PROCEEDINGS OF SCIENCE

Mega ALPACA to explore multi-PeV gamma-ray sky in the southern hemisphere

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To explore the southern gamma-ray sky in the sub-PeV region ALPACA is now under construction near the Chacaltaya mountain in Bolivia. ALPACA is expected to discover various sub-PeV emitters, which are accelerating hadrons beyond PeV energy. To determine the maximum acceleration energy in the galaxy, a square kilo meter (a Mega square meters) air shower array, Mega ALPACA is discussed as a next generation observatory. With high-statistics observations not only the highest energy object, but also distribution of diffuse gamma rays, nearby active galaxies and space weather are also in the main scope of Mega ALPACA. Design and possible scientific potentials of Mega ALPACA are presented.

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1. Introduction

Since the discovery of sub-PeV (>100 TeV) gamma-ray emission from the Crab nebula by the Tibet ASγ collaboration in 2019 [1], gamma-ray astronomy entered in a new era. HAWC [2] and LHAASO [3] also report very-high-energy emissions from a variety of sources and revealed this energy range has rich astrophysical information. One of the most important topics in this energy region is to find the origin of the galactic cosmic rays where the protons are accelerated up to the energy of knee, a few PeV. Some objects such as the Cygnus region [4] and SNR G106.3+2.7 [5] are proposed as possible cosmic accelerators but the total energy released from these candidates is not sufficient to explain the energy density of cosmic rays observed at the solar system. To understand the total energy budget of the cosmic rays in our galaxy, the sub-PeV observations in the southern hemisphere is essential.

As the first southern sub-PeV observatory the Andes Large area PArticle detector for Cosmic ray physics and Astronomy (ALPACA) is under construction near the Chacartaya mountain in Bolivia [6]. ALPACA will cover the 82,800 m^2 surface area with 3,600 m^2 underground muon detectors, A prototype array of ALPACA called ALPAQUITA [7] started its operation of the ground detectors [8] and will start a construction of the underground muon detectors soon.

This paper describes a possible future plan of ALPACA called Mega ALPACA to expand the area up to Mega square meter (1 km^2).

2. Mega ALPACA

2.1 Mega ALPACA design

The design of Mega ALPACA is shown in Fig.1 compared with the ALPACA array drawn at the center. The 1 km^2 surface area is covered by about 1,000 scintillation counters where each counter has 1 m^2 area. Gray hatched areas in the figure indicate the location of the underground muon detectors. The muon detectors are water Cherenkov detectors constructed as reinforced concrete structure with 2 m soil overburden. By detecting particles penetrating to the muon detectors, they are predominantly muons, gamma-ray initiated showers are discriminated from the dominant hadronic showers. The basic idea is same as the Tibet AS+MD array and ALPACA.

2.2 Source sensitivity

The flux sensitivity of Mega ALPACA is shown in Fig.2. Two red curves are the 5σ sensitivities for point-like sources after 1 and 10 years observations. Comparing with the 1 yr sensitivity of ALPACA shown by the thick black curve, one order of magnitude better sensitivity can be achieved above 100 TeV. The thin lines are the energy spectra of known sources based on the H.E.S.S. galactic plane survey [9] within the field of view of Mega ALPACA. The solid lines are the best fit spectra in the measured energy range while the dashed lines are the extrapolations. Half of the known sources are studied at 100 TeV with ALPACA but almost all sources are within the reach of the Mega ALPACA sensitivity. It is also remarkable that the sensitivity is extended even beyond PeV for almost sources. This enables us not only to discover multiple PeV emitters, but also to determine the cutoff energy of individual source if it is in the 100-1,000 TeV range.

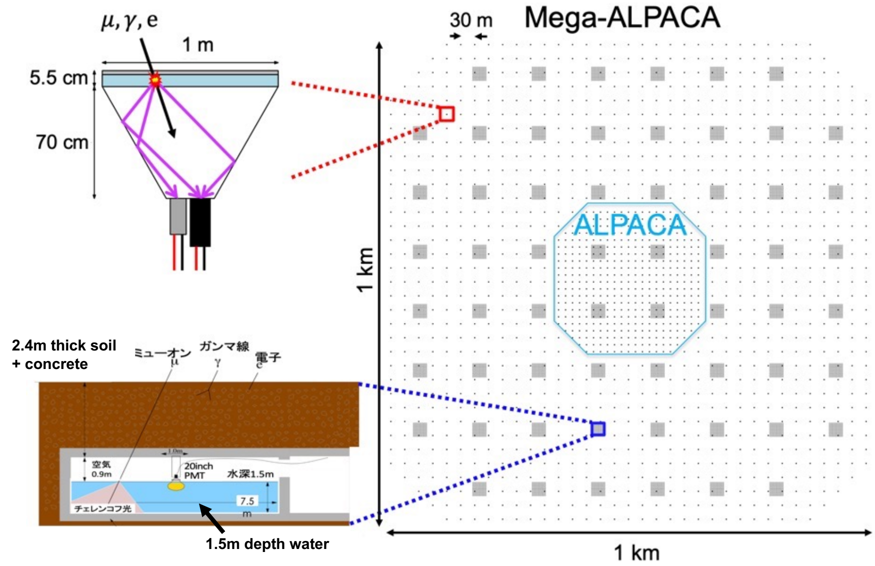

Figure 1: (Right) Layout of the Mega ALPACA array. Small dots indicate scintillation detectors and grey hatched areas indicate underground muon detectors (MD). The enclosed area at the center is the ALPACA array under construction. (Left Top) A schematic view of a scintillation detector. (Left Bottom) A schematic view of an MD zooming in a single cell. A reinforced concrete structure is constructed under 2 m soil. MDs are filled with water of 1.5 m depth and Cherenkov lights in each of 56 m^2 cell are monitored by a 20" PMT. Each MD unit is composed of 16 cells.

2.3 Galactic diffuse gamma rays

The detection of the galactic diffuse gamma rays by the Tibet ASγ collaboration in 2021 [10] is one of the highlights in this field. The detected flux was reasonably explained by the theoretical model and it is recently supported by the observation of the diffuse neutrino flux by the IceCube collaboration [11]. The gamma-ray observation in the southern hemisphere is also important to know the density variation of cosmic rays in our galaxy. The expected gamma-ray fluxes have stronger model dependence than the flux predictions in the northern hemisphere [12]. Figure 3 shows the 1 yr sensitivity of Mega ALPACA for the galactic diffuse emission as a function of the galactic longitude. Depending on the cosmic-ray density model the flux significantly differs and Mega ALPACA can clearly verify the models. Not only detecting the diffuse gamma rays, Mega ALPACA enables the study of spatial distribution of galactic cosmic rays.

2.4 Extragalactic astrnomy

It is well known that the photons above 100 TeV meet a strong absorption due to the interaction with ambient photons in the interstellar or intergalactic space. The attenuation peaks at PeV and the horizon is limited to about 10 kpc. Beyond PeV the flux slowly recovers but the power law nature of the source spectrum makes the detection of extragalactic sources difficult. Only nearby sources with hard spectra are possible candidates. As shown in Fig.4, the recently measured spectrum of Centaurus A by Femi LAT and H.E.S.S. [13] [14] can be extrapolated to the 100 TeV range. If

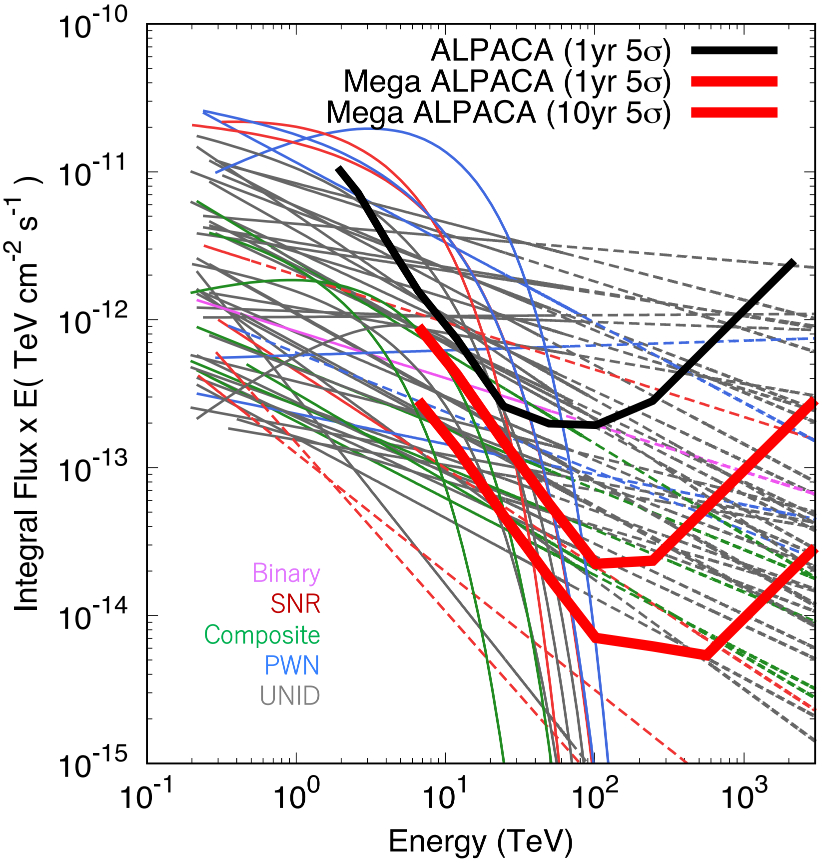

Figure 2: Sensitivities of Mega ALPACA for 1 year and 10 years observation periods (red thick curves) compared to the 1 yr sensitivity of ALPACA (black thick curve. Various thin curves are the fluxes of known gamma-ray sources within the field of view of Mega ALPACA. The solid lines are the measured fluxes while the dashed lines are the extrapolations of the fitting.

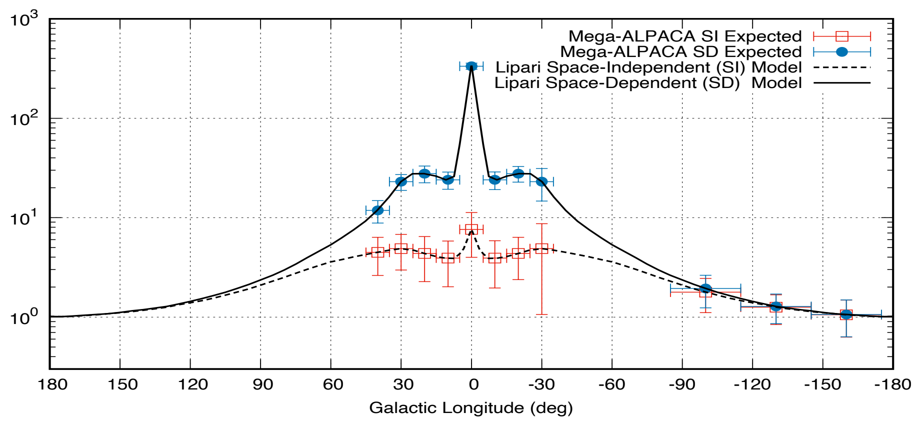

Figure 3: The 1 year sensitivity of Mega ALPACA for the galactic diffuse gamma-ray emission with respect to the two cosmic-ray density models [12]. The vertical axis is the relative flux to the flux at the anti-galactic center.

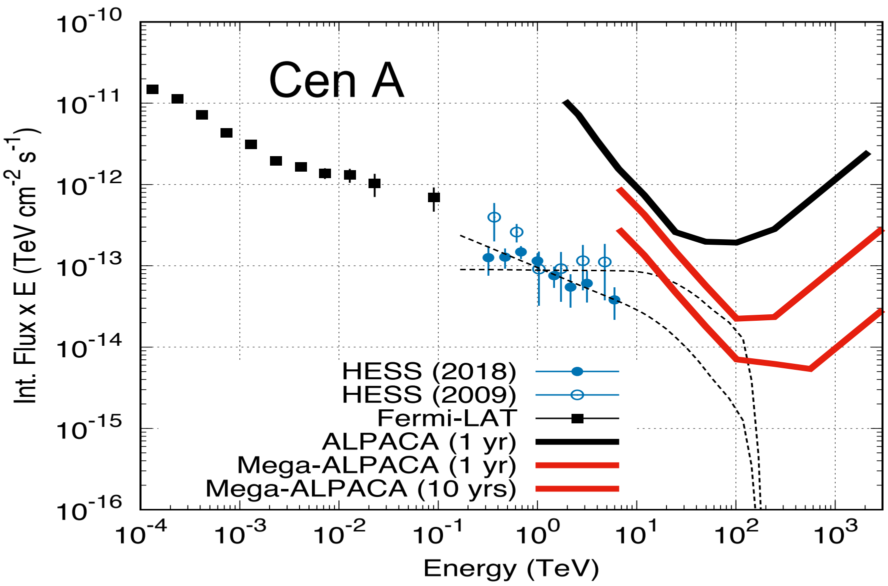

Figure 4: Sensitivity of Mega ALPACA for a nearby extragalactic object Cen A.

the spectrum is hard enough, gamma-rays can be detected by Mage ALPACA after a few years of operation.

3. Summary

ALPACA will start exploring the southern sub-PeV sky soon. As a next generation observatory, Mega ALPACA is a promising and robust idea to extend the sensitivity. In the southern hemisphere SWGO is also proposed as a 1 km^2 scale air shower array using the water Cherenkov tanks [15]. To construct a cost effective array the best mix of scintillation detectors and water Cherenkov tanks is worth investigating.

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References

[1] The Tibet ASγ Collaboration, Phys. Rev. Lett., 123, 051101 (2019).

[2] The HAWC Collaboration, Astrophys. J., 881:134 (2019).

[3] The LHAASO Collboration, Chinese Phys. C, 45, 025002 (2021).

[4] A. U. Abeysekara, A. Albert, R. Alfaro et al., Nature Astronomy 5, 465-471 (2021).

[5] The Tibet ASγ Collaboration, Nature Astronomy 5, 460-464 (2021).

[6] M. A. Subieta Vasquez (ICRC2023)

[7] The ALPACA Collaboration, Exp. Astron. (2021) 52:85-107.

[8] K. Kawata (ICRC2023)

[9] The H.E.S.S. Collaboration, A&A 612, A1 (2018).

[10] The Tibet ASγ Collaboration, Phys. Rev. Lett., 126, 141101 (2021).

[11] The IceCube Collaboration, Science 380, 1338-1343 (2023).

[12] P. Lipari and S. Vernetto, PRD 98, 043003 (2018).

[13] H.E.S.S. and LAT Collaborations, A&A 619, A71 (2018).

[14] The H.E.S.S. Collaboration, Nature, 582, 356-359 (2020).

[15] The SWGO Collaboration, PoS (ICRC2021) 023.

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