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Overview of MAGIC results

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Abstract

MAGIC is a system of two 17-m diameter Cherenkov telescopes, located at the Observatorio del Roque de los Muchachos, in the Canary island La Palma (Spain). MAGIC performs astronomical observations of gamma-ray sources in the energy range between 50 GeV and 10 TeV. The first MAGIC telescope has been operating since 2004, and in 2009 the system was completed with the second one. During 2011 and 2012 the electronics for the readout system were fully upgraded, and the camera of the first telescope replaced. After that, no major hardware interventions are foreseen in the next years, and the experiment has undertaken a final period of steady astronomical observations.

MAGIC studies particle acceleration in the most violent cosmic environments, such as active galactic nuclei, gamma-ray bursts, pulsars, supernova remnants or binary systems. In addition, it addresses some fundamental questions of Physics, such as the origin of Galactic cosmic rays and the nature of dark matter. Moreover, by observing the gamma-ray emission from sources at cosmological distances, we measure the intensity and evolution of the extra-galactic background radiation, and perform tests of Lorentz Invariance.

In this paper I present the status and some of the latest results of the MAGIC gamma-ray telescopes.

Keywords: Gamma-ray Astronomy, Cherenkov telescopes, MAGIC, Review of experimental results

1. The MAGIC telescopes

MAGIC is a system of two Cherenkov telescopes, located at Observatorio del Roque de los Muchachos in the Canary island La Palma (Spain), for the observation of cosmic gamma rays in the energy range between 50 GeV and 10 TeV (known as Very High Energy or VHE band). This kind of instrument images the Cherenkov light produced in the particle cascade initiated by gamma rays in the atmosphere. With Cherenkov telescopes, we study the so-called non-thermal Universe, i.e. astronomical objects where extreme particle acceleration takes place, including pulsars and their winds, supernova remnants, compact binary systems or active galactic nuclei. Moreover, dark matter annihilation or decay at over-density sites may produce VHE gamma rays. In addition, by studying gamma rays from distant sources, we can measure propagation effects caused by, e.g. the presence of the extragalactic background light, or the quantum structure of space-time.

The two MAGIC telescopes have been built and are currently operated by a collaboration of institutions from Bulgaria, Croatia, Finland, Germany, Italy, Poland, Japan, Spain, and Switzerland [1].

The first MAGIC telescope started operations in 2004 and was at the time the largest Cherenkov telescope ever constructed (17-m diameter mirror), a fact that translates into a low energy threshold. The introduction of a second MAGIC telescope in 2009 enabled the instrument to perform stereoscopic observations, yielding a significant improvement in sensitivity, and angular and spectral resolutions. Today the MAGIC telescopes remain the Cherenkov telescope array with the largest mirrors in the world. In addition, MAGIC features significant novelties in the field of Cherenkov astronomy, such as the fastest sampling of Cherenkov signals (2 GSps) or active mirror control. Its ultralight carbon fiber frame and mirrors enable very fast repositioning of the telescope (<20 s for half a turn), a crucial fact to study

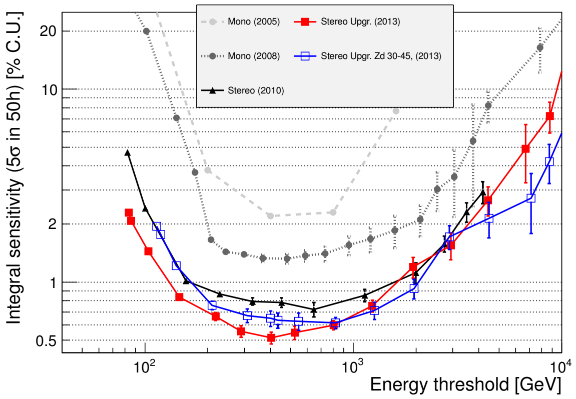

Figure 1: Integral sensitivity of the current MAGIC Stereo system and previous experimental setups, defined as the flux for which $N_{\rm excess}/\sqrt{N_{\rm bgd}} = 5$ after 50 h, and calculated using data from observations of the Crab nebula. Figure taken from [3].

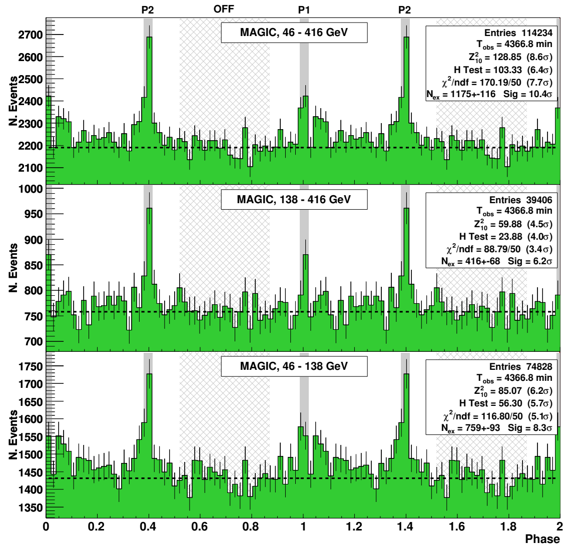

Figure 2: MAGIC folded light curves of the Crab pulsar for our total range in estimated energy and for two separate sub-bins. The shaded areas are the on-phase regions $P1_M$ and $P2_M$, the light shaded area is the off-region [0.52 – 0.87]. The dashed line is the constant background level calculated from that off-region. Figure taken from [6].

the prompt emission of GRBs.

The second telescope was built as an improved copy of the first one. The main difference between them was the PMT camera, which contained different number of pixels and of different sizes. Moreover, the readout systems used very different electronics. During the Summers of 2011-2012 the instrument underwent a major upgrade [2]: the readout was replaced by a homogeneous system based on the DRS4 analog memory sampling chip and the PMT camera of the first telescope was replaced by a new one, identical to that of the seconde one, with an increased trigger area with respect to the original one. After this, both telescopes are essentially identical, which simplifies their maintenance and operation.

The energy threshold (defined as the peak of the energy distribution of triggering gamma rays) of MAGIC is 50 GeV. Figure 1 shows the sensitivity of the instrument as a function of energy. For energy above 400 GeV the sensitivity is ∼0.5% of the Crab nebula flux. There is a good agreement with the predictions from Monte Carlo simulations. Compared to single telescope observations, a factor ∼2 improvement in significance is achieved at a few hundred GeV and up to a factor ∼3 at lower energies. The differential sensitivity remains acceptable (10% Crab units) below 100 GeV. An angular resolution of 0.07° is reached at 300 GeV. The best spectral resolution of 16% is reached at a few hundred GeV. Find more details about the instrument's performance in [3].

2. Pulsars and pulsar wind nebulae

2.1. Crab pulsar

With Cherenkov telescopes we study the highest-energy particles that a pulsar is able to accelerate. In 2008 MAGIC reported the first observation of pulsed emission with $E > 25$ GeV, from the Crab pulsar [4]. VERITAS discovered that the pulsed spectrum extends up to $E > 100$ GeV [5]. Some months later, MAGIC measured the phase-resolved spectrum up to 400 GeV [6] (see Figure 2). More recently, MAGIC has discovered emission during the *bridge* (the period between the two pulsed peaks) at energies exceeding 100 GeV [7]. The presence of emission during the bridge and the fact that both peaks are very narrow is hard to explain within existing models. Aharonian et al. [8], for instance, propose that VHE γ-rays are not produced inside the magnetosphere but in the wind region. If true, VHE observations would allow to study the wind, which is totally dark at other wavelengths. This model is successful in reproducing the bridge emission, but predicts much broader peaks than those measured by MAGIC. Hirotani [9] is be able to explain the shape of the light curve assuming that there is an additional toroidal component in the pulsar's magnetic field.

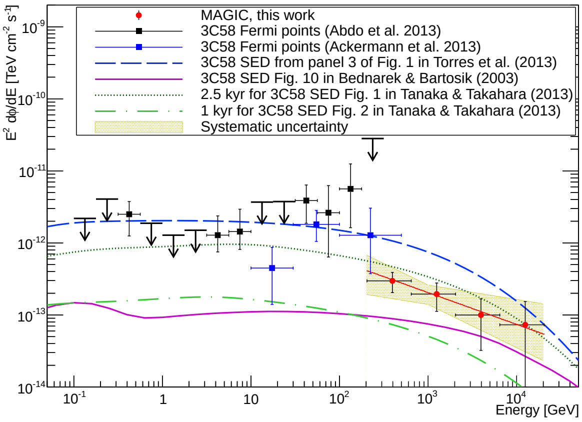

Figure 3: 3C 58 spectral energy distribution in the range between 0.1 GeV and 20 TeV. Red circles are the VHE points reported in this work. The best-fit function is drawn in red and the systematic uncertainty is represented by the yellow shaded area. Black squares and arrows are taken from the *Fermi*-LAT second pulsar catalog. Blue squares are taken from the *Fermi*-LAT high-energy catalog. The magenta, clear green dashed-dotted, dark green and blue dashed lines correspond to different models of the source. Figure taken from [10].

2.2. *3C 58*

The largest population of Galactic sources in the TeV catalogue are pulsar wind nebulae (PWN). MAGIC has recently discovered a new gamma-ray emitting PWN: 3C 58 [10]. Together with the Crab nebula, they are the only two PWN detected by MAGIC. These are however extreme PWN. Crab is the brightest one, while 3C 58 is the weakest and least luminous. They are both the least efficient VHE PWN. 3C 58 has in fact a γ-ray luminosity which is as low as 10^{-5} of the pulsar spindown power.

3C 58 is a PWN centered in PSR J0205+6449, one of the highest spin-down pulsars in the sky ($\dot{E}$=2.7×10^{37} erg s^{-1}, or 2% of the Crab pulsar's $\dot{E}$). The distance and age of this PWN are controversial. The distance may range between 2 and 3.2 kpc. It may be very young and associated to the historical supernova SN1181 or as old as 7000 years. The X-ray thermal emission from the central objects seems to be too weak for a neutron star in this range of ages, so it has been speculated that it may not be a simple neutron star, but contain a more exotic sort of matter [11]. Like Crab, it shows a torus and a jet in X-rays. *Fermi*-LAT detected pulsed emission at E<4 GeV and steady emission up to ~100 GeV [12].

MAGIC has discovered 3C 58 at VHE after a 85-h observation [10]. Its flux is 0.65% that of the Crab nebula, the weakest PWN detected at these energies. For existing models, a short distance of 2 kpc or a high IR density are required in order to reproduce the data from radio to VHE (see Figure 3). The IR density is probably unrealistically high, so the distance of 2 kpc is favored. The derived magnetic field by all the models fitting the γ-ray data is smaller than 35 μG, very far from equipartition.

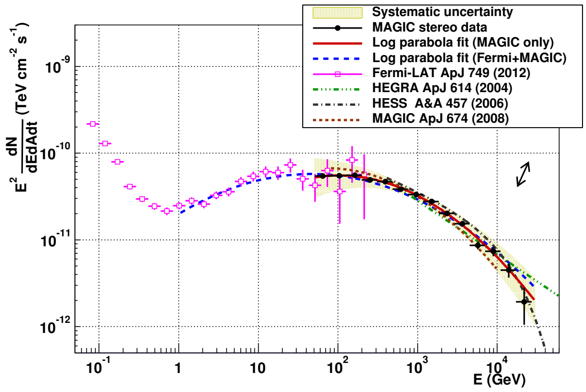

Figure 4: Spectral energy distribution of the Crab Nebula obtained with the MAGIC telescopes, together with the results from other γ-ray experiments. The black arrow indicates the systematic uncertainty on the energy scale. The solid red line is the log-parabola fit to the MAGIC data alone, whereas the blue dashed line is a combined fit to the *Fermi*-LAT and MAGIC data. Figure taken from [13].

2.3. *Crab Nebula*

The latest MAGIC measurement on the spectrum of the Crab nebula (see Figure 4) is based on a 70-h stereo observation spanning from 2009 to 2011 [13]. It extends from 50 GeV up to 30 TeV, with a statistical precision as low as 5% at E<100 GeV. Combined with the *Fermi*-LAT result, these data yield the most precise measurement of the inverse Compton peak so far, at (52.5±2.6) GeV (statistical error only).

The spectrum has been fitted to two different models. A static, constant B-field model [14] predicts however too broad an IC peak. Most probably this implies that the assumption of the homogeneity of the magnetic field inside the nebula is incorrect. A time-dependent model [15] is successful in reproducing the spectral shape under the assumptions of a low magnetic field of less than hundred μG. However, this model fails to provide a good fit of the new spectral data if the observed morphology of the nebula is taken into account.

3. The radiogalaxy IC 310

Radiogalaxies (active galaxies displaying a radio jet) generate cosmic ray (electron or proton) bubbles in the intergalactic medium. The same process injects magnetic field into the intracluster medium. The total injected energy is huge (10^{60} – 10^{61} erg): it represents a few % of the total energy of accretion into the central supermassive black hole. Relativistic electrons produce synchrotron which can be studied using radiotelescopes, but they also produce VHE γ-rays through inverse Compton scattering.

In fact radiogalaxies are interesting VHE sources because the emission is not so strongly beamed, i.e. the jet is not as aligned with the line of sight as in blazars, and because they are nearby objects, i.e. we can study them in more detail. Cherenkov telescopes have discovered four radiogalaxies at VHE: Cen-A, M 87, NGC 1275 and IC 310. MAGIC has discovered the last two sources, which actually belong to the same cluster of galaxies: Perseus.

MAGIC discovered the radiogalaxy IC 310 at VHE [16] during a flare in 2011, which revealed that the source is variable on one-day time scale [17]. The observation of a second flare in 2012 showed even faster variability with time scales of 1-10 minutes [18]. Even faster variability has been observed in blazars like Mrk 501 and PKS 2155304, but emission in blazars is doppler-shifted by a larger factor than in a radiogalaxy like IC 310 for which the largest possible Doppler factor is around 4. The intrinsic variability of the source may in fact be so fast that the emission region is smaller than the event horizon light-crossing time. Hardly any model can accomodate such a small emission region.

4. Dark Matter Searches

There is overwhelming experimental evidence for the existence of dark matter, mainly from its gravitational effects on the dynamics of galaxies and galaxy clusters and measurements of the power spectrum of temperature anisotropies of the Cosmic Microwave Background [19]. The latter shows that dark matter accounts for about 85% and 27%, respectively, of the total mass and energy contents of the Universe.

Nevertheless, despite strong efforts over the years, no experiment so far has been able to detect dark matter, directly or indirectly. The main focus of current searches is on dark matter composed of weakly interacting massive particles (WIMPs), that are of non-baryonic nature, thermally produced in the early Universe and stable on cosmological timescales. Furthermore, in order to have the correct relic density and to be in agreement with the Big Bang nucleosynthesis, WIMPs should also be cold – i.e. non-relativistic at the onset of the large structure formation. WIMPs are predicted to annihilate or decay into Standard Model (SM) particles, such as photons, that could be detected by the existing experiments. With the mass range predicted for these dark matter particles spaning from tens of GeV to few TeV, those photons might be visible in the gamma ray domain, in particular by the Cherenkov telescopes like MAGIC.

One of the most promising observational targets in dark matter searches with Cherenkov telescopes are the dwarf satellite galaxies. Those have very high mass-to-light ratio (they are the most dark matter-dominated known systems [20]), and have the advantage of being free of astrophysical gamma ray sources. In addition, because they are relatively close, they appear as (quasi) point-like sources for Cherenkov telescopes, with relatively high expected gamma ray fluxes, albeit typically below the one expected for the Galactic center.

Among the known satellite galaxies, the ultra-faint galaxy Segue 1 stands out with an estimated mass-to-light ratio of 3400 $M_{\odot}/L_{\odot}$ [21]. Furthermore, given its distance of only ~23 kpc and position in the Northern Hemisphere outside of the Galactic plane, Segue 1 has been dubbed an excellent candidate source for dark matter searches with MAGIC. Segue 1 was observed between January 2011 and February 2013 for a total time of 158 h [22], which makes these observations the longest exposure of any dwarf satellite galaxy by any Cherenkov telescope so far.

The Segue 1 observations were analyzed using the *full likelihood* approach [23], an analysis method optimized for dark matter searches. It is based on the full exploitation of the spectral information of the recorded events in a maximum likelihood analysis. The sensitivity gain achieved from the use of this approach is (depending on the signal model) about a factor of 2 with respect to that of the so-called conventional method [24], currently standard for in the analyses of Cherenkov telescope data.

No significant gamma-ray excess above the background was found in the analysis of Segue 1 observations with MAGIC. Consequently, 95% confidence level upper limits on the velocity-averaged annihilation cross section ($\langle \sigma v \rangle$), and lower limits on the dark matter particle lifetime were derived, assuming different annihilation and decay channels.

We have searched for gamma rays from dark matter annihilation and decay into the following channels: quark-antiquark ($b\bar{b}$, $t\bar{t}$), lepton-antilepton ($\mu^+\mu^-$, $\tau^+\tau^-$) and gauge boson pairs (W^+W^-, ZZ). Some of the results are shown in Figure 5. These are the strongest bounds from observations of satellite galaxies by any Cherenkov telescope. Furthermore, our limits are more stringent than *Fermi*-LAT bounds, obtained from the

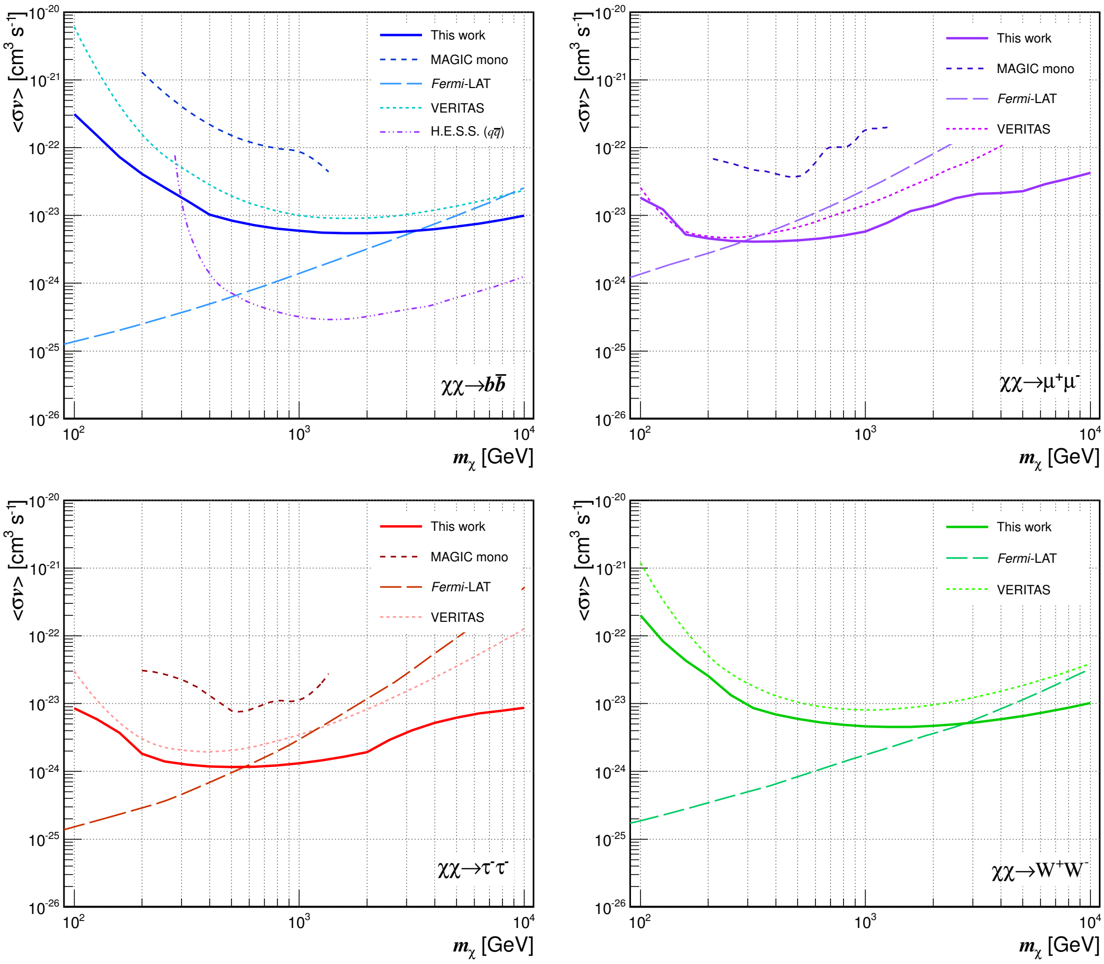

Figure 5: MAGIC upper limits on $\langle\sigma v\rangle$ for different final state channels (from top to bottom and left to right): $b\bar{b}$, $\mu^+\mu^-$, $\tau^+\tau^-$ and W^+W^-, from the Segue 1 observations with MAGIC (solid lines, [22]), compared with the exclusion curves from *Fermi*-LAT (long-dashed lines, [25]), HESS (dot-dashed line, [26]), VERITAS (dotted lines, [27]) and MAGIC in single telescope mode (dashed lines, [28]). Figure taken from [22].

joint analysis of 15 satellite galaxies [25], for $m_{\rm dm}$ above few hundred GeV. For higher $m_{\rm dm}$ values, the most constraining bounds are derived from the HESS observations of the Galactic center halo [26]. We note, however, that the HESS result is sensitive to the *difference* in the dark matter-induced gamma-ray fluxes between the considered signal and background regions, which according to observations could be much lower than assumed. In addition, our results are at least a factor of 2 stronger than those obtained by VERITAS [27] with Segue 1 observations (note, however, that the these results have been questioned in reference [23], where it is discussed how they are over-constraining by a factor two or more).

Finally, our new bounds are at least one order of magnitude stronger than the previous most sensitive MAGIC results, obtained from ~30 hours of Segue 1 observations with one telescope only [28]. This improvement has been achieved thanks to deeper observations (providing a factor $\sim\sqrt{5}$ improvement in sensitivity), a better instrument (one vs. two telescopes, providing an improvement in sensitivity by a factor of ~2) and the use of the full likelihood analysis (which provides an improvement of a factor ~2).

Another important characteristic of the full likelihood method (and any likelihood function-based analysis) is that it allows a rather straightforward combination of the results obtained by different instruments and from different targets. For a given dark matter model $M(\theta)$, and N different instruments (or measurements), a global likelihood function can be simply written as $\mathcal{L}_T(M(\theta)) = \prod_{i=1}^{N} \mathcal{L}_i(M(\theta))$, which can be maximized in a rather trivial way. This approach eliminates the complexity required for a common treatment of data and response functions of different telescopes or analyses. Since dark matter signals are universal and do not depend on the observed target, the results from different sources can also be combined through the overall likelihood function, providing therefore a more sensitive dark matter search. This could be the basis for obtaining in the future a global dark matter result combining the observations of all gamma-ray instruments.

5. Conclusions and prospects

The MAGIC telescopes have been recently successfully upgraded and have entered into a phase of steady astronomical observations. The performance of the telescopes is better than ever, and new results are continuously produced. Here, I have summarized a few of the most relevant recent MAGIC results. Complete and updated information can be found in [1].

We plan to operate the telescopes during the next few (3-5) years, at least until the first CTA telescope will start to operate. We have recently setup a program of Key Observation Projects to identify and pursue the most relevant scientific objectives to which MAGIC will give priority during that time.

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