Boosted Dark Photons: Minimal Model of Boosted Dark Matter

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(Dated: July 26, 2022)

We investigate a class of models in which pairs of dark matter particles decay into two low-mass dark photons. These dark photons are subsequently "boosted" (moving relativistically) due to conservation of energy. Dark photons are unstable due to mixing with ordinary photons, but they are long-lived enough to reach Earth for small mixing. The predicted flux of dark photons arriving at Earth can produce distinctive experimental signatures via dark photon scattering in neutrino detectors. We derive new constraints on important parameters governing this interaction, including the kinetic mixing parameter and the dark photon mass. Our theoretical constraints will then be compared to existing data from the Super-K detector. This will give a better understanding of the detection prospects for dark matter of this type using existing detectors such as Super-K or future neutrino detectors like DUNE and Hyper-K.

I. INTRODUCTION

It has long been known that there must be more mass in the universe than that which we can observe by conventional methods. This unseen matter only interacts with standard model matter through gravitational forces, and is seemingly unaffected by electromagnetic forces, giving rise to the name "dark matter". However, the specific nature of this dark matter remains largely unknown, as no observations have been made of particle dark matter despite numerous searches using multiple detection methods.

There are many different pieces of evidence for the existence of dark matter, but one of the most compelling comes from observations of the Bullet Cluster. The mass distribution in the Bullet Cluster merger was mapped out using weak gravitational lensing[1]. This involved measuring the distortions in the images of background galaxies, which were caused by the gravitational influences of the cluster's mass. The results of this study are considered strong evidence for the existence of dark matter.

II. BOOSTED DARK MATTER MODELS

Many dark matter models consider cold (non-relativistic) dark matter particles, whose thermal relic abundance is directly determined by standard model couplings[2]. This model instead considers that some small portion of the dark matter is relativistic, which is referred to as the boosted dark matter or "dark photons". A pair of non-relativistic dark matter particles can annihilate into two low-mass dark photons, which are then "boosted" (moving relativistically) due to conservation of energy. In this case, the thermal relic abundance is determined by this annihilation process. The proposed dark photons can interact with standard model electrons through a process similar to Compton scattering. This allows for possible Earth-based detection using neutrino detection experiments such as Super-K or the proposed Hyper-K.

III. CONSTRAINTS ON BOOSTED DARK MATTER MODEL

We aim to place constraints on this boosted dark matter model to better understand the Earth detection prospects. We derive constraints first from the dark photon decay width equation. Detection constraints from Super-K data are also considered.

$$d = \gamma\beta\tau c \tag{1}$$

The above equation shown above represents the distance (d) travelled by a dark photon before its decay. Here, γ represents the relativistic Lorentz factor and β = v/c. The lifetime of the dark photon can be found from the decay width ($\tau = \Gamma_{EH}^{-1}$). An approximate version of the dark photon decay width[3] was used here, as shown below.

$$\Gamma_{EH} = \frac{17\epsilon^2\alpha_{EM}^4}{11664000\pi^3}\frac{m_x^9}{m_e^8} \tag{2}$$

More precisely, the dark photon decay width can be expressed as a series with Γ_{EH} as its leading term[3]. Here, only Γ_{EH} is considered for simplicity. Future work could be expanded to use this more precise definition.

Plugging the above definition of Γ_{EH} into the equation for d (remembering that $\tau = \Gamma_{EH}^{-1}$), leads to an expression for d in terms of ϵ, m_x, and E_{dark}. We set d = 8 kpc, as the dark photons would have to travel at least that far to ensure Earth detection (assuming production in the galactic center). E_{dark} was also fixed to a few separate values that are within a probable range. This allowed us to create the plot shown in fig. 1, specifically the four solid curves. The dashed curves shown on this plot are the result of constraints calculated from Super-K data.

The four solid curves are the results of the plotted distance equation. The linear region to the far left is where the decay to 3 photons dominates. At $m_x \geq 0.001$ GeV, other decay channels begin to open up. First, we see the decay to e^+e^- pairs open up at $m_x = 0.001$ GeV, causing the sudden drop seen in the curves. We then also see the decay to $\mu^+\mu^-$ open up around $m_x = 0.2$ GeV, causing a slight kink around this point. Finally, it's important to note that we also see specific curves dropping off where $m_x \approx E_{dark}$. This happens because of the physical constraints on the relationship between mass and energy–namely, a particle cannot have more mass than it does total energy.

The most probable region for detection is

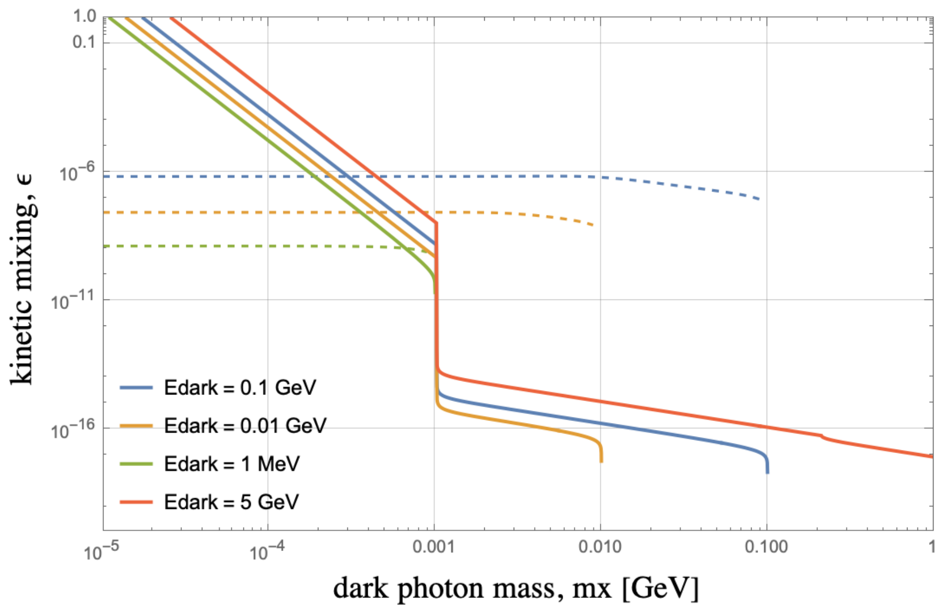

FIG. 1. Constraints on the boosted dark photon model are shown. The dashed curves shown are minimal constraints on ϵ from existing Super-K data. The other four curves were derived from eq. 1 and show constraints on both ϵ and m_x. The most probable region for detection is thought to be the area between curves from approximately 10^{-5} GeV $\leq m_x \leq 2 \times 10^{-4}$ GeV.

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IV. ANNIHILATION CONCERNS

While dark matter annihilation is a central component of this class of models, it is also important to consider the dangers of destroying too much dark matter. If a significant portion of the dark matter were to annihilate into boosted dark photons, the dark matter mass density would be reduced, conflicting with the known mass density of the universe. To determine the validity of this issue, a simple estimate was performed using eq. 3.

$$N_{ann} = (\sigma v)(n_x \bar{n}_x)(T_{gal} V_{gal}) \tag{3}$$

Here, N_{ann} is the number of annihilations, σis the cross section of the DM particles, v is the velocity of the particles, n_x and $\bar{n}_x$ represent the number density of the particles, and T_{gal} and V_{gal} represent the age and volume of the galaxy, respectively. We made the assumption that $n_x = \bar{n}_x$, and then defined $n_x = \frac{\rho}{m_x}$, with ρrepresenting the mass density of dark matter particles. We also defined $N_{ann} = n_x V_{gal}$, allowing us to simplify to eq. 4 (where k represents the percentage of dark matter destroyed).

$$\sigma v = \frac{m_x k}{\rho T_{gal}} \tag{4}$$

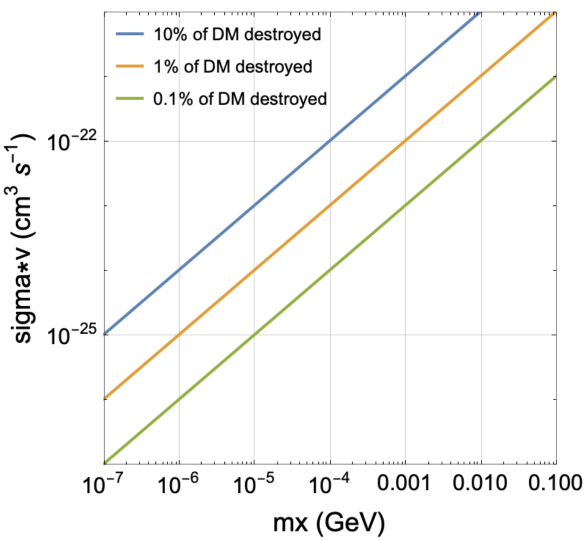

FIG. 2. This plot shows the necessary values of m_x and σv to destroy a significant percentage of dark matter. With the value of σv predicted by thermal relics and at the mass range considered here, we would not see a significant percentage of dark matter destroyed.

Using eq. 4, we were able to create the plot shown in fig. 2. This plot shows the relationship between σv and m_x for different amounts of dark matter annihilation. Assuming that $\sigma v \approx 6 \times 10^{-26}$ cm^3 s^{-1}, as is required by the thermal relic abundance, we see that there is no significant destruction of dark matter at the mass range considered in this paper (10^{-5} GeV $\leq m_x \leq$ 0.001 GeV).

V. CONCLUSION

A new minimal model of boosted dark matter using boosted dark photons has been introduced. New constraints on this minimal model of boosted dark matter have been derived. Future work is planned to continue refining the constraints on this model and evaluating detection prospects using neutrino detectors such as Super-K and the proposed Hyper-K. Concerns that dark matter annihilation could destroy a significant portion of dark matter were also explored, and were not found to be of consequence.

VI. ACKNOWLEDGEMENTS

I would like to thank Prof. Ian Shoemaker for his support and guidance over the duration of this research project. I would also like to thank Varun Mathur and Natalia Tapia Arellano for their help throughout the course of the project.

We acknowledge the outstanding support from the National Science Foundation, the Virginia Tech Physics department and the Virginia Tech Center for Neutrino Physics. This work was made possible by the National Science Foundation under grant No. PHY-2149165.

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