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A decade of dark matter searches with ground-based Cherenkov telescopes ☆

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ABSTRACT

In the general scenario of Weakly Interacting Massive Particles (WIMP), dark matter (DM) can be observed via astrophysical gamma-rays because photons are produced in various DM annihilation or decay processes, either as broad-band or line emission, or because of the secondary processes of charged particles in the final stages of the annihilations or the decays. The energy range of the former processes is accessible by current ground-based Imaging Atmospheric Cherenkov telescopes (IACTs, like H.E.S.S., MAGIC and VERITAS). The strengths of this technique are (a) the expected DM gamma-ray spectra show peculiar features like bumps, spikes and cutoff that make them clearly distinguishable from the smoother astrophysical spectra and (b) the expected DM spectrum is universal and therefore by observing two or more DM targets with the same spectrum, a clear identification (besides detection) of DM would be enabled. The role of IACTs may gain more importance in the future as the results from the LHC may hint to a DM particle with mass at the TeV or above, where the IACTs sensitivity is unsurpassed by other experiments. In this contribution, a review of the search for DM with the current generation of IACT will be presented.

1. Introduction

One of the most interesting and compelling observations that ground-based Cherenkov telescopes operating in the very-high-energy gamma-ray band can perform is that looking at targets in the sky where a large concentration of dark matter (DM) is expected. There are several reasons in support of this. *First* of all, DM is indeed expected in the sky. 80% of the total matter content of the Universe is constituted by one or more new types of particles. The DM has shaped the formation of the first stars and galaxies, so thoroughly that the concordance cosmological model is called Λ CDM where CDM stands for Cold DM. We also know that there are places in the sky where DM is expected to be particularly concentrated. We do not know the DM nature and if it could finally be detected via primary or secondary radiation associated with its annihilation or decay, but there are several models that predict such signatures and it is therefore worth "sailing" our telescopes to these promised lands, despite no Earth! signal has arrived so far. *Second*, the gamma-ray band is a very privileged one, for several reasons: (a) gamma-ray is neutral and trace back to the point of origin, where we expect DM, (b) the gamma-ray spectrum emerging from DM interactions (either annihilations or decays) is universal. All DM targets are expected to show exactly the same gamma-ray spectrum. The observation of multiple spectra from different targets would therefore constitute an excellent result, (c) gamma-ray spectra from DM annihilations or decay typically show several characteristic features, naturally depending on the specific dark matter model, but in general classifiable in sharp cutoff, bumps, or even line emissions. This makes the DM spectra hardly confusable with typical astrophysical spectra. *Third*, the recent experimental results of the LHC experiments: the quite large Higgs boson mass and the non-evidence for New Physics beyond the Standard Model are possibly hinting to DM particle being more massive than expected, about the TeV [1]. This region is where ground-based telescopes have highest sensitivity.

And indeed this is what was done in the last decade, specially with the H.E.S.S., MAGIC and VERITAS experiments. These very successful experiments, all together, invested quite a large fraction of their observation times in the last years to cover the targets where DM was expected. In this contribution, we will try to review these observations. For additional details on gamma-ray signals from dark matter, we refer the reader to Ref. [2].

2. Ground-based imaging Cherenkov telescopes

Gamma rays produced in Space cannot cross the Earth atmosphere. After few radiation lengths, they interact with the electrostatic field of

☆The original title of the invited talk was "Dark matter searches with Cherenkov Telescopes".

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the atmospheric atoms and convert into an electron–positron pair. However, these leptons are extremely energetic (they share the energy of the primary gamma ray), and therefore are able to initiate an electromagnetic showers thanks to subsequent emission of bremsstrahlung gamma rays which in turn pair produce again. The shower is few km long and few hundreds of meter large. It has a maximum at about 10–12 km asl (at the GeV–TeV) and dies out when the lepton energy goes below the threshold for ionization, which in air is 83 MeV. Even if the shower particles are lost in the atmosphere, the fact that most of the time the leptons were travelling faster than the speed of light in the atmosphere allowed for the radiation of Cherenkov light from the atmospheric medium swept up by the shower. This light has a continuous spectrum, peaked at about 300 nm, and it is a flash of light of the duration of few ns, expanding within a cone of aperture of about 1° radius, which at the ground illuminates an area of about 100 m radius. For this reason, if one puts a telescope in this Cherenkov light pool, the “effective” area of the telescope is not simply the geometrical area of the dish, but almost the entire Cherenkov pool, which sums up to about 10^5 sqm. One could compare this number with the typical areas of satellite-borne gamma-ray detectors, of about 1–2 sqm, hardly expandable in the near future. The drawback is that gamma-ray showers at few GeV produce too little Chernenkov photons to be detected, and the technique is fully sensitive at the TeV scale and above.

Ground-based Cherenkov telescopes are also called Imaging Atmospheric Cherenkov Telescopes (IACTs) because they “image” the shower, in the sense that if a multipixel camera is placed at the telescope focal plane, the image of a typical electromagnetic shower is an oblate ellipse pointing to the center of the camera (corresponding to an inclined section of the Cherenkov light cone). Through the careful analysis of shower primary, secondary and sometimes tertiary moments, and in some cases its time evolution, one can reconstruct the energy and direction of the primary gamma ray. The main source of background is constituted by the so-called hadronic showers. These are mixed sub-hadronic and sub-electromagnetic showers initiated by primary cosmic rays in the top atmosphere like protons, helium, and heavier nuclei. They are by far more abundant than gamma rays, which are seen roughly every 10,000 hadrons. Therefore, the technique relies on a first telescope topological trigger system that rejects about 99% of the hadrons, and later on a gamma/hadron separation at the analysis level. The technique was pioneered by the Whipple observatory that after tens of years of hunting, finally detected the Crab Nebula in 1989, and it is now superseded by the H.E.S.S., MAGIC and VERITAS arrays.

Table 1 collects some information regarding the major IACT experiments. We mention also that the Whipple telescope terminated operation this year.

3. Gamma-ray signatures from dark matter

There is no space in this review to account for all the particles that are valid candidate for DM. We refer to Ref. [3] for a recent review. In this context, we concentrated more on a Weakly Interacting Massive Particle (WIMP) scenario, which foresees a particle at the GeV–TeV scale, whose annihilation or decay products are found in the Standard Model (SM) particle zoo. There are valid scenarios of decaying DM, however, the prospects for detection with IACT are less promising and will be not further treated here.

Now, if DM is coupled to the SM with some interactions, in the final products of annihilations or decays one can find either leptons or hadrons or gauge bosons, often the heaviest one because of the scale of the DM mass, which is at the GeV–TeV. It is therefore expected naively to find also gamma-rays in the final products. More precisely, the gamma-ray emission can be originated as follows (see Fig. 1): (a) from pion decays after hadronization of quarks. This gives origin to a broadband spectrum terminating with a cutoff at the DM mass; (b) from final state radiation of leptons. This also gives origin to a broadband spectrum and a cutoff but with harder photons; (c) gamma rays from internal bremsstrahlung, when the annihilation is to sfermions and the annihilation is in the t-channel, which gives rise to a pronounced bump of gamma rays toward the mass cutoff [2]; (d) from line-processes ending in γX, where X could be γ, Z_0, h. These are loop processes, whose intensity strongly depends on the specific DM realization, which give rise to line emissions that constitute smoking guns detection for DM, because an astrophysical explanation of these lines would be extremely challenging. There are other gamma-ray emission processes, following other particle models, which are not described here.

All in all, IACT observes photons. Therefore, every process is valuable as long as it provides enough photons to detect. However, the more features the spectrum exhibits, the easier is the consequent DM identification. In this sense, not only the total flux is relevant. Generally, the DM annihilation flux in gamma rays is expressed as

$$\frac{d\Phi}{dE}(E;\Delta\Omega) = \frac{B_F}{4\pi}\frac{\langle\sigma_{\rm ann}v\rangle}{2m_\chi^2}\frac{dN_\gamma}{dE}\int_{\Delta\Omega}\int_{\rm los} d\theta\, ds\, \rho^2(\theta,s) \tag{1}$$

where $\langle\sigma_{\rm ann}v\rangle$ is the averaged annihilation cross-section times the velocity, m_χ the DM particle mass, dN_γ/dE is the total number of photons produced during one annihilation event, and their product is conventionally called the particle physics factor. The second term of the equation is called the *astrophysical factor* or *J-factor* and it is computed as the line of sight s integral of the *square* of the DM density, and over a certain solid angle $\Delta\Omega = 2\pi(1-\cos(\theta))$ under which the source is observed. Finally, B_F is the so-called *intrinsic boost factor*, and it is a measure of the uncertainty in either the particle physics or the astrophysics terms for unaccounted intrinsic

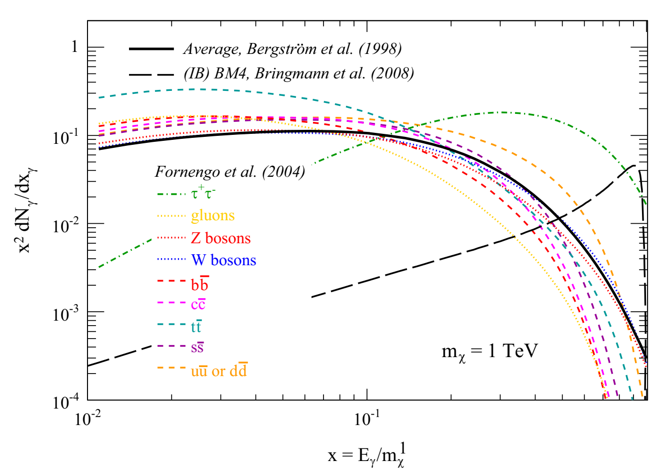

Fig. 1. Differential spectra (multiplied by x^2) of gamma-rays from several neutralino annihilation products. Taken from [4, Fig. 1].

Table 1
Current major operating ground-based Cherenkov telescopes. Given are the starting year, the array multiplicity and dish diameter *in the latest configuration*, and the location.

IACT	Year	Nr. tels & diameter	Location
Whipple	1968	1×12 m	Arizona, USA
H.E.S.S.	2003	4×12 m$+1\times28$ m	Gambserg, Namibia
MAGIC	2004	2×17 m	La Palma, Spain
VERITAS	2007	4×12 m	Arizona, USA