

PAPER • OPEN ACCESS

Combined search in dwarf spheroidal galaxies for branon dark matter annihilation signatures with the MAGIC telescopes

To cite this article: S. Abe *et al* JCAP03(2025)020

View the [article online](#) for updates and enhancements.

You may also like

- [Constraining branon dark matter from observations of the Segue 1 dwarf spheroidal galaxy with the MAGIC telescopes](#)
T. Miener, D. Nieto, V. Gammaldi et al.
- [Cherenkov Telescope Array sensitivity to branon dark matter models](#)
A. Aguirre-Santaella, V. Gammaldi, M.A. Sánchez-Conde et al.
- [Searches for gamma-ray lines and 'pure WIMP' spectra from Dark Matter annihilations in dwarf galaxies with H.E.S.S.](#)
M. Cirelli, P. Panci, F. Sala et al.

Combined search in dwarf spheroidal galaxies for branon dark matter annihilation signatures with the MAGIC telescopes



The MAGIC collaboration

S. Abe et al.

Full author list at the end of the paper

E-mail: contact.magic@mpp.mpg.de

ABSTRACT: Massive brane fluctuations, called branons, behave as weakly interacting massive particles, which is one of the most favored class of candidates to fulfill the role of the dark matter (DM), an elusive kind of matter beyond the Standard Model. We present a multi-target search in dwarf spheroidal galaxies for branon DM annihilation signatures with a total exposure of 354 hours with the ground-based gamma-ray telescope system MAGIC. This search led to the most constraining limits on branon DM in the sub-TeV and multi-TeV DM mass range. Our most stringent limit on the thermally-averaged annihilation cross-section (at 95% confidence level) corresponds to $\langle\sigma v\rangle \simeq 1.9 \times 10^{-24} \text{ cm}^3\text{s}^{-1}$ at a branon mass of $\sim 1.5 \text{ TeV}$.

KEYWORDS: dark matter experiments, gamma ray experiments, cosmology of theories beyond the SM

ARXIV EPRINT: [2408.08009](https://arxiv.org/abs/2408.08009)



Contents

1	Introduction	1
2	Gamma rays from branon annihilation	2
3	dSph observations by the MAGIC telescopes	3
4	Analysis technique	4
4.1	Data reduction	4
4.2	Likelihood analysis	5
5	Results	6
6	Discussion and conclusions	7
	The MAGIC collaboration	15

1 Introduction

The nature of dark matter (DM) is still an open question for modern physics. This non-baryonic and non-relativistic kind of matter is suggested to be accountable for 84% of the matter density of the Universe [1]. Among many other DM candidates [2], massive brane fluctuations (branos) emerging from the brane-world theory [3] have been proposed as DM candidates, since their characteristics match the ones of weakly interacting massive particles (WIMPs) [4]. Gamma-ray telescopes could potentially detect DM, in particular branos, indirectly by observing photons, e.g. via quark hadronization or final state radiation from charged particles, in the very-high energy (VHE, $\gtrsim 50$ GeV) domain of astrophysical regions presenting large DM densities.

Dwarf spheroidal galaxies (dSphs) are preferred targets for indirect DM searches. Contrary to the Galactic Center (GC) and galaxy clusters, also very prominent targets for DM searches [5, 6], dSphs are not expected to host any strong conventional gamma-ray emitter that may hinder the detection of a subdominant DM signal. In addition, dSphs are not as extended targets as the GC or galaxy clusters, with source angular extension presenting a challenge for ground-based gamma-ray telescopes due to their angular resolution. Nevertheless, the determination of the DM content in those objects remains the most uncertain ingredient in most DM analyses. Previous work, the first branon DM search in the VHE domain with the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescopes [7, 8], utilized the deepest exposure on any single dSph to date, namely Segue 1. Being an interesting target for DM searches, the DM content of Segue 1 has been an active subject of debate [9]. A refined analysis was carried out in [9, 10] with a more accurate determination of member stars in Segue 1, leading to a lower and more uncertain value for its DM content than previously determined in [11]. With the aim of providing more robust and more constraining

results, in this work we performed a multi-target branon DM search using two independent determinations of the DM content from the literature.

The present article provides a search for branon DM with gamma rays by combining MAGIC observations of dSphs with a total accumulation of 354 hours leading to the most stringent and robust branon DM limits in the sub-TeV and multi-TeV DM mass range to date. In section 2, we briefly review the brane-world theory and we present the expected photon flux from branon DM annihilation. The observational campaigns on dSphs by the MAGIC telescopes and the adopted estimations of the DM content in those objects are summarized in section 3. The analysis methodology is explained in section 4, while the final results in terms of upper limits (ULs) on the annihilation cross section of branon DM particles and the tension of the brane are presented in section 5. Finally, we discuss the ULs and compare them with the model-independent ULs from MAGIC [12] in section 6.

2 Gamma rays from branon annihilation

Standard Model (SM) fields could exist on a tridimensional brane embedded in a higher dimensional spacetime, where gravity propagates. These extra-dimensional models [13–16] were originally proposed as a potential solution to the hierarchy problem. However, they also provide us with natural DM particle candidates. In the context of the *brane-world scenario* with low¹ brane tension f , massive brane fluctuations (branons) in the direction of the N extra-dimensions are natural DM candidates [3, 18]. The lowest-order effective Lagrangian for branon DM reads [19, 20]

$$\mathcal{L} = \frac{1}{2}g^{\mu\nu}\partial_\mu\pi^\alpha\partial_\nu\pi^\alpha - \frac{1}{2}m_\chi^2\pi^\alpha\pi^\alpha + \frac{1}{8f^4}\left(4\partial_\mu\pi^\alpha\partial_\nu\pi^\alpha - m_\chi^2\pi^\alpha\pi^\alpha g_{\mu\nu}\right)T_{\text{SM}}^{\mu\nu}, \quad (2.1)$$

where π is the branon field and α runs over the N extra-dimensions, m_χ is the particle mass of the branon, and $T_{\text{SM}}^{\mu\nu}$ is the energy-momentum tensor of the SM fields. The coupling of the branons to the SM particles is suppressed by the fourth power of the tension of the brane, rendering them as WIMPs.

The expected differential photon flux produced by branon DM annihilation [20] is composed of the two terms: (i) the *astrophysical* factor (J -factor; see section 3), which depends on both the distance l to the target, and the DM distribution ρ_{DM} at the source region denoted by its subtended solid angle $\Delta\Omega$, and (ii) the particle physics factor, which includes the branon DM annihilation photon yield. It reads as

$$\frac{d\Phi}{dE}(\langle\sigma v\rangle) = \frac{1}{4\pi} \underbrace{\int_{\Delta\Omega} d\Omega' \int_{\text{l.o.s.}} dl \rho_{\text{DM}}^2(l, \Omega')}_{J\text{-factor}} \cdot \underbrace{\frac{\langle\sigma v\rangle}{2m_\chi^2} \sum_{i=1}^n \text{Br}_i \frac{dN_i}{dE}}_{\text{DM annihilation}}, \quad (2.2)$$

where $\langle\sigma v\rangle$ is the thermally-averaged annihilation cross section and l.o.s. stands for line-of-sight. The branon branching ratios Br_i as a function of m_χ have been calculated following the prescriptions in [20] including annihilation into the SM pairs W^+W^- , ZZ , hh , e^+e^- , $t\bar{t}$, $c\bar{c}$, $\mu^+\mu^-$, $\tau^+\tau^-$ and $b\bar{b}$. However, the W^+W^- , ZZ and hh channels are the dominant

¹The low brane tension regime refers to when the tension of the branon is greater than the mass of the branon, where the branon dynamic is given by the Nambu-Goto action added to the usual SM action [17].

contributors in our search for TeV branon DM. The differential photon yields per annihilation dN_i/dE , including electroweak (EW) corrections, are taken from the PPPC 4 DM ID distribution for this work [21]. The resulting differential photon yield per branon annihilation for a set of branon DM masses can be found in [7, 8, 22, 23].

3 dSph observations by the MAGIC telescopes

The *Florian Goebel* Major Atmospheric Gamma-ray Imaging Cherenkov (MAGIC) telescopes² are two 17-m diameter reflector imaging atmospheric Cherenkov telescopes (IACTs) situated at an altitude of 2200 m a.s.l. at the Roque de los Muchachos Observatory (28.8° N, 17.9° W) on the Canary Island of La Palma, Spain. MAGIC inspects the VHE gamma-ray sky (above $\gtrsim 30$ GeV) with a 3.5° field of view probing the most extreme astrophysical environments in our universe. The point-source 5σ sensitivity above 220 GeV of MAGIC is $\sim 0.7\%$ of the Crab Nebula flux for 50 h of observations near zenith with an associated energy resolution of $\sim 16\%$ and a 0.07° angular resolution measured as the 68% containment radius of the gamma-ray excess. A detailed performance study of the MAGIC telescopes can be found in [24].

The MAGIC Collaboration has carried out extensive observational campaigns on dSphs in the Northern Hemisphere throughout the years, motivated by the search for DM signals in these objects. At first, MAGIC observed the dSphs Draco, Willman 1, and Segue 1 with the MAGIC-I telescope in single telescope mode around 2009 [25, 26]. Those data have not been used in this work because of the superseding sensitivity by the additional MAGIC-II telescope. After upgrading MAGIC to a stereoscopic IACT system, Segue 1 was observed between 2011 and 2013 with an exposure of 158 hours [27, 28]. This is still the deepest observation of any dSph by an IACT to date. Additionally, MAGIC observed Ursa Major II between 2014 and 2016 [29], Draco in 2018, and Coma Berenices in 2019 leading to a total accumulation of 354 hours of dSph observations [12]. The observation of Triangulum II by the MAGIC telescopes [30] has been excluded due to the statistical uncertainty on the determination of the DM distribution in this object [31]. The dSph observations by the MAGIC telescopes included in this combined search for branon DM are summarized in table 1. No effects of the extragalactic background light absorption [32] are considered in our analysis, since the observed dSphs are positioned only a few tens of kpc away from us (see table 2).

The driving factor of the search for DM annihilation signatures in dSphs is the estimation of the DM content in those objects. This is a challenging task resulting in rather large uncertainties, which are dominant in our analysis. Therefore, this work includes a systematic study on the impact of the estimation of the J -factors to our derived constraints by performing the same likelihood analysis (see section 4.2) with two different sets of the J -factors from the literature, i.e. Geringer-Sameth et al. [11] (henceforth referred to as GS15) and Bonivard et al. [10] (henceforth referred to as B16). The derivation of the two J -factor sets was carried out in [10, 11] using a Jeans analysis [34] of the same kinematic stellar data for Segue 1, Ursa Major II, and Coma Berenices (a detailed description can be found in [11]). B16 [10] adopted the kinematic stellar data for the classical dSph Draco from [35], which differs from the data used by [11]. The main differences between the two approaches are the

²<https://magic.mpp.mpg.de>.

Name	zd [°]	T_{obs} [h]	E [TeV]	θ [°]	$S_{\text{Li\&Ma}}[\sigma]$
Coma Berenices	5 – 37	49	0.06 – 10	0.17	0.8
Draco	29 – 45	52	0.07 – 10	0.22	–0.7
Segue 1	13 – 37	158	0.06 – 10	0.12	–0.5
Ursa Major II	35 – 45	95	0.12 – 10	0.30	–2.1

Table 1. Summary of the considered dSph observations by the MAGIC telescopes [12]. We report the zenith distance (zd) range, the total observation time (T_{obs}), and the energy range (E). We also list the angular radius (θ) of the signal region and the significance of detection ($S_{\text{Li\&Ma}}$) calculated by following Li&Ma [33]. Please note that the significance of detection is not reported for Coma Berenices and Draco in [12], but no gamma-ray excess has been found.

Name	Distance [kpc]	l, b [°]	$\log_{10} J(\theta_{\text{max}})$ {GS15} [$\log_{10}(\text{GeV}^2\text{cm}^{-5}\text{sr})$]	$\log_{10} J(\theta_{\text{max}})$ {B16} [$\log_{10}(\text{GeV}^2\text{cm}^{-5}\text{sr})$]
Coma Berenices	44	241.89, 83.61	$19.02^{+0.37}_{-0.41}$	$20.13^{+1.56}_{-1.08}$
Draco	76	86.37, 34.72	$19.05^{+0.22}_{-0.21}$	$19.42^{+0.92}_{-0.47}$
Segue 1	23	220.48, 50.43	$19.36^{+0.32}_{-0.35}$	$17.52^{+2.54}_{-2.65}$
Ursa Major II	32	152.46, 37.44	$19.42^{+0.44}_{-0.42}$	$20.60^{+1.46}_{-0.95}$

Table 2. Summary of the dSph properties. We report the heliocentric distance and Galactic coordinates of each dSph, as well as the total J -factor values and its $\pm 1\sigma$ uncertainties from GS15 [11] and B16 [10] used in the present work. The maximum angular distance θ_{max} is the angular distance from the center to the outermost member star considered in the J -factor calculation.

selection of the DM density, velocity anisotropy, and light profiles, as well as the inclusion of systematic uncertainties in [10]. The J -factor values and its uncertainties are listed in table 2 and visualized in figure 1. The largest discrepancy is found for the J -factor of Segue 1, since the Jeans analysis in B16 [10] is extremely sensitive on the determination of the member stars. The contamination of the dSph stellar sample by a foreground population with different velocity properties complicates membership determination [9] leading to an artificially inflated J -factor estimation in GS15 [11], where the foreground population is wrongly included in the Jeans analysis.

4 Analysis technique

4.1 Data reduction

The low-level data reduction of the four dSph observations was performed in [12] using the standard MAGIC analysis software MARS [36]. We re-analyse the resulting high-level data of four dSph observations [12] in the context of brane-world extra-dimensional theories using the same open-source analysis software tools [37] for multi-instrument and multi-target DM searches gLike³ [38] and Lk1Com⁴ [39].

³<https://github.com/javierrico/gLike>.

⁴https://github.com/TjarkMiener/likelihood_combiner.

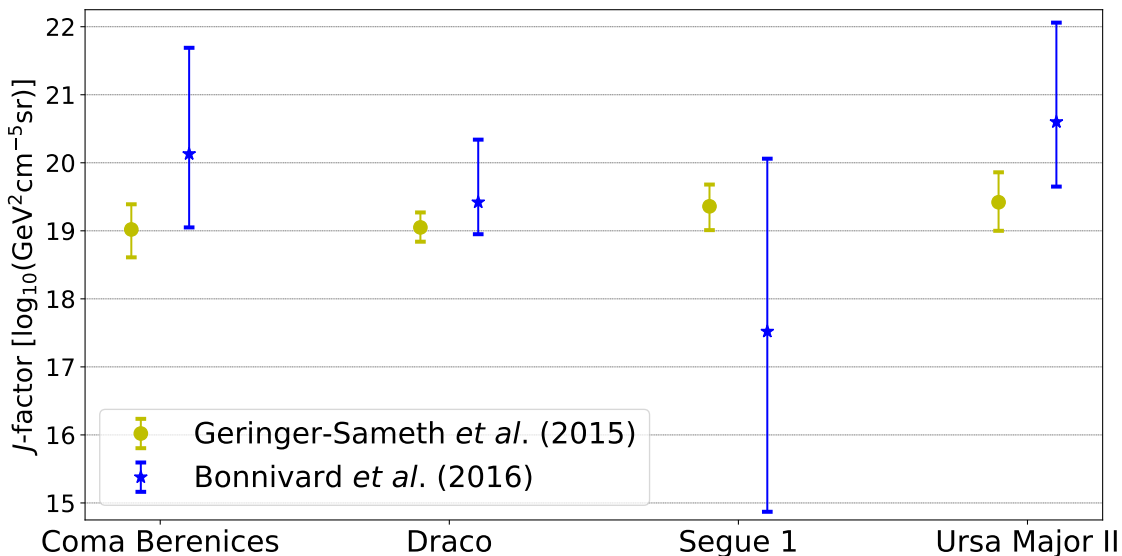


Figure 1. Comparison of the J -factor values and its uncertainties from GS15 [11] (green dots) and B16 [10] (blue stars) for all considered dSphs.

4.2 Likelihood analysis

In this work, we used the same likelihood analysis as [12], which was originally proposed in [40], further utilized in [28, 29] and discussed in [41]. In order to obtain the expected branon DM signal for the MAGIC telescopes, the theoretical branon DM flux (eq. 2.2) is convolved with the instrument response functions (IRFs) for the signal (ON) region $\text{IRF}_{\text{ON}}(E, E')$ including the morphology of the dSph via the “Donut” MC method [29], which can be described by the PDF for the energy estimator and the effective collection area. The *Donut MC method* is the procedure to build the IRFs with a specific MC sample representing the source morphology rather than using MC for an assumed point-like source. The specific MC samples are produced by selecting events from the diffuse MC resulting in a donut-shaped distribution. E and E' are the true and estimated energy of the gamma-ray photon, respectively. The expected number of signal events in the i -th energy bin yields

$$s_i(\langle\sigma v\rangle) = T_{\text{obs}} \int_{E_{\text{min},i}}^{E_{\text{max},i}} dE' \int_0^\infty \frac{d\Phi(\langle\sigma v\rangle)}{dE} \text{IRF}_{\text{ON}}(E, E') dE, \quad (4.1)$$

where T_{obs} is the total observation time and $E_{\text{min},i}$ and $E_{\text{max},i}$ are the lower and upper limits of the i -th energy bin. The thermally-averaged annihilation cross section $\langle\sigma v\rangle$ is our parameter of interest and therefore the only free parameter in our likelihood analysis.

The binned ($N_{\text{bins}} = 30$) likelihood function of the dataset \mathcal{D}' with nuisance parameters ν reads as:

$$\mathcal{L}_{\text{bin}}(\langle\sigma v\rangle; \nu | \mathcal{D}') = \prod_{i=1}^{N_{\text{bins}}} \left[\mathcal{P}(s_i(\langle\sigma v\rangle) + b_i | N_{\text{ON},i}) \cdot \mathcal{P}(\tau b_i | N_{\text{OFF},i}) \right] \times \mathcal{T}(\tau | \tau_0, \sigma_\tau) \quad (4.2)$$

where $\mathcal{P}(x|N)$ stands for a Poisson distribution with mean x and measured value N , while $N_{\text{ON},i}$, $N_{\text{OFF},i}$ are the total number of observed events in the i -th energy bin in the signal

(ON) and background (OFF) regions, respectively. The background events in the 30 bin in energy and the normalization between background and signal regions τ are nuisance parameters, which leads to a total of 31 nuisance parameters in eq. 4.2. The likelihood function $\mathcal{T}(\tau | \tau_o, \sigma_\tau)$ is a Gaussian with mean $\tau_o = 1.0$ and variance σ_τ^2 , which include statistical and systematic uncertainties on τ following $\sigma_\tau = \sqrt{\sigma_{\tau_{\text{stat}}}^2 + \sigma_{\tau_{\text{syst}}}^2}$. Based on a dedicated performance study of the MAGIC telescopes [24], we typically considered a systematic uncertainty of $\sigma_{\tau_{\text{syst}}} = 1.5\% \cdot \tau$ on the estimate of the residual background.

The joint likelihood function \mathcal{L} is a nested product of the binned likelihood function $\mathcal{L}_{\text{bin},kl}$ (eq. 4.2) for each dSphs ($N_{\text{dSphs}} = 4$) and their distinct observational datasets \mathcal{D}_{kl} with individual set of IRFs due to different observational conditions or hardware setup of the instrument. It reads as:

$$\mathcal{L}(\langle\sigma v\rangle) = \prod_{k=1}^{N_{\text{dSphs}}} \prod_{l=1}^{N_{\text{obs},k}} \left[\mathcal{L}_{\text{bin},kl}(\langle\sigma v\rangle, \boldsymbol{\nu}_{kl} | \mathcal{D}_{kl}) \right] \times \mathcal{J}_k(J_k | J_{o,k}, \sigma_{\log_{10} J_k}) \quad (4.3)$$

where $N_{\text{obs},k}$ is the number of observations for the k -th dSph and $\boldsymbol{\nu}_{kl}$ represents the set of nuisance parameters different from the J -factor affecting the analysis of dataset \mathcal{D}_{kl} . Given the importance of the J -factors and their uncertainties (see section 3), we treat the J -factors as nuisance parameters using the likelihood \mathcal{J}_k for the J -factor of the k -th dSph (ignoring index k in the following for the sake of clarity)

$$\mathcal{J}(J | J_o, \sigma_{\log_{10} J}) = \frac{1}{\ln(10) J_o \sqrt{2\pi} \sigma_{\log_{10} J}} \exp\left(-\frac{(\log_{10} J - \log_{10} J_o)^2}{2\sigma_{\log_{10} J}^2}\right), \quad (4.4)$$

where J is the true value of the J -factor and J_o is the observed J -factor with error $\sigma_{\log_{10} J}$ [42].

In the absence of a branon DM signal, ULs on $\langle\sigma v\rangle$ for all datasets \mathcal{D} are set using a test statistic defined as

$$\text{TS} = -2 \ln \left(\frac{\mathcal{L}(\langle\sigma v\rangle; \hat{\boldsymbol{\nu}} | \mathcal{D})}{\mathcal{L}(\widehat{\langle\sigma v\rangle}; \hat{\boldsymbol{\nu}} | \mathcal{D})} \right), \quad (4.5)$$

where $\widehat{\langle\sigma v\rangle}$ and $\hat{\boldsymbol{\nu}}$ are the values that globally maximize \mathcal{L} , and $\hat{\boldsymbol{\nu}}$ is the set of values that maximize \mathcal{L} for a particular value of $\langle\sigma v\rangle$. In particular, the ULs on $\langle\sigma v\rangle$ are computed by solving $\text{TS} = 2.71$, where 2.71 corresponds to a one-sided 95% confidence level [43]. No additional boosts from the presence of substructures [44] or quantum effects [45] entered the computation of the final results.

5 Results

Our likelihood analysis is coherent with all previously reported results [26–28, 46] in that no gamma-ray signal has been detected (see also table 1). Thus, we present the 95% confidence level upper limits (ULs) on the thermally-averaged cross-section $\langle\sigma v\rangle$ for branon DM annihilation in a particle mass range from 100 GeV to 100 TeV. The ULs are obtained with the before-mentioned combined analysis of multiple dSph observations with the MAGIC telescopes for two different sets of J -factors (see figure 2). We include systematic uncertainties

in the residual background intensity and statistical uncertainties in the J -factor in our likelihood analysis. Our strongest limit is $\langle\sigma v\rangle \simeq 1.9 \times 10^{-24} \text{ cm}^3\text{s}^{-1}$ for a ~ 1.5 TeV mass branon DM particle.

We obtain the two-sided 68% and 95% containment bands as well as the median from the distribution of ULs performing the same analysis of 300 fast simulations of the source and background regions assuming no DM signal ($\langle\sigma v\rangle = 0$). As expected, our constraints are located within the 68% containment band for both sets of J -factors. The ULs from each individual dSph observation are also depicted in figure 2. For GS15, the combined analysis is dominated by Ursa Major II and Segue 1, while the latter target does not have any substantial contribution in the combination for B16. Given the rather huge negative fluctuation of the Ursa Major II observation (-2.1σ for a conventional IACT analysis; see table 1) and Ursa Major II being the most dominant dSph in the analysis for B16, the combined limit for B16 locates significantly below the median. The estimated branon sensitivity for 300 h observation on the dSph Draco with the future Cherenkov Telescope Array (CTA) [22] lays an order of magnitude below the median of both presented analyses, as expected.

We set constraints to the specific parameter space of the branon DM model (see figure 3), i.e. the tension of the brane $f(m_\chi)$ versus the branon DM mass ranging from 100 GeV to 100 TeV, by translating our $\langle\sigma v\rangle$ ULs to constraints on f [7, 8]. The combined analysis of this work allows us to exclude a significantly larger portion of the brane tension parameter space than previous branon ULs in the literature by CMS [47], Cembranos et al. [48] with AMS-02 e^+e^- data [49], and MAGIC with the observation of Segue 1 [7, 8], for both sets of J -factors, GS15 and B16. Although, the constraints obtained by Cembranos et al. [48] with AMS-02 data [49] would require an updated analysis including more recent AMS-02 data from [50].

6 Discussion and conclusions

The branon DM exclusion limits are compared with the dominant annihilation mode W^+W^- , ZZ , and hh in the branon DM model at VHE. The model-independent ULs in figure 4 are taken from [12], which rely on the same dSph datasets with the same analysis scheme. In [12], the J -factor values of GS15 were used to compute the model generic DM exclusion limits. The ULs for branon DM annihilation are enclosed by the dominant annihilation channels verifying the correctness of the performed analysis (see figure 4).

In comparison with the model-independent search for DM [12], this work is not only capable of constraining the thermally-averaged cross-section $\langle\sigma v\rangle$, but also the brane tension $f(m_\chi)$. The tension of the brane can be affected by various factors, such as the curvature of the spacetime, the number of dimensions in the brane, and the type of matter present in the brane. It plays a crucial role in theories such as string theory and brane cosmology, which aim to explain the fundamental nature of our universe. It helps to determine the dynamics and behavior of branes within a given spacetime.

This work supersedes the exclusion limits from CMS [47] and Cembranos et al. [48] with AMS-02 data even at the upper edge of the sub-TeV DM mass range leading to the most constraining branon DM limits above ~ 700 GeV by combining all major dSph observations of the MAGIC telescopes. Even more stringent and robust exclusion limits of the branon DM annihilation over a wider range of branon DM masses can be achieved in the framework

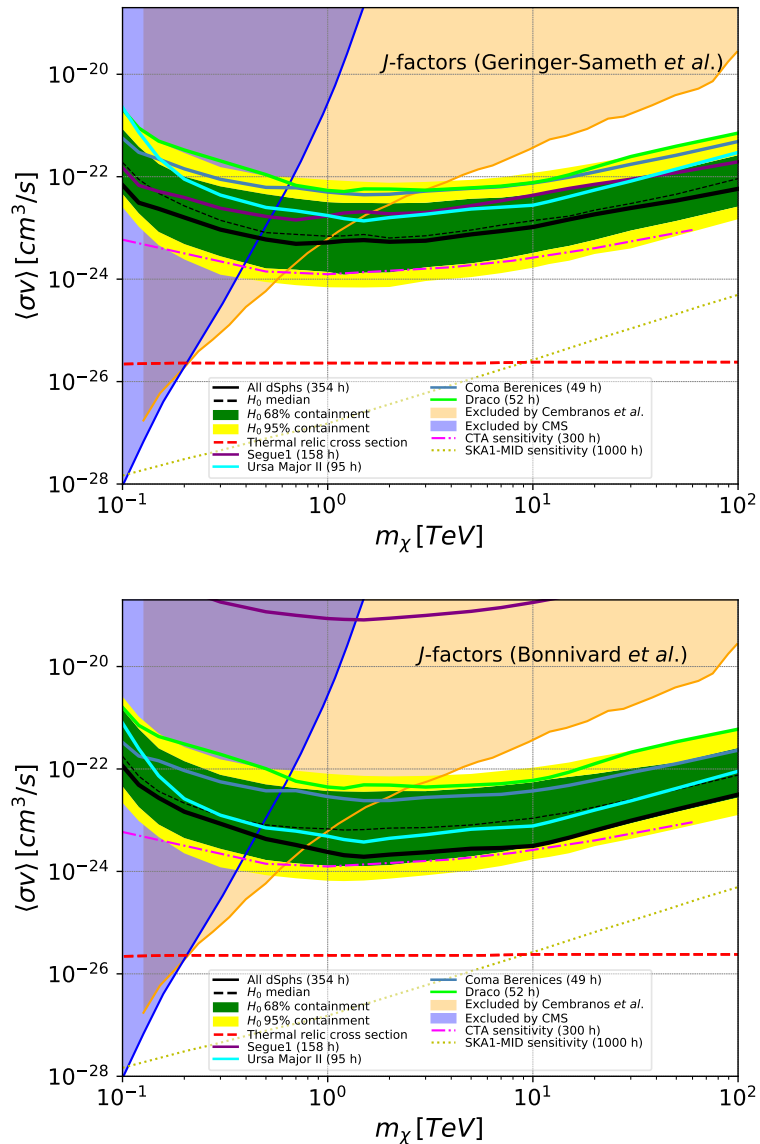


Figure 2. 95% ULs on $\langle\sigma v\rangle$ for branon DM annihilation from the combined analysis (solid black line) and the analysis of the individual dSphs (Segue 1 purple, Ursa Major II cyan, Draco lime green, and Coma Berenices steel blue). The median and the two-sided 68% and 95% containment bands of the combined analysis are depicted by the dotted black line, green and yellow bands, respectively. The red dashed line indicates the thermal relic cross-section from [4]. The blue exclusion region represents the tightest constraints to branons model by colliders obtained from CMS data [47] and the orange exclusion region was obtained by Cembranos et al. from an analysis [48] of AMS-02 e^+e^- data [49]. They were translated to the $\langle\sigma v\rangle$ parameter space from [17]. The estimated branon sensitivity for 300 h observation of Draco with the future CTA is depicted by the purple dashed-dotted line [22]. The yellow dotted line represents the estimated sensitivity for 1000 h observation of Draco with the planned SKA assuming the W^+W^- annihilation mode [17].

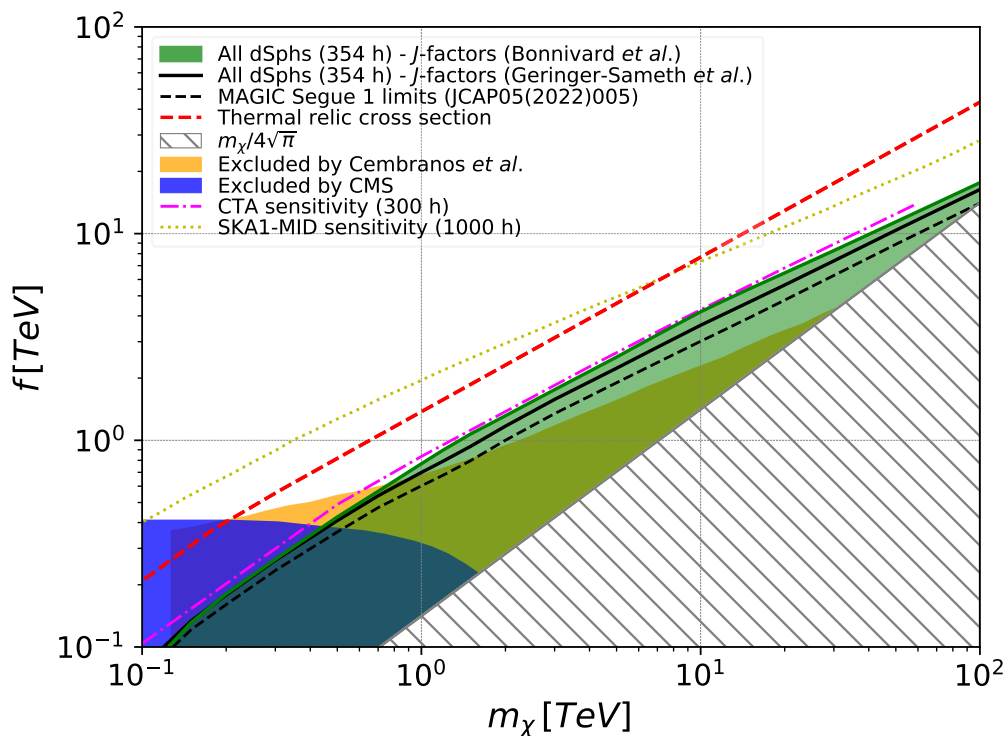


Figure 3. 95% ULs on f for branon DM annihilation from the combined analysis with the B16 J -factors set (green exclusion region) and the GS15 J -factors set (solid black line). The ULs previously obtained with the MAGIC observation of Segue 1 are depicted by the dashed black line [7, 8]. The grey dashed region depicts the model validity limit in the $f(m_\chi)$ parameter space.

of multi-instrument and multi-messenger DM searches [51, 52] by performing a global branon DM search with a joint analysis of observational data from different ground/space-based gamma-ray and neutrino telescopes. Future instruments, such as CTA and SKA, will probe even a larger fraction of the exclusion region, providing valuable complementary information in both gamma-ray and radio observations, respectively.

Acknowledgments

T. Miener: Principal investigator, MAGIC data analysis, publication coordination; D. Kerzberg: MAGIC data analysis, publication coordination; V. Gammaldi: Branon Dark Matter theory, interpretation J. Rico: Statistical analysis supervision and software framework development; D. Nieto: supervision and coordination, interpretation. The rest of the authors have contributed in one or several of the following ways: design, construction, maintenance, and operation of the instrument(s); preparation and/or evaluation of the observation proposals; data acquisition, processing, calibration and/or reduction; production of analysis tools and/or related Monte Carlo simulations; discussion and approval of the contents of the draft. We would like to thank the Instituto de Astrofísica de Canarias for the excellent working conditions at the Observatorio del Roque de los Muchachos in La Palma. The financial support

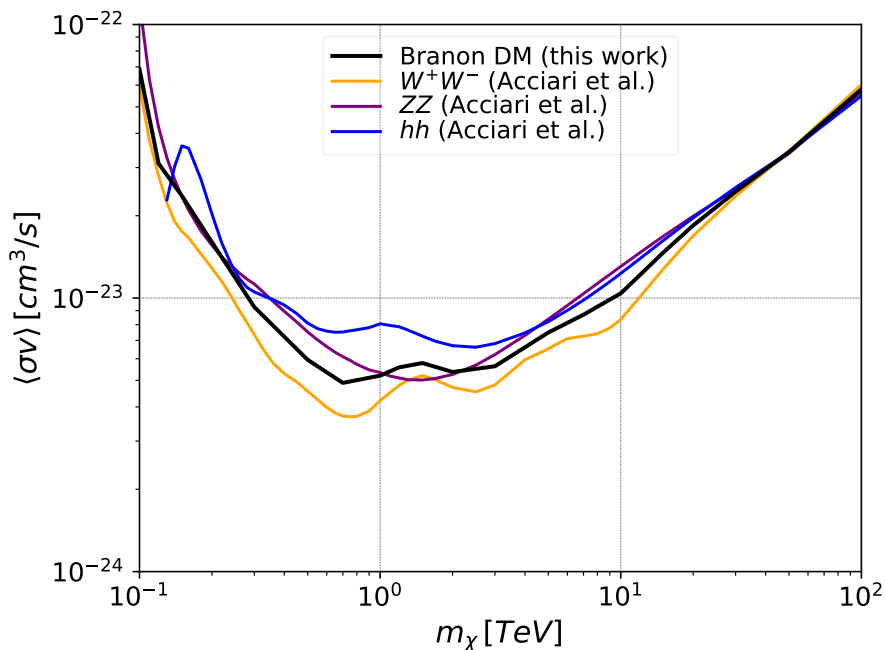


Figure 4. Comparison of the 95% ULs on $\langle\sigma v\rangle$ for branon DM annihilation (black, this work) and the dominant annihilation mode W^+W^- (yellow), ZZ (purple), and hh (blue) in the branon DM model (extracted from [12]).

of the German BMBF, MPG and HGF; the Italian INFN and INAF; the Swiss National Fund SNF; the grants PID2019-104114RB-C31, PID2019-104114RB-C32, PID2019-104114RB-C33, PID2019-105510GB-C31, PID2019-107847RB-C41, PID2019-107847RB-C42, PID2019-107847RB-C44, PID2019-107988GB-C22, PID2022-136828NB-C41, PID2022-137810NB-C22, PID2022-138172NB-C41, PID2022-138172NB-C42, PID2022-138172NB-C43, PID2022-139117NB-C41, PID2022-139117NB-C42, PID2022-139117NB-C43, PID2022-139117NB-C44 funded by the Spanish MCIN/AEI/ 10.13039/501100011033 and “ERDF A way of making Europe”; the Indian Department of Atomic Energy; the Japanese ICRR, the University of Tokyo, JSPS, and MEXT; the Bulgarian Ministry of Education and Science, National RI Roadmap Project DO1-400/18.12.2020 and the Academy of Finland grant nr. 320045 is gratefully acknowledged. This work was also been supported by Centros de Excelencia “Severo Ochoa” y Unidades “María de Maeztu” program of the Spanish MCIN/AEI/ 10.13039/501100011033 (CEX2019-000920-S, CEX2019-000918-M, CEX2021-001131-S) and by the CERCA institution and grants 2021SGR00426 and 2021SGR00773 of the Generalitat de Catalunya; by the Croatian Science Foundation (HrZZ) Project IP-2022-10-4595 and the University of Rijeka Project uniri-prirod-18-48; by the Deutsche Forschungsgemeinschaft (SFB1491) and by the Lamarr-Institute for Machine Learning and Artificial Intelligence; by the Polish Ministry Of Education and Science grant No. 2021/WK/08; and by the Brazilian MCTIC, CNPq and FAPERJ. This work was supported by the Grant RYC2021-032552-I funded by MCIN/AEI/10.13039/501100011033 and by the European Union NextGenerationEU/PRTR.

VG’s contribution to this work has been supported by Juan de la Cierva-Incorporación IJC2019-040315-I grant, and by the PGC2018-095161-B-I00, PID2022-139841NB-I00 and CEX2020-001007-S projects, both funded by MCIN/AEI/10.13039/501100011033 and by “ERDF A way of making Europe”. VG thanks J.A.R. Cembranos for useful discussions.

References

- [1] PLANCK collaboration, *Planck 2018 results. VI. Cosmological parameters*, *Astron. Astrophys.* **641** (2020) A6 [*Erratum ibid.* **652** (2021) C4] [[arXiv:1807.06209](#)] [[INSPIRE](#)].
- [2] G. Bertone and D. Merritt, *Dark matter dynamics and indirect detection*, *Mod. Phys. Lett. A* **20** (2005) 1021 [[astro-ph/0504422](#)] [[INSPIRE](#)].
- [3] J.A.R. Cembranos, A. Dobado and A.L. Maroto, *Brane world dark matter*, *Phys. Rev. Lett.* **90** (2003) 241301 [[hep-ph/0302041](#)] [[INSPIRE](#)].
- [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 [[arXiv:1204.3622](#)] [[INSPIRE](#)].
- [5] D. Merritt, M. Milosavljevic, L. Verde and R. Jimenez, *Dark matter spikes and annihilation radiation from the galactic center*, *Phys. Rev. Lett.* **88** (2002) 191301 [[astro-ph/0201376](#)] [[INSPIRE](#)].
- [6] SDSS collaboration, *Cats and dogs, hair and a hero: a quintet of new Milky Way companions*, *Astrophys. J.* **654** (2007) 897 [[astro-ph/0608448](#)] [[INSPIRE](#)].
- [7] T. Miener et al., *Constraining branon dark matter from observations of the Segue 1 dwarf spheroidal galaxy with the MAGIC telescopes*, *JCAP* **05** (2022) 005 [[arXiv:2201.03344](#)] [[INSPIRE](#)].
- [8] T. Miener et al., *Constraining branon dark matter from observations of the Segue 1 dwarf spheroidal galaxy with the MAGIC telescopes*, *JCAP* **05** (2022) 005 [[arXiv:2201.03344](#)] [[INSPIRE](#)].
- [9] V. Bonnavard, D. Maurin and M.G. Walker, *Contamination of stellar-kinematic samples and uncertainty about dark matter annihilation profiles in ultrafaint dwarf galaxies: the example of Segue I*, *Mon. Not. Roy. Astron. Soc.* **462** (2016) 223 [[arXiv:1506.08209](#)] [[INSPIRE](#)].
- [10] V. Bonnavard et al., *Dark matter annihilation and decay in dwarf spheroidal galaxies: the classical and ultrafaint dSphs*, *Mon. Not. Roy. Astron. Soc.* **453** (2015) 849 [[arXiv:1504.02048](#)] [[INSPIRE](#)].
- [11] 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 [[arXiv:1408.0002](#)] [[INSPIRE](#)].
- [12] MAGIC collaboration, *Combined searches for dark matter in dwarf spheroidal galaxies observed with the MAGIC telescopes, including new data from Coma Berenices and Draco*, *Phys. Dark Univ.* **35** (2022) 100912 [[arXiv:2111.15009](#)] [[INSPIRE](#)].
- [13] N. Arkani-Hamed, S. Dimopoulos and G.R. Dvali, *The hierarchy problem and new dimensions at a millimeter*, *Phys. Lett. B* **429** (1998) 263 [[hep-ph/9803315](#)] [[INSPIRE](#)].
- [14] N. Arkani-Hamed, S. Dimopoulos and G.R. Dvali, *Phenomenology, astrophysics and cosmology of theories with submillimeter dimensions and TeV scale quantum gravity*, *Phys. Rev. D* **59** (1999) 086004 [[hep-ph/9807344](#)] [[INSPIRE](#)].

- [15] L. Randall and R. Sundrum, *A large mass hierarchy from a small extra dimension*, *Phys. Rev. Lett.* **83** (1999) 3370 [[hep-ph/9905221](#)] [[INSPIRE](#)].
- [16] L. Randall and R. Sundrum, *An alternative to compactification*, *Phys. Rev. Lett.* **83** (1999) 4690 [[hep-th/9906064](#)] [[INSPIRE](#)].
- [17] 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*, *Phys. Dark Univ.* **27** (2020) 100448 [[arXiv:1905.11154](#)] [[INSPIRE](#)].
- [18] J.A.R. Cembranos, A. Dobado and A.L. Maroto, *Cosmological and astrophysical limits on brane fluctuations*, *Phys. Rev. D* **68** (2003) 103505 [[hep-ph/0307062](#)] [[INSPIRE](#)].
- [19] J. Alcaraz, J.A.R. 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](#)] [[INSPIRE](#)].
- [20] 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 [[arXiv:1111.4448](#)] [[INSPIRE](#)].
- [21] M. Cirelli et al., *PPPC 4 DM ID: a Poor Particle Physicist Cookbook for Dark Matter Indirect Detection*, *JCAP* **03** (2011) 051 [Erratum *ibid.* **10** (2012) E01] [[arXiv:1012.4515](#)] [[INSPIRE](#)].
- [22] 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 [[arXiv:2006.16706](#)] [[INSPIRE](#)].
- [23] MAGIC collaboration, *Combined search in dwarf spheroidal galaxies for branon dark matter annihilation signatures with the MAGIC telescopes*, *PoS Gamma2022* (2024) 196 [[arXiv:2211.07979](#)] [[INSPIRE](#)].
- [24] MAGIC collaboration, *The major upgrade of the MAGIC telescopes, part II: a performance study using observations of the Crab nebula*, *Astropart. Phys.* **72** (2016) 76 [[arXiv:1409.5594](#)] [[INSPIRE](#)].
- [25] MAGIC collaboration, *Search for dark matter signatures with MAGIC-I and prospects for MAGIC phase-II*, [arXiv:0907.0738](#) [[INSPIRE](#)].
- [26] MAGIC collaboration, *Searches for dark matter annihilation signatures in the Segue 1 satellite galaxy with the MAGIC-I telescope*, *JCAP* **06** (2011) 035 [[arXiv:1103.0477](#)] [[INSPIRE](#)].
- [27] J. Aleksić et al., *Optimized dark matter searches in deep observations of Segue 1 with MAGIC*, *JCAP* **02** (2014) 008 [[arXiv:1312.1535](#)] [[INSPIRE](#)].
- [28] MAGIC and FERMI-LAT collaborations, *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 [[arXiv:1601.06590](#)] [[INSPIRE](#)].
- [29] MAGIC collaboration, *Indirect dark matter searches in the dwarf satellite galaxy Ursa Major II with the MAGIC telescopes*, *JCAP* **03** (2018) 009 [[arXiv:1712.03095](#)] [[INSPIRE](#)].
- [30] MAGIC collaboration, *A search for dark matter in Triangulum II with the MAGIC telescopes*, *Phys. Dark Univ.* **28** (2020) 100529 [[arXiv:2003.05260](#)] [[INSPIRE](#)].
- [31] E.N. Kirby et al., *Triangulum II. Not especially dense after all*, *Astrophys. J.* **838** (2017) 83 [[arXiv:1703.02978](#)].

- [32] A. Saldana-Lopez et al., *An observational determination of the evolving extragalactic background light from the multiwavelength HST/CANDELS survey in the Fermi and CTA era*, *Mon. Not. Roy. Astron. Soc.* **507** (2021) 5144 [[arXiv:2012.03035](#)] [[INSPIRE](#)].
- [33] T.-P. Li and Y.-Q. Ma, *Analysis methods for results in gamma-ray astronomy*, *Astrophys. J.* **272** (1983) 317 [[INSPIRE](#)].
- [34] V. Bonnivard, C. Combet, D. Maurin and M.G. Walker, *Spherical Jeans analysis for dark matter indirect detection in dwarf spheroidal galaxies — impact of physical parameters and triaxiality*, *Mon. Not. Roy. Astron. Soc.* **446** (2015) 3002 [[arXiv:1407.7822](#)] [[INSPIRE](#)].
- [35] M.G. Walker, E.W. Olszewski and M. Mateo, *Bayesian analysis of resolved stellar spectra: application to MMT/Hectochelle observations of the Draco dwarf spheroidal*, *Monthly Notices of the Royal Astronomical Society* **448** (2015) 2717 [[arXiv:1503.02589](#)].
- [36] A. Moralejo et al., *MARS, the MAGIC Analysis and Reconstruction Software*, [arXiv:0907.0943](#).
- [37] T. Miener et al., *Open-source analysis tools for multi-instrument dark matter searches*, *ASP Conf. Ser.* **535** (2024) 17 [[arXiv:2112.01818](#)] [[INSPIRE](#)].
- [38] J. Rico et al., *gLike: numerical maximization of heterogeneous joint likelihood functions of a common free parameter plus nuisance parameters* [Zenodo](#), March 2021.
- [39] T. Miener and D. Nieto, *LklCom: combining likelihoods from different experiments*, [Zenodo](#), March 2021.
- [40] J. Aleksic, J. Rico and M. Martinez, *Optimized analysis method for indirect dark matter searches with imaging air Cherenkov telescopes*, *JCAP* **10** (2012) 032 [[arXiv:1209.5589](#)] [[INSPIRE](#)].
- [41] J. Rico, *Gamma-ray dark matter searches in Milky Way satellites — a comparative review of data analysis methods and current results*, *Galaxies* **8** (2020) 25 [[arXiv:2003.13482](#)] [[INSPIRE](#)].
- [42] FERMI-LAT collaboration, *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 [[arXiv:1503.02641](#)] [[INSPIRE](#)].
- [43] W.A. Rolke, A.M. López and J. Conrad, *Limits and confidence intervals in the presence of nuisance parameters*, *Nucl. Instrum. Meth. A* **551** (2005) 493 [[physics/0403059](#)] [[INSPIRE](#)].
- [44] 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](#)] [[INSPIRE](#)].
- [45] J. Hisano, S. Matsumoto and M.M. Nojiri, *Explosive dark matter annihilation*, *Phys. Rev. Lett.* **92** (2004) 031303 [[hep-ph/0307216](#)] [[INSPIRE](#)].
- [46] VERITAS collaboration, *VERITAS deep observations of the dwarf spheroidal galaxy Segue 1*, *Phys. Rev. D* **85** (2012) 062001 [Erratum *ibid.* **91** (2015) 129903] [[arXiv:1202.2144](#)] [[INSPIRE](#)].
- [47] 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 [[arXiv:1410.8812](#)] [[INSPIRE](#)].
- [48] J.A.R. Cembranos, A. 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 [[arXiv:1709.09819](#)] [[INSPIRE](#)].
- [49] AMS collaboration, *First result from the Alpha Magnetic Spectrometer on the International Space Station: precision measurement of the positron fraction in primary cosmic rays of 0.5–350 GeV*, *Phys. Rev. Lett.* **110** (2013) 141102 [[INSPIRE](#)].

- [50] AMS collaboration, *The Alpha Magnetic Spectrometer (AMS) on the International Space Station: part II — results from the first seven years*, *Phys. Rept.* **894** (2021) 1 [[INSPIRE](#)].
- [51] FERMI-LAT et al. collaborations, *Combined dark matter searches towards dwarf spheroidal galaxies with Fermi-LAT, HAWC, HESS, MAGIC and VERITAS*, *PoS ICRC2019* (2021) 012 [[arXiv:1909.06310](#)] [[INSPIRE](#)].
- [52] HESS et al. collaborations, *Combined dark matter searches towards dwarf spheroidal galaxies with Fermi-LAT, HAWC, H.E.S.S., MAGIC, and VERITAS*, *PoS ICRC2021* (2021) 528 [[arXiv:2108.13646](#)] [[INSPIRE](#)].

The MAGIC collaboration

S. Abe¹, J. Abhir², A. Abhishek³, V. A. Acciari⁴, A. Aguasca-Cabot⁵, I. Agudo⁶, T. Aniello⁷, S. Ansoldi^{8,40}, A. Arbet Engels⁹, C. Arcaro¹⁰, K. Asano¹, D. Baack¹¹, A. Babić¹², U. Barres de Almeida¹³, J. A. Barrio¹⁴, I. Batković¹⁰, A. Bautista⁹, J. Baxter¹, J. Becerra González¹⁵, W. Bednarek¹⁶, E. Bernardini¹⁰, J. Bernete¹⁷, A. Berti⁹, J. Besenrieder⁹, C. Bigongiari⁷, A. Biland², O. Blanch⁴, G. Bonnoli⁷, Ž. Bošnjak¹², E. Bronzini⁷, I. Burelli⁸, A. Campoy-Ordaz¹⁸, R. Carosi¹⁹, M. Carretero-Castrillo⁵, A. J. Castro-Tirado⁶, D. Cerasole²⁰, G. Ceribella⁹, Y. Chai¹, A. Cifuentes¹⁷, E. Colombo⁴, J. L. Contreras¹⁴, J. Cortina¹⁷, S. Covino⁷, G. D’Amico²¹, V. D’Elia⁷, P. Da Vela⁷, F. Dazzi⁷, A. De Angelis¹⁰, B. De Lotto⁸, R. de Menezes²², J. Delgado^{4,41}, C. Delgado Mendez¹⁷, F. Di Pierro²², R. Di Tria²⁰, L. Di Venere²⁰, D. Dominis Prester²³, A. Donini⁷, D. Dorner²⁴, M. Doro¹⁰, D. Elsaesser¹¹, J. Escudero⁶, L. Fariña⁴, A. Fattorini¹¹, L. Foffano⁷, L. Font¹⁸, S. Fröse¹¹, S. Fukami², Y. Fukazawa²⁵, R. J. García López¹⁵, M. Garczarczyk²⁶, S. Gasparyan²⁷, M. Gaug¹⁸, J. G. Giesbrecht Paiva¹³, N. Giglietto²⁰, F. Giordano²⁰, P. Gliwny¹⁶, T. Gradetzke¹¹, R. Grau⁴, D. Green⁹, J. G. Green⁹, P. Günther²⁴, D. Hadasch¹, A. Hahn⁹, T. Hassan¹⁷, L. Heckmann⁹, J. Herrera Llorente¹⁵, D. Hrupec²⁸, R. Imazawa²⁵, K. Ishio¹⁶, I. Jiménez Martínez⁹, J. Jormanainen²⁹, S. Kankkunen²⁹, T. Kayanoki²⁵, D. Kerszberg^{4,47,*}, G. W. Kluge^{21,42}, Y. Kobayashi¹, P. M. Kouch²⁹, H. Kubo¹, J. Kushida³⁰, M. Láinez¹⁴, A. Lamastra⁷, F. Leone⁷, E. Lindfors²⁹, S. Lombardi⁷, F. Longo^{8,43}, R. López-Coto⁶, M. López-Moya¹⁴, A. López-Oramas¹⁵, S. Loporchio²⁰, A. Lorini³, E. Lyard³¹, P. Majumdar³², M. Makariev³³, G. Maneva³³, M. Manganaro²³, S. Mangano¹⁷, K. Mannheim²⁴, M. Mariotti¹⁰, M. Martínez⁴, M. Martínez-Chicharro¹⁷, A. Mas-Aguilar¹⁴, D. Mazin^{1,44}, S. Menchiari⁶, S. Mender¹¹, D. Miceli¹⁰, T. Miener^{14,48,*}, J. M. Miranda³, R. Mirzoyan⁹, M. Molero González¹⁵, E. Molina¹⁵, H. A. Mondal³², A. Moralejo⁴, D. Morcuende⁶, T. Nakamori³⁴, C. Nanci⁷, V. Neustroev³⁵, M. Nievas Rosillo¹⁵, C. Nigro⁴, L. Nikolić³, K. Nishijima³⁰, T. Njoh Ekoume⁴, S. Nozaki⁹, A. Okumura³⁶, J. Otero-Santos⁶, S. Paiano⁷, D. Paneque⁹, R. Paoletti³, J. M. Paredes⁵, M. Peresano⁹, M. Persic^{8,45}, M. Pihet¹⁰, G. Pirola⁹, F. Podobnik³, P. G. Prada Moroni¹⁹, E. Prandini¹⁰, G. Principe⁸, W. Rhode¹¹, M. Ribó⁵, J. Rico⁴, C. Righi⁷, N. Sahakyan²⁷, T. Saito¹, F. G. Saturni⁷, K. Schmidt¹¹, F. Schmuckermaier⁹, J. L. Schubert¹¹, A. Sciacaluga⁷, G. Silvestri¹⁰, J. Sitarek¹⁶, V. Sliusar³¹, A. Spolon¹⁰, D. Sobczynska¹⁶, J. Strišković²⁸, D. Strom⁹, M. Strzys¹, Y. Suda²⁵, H. Tajima³⁶, R. Takeishi¹, P. Temnikov³³, K. Terauchi³⁷, T. Terzić²³, M. Teshima^{9,46}, S. Truzzi³, A. Tutone⁷, S. Ubach¹⁸, J. van Scherpenberg⁹, M. Vazquez Acosta¹⁵, S. Ventura³, G. Verna³, I. Viale¹⁰, C. F. Vigorito²², V. Vitale³⁸, I. Vovk¹, R. Walter³¹, F. Wersig¹¹, M. Will⁹, C. Wunderlich³, T. Yamamoto³⁹, V. Gammaldi^{49,50,51,a,*}, D. Nieto^{14,a}

¹ Japanese MAGIC Group: Institute for Cosmic Ray Research (ICRR), The University of Tokyo, Kashiwa, 277-8582 Chiba, Japan

² ETH Zürich, CH-8093 Zürich, Switzerland

³ Università di Siena and INFN Pisa, I-53100 Siena, Italy

⁴ Institut de Física d’Altes Energies (IFAE), The Barcelona Institute of Science and Technology (BIST), E-08193 Bellaterra (Barcelona), Spain

⁵ Universitat de Barcelona, ICCUB, IEEC-UB, E-08028 Barcelona, Spain

- ⁶ *Instituto de Astrofísica de Andalucía-CSIC, Glorieta de la Astronomía s/n, 18008, Granada, Spain*
- ⁷ *National Institute for Astrophysics (INAF), I-00136 Rome, Italy*
- ⁸ *Università di Udine and INFN Trieste, I-33100 Udine, Italy*
- ⁹ *Max-Planck-Institut für Physik, D-85748 Garching, Germany*
- ¹⁰ *Università di Padova and INFN, I-35131 Padova, Italy*
- ¹¹ *Technische Universität Dortmund, D-44221 Dortmund, Germany*
- ¹² *Croatian MAGIC Group: University of Zagreb, Faculty of Electrical Engineering and Computing (FER), 10000 Zagreb, Croatia*
- ¹³ *Centro Brasileiro de Pesquisas Físicas (CBPF), 22290-180 URCA, Rio de Janeiro (RJ), Brazil*
- ¹⁴ *IPARCOS Institute and EMFTEL Department, Universidad Complutense de Madrid, E-28040 Madrid, Spain*
- ¹⁵ *Instituto de Astrofísica de Canarias and Dpto. de Astrofísica, Universidad de La Laguna, E-38200, La Laguna, Tenerife, Spain*
- ¹⁶ *University of Lodz, Faculty of Physics and Applied Informatics, Department of Astrophysics, 90-236 Lodz, Poland*
- ¹⁷ *Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, E-28040 Madrid, Spain*
- ¹⁸ *Departament de Física, and CERES-IEEC, Universitat Autònoma de Barcelona, E-08193 Bellaterra, Spain*
- ¹⁹ *Università di Pisa and INFN Pisa, I-56126 Pisa, Italy*
- ²⁰ *INFN MAGIC Group: INFN Sezione di Bari and Dipartimento Interateneo di Fisica dell'Università e del Politecnico di Bari, I-70125 Bari, Italy*
- ²¹ *Department for Physics and Technology, University of Bergen, Norway*
- ²² *INFN MAGIC Group: INFN Sezione di Torino and Università degli Studi di Torino, I-10125 Torino, Italy*
- ²³ *Croatian MAGIC Group: University of Rijeka, Faculty of Physics, 51000 Rijeka, Croatia*
- ²⁴ *Universität Würzburg, D-97074 Würzburg, Germany*
- ²⁵ *Japanese MAGIC Group: Physics Program, Graduate School of Advanced Science and Engineering, Hiroshima University, 739-8526 Hiroshima, Japan*
- ²⁶ *Deutsches Elektronen-Synchrotron (DESY), D-15738 Zeuthen, Germany*
- ²⁷ *Armenian MAGIC Group: ICRANet-Armenia, 0019 Yerevan, Armenia*
- ²⁸ *Croatian MAGIC Group: Josip Juraj Strossmayer University of Osijek, Department of Physics, 31000 Osijek, Croatia*
- ²⁹ *Finnish MAGIC Group: Finnish Centre for Astronomy with ESO, Department of Physics and Astronomy, University of Turku, FI-20014 Turku, Finland*
- ³⁰ *Japanese MAGIC Group: Department of Physics, Tokai University, Hiratsuka, 259-1292 Kanagawa, Japan*
- ³¹ *University of Geneva, Chemin d'Ecogia 16, CH-1290 Versoix, Switzerland*
- ³² *Saha Institute of Nuclear Physics, A CI of Homi Bhabha National Institute, Kolkata 700064, West Bengal, India*
- ³³ *Inst. for Nucl. Research and Nucl. Energy, Bulgarian Academy of Sciences, BG-1784 Sofia, Bulgaria*
- ³⁴ *Japanese MAGIC Group: Department of Physics, Yamagata University, Yamagata 990-8560, Japan*
- ³⁵ *Finnish MAGIC Group: Space Physics and Astronomy Research Unit, University of Oulu, FI-90014 Oulu, Finland*
- ³⁶ *Japanese MAGIC Group: Institute for Space-Earth Environmental Research and Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, Nagoya University, 464-6801 Nagoya, Japan*
- ³⁷ *Japanese MAGIC Group: Department of Physics, Kyoto University, 606-8502 Kyoto, Japan*
- ³⁸ *INFN MAGIC Group: INFN Roma Tor Vergata, I-00133 Roma, Italy*
- ³⁹ *Japanese MAGIC Group: Department of Physics, Konan University, Kobe, Hyogo 658-8501, Japan*
- ⁴⁰ *Also at International Center for Relativistic Astrophysics (ICRA), Rome, Italy*
- ⁴¹ *Also at Port d'Informació Científica (PIC), E-08193 Bellaterra (Barcelona), Spain*
- ⁴² *Also at Department of Physics, University of Oslo, Norway*
- ⁴³ *Also at Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy*
- ⁴⁴ *Max-Planck-Institut für Physik, D-85748 Garching, Germany*
- ⁴⁵ *Also at INAF Padova, Padova, Italy*

⁴⁶ *Japanese MAGIC Group: Institute for Cosmic Ray Research (ICRR), The University of Tokyo, Kashiwa, 277-8582 Chiba, Japan*

⁴⁷ *Now at Sorbonne Université, CNRS/IN2P3, Laboratoire de Physique Nucléaire et de Hautes Energies, LPNHE, 4 place Jussieu, 75005 Paris, France*

⁴⁸ *Now at Département de physique nucléaire et corpusculaire, University de Genève, Faculté de Sciences, 1205 Genève, Switzerland*

⁴⁹ *Departamento de Física Teórica, Facultad de Ciencias, Mod. 15, Universidad Autónoma de Madrid, E-28049 Madrid, Spain*

⁵⁰ *Instituto de Física Teórica, UAM-CSIC, Calle Nicolás Cabrera 13-15, Campus de Cantoblanco, E-28049 Madrid, Spain*

⁵¹ *Now at Department of Information Technology, Escuela Politecnica Superior, Universidad San Pablo-CEU, CEU Universities, Campus Monteprincipe, Boadilla del Monte, Madrid 28668, Spain*

* *Corresponding author*

^a *Not a member of the MAGIC collaboration.*