Search for Dark Matter signatures with MAGIC-I and prospects for MAGIC Phase-II

S. Lombardi[*], **J. Aleksic**[†], **J.A. Barrio**[§], **A. Biland**[¶], **M. Doro**[*], **D. Elsaesser**[‖], **M. Gaug**[**], **K. Mannheim**[‖], **M. Mariotti**[*], **M. Martinez**[†], **D. Nieto**[§], **M. Persic**[††], **F. Prada**[‡‡], **J. Rico**[‡†], **M. Rissi**[¶], **M.A. Sanchez-Conde**[‡‡], **L.S. Stark**[¶] and **F. Zandanel**[‡‡] **on behalf of the MAGIC Collaboration**[x]

[*]*Università di Padova and INFN, I-35131 Padova, Italy*
[†]*IFAE, Edifici Cn., Campus UAB, E-08193 Bellaterra (Barcelona), Spain*
[‡]*ICREA, E-08010 Barcelona, Spain*
[§]*Universidad Complutense, E-28040 Madrid, Spain*
[¶]*ETH Zurich, CH-8093 Switzerland*
[‖]*Universität Würzburg, D-97074 Würzburg, Germany*
[**]*Inst. de Astrofísica de Canarias, E-38200 La Laguna, Tenerife, Spain*
[††]*Università di Udine, and INFN Trieste, I-33100 Udine, Italy*
[‡‡]*Inst. de Astrofísica de Andalucia (CSIC), E-18080 Granada, Spain*
[x]*See http://wwwmagic.mppmu.mpg.de/collaboration/members/*

Abstract. **In many Dark Matter (DM) scenarios, the annihilation of DM particles can produce gamma rays with a continuum spectrum that extends up to very high energies of the order of the electroweak symmetry breaking scale (246 GeV).**
Astrophysical structures supposed to be dynamically dominated by DM, such as dwarf Spheroidal Galaxies, Galaxy Clusters (the largest ones in the local Universe being mostly observable from the northern hemisphere) and Intermediate Mass Black Holes, can be considered as interesting targets to look for DM annihilation with Imaging Atmospheric Cherenkov Telescopes (IACTs). Instead, the center of our Galaxy seems to be strongly contaminated with astrophysical sources.
The 17m Major Atmospheric Gamma-ray Imaging Cherenkov (MAGIC-I) Telescope, situated in the Canary island of La Palma (2200 m a.s.l.), is best suited for DM searches, due to its unique combination of high sensitivity and low energy threshold among current IACTs which can potentially allow to provide clues on the high energy end, and possibly peak, of the gamma-ray DM induced spectrum constrained at lower energies with the FERMI Space Telescope. The recent results achieved by MAGIC-I for some of the best candidates, as well as the DM detection prospects for the MAGIC Phase II, are reported.
Keywords: **MAGIC, Dark Matter, Dwarf Galaxies**

I. INTRODUCTION

Nowadays there are compelling experimental evidences for a large non-baryonic component of the matter density of the Universe at all observed astrophysical scales, such as galaxies, galaxy clusters and cosmic background radiation [1]. The so-called Dark Matter (DM) makes its presence known through gravitational effects and it could be made of so far undetected relic particles from the Big Bang. In the Cold Dark Matter cosmological scenario (ΛCDM) about 80% of the matter of our Universe is believed to be constituted by cold, neutral, non-baryonic, weakly-interacting massive particles (WIMPs) [2]. Although plenty of experimental and theoretical efforts have taken place so far and despite recent exciting and controversial results which can be interpreted as possible DM detection [3] [4] [5], the nature of DM has not yet been clarified.

Among the huge plethora of cold DM candidates proposed in literature, the best motivated ones are related to the Super Symmetrical (SUSY) and Unified Extra Dimensional (UED) extensions of the Standard Model of particle physics (see [1] and references therein). In the widely studied Minimal Supersymmetric extension of the Standard Model (MSSM) the lightest neutralino ($\chi \equiv \chi_1^0$), a linear combination of the neutral superpartners of the W^3, B^0 and the neutral Higgs bosons (H_1^0, H_2^0), is the most studied candidate. If the neutralino is the lightest SUSY particle (LSP) and R-parity is conserved then it must be stable and it can represent an excellent cold DM candidate with a relic density compatible with the WMAP bounds and a mass at the GeV-TeV scale.

The most relevant neutralino interaction for the purposes of indirect DM searches is the self annihilation in fermion-antifermion pairs, gauge bosons pairs and final states containing Higgs bosons. The subsequent hadronization results in a gamma-ray power-law spectrum with a sharp cutoff at the neutralino mass (expected to be between 50 GeV and several TeV). A direct annihilation in gamma rays (such as $\chi\chi \rightarrow Z^0\gamma$ or $\gamma\gamma$) provides line emissions but those processes are loop-suppressed. WMAP relic density measurements provide an upper limit to the total neutralino cross section of the

order of $\langle \sigma v \rangle \sim 10^{-26}$ cm^3 s^{-1}, which implies that the neutralino is an extremely low interacting particle.

Recently it has been pointed out that the Internal Bremsstrahlung (IB) process may boost the gamma-ray yield of the neutralino self-annihilation at the higher energies by up to four orders of magnitude, even for neutralino masses considerably below the TeV scale [6]. This discovery represents a very important issue for the indirect DM search, particularly for the IACTs which are sensitive to the energy range most affected by the gamma-ray flux enhancement due to the IB process. Moreover, the IB introduces features in the gamma-ray spectrum that potentially allow an easier discrimination between a DM source and the standard astrophysical sources located in the vicinity, whose spectrum is usually a featureless power law.

The DM is believed to be structured as smooth halos with several clumps down to very small scales (the size of the Earth or less, depending on the models). Since the expected gamma ray flux from DM annihilation is proportional to the square of the DM density, any DM density enhancement, due to the presence of substructures (expected to be present in any DM halo [7]) and possibly to adiabatic compression of the DM in the innermost regions of the halos [8], can provide boost factors up to two orders of magnitude.

II. EXPECTED GAMMA-RAY FLUX FROM DM SELF-ANNIHILATION

The gamma-ray flux from DM particle self annihilations can be factorized into a contribution called the astrophysical factor $J(\Psi)$ and a contribution called the particle physics factor Φ^{PP}

$$\Phi(E > E_0) = J(\Psi) \cdot \Phi^{PP}(E > E_0), \qquad (1)$$

where E_0 is the energy threshold of the detector and Ψ is the angle under which the observation is performed. The astrophysical factor can be written as

$$J(\Psi_0) = \frac{1}{4\pi} \int_V d\Omega \int_{l.o.s.} d\lambda [\rho^2 * B_{\theta_r}(\theta)], \qquad (2)$$

where Ψ_0 denotes the direction of the target. The first integral is performed over the spatial extension of the source, the second one over the line-of-sight variable λ. The DM density ρ is convoluted with a Gaussian function $B_{\theta_r}(\theta)$ in order to consider the telescope angular resolution ($\sim 0.1°$), where $\theta = \Psi - \Psi_0$ is the angular distance with respect to the center of the object.

The particle physics factor can be expressed as a product of two terms. The first one depends only on the DM candidate mass and cross section, whereas the second term depends on the annihilation gamma-ray spectrum and must be integrated above the energy threshold E_0 of the telescope

$$\Phi^{PP}(> E_0) = \frac{\langle \sigma v_{\chi\chi} \rangle}{2m_\chi^2} \int_{E_0}^{m_\chi} S(E)dE, \qquad (3)$$

where $\langle \sigma v_{\chi\chi} \rangle$ is the total averaged thermal cross section times the relative velocity of the particles, m_χ is the DM particle mass, and $S(E)$ is the resulting gamma-ray annihilation spectrum.

The indirect search for DM is nowadays affected by large uncertainties in the flux prediction which put serious hindrances to the estimation of the observability: on the one hand, the astrophysical factor uncertainties can raise up to two orders of magnitude, on the other hand, the allowed parameter space for the mass and the annihilation cross section of the DM particle spans many orders of magnitude giving rise to flux estimations which can differ up to six orders of magnitude (or even more).

III. INTERESTING ASTROPHYSICAL OBJECTS FOR INDIRECT DM SEARCHES

Since the gamma-ray flux is proportional to the square of the DM density (see eq. 2), a relevant question concerning the indirect search for DM annihilation products is where to look for *hot DM spots* in the sky.

In the past, the Galactic Center (GC) was considered the best option. However, this is a very crowded region, which makes it difficult to discriminate between a possible gamma-ray signal due to DM annihilation and that from other astrophysical sources. WHIPPLE, CANGAROO and especially HESS and MAGIC-I [9] have already carried out detailed observations of the GC and all of them reported a point-like emission spatially close to Sgr A* location. Only very massive neutralino of the order of 10-20 TeV could explain the results, and, in addition, boost factors of 2-3 orders of magnitude are required to match the measured flux [10].

Very promising targets with high DM density in relative proximity to the Earth (less than 100 kpc) are the dwarf Spheroidal (dSph) satellite galaxies of the Milky Way. These galaxies are believed to be the smallest (size $\sim$ 1 kpc), faintest (luminosities 10^2–10^8 L$_\odot$) astronomical objects whose dynamics are dominated by DM, with a DM halo of the order of 10^5–10^9 M$_\odot$, very high mass–to–light ratios (up to $\sim 10^3$ M$_\odot$/L$_\odot$) [11] and no expected astrophysical gamma-ray sources located in the vicinity.

Clusters of galaxies are the largest and most massive gravitationally bound systems in the universe, with radii of the order of the Mpc and total masses around 10^{14}–10^{15} M$_\odot$. These systems are thought to host enormous amounts of DM, which should gravitationally cluster at their center and present numerous local substructures which could lead to a significant boost in the flux.

Another interesting DM target scenario is represented by the so-called intermediate mass black holes (IMBHs). The model described in ref. [12] shows that studying the evolution of super massive black holes, a number of IMBHs do not suffer major merging and interaction with barions along the evolution of the Universe. DM accretes on IMBH in adiabatic growth in a way that the final radial profile is spiky so that the IMBHs could be bright gamma-ray emitters. These targets could be related to the unidentified FERMI sources [13].

IV. THE IACT TECHNIQUE AND THE MAGIC TELESCOPES

When the primary VHE gamma rays reach the top of the Earth atmosphere, they produce positron-electron pairs which then emit energetic gamma rays via Bremmsstrahlung. The secondary gamma rays in turn emit positron-electron pairs giving rise to the so-called electromagnetic cascade where highly relativistic particles cause a flash ($\sim$ 3 ns) of UV-blue Cherenkov light which propagates in a cone with an opening angle of $\sim$ 1°. The resulting circle of projected light, at 2000 m a.s.l., has a radius of about 130 m. The light is collected by a reflective surface and focused onto a multipixel camera which records the shape of the image produced by the shower which has an elliptical shape pointing to the center of the camera. Since Cherenkov light is emitted also by charged particles produced in atmospheric showers induced by charged isotropic cosmic rays, an image reconstruction algorithm [14] is used in order to recover the energy and the direction of the primary particle and to determine whether it was more likely a hadron or a photon, allowing the rejection of more than 99% of the background.

Among all the IACTs, the MAGIC-I Telescope, located on the canary island of La Palma (28.8°N, 17.9°W, 2200 m a.s.l.), is the largest single dish facility in operation (see [15] for detailed descriptions). The 17m diameter tessellated reflector of the telescope consists of 964 0.5×0.5 m^2 diamond-milled aluminium mirrors, mounted on a light weight frame of carbon fiber reinforced plastic tubes. The MAGIC-I camera has a field-of-view of 3.5° and consists of 576 enhanced quantum efficiency photomultipliers (PMTs). The analog signals recorded by the PMTs are transported via optical fibers to the trigger electronics and are read out by a 2GSamples/s FADC system. The collection area reaches a maximum value of the order of 10^5 m^2 and the trigger energy threshold is about 60 GeV for gamma rays at zenith angles (ZA) below 30°.

A second 17m diameter telescope (MAGIC-II) is currently in opening operation phase. The stereoscopic observation of the sky will bring a significant improvement of the shower reconstruction (especially for the incoming direction) and of the background rejection and consequently a better angular ($\sim$ 20%) and energy ($\sim$ 40%) resolutions, a lower energy threshold ($\sim$ 30%) and a $\sim$2–3 times higher sensitivity (see [16] and [17] and references therein for more details).

V. MAGIC-I OBSERVATIONS FOR DM SEARCHES AND PROSPECTS FOR MAGIC PHASE II

Besides the GC [9], MAGIC-I has observed two of the most promising DM targets: the dSph Draco [18] and the ultra faint dSph Willman 1 [19]. Both these objects, together with other very interesting sources, as
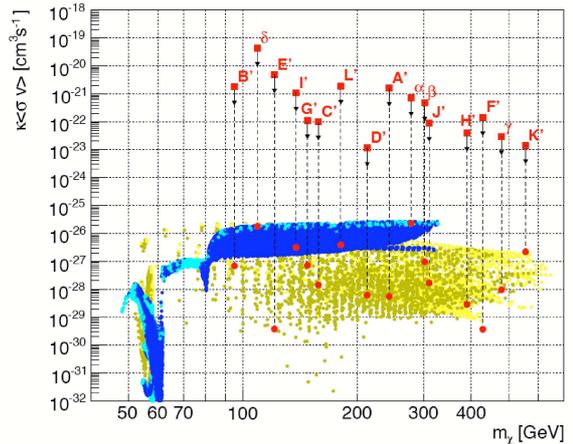

Fig. 1. Draco observation: thermally averaged neutralino annihilation cross section as a function of the neutralino mass for the chosen mSUGRA models [23] after renormalization to the relic density. The red boxes indicate the experimental flux upper limits, displayed in units of $\langle \sigma v \rangle$, assuming a smooth Draco halo as suggested in [24].

Segue 1 [20][1] and the large clusters of galaxies Perseus and Coma, are well observable from the MAGIC site at low ZA which assure the lowest reachable energy threshold.

A. Draco observation

Draco is a dSph galaxy accompanying the Milky Way at a galactocentric distance of about 82 kpc. From a kinematical analysis of a sample of 200 stellar line–of–sight velocities it was possible to infer the DM profile: the result of the fit, assuming a Navarro-Frenk-White (NFW) smooth profile [21], indicates a virial mass of the order of 10^9 M$_\odot$, with a corresponding mass–to–light ratio of M/L$\sim$ 200 M$_\odot$/L$_\odot$ [22]. With 7.8 hours of observation performed in 2007 a 2σ upper flux limit on steady emission of 1.1×10^{-11} photons cm^{-2} sec^{-1} was found, under the assumption of a generic annihilation spectrum without cutoff and a spectral index of -1.5 for photon energies above 140 GeV. For different mSUGRA model parameters using the benchmark points defined by Battaglia et al. [23] and for other models, the gamma-ray spectrum expected from neutralino annihilations was computed. Assuming these underlying spectra and a smooth DM density profile as suggested in [24], the upper limits on the integrated flux above 140 GeV were calculated and compared to the experimental ones. As can be seen from fig. 1, while the results do not constrain the considered mSUGRA phase–parameter space, a very high flux enhancement could be ruled out ($O(10^3 - 10^9)$).

B. Willman 1 observation

Willman 1 dSph galaxy is located at a distance of 38 kpc in the Ursa Major constellation. It represents one of the least massive satellite galaxies known to date

---

[1]The ultra faint dSph Segue 1 has been observed by MAGIC-I during the beginning of 2009. The data analysis is ongoing.

BM	$m_{1/2}$ [GeV]	m_0 [GeV]	$\tan\beta$	A_0	$sign(\mu)$	m_χ [GeV]	$\langle\sigma v_{\chi\chi}\rangle$ [cm^3/s]	$\Phi^{PP}(>100)$ [cm^3 GeV^{-2} s^{-1}]
I'	350	181	35	0	+	141	3.62×10^{-27}	7.55×10^{-34}
J'	750	299	35	0	+	316	3.19×10^{-28}	1.23×10^{-34}
K'	1300	1001	46	0	−	565	2.59×10^{-26}	6.33×10^{-33}
F^*	7792	22100	24.1	17.7	+	1926	2.57×10^{-27}	5.98×10^{-34}

TABLE I

WILLMAN 1 OBSERVATION: DEFINITION OF BENCHMARK MODELS AS IN BRINGMANN ET AL. [26] AND COMPUTATION OF THE PARTICLE PHYSICS FACTOR Φ^{PP} ABOVE 100 GEV.

BM	Φ^{model}	$\Phi^{u.l.}$	$B^{u.l.}$
I'	2.64×10^{-16}	9.87×10^{-12}	3.7×10^4
J'	4.29×10^{-17}	5.69×10^{-12}	1.3×10^5
K'	2.32×10^{-15}	6.83×10^{-12}	2.9×10^3
F^*	2.09×10^{-16}	7.13×10^{-12}	3.4×10^4

TABLE II

WILLMAN 1 OBSERVATION: COMPARISON OF ESTIMATED INTEGRAL FLUX ABOVE 100 GEV FOR THE CHOSEN BENCHMARK MODELS AND THE UPPER LIMIT IN THE INTEGRAL FLUX $\Phi^{u.l.}$ ABOVE 100 GEV COMING FROM MAGIC-I DATA IN UNITS OF PHOTONS CM^{-2} S^{-1}. ON THE RIGHTMOST COLUMN, THE CORRESPONDING UPPER LIMIT ON THE BOOST FACTOR $B^{u.l.}$ REQUIRED TO MATCH THE TWO FLUXES IS CALCULATED.

(M$\sim 5\times10^5$ M$_\odot$) with a very high mass–to–light ratio, M/L$\sim 500-700$ M$_\odot$/L$_\odot$, making it one of the most DM dominated objects in the Universe. Following ref. [25], its DM halo was parametrized with a NFW profile. The observation of Willman 1 took place in 2008 for a total amount of 15.5 hours. No significant gamma-ray emission was found above 100 GeV, corresponding to 2σ upper flux limits on steady emission of the order of 10^{-12} photons cm^{-2} sec^{-1}, taking into account a subset of four slightly modified Battaglia mSUGRA benchmark models, as defined by Bringmann et al. [26] (see table I). These benchmark models represent each a different interesting region of the mSUGRA parameter space, namely the *bulk* (I'), the *coannihilation* (J'), the *funnel* (K') and the *focus* (F^*) point regions, and they include for the first time the contribution of IB process in the computation of the cross sections and spectra.

A comparison with the measured flux upper limit and the fluxes predicted assuming the underlying mSUGRA benchmark spectra and the chosen Willman 1 density profile was computed. The results are summarized in table II. Although the boost factor upper limits seem to show that a DM detection could still be far (the most promising scenario, K', being three orders of magnitude below the sensitivity of the telescope), it is important to keep in mind the large uncertainties in the DM profile and particle physics modeling that may play a crucial role in detectability. In particular the possible presence of substructures in the dwarf, which is theoretically well motivated, may increase the astrophysical factor and therefore the flux of more than one order of magnitude. Furthermore, since the parameter space was not fully scanned, it is likely that there are models of neutralino with higher Φ^{PP}.

C. Prospects for MAGIC Phase II

The use of a more advanced detector like MAGIC Telescopes, already in opening operation phase, with a much increased combination of energy threshold, energy resolution and flux sensitivity [17], could favour possible scenarios of DM detection or at least the exclusion of parts of the mSUGRA parameter space. Nonetheless, while all other current IACTs can only cover SUSY models with a large IB contribution due to their higher energy threshold, MAGIC Telescopes will explore a much larger region of DM annihilation models where the peak of the emission is at lower energy.

Indeed, it has been shown by Bringmann et al. [26] that in case of the observation of Draco and Willman 1, MAGIC Telescopes performances, and in particular those of CTA (Cherenkov Telescope Array, a new generation IACT currently in the design phase [27]), are very close to allow the constraint of some points of the mSUGRA parameter space, with the lowest predicted boost upper limits of the order of ~ 10. These results are of course strengthened once all the already mentioned uncertainties for the gamma-ray DM annihilation flux are taken into account.

REFERENCES

[1] G. Bertone et al., *Phys. Rept.*, 405:279-390, 2005.
[2] E. Komatsu et al., *Astrophys. J. Suppl.*, 180:330-376, 2009.
[3] R. Bernabei et al., *Eur. Phys. J.*, C56:333-355, 2008.
[4] O. Adriani et al., *Nature*, 458:607-609, 2009.
[5] J. Chang et al., *Nature*, 456:362-365, 2008.
[6] T. Bringmann et al., *JHEP*, 01:049, 2008.
[7] M. Kuhlen et al., arXiv:astro-ph/0805.4416.
[8] F. Prada et al., *Phys. Rev. Lett.*, 93:241301, 2004.
[9] J. Albert et al., *Astrophys. J.*, 638:L101-L104, 2006.
[10] F. Aharonian et al., *Phys. Rev. Lett.*, 97:221102, 2006.
[11] G. Gilmore et al., *Astrophys. J.*, 663:948-959, 2007.
[12] G. Bertone, *Phys. Rev.*, D72:103517, 2005.
[13] A.A. Abdo et al., arXiv:astro-ph/0902.1340.
[14] A.M. Hillas, *Proc. of the 19th ICRC*, p445, 1985.
[15] C. Baixeras et al., *Nucl. Instrum. Meth.*, A518:188192, 2004.
[16] J. Cortina et al., "Technical Performance of the MAGIC Telescopes", *these proceedings*.
[17] P. Colin et al., "Performance of the MAGIC telescopes in stereoscopic mode", *these proceedings*.
[18] J. Albert et al., *Astrophys. J.*, 679:428-431, 2008.
[19] J. Albert et al., arXiv:astro-ph/0810.3561.
[20] M. Geha et al., arXiv:astro-ph/0809.2781.
[21] J.F. Navarro et al., *Astrophys. J.*, 490:493-508, 1997.
[22] M.G. Walker et al., arXiv:astro-ph/0708.0010.
[23] M. Battaglia et al., *Eur. Phys. J.*, C33:273-296, 2004.
[24] M.A. Sanchez-Conde et al., *Phys. Rev.*, D76:123509, 2007.
[25] L.E. Strigari et al., *Astrophys. J.*, 678:614-620, 2008.
[26] T. Bringmann et al., *JCAP*, 01, 016, 2009.
[27] *http://www.mpi-hd.mpg.de/hfm/CTA/*.