Frascati Physics Series Vol. 69 (2019)
PHOTON 2019 - International Conference on the Structure and the Interactions of the Photon
Jun 3-7, 2019

OBSERVATION OF HIGH-ENERGY COSMIC PHOTONS WITH NEW-GENERATION SPACE TELESCOPES

Piergiorgio Fusco
Dipartimento di Fisica "M. Merlin" dell'Università e del Politecnico di Bari, I-70126 Bari, Italy
Istituto Nazionale di Fisica Nucleare (INFN) Sezione di Bari, I-70125 Bari, Italy

Abstract

While the Fermi gamma-ray telescope lives its 11^{th} year in orbit, new particle and gamma-ray space detectors are in operation as DAMPE (DArk Matter Particle Explorer), or are in the development stage as HERD (High Energy cosmic Radiation Detector). DAMPE was launched in 2015 by a collaboration of Chinese, Italian and Swiss scientific institutions and performs high-quality observations of cosmic electrons, protons, nuclei and gamma rays up to 10 TeV with good angular and energy resolution. HERD will be installed on board the Chinese Space Station to be launched in 2022 and will perform accurate measurements of energy and direction of cosmic rays and photons. An overview on these experiments and a summary of the main gamma-ray results and expectations will be presented.

1 Introduction

Cosmic photons of energy from a few 100 keV to about 1 PeV are produced in non-thermal processes involving the decay, the annihilation and the interaction of high-energy particles and nuclei. In particular, gamma rays are unique since they are free from thermal radiation and can propagate with negligible attenuation and deflection through the galaxy; however, they can not pass the atmosphere. Thus, the observation of gamma rays from space is of fundamental importance to achieve the clearest view onto non-thermal physics in local sources, as the Earth's limb, the Moon and the Sun; in galactic ones, like pulsars and supernova remnants; and in extragalactic ones, like blazars, gamma-ray bursts and gravitational waves production events. It can also shed light on exotic or unknown sources, like dark matter.

2 The DAMPE experiment

The DArk Matter Particle Explorer (DAMPE) [1] is a particle detector launched on 17 December 2015 in a Sun-synchronous orbit at a 500 km altitude. Its main scientific goals are the study of high energy cosmic electrons, positrons, photons, protons and nuclei; the observation of gamma rays from astrophysical sources; the search for dark matter signatures, for electromagnetic counterparts of gravitational waves and for exotic particles. DAMPE has been designed to have an excellent performance: it can detect particles with energy from some GeV up to tens of TeV with a good energy resolution, an accurate angular resolution and a large field of view.

2.1 The DAMPE instrument

DAMPE is composed by four sub-detectors (Figure 1): a Plastic Scintillator Detector (PSD), a Silicon-Tungsten Tracker (STK), a BGO Calorimeter (CALO) and a Neutron Detector (NUD).

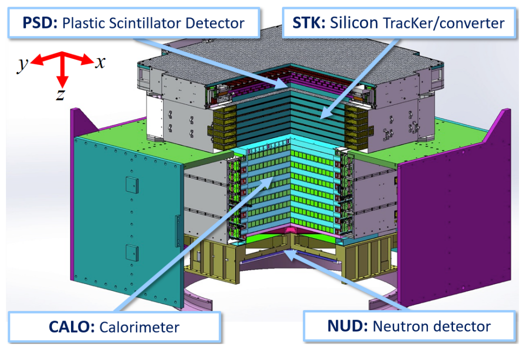

Figure 1: *The DAMPE instrument with its sub-detectors.*

The PSD detects charged particles and measures they charge number Z. It is made by two layers of orthogonal scintillator bars, providing information on the x and y coordinates. The STK is devoted to reconstruct the particle tracks and to convert photons into electron-positron pairs. It consists of 12 position-sensitive silicon detector planes (6 for the x-, 6 for the y-coordinate); 3 planes are equipped with 1 mm thick layers of tungsten to enhance the conversion of gamma rays. The BGO calorimeter measures the energy deposition of incident particles and analyzes the electromagnetic shower profile. It is composed of 308 BGO crystal bars arranged in 14 layers of 22 bars each; the bars of a layer are orthogonal to those of the adjacent one, to observe the shower in the xz and yz views. The total depth of the calorimeter is 32 radiation lengths and 1.6 nuclear interaction lengths. The last sub-detector is the NUD, made of four boron-loaded plastic scintillators, that improves the overall hadron identification efficiency.

We developed [2)] a method to determine the absolute energy scale of DAMPE using the energy cutoff in the spectrum of cosmic-ray electrons and positrons that, below a certain rigidity, are bent back to space by the Earth's magnetic field. The expected cutoff was computed with a Monte Carlo simulation and compared with the measured one, yielding a correction factor of 1.2% to be applied to DAMPE data.

2.2 Observation of high-energy photons

DAMPE is a multi-purpose space detector and it has already produced relevant results in the study of cosmic electrons and positron, discovering a break in their spectrum [3)], of cosmic protons, extending the study of their flux up to 100 Tev [4)] and on the distribution of elements in cosmic rays [5)]; other searches are ongoing on cosmic helium nuclei, on dark matter signatures, and many other subjects. However, DAMPE is also an excellent gamma-ray space telescope and many searches are done on cosmic photons.

The photon selection is a challenging tasks, since the background of charged particles (electrons, protons and nuclei) has fluxes much higher than the galactic gamma-ray emission; the minimum rejection power required at 100 GeV is 10^5 for protons and 10^3 for electrons.

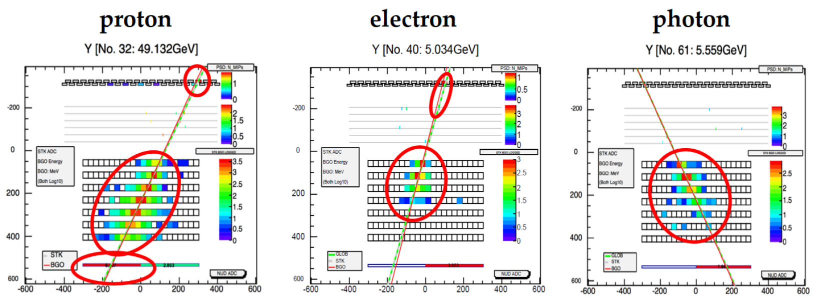

Figure 2: *Typical responses of DAMPE sub-detectors to various particles.*

The rejection techniques are based on the event topology (Figure 2). Protons are mainly suppressed using the PSD response and the shower profile in the BGO calorimeter with a contribution from the NUD, while electrons are mainly rejected using the PSD response and the first plane of the STK. Charged particles are detected by all planes of STK, while photons convert in e^+e^- couples mainly in tungsten layers and are detected only in the following planes. We are also testing the particle identification with Convolutional Neural Networks and Random Forest Classifiers [6]. Figure 3 shows the performance in photon detection, after the application of the selection criteria: the acceptance is over 0.1 m^2sr from 10 GeV to 1000 GeV and the angular resolution is 1° at 1 GeV, 0.1° at 100 GeV and 0.05° at 1 GeV.

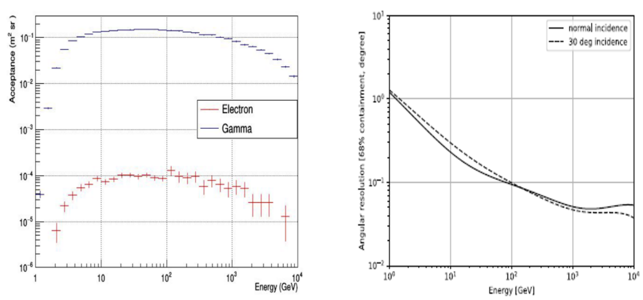

Figure 3: *DAMPE performance in photon detection: acceptance (left) and angular resolution(right).*

Figure 4 shows the gamma-ray sky as observed by DAMPE after 3 years: the main sources are well resolved and their positions agree with those measured by the Fermi/LAT.

DAMPE is also studying the gamma-ray emission of pulsars: counts maps, spectral energy distributions and pulse time profile are analyzed. For example, Figure 5 shows the results for Geminga.

DAMPE can detect the variability of some extragalactic sources, contributing to the study of transients. In some cases, for example with CTA 102, the detection was announced with an “Astronomer’s Telegram” [7]. DAMPE also participates to the multi-messenger observation of high-energy cosmic phenomena: for example it has observed the extragalactic source TXS 0506+056 at 5.7 billion light-years that is the possible origin of the 290 TeV muon neutrino observed by IceCube in September 2017 [8], though no variability was detected due to the limited statistics.

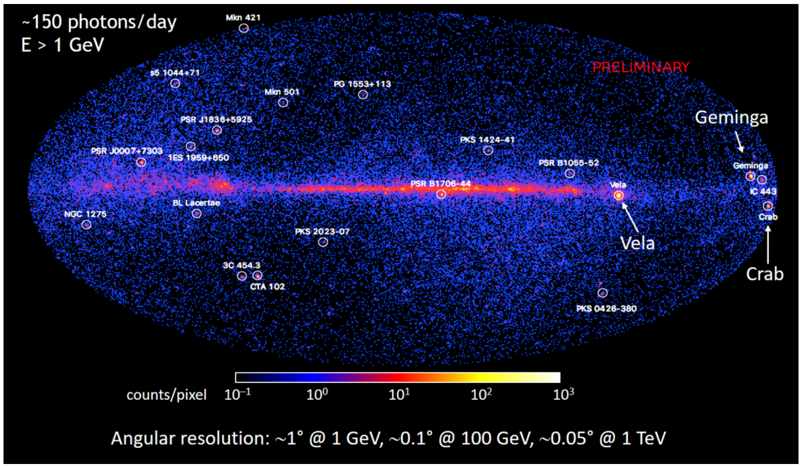

Figure 4: *The gamma-ray sky as observed by DAMPE. The major sources are well detected.*

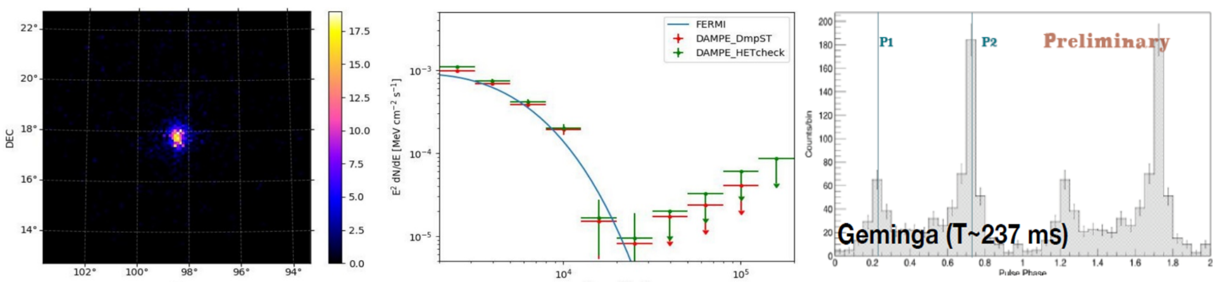

Figure 5: *The Geminga pulsar as observed by DAMPE: counts map (left), spectral energy distribution (center), phase profile (right).*

3 The HERD experiment

The High Energy cosmic Radiation Detector (HERD) [9)] is a new-generation particle detector to be installed on the future Chinese Space Station in 2025. It will search for dark matter signatures and study cosmic rays, electrons, and gamma-rays. Its key features will be the large exposure (about 15 m^2sr yr, 10 times larger than previous space experiments) and an unprecedented gamma-ray sensitivity. It will perform high-statistics observations of electrons and photons from 100 GeV to 10 TeV and better spectral and composition measurements of cosmic rays from 300 GeV to 1 PeV.

3.1 The HERD instrument

HERD (Figure 6) will consist of a LYSO calorimeter (CALO) inside 5 sides of Silicon-Tungsten Trackers (STK) and 6 sides of Plastic Scintillator Detectors (PSD), plus a Transition Radiation Detector (TRD).

The trackers will be made of 7 layers (top) or 3 layers (sides) of SSDs with xy coordinates readout, interleaved with tungsten foils. They will be devoted to gamma-ray conversion and tracking, charge measurement, shower analysis and backsplash rejection. Optimization is ongoing, taking into account

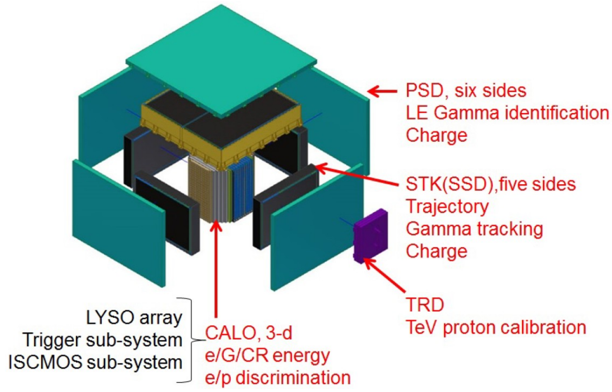

Figure 6: *An exploded view of the HERD instrument with its sub-detectors.*

that cosmic-ray calorimetry requires a shallow tracker, multiple energy measurements require many planes and gamma-ray acceptance requires a thick tracker. A depth of ~ 2 radiation lengths is expected.

The calorimeter will consist of more than 7500 LYSO crystals $3 \times 3 \times 3$ cm^3 each, with high light output and quick decay time, read by WLS fibers to be connected to image intensifiers and high resolution IsCMOS cameras. Its depth will be 55 radiation lengths and 3 nuclear interaction lengths. These features will allow an excellent energy resolution and a high-definition 3D imaging of the showers. A prototype has already been implemented and tested on particle beams at CERN in December 2018 [10]: Figure 7 shows the calorimeter energy resolution obtained for electrons, protons and photons.

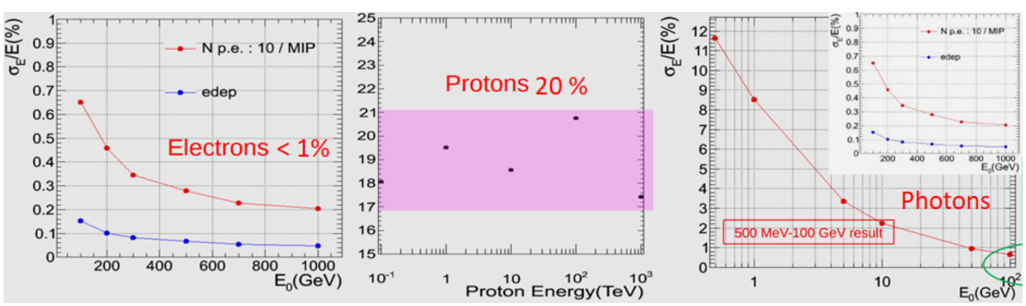

Figure 7: *HERD calorimeter beam tests results: electrons (left), protons (middle) and photons (right).*

The PSD will contribute in detecting charged particles, selecting gamma rays, building the trigger, and measuring the cosmic nuclei charges. It is being tested on particle and ion beams: several configurations and segmentations are under study to optimize performance and reduce background and backsplash. Finally, the TRD will be made of PP foils and will be devoted to the calibration at high energies.

3.2 HERD perspectives

The baseline HERD detector is defined and fulfills the requirements; further improvements and optimization are ongoing. The calorimetric detector with unprecedented depth and geometrical factor and the other high-performance sub-detectors will allow a significant improvement in cosmic-ray physics above the PeV, high-energy (and maybe also sub-GeV) cosmic photons observations and dark matter searches.

As an example, here we present our analysis of the expected sensitivity to a gamma-ray line signal: for monochromatic photons from a ~ 400 GeV dark matter particle, a sensitivity much greater than other experiments would allow to discriminate the signal over the other particles' background.

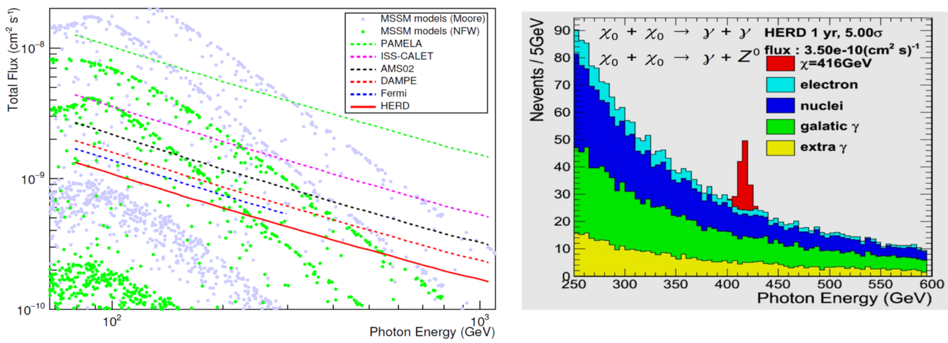

Figure 8: *The sensitivity of HERD to a gamma-ray line, compared to other instruments (left); a simulation of a* ~ 400 *GeV line over the background after 1 year of observations (right).*

4 Conclusions

DAMPE is operating stably since more than three years; 6 billion charged cosmic rays and 0.2 million gamma-rays have been collected over a wide energy range. Important results on charged particles have been obtained and others are expected. A significant contribution is given to photon studies: many sources and items are studied, more statistics is being accumulated and several publications are in preparation.

HERD will be taking data on board the CSS from 2025 for more than 10 years. It will be a calorimetric and tracking detector with unprecedented acceptance and will play a fundamental role in cosmic ray physics, dark matter search and gamma-ray astronomy. It will be the only high-energy gamma-ray detector operating in space in the next future, and with excellent performance.

References

1. J. Chang *et al*, Astropart. Phys. **95**, 6 (2017).
2. J. Zang *et al*, Proc. of Sci., PoS(ICRC2017), 197 (2017).
3. G. Ambrosi *et al*, Nature **552**, 63 (2017).
4. C. Yue *et al.*, Proc. of Sci., PoS(ICRC2019), 163 (2019).
5. T. Dong *et al*, Astropart. Phys. **105**, 31 (2019).
6. S. Garrappa *et al*, Proc. of Sci., PoS(ICRC2017), 603 (2017).
7. Z.L. Xu *et al*, Astronomer's Telegram No. 9901 (2016).
8. M.G. Aartsen *et al*, Science **361**, 6398 (2018).
9. S.N. Zhang *et al*, Proc. of SPIE **9144**, 91440X (2014).
10. Y. Dong *et al*, Proc. of SPIE **9905**, 99056D-1 (2016).