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Energy peak: Back to the Galactic Center GeV gamma-ray excess

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ABSTRACT

We propose a *novel* mechanism enabling us to have a *continuum* bump as a signature of gamma-ray excess in indirect detection experiments of dark matter (DM), postulating a *generic* dark sector having (at least) two DM candidates. With the assumption of non-zero mass gap between the two DM candidates, the heavier one directly communicates to the partner of the lighter one. Such a partner then decays into a lighter DM particle along with an "axion-like" particle (ALP) or dark "pion", which subsequently decays into a pair of photons, via a more-than-one step cascade decay process. Since the cascade is initiated by the dark partner obtaining a non-trivial fixed boost factor, a continuum γ-ray energy spectrum naturally arises even with a particle directly decaying into two photons. We apply the main idea to the energy spectrum of the GeV γ-rays from around the Galactic Center (GC), and find that the relevant observational data is well-reproduced by the theory expectation predicted by the proposed mechanism. Remarkably, the relevant energy spectrum has a *robust* peak at half the mass of the ALP or dark pion, as opposed to popular DM models directly annihilating to Standard Model particles where physical interpretations of the energy peak are *not* manifest. Our data analysis reports substantially *improved* fits, compared to those annihilating DM models, and ~900 MeV mass of the ALP or dark pion.

1. Introduction

There is astrophysical and cosmological evidence that DM exists in the Universe (see, for example, Ref. [1]). Relevant observations, mostly rooted in its gravitational effects, can be explained by postulating new stable particles, not belonging to particle species in the Standard Model (SM). With this situation, there is a tremendous amount of effort to detect DM candidates: (1) direct detection experiments by measuring recoil energy of nuclei scattered off by DM, (2) indirect detection experiments by observing signals stemming from DM annihilation or decay, and (3) collider searches by actively producing DM particles and observing associated collider signatures. Among those experimental efforts, satellite-based cosmic-ray detection experiments such as PAMELA [2,3], AMS-02 [4,5], and Fermi-LAT [6,7] have received particular attention due to their great sensitivity to cosmic-ray signals, giving rise to better chance to have not only confirmation of the existence of DM but also the information for deducing DM properties.

The Fermi-LAT Collaboration has provided the public data based on their observations, and a γ-ray excess at $\mathcal{O}$(GeV) coming from the GC has been found. In particular, it has recently reported in Ref. [8] that the excess exists, even assuming different foreground/background models. The relevant program was initiated by Ref. [9], and their intriguing observation has been strengthened by a series of their follow-up analyses and other independent groups [10–20]. Unlike other photon excesses such as 3.5 keV line [21,22], 511 keV line [23], and 130 GeV line [24,25], this is characterized by a *continuum* bump. The basic claim is that the γ-ray excess spectrum is sufficiently consistent with the expected emission spectrum from charged particles in the SM into which DM particles are annihilated. More specifically, the GeV excess is well-accommodated by a DM scenario where a pair of DM particles with a mass of ~30–40 GeV annihilate into a $b\bar{b}$ pair with an annihilation cross section of $\langle \sigma v \rangle \sim 2 \times 10^{-26}\text{cm}^3/\text{s}$ [17,20]. As an alternative annihilation channel, lepton pairs have been studied as well in Ref. [18] where they pointed out the significance of the contributions coming from the diffuse photons from primary and secondary electrons that are produced in DM annihilation processes. They further analyzed the data including the inverse Compton scattering and bremsstrahlung contributions from electrons, and found that the data is well-described by ~10 GeV DM annihilating into a $\ell\bar{\ell}$ pair, for which the associated annihilation cross section is given by $\langle \sigma v \rangle \approx (1-2) \times 10^{-26}\text{cm}^3/\text{s}$ [18]. Moreover, Ref. [26] showed that the GeV excess can be reproduced by other heavy SM final

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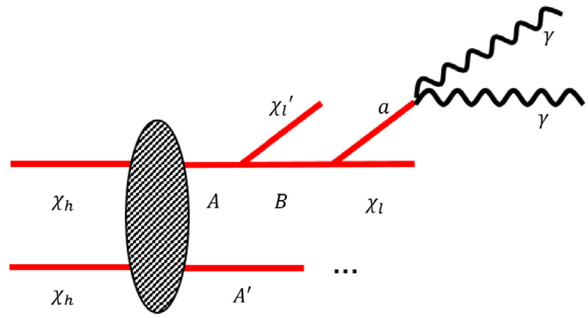

Fig. 1. The example "dark" cascade scenario under consideration.

states such as $W^+W^-/ZZ/hh/t\bar{t}$ with a DM particle of $m_{\rm DM} \approx$ 80–200 GeV and $\langle\sigma v\rangle \approx (2-8)\times10^{-26}\rm cm^3/s$, depending on the final state with the systematic uncertainties in the gamma-ray background modeling taken into account. In Ref. [20], it was also shown that $gg/W^+W^-/ZZ/hh/t\bar{t}$ final states can provide a good fit to the excess with $m_{\rm DM} \approx$ 40–200 GeV and $\langle\sigma v\rangle \approx (1-8)\times10^{-26}\rm cm^3/s$.

We remark that some of the realistic DM models have been proposed and studied: for example, Refs. [27–32] for the $b\bar{b}$ final state through a Higgs portal type interaction, Refs. [33,34] for the $\ell\bar{\ell}$ final state, Refs. [35–37] for DM annihilating to a pair of on-shell particles that subsequently decay into SM $f\bar{f}$ pairs, Ref. [38] even for 2^n pairs of SM $f\bar{f}$ final states from on-shell mediator pairs through multi-step cascades, and Ref. [39] for generic model constraints. Although the recent report from the AMS-02 Collaboration [40] has started to rule out the $q\bar{q}$ final state dominant DM scenarios explaining the measured relic abundance [41], it is straightforward to invoke hybrid scenarios where $b\bar{b}$ and $\ell\bar{\ell}$ modes are mixed together.

One should notice that the astrophysical uncertainty in γ-rays coming from the GC in conjunction with the background modeling for the emission in the inner galaxy is still large. In addition, pions from the collision between cosmic-rays and gas [10–12,14] and millisecond pulsars [10–12,14,16,42] can be sources to the GeV scale γ-rays. Therefore, they have been proposed as a different approach to interpret the excess although the relevant spectral shape appears too soft at the sub-GeV energy regime to accommodate the observed energy spectrum [43]. When it comes to the morphological feature for the observed excess, it is extended to more than $\sim10^\circ$ from the GC beyond the boundary of the central stellar cluster that could contain a large number of millisecond pulsars [18], and observed distributions of gas seem to give a poor fit to the spatial distribution of the signal [18,44,45]. We finally point out that very recently, another non-DM interpretation has been suggested by Ref. [46,47]. They basically came up with a new method to characterize unresolved point sources based on which the excess can be explained by a population of unresolved point sources, giving a distribution consistent with the observed GeV γ-ray excess in the relevant region.

Notwithstanding those potential issues, we here propose another *novel* mechanism to attain continuum energy spectra of the γ-ray excess, positing the DM interpretation. We first remark that there could exist multiple DM species, and the DM models based on such a DM framework can give rise to not only non-trivial cosmological implications (e.g., "*assisted freeze-out*" [48]) but interesting phenomenology (see, e.g., "*boosted DM*" [49–51]). In this context, we assume a DM partner having a non-trivial and fixed boost, which could be achieved by the annihilation of another (heavier) DM. The DM partner is further assumed to undergo a $\geq$2 step "dark" cascade decay, and emit, in the final step, a (lighter) DM particle along with an ALP or dark pion that subsequently decays into two photons. Fig. 1 schematically depicts the example "dark" cascade scenario of our interest. We shall discuss the minimality of this DM scenario in conjunction with the elaboration of formalism later. We emphasize that the relevant ALP or dark pion comes with a non-trivial boost distribution, typically rise-and-fall-shaped. As a consequence, the resulting photon energy spectrum becomes a broad distribution.[1]

A *novel* feature of this type of energy distribution is that the peak of the photon energy distribution is exactly the same as half the mass of the ALP or dark pion [52,53]. In other words, such a peak position is *robustly* connected to a physical property. This is *not* the case for other interpretations such as the DM models directly annihilating to SM particles because their energy peak highly depends on models of parton showering, diffusion mechanism, and so on from which the final photon spectrum is generated. We emphasize that the proposed strategy is completely generic to be applicable to any continuum bump in cosmic-ray energy spectra, not restricted to the γ-ray excess at hand even if we employ it as a concrete and realistic example.

2. Model set-up and formalism

To set up the dark matter scenario to which our strategy is applied,[2] we first introduce a dark sector containing (at least) two DM candidates. We then assume that one of the DM particles is heavier than the other and the heavier one (henceforth denoted by χ_h) communicates to the SM sector via the lighter one (henceforth denoted by χ_l), i.e., relevant relic abundance can be evaluated by the assisted freeze-out [48]. However, we further assume that χ_h's do *not* directly communicate to χ_l's, but through an intermediate state A which subsequently decays into a χ_l and dark sector particle a via, in general, multiple intermediate states. For simplicity, a single intermediate state B is taken throughout this letter, but we later discuss the necessity of it.[3] Particle a eventually decays into a photon pair, being taken as a source of γ-ray excess. In this sense, it could be regarded as an ALP and dark pion. We again refer to Fig. 1 demonstrating the example dark cascade scenario that we shall discuss in more detail. Here χ_h pairs annihilate into A plus A' and A decays into B and a dark sector particle χ_l' solely for full generality. Since subsequent dynamics of A' and χ_l' is irrelevant to the later argument,[4] we simply omit their further processes.

Throughout the later argument, we take the assumption that particles A and B are scalars or produced in an *un*polarized way unless specified otherwise. With the assumption that χ_h is non-relativistic, it is straightforward to have the range of the boost factor of B, γ_B:

$$\gamma_B^- \leq \gamma_B \leq \gamma_B^+,$$
$$\gamma_B^\pm \equiv \frac{E_B^*}{m_B}\gamma_A \pm \frac{P_B^*}{m_B}\sqrt{\gamma_A^2-1}, \tag{1}$$

where γ_A denotes the fixed boost factor of A (i.e., m_{χ_h}/m_A) and E_B^* (P_B^*) denotes the energy (momentum) of B measured in the rest frame of A. As is well-known, the distribution in γ_B is flat. To develop the intuition on the boost of particle a, we cast its energy

[1] It is well-known that sequential decays through and into SM particles typically invoke broadly-distributed energy spectra. See, for example, Ref. [52] in the context of cosmic gamma-ray physics and Refs. [53,54] in the context of collider physics.

[2] More dedicated dark matter model building to satisfy all features of the generic set-up is beyond the scope of this paper. We instead leave it as a future work [55].

[3] In general, χ_l may be either an unstable particle which subsequently decays into lighter particles, or even particle a. However, our argument does *not* depend on the attributes of χ_l. In addition, A and B can be generally either dark or SM sector particles, but we just assume that A and B are dark sector particles for simplicity.

[4] Particles A' and χ_l' could even decay into SM particles unless they are severely constrained by other observational data (e.g., excess in cosmic-ray positron measurements, [2–5]) or cosmological bounds.