based on next-generation baseline designs [97] and the Asimov median significance defined in Ref. [80], we expect the sensitivity to improve by $\mathcal{O}(10)$ in terms of event rate, leading to a factor of ~ 3 improvement for models whose rates are quadratic in the coupling and ~ 2 for models with quartic coupling dependence. A more detailed sensitivity calculation for next-generation xenon-based experiments is left to future work. Nevertheless, with these advancements, significant new parameter space for solar ALPs and MDM can be explored, and the sensitivity to the neutrino magnetic moment will become comparable to current astrophysical constraints.

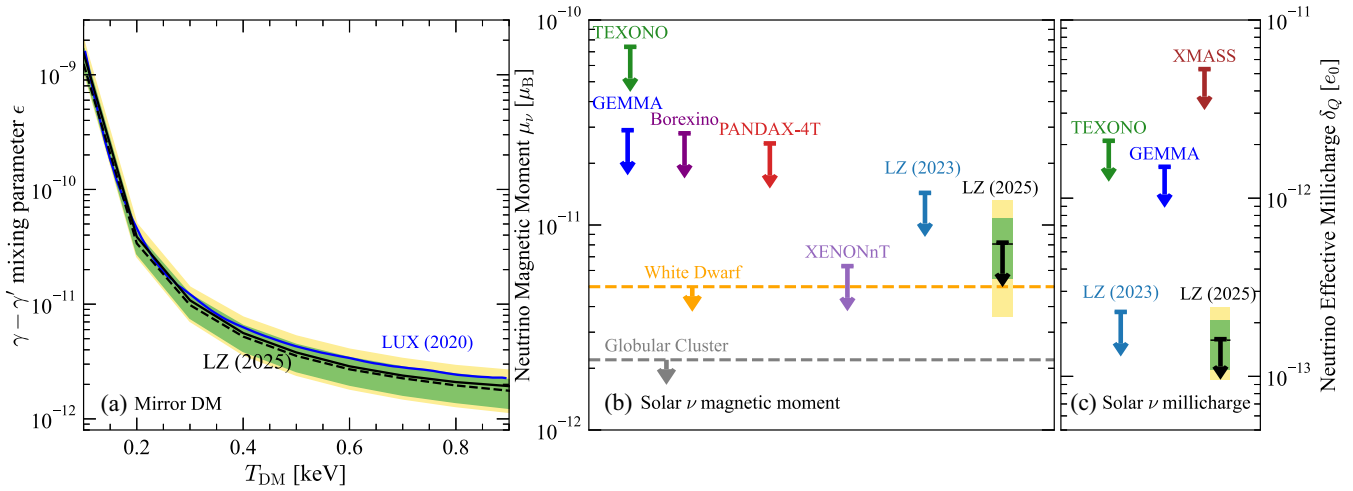


FIG. 4. Sensitivities and 90% C.L. limits on the new physics models tested using 2D statistical inference: (a) mirror dark matter, (b) solar neutrino magnetic moment, and (c) millicharge. Constraints from terrestrial experiments [13,47,53,90–93] and astrophysical observations [94,95] are also shown. The black curves and colored bands follow the same plotting conventions as in Fig. 3.

In conclusion, we have searched for ER signals indicative of new physics using the combined dataset from the first two science runs of the LZ experiment. Finding no significant excess above the background model, we set stringent limits on various signal hypotheses, due to a combination of a low background rate, large exposure, and the introduction of the radon tagging technique. The results provide the strongest constraints on Primakoff and ^{57}Fe deexcitation ALPs, solar ν millicharge, and mirror dark matter, while the constraints on ABC solar ALPs, solar neutrino magnetic moment, and bosonic dark matter absorption remain highly competitive. These results further establish low-energy ER searches in liquid xenon TPCs as a competitive avenue for probing new physics, and we expect further gains from larger exposures and improved background control.

Acknowledgments—The research supporting this work took place in part at the Sanford Underground Research Facility (SURF) in Lead, South Dakota. Funding for this work is supported by the U.S. Department of Energy, Office of Science, Office of High Energy Physics under Contracts No. DE-AC02-05CH11231, No. DE-SC0020216, No. DE-SC0012704, No. DE-SC0010010, No. DE-AC02-07CH11359, No. DE-SC0015910, No. DE-SC0014223, No. DE-SC0010813, No. DE-SC0009999, No. DE-NA0003180, No. DE-SC0011702, No. DE-SC0010072, No. DE-SC0006605, No. DE-SC0008475, No. DE-SC0019193, No. DE-FG02-10ER46709, No. UW PRJ82AJ, No. DE-SC0013542, No. DE-AC02-76SF00515, No. DE-SC0018982, No. DE-SC0019066, No. DE-SC0015535, No. DE-SC0019319, No. DE-SC0025629, No. DE-SC0024114, No. DE-AC52-07NA27344, and No. DE-SC0012447. This research was also supported by the U.S. National

Science Foundation (NSF); the UKRI’s Science and Technology Facilities Council under Awards No. ST/W000490/1, No. ST/W000482/1, No. ST/W000636/1, No. ST/W000466/1, No. ST/W000628/1, No. ST/W000555/1, No. ST/W000547/1, No. ST/W00058X/1, No. ST/X508263/1, No. ST/V506862/1, No. ST/X508561/1, No. ST/V507040/1, No. ST/W507787/1, No. ST/R003181/1, No. ST/R003181/2, No. ST/W507957/1, No. ST/X005984/1, and No. ST/X006050/1; the Portuguese Foundation for Science and Technology (FCT) under Award No. PTDC/FIS-PAR/2831/2020; the Institute for Basic Science, Korea, under Budget No. IBS-R016-D1; and the Swiss National Science Foundation (SNSF) under Award No. 10001549. This research was supported by the Australian Government through the Australian Research Council Centre of Excellence for Dark Matter Particle Physics under Award No. CE200100008. We acknowledge additional support from the U.K. Science and Technology Facilities Council (STFC) for PhD studentships and the STFC Boulby Underground Laboratory in the United Kingdom; the GridPP [98,99] and IRIS Collaborations, in particular at Imperial College London and additional support by the University College London (UCL) Cosmoparticle Initiative; and the University of Zürich. We acknowledge additional support from the Center for the Fundamental Physics of the Universe, Brown University. Y. X. received funding from the European Union’s Horizon Europe research and innovation programme under the Marie Skłodowska-Curie Grant Agreement No. 101126636. K. T. Lesko acknowledges the support of Brasenose College and Oxford University. The LZ Collaboration acknowledges the key contributions of Dr. Sidney Cahn, Yale University, in the production of calibration sources. This research used resources of the National Energy

Research Scientific Computing Center, a DOE Office of Science User Facility supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. We gratefully acknowledge support from GitLab through its GitLab for Education Program. The University of Edinburgh is a charitable body, registered in Scotland, with the registration number SC005336. The assistance of SURF and its personnel in providing physical access and general logistical and technical support is acknowledged. We acknowledge the South Dakota Governor's office, the South Dakota Community Foundation, the South Dakota State University Foundation, and the University of South Dakota Foundation for use of xenon. We also acknowledge the University of Alabama for providing xenon. Finally, we respectfully acknowledge that we are on the traditional land of Indigenous American peoples and honor their rich cultural heritage and enduring contributions.

Data availability—Selected data from this analysis are publicly available [100], including the following: Fig. 1: the total efficiencies of data selection cuts for both ROIs and datasets, Fig. 2: the 1D histograms and the data in reconstructed energy used to create those histograms, and Figs. 3 and 4: the power-constrained observed upper limits on signal models reported in this analysis.

- [1] J. Aalbers *et al.* (LZ Collaboration), *Phys. Rev. D* **108**, 012010 (2023).
- [2] J. Aalbers *et al.* (LZ Collaboration), *Phys. Rev. Lett.* **135**, 011802 (2025).
- [3] E. Aprile *et al.* (XENON Collaboration), *Phys. Rev. Lett.* **135**, 221003 (2025).
- [4] Z. Bo *et al.* (PandaX Collaboration), *Phys. Rev. Lett.* **134**, 011805 (2025).
- [5] J. Aalbers *et al.* (LZ Collaboration), *Phys. Rev. Lett.* **131**, 041002 (2023).
- [6] J. Aalbers *et al.* (LZ Collaboration), *Phys. Rev. D* **109**, 112010 (2024).
- [7] J. Aalbers *et al.* (LZ Collaboration), *Phys. Rev. Lett.* **133**, 221801 (2024).
- [8] J. Aalbers *et al.* (LZ Collaboration), *Commun. Phys.* **7**, 292 (2024).
- [9] J. Aalbers *et al.* (LZ Collaboration), *Phys. Rev. Lett.* **134**, 241801 (2025).
- [10] Y. Meng *et al.* (PandaX-4T Collaboration), *Phys. Rev. Lett.* **127**, 261802 (2021).
- [11] E. Aprile *et al.* (XENON Collaboration), *Phys. Rev. Lett.* **131**, 041003 (2023).
- [12] J. Aalbers *et al.* (LZ Collaboration), *Phys. Rev. D* **108**, 072006 (2023).
- [13] E. Aprile *et al.* (XENON Collaboration), *Phys. Rev. Lett.* **129**, 161805 (2022).
- [14] X. Zeng *et al.* (PandaX Collaboration), *Phys. Rev. Lett.* **134**, 041001 (2025).
- [15] J. Aalbers *et al.* (LZ Collaboration), *Phys. Rev. Lett.* **134**, 241802 (2025).
- [16] R. D. Peccei and H. R. Quinn, *Phys. Rev. Lett.* **38**, 1440 (1977).
- [17] M. Cirelli, A. Strumia, and J. Zupan, *SciPost Phys. Rev.* **1** (2026).
- [18] P. Carenza, R. Pasechnik, and Z.-W. Wang, *Phys. Rev. Lett.* **135**, 021001 (2025).
- [19] G. G. Raffelt, *Stars as Laboratories for Fundamental Physics: The Astrophysics of Neutrinos, Axions, and Other Weakly Interacting Particles* (University of Chicago Press, Chicago, IL, 1996).
- [20] A. Caputo and G. Raffelt, *Proc. Sci. COSMICWISPerS* (2024) 041 [arXiv:2401.13728].
- [21] S. Dimopoulos, J. A. Frieman, B. W. Lynn, and G. D. Starkman, *Phys. Lett. B* **179**, 223 (1986).
- [22] S. Dimopoulos, G. D. Starkman, and B. W. Lynn, *Mod. Phys. Lett. A* **1**, 491 (1986).
- [23] M. Pospelov, A. Ritz, and M. B. Voloshin, *Phys. Rev. D* **78**, 115012 (2008).
- [24] G. G. Raffelt, *Phys. Rev. D* **33**, 897 (1986).
- [25] A. R. Zhitnitsky and Y. I. Skovpen, *Yad. Fiz.* **29**, 995 (1979) [*Sov. J. Nucl. Phys.* **29**, 513 (1979)].
- [26] L. M. Krauss, J. E. Moody, and F. Wilczek, *Phys. Lett.* **144B**, 391 (1984).
- [27] K. O. Mikaelian, *Phys. Rev. D* **18**, 3605 (1978).
- [28] M. Fukugita, S. Watamura, and M. Yoshimura, *Phys. Rev. Lett.* **48**, 1522 (1982).
- [29] M. Fukugita, S. Watamura, and M. Yoshimura, *Phys. Rev. D* **26**, 1840 (1982).
- [30] A. Serenelli, S. Basu, J. W. Ferguson, and M. Asplund, *Astrophys. J. Lett.* **705**, L123 (2009).
- [31] S. Moriyama, *Phys. Rev. Lett.* **75**, 3222 (1995).
- [32] W. C. Haxton and K. Y. Lee, *Phys. Rev. Lett.* **66**, 2557 (1991).
- [33] Q.-f. Wu and X.-J. Xu, *J. Cosmol. Astropart. Phys.* **07** (2024) 013.
- [34] T. Abe, K. Hamaguchi, and N. Nagata, *Phys. Lett. B* **815**, 136174 (2021).
- [35] S. Andriamonje *et al.* (CAST Collaboration), *J. Cosmol. Astropart. Phys.* **12** (2009) 002.
- [36] E. Armengaud *et al.*, *J. Cosmol. Astropart. Phys.* **11** (2013) 067.
- [37] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/wnxl-yf95> for detailed signal modeling and spectra for solar axions and axionlike particles, bosonic dark matter, mirror dark matter, and solar-neutrino electromagnetic interactions, which includes Refs. [38–41].
- [38] J. Redondo, *J. Cosmol. Astropart. Phys.* **12** (2013) 008.
- [39] A. V. Derbin, I. S. Drachnev, A. S. Kayunov, and V. N. Muratova, *JETP Lett.* **95**, 339 (2012).
- [40] M. Benito, F. Iocco, and A. Cuoco, *Phys. Dark Universe* **32**, 100826 (2021).
- [41] O. Bienaymé, A. Robin, J.-B. Salomon, and C. Reylé, *Astron. Astrophys.* **689**, A280 (2024).
- [42] J. Preskill, M. B. Wise, and F. Wilczek, *Phys. Lett.* **120B**, 127 (1983).
- [43] C. B. Adams *et al.*, Axion dark matter, arXiv:2203.14923.
- [44] M. Fabbrichesi, E. Gabrielli, and G. Lanfranchi, *The Physics of the Dark Photon* (Springer Cham, Switzerland, 2020).
- [45] J. M. Cline, in *58th Rencontres de Moriond on Electroweak Interactions and Unified Theories* (2024), arXiv:2405.08534.

- [46] A. E. Nelson and J. Scholtz, *Phys. Rev. D* **84**, 103501 (2011).
- [47] E. Aprile *et al.* (XENON Collaboration), *Phys. Rev. D* **102**, 072004 (2020).
- [48] I. M. Bloch, R. Essig, K. Tobioka, T. Volansky, and T.-T. Yu, *J. High Energy Phys.* **06** (2017) 087.
- [49] P. F. de Salas, K. Malhan, K. Freese, K. Hattori, and M. Valluri, *J. Cosmol. Astropart. Phys.* **10** (2019) 037.
- [50] J. D. Clarke and R. Foot, *Phys. Lett. B* **766**, 29 (2017).
- [51] R. Foot, *Int. J. Mod. Phys. A* **29**, 1430013 (2014).
- [52] R. Foot, H. Lew, and R. R. Volkas, *Phys. Lett. B* **272**, 67 (1991).
- [53] D. S. Akerib *et al.* (LUX Collaboration), *Phys. Rev. D* **101**, 012003 (2020).
- [54] R. Foot, *Phys. Lett. B* **789**, 592 (2019).
- [55] K. Fujikawa and R. Shrock, *Phys. Rev. Lett.* **45**, 963 (1980).
- [56] J. Schechter and J. W. F. Valle, *Phys. Rev. D* **24**, 1883 (1981); **25**, 283(E) (1982).
- [57] N. F. Bell, V. Cirigliano, M. J. Ramsey-Musolf, P. Vogel, and M. B. Wise, *Phys. Rev. Lett.* **95**, 151802 (2005).
- [58] N. F. Bell, M. Gorchtein, M. J. Ramsey-Musolf, P. Vogel, and P. Wang, *Phys. Lett. B* **642**, 377 (2006).
- [59] N. Vinyoles, A. M. Serenelli, F. L. Villante, S. Basu, J. Bergström, M. C. Gonzalez-Garcia, M. Maltoni, C. Peña Garay, and N. Song, *Astrophys. J.* **835**, 202 (2017).
- [60] C. Giunti and A. Studenikin, *Rev. Mod. Phys.* **87**, 531 (2015).
- [61] C.-C. Hsieh, L. Singh, C.-P. Wu, J.-W. Chen, H.-C. Chi, C. P. Liu, M. K. Pandey, and H. T. Wong, *Phys. Rev. D* **100**, 073001 (2019).
- [62] D. S. Akerib *et al.* (LZ Collaboration), *Nucl. Instrum. Methods Phys. Res., Sect. A* **953**, 163047 (2020).
- [63] C. E. Dahl, The physics of background discrimination in liquid xenon, and first results from Xenon10 in the hunt for WIMP dark matter, Ph.D. thesis, Princeton University, 2009.
- [64] J. Aalbers *et al.* (LZ Collaboration), *J. Instrum.* **19**, P08027 (2024).
- [65] C. H. Faham, V. M. Gehman, A. Currie, A. Dobi, P. Sorensen, and R. J. Gaitskell, *J. Instrum.* **10**, P09010 (2015).
- [66] B. López Paredes, H. M. Araújo, F. Froborg, N. Marangou, I. Olcina, T. J. Sumner, R. Taylor, A. Tomás, and A. Vacheret, *Astropart. Phys.* **102**, 56 (2018).
- [67] J. Aalbers *et al.* (LZ Collaboration), *Phys. Rev. D* **109**, 092003 (2024).
- [68] M. Szydagis *et al.*, *Front. Det. Sci. Technol.* **2**, 1480975 (2024).
- [69] J. McLaughlin, Modelling of inner-shell scatters in liquid Xenon, and flow based ^{214}Pb vetoes in LUX-ZEPLIN, Ph.D. thesis, Northwestern University, 2024.
- [70] J. Aalbers *et al.* (LZ Collaboration), *arXiv:2508.19117*.
- [71] J. Aalbers *et al.* (LZ Collaboration), *Phys. Rev. D* **112**, 012024 (2025).
- [72] D. J. Temples, J. McLaughlin, J. Bargemann, D. Baxter, A. Cottle, C. E. Dahl, W. H. Lippincott, A. Monte, and J. Phelan, *Phys. Rev. D* **104**, 112001 (2021).
- [73] J. Xu *et al.*, *Phys. Rev. D* **112**, 012014 (2025).
- [74] J. Aalbers *et al.* (LZ Collaboration), *Phys. Rev. D* **105**, 082004 (2022).
- [75] D. S. Akerib *et al.* (LZ Collaboration), *Phys. Rev. D* **104**, 092009 (2021).
- [76] M. Szydagis *et al.*, *Instruments* **5**, 13 (2021).
- [77] L. W. Goetzke, E. Aprile, M. Anthony, G. Plante, and M. Weber, *Phys. Rev. D* **96**, 103007 (2017).
- [78] D. S. Akerib *et al.* (LZ Collaboration), *Astropart. Phys.* **125**, 102480 (2021).
- [79] D. Baxter *et al.*, *Eur. Phys. J. C* **81**, 907 (2021).
- [80] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, *Eur. Phys. J. C* **71**, 1554 (2011); **73**, 2501 (2013).
- [81] F. Alessandria *et al.* (CUORE Collaboration), *J. Cosmol. Astropart. Phys.* **05** (2013) 007.
- [82] Y. Wang *et al.* (CDEX Collaboration), *Phys. Rev. D* **101**, 052003 (2020).
- [83] E. Armengaud *et al.* (EDELWEISS Collaboration), *Phys. Rev. D* **98**, 082004 (2018).
- [84] R. Z. Ferreira, M. C. D. Marsh, and E. Müller, *Phys. Rev. Lett.* **128**, 221302 (2022).
- [85] H. An, M. Pospelov, J. Pradler, and A. Ritz, *Phys. Lett. B* **747**, 331 (2015).
- [86] F. Capozzi and G. Raffelt, *Phys. Rev. D* **102**, 083007 (2020).
- [87] N. Vinyoles, A. Serenelli, F. L. Villante, S. Basu, J. Redondo, and J. Isern, *J. Cosmol. Astropart. Phys.* **10** (2015) 015.
- [88] J. E. Kim, *Phys. Rev. Lett.* **43**, 103 (1979).
- [89] M. Dine, W. Fischler, and M. Srednicki, *Phys. Lett.* **104B**, 199 (1981).
- [90] M. Deniz *et al.* (TEXONO Collaboration), *Phys. Rev. D* **81**, 072001 (2010).
- [91] A. G. Bida, E. V. Demidova, A. S. Starostin, V. B. Brudanin, V. G. Egorov, D. V. Medvedev, M. V. Shirchenko, and T. Vylov, *Phys. Part. Nucl. Lett.* **7**, 406 (2010).
- [92] M. Agostini *et al.* (Borexino Collaboration), *Phys. Rev. D* **96**, 091103 (2017).
- [93] K. Abe *et al.* (XMASS Collaboration), *Phys. Lett. B* **809**, 135741 (2020).
- [94] A. H. Córscico, L. G. Althaus, M. M. Miller Bertolami, S. O. Kepler, and E. García-Berro, *J. Cosmol. Astropart. Phys.* **08** (2014) 054.
- [95] N. Viaux, M. Catelan, P. B. Stetson, G. Raffelt, J. Redondo, A. A. R. Valcarce, and A. Weiss, *Phys. Rev. Lett.* **111**, 231301 (2013).
- [96] E. Aprile *et al.* (XENON Collaboration), *Phys. Rev. X* **15**, 031079 (2025).
- [97] J. Aalbers *et al.* (XLZD Collaboration), *Eur. Phys. J. C* **85**, 1192 (2025).
- [98] P. J. W. Faulkner *et al.* (GridPP Collaboration), *J. Phys. G* **32**, N1 (2006).
- [99] D. Britton *et al.*, *Phil. Trans. R. Soc. A* **367**, 2447 (2009).
- [100] LZ Collaboration, Search for new physics via low-energy electron recoils with a 4.2 tonne year exposure from the LZ experiment, HEPData (2026), <https://www.hepdata.net/record/181350>.