Search for Light Dark Matter Interactions Enhanced by the Migdal Effect or Bremsstrahlung in XENON1T

XENON Collaboration; Aprile, E.; Aalbers, J.; Breur, P.A.; Brown, A.; Colijn, A.P.; Decowski, M.P.; Gaemers, P.

DOI
10.1103/PhysRevLett.123.241803

Publication date
2019

Document Version
Final published version

Published in
Physical Review Letters

License
CC BY

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 Light Dark Matter Interactions Enhanced by the Migdal Effect or Bremsstrahlung in XENON1T

E. Aprile,1 J. Aalbers,2 F. Agostini,3 M. Alfonsi,4 L. Althueser,5 F.D. Amaro,6 V.C. Antochi,2 E. Angelino,7 F. Arneodo,8 D. Barge,2 L. Baudis,9 B. Bauermeister,2 L. Bellagamba,3 M.L. Benabderrahmane,8 T. Berger,10 P.A. Breur,11 A. Brown,9 E. Brown,10 S. Bruenner,12 G. Bruno,8 R. Budnik,13 C. Capelli,9 J.M.R. Cardoso,6 D. Cichon,12 D. Coderre,14 A.P. Colijn,11 J. Conrad,2 J.P. Cussonneau,15 M.P. Decowski,11 P. de Perio,1 A. Depoian,16 P. Di Gangi,3 A. Di Giovanni,8 S. Diglio,15 J.A.M. Lopes,6 J.M. R. Lopes Fune,22 C. Macolino,23 J. Mahlstedt,2 M. Manenti,8 A. Manfredini,9,13 F. Marignetti,20 T. Marrodán Undagoitia,12 J. Masbou,2 Y. Morris,21, K. Micheneau,15 K. Miller,19 A. Molinaro,18 K. Morå,2 Y. Mosbacher,13 M. Murra,5 J. Nagano,18,24 K. Ni,17 U. Oberlack,9 K. Odgers,10 J. Palacio,15 B. Pelssers,2 R. Peres,9 J. Pienaar,19 V. Pizzella,12 G. Plante,1 R. Podviianiuk,18 J. Qin,16 H. Qiu,13 D. Ramirez Garcia,14 S. Reichard,13 B. Riedel,19 A. Rocchetti,14 N. Rupp,12 J.M.F. dos Santos,6 G. Sartorelli,3 N. Šarčević,14 M. Scheibehut,24 S. Schindler,4 J. Schreiner,12 D. Schulte,5 M. Schumann,14 L. Scoffetta,22 M. Selvi,24 J. Shockley,19 M. Silva,6 H. Simgen,12 C. Therreau,15 D. Thers,15 F. Toschi,14 G. Trinchero,7 C. Tunnell,24 N. Uple,19 M. Vargas,5 G. Volta,9 O. Wack,12 H. Wang,25 Y. Wei,17 C. Weinheimer,5 D. Wenz,4 C. Wittweg,5 J. Wulf,9 J. Ye,17 Y. Zhang,1 T. Zhu,1 and J.P. Zopounidis22

(XENON Collaboration)†

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
4Institut für Physik and Exzellenzcluster PRISMA, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany
5Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, 48149 Münster, Germany
6LIBPhys, Department of Physics, University of Coimbra, 3004-516 Coimbra, Portugal
7INAF-Astrophysical Observatory of Torino, Department of Physics, University of Torino and INFN-Torino, 10125 Torino, Italy
8New York University Abu Dhabi, P.O. Box 129188, Abu Dhabi, United Arab Emirates
9Physik-Institut, University of Zurich, 8057 Zurich, Switzerland
10Department of Physics, Applied Physics and Astronomy, Rensselaer Polytechnic Institute, Troy, New York 12180, USA
11Nikhef and the University of Amsterdam, Science Park, 1098XG Amsterdam, Netherlands
12Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany
13Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot 7610001, Israel
14Physikalisches Institut, Universität Freiburg, 79104 Freiburg, Germany
15SABATECH, IMT Atlantique, CNRS/IN2P3, Université de Nantes, Nantes 44307, France
16Department of Physics and Astronomy, Purdue University, West Lafayette, Indiana 47907, USA
17Department of Physics, University of California, San Diego, California 92093, USA
18INFN-Laboratori Nazionali del Gran Sasso and Gran Sasso Science Institute, 67100 L’Aquila, Italy
19Department of Physics and Kavli Institute for Cosmological Physics, University of Chicago, Chicago, Illinois 60637, USA
20Department of Physics “Ettore Pancini,” University of Napoli and INFN-Napoli, 80126 Napoli, Italy
21Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8602, Japan
22LPNHE, Université Pierre et Marie Curie, Université Paris Diderot, CNRS/IN2P3, Paris 75252, France

123, 241803 (2019)
Direct dark matter detection experiments are leading the search for dark matter particles with masses above ~5 GeV/c^2, but have limited sensitivity to lighter masses because of the small momentum transfer in dark matter-nucleus elastic scattering. However, there is an irreducible contribution from inelastic processes accompanying the elastic scattering, which leads to the excitation and ionization of the recoiling atom (the Migdal effect) or the emission of a bremsstrahlung photon. In this Letter, we report on a probe of low-mass dark matter with masses down to about 85 MeV/c^2 by looking for electronic recoils induced by the Migdal effect and bremsstrahlung using data from the XENON1T experiment. Besides the approach of detecting both scintillation and ionization signals, we exploit an approach that uses ionization signals only, which allows for a lower detection threshold. This analysis significantly enhances the sensitivity of XENON1T to light dark matter previously beyond its reach.

DOI: 10.1103/PhysRevLett.123.241803

The existence of dark matter (DM) is supported by various astronomical and cosmological observations [1–3], but its nature remains unknown. The most promising DM candidate is the so-called weakly interacting massive particle (WIMP) [4], which explains the current abundance of dark matter as a thermal relic of the big bang [5]. In the past three decades, numerous terrestrial experiments have been built to detect the faint interactions between WIMPs and ordinary matter. Among them, experiments using dual-phase (liquid-gas) xenon time projection chambers (TPCs) [6–8] are leading the search for WIMPs with masses from a few GeV/c^2 to TeV/c^2. The mass of the WIMP is expected to be larger than about 2 GeV/c^2 from the Lee-Weinberg limit [5] assuming a weak scale interaction. On the other hand, DM in the sub-GeV/c^2 mass range has more recently been proposed in several models [9]. In this Letter, we report on a probe of light DM-nucleon elastic interactions by looking for electronic recoils (ERs) in XENON1T, induced by secondary radiation, bremsstrahlung (BREM) [10] and the Migdal effect [11,12], that can accompany a nuclear recoil (NR). ER signals induced by the Migdal effect and BREM can go well below 1 keV, where the detection efficiency for the scintillation signal is low. Therefore, in addition to the analysis utilizing both ionization and scintillation signals, we performed an analysis using the ionization signal only, which improves the detection efficiency for sub-keV ER events. We present results from a probe of light DM (LDM) with masses as low as 85 MeV/c^2.

The XENON1T direct dark matter detection experiment [13] uses a dual-phase TPC containing 2 tonnes of ultrapure liquid xenon (LXe) as the active target material. It is located at the INFN Laboratori Nazionali del Gran Sasso (LNGS) in Italy, which has an average rock overburden of 3600 m water equivalent. The prompt primary scintillation (S1) and secondary electroluminescence of ionized electrons (S2) signals are detected by top and bottom arrays of 248 Hamamatsu R11410-21 3" photomultiplier tubes (PMTs) [14,15]. They are used to reconstruct the deposited energy and the event interaction position in three dimensions, which allows for fiducialization of the active volume [16,17]. The XENON1T experiment has published WIMP search results by looking for NRs from WIMP-nucleus elastic scattering using data from a one-tonne-year exposure, achieving the lowest ER background in a DM search experiment [8]. The excellent sensitivity of LXe experiments to heavy WIMPs comes from the heavy xenon nucleus which gives a coherent enhancement of the interaction cross section and from the large NR energy. The sensitivity to sub-GeV/c^2 LDM, on the other hand, decreases rapidly with lowering DM mass since detectable scintillation and ionization signals produced by these NRs become too small. The energy threshold (defined here as the energy at which the efficiency is 10%) in a LXe TPC is mainly limited by the amount of detectable S1 signals. A significant fraction of deposited NR energy is transferred into heat due to the Lindhard quenching effect [18]. Thus the detection efficiency for these NRs becomes extremely low, with less than 10% for NRs below 3.5 keV in XENON1T [8]. It is challenging to detect the NR signals from LDM interactions.

Unlike NRs, ERs lose negligible energy as heat because recoil electrons have small masses compared with xenon nuclei. This leads to a lower energy threshold for ER signals. Probing the ER signals induced by the Migdal
effect (MIGD) and BREM enables a significant boost of XENON1T’s sensitivity to LDMs, thanks to the lowered threshold.

When a particle elastically scatters off a xenon nucleus, the nucleus undergoes a sudden momentum change with respect to the orbital atomic electrons, resulting in the polarization of the recoiling atom and a kinematic boost of the electrons. The depolarization process can lead to MIGD emission [10], and the kinematic boost of atomic electrons can result in ionization and/or excitation of the atom, which eventually causes secondary radiation, known as the Migdal effect [11, 12].

The differential rate of MIGD process giving a NR accompanied by an ER of energy \( E_{ER} \) is given by

\[
\frac{dR}{dE_{ER} dv} \propto \frac{f(E_{ER})^2}{E_{ER}} \sqrt{1 - \frac{2E_{ER}}{\mu_N v^2} \left( 1 - \frac{E_{ER}}{\mu_N v^2} \right)},
\]

where \( v, \mu_N \), and \( f(E_{ER}) \) are the velocity of DM, the reduced mass of the xenon nucleus and DM, and the atomic scattering factor, respectively [10].

The differential rate of the MIGD process giving a NR of energy \( E_{NR} \) accompanied by an ER of energy \( E_{ER} \) is given by

\[
\frac{dR}{dE_{ER} dv} \approx \int dE_{NR} \frac{d^2R}{dE_{NR} dv} \left[ \frac{1}{2\pi} \sum_{n,l} \frac{d}{E_{ER}} \rho_{q_{n,l}}(n, l \to E_{ER} - E_{n,l}) \right],
\]

where \( \rho_{q_{n,l}} \) is the probability for an atomic electron, with quantum numbers \( (n, l) \) and binding energy \( E_{n,l} \), to be ionized and receive a kinetic energy \( E_{ER} - E_{n,l} \) [12]. \( \rho_{q_{n,l}} \) is related to \( q_{n,l} \), which is the momentum of each electron in the rest frame of the nucleus after the scattering. The shell vacancy is immediately refilled, and an x ray or an Auger electron with energy \( E_{n,l} \) is emitted. \( E_{n,l} \) is measured simultaneously with the energy deposited by the ionized electron, since the typical timescale of the deexcitation process is \( O(10) \) fs. Atomic electrons can also undergo excitation instead of ionization, in which case an x ray is emitted during deexcitation [12]. Excitation, however, is subdominant compared to the ionization process, and thus is not considered in this analysis. Only the contributions from the ionization of M-shell \( (n = 3) \) and N-shell \( (n = 4) \) electrons are considered in this work, as inner electrons \( (n \leq 2) \) are too strongly bound to the nucleus to contribute significantly.

The region of interest in the S1-S2 data is from 3 to 70 photoelectrons (PEs) in cS1, which corresponds to median ER energies from 1.4 to 10.6 keV in the 1.3-tonne fiducial volume of XENON1T. The lower value is dictated by the requirement of the threefold PMT coincidence for defining a valid S1 signal [16]. A detailed signal response model [17] is used to derive the influence of various detector features, including the requirement of the threefold PMT coincidence, on the reconstructed signals. The effective exposure, which is defined as exposure times detection efficiency, and its uncertainty as a function of deposited ER energy for the S1-S2 data are shown in Fig. 2, with the signal spectra from MIGD and BREM induced by 0.1 and 1 GeV/c\(^2\) DM masses overlaid. The (cS2b, cS1) distribution of S1-S2 data are shown in Fig. 3. The rise of the event rate at around 0.85 keV for DM mass of 1.0 GeV/c\(^2\) is contributed by the ionization of M-shell electrons [10, 12].
In our signal models, deposited energy below 1 keV, at which the median detection efficiency in 1.3-ton fiducial volume is 10%, from MIGD and BREM is neglected for the S1-S2 data in the following analysis. There are only two sub-keV measurements of ionization yield for ER in LXe [19,20].

The S1-S2 data selections [16] provide excellent rejection of noise and backgrounds, and are characterized as well by the well-established background models [17] and a fully blind analysis [8]. However, they also limit the detection efficiency of $O(1)$ keV energy depositions. We therefore consider also the events with no specific requirement on S1 (S2-only data) in this work. Although the reduction of available information in the S2-only data implies less background discrimination, the increased detection efficiency in the < 1 keV ER energy region, shown in Fig. 2, enables a more sensitive search for LDM-nucleus interactions through MIGD and BREM. The interpretation of such S2-only data is based on the uncorrected S2 signal, combining both signals from top and bottom PMT arrays.

We analyze the S2-only data as in Ref. [21], using the LDM signal models appropriate for MIGD and BREM. As detailed in Ref. [21], 30% of the data were used for choosing regions of interest (ROIs) in S2 and event selections. A different S2 ROI is chosen for each dark matter model and mass to maximize the signal-to-noise ratio, based on the training data. The event selections used for this work are the same as in Ref. [21], and mainly based on the width of each S2 waveform, reconstructed radius, and PMT hit pattern of the S2. Figure 4 shows the observed S2 spectra for the S2-only data, along with the expected DM signal distributions by MIGD with masses of 0.1, 0.5, and 1.0 GeV/c^2, respectively. The S2 ROIs for these three DM models shown in Fig. 4 are indicated by the colored arrows. Conservative estimates of the background from $^{214}$Pb-induced $\beta$ decays, solar-neutrino-induced NRs, and surface backgrounds from the cathode electrode are used in the inference [21]. The background model is shown in Fig. 4 as a shaded gray region.

FIG. 2. Median effective exposures of ER signals after event selections as a function of recoil energy for the S1-S2 data (black line) and S2-only data (red line). The 68% credible regions of the effective exposures are also shown as the shaded regions. The expected event rate of DM-nucleus scattering from MIGD (BREM) for DM masses of 0.1 and 1.0 GeV/c^2 are overlaid as well, in magenta (green) dashed and solid lines, respectively, assuming a spin-independent DM-nucleon interaction cross section of $10^{-35}$ cm^2.

FIG. 3. Comparison of cS1 and cS2_b spectra between the S1-S2 data and the signal response model [17]. In upper panel (I), the distribution of the S1-S2 data in (cS2_b, cS1) space is shown as light blue dots, along with the best-fit ER background model (black shaded region). The contours containing 90% of the expected signals from MIGD for 0.3, 0.5, and 1 GeV/c^2 DM are shown in red dotted, dashed, and solid lines, respectively. Gray lines show isoenergy contours in ER energy. The events having lower cS2_b than what we expect for ER are mostly surface backgrounds [8], which have minimal impact to the results of this study. The lower panel (II) shows the projected cS1 distribution of the S1-S2 data, where cS2_b is within the 2σ contour of ER model shown in (I). For comparison, the 68% credible region of cS1 distribution from ER background model (blue shadow) is shown, which is mainly attributed to the systematic uncertainties of the model. The cS1 distributions of the expected signals from MIGD for 0.3, 0.5, and 1 GeV/c^2 DM with assumed spin-independent DM-nucleon cross sections of $2 \times 10^{-28}$, $10^{-28}$, and $10^{-28}$ cm^2, respectively, are shown as well. The vertical dashed lines indicate the region of interest (3–70 PE). The inset, panel (III), shows the cS2_b distribution, with cS1 in (3,10) PE, compared with the 68% credible region of the cS2_b spectra from the ER background model (blue shadow).
using background models defined in c
profile likelihood ratio as the test statistic, as detailed in
ER and NR energy depositions. We use the inference only
BREM in this analysis and there is no measurement of
since it is small compared with ERs from MIGD and
bution of NRs in the signal model of MIGD and BREM,
are not sensitive to incident dark matter velocity as long as
ERs from MIGD. Signal contours for different DM masses
components, are taken into account in the inference[17].
uncertainties in the estimated rates of each background
ionization yields of ER backgrounds, along with the
coordinates. The uncertainties from the scintillation and

above which the contri-

The detector response to ERs from MIGD and BREM in
(cS2h, cS1) space (for the S1-S2 data) and in reconstructed
number of electrons (for the S2-only data) is derived using
the signal response model described in Ref. [17]. Note that
the ionization yield used for the S2-only data is more
conservative than the noble element simulation technique
(NEST) v2 model [22]. Figure 3 shows the comparison
between the expectation from our signal response model
and the S1-S2 data, as well as the (cS2h, cS1) distribution of
ERs from MIGD. Signal contours for different DM masses
are similar since the energy spectra from MIGD and BREM
are not sensitive to incident dark matter velocity as long as
it is kinematically allowed. We have ignored the contribu-
tion of NRs in the signal model of MIGD and BREM,
since it is small compared with ERs from MIGD and
BREM in this analysis and there is no measurement of
scintillation and ionization yields in LXe for simultaneous
ER and NR energy depositions. We use the inference only
for DM mass below 2 GeV/c^2, above which the contribu-
tion of a NR in the signal rate becomes comparable with
or exceeds the signal model uncertainty.

The S1-S2 data are interpreted using an unbinned
profile likelihood ratio as the test statistic, as detailed in
Ref. [17]. The unbinned profile likelihood is calculated
using background models defined in cS2h, cS1, and spatial
coordinates. The uncertainties from the scintillation and
ionization yields of ER backgrounds, along with the
uncertainties in the estimated rates of each background
component, are taken into account in the inference [17].
The inference procedure for the S2-only data is detailed in
Ref. [21], which is based on simple Poisson statistics
using the number of events in the S2 ROI. The event rates
of spin-independent (SI) and -dependent (SD) DM-nucleon
elastic scattering are calculated following the approaches
described in Refs. [8,23] and Ref. [24], respectively.

The results are also interpreted in a scenario where LDM
interacts with the nucleon through a scalar force mediator φ
with equal effective couplings to the proton and neutron as
in the SI DM-nucleon elastic scattering. In this scenario,
the differential event rates are corrected by

\[ \frac{m_\phi^4}{m_N^2 + q^2/c^2} \]

where \( q = \sqrt{2m_N E_N} \) and \( m_N \) are the
momentum transfer and the nuclear mass, respectively. We
take the light mediator (LM) regime where the momentum
transfer is much larger than \( m_\phi \) and thus the interaction
cross section scales with \( m_\phi^4 \). In this regime, the
contribution of NRs is largely suppressed compared with SI DM-
nucleon elastic scattering due to the long-range nature of
the interaction. Therefore, the results are interpreted for
DM mass up to 5 GeV/c^2 for SI-LM DM-nucleon elastic
scattering.

In addition, we also take into account the fact that a
DM particle may be stopped or scatter multiple times
when passing through Earth’s atmosphere, mantle, and
core before reaching the detector (Earth-shielding effect)
[27–29]. If the DM-matter interaction is sufficiently strong,
the sensitivity for detecting such DM particles in terrestrial
detectors, especially in an underground laboratory, can be
reduced or even lost totally. Following Ref. [30], the VERNE
code [31] is used to calculate the Earth-shielding effect for
SI DM-nucleon interaction. A modification of the VERNE
code based on the methodology in Ref. [32] is applied for
the calculations of SD and SD-LM DM-nucleon inter-
actions. To account for the Earth-shielding effect for SD
DM-nucleon interaction, \(^{14}\)N in the atmosphere and \(^{28}\)Si in
Earth’s mantle and core are considered, and their spin
expectation values, \( \langle S_n \rangle \) and \( \langle S_p \rangle \), are taken from Ref. [33].

Both the lower and upper boundaries of excluded parameter
space are reported in this work. The lower boundaries are
conventionally referred to as upper limits in later context,
and are the primary interest of this work. The upper
boundaries are dominated by the overburden configuration
of the Gran Sasso laboratory which hosts the detector.

No significant excess is observed above the background
expectation in the search using the S1-S2 data. Figure 5
shows the 90% confidence level (C.L.) limits [34] on the SI
and SD (proton-only and neutron-only cases) DM-nucleon
interaction cross section using signal models from MIGD
and BREM with masses from about 85 MeV/c^2 to
2 GeV/c^2, and Fig. 6 shows the 90% C.L. limits [34]
on the SI-LM DM-nucleon interaction cross section with
masses from about 100 MeV/c^2 to 5 GeV/c^2. The sensi-
tivity contours for the results derived using S2-only data are
not shown because of the conservativeness of the back-
ground model. The upper limits derived using the S1-S2
data deviate from the median sensitivity by about $1 \sigma \sim 2 \sigma$ due to the underfluctuation of the ER background in the low energy region. As described in Ref. [21], the jumps in the $S_2$-only limits are originating from the changes in the observed number of events due to the mass-dependent $S_2$ ROIs. The results, by searching for ER signals induced by MIGD, give the best lower exclusion boundaries on SI, SD, proton-only, SD neutron-only, and SI-LM DM-nucleon interaction cross section for mass below about 1.8, 2.0, and 4.0 GeV/$c^2$, respectively, as compared to previous experiments [30,35–42]. The upper limits derived from the $S_1$-$S_2$ data become comparable with those from the $S_2$-only data at $\sim$GeV/$c^2$ since the efficiency of the $S_1$-$S_2$ data to DM signals with mass of $\sim$GeV/$c^2$ becomes sufficiently high. However, the upper limits derived from the $S_1$-$S_2$ data do not provide significantly better constraints than those from the $S_2$-only data for DM masses larger than 1 GeV/$c^2$, because both data are dominated by the ER background, which is very similar to the expected DM signal.

In summary, we performed a search for LDM by probing ER signals induced by MIGD and BREM, using data from the XENON1T experiment. These new detection channels significantly enhance the sensitivity of LXe experiments to masses unreachable in the standard NR searches. We set the most stringent upper limits on the SI and SD DM-nucleon interaction cross sections for masses below 1.8 and 2 GeV/$c^2$, respectively. Together with the standard NR search [8], XENON1T results have reached unprecedented sensitivities to both low-mass (sub-GeV/$c^2$) and high-mass (GeV/$c^2$–TeV/$c^2$) DM. With the upgrade to XENONnT, we expect to further improve the sensitivity to DM with masses ranging from about 85 MeV/$c^2$ to beyond a TeV/$c^2$.

The authors would like to thank Masahiro Ibe and Yutaro Shoji for helpful discussions on MIGD and for providing us with the code for calculating the rate of MIGD radiation in xenon. We would like to thank Bradley Kavanagh for helpful discussion on the Earth-shielding effect. We gratefully acknowledge support from the National Science Foundation, Swiss National Science Foundation, German Ministry for Education and Research, Max Planck Gesellschaft, Deutsche Forschungsgemeinschaft,
Netherlands Organisation for Scientific Research (NWO), Netherlands eScience Center (NLeSC) with the support of the SURF Cooperative, Weizmann Institute of Science, Israeli Centers Of Research Excellence (I-CORE), Pazy-Vatat, Fundacao para a Ciencia e a Tecnologia, Region des Pays de la Loire, Knut and Alice Wallenberg Foundation, Kavli Foundation, and Istituto Nazionale di Fisica Nucleare. This project has received funding or support from the European Union’s 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 and European Grid Initiative. We are grateful to Laboratori Nazionali del Gran Sasso for hosting and supporting the XENON project.


Correction: The second sentence of the caption to Figure 4 contained an error and has been fixed.