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Prospects for a Dark Matter annihilation signal towards the Sagittarius dwarf galaxy with ground based Cherenkov telescopes

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Abstract. Dwarf galaxies are widely believed to be among the best targets for indirect dark matter searches using high-energy gamma rays; and indeed gamma-ray emission from these objects has long been a subject of detailed study for ground-based atmospheric Cherenkov telescopes. Here, we update current exclusion limits obtained on the closest dwarf, the Sagittarius dwarf galaxy, in light of recent realistic dark matter halo models. The constraints on the velocity-weighted annihilation cross section of the dark matter particle are of a few 10^{-23} cm^{3}s^{-1} in the TeV energy range for a 50 h exposure. The limits are extrapolated to the sensitivities of future Cherenkov Telescope Arrays. For 200 h of observation time, the sensitivity at 95% C.L. reaches 10^{-25} cm^{3}s^{-1}. Possible astrophysical backgrounds from gamma-ray sources dissembled in Sagittarius dwarf are studied. It is shown that with long-enough observation times, gamma-ray background from millisecond pulsars in a globular cluster contained within Sagittarius dwarf may limit the sensitivity to dark matter

1. Introduction

Dark matter (DM) plays a key role in the dynamics of a large class of astrophysical systems in the Universe. Though halos of dark matter are predicted to exist around all galaxies, dwarf spheroidal galaxies in particular are ideal targets for DM annihilation searches because: (i) their stellar dynamics show that they are among the most DM-dominated objects in the Universe; (ii) due to the lack of recent star formation activity, their environment is relatively quiet in terms of background astrophysical gamma-ray emission ; (iii) many of them lie at distances below 100 kpc from the Galactic Center.

The search for secondary gamma-rays from annihilations of dark matter particles is a powerful indirect detection technique because gamma-rays do not suffer from propagation effects and the gamma-ray signal should be proportional to the square of the DM density. Since the flux of the expected gamma-ray signal is inversely proportional to the square of distance, one would expect the best dwarf spheroidal target to be the nearest one. However such dwarfs are also the closest to the Galactic Center and experience the tidal effect of the Milky Way (MW). Recently, it has been shown that one could take advantage of this effect to trace back the evolution history of the object [1].

2. Dark matter searches with IACTs: current and future instruments

The present generation of IACTs (HESS, MAGIC and VERITAS) consists of multiple-telescope arrays detecting very high energy (VHE, $E_\gamma \geq 100$ GeV) gamma-rays. The stereoscopic view of extensive air showers generated in the atmosphere by VHE gamma-rays allows these instruments to accurately reconstruct the direction and the energy of the primary gamma-ray with an angular resolution reaching 0.1° per gamma-ray event (see, for instance, [2]).

The plan for the next generation of IACTs, the Cherenkov Telescope Array (CTA, [3]), involves building two large arrays, one in each hemisphere, with an order of magnitude more telescopes than current instruments. This future instrument is expected to increase the flux sensitivity by a factor of 10 compared to current instruments, and enlarge the accessible energy range both towards the lower and higher energies. Based on the current CTA design study, a factor of about ten in effective area and a factor of two better in hadron rejection are expected.

3. Modelling the Sagittarius dwarf dark matter halo

The Sagittarius dwarf (Sgrdw) is the only satellite galaxy in the MW that shows clear evidence of ongoing tidal mass stripping [4] in the form of an associated tidal stream. This galaxy is currently located at a close distance from the MW centre ($\approx$ 17 kpc). The proximity of the Sgrdw to the Milky Way plus the fact that this galaxy is shedding stars to tides complicates its dynamical modelling in a number of ways. These difficulties have not deterred a large body of theoretical work devoted to uncover the actual content and distribution of DM in the Sgrdw. To date these efforts have focused on (i) analytical models of the dynamical properties of the remnant core and (ii) N-body simulations that aim to reproduce the spatial and kinematical distribution of the tidal tails. The simplest analytical models assume dynamical equilibrium and adopt a cosmologically-motivated halo density profile to describe the kinematics of individual stars. A prominent parametrization of such halos is the *Navarro, Frenk, and White* (NFW) profile [5]. However, numerical N-body models that aim to describe the observed structural and kinematical distributions of stars in the tidal tails as well as the remnant core provide a more consistent approach to the dynamical analysis of the Sgrdw. Yet, most of the existing N-body models of this galaxy assume for simplicity that dark matter and stars share the same spatial distribution (the so-called "mass-follows-light models"), an assumption that is not supported by detailed kinematic data of dwarf spheroidal galaxies (e.g. [6]). The only exception to date corresponds to recent N-body models constructed by [7], who explore the possibility that the Sgrdw may have originally been a rotating galaxy. In these models the galaxy is composed of an exponential stellar disk embedded in an extended DM halo. The DM density profile is taken as a cored isothermal (ISO) [7]. An evolution code allows to recover the actual DM profile by using the constraint of the observed stellar distribution.

4. Exclusion limits on the dark matter annihilation cross section

4.1. Generic case for exclusion limits

The gamma-ray flux from the annihilations of DM particles of mass $m_{\rm DM}$ in a DM halo is given by a particle physics term times an astrophysics term:

$$\frac{{\rm d}\Phi_\gamma(\Delta\Omega, E_\gamma)}{{\rm d}E_\gamma} = \frac{1}{8\pi} \underbrace{\frac{\langle\sigma v\rangle}{m_{\rm DM}^2} \frac{{\rm d}N_\gamma}{{\rm d}E_\gamma}}_{\rm Particle\,Physics} \times \underbrace{\bar{J}(\Delta\Omega)\Delta\Omega}_{\rm Astrophysics}, \quad (1)$$

where the astrophysical factor $\overline{J}$ is defined as

$$\overline{J}(\Delta\Omega) = \frac{1}{\Delta\Omega}\int_{\Delta\Omega} {\rm d}\Omega \int_{\rm los} \rho^2[r(s)]{\rm d}s\,. \quad (2)$$

In Eq. (2) the squared density of DM (ρ^2) is integrated along the line of sight (los) and over the solid angle $\Delta\Omega$. The solid angle is fixed to match the angular resolution of the telescope for a point-like source search. Two hypotheses for spherical DM halo profiles are used: the cored isothermal profile (ISO), and the NFW profile (NFW). The particle physics term contains the DM particle mass, $m_{\rm DM}$, the velocity-weighted annihilation cross section, $\langle\sigma v\rangle$, and the differential gamma-ray spectrum from all final states weighted by their corresponding branching ratios, $\mathrm{d}N_\gamma/\mathrm{d}E_\gamma$.

In the case where the background is not measured experimentally, it can still be estimated assuming that the background consists of misidentified hadron showers. The estimate of the expected number of background events in the signal region can be determined using the hadron flux parametrization from [8], with a hadron detection efficiency equal to 0.1 for the future IACTs. In case of no gamma-ray signal, a limit on the number of gamma rays at 95% confidence level (C.L.), $N_\gamma^{95\%\rm C.L.}$, can be calculated using the method of [9] (see [10] for more detail). The 95% C.L. upper limit on the velocity-weighted annihilation cross section as function of the DM particle mass for a given halo profile is then given by

$$\langle\sigma v\rangle_{\rm min}^{95\%\,\rm C.L.} = \frac{8\pi}{\overline{J}(\Delta\Omega)\Delta\Omega} \times \frac{m_{\rm DM}^2\, N_{\gamma,\,\rm tot}^{95\%\,\rm C.L.}}{T_{\rm obs}\int_0^{m_{\rm DM}} A_{\rm eff}(E_\gamma)\,\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}(E_\gamma)\,\mathrm{d}E_\gamma}\,, \tag{3}$$

where the parametrization of $\mathrm{d}N_\gamma/\mathrm{d}E_\gamma$ is taken from [8] for neutralino self-annihilation. $A_{\rm eff}(E_\gamma)$ and $T_{\rm obs}$ are the effective area of the detector as function of the gamma ray energy and the observation live time, respectively. Fig. 1 shows the upper limits of current IACTs on $\langle\sigma v\rangle$ as a function of the DM mass m for $\Delta\Omega = 2\times10^{-5}$ sr. Using the HESS published upper limits, the new upper limits are calculated for the NFW and ISO DM halo profiles and 11h of observation time; the projected upper limits for 50h of observation time is also plotted. The limits are at the level of 5×10^{-23} cm^3 s^{-1} around 1 TeV for 50h. The sensitivity of H.E.S.S. for 50 h observation time is also displayed. The sensitivity limits for CTA on $\langle\sigma v\rangle$ as a function of the DM mass m are presented in Fig. 2 for 50 h and 200 h observation times. The limits are calculated with $\Delta\Omega = 2\times10^{-6}$ sr for the NFW DM halo profile and $\Delta\Omega = 10^{-3}$ sr for the ISO DM halo profile. The sensitivity limits at 95% C.L. reach the level of 10^{-25} cm^3 s^{-1} for DM masses of about 1 TeV in the case of the ISO DM halo profile.

4.2. Enhancement effects of the gamma-ray flux

Two additional contributions to the overall gamma-ray flux that can modify the limits are considered: namely the *Sommerfeld effect* (SE) and *Internal Bremsstrahlung* (IB) from the DM annihilation. The Sommerfeld effect is a non-relativistic effect which arises when two DM particles interact in an attractive potential. When the relative velocity between the DM particles is sufficiently low, the Sommerfeld effect can substantially boost the annihilation cross section [11], since it is particularly effective in the very low-velocity regime. The actual velocity-weighted annihilation cross section of the neutralino can then be enhanced by a factor S defined as

$$\langle\sigma v\rangle = S\,\langle\sigma v\rangle_0\,, \tag{4}$$

where the value of S depends on the mass and relative velocity of the DM particle. Assuming that the DM particles only annihilate to a W boson, the attractive potential created by the Z gauge boson through the weak force before annihilation would give rise to an enhancement. Assuming that the DM velocity dispersion inside the halo is the same as for the stars, the value of the DM velocity dispersion is fixed at 11 kms^{-1} for SgrDw [12]. The value of the enhancement is numerically calculated as done in [11] and then used to improve the upper limits on the velocity-weighted annihilation cross section, $\langle\sigma v\rangle/S$ as a function of the DM particle mass. Additionally,

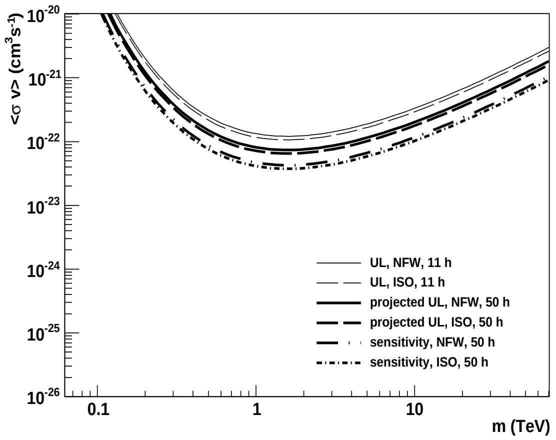

Figure 1. 95% C.L. upper limits (UL) on the $\langle\sigma v\rangle$ versus the DM mass m for a NFW and ISO DM halo profiles respectively for 11 h observation time and $\Delta\Omega = 2\times10^{-5}$ sr. The projected upper limits are displayed for 50 h observation time. The sensitivities at 95% C.L. for 50 h are also shown for NFW and ISO DM halo profiles.

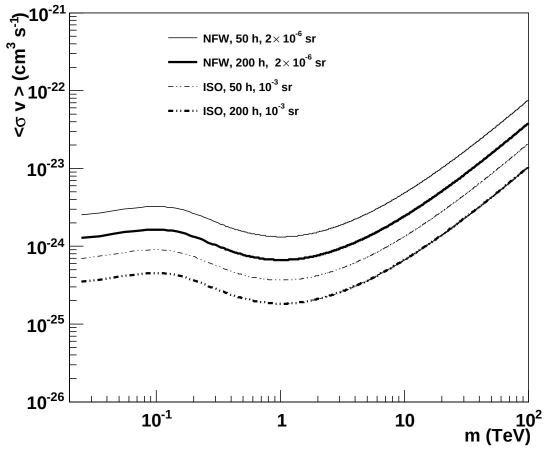

Figure 2. Sensitivity at 95% C.L. for CTA on the $\langle\sigma v\rangle$ versus the DM mass m for a NFW and ISO DM halo profiles. The sensitivity is shown for 50 and 200 h observation times and different solid angles of observation depending on the DM halo profile (see [10] for more detail).

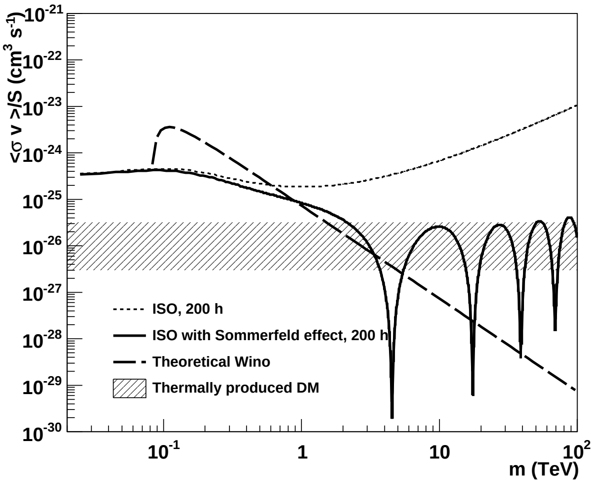

Figure 3. Sensitivity at 95% C.L. for CTA on the $\langle\sigma v\rangle$/S versus the DM mass m enhanced by the SE for the ISO profile. The sensitivity is shown for 200 h observation times and $\Delta\Omega = 10^{-3}$ sr.

every time a DM particle annihilates into charged particles, the electromagnetic radiative correction to the main annihilation channel can give a more or less significant enhancement to the expected gamma-ray flux in the observed environment due to internal Bremsstrahlung (IB) [13, 14]. Restraining the MSSM parameters space to the *stau co-annihilation region* of the minimal supergravity (mSUGRA) models, for instance, the wino annihilation spectrum would receive a considerable contribution from Internal Bremsstrahlung [14]. The sensitivity at 95%

C.L. for CTA on $\langle\sigma v\rangle/S$ as a function of the DM mass m is presented in Fig. 3. The limits are calculated for the ISO DM halo profile, with 200h observation time and $\Delta\Omega = 10^{-3}$ sr. The effect of the IB is only significant below $\sim$ 1TeV. The values of $\langle\sigma v\rangle$ corresponding to cosmological thermally-produced DM, $\langle\sigma v\rangle \sim 3\times10^{-26}$ cm^{3}s^{-1}, can be tested for TeV DM masses due to the Sommerfeld effect.

5. Astrophysical background emission

Dwarf galaxies are generally believed to contain very little background emission from conventional astrophysical sources at VHE energies, and are therefore easy targets for DM searches. This assumption is based on their low gas content and stellar formation rate. However, some gamma-ray emitting sources may still exist within them: in particular from pulsars. The Sagittarius dwarf galaxy hosts the M54 globular cluster (located at its center), and globular clusters are known to host millisecond pulsars (MSPs). The collective emission of high energy gamma-rays by MSPs in globular clusters has been detected by *Fermi-LAT* [15]. The emission in the VHE energy range has been predicted by several authors (see [10] for more details) for these objects but has not yet been observed. The possible emission of very high energy radiation by millisecond pulsars from the M54 globular cluster is calculated and it would give a signal superior to the 4 σ level in CTA observations after just a one hour observation for different MSP collective emission models. For a cosmological thermally produced DM particle, $\langle\sigma v\rangle = 3\times10^{-26}$ cm^{3}s^{-1}, the corresponding signal would have a significance of 0.1σ, after 200 hours of observation and without any boost factor. The collective MSP signal would be a few orders of magnitude stronger than the DM annihilation signal.

6. Conclusions

Older publications on DM searches towards SgrDw [16] used dark matter mass profiles which lead to somewhat optimistic constraints on particle dark matter self-annihilation cross sections. These models were used because no accurate modelling of SgrDw existed at that time. Several realistic models are now published that loosen the existing constraints by more than one order of magnitude [10]. The future CTA array will be sensitive to $\langle\sigma v\rangle$ values around a few 10^{-25}cm^{3}s^{-1}. Some models could be excluded after 200 hours of observation, if boosts factors are taken into account. However, the very high energy emission of several astrophysical objects could give an observable signal for long-enough observation times. The collective very high energy emission of the MSPs of the M54 globular cluster, which is predicted by several models, could be much stronger than a DM signal. It could be observed in just a few tens of hours with CTA [10].

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