PROCEEDINGS OF SCIENCE

Cosmic rays and gamma rays with DAMPE and HERD

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Cosmic photons and neutrinos, charged cosmic rays and gravitational waves are all messengers carrying complementary information about properties and processes of the universe. In this contribution I present the cosmic ray and gamma ray measurements performed with the satellite-borne DAMPE (DArk Matter Particle Explorer) detector which is smoothly taking data since December 2015. I also introduce design and prospects of the High Energy cosmic-Radiation Detection facility (HERD) which will be the future calorimeter experiment on board the Chinese Space Station (CSS).

Neutrino Oscillation Workshop-NOW2022
4-11 September, 2022
Rosa Marina (Ostuni, Italy)

*Speaker

PoS(NOW2022)047

1. Introduction

The DArk Matter Particle Explorer (DAMPE) is a satellite-based experiment operating since December 2015 in a Sun-synchronous orbit around Earth at an altitude of $\sim$ 500 km, with a period of $\sim$ 95 minutes and an inclination of $\sim 97°$. The main scientific objectives of DAMPE are the indirect search for dark matter (DM) in the electron + positron and gamma-ray fluxes, the study of the gamma-ray sky, the detection of cosmic electrons and positrons, protons and heavier nuclei to investigate the origin, acceleration and propagation of cosmic particles. DAMPE is composed of four subdetectors (Fig. 1 left): a Plastic Scintillator Detector (PSD), a Silicon-Tungsten tracKer-converter (STK), an imaging calorimeter made of Bismuth Germanium Oxide (BGO) bars with a total depth of about 32 radiation lengths and 1.6 nuclear interaction lengths and a NeUtron Detector (NUD). Thanks to them, DAMPE is able to detect electrons, positrons and gamma rays from 5 GeV to 10 TeV, as well as protons and heavier nuclei from 50 GeV to hundreds TeV, with excellent energy and angular resolutions [1].

The High Energy cosmic-Radiation Detection facility (HERD) is a space-borne experiment which will be launched and installed on board the Chinese Space Station (CSS) in 2027, and will take data for at least 10 years. The physics goals of HERD are the same of DAMPE but, thanks to its design, HERD will be able to detect electrons and positrons from 10 GeV to 100 TeV, gamma rays from 500 MeV to 100 TeV, as well as protons and heavier nuclei from 30 GeV to few PeV. HERD will be composed of five subdetectors (Fig. 1 right) [2]: a 3D, homogeneous, isotropic and finely-segmented calorimeter (CALO) with a total depth of about 55 radiation lengths and 3 nuclear interaction lengths, a scintillating FIber Tracker (FIT), a Plastic Scintillator Detector (PSD), a Silicon Charge Detector (SCD) and a Transition Radiation Detector (TRD). The design of the HERD detector is being studied to maximize its acceptance, reduce the systematic uncertainties and control the nuclei fragmentation. These objectives will be respectively achieved with the 3D calorimeter in the center and a sector of FIT, PSD and SCD on the four lateral sides and on the top, a double CALO readout system and an in-flight CALO calibration with TRD and with the charge detector as the outermost detector.

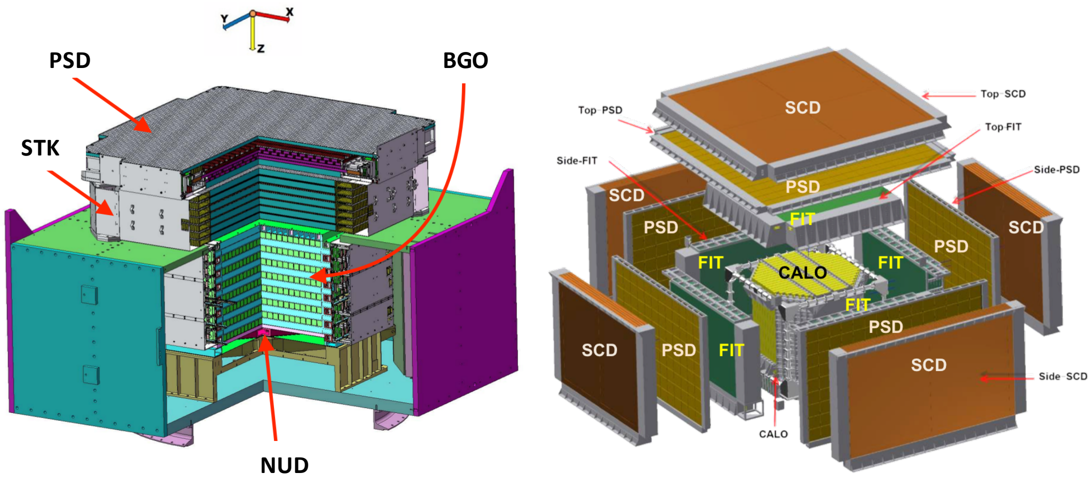

Figure 1: Left: Schematic view of the DAMPE detector. Right: Exploded view of the HERD detector.

2. Cosmic rays with DAMPE

DAMPE measured the **electron + positron** (CRE) spectrum from 25 GeV to 4.6 TeV, with $\sim$ 18 months of data [3]. The study of the CRE flux above 1 TeV is interesting because electrons from 100 GeV lose their energy via inverse Compton scattering and synchrotron radiation resulting in limited lifetime and propagation distance. Therefore, electrons above few TeV are expected from local sources (< 1 kpc distance) or from dark matter annihilation and/or decay. The CRE spectrum (Fig. 2 left) exhibits a spectral hardening at $\sim$ 50 GeV. The break found with a significance of 6.6 σ at about 0.9 TeV confirms the break suggested (with large uncertainties) by the ground-based experiment H.E.S.S. [4]. With 30 months of data, DAMPE measured the **proton** spectrum from 40 GeV to 100 TeV [5]. It has a hardening at about 300 GeV (Fig. 2 right) and revealed for the first time a softening at about 14 TeV found with a significance of 4.7 σ. The **helium** spectrum was measured by DAMPE from 70 GeV to 80 TeV with 54 months of data. The helium flux (Fig. 3 left) has a hardening at few TeV and a softening at $\sim$ 34 TeV detected for the first time and with a significance of 4.3 σ [6]. The comparison between the proton and helium fluxes shed light on the cosmic ray acceleration and propagation mechanisms; in particular, the energy at which the softening occurs suggests that this energy is charge-dependent, although a mass-dependent softening energy cannot be excluded with the current measurement uncertainties. A deep learning method [7] for the particle trajectory reconstruction with DAMPE was developed. It facilitates the identification of the particle absolute charge with the tracker enabling the measurement of the cosmic proton and helium spectra at extreme energies, towards the PeV scale, hardly achievable with the standard track reconstruction methods. DAMPE also measured the **proton+helium** flux. Since the abundance of nuclei heavier than helium is much lower, the acceptance of the combined analysis is much larger than the acceptances of the proton and helium independent analyses. The larger acceptance enables the extension of the energy range up to hundreds TeV and therefore the comparison with the measurements made with ground-based experiments. The spectrum obtained with a preliminary analysis (Fig. 3 right) ranges up to 300 TeV and is characterized by a hardening at $\sim$ 600 GeV and a softening at $\sim$ 25 TeV, due to the combination of the proton and helium spectra. This analysis is now being finalized but previous results are published in [8]. Several independent analyses are ongoing for Li, Be, B, C, N, O, Ne, Mg, Si and Fe nuclei. Recently DAMPE published the secondary-to-primary **B/C and B/O** flux ratios from 10 GeV/nucleon to 5.6 TeV/nucleon [9]. The observed flux ratios (Fig. 4) were obtained with six years of data and both show a spectral hardening at $\sim$ 100 GeV/nucleon.

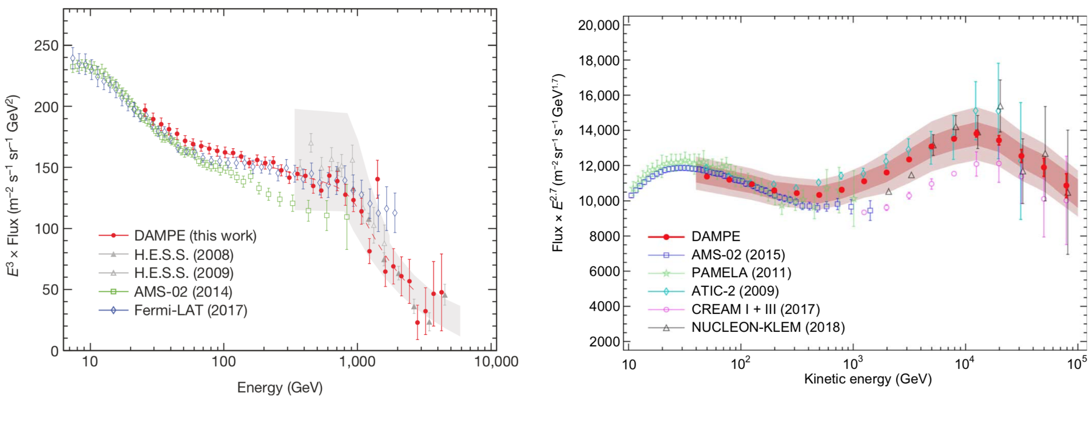

Figure 2: DAMPE electron + positron (left) and proton (right) spectra.

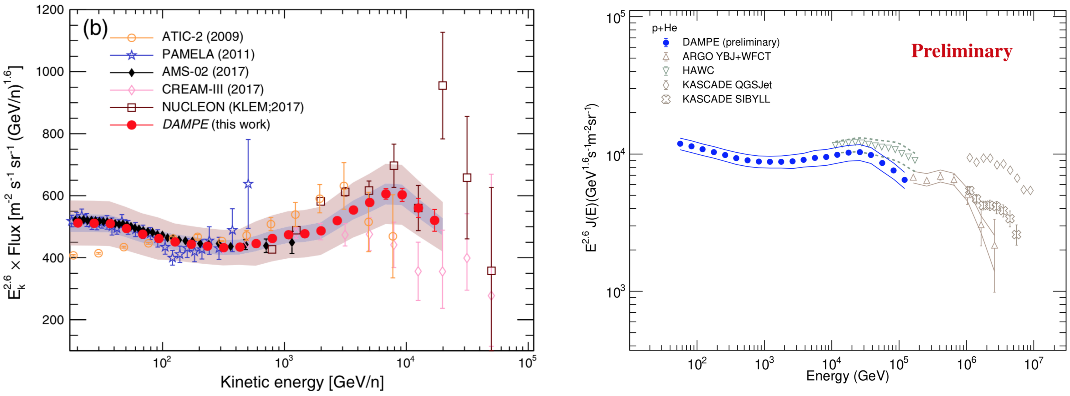

Figure 3: DAMPE helium (left) and proton + helium (right) spectra.

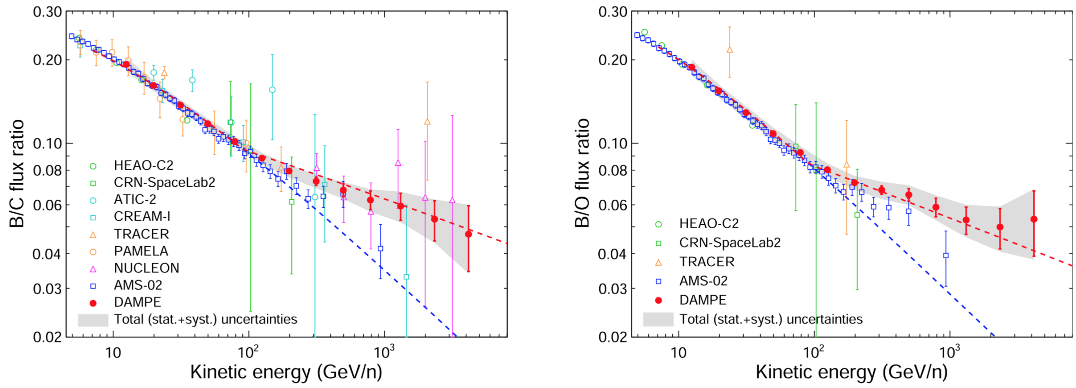

Figure 4: DAMPE boron-to-carbon (left) and boron-to-oxygen (right) spectra.

3. Gamma rays with DAMPE

DAMPE performed the search for line signals in the gamma-ray spectrum between 10 GeV and 300 GeV [10] looking for monoenergetic gamma-ray emissions due to the neutralino annihilation $\chi\bar{\chi} \to \gamma X$ ($X = \gamma, Z, H$) or the gravitino decay $\tilde{G} \to \gamma\nu$ with R parity violation. No line signal was found and upper limits on the velocity-averaged cross section for $\chi\bar{\chi} \to \gamma\gamma$ and lower limits on the decay lifetime for $\tilde{G} \to \gamma\nu$, both at 95% confidence level, were set (Fig. 5). These constraints are similar to the ones put by Fermi-LAT below 100 GeV while the lower limits on the decay lifetime are stronger. DAMPE searches for sources of gamma rays above 2 GeV. The sky map and the position of the 260 identified gamma-ray sources is shown in Fig. 6. 251 sources (out of 260) were associated with the sources of the Fermi-LAT catalog (4FGL). Most of the sources are active galactic nuclei and pulsars. This analysis is now being finalized but previous results and more details can be found in [11].

4. Cosmic rays with HERD

HERD will perform high statistic precise measurements of **electrons + positrons** in the energy range of DAMPE and beyond, up to 100 TeV. With only one year of data, HERD will be able to distinguish if the excess of the CRE flux at $\sim$ 1 TeV is due to an astrophysical source, like a pulsar wind nebula (PWN), or to dark matter (Fig. 7 left). The measurement of the energy spectrum

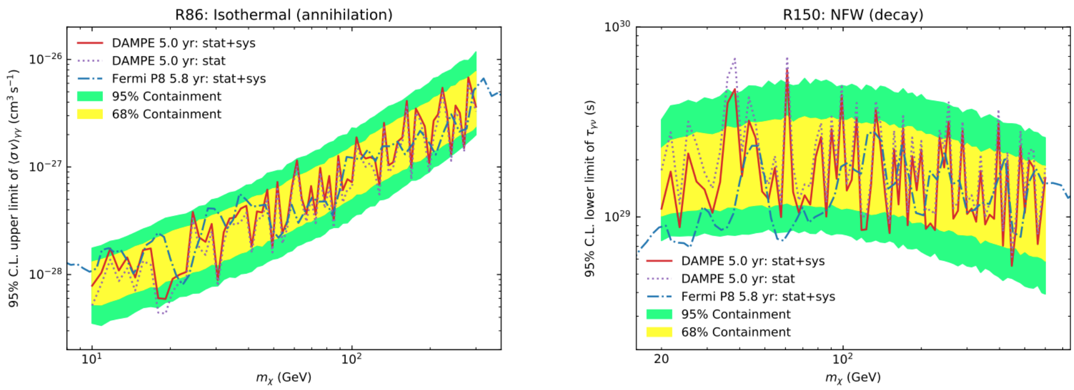

Figure 5: DAMPE 95% confidence level (C.L.) upper limits on the velocity-averaged DM annihilation cross section assuming the isothermal DM profile (left). 95% C.L. lower limits on the DM decay lifetime assuming the Navarro-Frenk-White DM profile (right).

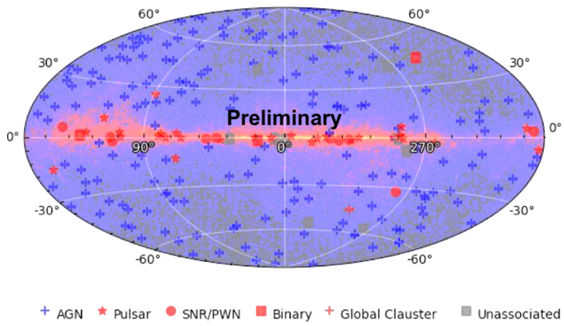

Figure 6: DAMPE gamma-ray sky map, position and classification of the identified sources

of **protons** and heavier **nuclei** (|Z| < 28) up to few hundreds TeV/nucleon will provide further insights into the production, acceleration and propagation mechanisms of cosmic rays. HERD will explore directly in space the “knee” of the all-particle flux that is the region where ground-based experiments observed a change of the spectral index, that could indicate the confinement limit of high energy particles by the galactic magnetic field, and the contribution of extra-galactic sources. Fig. 7 (right) shows the simulated proton flux as measured by HERD with 5 years of data.

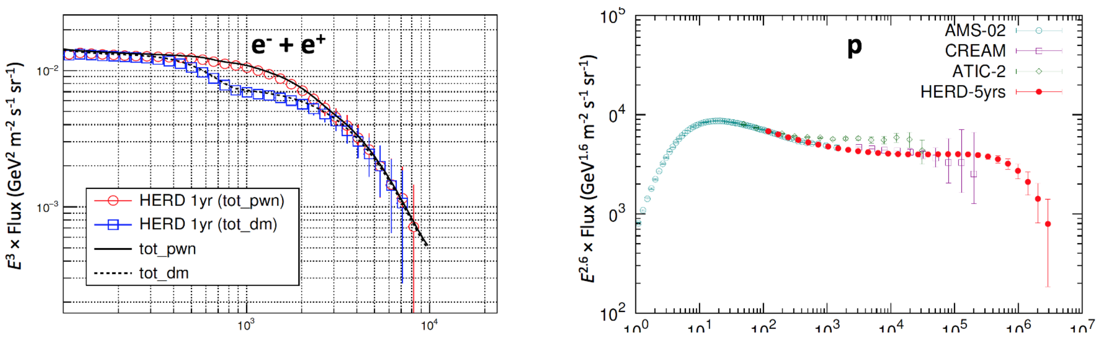

Figure 7: Expected $e^- + e^+$ flux as measured by HERD with one year of data (left). Expected proton flux as measured by HERD with five years of data (right).

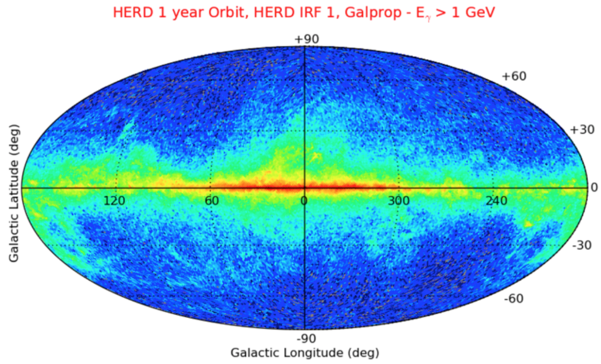

Figure 8: Expected HERD one-year map of the gamma-ray sky.

5. Gamma rays with HERD

Thanks to its large acceptance and sensitivity, HERD will be able to perform a full gamma-ray sky survey from 100 MeV to study galactic and extragalactic gamma-ray sources and diffuse emission. The monitoring of high energy gamma-ray sources in space is very crucial in the era of the multimessenger and multiwavelength astronomy, as demonstrated by the Fermi-LAT detection [12] of gamma-ray counterpart of the gravitational wave detected by LIGO. HERD will play a dominant role in the GeV-TeV astronomy in 2027-2037. The sky map expected from HERD after 1 year of activity is illustrated in Fig. 8. HERD will also search for DM signatures in the gamma-ray spectrum from 10 GeV to 100 TeV with the best sensitivity ever achieved.

6. Conclusions

The DAMPE particle experiment is taking data smoothly since December 2015 providing several results in the cosmic ray spectra up to energies never reached before in space. HERD will operate on board the CSS from 2027 for at least 10 years. Thanks to its unprecedented acceptance, HERD will achieve fundamental and frontier objectives in dark matter search, cosmic ray physics and gamma-ray astronomy. To improve the detector design, several simulation works and tests both in laboratory and with particle beams are ongoing [13–17].

Acknowledgments

The author gratefully acknowledge the financial support from the Swiss National Science Foundation (SNSF-PZ00P2_193523).

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PoS(NOW2022)047