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

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One of the most pressing questions for modern physics is the nature of dark matter (DM). Several efforts have been made to model this elusive kind of matter. The largest fraction of DM cannot be made of any of the known particles of the Standard Model (SM). We focus on brane world theory as a prospective framework for DM candidates beyond the SM of particle physics. The new degrees of freedom that appear in flexible brane world models, corresponding to brane fluctuations, are called branons. They behave as weakly interacting massive particles (WIMPs), which are one of the most favored candidates for DM. We present a multi-target DM search in dwarf spheroidal galaxies for branon DM annihilation signatures with the ground-based gamma-ray telescope MAGIC leading to the most constraining branon DM limits in the TeV mass range.

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## 1. Introduction

The nature of dark matter (DM) is still an open question for modern physics. According to the *Planck 2018 results* [1], non-baryonic cold DM accounts for 84% of the matter density of the Universe based on astrophysical and cosmological evidences. Brane-world theory as a prospective framework for DM candidates [2] proposes massive brane fluctuations (branons) as a natural TeV DM candidate, since their characteristics match the ones of weakly interacting massive particles (WIMPs) [3].

Dwarf spheroidal galaxies (dSphs) are preferred targets for indirect DM searches because they are not expected to host strong conventional gamma-ray emitters that may hinder the detection of a subdominant DM signal. In addition, they are close by, and have high mass-to-light ratios. Finally, compared to other very prominent targets for DM searches the Galactic Center (GC) and galaxy clusters [4, 5], dSphs are spatially less extended. In this work, we are searching for branon dark matter annihilation signatures in dSphs with the MAGIC telescopes.

## 2. Branon dark matter

The expected photon flux produced by branon DM annihilation is composed of the *astrophysical* factor ($J$-factor), which depends on both the distance $l$ and the DM distribution at the source region $\rho_{\mathrm{DM}}$, and the *particle physics* factor, mainly the differential photon yield per branon annihilation. It can be expressed from a given solid angle region in the sky, $\Delta\Omega$, as

$$\frac{\mathrm{d}\Phi_{\mathrm{BDM}}}{\mathrm{d}E}(\langle\sigma v\rangle) = \underbrace{\int_{\Delta\Omega} d\Omega' \int_{\mathrm{l.o.s.}} dl\, \rho^2_{\mathrm{DM}}(l,\Omega')}_{\text{Astrophysics}} \cdot \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m^2_\chi}\frac{\mathrm{d}N_{\mathrm{BDM}}}{\mathrm{d}E}}_{\text{Particle physics}} \tag{1}$$

with

$$\frac{\mathrm{d}N_{\mathrm{BDM}}}{\mathrm{d}E} = \sum_{i=1}^{n} \mathrm{Br}_i \frac{\mathrm{d}N_i}{\mathrm{d}E}, \tag{2}$$

where $\langle\sigma v\rangle$ is the thermally-averaged annihilation cross section (our parameter of interest and therefore the only free parameter in our likelihood analysis of Sec. 4), $m_\chi$ is the mass of the branon DM particle and l.o.s. stands for line-of-sight. The differential photon yields per annihilation into SM pairs $\mathrm{d}N_i/\mathrm{d}E$ are taken from the PPPC 4 DM ID distribution [6]. The left panel of Fig. 1 shows the branon branching ratios $\mathrm{Br}_i$ as a function of $m_\chi$ [7]. The differential photon yield per branon annihilation $\mathrm{d}N_{\mathrm{BDM}}/\mathrm{d}E$ is depicted for a set of DM masses in the right panel of Fig. 1.

## 3. Dwarf spheroidal galaxies observations with the MAGIC telescopes

The *Florian Goebel* Major Atmospheric Gamma-ray Imaging Cherenkov (MAGIC) telescopes[1] are located at the Roque de los Muchachos Observatory (28.8° N, 17.9° W) on the Canary Island of La Palma, Spain. MAGIC consists of two 17-m diameter reflector imaging atmospheric Cherenkov telescopes (IACTs), which inspect the very-high energy (VHE, $\gtrsim 50$ GeV) gamma-ray sky probing the most extreme astrophysical environments in our universe.

[1] https://magic.mpp.mpg.de/



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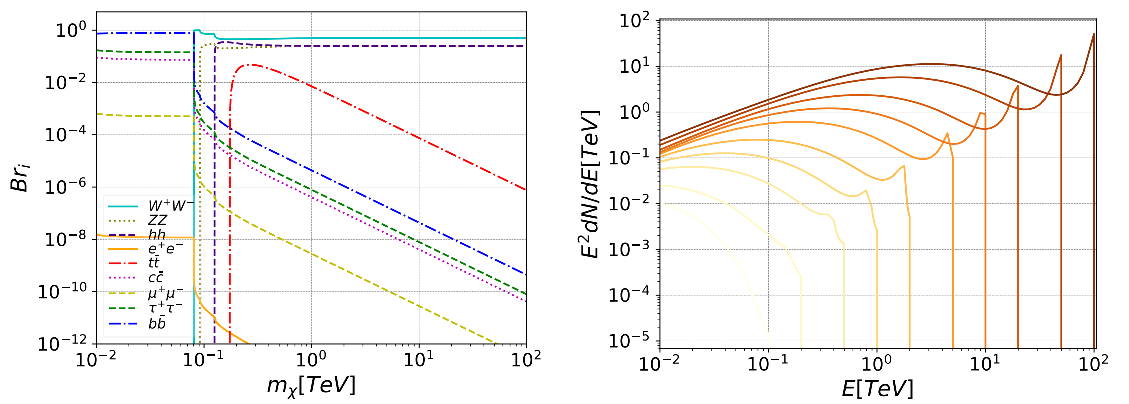


**Figure 1:** Taken from [7]. *Left:* The branon branching ratios as a function of $m_\chi$ for DM masses from 10 GeV up to 100 TeV. *Right:* The differential photon yield per branon annihilation $\mathrm{d}N_{\mathrm{BDM}}/\mathrm{d}E$ (Eq. 2) for a set of DM masses (from light to dark: 0.1, 0.2, 0.5, 1, 2, 5, 10, 20, 50 and 100 TeV).

The MAGIC Collaboration has carried out extensive observations on dSphs in the Northern Hemisphere throughout the years, motivated by the search for DM signals in these objects. We include the dSph observations of Segue 1 (158h), Ursa Major II (95h), Draco (52h), and Coma Berenices (49h) with a total exposure of 354h in our work to align with the combined model independent DM search by MAGIC in [8]. We are also using the total $J$-factor and its statistical uncertainty from Geringer-Sameth *et al.* [9] (GS15) as [8]. Their corresponding values and its $\pm 1\sigma$ uncertainties are listed in Tab. 1 and visualized in Fig. 2.

| Name | Distance [kpc] | $l, b$ [°] | $\log_{10} J$ [$\log_{10}(\mathrm{GeV}^2\mathrm{cm}^{-5}\mathrm{sr})$] | Zd [°] | $T_{\mathrm{obs}}$ [h] | E [TeV] | $\theta$ [°] | $S_{\mathrm{Li\&Ma}}$ [$\sigma$] |
|---|---|---|---|---|---|---|---|---|
| Coma Berenices | 44 | 241.89, 83.61 | $19.02^{+0.37}_{-0.41}$ | 5 – 37 | 49 | 0.06 – 100 | 0.17 | – |
| Draco | 76 | 86.37, 34.72 | $19.05^{+0.22}_{-0.21}$ | 29 – 45 | 52 | 0.07 – 100 | 0.22 | – |
| Segue 1 | 23 | 220.48, 50.43 | $19.36^{+0.32}_{-0.35}$ | 13 – 37 | 158 | 0.06 – 100 | 0.12 | −0.5 |
| Ursa Major II | 32 | 152.46, 37.44 | $19.42^{+0.44}_{-0.42}$ | 35 – 45 | 95 | 0.12 – 100 | 0.30 | −2.1 |

**Table 1:** Summary of the dSph properties and observations by the MAGIC telescopes. 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 [9] used in the present work. We also report the zenith distance (Zd) range, the total observation time ($T_{\mathrm{obs}}$), and the energy range (E). We then list the angular radius ($\theta$) of the signal region, the normalization between background and signal regions ($\tau$), and the significance of detection ($S_{\mathrm{Li\&Ma}}$) calculated by following Li&Ma [10]. Note that the significance of detection is not reported for Coma Berenices and Draco in [8], but no gamma-ray excess have been found in any of these sources.

## 4. Likelihood analysis method

The low-level data of the four dSph observations (see Sec. 3) were reduced by the MAGIC Collaboration using the standard MAGIC analysis software MARS [11] and published in [8]. We re-analysed the high-level data products (event lists for `gLike`; likelihood curves for `LklCom`) in the context of brane-world extra-dimensional theories using the open-source analysis software tools [12] for multi-instrument and multi-target DM searches `gLike` [13] and `LklCom` [14].



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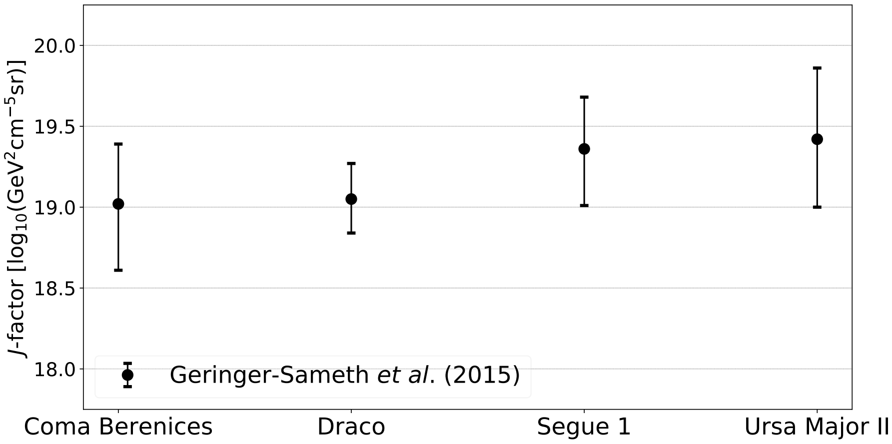


**Figure 2:** The total $J$-factor values and its uncertainties from GS15 [9] for all considered dSphs.

We followed the likelihood analysis scheme proposed by Aleksić, Rico and Martinez in [15], which is the standard DM analysis framework within the MAGIC Collaboration [8, 16–19]. Our final joint likelihood function $\mathcal{L}$ is a nested product of the binned likelihood function for each dSphs ($N_{\text{dSphs}} = 4$) and their distinct observational datasets ($N_{\text{obs},k}$ refers to the number of datasets of dSph $k$) with their corresponding set of instrument response functions (IRFs) caused by different observational conditions or hardware setup of the instrument. It reads for all datasets $\mathcal{D}$ with nuisance parameters $\boldsymbol{\nu}$ as

$$\mathcal{L}\left(\langle\sigma v\rangle; \boldsymbol{\nu} \mid \mathcal{D}\right) = \prod_{k=1}^{N_{\text{dSphs}}} \left\{ \prod_{l=1}^{N_{\text{obs},k}} \left[ \prod_{i=1}^{N_{\text{bins}}} \left( \mathcal{P}(s_{kli}(\langle\sigma v\rangle) + b_{kli} \mid N_{\text{ON},kli}) \cdot \mathcal{P}(\tau_{kl} b_{kli} \mid N_{\text{OFF},kli}) \right) \right] \times \mathcal{T}_{kl}\left(\tau_{kl} \mid \tau_{\text{o},kl}, \sigma_{\tau_{kl}}\right) \right\} \times \mathcal{J}_k\left(J_k \mid J_{\text{o},k}, \sigma_{\log_{10} J_k}\right) \tag{3}$$

where $\mathcal{P}(x|N)$ is the Poisson distribution of mean $x$ and measured value $N$, $s_{kli}(\langle\sigma v\rangle)$ and $b_{kli}$ are the expected numbers of signal and background events in the $i$-th energy bin, respectively, and $N_{\text{ON},kli}$, $N_{\text{OFF},kli}$ are the total number of observed events in a given energy bin $i$ of the $l$-th distinct dataset of the $k$-th dSph in the signal (ON) and background (OFF) regions, respectively. Besides $b_{kli}$, the normalization between background and signal regions $\tau_{kl}$, described by the likelihood function $\mathcal{T}_{kl}$[2], is a nuisance parameter in the analysis [8]. We treat also the $J$-factors as a nuisance parameters using the likelihood $\mathcal{J}_k$ for the $J$-factor of the $k$-th dSph following [20]. In the absence of a branon DM signal, upper limits (ULs) on $\langle\sigma v\rangle$ are set using a test statistic following [20].

[2]The likelihood function $\mathcal{T}_{kl}\left(\tau_{kl} \mid \tau_{\text{o,kl}}, \sigma_{\tau_{kl}}\right)$ of the $l$-th distinct dataset of the $k$-th dSph is a Gaussian with mean $\tau_{\text{o,kl}}$ and variance $\sigma^2_{\tau_{kl}}$, which include statistical and systematics uncertainties. We consider a systematic uncertainty of $\sigma_{\tau_{\text{syst}}} = 1.5\% \cdot \tau_{kl}$ on the estimate of the residual background based on a dedicated performance study of the MAGIC telescopes [21].



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## 5. Results and Outlook

We present the observational 95% confidence level ULs on the thermally-averaged cross-section $\langle \sigma v \rangle$ and on the brane tension $f$ (see further details in [7]) for branon DM annihilation obtained with 354 hours of dSph observations by the MAGIC telescopes (see Fig. 3)). We perform a multi-target search for branon DM particles of masses between 100 GeV and 100 TeV. As expected from the no significant gamma-ray excess in the dSph observations by the MAGIC telescopes [8], our constraints for branon DM annihilation are located within the 68% containment band, which is consistent with the no-detection scenario.

This work leads to the most constraining branon DM limits in the TeV mass range, superseding previous constraints by CMS [22] (blue), AMS-02 [23] (orange) and MAGIC limits for Segue1 alone [7, 24] (purple). The prospects of the future CTA [25] (magenta) and SKA [26] (yellow) are also depicted in Fig. 3. We obtain our strongest limit $\langle \sigma v \rangle \simeq 4.9 \times 10^{-24}\,\mathrm{cm^3 s^{-1}}$ for a $\sim 0.7$ TeV branon DM particle mass. We can achieve even more stringent and robust exclusion limits by adding further dSph observations of the MAGIC telescopes or other gamma-ray [27, 28] or neutrino telescopes to this analysis scheme.

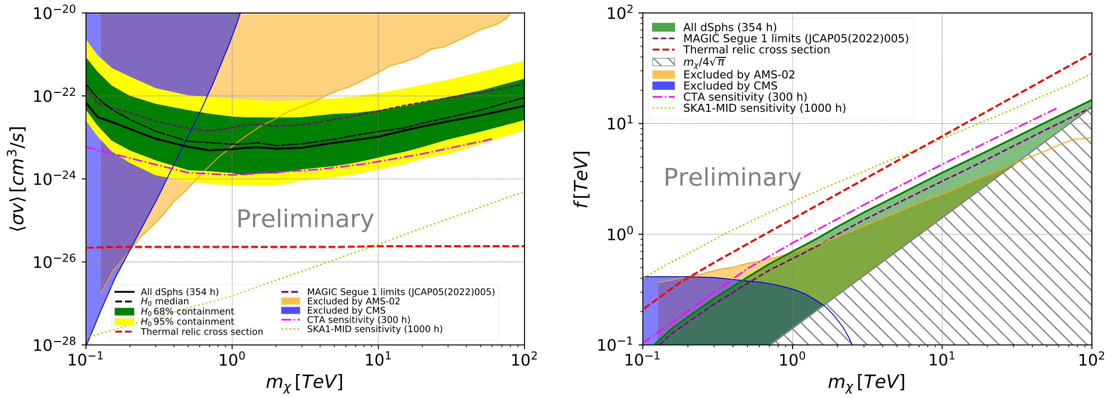


**Figure 3:** 95% confidence level ULs on $\langle \sigma v \rangle$ (left panel) and on $f$ (right panel) for branon DM annihilation from the combined analysis of 354 hours of dSph observations. See text for more details.

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