First Axion Results from the XENON100 Experiment

E. Aprile,1 F. Agostini,2• M. Alfonsi,3 K. Arisaka,4 F. Arneodo,5• M. Auger,6 C. Balan,7 P. Barrow,6 L. Baudis,6 B. Bauermeister,8 A. Behrens,6 P. Beltrame,9• K. Bokeloh,10 A. Brown,11 E. Brown,10 S. Bruenner,12 G. Bruno,5 R. Budnik,9 J. M. R. Cardoso,7 A. P. Colijn,3 H. Contreras,1 J. P. Cussonneau,13 M. P. Decowski,3 E. Duchovni,9 S. Fattori,8 A. D. Ferella,8 W. Fulgione,14 F. Gao,15• M. Garbini,2 C. Geis,8 L. W. Goetzke,1 C. Grignon,8 E. Gross,9 W. Hampel,12 R. Itay,9 F. Kaether,12 G. Kessler,6 A. Kish,8 H. Landsman,9 R. F. Lang,11 M. Le Calloch,7,13 D. Lellouch,3 C. Levy,10 S. Lindemans,12 M. Lindner,12 J. A. M. Lopes,7• K. Lung,4 A. Lyashenko,4 S. MacMullin,11 T. Marrodán Undagoitia,12 J. Masbou,13 F. V. Massoli,2 D. Mayani Paras,6 A. J. Melgarejo Fernandez,1 Y. Meng,4 M. Messina,1 B. Miguel,14 A. Molinaro,14 M. Murra,10 J. Naganoma,16 K. Ni,15 U. Oberlack,8 S. E. A. Orrigo,7• E. Pantic,4 R. Persiani,2 F. Piastra,6 J. Pienaar,11 G. Plante,1 N. Priel,9• S. Reichard,11 C. Reuter,11 A. Rizzo,1 S. Rosendahl,10 J. M. F. dos Santos,7 G. Sartorelli,2 S. Schindler,8 J. Schreiner,12 M. Schumann,17 L. Scotto Lavina,13 M. Selvi,2 P. Shagin,16 H. Singen,12 A. Teymourian,4 D. Thers,13 A. Tiseni,3 G. Trinchero,14 O. Vitells,9 H. Wang,4 M. Weber,12 and C. Weinheimer.10

(The XENON100 Collaboration)

1Physics Department, Columbia University, New York, NY, USA
2University of Bologna and INFN-Bologna, Bologna, Italy
3Nikhef and the University of Amsterdam, Science Park, Amsterdam, Netherlands
4Physics & Astronomy Department, University of California, Los Angeles, CA, USA
5INFN, Laboratori Nazionali del Gran Sasso, Assergi (AQ), Italy
6Physics Institute, University of Zurich, Zurich, Switzerland
7Department of Physics, University of Coimbra, Coimbra, Portugal
8Institut für Physik & Ezzellenzcluster PRISMA, Johannes Gutenberg-Universität Mainz, Mainz, Germany
9Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot, Israel
10Institut für Kernphysik, Wilhelms-Universität Münster, Münster, Germany
11Department of Physics, Purdue University, West Lafayette, IN, USA
12Max-Planck-Institut für Kernphysik, Heidelberg, Germany
13SUBATECH, École des Mines de Nantes, CNRS/In2p3, Université de Nantes, Nantes, France
14INFN-Torino and Osservatorio Astrofisico di Torino, Torino, Italy
15Department of Physics & Astronomy, Shanghai Jiao Tong University, Shanghai, China
16Department of Physics and Astronomy, Rice University, Houston, TX, USA
17Albert Einstein Center for Fundamental Physics, University of Bern, Bern, Switzerland

We present the first results of searches for axions and axion-like-particles with the XENON100 experiment. The axion-electron coupling constant, $g_{Ae}$, has been probed by exploiting the axio-electric effect in liquid xenon. A profile likelihood analysis of 224.6 live days $\times$ 34 kg exposure has shown no evidence for a signal. By rejecting $g_{Ae}$ larger than $7.7 \times 10^{-12}$ (90% CL) in the solar axion search, we set the best limit to date on this coupling. In the frame of the DFSZ and KSVZ models, we exclude QCD axions heavier than 0.3 eV/c$^2$ and 80 eV/c$^2$, respectively. For axion-like-particles, under the assumption that they constitute the whole abundance of dark matter in our galaxy, we constrain $g_{Ae}$ to be lower than $1 \times 10^{-12}$ (90% CL) for mass range from 1 to 40 keV/c$^2$, and set the best limit to date as well.

PACS numbers:
Keywords: Dark Matter, Axion, Xenon

I. INTRODUCTION

Axions were introduced in the Peccei-Quinn solution of the strong CP problem as pseudo-Nambu-Goldstone bosons emerging from the breaking of a global U(1) symmetry [1–3]. Although this original model has been ruled out, “invisible” axions arising from a higher symmetry-breaking energy scale are still allowed, as described, for example, in the DFSZ and KSVZ models [4–7]. In addition to QCD axions, axion-like particles (ALPs) are pseudoscalars that do not necessarily solve the strong CP problem, but which have been introduced by many extensions of the Standard Model of particle physics. Ax-
ions as well as ALPs are well motivated cold dark matter candidates [8].

Astrophysical observations are thought to be the most sensitive technique for detecting axions and ALPs [9]; the Sun would constitute an intense source of this particles (referred to as solar axions), where they can be produced via Bremsstrahlung, Compton scattering, axio-recombination and axio-deexcitation [10]. Additionally, searches can be conducted for ALPs that may have been generated via a non-thermal production mechanism in the early universe and which now constitute the dark matter in our galaxy (referred to as galactic ALPs).

Axions and ALPs may give rise to observable signatures in detectors through their coupling to photons (g_{Aγ}), electrons (g_{ Ae}) and nuclei (g_{AN}). The coupling g_{Ae} may be tested via scattering off the electron of a target, such as liquid xenon (LXe), through the axio-electric effect [11–15]. This process is the analogue of the photo-electric process with the absorption of an axion instead of a photon.

We report on the first axion searches performed with the XENON100 experiment. The expected interaction rate is obtained by the convolution of the flux and the axio-electric cross section. The latter is given, both for QCD axions and ALPs, by

\[ \sigma_{Ae} = \sigma_{pe}(E_A) \frac{g_{Ae}^2}{\beta_A^3} \frac{3E_A^2}{16\pi\alpha_{em}m_e^2} \left(1 - \frac{\beta_A^2}{3}\right), \]  

as described in [12–16]. In Eq. (1), \( \sigma_{pe} \) is the photoelectric cross section for LXe [17], \( E_A \) is the axion energy, \( \alpha_{em} \) is the fine structure constant, \( m_e \) is the electron mass, and \( \beta_A \) is the axion velocity over the speed of light, c.

The solar axion flux has recently been recalculated in [10]. This incorporates four production mechanisms that depend upon \( g_{Ae} \): Bremsstrahlung, Compton scattering, atomic recombination, and atomic deexcitation. The corresponding flux is 30% larger than previous estimates due to atomic recombination and deexcitation, which previously were not taken into account. However, [10] does not include corrections for axions heavier than 1 keV/e², which we therefore takes as an upper mass limit for our analysis. For solar axions, both flux and cross-section depend upon \( g_{Ae}^2 \), thus the interaction rate scales with the fourth power of the coupling.

For non-relativistic ALPs in the galaxy, assuming that they constitute the whole dark matter halo density (\( \rho_{DM} \approx 0.3 \text{ GeV/cm}^3 \) [18]), the total flux is given by \( \phi_{ALP} = c\beta_A \times \rho_{DM} / m_A \), where \( m_A \) is the ALP mass. The interaction rate for these ALPs depends on \( g_{Ae}^2 \), as the flux is independent from the axion coupling. As \( \beta_A \approx 10^{-3} \) in the non-relativistic regime, the velocities cancel out in the convolution between \( \sigma_{Ae} \) and the flux. Thus the expected electron recoil spectrum is independent from the particle speed. As the kinetic energy of the ALPs is negligible with respect to their rest mass, a monoenergetic peak at the axion mass is expected in the spectrum.

The XENON100 experiment’s primary aim is to detect dark matter in form of Weakly Interactive Massive Particle (WIMP) through their elastic nuclear scattering off nuclei in the liquid Xe target (LXe). The detector is a cylindrical (30 cm height × 30 cm diameter) dual phase-time projection chamber (TPC) with 62 kg of LXe, employed both as target and detection medium. It operates at the Laboratori Nazionali del Gran Sasso (LNGS). The detector is equipped of 242 radio pure photomultiplier tubes (PMTs) placed on top (in the xenon gas) and on the bottom of the TPC (immersed in the LXe below the cathode). A particle interaction in the LXe target creates both excited and ionized atoms. De-excitation leads to a prompt scintillation signal (S1). Due to the presence of an electric drift field of 530 V/cm, a large fraction of the ionization electrons is drifted away from the interaction site and extracted from the liquid into the gas phase by a strong extraction field of \( \sim 12 \text{ kV/cm} \), generating a light signal (S2) by proportional scintillation in the gas. Three-dimensional event vertex reconstruction is achieved using the time difference between the S1 and the S2 signals along with the S2-hit-pattern on the top PMTs, which is employed to estimate the (x, y) coordinate. The S1 signal is used to estimate the energy deposited in the detector, as explained below (Eq. 2). A detailed description of the instrument is given in [19].

The ratio \( S2/S1 \) is different whether the energy deposit in the LXe is due to electronic recoil (ER) or to nuclear recoil (NR). Therefore, this S2/S1 ratio is used to discriminate the two topologies of events. In the case of ERs, such as from interaction with \( \gamma \), \( \beta \) backgrounds and axion signals, the energy from the incoming particle is transferred to the electrons of the Xe atom. Conversely, neutrons or WIMPs scatter off the Xe nuclei.

The total background in the inner 34 kg super-ellipsoidal fiducial volume of the LXe target corresponds to \( 5.3 \times 10^{-3} \text{ events/(keV \times kg \times day)} \) [20], making XENON100 extremely sensitive to rare event searches in general. The ultra low background has been achieved by means of several techniques: the careful selection of materials [21]; the detector design, with radioactive parts far away from the target; the powerful passive shield as well as an active LXe veto; the self-shielding power of LXe, exploited by selecting only the inner part of the TPC for the analysis. The background is dominated by Compton events which scatter only once in the low-energetic region of interest, resulting in an almost flat spectrum [22]. Under an average depth of 3600 m water equivalent, the cosmic muon flux is suppressed by six orders of magnitude with respect to sea level.
and the science data passing all the selection cuts (black log is available in [24].

Detailed information on the procedure not be useful for this analysis targeted at ERs, and was hence not used. Detailed information on the procedure not be useful for this analysis targeted at ERs, and was hence not used.

The fiducial mass. Two main classes of analysis cuts have been applied. The first one consists of basic data quality selection, to remove either unidentified energy deposition peaks or excessive electronic noise level. Since only single-scatter events are expected from axion interactions, the second class of cuts identifies such events by using the number of coincidences from dark counts in the PMTs. In addition, a lower threshold of 150 PE in S2 has been imposed to be unaffected by the trigger threshold [24].

In order to reject ER events with an anomalously high or low S2/S1 ratio, signal candidates are required to be inside the 2σ band around the log_{10}(S2b/S1) median [24]. This is shown by the horizontal red dashed lines in Fig. 1 (top). The combined acceptance of all selection cuts for ER events is evaluated on calibration data, and is shown in Fig. 1 (bottom). Upper thresholds of 30 and 100 PE were employed for the axions from the Sun and the non-relativistic ALPs searches, respectively.

The energy deposited by each interaction is obtained using the observed S1 signal. The keV - PE conversion is performed using the NEST model (v0.98) [25]. This takes into account the scintillation efficiency R(E) relative to the 32.1 keV transition of 83mKr at zero electric field (as chosen by [26] and [27]) and the quenching factor Q(E) for a non-zero electric field (measured by [27] for values close to the field applied in XENON100). The model agrees with the direct measurements at zero field [26, 27], as well as the measurements with a non-zero field [27, 28]. The uncertainty on R(E) × Q(E) is taken from NEST and assumed to be Gaussian. This reflects the intrinsic uncertainty of the model (4%) as well as the spread in the measured data points, particularly relevant at low energies. The conversion from the energy deposition E to the observed signal n^{exp} in PE is therefore given by

\[ n^{exp}(E) = R(E) \times Q(E) \times f \times E \equiv L_Y(E) \times E, \]

where the factor \( f = 3.76 \) PE/keV is the derived

III. ANALYSIS

A. Data sample and analysis

In this work, we analyse the same data set used for the spin-independent [20] and spin-dependent [23] WIMP-searches, with an exposure of 224.6 live days and 34 kg fiducial mass. Two main classes of analysis cuts have been applied. The first one consists of basic data quality selection, to remove either unidentified energy deposition peaks or excessive electronic noise level. Since only single-scatter events are expected from axion interactions, the second class of cuts identifies such events by using the number of coincidences from dark counts in the PMTs. In addition, a lower threshold of 150 PE in S2 has been imposed to be unaffected by the trigger threshold [24].

In order to reject ER events with an anomalously high or low S2/S1 ratio, signal candidates are required to be inside the 2σ band around the log_{10}(S2b/S1) median [24]. This is shown by the horizontal red dashed lines in Fig. 1 (top). The combined acceptance of all selection cuts for ER events is evaluated on calibration data, and is shown in Fig. 1 (bottom). Upper thresholds of 30 and 100 PE were employed for the axions from the Sun and the non-relativistic ALPs searches, respectively.

The energy deposited by each interaction is obtained using the observed S1 signal. The keV - PE conversion is performed using the NEST model (v0.98) [25]. This takes into account the scintillation efficiency R(E) relative to the 32.1 keV transition of 83mKr at zero electric field (as chosen by [26] and [27]) and the quenching factor Q(E) for a non-zero electric field (measured by [27] for values close to the field applied in XENON100). The model agrees with the direct measurements at zero field [26, 27], as well as the measurements with a non-zero field [27, 28]. The uncertainty on R(E) × Q(E) is taken from NEST and assumed to be Gaussian. This reflects the intrinsic uncertainty of the model (4%) as well as the spread in the measured data points, particularly relevant at low energies. The conversion from the energy deposition E to the observed signal n^{exp} in PE is therefore given by

\[ n^{exp}(E) = R(E) \times Q(E) \times f \times E \equiv L_Y(E) \times E, \]

where the factor \( f = 3.76 \) PE/keV is the derived

FIG. 1: Top: Event distribution in the flattened log_{10}(S2b/S1) vs. S1 space for science data (black points) and calibration (grey points). Straight dashed lines show the selection cut on the flattened log_{10}(S2b/S1) (horizontal red lines) and the 3 PE threshold cut (red vertical line). Bottom: Global acceptance for electronic recoil events, evaluated on calibration data.

FIG. 2: Conversion function between energy recoil in keV and S1 in PE. The n^{exp} central value and the ±1σ uncertainty are indicated with solid blue and black dashed line, respectively.
XENON100 light yield at 32.1 keV and zero field [19, 28]. The function \( n^{\text{exp}}(E) \) is shown in Fig. 2, together with the \( \pm 1\sigma \) uncertainty.

**B. Statistical method**

A Profile Likelihood analysis, as described in [29] and analogous to [30], is used to constrain the coupling constant \( g_{Ae} \). The full likelihood function is given by

\[
\mathcal{L} = \mathcal{L}_1(g_{Ae}, N_b, n^{\text{exp}}) \times \mathcal{L}_2(n^{\text{exp}}),
\]

(3)

The parameter of interest is \( g_{Ae} \), whereas \( N_b \) and \( n^{\text{exp}} \) are considered as nuisance parameters. The first term,

\[
\mathcal{L}_1 = \text{Poiss}(N|N_s + N_b) \prod_{i=1}^{N} \frac{N_s f_s(S_{1i}) + N_b f_b(S_{1i})}{N_s + N_b},
\]

(4)

describes the measurement of the detector. The second term,

\[
\mathcal{L}_2(n^{\text{exp}}(t)) = e^{-t^2/2},
\]

(5)

is used to constrain the energy scale.

The energy scale term, \( \mathcal{L}_2 \), has been parametrised with a single parameter \( t \). The likelihood function is defined to be normally distributed with zero mean and unit variance, corresponding to where \( t = \pm 1 \) corresponds to a \( \pm 1\sigma \) deviation in \( n^{\text{exp}} \), as shown in Fig. 2, i.e.,

\[
t = (n^{\text{exp}} - n^{\text{mean}})/\sigma.
\]

In Eq.(4) \( N_s \) and \( N_b \) are the expected number of signal and background events in the search region, and \( N_s \) depends upon \( g_{Ae} \) and \( n^{\text{exp}} \). \( N \) is the total number of observed events, and \( S_{1i} \) corresponds to the \( S_1 \) of the \( i \)-th event. The functions \( f_s \) and \( f_b \) are the normalised signal and background probability distribution functions.

The event rate with a given number of detected photons, \( n \), is obtained by applying Poisson smearing to the predicted energy spectrum \( dR/dE \),

\[
\frac{dR}{dn} = \int_0^\infty \frac{dR}{dE} \times \text{Poiss}(n|n^{\text{exp}}(E)) dE,
\]

(6)

where \( n^{\text{exp}} \) is obtained from Eq.(2).

The rate as a function of the measured number of photoelectrons, \( S_1 \), is given by

\[
\frac{dR}{dS_1} = \sum_{n=1}^{\infty} \text{Gauss}(S_1|n, \sqrt{n}\sigma_{PMT}) \times \frac{dR}{dn} \times \epsilon(S_1),
\]

(7)

where \( \sigma_{PMT} = 0.5 \) PE is the PMT resolution [24], and \( \epsilon(S_1) \) is the acceptance of all criteria applied to the data, see Fig. 1 (bottom). It has a rather flat behavior above 10 PE. Below that, the acceptance decreases mainly due to data quality criteria.

The majority of the background events arises from gamma scattering off the atomic electrons of the LXe target, as well from intrinsic beta-background (\(^{222}\)Rn and \(^{85}\)Kr) [22]. To model these events, we use the \(^{60}\)Co and \(^{232}\)Th calibration data. The total spectrum is then analytically parametrised by means of a modified Fermi function, \( f_b(S_1) \), shown in Fig. 3 (grey line) along with the calibration data (empty blue dots). The spectrum is scaled to the science data exposure by normalizing it to the number of events seen outside the signal region, to avoid biases. For solar axions, it is done between 30 and 100 PE, and for galactic ALPs below \( m_A [\text{pe}] - 2\sigma \) and above \( m_A [\text{pe}] + 2\sigma \), where \( m_A [\text{pe}] \) is the ALP mass in units of PE and \( \sigma \) is the width of the expected signal peak, see Fig. 6. Then, the scaled background spectrum is integrated in the signal region to give the expected number of background events, \( N_b \). The background model scaled to the correct exposure, \( N_b \times f_b \), is shown in Fig. 3, along with the scaled calibration spectrum.

As downward statistical fluctuations of the background might lead to reject couplings to which the experiment is not sensitive, we used the CLs method to protect the result from this effect, as described in [30].

**IV. RESULTS**

**A. Solar axions**

The spectrum of the remaining 393 events, between 3 and 30 PE and after all the selection cuts, are shown in Fig. 4 as a function of \( S_1 \). The solid grey line shows the background model, \( N_b \times f_b \). The expected \( S_1 \) spectrum for solar axions, lighter than 1 keV/c\(^2\), is shown as a blue dashed line for \( g_{Ae} = 2 \times 10^{-11} \), i.e. the best limit so far, reported by the EDELWEISS-II collaboration [31]. The data are compatible with the background model, and no excess is observed for the background only hypothesis.

Figure 5 shows the new XENON100 exclusion limit on \( g_{Ae} \) at 90\% CL. The sensitivity is shown by the green/yellow band (\( 1\sigma/2\sigma \)). As we used the most recent and accurate calculation for solar axion flux from [10], which is valid only for light axions, we restrict the search...
Expected Mean Recoil Energy [keV]

FIG. 4: Event distribution of the data (black dots), and background model (grey) of the solar axion search. The expected signal for solar axions with $m_A < 1$ keV/c² is shown by the dashed blue line, assuming $g_{Ae} = 2 \times 10^{-11}$, the current best limit, from EDELWEISS-II [31]. The vertical dashed red line indicates the low S1 threshold, set at 3 PE. The top axis indicates the expected mean energy for electronic recoils as derived from the observed S1 signal.

Expected Mean Recoil Energy [keV]

FIG. 5: The XENON100 limits (90% CL) on solar axions is indicated by the blue line. The expected sensitivity, based on the background hypothesis, is shown by the green/yellow bands (1σ/2σ). Limits by EDELWEISS-II [31], and XMASS [32] are shown, together with the limits from a Si(Li) detector from Derbin et al. [33]. Indirect astrophysical bounds from solar neutrinos [34] and red giants [35] are represented by dashed lines. The benchmark DFSZ and KSVZ models are represented by black lines [4–7].

to $m_A < 1$ keV/c². For comparison, we also present other recent experimental constraints [31–33]. Astrophysical bounds [34–36] and theoretical benchmark models [4–7] are also shown. For solar axions with masses below 1 keV/c² XENON100 is able to set the strongest constraint on the coupling to electrons, excluding values of $g_{Ae}$ larger than $7.7 \times 10^{-12}$ (90% CL).

FIG. 6: Event distribution in the galactic ALPs search region between 3 and 100 PE (black dots). The grey line shows the background model used for the profile likelihood function. The red dashed line indicates the S1 threshold. The expected signal in XENON100 for various ALP masses, assuming $g_{A\gamma} = 9 \times 10^{-13}$, is shown as blue dashed lines. The top axis indicates the expected mean energy for electronic recoils as derived from the observed S1 signal.

FIG. 7: The XENON100 limit (90% CL) on ALP coupling to electrons as a function of the mass, under the assumption that ALPs constitute all the dark matter in our galaxy (blue line). The expected sensitivity is shown by the green/yellow bands (1σ/2σ). The other curves are constraints set by CoGeNT [39] (light brown dashed line), CDMS [40] (blue dashed line), and EDELWEISS-II [31] (brown dashed line). The indirect astrophysical bound from solar neutrinos [34] is represented as a grey line. The benchmark KSVZ model is represented by a black line [6, 7].

B. Galactic axions-like particles

For a specific axion model the limit on the dimensionless coupling $g_{Ae}$ can be translated to a limit on the axion mass. Within the DFSZ and KSVZ models [4–7] XENON100 excludes axion masses above 0.3 eV/c² and 80 eV/c², respectively. For comparison, the CAST experiment, testing the coupling to photons, $g_{A\gamma}$, has excluded axions within the KSVZ model in the mass range between 0.64 - 1.17 eV/c² [37, 38].
excluding an axion-electron coupling
mass range, XENON100 sets the best upper limit, ex-
very sensitive to fluctuations in individual bins because of
S/2
predicted sensitivity above 5 keV

A similar excess of events between 3 and 5 PE. A similar
effect is responsible for the limit oscillating around the
predicted sensitivity above 5 keV/c². The ALP limit is
very sensitive to fluctuations in individual bins because of
the expected monoenergetic signal. In the (1-40) keV/c²
mass range, XENON100 sets the best upper limit, ex-
cluding an axion-electron coupling g_{Ae} > 1 \times 10^{-12}
at the 90% CL, assuming that ALPs constitute all of
the galactic dark matter.

The impact of systematic uncertainties has been evalu-
ated for both analyses presented here. In particular, we
have considered the parametrisation of the cross section
of the axio-electric effect, the data selection based on a
band in the log_{10}(S_{2b}/S_{1}) vs. S_{1} space, the choice of
the fiducial volume, as well as the conversion of the S_{1}
signal into an ER energy and the energy resolution.

Previous works (e.g. [15, 32]) have used a different
parametrisation of the axion velocity term in σ_{A}, while
we chose to employ \((1 - \beta_{A}^{2}/3)\), Eq.(1), as suggested
by [31]. However, we also tested the other assumptions
and found the impact on the final limit to be negligible.

Varying the width of the band chosen to select the data
entering the analysis (shown in Fig. 1 (top) as horizontal
dashed red lines) from \pm 1σ up to \pm 4σ changes the final
result on g_{Ae} by 5%, i.e. well within the \pm 2σ of the
sensitivity band.

Similarly, a variation of the fiducial volume has a neg-
ligible impact on the sensitivity: the inner ellipsoid was
changed in size to accommodate between 28 kg and 40 kg,
but maintaining the same 224.6 days of live time. The
reduced background for smaller fiducial masses is com-
pensated by the smaller total exposure, resulting in a
variation of the limit well below 10%.

The uncertainty on the energy scale used for the con-
version from the observed S_{1} signal in PE into keV, Fig. 2
and Eq.(2), is taken into account in the profile likelihood
function and is profiled out via the nuisance parameter τ,
Eq.(5). The detector’s energy resolution is considered by
smearing the predicted energy spectrum dR/dE by Pois-
son and Gaussian processes, as described in Eq.(7). We
note that the final results on g_{Ae} are also robust against
further changes in the energy scale: even if L_{F}(E), as
defined in Eq.(2), is varied by 25%, the limits change by
less than 5% and about 10% for the solar and for the
galactic axion searches, respectively.

V. ACKNOWLEDGMENTS

We gratefully acknowledge support from NSF, DOE,
SNF, Volkswagen Foundation, FCT, Region des Pays de
la Loire, STCSM, NSFC, DFG, MPG, Stichting voor
Fundamenteel Onderzoek der Materie (FOM), the Weiz-
mann Institute of Science, the EMG research center and
INFN. We are grateful to LNGS for hosting and support-
ing XENON100.

[7] M. A. Shifman, A. I. Vainshtein, and V. I. Zakharov,
115012 (2008).
[16] F. Alessandria et al. (CUORE Coll.), JCAP 1305, 007
(2013).
xcom/html/xcom.html.
[19] E. Aprile et al. (XENON100 Coll.), Astropart. Phys. 35,
573 (2012).
[20] E. Aprile et al. (XENON100 Coll.), Phys. Rev. Lett. 109,
181301 (2012).
[21] E. Aprile et al. (XENON100 Coll.), Astropart. Phys. 35,
43 (2011).
[22] E. Aprile et al. (XENON100 Coll.), Phys. Rev. D 83,
082001 (2011).
[23] E. Aprile et al. (XENON100 Coll.), Phys. Rev. Lett. 111,
[38] K. Barth et al. (CAST Coll.), JCAP 1305, 010 (2013), 1302.6283.