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Boosted dark matter signals uplifted with self-interaction

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ABSTRACT

We explore detection prospects of a non-standard dark sector in the context of boosted dark matter. We focus on a scenario with two dark matter particles of a large mass difference, where the heavier candidate is secluded and interacts with the standard model particles only at loops, escaping existing direct and indirect detection bounds. Yet its pair annihilation in the galactic center or in the Sun may produce boosted stable particles, which could be detected as visible Cherenkov light in large volume neutrino detectors. In such models with multiple candidates, self-interaction of dark matter particles is naturally utilized in the *assisted freeze-out* mechanism and is corroborated by various cosmological studies such as *N*-body simulations of structure formation, observations of dwarf galaxies, and the small scale problem. We show that self-interaction of the secluded (heavier) dark matter greatly enhances the capture rate in the Sun and results in promising signals at current and future experiments. We perform a detailed analysis of the boosted dark matter events for Super-Kamiokande, Hyper-Kamiokande and PINGU, including notable effects such as evaporation due to self-interaction and energy loss in the Sun.

1. Introduction

Dark matter (DM) is one of the most profound mysteries in particle physics and cosmology. Recent observations show that 25% of our universe is made up of dark matter, yet we know very little about its nature and properties. Especially its microscopic nature such as its stabilizing mechanism, spin and mass, necessitates a balanced program based on various dark matter searches [1].

Among a myriad of possibilities, scenarios with multiple dark matter particles are well motivated and their implications have been studied at different scales from the large in cosmology to the small at the Large Hadron Collider (LHC) at CERN [2]. Several issues have been especially investigated on the cosmological side in the context of multiple dark matter candidates. While *N*-body simulations of structure formation based on cold dark matter (CDM) present a steep cusp density profile [3], observations of dwarf galaxies indicate a cored density profile rather than a cusped one [4] (so-called the "core vs. cusp problem"). Simulations also predict that CDM evolves to very dense subhalos of Milky Way type galaxies, which cannot host the brightest satellites, but it would be hard to miss the observation of these substructures (known as the "too big to fail problem") [5]. Warm dark matter has been proposed as a solution to the small scale conflict between the observations and the simulations with CDM, since it is expected to develop shallower density profiles at a small scale and would avoid unreasonably dense subhalos [6].

Self-interacting DM (SIDM) has been suggested as another interesting solution to those small scale problems [7]. Cosmological simulations with SIDM [8] show that SIDM with the ratio of the DM self-interaction cross section to the DM mass $\sigma_{\chi\chi}/m_\chi \sim \mathcal{O}(0.1\text{–}1\ \text{cm}^2/\text{g})$ can reconcile the inconsistency between simulations and observations at a small scale, while it does not modify the CDM behavior at a large scale. Analysis of the matter distribution of the Bullet Cluster [9] provides the most robust constraint on SIDM, $\sigma_{\chi\chi}/m_\chi < 1.25\ \text{cm}^2/\text{g}$. Another analysis based on the kinematics of dwarf spheroidals [10] shows that SIDM resolves the small scale conflicts of CDM only when $\sigma_{\chi\chi}/m_\chi \gtrsim 0.1\ \text{cm}^2/\text{g}$.

In this paper, we investigate detection prospects of two-component dark matter at large volume neutrino detectors. We focus on a scenario with a relatively large mass gap between the two components, where the heavier candidate interacts with the standard model (SM) particles only at loops. Its sister (the light one) is assumed to have interactions with both the heavier counterpart and the standard model particles. If the heavier dark matter is dominant in our current universe, the dark sector with such candidates is secluded and all current direct and indirect

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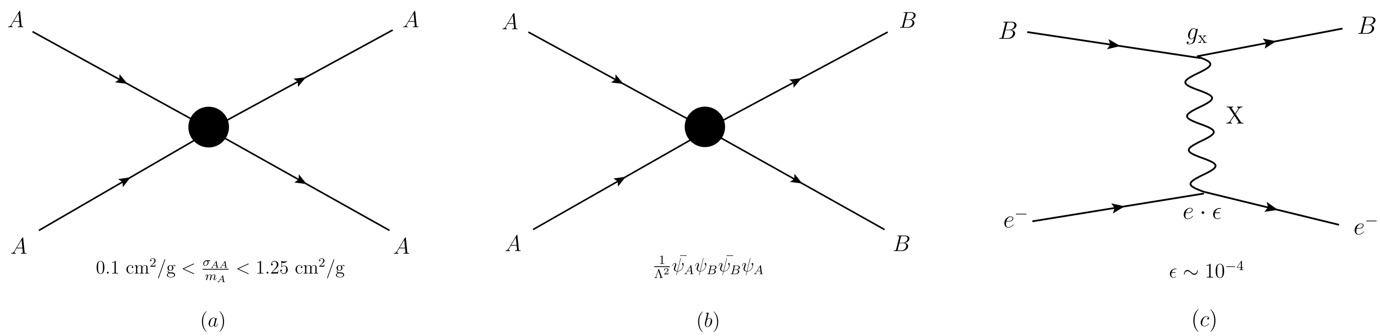

Fig. 1. Diagrams for (a) self-interaction of the heavier DM ψ_A, (b) production of the boosted DM ψ_B from the annihilation of ψ_A, and (c) elastic scattering of ψ_B off an electron.

bounds are evaded. Although the light dark matter particles are subdominant, they may be produced via the annihilation of the heavy sisters with a large boost due to the large mass difference. A boosted DM arises in various multi-component DM scenarios such as semi-annihilation $\psi_i\psi_j \to \psi_k\phi$ [11,12], assisted freeze-out $\psi_i\psi_i \to \psi_j\psi_j$ [13], and decay $\psi_i \to \psi_j + \phi$. Recently a possibility of detecting a boosted dark matter particle in large volume neutrino telescopes has been examined [14–16]. In Ref. [15], the heavier DM annihilates in the center of the galaxy, and its pair annihilation products travel to the Earth and leave Cherenkov light in the detector via a neutral current-like interaction, which points toward the galactic center (GC). Detection of boosted dark matter from the Sun has been studied in Ref. [16], where a search for proton tracks pointing toward the Sun is proposed in a different model.

We explore detection prospects of boosted dark matter from the Sun in the presence of self-interaction of the heavier component, which is well motivated by various cosmological studies as mentioned earlier. We include important effects that are neglected in literature such as evaporation of the dark matter and energy loss during traveling from the core to the surface of the Sun. As a concrete example, we consider a model that was studied in Ref. [15], which is revisited in Section 2. A detailed calculation of the boosted dark matter flux is outlined in Section 3, and detection prospects in Section 4. We focus on the discovery potential at Super-Kamiokande(Super-K), Hyper-Kamiokande(Hyper-K), and PINGU.

2. Boosted dark matter in assisted freeze-out

In this section, we present an explicit example of a model with two-component DM in order to discuss detection prospects of boosted DM from the Sun. We choose the model studied in Ref. [15] based on the assisted freeze-out mechanism [13]. Additionally we introduce DM self-interaction preferred by cosmological simulations and observations for the heavier constituent of the two DM components. We only briefly summarize the key points of our bench mark model and refer to Ref. [15] for details on the model.

2.1. Basic set-up

We consider the case where ψ_A and ψ_B are two stable DM candidate particles with masses $m_A > m_B$. This can be achieved with separate symmetries, for example, $\mathrm{U}(1)' \otimes \mathrm{U}(1)''$ [13] or $Z_2 \otimes Z_2'$ [15]. We assume that two DM species, ψ_A and ψ_B interact via a contact operator,

$$\mathcal{L}_{AB} = \frac{1}{\Lambda^2}\overline{\psi}_A\psi_B\overline{\psi}_B\psi_A\,, \tag{1}$$

and that ψ_A can only annihilate into ψ_B and not directly into SM particles. Moreover, the heavier component ψ_A is the dominant DM constituent in the universe. The boosted DM ψ_B is currently produced via the contact interaction (1). We additionally allow a self-interaction for ψ_A in the range of $0.1\ \mathrm{cm}^2/\mathrm{g} < \sigma_{AA}/m_A < 1.25\ \mathrm{cm}^2/\mathrm{g}$ (Fig. 1(a)), favored by simulations and observations [7–10].

The particle ψ_B is charged under a hidden $\mathrm{U}(1)_X$ gauge symmetry, with a charge $Q_X^B = 1$ for simplicity, which is spontaneously broken leading to the gauge boson mass m_X. In addition, a mass hierarchy, $m_A > m_B > m_X$ is assumed. The gauge coupling of $\mathrm{U}(1)_X$, g_X will be taken to be large enough, e.g. $g_X = 0.5$, so that the thermal relic density of ψ_B is small due to the large annihilation cross section of the process $\psi_B\overline{\psi}_B \to XX$. We assume that the DM sector couples to the SM sector only through a kinetic mixing between $\mathrm{U}(1)_X$ and $\mathrm{U}(1)_{\mathrm{EM}}$ (originally $\mathrm{U}(1)_Y$) [17,18],[1]

$$\mathcal{L} \supset -\frac{1}{2}\sin\epsilon\, X_{\mu\nu}F^{\mu\nu}\,. \tag{2}$$

Thus, ψ_B can scatter off SM particles via a t-channel X boson exchange.

This model can be described by a set of seven parameters:

$$\{m_A, m_B, m_X, \Lambda, g_X, \epsilon, \sigma_{AA}\}\,, \tag{3}$$

where Λ will be appropriately taken in our analysis to obtain the required DM relic density, $\Omega_A \simeq \Omega_{\mathrm{DM}} \approx 0.2$, as done in Ref. [15]. In all the interactions between DM and SM particles, g_X and ϵ always appear as a simple combination, $(g_X \cdot \epsilon)$. As a result, our analysis will mainly rely on five parameters, $\{m_A, m_B, m_X, g_X\cdot\epsilon, \sigma_{AA}\}$. For easier comparison, we choose the same benchmark scenario as in Ref. [15], except for ϵ,

$$m_A = 20\ \mathrm{GeV},\ m_B = 0.2\ \mathrm{GeV},\ m_X = 20\ \mathrm{MeV},$$
$$g_X = 0.5,\ \text{and}\ \epsilon = 10^{-4}\,. \tag{4}$$

However, we choose $\epsilon = 10^{-4}$, instead of 10^{-3} chosen as a reference value in Ref. [15], for boosted ψ_B to avoid too much energy loss during traversing the Sun as explained in Section 3.4. $\epsilon = 10^{-4}$ is well consistent with current limits on a hidden X gauge boson (or a dark photon), $\epsilon \lesssim \mathcal{O}(10^{-3})$ for $m_X \gtrsim 10$ MeV [19].

2.2. Relic abundance and scattering cross sections

A set of coupled Boltzmann equations describes the evolution of the relic density of two DM particles, ψ_A and ψ_B, in the assisted freeze-out mechanism [13,15,20].[2] The annihilation process

[1] One can find a general and detailed analysis on a hidden sector DM and the kinetic mixing in Ref. [18].

[2] See Ref. [13] for a numerical analysis and Ref. [15] for more details on analytic estimates.