Recent results in very high energy gamma ray astronomy

J-F. GLICENSTEIN
DSM/IRFU/SPP
CEA-Saclay, F-91191 Gif-sur-Yvette, France

The very high energy (E ¿50 GeV) gamma ray astronomy is an emerging field. Three major Imaging Atmospheric Cherenkov Telescope collaborations, HESS, MAGIC and VERITAS are presently in operation.Many new results in astroparticle physics have been obtained by these instruments. In this paper, Galactic Center observations, dark matter searches and limits on Lorentz invariance violation are reported.

1 Introduction

The very high energy (VHE) gamma ray astronomy is a new emerging field. This paper focuses on selected results from the VHE gamma ray instruments which are of interest to the particle physics community. The first section reviews the experimental status. Next, recent results on the Galactic Centre from the HESS collaboration are reported. These results constrain the source of the VHE gamma ray emission. The next section is dedicated to indirect dark matter searches.More than 15 Active Galactic Nuclei (AGN) have been observed in the TeV regime. These distant variable sources allow to test for Lorentz invariance breaking. The final section reports constraints on violations of the Lorentz invariance obtained by the MAGIC collaboration.

2 The very high energy gamma ray instruments

Ground based very high energy gamma ray instruments detect atmospheric cascades initiated by astrophysical gamma-rays. These intruments are sensitive to photons in the range 50 GeV to 100 TeV. The two major classes of instruments are imaging atmospheric Cherenkov telescopes (IACT) and shower particle detectors. The characterictics of major currently operating IACTs are summarized in table 1. These instruments are the HESS, VERITAS and CANGAROO-III arrays and the MAGIC telescope. Each of their telescope is equipped with a finely pixelized camera at its focus. A large fraction of the cosmic ray background is rejected with the analysis of the Cherenkov image. In addition,Cherenkov arrays use stereoscopy to improve their background rejection and their energy/angular resolution.

Table 1: Principal caracteristics of currently operating major IACTs

Instrument	lat. (deg)	long (deg)	Altitude (m)	Tels	Telescope Area (m^2)	Camera Pixels	FOV (deg)	Threshold (TeV)
HESS	-23	16	1800	4	107	960	5	0.1
MAGIC	29	18	2225	1	234	574	3.5	0.05
VERITAS	33	-111	1275	4	106	499	3.5	0.1
CANGAROO	-31	137	160	3	57.3	427	4	0.3

HESS [a] is an array of 4 12-meter diameter telescopes located in the Khomas highlands of Namibia. HESS was completed at the end of 2003. The typical angular resolution of the HESS instrument of 0.1 deg. allows to make detailed images of extended galactic objects such as the supernova remnant RXJ1713-3946[6]. The HESS collaboration is performing a galatic survey of TeV sources[7] which takes advantage of both the angular resolution and the large 5 deg field of view (FOV) of the cameras. A fifth telescope with a 28-meter diameter is being built and should be completed in 2009.

The VERITAS[b] array is an upgrade of the 1O-meter Whipple telescope. The Whipple telescope was a major IACT of the 1980s and 1990s. VERITAS is very similar in caracteristics to the HESS array and was completed in 2007.

The 17 meter diameter MAGIC[c] telescope is the largest operating IACT. It is located on La Palma island in the Canaries and started its operations in 2004. It is optimised for low-energy photons ($E \simeq 50$GeV) detection. The MAGIC collaboration is building a second similar telescope which should be completed in 2008. This second telescope will allow the MAGIC collaboration to use the stereoscopy technique.

The MILAGRO[d] instrument is a shower particle detector. It is a water Cherenkov detector located at Los Alamos, at an altitude of 2630 meters. It is in operation since 2000. It has a large FOV (2 sr) which compensates for the high trigger threshold ($\sim$ 1TeV) and the angular resolution of the order of 1 deg. MILAGRO has detected extended emission from the galactic plane (Abdo et al (2008)[2]) and 4 "point sources" at a significance $> 4\sigma$ (Abdo et al (2007)[1]).

3 Galactic Centre

VHE gamma ray emission from the Galactic Centre has been reported in the TeV range by the CANGAROO, HESS, Whipple and MAGIC collaborations. The published[3] position of the TeV source HESS J1745-290 is located within 20 arc seconds of the central black hole Sgr A*. The spectrum, which was obtained from 2004-2005 data is compatible with a pure power-law with spectral index $\Gamma = 2.29 \pm 0.04(\mathrm{stat}) \pm 0.1(\mathrm{syst})$ in the range 100 GeV to 10 TeV. The possible non-standard interpretation of the HESS J1745-290 signal as annihilation of dark matter particles has been investigated by the HESS collaboration (F.Aharonian et al.(2006)) [3]. The observed spectrum is not well fitted by expected dark matter annihilation spectra, implying a mostly non-dark matter origin for the signal. Assuming that the observed signal is a blend of an astrophysical source and dark matter annihilations in a Navarro-Frank-White halo, the 95 % C.L. upper limits on the velocity-weighted cross-section are $< \sigma v > \simeq 10^{-24} \mathrm{cm}^3 \mathrm{s}^{-1}$ for a neutralino mass in the range 100 GeV to 1 TeV.

The signal of HESS J1745-290 can been interpreted by a large variety of astrophysical models

[a] Web address http://www.mpi-hd.mpg.de/hfm/HESS/HESS.html
[b] Web address http://veritas.sao.arizona.edu
[c] Web address http://wwwmagic.mppu.mpg.de
[d] Web address http://www.lanl.gov/milagro

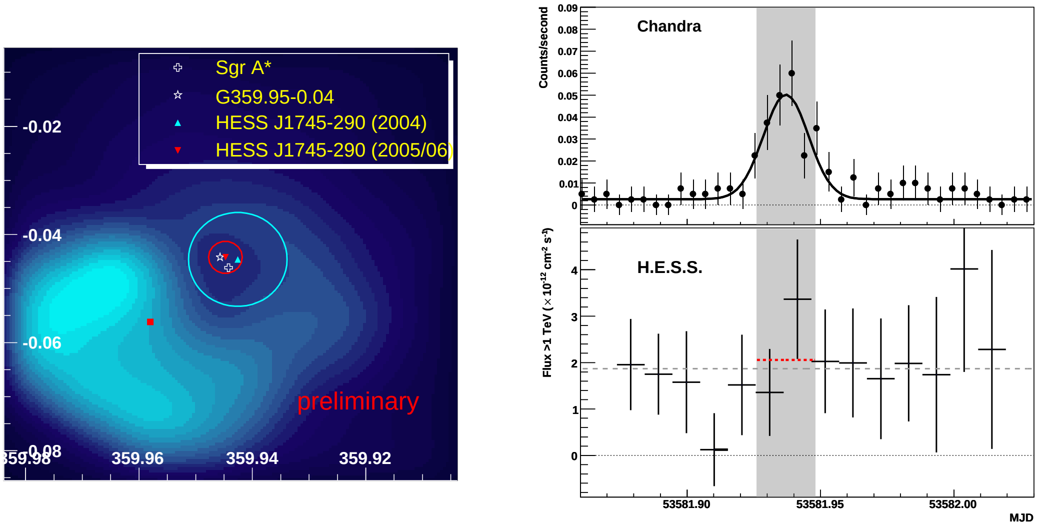

Figure 1: Left panel: VLA image of the Galactic Centre region. The extended source on the left is the supernova remnant Sgr A East. The outer circle shows the error on the position of HESS J1745-290 from F.Aharonian et al (2006). The inner circle is the error on the position of the same source from C.VanEldik et al (2007). Right panel: Simultaneous Chandra and Hess observation on July 30 2005, from J.Hinton et al (2007). Top: Chandra 1-10 keV count rate (400 seconds bins). Bottom: HESS light curve in 15 minutes bins.

(see e.g. Hinton and Aharonian (2007)[14] and references inside). Possible astrophysical sources for HESS J1745-290 include Sgr A*, the supernova remnant Sgr A East and the pulsar wind nebula G359.95-0.04. Recently, a careful study [20] allowed to lower the pointing errors of the HESS experiments down to the level of 8 arc seconds. The preliminary position of the source is located at an angular distance of $7.3\,'' \pm 8.7\,''(\text{stat}) \pm 8.5''(\text{syst})$ from the central galactic black hole Sgr A*. This position (see figure 1) is incompatible with the centroid of the radio emission of the supernova remnant Sgr A East, but still compatible with sources such as the pulsar wind nebula G359.95-0.04.

The Sgr A* black hole is well known to be a variable source in the infrared and X-ray passbands. The variability of the HESS J1745-290 source has been studied in M.Vivier et al. [21]. No significant variability or periodicity was found between 30 seconds and one year. Simultaneous data were also taken with the Chandra satellite during a flare of SgrA* on July 30 2005 (see figure 1 and J.Hinton et al. (2007)[15]). No significant TeV flare was seen during the X-Ray flare. This implies that the TeV emission is produced at a relatively large distance for the Sgr A* black hole.

4 Indirect dark matter searches

Popular particle physics models such as the Minimal Supersymmetric Standard Model (MSSM) or Universal Extra Dimensions ("Kaluza-Klein" [18]) predict WIMP (Weakly Interacting Massive Particles) dark matter annihilations in galactic halos. These annihilations could give observable signals in Cherenkov telescopes (for a review see Bertone, Hooper and Silk (2005)[12]). The flux $\mathrm{d}\Phi/\mathrm{d}E_\gamma$ of gamma rays is

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E_\gamma} = \frac{1}{4\pi}\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}\frac{<\sigma v>}{M_\chi^2}\bar{J}\Delta\Omega. \quad (1)$$

It is the product of an astrophysical term $\bar{J}$ and a particle physics term. The former depends on the mass density profile ρ of the dark halo

$$\bar{J} = < \int_{l.o.s} \rho^2 \mathrm{d}s > . \tag{2}$$

In equation 2, the average is taken over the solid angle $\Delta\Omega$ spanned by the Point Spread Function (PSF). The spatial resolution of H.E.S.S. is of the order of 5 arc minutes per event, giving $\Delta\Omega = 2\ 10^{-5}$. The particle physics term depends on the velocity averaged annihilation cross section $< \sigma v >$ and the WIMP mass M_χ.

The possible targets for WIMP annihilation searches can be ranked according to their values of $\bar{J}$. If the annihilation signal from a halo located at distance D is "point-like", then $\bar{J} \propto M^2/D^5$ where M is the (often measured) dark mass inside the PSF. The best astrophysical targets are thus the Galactic Center and nearby dwarf galaxies. The results of the Galactic center search have already been mentionned (section 3). Data towards several dwarf galaxies have been taken by the Atmospheric Cherenkov collaborations. These galaxies are Sagittarius (HESS[5]), Draco (MAGIC[9] and Whipple[22]) and Ursa minor (Whipple [22]). The expected flux from galaxy clusters such as Virgo or Coma is smaller by at least 3 orders of magnitude. It is also possible to look for dark matter clumps or dark matter annihilations in the vicinity of Intermediate Mass Black Holes [4].

The Sgr dwarf galaxy is a satellite of the Milky Way. It is located in the galactic plane in the direction of the Galactic Center, at a distance of 24 kpc. It is being torn apart by the tidal force of the Galaxy. The visible mass profile of the Sgr dwarf galaxy is difficult to obtain because of the contamination of galactic foreground stars. The center of the Sgr dwarf galaxy is coincident with the globular cluster M 54 [16]. The interpretation of velocity dispersion measurements is difficult because of the tidal interaction with the Milky Way. The central velocity dispersion has been measured by several groups (see e.g. Zaggia et al (2004) [23]). The HESS collaboration (F.Aharonian et al (2008) [5]) choose to describe Sagittarius galactic structure with two models. The first one is a Navarro-Frank-White model with parameters taken from Evans,Ferrer and Sarkar (2004) [13]. The other model ("core model") was fitted to the structural parameters (distribution of visible mass and central dispersion).

The Sgr dwarf galaxy has been observed by H.E.S.S. in June 2006. After quality cuts, a total exposure of 11 hours was obtained. No significant excess is seen at the position of M54. This translates into 95% C.L. upper limits of $< \sigma v > \simeq 10^{-23} \mathrm{cm}^3\mathrm{s}^{-1}$ for the NFW model and $< \sigma v > \simeq 2\ 10^{-25} \mathrm{cm}^3\mathrm{s}^{-1}$ in the "core model". These upper limits are valid in the 100 GeV - 1 TeV neutralino mass range.

The distance to the Draco dwarf galaxy is 80 kpc, more than 3 times the distance to the Sgr dwarf galaxy. On the other hand,the galactic structure of the Draco dwarf galaxy has been studied in details (see e.g Strigari et al (2007)[19], resulting in much smaller error bars on the astrophysical factor $\bar{J}$. The MAGIC and Whipple collaboration have published results on the Draco dwarf galaxy. The MAGIC collaboration has analyzed 7.8 hours of their data. They reach a sensitivity of $< \sigma v > \simeq 10^{-22} \mathrm{cm}^3\mathrm{s}^{-1}$ for neutralino masses in the range 140 GeV - 500 GeV. The Whipple collaboration reaches a sensitivity of $< \sigma v > \simeq 10^{-21} \mathrm{cm}^3\mathrm{s}^{-1}$ with 14.3 hours, for a neutralino mass in the range 500 GeV -2 TeV. They have also analyzed 17.2 hours of data towards the Ursa Minor dwarf galaxy. Their Ursa Minor upper limit is worse than their Draco limit by a factor of 2.

5 Bounds on Lorentz invariance violation

More than 15 AGN have been detected in the TeV regime. Most of them have jets directed along the line of sight (they are member of the so-called "blazar" class). The only known exception

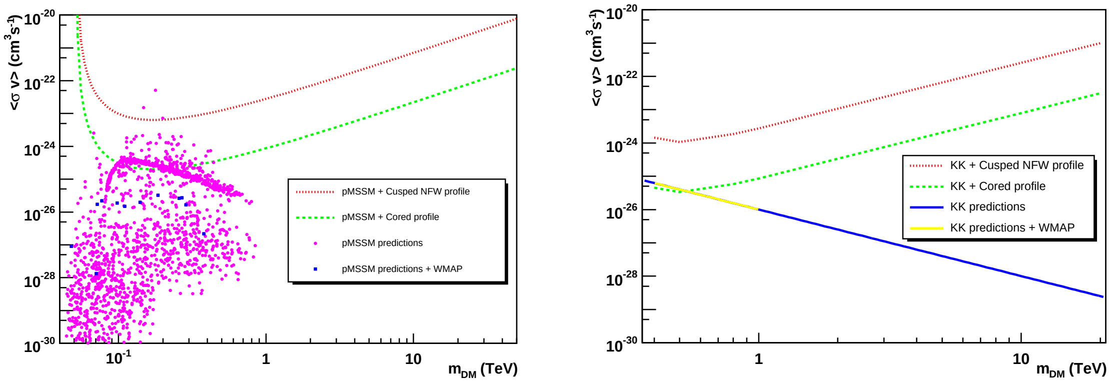

Figure 2: Results for HESS dark matter annihilations search towards the Sagittarius dwarf galaxy (Aharonian et al (2008)). Left panel: 95 % C.L. exclusion limits on MSSM models from HESS searches towards the Sgr dwarf galaxy. Right panel:95 % C.L. exclusion limits on the Universal Extra Dimensions model of Servant and Tait.

is the AGN associated to the M87 galaxy. This AGN has been observed in the TeV regime by the HEGRA, HESS, and VERITAS arrays.

The variability of the VHE emission of AGN can be used to test for Lorentz invariance in photon propagation. This is motivated by several quantum gravity theories (see Sarkar (2002)[17] for a review) in which photons and neutrinos are expected to have an energy dependent velocity in vacuum. The photon velocity $v(E)$ is parametrized by either a linear

$$v(E) = 1 - \eta \left(\frac{E}{M_1} \right) \tag{3}$$

or quadratic

$$v(E) = 1 - \eta \left(\frac{E}{M_1} \right)^2 \tag{4}$$

fonction of the energy E. $M_{1,2}$ is the scale of Lorentz invariance breaking. For quantum gravity theories, $M_{1,2}$ are expected to be of the order of the Planck scale.

An experiment observing two photons with an energy difference of ΔE, arriving from a source at distance L (or redshift $z = L/500\mathrm{Mpc}$) in a burst of duration Δt_{burst} is sensitive to a Lorentz invariance breaking scale

$$M_1 = \frac{L \Delta E}{c \Delta t_{burst}} = 10^{18} \mathrm{GeV} \left(\frac{z}{0.1} \right) \left(\frac{\Delta E}{1 \mathrm{TeV}} \right) \left(\frac{60\mathrm{s}}{\Delta t_{burst}} \right) \tag{5}$$

Equation 5 shows that Lorentz invariance breaking effects can be observed in short TeV photon bursts from AGN. The MAGIC collaboration has observed flares from Mkn501 [10], an AGN at a redshift of z=0.034. A very intense flare, with a VHE photon flux of more than 3.5 times the flux of the Crab nebula occured on July 9 2005 (figure 3). The outburst lasted 15 minutes, with a flux doubling time of ~ 2 minutes. The time of the flare maximum t_{max} was observed to depend on the energy. The slope of the time delay as a function of the energy is $\tau_1 = 0.030 \pm 0.012\mathrm{s/GeV}$, in the case of a linear dependence. In other words, there is a positive 2σ positive detection, (explanable by the astrophysical emission process) which gives [11] a lower limit on $M_1 > 0.26\ 10^{18}$ GeV (95% C.L). A similar analysis gives a lower limit on $M_2 > 0.39\ 10^{11}$ GeV (95% C.L).

The HESS collaboration has observed an intense flare[8] (more than 10 times the flux of the Crab nebula) from the blazar PKS2155-304, at a redshift of z=0.116. The flare, shown on figure 3, occured on July 28 2006, was roughly 1 hour long and composed of at least 5 smaller

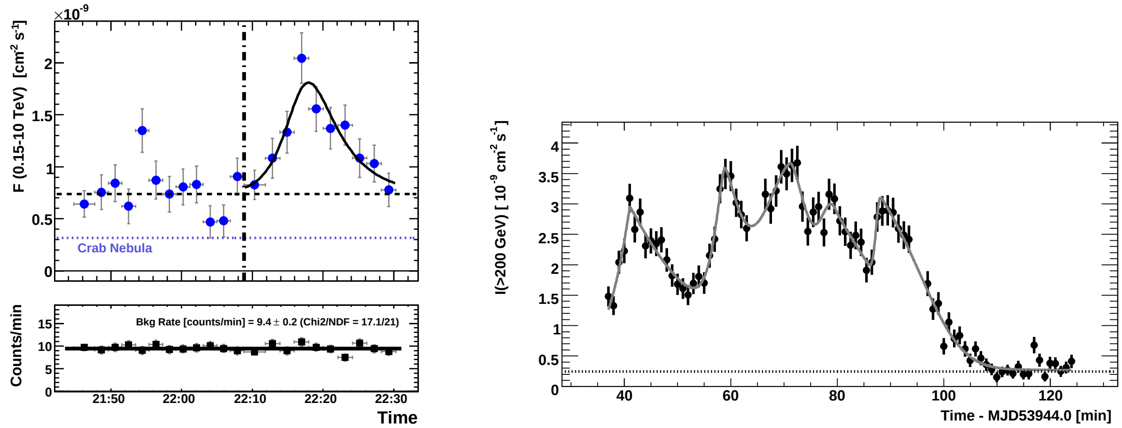

Figure 3: Left panel: MAGIC data taken during the July 9 2005 Mkn501 flare (from Albert et al (2007)). Right panel:HESS data taken during the July 28 2006 PKS2155-304 flare (from Aharonian et al (2007)).

outbursts. The shortest rise time was measured to be $\Delta t_{rise} = 173 \pm 28$ s. An analysis similar to the MAGIC analysis of Mkn501 is undergoing to improve their bounds on Lorentz invariance breaking scales.

6 Conclusion and perspectives

The VHE instruments, mostly IACT, have published a number of interesting new results. The Galactic Center source, HESS J1745-290 is probably not dark matter annihilations. It is not associated to the Sgr A East remnant. If associated to Sgr A*, the TeV emission is produced at a larger distance from the black hole than the X-ray emission. New results on indirect dark matter searches include limits from HESS towards Sgr dwarf, MAGIC and Whipple towards Draco and Whipple towards Ursa Minor. The MAGIC collaboration has given lower limits on the Lorentz invariance breaking scale based on the observation of a flare of Mkn501.

Three new instruments are coming very soon. The GLAST satellite was sucessfully launched on June 11 2008. The secong MAGIC telescope will be installed by the end of the year. Finally, the large 28-meter telescope of HESS will be completed in 2009. New astroparticle results from VHE instruments are likely to come soon.

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