Snowmass2021 - Letter of Interest

Cosmic Rays in the TeV to PeV Energy Range[*]

Thematic Areas: (check all that apply □/■)

□ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
□ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
□ (Other) *[Please specify frontier/topical group]*

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Abstract: The origin, propagation, and composition of cosmic rays remains an open area of research with several unanswered questions. For example, more than half a century after the discovery of the cosmic-ray "knee" feature, experimental observations are still conflicting as to its origin. Also, an anisotropy in the direction of cosmic rays has been observed but is not well understood. The Southern Wide-field Gamma-ray Observatory (SWGO) would be able to collect high-quality cosmic-ray data and contribute significantly to the elucidation of the outlined open questions in cosmic-ray physics.

[*] This Letter contains excerpts and material from White Papers submitted for the Astro2020 Decadal Survey [1;2]

The main feature in the high-energy spectrum of observed cosmic rays (CRs) is the so-called "*knee*," which is characterized by a steepening of the spectral index from $\sim$-2.7 to $\sim$-3.1 at about 3 PeV (=3×10^{15} eV). Understanding the origin of the knee is the key for a comprehensive theory of the origin of cosmic rays up to the highest observed energies. The knee is clearly connected with the issue at the end of the Galactic cosmic-ray spectrum and the transition from Galactic to extragalactic cosmic rays. Determining the elemental composition in the knee energy region is crucial to understand where the Galactic cosmic-ray spectrum ends. If the mass of the knee is light (dominated by protons and He nuclei), according to the Standard Model, the Galactic cosmic-ray spectrum is expected to end around 10^{17} eV. On the contrary, if the composition at the knee energies is heavier and dominated by CNO/MgSi nuclei, the interpretation of the cosmic-ray energy spectrum may not be straightforward[1].

Recent results obtained by the ARGO-YBJ experiment[3] (located at 4300 m a.s.l.) show, in multiple analyses, that the knee of the light component starts at $\sim7\times10^5$ GeV, well below the knee of the all-particle spectrum that is confirmed by ARGO-YBJ at $\sim 4\times10^6$ GeV[4] (see Figure 1 and the *Highest Energy Galactic Cosmic Rays* LOI submitted by Andreas Huangs to CF06, CF07, and EF06 for additional information).

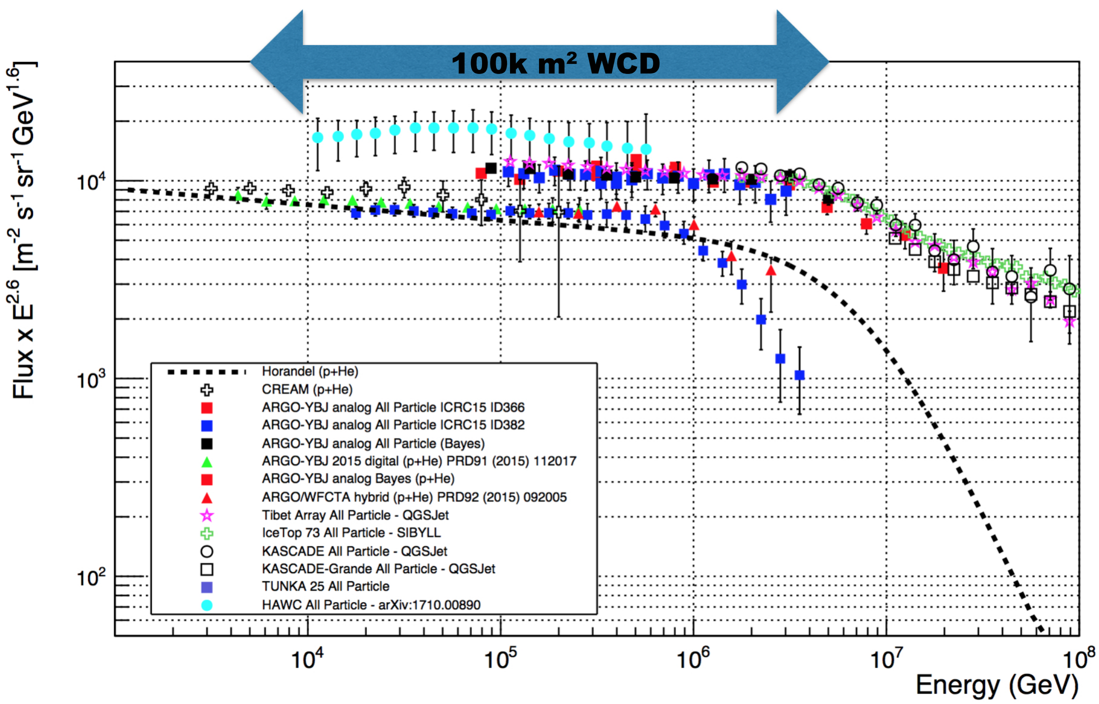

Figure 1: All-particle and light (p+He) component energy spectra of primary cosmic rays measured by ARGO-YBJ and compared to different experimental results[4–7]. Also shown is the expected energy range from a future $\sim$ 100,000 m^2 water Cherenkov detector[8]. The parametrization provided by Hörandel[9] for the spectrum of the light cosmic-ray component is shown for comparison. The systematic uncertainty is shown by the error bars.

In order to outperform the current state-of-the-art detectors and clarify the tension between different measurements in the knee energy region, a future experiment should:

- ideally be located above 4000 m a.s.l., to approach the atmospheric depth of maximum development of showers in the PeV energy region. In this way fluctuations are smaller and all nuclei produce the same size electromagnetic signal. As a consequence, the shower size–energy conversion is massindependent and the trigger efficiency is the same for all primary particles.

- be instrumented with detectors able to measure different shower mass-sensitive observables, such as the muon component and the lateral distribution in the shower core region. A detector able to study the core region is important also to investigate the hadronic interaction models in the forward region: the pseudo-rapidity corresponding to a region within about 10 m from the shower core is greater than eight
- have an energy threshold for cosmic rays on the order of TeV for absolute energy calibration purposes exploiting the *'Moon shadow'* technique, and to superimpose the measured spectra with direct observations over a wide energy range;
- have a sufficiently large instrumented area in order to enable sensitive measurements up to 10^{16} eV.

While conceived primarily as a high-energy gamma-ray observatory, a next generation wide-field-of-view TeV observatory like the Southern Wide-field Gamma-ray Observatory (SWGO)[8] will fulfill most of these requirements. This observatory will thus be able to collect high-quality cosmic-ray data and contribute significantly to the elucidation of the outlined open questions in cosmic-ray physics.

Sensitivity to astrophysical particle accelerators in the local Galactic neighborhood is one of the greatest strengths of SWGO. The detection of Geminga and PSR B0656+14 with HAWC suggests that nearby pulsars may strongly influence their surroundings[10], leading to a new understanding of particle propagation in the vicinity of PWNs [11]. The large angular extents of these TeV halos allow us to study the propagation of particles within them in unprecedented detail[12]. Locating SWGO in the Southern Hemisphere will place within reach $\sim$12 Geminga-like middle-aged pulsars within 1 kpc of Earth for study, along with many older and/or more distant pulsars likely to have similar TeV halos. A thorough understanding of these local accelerators is necessary for interpreting the unexpected excess of positrons observed at Earth[13], either as being due to a local source or some more exotic mechanism[14;15].

Sources of cosmic rays with energies in excess of 1 PeV are expected to produce VHE gamma rays above 100 TeV[16–19]. With its sensitivity to the highest energies, SWGO is uniquely suited to detect these sources and measure any cutoffs in their spectra that indicate the maximum energy to which they are able to accelerate particles. Strong evidence exists that such a source exists in the Galactic Center[20]. Measurements of the Galactic Center will take advantage of SWGO's wide field-of-view to provide energy-dependent morphology measurements for characterizing the propagation of particles in its vicinity. A combined study with VHE gamma rays and neutrinos also has the potential to reveal the processes responsible for these high-energy particles.

The measurement of spectra of five mass groups (p, He, CNO, MgSi, Fe) up to 10^{17} eV should be a high priority for future wide-field-of-view instruments in order to:

- measure the maximum acceleration energy of Galactic sources through the determination of the knee energy in the proton primary spectrum;
- investigate the origin of the knee— tracing the different components up to 10^{16} eV and measuring the cosmic-ray anisotropy as a function of rigidity;
- search for cosmic-ray factories through a combined mapping of the photon and proton spectra in different regions of the Galactic plane.

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