Testing the 130 GeV gamma-ray line with high energy resolution detectors

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Recently some hints of the existence of \(\gamma\)-ray line around 130 GeV are reported according to the analysis of Fermi-LAT data. If confirmed it would be the first direct evidence to show the existence of new physics beyond the standard model. Here we suggest that using the forthcoming high energy resolution \(\gamma\)-ray detectors, such as CALET and DAMPE, we may test whether it is real line structure or just the background effect. For DAMPE like detector with designed energy resolution \(\sim 1.5\%\), a line significance will reach 11\(\sigma\) for the same statistics as Fermi-LAT. For about 1.4 yr survey observation, DAMPE may detect a 5\(\sigma\) signal of such a \(\gamma\)-ray line.

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I. INTRODUCTION

It was recently reported through an analysis of the Fermi Large Area Telescope (Fermi-LAT) \(\gamma\)-ray data that there might be a monochromatic \(\gamma\)-ray line at energy \(\sim 130\) GeV \cite{1,2}. The significance is about 3 \(- 4\sigma\), taking into account the trial effect in the search. It was pointed out in Ref. \cite{2} that the bump-like structure might coincide with the emission of the Fermi bubbles \cite{4,5}. In Ref. \cite{6} the authors re-analyzed the Fermi-LAT data and showed that the spatial distribution of the line emission should not correlate with the Fermi bubbles (see also Ref. \cite{7}), but revealed some sub-structures. The further analysis found the existence of abundant spectral features (excesses and dips) of the diffuse \(\gamma\)-rays and the spectra suffered from spatial variations, which was against the dark matter origin of the spectral structures \cite{6}.

Several models employing dark matter annihilation/decay were proposed to explain this tentative line structure \cite{8,13}. See also the expectation of the line emission \cite{16}. Although the dark matter model may not easily to explain the above mentioned features of the emission, especially the spatial distribution, it would be meaningful to test such a line conjecture due to the potential importance of a high energy \(\gamma\)-ray in the fundamental physics. One way is to test the \(\gamma\)-ray emission from other targets where dark matter is expected to be abundant, like the dwarf galaxies, galaxy clusters and so on. However, the previous searches for line emission seem not sensitive enough to explore the recently reported 130 GeV line with annihilation cross section \(\sim 10^{-27}\) cm\(^3\) s\(^{-1}\) (see e.g. \cite{18,19}). The most recent search for \(\gamma\)-ray line in the Milky Way can marginally exclude the dark matter annihilation cross section \(\sim 10^{-27}\) cm\(^3\) at 130 GeV \cite{21}. The constraint on dark matter annihilation into \(\gamma\)-ray lines from observations of dwarf galaxies is relatively weaker \cite{22}. Another way is to use the accompanied annihilation/decay to other final states to test the dark matter scenario of the \(\gamma\)-ray line \cite{23}. The latter one depends on the detailed model of dark matter, however.

In this work we propose that this tentative \(\gamma\)-ray line structure can be tested with the forthcoming high energy resolution \(\gamma\)-ray detectors, such as CALorimeteric Electron Telescope (CALET)\textsuperscript{1} and DA\textit{k} Art Matter Particle Explorer (DAMPE, previously named TANSUO, \cite{24}). Both CALET and DAMPE are dedicated to detect the cosmic ray nuclei, electrons and \(\gamma\)-ray photons in a wide energy band with very high energy resolution. Thanks to the very thick calorimeter of these detector (30 radiation lengths for CALET and 34.5 radiation lengths for DAMPE), the energy resolution of them can reach or be better than 2\%. As a comparison, Fermi-LAT detector has only 10 radiation lengths. The designed geometry factor of CALET is about 0.12 m\(^2\) sr, which is several times smaller than that of DAMPE (\(\sim 0.5\) m\(^2\) sr). In addition, the energy resolution of CALET is about 2\% at \(\sim 100\) GeV, which is also a little bit worse than that of DAMPE (\(\sim 1.5\%\)). Therefore we will focus on the DAMPE mission in the following discussion.

In the next section we will show the expected detectability of such a line emission on the DAMPE detector. Sec. III is the conclusion.

II. DETECTABILITY OF THE LINE WITH HIGH ENERGY RESOLUTION DETECTOR

Here we choose several high significant regions shown in Refs. \cite{2,5} for discussion, including Reg3 of Weniger (2012), and the Central and West regions of Tempel et al. (2012). The definition of the sky regions and energy spectra of these three regions can be found in Refs. \cite{2,5,8}. The primary \(\gamma\)-ray spectrum before reaching the detector is assumed to be power-law plusing a monochromatic line. After convolving the energy spread function of Fermi-LAT detector, we fit the observed \(\gamma\)-ray spectra

\textsuperscript{1} http://calet.phys.lsu.edu/
to determine the primary spectra, including the energy and normalization of the \( \gamma \)-ray line. The energy spread function is assumed to be Gaussian,

\[
f(E, E_0) = \frac{1}{\sqrt{2\pi} \sigma(E_0)} \exp \left[ -\frac{(E - E_0)^2}{2\sigma^2(E_0)} \right],
\]

where the Gaussian width \( \sigma \) is the function of energy \( E \). A fit to the Monte Carlo simulation results presented in Fig. 4 of Ref. [21] gives \( \sigma(E)/E \approx 0.0944 - 0.0520 \log_{10}(E) + 0.0233 \log_{10}(E)^2 \). The fitted spectra corresponding to Fermi-LAT energy resolution are shown in Fig. 4 (dashed lines).

For DAMPE detector the energy resolution is much higher, and we would expect much sharper spectral feature if the \( \gamma \)-ray line is real. The detailed simulation of the DAMPE detector is still on-going. In this work we employ a typical 1.5% energy resolution for discussion. The expected energy spectra of the three sky regions after convolving the DAMPE energy spread function are shown by the solid lines in Fig. 4.

The energies of the \( \gamma \)-ray line for the three sky regions are fitted individually since we have no prior information about it. The results are slightly different from each other, and are shown in Table I. We then calculate the number of photon events around the line energy \( E_0 \). The photon number between \( E_1 \) and \( E_2 \) is

\[
N = \eta A_{\text{det}} \Delta \Omega t_{\text{obs}} \int_{E_1}^{E_2} \Phi(E) dE,
\]

where \( \Phi(E) \) is the energy spectrum, \( A_{\text{det}} \) is the effective area, \( \Delta \Omega \) is the solid angle of the diffuse emission, \( t \) is the observation time, and \( \eta \) is the detection efficiency taking into account the physical efficiency, variation of effective area with photon arrival direction and the effective observational time of the survey mode. For Fermi-LAT observations, the parameter \( \eta \) is determined by normalizing the resulting number to the detected one as listed in Table I of Ref. [6]. We integrate the spectrum within \( \pm 1\sigma \) range around \( E_0 \). For Fermi-LAT the width is about 0.089\( E_0 \) and for DAMPE it is about 0.015\( E_0 \).

The calculated numbers of events for the line component (signal) and power-law component (background) are compiled in Table I. For DAMPE we assume the same statistics as that of Fermi-LAT to show the numbers. It is shown that with high energy resolution detectors, such a line emission will be very significant (> 11\( \sigma \)) and can be easily to be identified. We also give the expected time to reach 5\( \sigma \) detection for both Fermi-LAT and DAMPE. Here all the parameters of DAMPE are assumed to be the same as Fermi-LAT, except a factor of two smaller of the detection area [24]. For the Central region defined in Ref. [6], after about 4.2 yr observation of Fermi-LAT the line will have a significance exceeding 5\( \sigma \). For DAMPE the time will be only 1.4 yr in spite that the effective area is smaller. Even if the line-like structure becomes more significant with the increase of the exposure of Fermi-LAT, it will still be difficult to distinguish from possible astrophysical origin of this spectral structure as discussed in Ref. [3]. However, for DAMPE experiment it will be much easier to identify whether it is a line or other spectral structure.

It was also discussed that the current bump observed by Fermi-LAT might consist with two lines and the detector can not resolve them due to relatively bad energy resolution [14]. Given the high energy resolution of DAMPE, we may have the potential to identify two lines if they contribute comparably to the flux. We take the dark matter annihilation to \( \gamma \gamma \) and \( \gamma Z \) with equal branching ratios for example. For dark matter mass \( m_\chi = 130 \) GeV, the two \( \gamma \)-ray lines will have energies 130 and 114 GeV respectively, and the emissivity for 114 GeV line will be two times smaller than that of 130 GeV line. The \( \gamma \)-ray spectra for the Central region of Ref. [6] are shown in Fig. 4. We can see that Fermi-LAT can not resolve the two lines with \( \sim 9\% \) energy resolution. The spectral profile is a little broader than that of single line. At DAMPE the two lines can be clearly separated.

Assuming the same statistics of the current Fermi-LAT data, the two lines will have significances 8.3\( \sigma \) (130 GeV) and 3.7\( \sigma \) (114 GeV) respectively.

III. CONCLUSION

It is very interesting that some hints of \( \gamma \)-ray line around 130 GeV were revealed by the Fermi-LAT data. It is not clear whether such a spectral feature is really a line, or some astrophysical behavior, or just the fluctuation of background. In this work we propose to test the line hypothesis with the forthcoming high energy resolution detectors. It is shown that for a \( \gamma \)-ray detector with 1.5% energy resolution, the significance of this spectral structure will reach \( \sim 11\sigma \) given the current statistics of photons, if it is indeed a line. Considering the fact that the detector area of DAMPE is two times smaller than Fermi-LAT, we expect that after \( \sim 1.4 \) yr operation of DAMPE in the survey mode such a line structure will reach a 5\( \sigma \) detection significance. For the fixed point observational mode it will be much sooner to get a firm detection given the existence of such a \( \gamma \)-ray line with high emissivity. We also discuss the potential to identify two nearby \( \gamma \)-ray lines as expected by some dark matter models by DAMPE.

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FIG. 1: The γ-ray spectra corresponding to Fermi-LAT energy resolution (dashed) and DAMPE energy resolution (solid). The vertical line in each panel shows the location of 130 GeV.

TABLE I: Fitted line energy $E_0$, calculated photon event number within ±1σ range around $E_0$, statistical significance and the expected time to reach 5σ detection.

| Region      | $E_0$ (GeV) | $N_{sig}/N_{bkg}$ | significance | $t(5\sigma)$ | $N_{sig}/N_{bkg}$ | significance | $t(5\sigma)$ |
|-------------|-------------|-------------------|--------------|--------------|-------------------|--------------|--------------|
| Weniger Reg3| 126.2       | 24.2/52.5         | 3.3          | 8.6          | 24.2/8.8          | 8.2          | 2.8          |
| Central     | 130.4       | 17.1/13.5         | 4.7          | 4.2          | 17.1/2.2          | 11.4         | 1.4          |
| West        | 129.8       | 11.8/12.0         | 3.4          | 8.1          | 11.8/2.0          | 8.4          | 2.6          |

$^a$Assuming the same exposure of Fermi-LAT and DAMPE;
$^b$The geometry factor of DAMPE is adopted to be half of that of Fermi-LAT.

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FIG. 2: The $\gamma$-ray spectra corresponding to two lines with energies 130 GeV and 114 GeV, for Fermi-LAT energy resolution (dashed) and DAMPE energy resolution (solid). The sky region is the Central region of Ref. [6].

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