Light WIMP Searches: The Effect of the Uncertainty in Recoil Energy Scale and Quenching Factor

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Taking liquid xenon detectors as a case study, the importance of a robust recoil energy calibration as a prerequisite to a search for light-mass Weakly Interacting Massive Particles (WIMPs) is emphasized. Important shortfalls in the analysis of existing measurements of the relative scintillation efficiency ($\mathcal{L}_{\text{eff}}$) and ionization yield ($Q_y$) for nuclear recoils in liquid xenon are described, leading to the conclusion that recent attempts to extract light-WIMP sensitivity limits from the XENON10 and XENON100 detectors are premature and overly optimistic.

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I: INTRODUCTION

Direct searches for dark matter WIMPs are remarkably difficult experiments where an attempt is made to extricate rare signals from backgrounds orders of magnitude more frequent. An additional complication arises from eventually having to demonstrate, if at all possible, that any irreducible events are more likely the result of WIMP interactions than a less exotic source. In the case that any irreducible events are more likely the result of physical processes presently neglected by this method described. A commentary is provided on how their inclusion should affect the energy scale, easing the disagreements described. A brief attempt at the interpretation under different energy-scale scenarios of a low-energy feature present in a recently released XENON10 ionization spectrum is offered. Section III describes an important systematic effect neglected in the analysis of all XENON10 and XENON100 measurements of relative scintillation efficiency\(^1\) ($\mathcal{L}_{\text{eff}}$) using monochromatic neutron scattering. A discussion of its impact on the energy dependence of $\mathcal{L}_{\text{eff}}$ is provided. Separately, the low quality of the experimental data in recent attempts by XENON100 to characterize $\mathcal{L}_{\text{eff}}$ is pointed out. Finally, these concerns are illustrated with data from ongoing quenching factor measurements at the University of Chicago. Section IV contains the conclusions.

II: UNCERTAINTY IN RECOIL ENERGY SCALE

In a recent workshop presentation [7], the XENON10 collaboration released a preliminary spectrum of events in their detector as a function of ionization yield, i.e., the energy scale for few keV$_r$ recoils in LXe, in particular via the so-called best-fit Monte Carlo method. Recent energy scales proposed using this method are compared to existing expectations and to independent measurements of ionization yield by low energy Xe$^+$ impact on surfaces, finding a large disagreement in both cases. Well-known methods. The conclusion drawn is that the knowledge necessary to allow a reliable exploration of this WIMP mass region is presently absent for LXe-based detectors.

The outline of this paper is as follows: Section II deals with the difficulties in establishing a reliable energy scale for few keV$_r$ recoils in LXe, in particular via the so-called best-fit Monte Carlo method. Recent energy scales proposed using this method are compared to existing expectations and to independent measurements of ionization yield by low energy Xe$^+$ impact on surfaces, finding a large disagreement in both cases. Well-known physical processes presently neglected by this method described. A commentary is provided on how their inclusion should affect the energy scale, easing the disagreements described. A brief attempt at the interpretation under different energy-scale scenarios of a low-energy feature present in a recently released XENON10 ionization spectrum is offered. Section III describes an important systematic effect neglected in the analysis of all XENON10 and XENON100 measurements of relative scintillation efficiency\(^1\) ($\mathcal{L}_{\text{eff}}$) using monochromatic neutron scattering. A discussion of its impact on the energy dependence of $\mathcal{L}_{\text{eff}}$ is provided. Separately, the low quality of the experimental data in recent attempts by XENON100 to characterize $\mathcal{L}_{\text{eff}}$ is pointed out. Finally, these concerns are illustrated with data from ongoing quenching factor measurements at the University of Chicago. Section IV contains the conclusions.

\(^1\) For the purpose of the present discussion $\mathcal{L}_{\text{eff}}$ can be considered the equivalent of the more broadly employed concept of “quenching factor”, in this case the ratio between the yield of direct (S1) scintillation light produced by a nuclear recoil and that from an electron recoil of the same energy, at zero drift field.
The number of electrons extracted from LXe via the application of an electric drift field $E_d = 0.73$ kV/cm. These electrons are further accelerated through the gaseous phase of the detector, producing a considerable VUV light emission via electroluminescence (the so-called S2 light), resulting in the registration of $\sim 25$ photoelectrons in the photomultipliers per each electron extracted from the liquid phase. The high gain provided by the electroluminescence permits the detection of single electrons with good resolution. It is therefore expected that this ionization spectrum should reach down to a threshold in recoil energy of $O(1)$ keV$_r$, allowing a search for light WIMPs. A dark matter search based exclusively on an analysis of the LXe ionization spectrum could in principle circumvent many recent discussions about the energy dependence of the relative scintillation efficiency $\mathcal{L}_{\text{eff}}$, and how it impacts LXe sensitivity to light WIMPs [8, 9]. While electron-recoil background rejection is lost when considering just the ionization (S2 light) spectrum, the low-energy counting rate achieved in XENON10 ($<1$ count / keV$_r$ kg day, Fig. 1) should be sufficient to investigate the remaining favored DAMA/LIBRA region [6], if the energy threshold is indeed as low as expected. However, an important requirement for the analysis of such ionization spectra in terms of sensitivity to light WIMPs is the establishment of a reliable correlation between the recoil energy scale and the ionization yield measured. During their recent presentation, XENON10 collaborators employed a new proposed recoil energy scale to generate the spectrum in Fig. 1 (top). If confirmed, it would amply exclude the WIMP phase-space regions presently compatible with a dark matter interpretation of DAMA/LIBRA, CoGeNT and recent preliminary CRESST data [6], at the very least for the standard present understanding of WIMP-nucleus interactions.

Reservations were expressed in [7] about the trustworthiness of the recoil energy scale employed to arrive at this spectrum. The vast extent to which this caution is advised is emphasized here, if the goal is to obtain reliable light-WIMP limits: Fig. 2 displays the most recent attempts [7, 11] by the XENON10 collaboration to establish a correlation between the ionization yield and the recoil energy scales, represented by solid color lines and matching color bands for the claimed one-sigma uncertainties (statistical error only). The ionization yield vs. recoil energy is typically represented by the normalized quantity $Q_y$ (units of electrons/keV$_r$). For clarity, here the actual measured quantity ($Q$, charge yield in number of electrons) is shown on the horizontal axis. All these energy calibrations originate in variations around a common method: a comparison is established at some point between experimental data obtained during exposure to a neutron source (commonly AmBe) and a Monte Carlo simulation of the expected spectrum of events vs. recoil energy. In the case of the latest attempt ([7], red line), this is accomplished by using a spline with mesh points fixed at arbitrary recoil energies (1, 2, 4, 8... 128, 256 keV$_r$) to describe $Q_y$, allowing $Q_y$ to float unconstrained until the best possible match between the experimental ionization spectrum and the simulated spectrum of events vs. recoil energy is reached$^3$. The so obtained $Q_y$ defines the correlation between recoil energy and ionization scales. As pointed out in [8], the original disagreement

$$^2$$ This background level ($\sim 0.06$ ckkd at 20 keV$_{ee}$ before fiducialization, $\sim 0.01$ ckkd following it), has been widely advertised in recent XENON100 presentations as being two orders of magnitude lower than in any competing dark matter detectors. In reality, it is comparable to the past generation of intrinsic germanium detectors ($\sim 0.03$ ckkd, [10]).

$$^3$$ No information was provided in [7] on how discrepancies in the overall rate of simulated and measured events are dealt with during this procedure, or about the selection of fitting range. These choices can, on their own, alter the extracted energy scale.

$$^4$$ A similar method has been used in the past to obtain $\mathcal{L}_{\text{eff}}$ [12]. At least there, the overall event rate normalization between simulation and data was treated as a free parameter, a highly questionable approach (see Sec. III) able to affect low energy $\mathcal{L}_{\text{eff}}$ and $Q_y$. 

![FIG. 1: Top: Spectrum of events in the XENON10 detector based on ionization yield only, as presented in [7]. The energy scale was defined by a “best-fit Monte Carlo” method. The original spectrum of events vs. electrons extracted from LXe can be found in [7]: the lowest bin shown here corresponds to an ionization yield of 3-4 electrons. The color code corresponds to different fiducial volume cuts [7]. The predicted signal for two example light WIMPs (dotted lines) is overlapped on the spectrum. Bottom: Similar to top panel, but using the dotted expectation curves in Fig. 2 to define the recoil energy scale (see text).]
between simulations and LXe data is typically severe at low recoil energy: spectra of direct (S1) scintillation display a lack of response to AmBe neutron-induced recoils below few keV, when compared to the expectations, regardless of $\mathcal{L}_{\text{eff}}$ adopted [13]. Possible reasons for this are described below. While no mention of this initial state of affairs for the S2 light (ionization) spectrum was made in [7], the limited information provided indicates that this is the case too. The XENON10 collaboration refers to these methods collectively under the unnerving denomination “best-fit Monte Carlo” [11].

A reader familiar with the energy calibration of radiation detectors will readily identify the risks involved in this approach: all uncertainties in the inputs to the simulation, limitations to its accuracy\(^5\), any experimental systematics, and most importantly, the effects of any physical processes not included in the simulation (such as the kinematic cutoff discussed below), will be automatically reflected as distortions in the inferred recoil energy scale. In other words, in this method, the reasons for any initially noticeable disagreements between simulation and experimental data are not investigated, instead the recoil energy scale is used as a buffer to absorb these.

Taking as a reference a yield of 10 electrons (the approximate endpoint for the observed low-energy rise in Fig. 1), the low-energy extrapolation of the colored curves in Fig. 2 indicates that this method of calibration results in recoil energy assignments for it anywhere in the $\sim0.2$ keV\(_r\) interval. No explanation is provided for the origin of the inflexion points and non-proportionality (particularly unrealistic at high energy) noticeable in those curves. The trend of a marked increase in $Q_\text{y}$ towards decreasing recoil energy in two of these curves (red, blue) is against all expectations: as pointed out in [8], a kinematic cut-off at $\sim40$ keV\(_r\) is expected for nuclear recoils in LXe, below which ionization should be adiabatically quenched. The same can be said of primary S1 scintillation, to the extent that it is expected to be mainly mediated by ionization [8]. Indeed, the observed traditional deficit of low-energy recoil events in LXe under AmBe neutron irradiations mentioned above is easily understood under this consideration.

The origin for this kinematic cutoff is in simple two-body kinematics: when the largest possible energy imparted to a valence electron by a slow-moving recoiling ion falls below the minimum excitation energy of the system (a 9.3 eV bandgap in LXe), a progressive quenching of scintillation and ionization should be observed (other secondary processes such as for instance potential electron emission from Auger de-excitation in an ionized projectile, whenever allowed, or transient autoionizing quasi-molecules can still play a role, leading to a smooth rather than sharp cutoff [19, 20, 26]). Contrary to an opinion recently expressed by the XENON100 collaboration [9], the basic principles behind this intrinsic limitation are well-known, with abundant references in the experimental and theoretical literature on transport of slow ions [19, 20, 26]. This quenching has been observed at the predicted kinematic cutoff for hydrogen recoils in organic scintillator [19]. Preliminary evidence for it in Cs and I recoils in CsI[Na], also at the expected cutoff energy, is provided in Sec. III of this paper. Due to an unfavorable combination of nuclear mass and electron band-gap energy, LXe-based dark matter detectors should be particularly affected by this limitation: the cutoff for Na recoils in NaI[Tl] and Ge recoils in germanium crystals is predicted to appear below the threshold of present dark matter detectors [8]. Other less well-known radiation effects left out by the best-fit Monte Carlo method could be listed: for instance, as recoil energies become very small, a diminishing recoil track length relative to the

\(^5\) To this author’s knowledge, Geant4 (used in [7]) has never been validated or verified in the $\sim$few keV to sub-keV recoil energy region, having historically exhibited difficulties in correctly modelling low-energy neutron transport. Several important improvements to the code in this respect are still in the making [18].

FIG. 2: Colored lines: correlations between recoil energy scale and ionization yield proposed by the XENON10 collaboration over the last two years, using best-fit Monte Carlo methods. The colored bands represent the claimed one-sigma statistical uncertainties (see text). Dotted lines correspond to the most recent expectations, based on the formalism presented in [14] (one based on “Columbia” detector data, the second on the “Case” detector). The dashed line indicates an earlier attempt to predict these [15]. All expectations are for $E_\text{c} = 0.73$ kV/cm. The data points correspond to measurements by Manzur et al. [16, 17]. Red arrows indicate the position of the endpoint for the low-energy rise in the spectra of Fig. 1 (see text). Inset: correlation between 2.8 MeV neutron scattering angle and recoil energy deposited in LXe in the measurements by Manzur et al. [16].
range of ionized electrons may lower the chances of recombination, helping any charge still being generated to escape and contribute to the S2 light [16].

It cannot be overemphasized that none of these microscopic physical processes mediating the generation of information carriers (free electrons, primary scintillation photons) following a nuclear recoil are included in popular simulation packages such as Geant4 or MCNP, which stop at generating a simple distribution of recoil energies. Just for this reason alone, the best-fit Monte Carlo method should be expected to generate extraneous structure in the correlation between recoil energy and ionization yield, aberrating the true relationship between these two magnitudes\(^6\). More specifically, an attempt to expand the method by including these processes prior to the reconciliation of simulation and data should alter the behavior of the colored curves in Fig. 2: for instance, the adoption of an adiabatic term [19] to include the reduced efficiency for electronic excitation below kinematic cutoff should bring those curves closer to or beyond the expectations discussed next (an adiabatic term would rather naturally account for any observed decrease in response to AmBe neutron recoils at low-energy). The best-fit Monte Carlo method, as it stands, cannot be accepted as a substitute for a genuine effort to understand these underlaying physical processes and the way they impact the recoil energy scale.

During this last attempt at defining a recoil energy scale, the XENON10 collaboration neglected any mention to the subject of expectations. These exist, and have been discussed by this collaboration and other workers before. The dotted lines in Fig. 2 show the expected correlation between recoil energy \(E_{\text{rec}}\) and ionization yield, calculated following the relationship described in a recent XENON10 publication [14], \(Q(E_{d}) = 0.2 \frac{L E_{\text{rec}}}{W_{r}}\), where \(L\) is the Lindhard nuclear quenching factor\(^7\) (extracted here from SRIM2010 [23]), \(W_{r} = 15.6\) eV is the average energy spent by an electron recoil to form an ion-electron pair [22], and the charge yield at a drift field \(E_{d}\) relative to that at infinite field \(Q(E_{d})/Q(\infty) = 0.2\) was measured at 56.5 keV\(_{r}\) in [14]. These expectations, based on the Lindhard-Scharff-Schiott theory through their dependence on \(L\), generate a \(Q_{y}\) roughly constant in energy, i.e., a proportionality between recoil energy and ionization. It must be kept in mind that the effects of the kinematic cutoff may not be completely accounted for in such models, as noticed experimentally in [19]. In other words, more sophisticated models generating expectations tending to the horizontal at few keV\(_{r}\) in Fig. 2 can be constructed.

There is an evident tension between these expectations and the ever mutable low-energy scales so far proposed by XENON10, most certainly the result of the artificial structure that the present best-fit Monte Carlo method is expected to introduce. However, it should be kept in mind that this expectation is itself subject to considerable uncertainty, and therefore should be regarded as simple guidance. For instance, the value of \(Q(E_{d})/Q(\infty) = 0.2\) employed to generate the dotted curves in Fig. 2 may have an unknown variation over the broad energy range depicted in this figure. Similarly, while the latest version of SRIM [23], used here to generate \(L\), offers a considerably better agreement with existing LXe measurements than previous ones [24], it should be kept in mind that SRIM predictions are semiempirical, i.e., biased by low-energy quenching factor measurements that may in turn be flawed. In particular, an absolute cutoff for \(L_{\text{eff}}\) at few keV\(_{r}\), a possibility strongly argued for in Sec. III, would suggest an expectation curve in Fig. 2 tending to the horizontal at this cutoff energy.

Just to illustrate the incipiency of the knowledge about the processes mediating the generation of ionization and scintillation by low-energy recoils in LXe, a dashed line in Fig. 2 shows the expectations for nuclear recoils put forward by XENON10 as recently as in [15], which were inferred from observations made using alpha particles.

Besides the colored curves in Fig. 2, generated via the best-fit Monte Carlo method, few other measurements of \(Q_{y}\) exist. Measurements of \(Q_{y}\) in [14], not shown in Fig. 2 for clarity, approximately follow the blue curve over the range 20-100 keV\(_{r}\). However, the recoil energy scale used to extract \(Q_{y}\) in [14] was derived using a debatable choice of \(L_{\text{eff}}\). The methodology of the calibrations that generated this \(L_{\text{eff}}\) curve will be sharply criticized in Sec. III of this paper. A rapidly decreasing \(L_{\text{eff}}\) towards zero recoil energy like the alternative proposed in Sec. III would result in changes to the recoil energy scale that would make the \(Q_{y}\) derived in [14] tend towards the

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\(^{6}\) Leaving aside the limitations of the best-fit Monte Carlo method in its present form, the derivation of the new WIMP exclusion plot presented in [7] begs justification: the one-sigma error bars on \(Q_{y}\), converted here to the red band in Fig. 2, are exclusively statistical. They are therefore vastly underestimated, not including the uncertainties in the energy scale generated by this method. The broad dispersion in the curves depicted in Fig. 2 gives an idea of the magnitude of this (hard to quantify) uncertainty in the energy scale. Even if this one-sigma band is accepted at face value, the customary WIMP exclusion contour should be extracted from a spectrum with recoil energy scale derived from a conservative excursion from a central \(Q_{y}\) value, as allowed by 90% C.L. uncertainties. Taking again the \(~10\) electron endpoint as a reference and using Fig. 2 as a guide, it is possible to estimate that the 90% C.L. dark matter sensitivity claimed in [7] should be relaxed by more than an order of magnitude. To add to the confusion, a markedly more conservative approach was recently presented in [21], using an identical \(Q_{y}\), i.e., the same proposed recoil energy scale as in [7].

\(^{7}\) A discussion of the relationship between \(L_{\text{eff}}\) and \(L\) (the second sometimes referred to as \(Q_{\text{mic}}\)) can be found in [16].
dotted expectation lines rather than the blue curve in Fig. 2. Erroneous conclusions from one LXe calibration can rapidly propagate to another, such is the complexity of the relationship between quantities and physical processes in LXe detectors.

The data points shown in Fig. 2 deserve special attention. They correspond to measurements by Manzur et al. [16] at a value of $E_d$ similar to that used in the XENON10 detector, with the important difference that their energy scale is in principle known, independently determined by the kinematics of the elastic scattering of monochromatic 2.8 MeV neutrons from a xenon target. The apparent trend in those measurements is one of an increasing $Q_y$ with decreasing recoil energy. Not only this clashes with the expected behavior below kinematic cutoff, but it also poses an interesting number of questions: the low-energy extrapolation of these datapoints in Fig. 2, if confirmed, would imply that the low-energy rise below $\sim 10$ electrons observed in the XENON10 ionization spectrum (Fig. 1) cannot originate in nuclear recoils. An alternative would be a process not the immediate result of a particle interaction, for instance, an “spontaneous” multiple electron emission. Spontaneous single-electron emission from LXe is known to follow large energy depositions by gamma rays, with a half-life of $\sim 100$ $\mu$s, and is possibly due to photoionization [25]. Delayed emissions are not uncommon in some detecting media: for instance, a few inorganic scintillators (e.g., CsI[Tl]) are notorious for an “afterglow” from long-lived phosphorescent states, involving the release of single scintillation photons. However, it is very hard to envision an atomic energy-storage mechanism in LXe that would lead to the delayed emission of up to $\sim 10$ electrons. The high gain afforded by the electroluminescence clearly points at a non-atomic origin in minimum ionizing particle interactions to this observed rise in rate below 10 electrons. The value of $Q(E_d)/Q(\infty)$ measured in [14] for electron recoils suggests that this rise would then have an endpoint at an electron-equivalent energy of a mere $\sim 0.25$ keV$_{ee}$. Compton scattering from gammas is not expected to generate any such features (the Klein-Nishina relation does not include a highly forward-peaked excess). Beta decay or Bremsstrahlung interpretations concentrated this low in energy are not plausible. The chance of this signal arising from degraded surface activity seems to be excluded by its survival under different fiducial volume cuts (Fig. 1, [7]). No other meaningful processes come readily to mind. While an understanding of this low-energy feature would be desirable, the apparent low-energy trend in the $Q_y$ measurements by Manzur et al. limits the interpretations.

The measurements of $Q_y$ by Manzur et al., taken at face value, generate a third concern. The processes governing electron emission by slow ions immediately prior and during impact on surfaces are not identical to those expected from recoils in bulk LXe, but the dominant mechanisms are in common. Therefore, it is educational to contrast the several tens of electrons generated by a 1 keV$_{ee}$ Xe recoil that would be implied by the extrapolated low energy $Q$ postulated by Manzur et al., with the observed electron yields of $O(10^{-3})$ $e^-$/ion generated by a Xe$^+$ ion impact of the same energy on W or Au electrodes [26]. In this energy regime the ion range and the mean escape depth of electrons from the electrode are comparable (few nm, [26]), i.e., the measured yield is representative of the actual total ionization generated. This very small yield is of the same order of magnitude of what would be predicted by the dotted expectation line in Fig. 2 after the introduction of an adiabatic term [19] to account for the kinematic cutoff.

In trying to find a solution to these wee conundrums, this author searched [16, 17] for a description of the method of alignment between 2.8 MeV neutron source, LXe cell, and scintillator cell used to detect scattered neutrons (the scattering angle defining the recoil energy in the measurements). None was found, and also an absence of treatment for the uncertainty in recoil energy that any angular misalignment would bring, therefore unrealistically assumed to be nil$^8$. Based on the geometry of this experiment, size of the detector cells and the relatively short distance between them, a modest misalignment in the relative position of the cells and source could enlarge the recoil energy error bars significantly and/or shift the datapoints in Fig. 2 in energy: as can be seen from the inset in Fig. 2, a cumulative misalignment by as little as 5$^\circ$, which amounts in the experiment by Manzur et al. to 2-3 cm of cumulative displacement in the assumed relative position between the detector cells and/or between them and the neutron source, is sufficient to remove the paradoxical situations described above (e.g., the lowest energy datapoint in Fig. 2 shifts from 4 keV$_{r}$ to 6 keV$_{r}$ over 5$^\circ$). A certain discomfort arises from the simultaneous realization that the XENON10 light-WIMP sensitivity claimed in [28] using the $L_{\text{eff}}$ measurements from Manzur et al. is also critically dependent on this matter: the same unaccounted-for displacements by few cm would result, quite literally, in a decrease in XENON10 light-WIMP sensitivity by orders of magnitude. While this should be reason enough to take the limits claimed in [28] with caution, much graver concerns about the methodology used by Manzur et al. and earlier authors to arrive to $L_{\text{eff}}$ and $Q_y$ will be expressed in Sec. III. Considerably less information (trigger and software efficiency, S2 gain, analysis procedure, etc.) is provided

$^8$ As it turns out, no goniometric equipment was employed by Manzur et al. The approximate scattering angles were derived from photographs of the setup taken from the vertical [27]. In the opinion of this author, this method does not guarantee the desired angular accuracy discussed in the main text.
by Manzur et al. in [16, 17] on the subject of their derivation of $Q_y$, as compared to their very extensive treatment of $L_{ef}$, preventing an additional investigation here of how the neglected systematic effect described in Sec. III may have affected the $Q_y$ datapoints in Fig. 2. A skewness similar to that affecting the low-energy S1 light peaks discussed in Sec. III can be noticed in the single S2 light example shown by Manzur et al. (Fig. 8c in [16]), possibly indicating the presence of S2 threshold effects at the level of $Q \sim$few electrons. The reader is referred to Sec. III for more details.

As a last remark on the difficulties in the determination of light-WIMP sensitivity via S2 light, the bottom panel in Fig. 1 shows the effect of adopting the *expected* energy scale (central value of dotted lines in Fig. 2) rather than that generated by the latest version of the best-fit Monte Carlo, taking into account the changes in bin width that the energy translation results in. It would be possible to obtain a near-perfect agreement between the example light WIMPs in the figure (intentionally chosen in the region of interest for DAMA, CoGeNT and CRESST [6]) and this spectrum, with the introduction of the adiabatic term to account for the expected kinematic cutoff or by examining other uncertainties in the expectations. It is sobering to realize that one can go from this bizarre coincidence to severe exclusion of the candidates over a shift in a notoriously ill-defined energy scale by a mere $\sim 3$ keV\textsubscript{r}. While the presence of a high-rate, homogeneously-distributed signal at very low-energy in the XENON10 or XENON100 detector would be hard to explain in an efficient self-shielding medium like LXe without invoking weakly-interacting particles, any such possible agreement with these other detectors should be presently de-emphasized: at the time of this writing, any low energy scale for LXe should be considered highly speculative, such is the paucity of reliable experimental data and detailed models of recoil response available for LXe.

### III: UNCERTAINTY IN QUENCHING FACTOR

The information presently available on scintillation and ionization yield from low-energy nuclear recoils in LXe is plagued by contradictory observations and interpretations. In particular, $L_{ef}$ is expected to decrease with decreasing recoil energy [8] for the reasons given above, but published measurements display all possible behaviors. Recent attempts to reconcile these [29] fall short, lacking in a critical examination of the analysis methods and experimental techniques utilized in the existing calibrations. In order to elucidate some of these issues, extensive MCNP-PoliMi [30] simulations of the most recent assessment of $L_{ef}$, by Manzur et al. in [16, 17], have been performed here. This examination has revealed several issues affecting this type of measurement\textsuperscript{9}. Attention was paid to follow the prescriptions given in [16, 17] regarding energy resolution, S1 light yield at different drift field values, cuts affecting the data, effect of threshold efficiency, etc., obtaining a good agreement with the particulars provided in [16, 17] on distribution of recoil energies, contributions from different types of events (inelastic scatters, multiple scatters, scattering on inert materials, etc.), and neutron time-of-flight (TOF) information. In this respect, Fig. 3 here allows a direct comparison to Fig. 9 in [16].

An important limitation to the measurements by Manzur et al. is not readily appreciated from a cursory inspection of [16]: the position of the peak or maximum in the measured distributions of S1 scintillation light for neutron scattering angles below $\theta \sim 60^\circ$ is entirely defined by the effect of the threshold efficiency (software and triggering). In other words, for recoil energies below $\sim 20$ keV\textsubscript{r}, the left shoulders responsible for the noticeable skewness in distributions of S1 light like those in Fig. 8a in [16] and Fig. 6.3 in [17] are solely the result of this threshold efficiency: the true scintillation maximum is expected at values much lower than the position of this peak. These true maxima are not reachable due to an scintillation yield (4.3 to 10.8 photoelectrons per keV of electron equivalent energy, PE/keV\textsubscript{ee}, depending on drift field and mode of operation) that is insufficient for

\textsuperscript{9} Several of these issues are minor, and yet indicative of the lack of scrutiny with which some of these results have been embraced. For instance, simple geometrical considerations suffice to demonstrate that the distance between LXe and scintillator cells quoted in [16] (16-20 cm, information not mentioned in [17]) would lead to an uncertainty in the recoil energies probed almost three times larger than claimed. This was confirmed by initial simulations. This issue is traceable to a mistake in units of distance in [16], where inches should have been used [27].
FIG. 4: Top: Simulated distributions of S1 light in the experimental setup of Manzur et al. [16, 17], for 5.7 keV\(_r\) recoils. Black histograms use the nominal \(L_{\text{eff}}\) claimed in [16, 17] for this recoil energy, red histograms a logarithmic fit to their datapoints above 20 keV\(_r\) (dashed line in Fig. 5 bottom, see text). The effect of the threshold efficiency is to shift the peak or maximum in the distributions to an artificially larger value. Both \(L_{\text{eff}}\) hypothesis remain distinguishable through their predicted event rate (area under solid histograms). Bottom: The ability to distinguish these two largely different values of \(L_{\text{eff}}\) is lost once a normalization to the experimental rate (data points from Fig. 8a in [16]) is performed, an unfortunate method of analysis followed by Manzur et al. and earlier authors [15, 31, 32].

FIG. 5: Top: Position of the peak or maximum in S1 scintillation (units of electron equivalent energy) observed by Manzur et al. as a function of recoil energy [33]. The dashed line is derived from the logarithmic fit in the bottom panel, under the premise that the ratio of peak keV\(_{ee}\) to keV\(_r\) should be equal to \(L_{\text{eff}}\) in ideal experimental conditions (see text). Bottom: \(L_{\text{eff}}\) datapoints from Manzur et al. together with the \(L_{\text{eff}}\) derived by the ZEPLIN collaboration (red band [34]). The dashed line is a logarithmic fit to datapoints not affected by threshold efficiency (\(>20\)keV\(_r\)). Lower energy datapoints deviate from the fit by the effect of the threshold efficiency (see text). Cutoffs to this fit anywhere in the range 3-6 keV\(_r\) produce fits to the experimental data similar in quality to those shown in the bottom panel of Fig. 4.

an optimal exploration of such low recoil energies. For instance, assuming a value of \(L_{\text{eff}}\) =0.1 at 6 keV\(_r\), this peak would then be expected at between 2.6 and 6.5 PE, whereas the effect of the threshold efficiency starts to be noticeable already at \(\sim15\) PE for both the single and two-phase modes of operation. The threshold efficiency is provided in Fig. 10 in [16] and top of Fig. 4 here.

This is not an insurmountable limitation, as long as careful attention is paid to the comparison between Monte Carlo simulations and data that ultimately leads to a best-fit \(L_{\text{eff}}\) for each scattering angle. Unfortunately, in the experiments described by Manzur et al. no attempt was made to include a comparison between the expected recoil rate and that observed\(^{10}\). Instead, the simulated distributions of S1 light yield were normalized to the observed event rate prior to the chi-square analysis leading to the best-fit value for \(L_{\text{eff}}\), a step mentioned in [16] and described with more detail in Sec. 6. 1. 2 of [17].

The nature of the problem created by this form of data analysis is illustrated in Fig. 4, using the 6 keV\(_r\) S1 single-phase measurement provided as an example in [16]. The top panel displays the expected S1 light yield distribution for the nominal \(L_{\text{eff}}\) =0.078 obtained by Manzur et al. at this energy\(^{11}\), derived from the present simulation following the data cuts and energy resolution prescribed in [17], before (dotted histograms) and after (solid histograms) including the effect of threshold efficiency. Its equivalent, but using a considerably smaller and energy-dependent \(L_{\text{eff}}\) derived from a logarithmic fit (Fig. 5, bottom) to \(L_{\text{eff}}\) datapoints with \(E_{\text{rec}} >20\) keV\(_r\) (i.e., those not af-

\(^{10}\)This was prevented by difficulties in controlling the stability of the DD neutron generator output towards the end of its target life, and by throughput limitations of the data acquisition system during runs at the smallest scattering angles [27].

\(^{11}\)\(L_{\text{eff}}\) is expected to be an energy-dependent quantity. Use of a constant value across the measured S1 spectrum during the chi-square analysis, as done in [16, 17] is less than ideal. An effort was nonetheless made in [17] to examine the effect of a linear energy dependence around the best-fit \(L_{\text{eff}}\).
ected by the effect of threshold efficiency) is also displayed. As can be observed from the solid histograms in the top panel of Fig. 4, these two possibilities lead to distinguishable predictions, specifically a decrease in recoil rate per unit exposure to the neutron source by 40% in the second scenario. However, once the normalization to the experimental rate is performed (Fig. 4, bottom), this information is lost and both $L_{\text{eff}}$ scenarios yield a comparable good fit to the experimental data. In conclusion, the method of analysis followed in [16, 17] (and earlier experiments discussed next) cannot distinguish between these two largely different values of $L_{\text{eff}}$.

Useful additional information was presented in an unpublished progress report [33] and reproduced here in the top panel of Fig. 5, where the position of the observed peak or maximum in S1 light yield (in units of keV$_{ee}$, rather than PE) is displayed as a function of mean recoil energy for early measurements by Manzur et al. For data points not affected by the threshold efficiency (>20 keV$_{r}$) the ratio between both energies is, as expected by the definition of $L_{\text{eff}}$, close to the value of $L_{\text{eff}}$ eventually obtained (Fig. 5, bottom). For smaller recoil energies, for which the threshold efficiency affects and defines the position of the peak, this approximation breaks down, as a result of the true position of this peak having been artificially “pushed up” in energy, the effect illustrated here in Fig. 4 (top). This can be observed in, for instance, Figs. 11 a,c in [16], where the chi-square minimum appears at $L_{\text{eff}}$~0.055, rather than at the larger ~0.12 that would be naively expected from said ratio and a 10.8 PE/keV$_{ee}$ light yield. This trend in [16, 17] for the chi-square minimum to appear well below an expectation based on the (artificial) position of the scintillation peak, is in itself pointing at a rapidly decreasing $L_{\text{eff}}$ towards zero recoil energy. But this is recognized in [16, 17] and not the point at stake: instead, the top panel in Fig. 5 reveals that the measurements by Manzur et al. not affected by the threshold efficiency may very well be pointing at a vanishing $L_{\text{eff}}$ somewhere in the few keV$_{r}$ region, a behavior not dissimilar to that claimed by the ZEPLIN collaboration [34]. The change in slope in Fig. 5 (top) appears exactly where expected from the limitations imposed by threshold efficiency and light yield in this experiment. It is inevitable to suspect that the combination of insufficient light yield and regrettable normalization of simulated to experimental rates used by Manzur et al. and others [15, 31, 32] may have biased $L_{\text{eff}}$ towards considerably larger values than those to be measured in more ideal conditions, or at least when properly taking into account systematic differences between expected and observed signal rates. The logarithmic fit to the points above 20 keV$_{r}$ employed to illustrate this discussion (Fig. 5, bottom) lays slightly beyond the one-sigma uncertainty in $L_{\text{eff}}$ quoted by Manzur et al.

The adoption of a similar $L_{\text{eff}}$ would dramatically relax claimed constraints on light-WIMPs from XENON10 and XENON100 [28, 35].

An attempt has not been made here to simulate earlier measurements of $L_{\text{eff}}$ as a function of neutron scattering angle. However, at least in the analysis of the experiments described in [15, 31, 32], not only the overall normalization in rate was left as a free parameter (enabling the same deleterious effects illustrated here by Fig. 4), but additional degrees of freedom were introduced into the fits by way of a background model intended to account for neutron scattering in inert components, largely dominant in those other geometries. This is clearly

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12 The asymmetry in the S1 distribution due to the effect of threshold efficiency is already clearly visible in the 10 keV$_{r}$ data in Fig. 6.3 of [17]. At 20 keV$_{r}$ and assuming a $L_{\text{eff}}$~0.1-0.15, at least the lower light yield, non-zero drift field measurements are expected to be affected (the $L_{\text{eff}}$ datapoints of Manzur et al. are an average of all conditions tested for each angle).

13 An unquantified very large increase in signal rate towards small scattering angles was noticed in the measurements by Manzur et al. [27]. Present simulations predict that this rate should have increased by a factor ~200 in going from $\theta$ =125° (67 keV$_{r}$) to $\theta$ =25° (4 keV$_{r}$), before accounting for threshold effects. Yet only a small deficit (~40%, Fig. 4 top panel) in rate is expected from an $L_{\text{eff}}$ much smaller than that determined by Manzur et al., leaving ample margin for a severe misidentification of the low-energy $L_{\text{eff}}$, even more dramatic than what has been contemplated here.

14 The detector used by Manzur et al. is properly designed for the job at hand, with only a bare minimum of inert parts around the LXe cell. The largely dominant “materials background” in [31, 32] arises from a suboptimal detector design, causing neutrons to have a very small probability of reaching and exiting the active cell without interacting on inert materials, creating a background
a flawed approach to the analysis of such experimental data. The dismaying poor quality of the calibration data in [31, 32] is worth emphasizing at this point: an interested reader is invited to inspect the discussion around Fig. 4-10 in [32] for crucial steps in the data analysis obviated in [31]. In the opinion of this author and others [27], once the obvious residual threshold effect surviving the subtraction of accidentals is corrected for, there is little to no evidence in the dataset of [31, 32] for any usable calibration information at and below 10 keV. This calibration played a central role in the attempted justification of recent XENON100 limits [35].

To finalize, Fig. 6 is offered to illustrate the reality of the concerns expressed in this paper. It displays the rate of single Cs or I recoils in a CsI[Na] scintillator irradiated by a 2.8 MeV DD neutron generator in a setup similar to that used by Manzur et al. These data are part of an ongoing series of precision quenching factor calibrations for CsI[Na], CsI[Tl] and NaI[Tl] at the University of Chicago, employing combined electron recoil (Compton scattering) and nuclear recoil measurements on a single goniometric table. While these recent data should be considered preliminary, a large deficit in signal rate is observed, with an onset coincident with the predicted kinematic cutoff for Cs,I recoils in CsI[Na] [8]. At the time of this writing, data acquisition triggering throughput and threshold efficiency effects are found to be far from sufficient to account for its magnitude (the measured low-energy light yield of this scintillator in this setup is $\sim 9$ PE/keV$_{ee}$).

Following the incorrect analysis procedure criticized in this section, a monotonically increasing quenching factor towards zero recoil energy would be naively derived from the CsI[Na] data at hand. The lowest energy data point centered at 5 keV would be assigned a quenching factor of $\sim 20\%$, with the highest energy points in agreement with earlier measurements [36] at $\sim 8\%$. With a correction in place for this systematic deficit in rate, the derived quenching factor should be much smaller for the lowest energies measured. An upcoming publication will discuss the implications of these measurements for the exact location of the DAMA favored region in light-WIMP phase space [6, 8], impact on efforts to reproduce the annual modulation effect using CsI[Tl] crystal arrays [37], and prospects for a low-energy neutrino measurement using CsI[Na] at an intense neutron spallation source [38].

IV: CONCLUSIONS

Even after considering the difficulties described in the introduction, common to all techniques, it is possible to distinguish between detector technologies more adapted to a search for light WIMPs than others, based exclusively on the existing knowledge of the response of the detector in the few keV recoil energy region. Two families of devices can be examined: those for which a reliable low-energy scale exists, and those for which it is presently lacking. Belonging to the first group, DAMA/LIBRA NaI[Tl] scintillators benefit from a convenient low-energy signal at 3.2 keV originating in a $^{40}$K internal contamination, able to anchor the energy scale near threshold, even if a relatively small uncertainty still remains in the quenching factors that define the recoil energy scale [6, 8]. CDMS germanium bolometers [39] profit from peaks at 1.3 keV and 10.4 keV from $^{71}$Ge activation following periodic neutron calibrations. The quenching factor measured in CDMS-Ge is similar to theoretical expectations and the observations from independent germanium experiments. CRESST bolometers are able to use narrow lines of known origin at 3.6 keV and 8 keV for a low-energy reference, having measured the quenching factors for the recoiling species in their crystals using a number of techniques [5]. CoGeNT detectors benefit from a number of known narrow cosmogenic lines in the range 1.1-11.1 keV and an optimal linearity and energy resolution. Their quenching factor has been measured in a dedicated reactor experiment down to sub-keV recoil energies, obtaining an excellent agreement with expectations and other measurements [40]. Belonging to the second group we can identify CDMS silicon bolometers: spatial corrections are known to affect their recoil energy scale, generating a large disagreement with theoretical values of the quenching factor (even larger when compared to other experimental values), and a potentially large shift in recoil energy [6]. At the time of this writing, detectors based on LXe lag behind all other dark matter detection techniques in a knowledge of the energy scale and of the mechanisms governing signal production by few keV nuclear recoils. Recent efforts to provide an electron-recoil low-energy calibration reference via a $^{83m}$Kr source [41] are a welcome step in the right direction.

To summarize, important flaws in the methodology used to determine the value of $L_{\text{eff}}$, $Q_y$ and the recoil energy scale in liquid xenon detectors have been described. Data-quality concerns affecting recent calibrations, such as those in [31, 32], have been pointed out. Once these issues are addressed, an agreement with the expected decrease in ionization and scintillation yield from nuclear recoils below kinematic cutoff should be obtained for this medium. In particular, the traditionally observed deficit in low-energy response to AmBe neutron-induced recoils in LXe should be easier to understand by the inclusion of well-known radiation effects presently being ignored. A proper control of the systematics affecting monochromatic neutron scattering measurements of $L_{\text{eff}}$ and $Q_y$ has been shown to be lacking: bold as this may sound, none of the measurements of this type performed up until now below $\sim 10$ keV$_{ee}$ by the XENON10 or XENON100
collaborations can be assigned much worth. Separately, an effort should be made to evolve the “best-fit Monte Carlo” method to include radiation effects known to mediate the generation of signal carriers (free electrons, direct scintillation) before an attempt to match simulations and data is made. Proper account of the uncertainty in the recoil energy scale should be taken before attempting to extract limits from spectra generated by this method. In its present naïve form, it is not possible to defend it.

Markedly different values of $\mathcal{L}_{\mathrm{eff}}$ and $Q_{\nu}$ should be expected from improved LXe calibration methodologies. The recoil energy scale of ionization (S2 light) spectra should also be affected by the proposed improvements, as described in the commentary around Figs. 1 and 2.

In view of the numerous issues raised here, one is forced to conclude that recent attempts to extract light-WIMP sensitivity from XENON10 and XENON100 data [28, 35] are premature and overly optimistic. The sensitivity from XENON10 and XENON100 data [28, 35] as described in the commentary around Figs. 1 and 2.

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[38] Todd Hossbach (CsI collaboration), presented in the Advances in Neutrino Technology workshop, Santa Fe, Sept. 2010. Available from http://www.physics.ucdavis.edu/~svoboda/ANT10/talks.html

[39] Z. Ahmed et al., Science 327 (2010) 1619.

[40] P. S. Barbeau et al., JCAP 09 (2007) 009; P. S. Barbeau el al., Nucl. Instr. Meth A574 (2007) 385; P. S. Barbeau, PhD Thesis, University of Chicago (2009). For a summary of germanium quenching factor measurements, see the preprint (arXiv:0712.1645) of S. T. Lin et al., Phys. Rev. D79 (2009) 061101.

[41] L. W. Kastens et al., Phys. Rev. C80 (2009) 045809.