Impact of operator interference in dark matter direct detection experiments

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Introduction

The non-relativistic effective field theory (EFT) of dark matter (DM)-nucleon interactions depends on 28 coupling strengths for DM particle spin up to $1/2$. Due to the vast parameter space of the EFT, most direct detection experiments interpret the results of their searches assuming that only one of the couplings is non-zero, but in the EFT, DM models generically lead to several interactions which interfere with one another, therefore, the published limits cannot be straightforwardly applied to model predictions. We present a method to determine a rigorous upper limit on the DM-nucleon couplings including the interference among operators. We illustrate the method using the null search results from the XENON1T and the PICO60 collaborations. We also present a method that allows to combine the results from different experiments, thus exploiting the synergy between different targets in exploring the parameter space of DM-nucleon interactions.

DM-nucleus scattering rate in the non relativistic EFT

In the EFT, the interaction Hamiltonian between a nucleus and a DM particle reads

$$H = \sum_{i}^{N} c_i^p \mathcal{O}_i^p + c_i^n \mathcal{O}_i^n, \qquad (1)$$

where $c_i^{p\,(n)}$ is the coupling between a DM particle and a proton (neutron), and i labels the N possible Galilean invariant interaction operators. Since the Hamiltonian is linear in the couplings, the total recoil rate R has a quadratic form, which can be cast as

$$R\left(\mathbf{c}\right) = \mathbf{c}^T \mathbb{R} \mathbf{c}, \qquad (2)$$

where the vector $\mathbf{c}$ contains $2 \cdot N$ couplings and $\mathbb{R}$ is a $(2 \cdot N)$ x $(2 \cdot N)$-matrix depending on the detector material, DM velocity distribution, local DM density and DM mass. Here, we consider DM particle spin up to $1/2$, meaning that $N = 14$. Using Eq. (2), we can constrain the couplings for a given upper limit on the interaction rate ($R^{u.l.}$).

Common vs. new conservative approach

For published results, it is commonly assumed that only one of the 14 operators is non-zero and that $c^p = c^n$, but DM models generically lead to several interactions which interfere with one another, therefore, the published limits cannot be straightforwardly applied to model predictions. This strict assumption might result in the exclusion of parameter space which is actually still allowed by data. We show an example for this in Fig. 1.

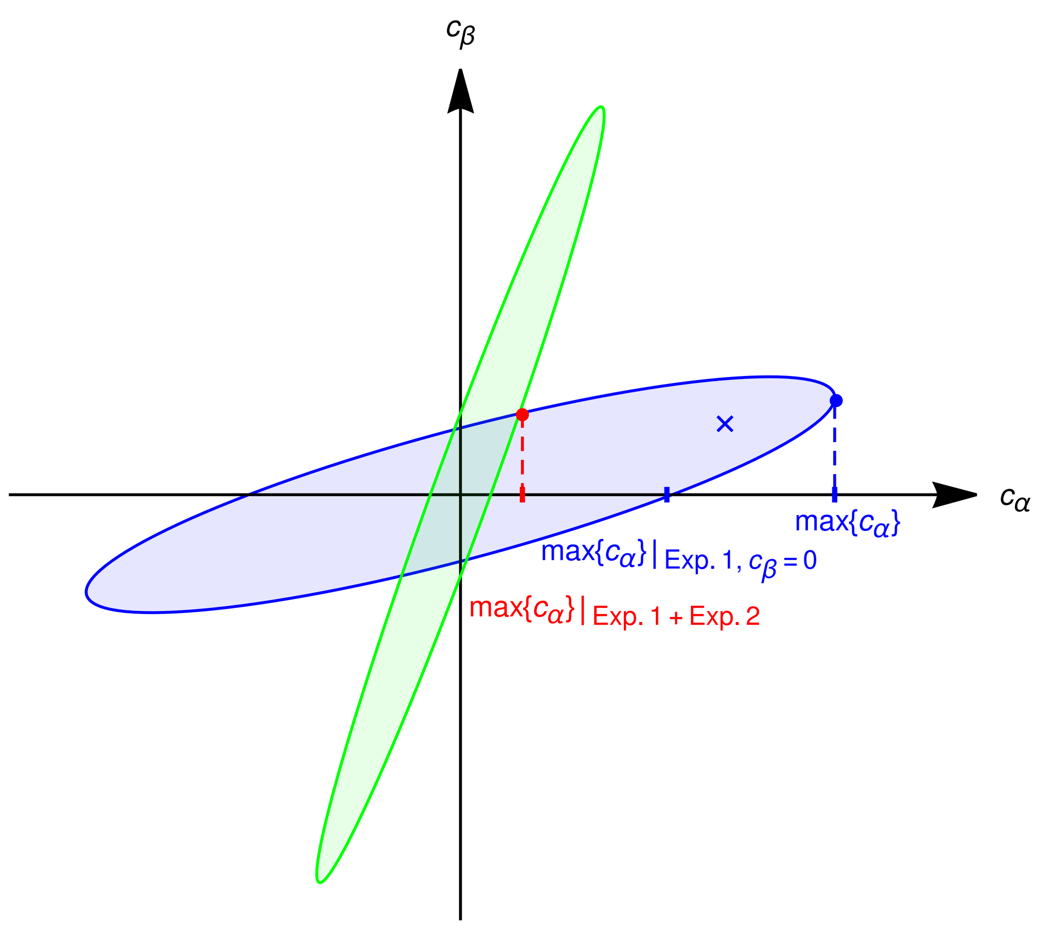

Figure 1: Ellipses in a two-dimensional parameter space spanned by couplings c_α and c_β. The point labeled with a blue cross is allowed by data of the blue experiment, but excluded by the corresponding published results. The interpretation of the green ellipse is analogous.

The analytical formula to determine the most conservative upper limit reads [1]

$$\max\{c_\alpha\} = \sqrt{(\mathbb{R}^{-1})_{\alpha\alpha}\, R^{\mathrm{u.l.}}}. \qquad (3)$$

As visible in red in Fig. 1, the combination of experiments (or ellipses) can have the power to further constrain the parameter space though being fully conservative. The analytical formula for the combined conservative limit only depends on the $\mathbb{R}$-matrices of the considered experiments, and the corresponding number of observed events and background events.

Results

Fig. 2 shows as dotted line the published results for the SD DM-proton cross-section taking the assumption that $c^p = c^n$, as dashed line considering the interference among proton and neutron, and as solid line considering the interference among proton and neutron, and all possible operators. We show these results for XENON1T in blue, PICO60 in green, and the combination of both experiments in red.

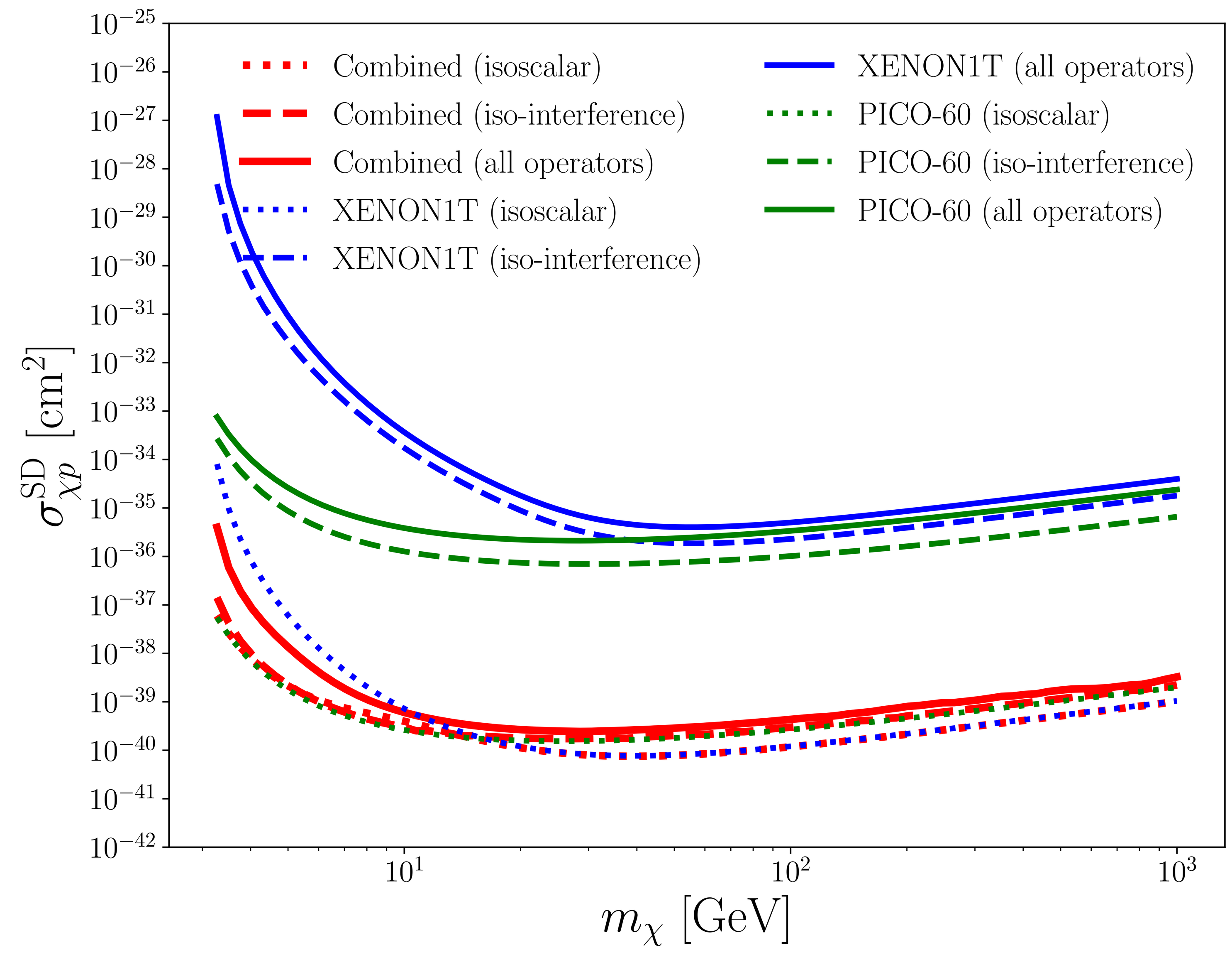

Figure 2: Limits on the SD DM-proton cross-section taking interference among operators and the combination of two experiments into account [2].

Conclusion

By taking the interference of operators into account, the limits on the DM-nucleon cross-section can be relaxed by up to four orders of magnitude.
Combining experiments can give stronger limits on the cross-section (but still being conservative).

References

[1] Anja Brenner, Alejandro Ibarra, and Andreas Rappelt. Conservative constraints on the effective theory of dark matter-nucleon interactions from icecube: the impact of operator interference. *Journal of Cosmology and Astroparticle Physics*, 2021(07):012, 2021.

[2] Anja Brenner, Gonzalo Herrera, Alejandro Ibarra, Sunghyun Kang, Stefano Scopel, and Gaurav Tomar. Impact of operator interference in dark matter direct detection experiments. *in progress*.