The gamma-ray spectrum from annihilation of Kaluza-Klein dark matter and its observability

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Introduction

The theory of Universal Extra Dimensions (UED) involves Kaluza-Klein (KK) particles. ***The lightest KK particle (LKP) is one of the good candidates of 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***, so we investigate the detectability of this peak structure by near-future detectors ***taking account of their energy resolution***. In addition, we calculate the expected count spectrum of gamma-ray signal. Then, we employ the χ-squared test in order to judge the count spectrum contains the LKP signal or not. We can set some constraints on the boost factor which is an uncertain factor dependent on substructure of the LKP distribution in the Galactic halo, if the signal is not detected. If the signal consistent with the peak structure is detected in the future, it will be a conclusive evidence that the dark matter is made of LKP.

Kaluza-Klein dark matter

- The theory of Universal Extra Dimensions (UED)
  ➡ Only one extra dimension
- The mass of KK particles

$$m^{(n)} = \sqrt{\left(\frac{n}{R}\right)^2 + m_{\mathrm{EW}}^2}$$

L. Bergstrom et al, Phys. Rev. Lett 94(2005) 131301

- Here n=1 noted as $m_{B^{(1)}}$ is LKP and its mass range is given as

$$500\ \mathrm{GeV} \lesssim m_{B^{(1)}} \lesssim 1000\ \mathrm{GeV}$$

G. Servant & T. Tait, Nucl. Phys. B 650, 391 (2003)

When LKP annihilates, there are many annihilation modes which contain gamma-rays as final products.

- **Continuum components**
  Quark pair
  Lepton pair
  Lepton-Lepton-Gamma
- **Line**
  Gamma-Gamma

Previous Study (L. Bergström *et al*)

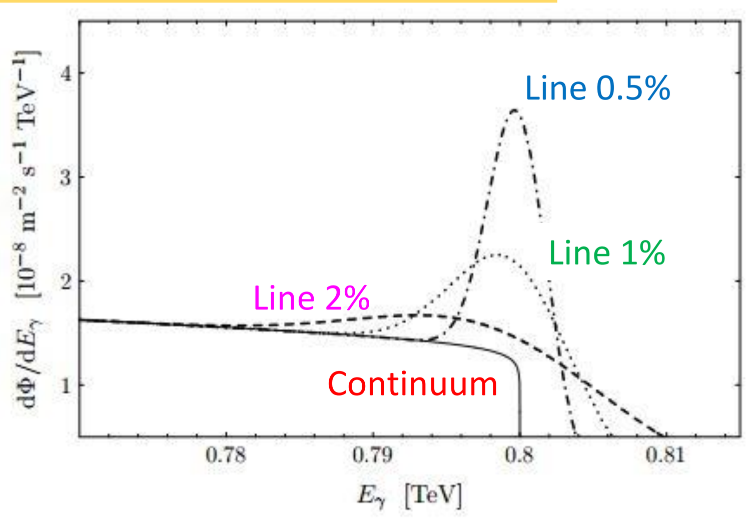


Fig.1 : Gamma-ray spectra of continuum plus line diffused ***without*** energy resolution.
The assumed LKP mass is 800 GeV.
L. Bergström *et al.*, Phys. Rev. Lett 94(2005) 131301

Our Result

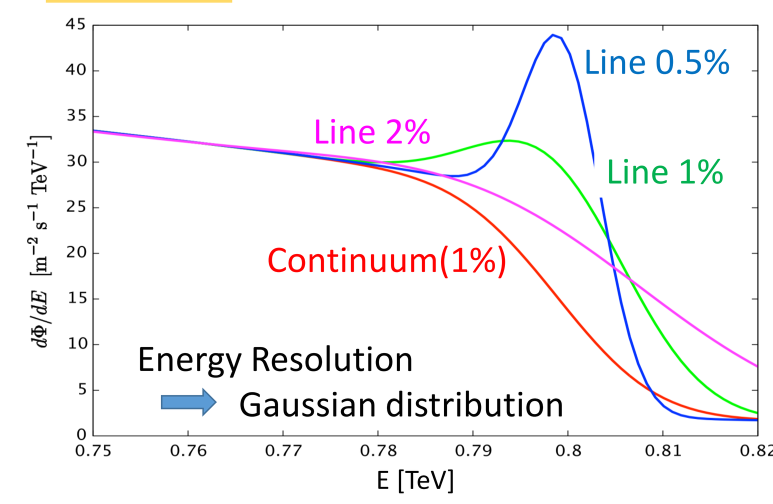


Fig.2 : Gamma-ray spectra of continuum plus line diffused ***with*** energy resolution.
The assumed LKP mass is 800 GeV and boost factor is 1000.

Counts

- We assume the typical CALET sensitivity :
  Observation time = 1 year , Effective area = 1000 cm^2
- To analyze observational data, we have to specify energy bin width to compare with observational data.
- The bin width is taken as one standard deviation of energy reconstruction.

Results

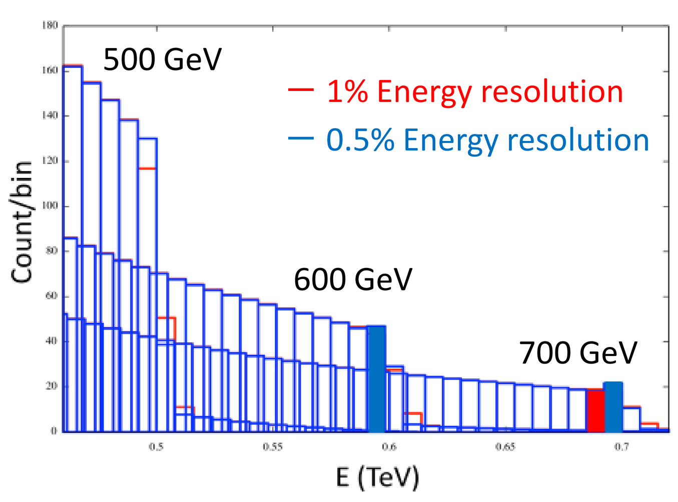


Fig.3 : Expected count spectra near the peak assuming energy resolution of 0.5% and 1% for 500 - 700 GeV LKP mass. The bin width of histograms is 8 GeV.
The assumed boost factor is 1000.

For light mass (500 - 700 GeV) cases:

- ***The continuum component relatively increases with decreasing the LKP mass***.
- ***The characteristic peaks are difficult to see, so we are not able to judge the spectra are made of LKP or not.***

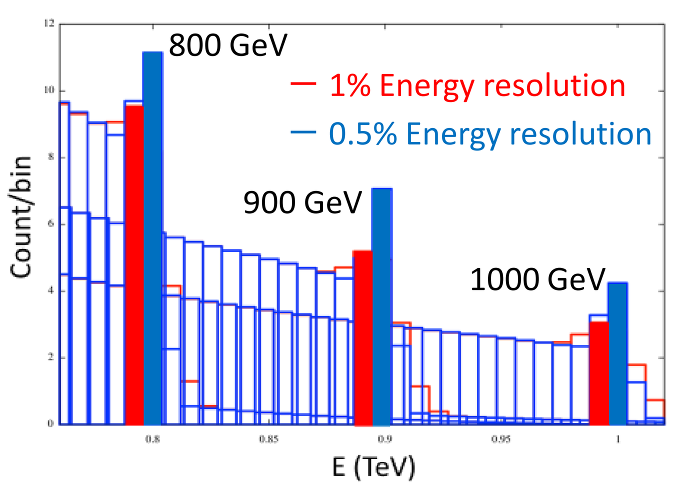


Fig.4 : Expected count spectra near the peak assuming energy resolution of 0.5% and 1% for 800 - 1000 GeV LKP mass. The bin width of histograms is 8 GeV.
The assumed boost factor is 1000.

For heavy mass (800 - 1000 GeV) cases:

- ***The continuum component relatively decreases with increasing the LKP mass.***
- ***The characteristic peaks are clear and easy to see, so we can judge the spectra are clearly made of annihilation of LKP.***

Observability

- We discuss the observability of the LKP signal in near-future detectors taking account of the observed background spectrum.
- Estimates for the accessible range of the boost factor is given when the observed counts have significant difference from the background spectrum.

- **Background**
  Gamma-ray spectrum from "HESS J1745-290" located near the center of Galaxy.

$$\frac{d\Phi}{dE} = (2.55 \pm 0.06 \pm 0.40)\left(\frac{E}{\mathrm{TeV}}\right)^{-2.10\pm0.04\pm0.10} \exp\left[-\frac{E}{(15.7\pm3.4\pm2.5)\mathrm{TeV}}\right] \times 10^{-8}\ \mathrm{TeV}^{-1}\ \mathrm{m}^{-2}\ \mathrm{s}^{-1}$$

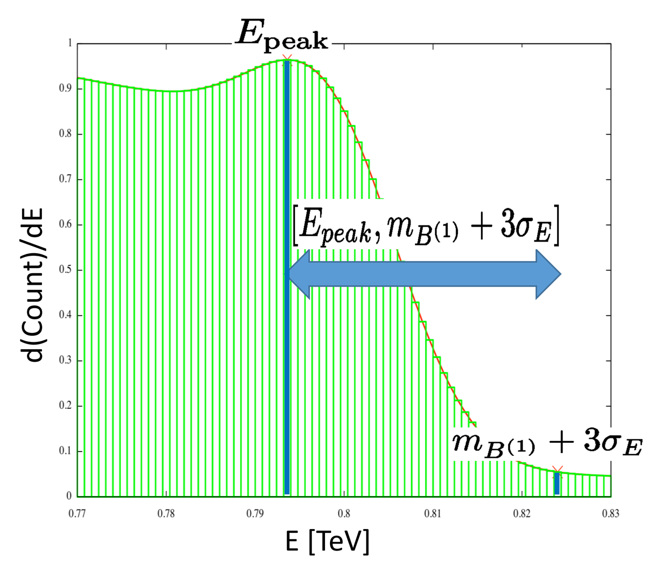
F. Aharonian *et al.*, A&A 503, 817-825 (2009)

- **χ-squared test**

To investigate the detectability quantitatively, a method of χ-squared test is used. This test judges the excess counts is statistically meaningful or not.
Hypothesis:
"The observed counts *do not* show significant differences."
The definition of χ-squared value:

$$\chi^2 = \sum^{N} \frac{([\mathrm{count}+\mathrm{background}] - \mathrm{background})^2}{\mathrm{background}}$$

- **A degree of freedom**
  - The upper edge of the energy range under this analysis is fixed as $m_{B^{(1)}} + 3\sigma_E$ to allow finite energy resolution, so at this energy a degree of freedom is one (N=1).
  - Then the lower edge of the energy range is varied to lower energies.
  - N at the Peak is $[E_{\mathrm{peak}},\ m_{B^{(1)}} + 3\sigma_E]$ where $\sigma_E = m_{B^{(1)}} \times$ Energy resolution



Results

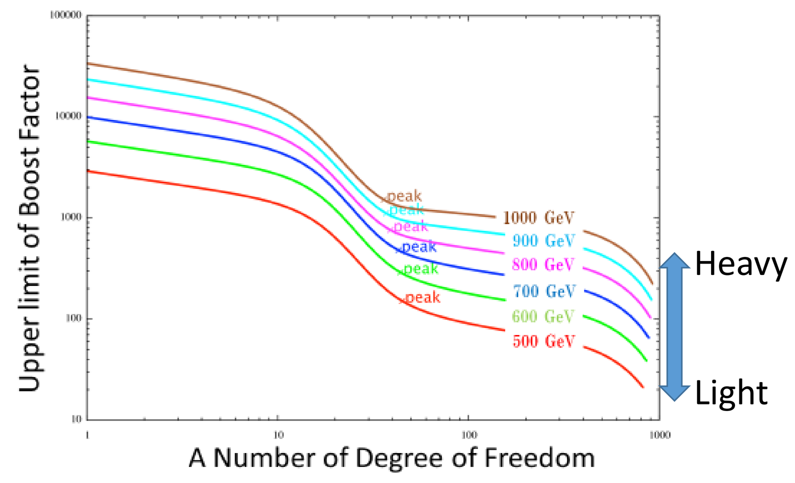


Fig.5 : Expected limits on the boost factor as a function of number of degrees of freedom of observed energy range. These lines show the boost factor when χ^2 values are bigger than critical values for each mass and 1% energy resolution.

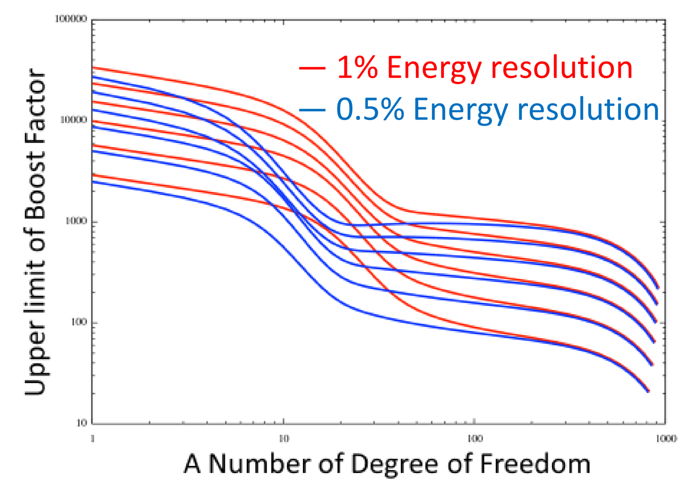


Fig.6 : Expected limits on the boost factor as a function of number of degrees of freedom of observed energy range compared for 1% energy resolution with 0.5% energy resolution. These lines show the boost factor when χ^2 values are bigger than critical values for each mass and each energy resolution.

- ***The upper limit is rapidly decreasing around the peak.***
- ***For better energy resolution, the constraint will be more strict.***
- ***More strict constraint is given for light LKP mass than for heavy.***
- ***By observing the whole energy range, the upper limit of the boost factor is explored down to about 100.***
  ➡ ***This is 2 orders of magnitude less than the present limit.***

A. A. Abdo *et al.*, (Fermi-LAT Collaboration), Astrophys. J. 712, 147 (2010)
F. Aharonian *et al.*, Astropart. Phys. 29, 55 (2008)

Conclusion

- The energy resolution required for gamma-ray detectors should be better than 1%, in order to "see the line" without the need for detailed analysis.
- If the LKP mass is heavy, observed gamma-ray spectrum will show characteristic peak, because the continuum component relatively decreases.
- On the other hand, if the LKP mass is light, constraint for the boost factor becomes strictly.

Boost Factor

- The gamma-ray flux from annihilation of LKP in the Galactic halo:

$$\Phi_\gamma = (\mathrm{Astrophys}) \times (\mathrm{Particle\ phys})$$

L. Bergström, New J. Phys. 11, 105006 (2009)

- The astrophysics factor is highly dependent on substructure of the dark matter distribution in the Galactic halo along the line-of-sight.
- Boost factor indicates relative concentration of the dark matter in astronomical bodies compared with some benchmark distribution.

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