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 annihilations.

Subject headings: Gamma-rays : observations - Dwarf Spheroidal galaxy, 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

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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, the gamma-ray signal should be proportional to the square of the DM density, and characteristic features such as lines or steps may be present in the energy spectrum at these energies (Bergström 2000; Bringmann *et al.* 2008). Imaging atmospheric Cherenkov telescopes (IACTs) such as HESS (2003), MAGIC (2003) and VERITAS (2007), are particularly well suited to deep searches of targeted objects because of their large effective areas ($\sim 10^5\,\mathrm{m}^2$ above 100 GeV). However, since IACTs are multipurpose astrophysical experiments and have a short duty cycle (∼1000 hours/year), the observation time dedicated to these objects is typically limited to tens of hours per year.

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. Recently, it has been shown that one could take advantage of this effect to trace back the evolution history of the object (Peñarrubia *et al.* 2008a). During the orbital motion of a dwarf galaxy, multiple crossings of the dwarf galaxy through the galactic disc of the Milky Way give rise to the formation of tidal streams, a careful study of which allows to one infer the gravitational potential of the dwarf galaxy.

In the case of the Sagittarius Dwarf galaxy (SgrDw), the tidal streams have been detected with multiple tracer populations (Yanny *et al.* 2000; Vivas *et al.* 2001; Watkins *et al.* 2009; Mateo 1998; Majewski *et al.* 1999; Martinez-Delgado *et al.* 2001; Newberg *et al.* 2002; Majewski *et al.* 2003) and have been used to derive the DM halo potential. Furthermore, measurements of stars within SgrDw and the luminosity of its core and surrounding debris, allows the estimate of the DM content *prior* to tidal disruption (Niederste-Ostholt *et al.* 2010; Peñarrubia *et al.* 2010). Other peculiar features of SgrDw include the presence of the M54 globular cluster coincident in position with its center of gravity (Ibata *et al.* 1994), and hints for the presence of a central Intermediate Mass Black Hole (Ibata *et al.* 2009) (IMBH). The latter point is supported by the observation of a deviation from a flat behavior in the surface brightness density profile towards the center of the object.

Constraints on a DM annihilation signal towards SgrDw, Canis Major, Sculptor and Carina have been reported by HESS (Aharonian *et al.* 2008, 2009; Abramowski *et al.* 2011), towards Draco, Willman 1 and Segue 1 by MAGIC (Albert *et al.* 2008; Aliu *et al.* 2009; Aleksic *et al.* 2011) and towards Draco, Ursa Minor, Boötes 1 and Willman 1 by VERITAS (Acciari *et al.* 2010), and towards Draco and Ursa Minor by Whipple (Wood *et al.*

2008). Because of its location in the Southern hemisphere, HESS is better suited for observations of SgrDw with respect to other currently-operating IACTs. Observations with the Fermi Large Area Telescope (*Fermi-LAT*, a space-based telescope sensitive to gamma-rays between 20 MeV and 300 GeV), are also well-suited due to its large duty cycle and wide field-of-view, though the energy range probed is lower than that of IACTs. The *Fermi-LAT* collaboration put strong constraints in the GeV DM mass range on dwarf spheroidal galaxy satellites of the Milky Way (Abdo *et al.* 2010a; Ackermann *et al.* 2011). However, their study is restricted to high galactic latitude ($|b| > 30°$) objects to avoid systematic contamination from galactic diffuse gamma-ray emission, and therefore no constraints on the measured flux in the direction of SgrDw have yet been published using *Fermi-LAT* data.

In this paper, the current constraints on a DM annihilation signal towards SgrDw are reassessed in light of more realistic DM halo models than previously used (Evans *et al.* 2004; Aharonian *et al.* 2008). The sensitivity of the future generation of IACTs, *i.e.* CTA (Cherenkov Telescope Array, 2010), is used to evaluate its potential for the detection of a DM annihilation signal. The CTA design-study sensitivity is used to investigate possible conventional gamma-ray emission, *e.g.* to the population of millisecond pulsars (MSP) in the globular cluster M54 at the center of SgrDw, or from the jet of a hypothetical central IMBH. It is shown that such standard astrophysical signals may limit the sensitivity to DM annihilations with CTA in case of long observation times, eventually requiring the modelling and subtraction of these astrophysical components.

The paper is structured as follows: Section 2 is dedicated to the description of current and future instruments as well as the calculation of the sensitivity to DM signals. In Section 3, the modelling of the DM halo of SgrDw is described together with the astrophysical contribution to the DM flux. In the absence of an astrophysical gamma-ray background, exclusion limits on the velocity-weighted annihilation cross section of DM are derived in Section 4. Section 5 deals with the estimate of the gamma-ray emission from the MSP population and the IMBH candidate of M54. Section 6 is devoted to the summary.

2. Dark matter searches with IACTs

2.1. Current and future instruments

The present generation of IACTs (HESS, MAGIC and VERITAS) consists of multiple-telescope arrays detecting very high energy (VHE, $E_\gamma \gtrsim 100$ 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. The angular resolution reaches 0.1° per gamma-ray event and the point source sensitivity is about a few percent of the Crab Nebula flux above 100 GeV (see, for instance, Aharonian *et al.* 2006).

The plan for the next generation of IACTs, the Cherenkov Telescope Array (CTA, 2010), 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. In this study, the estimated CTA effective area at the trigger level (before offline gamma-hadron separation) is extracted from Paz Arribas (2008). In order to mimic the effect of the analysis event selection, the effective area values for energies from ∼100 GeV down to ∼20 GeV are realistically lowered. The effective area then decreases from $\sim 10^6\,\mathrm{m}^2$ at 200 GeV down to $\sim 10^3\,\mathrm{m}^2$ at about 20 GeV.

2.2. Sensitivity calculation and background estimates

The sensitivity for IACTs is calculated by comparing the number of events expected from an assumed gamma-ray emission scenario with the expected level of background events. In the case of DM searches, the assumed emission is from the annihilation of DM particles of mass m in the halo of the host galaxy, the differential gamma-ray flux of which is given by:

$$\frac{\mathrm{d}\Phi(\Delta\Omega, E_\gamma)}{\mathrm{d}E_\gamma} = \frac{1}{8\pi} \underbrace{\frac{\langle\sigma v\rangle}{m^2} \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}}_{\text{Particle Physics}} \times \underbrace{\bar{J}(\Delta\Omega)\Delta\Omega}_{\text{Astrophysics}}, \tag{1}$$

where $\langle\sigma v\rangle$ is the velocity-weighted annihilation cross-section and $\mathrm{d}N_\gamma/\mathrm{d}E_\gamma$ the photon spectrum per annihilation. The astrophysical factor is defined as

$$\bar{J}(\Delta\Omega) = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} \mathrm{d}\Omega \int_{\mathrm{LOS}} \rho^2[r(s)]\mathrm{d}s\,. \tag{2}$$

When treating the self-annihilation of DM particles, this factor scales with the squared density of DM, ρ^2, over the whole observation cone. The integral is then taken along the line of sight (LOS) and inside the solid angle $\Delta\Omega$. The solid angle is chosen as the angular resolution for point-like searches. The number of expected signal events can be calculated by:

$$N_\gamma = T_{\mathrm{obs}} \int_0^\infty A_{\mathrm{eff}}(E_\gamma)\, \frac{\mathrm{d}\Phi_\gamma}{\mathrm{d}E_\gamma}\, \mathrm{d}E_\gamma\,, \tag{3}$$

where $T_{\rm obs}$ is the observation time, and $A_{\rm eff}(E_\gamma)$ is the effective area of the detector as a function of the gamma-ray energy. 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 following expression (see Bergström *et al.* 1998):

$$\frac{{\rm d}^2\Phi_{\rm had}}{{\rm d}\Omega {\rm d}E_\gamma} = 8.2\times 10^{-8}\epsilon_{\rm had}\left(\frac{E_\gamma}{1{\rm TeV}}\right)^{-2.7}[{\rm TeV}^{-1}{\rm cm}^{-2}{\rm s}^{-1}{\rm sr}^{-1}]\,, \qquad (4)$$

where $\epsilon_{\rm had}$ is the hadron detection efficiency. To take into account the performance of the future IACTs the hadron rejection is taken at the level of 90%, which corresponds to $\epsilon_{\rm had} = 0.1$. This parametrisation gives remarkable agreement with CTA background simulations (Di Pierro *et al.* 2011).

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 Rolke *et al.* (2005). In what follows two cases are considered. In the case of current IACTs, the $N_\gamma^{95\%{\rm C.L.}}$ calculation uses the numbers of gamma-ray and background events extracted from 11h H.E.S.S. measurements (Aharonian *et al.* 2008). The projected $N_\gamma^{95\%{\rm C.L.}}$ for 50 h observation time is obtained by extrapolating both the numbers of gamma-ray and background events from 11 h to 50 h. In the case of 95% C.L. sensitivity calculations, $N_\gamma^{95\%{\rm C.L.}}$ is calculated assuming the background-only hypothesis. For the H.E.S.S. sensitivity the number of background events is taken from the extrapolation at 50 h of observation. For the CTA sensitivity, the number of background events is calculated by integrating the background event flux given in Eq. (4) after multiplication by the effective area of the detector and the observation time. $N_\gamma^{95\%{\rm C.L.}}$ is then calculated using five off regions.

Replacing Eq. (1) in Eq. (3), the DM sensitivity can be then expressed in terms of the remaining particle physics parameters, $\langle\sigma v\rangle$, m and dN/dE_γ. The 95% C.L. limit on the velocity-weighted annihilation cross section is given by the following expression:

$$\langle\sigma v\rangle^{95\%{\rm C.L.}}_{\rm min} = \frac{8\pi}{\bar{J}(\Delta\Omega)\Delta\Omega}\times\frac{m^2\,N_\gamma^{95\%{\rm C.L.}}}{T_{\rm obs}\,\int_0^m A_{\rm eff}(E_\gamma)\,\frac{{\rm d}N_\gamma}{{\rm d}E_\gamma}(E_\gamma)\,{\rm d}E_\gamma}\,. \qquad (5)$$

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 (Ibata *et al.* 2001) in the form of an associated tidal stream (Mateo *et al.* 1998; Majewski *et al.* 1999, 2003; Martinez-Delgado *et al.* 2001, 2004; Belokurov *et al.* 2006; Watkins *et al.* 2009). This galaxy is currently located at a close distance from the MW centre ($\approx$ 17 kpc; Mateo *et al.* 1998). Indeed, it underwent its last perigalacticon passage only 17 Myr ago (Law and Majewski 2010; Peñarrubia *et al.* 2009), which is a relatively short time compared with its internal dynamical time $t_{\rm dyn} = R_c/\sigma_0 \approx 47$ Myr, where R_c is the galaxy core radius and σ_0 the central velocity dispersion (Mateo 1998).

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. On the one hand, the distribution of dark matter and stars has been clearly altered from its original configuration by tidal mass stripping. Given that the actual amount of stars and dark matter in the tidal tails is unknown (Niederste-Ostholt *et al.* 2010), the original mass, luminosity and size of the Sgrdw remain fairly uncertain quantities. On the other hand, the assumption of dynamical equilibrium may not be adequate, specially in the outskirts of the galaxy where the population of unbound stars may dominate in number over that of bound members (Peñarrubia *et al.* 2009).

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

$$\rho_{\rm NFW}(r) = \frac{\rho_{\rm s}}{(r/r_{\rm s})(1+r/r_{\rm s})^2}\,, \qquad (6)$$

where $r_{\rm s}$ is a scale radius and $\rho_{\rm s}$ is a characteristic density (Navarro, Frenk & White 1996, hereafter NFW). Note that this profile diverges at small radii as $\rho \propto r^{-1}$, which is typically referred as a dark matter "cusp". It was shown in Peñarrubia *et al.* (2008a) that the tightly bound dark matter cusp is more resilient to disruption than the more loosely bound stellar cored profile, which can be accurately described with a King (1966) profile (Mateo 1998), and that tidal stripping does not change the inner profile of DM haloes.

Assuming that the external tidal field does not influence the kinematics of stars that locate the central regions of the dwarf, and ignoring the effects of tidal stripping on the outer ($r \gg r_s$) dark matter halo profile, one can use the Jeans equations to search the DM halo parameters that best fit the stellar central velocity dispersion for a observed King core radius of this object. The King-NFW degeneracy gives rise to a family of NFW halo models which can reproduce the stellar dynamics (Peñarrubia *et al.* 2008b). One way to break this degeneracy is using the relationship between the virial mass and concentration found in cosmological N-body simulations (see for instance, Bullock *et al.* 2001). Using this procedure on the SDSS survey data provides a value of $r_s = 1.3$ kpc. Considering the scatter on the relationship between virial mass and concentration, the 2σ error on r_s is found to be $\sim$0.2 kpc. This correspond to the family of models with ρ_s spanning from 7.5×10^{-3} to 1.3×10^{-2} $M_{\odot} pc^{-3}$. In Table 1 we show the results of our fits together with the astrophysical factors $\bar{J}$ for different solid angles $\Delta\Omega$. Taking into account the error on the halo profile parameters the value of the astrophysical factor can vary by a factor of 2. Interestingly, an independent analysis by Łokas *et al.* (2010) provides similar values for these parameters. In this case the astrophysical factors are found to be of a few higher than the ones presented here.

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. Walker *et al.* (2009)). The only exception to date corresponds to recent N-body models constructed by Peñarrubia *et al.* (2010), 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) profile

$$\rho_{\rm ISO}(r) = \frac{m_{\rm h}\alpha}{2\pi^{3/2} r_{\rm cut}} \frac{\exp[-(r/r_{\rm cut})^2]}{(r_{\rm c}^2 + r^2)}\,, \tag{7}$$

where $m_{\rm h}$ is the halo mass, $r_{\rm c}$ is the core radius and $\alpha \simeq 1.156$ (Peñarrubia *et al.* 2010). The DM halo mass can be estimated using the initial luminosity and a given mass-to-light ratio. Using the results from Niederste-Ostholt *et al.* (2010) the initial luminosity is estimated to be $\sim 10^8\,{\rm L}_{\odot}$. Assuming a typical mass-to-light ratio for dwarf galaxies of 25 (Mateo 1998), the DM halo mass is found to be $m_{\rm h} = 2.4 \times 10^9\,{\rm M}_{\odot}$. To account for the initial tidal disruption of the SgrDw halo by the Milky Way, a truncation of the halo profile is imposed at $r_{\rm cut} = 12\,r_{\rm c}$. The evolution of the SgrDw in the Milky Way potential is obtained via a N-body model of SgrDw using the particle-mesh gravity code SUPERBOX (Fellhauer *et al.* 2000). The evolution code allows to recover the actual DM profile by using the constraint of the observed stellar distribution. The values of the parameters of the present ISO profile are given in Table 1.

4. Exclusion limits on the dark matter annihilation cross section

Theories beyond the Standard Model (SM) of particle physics propose several particle DM candidates. For instance, some supersymmetric extensions of the SM predict a *neutralino* as the lightest stable supersymmetric particle, which is a good candidate for DM (Jungman *et al.* 1996; Bergström 2000). The parametrization of the neutralino self-annihilation gamma-ray spectrum $\mathrm{d}N_\gamma/\mathrm{d}E_\gamma$ is taken from Bergström *et al.* (1998) for a typical neutralino annihilating into W and Z pairs. Fig. 1 shows the upper limits of current IACTs on $\langle\sigma v\rangle$ as a function of the DM mass m for $\Delta\Omega = 2\times10^{-5}\,\mathrm{sr}$. Using the HESS upper limits published in Aharonian *et al.* (2008), the new upper limits are calculated for the NFW and ISO DM halo profiles of Section 3 and 11 h of observation time; the projected upper limits for 50 h of observation time is also plotted. The limits are at the level of $5\times10^{-23}\,\mathrm{cm^3s^{-1}}$ around 1 TeV for 50 h. 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. 3 for 50 h and 200 h observation times. The limits are calculated with $\Delta\Omega = 2\times10^{-6}\,\mathrm{sr}$ for the NFW DM halo profile and $\Delta\Omega = 10^{-3}\,\mathrm{sr}$ for the ISO DM halo profile. The sensitivity limits at 95% C.L. reaches the level of $10^{-25}\,\mathrm{cm^3s^{-1}}$ for DM masses of about 1 TeV in the case of the ISO DM halo profile.

Two additional contributions to the overall gamma-ray flux that can modify the limits are considered: namely the *Sommerfeld effect* 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 (Lattanzi and Silk 2009), 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

$$\langle\sigma v\rangle = S\,\langle\sigma v\rangle_0\ , \tag{8}$$

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 $\mathrm{kms^{-1}}$ for SgrDw (Mateo 1998). The value of the enhancement is numerically calculated as done in Lattanzi and Silk (2009) 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, 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) (Bergström 1989; Bringmann *et al.* 2008). 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 (Bringmann *et al.* 2008). Fig. 2 shows the 95% C.L. upper limits on $\langle \sigma v \rangle / S$ as a function of the DM mass m for current IACTs. The projected upper limit is shown for the NFW profile, 50 h observation time and $\Delta\Omega = 2 \times 10^{-5}$ sr. The effect of the IB is only significant below ~ 1 TeV. Some specific wino masses can be excluded due to the resonant enhancement in the Sommerfeld effect. Outside resonances, the projected upper limits are improved by more than one order of magnitude for DM masses above 1 TeV. 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. 4. The limits are calculated for the ISO DM halo profile, with 200 h observation time and $\Delta\Omega = 10^{-3}$ sr. The values of $\langle \sigma v \rangle$ corresponding to cosmological thermally-produced DM, $\langle \sigma v \rangle \sim 3 \times 10^{-26}$ cm^{3}s^{-1}, can be tested for specific wino masses in the resonance regions of the Sommerfeld effect. Outside the resonances the sensitivity on $\langle \sigma v \rangle / S$ is improved by more than one order of magnitude for TeV DM masses, reaching the level of 10^{-26} cm^{3}s^{-1}.

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, and black hole accretion and/or jet emission processes. The Sagittarius and Carina dwarf galaxies both host globular clusters (the M54 globular cluster is located at the center of SgrDw), 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* (Abdo *et al.* 2010b), and emission in the VHE energy range has been predicted by several models 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 examined in section 5.1. Additionally, it has been suggested by some authors (see Lanzoni *et al.* 2007; Noyola *et al.* 2008, and references thereby) that globular clusters may host black holes with masses of around 10^2 to 10^4 solar masses (called *intermediate-mass black holes, or IMBHs*). Indeed, Ibata *et al.* (2009) suggest SgrDw may also be a possible host for a 10^4 $M_\odot$ IMBH . Their claim is based on the study of the density profile around the central point and the observed rise in the velocity dispersion of stars. The high energy emission from the IMBH candidate in the center of M54 is discussed in section 5.2

5.1. Millisecond pulsars in M54

The M54 globular cluster at the center of SgrDw is likely to harbor a large population of pulsars, especially MSPs. The number of MSPs in globular clusters has been shown by the *Fermi-LAT* collaboration (Abdo *et al.* 2010b) to be correlated with the collision rate Γ defined by

$$\Gamma = \rho^{3/2} r_{\rm c}^2 \,. \tag{9}$$

In this equation, ρ is the central luminosity and $r_{\rm c}$ is the core radius. Taking a central surface brightness of $\mu_{\rm V} \simeq (14.12\ - 14.9)\,{\rm mag\,arcsec^{-2}}$ from Table 4 of Bellazzini *et al.* (2008) and a core radius $r_c = 0.9$ pc , the collision rate is found to be

$$\Gamma_{\rm M54} \simeq \big(0.8 - 2.6\big) \times \Gamma_{\rm M62} \,, \tag{10}$$

where $\Gamma_{\rm M62} = 6.5 \times 10^6\,{\rm L_\odot^{3/2} pc^{-2.5}}$ is the reference collision rate of the M62 globular cluster. The predicted number $N_{\rm MSP}$ of MSPs in M54 is estimated from the collision rate (Abdo *et al.* 2010b) by the relation

$$N_{\rm MSP} = 18 + 50 \times \left(\frac{\Gamma_{\rm M54}}{\Gamma_{\rm M62}}\right) \,. \tag{11}$$

The collision rate from Eq. (10) gives the estimated number of MSPs in M54: $N_{\rm MSP} = 60 - 140$. Note however that no MSP has been discovered to date in M54.

The collective very-high-energy gamma-ray emission of millisecond pulsars from globular clusters has been predicted by several authors, notably Bednarek and Sitarek (BS) (Bednarek and Sitarek 2007), Venter, deJager and Clapson (VJC) (Venter *et al.* 2009) and Cheng et al. (CCDHK) (Cheng *et al.* 2010). Using the effective area of CTA described in section 2.1, one expects to observe respectively 1285 and 181 gamma-rays per hour towards the 47 Tucanae globular cluster, with the BS and CCDHK models. In the latter model, the relic gamma-rays are assumed to be the target population. The prediction of the VJC model is somewhat smaller, only 71 gamma-rays per hour are predicted assuming an interstellar magnetic field of 10 μG. The VJC model also predicts a synchrotron radiation emission. The emission in the keV range is predicted to be at the level of $10^{-16}\,{\rm TeV\,cm^{-2}\,s^{-1}}$ for a magnetic field of 10 μG. This is easily accommodated by the measured diffuse X-ray emission in M54 which is $\sim 2 \times 10^{-14}\,{\rm TeV\,cm^{-2}\,s^{-1}}$ (Bogdán and Gilfanov 2010).

As suggested by Venter and de Jager (2008), a rough estimate of the collective VHE emission of M54 can be obtained from their predicted emission of 47 Tucanae by scaling by the factor:

$$x = \left(\frac{N_{\rm MSP}}{100}\right) \left(\frac{d_{\rm 47Tuc}}{d_{\rm M54}}\right)^2 \left(\frac{< u_{\rm M54} >}{< u_{\rm 47Tuc} >}\right) . \tag{12}$$

In this equation, $d_{47\mathrm{Tuc}}$ and d_{M54} are the distances to 47 Tucanae and M54, and $< u_{\mathrm{M54}} >$ and $< u_{47\mathrm{Tuc}} >$ the average luminosity per cubic parsec of the globular cluster. Taking the distances, luminosity and half-mass radii of M54 and 47 Tucanae from Harris (1996) (2010 edition), one finds a correction factor $x \simeq 1.6 \times 10^{-2}$, assuming that M54 contains 100 MSPs. The expected number of gamma-rays per hour are thus 19.9 and 5.6 in the BS and CCDHK models. For the latter model, x was multiplied by an additional factor of 2 to take into account the different number of MSPs in 47 Tucanae and M54. For the VJC model, the number of expected gamma-rays per hour is about 1.1.

Whether this signal is observable or not depends crucially on its spatial extension. The half-mass radius of M54 has an angular size of less than $1'$ so that the signal would appear almost point-like in the BS and VJC models. The CCDHK predicts an extended signal. The electrons and positrons responsible for the inverse Compton scattering on the CMB radiation have a typical diffusion length of 100 pc, which corresponds to $\simeq 12'$ at the distance of M54. The signal integration regions are taken as $3'$ for the BS and VJC models and $12'$ for the CCDHK model. With an hadron rejection factor of 10% as in section 2.2, the number of background per hour is $\sim$10 inside a $3'$ radius centered on M54. The significance of the collective MSP signal depends thus on the observation time T_{obs} (in hours) as respectively $4.5\ \sqrt{T_{\mathrm{obs}}}$, $0.31\ \sqrt{T_{\mathrm{obs}}}$ and $0.25\ \sqrt{T_{\mathrm{obs}}}$ in the BS, CCDHK and VJC models. The BS model would give a signal at the $4.5\ \sigma$ level after just a one hour observation. The other models would give a much smaller signal, with a typical significance of 4σ after 200 hours of observation.

In summary, the millisecond pulsars of M54 could give a significant VHE gamma-ray signal in CTA with observation times of typically 200 hours. For a cosmological thermally produced DM particle, $\langle \sigma v \rangle = 3{\times}10^{-26}$ 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.

5.2. Intermediate-Mass Black hole

Significant radio and X-ray emissions are expected if the hypothesis of a central IMBH is valid. Unfortunately, only upper limits to the radio emission could be established from *VLA* and *MOST* observations. Nevertheless, these limits can be used to constrain the candidate black hole mass. As regards X-ray emission, Ramsay and Wu (Ramsay and Wu 2006a,b) have analyzed the data taken with *Chandra* satellite. They found 7 bright sources within the half-mass radius of M 54. Their source number 2 lies within 1” of the density center of

M54. Taking into account the *Chandra* astrometric accuracy of 0".6 and the systematics of 0."3 in the absolute position of the *Chandra* ACS camera, this source could be associated with the stellar cusp identified in Ibata *et al.* (2009). The source number 2 has an irregular shape and a luminosity of $L_X = 0.72 \times 10^{33}\,\mathrm{erg\,s^{-1}}$ (Ramsay and Wu 2006a,b).

The Ibata *et al.* (2009) estimate of the black hole mass is consistent with the (Massive Black Hole - host galaxy) correlation of Ferrarese *et al.* (2006) only if the host system is M54 ($M_{\mathrm{IMBH}}/M_{\mathrm{M54}} \sim 5\%$). For a similar mass ratio with SgrDw as the host system, a 1000 times more massive black hole would be necessary, suggesting this may be a system composed of a dwarf galaxy hosting a prominent stellar nucleus, itself hosting a central IMBH. We estimate the largest contribution of the IMBH to a possible VHE gamma-ray signal, and assume that the IMBH is active and has a jet inclined towards the line of sight with an angle θ. The contribution of the black hole to the VHE gamma-ray emission is estimated using the model developed by Reynoso *et al.* (2011), on the emission of relativistic jets associated with active galactic nuclei. The parameters of the model for the central black hole and jet are described in Reynoso *et al.* (2011). The calculation also uses the constraints from the upper limits in the radio band and the measured X-ray emission from the source number 2. The modeled gamma-ray emission is shown on Fig. 5. The parameters used in the model are given in Table 2. The emission depends only weakly on the black hole mass, but strongly on the assumed Lorentz factor Γ_{b} and inclination θ.

The peak on the X-ray band comes from the synchrotron of electrons while a strong contribution from the Synchrotron Self-Compton (SSC) scattering can be seen at GeV energies. At higher energies, in particular in the CTA energy range, the emission from *pp* interactions is dominant. However, for reasonable parameters, it is in the $10^{-18} - 10^{-17}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ flux range—too faint to be detected by CTA.

6. Summary

Older publications (e.g. Evans *et al.* 2004; Aharonian *et al.* 2008) on DM searches towards SgrDw 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. The future CTA array will be sensitive to $\langle \sigma v \rangle$ values around a few $10^{-25}\,\mathrm{cm^3\,s^{-1}}$. 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. The candidate IMBH located at the center is not expected to give an observable signal. Under favorable circumstances (active black hole and jet aligned towards the line of sight), it might nevertheless be detectable in observations of SgrDw.

Table 1:: Values of the *LOS*-integrated squared density averaged over the solid angle ($\bar{J}$) expressed in units of $10^{23}\,\mathrm{GeV}^2\,\mathrm{cm}^{-5}$, for different solid angles $\Delta\Omega$. The values of $\bar{J}$ are calculated for the NFW and ISO DM halo profiles. The parameters of these profiles are given in the first column.

DM halo profile	$\Delta\Omega = 10^{-3}$ sr	$\Delta\Omega = 2\times10^{-5}$ sr	$\Delta\Omega = 2\times10^{-6}$ sr
NFW	0.065	0.88	3.0
$r_\mathrm{s} = 1.3$ kpc			
$\rho_\mathrm{s} = 1.1\times10^{-2}\,\mathrm{M}_\odot\mathrm{pc}^{-3}$			
ISO	0.49	1.0	1.0
$r_\mathrm{c} = 0.34$ kpc			
$m_\mathrm{h} = 9.5\times10^{8}\,\mathrm{M}_\odot$			

Table 2:: Model parameters for the IMBH candidate in M54.

Parameter	Value
M_bh: black hole mass	$5\times10^{3}\mathrm{M}_\odot$
R_g: gravitational radius	7.38×10^{8}cm
$L_\mathrm{j}^{(\mathrm{kin})}$: jet kinetic power at z_0	6.28×10^{39}erg s^{-1}
q_j: ratio $2L_\mathrm{j}^{(\mathrm{kin})}/L_\mathrm{Edd}$	0.05
$\Gamma_\mathrm{b}(z_0)$: bulk Lorentz factor of the jet at z_0	4
θ: viewing angle	45°
ξ_j: jet's half-opening angle	5°
q_rel: jet's content of relativistic particles	0.05
a: hadron-to-lepton power ratio	1
z_0: jet's launching point	50 R_g
s: spectral index injection	2.1
η: acceleration efficiency	$1.\times10^{-2}$
N_H: column dust density	10^{21} cm^{-2}

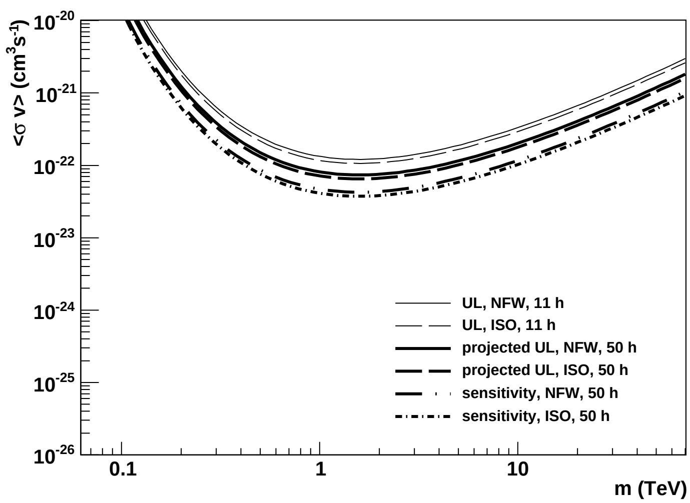

Fig. 1.—: 95% C.L. upper limits on the velocity-weighted annihilation cross section $\langle \sigma v \rangle$ versus the DM mass m for a NFW (solid line) and Isothermal (ISO) (dashed line) DM halo profiles respectively for 11 h observation time and $\Delta\Omega = 2 \times 10^{-5}$ sr. The projected upper limits are displayed for 50 h observation time. The sensitivities at 95% C.L. for 50 h are also shown for NFW (long-dashed dotted line) and ISO (dashed dotted line) DM halo profiles.

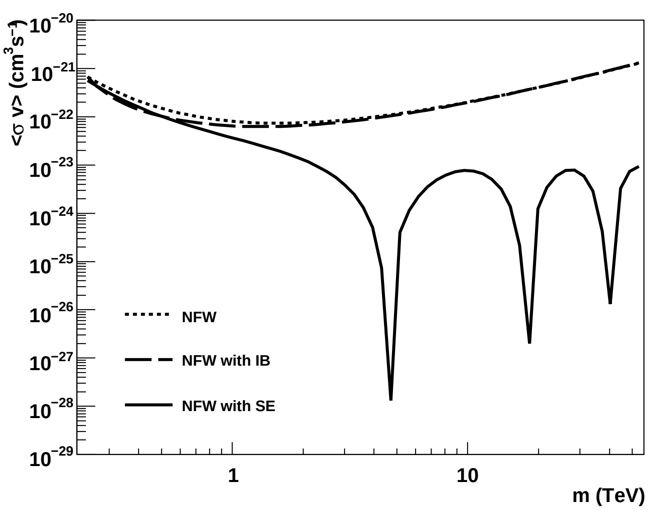

Fig. 2.—: Projected upper limits at 95% C.L. on the $\langle \sigma v \rangle$/S versus the DM mass m enhanced by the IB (dashed line) and SE (solid line) for the NFW profile. The projected upper limits are shown for 50 h observation times and $\Delta\Omega = 2 \times 10^{-5}$ sr.

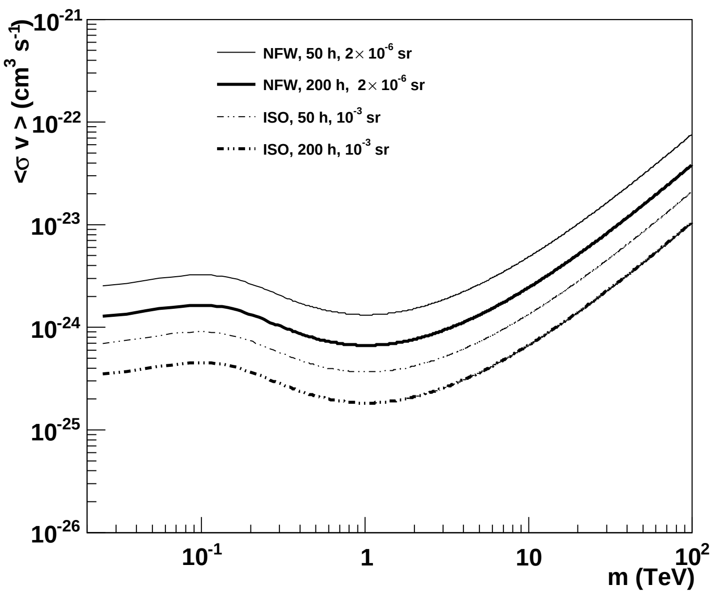

Fig. 3.—: Sensitivity at 95% C.L. for CTA on the velocity-weighted annihilation cross section $\langle \sigma v \rangle$ versus the DM mass m for a NFW (solid line) and Isothermal (ISO) (dashed line) DM halo profiles, respectively. The sensitivity is shown for 50 and 200 h observation times. The solid angle of observation is taken as $\Delta\Omega = 2 \times 10^{-6}\,\mathrm{sr}$ for the NFW DM halo profile and $\Delta\Omega = 10^{-3}\,\mathrm{sr}$ for the ISO DM halo profile.

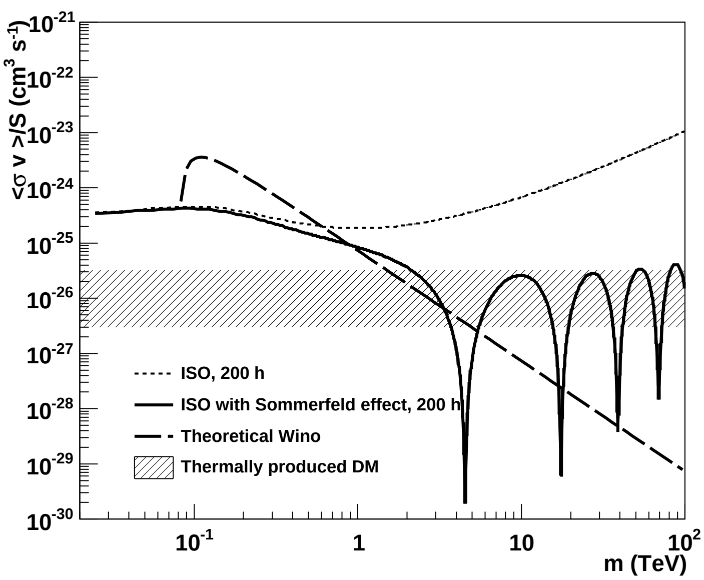

Fig. 4.—: Sensitivity at 95% C.L. for CTA on the $\langle \sigma v \rangle$/S versus the DM mass m enhanced by the SE for the ISO profile. The sensitivity is shown for 200 h observation times and $\Delta\Omega = 10^{-3}\,\mathrm{sr}$.

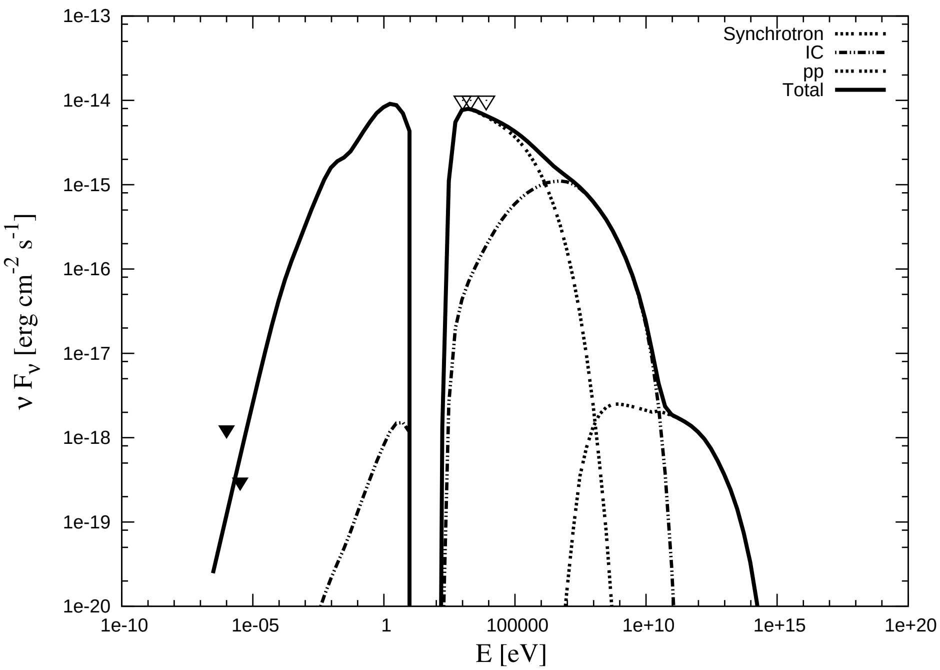

Fig. 5.—: Modeled emission of the candidate IMBH in M54. The inverted empty triangles show the X ray emission from source 2 of Ramsay and Wu (2006a; 2006b) and the inverted filled triangle show radio upper limits. The various contributions to the emission are shown. Only the *pp* emission contributes in the CTA energy range. The values of the parameters of the black hole model are displayed in Table 2.

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