Tentative wiggle in the cosmic ray electron/positron spectrum at ∼100 GeV: a dark matter annihilation signal in accordance with the 130 GeV $\gamma-$ray line?

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Recently, a tentative 130 GeV γ-ray line signal was identified by quite a few groups. If correct it would constitute a "smoking gun" for dark matter annihilations. Interestingly, the spectra of the sum of cosmic ray electrons and positrons detected by ATIC and PAMELA both show small wiggle-like structure at ∼ 100 GeV, which could be the result of the annihilation of ∼ 140 GeV dark matter particles into electrons/positrons with a velocity-weighted cross section $\langle\sigma v\rangle_{\chi\chi\to e^+e^-} \sim 10^{-26} - 10^{-25}$ cm^3 s^{-1}. Accurate measurements of the total spectrum of electron and positron cosmic rays by AMS-2 and the upcoming missions such as DAMPE and CALET are highly needed to pin down the profile of the wiggle-like structure and then its physical origin.

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I. INTRODUCTION

Gamma-ray line is generally thought to be a smoking gun observation of dark matter (DM). Recently, Bringmann *et al.* [1] and Weniger [2] reported that there might be hint of a monochromatic γ-ray line with energy ∼ 130 GeV in the data recorded by Fermi Large Area Telescope (LAT) [3]. This γ-ray line could be explained by ∼ 130 GeV DM particle annihilation, with the velocity-weighted cross section $\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma} \sim 10^{-27}$cm^3 s^{-1}. This phenomenon was confirmed by a series of independent analyses [4–6]. It was argued that such a line-like structure might originate from astrophysical emission related with the Fermi bubbles [7] but the morphology analysis indicated that the line emission is independent with Fermi bubbles [4, 6]. Based on the identified spectral and spatial variations of rich structures of the diffuse γ-ray emission in the inner Galaxy, Boyarsky *et. al.* argued against the DM origin of these structures [5]. However, the DM origin of the $\gamma-$ray line emission has been strengthened by Su & Finkbeiner [6]. The independent analyses to search for γ-ray lines in the Milky Way halo by Fermi-LAT collaboration [8] and in dwarf galaxies by [9] found no significant signal, but the constraints are not tight enough to exclude such a $\gamma-$ray line signal. It was also proposed that such a line-like signal could be tested with high energy resolution detectors in the near future [10]. Several models had been proposed to explain this tentative line structure [11].

Several years ago ATIC experiment discovered significant excess in the $e^+ + e^-$ energy spectrum between 300 – 800 GeV [12]. Moreover the $e^+ + e^-$ energy spectrum also showed wiggle-like structure at ∼ 100 GeV [12]. The newly reported total $e^+ + e^-$ spectra measured by PAMELA also revealed fine structure above ∼ 100 GeV [28] [14]. Therefore a natural question one would ask is whether there is any connection between the 130 GeV line-like structure of γ-rays and the wiggle structure of electrons.

In this Letter, we show that the DM scenario with mass ∼ 130 GeV corresponding to the possible γ-ray line, may be also responsible for the fine structure of the $e^+ + e^-$ spectra around 100 GeV. We find that if the same DM particles annihilate into e^+e^- pairs with a cross section $\langle\sigma v\rangle_{\chi\chi\to e^+e^-} \sim 10^{-26}-10^{-25}$ cm ^{3} s^{-1}, both the excess of the PAMELA positron fraction [15] and the fine structure of the $e^+ + e^-$ spectra can be reproduced. The results are consistent with all of the current bounds of the indirect detection measurements.

II. COSMIC RAY PROPAGATION

The cosmic ray (CR) propagation equation is written as follows [16]:

$$\frac{\partial\psi}{\partial t} = q(\mathbf{r}, p) + \nabla\cdot(D_{xx}\nabla\psi - \mathbf{V}\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{\psi}{p^2} - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\nabla\cdot\mathbf{V})\psi\right] - \frac{\psi}{\tau_f} - \frac{\psi}{\tau_r}, \quad (1)$$

where $\psi = \psi(\mathbf{r}, p, t)$ is the density per unit of total particle momentum, $q(\mathbf{r}, p)$ is the source distirbution function, D_{xx} is the spatial diffusion coefficient, $\mathbf{V} = dV/dz \times z$ is the convection velocity, D_{pp} is the diffusion coefficient in momentum space, $\dot{p} = dp/dt$ is the momentum loss rate, τ_f and τ_r are the time scales of fragmentation and radioavtive decay.

In general it is difficult to solve the propagation equation with analytical method, given the complicated distributions of the source, interstellar matter, radiation field and magnetic field. Numerical methods are developed to solve the propagation equations, such as GALPROP [16] and DRAGON [17]. In this work we adopt the GALPROP package to calculate the propagation of the CR particles, including the contribution from DM annihilation. The diffusion-convection model of CR propagation is adopted as an illustration. The main propagation and source injection parameters are compiled in Table. I. This set of propagation parameters can fit the observational B/C, ^{10}Be/^{9}Be and proton data [18].

We will also consider the possible contribution to the electrons/positrons from a local and fresh astrophysical source like pulsar [19]. For simplicity we employ the analytical solution given in Ref. [20] to calculate the propagation of e^+e^-

TABLE I: The propagation parameters in the diffusion convection model.

Z_h	D_0	diffusion index [a]	dV_c/dz	e^- injection [b]
(kpc)	(10^{28} cm^2 s^{-1})	δ_1/δ_2	(km s^{-1} kpc^{-1})	γ_1/γ_2 [a]
4	2.5	0/0.55	6	1.63/2.74

[a] Below/above the break rigidity $\rho_0 = 4$ GV.
[b] Below/above 25 GeV.

from a nearby pulsar. The propagation equation is simplified to be a spherical diffusion plus energy loss equation (neglecting convection and re-acceleration)

$$\frac{\partial \psi}{\partial t} = q(p)\delta(\mathbf{r}-\mathbf{r_0})\delta(t-t_0) + \frac{D_{xx}}{r^2}\frac{\partial}{\partial r}r^2\frac{\partial \psi}{\partial r} + \frac{\partial}{\partial p}(\dot{p}\psi). \quad (2)$$

The solution of the above equation, i.e., the Green's function with respect to r and t, is [20]

$$\psi(r,t,p) = \frac{q(p_t)\dot{p}(p_t)}{\pi^{3/2}\dot{p}(t)} \exp\left(-r^2/r_{\rm dif}^2\right), \quad (3)$$

where r and t are the distance and age of the source, p_t is the initial momentum which would cool down to p within time t, $r_{\rm dif}$ is the effective diffusion radius for electrons with momentum losing from p_t to p.

III. MODEL AND RESULTS

A. Two DM scenario

From the ATIC and PAMELA data of the total electrons/positrons [12, 14], we can see that there is a tiny excess above $\sim$ 100 GeV, and a significant excess above $\sim$ 300 GeV. Therefore we assume two DM components to fit the data. The first component with mass $\sim$ 140 GeV (DM 1) corresponds to γ-ray line, and the other one with mass $\sim$ 750 GeV (DM 2) is to reproduce the high energy part of the data. The possibility of existing more than one component of the $e^+ + e^-$ excesses was also investigated previously in e.g., [21].

The source function of electrons and positrons from DM annihilation is

$$q(E,r) = \frac{\langle\sigma v\rangle_{\chi\chi\to {\rm e^+e^-}}}{2m_\chi^2}\frac{{\rm d}N}{{\rm d}E} \times \rho^2(r), \quad (4)$$

where m_χ is the particle mass of DM, $\rho(r)$ is the spatial distribution of energy density, and ${\rm d}N/{\rm d}E$ is the electron and positron yield spectrum produced by one pair of DM annihilation. In this work we use the Einasto DM density profile [22]

$$\rho(r) = \rho_{-2}\exp\left(-\frac{2}{\alpha}\left[\left(\frac{r}{r_{-2}}\right)^\alpha - 1\right]\right), \quad (5)$$

where $\alpha = 0.17$, $r_{-2} \approx 15.7$ kpc and $\rho_s \approx 0.14$ GeV cm^{-3}.

We assume that the densities ratio of the two DM components are 1 : 1. The calculated total e^+e^- energy spectrum and positron fraction are shown in Fig. 1. The mass and cross section for DM 1 are 140 GeV and 1.2×10^{-25} cm^3 s^{-1}, and for DM 2 are 750 GeV and 8.8×10^{-24} cm^3 s^{-1} respectively. Note for the background positron flux we multiply a constant factor $c_{e^+} = 1.4$ to better fit the data [23], which may account for the uncertainties of the propagation model, interstellar gas distribution and the inelastic hadronic interaction model. We can see that the model expected results can basically describe the PAMELA data. For ATIC data the fit is not very good, but just reflects the wiggle behavior of the spectrum. We also note that the cross sections of both the DM components are larger than that expected assuming thermal production of DM, which means a boost factor or non-thermal production mechanism [24] is necessary. It is also possible that the observational DM is dominated by DM 1. Then the cross section for DM 1 is $\sim$ 4 times smaller and is consistent with the natural value to give the right relic density assuming the thermal production. In such a case the cross section for DM 2 should be much larger, which can only be produced non-thermally.

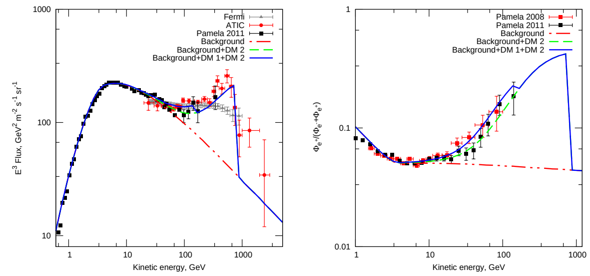

FIG. 1: Total $e^+ + e^-$ flux (left) and positron fraction (right) as functions of energy in two DM model compared with the data. The dash-dotted (red) line is the CR background component, the dashed (green) line represents the sum of background and DM 2 components, and the solid (blue) line is the sum of all the three components. The references of the data are: Fermi [13], ATIC [12], PAMELA 2008 [15] and PAMELA 2011 [14].

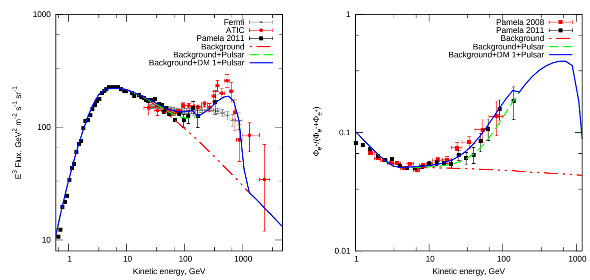

FIG. 2: Same as Fig. 1 but for the DM particle + pulsar model.

B. DM plus pulsar scenario

Pulsars are also the possible high energy positron and electron source (e.g., [19, 25]). For high energy electrons, energy loss dominates the propagation. Here we use the analytical solution derived by Atoyan *et. al.* [20] to calculate the propagation of electrons and positrons from nearby pulsars. The injection energy spectrum of e^+e^- can be parameterized by a power-law with an exponential cutoff [19]. The power-law index ranges from 1.4 to 2.2 according to the EGRET observations [26].

Fig. 2 shows the results for the model of $\sim$ 140 GeV DM plus a nearby pulsar. The age of the pulsar is adopted to be $\sim 2.2\times10^5$ years, the distance is $\sim$ 0.75 kpc and the explosive energy is $\sim 4.5\times10^{48}$ erg. The injection spectrum index is 1.4 and the cutoff energy is adopted to be 1 TeV. The mass of DM particle is also 140 GeV, and the cross section is also 3.7×10^{-26} cm^3 s^{-1}, which is consistent with the two DM scenario taking into account the postulated difference of DM density. Such a cross section is also consistent with the natural expectation to give the correct relic density of DM assuming thermal production. The fit to the observational data is comparable to the two DM scenario.

C. Constraints from other observations

The observations of γ-rays (the internal bremsstrahlung and inverse Compton radiation component) and/or radio emission (the synchrotron radiation component) may constrain the current scenario that DM annihilates into electrons/positrons [8, 27]. It was shown that the latest γ-ray observations by Fermi can constrain the $\langle\sigma v\rangle_{\chi\chi\to e^+e^-}$ to the level of 10^{-24} cm^3 s^{-1} for DM mass $\sim$ 100 GeV. For $\sim$ 1 TeV DM the constraint from Fermi data is about 10^{-23} cm^3 s^{-1}. Therefore the DM 1 component of this work should be well consistent with the present bounds. DM 2 is still consistent with the Fermi data [8], but might have tension with some other studies [27]. It is possible that the DM substructures will contribute a modest boost factor (BF) to the DM annihilation, with which the observed electron/positron flux gets considerably enhanced and the intrinsic cross section of annihilation into $e^+ + e^-$ will be lowered by the same factor. The $\gamma-$ray line emission from the very center of the Galaxy, however, is likely not modified since where no significant DM substructures are expected. For the pulsar component, the above bounds do not apply.

IV. CONCLUSION

The spectra of the $e^+ + e^-$ cosmic rays detected by ATIC and PAMELA both show small wiggle-like structure at $\sim$ 100 GeV, which could be the signal of annihilation of $\sim$ 140 GeV DM particles into electrons/positrons with a cross section $\langle\sigma v\rangle_{\chi\chi\to e^+e^-}\sim10^{-26}-10^{-25}$ cm^3 s^{-1}. Such a kind of interpretation is consistent with current bounds of the indirect detection measurements. Moreover the positron fraction data of PAMELA can be well reproduced. We then speculate that these electrons might have a DM origin, in accordance with the $\sim$ 130 GeV gamma-ray line emission discussed in recent literature. Our speculation will be tested by accurate measurements of the total spectrum of cosmic ray electrons and positrons by AMS-2 and the upcoming missions such as DAMPE and CALET.

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[28] Note, however, the $e^+ + e^-$ spectrum measured by Fermi-LAT has no evident structure [13]. Future more advanced and dedicated experimental observations (e.g., AMS-2, DAMPE and CALET) will pin down the shape of the spectrum more accurately.