Reply to the Comments on the XENON100 first Dark Matter Results

The XENON100 Collaboration

The recently submitted preprint on the first results from the XENON100 dark matter experiment [1] was followed by a criticism by J.I. Collar and D.N. McKinsey [2], focused on our extrapolation of the scintillation efficiency $\mathcal{L}_{\text{eff}}$ to the lowest nuclear recoil energies, where no data and no theoretical model exist. Here we add clarifications on our analysis and comment on their criticism.

The main XENON100 result demonstrates, with only 11 days of data, the potential of this ultra-low background experiment to exclude new parameter space in spin-independent WIMP-nucleon cross section. The high mass WIMP limit is unaffected by the controversy on the value of $\mathcal{L}_{\text{eff}}$. The light WIMP interpretation of the DAMA [3] and CoGeNT [4] data is excluded at 90% CL for a constant extrapolation of the global fit of all $\mathcal{L}_{\text{eff}}$ data from fixed-energy neutron experiments (see Fig. 1 of our preprint). However, when $\mathcal{L}_{\text{eff}}$ is assumed to follow the 90% lower limit of the global fit with a conservative logarithmic extrapolation to zero near 1 keV, a fraction of the CoGeNT parameter space remains uncovered.

We further argue that we don't see any events even down to a threshold of 3 PE, departing from our a priori chosen threshold of 4 PE, where, however, our acceptance is still quite high (as shown in Fig. 2 of the preprint). This excludes all of the DAMA favored region, with ion channeling, at 90% CL, for a constant extrapolation of the global fit of all $\mathcal{L}_{\text{eff}}$ data from fixed-energy neutron experiments (see Fig. 1 of our preprint). However, when $\mathcal{L}_{\text{eff}}$ is assumed to follow the 90% lower limit of the global fit with a conservative logarithmic extrapolation to zero near 1 keV, a fraction of the CoGeNT parameter space remains uncovered.

We will now comment on some of the statements made in [2] in more detail.

1. In [2] it is stated that we className $\mathcal{L}_{\text{eff}}$ as $0.12$ below $10 \text{ keV}_r$. This statement is not correct. As explained and shown in Fig. 1 in the preprint, and also shown in Fig. 1 here, the $\mathcal{L}_{\text{eff}}$ used in our analysis is not based on a single measurement (given the apparent disagreement within the quoted errors) but is the result from a global fit to all existing direct neutron scattering measurements. These results, where the recoil energy is measured by the scattering angle of mono-energetic neutrons, are systematically cleaner than results that are based solely on a comparison between neutron calibration data (featuring single nuclear recoils from a continuous neutron source) and Monte Carlo simulations. This is the reason why we have chosen not to include these $\mathcal{L}_{\text{eff}}$ results in the global fit, and we have clarified this in the preprint. For illustration, we have added them in Fig. 1 of this note. There are two studies of this type (while only one is mentioned in [2]).

2. In their footnote, the authors express their confusion about the $\mathcal{L}_{\text{eff}}$ curves used in the analysis and accuse us of trying to mislead the reader. We reject this notion. To avoid any misunderstandings, we have changed the text slightly to be more clear: In Fig. 1 of [1] (also in Fig. 1 here) there are 3 $\mathcal{L}_{\text{eff}}$ contours: The thicker one in the center is the result from the global fit with a constant
...to an electron by a slow-moving recoil ion, the system exceeds the maximum possible energy transfer. The electron cannot be treated separately from the Xe atom and the maximum energy transferred to an electron cannot be given by simple kinematics, as advocated in [2].

The collision mechanism for heavy ions at very low energies may be better described by, e.g., the molecular orbit theory [13], which involves many-body kinematics. The argument by Collar and McKinsey is based on two-body kinematics and would not apply for heavy ion collisions in the energy region concerned here. In fact, Ficenec et al. [10] state that “No evidence for a response cutoff is observed at velocities extending well below the electron-excitation threshold of $6 \times 10^{-4} \text{c}$ expected from two-body kinematics” even for protons. Besides, if $E_{\text{max}}$ for Xe-Xe is $39 \text{ keV}_r$, the kinematics argument cannot explain the scintillation observed below $39 \text{ keV}_r$ at all. Apart from the uncertainty in stopping power calculations which affect directly nuclear quenching, other factors may affect $L_{\text{eff}}$ through electronic quenching. However, the current experimental and theoretical situation is such that there is no proven mechanism which justifies a decreasing $L_{\text{eff}}$ with decreasing energy, as strongly advocated by Collar and McKinsey.

We are fully aware of the impact of $L_{\text{eff}}$ on the overall sensitivity of noble liquid dark matter experiments and our answer is simply that we will measure it again, extending it to the lowest possible energies. We need accurate data on this quantity and, within the XENON collaboration, we have already developed two new and independent set-ups optimized to measure the energy and field dependence of both electron and nuclear recoils in liquid xenon.

4. Finally, Collar and McKinsey doubt that we have properly taken into account the effects of the low number of photoelectrons at our threshold. (Note that this effect had not been accounted for in the preliminary plots presented in their reference [17].) We agree that this has a crucial impact on the XENON100 sensitivity to low mass WIMPs, however, it is a fact that an imperfect threshold due to a finite energy resolution leads to a mixing of events below threshold into the sample and vice versa. Since the expected WIMP spectrum is a steeply falling exponential (see Fig. 2), many more sub-threshold events fall in the energy region above threshold than vice versa.

Due to the low number of detected photoelectrons at the XENON100 threshold, the energy resolution is completely dominated by counting statistics, therefore the expected true differential rate is convoluted with a Poisson function to account for this behavior. We also point out that the XENON100 efficiency is still very high down to 3 PE.

Figure 2 shows the effect of Poisson broadening of our threshold for a DAMA benchmark case: There is a small amount of rate from a $10 \text{ GeV}/c^2$ WIMP with a cross...
FIG. 2: Expected spectrum of a 10 GeV/c^2 WIMP with a cross section of 1 \times 10^{-41} \text{cm}^2 (black, solid), a benchmark case at the lower edge of the DAMA region. The red (dashed) lines show the spectrum after a convolution with a Poisson distribution, the blue (thick dashed) line is corrected for the XENON100 efficiency. The straight lines are the 3 PE and 4 PE thresholds using the lower 90% CL \( \mathcal{L}_{\text{eff}} \) contour of the global fit as explained in the text.

section of 1 \times 10^{-41} \text{cm}^2 leaking into the XENON100 signal region, even at a threshold of 4 PE, corresponding to 9.6 keV\(_r\) in the case of the lower 90% CL \( \mathcal{L}_{\text{eff}} \) contour. Based on the light WIMP interpretation of the DAMA annual modulation signal, we would expect to see a total of 4.4 events above a lowered threshold of 3 PE (8.2 keV\(_r\) for the conservative \( \mathcal{L}_{\text{eff}} \) case), taking into account our reduced detection efficiency at lower energies (more than 18 events are expected for the best fit \( \mathcal{L}_{\text{eff}} \) above 3 PE corresponding to 7.0 keV\(_r\)). As explained in our manuscript (see Fig. 3 in [1]) no event is observed leading to an exclusion of this case at 90% CL.

The same effect at the lower end of the WIMP mass range favored by CoGeNT (7 GeV/c^2 WIMP, cross sections of 0.5 – 1 \times 10^{-40} \text{cm}^2) reduces the expectation to 0.73 – 1.5 events above a threshold of 3 PE in the case of the lower 90% CL \( \mathcal{L}_{\text{eff}} \) contour. Hence no significant conflict is found under this assumption and with the limited exposure used so far. For the global fit with constant extrapolation of \( \mathcal{L}_{\text{eff}} \) this region is excluded at 90% CL.

FIG. 3: 90% confidence limits for the global fit of \( \mathcal{L}_{\text{eff}} \) with a threshold of 4 PE (black), and curves for the 90% lower contour of \( \mathcal{L}_{\text{eff}} \) at thresholds of 4 PE (yellow) and 3 PE (magenta). We used the following astrophysical parameters: galactic escape velocity = 544 km/s, WIMP density = 0.3 GeV/cm^3, solar velocity = 220 km/s.

In conclusion, we agree with the authors that the current situation on \( \mathcal{L}_{\text{eff}} \) in LXe is far from optimal and must be clarified especially at the lowest Xe recoil energies. However, in our manuscript we have properly taken into account the uncertainty by using \( \mathcal{L}_{\text{eff}} \) obtained from a global fit to all published direct measurements and by cross-checking the results with the lower 90% CL contour together with a very conservative extrapolation for \( E_r < 5 \text{ keV}_r \).

[1] E. Aprile et al, (XENON100), arXiv:1005.0380v2 (2010).
[2] J.I. Collar, D.N. McKinsey, arXiv:1005.0838v3 (2010)
[3] C. Savage et al., JCAP 0904, 010 (2009).
[4] C.E. Aalseth et al., (CoGeNT), arXiv:1002.4703 (2010).
[5] P. Sorensen et al. (XENON10), Nucl. Instrum. Methods A 601, 339 (2009).
[6] V.N. Lebedenko et al., (ZEPLINIII), Phys. Rev. D 80, 052010 (2010).
[7] A. Manzur et al., Phys. Rev. C 81, 025808 (2010).
[8] E. Aprile et al., Phys. Rev. C 79, 045807 (2009).
[9] S. P. Ahlen, G. Tarl´e, Phys. Rev. D 80, 052010 (2010).
[10] D. J. Ficenec et al., Phys. Rev. C 79, 045807 (2009).
[11] J. Lindhard et al., Mat. Fys. Medd. Dan. Vid. Selsk. 33, 10 (1963).
[12] A. Mangiarotti et al., Nucl. Instrum. Methods A 580, 114 (2007).
[13] N. F. Mott, H. S. Massey, The Theory of Atomic Collisions (The International Series of Monographs in Physics), Oxford University Press, London, 3rd ed.(1987).
[14] M. C. Smith et al., Mon. Not. R. Astron. Soc. 379, 755 (2007).