Search for Coherent Elastic Scattering of Solar $^8$B Neutrinos in the XENON1T Dark Matter Experiment

Aprile, E.; Angevaare, J.R.; Bruenner, S.; Colijn, A.P.; Decowski, M.P.; Gaemers, P.; XENON Collaboration

DOI
10.1103/PhysRevLett.126.091301

Publication date
2021

Document Version
Final published version

Published in
Physical Review Letters

License
CC BY

Link to publication

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: https://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.

UvA-DARE is a service provided by the library of the University of Amsterdam (https://dare.uva.nl)
Search for Coherent Elastic Scattering of Solar $^8$B Neutrinos in the XENON1T Dark Matter Experiment


1Physics Department, Columbia University, New York, New York 10027, USA
2Oskar Klein Centre, Department of Physics, Stockholm University, AlbaNova, Stockholm SE-10691, Sweden
3Department of Physics and Astronomy, University of Bologna and INFN-Bologna, 40126 Bologna, Italy
4LPNHE, Sorbonne Université, Université de Paris, CNRS/IN2P3, Paris, France
5Institut für Physik & Exzellenzcluster PRISMA, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany
6Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, 48149 Münster, Germany
7LIBPhys, Department of Physics, University of Coimbra, 3004-516 Coimbra, Portugal
8Department of Physics and Astronomy, Rice University, Houston, Texas 77005, USA
9INAF-Astrophysical Observatory of Torino, Department of Physics, University of Torino and INFN-Torino, 10125 Torino, Italy
10Nikhef and the University of Amsterdam, Science Park, 1098XG Amsterdam, Netherlands
11New York University Abu Dhabi, Abu Dhabi, United Arab Emirates
12Physik-Institut, University of Zürich, 8057 Zürich, Switzerland
13Department of Physics, Applied Physics and Astronomy, Rensselaer Polytechnic Institute, Troy, New York 12180, USA
14Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot 7610001, Israel
15Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany
16Department of Physics “Etore Pancini”, University of Napoli and INFN-Napoli, 80126 Napoli, Italy
17Department of Physics and Astronomy, Purdue University, West Lafayette, Indiana 47907, USA
18Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, 48149 Münster, Germany
19Institute for Astroparticle Physics, Karlsruhe Institute of Technology, 76021 Karlsruhe, Germany
20SUBATECH, IMT Atlantique, CNRS/IN2P3, Université de Nantes, Nantes 44307, France
21Department of Physics and Chemistry, University of L’Aquila, 67100 L’Aquila, Italy
22INFN-Laboratori Nazionali del Gran Sasso and Gran Sasso Science Institute, 67100 L’Aquila, Italy
23Department of Physics & Center for High Energy Physics, Tsinghua University, Beijing 100084, China
24Department of Physics & Kavli Institute for Cosmological Physics, University of Chicago, Chicago, Illinois 60637, USA
25Kamioka Observatory, Institute for Cosmic Ray Research, and Kavli Institute for the Physics and Mathematics of the Universe (WPI), the University of Tokyo, Higashi-Mozumi, Kamioka, Hida, Gifu 506-1205, Japan
26Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, and Institute for Space-Earth Environmental Research, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8602, Japan
27Department of Physics, University of California San Diego, La Jolla, California 92093, USA

0031-9007/21/126(9)/091301(8) 091301-1 Published by the American Physical Society
We report on a search for nuclear recoil signals from solar \(^8\)B neutrinos elastically scattering off xenon nuclei in XENON1T data, lowering the energy threshold from 2.6 to 1.6 keV. We develop a variety of novel techniques to limit the resulting increase in backgrounds near the threshold. No significant \(^8\)B neutrino-like excess is found in an exposure of 0.6 t \(\times\) y. For the first time, we use the nondetection of solar neutrinos to constrain the light yield from 1–2 keV nuclear recoils in liquid xenon, as well as nonstandard neutrino-quark interactions. Finally, we improve upon world-leading constraints on dark matter-nucleus interactions for dark matter masses between 3 and 11 GeV c\(^{-2}\) by as much as an order of magnitude.

DOI: 10.1103/PhysRevLett.126.091301

---

**Introduction.**—Neutrinos from the Sun, atmospheric cosmic-ray showers, and supernovae can produce observable nuclear recoils (NRs) via coherent elastic scattering off nuclei in liquid xenon (LXe) detectors searching for dark matter (DM) [1]. The coherent elastic neutrino-nucleus scattering (CE\(\nu\)NS) process [2–5] produces the same signature as the one expected from DM-nucleus interactions, and thus the two can only be distinguished by their recoil spectra. Solar \(^8\)B neutrinos are expected to contribute to the greatest number of CE\(\nu\)NS events in LXe DM search experiments. These events fall near the energy thresholds of such detectors, with a spectrum indistinguishable from 6 GeV c\(^{-2}\) DM.

The XENON1T dark matter search experiment, operated at the INFN Laboratori Nazionali del Gran Sasso (LNGS) until December 2018, used a sensitive target of 2.0 t of LXe in a two-phase time projection chamber (TPC). Two arrays of photomultiplier tubes (PMTs) at the top and bottom of the TPC allowed simultaneous detection of scintillation light (S1) and, via electroluminescence, ionization electrons (S2) [6,7]. With the largest exposure of any LXe TPC, data from XENON1T has been used to search for a variety of DM candidates, resulting in world-leading upper limits for DM-nucleus interactions [8–11]. Though no excess of CE\(\nu\)NS from \(^8\)B neutrinos (\(^8\)B CE\(\nu\)NS) was observed due to the energy threshold in these analyses, they will soon become an important background given the large exposures of next-generation multi-ton LXe detectors [12–14]. In this Letter, we present a search for \(^8\)B CE\(\nu\)NS events in XENON1T data between February 2, 2017 and February 8, 2018 (“SR1” in Ref. [8]). In this new analysis, we achieve unprecedented sensitivity by reducing the energy threshold.

**Analysis strategy.**—The \(^8\)B CE\(\nu\)NS expectation in XENON1T depends on the \(^8\)B neutrino flux \(\Phi\), measured as \((5.25 \pm 0.20) \times 10^6\) cm\(^{-2}\) s\(^{-1}\); the CE\(\nu\)NS cross section, from the standard model; the nuclear recoil scintillation light yield in xenon \(L_s\); and the ionization yield \(Q_y\). We first present a search for \(^8\)B CE\(\nu\)NS events in XENON1T, expecting 2.1 CE\(\nu\)NS events given nominal estimates of the above variables. We then combine XENON1T data with external measurements, as appropriate, to constrain these variables. We constrain \(L_s\) by considering external measurements of \(Q_y\) and \(\Phi\). Next, by including external measurements of \(Q_y\) and \(L_s\), we use XENON1T data to determine \(\Phi\) independently. We also constrain nonstandard neutrino interactions by relaxing the standard model assumption on the CE\(\nu\)NS cross section. Finally, by considering \(^8\)B CE\(\nu\)NS as a background and applying external constraints on all variables, we use the data to set limits on DM-nucleus interactions.

**CE\(\nu\)NS signal.**—The expected recoil spectrum of \(^8\)B CE\(\nu\)NS in LXe is shown in Fig. 1 (top, dotted red). The scintillation and ionization responses are relatively uncertain at \(^8\)B CE\(\nu\)NS energies (<2 keV), and NR calibration measurements in XENON1T scarcely overlap this region, instead producing S1s and S2s similar to DM of mass \(\geq 30\) GeV c\(^{-2}\). Therefore, we modify the NR model in Refs. [8,17] by decoupling the light and charge yields to allow for additional freedom.

The NR charge yield \(Q_y\) has been measured down to 0.3 keV [19], providing strong constraints at \(^8\)B CE\(\nu\)NS energies which are included in v2.1.0 of the NEST package [21]. We use the best fit and uncertainty from NEST to define the shape of \(Q_y\), fitting a single free “interpolation parameter” \(q\) to the measurements which specifies \(Q_y\) within this uncertainty, resulting in the model shown in Fig. 1 (middle). The central black line (edges of the shaded interval) in the figure corresponds to \(q\) equaling 0 (±1). Measurements of the LXe NR light yield \(L_s\) [20] have a large (\(\approx 20\%\)) uncertainty near 1 keV. Since the NEST \(L_s\) uncertainty is largely set by measurements at energies far above our region of interest (ROI), we fit these measurements using a free parameter that scales the NEST best-fit...
efficiency loss comes from acceptance above the 0.5 keV cutoff to 5%. Another requirement is two hits within 50 ns, increasing the total acceptance above the 0.5 keV cutoff. We reduce this "tight-coincidence" requirement to two hits within 50 ns, increasing the total acceptance above the 0.5 keV cutoff to 5%. Another efficiency loss comes from the S2 analysis threshold. The sensitivity is therefore impaired by the presence of electronegative impurities in the LXe, which reduce S2s along the drift path. The 120 PE S2 analysis threshold, reduced from 200 PE, accepts 92% of CEνNS events that pass the software trigger. Acceptance losses due to new event selection criteria introduced to suppress backgrounds are described below. Figure 1 (top) shows the S1 tight-coincidence acceptances, software trigger, and S2 threshold acceptances, and total acceptances for this and previous analyses, and the resulting spectra of expected 8B CEνNS events. The Supplemental Material of this Letter provides details on the waveform simulation used to calculate all acceptances, and demonstrates excellent matching between real and simulated S1s and S2s [25]. The overall change in acceptance results in a lowering of the energy threshold, defined as the energy where 5% of recoils are detected, from 2.6 to 1.6 keV. The ROI for the CEνNS search is defined by S2s between 120 and 500 photoelectrons (PE), and S1s between 1.0 and 6.0 PE consisting of two or three hits. In this ROI, the 8B CEνNS signal expectation increases 20-fold with respect to previous NR searches [8,10,11] because of the relaxed tight-coincidence requirement and lower S2 threshold, derived from integrating the expected event rate in Fig. 1 (top). Because of the minimal overlap with previously studied data, we consider this a blind analysis.

**Backgrounds.**—This analysis considers all backgrounds described in Refs. [8,17]. Radon daughters decaying on the inner surface of the TPC wall produce events with reduced S2s, contributing to the background in the ROI. In order to reduce this background to a negligible level, we use a fiducial volume of 1.04 t, similar to the one chosen for Ref. [18] but smaller than the one used in Ref. [8].

The accidental coincidence (AC) of S1 and S2 peaks incorrectly paired by the XENON1T reconstruction software mimics real interactions. AC background events are modeled by sampling (with replacement) from isolated S1s and S2s and assigning a random time separation between them. Most S1s contributing to AC events originate from the pileup of lone hits from individual PMTs. Other sources include low-energy events occurring below the cathode or on the inner detector surface, and light leaking inside the active volume. AC forms the dominant background for this search, since the overall rate of isolated S1s increases by 2 orders of magnitude when we require only two hits. The rate and distribution of isolated S1s are determined using S1 peaks found in the extended event window of 1 ms before the S1 of high-energy events, as in Refs. [8,17]. For this analysis, the data is reprocessed with an updated algorithm [29] to better retain the isolated S1s preceding these high-energy events, eliminating the dominant systematic uncertainty in the AC rate [8].

High-energy events from gamma-ray backgrounds can also contaminate subsequent events with lone hits, a
dominant source of S1s in this analysis. For each event, the preceding event with the highest potential to produce lone hits is identified by dividing its largest S2 area by its time difference from the current event, denoted as $S_{2 \text{prev}}/\Delta t_{\text{prev}}$. The selection $S_{2 \text{prev}}/\Delta t_{\text{prev}} < 12$ PE $\mu s^{-1}$ reduces the rate of isolated S1s by 65%, accepting 87% of $^8$B CE$_{\nu}$NS signals. Furthermore, we require the PMT signal sum within the first 1 ms of an event to be <40 PE and that this interval contains at most a single S1, accepting 96% of remaining events. After these selections, the total isolated-S1 rate is 11.2 Hz, 10 times higher than for a threefold tight-coincidence requirement [8]. The total exposure after these selection criteria is 0.6 t x y.

The same high-energy events can also produce small S2s appearing in subsequent events [30], potentially leading to unaccounted-for correlations between the isolated-S1 and isolated-S2 samples. In order to reduce these correlations, we further require that no S2 signal is found within the first millisecond of the event, and apply a cut on the horizontal spatial distance between the current and previous S2. These selections, together with the selection on $S_{2 \text{prev}}/\Delta t_{\text{prev}}$, allow us to model the AC background for S2s down to 80 PE and reduce the isolated-S2 event rate therein to 1.0 mHz. For comparison, the isolated-S2 event rate in Ref. [8] was 2.6 mHz for S2s above 100 PE [8].

Selections that require both S1 and S2, such as the fiducial volume and S2 signal width [23] cuts (which depend on the interaction depth $Z$), are next applied to the combined synthetic AC events. Interactions on the TPC electrodes and in the xenon gas above the liquid surface contribute significantly to the isolated-S2 event rate, motivating a selection in a high-dimensional feature space as in Ref. [9]. In this analysis, a gradient boosted decision tree (GBDT) [31] ensemble is trained using the scikit-learn package [32] to optimize the signal and AC background discrimination based on the S2 area, the S2 rise time, the fraction of S2 area on the top array of PMTs, and $Z$. The GBDT selection reduces the AC background by 70% while accepting $\geq 85\%$ of $^8$B CE$_{\nu}$NS events.

A background control region with S2 < 120 PE contains $\geq 50\%$ of the AC background, and is excluded from the search for $^8$B CE$_{\nu}$NS due to its low detection probability. After closer inspection of the candidate waveforms in the control region, four events whose S1s contain more than one hit in the same channel, possibly due to afterpulsing of the PMTs [7], were removed. Twenty-three events remain, consistent with the AC background prediction of 27.7 ± 1.4 events in the control region. Though the methods above yield a $\leq 5\%$ uncertainty on the AC background, we conservatively use an uncertainty of 20% in the analysis to reflect the statistical uncertainty from the control region, but find that the CE$_{\nu}$NS search is not strongly dependent on the uncertainty value within this range. Figure 2 shows the AC model, events failing the GBDT cut, and science data projected onto $Z$ and quantiles of $S_{2 \text{prev}}/\Delta t_{\text{prev}}$.

Neutrons originating from radioimpurities inside detector materials produce NRs in the TPC, but the tight ROI reduces these to 0.039$^{+0.002}_{-0.001}$ events. To limit the electronic recoil (ER) background dominated by $\beta$ decays of $^{214}$Pb (a daughter of $^{222}$Rn), we additionally require cS2$_h$, the S2 area in the bottom array after a position-dependent correction [8], to be $< 250$ PE. This reduces the ER background to 0.21 ± 0.08 events in the ROI, leading to a 4.2% absolute acceptance loss for CE$_{\nu}$NS. The same simulation procedure described in Ref. [17] is used to assess the neutron and ER backgrounds, as well as the associated uncertainties. The selection on cS2$_h$ has negligible effect on the AC background.

In the interpretation of the data, we utilize several features that differ between true S1–S2 events and AC. Lone hits are spread uniformly across the top and bottom PMT arrays, whereas scintillation light from the LXe volume mostly falls on the bottom array. Furthermore, an S1 with more than 2 PE on one PMT is very unlikely to be part of an AC, since most lone hits in XENON1T consist of a single photoelectron. We split the data into six “hit categories” according to the number and arrangement of S1 hits, and the largest hit-area (LHA), listed in Table I.

Inference.—We analyze the data with a statistical model adapted from Ref. [17], with three continuous analysis
dimensions; S2, zero, and the quantiles of equal signal acceptance in $S_2_{\text{prev}}/\Delta t_{\text{prev}}$. The likelihood for XENON1T is the product of the likelihoods for each hit category, indexed with i

$$L_{Xe1T}(\Phi, Q_y, L_y, \tilde{\theta}) = \prod_{i=1}^{6} L_i(\Phi, Q_y, L_y, \tilde{\theta}) \times \prod_m [L_m(\theta_m)].$$ (1)

Here, $\tilde{\theta}$ are the nuisance parameters. The extended unbinned likelihood terms $L_i(\Phi, Q_y, L_y, \tilde{\theta})$ are of the same form as Eq. (20) in Ref. [17], and include models in S2, zero, and $S_2_{\text{prev}}/\Delta t_{\text{prev}}$ for the $^8B$ CE$_{\text{ns}}$ signal and AC, ER, and neutron backgrounds. The background component rates $\theta_m$ are constrained by the external measurement terms $L_m(\theta_m)$.

For the $^8B$ CE$_{\text{ns}}$ search, the nuisance parameters are the expectation values of the backgrounds, each with a constraint term, as well as the NR response parameters $Q_y$ and $L_y$. The total likelihood used in the CE$_{\text{ns}}$ search is the product of $L_{Xe1T}$, defined in Eq. (1), and external constraints on $Q_y$ and $L_y$, as detailed above. For these results, the models of CE$_{\text{ns}}$, DM, and the neutron background change both in shape and expectation value with $Q_y$ and $L_y$. The CE$_{\text{ns}}$ discovery significance as well as DM upper limits are computed using the log-likelihood-ratio test statistic calibrated with toy Monte Carlo (toy-MC) simulations [17,33].

To construct confidence intervals in $\Phi$, $Q_y$, and $L_y$, we define a test statistic from the sum of profiled log likelihoods of XENON1T and external constraints. By including external measurements of $Q_y$, we can constrain $L_y$. Since the CE$_{\text{ns}}$ signal spans a narrow energy range, we use a constant $L_y$ value to construct the intervals. This allows us to make use of the degeneracy between $\Phi$ and the NR response parameters $Q_y$ and $L_y$, all three of which primarily affect the CE$_{\text{ns}}$ expectation value. Details on the construction of these confidence intervals may be found in the Supplemental Material [25].

By including external constraints on $\Phi$, $Q_y$, and $L_y$, this analysis can be used to consider physics processes beyond the standard model. We consider a benchmark model in which nonstandard neutrino interactions modify the CE$_{\text{ns}}$ cross section [3,34,35]. Our confidence interval on $\Phi$ assuming the standard model cross section can be reinterpreted as a confidence interval on the modified CE$_{\text{ns}}$ cross section if we use the externally measured value of $\Phi$. We also consider DM-nucleus interactions, including CE$_{\text{ns}}$ as a background contribution, and $Q_y$ and $L_y$ as nuisance parameters. We use the same profile construction approach to compute upper limits as Ref. [17], including a power constraint [36].

Results.—We estimated the probability of observing a $3\sigma$ ($2\sigma$) CE$_{\text{ns}}$ excess in this data to be 20% (50%) for the nominal (NEST best fit) $Q_y$, $L_y$. Inverting the GBDT cut gave an AC-rich validation region that was unblinded first (Table I). Background-only goodness-of-fit (GOF) tests using a binned Poisson likelihood were performed on the validation region, both for the six S1 hit categories and in the continuous analysis space, with $p$ values of 0.95 and 0.33, respectively, which exceeded the 0.05 validation criterion. The science dataset was unblinded following the successful validation region unblinding. Six events were found, as listed in Table I. The events are compatible with the background-only hypothesis, with a CE$_{\text{ns}}$ discovery significance of $p > 0.50$. The same GOF tests used to assess the validation region unblinding show good agreement, with $p = 0.64$ and $p = 0.72$, respectively. The XENON1T confidence interval in $\Phi$, $Q_y$, and $L_y$ does not strongly constrain any of the parameters due to the significant correlation in particular between $\Phi$ and $L_y$, as

<table>
<thead>
<tr>
<th>S1 hit properties</th>
<th>Hit category</th>
<th>LHA</th>
<th>Science data</th>
<th>AC validation region</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>AC</td>
<td>ER</td>
</tr>
<tr>
<td></td>
<td>$\geq 2$ PE</td>
<td></td>
<td>0.09</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>&lt;2 PE</td>
<td></td>
<td>3.54</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>$\geq 2$ PE</td>
<td>&lt;2 PE</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>$\geq 2$ PE</td>
<td>&lt;2 PE</td>
<td>1.47</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>$\geq 2$ PE</td>
<td>&lt;2 PE</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>$\geq 2$ PE</td>
<td>&lt;2 PE</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td>5.14</td>
<td>0.21</td>
</tr>
</tbody>
</table>
shown by the green shaded region in Fig. 3 (top). On the other hand, \( \Phi \) can be constrained if the external constraints on \( Q_y \) and \( L_y \) are included, as shown in the pink region, with a 90\% upper limit on \( \Phi \) of \( 4.4 \times 10^7 \, \text{cm}^{-2} \, \text{s}^{-1} \). The blue region in Fig. 3 shows the confidence interval from a combination of the XENON1T likelihood, constraints on \( \Phi \) [16], and on \( Q_y \). The 90\% upper limit on \( L_y \) (assumed constant over the 0.9–1.9 keV energy range) is 9.4 ph/keV.

In the benchmark model of nonstandard neutrino interactions considered, the electron neutrino has vector couplings to the up (\( u \)) and down (\( d \)) quarks of \( e_{\nu e}^{\nu} \) and \( e_{\nu e}^{\nu} \), respectively [3,34,35]. The 90\% confidence interval for \( e_{\nu e}^{\nu} \) and \( e_{\nu e}^{\nu} \) from XENON1T data is shown in light blue in Fig. 4 (top).

The result for a spin-independent DM-nucleus interaction is shown in Fig. 4 (bottom). This constraint improves on previous world-leading limits [8,9] in the mass range between 3 and 11 GeV \( c^{-2} \) by as much as an order of magnitude. The limit lies at roughly the 15th percentile, reflecting the downwards fluctuation with respect to the background model (including CE\( \nu \)NS), but is not extreme enough to be power constrained.

**Outlook.**—The XENONnT experiment, currently being commissioned at LNGS, aims to acquire a 20 t \( \times \) y exposure [14]. As the isolated-S1 rate scales up with the larger number of PMTs and the isolated-S2 rate with the detector surface area, the AC background will be the biggest challenge for the discovery of \(^8\text{B}\) CE\( \nu \)NS. The AC background modeling and discrimination techniques used in this analysis will improve the sensitivity of XENONnT to \(^8\text{B}\) CE\( \nu \)NS and low-mass DM. The novel cryogenic...
liquid circulation system developed to ensure efficient purification in XENONnT will mitigate the reduction of S2s due to impurities, improving the acceptance of low-energy NRs from $^8$B neutrinos and DM. Additionally, the data will be analyzed in a triggerless mode to minimize efficiency loss and better understand the AC background. Together with the significantly larger exposure, these techniques give XENONnT strong potential to discover $^8$B CE$\nu$NS.

The large uncertainty in both $Q_\nu$ and $L_\nu$ will be the dominant systematic in constraining new physics from DM and nonstandard neutrino interactions. Improving these uncertainties by calibrating NRs in LXe using in situ low energy neutrion sources [46] and dedicated detectors [19] can crucially improve the sensitivity of next-generation experiments to both $^8$B CE$\nu$NS and light DM.

We would like to thank Matthew Szydagis and Ekaterina Kozlova for useful discussions concerning the NEST model. We gratefully acknowledge support from the National Science Foundation, Swiss National Science Foundation, German Ministry for Education and Research, Max Planck Gesellschaft, Deutsche Forschungsgemeinschaft, Helmholtz Association, Netherlands Organisation for Scientific Research (NWO), Weizmann Institute of Science, ISF, Fundacao para a Ciencia e a Tecnologia, Region des Pays de la Loire, Knut and Alice Wallenberg Foundation, Kavli Foundation, JSPS Kakenhi in Japan and Istituto Nazionale di Fisica Nucleare. This project has received funding or support from the European Unions Horizon 2020 research and Innovation programme under the Marie Sklodowska-Curie Grant Agreements No. 690575 and No. 674896, respectively. Data processing is performed using infrastructures from the Open Science Grid, the European Grid Initiative, and the Dutch national e-infrastructure with the support of SURF Cooperative. We are grateful to Laboratori Nazionali del Gran Sasso for hosting and supporting the XENON project.

---

[37] D. S. Akerib et al. (LUX Collaboration), Low-energy (0.7–74 keV) nuclear recoil calibration of the LUX dark matter experiment using d-d neutron scattering kinematics, arXiv:1608.05381.
[38] J. Dorenbosch et al. (CHARM Collaboration), Experimental verification of the universality of $\nu_e$ and $\nu_\mu$ coupling to the neutral weak current, Phys. Lett. B 180, 303 (1986).
[40] H. Jiang et al. (CDEX Collaboration), Limits on Light Weakly Interacting Massive Particles from the First 102.8 kg × day Data of the CDEX-10 Experiment, Phys. Rev. Lett. 120, 241301 (2018).