Observability of gamma-ray spectral feature from Kaluza-Klein dark matter

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Abstract. The theory of universal extra dimensions involves Kaluza-Klein (KK) particles. The lightest KK particle (LKP) is one of the good candidates for cold dark matter. Annihilation of LKP dark matter in the Galactic halo produces high-energy gamma-rays. The gamma-ray spectrum shows a characteristic peak structure around the LKP mass. This paper investigates the observability of this peak structure by present and near-future detectors taking account of their energy resolution, and calculates the expected count spectrum of the gamma-ray signal. Then, the maximum likelihood analysis is employed to judge whether the count spectrum contains the LKP signal. In the case where the signal is not detected, we set some constraints on the boost factor which is a product of the annihilation cross section relative to the thermal one and an uncertain factor dependent on the substructure of the LKP distribution in the Galactic halo. The constraints can be regarded as comparable with the results of analysis based on the HESS data. The observational data for the TeV or higher energy region are still limited, and the possible LKP signal is not conclusive. Thus, we expect near-future missions with better sensitivity will clarify whether the LKP dark matter should exist or not.

INTRODUCTION

The lightest Kaluza-Klein particle (LKP), which appears in the theory of universal extra dimensions [1], is one of the good candidates for cold dark matter. We assume the LKP (the first KK mode of the hypercharge gauge boson, denoted by $B^{(1)}$) mass, $m_{B^{(1)}}$, is in the range from 500 GeV to 1000 GeV, and focus on the LKP annihilation modes which contain gamma-rays as final products.

In this paper, we analyze the gamma-ray spectral features from $B^{(1)}$ pair annihilation in the Galactic halo taking account of the finite energy resolution of gamma-ray detector, and purposefully discuss the observability of the "line" at the $m_{B^{(1)}}$. We then give possible constraints on the boost factor, which describes extra concentration of dark matter in the Galactic halo, by present and near-future detectors.

The gamma-ray spectrum from LKP annihilation has two components [2, 3, 4, 5, 6]:

1. A characteristic peak structure near the LKP mass ("line") from two-body decays.
2. Continuum emission extending to lower energies via (i) quark pairs and (ii) charged lepton pairs which cascade or produce gamma-rays, or (iii) two leptons and one photon ($l^+l^-\gamma$) [Figure 1].

The gamma-ray flux from annihilation of dark matter particles of mass M in the Galactic halo can be expressed as [3]:

$$\Phi(E_\gamma,\psi) = \frac{\langle\sigma v\rangle}{8\pi M^2}\sum_i B_i \frac{\mathrm{d}N_\gamma{}^i}{\mathrm{d}E_\gamma}\int_{\text{line-of-sight}}\rho^2(l)\,\mathrm{d}l(\psi)$$

where ψ is the angle with respect to the Galactic center, $\langle\sigma v\rangle$ is a thermal average of annihilation cross section times relative velocity, B_i is a branching ratio into a mode i producing gamma rays, $\mathrm{d}N_\gamma{}^i/\mathrm{d}E_\gamma$ is a gamma-ray spectrum of mode i, ρ is the dark matter density and the integration is along the line of sight, $l(\psi)$. We define the boost factor

$$B_f = B_\rho \times B_{\sigma v} = \left(\frac{\langle\rho^2(l)\rangle_{\Delta V}}{\langle\rho_0^2(l)\rangle_{\Delta V}}\right)\left(\frac{\langle\sigma v\rangle}{3\times 10^{-26}\ \mathrm{cm^3 s^{-1}}}\right)_{\Delta V}$$

in order to include possible extra concentration of dark matter in the Galactic halo.

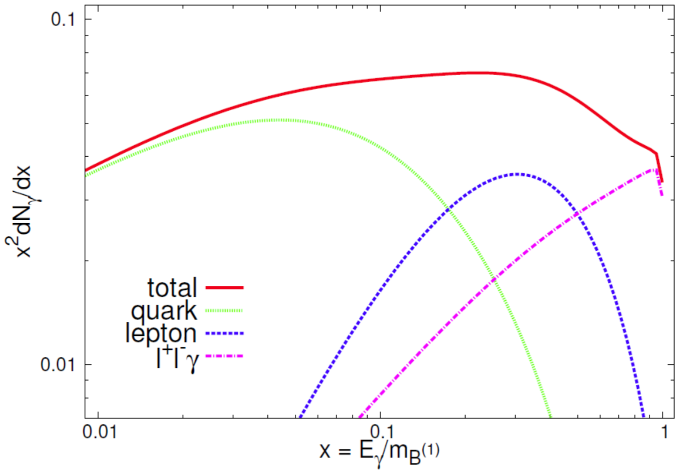

FIGURE 1. Gamma-ray spectra of the continuum emission. The lines show the number of photons multiplied by $x^2 = (E/m_{B^{(1)}})^2$ as follows: the solid line shows the total number of photons per $B^{(1)}B^{(1)}$ annihilation, the dotted line shows the number via quark fragmentation, the dashed line shows the number via lepton fragmentation, and the dot-dashed line shows the number from the $l^+l^-\gamma$ component. We have assumed $m_{B^{(1)}} = 800$ GeV and mass splitting is 5% at the first KK level.

EFFECT OF ENERGY RESOLUTION

Line shape degradation

If the measured energy dispersion for mono-energetic gamma-rays behaves as a Gaussian distribution and the energy resolution of the detector (σ_E) is finite, the measured gamma-ray spectrum is blurred as

$$g(E) \propto \int f(E') \times \exp\left[-\frac{(E-E')}{2\sigma_E^2}\right] \mathrm{d}E'.$$

Examples of the resulting spectra are shown in Figure 2.

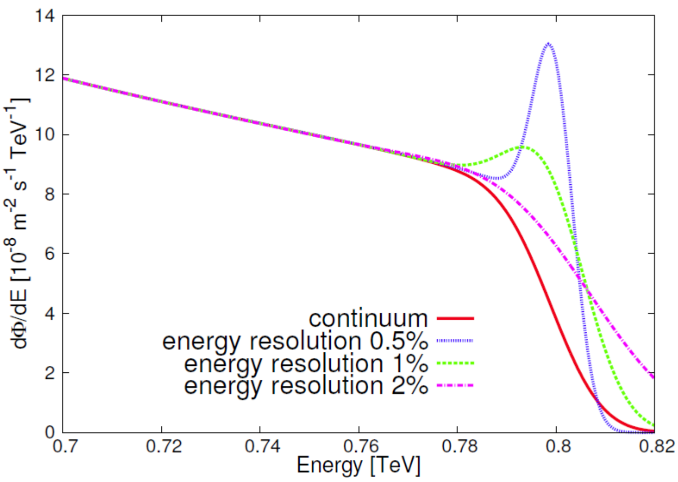

FIGURE 2. Gamma-ray spectra of continuum plus line diffused by the energy resolution assuming $m_{B^{(1)}} = 800$ GeV. The solid line shows the continuum component only, assuming the energy resolution of 1%, while the dotted, dashed and dot-dashed lines show the continuum plus ine components assuming energy resolution values of 0.5%, 1% and 2%, respectively. The assumed boost factor is 100.

Line fraction

Line fraction, LF, is defined as

$$LF = \frac{\sum_i F_i^l}{\sum_i F_i^c}$$

and is shown in Figure 3, where F_i^c , F_i^l are the fluxes of the continuum component and the line component of the i-th energy bin, respectively, with the energy bin of 0.5 GeV width.

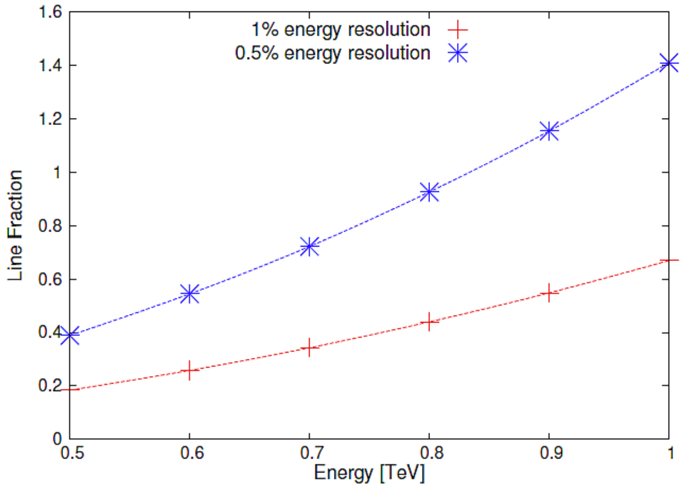

FIGURE 3. The line fraction as a functions of $m_{B^{(1)}}$, assuming an energy resolution of 0.5% and 1%. The dashed curves are drawn to guide to the eyes.

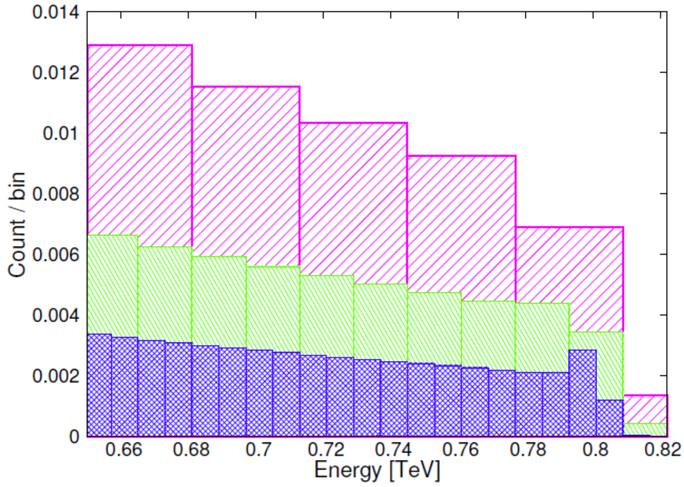

FIGURE 4. Expected count spectra, assuming energy resolutions of 0.5%, 1% and 2%, and 3×10^6 m^{2}s exposure, and $m_{B^{(1)}}$ = 800 GeV. The data spaces are twice as much as 0.5%, 1% and 2% of $m_{B^{(1)}}$. The assumed boost factor is 100.

Gamma-ray count spectrum

Count spectra assuming CALET [7]-type observation, assuming exposure of 3×10^6 m^{2}s (1 year $\times$ 0.1 m^2), are shown in Figure 4 for $m_{B^{(1)}}$ = 800 GeV case. Bin widths of twice as much as 0.5%, 1% and 2% of $m_{B^{(1)}}$ (about one standard deviation of energy reconstruction) to match the each energy resolution. Figure 5 is the similar plot to show the mass dependence for $m_{B^{(1)}} = 500, 600, \ldots, 1000$ GeV.

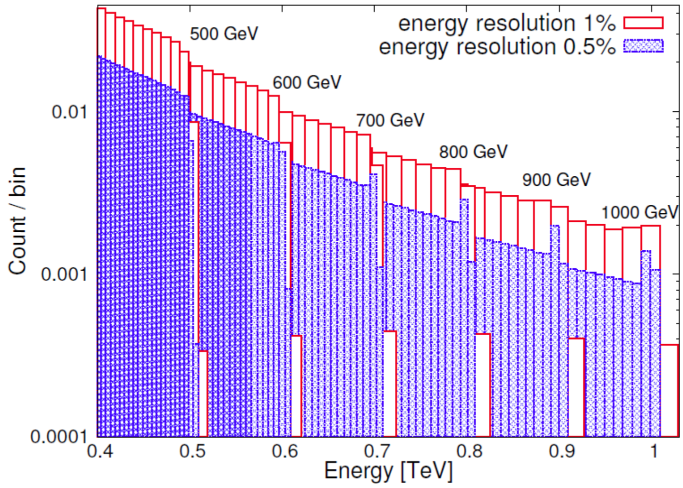

FIGURE 5. Expected count spectra, assuming energy resolutions of 0.5% and 1%, and 3×10^6 m^{2}s exposure. The data spaces are twice as much as 0.5% and 1% of $m_{B^{(1)}}$. The assumed boost factor is 100.

DISCUSSION

Gamma-ray flux from the Galactic center, Sgr A*

We check possible LKP signal using the H.E.S.S. measurement of the gamma-ray spectrum of the Galactic center, Sgr A* (> 200 GeV) [8]. Because of the limited energy resolution of HESS using the atmospheric Cherenkov technique (15–20%), the line structure will be blurred. Here we investigate the upper limit on the boost factor based on this result.

Upper limit on boost factor from HESS data

A simple model spectrum for the background plus signal

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{d\Phi_\gamma^{\mathrm{Bkgd}}}{dE_\gamma} + B_f \frac{d\Phi_\gamma^{\mathrm{LKP}}}{dE_\gamma}$$

where the background spectrum of the power-law plus exponential cut-off

$$\frac{d\Phi_\gamma^{\mathrm{Bkgd}}}{dE_\gamma} = C_B \left(\frac{E_\gamma}{\mathrm{TeV}}\right)^{\Gamma_B} \exp\left[-\frac{E_\gamma}{15.7\,\mathrm{TeV}}\right] \times 10^{-8}\,\mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{TeV}^{-1}$$

is assumed (we adopt the exponential cut-off given by HESS [8]), and χ^2-value between the model and the data are calculated which gives a maximally allowed value of the boost factor, B_f, at 99% confidence level by varying a normalization, C_B, and a power-law index, Γ_B. The results are shown in Table 1 and are plotted in Figure 6.

Upper limit on boost factor from CALET-type observation

The energy resolution of CALET which directly observe gamma-rays in space is much better then atmospheric Cherenkov telescopes, but since the detection area is much smaller and the event statistics is limited, we have to use the Poisson statistics. The likelihood method [9] was applied for the simulated observations (3×10^6 cm^{2}s) and

TABLE 1. The model parameter sets with upper limits on the boost factor at 99% confidence level.

$m_{B^{(1)}}$ (GeV)	C_B	Γ_B	Boost factor
500	2.30	-2.00	4
600	2.30	-2.00	7
700	2.25	-1.95	10
800	2.25	-1.95	15
900	2.25	-1.95	20
1000	2.25	-1.95	26

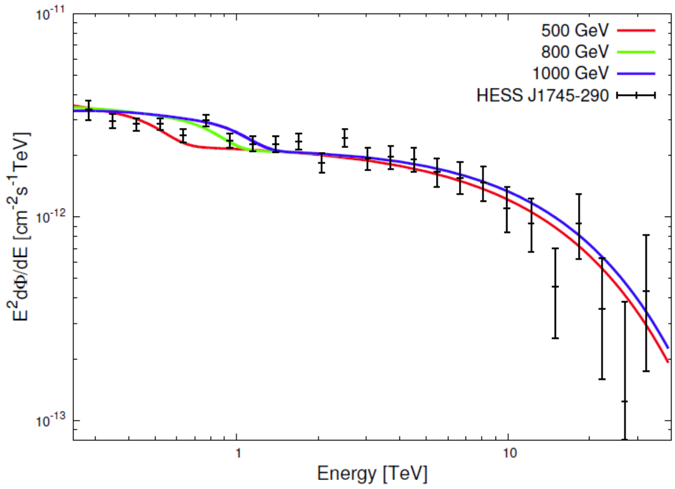

FIGURE 6. Comparison the LKP signal plus background fluxes assuming the model parameters given in Table 1 and HESS observational data assuming 20% energy resolution.

LKP spectra to test the observability. The results is shown in Figure 7 which is plotted against N, the number of energy bins to be analyzed between the lower threshold energy and the maximum, which we assume ($m_{B^{(1)}} + 3\sigma_E$), divided by energy resolution (σ_E). Details of this analysis will be presented elsewhere [10].

CONCLUSION

Energy resolution plays a key role in detecting the line structure of the gamma-ray spectral features expected from annihilation of LKP dark matter as predicted by UED theories. The characteristic peak indicating $m_{B^{(1)}}$ would be diffused if the energy resolution is 2% or worse.

Upper limits on the boost factor of 4 to 26, depending on $m_{B^{(1)}}$ from 500 to 1000 GeV, to account the possible concentration of dark matter in the Galactic halo have been calculated as a function of assuming a simple background spectrum with a power-law based on the HESS observation.

The accessible range of the boost factor was investigated using a maximum likelihood analysis. Assuming the detector having effective area of 1000 cm^2 like CALET or DAMPE [11], if the signal is not detected in 10 years observation, the upper limit of the factor is the order of 10^4 for $m_{B^{(1)}} = 800$ GeV if we only take data near the peak into account.

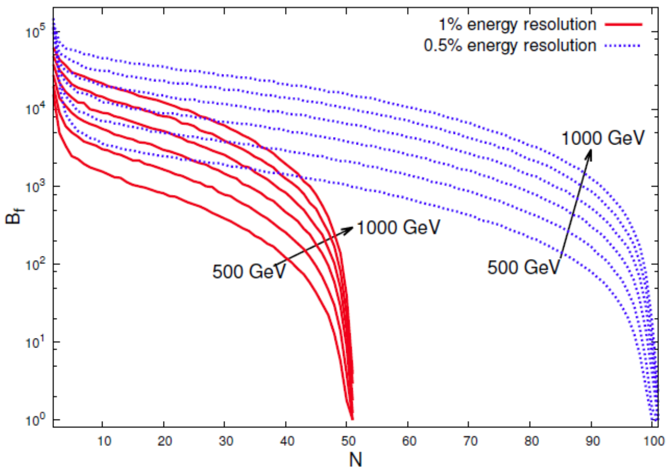

FIGURE 7. Comparison of the expected upper limits on the boost factor B_f (99% C.L.) with 1% and 0.5% energy resolution. The individual lines refer to the cases with $m_{B^{(1)}}$ varied from 500 GeV to 1000 GeV in 100 GeV intervals.

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