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2007 J. Phys. A: Math. Theor. 40 6757

(http://iopscience.iop.org/1751-8121/40/25/S20)

IOP PUBLISHING JOURNAL OF PHYSICS A: MATHEMATICAL AND THEORETICAL

J. Phys. A: Math. Theor. **40** (2007) 6757–6766 doi:10.1088/1751-8113/40/25/S20

Cosmology with VHE gamma-ray telescopes

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Received 12 October 2006, in final form 6 December 2006
Published 6 June 2007
Online at stacks.iop.org/JPhysA/40/6757

Abstract
Observation of the universe in the VHE gamma-ray domain with the new generation of Cherenkov telescopes is producing new measurements with a direct implication for cosmology. The present results and the future prospects will be discussed.

PACS numbers: 95.55.Ka, 88.80.Es

(Some figures in this article are in colour only in the electronic version)

1. Introduction

VHE cosmic gamma-ray observation is at present in a very special moment since a true revolution in the consolidation of Cherenkov telescopes as astronomical instruments is taking place. After many years of slow development, imaging air Cherenkov telescopes (IACTs) are now in the phase transition from being 'high-energy experiments' to being 'telescopic installations' in the astronomical sense. This fact is motivating an explosion of interest in a broad scientific community embracing astrophysics, particle physics and cosmology [1].

The reason for this phase transition is the big observational step that occurred within the last couple of years at the quantitative level (tripling the number of detected sources) but also at the qualitative level (producing extremely high quality detections allowing unprecedented detailed studies) due to the Cherenkov telescopes of the new generation coming into operation [2].

Among the broad spectrum of scientific opportunities offered by the observation of the sky in the VHE gamma-ray band with Cherenkov telescopes there are some which, given the quality of the observations provided by the instruments of the new generation, may have a relevant impact in observational and theoretical cosmology. Discussing them, reviewing its present status and discussing their prospects are the goal of this paper.

For that, the outline of this paper is as follows: in section 2 we will present the status of the indirect search for dark matter annihilation into VHE gamma rays discussing the impact of the detailed analyses of the galactic centre observations carried out by HESS and MAGIC.

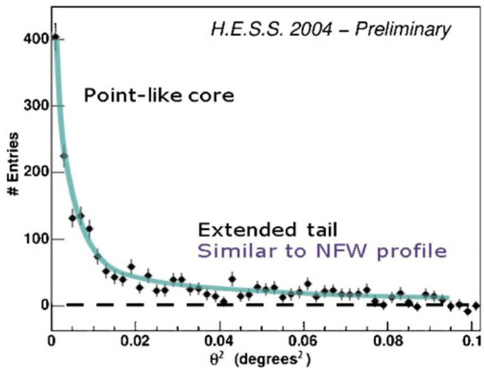

Figure 1. Radial profile of the galactic centre gamma-ray excess observed in 2004 HESS data.

In section 3, we will discuss the implications of the studies of the energy spectrum measured in distant Blazars by HESS and MAGIC, which allow to place an unexpectedly low upper bound on the density of the extragalactic background light by means of the analysis of the gamma–gamma absorption. As it will be argued, if confirmed this result may open the window for the use of that kind of observations to constrain dark energy by using the optical depth for the VHE gamma rays' propagation due to the absorption as a distance estimator in a similar manner as the one used with supernovae 1a. Finally, section 4 will review the use of light curves showing fast flares of VHE gamma-ray sources at cosmological distances to place constraints on the quantum structure of the gravitational vacuum.

2. Indirect searches for dark matter

If most of the dark matter is in form of weakly interacting massive particles (WIMP) as the ΛCDM scenarios, favoured by most of the observations, presently suggest, a favourite candidate for this dark matter is the LSP which in most supersymmetric extensions of the standard model is the so-called neutralino, the spin $1/2$ supersymmetric partner of the neutral bosons [3]. In that case, dark matter may be detected from the neutralino annihilation into pairs of VHE gamma rays from the centre of our galaxy, nearby galaxies, low surface brightness dwarf spheroidal galaxies, globular clusters or 'hidden' dark matter satellites [4].

Out of all the possible target candidates for the indirect detection of dark matter through its annihilation into VHE gamma rays, the one from which larger flux is expected is the centre of our galaxy. The reason is the very high dark matter density expected, which enters quadratically in the gamma-ray flux prediction, and its proximity when compared to other target candidates [5].

The galactic centre has been independently observed by HESS and MAGIC (in this case at large zenith angle, which implies larger effective area but at a higher energy threshold) providing spectrum measurements in nice agreement, which contradict the measurements previously published by the CANGAROO Collaboration.

The signal observed by HESS in 2003–2004 was consistent with point-like emission from Sgr A* [6] although it had a slight hint for extension which could be fit with a Navarro–Frenk–White dark matter halo profile as can be gleaned from figure 1. In addition, the signal was steady from year to minute scales. The spectrum obtained with the first data taken extended up to energies above 10 TeV and would have required invoking an unnaturally heavy neutralino to explain it.

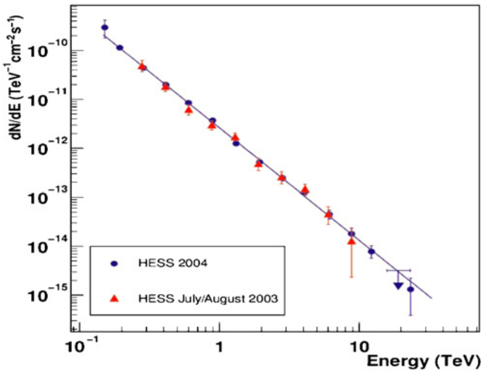

Figure 2. Differential energy spectrum of the galactic centre gamma-ray excess observed by HESS.

The final spectrum after analysing all the accumulated data can be seen in figure 2 which shows that it can be very well fitted by an unbroken power law with index 2.3 from about 150 GeV up to almost 30 TeV. This spectrum is in perfect agreement with the one obtained by the MAGIC Collaboration which has observed the galactic centre at large zenith angles (from 58° to 62°) and, hence, with somewhat different systematic uncertainties.

This spectrum shape and index are in agreement with the expectations from acceleration mechanisms in standard astrophysical sources and rule out most of the possible interpretations in terms of dark matter annihilation.

Nevertheless, a plausible explanation at that stage was that the signal from the dark matter annihilation in the galactic centre region could be outshined by the VHE gamma-ray emission from point-like astrophysical sources in the galactic centre region which, from observations in many wavelengths, is known to be a very busy region with many astrophysics sources and a lot of non-thermal activity.

Following this idea, HESS has been able to subtract from a deep exposure the point-like sources (given its point-spread function) [7] and the observed remaining signal turns out to be in good agreement with the distribution of the molecular gas traced by its CS emission as can be observed in figure 3.

Therefore, the high quality data on the galactic centre obtained in the last few years by HESS and MAGIC do not show any evidence of dark matter annihilation signal [8, 9]. In spite of that, it is very difficult to extract any quantitative conclusion of that observation since there are very large uncertainties in the predictions for the expected flux coming from:

- WIMP mass spectrum and couplings which should be known to determine the annihilation probabilities into the different channels. For these quantities, important accelerator and relic density constraints exist already but there is still a very broad parameter space open, which make predictions very uncertain. The start of LHC operation in the coming years may narrow down drastically the parameter space and allow for much more precise predictions.
- The cuspy region of the dark matter density profile, in the vicinity of the central supermassive black hole, which remains virtually unknown.
- The background due to astrophysical sources which may be much larger than the dark matter annihilation signal making the subtraction very uncertain.

Nevertheless, other target candidates, such as dwarf spheroidal satellites of our galaxy with high mass-to-light ratios which in comparison with the galactic centre are expected to produce

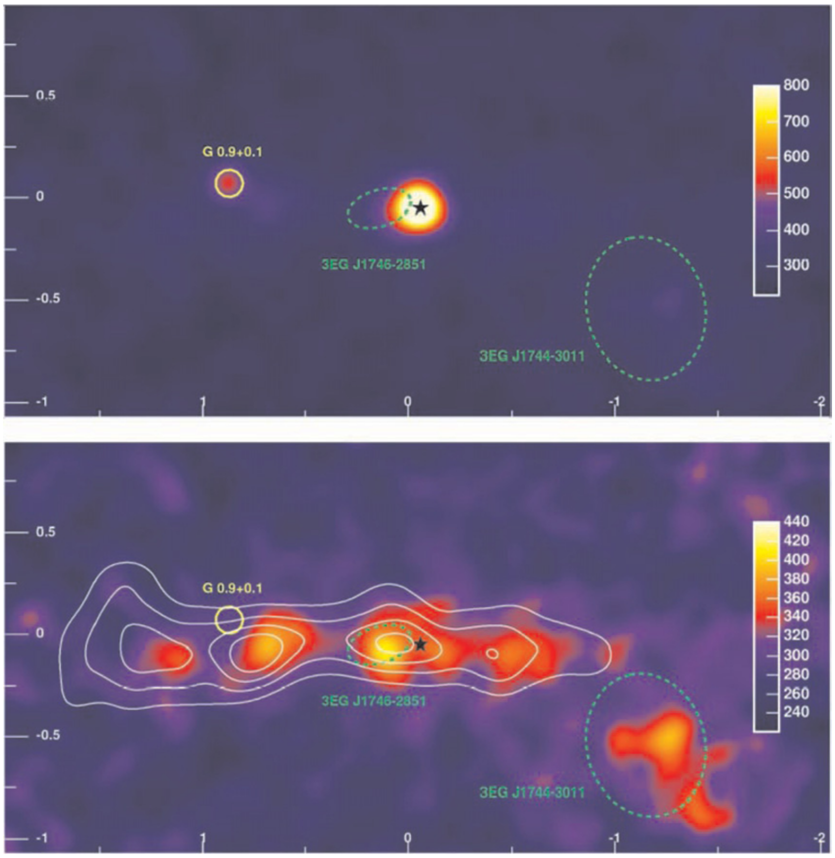

Figure 3. The galactic centre gamma-ray count map as observed by HESS (upper plot) and after subtracting point-like source contributions (lower plot) showing a clear correlation with the molecular gas traced by its CS emission.

lower fluxes and are more distant, but which may provide cleaner environments with much less astrophysical source backgrounds, are being explored. One of the most promising candidates is Draco, for which by the end of 2005 there was a claim of a highly significant VHE gamma-ray detection by the CACTUS Solar Array Collaboration [10]. Preliminary analyses of data taken by MAGIC [11] were in contradiction with that claim, which meanwhile was retired by the CACTUS Collaboration while studying in detail systematic effects.

An important step in this search for dark matter annihilation signals will be the sky survey catalogue which will be produced by GLAST in the near future since its unidentified sources may spot dark matter clumps and therefore be prime candidates to study in depth with Cherenkov telescopes in the quest for dark matter.

At any rate, it must be stressed that even if WIMP candidates are found in accelerator experiments it must be confirmed that they actually are constituents of the dark matter of our universe and for this purpose IACTs are among the most promising instruments.

3. The cosmological gamma-ray horizon

As it is very well known the intergalactic vacuum is not really empty. There is a sea of photons lying around which constitutes the so-called extragalactic background light (EBL).

For instance, one can find the well-studied cosmic microwave background but there are contributions from any photon energy [12].

The flux of high-energy gamma rays that travel through the universe is attenuated by the absorption of gamma rays in the diffuse extragalactic background light through the QED interaction $\gamma_{\mathrm{HE}}\gamma_{\mathrm{EBL}} \rightarrow f^+ f^-$. The cross section for this electromagnetic reaction decreases as the inverse of the square of the final state fermion mass and, hence, the most probable final state is an $\mathrm{e}^+\mathrm{e}^-$ pair.

Gamma rays of energy E can interact with low-energy photons of energy ϵ from the diffuse EBL over cosmological distance scales. The pair production is expected above the threshold energy condition

$$E\epsilon(1 - \cos\theta) > 2m^2c^4 \tag{1}$$

where θ is the gamma–gamma scattering angle and m the fermion mass.

Therefore, the relevant EBL for the Cherenkov telescopes is the visible and infrared background, for which there exists observational data with determinations and bounds of the background spectral energy density (SED) at $z = 0$ for several energies. The determinations come from direct measurements of the EBL density using instruments on satellites whereas the bounds happen mostly in the infrared part of the EBL and come from extrapolations using galaxy counting. Given the difficulty of observing 'cold galaxies' due to the zodiacal light background, they provide just lower limits.

Actually, the SED at $z = 0$ is not the end of the story since the EBL evolves with the redshift and the high-energy γ-rays originated at cosmological distances will interact with the EBL at different redshifts. The main contribution to the EBL comes from low-energy photons produced by stars in ordinary galaxies. Therefore, either the star formation rate or the star evolution will play an important role to the EBL as a function of redshift determination.

The flux attenuation is a function of the gamma energy E and the redshift z of the gamma-ray source and can be parameterized by the optical depth $\tau(E, z)$, which is defined as the number of e-fold reductions of the observed flux as compared with the initial flux at z. This means that the optical depth introduces an attenuation factor $\exp[-\tau(E, z)]$ modifying the gamma-ray source energy spectrum:

$$\tau(E, z) = \int_0^z \mathrm{d}z'\, c\frac{\mathrm{d}t}{\mathrm{d}z'} \int_0^2 \mathrm{d}x\, \frac{x}{2} \int_{\frac{2m^2c^4}{Ex(1+z')^2}}^{\infty} \mathrm{d}\epsilon \cdot n(\epsilon, z') \cdot \sigma[2xE\epsilon(1 + z')^2] \tag{2}$$

where $n(\epsilon, z')$ is the EBL spectral density at redshift z', σ is the cross section for $\gamma_{\mathrm{HE}}\gamma_{\mathrm{EBL}} \rightarrow \mathrm{e}^+\mathrm{e}^-$ and $\mathrm{d}t/\mathrm{d}z$ the lookback time.

For any given gamma-ray energy, the gamma-ray horizon (GRH) is defined as the source redshift for which the optical depth is $\tau(E, z) = 1$. Therefore, the GRH gives, for each gamma-ray energy, the redshift location z of a source for which the intrinsic gamma flux suffers an e-fold decrease when observed on Earth $z = 0$ due to the gamma–gamma absorption.

In practice, the cut-off due to the optical depth is completely folded with the spectral emission of the gamma source. But, on the other hand, the suppression factor in the gamma flux due to the optical depth depends only (assuming a specific cosmology and spectral EBL density) on the gamma energy and the redshift of the source. Therefore, a common gamma energy spectrum behaviour of a set of different gamma sources at the same redshift is most likely due to the optical depth.

To compute the optical depth using equation (2) there are two quantities which have to be known: on the one hand, the density of the EBL and its redshift dependence and, on the other hand, the cosmological evolution of our universe cast in the lookback time expression.

The direct measurement of the EBL density in the wavelength range relevant for VHE gamma-ray absorption (from 0.1 μm to 10 μm) is very difficult because of our light-polluted

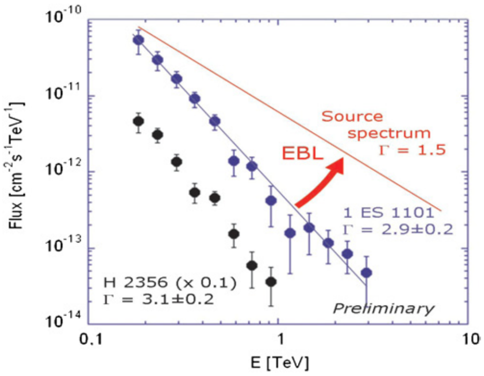

Figure 4. Measured differential energy spectrum of two of the farthest Blazars detected by HESS compared with an intrinsic spectrum of index 1.5.

environment, in particular by zodiacal light—sunlight reflected from dust clouds in our solar system. For this reason, the absorption measured by studying the distortion in the energy spectrum of distant sources has already been widely used to try to bound the EBL density.

HESS [13] and MAGIC [14] have observed VHE gamma rays from few relatively distant active galaxies. In the case of HESS two objects, identified as the Blazars H2356-309 and 1ES1101-232 at redshifts of $z = 0.165$ and 0.186, respectively, have been detected. The multiwavelength observations of Blazars as well as theoretical shock acceleration models in jets have serious difficulties to predict intrinsic gamma-ray spectral energy slopes harder than $\Gamma = 1.5$[1] while the observed slope for these two sources and for the 1ES1218 + 304 Blazar at redshift $z = 0.182$ discovered by MAGIC are unexpectedly very hard, of about $\Gamma \approx 3$ as can be seen in figure 4. The observation of such hard spectra hints to a universe more transparent to VHE gamma rays than what was expected based on the direct measurements and the model predictions of the EBL density.

Actually, using these spectra and the energy dependence of the optical depth through electron–positron pair production which can be obtained from equation (2), the HESS Collaboration has been able to set a firm upper limit on the absorption of gamma ray and hence on the amount of extragalactic background light [15].

This limit is sensibly less than—and hence in conflict with—the values derived by direct measurements of the extragalactic background light as can be seen in figure 5. Furthermore, being only about a factor of $\sim$1.5 above the lower limit given by direct observation of galaxies by the Hubble Space Telescope, the HESS observations seriously limit the possible contribution from sources other than galaxies. This is in good agreement with recent theoretical calculations and arguments against a strong extragalactic background from first-generation stars. This is bad news for the attempts at direct detection of the glow of these population III stars but the HESS results expand the horizon of the gamma-ray universe, allowing Cherenkov telescopes to detect many other remote active galaxies.

If the upper bound from HESS is confirmed, and taking into account that the correction of any possible observational biases in the galaxy count contribution to the EBL would very likely increase the lower bound, narrowing even further the distance between that lower bound and the HESS upper bound, one may think that the EBL density in the relevant region for VHE

[1] Nevertheless, it should be pointed out that this assumption could be relaxed in the case of significant absorption of gamma rays at the source, for instance with the optical radiation from the accretion disc or scattered along the jet, which could produce a spectral index harder than 1.5.

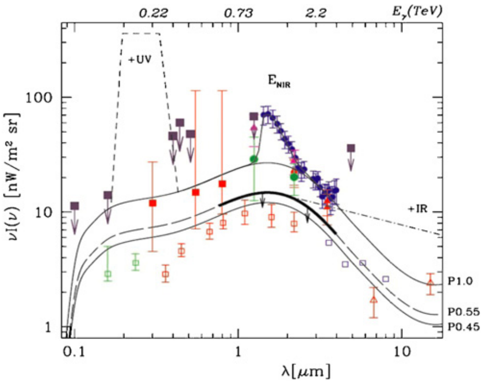

Figure 5. Direct measurements, limits and different possible scenarios explored by HESS to explain the observed gamma-ray absorption (see the text).

gamma-ray astronomy might be basically resolved as the sum of the contributions from the light of all the galaxies observed as point-like sources. Since there are many deep-exposure large astronomical surveys in operation and proposed for the coming years cartographing the galaxies in big volumes of the visible universe, it may then be possible to get a rather accurate determination of the EBL density as a function of redshift in the wavelength region relevant for VHE gamma-ray astronomy.

In that case, the only missing information in equation (2) would be the lookback time, and then the measurement of the optical depth using the distant Blazar spectrum absorption could be turned upside down and used to try to measure the cosmological parameters instead of the EBL density.

The idea would be using the spectrum absorption due to the interaction with the EBL to compute the 'absorption distance' and use it as a distance estimator, in a similar way as the observed luminosity of supernovae 1a is used, assuming they behave as standard candles, to compute the 'luminosity distance' and use it as a distance estimator. Both distance estimators have different redshift dependences and can be considered as complementary since they use very different targets (active galaxies versus supernovae), with very different assumptions (universal EBL versus 'standard candle') and with very different systematic uncertainties.

A study of the viability of such an approach was conducted few years ago [16, 17]. In that work, the sensitivity of the measurement of the gamma-ray horizon with respect to the cosmological parameters was studied showing that indeed there was a sizable dependence which, assuming the EBL density known, could allow for meaningful constraints in the cosmology. Moreover, a reasonable simulation of the gamma-ray horizon measurement as it could eventually be obtained from about 20 EGRET sources extrapolating the measured spectra was performed. By assuming reasonable observation periods and taking only statistical uncertainties into account, the constraints in the Ω_m versus Ω_Λ plane predicted were improving the supernovae constraints existing at that time by a factor $\sim$2. That work included as well a discussion on the possible systematic uncertainties from experimental and theoretical origin concluding that the uncertainty in the actual EBL density could be the dominant one although some strategies to try to squeeze it were also proposed.

Summarizing, there are two implications of the HESS results, namely:

- on the one hand, the universe is more transparent to gamma rays than expected and therefore the redshift reach of Cherenkov telescopes should be substantially larger than anticipated allowing to observe much more distant extragalactic sources,

- on the other hand, the EBL density in the wavelength region relevant for the VHE gamma-ray absorption might be actually resolved and hence the EBL density could be directly measured by surveys performing deep and detailed galaxy count.

If these implications are confirmed, the study of the absorption in the energy spectrum of extragalactic VHE gamma rays at different redshifts may provide a competitive complementary technique for the determination of the parameters which govern the expansion of our universe and, specifically, may help in constraining dark energy.

4. Tests of the invariance of the speed of light

Any quantum theory of gravitation introduces quantum fluctuations at the Planck scale ($E_P \approx 10^{19}$ GeV or correspondingly $L_P \approx 10^{33}$ cm), which would induce a deformed dispersion relation for photons of the form [18]

$$p^2c^2 = E^2[1 + f(E/E_{\mathrm{QG}})] \tag{3}$$

where E is the photon energy, E_{QG} is an effective quantum gravity energy scale (which might be as large as the Planck scale) and f is a model-dependent function of the ratio E/E_{QG}, p is the photon momentum and c is the velocity of light. At small energies $E \ll E_{\mathrm{QG}}$, a series expansion of the dispersion relation can be made:

$$p^2c^2 = E^2\left[1 + \xi E/E_{\mathrm{QG}} + O\left(E^2\big/E_{\mathrm{QG}}^2\right)\right] \tag{4}$$

where $\xi = \pm 1$ is a sign ambiguity which is fixed in the given theory. Equation (4) then leads to energy-dependent velocities of the photon:

$$v = \frac{\partial E}{\partial p} \approx c\left(1 - \xi\frac{E}{E_{\mathrm{QG}}}\right). \tag{5}$$

Gamma rays travelling cosmological distances should therefore encounter a 'vacuum' energy dispersion $\delta v \sim E/E_{\mathrm{QG}}$, violating Lorentz invariance. A gamma-ray signal of observed energy E_γ should acquire a time delay with respect to the Lorentz-invariant case, after having travelled a distance L (redshift z) [19]:

$$\Delta t \approx \xi\frac{E}{E_{\mathrm{QG}}}\int_0^Z (1+z)\frac{\mathrm{d}l}{\mathrm{d}z}\,\mathrm{d}z \xrightarrow{z<<1} \xi\frac{E}{E_{\mathrm{QG}}}\frac{L}{c}. \tag{6}$$

Gamma rays of different energies being emitted simultaneously should thus reach an observer at different times. In order to use equation (6) to test E_{QG}, a rapidly varying signal is required with typical time intervals δt smaller than the time delay Δt due to the quantum gravity effect and observed simultaneously at two different energies at least.

Gamma ray telescopes are specially well suited to measure this effect since they study photons of the highest energies, they study sources at cosmological distances such as Blazars and gamma-ray bursts, and these sources provide natural time stamps since they are either flaring or transient. The light curves of these fast flares can be recorded and studied in detail thanks to the huge effective areas of these telescopes.

Nevertheless, since possible energy-dependent time delays observed in a specific source could have an astrophysical origin and be produced either in the emission process or during the propagation of the photons thorough space for that specific region of the sky [20], a sinequanon condition to make a claim of observation of a quantum gravity effect should be the observation of delays in a sample of sources distributed across different regions in the sky and located within a broad range of distances, which should nevertheless adjust the simple mathematical relation cast in equation (6).

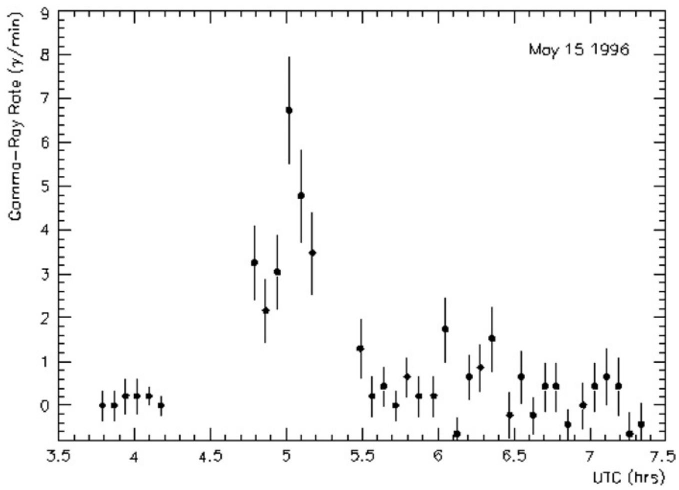

Figure 6. Light curve of the Mkn 421 flare in VHE gamma rays observed by WHIPPLE in 1999.

In 1999, the Whipple Collaboration published [21] a first bound on E_{QG}, obtained with that technique using a flare of Mrk 421 ($z = 0.031$) which was very fast ($\delta t \approx 280$ s as can be seen in the light curve of figure 6) and was observed up to a gamma-ray energy of 2 TeV. The analysis of that flare allowed the WHIPPLE Collaboration to place a constraint of $E_{QG}/\xi > 4 \times 10^{16}$ GeV at 95% confidence level.

At present there are claims by the MAGIC Collaboration [14] of recorded AGN flares even faster and with a much larger amount of gamma rays recorded than the one observed by WHIPPLE, allowing a broader and more detailed energy spectrum and therefore, perhaps, much better bounds than the aforementioned one.

In addition, if GRB are detected with Cherenkov telescopes, using the same method for GRBs, much higher sensitivities should be reached since the distances L are usually much larger and typical time intervals δt much shorter. For instance, assuming a GRB at a redshift of $z = 1$, observed simultaneously at 100 GeV and 1 MeV, with a time binning of 1 s, a hypothetical limit of $E_{QG}/\xi > 10^{19}$ GeV could be reached. Therefore, IACTs might provide the opportunity of directly testing the quantum nature of gravity up to effective scales of the order of the Planck mass.

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