A Realistic Assessment of the Sensitivity of XENON10 and XENON100 to Light-Mass WIMPs

J.I. Collar

1Enrico Fermi Institute, Kavli Institute for Cosmological Physics and Department of Physics, University of Chicago, Chicago, IL 60637

The underlaying assumptions and uncertainties involved in the derivation of WIMP exclusion limits from XENON10 and XENON100 detectors are examined. In view of these, recent claims of sensitivity to light-mass Weakly Interacting Massive Particles (WIMPs) are shown to be overstated. Specifically, bounds constraining regions of interest in WIMP parameter space from the DAMA/LIBRA, CoGeNT and CRESST experiments can be assigned only a very limited meaning.

PACS numbers:

The possibility of relatively-light (<10 GeV/c²) Weakly Interacting Massive particles (WIMPs) being the source of the annual modulation effect observed in the DAMA/LIBRA experiment was first proposed in and later revisited in . Since then, it has gained in popularity as constraints from other searches have depleted alternative dark matter scenarios, and several particle phenomenologies have generated plausible candidates in this mass range. The situation has recently gained in complexity with the observations from CoGeNT and CRESST, which may point at a light-WIMP parameter space compatible with DAMA/LIBRA.

Studies of detector sensitivity to such light dark matter particles must be regarded with caution. For presently-available technologies, light-WIMP signals would fall uncomfortably close to detector thresholds, a region where systematic effects can lead to rushed claims of exclusion or detection. Experimentalists should attempt not to aggravate what is a naturally murky area of study, by describing the assumptions made to arrive to their conclusions, and by including an assessment of the uncertainties involved in their analyses. Recent work by the XENON10 and XENON100 collaborations is lacking in these respects. The goal of this report is to provide this missing information as succinctly as possible.

I: RECENT MEASUREMENT OF \( L_{\text{eff}} \) BY G. PLANTE ET AL. [11].

A previous attempt to derive light-WIMP limits by the XENON100 collaboration was received with criticism pointing out the unphysical behavior of the quenching factor in the production of direct scintillation by nuclear recoils \( (L_{\text{eff}}) \) employed. An additional critique emphasized traceable mistakes made in the data analysis of previous \( L_{\text{eff}} \) measurements performed by the XENON10 and XENON100 collaborations.

A new recent \( L_{\text{eff}} \) measurement by the XENON100 collaboration (Plante et al. [11]) addresses the concerns in , specifically the systematic effect introduced by erroneously normalizing simulated recoil rates to their corresponding measured values, and the sub-optimal design of several earlier calibration detectors, prone to multiple scattering involving inert materials. The new detector used in features a compact design that bypasses this concern and maximizes light collection from the active liquid xenon (LXe) volume. Not surprisingly, the monotonically decreasing behavior of \( L_{\text{eff}} \) towards zero energy predicted in is now observed by Plante et al.

While great strides towards a better understanding of \( L_{\text{eff}} \) have been made in [11], significant room for improvement remains:

- An unnecessary degree of freedom in the fits comparing LXe scintillation measurements and simulations has been introduced by Plante et al., namely the energy resolution as a function of recoil energy, which is a predictable quantity, and not independent of \( L_{\text{eff}} \), as implicitly postulated in [11]. This is in contrast to an earlier measurement by Manzur et al. [14], also correctly pointing at a decreasing \( L_{\text{eff}} \), where the resolution was determined by measurements at energies well-above any threshold effects, and for all lower energies unambiguously defined according to its expected dependence on photoelectron yield (a function of \( L_{\text{eff}} \)). The introduction of this gratuitous degree of freedom can reinstate the deleterious effects described in [8], by substantially biasing \( L_{\text{eff}} \) towards artificially large values and reducing uncertainty. This concern is particularly important below ~6.5 keV, where threshold effects become dominant in [11]. The approach taken in does not necessarily have to constitute an issue, as long as the obtained best-fit resolution follows the expected behavior. No mention of this comparison is made in [11]. As described in Sec. II below, the extrapolated behavior of \( L_{\text{eff}} \) to zero energy critically determines LXe sensitivity to light-WIMPs, making attention to such details very important. A discussion of this comparison between expected and best-fit energy resolution would

1 Unfortunately, a sizable mismatch seems to be involved.
considerably improve the credibility of the lowest-energy $\mathcal{L}_{\text{eff}}$ values obtained by Plante et al.

- Measurements in [11] were performed in single-phase mode, i.e., in the absence of the electric drift field present during the operation of the XENON100 detector. This field is expected to suppress electron-ion recombination, reducing the scintillation yield. While this effect was found to be small by Manzur et al. [14], the $\mathcal{L}_{\text{eff}}$ values by Plante et al. should be considered an upper limit to the actual nuclear recoil scintillation yield in the XENON100 detector. This consideration as an upper limit is revisited in Sec. II within a different (instrumental) context.

- It must be kept in mind that the definition of $\mathcal{L}_{\text{eff}}$ used by the LXe detector community differs from the traditional one for a quenching factor, by relativizing the scintillation yield from low-energy nuclear recoils to that from electron recoils at a relatively high ionization energy (122 keV). The more conventional definition uses the ratio of scintillation yield from nuclear and electron recoils of identical energy. This may seem like a moot point, until the large non-proportionality typically observed in heavy scintillators [16], including LXe [17], is examined: a large increase in scintillation yield for electron recoils (the denominator in the traditional definition of quenching factor) is typically observed below few hundred of keV down to few keV. Compton scattering measurements complementary to those in [11] are clearly advisable.

II: NEW LIGHT-WIMP LIMITS FROM XENON100 [10]

The analysis of a 100 day exposure from the XENON100 detector [10] has resulted in a claim of sizable improvement in light-WIMP sensitivity with respect to a previous shorter (11 day) run [12]. A discussion of the strong assumptions implicitly made to arrive to this conclusion and of the uncertainties neglected in [10] is provided below.

- Contour “a” in Fig. 1 is similar to the exclusion curve in [10]. It is obtained by assuming the logarithmic extrapolation of the $\mathcal{L}_{\text{eff}}$ from Plante et al., as proposed in [10], and that only the lowest in energy of the three accepted nuclear-recoil events in [10] could be due to a light-WIMP. Contour “b” in the same curve represents the exclusion obtained when the $2\sigma$ C.L. uncertainty band in this $\mathcal{L}_{\text{eff}}$ is adopted instead. The resulting change in sensitivity is much larger than what is indicated by the very narrow uncertainty bands in Fig. 5 of [10]. This issue can be confirmed by performing a self-consistency test between the XENON100 exclusion curves in [10] and [12]: the two values of $\mathcal{L}_{\text{eff}}$ contemplated in [12] (Fig. 1 there) generated exclusion curves diverging by a very large factor for light WIMP masses (Fig. 5 in [12]). Those two values of $\mathcal{L}_{\text{eff}}$ are coincidently not very different from the central and $2\sigma$ C.L. boundaries of the $\mathcal{L}_{\text{eff}}$ from Plante et al. (Fig. 1 in [10]). However, in Fig. 5 of [10], the new XENON100 analysis assigns an insignificant impact on the exclusions to this large spread in $\mathcal{L}_{\text{eff}}$. The origin for this lack of self-consistency must be addressed.

- In a departure from the blind analysis initially intended by the XENON100 collaboration, three events next to threshold were rejected immediately following unblinding [10, 10]. These events have been ascribed to photomultiplier (PMT) noise affecting the S1 (direct scintillation) channel. Post-unblinding corrective actions are often required and no judgment on this decision should be passed until more details become available. However, it is worth remembering that this type of PMT noise was already present in XENON10 data [15] (and not rejected a posteriori) and is also ubiquitous in a XENON100 example event catalogued as “good” [20], indicating that data cuts originally deemed as adequate must have been in place against it.

2 This question may be extended to higher WIMP masses. For those, following basic statistical estimators, only a marginal increase in 90% C.L. sensitivity should be expected in going from zero to three irreducible events following an increase in exposure by a factor of ten. A much larger gain in heavy WIMP sensitivity has been claimed in going from 12 to 10.

3 A single example of noise-correlation provided in [20] corresponds
developed to reject these events while in the presence of robust S2 (ionization) signals will be of special interest. Contours labelled “c”, “d” and “h” in Fig. 1 display the non-negligible effect of including these three rejected events into the calculation of XENON100 exclusions.

- Dashed lines in Fig. 1 represent XENON100 exclusions using a logarithmic extrapolation of the alternative $L_{\text{eff}}$ obtained by Manzur et al. [14] using another optimally-designed LXe chamber. Differences in data treatment and mode of operation between [11] and [14] are described above. Criticisms concerning the data treatment in [14] are given in [5]. Contours labelled “g” and “h” use the logarithmic extrapolation of the lower 1σ C.L. boundary rather than the central $L_{\text{eff}}$ value (contours “e” and “f”).

- A lingering critical question is to what extent a determination of $L_{\text{eff}}$ performed using highly-optimized compact calibration detectors like those in [11, 14] can be applied with confidence to a much larger device like the XENON100 detector, featuring a small S1 light-detection efficiency (just ~6% [21]), different hardware trigger configuration, data processing, etc. For instance, simulations like those used within XENON100 to obtain a cumulative cut acceptance near threshold can only be regarded as best-effort estimates. Their limited meaning and tendency to significantly overestimate near-threshold efficiency has been recently encountered by Plante et al. [11], even for the near-ideal conditions of their small calibration chamber (~18 c.c. of LXe, with 4π PMT coverage). Another example of instrumental constraints is the negligibly small low-energy effective $L_{\text{eff}}$ derived by the 12 kg ZEPLIN LXe dark matter detector [22] when its measurement is attempted in situ (if adopted, this $L_{\text{eff}}$ generates essentially no LXe sensitivity to WIMP masses below 10 GeV/c$^2$ [13]). Going back some time, a dramatic deficit in observed neutron-induced recoil rates compared to few-keV$_r$ expectations was observed with the XENON10 detector [23]. Such comparisons should be revisited within the context of the existing XENON100 neutron calibrations: if the expected response to few-keV$_r$ recoils is still absent due to instrumental limitations, light-WIMP limits should not be distilled from sheer wishful thinking. As discussed next, light-WIMP limits are obtained by XENON100 under the strong assumption of positive Poissonian fluctuations in scintillation light from WIMP-induced recoils well-below the detector energy threshold. The agreement between expected and observed neutron-induced recoil rates should therefore be demonstrated into that energy range. The XENON100 collaboration is invited to produce this much needed validation of their claims$^4$.

- The mentioned assumption of Poissonian statistics governing the microscopic processes$^5$ of light and charge generation by few keV$_r$ nuclear recoils in LXe is not only presently unwarranted [13] but seemingly counter to the scarce available experimental information: the very small value of the Fano factor in LXe is for instance indicative of sub-Poissonian statistics ruling those processes [20]. Similarly, the electron emission statistics by few-keV, heavy-mass ions during surface collisions is known to be better described by binomial rather than Poissonian statistics [26]. Contours “d”, “f” and “h” in Fig. 1 display the effect of a small deviation from the Poisson assumption (a binomial distribution of same mean, taking a probability of S1 photon detection of 6% [21]). These contours should be considered as illustrative ansätze for information-carrier statistics that could generate even less light production. In this respect, it is worth emphasizing that a 7 GeV/c$^2$ light-WIMP is expected to impart a mean recoil energy in LXe of just ~0.6 keV$_r$, with an absolute maximum (occurring with infinitesimal probability) of ~4.1 keV$_r$. At this very endpoint, the probability of surpassing the XENON100 four-photoelectron (~8.5 keV$_r$) threshold is never larger than ~10%, even when the logarithmic extrapolation of the $L_{\text{eff}}$ by Plante et al. and Poisson fluctuations are adopted. Not all light-WIMP detecting media fare as poorly from this point of view of generation of information carriers: the same 7 GeV/c$^2$ WIMP at its spectral endpoint (~1.4 keV ionization) in CoGeNT germanium diodes would generate a readily detectable ~470 electron-hole pairs.

- Fig. 1 includes the present uncertainty in the quenching factor for sodium recoils in DAMA/LIBRA [13, 28], a subject of discussion avoided by the XENON100 collaboration in [10, 14]. This uncertainty extends the DAMA/LIBRA region to considerably lower WIMP masses than what is represented in [10, 14].

III: LIGHT-WIMP LIMITS FROM XENON10 VIA IONIZATION SIGNALS

A recent reanalysis of XENON10 data uses strictly the ionization channel in that detector to impose limits on

---

$^4$ This request for validation is not unfair: COUPP results consistently include a sensitivity penalty whenever any disagreement with neutron-induced recoil rate expectations arises [24]. A CoGeNT detector presently installed at Soudan has not been exposed to neutron sources to avoid activation during a search for an annual modulation [8]. However, the response to sub-keV$_r$ nuclear recoils was measured with a detector identical in properties (energy resolution, noise, bias) and crystal mass [23].

$^5$ Notice reference is made to those ab initio processes and not the ensuing statistics of photoelectron generation in PMTs.
light-mass WIMPs \[9\]. This S2 light emitted via electroluminescence from charge drifted into the gas phase of the device is, when examined alone, sufficient to extend the sensitivity of LXe detectors to recoils of O(1) keV\(_\gamma\). Not including the information from S1 (direct scintillation) allows a reduction in threshold at the expense of losing the ability to distinguish nuclear from electron recoils.

While this approach is promising, the few keV\(_\gamma\) nuclear recoil energy scale corresponding to this S2 channel is presently hopelessly ill-defined. This is a result of the inadequate “best-fit Monte Carlo” method \[29\] employed to arrive at it. An extensive critique of this method, ignored thus far by XENON10 authors, can be found in \[8\]. In a troubling case of double-standards, the gist of this critique (that with this method all uncertainties are absorbed into the energy scale) has been recently echoed by the XENON100 collaboration (Sec. I in \[11\]), when rebuking indirect measurements of \(L_{\text{eff}}\) using the same methodology.

In lieu of a reiteration of the criticisms in \[8\], the reader is invited to inspect Fig. 2: each of the colored energy scales shown there, generated by the “best-fit Monte Carlo” method \[29\], has been claimed to be the correct one by the XENON10 collaboration over the brief span of the last two years. The scale is observed to change as rapidly as from workshop presentation to its published proceedings. Its monotonic evolution has been towards the black curves, held in \[8\] to correspond to the most plausible energy scale (one derived from an earlier method laid out by XENON10 authors: see pertinent discussion in \[8\]). A critically-minded reader would (rightly) argue that none of these can be presently assigned any credibility at few keV\(_\gamma\). However, reasons have been provided in \[8\] to support the solid black curve, representing the Lindhard theory modified below a \(\sim 40\) keV\(_\gamma\), kinematic threshold \[13\] by an example of adiabatic correction, as in \[30\]:

- This energy scale generates a similar quenching for the ionization yield and the \(L_{\text{eff}}\) observed by Plante \textit{et al.} or Manzur \textit{et al.}, i.e., a monotonic decrease in the generation of information carriers (free charge, direct scintillation photons) below kinematic threshold \[13\], having an effective cutoff at \(\sim 1\) keV\(_\gamma\). That both processes should decrease hand-in-hand can be argued based on the dominant role of ionization as the main precursor to direct scintillation for low energy recoils in LXe \[13, 32\].

- The energy scales postulated thus far by XENON10 (color curves in Fig. 2) overestimate, by several orders of magnitude, the very small average charge yields observed in impact ionization experiments involving few keV and sub-keV xenon ions. The relevance of these measurements and examples from the literature are discussed in \[8\], where it is also emphasized that XENON10 workers are not without a reference on what to expect at these low energies. The introduction of the adiabatic correction proposed in \[30\] resolves this disagreement.

Of special interest is a population of XENON10 low energy ionization signals described in \[9\] as single electrons\(^7\). This definition is both surprising and misleading. As mentioned in \[8\], the large amplification gain provided by the electroluminescence provides a good resolution in the multiplicity of drifted charge in LXe. These events clearly include a multi-electron component and their population has been described as such by the contact author of \[9\], as recently as in \[35\]. Their origin is unknown, and hard to ascribe to minimum ionizing particles in an efficient self-shielding medium such as LXe \[8\]. While none of this is discussed in \[9\], their accumulation towards low values of S2 pulse-width is to be expected from the effect of charge multiplicity on this variable, and does not have to correspond to a radioactive contamination close to the \(z=0\) detector coordinate (this is unlikely, given that roughly the same number of PMTs, major sources of internal activity in the XENON10 detector, are placed at both extrema of \(z\)).

\(^7\) The well-know ionization “afterpulses” following large energy depositions in LXe, limited to single electrons but nevertheless mentioned in \[8\] as a possible origin for these multi-electron events, can be trivially removed through a \(\sim 100\mu\text{s}\) delayed-coincidence cut \[21, 34\]. No mention is made of the application of this cut to the dataset in \[9\]. This should be clarified.
IV: CONCLUSIONS

The inset in Fig. 2 represents the differential rate of few-electron S2 events in XENON10, obtained by applying the same five background cuts as in [9], extending the analysis down to the S2 = 1 e− boundary, and adopting the energy scale described by the black solid line in the same figure. This differential rate seems to be also compatible with Fig. 2 in [35], once the adopted energy scale is included. It offers a good match to the expected signal from a light WIMP in the region of interest of other searches (DAMA/LIBRA, CoGeNT, CRESST). The outcome of this exercise, performed here strictly for the sake of argument, should be strongly de-emphasized at this time, given the present lack of knowledge about this energy scale evidenced in Fig. 2. The reader should remember instead that a further evolution by a mere ∼1 keVr in the ever-changing S2 energy scales postulated by XENON10 can transform the “severe constraints” of [9] into a signal in principle compatible with a light-WIMP.

In conclusion, the claims in [9] are clearly presently untenable. Awaiting clarification of the several pending issues pointed out in Sec. I and II, light-WIMP limits obtained through a more conventional analysis of XENON100 data [10] can only be assigned the very limited meaning illustrated by Fig. 1. The XENON100 collaboration is congratulated for the recent advancement in their understanding of $\mathcal{L}_{\text{eff}}$, encouraged to develop improved methods of characterization of the S2 energy scale leading to a reliable exploration of light-WIMP candidates, and urged to employ transparency in the discussion of uncertainties and assumptions underlying their results, in view of the very limited performance of LXe as a light-WIMP detection medium. Finally, while several interesting phenomenological routes to alleviate tension between LXe constraints and other light-WIMP searches have been put forward recently [32], these deviations from arguably more conventional assumptions do not seem to be mandatory at this time.

N.B.: A new measurement of $\mathcal{L}_{\text{eff}}$ by the ZEPLIN-III collaboration appeared coincident with the release of this preprint [37]. Fig. 1 now reflects XENON100 exclusions obtained with it. ZEPLIN-III derives a $\mathcal{L}_{\text{eff}}$ decreasing below 40 keVr and vanishing at few keVr, in tight agreement with the LXe kinematic threshold described in [13].

[1] A.K. Drukier, K. Freese and D.N. Spergel, Phys. Rev. D33 (1986) 3495.
[2] R. Bernabei et al., Eur. Phys. J. C56 (2008) 333.
[3] A. Bottino et al., Phys. Rev. D69 (2004) 037302; G. Gelmini and P. Gondolo, hep-ph/0405278; P. Gondolo and G. Gelmini, Phys. Rev. D71 (2005) 123520.
[4] D. Hooper et al., Phys. Rev. D79 (2009) 015010.
[5] C.E. Aalseth et al., Phys. Rev. Lett. 106 (2011) 131301.
[6] CoGeNT collab., simultaneous submission to arXiv.
[7] W. Seidel (CRESST collaboration), presented at the 8th Intl. Workshop on Identification of Dark Matter, Montpellier, July 2010, available from http://indico.in2p3.fr/conferenceDisplay.py?confId=1565
[8] J.I. Collar, arXiv:1010.5187.
[9] J. Angle et al., arXiv:1104.3088.
[10] E. Aprile et al., arXiv:1104.2549.
[11] G. Plante et al., arXiv:1104.2587.
[12] E. Aprile et al., Phys. Rev. Lett. 105 (2010) 131302.
[13] J.I. Collar and D.N. McKinsey, arXiv:1005.0838, arXiv:1005.3723.
[14] A. Manzur et al., Phys. Rev. C81 (2010) 025808; A. Manzur, PhD dissertation, Yale University, 2009.
[15] G. Plante, priv. comm.
[16] W.W. Moses et al. Nucl. Instr. Meth. A487 (2002) 123; IEEE TNS 55 (2008) 1049.
[17] I.R. Barabanov, V.N. Gavrin and A.M. Psukhov, Nucl. Instr. Meth. A254 (1987) 355.
[18] J. Angle et al., Phys. Rev. Lett. 100 (2008) 021303.
[19] The New York Times, April 14, 2011.
[20] L. Bandis, presented at 2011 APS April meeting, Anaheim, CA, available from http://meetings.aps.org/Meeting/APR11/Event/146301.
[21] R.F. Lang, presented at 2010 HEFTI Light Dark matter Workshop, UC Davis, May 2010, available from http://particle.physics.ucdavis.edu/seminars/data/media/2010/apr/lang.pdf.
[22] V.N. Lebedenko et al., Phys. Rev. D80 (2009) 052010.
[23] A. Manzur, presented at 2007 APS April meeting, Jacksonville, FL, available from http://xenon.astro.columbia.edu/presentations.html.
[24] E. Behnke et al., Science 319 (2008) 933; Phys. Rev. Lett. 106 (2011) 021303.
[25] P.S. Barbeau, J.I. Collar and P.M. Whaley, Nucl. Instr. Meth. A574 (2007) 385; P.S. Barbeau, J.I. Collar and O. Tench, JCAP 0709:009, 2007; P.S. Barbeau, PhD dissertation, University of Chicago, 2009.
[26] T. Doke et al., Nucl. Instr. Meth. 134 (1976) 353; J. Seguinot, J. Tischhauser and T. Ypsilantis, A354 (1995) 280.
[27] F. Aumayr, G. Lakits and H. Winter, Rev. Sci. Instrum. 60 (1989) 3151; Appl. Surf. Sci. 60 (1991) 301; L. Ding et al., Phys. Scripta T80 (1999) 234.
[28] D. Hooper et al., Phys. Rev. D82 (2010) 123509.
[29] P. Sorensen, PhD dissertation, Brown University, 2008; P. Sorensen et al. Nucl. Instr. Meth. A601 (2009) 339.
[30] D.J. Ficenec et al., Phys. Rev. D85 (2011) 063501.
[31] T. Doke et al., Jpn. J. Appl. Phys. 41 (2002) 1538.
[32] P. Sorensen, presented at the 8th Intl. Workshop on Identification of Dark Matter, Montpellier, July 2010, available from http://indico.in2p3.fr/conferenceDisplay.py?confId=1565
[33] B. Edwards et al., Astropart. Phys. 30 (2008) 54.
[34] P. Sorensen et al., arXiv:1011.6439.
[35] P.J. Fox, J. Liu and N. Weiner, arXiv:1011.1915v1; A.L. Fitzpatrick and K.M. Zurek, arXiv:1007.5325.
[36] J.L. Feng et al., arXiv:1102.4331; M. Frandsen et al., arXiv:1105.3734; C. Arina et al., arXiv:1105.5121; E. Del Nobile et al., arXiv:1105.5451.
[37] M. Horn et al., arXiv:1106.0694.