Highlights from VHE Gamma Astronomy: Where do we stand and where do we go ?

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We're witnessing the down of VHE Gamma Astronomy thanks to a new generation of Cherenkov Telescopes which is producing a plethora of discoveries and new measurements with a direct implication for astrophysics, fundamental physics and cosmology. The main present results and future prospects are discussed.

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 exploding interest in a broad scientific community embracing astrophysics, particle physics and cosmology [1].

The reason for this phase transition is the big observational step 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 start into operation of the Cherenkov Telescopes of the new generation.

Nevertheless, given the limited extension of this manuscript, among the broad spectrum of new results obtained from the observations in the VHE gamma ray band with the new generation of Cherenkov Telescopes we shall concentrate in discussing three highlights with the largest impact in fundamental physics and cosmology.

For that, the outline of this write-up is as follows: in section 2 we'll 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 center observations carried out by HESS and MAGIC. In section 3 we'll 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. 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, favored by most of the observations, presently suggest, a favorite candidate

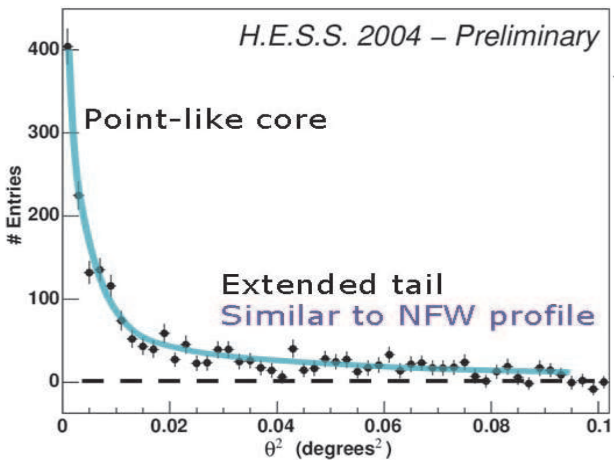

Figure 1: Radial profile of the Galactic Center gamma-ray excess observed in 2004 HESS data.

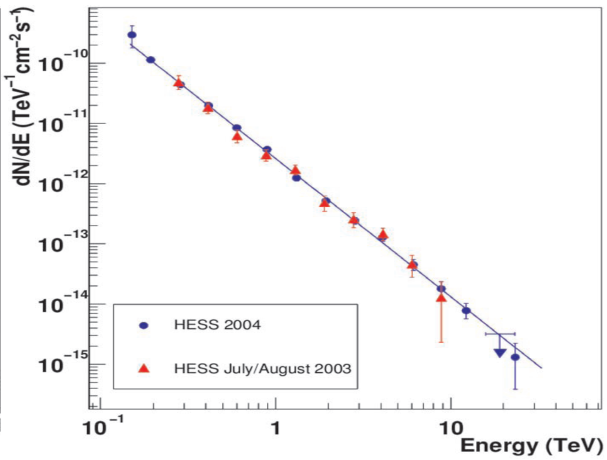

Figure 2: Differential energy spectrum of the Galactic Center gamma-ray excess observed by HESS.

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. In that case, Dark Matter may be detected from the neutralino annihilation into pairs of VHE gamma rays from the center of our galaxy, nearby galaxies, low surface brightness dwarf spheroidal galaxies, globular clusters or "hidden" dark matter satellites [2].

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 center 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 [3].

The galactic center 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* [4] although it had an 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.

The final spectrum after analyzing 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 Center at large zenith angles (from 58 to 62 degrees) 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 rules 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 Center region could be outshined by the VHE gamma ray emission from point-like astrophysical sources in the Galactic Center 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

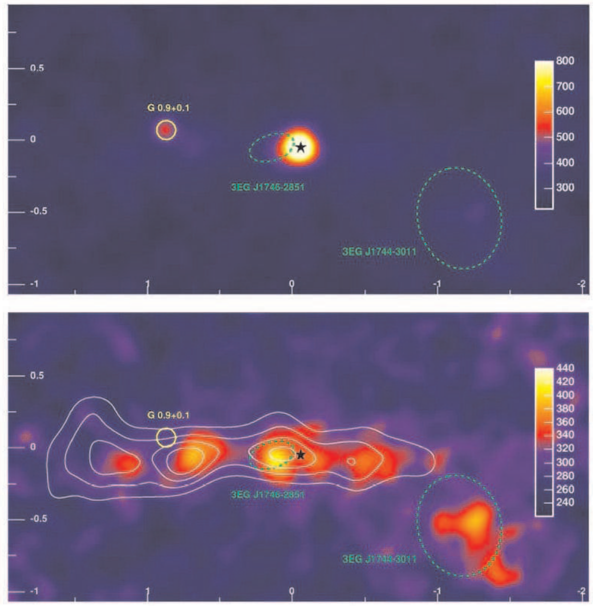

Figure 3: The Galactic Center gamma-ray count map as observed by HESS (upper plot) and after subtracting point-like source contributions (lower plot) showing a clear correlation with the molecular gas traced by its CS emission.

sources (given its point-spread-function) [5] 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 Center obtained in the last few years by HESS and MAGIC does not show any evidence of Dark Matter annihilation signal [6,7]. 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 Center are expected to produce lower fluxes and are more distant, but which may provide cleaner environments with much less astrophysical source backgrounds, are being explored.

An important step in this seach for Dark Matter annihilation signals will be the sky survey catalog 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 know the intergalactic vacuum is not really empty. There is a sea of photons lying around which constitute 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 [8].

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 $\gamma_{HE}\gamma_{EBL} \rightarrow f^+ f^-$. 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 a e^+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 infra-red 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 and 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 parameterised 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.

$$\tau(E,z) = \int_0^z dz'\, c\frac{dt}{dz'} \int_0^2 dx\, \frac{x}{2} \int_{\frac{2m^2c^4}{Ex(1+z')^2}}^{\infty} d\epsilon \cdot n(\epsilon, z') \cdot \sigma[2xE\epsilon(1+z')^2] \tag{2}$$

where $n(\epsilon, z')$ is the EBL spectral density at redshift z', σ the cross-section for $\gamma_{HE}\gamma_{EBL} \rightarrow e^+e^-$ and dt/dz 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

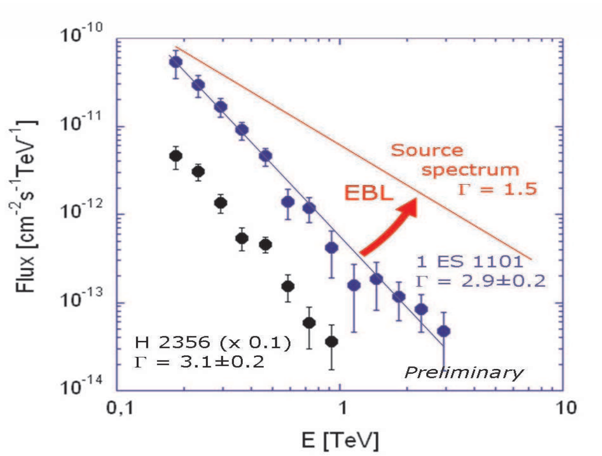

Figure 4: Measured differential energy spectrum of two of the farthest Blazars detected by HESS compared with an intrinsic spectrum of index 1.5 .

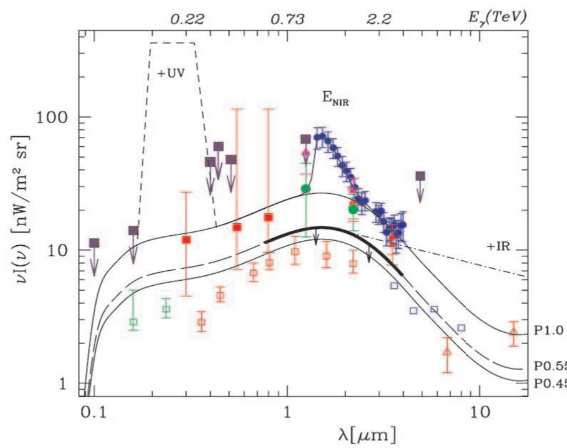

Figure 5: Direct measurements, limits and different possible scenarios explored by HESS to explain the observed gamma ray absorption (see text).

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 casted in the lookback time expression.

The direct measurement of the the EBL density in the wavelength range relevant for VHE gamma ray absorption (from $0.1\mu m$ to $10\mu m$) is very difficult because of our light-polluted 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 [9] and MAGIC [10] 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 $\Gamma = 1.5$ [a] 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 [11].

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 ~ 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

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

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.

The upper bound from HESS seems to be confirmed already by observations of new AGNs being recently reported by HESS and MAGIC. Terefore, 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 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 be then 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.

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 with govern the expansion of our universe and specifically, may help in constraining Dark Energy [12,13].

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 [14]:

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

where E is the photon energy, E_{QG} 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 $E \ll E_{QG}$ a series expansion of the dispersion relation can be made:

$$p^2c^2 = E^2[1 + \xi E/E_{QG} + O(E^2/E_{QG}^2)] \quad (4)$$

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

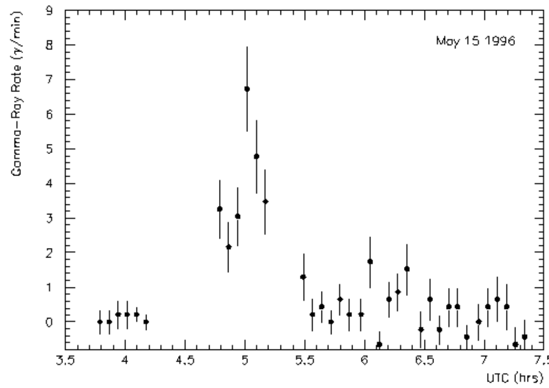

Figure 6: Light curve of the Mkn 421 flare in VHE Gamma Rays observed by WHIPPLE in 1999

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

Gamma rays travelling cosmological distances should therefore encounter a "vacuum" energy dispersion $\delta v \sim E/E_{QG}$, 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) [15]:

$$\Delta t \approx \xi \frac{E}{E_{QG}} \int_0^Z (1+z) \frac{dl}{dz} dz \stackrel{z<<1}{\longrightarrow} \xi \frac{E}{E_{QG}} \frac{L}{c} \tag{6}$$

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 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 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 [16], 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 casted in equation 6.

In 1999, the Whipple collaboration published [17] a first bound on E_{QG}, obtained with that technique using a flare of Mrk 421 (z = 0.031) which was very fast ($\delta t \approx 280s$ as can be seen in the lightcurve 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 $E_{QG}/\xi > 4\,10^{16}$ GeV at 95% confidence level.

The MAGIC collaboration has recently reported [10] recorded AGN flares from Mrk 501 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 which, therefore, may lead to 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 testing directly the quantum nature of Gravity up to effective scales of the order of the Planck mass.

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