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Development of wide-field stereoscopic water Cherenkov detector for 100 GeV - 100 TeV energy range at high altitude

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The Stereoscopic Water Cherenkov Detection Array (SWCDA) project is a next-generation ground-based array experiment for high-energy gamma-ray astronomy observation in the 100 GeV - 100 TeV range. It is an innovative three-dimensional water Cherenkov detection array. Its main scientific objective is to observe blazars, active galactic nuclei (AGNs or AGN flares), gamma-ray bursts (GRBs), Galactic microquasars, etc., in the 100 GeV - 100 TeV energy region. Its prototype has been built inside the Tibet ASγ air-shower array in Tibet at the end of 2024, with an area of 100 m^2, and data taking starts in 2025. This paper will introduce the development and design of the SWCDA, as well as its future applications.

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1. Introduction

In recent years, experiments such as the Tibet ASγ, HAWC, and LHAASO have achieved significant results, demonstrating the scientific potential of wide-field, high-duty-cycle ground-based gamma-ray array experiments. However, a major limitation of such extensive air shower (EAS) array detection techniques is their reliance on two-dimensional observations, which only provide the lateral distribution of cosmic-ray showers. This restricts the cosmic-ray/gamma-ray discrimination capability, preventing the gamma-ray observation sensitivity from meeting the requirements in the 100 GeV–TeV energy range. Meanwhile, space-based experiments like Fermi-LAT suffer from limited effective area, resulting in low sensitivity for gamma-ray observations above 100 GeV. Consequently, the 100 GeV–TeV range remains a sensitivity gap for wide-field high-energy gamma-ray observations, necessitating new detection technologies to address this issue. To overcome these challenges, we propose an innovative Stereoscopic Water Cherenkov Detector Array (SWCDA), which upgrades ground-based wide-field observations from one-dimensional (2D plane) to three-dimensional (3D) detection. The SWCDA can simultaneously measure both the lateral distribution and longitudinal development of air showers, significantly improving the cosmic-ray background rejection rate and enhancing gamma-ray sensitivity in this energy range. Combined with the advantages of high-altitude observation sites, the SWCDA can lower the energy threshold to 100 GeV, enabling the detection of higher-redshift extragalactic sources. This breakthrough technology promises to fill the sensitivity gap in the 100 GeV–TeV window, opening new possibilities for high-energy gamma-ray astronomy.

2. Scientific Objectives

By employing the three-dimensional stereoscopic detection technique of the SWCDA (Stereoscopic Water Cherenkov Detector Array) and leveraging the advantages of the high-altitude (5200 m) location in Tibet, this project aims to lower the energy threshold of ground-based EAS array experiments to 100 GeV while significantly improving gamma-ray sensitivity. This advancement will bridge the observational gap between satellite experiments and ground-based EAS arrays as shown in Fig.1(A).

The primary scientific objectives include observing extragalactic sources such as blazars, active galactic nuclei (AGNs and AGN flares), and gamma-ray bursts (GRBs), as well as numerous transient phenomena in the 100 GeV – 100 TeV energy range as shown in Fig.1(B).

3. Design Principles of the SWCDA

Due to the similar nuclear interaction lengths (83.6 g/cm^2 g/cm^2 for water vs. 90 g/cm^2 for air), radiation lengths (36.08 g/cm^2 vs. 36.66 g/cm^2), and ionization energy losses (1.991 $MeV/g/cm^2$ vs. 1.815 $MeV/g/cm^2$) between water and air, a multi-layer (e.g., 5-layer) stereoscopic water Cherenkov detector array (SWCDA) deployed at high-altitude sites in Tibet can achieve three-dimensional observations of extensive air showers (EAS). This enables simultaneous measurement of both the longitudinal development and lateral distribution of cosmic-ray showers, effectively providing multi-dimensional information by observing the same EAS at different atmospheric depths

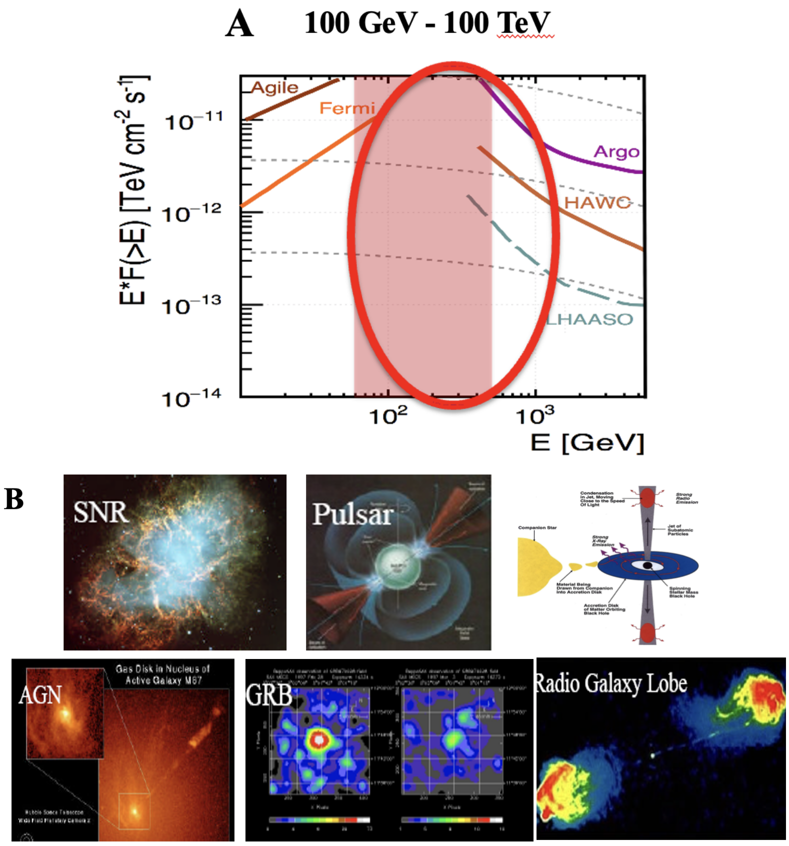

Figure 1: (A). The sensitivity curves of gamma rays from satellite experiments and ground EAS arrays. (B) Scientific objectives of the high-altitude SWCDA experiment (5200 m).

as shown in Fig.2. By leveraging the stereoscopic and multi-dimensional data obtained from the SWCDA, the detector can effectively reject cosmic-ray backgrounds (primarily hadrons, especially protons), significantly improving the hadron/gamma-ray discrimination capability. This results in a substantial enhancement of cosmic-ray background suppression and a significant improvement in gamma-ray observation sensitivity in the 100 GeV–TeV energy range.

Figure 2: Schematic Diagram of Cosmic Ray Shower Development in Atmosphere or Water.

4. Basic Structure of the SWCDA Detector

The SWCDA (Stereoscopic Water Cherenkov Detector Array) utilizes two functionally optimized detector types as shown in Fig.3.

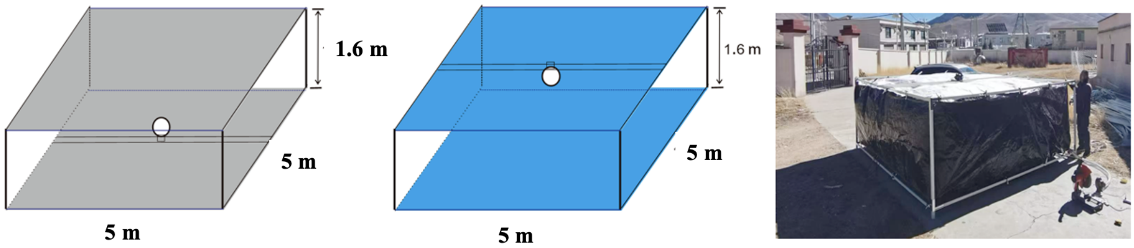

Figure 3: Basic Structure of the SWCDA Detector. Left: Non-reflective detectors are deployed in the topmost layer (Layer 1). Middle: High-diffusivity detectors occupy Layers 2–5. Right: Physical Photo of Each Detector Unit in the SWCDA Prototype.

1. Non-reflective detectors are deployed in the topmost layer (Layer 1) as shown in Fig.3. Each 5 m × 5 m × 1.6 m, light-tight unit features a black interior to suppress reflections, with an upward-facing 8-inch PMT installed at the base for direct Cherenkov light detection.

2. High-diffusivity detectors occupy Layers 2–5 as shown in Fig.3. These 5 m × 5 m × 1.6 m units employ diffusive interior lining and downward-facing 8-inch PMTs at the top to enhance shower profile reconstruction accuracy.

5. Observation signals of different secondary particles in the SWCDA detector

The SWCDA detector effectively discriminates between secondary particles through their distinct interaction signatures as shown in Fig.4:

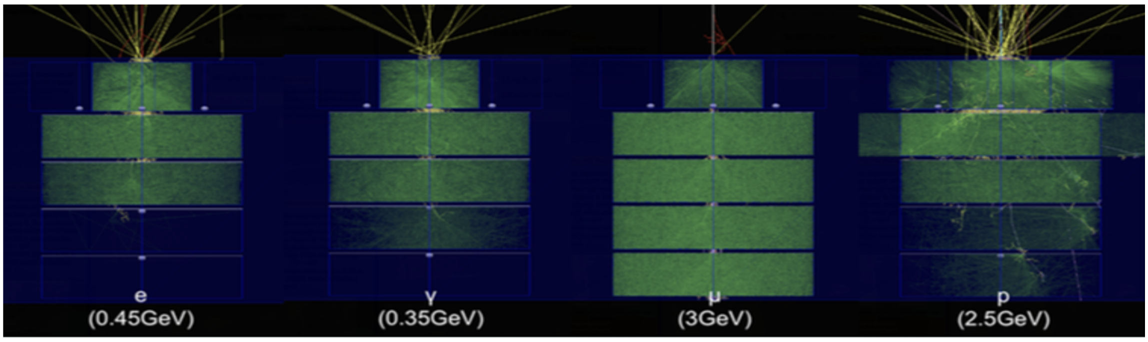

Figure 4: Observation signals of different secondary particles in the SWCDA detector.

1. Electromagnetic components ($\gamma/e^{\pm}$)(Fig.4):
Generate compact electromagnetic showers in upper layers exhibit rapid energy deposition and attenuation.

2. Hadrons (primary protons) (Fig.4):
Produce irregular hadronic showers with stochastic energy deposition

3. Muons (Fig.4):

Penetrate deeply with minimal shower development, show uniform signal distribution across all layers

These characteristic patterns enable the SWCDA detector to capture distinct physical signatures of various particles upon their entry, and when combined with machine learning methods, significantly enhance the capability to discriminate between protons and gamma rays.

6. Lake-based SWCDA Experiment

The carpet-type SWCDA experiment, composed of a large number of SWCDA detectors, will be deployed in a ultra-high-altitude lake (e.g., 5200 m above sea level) as shown in Fig.5.

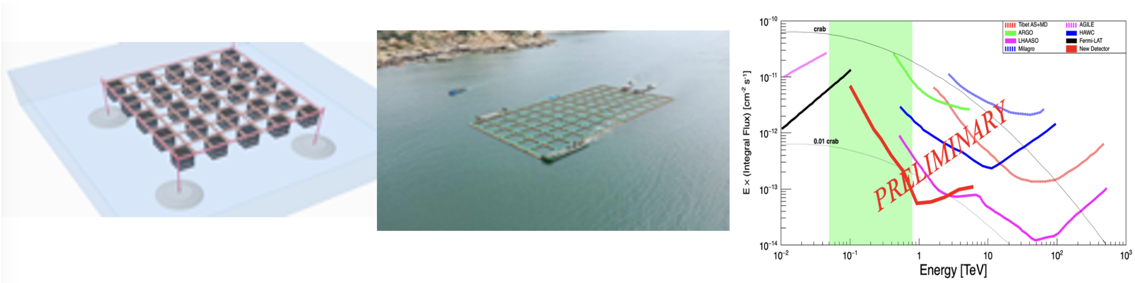

Figure 5: The high-altitude lake-based SWCDA experiment and its sensitivity curve for gamma-ray observation.

By combining high-sensitivity stereoscopic detection technology with the advantages of ultra-high altitude (5200 m), the experiment is expected to achieve an energy threshold as low as 100 GeV. Monte Carlo simulations [1] demonstrate that the SWCDA technology can improve the gamma-ray observation sensitivity by more than a factor of 10 in the 100 GeV energy range compared to traditional EAS experiments as shown in Fig.5.

7. Acknowledgements

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