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Recent Progresses of the DAMPE Mission*

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Abstract The DArk Matter Particle Explorer (DAMPE) is a space high-energy particle and γ-ray detector whose major scientific goals are the indirect detection of dark matter particles, the origin of cosmic rays and high-energy γ-ray astronomy. Since its successful launch in December 2015, the DAMPE has been operated smoothly in orbit for more than 8 years. The direct measurements of the boron-to-carbon and boron-to-oxygen flux ratios, and the proton+ Helium spectrum up to 316 TeV have been obtained, revealing new spectral features with very high significances. The search results of γ-ray spectral line and fractionally charged particles indicate a good potential of DAMPE for indirect dark matter detection and new physical discovery in space. The DAMPE measurements are expected to significantly advance our understanding of the fundamental problems in astroparticle physics.

Key words DAMPE, Dark matter, Indirect detection, Cosmic rays

Classified index P35, P1

1 Introduction

It has been well established that our Universe is made up of about 4.9% baryonic matter, 26.8% Dark Matter (DM), and 68.3% dark energy[1]. The physical nature of DM is one of the most important fundamental questions of modern physics. Many types of candidate DM models have been proposed, among which the leading one is a kind of Weakly Interacting Massive Particles (WIMPs) beyond the standard model of particle physics, as motivated by the relic abundance of DM and the bottom-up evolution pattern of the large scale structures of the Universe[2,3]. Many efforts have been made to search for the WIMP DM in laboratories, including the direct detection of the WIMP-nucleon scattering by underground detectors, the indirect detection of the annihilation or decay products in the cosmic radiation, and the collider detection of WIMP pairs produced in high-energy particle colliders[4]. After several decades of efforts, no convincing evidence has been found yet. Particularly, the direct detection experiments push the WIMP-nucleon scattering strength to a very low level[5], which has already severely constrained a series of WIMP models.

In recent years, some interesting anomalies have been found in Cosmic Ray (CR) and γ-ray observations, such as the positron excess discovered by PAMELA[6], Fermi-LAT[7], and AMS-02[8], and the associated total Cosmic Ray Electron plus positron (CRE) excess by ATIC[9], Fermi-LAT[10], and AMS-02[11]. The excesses of positrons and CREs can be explained by either the astrophysical sources such as pulsars and the DM annihilation or decay[12–17]. There are still debates on the astrophysical or DM origin of the positron and/or CRE excesses, in particular, that the most recent HAWC observations of two nearby pulsars tend to disfavor the pulsar interpretation[18]. Higher precision measurements

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in a wider energy band are crucial to identifying their physical origin. Other anomalies include the γ-ray excess in the Galactic center[19], and the potential excess of CR antiprotons[20,21].

The purpose of the DArk Matter Particle Explorer (DAMPE) is to search for possible annihilation/decay relics of DM in CREs, with unprecedentedly high energy resolution and low background[22,23]. DAMPE is also proposed as a high-energy particle detector for observations of γ-rays and CR nuclei, which can be particularly helpful in the study of high-energy astrophysical phenomena and CR physics[23]. The DAMPE mission was launched into a 500 km Sun-synchronous orbit on 17 December 2015, with an inclination angle of 97°. It orbits the Earth every 95 minutes. All the detectors perform excellently in space. The daily event rate of DAMPE is about 5 million. It has recorded in total over 8 billion CR events as of May 2020, most of which are CR nuclei. There are about 1% CREs and 3×10^{-5} γ-ray photons in the DAMPE data.

2 Detector

DAMPE is made of 4 sub-detectors, which are, from top to bottom, the Plastic Scintillator strip Detector (PSD[24]), the Silicon-Tungsten tracKer-converter (STK[25]), the BGO imaging calorimeter[26], and the NeUtron Detector (NUD[27]). A schematic plot of the DAMPE detector is shown in Figure 1[23]. The total weight of the payload (satellite) is about 1.5 (1.9) tons, and the power consumption is 300 (500) W. The size of the satellite is about 1.2 m×1.2 m×1.0 m.

The PSD is to measure the (absolute) charge of incident particles up to z=30 *via* the ionization process (dE/dx). It also serves as an anticoincidence detector for γ-rays. The PSD consists of two layers of orthogonally placed plastic scintillator bars. For each layer, 41 plastic scintillator bars are further placed in two sub-layers with a shift of 0.8 cm between them to reduce the gaps. The effective area of the PSD is 82.5 cm×82.5 cm[23]. The weight of the PSD is about 103 kg, and the power is 8.5 W.

The main function of STK is to measure the trajectory of a particle. The charge of light nuclei (z<8) can also be measured by the STK. The STK consists of 12 layers (6 for x direction and 6 for y direction) of silicon trackers, each with two sub-layers arranged orthogonally to measure the x and y positions of a track. The STK is also a γ-ray converter by means of three 1 mm thick tungsten plates inserted in the second, third, and fourth planes. Each silicon layer is made of 16 ladders, each formed by 4 silicon micro-strip detectors. Every ladder is segmented into 768 strips, half of which are readout strips and the other half are floating strips. In total, there are 384 ×16 ×12 = 73728 readout channels of the STK. The effective detection area of STK is 76 cm × 76 cm. The STK has a weight of 154 kg and a power consumption of 82 W.

The BGO calorimeter is the major instrument of DAMPE. It has three functions: (i) measuring the energy deposition of incident particles, (ii) imaging the 3D profile of the shower development, and providing electron/hadron discrimination, and (iii) providing the level 0 trigger for the DAMPE data acquisition system. The BGO calorimeter is made of 308 BGO bars, each is read out at two ends by PhotoMultiplier Tubes (PMTs). The BGO crystals are placed orthogonally in 14 layers, with a total depth of about 32 radiation lengths and about

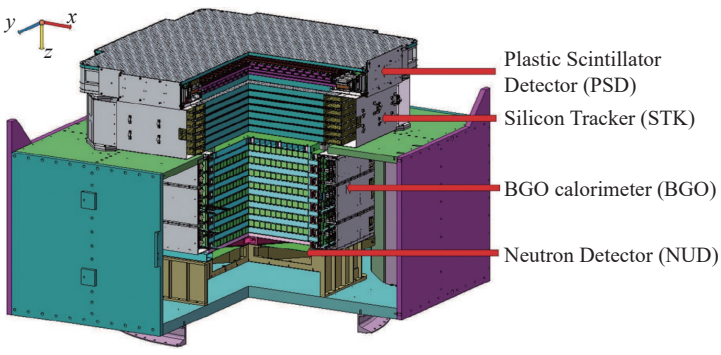


Fig. 1 Schematic plot of the DAMPE detectors

1.6 nuclear interaction lengths. The length of the BGO crystal is 60 cm, which is the longest in the world. The calorimeter has an effective area of 60 cm × 60 cm, a total weight of 1052 kg, and a power consumption of 42 W.

The NUD is at the bottom of the detector. The main purpose of the NUD is to perform electron/hadron discrimination by means of the fact that neutrons are much more abundant in hadronic showers than in electromagnetic ones. Once the neutrons are created, they are quickly thermalized in the BGO calorimeter, and then get captured by Boron-doped plastic scintillators. The NUD is made of four 30 cm ×30 cm ×1 cm plastic scintillators with 5% (weight) Boron element. The NUD has an effective area of 61 cm × 61 cm, a mass of 12 kg, and a power of 0.5 W.

Table 1 summarizes the expected detector performance of DAMPE, for observations of electrons, γ-rays, and protons[23]. With good measurements of the charge, direction, and energy of various types of particles, DAMPE is expected to play a significant role in exploring the high-energy Universe.

3 On-orbit Performance

Dedicated calibration of each unit of the detector has been done using the on-orbit data, which enables precise measurements of the physical quantities of each event[28]. Figure 2 gives the charge measurements by the PSD[29]. The absolute charge resolution is about 0.20e (e means unit charge) for z=8 (Oxygen) and 0.30e for z=26 (Iron). Such a good charge resolution is the basis of precise spectral measurements of each species. Using the bright γ-ray sources we can calibrate the angular resolution of the STK, which results in about 0.5º for energies higher than 5 GeV.

Table 1 Expected performance of DAMPE

Parameter	Value
Energy range (e/γ)	5 GeV to 10 TeV
Energy resolution (e/γ)	1.5% at 800 GeV
Energy range (p)	50 GeV to 500 TeV
Energy resolution (p)	40% at 800 GeV
Effective area (vertical γ)	1100 cm^2 at 100 GeV
Geometry factor (e)	0.3 m^2·sr above 30 GeV
Angular resolution (γ)	0.1º at 100 GeV
Field of view	1.0 sr

The very thick BGO calorimeter enables no significant leakage of electromagnetic showers from the bottom for energies as high as TeV. There is, however, a few percents of energy loss due to the dead materials of the calorimeter. An event-level energy correction method was developed and verified by MC simulations and the beam test data[30]. The beam test data and the MC simulations show that the energy resolution for CREs is better than 1.2% for energies above 100 GeV. DAMPE also has P- and N-side readouts for each BGO crystal, which have different gains. These two-side readouts give a consistency check of the energy measurement. We find that the energies measured by both sides agree with each other very well. Figure 3 presents the ratios of energies measured by the two sides, together

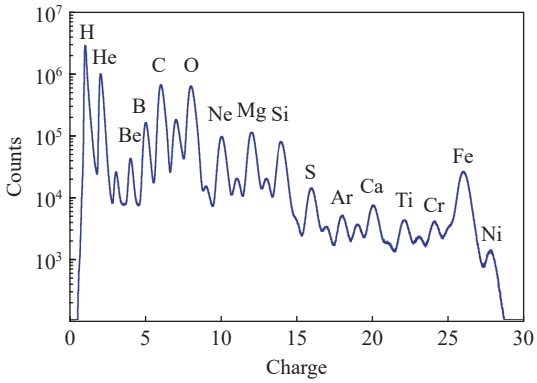


Fig. 2 Charge spectrum obtained using two years of on-orbit data

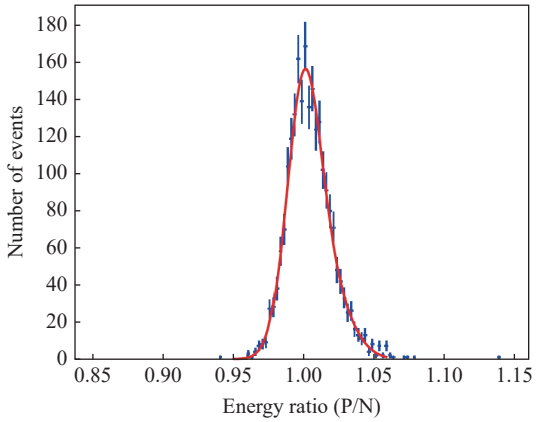


Fig. 3 Ratios of energies reconstructed with P- and N-side data

with a Gaussian fit that gives a mean of 1.005±0.005 and a width of 0.016±0.001[31]. Such a result further supports the quoted energy resolution of about 1%.

Particle identification is one of the most challenging things for the observations of CREs. The background of CREs is CR protons (heavier nuclei can be effectively rejected *via* the charge measurement in PSD). The fluxes of CREs are about three orders of magnitude lower than that of protons. Therefore, a high rejection power of protons is essential for reliable measurements of the CRE fluxes. DAMPE uses the morphology difference between CREs and protons in the calorimeter to distinguish them[32,33]. This is basically due to different developments of hadronic and electromagnetic showers in the calorimeter. A simple two-parameter method was adopted to describe the longitude and latitude developments of the showers. They are: (i) an energy-weighted Root-Mean-Square (RMS) value of hit positions in the calorimeter (shower spread, L_{ss}), and (ii) the deposited energy fraction of the last BGO layer (F_{last}). Figure 4 (a) shows the distributions of these two parameters for the flight data with BGO energies between 500 GeV and 1 TeV[31]. We can see clearly two populations of events in this plot, with the upper population being proton candidates and the lower one being CRE candidates. To better quantify the separation between these two populations, we further define a shape parameter, $\zeta=F_{last}\times(L_{ss}/\mathrm{mm})^4/(8\times10^6)$, which projects these two parameters into one dimension. The distributions of the ζ parameter for the flight data and Monte Carlo (MC) simulations for CREs and protons are shown in the right panel of Figure 5. We select CREs with $\zeta\leqslant8.5$, which gives only about 2% proton background in this energy range[31]. For energies below TeV, the proton background is lower than 3%. The highest background in the energy range from 25 GeV to 4.6 TeV is estimated to be about 18%[31].

The NUD provides additional help of the electron-proton discrimination, since the neutron yields for hadronic showers are much higher than those of the electromagnetic showers. Simulations show that using the NUD alone the proton background can be suppressed by a factor of about 25 when keeping a CRE efficiency of 95%, for 1–5 TeV deposited energies[34]. Together with the calorimeter, the total suppression power improves by a factor of about 2[34]. The NUD capability is expected to be more important at higher energies.

4 Scientific Results

Figure 4 shows the direct measurements of Boron-to-Carbon (B/C) and Boron-to-Oxygen (B/O) flux ratios in the energy range from 10 GeV/n (GeV per nucleon) to 5.6 TeV/n with 6 years of on-orbit data collected by DAMPE, with high statistics and well-controlled systematic uncertainties[35]. Boron nuclei in cosmic rays are believed to be mainly produced by the fragmentation of heavier nuclei, such as carbon and oxygen, *via* collisions with the interstellar matter. Therefore, the precise measurements of the B/C and B/O ratios are very essential for probes of the CR propagation. The energy dependence of both the B/C and B/O ratios measured by DAMPE can be well fitted by a broken power-law model rather than a single power-law model, suggesting

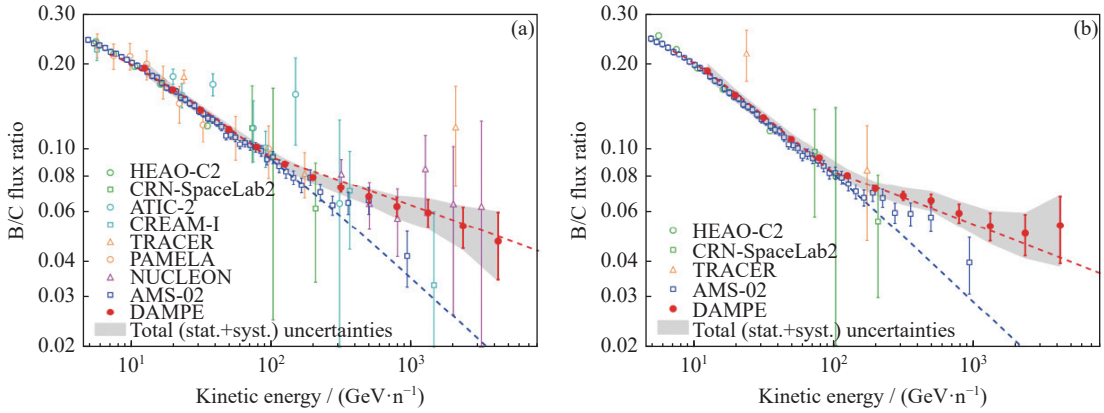


Fig. 4 Boron-to-carbon (a) and boron-to-oxygen (b) flux ratios as functions of kinetic energy per nucleon measured by DAMPE[35] (red filled dots), compared with measurements from other experiments[37–44]

the existence in both flux ratios of a spectral hardening at about 100 GeV/n. The significance of the break is about 5.6σ and 6.9σ for the GEANT4 simulation, and 4.46σ and 6.9σ for the alternative FLUKA simulation, forB/CandB/O,respectively.Theselatestmeasurementsdeviate from the predictions of conventional turbulence theories of the Interstellar Medium (ISM), which point toward a change of turbulence properties of the ISM at different scales or novel propagation effects of CRs, and should be properly incorporated in the indirect detection of dark matter *via* anti-matter particles. Improved measurements of the B/C, B/O, and other secondary-to-primary ratios in cosmic rays with higher statistics and lower systematics by DAMPE and future direct detection experiments such as HERD[36] are expected to eventually uncover the fundamental problems of the origin and propagation of CRs and shed new light on the indirect detection of dark matter particles.

Figure 6 shows the direct measurement of the CR proton+Helium (p+He) spectrum from 46 GeV to 316 TeV with 6 years of on-orbit data collected by DAMPE[45]. The selection of proton+helium, instead of individual proton and helium contributions, allows the collection of additional statistics, thus reaching higher energies with low background. The DAMPE p+He spectrum is in agreement with other direct/indirect-detection experiments, within the systematic uncertainties. The DAMPE measurement thus provides a link between direct and indirect CR measurements, exhibiting a good general agreement among very different techniques. The p+He spectrum in such a wide energy range deviates from a simple power-law behavior, and shows the pres-

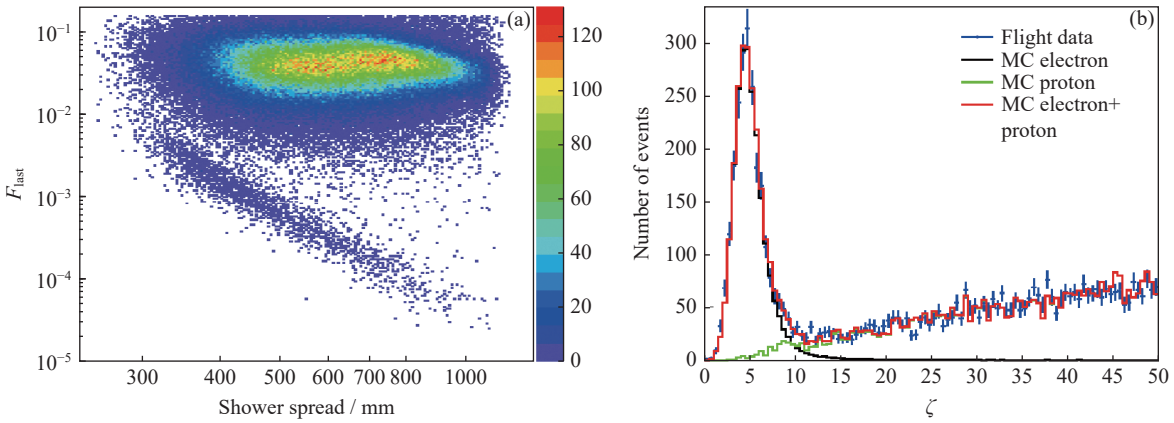


Fig. 5 (a) Shower spread versus the last layer energy fraction for selected events with BGO energies between 500 GeV and 1 TeV. (b) One-dimensional distributions of the shape parameter ζ, compared with MC simulations

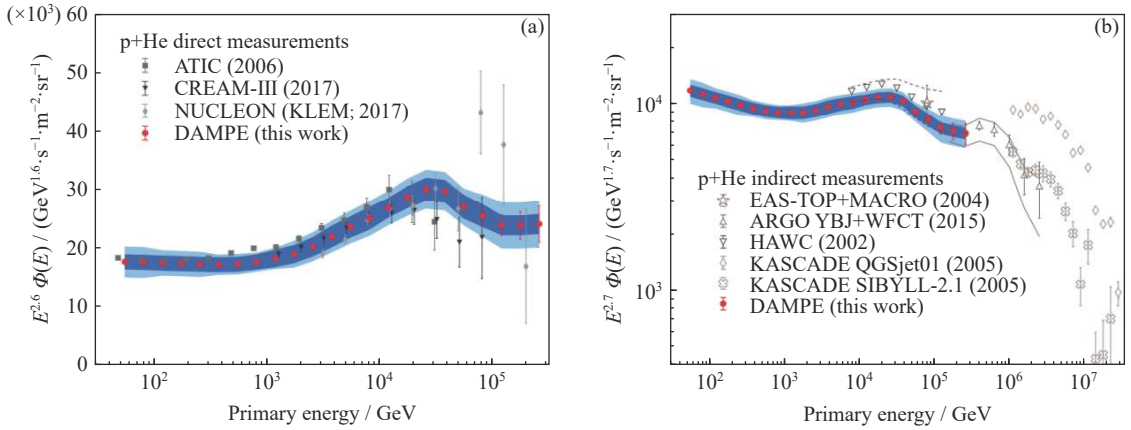


Fig. 6 P+He spectrum from 46 GeV to 316 TeV measured by DAMPE[45] (red fill dots), compared with direct measurements of p+He made by ATIC-02[48], NUCLEON[49] and CREAM[50] (a), and indirect measurements from ARGO-YBJ+WFCT[51], HAWC[52], KASCADE[53] and EAS-TOP+MACRO[54] (b)

ence of a spectral hardening around about 600 GeV followed by a softening at 28.8±4.5 TeV. The softening features revealed in both the individual proton[46] and helium[47] spectra measured by DAMPE are further confirmed by the p+He spectrum, with an unprecedented significance of 6.6σ. Moreover, The p+He spectrum shows a novel hint regarding a possible direct detection of a second hardening around 150 TeV, for the first time in space.

Figure 7 shows the results of the Fractionally Charged Particle (FCP) search based on the on-orbit data of the DAMPE experiment[55]. Unlike underground experiments, which require an FCP energy of the order of hundreds of GeV, the FCP search with DAMPE starts at only a few GeV. Based on the analysis using 5 years of comic-ray events recorded by DAMPE, no FCP signal is observed (Figure 7a) and the flux upper limit of $\frac{2}{3}$e FCP is found to be $\Phi<6.2\times10^{-10}$ cm$^{-2}\cdot$sr$^{-1}\cdot$s^{-1} at the 90% CL (Confidence Level, see Figure 7b). Our results demonstrate that DAMPE exhibits higher sensitivity than experiments of similar types by three orders of magnitude that more stringently restricts the conditions for the existence of FCP in primary cosmic rays. In the future, with the accumulation of more on-orbit data, DAMPE is expected to perform even more sensitive FCP searches.

Thanks to the unprecedented high energy resolution, DAMPE is well-suitable for searching for monochromatic and sharp γ-ray structures in the energy range from GeV to TeV. With the first 5 years of DAMPE data, we carry out the search for spectral γ-ray lines from 10 to 300 GeV[63]. To improve the sensitivity, we develop two types of dedicated data and adopt the signal-to-noise ratio optimized Regions of Interest (ROIs) for different DM density profiles. No line signals or candidates with TS value $\geqslant$9 are detected between 10 and 300 GeV in the Galaxy. The 95% CL constraints on the annihilation cross section for $\chi\chi\rightarrow\gamma\gamma$ and the decay lifetime for $\chi\rightarrow\gamma\nu$, with proper addressing of the systematic uncertainties, are presented in Figure 8. Most of our constraints are comparable to the 5.8-year results of Fermi-LAT thanks to the better energy resolution and the smaller influence of the systematic uncertainties. For the decaying DM, the DAMPE lower limits on the decay lifetime are stronger for DM with mass $\leqslant$100 GeV by a factor of about 2. In view of the fact that the DAMPE data set is about ten times smaller than that of Fermi-LAT, our findings demonstrate the potential of high-energy-resolution observations on dark matter detection.

Figure 9 shows the all-sky γ-ray map above 2 GeV along with the identified point-like sources obtained using 7.2 years of the DAMPE data[65]. The luminous Galactic plane and some bright sources can be clearly seen. Using the blind search method based on the Li-Ma formula[66], 248 point sources in total are detected with TS values larger than 25 and their locations are shown in Figure 10. By associating the observed sources with the Fermi-LAT 4 FGL-DR3 catalog[67], the types of these sources are determined. The analysis reveals that a significant portion of the sources are associated with Ac-

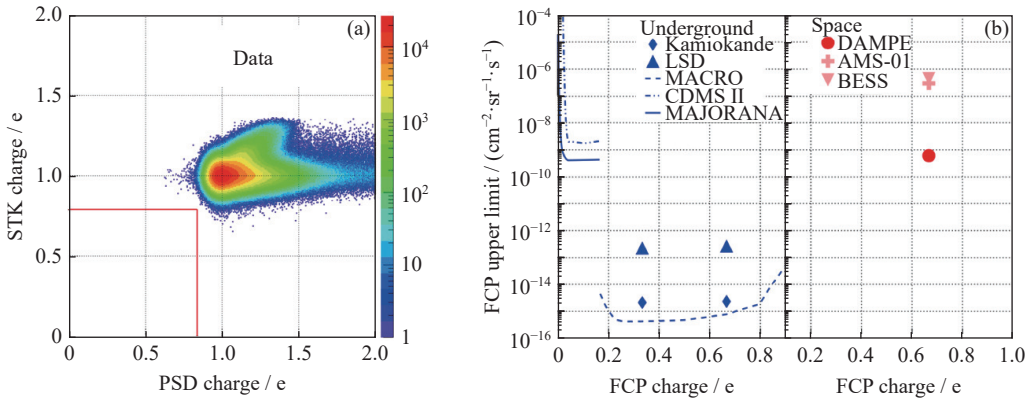


Fig. 7 (a) Distribution of PSD-STK charge for the on-orbit data of DAMPE, the red lines indicate the signal region for FCPs. (b) FCP flux upper limit of DAMPE[55] (red dots), compared with the other space experiments[56,57] and underground experiments[58–62]

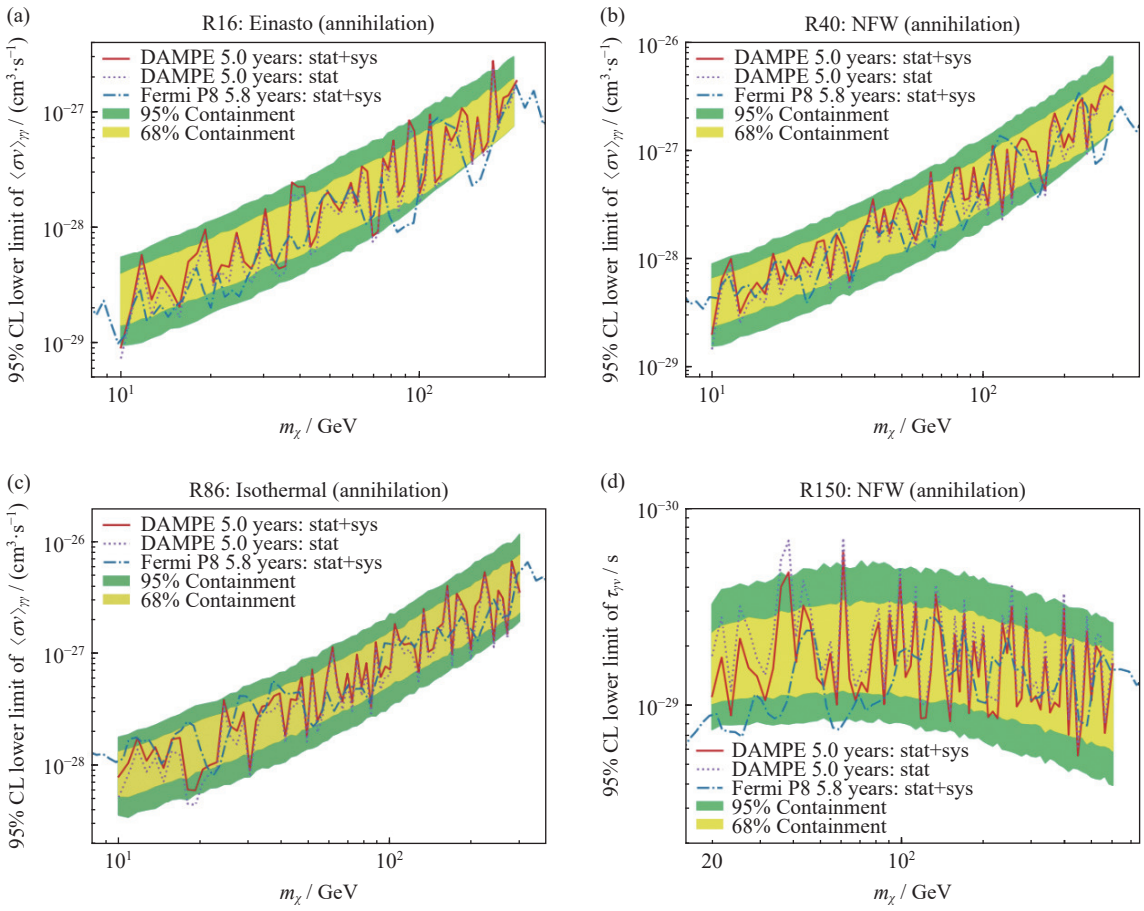
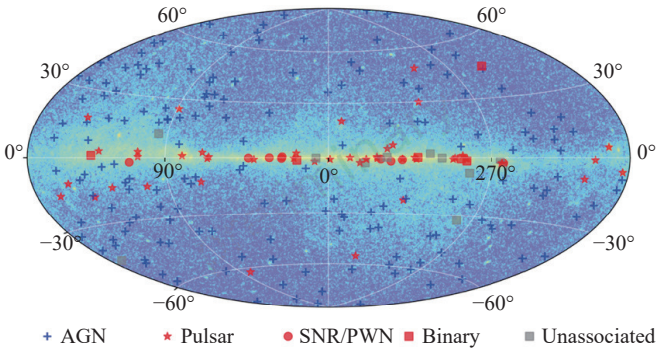


Fig. 8 95% CL constraints for different DM density profiles with the DAMPE experiment[63]. Blue dot-dashed lines show the 5.8-year Fermi-LAT constraints[64]



Source type	Number
AGN	175
Pulsar	46
SNR/PWN	10
Binary	6
Unassociated	11
Total	248

Fig. 9 Significant point sources (TS≥25) detected in 7.2-year DAMPE data[65]. Markers present the types of the associated sources. The numbers of different source types are listed in the right table

tive Galactic Nuclei (AGNs) and pulsars, indicating their origin in high-energy astrophysical processes associated with these objects.

Figure 10 shows the preliminary spectral measurement of the Galactic Center Excess (GCE) by DAMPE and the preferred DM parameter space for the annihilation channel $\chi\chi \to b\bar{b}$[68]. The GCE is searched with 7.2 years of the DAMPE photon data. It is detected with a TS value of 81.3, which corresponds to a significance of 7.9σ with 6 degrees of freedom. The spatial distribution is fitted with the DM annihilation distribution of the generalized NFW profile $\rho_{\rm NFW}(r) = \rho_0 / [(r/r_{\rm s})^{\gamma}$

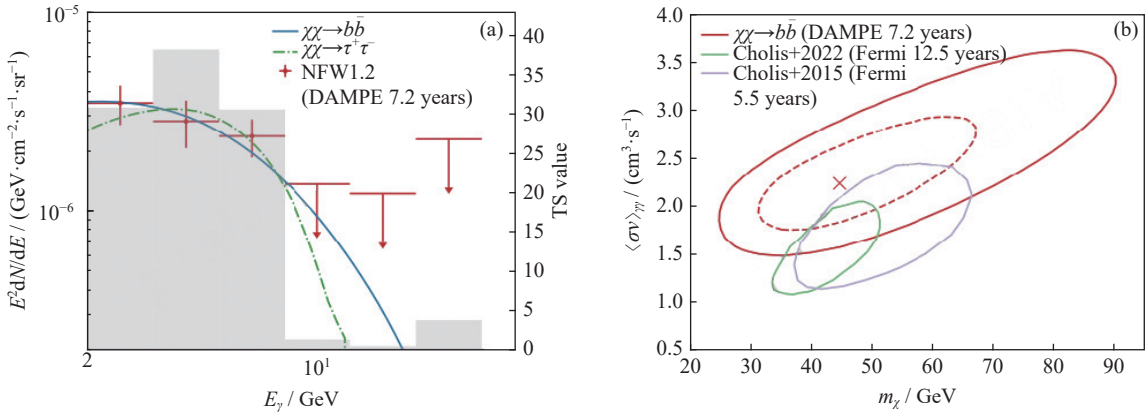


Fig. 10 Preliminary spectral measurement of the Galactic center excess (GCE) by DAMPE (a) and the preferred DM parameter space for the annihilation channel $\chi\chi\to b\bar{b}$ (b)[68]

$(1+r/r_s)^{3-\gamma}]$ and the optimal inner slope is γ= 1.16±0.10, which is consistent with that of the Fermi-LAT[69]. If the excess is explained with the DM annihilation into $b\bar{b}$, DM particles with mass m_χ=45±11 GeV and cross section $\langle\sigma\nu\rangle=(2.2\pm0.3)\times10^{-26}$ cm$^3\cdot$s^{-1} is required. The DM parameter space is also consistent with the Fermi-LAT[70,71].

5 Summary

DAMPE has been operating smoothly in orbit for more than eight years. Based on the accumulated high-quality data recorded by DAMPE, multiple latest scientific results have been obtained, regarding CR physics, indirect DM detection and γ-ray astronomy. The precise measurements of the B/C and B/O ratios reveal a common spectral hardening at about 100 GeV/n with very high significances, which provides important implications in understanding the CR propagation. The latest measurements of the p+He spectrum up to 316 TeV suggest a hint of hardening structure at about 150 TeV for the first time in space. The FCP search provides the strictest restriction in space for the existence of FCP in primary cosmic rays. Benefiting from the unprecedented high energy resolution of DAMPE, the γ-ray line search achieves even stronger DM constraints for the lower limits on the decay lifetime below 100 GeV. In the near future, more scientific progresses from DAMPE are expected to shed new light on our understandings of DM and the high-energy Universe.

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