The Future of Cherenkov Astronomy

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In the last ten years, the field of Cherenkov astronomy has become an important contributor to high energy astrophysics with the detection of eight objects at energies above 300 GeV. These observations have advanced our understanding of active galactic nuclei, supernova remnants, the extragalactic background light and cosmic-ray acceleration and production. Several efforts are now underway to develop new Cherenkov telescopes which will cover a wider range of energies (10 GeV - 50 TeV), improve the flux sensitivity by at least an order of magnitude and provide more accurate measures of particle energy and direction. I describe some of the new Cherenkov telescopes and discuss their potential to improve our understanding of astrophysics and fundamental physics.

I. INTRODUCTION

Cherenkov telescopes indirectly detect γ-rays by observing the flashes of Cherenkov light emitted by particle cascades initiated when the γ-rays interact with nuclei in the atmosphere. These telescopes have effective areas of 10,000 m^2 to 100,000 m^2, making them efficient at detecting very short time-scale variations. Telescopes with pixellated cameras that "image" the shower utilize the differences in the Cherenkov images from γ-ray and cosmic-ray primaries to reject the dominant cosmic-ray background with >99.7% efficiency. These telescopes are used singly or as arrays that stereoscopically image the Cherenkov flash and they currently detect 250 GeV to 20 TeV γ-rays. Primary particle directions are reconstructed with accuracies of about 0.15° and 0.1° and the energy resolution is about 35% (RMS) and 20% for current single telescopes and arrays, respectively.

The first clear detection of a γ-ray source by a Cherenkov telescope was the Crab Nebula by the Whipple collaboration in 1989 [1]. At present, seven other objects have been detected with high statistical significance: one shell-type supernova remnant (SNR), two pulsar-powered nebulae, and four active galactic nuclei (AGN). Thorough reviews of the current status of the field of very high energy (VHE, E$\geq$100 GeV) astrophysics can be found elsewhere [2].

The observations of AGN reveal extremely large amplitude and rapid flux variations [3,4] which correlate with variations at longer wavelengths [5] (see Figure 1). These provide estimates of the magnetic field in the AGN jets and the amount of relativistic Doppler boosting of the emission and are most easily explained if the γ-rays are produced through inverse Compton scattering of low energy photons and electrons. However, the energy spectra of the AGN extend to >10 TeV [6] which is more easily explained by proton models because the electron inverse Compton process becomes inefficient above a few TeV. In travelling to Earth, the TeV γ-rays emitted by AGN are attenuated by pair-production with optical/IR photons [8]. While this eliminates γ-rays from very distant sources, the effect on the TeV spectra from nearby AGN can be used to estimate the density of the extragalactic background light (EBL) [9]. With the spectra from Mrk 421 and Mrk 501, upper limits on the IR background are already, at some wavelengths, more than 10 times better than those achieved with direct measurements [10]. VHE γ-ray measurements of the spectrum of the Crab Nebula are consistent with the emission being produced by inverse-Compton scattering of electrons and photons in the synchrotron nebula (see Figure 2) and provide estimates of the nebular magnetic field [11]. Similarly, TeV γ-rays from the shell-type SNR, SN 1006 [12], provide estimates of the magnetic field and the acceleration time of the electrons in the SNR, both previously unknown variables in modelling the emission from this object.

Despite these exciting results, the current generation of Cherenkov telescopes only scratches the surface of the science to which the field can contribute. The fact that EGRET detected over 250 objects [13] above 100 MeV while only eight objects have been detected above 300 GeV indicates that much can be gained by lowering the energy range covered by Cherenkov telescopes. New instruments also need to improve flux sensitivity and estimates of the γ-ray

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energy and direction in order to detect more sources and better test emission models. Here I discuss how proposed Cherenkov telescopes will accomplish these goals and what we hope to learn from the data they will collect.

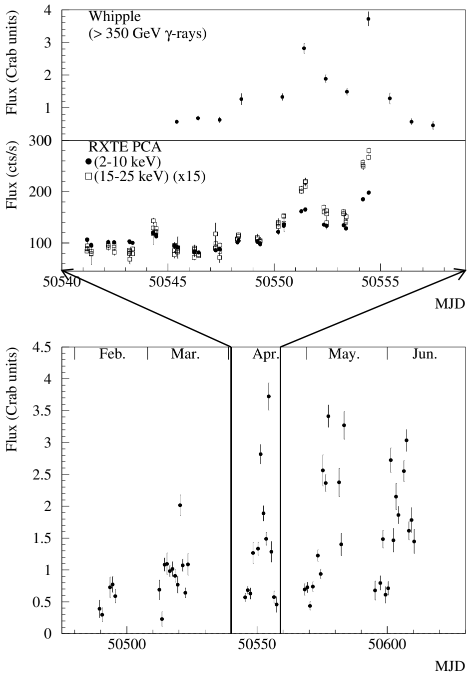

FIG. 1. *Upper panel*: Observations of Mrk 501 in VHE γ-rays (top) and X-rays (bottom) taken during 1997 April 2-20 (MJD 50540-50559). Figure adapted from [7]. *Lower panel*: Average daily γ-ray rates observed with Whipple for Mrk 501 in 1997. Figure from [3].

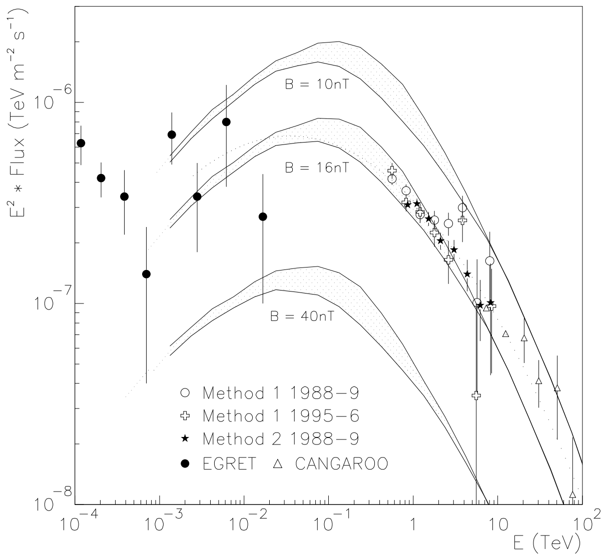

FIG. 2. Crab spectrum from EGRET and VHE observations showing inverse Compton model fits for various values of the nebular magnetic field. Figure from [11].

II. NEW CHERENKOV TELESCOPE PROJECTS

A. Imaging telescopes

Proposed imaging arrays have good sensitivity from 50 GeV to 50 TeV. The energy threshold is lowered by increasing the mirror area and using a multiple telescope trigger to eliminate the background triggers from local penetrating muons and fluctuations of the night sky background light. Also, because arrays measure a shower in several telescopes, less light need be recorded in individual telescopes to reconstruct the shower - further reducing the achievable energy threshold. With multiple images of the shower, its geometry and development is better characterized, improving the angular resolution, the ability to identify γ-ray induced showers, and determination of the primary γ-ray energy.

The Very Energetic Radiation Imaging Telescope Array System (VERITAS) [14] is one such proposed array of seven 10 m telescopes (Figure 3) to be located at the base of Mt. Hopkins in the Whipple Observatory in Arizona. Six of the telescopes will be arranged at the corners of a hexagon with 80 m sides and the seventh telescope will sit at the center. Each telescope will have an imaging camera of 499 photomultiplier tubes (PMTs) viewing a $3.5°$ diameter area of the sky. An energy threshold of 75 GeV will be achieved and the sensitivity will be approximately 20 times better than the current Whipple telescope. VERITAS will have an angular resolution of $0.09°$ at 100 GeV which improves to $0.03°$ at 1 TeV and its RMS energy resolution will be $<15\%$. The High Energy Stereoscopic System (HESS) [15] is a proposed array with similar performance to VERITAS, planned for operation in the southern hemisphere, likely Namibia. HESS could eventually consist of sixteen 10 m diameter telescopes on a square grid with 100 m spacing.

The Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescope [16] attempts to maximize the performance of a single imaging telescope. The baseline proposal for MAGIC is a 17 m diameter mirror, equipped with a camera of approximately 530 pixels viewing a 3.6° diameter field of view. If high quantum efficiency (∼45%) hybrid PMTs become economically viable, MAGIC is predicted to achieve an energy threshold of 30 GeV.

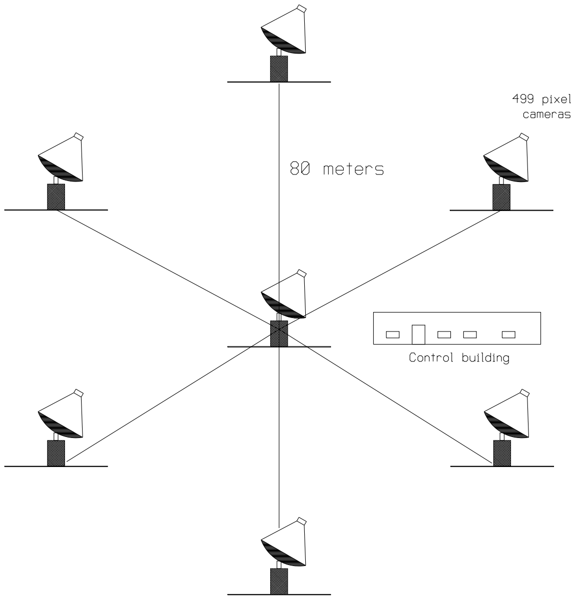

FIG. 3. Conceptual arrangement of the telescopes for VERITAS.

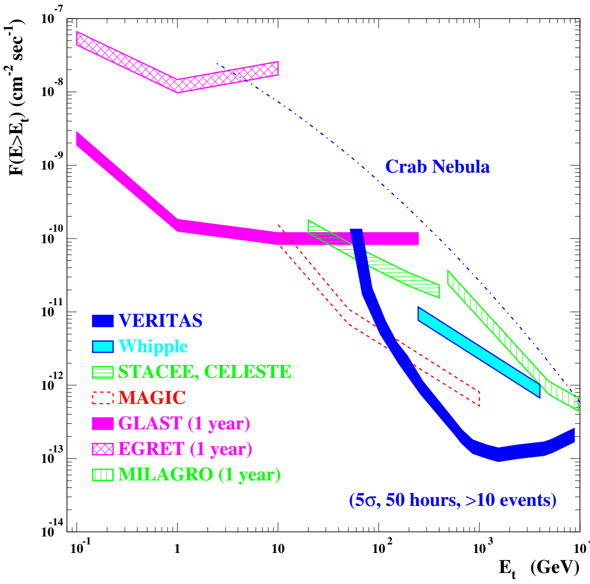

FIG. 4. Point source sensitivities of several existing and proposed γ-ray telescopes. The sensitivities of the pointed instruments (VERITAS, Whipple, STACEE/CELESTE, and MAGIC) are for 50 hours of observations while the wide field instruments (EGRET, GLAST [19], and MILAGRO [20]) are for 1 year of observations.

B. Solar arrays

Heliostat arrays have mirror areas of several thousand square meters, so they can efficiently detect 20 – 300 GeV γ-ray induced Cherenkov flashes. Secondary mirrors at a central tower focus the light from individual heliostats onto PMTs (each PMT views one heliostat) to sample the Cherenkov wavefront rather than image its development. Cosmic-ray background rejection is achieved by measuring the lateral distribution of the Cherenkov light. Two groups (CELESTE [17] and STACEE [18]) have begun operation of prototypes of these solar arrays. During 1999, they should become fully operational and achieve an energy threshold of ∼50 GeV.

The sensitivities to point sources of the different types of telescope operating in this energy range are shown in Figure 4. Clearly, imaging arrays will have the greatest sensitivity in their energy range, but the solar arrays and MAGIC can achieve lower energy thresholds.

III. SCIENTIFIC MOTIVATION

A. Extragalactic astrophysics

1. Active galactic nuclei

Outstanding questions about AGN include the particle which dominates the production of γ-rays (protons or electrons), the mechanism by which γ-rays are produced, and the acceleration mechanism for the particles. Variability studies are important to understanding the physics of the central source of AGN because the core regions cannot be resolved with existing interferometers. The large effective area of Cherenkov telescopes enables accurate measurements of extremely short variations in the γ-ray flux as indicated in Figure 5. The left part of the figure shows Whipple observations of the fastest flare ever recorded at γ-ray energies [4]. While the flare is clearly detected, the structure of the flare is not resolved. The dashed curve is a hypothetical flux variation which matches the Whipple data. The right part of the figure shows a simulation of how an imaging array would clearly resolve all features of the flare.

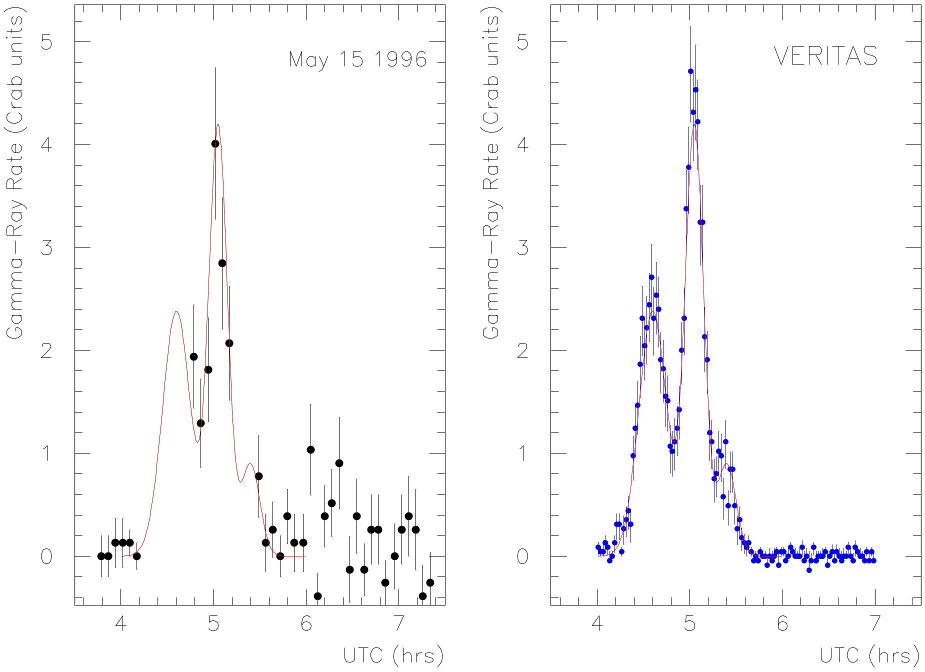

FIG. 5. *Left*: Whipple observations of a flare from Mrk 421 on 1996 May 15 [4]. The dashed curve is a possible intrinsic flux variation which is consistent with the VHE data. *Right*: Simulated response of VERITAS to the flare above 200 GeV.

Because blazars are extremely variable at all wavelengths, the best way to understand the physical processes at work in them is to conduct detailed observations spanning as wide an energy range as possible. The new Cherenkov instruments and space-based telescopes will make measurements spanning 6 orders of magnitude in γ-ray energies. In addition, the arrays of telescopes will have significantly improved energy resolution to better measure the AGN spectra which is crucial to understanding the emission and flaring mechanisms.

The new Cherenkov telescopes should also significantly increase the number of sources detected at VHE energies. A lower energy threshold will permit viewing objects further from Earth (the optical depth for pair production with low energy photons decreases rapidly with decreasing energy) and those objects which have spectral cut-offs below the sensitive range of existing telescopes (e.g., EGRET sources). The improved flux sensitivity of the imaging arrays will permit the detection of more of the AGN already detected with the Cherenkov telescopes. Measurements of the ends of the spectra for a wide range of AGN types at different redshifts can help determine what particles produce the γ-ray emission and refine or eliminate unification models of blazar-type AGN [21].

2. Infrared background radiation

The current limits on the IR density derived from measurements of the TeV spectra of AGN are approximately 5 to 10 times higher than predicted from galaxy evolution [22]. However, they place substantial restrictions on several proposed particle physics and cosmological models which would contribute to the IR background [10]. The new Cherenkov telescopes should substantially improve these limits to the EBL. With a large ensemble of sources, the energy resolution of the imaging telescope arrays may resolve the intrinsic spectra of the AGN from the external absorption features so that it may even be possible to detect the EBL itself. Because the EBL is predominantly the result of galaxy formation, these measurements will add to our understanding of that process as well.

3. Gamma-ray bursts

X-ray and optical afterglows confirm that γ-ray bursts are extragalactic but the sources and mechanism for producing the γ-ray bursts remain unknown. The delayed GeV photons from γ-ray bursts [23] demonstrate that high energy γ-rays play an important role in γ-ray bursts that can be pursued with rapid follow-up observations. With low energy thresholds, new Cherenkov telescopes will be able to see bursts out to z$\sim$1 or more. Because of the difficulty in producing VHE γ-rays and in getting them out of the region where the burst originates, the detection of a VHE component would place stringent limits on the viable models for γ-ray bursts. Attenuation from interaction with the EBL can also provide an independent distance estimate if optical follow-up observations do not reveal spectral lines.

B. Galactic astrophysics

1. Shell-type supernova remnants and cosmic rays

SNRs are widely believed to be the sources of hadronic cosmic rays up to energies of approximately $Z \times 10^{14}$ eV, where Z is the nuclear charge of the particle. The existence of energetic *electrons* in SNRs is well-known from observations of synchrotron emission at radio and X-ray wavelengths and TeV γ-rays from SN 1006 [12], most likely generated by electrons through inverse Compton scattering. However, a clear indication for the acceleration of hadronic particles in SNR is lacking. The evidence for such particles would be a characteristic spectrum of γ-rays produced mostly via π^0 decay subsequent to nuclear interactions in the SNR. While EGRET has detected signals from several regions of the sky that are consistent with the positions of shell-type SNRs [24], upper limits from the Whipple collaboration at E>300 GeV are well below the extension of the EGRET spectra [25].

As shown in Figure 6, there are predictions for strong γ-ray emission from shell-type SNRs by hadron *and* electron interactions. Model fits to EGRET and Whipple data [26] indicate that if the emission detected by EGRET is from the SNR, inverse Compton and bremsstrahlung scattering of electrons contribute to the flux and the hadronic spectrum is steeper than the $E^{-2.1}$ expected from direct cosmic-ray measurements. The new Cherenkov telescopes, particularly the imaging arrays, and GLAST will provide excellent sensitivity and energy reconstruction for resolving the various emission components in these objects. In addition, the imaging arrays will provide detailed mapping of the emission regions in the SNRs. For a typical SNR luminosity and angular extent, an imaging array should be able to detect approximately 20 objects within 4 kpc of Earth according to one popular model of γ-ray production by hadronic interactions [27], permitting investigation of which characteristics in SNR are necessary for particle acceleration.

2. Compact Galactic Objects

VHE emission from the Crab, PSR 1706-44 and Vela suggest that they may be the most prominent members of a large galactic population of sources. An accurate VHE spectrum is crucial to understanding the production mechanism of γ-rays from these pulsar-powered nebulae. The new imaging arrays should be sensitive to Crab-like objects anywhere within the Galaxy. The energy resolution of the arrays and the broad energy coverage available by combining the data with GLAST measurements will significantly improve tests of γ-ray emission models. Finally, the imaging arrays may even be able to resolve the VHE emission region of nearby objects like the Crab Nebula.

VHE γ-rays produced near a pulsar will pair produce with the intense magnetic fields there, leading to a sharp spectral cut-off. Thus, VHE observations constrain the location of the pulsar particle acceleration region. The high energy emission of the six pulsars detected at EGRET energies [13] is already seriously constrained by the VHE upper limits [2]. The energy threshold of the new telescopes should permit the detection of these bright GeV sources.

Of the EGRET sources, 170 have no known counterpart at longer wavelengths [13], mostly due to their positional uncertainty. With their sensitivity and energy threshold, Cherenkov telescopes should detect many of these objects and source locations from imaging arrays could lead to identifications with objects at longer wavelengths.

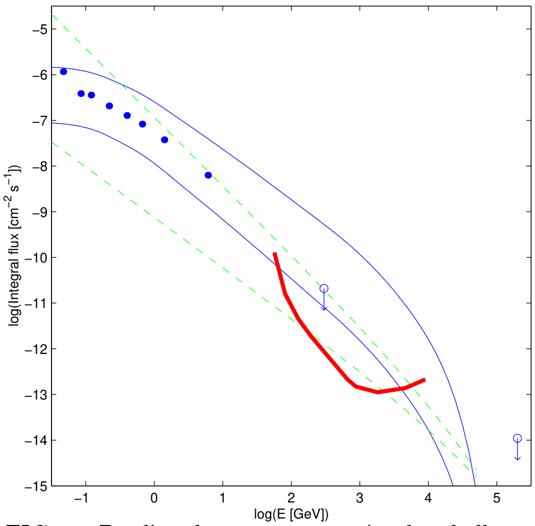

FIG. 6. Predicted γ-ray spectra in the shell-type SNR IC 443. The solid lines depict a range of spectra from hadronic interactions (adapted from [25]). The dashed lines depict inverse-Compton spectra for a range of parameters allowed by X-ray data. EGRET data (filled circles) and upper limits (open circles) from Whipple and Cygnus are shown. The predicted sensitivity of VERITAS for a 50 hour observation is indicated by the thick curve.

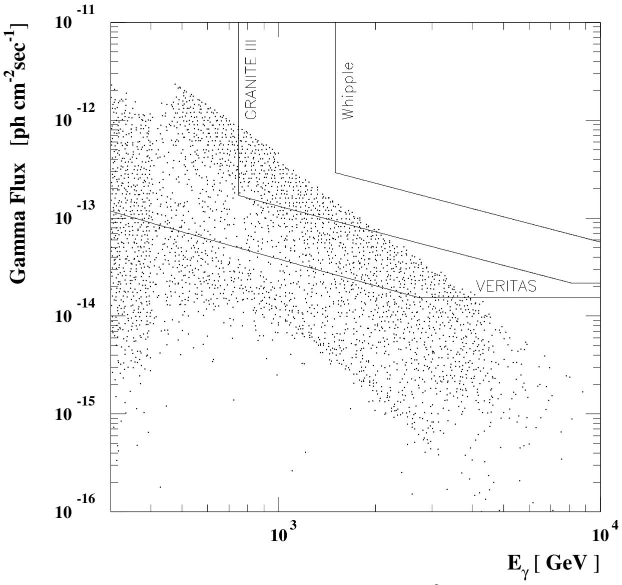

FIG. 7. Neutralino annihilation rate from the Galactic center. Shown are the sensitivity curves for Whipple, the Granite III upgrade of the Whipple telescope, and VERITAS. Each point represents a particular choice of supersymmetry model parameters in the experimentally allowed range. Figure from [28].

A survey is an efficient means of observing a large sample of sources and the only way to efficiently detect new types of sources. Imaging arrays will be able to survey the sky in the 100 GeV – 10 TeV energy range. An 80-night survey of the Galactic plane region $0° < l < 85°$ with VERITAS will be sensitive to fluxes down to $\sim$0.02 Crab above 300 GeV and encompass more than 40 potential VHE sources, and so should significantly increase the VHE catalog.

C. Fundamental Physics

1. *Neutralino annihilation in the Galactic center*

Current astrophysical data indicate the need for a cold dark matter component with $\Omega \approx 0.3$. A good candidate for this component is the neutralino, the lightest stable supersymmetric particle. If neutralinos do comprise the dark matter and are concentrated near the center of our galaxy, their direct annihilation to γ-rays should produce a monoenergetic annihilation line with mean energy equal to the neutralino mass. Cosmological constraints and limits from accelerator experiments restrict the neutralino mass to the range 30 GeV - 3 TeV. Thus, the new Cherenkov telescopes and GLAST together will allow a sensitive search over the entire allowed neutralino mass range. Recent estimates of the annihilation line flux for neutralinos at the galactic center [28] predict a γ-ray signal which may be of sufficient intensity to be detected with an imaging array (Figure 7) and GLAST.

2. *Quantum gravity*

Quantum gravity can manifest itself as an effective energy-dependence to the velocity of light in vacuum caused by propagation through a gravitational medium containing quantum fluctuations. In some formulations [29], this time dispersion can have a first-order dependence on photon energy:

$$\Delta t \simeq \xi \frac{E}{E_{QG}} \frac{L}{c} \tag{1}$$

where Δt is the time delay relative to the energy-independent speed of light, c; ξ is a model-dependent factor of order 1; E is the energy of the observed radiation; E_{QG} is the energy scale at which quantum gravity couples to electromagnetic radiation; and L is the distance over which the radiation has propagated. Recent work within the context of string theory indicates that quantum gravity may begin to manifest itself at a much lower energy scale than the Planck mass, perhaps as low as 10^{16} GeV [30]. VHE observations of variable emission from distant objects provide an excellent means of searching for the effects of quantum gravity. For example, the Whipple Collaboration has recently used data from a rapid TeV flare of the AGN Mrk 421 to constrain E_{QG}/ξ to be $> 4 \times 10^{16}$ GeV, the highest convincing limit determined to date [31]. This limit can be vastly improved with the new Cherenkov telescopes because they will be more sensitive to short time-scale variability and able to detect more distant objects. In addition to AGN flares, γ-ray bursts and pulsed emission from Galactic sources may provide avenues for investigating the effects of quantum gravity.

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