Constraining branon dark matter from observations of the Segue 1 dwarf spheroidal galaxy with the MAGIC telescopes

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Abstract. We present the first search for signatures of brane-world extra-dimensional dark matter (DM) in the very-high-energy gamma-ray band by scrutinizing observations of the dwarf spheroidal galaxy Segue 1 with the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescope system. Branons are new degrees of freedom that appear within flexible brane-world models: they are weakly interacting massive particles and natural DM candidates. The ground-based gamma-ray telescopes MAGIC could indirectly detect branon DM in the multi-TeV mass range by observing secondary products of DM annihilation into Standard Model particles. In the absence of a signal, we place constraints on the branon DM parameter space by using a binned likelihood analysis of almost 160-hours deep exposure on the Segue 1 dwarf spheroidal galaxy by the MAGIC telescopes. Our most stringent limit to the thermally-averaged annihilation cross-section (at 95% confidence level) corresponds to $\langle \sigma v \rangle \simeq 1.4 \times 10^{-23}$ cm$^3$s$^{-1}$ at a branon mass of $\sim 0.7$ TeV.
1 Introduction

Astrophysical and cosmological evidences suggest that non-baryonic cold DM constitutes 84\% of the matter density of the Universe [1]. Nonetheless, the nature of DM is still an open question for modern physics. In the particle DM paradigm, this elusive kind of matter cannot be made of any of the Standard Model (SM) particles. Many efforts have been made in order to determine the nature of the DM, and many candidates have been proposed so far emerging from diverse theories [2].

Among others, brane-world theory has been put forward as a prospective framework for DM candidates [3]. In this theory, the characteristics of the suggested massive brane fluctuations (branons) match the ones of weakly interacting massive particles (WIMPs), which are a well-motivated and widely considered class of cold DM candidates [4]. WIMPs presenting interaction cross-sections typical of the weak scale would naturally provide the required DM relic density (the so-called WIMP miracle, see e.g. [5]).

Interacting branons may annihilate into SM particles, consequently rendering them susceptible to be detected. The products of branon annihilation may in turn produce photons e.g. via quark hadronization or final state radiation from charged particles, opening the door to detecting branon annihilation signatures by observing astrophysical regions presenting large DM densities. Given the TeV-mass scale (\sim 10\, GeV up to \sim 100\, TeV) of WIMPs, the MAGIC telescopes, sensitive to very-high energy (VHE, \gtrsim 50\, GeV) gamma-rays, are an excellent tool to probe branon DM in the multi-TeV mass range.

One of the most promising targets for indirect DM searches are dwarf spheroidal galaxies (dSphs). The dSph satellites, orbiting the Milky Way, are usually less than a few hundred kpc away and have high mass-to-light ratios. In general, these nearby galaxies are less extended, have better determined DM content, and contain less astrophysical background than other DM sources, like the Galactic Center (GC) and galaxy clusters (see, e.g., [6, 7]). In this work, we are focusing on the dSph galaxy Segue 1.

This article is structured as follows: Section 2 succinctly introduces the main features of the brane-world theory and the expected photon flux from branon DM annihilation; the observational campaign on Segue 1 by the MAGIC telescopes is presented in Section 3 as...
well as the adopted analysis methodology. In Section 4, we present the first upper limits to the annihilation cross section of branon DM particles using very-high-energy gamma-ray observations. We then discuss our results and finally present our conclusions in Section 5.

2 Branon dark matter

2.1 Brane-world theory

The framework of extra-dimensional models [8, 9], theorizes that the SM fields exist on a tridimensional brane embedded into a higher dimensional spacetime - with \( D \) dimensions, where \( D = 4 + N \) and \( N \) is the number of extra dimensions - where gravity propagates. These models were proposed as a potential solution to the hierarchy problem, but also provide us with natural DM particle candidates. In the particular context of the so-called brane-world scenario, and for low brane tension as compared to the fundamental scale of gravity, branons are massive brane fluctuations in the direction of the \( N \)-extra-dimensions whose relic abundance can account for the cosmological DM [3, 10]. The lowest-order effective Lagrangian for branon dark matter (BDM) reads [11, 12]

\[
\mathcal{L}_{\text{BDM}} = \frac{1}{2} g^{\mu \nu} \partial_\mu \pi^\alpha \partial_\nu \pi^\alpha - \frac{1}{2} m_\chi^2 \pi^\alpha \pi^\alpha + \frac{1}{8f^4} \left( 4\partial_\mu \pi^\alpha \partial_\nu \pi^\alpha - m_\chi^2 \pi^\alpha \pi^\alpha g_{\mu \nu} \right) T_{\text{SM}}^{\mu \nu},
\]

where \( \pi \) denotes the branon field and \( \alpha \) runs over the number of extra dimensions \( N \), \( f \) and \( m_\chi \) are the tension of the brane and the mass of the branon respectively, and \( T_{\text{SM}}^{\mu \nu} \) is the energy-momentum tensor of the SM fields. As can be seen in Eq. 2.1, the coupling of the branons to the SM particles is suppressed by the fourth power of the tension of the brane, rendering them as weakly interacting particles. In the simplest case of this effective field theory, there is only one extra-dimension, i.e. \( \alpha = 1 \), and thus a single branon particle.

Branons may self-annihilate into SM particles. For non relativistic branons, the leading term in the thermally averaged cross section of annihilation into, respectively: Dirac fermions \( \psi \) with mass \( m_\psi \), massive gauge fields (\( W \) or \( Z \)) with mass \( m_{W,Z} \) and (complex) scalar field \( \Phi \) with mass \( m_\Phi \) can be expressed as [12]

\[
\langle \sigma \psi v \rangle = \frac{m_\psi^2 m_\chi^2}{16\pi^2 f^8} \left( m_\chi^2 - m_\psi^2 \right) \sqrt{1 - \frac{m_\psi^2}{m_\chi^2}},
\]

\[
\langle \sigma_{W,Z} v \rangle = \frac{m_\chi^4}{64\pi^2 f^8} \left( 4m_\chi^4 - 4m_\chi^2 m_{W,Z}^2 + 3m_{W,Z}^4 \right) \left( 1 - \frac{m_{W,Z}^2}{m_\chi^2} \right),
\]

\[
\langle \sigma_{\Phi} v \rangle = \frac{m_\chi^2}{32\pi^2 f^8} \left( 2m_\chi^2 + m_\Phi^2 \right)^2 \sqrt{1 - \frac{m_\Phi^2}{m_\chi^2}}.
\]

By considering the annihilation in quark channels, a factor 3 was required in 2.2, in order to take into account the three different quark colors (with respect to the annihilation in leptonic channels); since the massive gauge field \( W \) is complex, an additional factor of 2 was added to 2.3 for the \( W^+W^- \) annihilation channel; finally, a factor 1/2 was included in Eq. 2.4, to consider that the Higgs boson is a real (non-complex) scalar field. For a massless gauge field \( \gamma \), the leading order of the cross section is essentially zero, since this is a \( d\)-wave annihilation process and is thus highly suppressed.
The branching ratios into each possible annihilation channel can then be expressed as
\[ BR_i(m_\chi) = \frac{\langle \sigma v \rangle_i}{\langle \sigma v \rangle}, \]
with \( \langle \sigma v \rangle = \sum_j \langle \sigma j v \rangle \).
(2.5)

It can be seen from Eqs. 2.2 to 2.4 that the mass of the branon is the only variable determining the values of the branching ratios, \( BR_i \), whereas the total thermally-averaged annihilation cross section, \( \langle \sigma v \rangle \), depends on both the tension of the brane and the mass branon.

2.2 Expected branon dark matter flux

In our derivations below we assume a single extra-dimension and therefore a single type of branon. The expected differential photon flux produced by branon DM annihilation in a given region of the sky, \( \Delta \Omega \), and observed at Earth can be expressed as
\[ \frac{d\Phi_{\text{BDM}}}{dE} (\Delta \Omega, \langle \sigma v \rangle) = J \cdot \frac{1}{4\pi} \frac{\langle \sigma v \rangle}{2m_\chi^2} \frac{dN_{\text{BDM}}}{dE}, \]
(2.6)

where \( \langle \sigma v \rangle \) and \( m_\chi \) are, respectively, the thermally-averaged annihilation cross section and the mass of the branon DM particle as previously introduced, and
\[ \frac{dN_{\text{BDM}}}{dE} = \sum_{i=1}^n BR_i \frac{dN_i}{dE} \]
(2.7)
is the differential photon yield per annihilation, which is a weighted sum over all the \( n \) possible SM annihilation channels whose products can produce photons. All the information regarding the spectral shape of the gamma-ray flux produced by branon DM annihilation (see right panel of Fig. 1) is contained in the \( dN_{\text{BDM}}/dE \) term.

The astrophysical factor (J-factor) depends on both the distance and the DM distribution at the source region. It is given by
\[ J = \int_{\Delta \Omega} d\Omega' \int_{\text{l.o.s.}} dl \rho_{\text{DM}}^2(l, \Omega'), \]
(2.8)
where l.o.s. stands for line-of-sight and \( \rho_{\text{DM}} \) is the DM density.

3 Observations and analysis method

3.1 Segue 1 observation by the MAGIC telescopes

The ultra-faint dSph Segue 1, of absolute magnitude \( M_V = -1.5^{+0.6}_{-0.8} \), was discovered in the Sloan Digital Sky Survey (SDSS) imaging data in 2006 [7] and is with an estimated \( \sim 3400 M_\odot/L_\odot \) mass-to-light ratio one of the most DM-dominated object known so far [13]. Besides, Segue 1 is positioned in the Northern Hemisphere and outside of the Galactic plane (RA = 10.12 h, DEC = 16.08°) only 23±2 kpc away from us, which leads to an excellent target for indirect DM searches in the VHE gamma-ray bands with the MAGIC telescopes [14–17].

The MAGIC telescopes consist of a system of two 17 m diameter telescopes operating in stereoscopic mode at the Roque de los Muchachos Observatory (28.8° N, 17.9° W; 2200 m a.s.l.) on the Canary Island of La Palma, Spain. The fast imaging cameras with a field of view of 3.5°, installed in the two telescopes, detect the Cherenkov light produced by the atmospheric showers initiated by cosmic particles entering the Earth atmosphere. The system is able to identify and reconstruct cosmic gamma-ray events in the VHE domain [18].
In our analysis, we use the stereoscopic observation of the dSph galaxy Segue 1 with MAGIC, which were already described and analyzed in [16, 17]. This observational campaign was carried out between 2011 and 2013 and is with 157.9 h the deepest observation of any dSph by a Cherenkov telescope to date.

### 3.2 Likelihood analysis

The data reduction of the Segue 1 observation have been kindly provided by the MAGIC Collaboration. It was performed with the standard MAGIC analysis software MARS [19] and is exactly the same as for [16, 17]. In this project, we re-analyse those high-level data in the context of brane-world extra-dimensional theories using gLike [20] and LklCom [21]. In particular, we are using a DM-oriented approach for our likelihood analysis that takes the expected signal spectral shape of the specific DM model into account. Aleksić, Rico and Martinez have shown in [22] that this approach significantly improves the sensitivity to gamma-ray signals of DM origin with respect to a Poisson likelihood approach. Different to [16], we are using a binned likelihood function and include the systematic uncertainty on the residual background contamination in our analysis as described in the following. The same binned version of the likelihood analysis is being used by the MAGIC Collaboration to produce limits to the annihilation of generic WIMPs using all dSph observations by MAGIC [23] and the current generation of gamma-ray instruments Fermi-LAT, HESS, MAGIC, VERITAS and HAWC [24, 25].

We model the gamma-ray emission in the source region with the branon DM model and then compare the expected spectral distribution to the measured one. Since the spectral shape is known for the model (see Section 2), the intensity of the gamma-ray signal $\langle \sigma v \rangle$ is the only free parameter. The corresponding binned ($N_{\text{bins}} = 30$) likelihood function of the dataset $D$ with nuisance parameters $\mu$ can be written as:

$$
\mathcal{L}_{\text{bin}}(\langle \sigma v \rangle, J, \mu \mid D) = \prod_{i=1}^{N_{\text{bins}}} \left[ \mathcal{P}(s_i(\langle \sigma v \rangle, J) + b_i \mid N_{\text{ON},i}, N_{\text{OFF},i}) \cdot \mathcal{P}(\tau b_i \mid N_{\text{OFF},i}) \right] \times \mathcal{T}(\tau \mid \tau_0, \sigma_{\tau})
$$

(3.1)

where $\mathcal{P}(x \mid N)$ is the Poisson distribution of mean $x$ and measured value $N$ and $s_i(\langle \sigma v \rangle, J)$ (see Eq. 3.2) and $b_i$ are the expected numbers of signal and background events in the $i$-th energy bin. The total number of observed events in a given energy bin $i$ in the signal (ON) and background (OFF) regions are $N_{\text{ON},i}$, $N_{\text{OFF},i}$, respectively. The normalization between background and signal regions is denoted with $\tau$. Besides the expected number of background events $b_i$, $\tau$, described by the likelihood function $\mathcal{T}$, is also a nuisance parameter in the analysis. $\mathcal{T}(\tau \mid \tau_0, \sigma_{\tau})$ is a Gaussian function with mean $\tau_0$ and variance $\sigma_{\tau}^2$, which include statistical and systematics uncertainties. We considered a systematic uncertainty of $\sigma_{\text{syst}} = 1.5\% \cdot \tau$ on the estimate of the residual background based on the dedicated performance study of the MAGIC telescopes [18].

The expected number of signal events in the $i$-th energy bin is

$$
s_i(\langle \sigma v \rangle, J) = T_{\text{obs}} \int_{E_{\text{min},i}}^{E_{\text{max},i}} dE' \int_0^\infty d\Phi_{\text{BDM}}(\langle \sigma v \rangle, J) R_{\text{ON}}(E, E') dE,
$$

(3.2)

The observation performed by the MAGIC-I telescope in single telescope mode [14] are not included in our analysis.
where $T_{\text{obs}}$ is the total observation time, $E$ and $E'$ are respectively the true and reconstructed energy, $E_{\text{min},i}$ and $E_{\text{max},i}$ are the lower and upper limits of the $i$-th energy bin, $d\Phi_{\text{BDM}}/dE$ is the expected branon DM flux (Eq. 2.6) in the signal region, and $R_{\text{ON}}(E, E')$ is the telescope response function for the signal region, which can be described by the effective collection area ($A_{\text{eff}}$) and by the PDF for the energy estimator.

In our analysis, we are calculating the branon branching ratios $BR_i$ (Eq. 2.5) including annihilation into the SM pairs $W^+W^-, ZZ, hh, e^+e^-, tt, c\bar{c}, \mu^+\mu^-, \tau^+\tau^-$ and $bb$ (see left panel of Fig. 1). The $bb$ channel dominates for lower masses, while for masses above 80 GeV the $W^+W^-$ channel has the largest impact [12]. Hence, given our energy sensitivity, the $W^+W^-$, ZZ and hh channels are the most significant contributors in our analysis. The differential gamma-ray yields per annihilation $dN_i/dE$ are taken from the PPPC 4 DM ID distribution [26].

![Figure 1: Left: The branon branching ratios (Eq. 2.5) as a function of the only free parameter $m_\chi$ in the expected mass range (10 GeV up to 100 TeV) of WIMPs. Right: The differential photon yield per branon annihilation $dN_{\text{BDM}}/dE$ (Eq. 2.7) for a set of branon DM masses (from light to dark: 0.1, 0.2, 0.5, 1, 2, 5, 10, 20, 50 and 100 TeV).](image)

The Segue 1 observational campaign $D_{\text{Segue1}}$ results in $N = 4$ distinct datasets\(^2\). The joint likelihood function

$$L((\langle \sigma v \rangle; J, \nu | D_{\text{Segue1}}) = \prod_{k=1}^{N} \left[ L_{\text{bin},k}((\langle \sigma v \rangle; J, \nu_k | D_k) \right] \times J \left( J | J_0, \sigma_{\log J_0} \right)$$

is the product of the likelihood function of each dataset. We treat the $J$-factor as a nuisance parameter and include the likelihood $J$ for the $J$-factor following [29]. $\nu_k$ represents the set of nuisance parameters different from the $J$-factor affecting the analysis of the $k$-th dataset.

In our analysis, we are using the $J$-factor and its statistical uncertainty for Segue 1 from [30], where the DM density distribution is modeled assuming a Navarro-Frenk-White (NFW) DM density profile [31]. Thus, we consider the value of $\log_{10} \left( J(\theta) \text{[GeV}^2\text{cm}^{-5}] \right) = 19.0^{+0.32}_{-0.35}$ integrated up to the angular distance $\theta = 0.125^\circ$ of the Segue 1 DM halo according to the signal region.

\(^2\)Due to major hardware upgrade [27], the data set is divided into four different observation periods and each period is treated with an individual set of instrument response functions (IRFs). Besides that the data were taken in wobble mode [28] with two pointing (wobble) positions, which leads to eight samples in total.
4 Results

We present the first observational 95% confidence level (CL) upper limits on the thermally-averaged cross-section $\langle \sigma v \rangle$ (see Fig. 2), in the context of brane-world extra-dimensional theories, obtained with 157.9 hours of good quality stereoscopic data from the Segue 1 observation with the MAGIC telescopes. These limits were computed by following the prescription from [17, 29], with $\langle \sigma v \rangle$ restricted to the physical region ($\langle \sigma v \rangle \geq 0$). Different from previous works [14, 16, 17, 29, 32], we performed a model dependent search for branon DM particles of masses between 100 GeV and 100 TeV. The final results were computed assuming no additional boosts from the presence of substructures [33] or quantum effects [34].

We used a binned likelihood analysis, including systematic uncertainties in the residual background intensity and statistical uncertainties in the $J$-factor, to set these first constraints on the branon DM model from gamma-ray observations. The two-sided 68% and 95% containment bands as well as the median were estimated from the distribution of the upper limits obtained when performing the same analysis of 300 fast simulations of the source and background regions assuming no DM signal ($\langle \sigma v \rangle = 0$).

![Figure 2](image)

**Figure 2:** The 95% CL upper limits on $\langle \sigma v \rangle$ for branon DM annihilation. The solid black line shows our branon limits, while the dotted black line, green and yellow bands show the median and the two-sided 68% and 95% containment bands, respectively. The thermal relic cross-section from [4] is indicated by the red-dashed line. The tightest constraints to branons model by colliders are obtained from CMS data and represented by the blue exclusion region [35]. The analysis of AMS-02 $e^+e^-$ data excludes the orange region [36]. Both exclusion regions were translated to the $\langle \sigma v \rangle$ parameter space from [37]. The purple dashed-dotted line represents the estimated branon sensitivity for 500 h observation on the dSph Draco with the future CTA [38]. The estimated sensitivity for 1000 h observation on the classical dSph Draco with the planned SKA, assuming the $W^+W^-$ annihilation mode, are represented by the yellow dotted line [37].
Our constraints are located within the 68% containment band, which is consistent with the no-detection scenario. As already reported in [14–17], no significant gamma-ray excess has been found in the Segue 1 data. Our strongest limit is $\langle \sigma v \rangle \simeq 1.4 \times 10^{-23}$ cm$^3$s$^{-1}$ for a $\sim 0.7$ TeV mass branon DM particle. Differently from model independent DM searches, we are able to set constraints to a specific parameter space of the branon DM model, i.e. the tension of the brane $f$ versus the DM mass. In fact, since the total annihilation cross section $\langle \sigma v \rangle = \sum_j \langle \sigma_j v \rangle$ only depends on $m_\chi$ and $f$, we can translate our $\langle \sigma v \rangle$ limits to constraints on $f$. This allows us to exclude a significant portion of the brane tension versus branon mass parameter space, $f(m_\chi)$, ranging from 0.1 to 100 TeV in branon mass, as shown in figure 3. We note that MAGIC enlarges the region of the parameter space that has already been excluded by AMS-02 [36] and CMS [35], especially for branon masses above 1 TeV. In future, the Cherenkov Telescope Array (CTA) and the Square Kilometer Array (SKA) will probe a larger fraction of the exclusion region, providing valuable complementary information in both gamma-ray and radio observations, respectively.

![Figure 3: The 95% CL upper limits on the brane tension $f$ for branon DM annihilation. Our branon limits are depicted by the green exclusion region. The thermal relic cross-section from [4] is indicated by the red-dashed line. The tightest constraint to branons model by colliders are obtained from CMS data and represented by the blue exclusion region [35]. The analysis of AMS-02 $e^+e^-$ data excludes the orange region [36]. Both exclusion regions were taken from [37]. The model validity limit in the $f(m_\chi)$ parameter space is depicted by the grey dashed region. The purple dash-dotted line represents the estimated branon sensitivity for 500 h observation on the dSph Draco with the future CTA [38]. The estimated sensitivity to branons for 1000 h observation on the dSph Draco with the planned SKA are represented by the yellow dotted line [37].](image-url)
5 Discussion and conclusions

We have reported the indirect search for branon DM in the dSph galaxy Segue 1 using the MAGIC telescopes data. This observational campaign is still with 157.9 hours the deepest survey of any dSph by any imaging atmospheric Cherenkov telescope to date. The data of each observation period have been analyzed by means of the binned likelihood method, taking the spectral shape from branon DM annihilation into account. Subsequently, the likelihood functions of each dataset were combined in a joint analysis, which is treating the normalization between background and signal regions $\tau$ and the $J$-factor as nuisance parameters in the likelihood.

Above $\sim 1$ TeV, this work is superseding the limits previously obtained from analysis from AMS-02 [36] and CMS [35] and leading to the most constraining branon DM limits in the multi-TeV mass range. Even more stringent exclusion limits of the branon DM annihilation can be achieved by combining further dSph observations of the MAGIC telescopes [23]. In the framework of multi-instrument and multi-messenger DM searches [24, 25] a global branon DM limit over a wider range of DM masses can be obtained with a joint analysis of observational data from different gamma-ray and neutrino telescopes.

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References

[1] Planck collaboration, Planck 2018 results. VI. Cosmological parameters, Astron. Astrophys. 641 A6 [1807.06209].

[2] G. Bertone and D. Merritt, Dark matter dynamics and indirect detection, Mod. Phys. Lett. A 20 (2005) 1021 [astro-ph/0504422].

[3] J. A. Cembranos, A. Dobado and A. L. Maroto, Brane-World Dark Matter, Phys. Rev. Lett. 90 (2003) 241301 [hep-ph/0302041].

[4] G. Steigman, B. Dasgupta and J. F. Beacom, Precise relic WIMP abundance and its impact on searches for dark matter annihilation, Phys. Rev. D 86 (2012) 023506 [1204.3622].

[5] P. Salati, Dark matter annihilation in the universe, in International Journal of Modern Physics Conference Series, vol. 30, pp. 1460256, 2014, [1403.4495].
[6] D. Merritt, M. Milosavljević, L. Verde and R. Jimenez, *Dark Matter Spikes and Annihilation Radiation from the Galactic Center*, Phys. Rev. Lett. 88 (2002) 191301 [astro-ph/0201376].

[7] V. Belokurov, D. B. Zucker, N. W. Evans, J. T. Kleyna, S. Koposov, S. T. Hodgkin et al., *Cats and Dogs, Hair and a Hero: A Quintet of New Milky Way Companions*, Astrophys. J. 654 (2007) 897 [astro-ph/0608448].

[8] N. Arkani-Hamed, S. Dimopoulos and G. Dvali, *The hierarchy problem and new dimensions at a millimeter*, Physics Letters B 429 (1998) 263 [hep-ph/9803315].

[9] N. Arkani-Hamed, S. Dimopoulos and G. Dvali, *Phenomenology, astrophysics, and cosmology of theories with submillimeter dimensions and TeV scale quantum gravity*, Phys. Rev. D 59 (1999) 086004 [hep-ph/9807344].

[10] J. A. Cembranos, A. Dobado and A. L. Maroto, *Cosmological and astrophysical limits on brane fluctuations*, Phys. Rev. D 68 (2003) 103505 [hep-ph/0212269].

[11] J. Alcaraz, J. A. Cembranos, A. Dobado and A. L. Maroto, *Limits on the brane fluctuations mass and on the brane tension scale from electron-positron colliders*, Phys. Rev. D 67 (2003) 075010 [hep-ph/0212269].

[12] J. A. R. Cembranos, A. de La Cruz-Dombriz, V. Gammaldi and A. L. Maroto, *Detection of branon dark matter with gamma ray telescopes*, Phys. Rev. D 85 (2012) 043505 [1111.4448].

[13] J. D. Simon, M. Geha, Q. E. Minor, G. D. Martinez, E. N. Kirby, J. S. Bullock et al., *A Complete Spectroscopic Survey of the Milky Way Satellite Segue 1: The Darkest Galaxy*, Astrophys. J. 733 (2011) 46 [1007.4198].

[14] J. Aleksić, E. A. Alvarez, L. A. Antonelli, P. Antoranz, M. Asensio, M. Backes et al., *Searches for dark matter annihilation signatures in the Segue 1 satellite galaxy with the MAGIC-I telescope*, JCAP 06 (2011) 035 [1103.0477].

[15] E. Aliu, S. Archambault, T. Arlen, T. Aune, M. Beilicke, W. Benbow et al., *VERITAS deep observations of the dwarf spheroidal galaxy Segue 1*, Phys. Rev. D 85 (2012) 062001 [1202.2144].

[16] J. Aleksić, S. Ansoldi, L. A. Antonelli, P. Antoranz, A. Babic, P. Bangale et al., *Optimized dark matter searches in deep observations of Segue 1 with MAGIC*, JCAP 02 (2014) 008 [1312.1535].

[17] MAGIC Collaboration, M. L. Ahnen, S. Ansoldi, L. A. Antonelli, P. Antoranz, A. Babic et al., *Limits to dark matter annihilation cross-section from a combined analysis of MAGIC and Fermi-LAT observations of dwarf satellite galaxies*, JCAP 02 (2016) 039 [1601.06590].

[18] J. Aleksić, S. Ansoldi, L. A. Antonelli, P. Antoranz, A. Babic, P. Bangale et al., *The major upgrade of the MAGIC telescopes, Part II: A performance study using observations of the Crab Nebula*, Astroparticle Physics 72 (2016) 76 [1409.5594].

[19] R. Zanin, E. Carmona, J. Sitarek, P. Colin, K. Frantzen, M. Gaug et al., *MARS, The MAGIC Analysis and Reconstruction Software*, in 33th International Cosmic Ray Conference (ICRC2013), vol. 33, pp. 2937, 2013. [33.29372].

[20] J. Rico, C. Nigro, D. Kerszberg, T. Miener and J. Aleksić, *gLike: numerical maximization of heterogeneous joint likelihood functions of a common free parameter plus nuisance parameters*, Mar., 2021. 10.5281/zenodo.4601451.

[21] T. Miener and D. Nieto, *LklCom: Combining likelihoods from different experiments*, Mar., 2021. 10.5281/zenodo.4597500.

[22] J. Aleksić, J. Rico and M. Martinez, *Optimized analysis method for indirect dark matter searches with imaging air Cherenkov telescopes*, JCAP 10 (2012) 032 [1209.5589].
[23] MAGIC Collaboration, V. A. Acciari, S. Ansoldi, L. A. Antonelli, A. Arbet Engels, M. Artero et al., Combined searches for dark matter in dwarf spheroidal galaxies observed with the MAGIC telescopes, including new data from Coma Berenices and Draco, arXiv e-prints (2021) arXiv:2111.15009 [2111.15009].

[24] L. Oakes et al., Combined Dark Matter Searches Towards Dwarf Spheroidal Galaxies with Fermi-LAT, HAWC, HESS, MAGIC and VERITAS, in 36th International Cosmic Ray Conference (ICRC2019), vol. 36, pp. 539, 2019, [1909.06310].

[25] C. Armand et al., Combined Dark Matter Searches Towards Dwarf Spheroidal Galaxies with Fermi-LAT, HAWC, HESS, MAGIC and VERITAS, in 37th International Cosmic Ray Conference (ICRC2021), vol. 37, pp. 528, 2021, [2108.13646].

[26] M. Cirelli, G. Corcella, A. Hektor, G. Hütsi, M. Kadastik, P. Panci et al., PPC 4 DM ID: a poor particle physicist cookbook for dark matter indirect detection, JCAP 03 (2011) 051 [1012.4515].

[27] J. Aleksić, S. Ansoldi, L. A. Antonelli, P. Antoranz, A. Babic, P. Bangale et al., The major upgrade of the MAGIC telescopes, Part I: The hardware improvements and the commissioning of the system, Astroparticle Physics 72 (2016) 61 [1409.6073].

[28] V. P. Fomin, A. A. Stepanian, R. C. Lamb, D. A. Lewis, M. Punch and T. C. Weekes, New methods of atmospheric Cherenkov imaging for gamma-ray astronomy. I. The false source method, Astroparticle Physics 2 (1994) 137.

[29] M. Ackermann, A. Albert, B. Anderson, W. B. Atwood, L. Baldini, G. Barbiellini et al., Searching for Dark Matter Annihilation from Milky Way Dwarf Spheroidal Galaxies with Six Years of Fermi Large Area Telescope Data, Phys. Rev. Lett. 115 (2015) 231301 [1503.02641].

[30] A. Geringer-Sameth, S. M. Koushiappas and M. Walker, Dwarf Galaxy Annihilation and Decay Emission Profiles for Dark Matter Experiments, Astrophys. J. 801 (2015) 74 [1408.0002].

[31] J. F. Navarro, C. S. Frenk and S. D. M. White, The Structure of Cold Dark Matter Halos, Astrophys. J. 462 (1996) 563 [astro-ph/9508025].

[32] M. L. Ahnen, S. Ansoldi, L. A. Antonelli, C. Arcaro, D. Baack, A. Babić et al., Indirect dark matter searches in the dwarf satellite galaxy Ursa Major II with the MAGIC telescopes, JCAP 03 (2018) 009 [1712.03095].

[33] L. E. Strigari, S. M. Koushiappas, J. S. Bullock and M. Kaplinghat, Precise constraints on the dark matter content of Milky Way dwarf galaxies for gamma-ray experiments, Phys. Rev. D 75 (2007) 083526 [astro-ph/0611925].

[34] J. Hisano, S. Matsumoto and M. M. Nojiri, Explosive dark matter annihilation, Phys. Rev. Lett. 92 (2004) 031303 [hep-ph/0307216].

[35] CMS collaboration, Search for new phenomena in monophoton final states in proton-proton collisions at $\sqrt{s} = 8$ TeV, Phys. Lett. B 755 (2016) 102 [1410.8812].

[36] J. A. R. Cembranos, Á. de la Cruz-Dombriz, P. K. S. Dunsby and M. Mendez-Isla, Analysis of branon dark matter and extra-dimensional models with AMS-02, Phys. Lett. B 790 (2019) 345 [1709.09819].

[37] J. A. R. Cembranos, Á. de la Cruz-Dombriz, V. Gammaldi and M. Méndez-Isla, SKA-Phase 1 sensitivity to synchrotron radio emission from multi-TeV Dark Matter candidates, Physics of the Dark Universe 27 (2020) 100448 [1905.11154].

[38] A. Aguirre-Santaella, V. Gammaldi, M. A. Sánchez-Conde and D. Nieto, Cherenkov Telescope Array sensitivity to branon dark matter models, JCAP 10 (2020) 041 [2006.16706].