Boosted Diurnal Effect of Sub-GeV Dark Matter at Direct Detection Experiment

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We point out a new type of diurnal effect in the direct detection of cosmic ray boosted dark matter (DM). The DM-nucleon interactions not only allow the direct detection of DM with nuclear recoil, but also allow cosmic rays to scatter with and boost the non-relativistic DM to higher energies. If the DM-nucleon scattering cross section is large enough, the DM flux is attenuated when DM propagating through the Earth. The direct detection of the boosted DM thus shows strong diurnal modulation due to the anisotropic boosted DM flux and the Earth attenuation. This diurnal modulation and the high energy recoil events are two prominent signatures of the boosted sub-GeV DM.

Introduction – Various strong evidence from astrophysical and cosmological observations supports the existence of dark matter (DM) in the Universe [1]. Most of them come from the gravitational effect of DM since DM is invisible by light. Although astrophysical observations can put some constraints on the DM interactions, to date, the properties of DM are very poorly known (e.g., the possible DM mass still spans nearly 80 orders of magnitude [2]). The direct detection experiments [3] aim to verify the existence of DM particles and measure their interaction properties by the nuclear recoil from the scattering with DM, which are believed to be the most direct way to unveil the nature of DM [4, 5].

The key ingredient of the direct detection experiment is the conventional nonrelativistic DM confined in the Milky Way galaxy. The gravitational potential of the Galaxy puts an upper limit on the DM velocity, $v_{\chi} \lesssim 600$ km/s above which DM can escape [6, 7]. Due to energy threshold, which is typically $\mathcal{O}$(keV), the sensitive mass window of the direct detection experiments can only extend down to 1 GeV which has already been noticed in [3]. If the DM is light (with sub-GeV mass), it can not produce large enough recoil energy since its kinetic energy, $T_{\chi} = \frac{1}{2} m_{\chi} v_{\chi}^2$, is suppressed by its mass $m_{\chi}$. For the sub-GeV DM, or even smaller masses, the parameter space is still largely unexplored yet [8, 9].

Two approaches allow to search for the sub-GeV DM, either using new techniques to lower the energy threshold [10–17] or utilizing the effect that cosmic rays (CR) could boost the energy of DM [18, 19]. As long as DM interacts with matter, it is unavoidable for the non-relativistic DM to be boosted by the energetic CRs that are mainly protons and helium nuclei. During this process, the energy is transferred from a CR particle to a DM particle. With relativistic CR boosted DM (CRDM) population, the direct detection experiments can extend its sensitive mass window from $\mathcal{O}(1 \sim 100)$ GeV down to sub-GeV DM candidates. Compared to the conventional non-relativistic DM particles, the number of CRDM is a tiny fraction and therefore has a small impact to the DM direct detection in the standard channel. However, for the sub-GeV DM, the boosted energies for even such a small fraction of DM allow previously impossible detection. In addition to the reversed direct detection [18] and direct detection [19, 20], CRDM can also produce signals in large neutrino experiments [21–23].

Since the parameter space for sub-GeV DM is largely unexplored yet, the cross section of DM scattering with nucleon can be quite sizable, e.g., as large as $10^{-21}$ cm$^2$ (see [24] and the references in [18]). With this allowed interaction strength, DM particles experience multiple scatterings and hence become attenuated when traveling across the Earth [25–28]. If the DM flux is anisotropic, it is possible to have a diurnal effect at direct detection experiments [29, 30]. Note that the conventional diurnal effect is mainly for non-relativistic DM. In this paper, we point out a new diurnal effect from CRDM.

Sub-GeV Dark Matter Boosted by Cosmic Rays – The spatial and spectral distributions of the CRDM flux depends on the DM and CR distributions in the Galaxy as well as the CR-DM scattering process. Both the DM density and the CR intensities vary with their locations in the Galaxy, mainly concentrating in the Galaxy center (GC). So that CRs are much more likely to scatter with and boost DM in the inner Galaxy region. Even for isotropic scattering, the CRDM flux is highly anisotropic over the sky.

Although the CR-DM scattering also affects the CRs, the effect is important only for very large scattering cross section ($\sigma_{xp} > 10^{-27}$ cm$^2$) [18]. For simplicity, we assume that the CR energy distribution is not affected when boosting DM. The CRDM emissivity, which describes both the spatial and spectrum distributions, is
shows the relative all-sky map of the CRDM fluxes in the Galactic coordinate normalized to unit for the GC direction.

given by [19]

\[
\zeta_\chi(r, T_\chi) = \frac{\rho_\chi(|r|)}{m_\chi} \sum_{i=\text{p,He}} \int_{T_{\text{min}}}^{\infty} dT_i \frac{n_{\text{CR},i}(r, T_i)}{T_\chi^{\text{max}}(T_i)} \times v_i \sigma_\chi G_\chi^2(Q^2) \tag{1}
\]

where \(T_i\) and \(T_\chi\) are the kinetic energies of the CR species \(i\) and the boosted DM, \(T_{\text{min}}\) is the minimum CR energy required to give a DM energy \(T_\chi\), \(T_{\text{max}}\) is the maximum kinetic energy a DM particle can obtain given \(T_i\) [19], and \(n_{\text{CR},i}\) is the CR number density of species \(i\). There are three main ingredients in Eq. (1): the DM density, the CR density, and the scattering cross section.

The first ingredient of Eq. (1) is the DM number density. In this work we adopt the Navarro-Frenk-White (NFW) [31] profile for the DM mass distribution, \(\rho_\chi(r) = \rho_s / [(r/r_s)(1 + r/r_s)^2]\), where \(r_s = 20\) kpc, \(\rho_s = 0.35\) GeV cm\(^{-3}\). These parameters correspond to a local density of \(0.4\) GeV cm\(^{-3}\) [32] in our solar system.

For the CR contribution in the second line of Eq. (1), we employ the GALPROP [33] code (version 54) to simulate its distribution. The propagation parameters are obtained by fitting the most recent AMS-02 measurements of the secondary and primary nuclei [34, 35]. The diffusion plus reacceleration propagation framework is found to best match the current data [36]. The best-fit propagation parameters are: the diffusion coefficient \(D(R) = \beta^0 D_0 (R/4\,\text{GV})^\delta\) with \(D_0 = 7.16 \times 10^{28}\) cm\(^2\) s\(^{-1}\), \(\delta = 0.358\), \(\eta = 0.0\), the half-height of the propagation cylinder \(z_h = 5.6\) kpc, and the Alfven velocity \(v_A = 34.4\) km s\(^{-1}\) [36] that characterizes the reacceleration effect. In this paper, we only consider the dominating proton and helium species of CRs, and leave the rest, in particular electrons and positrons for future discussions. The proton and helium data are measured in a wide energy range by Voyager-1 [37], AMS-02 [38, 39], CREAM-III [40], and DAMPE [41], which are employed to determine the source spectra of CRs. To connect the local interstellar spectra of CRs with the measured ones around the Earth, a force-field solar modulation model is applied [42].

The DM-nucleus interaction is the least known part. For simplicity, we adopt the general assumption that the DM-nucleus cross section \(\sigma_\chi A\) has a coherent enhancement,

\[
\sigma_\chi A = \sigma_\chi p A^2 \left[ \frac{m_A(m_\chi + m_p)}{m_p(m_\chi + m_A)} \right]^2, \tag{2}
\]

where \(\sigma_{\chi n} = \sigma_\chi p\) is the constant DM-nucleon cross section. For \(m_\chi \ll m_p, m_A\), the enhancement mainly comes from the \(A^2\) factor. Extra enhancement may come from \((m_\chi + m_p)^2/m_p^2\) when \(m_\chi\) goes beyond \(m_p\). But suppression starts to arise when \(m_\chi\) exceeds \(m_A\). The dipole hadronic elastic scattering from factor \(G_i(Q^2) = 1/(1 + Q^2/\Lambda_i^2)\) [43], with \(\Lambda_p \approx 710\) MeV and \(\Lambda_{He} \approx 410\) MeV [44] is further employed, which suppresses the interaction at large momentum transfer \(Q^2\).

The CRDM flux arriving at the Earth along a given direction \(\hat{\mathbf{n}}\) is a line-of-sight integral of all the contributions along the way,

\[
\frac{d\Phi}{dT_\chi}(\hat{\mathbf{n}}, T_\chi) = \frac{1}{4\pi} \int \zeta_\chi(r, T_\chi) \, dl. \tag{3}
\]

Fig. 1 shows the relative all-sky map of the CRDM fluxes in the Galactic coordinate, with peak value from the GC set to be 1. The CRDM fluxes are clearly anisotropic, with the maximum (the GC direction) and the minimum (with Galactic longitude \(l \sim 180^\circ\) and Galactic latitude \(|b| \sim 60^\circ\)) differs by about two orders of magnitude although the energy spectra are nearly the same in all directions. Note that within 0.5 kpc of the galactic center, we smooth the DM density profile to match with the grid resolution of GALPROP. This smoothing does not affect our results significantly since the change can only be visible with very precise angular resolution which is not achievable at current direct detection experiments.
Fig. 2 shows the CRDM spectra from the GC direction for different DM masses. With larger DM masses, it is more difficult for CRs to boost the DM particles and hence the flux normalization decreases. The decreasing flux normalization also comes from the DM number density reduction that is reflected by the $1/m_\chi$ factor in Eq. (1). When the DM mass approaches to infinity, the boosted DM spectrum would reduce to the non-relativistic DM spectrum, manifesting itself as the reduced peak energy. In addition, the high energy tail is suppressed by the form factor $G_f(Q^2)$ with $Q^2 = 2m_\chi T_\chi$.

At the low energy end, it is interesting to see that the CRDM has higher flux for smaller DM mass. This seemingly counter-intuitive feature can be understood by the kinematics. With a constant cross section, the DM recoil energy $T_\chi$ is evenly distributed in the range, $0 \leq T_\chi \leq T_\chi^2/(T_\chi + m_\chi^2/2m_\mu)$ for $m_\chi \ll m_\mu$. The DM mass has a sizable effect when it is very small, $m_\chi / m_\mu \approx 1$ GeV, where the reduced mass $m_\mu^* \equiv (m_\mu + m_\chi^2/2m_\mu \approx m_\mu^2/2m_\chi$ takes some seesaw-type amplification and can compete with the CR energy $T_\chi$. For smaller $m_\chi$, the DM recoil energy $T_\chi$ has much narrower window. Correspondingly, the CRDM flux in Fig. 2 squeezes to the low energy end.

We find that the CRDM spectra depend very weakly on directions, mainly due to the similar CR spectral shapes throughout the Galaxy. In the following discussion we will separate the energy and angular distributions of the CRDM fluxes for simplicity.

**Earth Attenuation** – With large enough scattering cross section, DM can frequently scatter with matter when traveling through the Earth [25–28]. Through scattering, DM loses its energy to the matter nucleus. Although the decelerated DM particle may still reach the detector, the DM energy spectrum is shifted to lower energies, leading to less events above the detector’s energy threshold. For simplicity, we use an average nucleon numbers, $A_m = 24$ in the mantle and $A_c = 54$ in the core to approximate the matter compositions [45]. Given $\sigma_{xp} = 10^{-32}$ cm$^2$, the mean free path, $L_{\text{free}} \equiv m_N/\rho_N\sigma_{xp}$, is around 2.7/17 km in the Earth core/mantle when omitting the form factor. Thousands of scatterings can happen when crossing the Earth for a radius of $R_\oplus = 6371$ km.

The CRDM flux $d\Phi(l, T_\chi)/d\ln T_\chi$, at the distance $l$ traveled through the Earth, depends on two effects: 1) the loss of the DM particles with energy $T_\chi$ that transfer to lower energies, and 2) the gain from the DM particles with higher energies $T_\chi^\prime$ transferring to $T_\chi$. For an incoming DM particle with a higher energy $T_\chi^\prime$, the nucleon recoil energy is evenly distributed in the range, $0 \leq T_\chi \leq T_\chi^\prime (T_\chi^\prime + 2m_\mu)/(T_\chi^\prime + m_\mu) \equiv T_\chi^\text{max}$. With reduced mass $m_\mu^* \equiv (m_\mu + m_\chi^2)/2m_\mu$. Due to energy conservation, $T_\chi$ is also evenly distributed, $T_\chi (m_\mu - 2m_\mu)/(T_\chi^\prime + m_\mu) \leq T_\chi \leq T_\chi^\prime$. For given $T_\chi$, the DM particles with energy $T_\chi^\prime$ in the range $T_\chi \leq T_\chi^\prime \leq m_\mu T_\chi/(m_\mu - 2m_\mu - T_\chi)$ can increase the flux at $T_\chi$. Adopting the energy loss ansatz, the CRDM flux evolution contains two contributions,

$$
\frac{\partial}{\partial l} \frac{d\Phi(l, T_\chi)}{d\ln T_\chi} = \frac{\rho_N(l)}{m_N} \sigma_{xp} \left[ -\frac{d\Phi(l, T_\chi)}{d\ln T_\chi} + \int \frac{d\Phi(l, T_\chi^\prime)}{d\ln T_\chi^\prime} \frac{T_\chi^\prime (T_\chi^\prime + m_\mu^*)}{T_\chi^\prime (T_\chi^\prime + 2m_\chi)} d\ln T_\chi^\prime \right]. \tag{4}
$$

The weighting factor, $T_\chi / T_\chi^\text{max}$, in the second term comes from the differential cross section, $d\sigma = \sigma dT_\chi / T_\chi^\text{max} = \sigma d\ln T_\chi (T_\chi / T_\chi^\text{max})$. The attenuated DM flux can be obtained by integrating Eq. (4) step by step over the traveled distance. Fig. 3 shows the attenuated CRDM fluxes with different nadir angles to the underground detector. To be realistic, we set the detector 2 km underground. Then for $\theta_{\text{nadir}} = 90^\circ$, DM needs to travel 160 km before reaching the detector, corresponding to 9 mean free path in the mantle. This is already large enough to see sizable attenuation effect at the high energy end. With longer distance, the overall CRDM flux is significantly suppressed, and the energy spectrum is squeezed to lower energies.

**Boosted Diurnal Effect** – Two anisotropies from the Earth and the Galaxy interplay with each other to give the diurnal effect. First, the path lengths DM particles travel are anisotropic since the underground lab is not at the Earth center and its depth is typically much smaller than the Earth radius. Second, the CRDM flux is strongly peaked towards the GC due to both the DM and the CR distributions. The CRDM flux is thus significantly attenuated by the Earth when the GC and the detector are on opposite sides of the Earth, but much less affected if they are on the same side. Without the intrinsic anisotropy in the CRDM, this diurnal effect would not be present. To avoid confusion with the usual diur-
are obtained by Monte Carlo simulations. The diurnal modulation of the CRDM at a underground lab at latitude 28° and depth of 2 km. The red curve contains all DM arriving at detector, the blue one with detector threshold ($T_r > 3\text{keV}$), and the green one further with detection efficiency.

The diurnal effect for nonrelativistic GeV-scale DM [29, 30], we call it the boosted diurnal effect.

Fig. 4 shows the diurnal modulation of the CRDM at a direct detection experiment located at a latitude of 28°N and a depth of 2 km underground (approximate location of the China Jinping Underground Laboratory). Within one sidereal day, the underground lab rotates around the Earth axis and its position is parameterized with the sidereal hour in the range of [0, 24] hours. We define a survival probability as the ratio between the attenuated CRDM event number and the full event number without the Earth attenuation. Although the line-of-sight between the GC and the detector does not cross the Earth center, there is still significant boosted diurnal effect with the survival probability varying within the range of 0 ~ 95%. For a more realistic situation, we take the detection efficiency from the PandaX experiment for the low energy nuclear recoil events [46]. For higher energy recoil events, the upper range cut in the traditional analysis is assumed to be lifted, and we assume a flat efficiency of 88% above the nuclear recoil energy of 18 keV. The diurnal modulation after taking into account the detector efficiency is also shown in Fig. 4.

The curves in Fig. 4 are obtained by Monte Carlo simulations. Since the spectrum of the CRDM is almost independent of the sky map, it is a good approximation to first sample the direction of the incoming DM particles according to the flux normalization sky map in Fig. 1 and then sample the DM kinetic energy $T_r$ according to the spectrum in Fig. 2. The incoming DM particle would experience multiple scattering when crossing the Earth. For each interaction step, we first sample the length that the DM particle travels before the scattering happens according to an exponential distribution, and then sample the reduced kinetic energy. The simulation stops when the DM particle reaches the underground detector.

As shown in Fig. 3, the kinetic energy of a CRDM particle can reach O(1 GeV). Consequently, the direct detection experiment can see high energy recoil events. Fig. 5 shows the recoil energy spectrum after taking into account the nuclear form factor and detection efficiency. The recoil energy extends to $O(1\text{MeV})$ when the flux drops by 3 orders of magnitude from the peak flux. This is much larger than the detection energy threshold which is typically $O(1\text{keV})$. It is thus necessary for the experiment to remove the upper energy cut in the event selection. Seeing high energy recoil event serves as smoking gun for the CRDM, especially when the detector and the GC are on the same side of the Earth. This feature can be further enhanced if the cross section depends on energies (usually the cross section will be larger at higher energies). Statistically, the boosted diurnal modulation can help to identify such high energy recoil signal and suppress the background which is expected to be constant over time.

**Conclusion** – The CRDM provides a new possibility for the conventional DM direct detection experiments to extend their sensitive window down to the sub-GeV mass range, in which the parameter space is largely unconstrained. If the DM-nucleon cross section is large enough, the CRDM is significantly attenuated when traveling through the Earth. Due to the interplay between the intrinsic anisotropy of the CRDM fluxes and the Earth attenuation, the cumulative number of events and energy spectrum of direct detection shows a characteristic diurnal modulation. The diurnal modulation would be very helpful in suppressing the background of direct detection experiments and increase the DM search sensitivities in the low-mass window. The high energy recoil events and diurnal modulation serve as two typical signatures of the CRDM direct detection. Future work can utilize the electron component in the CR and extend this exploration
to DM-electron interactions. In addition, the future directional detection experiments may directly image the anisotropic sky map of the CRDM.

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