Revisiting Multi-Component Dark Matter with New AMS-02 Data

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Abstract

We revisit the multi-component leptonically decaying dark matter (DM) scenario to explain the possible electron/positron excesses with the recently updated AMS-02 data. We find that both the single- and two-component DM models can fit the positron fraction and $e^+/e^-$ respective fluxes, in which the two-component ones provide better fits. However, for the single-component models, the recent AMS-02 data on the positron fraction limit the DM cutoff to be smaller than 1 TeV, which conflicts with the high-energy behavior of the AMS-02 total $e^+ + e^-$ flux spectrum, while the two-component DM models do not possess such a problem. We also discuss the constraints from the Fermi-LAT measurement of the diffuse $\gamma$-ray spectrum. We show that the two-component DM models are consistent with the current DM lifetime bounds. In contrast, the best-fit DM lifetimes in the single-component models are actually excluded.

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I. INTRODUCTION

Recently, the AMS-02 collaboration has updated the measurements on the positron fraction \[1\] and electron/positron respective fluxes \[2\] in the cosmic rays (CRs), which have further confirmed the electron/positron excesses observed by the previous experiments, such as AMS \[3, 4\], ATIC \[5\], PAMELA \[6, 7\], and Fermi-LAT \[8–10\]. More interestingly, the new data show some features which have not been observed previously. The most important message is that the positron fraction stops increasing with energy \[1\]. For the electron/positron fluxes, both spectra become harder at \(\sim 30\) GeV \[2\] so that they cannot be fitted with the usual single power-law functions. Moreover, from 20 to 200 GeV, the positron spectral index is larger than the electron one, which indicates that the uprise behavior in the positron fraction originates from the hardening of the positron fluxes, a typical hint towards the need for the primary \(e^+ / e^-\) sources. Among the possible primary \(e^+ / e^-\) origins, pulsars \[11–13\] and annihilating \[12–18\]/decaying \[12, 18–27\] dark matters (DMs) are two popular interpretations extensively studied in the literature. One stringent constraint on the DM interpretation is the PAMELA measurement of the anti-proton flux \[28\], which agrees with the conventional astrophysical prediction very well. A simple way to avoid such constraint is to assume that the DMs couple to the Standard Model (SM) only via the lepton sector, which is usually called the leptophilic DM scenario.

Before the recent release of the AMS-02 data, the AMS-02 positron fraction published last year \[4\] and the Fermi-LAT total \(e^+ + e^-\) flux \[8\] represented two of the most precise measurements of the CRs. However, the simplest scenario in which a single DM component annihilating or decaying into lepton pairs cannot fit these two datasets simultaneously \[27\]. In Refs. \[29, 30\], we have proposed a multi-component DM scenario \[31\] in order to overcome this difficulty. In particular, two DM components with the heavy DM decaying solely to \(\mu^+ \mu^-\) and the light one predominantly to \(\tau^+ \tau^-\) with the energy cutoff at \(E_{cL} = 100\) GeV could already provide a good fit to the combined dataset of the AMS-02 positron fraction and Fermi-LAT total \(e^+ + e^-\) flux. As a result, this two-component DM model can explain the apparent substructure at around 100 GeV in both spectra as the light DM drops at that energy. Another advantage of this multi-component scenario is that it gives us a mechanism to evade the strong DM lifetime bound from the diffuse \(\gamma\)-ray spectrum measured recently by Fermi-LAT \[32\], which has already greatly constrained the simple two-body leptonically
decaying DM models.

In the light of the updated data from AMS-02, it is useful and necessary to revisit the single- and two-component DM models. More remarkably, the new data from AMS-02 still show the substructure around 100 GeV, which strengthens our confidence of the investigation of the multi-component DM scenario. In this work, we shall only use the latest AMS-02 measurements of the positron fraction and fluxes of $e^-$ and $e^+$ in our fitting procedure. In this way, we can avoid many systematic uncertainties involved in the AMS-02/Fermi-LAT combined dataset [12], due to the differences in the experiment designs, detector responses and data-taking periods in the solar cycle. Thus, we expect that the final fitting result should be more consistent, which is another motivation for the present work.

The paper is organized as follows. In Sec. II we briefly introduce our multi-component decaying DM models and the propagation physics of CRs in the Galaxy. The fitting results about the single- and two-component DM models are presented in Sec. III. In Sec. IV we discuss the Fermi-LAT diffuse $\gamma$-ray constraints on these models. Finally, we give a short summary in Sec. V.

II. SIGNALS AND BACKGROUNDS

In our multi-component DM framework, the total electron flux is composed of primary, secondary and DM-decay-induced electrons, while only secondary positrons and the ones from the DM decays contribute to the total positron flux, which can be written as follows:

$$\Phi_e^{(\text{tot})} = \kappa_1 \Phi_e^{(\text{primary})} + \kappa_2 \Phi_e^{(\text{secondary})} + \Phi_e^{\text{DM}},$$

$$\Phi_p^{(\text{tot})} = \kappa_2 \Phi_p^{(\text{secondary})} + \Phi_p^{\text{DM}}.$$  \hfill (1)

The primary electrons are widely believed to be generated from the supernova remnants distributed in our Galaxy [33], and the injection spectrum is usually assumed to be a broken power-law function with respect to the rigidity. Here, we choose the reference electron primary injection spectrum to be the three-piece broken power law with the relevant parameters shown in Table II. Note that we insert a parameter $\kappa_1$ to account for the normalization uncertainty in the primary electrons. Secondary electron/positron fluxes $\Phi_{e,p}^{(\text{secondary})}$ are the final products of the collisions of the charged particles in the CRs, such as protons and other nuclei, with the interstellar medium (ISM) in the Galaxy. In the present work, we use
TABLE I. Parameters for the diffuse propagation, primary electron, and primary proton.

| Parameter | Diffuse Coefficient | Primary Electron | Primary Proton |
|-----------|---------------------|------------------|----------------|
| $D_0$ (cm$^2$s$^{-1}$) | 5.3 x 10$^{28}$ | 4.0 | 11.5 |
| $\rho_r$ (GV) | 4.0 | 67.6 | 1.88 |
| $\delta$ | 0.33 | 1.46 | 2.39 |
| $v_A$ (km s$^{-1}$) | 33.5 | 2.72 | 2.90 |
| $\gamma_{el}$ | 4.0 | 67.6 | 11.5 |
| $\gamma_{e2}$ | 2.72 | 2.90 | 2.0 |
| $\gamma_{e3}$ | 2.6 | 1.46 | 1.46 |
| $\gamma_{n1}$ | 2.72 | 2.90 | 2.90 |
| $\gamma_{n2}$ | 2.6 | 1.46 | 1.46 |

the GALPROP code [34] to simulate the productions and propagations of these background electrons and positrons with the fixed diffusion coefficients and primary proton parameters shown in Table I. For other details of the calculation, especially the choice of the astrophysical parameters, we refer to our earlier work in Ref. [29]. However, the calculation of secondary $e^-/e^+$ fluxes involves the uncertainties from, for instance, nuclei collision cross sections, form factors of heavy nuclei, and propagation coefficients, which are partially taken into account with the parameter $\kappa_2$ to rescale the calculated secondary fluxes [12]. The parameters $\kappa_{1,2}$ will be determined with other model parameters in the following fitting procedure.

As for the DM signal $\Phi_{e,p}^{DM}$, we assume that the whole DM density in the Galaxy and Universe is carried out by a single- or multiple-component DM particles $\chi_i$, whose decays can explain the positron/electron anomalies. The dominant decay channels for all DM components are taken to be

$$\chi_i \rightarrow l^\pm Y^\mp, \quad (2)$$

where $l = e, \mu$ and $\tau$, and $Y$ is another charged particle whose further decay is irrelevant to our following discussion. Such decay channel naturally realizes the leptophilic scenario so that it can satisfy the PAMELA constraint on the antiproton [28]. The $e^+/e^-$ source terms $Q_{e,p}^{DM}$ induced by the DM decays can be parametrized as:

$$Q_{e,p}^{DM}(x,p) = \sum_i \frac{\rho_i(x)}{\tau_i M_i} \left( \frac{dN_{e,p}}{dE} \right), \quad (3)$$

where $M_i$, $\tau_i$ and $\rho_i(x)$ are the mass, lifetime and energy density distribution for the $i$-th DM component, respectively. For simplicity, we assume that each DM component carries the same fraction of the entire energy density, so that $\rho_i(x) = \rho(x)/N$, where $\rho(x)$ is the DM density distribution in the Galaxy as the isothermal profile [35]. Here, $(dN_{e,p}/dE)$, is the differential $e^-/e^+$ multiplicity for each annihilation, given by the mixture of the three
leptonic channels:

\[
\left( \frac{dN_{e,p}}{dE} \right)_i = \frac{1}{2} \left[ \epsilon^e_i \left( \frac{dN^e}{dE} \right)_i + \epsilon^\mu_i \left( \frac{dN^\mu}{dE} \right)_i + \epsilon^\tau_i \left( \frac{dN^\tau}{dE} \right)_i \right],
\]

(4)

where \( \epsilon^{e,\mu,\tau}_i \) denote the corresponding branching ratios satisfying the normalization condition \( \epsilon^e_i + \epsilon^\mu_i + \epsilon^\tau_i = 1 \) and the factor \( 1/2 \) takes into account that \( e^+ \) and \( e^- \) are generated in two separated channels. Since the decay channels shown in Eq. (2) are all two-body processes, we can easily determine the normalized injection spectrum for each decay process only by the kinematics. Concretely, the injection spectra for \( e^- \) and \( \mu^- \) channels can be calculated analytically,

\[
\left( \frac{dN^e}{dE} \right)_i = \frac{1}{E_{ci}} \delta(1 - x),
\]

(5)

\[
\left( \frac{dN^\mu}{dE} \right)_i = \frac{1}{E_{ci}} \left[ 3(1 - x^2) - \frac{4}{3} (1 - x) \right] \theta(1 - x),
\]

(6)

with \( x = E/E_{ci} \), while the \( \tau^- \) channel spectrum is simulated with PYTHIA \cite{36} due to the complicated \( \tau^- \) hadronic decays. The propagation of electrons and positrons between the DM \( e^-/e^+ \) sources and the Earth is very complicated \cite{37}, which involves the deflection of \( e^-/e^+ \) in the galactic magnetic fields and energy loss via the inverse Compton (IC) scattering, bremsstrahlung and synchrotron radiation. In this work, such a sophisticated propagation is consistently solved by the GALPROP codes with the same set of diffusion coefficients as the background fluxes shown in Table I. Finally, it is generally believed that the solar modulation affects the \( e^-/e^+ \) flux spectra greatly, especially at energies below and around 10 GeV. Here, we follow the simple force-field approximation \cite{38} with the potential \( \phi_F = 0.55 \) GV.

III. FITTING RESULTS

The datasets used in our study include the latest AMS-02 measurements of the positron fraction \cite{1} and electron and positron respective fluxes \cite{2}. These three groups of the data may correlate to each other, as the positron fraction can be calculated from positron and electron fluxes. Nevertheless, since they have different systematic uncertainties, we adopt all of them simultaneously in our fitting procedure. Furthermore, we restrict to the data with the energy above 10 GeV in order to reduce the effects of the solar modulation. Thus, we have totally 140 data points. For the fitting procedure, we use the simple \( \chi^2 \)-minimization method to obtain the best-fit point and assess the goodness of the fit. In the following two
subsections, we present the fitting results for the single- and two-component decaying DM models, which are the simplest ones in the general multi-component DM scenario. After fixing the best-fit model parameters, we can predict the total $e^+ + e^-$ flux spectrum and compare it with the latest measurement by AMS-02 \[39\].

A. Results for Single-Component Dark Matter Models

In this section, we focus on the simplest case with a single DM component. In order to obtain the meaningful physical results, we fix the DM mass to be $M = 3030$ GeV. Therefore, we have totally 6 parameters: the primary and secondary normalization factors $\kappa_1$ and $\kappa_2$, energy cutoff $E_c$, DM lifetime $\tau$ and two independent decay branching ratios $\epsilon^e$ and $\epsilon^\tau$, together with the constraint $\epsilon^e + \epsilon^\tau \leq 1$. In order to simplify the fitting procedure, we fix the cutoff $E_c$ to be 600, 800, 1000 and 1500 GeV, respectively, and fit other five parameters for each $E_c$. 

| $E_c$(GeV) | $\kappa_1$ | $\kappa_2$ | $\epsilon^e$ | $\epsilon^\mu$ | $\epsilon^\tau$ | $\tau (10^{26}s)$ | $\chi^2_{\min}$ | $\chi^2_{\min}/$d.o.f. |
|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|------------------|
| 600       | 0.94      | 1.60      | 0.07      | 0.93      | 0.62      | 115       | 0.85      |
| 800       | 0.94      | 1.62      | 0.02      | 0.98      | 0.67      | 128       | 0.95      |
| 1000      | 0.94      | 1.65      | 0         | 0         | 1         | 0.73      | 145       | 1.08             |
| 1500      | 0.94      | 1.65      | 0.16      | 0.84      | 0.78      | 215       | 1.60      |

The best-fit results are summarized in Table II and Fig. I for different energy cutoffs. From Table II, we find that for the first three cases with the energy cutoff smaller than 1 TeV, the single-component DM model can already give good fits to the AMS-02 measurements of the positron fraction and $e^+/e^-$ respective fluxes, while the last benchmark with $E_c = 1.5$ TeV is not very reasonable due to the too large value of $\chi^2_{\min}/$d.o.f. Note that in Fig. I(d), we show the predictions of the total $e^+ + e^-$ flux with the best-fit parameters. By comparing these predictions with the latest AMS-02 data on the total $e^+ + e^-$ flux, we find that the $e^+ + e^-$ spectrum for $E_c \geq 1$ TeV either stops too early or decays too fast, so that it cannot follow the measured high energy behavior, especially for the data with energies larger than 6.
FIG. 1. (a) Electron flux, (b) positron flux, (c) positron fraction, and (d) total $e^+ + e^-$ flux from the single-component DM contributions with the best-fitting parameters given in Table II for $E_{cH}=600, 800, 1000$ and 1500 GeV, respectively.

400 GeV. In contrast, the case with $E_c = 1.5$ TeV can give a good description at the high energy, though it proves a bad fit for the other three datasets. From this point of view, the single-component DM models encounter some problems: the AMS-02 data for the positron fraction and $e^+ / e^-$ fluxes seem to favor a DM with its cutoff smaller than 1 TeV, but such a DM makes the total $e^+ + e^-$ flux at the high energy region difficult to be explained.

B. Results for Two-Component Dark Matter Models

We now turn to the two-component DM case, in which we use $\text{DM}_{L(H)}$ to represent the light (heavy) DM. Note that we want to explain the substructure around 100 GeV in terms of the light DM stopping to decay at the energy, resulting in that the cutoff $E_{cL}$ of $\text{DM}_L$ is fixed to be 100 GeV. However, the cutoff $E_{cH}$ of the heavy DM is free, which is taken to be 600, 800, 1200, 1500 GeV in our numerical investigations, respectively. Here, we choose the
mass of the heavy particle $Y$ to be 300 GeV for simplicity, so that the two DM masses can be determined by the kinematics of the two-body decays with the corresponding cutoffs.

The fitting results are presented in Table III, and the predictions with the best-fit parameters are shown in Fig. 2. Generally speaking, all of the four two-component DM models can fit to the AMS-02 data pretty well as $\chi^2_{\text{min}}/\text{d.o.f.} < 1$, which are much better than any single-component DM model considered in the previous subsection. The flavor structures are almost the same in these cases, in which the heavy DM decays primarily through the $\mu$-channel, while the light one favors the $\tau$-channel. The hardening feature observed in the $e^+/e^-$ flux spectra around 30 GeV is explained by the transition from the background-dominated region to the DM-dominated one. Even better, the positron fraction spectrum with $E_{cH} = 800$ GeV shows the start of the decreasing behavior with the maximum at around 300 GeV, which coincides with the striking claim in Ref. [1]. Unfortunately, the predicted total $e^+ + e^-$ flux spectrum for this heavy DM cutoff goes back to the background level too early as compared with the most recent AMS-02 data, giving a bad description to the last two points. In contrast, the spectra with $E_{cH} = 1200$ and 1500 GeV can reduce or solve this problem by extending the DM $e^+ + e^-$ flux to high energies. However, in the latter two cases, the increasing behaviors in the positron fraction also continue to high energies, already exceeding 500 GeV, which disagrees with the conclusion in Ref. [1]. In sum, similar to the single-component cases, the current AMS-02 data on the positron fraction seems to be best fitted with a relatively small heavy-DM cutoff, which is in mild tension with the excesses at higher energies in the total $e^+ + e^-$ flux. But all the benchmarks can give good enough fit to the AMS-02 data, which cannot be achieved by the single-DM models with the cutoff larger than 1 TeV.

TABLE III. Parameters leading to the minimal values of $\chi^2$ with the cutoffs of heavy DM being 600, 800, 1200, and 1500 GeV, respectively.

| $E_{cH}$ (GeV) | $\kappa_1$ | $\kappa_2$ | $\epsilon^e_{H,L}$ | $\epsilon^\mu_{H,L}$ | $\epsilon^\tau_{H,L}$ | $\chi^2_{\text{min}}$ | $\chi^2_{\text{min}}/\text{d.o.f.}$ |
|---------------|-----------|-----------|--------------------|--------------------|--------------------|----------------|--------------------------|
| 600           | 0.94      | 1.49      | 0.18               | 0.02               | 0.74               | 0.00           | 0.08                 | 0.98           | 0.00           | 0.08           | 0.98           | 1.52           | 1.34           | 0.78          |
| 800           | 0.94      | 1.49      | 0.05               | 0.02               | 0.65               | 0.00           | 0.03               | 0.98           | 0.98           | 0.00           | 0.03               | 1.08           | 1.39           | 0.78          |
| 1200          | 0.94      | 1.50      | 0.00               | 0.01               | 0.80               | 0.00           | 0.20               | 0.99           | 0.99           | 0.00           | 0.20               | 0.62           | 1.61           | 0.78          |
| 1500          | 0.94      | 1.50      | 0.00               | 0.04               | 1.00               | 0.17           | 0.00               | 0.79           | 0.79           | 0.00           | 0.00               | 0.60           | 1.98           | 0.81          |
FIG. 2. (a) Electron flux, (b) positron flux, (c) positron fraction, and (d) total $e^+ + e^-$ flux from the two-component DM contributions with the best-fitting parameters given in Table III for $E_{cH} =$600, 800, 1200 and 1500 GeV, respectively.

IV. REMARKS ON THE DIFFUSE $\gamma$-RAY CONSTRAINTS

Finally, we would make some comments on the diffuse $\gamma$-ray constraints in the present single- and two-component decaying DM scenarios. As pointed in Refs. [20, 40–46], the current diffuse $\gamma$-ray measurement by Fermi-LAT has already excluded a large range of the parameter space of the single-component leptophilic decaying DM models trying to explain the positron/electron excesses. However, it has been shown in Refs. [29, 30] that the present two-component decaying DM scenario is promising to reconcile the tension between these two kinds of experiments, in which the prediction of the diffuse $\gamma$-ray spectrum is done by summing all the contributions to the background and DM signals. In the following, we shall argue that this feature persists for the results in Tables II and III. Since the final predictions of the diffuse $\gamma$-ray spectrum are similar to those shown in Refs. [29, 30], we shall not repeat such calculation again. Instead, we would like to reach this conclusion by arguing the reasons
behind.

Refs. [40, 41] have made the detailed discussions of the diffuse $\gamma$-ray constraints on the single-component decaying DM models with the conventional decay channels, representing the standard references in the literature. Our present study is mainly based on the comparison between our scenario with these two papers. First of all, the interpretation of the Fermi-LAT diffuse $\gamma$-ray data in Ref. [40], which assumes that the measured spectrum should be fitted with a simple power law function arising from the conventional astrophysical sources, is very different from our viewpoint. The possible contribution from DM could only be manifested as the residue after the subtraction of the data to this background, leading to very stringent DM lifetime bounds. From our perspective, however, the measured spectrum is the total summation of the astrophysical background and the signals from DM decays. Therefore, the constraints in Ref. [40] cannot be applied to our cases.

On the other hand, the constraints from Ref. [41] are more relevant to our present scenario since the authors, Papucci and Strumia (PS), did not assume any astrophysical background in their derivation. The bounds $\tau_{PS}$ for various decay channels are shown in Fig. 8 in Ref. [41], from which we can read off the lowest DM lifetime bounds for the corresponding DM masses. However, these DM lifetime bounds have to be transformed before they can be used here. One prominent difference lies in that in our scenario we have $N$ components with an equal amount DM density by assumption, so that there is a factor $1/N$ suppression for each channel. Moreover, the DM decay processes in this paper have only one lepton in the final states, rather than a lepton pair in the usual models in Ref. [41], so that additional $1/2$ suppression should be also taken into account. Another aspect is that the DM masses in our scenario are different from those in the lepton pair decay processes in which $m_{DM}^{PS} = 2E_c$. By considering all these effects, we can transform the DM lifetime bounds shown in Ref. [41] into those for our models via

$$
\tau_l = \frac{M_{DM}^{PS} \tau_{l,PS}}{2NM_i},
$$

where the subscript $l$ denotes the corresponding lepton channel.

For the single-component DM models in Table III, the dominant decay channels are all $\tau$ modes. Since the DM cutoffs are 600, 800, 1000, and 1500 GeV, the corresponding lifetime bounds for the tau-pair final state lie in the range $2 \sim 3 \times 10^{26}$ s, from which the lifetime bounds for our scenario can be obtained via Eq. (7) as $1 \sim 1.5 \times 10^{26}$ s. Obviously, the
best-fit lifetimes in Table II are already excluded by these bounds. Therefore, it is seen that the single-component DM models used to explain the AMS-02 excesses have some kind of tension with the Fermi-LAT diffuse $\gamma$-ray results.

However, our two-component DM models do not possess this problem. For example, the light DM with $E_{cL} = 100$ GeV predominantly decays via the $\tau$-channel as shown in Table III. The relevant lifetime bound in Ref. [41] is $\tau_{PS}^{\tau} = 1.5 \times 10^{26}$ s for $\text{DM} \rightarrow \tau^+\tau^-$ with $M_{DM}^{PS} = 200$ GeV, which corresponds to $\tau_{PS} = 2 \times 10^{25}$ s with the light DM mass $M_L = 416$ GeV. The same argument can also lead us to the heavy DM lifetime bounds $\tau_{\mu} = 0.75 \sim 1.25 \times 10^{25}$ s for the dominant $\mu$ channels with $E_{cH} = 600 \sim 1500$ GeV. It is clear that these bounds are still much lower than the two best-fit DM lifetimes in all of the four benchmarks listed in Table III, from which we can obtain the conclusion that the two-component decaying DM models are more favorable than their single-component cousins by the Fermi-LAT diffuse $\gamma$-ray data.

V. CONCLUSION

The recent release of the AMS-02 data on the positron fraction and electron/positron respective fluxes has given us some new hints toward the DM interpretation of the positron/electron excesses. In the present paper, we have revisited the multi-component decaying DM scenario introduced in our previous work [29, 30] with the updated AMS-02 datasets. It is found that both single- and two-component DM models can yield consistent fits to the aforementioned datasets, with the two-component cases even better. The hardening behavior in $e^+/e^-$ fluxes around 30 GeV can be explained by the transition from the background-dominated to the DM-signal regions. For the single-component DM models, the AMS-02 data, especially the positron fraction, constrain the dominant DM decay channel to be the $\tau$-mode with its cutoff lighter than 1 TeV, resulting in that the total $e^+ + e^-$ flux stops excessive too early to explain the data. In comparison, the two-component DM models provide even better fit to the AMS-02 data, in which the heavy DM decays predominately via the $\mu-$channel, while the light one with $E_{cL} = 100$ GeV mostly via the $\tau$-channel. We have also made some comments on the diffuse $\gamma$-ray constraint from the Fermi-LAT measurement. We have found that the corresponding dataset has already excluded the best-fit lifetimes of the single-component DM models with the dominant $\tau$ decay channels, while still allows the
two-component DM models benchmarks listed in Table III. In sum, the two-component DM models are more favored by the current indirect DM searches, providing a better fit to the AMS-02 $e^+/e^-$ data, which are also in good agreement with the Fermi-LAT diffuse $\gamma$-ray data.

Moreover, our best-fit parameters with the heavy DM’s cutoff $E_{cH} = 800$ GeV predicts the decline tendency above 300 GeV claimed in Ref. [1], while a heavy DM with $E_{cH} = 1200$ or 1500 GeV can give a better description of the high energy behavior of the AMS-02 $e^+ + e^-$ flux data. However, there is no model to accommodate both high-energy features, regarded as some tensions among the AMS-02 datasets. We hope that the more precise AMS-02 data in the near future can settle down this problem.

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