Sub-GeV Gravity-mediated Dark Matter in Direct Detections

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Detection of non-gravitational interactions of massive dark matter with visible sector so far have given null results. The DM may communicate with the ordinary matter only through gravitational interactions. Besides, the majority of traditional direct detections have poor sensitivity of searching for light DM particle because of the small recoil energy. Thanks to the high energy cosmic rays (CRs), the light DM can be boosted by scattering with CRs and thus may be detected in those existing experiments. In this work, we first derive the exclusion limits of the cosmic ray boosted sub-GeV Dark Matter with gravitational mediator from the Xenon1T data.

INTRODUCTION

The existence of dark matter (DM) in the Universe has been confirmed by astrophysical and cosmological observations. However, the nature of DM is one of the most pressing puzzles of modern physics. Weakly Interacting Massive Particle (WIMP) [1] as a compelling dark matter candidate has been searched for in various (in)direct detections [2] and collider experiments [3], most of which aim for DM at the GeV mass scale and above. Recently, the non-observation of WIMPs in those experiments has led to significant efforts focussing on the sub-GeV DM [4]. Such a light DM is also theoretically motivated and appears in many new physics models (for recent reviews, see e.g. [5]), for example, gravitino [6] and sterile neutrino DM [7].

As known, the traditional direct detection based on liquid xenon rapidly loses sensitivity for sub-GeV DM, due to the small recoil energy imparted by DM to a nucleus in elastic scattering [8–10]. The lighter nuclei and lower energy thresholds used in the detectors are able to probe DM in low mass range [11–14]. However, these experiments will lose good discrimination between signal and background events as the DM becomes extremely light. Instead, the searching for DM scattering off electrons may access the lighter DM [15, 16]. Besides, other new methods [17–19] and new types of detectors [20, 21] have been proposed in the past few years.

On the other hand, an observable energy may be imparted to terrestrial nuclear targets by a boosted light DM. There are several acceleration mechanisms of light DM discussed in literature. Among them, the cosmic ray boosted dark matter (CRDM) is an interesting scenario [22, 23], in which some fraction of the DM halo scattering with the high energy cosmic rays are accelerated to (semi-)relativistic speeds that can produce the detectable scintillation signal in conventional terrestrial experiments [24–27]. For non-relativistic DM, the cross section of DM scattering with nucleons is often assumed to be momentum independent. However, when the mediator mass is less than the transferred momentum, the full propagator should be included in the scattering cross section to obtain the more accurate results. In Ref. [28, 29], the sub-GeV CRDM with scalar and vector mediators have been considered in simplified models. Besides, the energetic light CRDM may affect the energy density around $T \sim$ few MeV, and thus is constrained by the BBN data [30].

In this work, we will focus on the gravitational mediator that couples to light Dirac DM and the SM particles through the energy-momentum tensor. By considering the cosmic ray acceleration mechanism, we will derive the bounds on such a light CRDM with the available traditional direct detections. This paper is organized as follows: in Sec. 2, we formulate the framework of cosmic ray boosted dark matter in the simplified DM model with a gravitational mediator. Then, we present the numerical results and discussions in Sec. 3. The conclusion is drawn in Sec. 4.

MODEL AND CRDM

Till now all attempts to detect DM non-gravitational interactions with ordinary matter have failed. Thus, it is naturally to consider the gravity-mediated DM, which is realized in warped extra dimensions [31–34]. The DM is located in the IR brane, while the Standard Model particles are located in the UV brane, as shown in Fig. 1. The gravitational mediators arising from the compactification of extra-dimensions can produce thermally the
correct abundance of DM in the Universe. As a phenomenological study, we parameterize the interactions of the gravity-mediated DM and the SM fermion (Here it is referred to nucleon) as following,

\[ \mathcal{L}_G = - \frac{i}{2} \left[ c_{\text{SM}} G^{\mu \nu} T_{\mu \nu}^\text{SM} + c_{\text{DM}} G^{\mu \nu} T_{\mu \nu}^\text{DM} \right]. \]  

(1)

where \( G^{\mu \nu} \) is the massive KK graviton and \( T_{\mu \nu}^\text{DM,SM} \) is the energy-momentum tensor for dark matter and the SM particles. \( \Lambda \) is inverse of extra dimension length \( \ell \). These effective interactions allow us to still remain the feature of warped dark sector [34].

With Eq. 1, the tree-level scattering amplitude between fermionic DM and the SM fermion through the spin-2 mediator can be written as,

\[ M = \frac{i c_{\text{DM}} c_{\text{SM}}}{2m^2} \left( 2 \tilde{T}_{\mu \nu}^\text{DM} \tilde{T}_{\mu \nu}^\text{SM,\mu \nu} - \frac{1}{6} T_{\mu \nu}^\text{DM} T_{\mu \nu}^\text{SM} \right), \]  

(2)

where \( \tilde{T}_{\mu \nu} \) and \( T \) is the traceless and trace parts of energy-momentum tensor. In momentum space, they are given by,

\[ \tilde{T}_{\mu \nu} = - \frac{1}{4} \bar{\psi}(p_2) \left[ \gamma_\mu(p_{1\nu} + p_{2\nu}) + \gamma_\nu(p_{1\mu} + p_{2\mu}) \right. \]
\[ \left. - 2 \eta_{\mu \nu} \bar{\psi}(p_1) \right] u_\psi(p_1), \]

(3)

\[ T = \frac{1}{4} \bar{\psi}(p_2) \left[ -6(p_1^2 + p_2^2) + 16m^2 \right] u_\psi(p_1), \]  

(4)

where \( \psi \) stand for the fermionic DM or the SM fermions. We present the explicit form of the differential scattering cross section of the DM with CRs in the appendix.

We present the explicit form of the differential scattering cross section \( \sigma_i \), where \( i \) stands for the specific species of the cosmic rays. We only consider the contributions of \( p \) and \( ^4\text{He} \) in our calculations. \( T_1 \) and \( T_2 \) denote the kinetic energy of CRs and DM, respectively. \( d\Phi_i^\text{LIS}/dT_i \) is the spectrum of the incoming CR flux taken in the local interstellar (LIS) [35, 36]. \( p_\chi \) is the local DM density and \( d\sigma_{\chi i}/dT \) is the differential scattering cross section of CR and DM. For simplicity, the source density of CRDM is assumed roughly the same as it is locally within the effective length \( D_\text{eff} \sim 8 \text{ kpc} \).

**Attenuation of CRDM by the dense matter of the Earth.** When the boosted DM particles travel from the top atmosphere to the location of detector, the dense matter will degrade the energy of DM [37–40], which can be numerically determined by,

\[ \frac{dT_\chi}{dz} = - \sum N \int_{T_\chi^{\text{min}}}^{T_\chi^{\text{max}}} \frac{d\sigma_{\chi N}}{dT_N} T_N dT_N. \]  

(6)

Here \( T_\chi \) is DM energy at the depth \( z \) from the top of the atmosphere. \( T_N \) refers to the recoil energy of nucleus \( N \). The average density \( n_N \) of Earth’s 11 most abundant elements between surface and depth \( z \) is calculated by DarkSUSY 6 [41]. \( d\sigma_{\chi N}/dT_N \) is the differential cross section of the CRDM scattering with the dense matter at the depth \( z \). Then, the attenuated CRDM flux \( d\Phi_\chi/dT_\chi \) at the depth \( z \) can be related with the flux \( d\Phi_\chi/dT^\text{z} \) at the top of the atmosphere by,

\[ \frac{d\Phi_\chi}{dT_\chi} = \left( \frac{dT_\chi}{dT^\text{z}} \right) \frac{d\Phi_\chi}{dT^\text{z}}. \]  

(7)

**Scattering between the CRDM and ordinary matter in the detector.** In order to derive the bounds on CRDM with the reported limits for heavy DM from conventional detections, we define recoil rate per target particle \( N \) mass within the experimentally accessible window of recoil energies \( T_1 < T_N < T_2 \) as,

\[ R = \int_{T_1}^{T_2} \frac{1}{m_N} dT_N \int_{T_\chi^{\text{min}}}^{T_\chi^{\text{max}}} dT_\chi \frac{d\sigma_{\chi N}}{dT_N} \frac{d\Phi_\chi}{dT_\chi}. \]  

(8)

where \( \sigma_{\chi N} \) is the cross section of DM-nucleus elastic scattering. To present the results in terms of the cross section per nucleon, \( \sigma_{\chi N} \), we use the approximate rescaling relation,

\[ \sigma_{\chi N} (Q^2) = \sigma_{\chi N} \times A^2 \times \frac{m_A (m_\chi + m_N)}{m_N (m_\chi + m_A)} \times F_\chi^2 (Q^2). \]  

(9)

with the nuclear form factor \( F_\chi^2 (Q^2) \) [42],

\[ F_\chi^2 (Q^2) = 1/(1 + Q^2/A_n^2), \]  

(10)

where the typical momentum transfer \( Q = 35 \text{ MeV} \) for Xenon1T [8] and \( A_{p, ^4\text{He}} = 770, 480 \text{ MeV} \) [43].
NUMERICAL RESULTS AND DISCUSSIONS

With the above setup, we use the package DarkSUSY [41] to numerically calculate the flux of CRDM with the spin-2 mediator and then obtain the constraint on its scattering cross section from the Xenon1T experiments [8]. We parameterize the CR flux of Protons and Helium as Ref. [35, 36]. In Fig. 2, we show the flux of CRDM with the spin-2 mediator for different DM masses $m_\chi = 0.001, 0.01, 0.1, 1$ GeV. We take the couplings $c_{DM} = c_{SM}$ and the cut-off scale $\Lambda = 1$ GeV for example 1. From Fig. 2, we can see that the flux of CRDM has a peak in the (semi-)relativistic velocity region. As expected, the lighter DMs obtain more kinetic energy through scattering with the CRs. While different from the scalar and vector cases, the flux of heavy DM in the low velocity region will be larger than that of light DM because the flux are proportional to $m_\chi^2$ in the limit of $T_\chi \to 0$, which can be seen from Eq. 5 and Eq. 13.

In Fig. 3, we display the kinetic energy $T_\chi^z$ at different depth of the earth ($z = 600, 1000, 1400$ m) versus the initial energy of CRDM $T_\chi$.

![Figure 2. The expected flux of CRDM with the spin-2 mediator. The curves from left to right corresponds to DM mass $m_\chi = 1, 0.1, 0.01, 0.001$ GeV, respectively. The cut-off scale $\Lambda$ is set at 1 GeV and the couplings $c_{DM}$ and $c_{SM}$ are assumed to be unity.](image)

![Figure 3. The kinetic energy $T_\chi^z$ at different depth of the earth ($z = 600, 1000, 1400$ m) versus the initial energy of CRDM $T_\chi$.](image)

1 Such a low cut-off scale $\Lambda$ can be realized in warped dark sector [34], which is a slice of AdS space in the Poincare patch with the following metric $ds^2 = (kz)^{-2} (\eta_{\mu\nu} x^\mu x^\nu - dz^2)$. Here the fifth dimension $z$ is compact and evaluated in the interval $z \in [z_0, z_1]$. We mention that $z_0$ is the location of UV-brane where the SM particles live, and $z_1$ is IR-brane where only dark matter lives. The IR scale $\Lambda = 1/z_1$ is a free parameter because there is no Higgs boson in IR brane. It can thus provide a dynamical mechanism of generating a GeV cut-off scale of DM.

\[ \frac{d\theta}{d\chi} = \frac{1}{2} \sigma_{SI} \frac{m_\chi}{T_\chi} \]

\[ T_\chi = \frac{E}{m_\chi} \]

\[ \sigma_{SI} \approx \sigma_{N} \approx \sigma_{G} \]

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The main uncertainties arise from astrophysical inputs, such as the local DM density and CR flux. We assume an NFW profile for the DM distribution [48, 49] and a homogeneous CR distribution. We consider the DM within only 1 kpc of Earth (corresponds to $D_{\text{eff}} = 0.997$ kpc), which produces limits that are within a factor of 2 of the limits obtained by including the entire CR halo. This will reduce the uncertainties from the shape of the DM density profile.

Several new mechanisms have been proposed to achieve the correct relic density of a thermal sub-GeV DM. Among them, the secluded DM framework [50], in which DM interacts with visible sector through a low-mass mediator, can be naturally realized in the warped dark sector by locating the Dirac fermionic DM on the IR brane. The corresponding annihilation cross section is given by,

$$\langle \sigma v_{\text{rel}} \rangle_{\chi\chi \rightarrow GG} \approx \frac{c_{\text{SM}}^2 m_D^2 m_\chi^2 (1 - r)^{7/2}}{16 \pi \Lambda^4 r^2 (2 - r)^2},$$  \hspace{1cm} (11)

where $r = m_G / m_\chi$. Such a process is suppressed by $p$-wave so that it can avoid the constraints from CMB and indirect detections.

**CONCLUSION**

In this paper, we studied the direct detection of the cosmic ray scattering dark matter with a gravitational mediator. Due to the acceleration effect, the sub-GeV CRDM can become (semi-)realistic and thus be accessible in the conventional direct detections. In contrast with the scalar and vector mediators, the spin-2 mediator produce a larger flux behavior of DM in low energy region due to the nature of tensor interaction, which greatly enhances the sensitivity of heavier DM. By including the momentum-dependent effects, we obtained the exclusion limit of the SI cross section $\sigma_{SI} < \mathcal{O}(10^{-35})$ cm$^2$ for 0.1 MeV < $m_\chi$ < 10 MeV with the Xenon1T data, which significantly extends the existing limits on such a light DM.

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**APPENDIX**

The differential cross section of the CR scattering with DM in Eq. 5 is given by,

$$\frac{d\sigma_{\chi_i}}{dT_\chi} = \Delta_0(T_\chi^0) + \Delta_1(T_\chi^1) + \Delta_2(T_\chi^2) + \Delta_3(T_\chi^3) + \Delta_4(T_\chi^4)$$  \hspace{1cm} (12)
\[ \Delta_0(T_\chi^0) = \frac{m_\chi (6T_im_N + 3T_i^2 + 2m_T^2) T_i + 2m_N}{18\pi\Lambda_c^2 T_i (m_T^2 + 2m_T^2) T_i (T_i + 2m_N)} \]  
\[ \Delta_1(T_\chi^1) = -\frac{T_\chi^1 (3T_i + 4m_T + 8m_\chi)}{36\pi\Lambda_c^2 T_i (m_T^2 + 2m_T^2) T_i (T_i + 2m_N)} \]  
\[ \Delta_2(T_\chi^2) = \frac{T_\chi^2 (9T_i m_N (21T_i + 4m_\chi))}{288\pi\Lambda_c^2 T_i (m_T^2 + 2m_T^2) T_i (T_i + 2m_N)} \]  
\[ \Delta_3(T_\chi^3) = -\frac{T_\chi^3 (10T_i + 3m_\chi)}{64\pi\Lambda_c^2 T_i (m_T^2 + 2m_T^2) T_i (T_i + 2m_N)} \]  
\[ \Delta_4(T_\chi^4) = \frac{m_\chi T_i^4}{64\pi\Lambda_c^2 T_i (m_T^2 + 2m_T^2) T_i (T_i + 2m_N)} \]

where

\[ \frac{1}{\Lambda_c^2} = \frac{\Lambda^2}{q^2} \epsilon_{SM,DM} m_\chi^2 \]

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