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Latest results from the DAMPE space mission

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The DArk Matter Particle Explorer (DAMPE) is a particle detector hosted on board a satellite orbiting around the Earth since December 2015. The space mission has been promoted by the Chinese Academy of Science and results from an international effort also including Italian and Swiss institutions. The scientific goals include: indirect detection of Dark Matter signatures in cosmic lepton spectra, study of Cosmic Ray energy spectra up to energies of hundreds of TeV and high-energy gamma ray astronomy. A general overview of the mission will be presented and its main results about the all-electron, proton, helium, light-component (p+He) and heavier nuclei energy spectra, as well as studies on gamma-ray sources, will be discussed.

Keywords: Galactic cosmic rays; high-energy gamma ray astronomy; space detectors.

1. Introduction

DAMPE is a multi-purpose cosmic ray satellite detector that has been taking data since its launch in 2015. The data collected by the experiment has led to some important results and breakthroughs in the field of cosmic ray physics in the past few years. After a brief description of the current state of understanding of cosmic ray physics and direct detection techniques, DAMPE latest results will be presented together with preliminary studies from ongoing analyses.

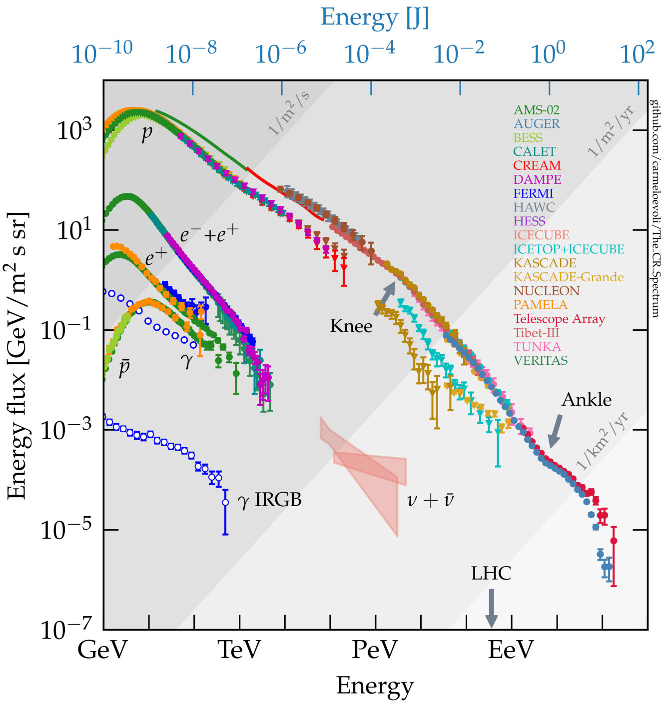

Fig. 1. The cosmic ray energy spectrum.[1]

2. Cosmic Ray Physics

Cosmic rays (CRs) are particles that are produced and accelerated by astrophysical objects, travel through space and can be detected once they reach the Earth. They span a wide energy range, going from the GeV up to the highest energies ever detected of 10^{20} eV. CRs are approximately 90% protons and 9% helium nuclei, even though their composition changes with energy; the remaining fraction is made of all the heavier nuclei up to iron, electrons and a small fraction of anti-matter in the form of anti-protons and positrons. Neutral particles such as astrophysical neutrinos and gamma-rays can also be considered cosmic rays.

The CR energy spectrum follows a well known power-law, shown in Fig. 1. Even though CRs have been studied since the beginning of the 20th century and have already led to many discoveries both in the field of particle physics and astrophysics, there are still many open questions. Their origin and mechanisms of acceleration and propagation are still not completely understood, while the nature of the knee and the way in which the transition from galactic to extra-galactic CRs happens are some of the unsolved issues, among many others.

Precisely measuring the CR spectrum in all of its components is fundamental to improve our current knowledge. For energies up to few hundreds of TeV, direct detection is the best tool. It consists in placing the detector in space, orbiting around the Earth, to detect CRs before they reach the atmosphere. Two distinct classes of experiments can be distinguished based on the detection technique: spectrometers and calorimeters. The former have the advantage of being sensitive to the particle sign which is fundamental to study the antimatter component of CRs; due to the presence of a magnet the geometrical factor is usually small and the energy range limited since the resolution worsens with the increase of the particle momentum ($\frac{\Delta p}{p} \propto p$). The calorimetric technique allows to push the measurements to higher energies, granting a larger geometrical factor and a resolution that improves as the energy increases ($\frac{\Delta E}{E} \propto \frac{1}{\sqrt{E}}$). On the other hand it doesn't provide any information on the sign of the particle charge. Furthermore, since the constraints on size and weight for space-based detectors are prohibitive for a hadronic calorimeter, an electromagnetic one is always chosen, leading to a lower energy resolution for hadrons. Examples of spectrometers for CR detection are the PAMELA[2] and AMS-02[3] experiments while CALET[4] and DAMPE[5] use a calorimeter as their core detector.

3. The DAMPE Space Mission

The DArk Matter Particle Explorer (DAMPE) is a multi-purpose space-based particle detector launched in December 2015 in a sun-synchronous orbit at 500 km of altitude. It was built by the Chinese Academy of Science in collaboration with Italian and Swiss institutes. Its scientific objectives are the study of high energy cosmic electrons and positrons, high energy galactic CRs and gamma-ray detection to study astrophysical sources and to look for Dark Matter (DM) signatures.

3.1. *The detector*

DAMPE consists of 4 sub-detectors (see Fig. 2) used to ensure proper particle identification, tracking and energy measurement of the incoming CRs. The total mass of the payload is 1400 kg and its power consumption is 400 W.

Starting from the top the first sub-detector is the Plastic Scintillator Detector[6](PSD) whose aim is to measure the absolute value of the particle charge through the energy deposit in its bars ($\frac{dE}{dx} \propto Z^2$) and provide gamma-ray identification in an anti-veto mode. The PSD consists of two planes of plastic scintillator bars oriented in the X and Y direction (see Fig. 2 for the chosen reference frame) and staggered to provide better hermeticity. Each plane includes 41 bars which are 884 mm long, 28 mm wide and 5 mm thick. The Silicon-Tungsten Tracker[7] (STK) follows the PSD to provide particle tracking and conversion of the impinging gamma-rays. It is made of 6 silicon planes interleaved with 3 tungsten plates to increase the gamma-ray pair-conversion probability. Each plane has two layers segmented in micro-strips along the X and Y directions. The energy deposit in the silicon planes can also provide an additional information on the particle charge. The core detector, a BGO calorimeter,[8] is placed under the STK with the purpose of measuring the particle energy and distinguishing between electrons/positrons and protons. It is made of 14

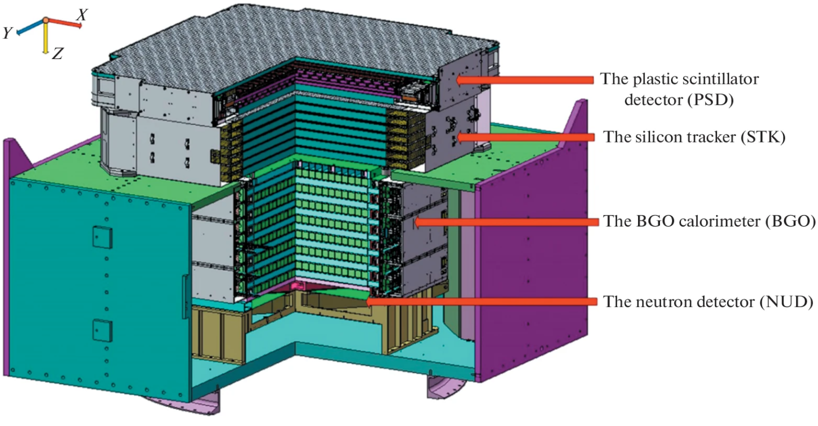

Fig. 2. A schematic view of DAMPE four sub-detectors.[5]

layers, each one with 22 Bismuth Germanium Oxide (BGO) bars whose orientation is alternated between the X and Y directions in successive layers. It is 32 radiation lengths X_0 and 1.6 interaction lengths Λ_I deep. Its high segmentation allows a reconstruction of the shower image and topology that can be used to discriminate electromagnetic showers from hadronic ones. Finally the Neutron Detector[9] (NUD) gives auxiliary information to further separate hadrons from electrons/positrons by measuring the neutron content of the shower developed inside the calorimeter. It is made of one layer of four 30×30 mm^2 boron-loaded scintillator tiles. The slowed neutrons are captured by the ^{10}B atoms through the reaction $n + ^{10}B \rightarrow ^7 Li + \alpha + \gamma$ and therefore produce optical photons that can be detected.

Thanks to this setup DAMPE can achieve excellent performances. The detector acceptance for electrons is 0.3 m^2 sr above 30 GeV with an angular resolution of 0.2^o at 100 GeV and an energy resolution of 1.2% at 100 GeV. The energy of CR nuclei can be measured with a resolution $< 40\%$ at 800 GeV. These characteristics make DAMPE a powerful CR telescope capable of probing electrons/positrons in an energy range from 10 GeV to 10 TeV and protons and nuclei from 40 GeV to 200 TeV.

3.2. *Test beam activities at CERN*

During 2014 and 2015, before the satellite launch, the DAMPE detector underwent a thorough test beam campaign at CERN.[5] The experimental apparatus performance was tested using the Proton Syncrotron and Super Proton Synchrotron facilities that provide electron and proton beams, among other particles. In particular, the BGO calorimeter behaviour was studied in detail, looking at the linearity of its response, its capabilities of electron/proton separation and its energy resolution. The results obtained with a beam of electrons ranging from 0.5 to 243 GeV are

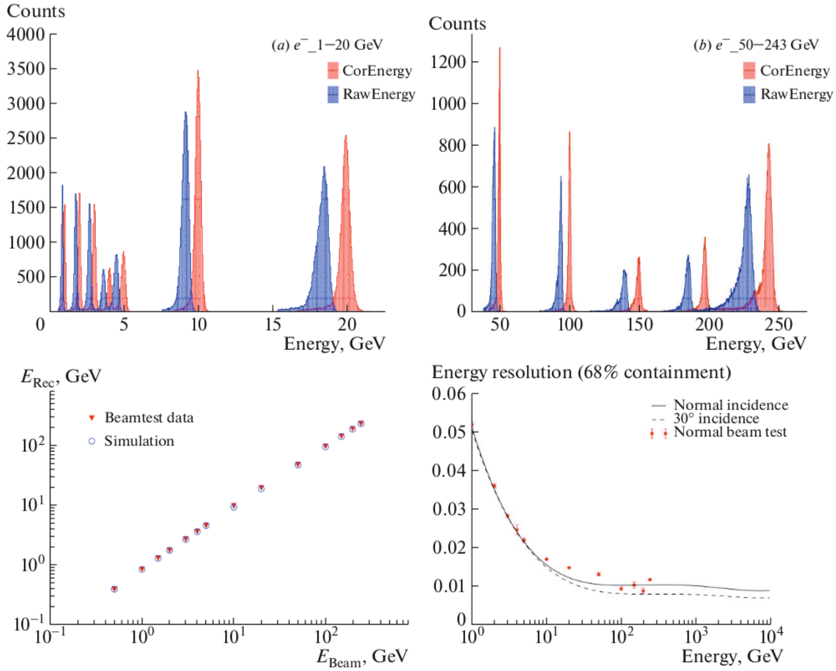

Fig. 3. Results from test beam activities at CERN[5] with electrons in 0.5 − 243 GeV energy range. The two upper plots show the reconstructed energy before and after applying the appropriate corrections. The bottom left plot shows the linear response of the detector as well as the good agreement with simulation, while the bottom right one shows the energy resolution.

shown in Fig. 3. The reconstructed energy, after a correction applied to account for the energy loss due to absorber material in the support structure, is consistent with the beam energy; the calorimeter response is linear in the investigated energy range and the energy resolution follows the expected behaviour, decreasing as the beam energy increases.

3.3. *On-orbit performance and calibration*

Ever since its launch in December 2015, DAMPE has been smoothly collecting data. The live time of the detector is roughly 75.7%: the losses are due to the time spent inside the South Atlantic Anomaly (4.5%), the instrumental dead-time (18%) and the periodically performed on-orbit calibration (1.8%). Triggers dedicated to different analyses and tasks have been defined,[10] applying a pre-scale factor with different values inside and outside the latitude region $\pm 20^o$. The global trigger rate is 70 Hz, daily transmitting a total of 15 GB of data to ground. The on-orbit calibration of each sub-detector is performed using MIP-like particles crossing the volume of interest. In its first five years of operation, from 2016 to 2020, DAMPE has collected more than 10 billion CR events.

4. DAMPE Main Results

4.1. *The electron-positron spectrum*

The cosmic electron+positron spectrum, also called all-electron (CRE) spectrum has been measured up to the TeV scale by both space-based[11–15] and ground-based experiments. The H.E.S.S. experiments produced some results,[16,17] characterized by large systematic uncertainties, suggesting a break in the spectrum at the tera-electronvolt scale. With 530 days of data, DAMPE measured the CRE spectrum[18] in the energy range from 25 GeV to 4.6 TeV. An excellent electron/proton separation is crucial for this measurement. DAMPE is able to discriminate between the two on the basis of two variables related to the BGO calorimeter. The first one $\mathcal{F}_{last}$ is defined as the ratio between the energy deposited in the last BGO layer and the total energy released in the calorimeter. The second one $sumRMS$ describes the shower transverse spread and is defined as:

$$sumRMS = \sum_{i=1}^{N_{layers}} RMS_i = \sum_{i=1}^{N_{layers}} \sqrt{\frac{\sum_j (x_{j,i} - x_{c,i})^2 E_{j,i}}{\sum_j E_{j,i}}} \qquad (1)$$

where $x_{j,i}$ is the coordinate of the j-th bar of the i-th layer, $x_{c,i}$ the coordinate of the identified shower center in the i-th layer and $E_{j,i}$ the energy deposit in the j-th bar of the i-th layer. These two variables can also be combined in a single dimensionless one, ζ:

$$\zeta = \frac{\mathcal{F}_{last} \times (sumRMS/mm)^4}{8 \times 10^6} \qquad (2)$$

As shown in Fig. 4 these variables allow a powerful discrimination between electrons and protons, up to a factor of $10^5 - 10^6$. A proton rejection efficiency of 99.99% can be achieved with an electron/positron efficiency as high as 90%. This powerful

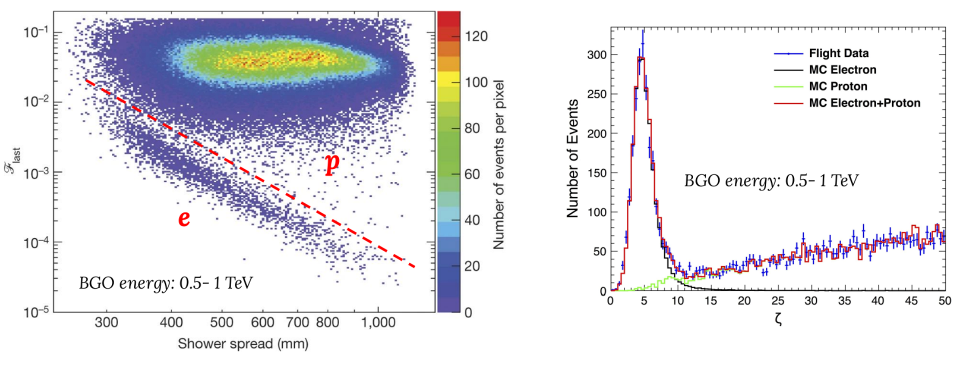

Fig. 4. Variables used to separate electron/positrons from protons, for events of reconstructed energy in the BGO calorimeter in the range $0.5 - 1$ TeV. The left plot shows the regions populated by the different particles in terms of the two variables $\mathcal{F}_{last}$ and $sumRMS$. A similar distinction can be achieved with the dimensionless variable ζ showed in the plot on the right for both flight data and MC simulation.

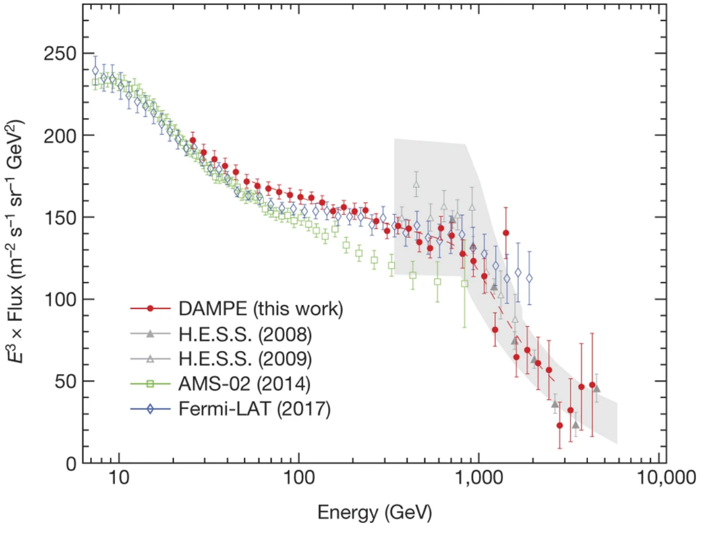

Fig. 5. DAMPE electron-positron flux showing the hardening at the TeV scale, plotted with the results from other experiments. The gray shaded region represents the systematic uncertainty on the H.E.S.S. measurement.[18]

background rejection, together with the excellent energy resolution of the deep electromagnetic calorimeter made the measurement of the CRE spectrum shown in Fig. 5 possible. It shows a hardening at ~ 50 GeV in agreement with the findings of FERMI-LAT[12] and AMS-02[13] and provides the first direct evidence of a break in the spectrum at 0.9 TeV, confirming with high precision what was hinted by H.E.S.S. In fact the DAMPE spectrum is best described by a broken power law model, with a spectral index change from $\gamma \sim 3.1$ to $\gamma \sim 3.9$. Future plans for this analysis include the update of the measurement with a larger statistics sample as well as the implementation of machine learning algorithms and neural networks[19] to further improve the background rejection. Extending the measurement to even higher energy could possibly unveil a contribution from nearby sources or a DM signature.[20–22]

4.2. *The CR light component spectra*

Thanks to its large acceptance and good calorimetric features, the DAMPE detector can measure the most abundant CR species up to ~ 100 TeV. The absolute value of the charge of the incoming particle can be measured with good resolution using information from the PSD so that the different nuclei can be identified.

For what concerns the proton spectrum, the main background comes from electrons/positrons which can be powerfully rejected thanks to the aforementioned calorimetric variables and from helium, that can be discarded by selecting the proton charge with the PSD. The remaining helium contamination after background rejection is estimated with a template fit based on the MC simulation. For events

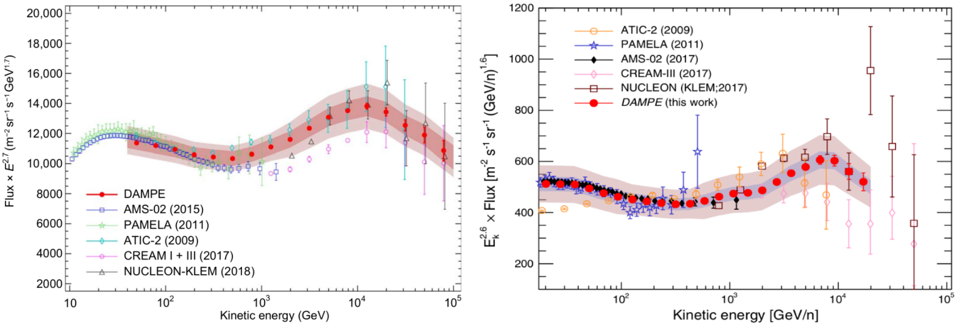

Fig. 6. DAMPE proton[23] (left) and helium[30] (right) spectra plotted with results from previous experiments. The dark (light) gray shaded area represents the statistical (systematic) uncertainty.

with energy reconstructed in the calorimeter lower than 10 TeV the helium fraction is found to be below 1%, it then increases to 5% at 50 TeV.

DAMPE measured the proton spectrum[23] (see Fig. 6) in the energy range 40 GeV − 100 TeV with its first 30 months of data. A hardening at a few hundred GeV previously observed by other experiments[24–29] was found, as well as the first evidence of a softening at 14 TeV indicating a new feature in the spectrum with a significance of 4.7σ. Above the hardening the spectrum is best described by a smoothly broken power law (SBPL). The fit of this model gives a break energy of $13.6^{+4.1}_{-4.8}$ TeV with a spectral index of $\gamma = 2.60 \pm 0.01$ that softens with a variation of $\Delta\gamma = +0.25 \pm 0.07$.

A similar analysis procedure was used to measure the spectrum of helium from 70 GeV to 80 TeV with 54 months of flight data (see Fig. 6). The sample was selected using the PSD-reconstructed charge as well as a loose charge selection using the first plane of the STK tracker to reduce the proton contamination. In this way the estimated fraction of protons goes from 0.05% for events with reconstructed energy of 20 GeV to 4% at 60 TeV. The DAMPE helium spectrum confirms a hardening observed by other experiments at the TeV scale[24,25,28,29,31] and reveals a softening at ~ 34 TeV with a significance of 4.3σ. Similarly to the proton flux, a fit of a broken power law model above the hardening well describes the data and estimates the softening at and energy of $34.4^{+6.7}_{-9.8}$ TeV with a spectral index change of $\Delta\gamma = +0.51^{+0.18}_{-0.20}$.

Looking at proton and helium together suggests a charge-dependent energy softening, although a mass-dependent one cannot be excluded with the currently available data. The complex structure of these spectra shifts away from a simple power law CR paradigm, offering new insight into the properties of galactic CRs.

Another independent analysis, currently in progress, aims at measuring the flux of proton and helium together. In this way the sample will inherently have a very low background and the flux measurement can be extended to energies higher than the single proton and helium ones. A preliminary result,[32] shown in Fig. 7, features

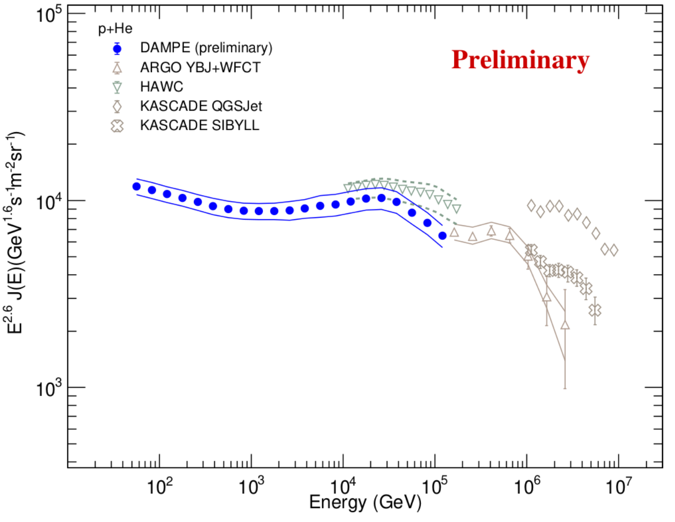

Fig. 7. DAMPE preliminary proton plus helium spectrum[32] with the results of some ground based experiments. The statistical errors are represented by the error bars while the lines represent the systematic uncertainties.

a hardening at ~ 600 GeV and a softening at ~ 25 TeV. Another interesting aspect of this analysis is the possibility of a comparison with measurements from some CR ground-based experiments.[33–35] The analysis is still in a preliminary stage aiming at a final spectrum reaching even higher energies and including a complete evaluation of the systematic uncertainty.

4.3. *Medium to heavy mass CR nuclei*

Many other analyses are currently ongoing regarding the spectra of CR nuclei including primaries C, O and Fe and secondaries Li, Be and B. Each nuclear species can be identified thanks to the good PSD charge resolution and further background suppression can be achieved with the auxiliary information from the energy deposit in the STK planes.

In particular the behaviour of secondary over primary ratios such as B/C offers a direct handle on the energy dependence of the galactic diffusion coefficient, fundamental to study CR propagation. Preliminary results from DAMPE data[36] (see Fig. 8) in the energy range $20 - 400$ GeV/n are in agreement with PAMELA[37] and AMS-02,[38] whose measurement stops at $\sim$ TeV/n. DAMPE aims at extending the measurement to higher energy with its final result.

Another objective of current analyses is to measure the flux of the primaries C, O and Fe up to the TeV/n scale. Systematic contributions to the Carbon and Oxygen analyses[41] are currently being estimated while the Iron analysis[42] needs a detailed study of the nuclei fragmentation inside the detector.

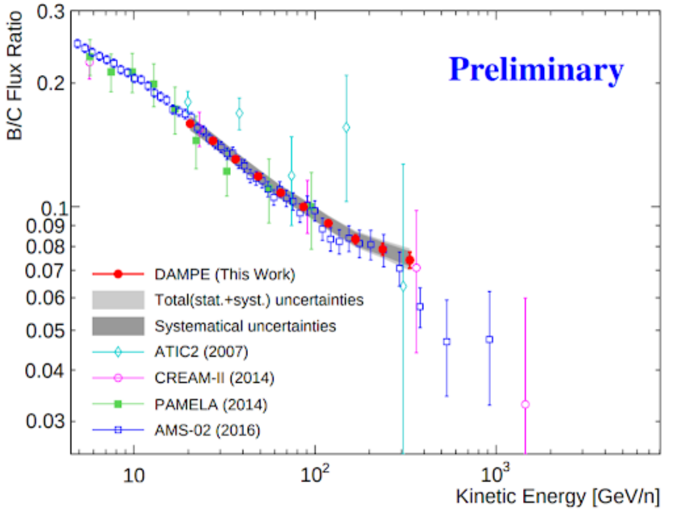

Fig. 8. DAMPE preliminary B/C flux ratio[36] compared to results from other experiments.[37–40]

5. Gamma-Ray Physics

As previously mentioned, DAMPE can also act as a powerful gamma-ray telescope. Gamma-ray detection is possible using the PSD to tag and discard most of the background from charged particles. The remaining contamination from protons is further reduced looking at the topology of the shower developed inside the BGO calorimeter and residual electrons are discarded using the signal in the first STK plane. The DAMPE detector has an effective area for gamma-rays of 1200 cm^2 at 100 GeV and can detect them at energies from 20 GeV up to 10 TeV.

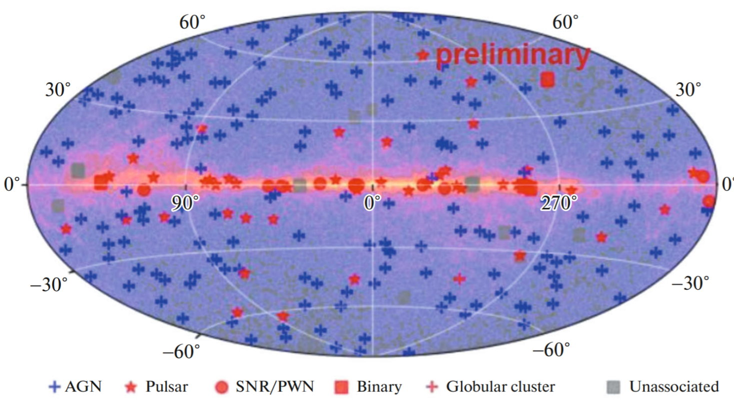

Fig. 9. Gamma-ray sources identified by DAMPE[43] with the associated type, in galactic coordinates (preliminary).

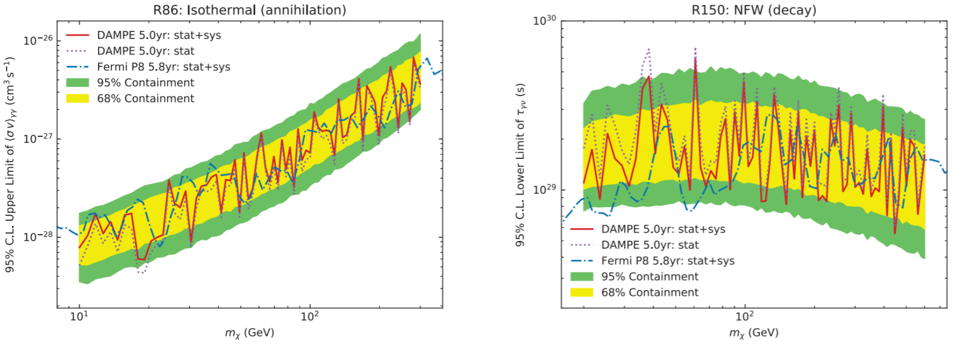

Fig. 10. The 95% confidence level limits on different DM models.[44,45] The plot on the left shows the upper limit on DM annihilation cross section $\langle \sigma v \rangle_{\gamma\gamma}$ under the assumption of an Isothermal profile, with the search performed in the R86 region. The plot on the right instead shows the lower limit on the DM decay time $\tau_{\gamma\nu}$ under the assumption of the Navarro-Frenk-White profile, with the search performed in the R150 region. Light and dark gray bands respectively show the 68% and 95% containment regions.

The first 5 years of data have been used to construct a sky map of the identified gamma-ray sources[43] (see Fig. 9). The catalog of 222 sources includes more than 160 AGNs and more than 40 pulsars.

DAMPE excellent energy resolution for photons allows for a search of line-like features in the gamma-ray spectrum. Such features are unlikely to be produced by standard astrophysical processes, therefore a detection could be a hint of a possible DM candidate. A search was performed[44,45] in two radial regions around the galactic center, with extension of 86^o (R86) and 150^o (R150). In both cases a small rectangular region around the galactic center was masked. In the search no line structures were found, leading to constraints on DM annihilation cross section or decay time, depending on the adopted model, as shown in Fig. 10. The limits imposed by DAMPE improve on those of FERMI-LAT[46] for decaying DM with a particle mass lower than 100 GeV, while they are comparable for other mass values and for interacting DM.

6. Conclusions

The DAMPE detector was launched in December 2015 and has been smoothly taking data ever since. Thanks to its excellent energy resolution, tracking capabilities and powerful electron/proton discrimination it has produced important results regarding galactic CRs.

The CRE spectrum was measured in the energy range 25 GeV − 4.6 TeV providing evidence of a break at 0.9 TeV. The proton spectrum from 40 GeV to 100 TeV gave the first evidence of a softening at 14 TeV. Similarly, the helium spectrum was measured from 70 GeV to 80 TeV revealing a softening at ~ 34 TeV. The DAMPE proton and helium fluxes seem to favour the hypothesis of a charge-dependent softening but a mass-dependent one can't be ruled out.

A preliminary result of the p+He spectrum shows the potential of this analysis to reach even higher energies than the single proton and helium spectra, with the interesting possibility of comparison with the measurements from ground-based experiments. A preliminary measurement of the B/C ratio in the range $20-400$ GeV/n is in agreement with PAMELA and AMS-02. The final aim of the analysis is to extend the measurement beyond the TeV/n scale. Future plans concerning CR nulcei also include the measurement of medium and heavy mass primaries Carbon, Oxygen and Iron as well as secondaries Lithium, Beryllium and Boron, aiming at extending current measurements at higher energies with unprecedented precision.

DAMPE can also efficiently detect gamma-rays. With its first 5 years of data it has produced a preliminary catalog of gamma-ray sources with a high-resolution sky map. Out of the 222 detected sources more than 160 are AGNs and more than 40 are pulsars. DAMPE also performed a search for line-like features in the gamma-ray spectrum as a signature of DM. No lines were found and constraints were put on DM parameters for different models, in particular for decaying DM the lower limit on the decay time for a particle mass lower than 100 GeV improves on the one previously imposed by FERMI-LAT.

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