Constraining branon dark matter from observations of the dwarf spheroidal galaxies with the MAGIC telescopes

T. Miener, D. Nieto, V. Gammaldi, D. Kerszberg, and J. Rico

1 Instituto de Física de Partículas y del Cosmos and Department of EMFTEL, Universidad Complutense de Madrid, E-28040 Madrid, Spain; tmiener@ucm.es

2 Departamento de Física Teórica, Universidad Autónoma de Madrid, Madrid, Spain & Instituto de Física Teórica, UAM/CSIC, E-28049 Madrid, Spain

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

We present the first branon dark matter (DM) search in the very high-energy gamma-ray band with observations of the dwarf spheroidal galaxy Segue 1 carried out by the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescope system. Branons are new degrees of freedom that appear in flexible brane-world models corresponding to brane fluctuations. They behave as weakly interacting massive particles, which are natural DM candidates. In the absence of a gamma-ray signal in the Segue 1 data, we place constraints on the branon DM parameter space by using a binned likelihood analysis. Our most constraining 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 DM mass of $\sim 0.7$ TeV.

1 Introduction

Astrophysical and cosmological evidences propose that non-baryonic cold dark matter (DM) accounts for 84% of the matter density of the Universe$^1$. Nevertheless, the nature of DM is still an open question for modern physics, as this elusive kind of matter can not be made of any of the Standard Model (SM) particles. Brane-world theory has been put forward as a prospective framework for DM candidates$^2$. The characteristics of the suggested massive brane fluctuations (branons) in this theory match the ones of weakly interacting massive particles (WIMPs), which are one of the most favored candidates of cold DM$^3$.

Dwarf spheroidal galaxies (dSphs) are preferred targets for indirect DM searches, due to their close proximities and high mass-to-light ratios. In this work, we are focusing on the ultra-faint dSph Segue 1 located in the Northern Hemisphere and outside of the Galactic plane (RA = 10.12h, DEC = 16.08°) only 23 ± 2 kpc away from us$^4$. The Segue 1 observational campaign was carried out by the ground-based gamma-ray telescope MAGIC between 2011 and 2013 and is with 157.9 hours the deepest observation of any dSph by a Cherenkov telescope to
2 Expected branon dark matter gamma-ray flux

The expected gamma-ray flux produced by branon DM annihilation is composed of the astro-
physical factor ($J$-factor), which depends on both the distance $l$ and the DM distribution at
the source region $\rho_{DM}$, and the branon DM annihilation photon yield. It can be expressed in a
given region of the sky, $\Delta \Omega$, and observed at Earth as

$$\frac{d\Phi}{dE}(\langle \sigma v \rangle) = \int_{\Delta \Omega} d\Omega \int_{\text{l.o.s.}} dl \rho_{DM}^2(l, \Omega') \cdot \frac{1}{4\pi} \frac{\langle \sigma v \rangle}{2m_{\chi}^2} \sum_{i=1}^{n} Br_i \frac{dN_i}{dE},$$

(1)

where $\langle \sigma v \rangle$ is the thermally-averaged annihilation cross section, $m_{\chi}$ is the mass of the branon DM particle and l.o.s. stands for line-of-sight. The left panel of Fig. 1 shows the branon branching ratios $Br_i$ as a function of $m_{\chi}$. The differential photon yield per branon annihilation $dN/dE$ is depicted 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) in the right panel of Fig. 1.

![Figure 1: Taken from JCAP05(2022)005. See text for more details.](image)

In our analysis, we are using the $J$-factor and its statistical uncertainty for Segue 1 from $^6$ with the value of $\log_{10}(J(\theta)[\text{GeV}^2\text{cm}^{-5}]) = 19.02^{+0.32}_{-0.35}$. The differential gamma-ray yields per annihilation $dN_i/dE$ (see Eq. 1) are taken from the PPPC 4 DM ID distribution $^7$.

3 Likelihood analysis method

The data reduction of the Segue 1 observation have been published by the MAGIC Collabora-
tion $^5,8$. We re-analyse those high-level data in the context of brane-world extra-dimensional
theories using the likelihood analysis described in Aleksić, Rico and Martinez $^9$. The binned
($N_{\text{bins}} = 30$) likelihood function of the dataset $\mathcal{D}$ with nuisance parameters $\nu$ reads as:

$$\mathcal{L}_{\text{bin}}(\langle \sigma v \rangle; \nu | \mathcal{D}) = \mathcal{L}_{\text{bin}}(\langle \sigma v \rangle; \{b_i\}_{i=1,\ldots,N_{\text{bins}}}, \tau | \{N_{\text{ON},i}, N_{\text{OFF},i}\}_{i=1,\ldots,N_{\text{bins}}})$$

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

(2)

where $\mathcal{P}(x|N)$ is the Poisson distribution of mean $x$ and measured value $N$ and $s_i(\langle \sigma v \rangle)$ and $b_i$ are the expected numbers of signal and background events in the $i$-th energy bin. Besides $b_i$, the
normalization between background and signal regions $\tau$, described by the likelihood function $T$, is also a nuisance parameter in the analysis \textsuperscript{10}. 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 Segue 1 observational campaign $\mathcal{D}_{\text{Segue1}}$ results in $N = 8$ distinct datasets with an individual set of instrument response functions (IRFs). The joint likelihood function

$$
L(\langle \sigma v \rangle; J, \nu | \mathcal{D}_{\text{Segue1}}) = \prod_{k=1}^{N} L_{\text{bin},k}(\langle \sigma v \rangle, \nu_k | \mathcal{D}_k) \times J(J_0, \sigma_{\text{log10}}) \tag{3}
$$

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 \textsuperscript{11}. $\nu_k$ represents the set of nuisance parameters different from the $J$-factor affecting the analysis of the $k$-th dataset $\mathcal{D}_k$.

The same analysis technique, implemented in the open-source DM analysis software packages \textsuperscript{12} gLike \textsuperscript{13} and LklCom \textsuperscript{14}, has been used by the MAGIC Collaboration \textsuperscript{10,15} and other gamma-ray observatories in several DM searches\textsuperscript{16,17}.

4 Results

As reported in \textsuperscript{18}, we present the observational 95% confidence level (CL) upper limits on the thermally-averaged cross-section $\langle \sigma v \rangle$ (see left panel of Fig. 2) and on the brane tension $f$ (see right panel of Fig. 2) for branon DM annihilation obtained with almost 160 hours of Segue 1 observation with the MAGIC telescopes. We perform a model dependent search for branon DM particles of masses between 100 GeV and 100 TeV. Previous branon DM limits from CMS \textsuperscript{19} (blue) and AMS-02 \textsuperscript{20} (orange) as well as the prospects of the future CTA \textsuperscript{21} (purple) and SKA \textsuperscript{22} (yellow) are depicted in Fig. 2.

As expected from the no significant gamma-ray excess in the Segue 1 data \textsuperscript{5}, our constraints for branon DM annihilation are located within the 68% containment band, which is consistent with the no-detection scenario. We obtain our strongest limit $\langle \sigma v \rangle \simeq 1.4 \times 10^{-23} \text{cm}^3\text{s}^{-1}$ for a $\sim 0.7 \text{TeV}$ branon DM particle mass.

![Figure 2: Taken from JCAP05(2022)005. See text for more details.](Image)

5 Conclusion and outlook

This work leads to the most constraining branon DM limits in the multi-TeV mass range, superseding previous constraints by CMS \textsuperscript{19} and AMS-02 \textsuperscript{20} above $\sim 1 \text{TeV}$. We can achieve even more stringent exclusion limits by adding further dSph observations of the MAGIC telescopes\textsuperscript{10} or other gamma-ray telescopes\textsuperscript{16,17} to this analysis.
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References

1. Aghanim et al. Planck 2018 results. VI. Cosmological parameters, A&A 641, A6 (2020).
2. Cembranos et al. Brane-World Dark Matter, Phys. Rev. Lett. 90, 241301 (2003).
3. Steigman et al. Precise relic WIMP abundance and its impact on searches for dark matter annihilation, Phys. Rev. D 86, 023506 (2012).
4. Belokurov et al. Galaxies: Dwarf, Galaxies: Local Group, Astrophysics, Astrophys. J. 654 2, 897 (2007).
5. Aleksic et al. Optimized dark matter searches in deep observations of Segue 1 with MAGIC, JCAP 02, 008 (2014).
6. Geringer-Sameth et al. Dwarf Galaxy Annihilation and Decay Emission Profiles for Dark Matter Experiments, Astrophys. J. 801 2, 74 (2015).
7. Cirelli et al. PPPC 4 DM ID: a poor particle physicist cookbook for dark matter indirect detection, JCAP 03, 051 (2011).
8. Ahnen 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, 039 (2016).
9. Aleksic et al. Optimized analysis method for indirect dark matter searches with imaging air Cherenkov telescopes, JCAP 10, 032 (2012).
10. Acciari et al. Combined searches for dark matter in dwarf spheroidal galaxies observed with the MAGIC telescopes, including new data from Coma Berenices and Draco, Physics of the Dark Universe 35, 100912 (2022).
11. Ackermann 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, 231301 (2015).
12. Miener et al. Open-source Analysis Tools for Multi-instrument Dark Matter Searches, Proceedings of XXXI Astronomical Data Analysis Software and Systems (ADASS) conference [arXiv:2112.01818], (2021).
13. Rico et al. gLike: numerical maximization of heterogeneous joint likelihood functions of a common free parameter plus nuisance parameters, Zenodo [10.5281/zenodo.4601451], (2021).
14. Miener et al. LklCom: Combining likelihoods from different experiments, Zenodo [10.5281/zenodo.4597500], (2021).
15. Ahnen et al. Indirect dark matter searches in the dwarf satellite galaxy Ursa Major II with the MAGIC telescopes, JCAP 03, 009 (2018).
16. Oakes et al. Combined Dark Matter Searches Towards Dwarf Spheroidal Galaxies with Fermi-LAT, HAWC, HESS, MAGIC and VERITAS, Proceedings of 36th International Cos-
mic Ray Conference (ICRC) 36, 539 (2019).
17. Armand et al. Combined Dark Matter Searches Towards Dwarf Spheroidal Galaxies with Fermi-LAT, HAWC, HESS, MAGIC and VERITAS. Proceedings of 37th International Cosmic Ray Conference (ICRC) 37, 528 (2021).
18. Miener et al. Constraining branon dark matter from observations of the Segue 1 dwarf spheroidal galaxy with the MAGIC telescopes, JCAP 05, 005 (2022).
19. Khachatryan et al. Search for new phenomena in monophoton final states in proton-proton collisions at \( \sqrt{s} = 8 \) TeV, Phys. Lett. B 755, 102 (2016).
20. Cembranos et al. Analysis of branon dark matter and extra-dimensional models with AMS-02, Phys. Lett. B 790, 345 (2019).
21. Aguirre-Santaella et al. Cherenkov Telescope Array sensitivity to branon dark matter models, JCAP 10, 041 (2020).
22. Cembranos et al. SKA-Phase 1 sensitivity to synchrotron radio emission from multi-TeV Dark Matter candidates, Physics of the Dark Universe 27, 100448 (2019).