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



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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

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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 Bonnivard 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.

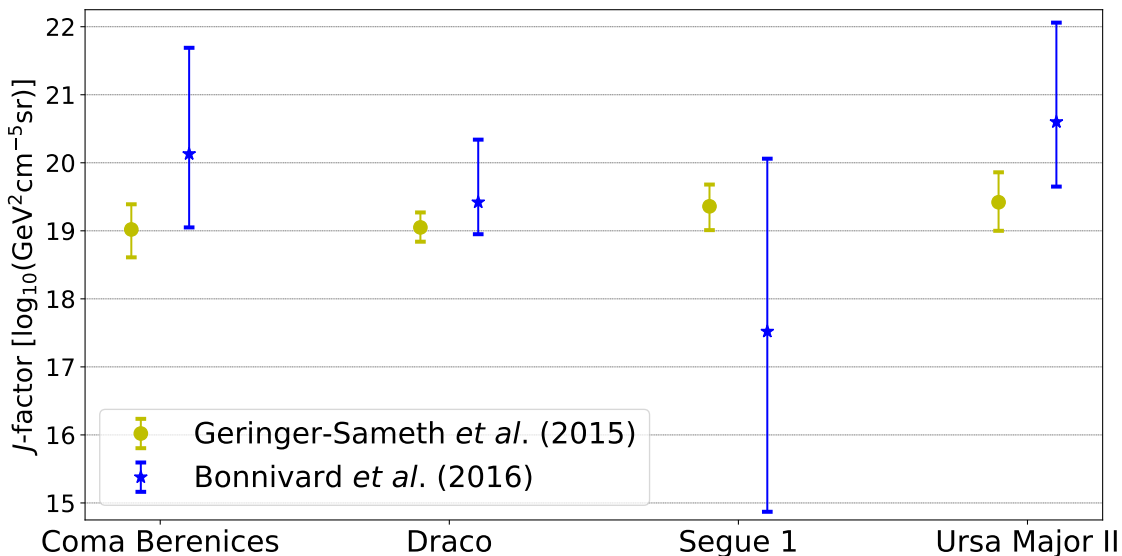


Figure 1. Comparison of the J -factor values and its uncertainties from GS15 [11] (green dots) and B16 [10] (blue stars) for all considered dSphs.

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:

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

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

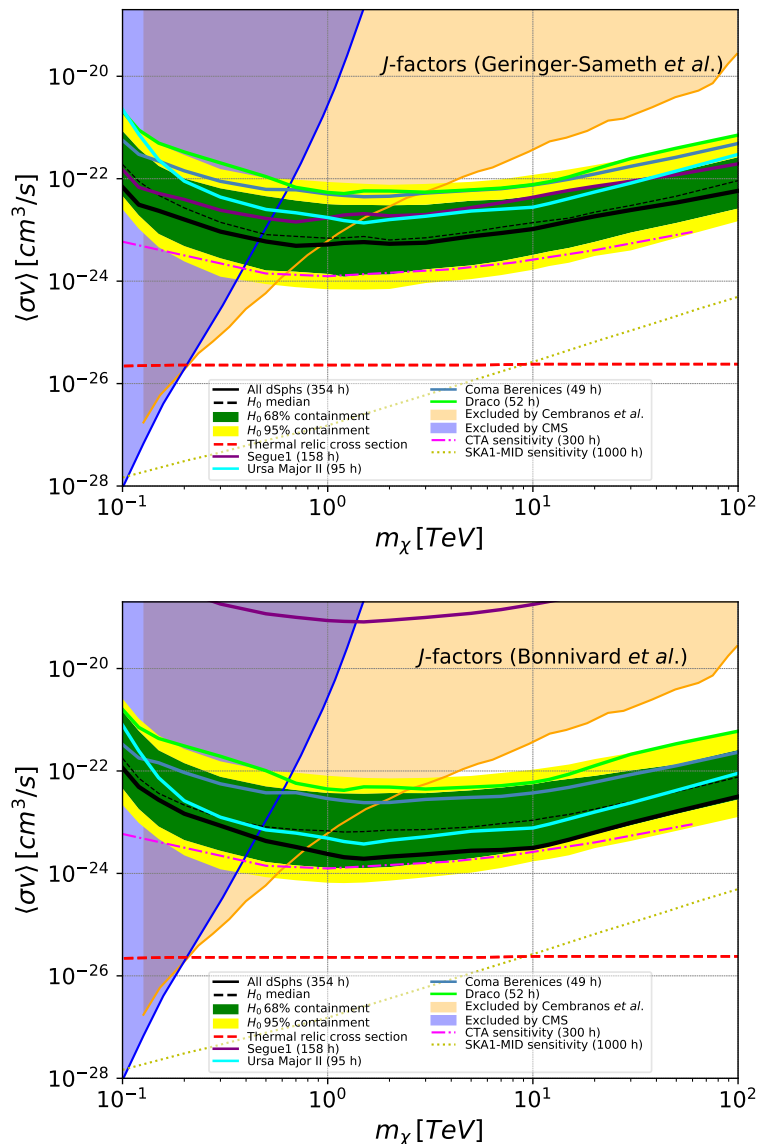


Figure 2. 95% ULs on $\langle\sigma v\rangle$ for branon DM annihilation from the combined analysis (solid black line) and the analysis of the individual dSphs (Segue 1 purple, Ursa Major II cyan, Draco lime green, and Coma Berenices steel blue). The median and the two-sided 68% and 95% containment bands 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].

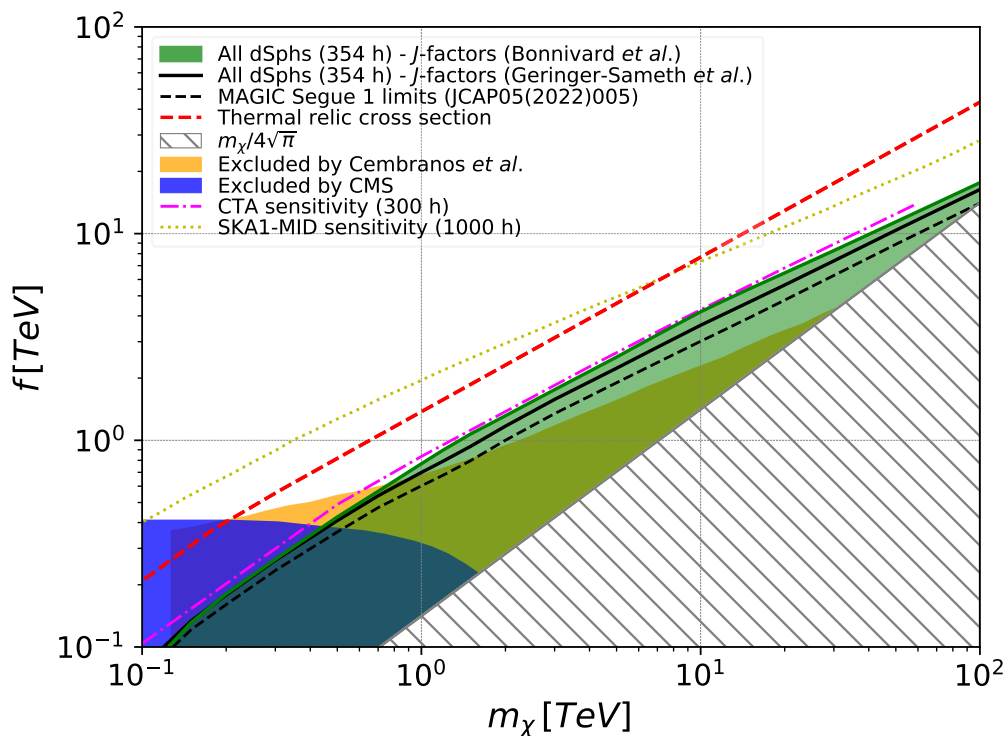


Figure 3. 95% ULs on f for branon DM annihilation from the combined analysis with the B16 J -factors set (green exclusion region) and the GS15 J -factors set (solid black line). The ULs previously obtained with the MAGIC observation of Segue 1 are depicted by the dashed black line [7, 8]. The grey dashed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

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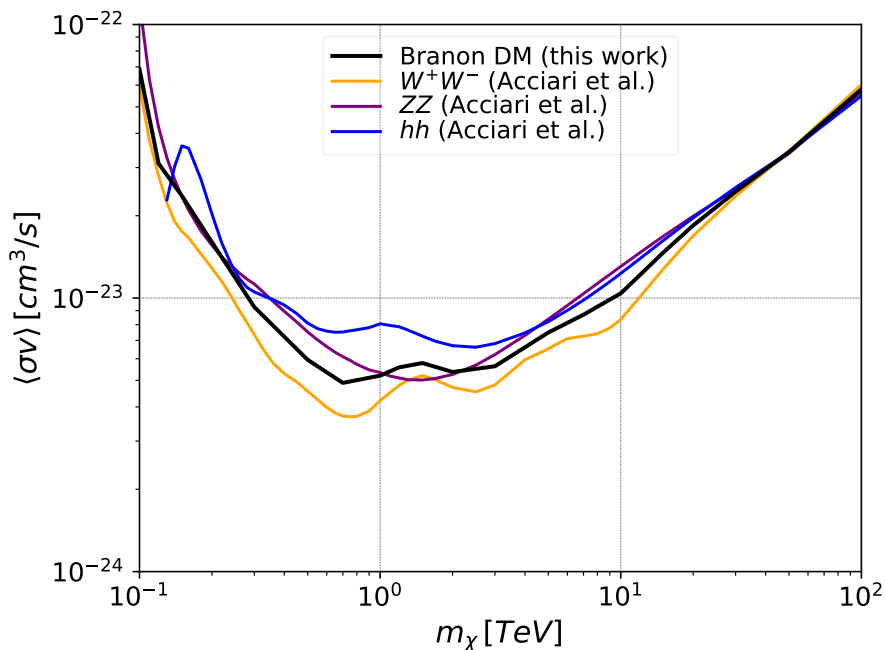


Figure 4. Comparison of the 95% ULs on $\langle\sigma v\rangle$ for branon DM annihilation (black, this work) and the dominant annihilation mode W^+W^- (yellow), ZZ (purple), and hh (blue) in the branon DM model (extracted from [12]).

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