Decaying Dark Matter in Supersymmetric Model and Cosmic-Ray Observations

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Abstract

We study cosmic-rays in decaying dark matter scenario, assuming that the dark matter is the lightest superparticle and it decays through a $R$-parity violating operator. We calculate the fluxes of cosmic-rays from the decay of the dark matter and those from the standard astrophysical phenomena in the same propagation model using the GALPROP package. We reevaluate the preferred parameters characterizing standard astrophysical cosmic-ray sources with taking account of the effects of dark matter decay. We show that, if energetic leptons are produced by the decay of the dark matter, the fluxes of cosmic-ray positron and electron can be in good agreements with both PAMELA and Fermi-LAT data in wide parameter region. It is also discussed that, in the case where sizable number of hadrons are also produced by the decay of the dark matter, the mass of the dark matter is constrained to be less than 200–300 GeV in order to avoid the overproduction of anti-proton. We also show that the cosmic $\gamma$-ray flux can be consistent with the results of Fermi-LAT observation if the mass of the dark matter is smaller than $\sim 4$ TeV.
1 Introduction

An anomaly has been discovered in the recent observation of cosmic-ray positron. The PAMELA satellite has observed positron excess in the flux around the energy range of $10^{14}$–$100$ GeV, which cannot be explained by standard astrophysical phenomena in our Galaxy [1]. A possible solution is to consider non-standard phenomena in astrophysics such as nearby pulsars [2]. On the other hand, the PAMELA experiment has motivated us to settle this problem in the viewpoint of particle physics; the anomaly can be explained by the decay or the annihilation of dark matter of the universe. Indeed, various scenarios with decaying [3] and annihilating [22]–[29] dark matter have been discussed in much literature.

A well-motivated scenarios is decaying dark matter scenario in the framework of supersymmetric model. Supersymmetric model provides natural candidate for dark matter, i.e., the lightest superparticle (LSP). In addition, supersymmetric model is one of the most attractive models beyond the standard model; it gives a solution to hierarchy problem and enables the three gauge coupling constants to unify at $\sim 10^{16}$ GeV. A very long lifetime of the LSP, which is required to solve the PAMELA anomaly, can be realized with a very weak $R$-parity violation (RPV). In the scenario with unstable LSP dark matter, not only positron but also electron, $\gamma$-ray, and/or anti-proton give significant contribution to cosmic-ray fluxes. Thus, in order to solve the PAMELA anomaly in this framework, it is necessary to check if the fluxes of all the cosmic-ray particles are in agreement with observation. For such a purpose, one should calculate the fluxes of cosmic-rays from standard astrophysical source, i.e., supernova remnant (SNR), as well as those from the decay of dark matter. In many of the previous studies, however, fluxes of cosmic-rays from different sources are evaluated using different propagation models and/or different SNR injection parameters. For a complete study of the decaying dark matter scenario, the fluxes of all the cosmic-ray species should be calculated in a consistent way.

In this paper, we consider the case that dark matter is unstable (and long-lived) and it becomes the significant source of high energy cosmic-rays. We pay particular attention to the case where the LSP is dark matter, and study the cosmic-ray fluxes in light of PAMELA and other cosmic-ray observations. We use the GALPROP

\footnote{For the decaying dark matter scenario, it was pointed out that unstable dark matter seems to be suggested by the HEAT results [30] and that the signal of decaying dark matter could be observed by PAMELA as a positron excess before the PAMELA result showed up [31, 32].}
package so that the cosmic-ray fluxes from different sources are evaluated with the same propagation models. We reevaluate some of the parameters characterizing the SNR injection spectra taking account of the effects of the decay of dark matter. We then discuss constraints on the decaying scenario from observations. We will show that, by properly choosing model parameters, the PAMELA anomaly can be well explained in the decaying dark matter scenario without conflicting other constraints.

The organization of this article is as follows. In the next section, we explain how we calculate cosmic-rays from the standard astrophysical phenomena and decaying dark matter. Here important parameters in our analysis are described. Numerical results are then shown in section 3. Section 4 is devoted to conclusion.

2 Cosmic-Rays from SNR and Dark Matter

Spectra of cosmic-ray particles which we observe depend on what the sources of cosmic-rays are and how the particles from the sources propagate. In this section, we first consider cosmic-rays from SNR which is supposed to be standard source of high energy cosmic-rays. Cosmic-rays from decaying dark matter are then discussed. In our numerical calculation, all the cosmic-ray fluxes are obtained by using the single numerical code, GALPROP, in order to perform a consistent analysis. We explain relevant parameters characterizing energetic cosmic-rays from astrophysical sources and dark matter decay.

2.1 Cosmic-rays in standard Galactic model

Cosmic-rays mainly consist of nuclei, electron, positron, anti-proton, and \( \gamma \)-ray. Among those, electron and nuclei, \textit{e.g.}, proton, helium, carbon, oxygen, and iron, are considered to be from the remnants of supernovae and pouring to the earth after they have drifted by interaction with interstellar matters and magnetic field in our Galaxy. These are called primary cosmic-rays. On the other hand, cosmic-rays are also generated secondarily in a consequence of interaction processes; we call them secondary cosmic-rays. (See Table I.) In the collisions of cosmic-ray with interstellar gas, such as \textit{pp}-collision, anti-protons and other nuclei such as lithium, beryllium, boron, and sub-Fe (scandium, titanium, and vanadium), are produced. In the col-

\[^{2}\text{For the former study of decaying scenario by using GALPROP, see Refs. [1], [33]–[40].}\]
lision processes, pion and kaon are also produced; secondary positron and electron are then emitted in the cascade decay of such mesons.

The primary spectra of electron and proton from SNR are assumed to obey power law, since they are assumed to be produced through Fermi-acceleration mechanism. The source terms of these cosmic-ray particles are then parametrized as

\[
Q_{\text{SNR}}^e = A_e E_{\text{GeV}}^{-\gamma_e}, \quad (2.1)
\]

\[
Q_{\text{SNR}}^p = A_p p_{\text{GeV}}^{-\gamma_p}. \quad (2.2)
\]

Here, \(A_e\) and \(\gamma_e\) (\(A_p\) and \(\gamma_p\)) are normalization and power index of electron (proton) injected from SNR, while \(E_{\text{GeV}}\) (\(p_{\text{GeV}}\)) is GeV-normalized energy (momentum) of electron (proton). Following the treatment adopted in “Conventional model” of cosmic-ray [41, 42], the power indices are assumed to take different values for high and low energy region as in Table 2. If SNR is the dominant source of high energy cosmic-rays, the shapes of those spectra are sensitive to the index parameters \(\gamma_e\) and \(\gamma_p\). In particular, primary electron generally dominates the total \((e^+ + e^-)\) flux, and its spectrum in the energy region over 10 GeV is sensitive to the value of \(\gamma_e\).

If we adopt the Conventional model, predicted cosmic-ray fluxes such as boron to carbon (B/C) ratio, proton, helium, and anti-proton fluxes are in good agreements with observations. The values of parameters adopted in the model are summarized in Table 2 [3]. Within this model, however, cosmic-ray \(e^+\) from SNR cannot explain the positron fraction data reported by PAMELA, which is now known as the “PAMELA anomaly”. In addition, the \((e^+ + e^-)\) spectrum observed by Fermi-LAT [43] is slightly

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Table 1: Propagation and production of cosmic-ray \(e^\pm, p, \bar{p}\), and \(\gamma\) from SNR. Here \(e^-_{\text{prim}} (p_{\text{prim}})\) and \(e^\pm_{\text{sec}} (p_{\text{sec}}, \bar{p}_{\text{sec}})\) are primary and secondary \(e^-\) (\(p\)) and \(e^\pm\) (\(p, \bar{p}\)), respectively.

| Source | (Propagation and interaction process) | Products |
|--------|--------------------------------------|----------|
| SNR \(e^-\) | \(\rightarrow\) (propagate) \(\rightarrow\) | \(e^-_{\text{prim}}\) |
| SNR \(p\) | \(\rightarrow\) (pp-collision) \(\rightarrow\) (\(\pi, K\) decay) \(\rightarrow\) | \(e^\pm_{\text{sec}}\) |
| SNR \(p\) | \(\rightarrow\) (propagate) \(\rightarrow\) | \(p_{\text{prim}}\) |
| SNR \(p\) | \(\rightarrow\) (pp-collision) \(\rightarrow\) | \(p_{\text{sec}}, \bar{p}_{\text{sec}}\) |
| \(e^-_{\text{prim/sec}}, e^\pm_{\text{sec}}\) | \(\rightarrow\) (IC + brems + synch) \(\rightarrow\) | \(\gamma\) |
| SNR \(p\) | \(\rightarrow\) (pp-collision) \(\rightarrow\) (\(\pi, K\) decay) \(\rightarrow\) | \(\gamma\) |

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\#3 One can consider diffusive reacceleration or diffusive convection; we adopt the former one.
In the study of high energy cosmic-ray, it is also important to consider cosmic \( \gamma \)-ray and radiation fluxes. Inside the Galaxy, high energy \( \gamma \)-ray is necessarily produced by several processes (see Table 1): the inverse-Compton (IC) scattering of \( e^\pm \) with interstellar radiation field (ISRF), the bremsstrahlung of \( e^\pm \) with interstellar gas, the synchrotron radiation from \( e^\pm \) under magnetic field, and the decay of pion which is produced in the hadronic reaction of cosmic nuclei in interstellar gas. The spectra of \( \gamma \)-ray and synchrotron radiation depend on the injection spectra of SNR electron and proton. According to Ref. [41], the Conventional model gives \( \gamma \)-ray flux well below the observed flux and radiation flux consistent with observation. It is also shown that the consistency is hold if \( \gamma^e \lesssim 2.0 \) for \( E \lesssim 10 \) GeV is satisfied [41].

Electron in this energy range is, however, considered to be subject to relatively large effect of the solar modulation.

Since we are interested in the scenario where cosmic-rays are produced from the decay of dark matter, we do not necessarily restrict ourselves to the Conventional model. We should rather reevaluate some of the parameters characterizing the SNR injection spectra with taking account of the effects of the decaying dark matter. In this paper, we take \( A^e_\gamma \) and \( \gamma^e \) to be free parameters. (The other parameters are taken as the same as in Conventional model unless otherwise mentioned.)

Hereafter, the cosmic-rays originating in SNR are called as background (BG):

\[
\Phi^{(0)}_{e_{\text{BG}}} = \Phi^{(0)}_{e_{\text{prim}}} + \Phi^{(0)}_{e_{\text{sec}}},
\]

\[
\Phi^{(0)}_{p_{\text{BG}}} = \Phi^{(0)}_{p_{\text{prim}}},
\]

Table 2: Important parameters of cosmic-ray used to calculate fluxes from SNR. The primary electron (proton) is normalized to fit observations, and \( \gamma^e \) (\( \gamma^p \)) is chosen to reproduce the observed spectrum. Those values are adopted in Conventional model.

| \( \Phi^{(0)}_{e_{\text{prim}}} \) | \( 1.3 \times 10^{-11} \text{ GeV}^{-1} \text{m}^{-2} \text{sec}^{-1} \text{str}^{-1} \) (at 100 GeV) |
| \( \gamma^e \) | \( 2.54/1.6 \) (above/below 4 GeV) |
| \( \Phi^{(0)}_{p_{\text{prim}}} \) | \( 5.0 \times 10^{-2} \text{ GeV}^{-1} \text{m}^{-2} \text{sec}^{-1} \text{str}^{-1} \) (at 100 GeV) |
| \( \gamma^p \) | \( 2.42/1.98 \) (above/below 9 GeV) |
where $\Phi_{e^-}$ and $\Phi_{e^\pm}$ are fluxes of primary $e^-$ and secondary $e^\pm$, respectively. Besides electron and positron, hadrons are also produced which result in background proton and anti-proton. We also calculate BG fluxes of these particles:

$$\Phi_{p_{BG}} = \Phi_{p_{prim}} + \Phi_{p_{sec}},$$

(2.5)

$$\Phi_{\bar{p}_{BG}} = \Phi_{\bar{p}_{sec}},$$

(2.6)

where $\Phi_{p_{prim}}$ is primary $p$ flux, while $\Phi_{p_{sec}}$ ($\Phi_{\bar{p}_{sec}}$) is secondary $p$ ($\bar{p}$) flux. In the calculation of cosmic-ray fluxes of $p$ and $\bar{p}$, we use force-field model \[^4\] with the use of the solar modulation potential of $\phi = 550$ MV.\[^5\] In addition, for later convenience, we introduce normalization parameter (donated as $a_e$), which is defined by $\Phi_{e^-_{prim}} (E) = a_e \Phi_{(0)_{e^-_{prim}}} (E)$, with $\Phi_{(0)_{e^-_{prim}}}$ being the reference flux normalized as $\Phi_{(0)_{e^-_{prim}}} (E = 100 \text{ GeV}) = 1.3 \times 10^{-11} \text{ GeV}^{-1} \text{m}^{-2} \text{sec}^{-1} \text{str}^{-1}$.

For the estimation of the BG $\gamma$-ray flux, we also use the GALPROP package. There may exist other astrophysical contributions which are not taken into account in the GALPROP package; we do not consider such contributions in our analysis because they are expected to have large uncertainties.\[^6\]

### 2.2 Cosmic-rays from decaying dark matter

Now we consider cosmic-rays from the decay of dark matter. In the decaying scenario, it is assumed that the lifetime of dark matter is much longer than the present age of the universe. Most of dark matter therefore survives today. Even though the decay of dark matter is suppressed by the long lifetime, it can be a significant source of cosmic-ray if standard-model particles are produced through the decay. Cosmic-rays from dark matter depend on the spectra of particles injected from the decay and how they propagate in the universe.

Important quantities in the calculation of cosmic-ray fluxes from unstable dark matter are lifetime of dark matter ($\tau_{DM}$), mass of dark matter ($m_{DM}$), and spectra of emitted particles. With these, source term of cosmic-ray is given by

$$Q^X_{DM} = \frac{1}{\tau_{DM} m_{DM}} \frac{dN^X}{dE},$$

(2.7)

\[^5\] This is a method proposed in order to take into account the effect of solar modulation. Estimation of the effect of solar modulation is, however, still uncertain. We thus focus on the energy region where the effect is small enough in our numerical analysis. (See the discussion below.)

\[^6\] Unidentified cosmic $\gamma$-ray may have various origins, for example, galaxy clusters, energetic particles in the shock waves associated with large-scale cosmological structure formation, distant gamma-ray burst events, baryon-antibaryon annihilation.
where $X$ is cosmic-ray particle (e.g., $X = e^\pm, p, \bar{p},$ and $\gamma$), and $dN_X/dE$ is the spectrum of $X$ from the decay of a single dark matter. In addition, $\rho_{DM}$ is mass density of dark matter. In the decaying scenario, the fluxes of cosmic-rays are insensitive to the profile of dark matter density except for cosmic-ray $\gamma$ from Galactic center. Since we will not study such $\gamma$-ray, we adopt the isothermal profile for Galactic halo;

$$\rho_{DM}^{(\text{Galaxy})}(r) = \rho_\odot \frac{r^2}{r^2_{\text{core}} + r^2},$$

(2.8)

where $\rho_\odot \simeq 0.43$ GeV/cm$^3$ is the local halo density, $r_{\text{core}} \simeq 2.8$ kpc is the core radius, $r_\odot \simeq 8.5$ kpc is the distance between the Galactic center and the solar system, and $r$ is the distance from the Galactic center. We have checked that our numerical results are almost unchanged even if we use other dark matter profiles such as the NFW profile [48].

In the decaying dark matter scenario, cosmic $\gamma$-ray from extra-Galactic region may have significant flux because the $\gamma$-ray is produced by the IC process induced by the energetic $e^\pm$ from dark matter decay [49]. It was shown that the flux could be comparable to the observed $\gamma$-ray flux. (For the discussion of constraint from isotropic $\gamma$-ray observation, see also [50, 51].) We calculate the extra-Galactic $\gamma$-ray by following formula given in [49]. In the calculation of cosmic $\gamma$-ray from extra-Galactic region, we use averaged dark matter density as

$$\rho_{DM}^{(\text{extra-Galaxy})} = 1.2 \times 10^{-6} \text{ GeV/cm}^3.$$  

(2.9)

Notice that the $\gamma$-ray from the extra-Galactic region is isotropic. $\gamma$-ray is also produced at the central region of our Galaxy. However, the flux from the Galactic center strongly depend on the dark matter profile [50]. Thus, in order to derive conservative constraint, we only consider $\gamma$-ray from high Galactic latitude.

In supersymmetric model, there are many candidates for dark matter which can decays under RPV. One of the possibilities motivated by the PAMELA anomaly is unstable dark matter which decays into final state which consists of only energetic leptons. Then, charged leptons can make prominent rise in positron fraction to explain the anomaly without conflicting the observation of cosmic-ray anti-proton. In such a case, $\gamma$-ray is inevitably produced by IC process as secondary cosmic-ray. (Those production mechanism are summarized in Table 3, including the following

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#7Because we only consider the $\gamma$-ray flux averaged over large solid angle in the decaying dark matter scenario, we do not have to worry about the effects of sub-halo. These effects may be important in the annihilating dark matter scenario as shown in Refs. [52]–[58].
case to be described below.) On the other hand, one can also consider a case where significant amount of hadrons (as well as leptons) are contained in the final state of the decay of dark matter. In such a case, anti-proton as well as γ-ray may provide stringent constraints on the scenario. Here, notice that scenario with similar final state results in similar cosmic-ray fluxes. We thus focus on several cases which give typical results; gravitino and sneutrino dark matter scenarios with bi-linear and/or tri-linear RPV. In each case, we calculate $dN_X/dE$, including contributions of particles from cascading decay after hadronization, with the use of the PYTHIA package \cite{59}.

Let us first consider the case where gravitino is the LSP. In the present case, because of the smallness of RPV, the production mechanism of gravitino is unaffected by the RPV interaction; gravitino can be produced by scattering processes of thermal particles \cite{60}, decay of the LSP in minimal supersymmetric standard model sector (MSSM-LSP) after freeze-out \cite{60,61} or a non-thermal process \cite{62} (Sneutrino, which we will discuss below, can be also produced by non-thermal process \cite{63}).

The spectra of final-state particles, on the other hand, strongly depend on how the $R$-parity is violated. Because we are interested in the PAMELA anomaly, we only consider RPV operators by which the LSP decays into final states with energetic lepton. Then, one possibility is to introduce the following soft breaking bi-linear RPV operators:

$$\mathcal{L}_{\text{bi-RPV}} = B_i \bar{L}_i H_u + m^2_{L_i H_d} \bar{L}_i H_d^* + \text{h.c.,}$$  

(2.10)

where $\bar{L}_i$ is left-handed slepton doublet (with $i = 1 - 3$ being the generation index), while $H_u$ and $H_d$ are up- and down-type Higgs boson doublets, respectively. (Here, $L_i$ and $H_d$ are defined in the bases in which the bi-linear RPV terms in superpotential are rotated away.) With the operators given in Eq. (2.10), gravitino decays into two-
body final states: $\psi_\mu \rightarrow \gamma \nu_i, Z \nu_i, W l_i, \text{and } h \nu_i$. (Here and thereafter, gravitino is denoted as $\psi_\mu$.) Decay width of each process is given in Ref. [31]; the decay process is dominated by the mode $\psi_\mu \rightarrow W l_i$ if the gravitino is heavier than $W$-boson. The lifetime is related to the bi-linear RPV parameter as [31],

$$\tau_{3/2} \simeq 8 \times 10^{25} \text{ sec} \times \left( \frac{\kappa}{10^{-8}} \right)^{-2} \left( \frac{m_{3/2}}{200 \text{ GeV}} \right)^{-3}, \quad (2.11)$$

where $m_{3/2}$ is gravitino mass. In addition, $\kappa^2 \equiv \sum_i \kappa_i^2$, where

$$\kappa_i = \frac{B_i \sin \beta + m_{L_i} H_d \cos \beta}{m_{\tilde{\nu}_i}}, \quad (2.12)$$

with $\tan \beta = \langle H_u^0 \rangle / \langle H_d^0 \rangle$ (here $\langle H_u^0 \rangle$ and $\langle H_d^0 \rangle$ are the vacuum expectation values of up- and down-type Higgs bosons, respectively), and $m_{\tilde{\nu}_i}$ being the mass of sneutrino in $i$-th generation. We will see that the lifetime of dark matter should be $O(10^{26})$ sec in order to explain the PAMELA anomaly. Such a lifetime is realized when $\kappa \sim O(10^{-9} - 10^{-10})$.

Another important possibility is the decay through tri-linear RPV:

$$W_{\text{tri-RPV}} = \frac{1}{2} \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{E}_k^c, \quad (2.13)$$

where $\hat{L}_i = (\hat{\nu}_{L_i}, \hat{L}_{Li})$ and $\hat{E}_k^c$ are left-handed lepton doublet and right-handed lepton singlet, respectively, where “hat” is for superfield. With the operator given in Eq. (2.13), gravitino decays as $\psi_\mu \rightarrow \nu_i L_{L_i}^\pm L_{R_i}^\mp$ through diagrams with virtual slepton. Here, for simplicity, we assume that the right-handed sleptons are much lighter than the left-handed ones. The energy distribution of the final-state leptons is given

$$\frac{d\Gamma_{\psi_\mu \rightarrow \nu_i L_{L_i}^\pm L_{R_i}^\mp}}{dE_{L_i}dE_{R_i}} = \frac{\lambda^2 m_{3/2}}{768\pi^3 M_{Pl}^2} \frac{z_R^3(1 - z_R)}{(m_{3/2}/m_{\tilde{\nu}_i})^2} \left( \frac{m_{3/2}}{200 \text{ GeV}} \right)^{-3}, \quad (2.14)$$

where $M_{Pl} \simeq 2.4 \times 10^{18} \text{ GeV}$ is the reduced Planck scale, $m_{\tilde{\nu}_i}$ is the right-handed sneutrino mass, and $z_R = 2E_{R_i}/m_{3/2}$. In our analysis, $\lambda_{ijk}$ is determined so that the preferred value of the lifetime of gravitino is obtained. Notice that, taking $m_{\tilde{\nu}_i} \sim m_{3/2}$ for simplicity, the lifetime is estimated as

$$\tau_{3/2} \simeq 7 \times 10^{26} \text{ sec} \times \left( \frac{\lambda}{10^{-8}} \right)^{-2} \left( \frac{m_{3/2}}{200 \text{ GeV}} \right)^{-3}. \quad (2.15)$$

Here, $\lambda_{ijk}$ must satisfy the condition $\lambda_{ijk} \lesssim 10^{-7}$ in order not to wash out baryon asymmetry [61]; this constraint is satisfied in the parameter space we will be interested in.
|   | Decay mode               | \( m_{DM} \) (TeV) | \( \tau_{DM} \) (sec) | \( a_e \) | \( \gamma^e \) | \( \gamma^p \) | \( \chi^2_{Pamela} \) | \( \chi^2_e \) |
|---|-------------------------|---------------------|-----------------------|---------|--------------|--------------|----------------|----------------|
| (I-1) | \( \psi_{\mu} \to eW, \nu_e Z, \) | 0.20               | 9.6 \times 10^{26}   | 1.02    | 2.35         | 2.42         | 9.8            | 41.0           |
| (I-2) | \( \nu_e h, \nu_e \gamma \) | 1.0                | 2.5 \times 10^{26}   | 0.80    | 2.60         | 2.42         | 11.0           | 69.6           |
| (I-3) | \( \psi_{\mu} \to \mu W, \nu_{\mu} Z, \) | 4.0                | 1.7 \times 10^{26}   | 0.88    | 2.54         | 2.42         | 8.8            | 20.5           |
| (I-4) | \( \nu_{\mu} h, \nu_{\mu} \gamma \) | 0.20               | 8.4 \times 10^{26}   | 1.02    | 2.34         | 2.52         | 9.8            | 46.3           |
| (I-5) | \( \psi_{\mu} \to \mu W, \nu_{\mu} Z, \) | 0.25               | 4.2 \times 10^{26}   | 1.02    | 2.42         | 2.42         | 10.9           | 43.6           |
| (I-6) | \( \nu_{\mu} h, \nu_{\mu} \gamma \) | 1.0                | 2.6 \times 10^{26}   | 0.94    | 2.43         | 2.42         | 10.7           | 45.8           |
| (I-7) | \( \psi_{\mu} \to eW, \nu_e Z, \) | 4.0                | 1.5 \times 10^{26}   | 0.88    | 2.52         | 2.42         | 7.2            | 10.0           |
| (I-8) | \( \nu_{\mu} h, \nu_{\mu} \gamma \) | 0.25               | 3.7 \times 10^{26}   | 1.04    | 2.41         | 2.52         | 10.9           | 46.4           |
| (II-1) | \( \psi_{\mu} \to \nu_{\mu} \tau \) | 0.25               | 9.2 \times 10^{26}   | 1.02    | 2.36         | 2.42         | 10.5           | 31.8           |
| (II-2) | \( \nu_{\mu} h, \nu_{\mu} \gamma \) | 1.0                | 4.4 \times 10^{26}   | 0.90    | 2.46         | 2.42         | 11.0           | 49.4           |
| (II-3) | \( \psi_{\mu} \to \nu_{\mu} \tau \) | 4.0                | 1.4 \times 10^{26}   | 0.72    | 2.62         | 2.42         | 11.0           | 98.8           |
| (III-1) | \( \tilde{\nu} \to \mu \mu \) | 0.40               | 9.6 \times 10^{26}   | 1.00    | 2.36         | 2.42         | 6.0            | 42.1           |
| (III-2) | \( \nu_{\mu} h, \nu_{\mu} \gamma \) | 1.0                | 5.7 \times 10^{26}   | 0.90    | 2.44         | 2.42         | 10.9           | 75.8           |
| (III-3) | \( \nu_{\mu} h, \nu_{\mu} \gamma \) | 4.0                | 1.8 \times 10^{26}   | 0.68    | 2.58         | 2.42         | 10.9           | 250.6          |

Table 4: Scenarios of decaying dark matter considered in this paper. Model parameters giving the “best-fit” results to cosmic-ray observations are also shown in each case.

If the sneutrino is the LSP, monochromatic leptons are produced by its decay via the tri-linear RPV superpotential given in Eq. (2.13). Indeed, the sneutrino can decay as \( \tilde{\nu} \to l^+_L l^-_R \). Because the sneutrino is a viable candidate for dark matter irrespective of its handedness [65, 63], and also because the fluxes of high energy cosmic-rays are sensitive to the spectra of emitted particles from the decay of dark matter, we also consider the case of unstable sneutrino LSP. In this case, the lifetime is determined as [66],

\[
\tau_{\tilde{\nu}} \sim 2 \times 10^{26} \text{ sec} \left( \frac{\lambda \sin \theta_{\tilde{\nu}}}{10^{-26}} \right)^{-2} \left( \frac{m_{\tilde{\nu}}}{200 \text{ GeV}} \right)^{-1},
\]

where \( \theta_{\tilde{\nu}} \) is the sneutrino mixing angle.

### 3 Numerical Results

Now we are at the position to quantitatively discuss the cosmic-ray fluxes. As we have already mentioned in the previous section, we assume that the dominant sources of the cosmic-rays are supernova remnants and decaying dark matter. In order to study the cosmic-ray fluxes from both sources using the same propagation model as well as to take account of the production of secondary cosmic-rays, we utilize the
GALPROP package for the calculation of all the cosmic-ray fluxes (except for the extra-Galactic γ-ray flux).

The spectral shape of each cosmic-ray particle from dark matter depends on properties of the decay of dark matter. We take \( m_{\text{DM}} \) and \( \tau_{\text{DM}} \) as free parameters in this paper, and consider three typical cases summarized in Table 4: (I) the emission of a charged lepton as well as a weak boson resulting in energetic jets after the decay (i.e., the gravitino LSP with bi-linear RPV), (II) the emission of only non-monochromatic leptons (i.e., the gravitino LSP with tri-linear RPV), and (III) the emission of only monochromatic leptons (i.e., the sneutrino LSP with tri-linear RPV). It should be noted that there are other candidates for the LSP; the lightest neutralino is a popular one. Cosmic-ray fluxes from the decay of the lightest neutralino are similar to those obtained in the gravitino LSP case. We thus omit to study the case of neutralino LSP.

For the BG electron flux which originates in SNR, we take \( \gamma_e \) and the normalization of SNR electrons to be free parameters. We then discuss when the decaying dark matter scenario gives consistent result with the present cosmic-ray observations. At the beginning of this section, we first give our numerical procedure to determine the “best-fit” values of the model parameters. Then, we will show the results of our numerical analysis.

### 3.1 Numerical procedure

In order to determine the values of the model parameters preferred by the results of PAMELA and Fermi-LAT experiments, we define the \( \chi^2_e \)-variable as

\[
\chi^2_e = \chi^2_{\text{PAMELA}} + \chi^2_{\text{Fermi}}.
\]

Here, variables \( \chi^2_{\text{PAMELA}} \) and \( \chi^2_{\text{Fermi}} \) are defined as

\[
\chi^2_{\text{PAMELA}} = \sum_{i} \frac{\left( R^{(\text{th})}_{e^+,-i} - R^{(\text{obs})}_{e^+,-i} \right)^2}{\Delta R^2_{e^+,-i}}, \quad \chi^2_{\text{Fermi}} = \sum_{i} \frac{\left( \Phi^{(\text{th})}_{e^+e^+e^-,-i} - \Phi^{(\text{obs})}_{e^+e^+e^-,-i} \right)^2}{\Delta \Phi^2_{e^+e^+e^-,-i}},
\]

where \( R^{(\text{th})}_{e^+,-i} \) (\( R^{(\text{obs})}_{e^+,-i} \)) is simulated (observed) positron fraction in the \( i \)-th bin, and \( \Phi^{(\text{th})}_{e^+e^+e^-,-i} \) (\( \Phi^{(\text{obs})}_{e^+e^+e^-,-i} \)) is simulated (observed) total \((e^++e^-)\) flux. \( \Delta R_{e^+,-i} \) and \( \Delta \Phi_{e^+e^+e^-,-i} \) are observational errors in the \( i \)-th bin, and \( N_P \) and \( N_F \) are the number of data points for those. Since effects of the solar modulation to cosmic-ray \( e^\pm \) is conspicuous in the energy range below \( O(10 \text{ GeV}) \), we use five data points of the PAMELA experiment.
above 15 GeV in the calculation of $\chi^2_{\text{Pamela}}$. Then, $N_F = 5$ (whereas $N_F = 26$). In addition, we neglect the systematic error from the energy calibration in the Fermi-LAT data unless otherwise mentioned; the effect of the systematic error is not so important for most of the cases.

We calculate the $\chi^2_e$-variable defined above as a function of $m_{\text{DM}}$, $\tau_{\text{DM}}$, $\gamma^e$, and $a_e$. Because our primary purpose is to find a solution to the PAMELA anomaly, we first calculate $\chi^2_{\text{Pamela}}$ with $m_{\text{DM}}$ being fixed, and identify 95% C.L. allowed region (corresponding to $\chi^2_{\text{Pamela}} < 11.07$) on the $(\tau_{\text{DM}}, \gamma^e, a_e)$-space. After that, in the parameter region allowed by the PAMELA data, we find out parameter space which satisfies $\chi^2_e < 44.99$, which corresponds to the 95% C.L. allowed region (for 31 degrees of freedom). We also search the point where the total $\chi^2_e$ is minimized; we call such a point as the “best-fit” point. Using the parameters, we also simulate cosmic $\gamma$-ray and cosmic-ray $p$ and $\bar{p}$ to check consistency with those latest observations.

### 3.2 Gravitino dark matter with bi-linear RPV

To begin with, we study the case where the gravitino dark matter decays dominantly into the first generation lepton through the bi-linear RPV operator, which is the case when $B_1 \gg B_2, B_3$. Using the $\chi^2_e$-variable, we have found the 95% allowed region at $m_{3/2} \sim 200$ GeV and $m_{3/2} \gtrsim 1$ TeV. The best-fit parameters in this case are summarized in Table 4 as cases (I-1) to (I-3), where the values of $\chi^2_{\text{Pamela}}$ and $\chi^2_e$ in each case are also shown. Positron fraction and the total ($e^+ + e^-$) flux are depicted in Fig. 1 (top two panels), where observational data are also given in each panel; the PAMELA data [1] on the top left panel, while Fermi-LAT [43], ATIC [67], PPB-BETS [68], and HEAT data [30] on the top right one.

Our result shows that, if $m_{3/2} \sim 200$ GeV, the decaying gravitino LSP may explain the PAMELA data with being consistent with the Fermi-LAT observation. In the present case, a monochromatic $e^\pm$ is emitted in the decay, resulting in a sharp edge in the positron fraction at $E \sim 100$ GeV. On the other hand, in the total flux, $e^\pm$ from dark matter is overwhelmed by BG flux, and hence the edge in the total flux is almost hidden by BG. Even though a small edge is visible in the total flux, the value of $\chi^2_e$ indicates that the model is allowed at 95% C.L. (See Table 4). In addition, we have also checked that the $\chi^2_{\text{Fermi}}$ variable calculated solely from the total flux is smaller than the 95% C.L. bound #9. Thus, we conclude that reasonable agreements

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#9It is also described in [69] that the scenario which gives such a sharp edge in the flux is not
Figure 1: Cosmic-rays from the decaying gravitino LSP in cases (I-1) to (I-4) in Table 4 where positron fraction (top left), total \((e^+ + e^-)\) flux (top right), anti-proton flux (middle left), anti-proton to proton ratio (middle right), extra-Galactic \(\gamma\)-ray flux (bottom left), and the flux from inside and outside of the Galaxy (bottom right) are shown. In each panel, results with \(\gamma_p = 2.42\) (corresponding to case (I-1), (I-2), and (I-3), where gravitino mass is taken as \(m_{3/2} = 200\) GeV, 1 TeV, and 4 TeV, respectively) are shown in magenta lines from left to right, whereas blue line is used for those with \(\gamma_p = 2.52\) (corresponding to the case (I-4) where \(m_{3/2} = 200\) GeV is chosen). Signal from the decaying dark matter and astrophysical BG are depicted by dotted and dashed lines, respectively, while solid lines correspond to signal + BG.
with both the PAMELA and Fermi-LAT data are realized when $m_{3/2} \approx 200$ GeV. Such a possibility has not been explicitly described in previous works after the Fermi-LAT ($e^+ + e^-$) data was released. On the other hand, with larger gravitino mass, agreement with the PAMELA data becomes good but not with the Fermi-LAT data.

Concerning cosmic-ray proton and anti-proton, the $\bar{p}$ flux is shown in the middle left panel of Fig. 1. Here we take the same model parameters as in top two panels. Observational data by BESS [70], CAPRICE [71] and PAMELA [72] experiments are also shown in the panel. It can be seen that the signal from the decay of dark matter is smaller than background in most of the energy range, irrespective of the gravitino mass. However, if we compare the simulated result with the latest observation of the ratio between anti-proton and proton ($\bar{p}/p$) by the PAMELA experiment, the scenario turns out to be strongly constrained. On the middle right panel in Fig. 1 we plot the ratio, where observational data of the PAMELA experiment [72, 74] is also shown. From the figure, it can be seen that the ratio becomes significantly larger than the observed one if the gravitino mass is large. Even in the case of $m_{3/2} \approx 200$ GeV, the predicted ratio is slightly larger than the observation.

Here, we should recall that the BG proton flux depends on injection index and normalization of SNR nucleon spectrum, whose values are determined by fitting the observed flux of proton, B/C ratio, and so on. By taking account of the uncertainties of these observations, one can vary the values of injection index and normalization these parameters, which may relax the severe constraint. Let us take $\gamma^p = 2.52$ instead of $\gamma^p = 2.42$ above 4 GeV with the normalization being unchanged from the value adopted in the Conventional model. The result with this choice is summarized in Table 4 as the case (I-4), and $\bar{p}$ flux and $\bar{p}/p$ ratio are depicted in middle two panels of Fig. 1 (blue line). We calculated $\chi^2$ variable based on the $\bar{p}/p$ ratio given in the latest PAMELA data [72]. Then, we found $\chi^2_{\bar{p}/p} = 12.3$ (with the degree of freedom being 23), and hence the $\bar{p}/p$ ratio becomes consistent with

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\#10 This possibility in the framework of the decaying dark matter with a few hundred GeV mass was pointed out in the scenario where the dark matter decays dominantly into $\mu^+\mu^-$ pair [35].

\#11 Some people may think that the result seems to be inconsistent with the previous understanding about $\bar{p}$ from the hadronic decay. In fact, the flux simulated in the transport equation within the GALPROP code gives that between MED and MIN models proposed in Ref. [73].

\#12 By the explicit simulation of proton and B/C ratio, we have checked that their spectra are not affected by this change over 10 GeV. Less than 10 GeV, the flux is significantly affected by solar modulation. We thus ignore the flux under such low energy. Also, we have checked that the spectrum of $\gamma$-ray from pion decay is almost unchanged. See later discussion and Appendix.
the PAMELA observation at 95 % C.L. We also reevaluate positron fraction and total \((e^+ + e^-)\) flux taking \(\gamma^p = 2.52\) above 4 GeV. The results are also shown in top two panels in Fig. 1 (blue lines). One can see that the fluxes of \(e^\pm\) are almost unchanged. Therefore, \(p\) and \(\bar{p}\) fluxes in the decaying gravitino scenario can be in a reasonable agreement with the PAMELA data if \(m_{3/2} \sim 200\) GeV. On the contrary, when the gravitino mass is larger, the spectrum of \(\bar{p}/p\) becomes inconsistent with the observation of PAMELA.

We also simulate \(\gamma\)-ray flux, since it is inevitably produced from cosmic-ray \(e^\pm\) via IC and bremsstrahlung processes inside Galaxy as well as via IC process in extra-Galactic region. Furthermore, in the present case, \(\gamma\)-rays are also directly produced as a consequence of gravitino decay and following cascade decays. In the bottom left panel in Fig. 1, \(\gamma\)-ray from extra-Galactic region due to the decaying gravitino is given. Again, we take model parameters as in top two panels. Extra-Galactic \(\gamma\)-ray background (EGB) data given by EGRET [75] and Fermi-LAT [76] experiments are also shown. One can see that \(\gamma\)-ray flux from the decaying dark matter is expected to be smaller than the observed value when \(m_{3/2} \lesssim a\) few TeV. On the other hand, the flux becomes too large to be consistent with the observation in high energy region \(E_\gamma > 10\) GeV when \(m_{3/2} \sim 4\) TeV; in such an energy region, the \(\gamma\)-ray is mainly from the IC process of \(e^\pm\) produced by the decay of dark matter. The gravitino LSP in this scenario with \(m_{3/2} \gtrsim 4\) TeV is thus disfavored.

In addition to extra-Galactic \(\gamma\)-rays, we have simulated the contribution from the decaying gravitino LSP inside the Galaxy. Here, we have averaged IC-induced, bremsstrahlung-induced, and primary \(\gamma\)-ray in the region \(b > 10^\circ\) with \(b\) being Galactic latitude, and added them to the flux from extra-Galactic region to obtain the total flux from the gravitino LSP. (We have checked that the contribution from the bremsstrahlung process is subdominant.) The result is shown on the bottom right panel in Fig. 1 with the observational data of the Fermi-LAT experiment [76]. From the figure, one can see that the calculation leads to almost the same conclusion as that from the extra-Galactic \(\gamma\)-ray; both primary and IC-induced one are expected to be smaller than the observation as far as \(m_{3/2} \lesssim a\) few TeV. Therefore, by taking into account the constraints from anti-proton and \(\gamma\)-ray, we can conclude that the PAMELA anomaly can be solved with the unstable gravitino LSP with \(m_{3/2} \sim 200\) GeV without conflicting with other observations.

Next, we consider the case where the gravitino LSP decays into the second generation lepton. We have found the allowed region of 200 GeV \(\lesssim m_{3/2} \lesssim 500\) GeV and
Figure 2: Cosmic-rays from the decaying gravitino LSP in cases (I-5) – (I-8) in Table 4. Each panel shows cosmic-ray as the same way as in Fig. 1. Results with $\gamma_p = 2.42$ (corresponding to case (I-5), (I-6), and (I-7), where gravitino mass is taken as $m_{3/2} = 250$ GeV, 1 TeV, and 4 TeV, respectively) in magenta from left to right, and one with $\gamma_p = 2.52$ (corresponding to the case (I-8) where the mass is taken to be 250 GeV) in blue are shown.
$m_{3/2} \gtrsim 1$ TeV. Model parameters giving the best-fit results to cosmic-ray observations are summarized in Table 4 as the cases (I-5) to (I-8). The predicted cosmic-ray fluxes using the best-fit parameters are shown in Fig. 2. It can be seen that the positron fraction as well as the total $(e^+ + e^-)$ flux well agree with the results of PAMELA and Fermi-LAT experiments irrespective of the gravitino mass (top two panels). It is also found that the gravitino LSP with its mass over 1 TeV results in a better agreement with the Fermi-LAT data than the previous case.

As in the previous case, the observations of anti-proton flux give stringent constraint on the gravitino mass. In middle two panels in Fig. 2 we show the anti-proton flux and $\bar{p}/p$ ratio. The numerical result shows that large gravitino mass is disfavored from the observation of $\bar{p}/p$ at the PAMELA experiment. However, when the gravitino mass is small, the simulated $\bar{p}/p$ is consistent with the latest observation at 95% C.L.. (For $m_{3/2} = 250$ GeV, for example, we found $\chi^2_{\bar{p}/p} = 31.3$.) We also plot $\gamma$-rays in bottom two panels in Fig. 2, from which we see that the $\gamma$-ray flux becomes comparable to the observation when $m_{3/2} \sim 4$ TeV. This $\gamma$-ray is mainly the primary one directly produced by the decay of the gravitino LSP. The IC-induced $\gamma$-ray is not significant, because the primary $e^\pm$ produced by the gravitino LSP is softer than the previous case, so that the IC-induced $\gamma$-ray is suppressed. Therefore, we conclude that PAMELA anomaly can be solved in the present scenario for $200 \text{ GeV} \lesssim m_{3/2} \lesssim 500$ GeV.

### 3.3 Gravitino dark matter with tri-linear RPV

When the gravitino LSP decays mainly through the tri-linear RPV operator given in Eq. (2.13), the final state of the decay is composed of only (three) leptons. In such a case, constraints from anti-proton flux as well as the ratio between anti-proton and proton are irrelevant in the study of the decaying dark matter scenario.

With the $\chi^2$-analysis, we have found the region consistent with $e^\pm$ observations at 95% C.L. in $200 \text{ GeV} \lesssim m_{3/2} \lesssim 400$ GeV and $1 \text{ TeV} \lesssim m_{3/2} \lesssim 3$ TeV. (In the numerical calculation, we take $m_{\tilde{l}_R} = 1.2 m_{3/2}$.) The model parameters for the best-fit results are again summarized in Table 4 as cases (II-1) to (II-3), and simulated results for cosmic-ray $e^\pm$ and $\gamma$-rays are shown in Fig. 3. In upper two panels, positron fraction and total $(e^+ + e^-)$ flux are shown. Here, we consider the case where the component $\lambda_{123}$ is dominant compared to others. It can be seen that the fitting to the Fermi-LAT data becomes worse in the large $m_{3/2}$ region though it
Figure 3: Cosmic-rays from the decaying gravitino LSP in the cases (II-1) to (II-3) in Table 4, where positron fraction (upper left), total $(e^+ + e^-)$ flux (upper right), extra-Galactic $\gamma$-ray flux (lower left), and the flux from inside and outside of the Galaxy (lower right) are shown. Line type is assigned as the same as in Fig. 1, i.e., signal from the decaying dark matter and astrophysical BG are depicted by dotted and dashed lines, respectively, while solid lines correspond to signal + BG. In each panel, numerical results correspond to (II-1), (II-2), and (II-3) from left to right (bottom to top in lower left panel), where gravitino mass are taken as $m_{3/2} = 250$ GeV, 1 TeV, and 4 TeV, respectively.
is possible to explain the PAMELA data well.

We have calculated $\gamma$-ray flux. Here, we consider the case in which $\lambda_{123}$ is the only relevant RPV parameter, so we also calculate primary $\gamma$-ray flux from the decay of $\tau$, along with the one from the IC process. The results are shown in lower two panels in Fig. 3: the left one is extra-Galactic contribution and the right one is extra- plus inner-Galactic contribution. For the extra-Galactic one, the simulated flux is much smaller than the observation unless $m_{3/2} \gtrsim 4$ TeV. The observation of total $\gamma$-ray (for $b > 10^\circ$) gives almost the same upper bound on the mass. As a consequence, the parameter region favored by the observation of $e^\pm$ (i.e., $200$ GeV $\lesssim m_{3/2} \lesssim 400$ GeV and $1$ TeV $\lesssim m_{3/2} \lesssim 3$ TeV) are not excluded by the $\gamma$-ray observation at the Fermi-LAT experiment. It can be also seen that the total $\gamma$-ray flux at high energy region is noticeable when $m_{3/2} \gtrsim 4$ TeV. This intense flux comes from the decay of $\tau$.

In addition to the case where the component $\lambda_{123}$ dominates, we have also considered the case in which only $\lambda_{121}$ or $\lambda_{122}$ is relevant. In the former case, however, injected $e^\pm$ is too hard to be consistent with observations at 95% C.L. in the entire range of $m_{3/2}$. On the other hand, in the latter case, the same conclusion as in the case $\lambda_{123}$ dominates holds except that the allowed region at the TeV scale disappears because the predicted total ($e^+ + e^-$) flux hardly agrees with the Fermi result.

### 3.4 Sneutrino dark matter with tri-linear RPV

So far, we have discussed the gravitino LSP cases. However, there are other candidates for LSP. In particular, as we have mentioned, the sneutrino LSP may provide decay modes different from the gravitino LSP. In particular, with the superpotential given in Eq. (2.13), the sneutrino LSP may decay into two charged leptons. We then expect different cosmic-ray spectra from those of the gravitino LSP. In this subsection, we briefly comment on the behaviors of cosmic-ray fluxes in the sneutrino dark matter scenario with tri-linear RPV. The important effects are on $e^\pm$ and $\gamma$-ray fluxes, but not on anti-proton flux.

In Fig. 4, we show the positron fraction (upper left) and the total ($e^+ + e^-$) flux (upper right) for the case where the sneutrino dominantly decays through the process $\tilde{\nu} \rightarrow \mu^+ \mu^-$. The parameters to give those results are summarized in Table 4 as cases (III-1) to (III-3).

In those cases, there is no $\gamma$-ray primarily produced by the decay.
Figure 4: Cosmic-rays from the decaying sneutrino LSP in the cases (III-1) to (III-3) in Table 4. The panel position and line contents are the same as in Fig. 3. In each panel, lines from left to right (bottom to top in lower left panel) correspond to the case (III-1), (III-2), and (III-3), where sneutrino mass is taken as $m_{\tilde{\nu}} = 400 \text{ GeV}, 1 \text{ TeV},$ and $4 \text{ TeV}$, respectively.
With the use of the $\chi^2_e$-analysis, we have found 95% C.L. allowed region in $300 \text{ GeV} \lesssim m_{\tilde{\nu}} \lesssim 500 \text{ GeV}$, with neglecting the possible systematic error from the energy calibration in the Fermi-LAT data. For $m_{\tilde{\nu}} \gtrsim 500 \text{ GeV}$, the total flux becomes inconsistent with Fermi-LAT data, while positron fraction still agrees with the PAMELA data. If we take account of the effect of systematic error in Fermi-LAT data, the allowed region may become larger; in particular, adopting the 10% reduction of the energy, the region $1 \text{ TeV} \lesssim m_{\tilde{\nu}} \lesssim 3 \text{ TeV}$ becomes allowed at 95% C.L. This result is consistent with [35]. We also give $\gamma$-ray flux in Fig. 4. The only relevant process to produce $\gamma$-ray here is the IC scattering. In the figure, IC-induced $\gamma$-ray from extra-Galactic region (inner-plus extra-Galactic region) is given lower left (right) panel. Although the flux is less than the observed data in $b > 10^\circ$, IC-induced $\gamma$-ray in the extra-Galactic region becomes comparable to or larger than the data when $m_{\tilde{\nu}} \gtrsim 4 \text{ TeV}$. This is the same result obtained in the previous three-body decay case. We thus conclude that the parameter region $300 \text{ GeV} \lesssim m_{\tilde{\nu}} \lesssim 500 \text{ GeV}$ gives good fit with PAMELA and Fermi-LAT ($e^+ + e^-$) data and the region is not constrained by $\gamma$-ray observation.

We have also considered the decaying scenario of $\tilde{\nu} \rightarrow e^+ e^-$. In such a case, however, we could not find the allowed region. This is because the monochromatic electron and positron gives very sharp edge in the flux so that the flux does not agree with the data of ($e^+ + e^-$) flux though the fit with the PAMELA data is good.

4 Conclusion

In this article, we have calculated cosmic-ray fluxes from decaying dark matter as well as background in the same propagation model by using GALPROP. Aiming for explaining the PAMELA anomaly with being consistent with other cosmic-ray observations, we have reevaluated the background cosmic-ray fluxes. Cosmic-rays from decaying dark matter, on the other hand, is strongly dependent on the spectra of final-state particles. If one specifies the distributions of final-state particles, the cosmic-ray spectra are determined independently of detailed framework of the model of decaying dark matter.

To make our discussion concrete, we have studied gravitino dark matter in $R$-
parity violated supersymmetric model. Under $R$-parity violation, gravitino dominantly decays to $Wl_i$ in bi-linear RPV, while it decays to $\nu_l^+ l_j^-$ in tri-linear one. In the former scenario, we have found that the simulated cosmic-ray $e^\pm$ flux from dark matter and background agrees with the PAMELA and Fermi-LAT data, irrespective of gravitino mass. However, it has been shown that the production of cosmic-ray $\bar{p}$ becomes enhanced when the mass is large; thus the gravitino mass larger than $\sim 300$ GeV is disfavored. For $\gamma$-ray, the flux is consistent with the observation as far as $m_{3/2} \lesssim 4$ TeV. In the latter case, it has been found that the PAMELA anomaly can be explained in the mass region $200$ GeV $\lesssim m_{3/2} \lesssim 400$ GeV or $1$ TeV $\lesssim m_{3/2} \lesssim 3$ TeV, being consistent with Fermi-LAT data. When the mass is larger than $\sim 4$ TeV, the fit with each data becomes worse. In addition, IC-induced $\gamma$-ray constrain such large mass region.

We have also considered the case where sneutrino is the LSP, assuming that it decays into lepton pair via tri-linear RPV interaction. We have seen that, when the dominant decay mode is $\tilde{\nu} \to \mu^+ \mu^-$, the positron fraction can be in a good agreement with the PAMELA data without conflicting the Fermi result when $300$ GeV $\lesssim m_{\tilde{\nu}} \lesssim 500$ GeV. With such a choice of the sneutrino mass, $\gamma$-ray flux induced by the dark matter decay is much smaller than the observed one. In addition, in this case, it should be noted that the constraint from anti-proton flux is irrelevant because hadrons are hardly produced by the decay of $\tilde{\nu}$.

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A Background Cosmic-Rays

We consider background cosmic-rays predicted in the Conventional model, except for taking $\gamma_p = 2.52$ (instead of 2.42) above 4 GeV. The main purpose in this appendix is to show that the change of $\gamma_p$ does not significantly affect background cosmic-ray fluxes, and that such a choice is consistent with observations. Cosmic-ray $p$ flux and the B/C ratio are shown in Fig. 5, where simulated results are depicted with a blue line. The results with $\gamma_p = 2.42$ above 4 GeV are also shown for comparison with a magenta line. For the $p$ flux shown in the left panel of the figure, it can be seen that the spectrum with $\gamma_p = 2.52$ becomes slightly softer than that with $\gamma_p = 2.42$ as expected, and both spectra are well consistent with observations.

On the other hand, the B/C ratio is expected to be hardly changed. This is because the fluxes of B and C are mostly determined by the secondary and primary fluxes from SNR and hence the B/C ratio depends strongly on diffusion parameters but is insensitive to SNR spectra. In fact, as shown in the right panel of Fig. 5, there is no difference between $\gamma_p = 2.42$ and 2.52 cases, which are consistent with observations. The intensity in $E \lesssim 1$ GeV is larger than the one appeared in Ref. [42]. This is due to the different choice of solar modulation potential; we take $\phi = 550$ MV, whereas $\phi = 450$ MV is chosen in Ref. [42].

#15In the region $E \lesssim 10$ GeV, the flux with $\gamma_p = 2.52$ seems to slightly exceed the observations, it can be, however, optimized by choosing a proper normalization of the SNR $p$ flux. Moreover, in this region, the flux is affected by the effect of solar modulation, which leads to further uncertainties.
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