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Indirect search for dark matter with Cherenkov telescopes

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Summary. — Ground-based Cherenkov telescopes, also referred to as Imaging Atmospheric Cherenkov Telescopes, (IACTs) are array of large detectors, placed at moderate altitude, that catch the secondary induced Cherenkov emission produced in extensive atmospheric showers of particles generated by cosmic gamma rays. They are sensitive in the GeV-TeV region, and complete at high energy the MeV-GeV sensitivity of gamma-ray satellite experiments such as Fermi-LAT. In many of the possible realization of dark matter, this particle is stable because it is the lightest in some extension of the Standard Model. For this reason, indirect signatures from dark matter can come from annihilation events that take place in astrophysical environment. In this report, we briefly summarize the importance of gamma rays as probe for dark matter particle annihilations. We summarize current achievements and discuss future prospects.

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PACS `95.35.+d` – Dark matter (stellar, interstellar, galactic, and cosmological).

1. – Why gamma rays are important for DM searches

Let us restrict here to theories where dark matter (DM) is a particle, or a set of particles, and it is the lightest particle in models that extend the Standard Model of Particle, like, *e.g.*, the Super-Symmetry. There is indeed a universe of possible DM candidates, either in the scenario above, but here we focus on weakly interacting massive particle (WIMPs) because they are very well motivated or those where a detection is in principle more at reach than in other cases.

WIMPs have typical masses between few GeV and some TeV, and annihilation rate (in current times) of the order or below what is called the "thermal value": $\langle \sigma v \rangle = 3 \times 10^{-26}\,\mathrm{cm}^{-3}\mathrm{s}^{-1}$. This region is in principle accessible by either accelerator experiments, like the LHC at CERN, that thanks to the large center-of-mass energy available, can directly produce DM particles (invisible in the detector) that can in turn decay into some detectable signals, or direct detection experiments, that make use of the energy deposited during nuclear recoil events in noble gas or pure crystal. There is a third way

to "rule" DM, dubbed indirect, that makes use of the products of annihilation events between two DM particle in astrophysical environment.

There are three main reasons why astrophysical gamma rays are extremely important for DM searches:

1) Gamma rays are neutral, and therefore trace back their origin, so that telescopes can be actually pointed to targets where *e.g.* gravitational signatures confirmed the existence of strong DM overdensities;

2) Gamma ray spectra from DM annihilations are extremely sophisticated. They all present a clear and abrupt cutoff at the DM scale, which — if observed — would constitute then a precise (10%) estimation of the DM mass, hardly achievable at this level of precision by accelerators and direct detection experiments;

3) Gamma ray spectra are universal. Observation of similar spectra from different targets where DM is expected would constitute a robust detection of DM

The capability of IACTs to observe DM is to be discussed comparing current and future telescope sensitivity, with respect to the expectation we have in term of gamma-ray flux from DM annihilation. This can be written as

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E} = \phi^{PP}(E) \cdot J(\mathrm{d}\Omega),$$
(1)

where $\phi^{PP}(E)$ is called the particle-physics factor, depends on the mass of the DM particle m_χ^2, its annihilation rate $\langle\sigma v\rangle$ and the number of photons during an annihilation event N_{ph}, and J is the astrophysical factor, which is the integral over the line of sight and a given solid angle of the square of the DM density $\rho(r)$ at a target:

$$\phi^{PP}(E) = \frac{\langle\sigma v\rangle}{8\pi m_\chi^2} N_{ph}$$
(2)

$$\text{and} \quad J(\mathrm{d}\Omega) = \int\int \rho^2(s,\theta)\mathrm{d}s\mathrm{d}\omega.$$

The particle physics factor is related to the actual nature of DM particle, it is what it is, and we cannot control it. The J-factor depends on the amount and concentration of DM in a certain target, we cannot control this one either, but indeed we can devise strategy to point the telescope to places where this factor is maximal.

2. – H.E.S.S., MAGIC and VERITAS. Current searches

H.E.S.S., MAGIC and VERITAS[1] and the current larger ground-based Cherenkov observatories in the world. They cover both hemisphere (H.E.S.S. in the South, MAGIC and VERITAS in the North). They are in use for almost a decade now and have provided very important results in terms of gamma-ray astronomy. In addition to this, they have performed an extensive DM oriented program in the past decade, with hundreds of hours devoted to this search. A detailed discussion of these observations is reported in ref. [1] (and references therein), here we summarize the main points.

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[1] www.mpi-hd.mpg.de/hfm/HESS/, magic.mpp.mpg.de, veritas.sao.arizona.edu.

There are several use of IACTs for DM searches, according to targets in the sky but not only. Here are the main proxy for DM searches:

Galactic Center. The Galactic Center is believed to be also the barycenter of the DM halo, *i.e.* an almost spherical distribution of DM, with density increasing from the outer parts (more than 10 times more extended than the visible galaxy) to the inner parts. At its center, DM annihilation is very efficient and therefore the J-factor mentioned above is high. Especially H.E.S.S. [2] performed searches at this target. This target however suffers from the poor knowledge we have in terms of interaction within baryons and matter that can devoid the central region from DM after *e.g.*, supernova events.

Dwarf Spheroidal Galaxies. There are small $(10^7 \, M_\odot)$ galaxies, gravitationally bound to the Milky Way, and located in its DM halo at a distance between few tens of kpc and few hundreds. They provide smaller J-factor than the GC, but they are the cleanest of all DM targets, because they are DM-dominated objects, where baryons have had only a minor role in their shaping, and stellar and gas activity is extremely reduced. A large number of these objects has been searches from H.E.S.S., MAGIC and VERITAS. The current strongest limit is obtained with 160 h of observation of Segue 1 with MAGIC [3].

Galaxy Clusters. Because of the strong gravitational pull, also galaxy clusters are expected to have accreted a substantial amount of DM at their gravitational center. From observation, gas and stars can only account for 20% or their total matter content. However, galaxy clusters are typically far, and therefore their gamma-ray emission is less intense. In addition, the overall DM profile around them is not clearly determined. The current strongest limits are obtained with H.E.S.S. observation of the Fornax galaxy cluster [4].

Other. Other searches include other targets like intermediate mass black hole candidates, globular clusters, high-velocity cloud, or the Large Magellanic clouds, but apparently all of the above have worse chance of detection than the galactic center, or the dwarf spheroidal galaxies. In addition, IACTs can perform DM searches in looking at anisotropies in the diffuse extragalactic gamma-ray background sky (a technique which is currently probably not at reach for the current generation of IACTs, but possible with CTA, see later), as well as searches for DM-annihilation into lines.

A summary of the achievements of the current generation of IACTs is shown in fig. 1, which is discussed below in the text.

3. – A bright future: CTA

The Cherenkov Telescope Array (CTA) [5] is a project for a next-generation observatory for very high energy (GeV-TeV) ground-based gamma-ray astronomy, currently in its construction phase, and foreseen to be operative a few years from now. Several tens of telescopes of 3–4 different sizes, distributed over a large area, will allow for a sensitivity about a factor 10 better than current instruments such as H.E.S.S, MAGIC and VERITAS, an energy coverage from a few tens of GeV to several tens of TeV, and a field of view of up to 10 deg. The search for new physics beyond the Standard Model (SM) of particle physics is among the key science drivers of CTA [6]. CTA is expected to improve the
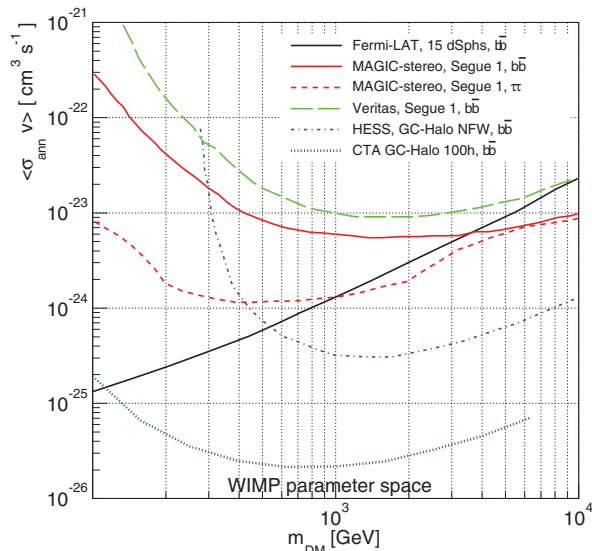
Fig. 1. – Comparison of some exclusion lines for the Fermi-LAT observation of 15 combined DSGs for $b\bar{b}$ (solid black) [7], H.E.S.S. observation of the galactic center halo for the NFW (dot-dashed blue [8]) for the $b\bar{b}$ channel, MAGIC-stereo observations of the Segue 1 DSG for the $b\bar{b}$ (solid red) and $\tau^{+}\tau^{-}$ (dashed red) channels [3], VERITAS observations of the Segue 1 DSG for $b\bar{b}$ (dashed green) [9], and for the estimation for 100 h observation at the galactic center halo with CTA (thick dashed blue) [6]. Taken from [1].

prospects for DM searches with IACTs on the following basis: *a*) naively, the improved sensitivity, compared to current instruments, will generically improve the probability of detection, or even *identification* of DM, through the observation of spectral features, *b*) the energy range will be extended. At low energies, this will allow overlap with the Fermi-LAT or other similar future instruments, and will provide sensitivity to WIMPs with low masses. For WIMPs with mass larger than about 100 GeV, CTA will be the experiment with highest sensitivity; *c*) the increased FOV (about 10 deg versus 2–5 deg) with a much more homogeneous sensitivity, as well as the improved angular resolution, will allow for much more efficient searches for extended sources like galaxy clusters and spatial anisotropies; *d*) finally, the improved energy resolution will allow much better sensitivity to the possible spectral feature in the DM-generated photon spectrum. The observation of a few identical such spectra from different sources will allow both precision determination of the mass of the WIMP and its annihilation cross-section.

In ref. [6], a detailed report of the performance for CTA DM searches, estimated employing Monte Carlo simulations of different possible CTA realizations, is given, as well as for other fundamental physics issues, like the possible existence of axion-like particles, expected violation of Lorentz Invariance by quantum gravity effects. In [6], fig. 23, the expected performance of CTA for WIMPs annihilating purely into $b\bar{b}$ in 100 h observation at DSGs, galaxy clusters, and at the Galactic Center Halo is shown, together with extrapolation of the Fermi-LAT performance for 10 years of data. As expected, the best results are achieved for the observation in the vicinity of the Galactic Center, where the thermal annihilation cross-section for WIMP DM of 10^{-26} cm^{3}s^{-1} is at reach. This would be the first time that ground-based Cherenkov telescopes could reach this sensitivity level.

4. – Conclusions

In fig. 1 we collect few results on the exclusion curves for WIMP annihilation cross-section. On the bottom left side of the plot, we see the exclusion power of Fermi-LAT observation of 15 combined DSGs for the $b\bar{b}$ (solid black line) [7] We also show the best limit obtained on DSG observation with Segue 1 observed during 158 h with the MAGIC stereo experiment again for the $b\bar{b}$ (solid red line) and $\tau^+\tau^-$ (dashed red line) channels [3]. These two channels somehow represent two extreme cases, a very soft spectrum ($b\bar{b}$) and a very hard spectrum ($\tau^+\tau^-$). One can see that because of the better sensitivity of MAGIC at higher energies, the harder $\tau^+\tau^-$ channel is better constrained. The same target was observed in 48 h of observation with VERITAS (dashed green) [9]. In blue, we show the H.E.S.S. exclusion curve from the galactic center halo for the NFW (dot-dashed blue line) [8] for the $b\bar{b}$ channel only. Finally, we show estimates for 100 h observation of the Galactic Center halo region with CTA (thick dashed blue, [6]) considering again a NFW profile.

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