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The electron spectrum from annihilation of Kaluza-Klein dark matter in the Galactic halo

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The Kaluza-Klein (KK) particles, which are the feasible candidate for the dark matter, produce electrons and positrons when they annihilate in the Galactic halo. When the electrons and positrons propagate in the Universe, their directions are randomized by the Galactic magnetic field, and their energies are reduced by some energy loss mechanisms. We calculate the electron and positron spectrum expected from KK particle annihilation to be observed at Earth, taking account of propagation effects in the Galaxy. We assume the lightest KK particle (LKP) in the mass range from 500 GeV to 1000 GeV is the dark matter consisting of the Galactic halo, and we treat the particle spectra from LKP annihilation which include electron–positron component from two–body decays and "continuum" emission. We calculate the effect of diffusion and energy loss in the Galaxy, and analyze the resulting spectra. These spectra strongly depend on the LKP mass and will be compared with recent observational data taking account of energy resolution of detectors. We can set some constraints for the boost factor of dark matter concentration in the Galactic halo, taking account of the recent results on positron fraction measurements based on our calculation.

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1. Introduction

The fact that the most of the matter in the Universe consists of non–baryonic dark matter is supported further by the Planck observational data [1]. Thus, dark matter should be made of particles which do not exist in standard model of particle physics. We employ the theory of universal extra dimension (UED), and we assume the lightest Kaluza–Klein particle (LKP), which appears in UED, is a good candidate for non–baryonic dark matter. In the UED, the extra dimension is compactified with radius R, and the LKP mass, which we denote as $m_{B^{(1)}}$, is inversely proportional to R. The relevant mass for the LKP ranges from a few 100 GeV to 1 TeV, if we assume the LKP contributes significantly to cold dark matter. We vary the LKP mass from 300 GeV to 1 TeV in 100 GeV intervals, and we analyze the electron–positron spectrum from LKP annihilation.

Cheng *et al*. [2] predicted that the electron–positron spectrum from annihilation of LKP would show a characteristic edge structure near the LKP mass. The edge structure was calculated in Ref. [3] for Fermi–LAT detection, but, at least in the energy range below 300 GeV, such structure has not established so far. On the other hand, above 300 GeV, the observational data is still limited, so the characteristic structure could be observed in near–future mission. For example, the Calorimetric Electron Telescope (CALET), which is a Japanese–led detector and is a fine resolution calorimeter for cosmic–ray observation to be installed on the International Space Station in August 2015, will explore the energy range up to 20 TeV.

When LKP pairs annihilate, there are some modes which produce electrons and positrons as final products, and we categorize them into two components. One of them is a "line" component, which gives rise to edge structure near the LKP mass and consists of electron–positron pairs directly produced by annihilation. Another one is a "continuum" component, which consists of secondary–produced electrons and positrons by annihilation via muon pairs, tauon pairs, quark pairs, and gauge bosons. We adopt the spectrum of continuum emission given in Ref. [4]. In Ref. [4], the LKP mass $m_{B^{(1)}}$ is assumed to be 300 GeV, so we scaled it to various masses, and calculated the spectrum for each components. The results of the calculation are shown in Fig.1, where each line indicates the positron spectrum from muon pairs (dashed line), tauon pairs (dotted line), quark pairs (dot–dashed line), gauge bosons (dot–dot–dashed line), and total continuum emission (solid line), respectively. Note that here the continuum emission via quark pairs includes the effect from bottom quark pairs ($b\bar{b}$), but we should take account of the effects from other type quarks. More detailed discussion will be given in the forthcoming paper.

The continuum spectra shown in Fig.1 are those just after the pair annihilation, and we have to take account of the effects of propagation in the Galactic halo, such as diffusion and energy loss processes. For this purpose, we follow the Green function approach given in Ref. [5], assuming the "Isothermal model" as the halo profile. In addition, we should include the "boost factor" B_f, which enhances the signal from dark matter annihilation in the Galactic halo. N–body simulation study given in Ref. [6], for example, indicates the value of B_f could be large.

In this paper, we consider the total positron plus electron spectrum from LKP annihilation including the effects of propagation. Then, we calculate the positron fraction containing flux from LKP annihilation and compare the results with recent measurements. Then, we derive the constraints on the boost factor.

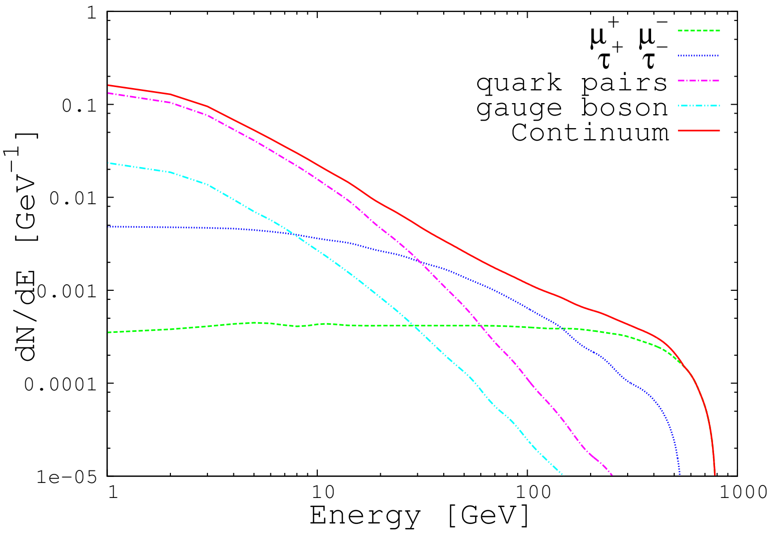

Figure 1: (Color Online). The "continuum" positron spectrum from LKP annihilations for $m_{B^{(1)}} = 800$ GeV. The dashed, dotted, dot–dashed, dot–dot–dashed, and solid lines correspond to the positron spectrum per annihilation via muon pairs, tauon pairs, quark pairs, gauge bosons, and total continuum emission, respectively.

2. The effect of propagation

Charged particles, such as electrons and positrons, produced by LKP annihilation change their direction randomly by the irregular component of the Galactic magnetic field, and lose their energies by bremsstrahlung in the interstellar matter. Thus, the observational positron fluxes have different shapes from initial ones. The effects of propagation is studied by Moskalenko & Strong [5], We calculate the modulated flux by using their results given as Green functions.

The differential positron flux is taken from Ref. [7], and the slightly modified expression is written as

$$\begin{aligned}\frac{d\Phi_{e^+}}{d\Omega dE} = & \; 2.7\times 10^{-4} B_f \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{GeV}^{-1} \\ & \times B\frac{\langle\sigma v\rangle}{\text{pb}}\left(\frac{\rho_0}{0.3\text{ GeV/cm}^3}\right)^2\left(\frac{1000\text{ GeV}}{m_{B^{(1)}}}\right)^2 g\left(1,\frac{E}{m_{B^{(1)}}}\right)\end{aligned} \tag{2.1}$$

where B means branching ratios for each particles, and ρ_0 is a local dark matter density. The annihilation cross section $\langle\sigma v\rangle$ is given as [2]

$$\langle\sigma v\rangle = \frac{e^4}{9\pi\cos^4\theta_w}\left[\frac{Y^4_{e_L^{(1)}}}{m^2_{B^{(!)}} + m^2_{e_L^{(1)}}} + (L\to R)\right], \tag{2.2}$$

where θ_w is the Weinberg angle, $Y_{e_L^{(1)}}$ is a hypercharge for first excited mode for left–handed electron. The value of $\langle\sigma v\rangle$ is approximately $2\times 10^{-32}\,(1\text{ GeV}/m_{B^{(1)}})^2$ cm^2, and we define the boost factor relative to this cross section and $\rho_0 = 0.43$ GeV/cm^3 for Isothermal model. The Green's function g is defined as

$$g\left(1,\frac{E}{m_{B^{(1)}}}\right) = 10^{a(\log_{10}E)^2+b(\log_{10}E)+c}\,\theta\left(m_{B^{(1)}} - E\right)\times\frac{1}{E^2} \tag{2.3}$$

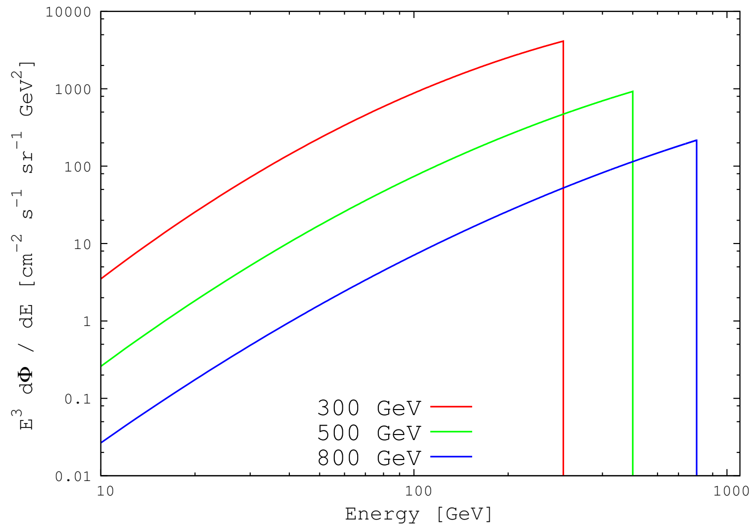

Figure 2: (Color Online). The "line" spectrum of electrons and positrons from LKP annihilation including the effect of propagation for three LKP masses. We assume the boost factor $B_f = 1$.

The parameters a, b and c are given in Ref. [5], and these parameters determine the spectra of electron and positron after propagation.

The line component is in the form of δ–function before propagation in the Galactic halo. After propagation the line spectrum extends to lower energy regions caused by the effects of diffusion and energy loss processes. The resulting spectrum is shown in Fig.2.

In addition to the line component, we also calculate the continuum component. The continuum component has a broad spectrum extending to lower energies when it is produced by LKP annihilation as shown in Fig.1. Then we calculated the spectrum after propagation using the Green's function similarly to the case of the line component. The result is shown in Fig.3, where the dashed lines show the spectra for the line component only, and the solid lines show the total flux from LKP annihilation (continuum plus line) for three LKP masses. This figure indicates the continuum component is dominant in lower energies, and it is larger by two orders of magnitude around 10 GeV.

3. Discussion

Now, we discuss the electron and positron fluxes from LKP annihilation taking the measured positron fraction into account to derive the allowed value of the boost factor. Figure 4 shows the positron fraction given by recent measurements [8, 9, 10] with a prediction by the diffusion model [11].

We derive the LKP flux, F_{LKP}, which fits the measured positron fraction assuming the 'conventional" electron and positron flux in the differential form, F_{Conv}, as given in Ref. [12]. The LKP pair annihilation creates the same number of electrons and positrons, so the positron fraction of the LKP flux always equals to 0.5, and we denote it as f_{LKP}. On the other hand, the positron fraction for conventional flux calculated by the diffusion model [11] is < 0.1, depending on energy, and it

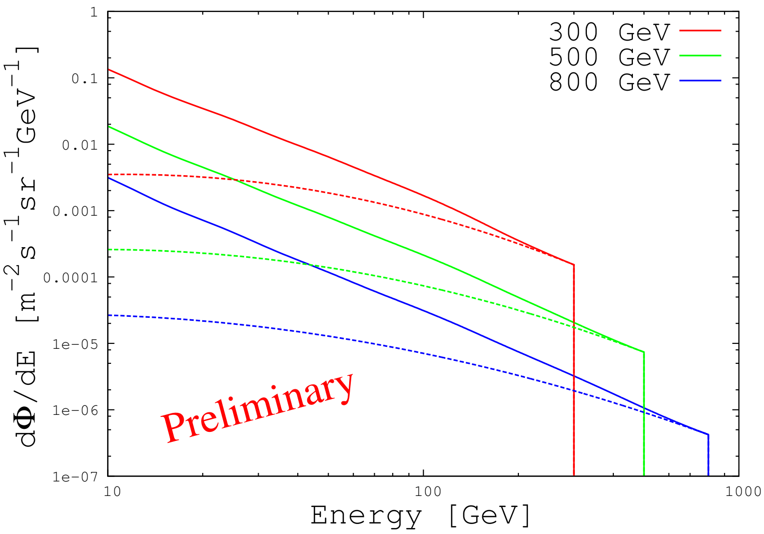

Figure 3: (Color Online). The electron and positron flux from LKP annihilation. The solid lines show the flux of "continuum" plus "line" components, and the dashed lines show the flux of only "line" components for each LKP mass, respectively. We assume the boost factor $B_f = 1$.

is denoted as f_{Conv}. Then, the total positron fraction is given as following expression;

$$\text{Positron Fraction} = \frac{F_{\text{LKP}} \times B_f \times f_{\text{LKP}} + F_{\text{Conv}} \times f_{\text{Conv}}}{F_{\text{LKP}} \times B_f + F_{\text{Conv}}} \tag{3.1}$$

where the B_f is the boost factor. With this prescription, we calculate the positron fractions for several LKP masses, to fit the AMS–02 data [10] at 100 GeV, and the positron fractions are shown in Fig.4. The values of boost factor thus determined for each LKP mass are shown in Fig.5,

With the derived boost factors from the positron fraction, we compare the expected electron plus positron spectra, $E^3 \times (F_{\text{LKP}} + F_{\text{Conv}})$, with recent observational data shown in Fig.6. This figure indicates that light LKP, such as $m_{B^{(1)}} = 300$ GeV, is not compatible with measurements as the dominant component of the Galactic halo dark matter.

4. Conclusion

Electron and positron spectra from LKP annihilation have been calculated taking account of propagation effects in the Galaxy. We paid particular attention to the calculation of the "continuum" emission, which is a secondary product of LKP annihilation. The result shown in Fig.3 indicates the "continuum" component dominates over the "line" component in the low energy region after propagation in the Galactic halo.

We estimated the constraint for the boost factor by using the positron fraction measurement by AMS–02. The result implies the boost factor should be in the range from about 0.02 to 2.5, depending on the LKP mass, assuming $\langle \sigma v \rangle \cong 2 \times 10^{-32} \, (1 \text{ GeV}/m_{B^{(1)}})^2$ cm^2. We use these values to compare the flux from LKP annihilation with recent observational electron plus positron data such as AMS–02, indicating the light LKP, such as $m_{B^{(1)}} = 300$ GeV, may be excluded. The details concerning with this topic will be discussed in the forthcoming paper.

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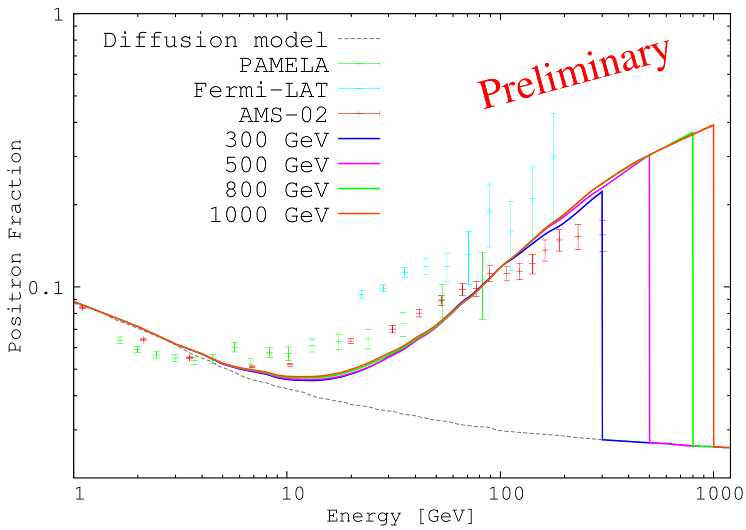

Figure 4: (Color Online). The positron fraction with LKP compared with recent measurements [8, 9, 10], and diffusion model [11].

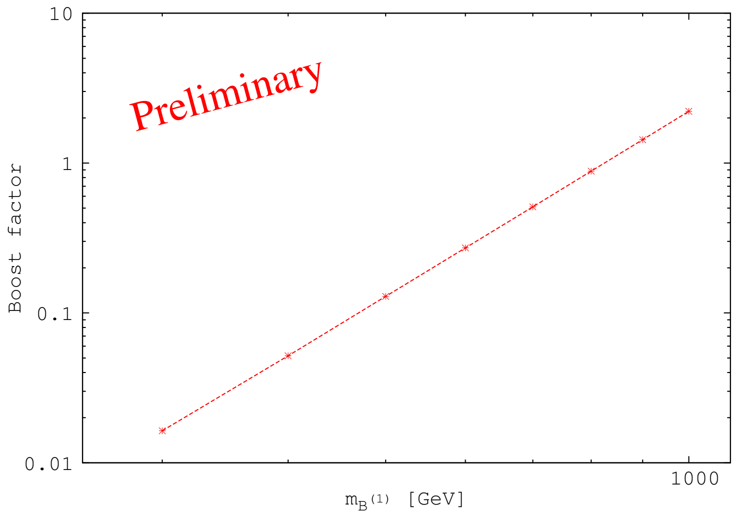

Figure 5: (Color Online). The boost factor for each LKP mass derived from the fit to the positron fraction of the AMS–02 data at 100 GeV. Here we assume $\langle \sigma v \rangle \cong 2 \times 10^{-32} \left(1 \text{ GeV}/m_{B^{(1)}}\right)^2$ cm^2.

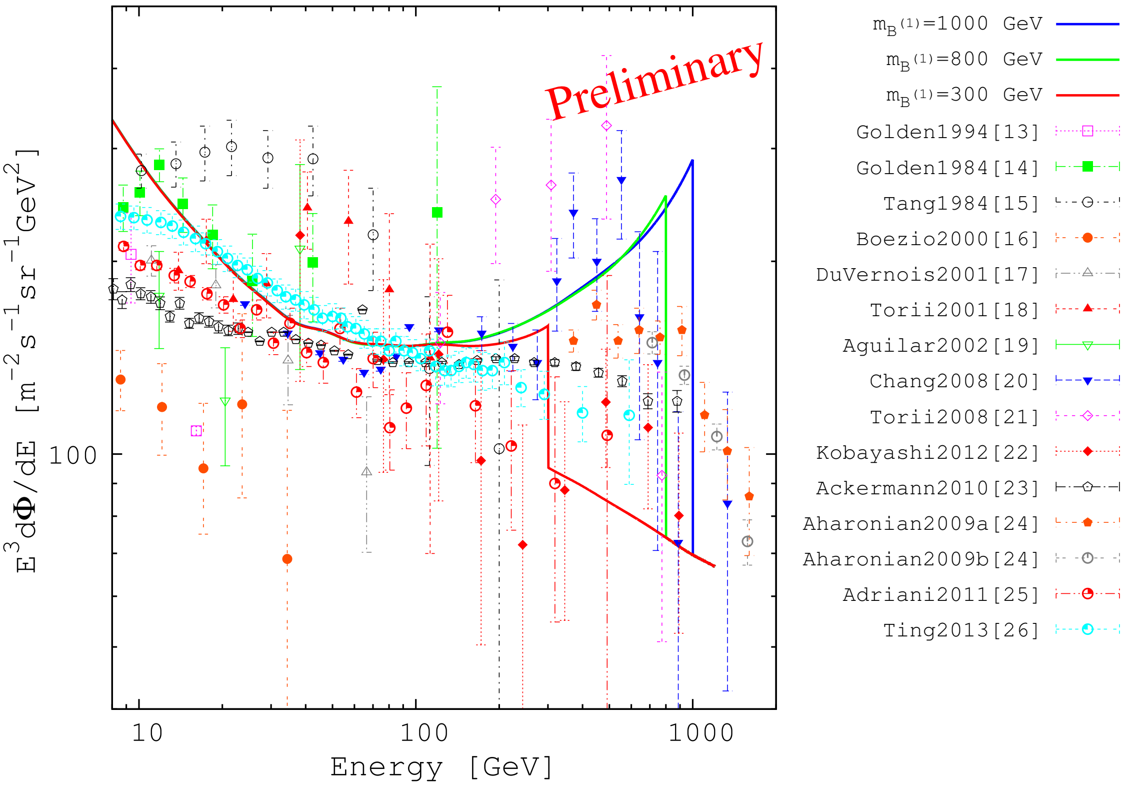

Figure 6: (Color Online). The electron plus positron spectra of $F_{\mathrm{LKP}} + F_{\mathrm{Conv}}$ for each LKP mass compared with recent observational data [13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26] .