PROCEEDINGS OF SCIENCE

Phenomenology of anapole dark matter

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In this work, we investigate the constraints on anapole dark matter characterized by its derivative coupling to standard model photons. This momentum-dependent interaction significantly enhances the scattering between dark matter and standard model states within compact stars making celestial capture a valuable probe of such tiny interactions. We find that for higher dark matter masses, constraints derived from solar neutrinos produced by captured dark matter are more stringent than those obtained by the recent DarkSide-50 and LUX-ZEPLIN experiments. Additionally, we demonstrate that the projected sensitivity from observing cold neutron stars in the near future offers the potential to explore much deeper regions of the parameter space.

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1. Introduction

Weakly Interacting Massive Particles (WIMPs) with derivative couplings with the Standard Model (SM) particles present a compelling framework for studying dark matter capture within celestial objects. The gravitational focusing effect of such bodies can accelerate dark matter particles to velocities as high as $\sim 0.6\,c$, particularly in compact stars like neutron stars. This velocity boost significantly enhances the scattering rates for momentum-dependent dark matter (DM) models, especially when compared to those observed in laboratory experiments [1]. In this study, we explore the scattering cross-section of anapole dark matter within the Sun and neutron stars through the celestial capture mechanism and analyzing the subsequent annihilation and heating signatures. We have also updated the direct detection limits using the latest results from DarkSide-50 and LUX-ZEPLIN (LZ). We find that the combination of updated direct detection bounds and solar neutrino constraints from captured dark matter can effectively constraint a substantial portion of the parameter space for anapole dark matter. Additionally, the potential observation of a cold neutron star using telescopes like the James Webb Space Telescope (JWST) can significantly improve these constraints.

2. Anapole dark matter

For a Majorana fermion, dipole interactions are forbidden as they violate CPT invariance. The only permissible multipole interaction is of an anapole nature [2]. The corresponding dimension-6 interaction Lagrangian for a spin-$\frac{1}{2}$ Majorana fermion can be expressed as [3]

$$\mathcal{L}_{\text{anapole}} = \frac{1}{\Lambda^2}\,\bar{\chi}\gamma_\mu\gamma_5\chi\,\partial_\nu F^{\mu\nu}, \tag{1}$$

where $F^{\mu\nu}$ represents the electromagnetic field strength tensor, while χ denotes the Majorana dark matter field, with Λ serving as the cut-off scale up to which the effective operator remains applicable. In this work, we primarily focus on the anapole interaction between DM fields and SM photons. However, more broadly, the DM can interact with the hypercharge gauge bosons [4].

3. Phenomenology study

In this section, we detail the analysis of the relic density for anapole dark matter under the freeze-out mechanism. Additionally, we will outline the constraints on the dark matter parameter space taking into account both direct detection methods and dark matter capture within celestial bodies.

3.1 Relic density

We consider that the DM remains in thermal equilibrium with the primordial plasma in the early Universe. As the Universe expands, the rate of expansion eventually surpasses the rate of dark matter annihilation causing the comoving number density of DM particles to freeze out. The relic abundance of these particles is determined by numerically solving the Boltzmann equation given by

$$\frac{dY_\chi}{dz} = -\frac{z\,s\langle\sigma_{\text{ann}}v\rangle}{H(m_\chi)}\left(Y_\chi^2 - Y_{\text{eq}}^2\right), \tag{2}$$

where Y_χ denotes the comoving number density of dark matter with $z = m_\chi/T$ representing a dimensionless variable and $H(m_\chi)$ corresponding to the Hubble expansion rate. In Eq. (2), the term $\langle\sigma_{\rm ann}v\rangle$ refers to the thermally averaged annihilation cross-section of dark matter which is calculated assuming s-channel annihilation of the dark matter particles into SM fermions.

3.2 Direct detection

Since the DM particles considered in this study interact with SM fermions, they can scatter off SM fermions in a typical detector target material. The resulting nuclear recoil from these interactions can be detected in direct detection experiments. The differential recoil rate for such scattering processes is expressed as

$$\frac{dR}{dE_{\rm nr}} = \frac{\eta_{\rm exp}}{m_k}\left(\frac{\rho_0}{m_\chi}\right)\int_{u_{\rm min}}^{u_{\rm max}} du_\chi\, u_\chi\, f\left(u_\chi\right)\frac{d\sigma}{dE_{\rm nr}}, \tag{3}$$

where ρ_0, m_χ and $f\left(u_\chi\right)$ are the neighnourhood density, mass and velocity distribution profile of DM respectively and $\eta_{\rm exp}$ is the exposure time while m_k be the mass of the target material of the detector. We have updated the direct detection constraints on the anapole dark matter parameter space by implementing the recent results from DarkSide-50 [5] and LZ [6].

3.3 Dark matter capture

As a celestial body moves through the dark matter halo, its strong gravitational potential can focus abundant dark matter particles into its interior. If the DM interacts with SM states through non-gravitational interactions, it can scatter off the constituents of the celestial body, losing enough energy to become gravitationally bound within the stellar environment. Beyond gravitational focusing, the momentum-dependent coupling characteristic of anapole dark matter enhances the scattering cross-section inside compact stars, allowing even tiny interactions to be probed through celestial capture. Once trapped within the celestial body, the dark matter particles may annihilate, leading to either heating effects or detectable annihilation signatures. We will now discuss these two complementary signals of dark matter capture in the context of anapole dark matter.

3.3.1 Neutrinos from Sun

Once dark matter particles are captured within the celestial atmosphere, they thermalize with the stellar constituents. After sufficient accumulation of dark matter in the core, these particles start to annihilate. Neutrinos produced from such annihilation processes can escape from gaseous stars like the Sun, and potentially be detected by Earth-based observatories. Since the Sun is a main-sequence star, calculating the dark matter capture rate requires taking its chemical composition into account, which can be expressed as

$$C_\odot = \sum_k \left(\frac{\rho_0}{m_\chi}\right)\int_0^{R_\odot} 4\pi r^2\, dr \int_0^{u_{\rm esc}} du_\chi \frac{f\left(u_\chi\right)}{u_\chi} w(r)\,\Omega_k^-(w), \tag{4}$$

where the summation extends over all nuclei within the solar interior, $w(r)$ represents the velocity of DM particles at a radial distance r from the center of the Sun and $\Omega_k^-(w)$ is the capture probability of DM after scattering with nucleus k. In Eq. (4), the velocity distribution function $f\left(u_\chi\right)$ is

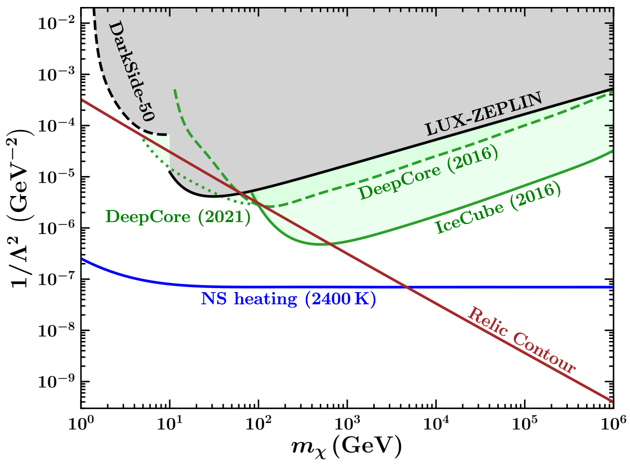

Figure 1: Constraints on the coupling of anapole dark matter derived from direct detection (DarkSide-50 and LZ), along with limits based on heating and annihilation signatures resulting from dark matter capture in neutron stars and the Sun respectively.

assumed to follow a Maxwell-Boltzmann distribution, the deviations from this approximation have been studied in detail in [7].

Anapole DM particles can undergo annihilation into SM states, generating neutrinos as secondary products through cascade processes. The resulting differential neutrino flux observed at the surface of the Earth can be expressed as

$$E_\nu^2 \frac{d\phi_\nu}{dE_\nu} = \frac{\Gamma_{\rm ann}}{4\pi D_\odot^2} \times \left(E_\nu^2 \frac{dN_\nu}{dE_\nu} \right), \tag{5}$$

where the annihilation rate under equilibrium conditions is given by $\Gamma_{\rm ann} = C_\odot/2$. In Eq. (5), the term $D_\odot$ denotes the distance between the Earth and the Sun, while (dN_ν/dE_ν) refers to the neutrino spectrum produced per dark matter annihilation, appropriately weighted by the corresponding branching ratios. The production spectra have been obtained using the χaroν [8], and the effects of neutrino oscillations and scattering are evaluated using the `nuSQuIDS` [9]. We have utilized the IceCube and DeepCore solar neutrino measurements [10, 11] to provide limits on the anapole DM interactions.

3.3.2 Neutron star heating

Due to their extremely high density, neutron stars can efficiently capture dark matter particles. However, within this dense environment even the neutrinos produced in the relevant energy range are unable to escape from the stellar interior. Consequently, all SM annihilation products remain confined within the stellar medium leading to a rise in the neutron star temperature. For a typical neutron star, the increase in effective temperature can be expressed as

$$T_{\rm eff} = 2410\, f_{\rm cap}^{\frac{1}{4}} \left(\frac{\rho_\chi}{0.4\,{\rm GeV/cm^3}} \right)^{\frac{1}{4}}, \tag{6}$$

where $f_{\rm cap}$ represents the fraction of DM particles captured within the neutron star that depends on the scattering cross-section of DM with SM states. As highlighted in [12], the capture efficiency of

DM decreases as the mediator becomes lighter. However, in the case of anapole DM, the derivative coupling significantly affects the kinematics leading to an enhanced energy transfer. This ensures that single scattering capture that influences the temperature increase outlined in Eq. (6) remains valid for the anapole DM scenario [1].

4. Results

In Fig. 1, we present the constraints on anapole dark matter coupling derived from direct and indirect detection methods. The brown curve represents the relic density contour within the freeze-out scenario for anapole dark matter consistent with the *Planck* 2018 observations [13]. Fig. 1 also illustrates the limits from direct detection experiments, where the solid and dashed black lines correspond to the constraints from LZ and DarkSide-50 respectively. While DarkSide-50 sets stringent constraints upto dark matter mass of 10 GeV, LZ provides stronger bounds at higher masses. The green lines represent constraints from neutrino observations due to dark matter captured in the Sun, with dashed and solid lines corresponding to DeepCore and IceCube data respectively [10]. The green dotted line indicates limits derived from the most recent DeepCore analysis [11]. Additionally, the blue solid line shows projected constraints from dark heating in an old cold neutron star with a surface temperature of 2400 K, which could be detectable by JWST in the near future [14]. Similar constraints for dipole dark matter models are discussed in [1].

5. Conclusion

In this study, we have systematically analyzed the constraints on the anapole dark matter model over a mass range of 1 - 10^6 GeV. The momentum-dependent coupling inherent in the anapole DM interaction topology enhances the scattering cross-section within compact celestial objects making celestial capture a crucial method for probing this interaction. Constraints derived from solar neutrino signals due to captured DM, as observed by IceCube and DeepCore, explore new regions of the parameter space that remain unconstrained by the updated direct detection limits from DarkSide-50 and LZ. Additionally, we found that the projected sensitivity from observing a neutron star with a surface temperature of 2400 K via JWST offers the potential to probe even deeper into the parameter space in the near future.

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