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A review of the past and present MAGIC dark matter search program and a glimpse at the future

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The MAGIC TeV gamma-ray telescopes have devoted several hundreds hour of observation time in about a decade, to hunt for particle dark matter indirect signatures in gamma rays, from various candidate targets of interest in the sky: the galactic center, satellite galaxies, galaxy clusters and unidentified objects in other bands. Despite the effort, no hints are present in MAGIC data. These observations are nevertheless not unusable. MAGIC indeed derived the most robust upper limits in the TeV range than any other instrument. These results, for the time being, only mildly constrain some classic dark matter models, but are of use in the construction of dark matter models for the next searches, that consider also the negative results from accelerator and direct-detection experiments.

In the contribution, we discuss and review MAGIC results, putting them into context, and in perspective with the next generation of ground-based Cherenkov telescopes. We will briefly inform about future MAGIC projects regarding dark matter searches.

I. INTRODUCTION

The understanding of the nature of Dark Matter (DM), either as a new particle [1] or as a modification of the gravitational law [2], is keeping hundreds of scientists and instruments occupied in hunting for significant signatures, especially in the past two decades. The need of DM appears from several observations, all connected to gravitational effects, at all cosmological scales: from the galactic motion of stars, to that of galaxies in clusters, and farther away into the signatures in acoustic oscillations in the cosmic microwave background [3]. It is very hard to disprove such strong hints of gravitational imbalances, as well as it is easier to explain those with the introduction of one (or more) new particle(s), to be the candidate for DM. This new particle should be either stable, or very long lived, to guarantee the relic density we see today $\Omega_{DM} = 0.259 \pm 0.006$ [3]. This one parameter, allows anyhow for a very large parameter space in terms of DM particle mass and annihilation or decay rates. However, the current paradigm focuses on a “cold” DM scenario, in which the particle has been non relativistic since its decoupling. The velocity of DM particles determines their free-streaming length, and thus strongly affect the cosmic structures formation, at least in the current preferred bottom-up scenario of merging of smaller structures into larger ones. The best CDM candidate is a particle that does not have any standard interaction, and is a WIMP (Weakly Interacting Massive Particles). The WIMP may live in a dark sector (no interaction with the standard model particles), which would make the detection prospects difficult, or have some channels to the standard models, like in the case of Super-symmetrical extensions of the standard models (SUSY), or Unified Extra Dimensions theories. The non-observation of such particle at LHC, albeit with maximum luminosity, has pushed the searches to a mass range of several tens or

hundreds of GeV for the mass of the particle [4].

In this energy range, ground based Imaging Atmospheric Cherenkov Telescope Arrays (IACTAs), observing the Cherenkov light produced in Extended Atmospheric Showers (EAS) generated in the stratosphere by cosmic gamma rays, are an optimal instrument to search for WIMPs, for the following reasons: *a)* in many scenarios, WIMPs produce a strong gamma-ray yield in the annihilation or decay products, *b)* the neutrality of photons guarantee that telescopes can be pointed to astronomical places where DM is expected, *c)* annihilation or decay spectrum would be universal, and therefore multiple observations of such spectra from multiple sources would provide a strong claim, and finally *d)* the annihilation or decay spectra often show like a cutoff connected to the DM mass, and sometimes peculiar bumps that could disentangle its origin from a standard astrophysical one.

The Major Atmospheric Gamma-ray Imaging Cherenkov (MAGIC) instrument of the IACTA class, is a pair of 17-m diameter parabolic dishes, operating since 2009 at the Observatorio Roque de Los Muchachos (ORM, La Palma, Canary Islands, Spain) at 2,200 m. a.s.l, in the Northern Hemisphere¹. MAGIC operates between few tens of GeV and several tens of TeV, with a peak sensitivity of 0.66% of the Crab Nebula flux above 280 GeV, an energy resolution of 10 – 20% and an angular resolution below 0.1° [5]. MAGIC observes during night time, with about 1,500 h of available time per year (1,000 h with moonless night). MAGIC, as well as other IACTA in the field, is a wide-scope detector, focused mainly on galactic and extragalactic astrophysics with gamma rays, but with good potential also as particle detec-

¹ MAGIC started its operations in 2004 as a single telescope.

tors (electron/positron, proton/antiproton, and perhaps neutrino) and exotic physics detectors (see [6] for a recent review). MAGIC has devoted a significant fraction of its observation time, reaching now several hundreds of hours, to DM-related searches at several candidate targets. These include the Milky Way (MW) barycenter region, dwarf satellite galaxies (DSGs) orbiting in the MW DM halo, unidentified Fermi-LAT objects, galaxy clusters, and others (see also [7] for a recent collection of DM searches from IACTA in the past decade). In these 10 years, the preferred targets, campaigns duration and data reconstruction have changed. In this contribution, we put the MAGIC search into context, showing the evolution of this science field, and concluding with some remarks on the possible future extension of the MAGIC DM program and the validity of its contribution in the field.

The gamma-ray flux from DM annihilation or decay at Earth can be factorized as a product of a particle-physics factor depending on the nature of the DM, and an astrophysical factor, depending on the target distance and DM distribution, and reads as:

$$\Phi^\gamma = \frac{\hat{P} N^\gamma}{4\pi k m^k} \cdot \iint_{\Omega, los} \rho^k ds d\omega \quad (1)$$

$$\text{Annihilating DM : } \hat{P} = \langle \sigma v \rangle; \quad k = 2;$$

$$\text{Decaying DM : } \hat{P} = \tau^{-1}; \quad k = 1;$$

where $\langle \sigma v \rangle$ is the velocity average DM annihilation rate and τ is DM particle lifetime, N^γ is the number of photons promptly produced during an annihilation or decay event, and the integrals in the astrophysical factor run over the angular extension of the searched region Ω , and along the line of sight. The term ρ represents the DM density.

II. EARLY SEARCHES

Before the launch of the Fermi-LAT gamma-ray satellite-borne instrument (at the time called GLAST), back in 2004, there were great expectations about both ground-based and satellite-borne gamma-ray instruments to detect gamma rays from DM annihilation in a reasonable observation time, at least in some optimistic scenarios (see, e.g., [8]). Table I reports the full list of MAGIC DM targets from the time of this early estimation until present times. Observations are ordered by telescopes setup, and year and the table provides information about the source class, the observation time, whether results were discussed in terms of annihilating or decaying DM scenarios, as well as links to references. However, it is not straightforward to draw conclusions based only on the observation time devoted to specific targets in the table. This is due to the fact that MAGIC performance

evolved significantly with time. MAGIC started its operations in 2004 as single telescope, and was coupled with a second telescope only in 2009. Both the first and second MAGIC telescopes had undergone major upgrades along the years, that have substantially changed their performance: from the first single-telescope setup, to the current, MAGIC has improved its sensitivity by a factor of 4 (meaning a factor of 16 less time required) at 300 GeV, and a factor of 10 at 50 GeV. In the following, we discuss the early searches by target class.

Dwarf Satellite Galaxies (DSGs) are small galaxies with a common mass scale [9] commonly believed to be originated in DM overdensities present in the MW DM halo. DSGs have a small stellar content, and especially are almost depleted of gas, showing no or little stellar activity in the past Gy. Their star velocity distribution normally hints to large DM content, with mass-to-light ratio of $1000 M_\odot/L_\odot$ or even more, depending on the target object. They are optimal DM targets because of no expected astrophysical radiation and short distance. As such, DSGs have been dominating the MAGIC DM observation program since the beginning. One can easily see that the first MAGIC DM observations, with the single-telescope, were devoted mostly to short (less than 30h) observation of DSGs: Draco, Willman 1 and Segue 1. Draco was considered one of the best candidate at that time, because of its large mass-to-light ratio, and precise estimation of the stellar motion thanks to a sample of thousands of star members. It was observed for about 8h. In 2007, the Sloan Digital Sky Survey started to produce high-precision photometric data on a newly discovered class of DSG, the so-called “ultra-faint”, due to the fact that the number of member stars were a factor of 10 less than the previously discovered “classical” DSG (including Draco). Two ultra-faint targets were observed: Willman 1 and Segue 1. The latter is an ultra-faint DSG, largely debated in the literature. It currently comprises about 70 member stars. The result of the J-factor estimation based on Jeans analysis goes from ranking Segue 1 as the best candidate [24] to an unreliable candidate [25]. MAGIC is recently computing the J-factors using the public CLUMPY code [26] and the conclusions is that Segue 1 is still one of the candidate with the largest J-factor. MAGIC devoted again a limited observation time to these two targets: about 16h for Willman 1 and about 30h for the Segue 1. As a result, we put upper limits at a level of $\langle \sigma v \rangle = 10^{-22} \text{cm}^3 \text{s}^{-1}$. The collection of some of the discussed MAGIC upper limits is shown in Fig. 1.

Luminous structures like star or gas clouds are believed to form by gravitational contraction onto primordial DM overdensities. In this sense, “light traces matter”, however, several cases were discussed where DM overdensities could be almost completely dark at all wavelengths but in gamma-rays, due to negli-

MAGIC	Class	Target	Year	Obs. Time	Ann. Decay		Ref.	Comments
Mono	MW	Galactic Center	2006/07	25	-	-	[33]	
	DSG	Draco	2007	7.8	X	-	[19]	
		Willman 1	2008	15.5	X	-	[20]	
		Segue 1	2008/09	29.4	X	-	[21]	
	Unid	3EG1835	2007	25	X	-	[11]	
	GC	Perseus	2008	24.4	-	-	[15]	
	CR	All-electrons	2009/10	14	-	-	[17]	
Stereo	Unid	Many	2009/12	71.3	F	-	[31]	Paper in prep.
	DSG	Segue 1	2010/13	158	X	X	[34]	
	GC	Perseus	2009/14	253	F	F	[30]	Paper in prep.
	CR	All-electrons	2012/14	40	-	-	[18]	
		Positrons			F	-	[22]	Paper in prep.
	MW	Galactic Center	2012/16	67	F	F	[32]	Paper in prep.

TABLE I. Compound of observational targets for indirect dark matter searches with MAGIC. Observations are grouped in two blocks for MAGIC results when in single-telescope (mono) configuration and as telescope-pair (stereo). Classes are: MW (Milky Way), DSG (Dwarf Satellite Galaxy), Unid (Unidentified HE source), GC (Galaxy Cluster), CR (Cosmic Ray). The observation time is given in hours. For the DM models, “X” means the reference provides constraints on that model, “-” that the reference does not discuss that model, “F” means that constraints about that model are foreseen.

gible stellar activity. This was the case that motivated our search for Intermediate Mass Black Holes (IMBHs), following [10]. It was at the time believed that IMBHs in the range $10^2 - 10^6 M_\odot$ could have formed at the place of DM overdensities and have increased the DM concentration (and hence the annihilation rate) due to the gravitational pull not strongly affected by the possible diluting effect of stellar activity. Such objects, yet undiscovered, could have been bright in gamma-rays and dark in other wavelengths. Possible candidates were the (back then) unidentified EGRET sources (EGRET is a precursor of Fermi-LAT). The source 3EG1835 was, at that time, the brightest of the unidentified EGRET sources. Unfortunately, the MAGIC data taken on that target were affected by telescope technical problem that prevented a journal publication. The results were discussed in conference [11].

Moving to non-galactic targets, galaxy clusters are expected to host enormous amount of DM. Considering that 80% of the total mass content of the Universe is in the form of DM, and considering the total mass of a galaxy clusters, for example the Perseus cluster may host something like $10^{14-15} M_\odot$ in DM. Answering the question whether galaxy clusters are optimal target for DM searches is not trivial, because there are many processes at work. On one side, that huge DM content may hint to large concentrations at the barycenter, however, the same central region maybe affected by strong outward winds of baryonic matter due to standard astrophysical activity (GRBs, supernova, etc) which may counteract the gravitational pressure and reduce the central DM content. On the other side, in the case of annihilating DM, the contribution of the DM substructures could be extremely high, with authors claiming a factor of 10 to 1000 higher flux with respect to the “smooth-halo” case [12–14]. All

in all, robust predictions in this case are very hard to achieve. Less problematic is the case of the decaying DM in galaxy clusters, because of the linear dependence on the DM density (see Eq. 1). MAGIC preliminary results in single-telescope were presented in [15]. In terms of annihilating DM, the constraints were weak. In Sec. III, we will update this consideration with the very-large Perseus campaigns performed with the stereoscopic MAGIC.

MAGIC is also an instrument capable of measuring cosmic ray particles [6]. Cosmic electrons, constituting a few percents of the total cosmic ray flux arriving at the Earth, initiate EAS totally similar to gamma-ray induced ones. The trick to separate them is to consider only sky regions where no gamma-rays are detected, and consider as control background that obtained with MC simulations. Clearly the analysis is complex because of: *a)* of the very precise control of the MC-instrument matching required, and *b)* of the fact that e-induced showers have an isotropic origin, and images are more complex to reconstruct. The interest stems from the fact that an excess in the positron spectrum was detected and confirmed in the past years by several instruments [16, and references therein]. This discrepancy can be explained by standard astrophysical mechanisms like the emission from local pulsar(s), or by secondary electrons produced in DM decay or annihilation products. MAGIC can contribute significantly in an energy range hardly at reach of satellite instruments such as AMS-II or Fermi-LAT. MAGIC reported some preliminary results at conferences [17]. The follow-up study was performed in stereoscopic mode, however, our data are strongly dominated by systematic uncertainties, which make the all-electron spectrum only moderately informative [18].

III. RECENT RESULTS

Figure 1 show the collection of some DM related MAGIC results and their evolution. With the advent of the second telescope, the strategy to hunt DM with MAGIC improved because:

1. As mentioned in Sec. II, besides the obvious improvement from mono to stereo, the performance of the instrument received a strong boost along the years by instrumental upgrades;
2. It was clear that substantial effort in observation time should be devoted in order to gain interesting results. From Table I one can see that hundreds of hours were devoted to some targets;
3. The data reconstruction and analysis was optimized in several ways: *a)* using a full likelihood approach that takes into account the DM spectral features, the instrument response function, the uncertainties in the background and the J-factor model, all resulting in a performance boost of a factor of 2 as well as preciser results [23], *b)* enlarging the search region to a larger range of DM masses, *c)* providing model-independent results for pure annihilation/decay channels instead of benchmarks models (that were based on LHC searches and lost importance as long as LHC was ruling them out)

As a result, the MAGIC exclusion curves have grown substantially better. MAGIC devoted 160 h to the best DSG candidate (at that time): Segue 1. The Segue 1 stereo paper [34] provided the absolute strongest upper limits from DSG for DM particles above few hundreds GeV (at lower DM masses, the results from Fermi-LAT are the most constraining). These MAGIC results made into the PDG's Review of Particle Physics [27]. In addition, MAGIC data were used for the first time in combination with Fermi-LAT data to provide stronger constraints [28]. It is important to stress that any further DSG observed with either Fermi-LAT or MAGIC can be simply combined with previous observations thus resulting in a global evolution toward stronger limits.

With the successful multi-year campaign on the Perseus Galaxy Cluster, originally motivated also by cosmic ray astrophysics, MAGIC collected a total of more than 250 h. These allowed to provide very strong constrain on the Perseus core dynamics, and thermal-to-nonthermal radiation balance [29]. The DM expectations in Perseus were computed by several authors [12–14] and disagree of a factor of 100 one another due to different computation of the additional boost due to substructures of the DM halo, as discussed in Sec. II. For MAGIC, computing limits from Perseus is hindered by the presence of a bright source at the center, the radio galaxy NGC1275, and therefore an optimized analysis was performed. The annihilating DM case can be constrained less effectively

than with DSG, however, for the decaying DM case, Perseus is expected to deliver the strongest lower limits in decay lifetime for DM particles above few hundreds GeV [30]. The full paper is in preparation.

The Galactic Center was observed by MAGIC-mono for 25 h in 2006 [33], however, the paper focused only on the astrophysical interpretation. A larger campaign was made with MAGIC-stereo in year 2012–16 [32]. The GC is observable only at large zenith angles from MAGIC. This has a double effect of largely increasing the energy threshold (because of stronger extinction of the Cherenkov light in the atmosphere), but at the same time increasing the effective area at high energies (due to a larger footprint of Cherenkov photons at the ground). More than 70 h were collected. The GC presents difficulties connected to the presence of one or more bright and extended astrophysical targets at its center, as well as diffuse gamma-ray emission. For this reason, we expect MAGIC results to be competitive. The DM related paper is under preparation.

Furthermore, about 50 h were devoted to the search of unidentified HE targets, as described in Sec. II. This time, the Fermi-LAT all-sky catalogs were searched for stable, unassociated sources off the galactic plane, optimal candidates to be DM overdensities. Results were shown in conferences [31]. No detection was found. The paper is in preparation too.

IV. DISCUSSION AND OUTLOOK

The previous two sections have shown that MAGIC devoted a substantial effort toward DM searches, which has increase from first “snapshot” observation to long-term observation campaigns. The capability of extracting robust and optimized results has also increased, specially by using a tailored full likelihood method as well as combining results with other instruments. However, Fig. 1 shows that MAGIC upper limits are still some two orders of magnitude above the thermal relic annihilation rate.

One could wonder whether we are too far from detection. The opinion of the author is that the plot does not bear this information, due to the following reasons: *a)* there are several mechanisms for which a DM particle satisfying all known constraints (e.g. the Sommerfeld effect, which is expected because DM is cold) can have $\langle\sigma v\rangle$ larger than the thermal value, *b)* the presence of more than one DM particle would translate into a higher relic annihilation rate that what computed considering only 1 thermal relic, *c)* MAGIC and the other IACTA are the most sensitive instruments at a TeV DM mass range, with no other competitors in the field, and as such, regardless of the true nature of DM (to be discovered!), these results constitute long-lasting unique information, *d)* even null results from present and future direct detec-

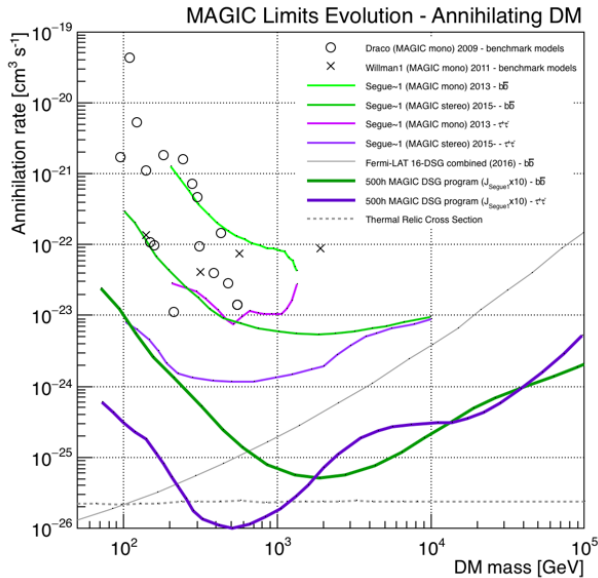


FIG. 1. Collection of upper limits obtained with MAGIC. With Draco and Willman1 we used benchmark models. For Segue 1 we report results in the case of annihilating DM for the $b\bar{b}$ and $\tau^+\tau^-$ channels in case of MAGIC-mono, MAGIC-stereo and an extrapolation of MAGIC performance for a target 10 times brighter than Segue 1 observed for 500 h. Additional Fermi-LAT [45] exclusion curve and the thermal relic cross-section [46] are shown. Further details and discussion are given in the text.

tion or accelerator experiments for DM, there is always a portion of the parameter space only accessible to TeV instruments [35] e) Fig. 1 also plots an estimation of what exclusion curve MAGIC could provide if observing a DSG for 500 h (this can be done over

several years) with an astrophysical factor 10 times larger than of Segue 1 (as in Ref. [28])². These curves would be then very close to the thermal annihilation rate curve, even crossing it in the hard $\tau^+\tau^-$ annihilation channel. Considering that such a target may exist, this is definitely a motivating point for MAGIC to maintain this effort.

Consequently, MAGIC will continue pursuing DM searches. The most promising targets remain the DSGs, because of their clean environment, and strong expected signal, which - if detected - would constitute a clear detection compared to targets with strong astrophysical background. This is also justified by the fact that many new DSGs have been discovered in the recent times [36–43], and more are expected in future campaigns. Some of these are also modeled with extremely large DM content (expected from simulations, see Fig.3 of [44]). All future MAGIC DSGs observation could be combined together as done in [28].

V. CONCLUSIONS

In this contribution, we have shown the evolution of MAGIC results for dark matter searches at different target of interests. The dedication of hundreds of hours allowed MAGIC to place the most robust upper limits above few hundreds GeV on annihilating dark matter particle models through the observation of highly dark matter dominated satellite galaxies. The long campaign on Perseus will allow to put similar strong constraints on the lifetime of decaying dark matter. MAGIC continues its dark matter program in order to provide legacy results before the times of CTA.

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² The reader should be warned that this is a simple rescaling of the Ref. [28] curve, which refers to a specific dataset (with its fluctuations) and does not make a full computation using the expected sensitivity, for simplicity. The order of magnitude of the result is still valid.

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