

Abstract

DEAP-3600 is a single-phase liquid argon dark matter experiment optimized for searching WIMP signatures. After analyzing the first year of data, zero candidate events were observed, resulting in limits on the isoscalar, spin-independent WIMP-nucleon cross-section above $3.9 \times 10^{-45} \text{ cm}^2$ ($1.5 \times 10^{-44} \text{ cm}^2$) for 100 GeV/c² (1 TeV/c²) WIMP masses. This new study reinterprets these results by using a Non-Relativistic Effective Field Theory (NREFT) framework and further examines how the exclusion curves are modified due to the presence of potential substructures in the local dark matter halo, motivated by the observations of stellar distributions from the Gaia satellite and other astronomical surveys.

Introduction

DEAP-3600 is a dark matter (DM) direct-detection experiment located ~ 2 km underground at the SNOLAB facility (Sudbury, Canada). It consists of a spherical acrylic vessel with ~ 3.3 t of liquid argon (LAr) where scintillation light is emitted once the particles interact [1]. The aim is to record the elastic scattering of WIMPs with ^{40}Ar nuclei, with the electron recoils signals rejected using Pulse Shape Discrimination [2]. The results of 231 days of search, with zero WIMP candidates in the region of interest, are reported in [3] where the most stringent upper limit on the spin-independent WIMP-nucleon cross-section for a LAr target was set. Despite this null result, a reinterpretation of the data modifying the particle physics (NREFT) and astrophysics models (new halo substructures) was conducted that could help to disentangle the nature of the DM in case of a future detection.

NREFT

The NREFT formalism parameterizes various potential DM-nucleus interactions (15 effective operators) under a full DM theory [4,5]. The non-zero operators for ^{40}Ar that are not sub-dominant terms: \mathcal{O}_1 , \mathcal{O}_3 , \mathcal{O}_5 , \mathcal{O}_8 , and \mathcal{O}_{11} were explored. Combining some of the operators, allowed to study more complex interactions [6]: Anapole, Millicharged, Electric, and Magnetic dipole DM. The research also included cases of isospin-violation (isovector, xenonphobic).

DM substructures

Data analysis of the Gaia mission in combination with SDSS[7] has revealed new stellar substructures in the local halo which could have DM associated. Thus, the DM velocity distribution may differ from the classical Maxwell-Boltzmann. This work examined the next stellar debris [8]: Gaia Sausage, Nyx, S1, Helmi, Koppelman, and a generic model of in-falling clumps, using their kinematic properties to track a potential DM component and thus to build a model of the velocity distribution. They were assumed with a relative DM density ($\eta_{\text{sub}} = \rho_{\text{sub}}/\rho_0$).

Results

Fig. 1 shows velocity distributions obtained for each substructure. Constraints on the 5 effective operators were computed for Isoscalar (IS), Isovector (IV), and Xenonphobic (XP) isospin-symmetry cases (Fig. 2). The effect of ranging η_{sub} with a Sausage velocity model was also estimated (Fig. 3). Velocity-dependent operators (\mathcal{O}_5 , \mathcal{O}_8) are sensitive to the substructure used and particularly affect the limits for heavy WIMPs. A summary plot with all models variation is presented in Fig. 4. For a XP scenario (Fig. 5), there is a region of the parameter space where DEAP-3600 sets a stronger limit than Xenon1T. The coupling strength of NREFT-derived specific interactions was constrained (Fig.6).

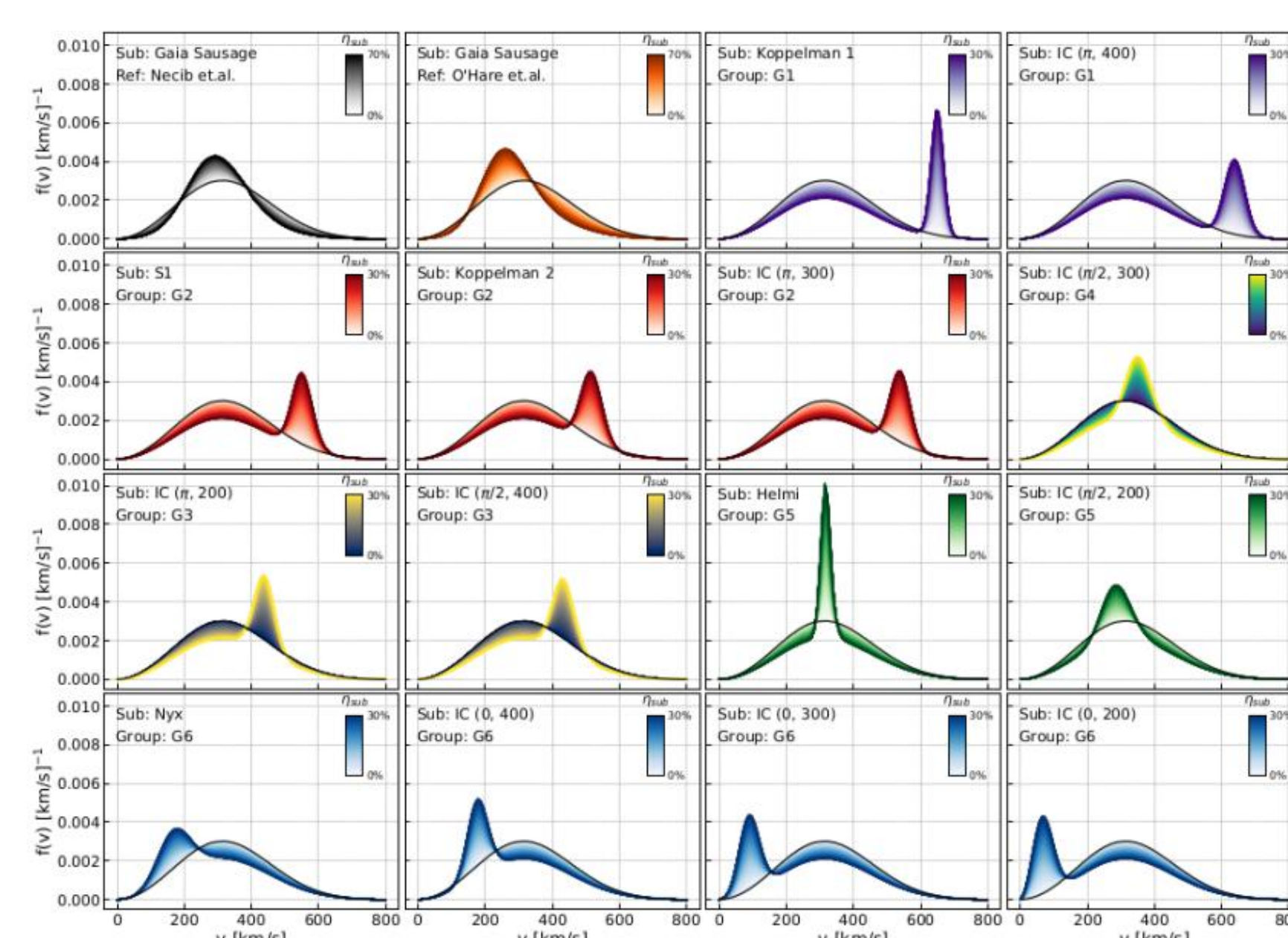


Figure 1. Velocity distributions modeled. The solid black line corresponds to the SHM (Maxwell-Boltzmann distribution).

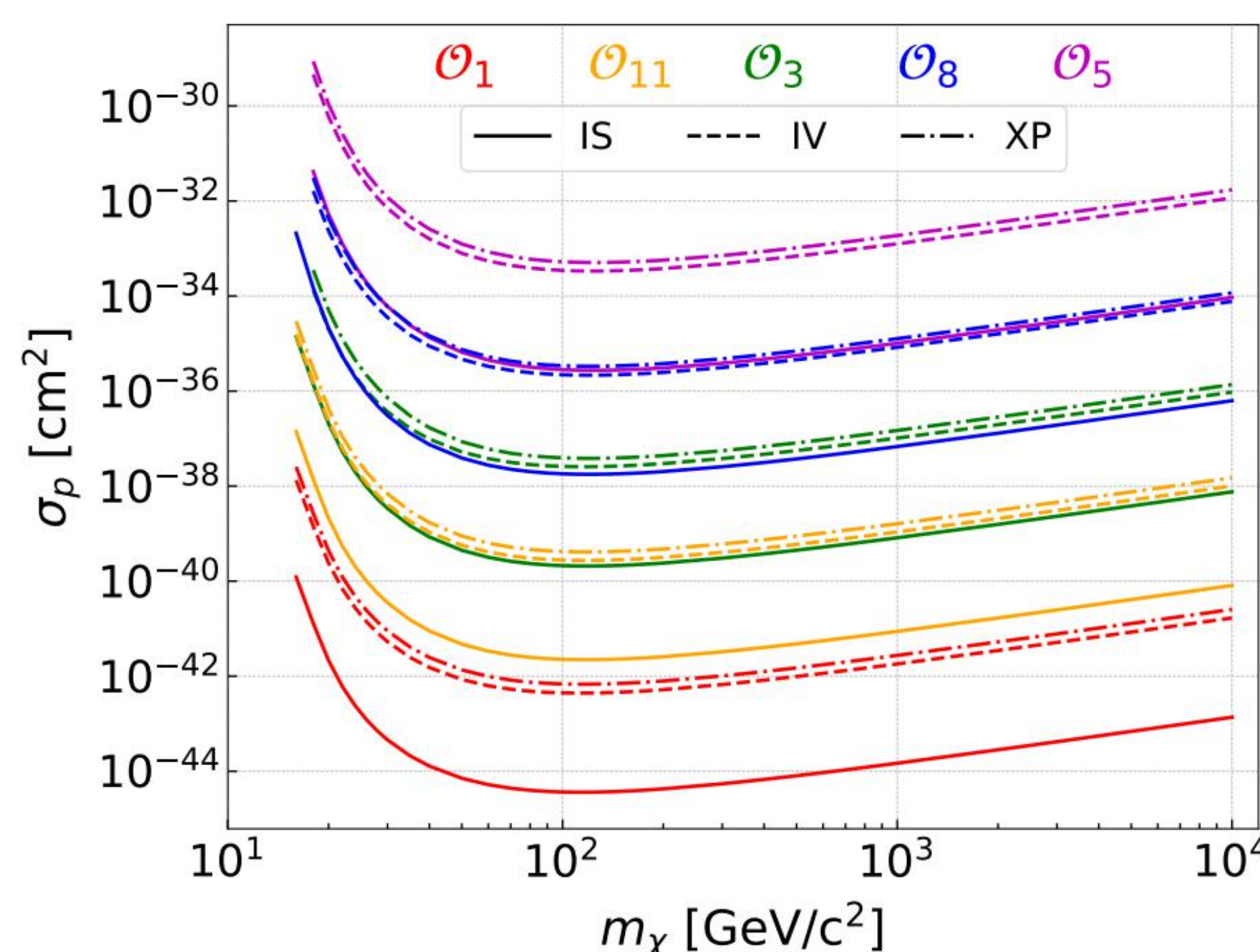


Figure 2. Limits on the DM-proton cross-section for the operators \mathcal{O}_1 , \mathcal{O}_3 , \mathcal{O}_5 , \mathcal{O}_8 , and \mathcal{O}_{11} using the SHM.

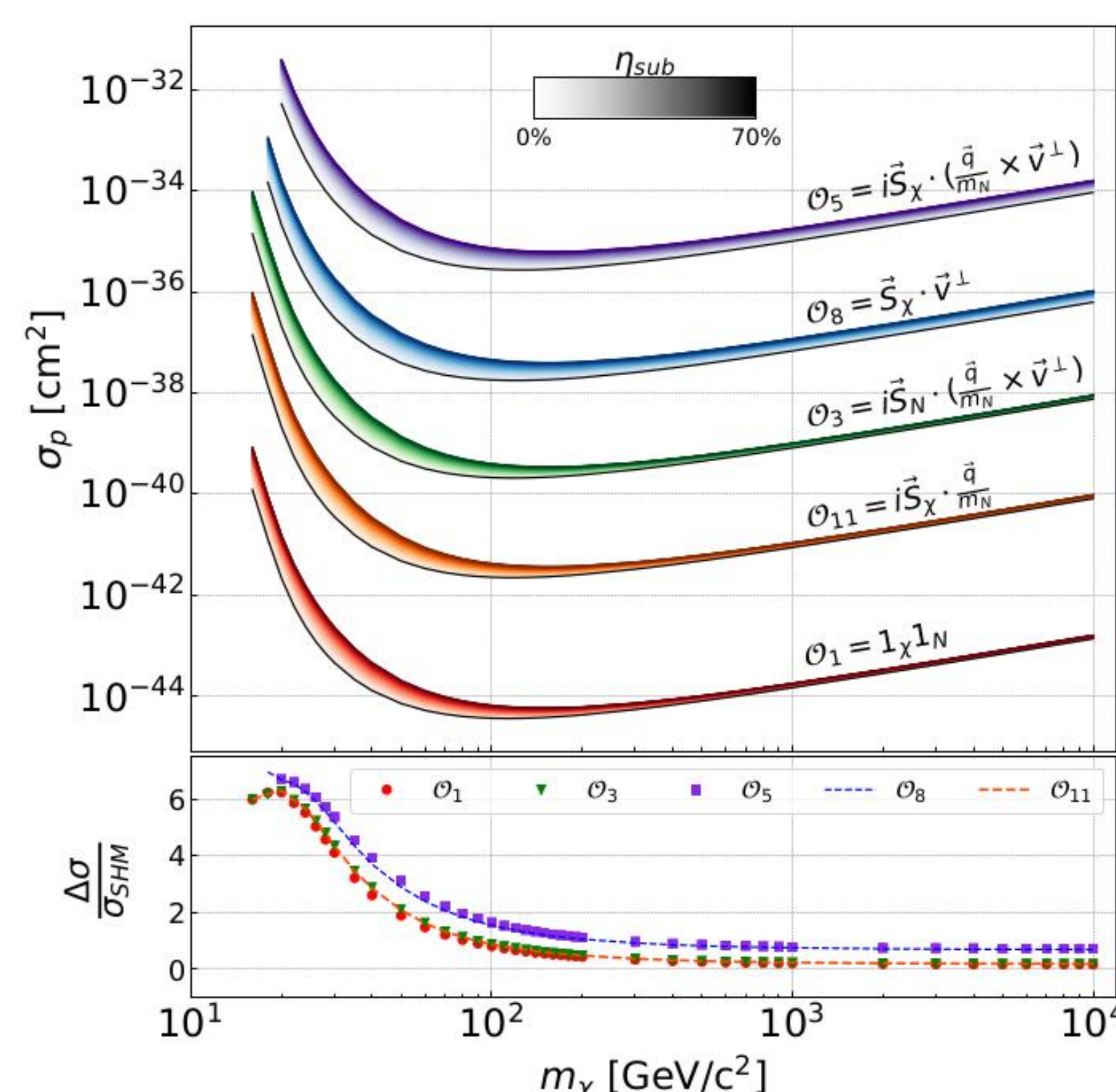


Figure 3. Results with the Gaia Sausage velocity distribution. The limits become weaker by increasing η_{sub} .

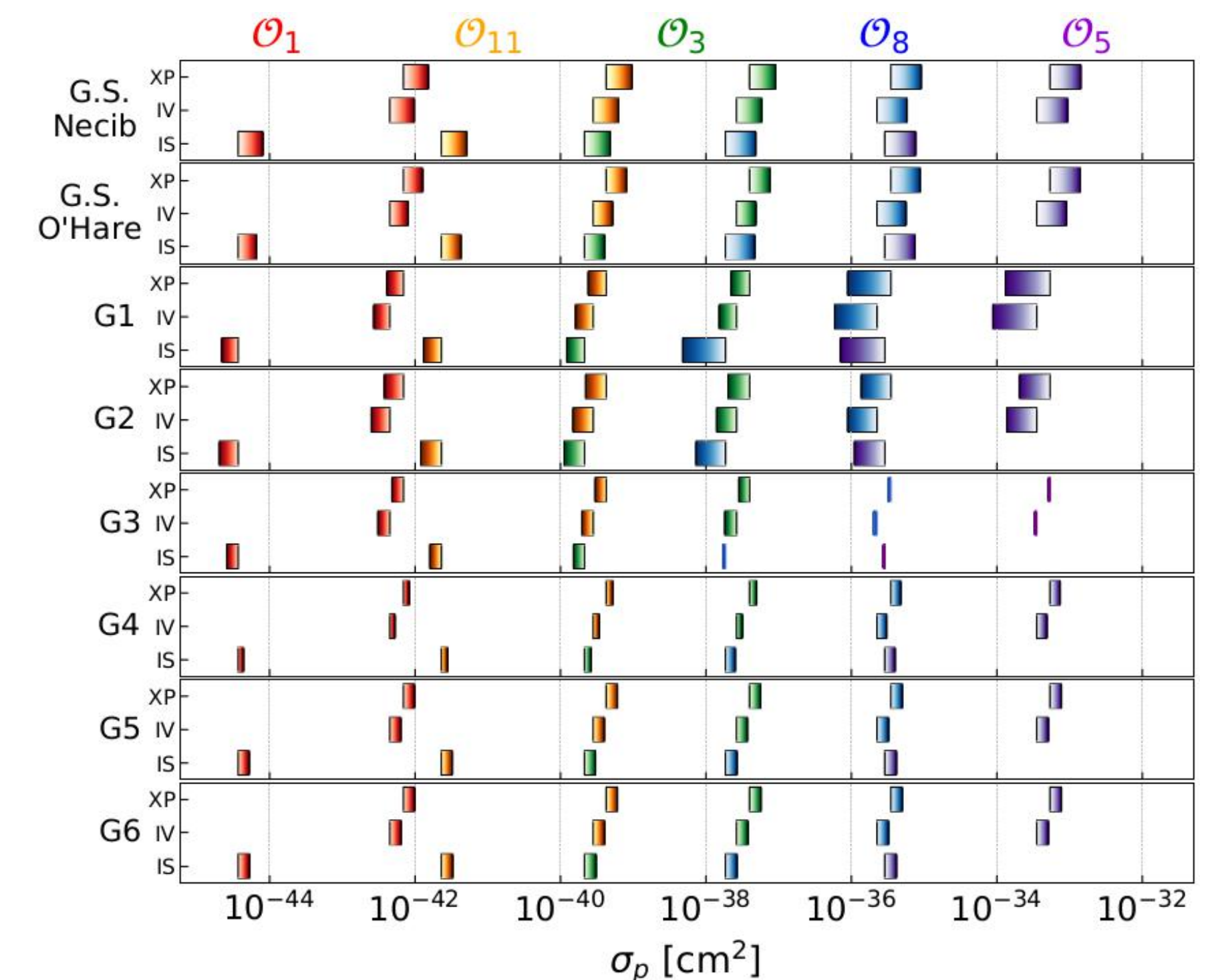


Figure 4. Limits on the DM-proton cross-section for each operator, substructure, and isospin scenario ($m_\chi = 100 \text{ GeV/c}^2$). The shading indicates the variation of η_{sub} .

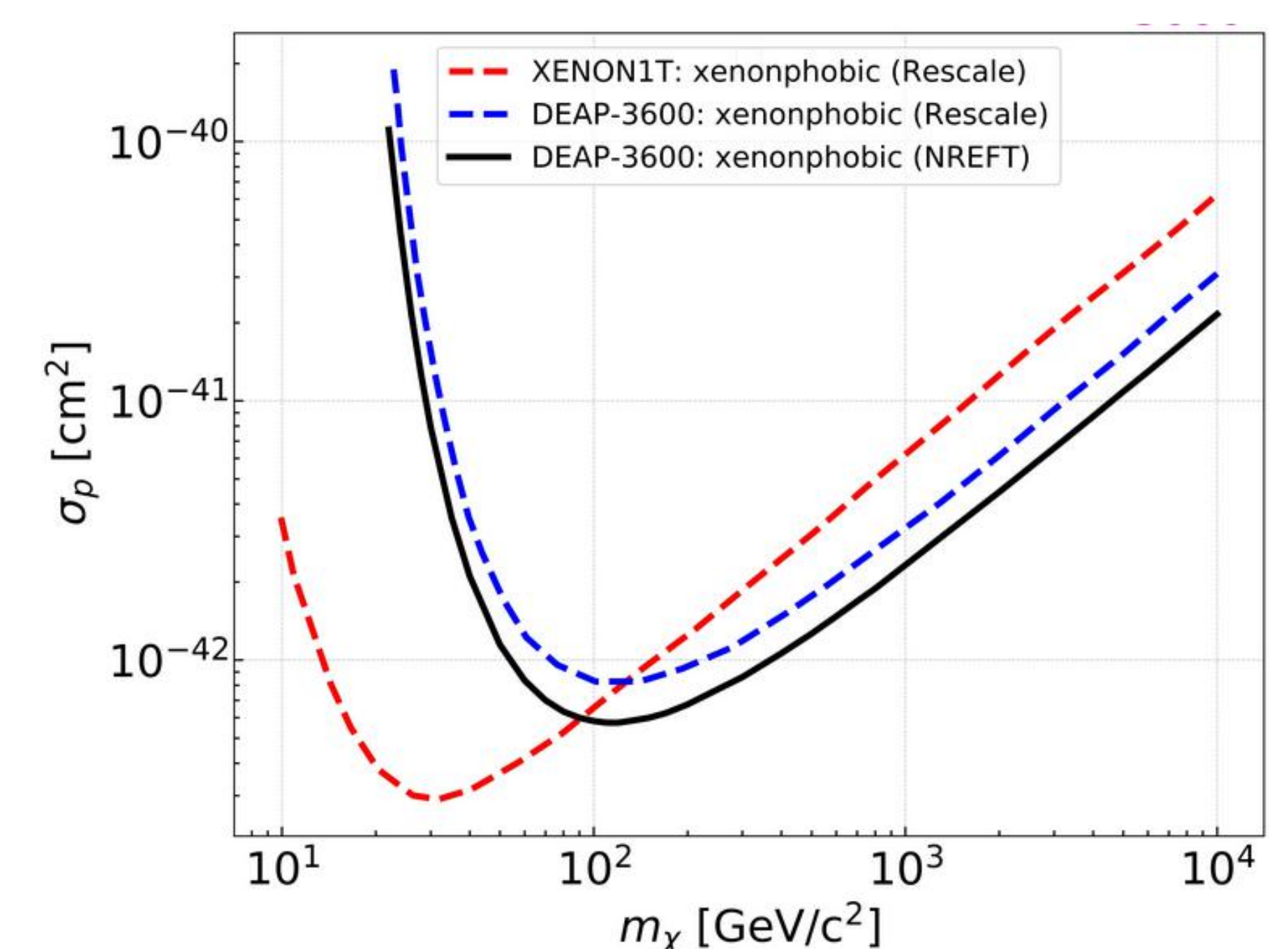


Figure 5. Constraints on the \mathcal{O}_1 interaction from Xenon1T and DEAP-3600 for the XP scenario. WIMPs would couple differently with neutrons and protons ($c_n/c_p = -0.7$).

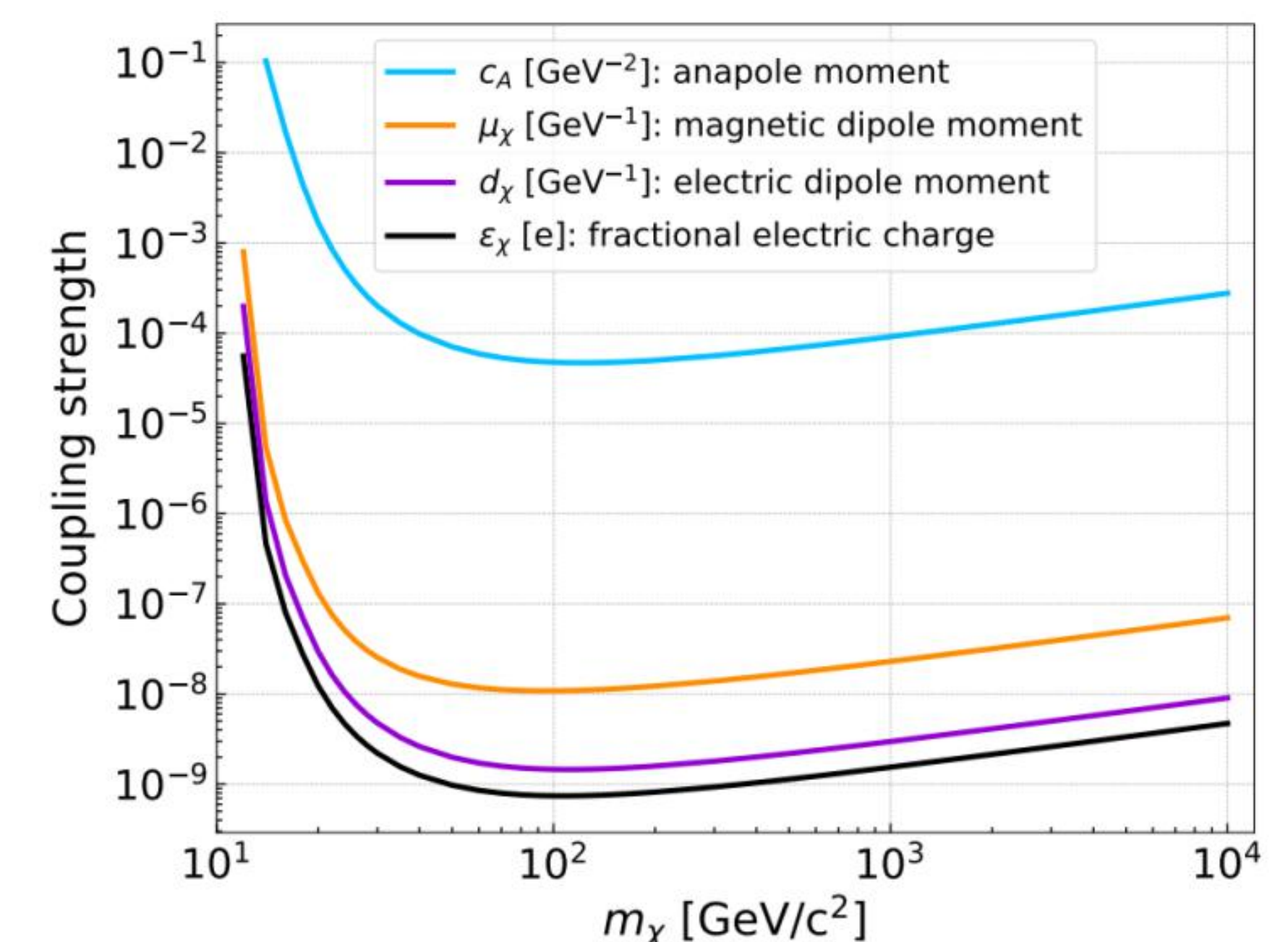


Figure 6. Limits on specific interactions (Anapole, Magnetic/Electric dipole, and Millicharged DM) using the SHM.

Conclusions

This work presents a recent study of the DEAP-3600 collaboration on reinterpreting the null result of 231 live-days of WIMP search within a NREFT framework and with potential DM halo substructures, concluding that the astrophysical and particle physics uncertainties can significantly affect how the parameter space is constrained.

Contact

Ariel Zuñiga Reyes
 Instituto Física - UNAM
 Email: arzure89@gmail.com

References

1. DEAP collaboration, *Astropart. Phys.* 108 (2019) 1-23
2. DEAP collaboration, *Eur. Phys. J. C* 80, 303 (2020)
3. DEAP collaboration, *Phys. Rev. D* 100, 022004 (2019)
4. J. Fan et al, *JCAP* 11, 042 (2010).
5. A. L. Fitzpatrick et al, *JCAP* 02, 004 (2013)
6. E. del Nobile et. al., *JCAP* 1310:019,2013
7. Lina Necib et al 2019 *ApJ* 874 3
8. DEAP collaboration, *Phys. Rev. D* 102, 082001 (2020)