Observations of gamma-ray sources with DAMPE

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DArk Matter Particle Explorer (DAMPE), a space-borne high energy cosmic ray and gamma-ray detector, has surveyed the whole sky for five years and collected more than 220,000 gamma-ray events above 2 GeV since the launching on Dec. 17, 2015. The instrument response functions (IRFs) are derived and a dedicated software named DmpST is developed for the gamma-ray data analysis of DAMPE. Here we present the method of DAMPE bright gamma-ray sources search and the spectral analyses of these sources.

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1. Introduction

The DArk Matter Particle Explorer (DAMPE) is a space-borne high energy particle detector dedicated to measure charged cosmic rays and gamma-rays in a broad energy range [1, 2] for the study of high energy astrophysics as well as the nature of dark matter particles[3, 4]. It consists of a Plastic Scintillator strip Detector (PSD), a Silicon-Tungsten tracKer-converter (STK), a BGO imaging calorimeter (BGO) and a NeUtron Detector (NUD)(Fig 1).
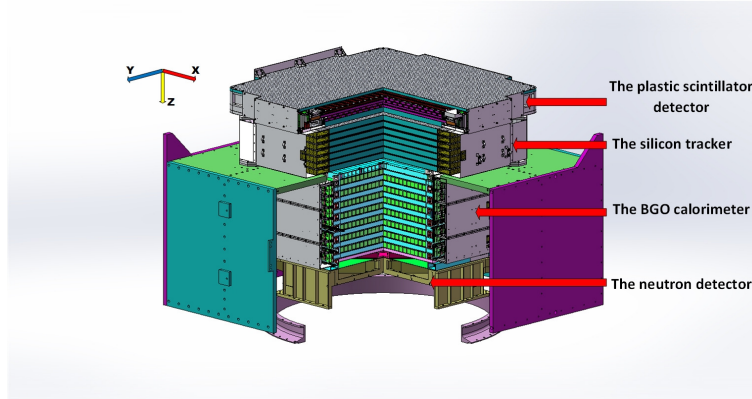

Figure 1: Schematic view of the DAMPE detector.

For gamma-ray observation, the energy range of DAMPE is from 2 GeV to 10 TeV, the effective area is about $1200\,\mathrm{cm}^2$ for normal incident events, the angular resolution is about $0.2°$ and the energy resolution is about 1% at 100 GeV[2]. DAMPE is operating in a 500 km solar-synchronous orbit with an inclination of $\sim 97°$ and a period of about 95 minutes. During the on-orbit operation, we have been carrying out its calibrations since its launch[5]. All these calibrations ensured the accuracy of the data.

2. Gamma-ray data of DAMPE

After more than five years' operation, DAMPE have collected more than 220,000 gamma-ray events above 2 GeV, selected from all events detected by DAMPE with gamma-ray photon selection algorithm [6]. We have carried out the calibration of boresight alignment for gamma-ray data [7], and derived the instrument response functions and developed a dedicated software named DmpST for gamma-ray data analysis [8].

In this work, we select the first five years' gamma-ray data from 1 Jan. 2016 to 31 Dec. 2020 and remove the events when DAMPE travels through the South Atlantic Anomaly (SAA) and during the solar flare time. Fig 2 shows the counts map of DAMPE five years' gamma-ray data in galactic coordinate. Fig 3 shows the time and energy distribution of DAMPE five years gamma-ray data. The periodicity of time distribution is caused by the orbit of DAMPE which surveys the whole sky per year.
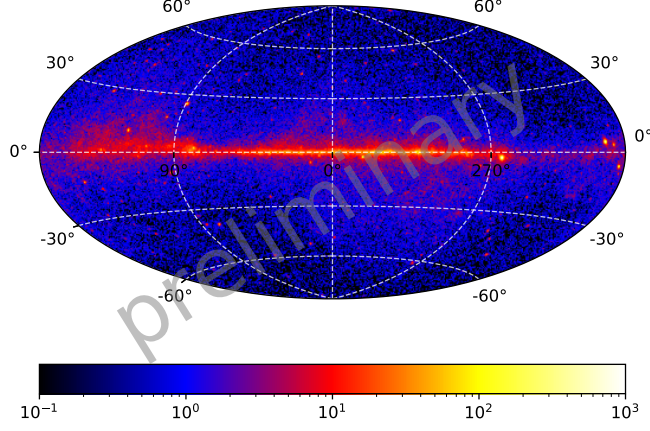
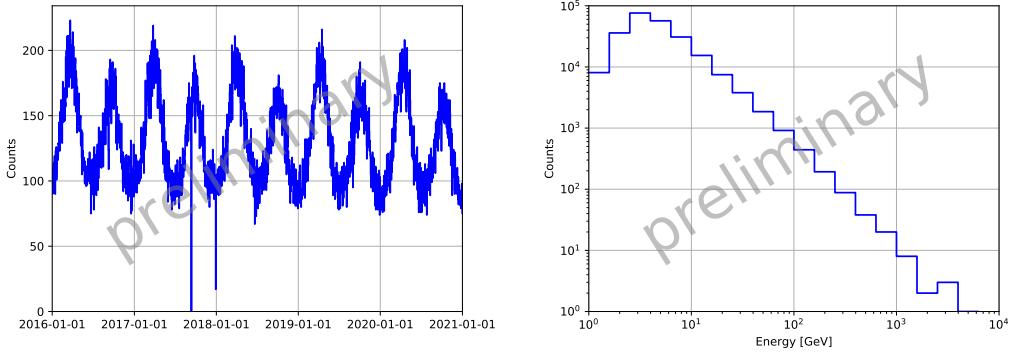**Figure 2:** Counts map of DAMPE five years gamma-ray data in galactic coordinate with Aitoff projection.

Figure 3: Time and energy distribution of DAMPE five years gamma-ray data.

3. Method of blind search for source candidates

The gamma-ray data contains three parts: galactic diffuse emission, resolved sources and isotropic diffuse emission. For detecting the resolved sources effectively, we apply the Li-Ma method[9] to blind search the source candidates firstly. We estimate the expected contribution of galactic diffuse emission with the model from Fermi-LAT's observations[10]. The significance of on region is defined as:

$$S = \sqrt{2}\sqrt{N'_{\text{on}} \ln\left[\frac{1+\alpha}{\alpha}\left(\frac{N'_{\text{on}}}{N'_{\text{on}} + N'_{\text{off}}}\right)\right] + N'_{\text{off}} \ln\left[(1+\alpha)\left(\frac{N'_{\text{off}}}{N'_{\text{on}} + N'_{\text{off}}}\right)\right]},$$

where $N'_{\text{on}} = N_{\text{on}} - N_{\text{gal,on}}$, $N'_{\text{off}} = N_{\text{off}} - N_{\text{gal,off}}$, $N_{\text{gal,on}}$ and $N_{\text{gal,off}}$ are the expected number of photons contributed by galactic diffuse emission in the on and off region. α is the ratio of exposure between off region and on region. We binned the data into more than 3 million equal solid angle's

pixels with N_{side}=512 in HEALPix prejection[11] and chose each pixel as well as its 8 neighbours as on region. The angular size of one pixel and on region are 0.1° and 0.3°. In order to exclude the effect of sources and galactic diffuse emission, two step are used to determine the off region. We chose the neighbours with N_{side}=16 for each pixel as off region firstly to get the initial significance of sky, and then chose the pixels which located in the high galactic latitude (|b|>30°) and significance less than 2.5 as the off region to get the finial significance map. Fig 4 shows the significance map of DAMPE gamma-ray data with the Li-Ma method.
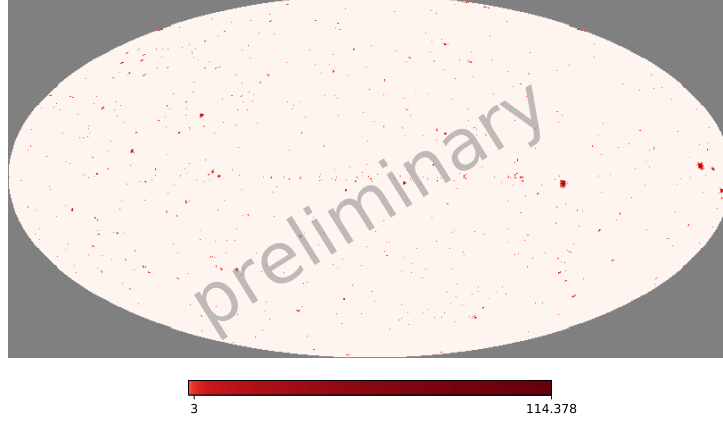

Figure 4: Significance map of DAMPE gamma-ray data with the Li-Ma method.

We chose the pixels which significance larger than 3 as the source candidates. Here we get 2130 candidates totally, and then we carried out likelihood analyses for each candidate with DmpST.

4. Detection of gamma-ray sources

We select the data around each candidate in 5 degree, and binned the data into 15 energy bin in log scale and 0.05 degree spatial bins. We set a point source with PowerLaw spectrum in each candidate's direction, and use the galactic diffuse model from Fermi-LAT's observation and isotropic diffuse model with PowerLaw spectrum to fit the data and get the TS value of source $TS_{source} = 2\ln(L_{with}/L_{without})$. The 283 sources which TS value larger than 20 (TS > 20) make up the initial catalog. For reducing the effect of nearby sources, the sources in the 10 degree circle be included in the model to refit the data. The 222 sources which TS value larger than 25 (TS > 25) after the refit make up the finial catalog. Fig 5 shows the distribution of gamma-ray sources' flux and index observed by DAMPE fitted with the PowerLaw spectrum.

We also fit the data with curved spectrum including LogParabola $\frac{dN}{dE} = N_0(E/E_b)^{-\alpha+\beta\log(E/E_b)}$ and PLSuperExpCutoff $\frac{dN}{dE} = N_0(E/E_0)^{\gamma}\exp(-(E/E_c)^b)$ to get the TS value for curved spectrum $TS_{curved} = 2\ln(L_{curved}/L_{PowerLaw})$. If the TS_{curved} is larger than 9, the significance for curved spectrum is larger than 3σ. We find that one source favored LogParabola spectrum and two sources favored PLSuperExpCutoff spectrum. Fig. 6 shows the SED of the sources with PowerLaw and curved spectra observed by DAMPE.
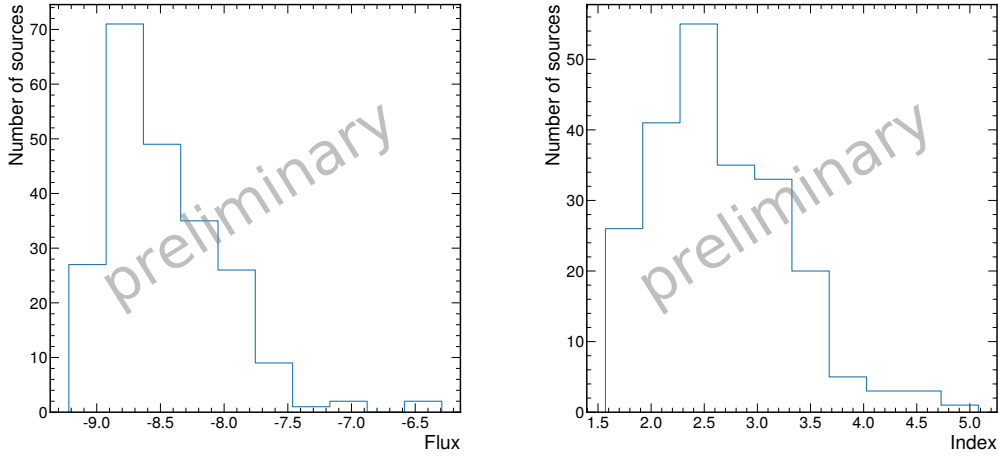
Figure 5: distribution of gamma-ray sources' flux and index observed by DAMPE fitted with the PowerLaw spectrum.

We associated these sources with Fermi-LAT's 4FGL[12] to detemine the types of these sources. We calculate the separations between the sources observed by DAMPE and sources in 4FGL, and consider the nearest source in 4FGL as the association of source observed by DAMPE. Fig 7 shows the separations distribution between sources observed by DAMPE and their associations in 4FGL. Fig 8 shows the types and spatial distribution of gamma-ray sources observed by DAMPE. Table 1 lists the types of sources observed by DAMPE.

Table 1: The types of sources observed by DAMPE.

Type	AGN	Pulsar	SNR and/or PWN	binary	globular cluster	unassociated
Number	163	44	7	3	1	4

5. Summary

After five years operation, DAMPE have collected more than 220,000 photons above 2 GeV. With the first five years' data, we detected 222 gamma-ray sources observed by DAMPE and detemine the spectra of these sources. Most of sources favors PowerLaw spectrum, and 3 sources favors curved spectra. Associated with 4FGL, we determined the types of sources. Most of sources are associated with AGNs and pulsars.
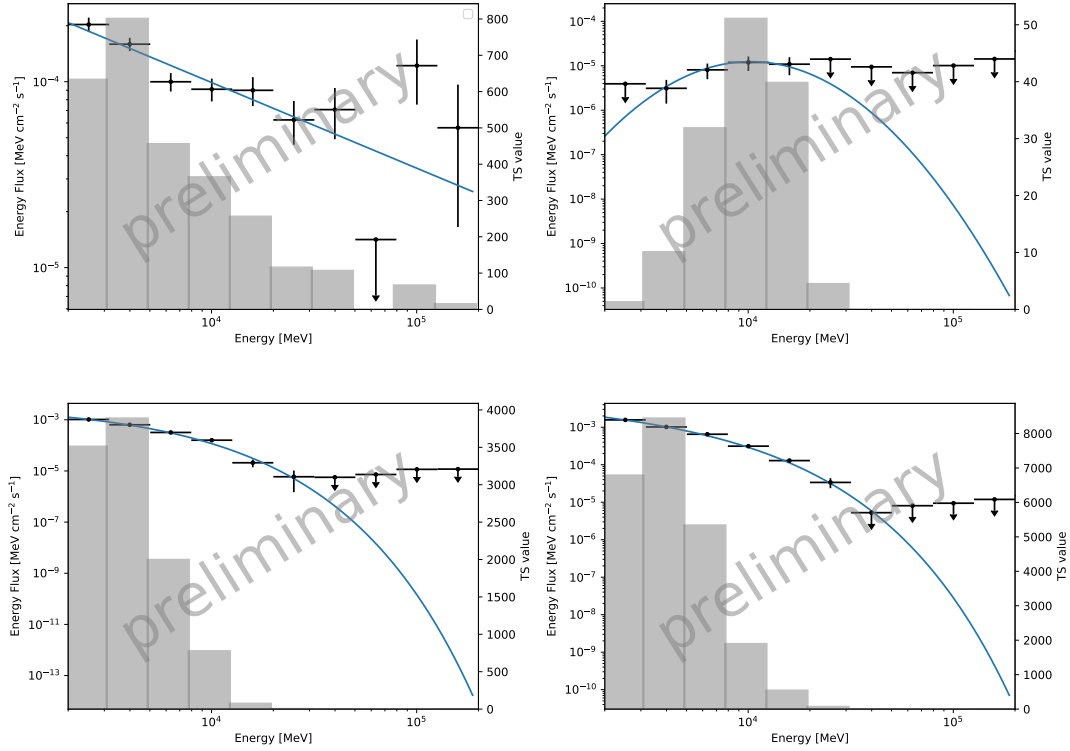
Acknowledgments

Figure 6: SED of sources with PowerLaw and curved spectra observed by DAMPE (Crab, 4FGL J1653.8+3945, Vela and Geminga).

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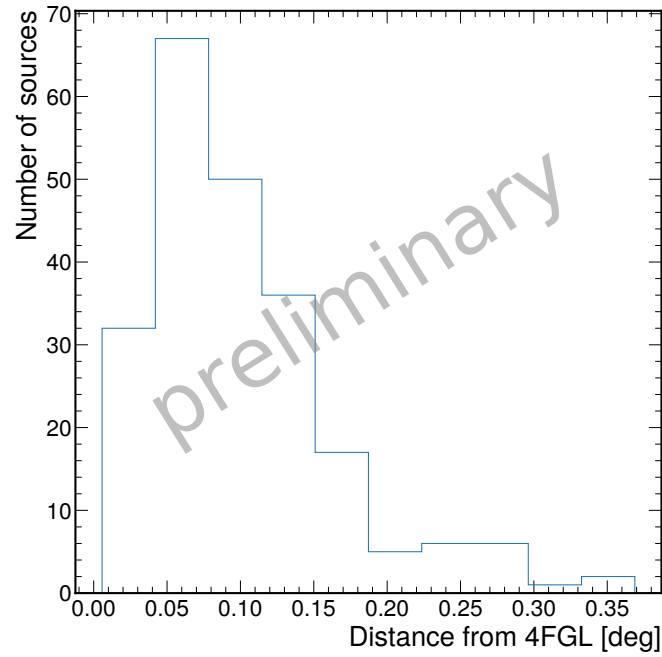
Figure 7: Separation distribution between sources observed by DAMPE and their associations in 4FGL.

Figure 8: Types and spatial distribution of gamma-ray sources obseved by DAMPE

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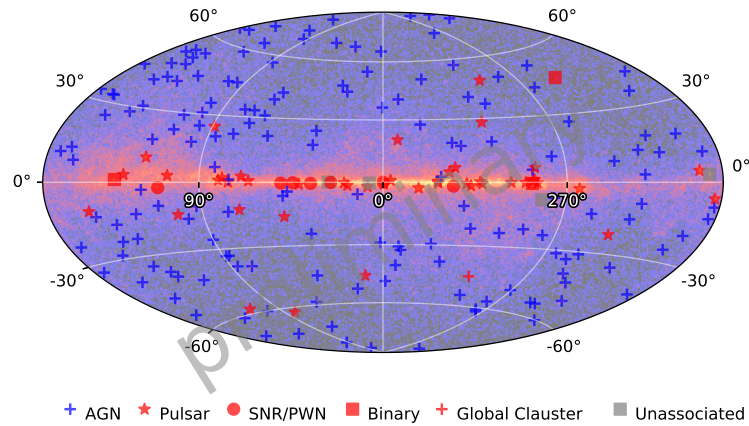[7] W. Jiang, X. Li, K.-K. Duan, et al., *The boresight alignment of the DArk Matter Particle Explorer*, *Research in Astronomy and Astrophysics*, 20 (2020) 092.

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