Boosted Dark Photons: A Minimal Model of Boosted Dark Matter

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Introduction

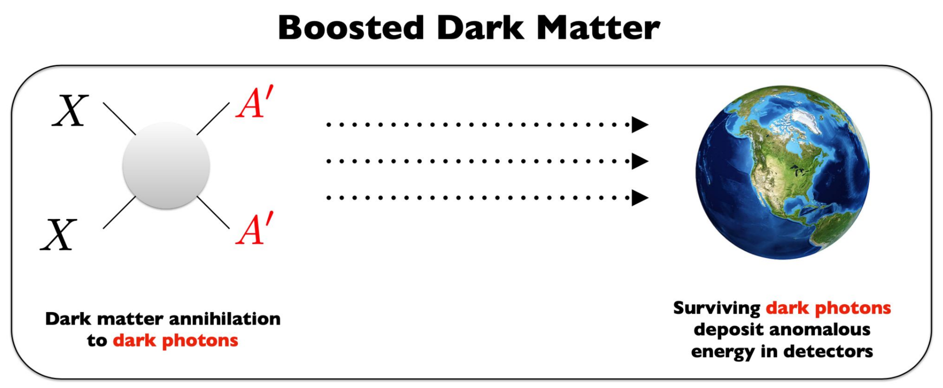
It has long been known that there must be more mass in the universe than that which we can observe by conventional methods. This unseen matter only interacts with standard model matter through gravitational forces, and is seemingly unaffected by electromagnetic forces, giving rise to the name “dark matter”. 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.

The Boosted Dark Matter Class of 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 decay 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.

The image to the right shows a pictorial representation of the proposed annihilation and detection processes.



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Citations

[1] Clowe, Douglas, Marusa Bradac, Anthony H. Gonzalez, Maxim Markevitch, Scott W. Randall, Christine Jones, and Dennis Zaritsky. “A Direct Empirical Proof of the Existence of Dark Matter.” *The Astrophysical Journal* 648, no. 2 (September 10, 2006): L109–13. https://doi.org/10.1086/508162.

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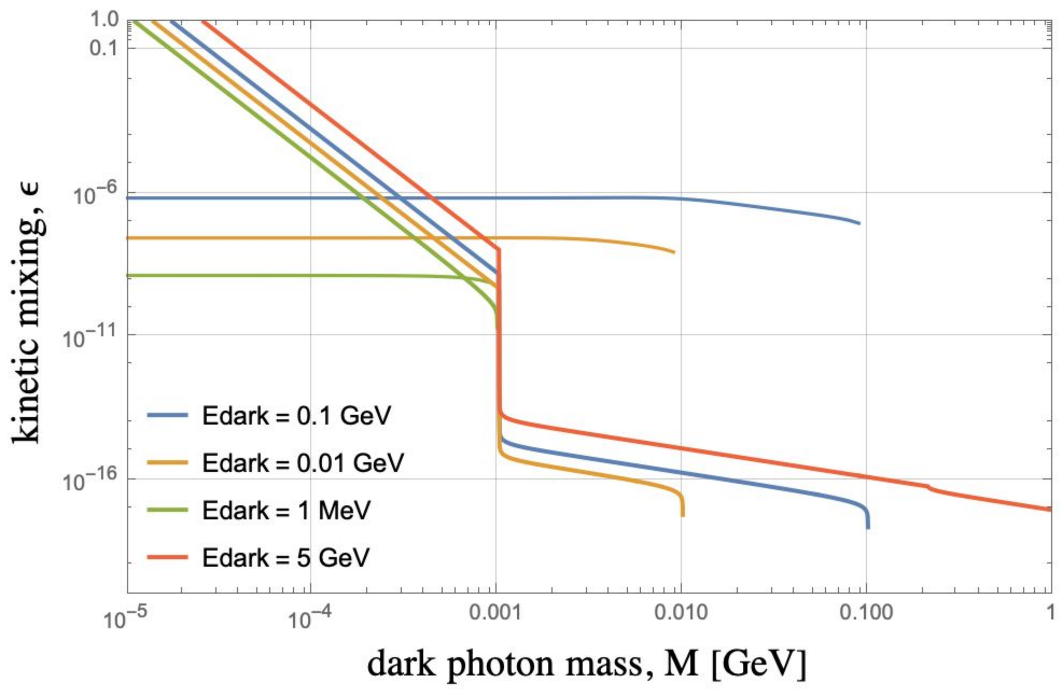
Constraints on Boosted Dark Matter Model

$$d = \gamma\beta\tau c$$

The above equation shown above represents the distance (d) travelled by a dark photon before its decay. We set this distance to 8 kpc, as the dark photons would have to travel at least that far to ensure Earth detection (assuming production in the galactic center). Here, γ represents the relativistic Lorentz factor and $\beta = v/c$. 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.

$$\Gamma_{\rm EH} = \frac{17\epsilon^2\alpha_{\rm EM}^4}{11664000\,\pi^3}\frac{m'^9}{m_e^8}$$



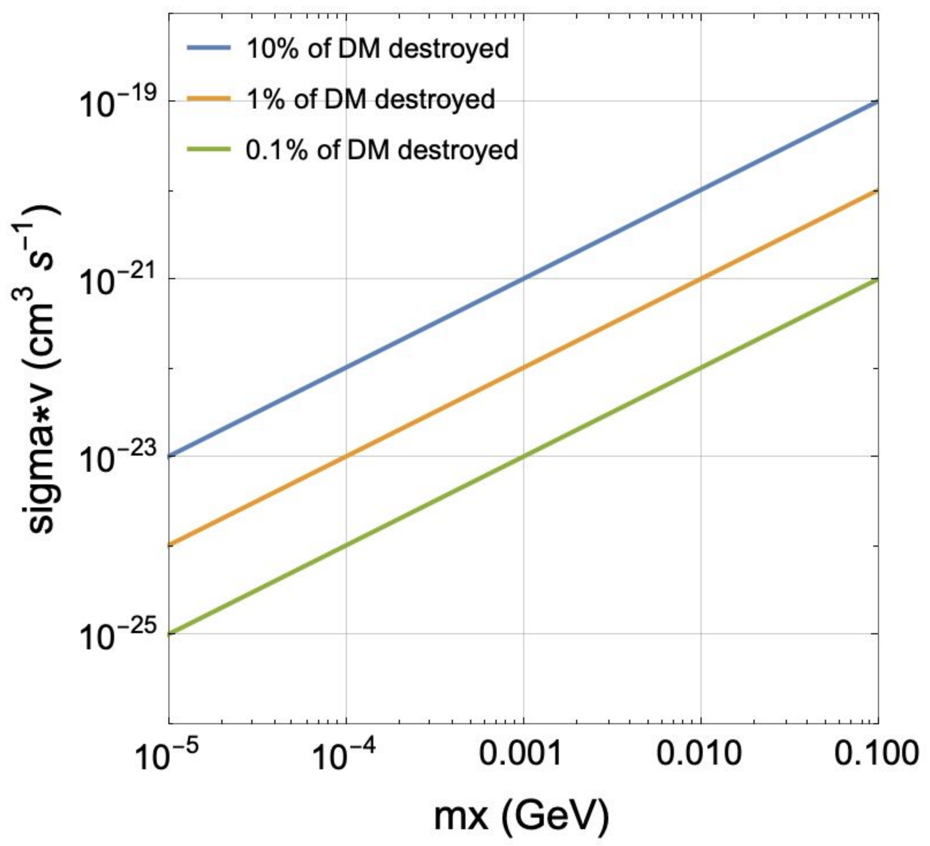
Using this definition of Γ_{EH}, we were able to define d in terms of three key parameters: ε (the kinetic mixing parameter), m_x (dark photon mass, also referred to as m’), and E_{dark} (the energy of the dark photon).

The plot above shows the constraints on ε and m_x for different set values of E_{dark}. It is important to note that at $m_x <$ 0.001 GeV, only decay to three photons is possible. This plot is extended to large dark photon masses to allow for visualization of the effects of different decay channels opening up and becoming dominant, although we do not believe dark photon masses would exceed this 0.001 GeV threshold. The horizontal lines shown are minimal constraints on Earth-based detection calculated from Super-K data.

Dark Matter 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.

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



To determine the validity of this issue, a simple estimate was performed using the equation shown above. Here, N_{ann} is the number of annihilations, σ is 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 were then able to define the number density in terms of mass and density, producing the plot to the left. This plot shows that for the dark matter masses used in our model, a much larger cross section value than calculated would be needed to destroy a significant portion of the dark matter.