Dark Matter Searches with Imaging Atmospheric Cherenkov Telescopes and Prospects for Detection of the Milky Way Halo

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Gamma rays lend themselves to indirect Dark Matter (DM) searches due their wide range, propagation on straight lines, and comparatively easy detection. This article provides references to DM searches with imaging atmospheric Cherenkov telescopes (IACTs) at very high energies (VHE; $> 100\,\mathrm{GeV}$) and argues that the halo of the Milky Way is a promising target for searches if the results of recent supercomputer simulations of DM halos are correct.

1 Dark Matter Searches with Cherenkov Telescopes

DM searches with IACTs have targeted the Galactic Centre [1], globular clusters [2], dwarf spheroidal galaxies [3, 4, 5, 6] and galaxy clusters [7], and allowed the calculation of upper limits on the annihilation cross-section of weakly interacting massive particles (WIMPs) in specific scenarios. The sensitivity of current instruments and order-of-magnitude uncertainties in the modelling of DM densities inside the above astrophysical objects imply that the obtained limits are at least one order of magnitude higher than the cross-section predicted by theories beyond the Standard Model (supersymmetry, supergravity, extra dimensions).

2 Prospects for DM Searches in the Galactic Halo

In the VHE domain, DM searches close to the Galactic Centre are made difficult by the presence of the Galactic Centre source HESS J1745$-$290 [1] and of diffuse emission from the Galactic plane that can be plausibly explained by hadronic cosmic rays interacting in giant molecular clouds [8]. Searches at larger distances from the Galactic Center ($\sim 1^\circ$) appear still promising in the light of recent high-resolution N-body simulations of Cold Dark Matter (CDM) halos featured by galaxies like the Milky Way. The simulations performed within the framework of the Virgo Consortium's Aquarius Project [9] attained a minimal particle mass of 1712 $\mathrm{M}_\odot$ and a converged length of $120\,\mathrm{pc}$ [10]. A factor of three improvement over the *Via Lactea II* simulations [11] resulted in predictions that contrast earlier findings, in particular that the annihilation signal seen by an observer located within the halo is not dominated by small clumps (whose clustering in DM halos would make dwarf galaxies attractive targets), but is dominated by the radiation produced by diffuse DM in the main halo.

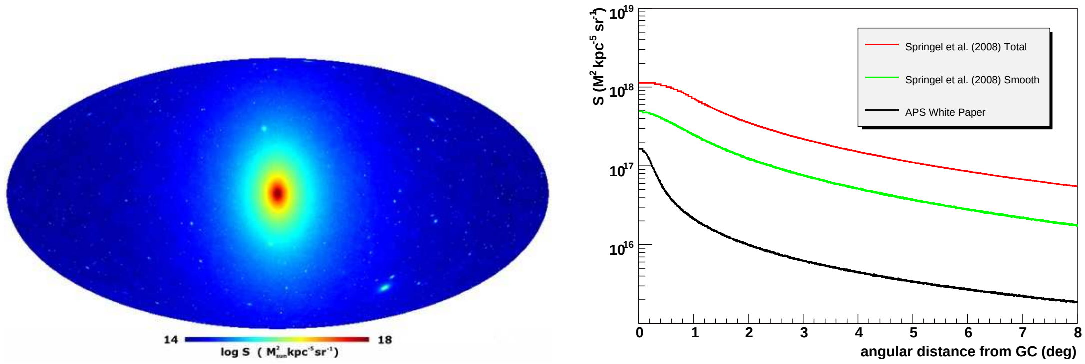

Figure 1: (**Left:**) Visualization of the astrophysical factor (Eq. (1)) for the Aquarius Simulation. (Taken from [9].) (**Right:**) Astrophysical factor as function of the distance from the Galactic Centre. See text for details.

The left panel of Figure 1 shows (in galactic coordinates) the astrophysical factor

$$S = \frac{1}{4\pi} \int_{\text{los}} \rho^2(r(s)) ds \tag{1}$$

inferred from the simulation of one particular halo (*Aq-A-1*) which is thought to roughly resemble the Milky Way. The astrophysical factor was calculated for an observer placed at a distance of ~ 8 kpc from the halo centre and depends to first order only in the angular distance from the Galactic Centre, as illustrated in Fig. 1 (right). The total astrophysical factor from the *Aq-A-1* simulation (red line in right panel of Fig. 1) exceeds earlier estimates (e.g. from [12] (black line)) by an order of magnitude and includes a factor of ~ 3 enhancement due to substructure in the DM distribution when compared to estimates of the smooth component only (green line). It is also evident that the astrophysical factor and hence any diffuse photon flux falls by more than one order of magnitude when going from an angular distance of $1°$ to $7°$.

Under the assumption of a Majorana WIMP and negligible line emission, the astrophysical factor translates itself into a differential continuum photon flux according to

$$\frac{d\Phi}{dE} = \frac{\langle \sigma v \rangle}{2} \frac{1}{M^2} \frac{dN_\gamma}{dE} \cdot S$$

where $\langle \sigma v \rangle$ is the velocity-averaged self annihilation cross-section, M the WIMP mass and dN_γ/dE the differential photon spectrum produced in the WIMP annihilation. In order to estimate the photon flux from annihilation in the halo at H.E.S.S. energies the velocity-averaged annihilation cross-section was set to $\langle \sigma v \rangle = 4 \cdot 10^{-26}\,\text{cm}^3\,\text{s}^{-1}$ (see, e.g., Fig. 13 of [12] for an overview of annihilation cross-sections in supersymmetric models that satisfy current accelerator and WMAP constraints) and WIMP masses above 0.5 TeV (i.e. well above the H.E.S.S. threshold) were investigated. For the H.E.S.S. array which measures photon energies above an analysis threshold of $E_t \simeq 0.2$ TeV up to the WIMP mass the accessible flux is proportional to

$$G(E_t|M) = \frac{1}{M^2} \int_{E_t}^{M} \frac{dN_\gamma}{dE} dE. \tag{2}$$

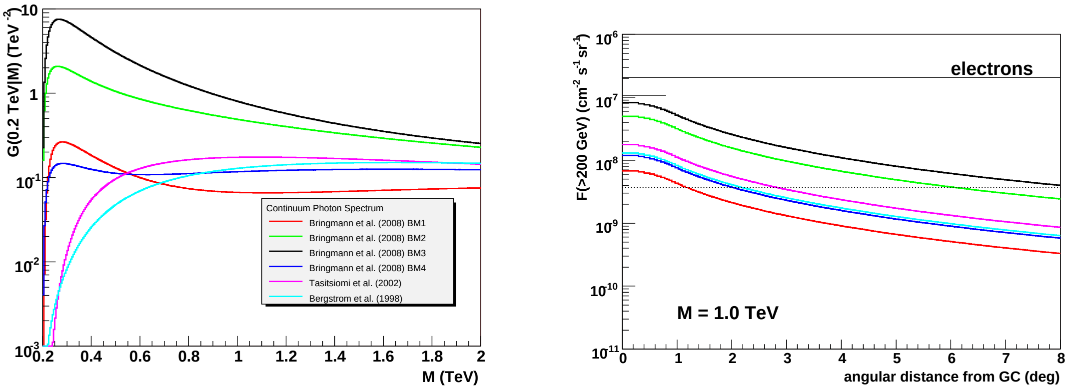

Figure 2: (**Left:**) The quantity $G(E_t|M)$ (Eq. (2)) for $E_t = 0.2\,\mathrm{TeV}$ and six different photon spectra produced in WIMP annihilations. The models BM1–BM2 include internal bremsstrahlung, the other two models do not. See text for details. (**Right:**) Diffuse photon and electron fluxes as a function of the angular distance from the Galactic Centre. The same color coding as in the left panel was used. See text for a detailed discussion.

The quantity $G(E_t|M)$ as a function of the WIMP mass M is shown in the left panel of Fig. 2 for six assumptions for the photon spectrum dN_γ/dE from the WIMP annihilation. It is seen that the interplay of dN_γ/dE and the $1/M^2$ term produces a peak close to E_t for MSSM and mSUGRA benchmark models with internal bremsstrahlung (BM1–BM4, taken from [13]). This peak is due to a high fraction of bremsstrahlung photons close to the kinematic limit at $E_\gamma = M$, but it is also known that models with enhanced bremsstrahlung tend to have smaller values of $\langle\sigma v\rangle$. As examples for two models without sizable bremsstrahlung the Tasitsiomi spectrum [14] (magenta line, photon emission primarily from π^0s created in quark jets) and an approximation [15] for dominant annihilation into W-bosons (cyan line) are shown. These models have a suppressed photon yield close to E_t but also reach a level of $G(0.2\,\mathrm{TeV}|M) \sim 0.1\,\mathrm{TeV}^{-2}$ for WIMP masses well above $0.2\,\mathrm{TeV}$, so in the following discussion the Tasitsiomi spectrum will be emphasised as a reasonably conservative estimate of the photon yield.

It is instructive to compare the predicted photon flux from WIMP annihilation with other diffuse fluxes. Using the above assumption for $\langle\sigma v\rangle$ and a WIMP mass of $M = 1\,\mathrm{TeV}$, Fig. 2 (right) shows integral fluxes above $E_t = 0.2\,\mathrm{TeV}$ as a function of the angular distance from the Galactic center. The shape of the six different models curves (with the same color coding as in the left panel) is given by the angular dependence of the astrophysical factor and its convolution with the angular resolution of the photon detector. In the intermediate case of the Tasitsiomi annihilation spectrum (magenta line), the photon flux at an angular distance of 1° is a factor ~ 20 smaller than the diffuse electron flux (long black line, [16]) and lies about one order of magnitude below the diffuse emission from the Galactic plane (black line up to 1°, [8]).

The detection of such a tiny diffuse flux presents a substantial challenge. Clearly, the regions of diffuse emission from the Galactic plane should be avoided (unless one tries to identify WIMP signatures on top of the diffuse photon spectrum which can be described by a power-law [8]), but a search at distances of $\sim 1^\circ$ from the Galactic Centre could be promising. Rough estimates using the above assumptions and the know effective area of the H.E.S.S. array indicate that a photon rate close to $\sim$ 100 events/h is predicted in the inner 4° of the 5°-diameter field of view when regions with galactic latitude $|b| < 0.8°$ are disregarded. This rate is tiny in comparison with the hadron and electron rate of $\sim$ 10 Hz and $\sim$ 1 Hz, respectively, that remain after application of cuts that seek to enrich photon events, but one can plausibly show that H.E.S.S. has sensitvity for a DM searches at a boost factor of essentially one.

One of the most difficult aspects of such a search for DM annihilation radiation from the Milky Way halo is the need for an absolute substraction of the remaining proton and electron background. The background substraction can only be achieved by comparing the data rate of field of views close to the Galactic Centre (i.e. an ON region with a sizable contribution from DM annihilation) with OFF regions at larger angular distances where the annihilation flux is much smaller. Currently, two approaches are investigated that could provide suitable data sets for the calculation of first limits on the flux of annihilation photons. The first approach is data-taking in an ON-OFF mode with an offset in Right Ascension which ensures the same zenith and azimuth coverage for the ON and the OFF regions. The second is approach is data-taking in the so-called drift-scan mode [17] where constant acceptance is obtained by pointing the telescopes to a fixed observation position. In this setting, regions of varying annihilation flux pass through the field of view and the residual rate at large distances from the Galactic Centre can be used to normalize the background rate. Clearly, many additional factors (absolute stability of detector and atmosphere in one observation night, variations of sky brightness between ON and OFF regions, presence of bright stars that switch off camera pixels etc.) must be controlled and understood but it is hoped that first results will be available in the not to distant future.

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