

# Astro2020 Science White Paper

## Searching for Sources of TeV Particle Dark Matter in the Southern Hemisphere

**Thematic Areas:**                     Planetary Systems     Star and Planet Formation  
 Formation and Evolution of Compact Objects             Cosmology and Fundamental Physics  
 Stars and Stellar Evolution     Resolved Stellar Populations and their Environments  
 Galaxy Evolution                     Multi-Messenger Astronomy and Astrophysics

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**Abstract:** Evidence suggests that the majority of the mass in the Universe is dark matter. Many promising models hypothesize that dark matter is a particle that can annihilate or decay and produce secondary gamma rays. Several searches have been performed by GeV and TeV gamma-ray experiments, none of which has detected a definitive signal. The Southern Hemisphere is home to many key dark matter targets, like the dwarf galaxy Reticulum II and the Fornax galaxy cluster. So far, only a few Southern Hemisphere targets have been observed by the current H.E.S.S. observatory due to its limited field of view. A wide field of view survey observatory is needed to probe the many dark matter targets in the Southern Hemisphere. We show that such an observatory would produce competitive, if not the best, limits for dark matter with masses from 100 GeV to PeV. The majority of the material is drawn from *Science Case for a Wide Field-of-View Very-High-Energy Gamma-Ray Observatory in the Southern Hemisphere* [7]. If you'd like to cite results presented in this white paper, please cite the original paper.

# 1 Introduction

Astronomical observations suggest that the majority of mass in the Universe is composed of non-baryonic dark matter [6, 22, 48]. There are several well-motivated theories that predict dark matter is a fundamental particle such as a Weakly Interacting Massive Particle [27]. In these models, the dark matter annihilates or decays producing Standard Model particles that may be observed by astrophysical observatories. Typically the dark matter interactions produce unstable particles that produce a spectrum of Standard Model particles like gamma rays (e.g.  $\chi\chi \rightarrow b\bar{b}$ ).

If the dark matter has a mass well above the TeV scale, the only discovery space may be astrophysical—these particles would be well above achievable collider searches for dark matter and would have number densities too low for direct-detection searches. However, with the high dark matter density regions observed astrophysically and the high-energy reach of astrophysical experiments, dark matter masses much greater than 1 TeV can be identified. In particular, the construction of a wide field-of-view TeV gamma-ray observatory in the Southern Hemisphere would enable robust searches for consistent dark matter signals in multiple source classes across the sky, as well as rigorous quantification of signal backgrounds. One possible design, used to quantify the predictions in this white paper, is a water Cherenkov detector 10x more sensitive than the present Northern-hemisphere High Altitude Water Cherenkov (HAWC) Observatory [12].

Note that in this work we discuss searches in dwarf galaxies, galaxy clusters, and the Large and Small Magellanic Clouds. A companion white paper has also been written focusing on searches for TeV gamma rays from the Galactic center.

## 2 Dark Matter J- and D-factors

The gamma-ray flux from the annihilations ( $d\Phi_{Ann}/dE_\gamma$ ) and decays ( $d\Phi_{Dec}/dE_\gamma$ ) of dark matter particles of mass  $M_{DM}$  in a dark matter halo are given by a particle physics term (left parenthesis) times an astrophysical term (right parenthesis):

$$\frac{d\Phi_{Ann}(\Delta\Omega, E_\gamma)}{dE_\gamma} = \left( \frac{1}{2} \frac{1}{4\pi} \frac{\langle\sigma v\rangle}{M_{DM}^2} \frac{dN}{dE_\gamma} \right) \times (J(\Delta\Omega)) , \quad (1)$$

and

$$\frac{d\Phi_{Dec}(\Delta\Omega, E_\gamma)}{dE_\gamma} = \left( \frac{1}{4\pi} \frac{1}{\tau_{DM} M_{DM}} \frac{dN}{dE_\gamma} \right) \times (D(\Delta\Omega)) . \quad (2)$$

The astrophysical factor, also called  $J$ -factor for annihilations and  $D$ -factor for decays, are defined as

$$J(\Delta\Omega) = \int_{\Delta\Omega} \int_{l.o.s.} d\Omega ds \rho_{DM}^2[r(s, \Omega)] , \quad (3)$$

and

$$D(\Delta\Omega) = \int_{\Delta\Omega} \int_{l.o.s.} d\Omega ds \rho_{DM}[r(s, \Omega)] , \quad (4)$$

where  $\rho_{DM}$  is the dark matter density distribution. Both astrophysical factors consist of an integral along the line-of-sight (l.o.s.) and over the solid angle  $\Delta\Omega$  of  $\rho_{DM}^2$  for annihilation, and  $\rho_{DM}$  for decay. The particle physics term contains the dark matter particle mass,  $M_{DM}$ , the velocity-weighted annihilation cross section,  $\langle\sigma v\rangle$ , dark matter lifetime,  $\tau_{DM}$ , and the differential spectrum of gamma rays in a specific annihilation or decay channel,  $dN/dE_\gamma$ .

Object	J-factor [ $\text{GeV}^2\text{cm}^{-5}$ ]	D-factor [ $\text{GeV cm}^{-2}$ ]
Ret. II dSph	$6.3 \times 10^{18}$	$4.0 \times 10^{17}$
Fornax Galaxy Cluster	$1.2 \times 10^{21}$	$1.8 \times 10^{19}$
LMC	$9.4 \times 10^{19}$	$7.7 \times 10^{18}$

Table 1: Dark matter annihilation and decay  $J$ - and  $D$ -factors for various targets in the Southern Hemisphere. The Reticulum II are the values for an integration angle of 0.1 degrees from Ref. [46]. The Fornax  $J$ -factor is model NFW RS08 from Ref. [2]; the Fornax  $D$ -factor is from Ref. [25]. The LMC  $J$ -factor is the NFW-mean model value from Ref. [17]; the  $D$ -factor is calculated using the CLUMPY software package [16, 21, 31] and the same parameters as the NFW-mean model used for the  $J$ -factor.

Table 1 gives representative values of the  $J$ - and  $D$ -factors for a sample of dark matter targets in the Southern Hemisphere. The expected dark matter gamma-ray flux is proportional to the  $J$ - and  $D$ -factors so dark matter searches of targets with larger values are more sensitive. It should be noted that the  $J$ -factors for Fornax and the LMC have much larger uncertainties ( $\sim$ an order of magnitude) than Reticulum II. The  $D$ -factors are less uncertain.

### 3 Dark Matter Searches Towards Dwarf Galaxies

Dwarf spheroidal galaxies (dSphs) are some of the most dark matter dominated objects known. Dozens are known to exist nearby in the Milky Way dark matter halo. Given their proximity and low astrophysical backgrounds, Milky Way dSphs are excellent targets for searching for gamma-ray emission from dark matter annihilation or decay. For example, HAWC has derived competitive limits on dark matter annihilation and decay using 14 dSphs with known dark matter content [8].

Recent deep observations with wide-field optical imaging surveys have discovered 33 new ultra-faint Milky Way satellites [14, 15, 23, 24, 29, 30, 33, 37, 38, 39, 43, 44, 49, 50, 51], mostly in the Southern Hemisphere. These objects are potentially dark matter dominated dSphs, but this needs to be confirmed with spectroscopic follow up observations. 15 of the new satellites have already been spectroscopically confirmed as dSphs [19, 32, 34, 35, 36, 37, 41, 42, 45, 46, 47, 51, 52]. These add to the existing 18 well-characterized dSphs known before these surveys [5].

Figure 1 shows the expected improvement in the dark matter annihilation and decay limits relative to the current HAWC limits for a 10x more sensitive HAWC-like array in the Southern Hemisphere and an increased number of dSphs. We assume the  $J$ -factor and  $D$ -factor distributions of the new dSphs matches that of the previously known dSphs. With the next generation of observations, we expect to be able to improve the present limits by nearly an order of magnitude. We also expect such an array's dSph searches to be more sensitive than dSph searches from current and future Imaging Air Cherenkov Telescopes (IACTs) like H.E.S.S. and CTA.

Additionally, with a survey instrument surveying the sky every day, additional dSph that haven't been discovered yet will have already been observed with the instrument's full sensitivity. The Large Synoptic Survey Telescope (LSST) will survey the Southern Hemisphere sky with unprecedented sensitivity and is expected to find 100's of new dSphs [28]. Legacy data at these locations could easily and immediately be analysed when new dSphs are found.

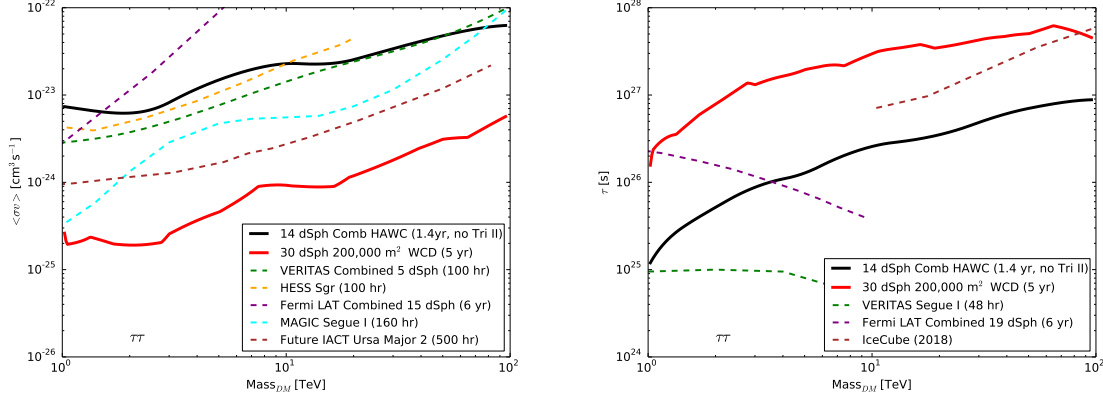


Figure 1: (left) Expected 95% confidence level dark matter annihilation cross section upper limits in dSphs with a 200,000 m<sup>2</sup> water Cherenkov detector (WCD) (10 times the HAWC area). Also shown are the observed dSph limits from VERITAS [11], HESS [3], Fermi LAT [5], and MAGIC [9] and the expected limits from CTA [40]. (right) Expected 95% confidence level dark matter decay lifetime lower limits for dark matter decay in dSphs. Also shown are the observed dSph limits from VERITAS [10], Fermi LAT [13], and IceCube [1].

## 4 Dark Matter Searches Toward Galaxy Clusters

Galaxy clusters are massive dark matter filled objects. Their  $J$ - and  $D$ -factors are lowered, though, by their large distances from the Milky Way. Nonetheless they are important targets for dark matter searches.

Galaxy cluster's halos are composed of a smooth component, which peaks in the center, and substructure. Substructure is composed of separate smaller over-densities of dark matter call subhalos. The number and concentration of the subhalos is uncertain and mostly constrained by N-body simulations. However, we know substructure exists as we observe subhalos in the Milky Way and elsewhere (e.g. dwarf galaxies). The effect of these substructures can lead to enhancements (so-called "boost factors") of the dark matter  $J$ -factor of more than an order of magnitude. However, because the amount of substructure is uncertain, these annihilation searches are model dependent.

The substructure and large dark matter density in galaxy clusters can cause extension by a few degrees in radius—the typical field of view of IACTs. However, a wide field-of-view observatory would allow for full observations of these extended objects.

Galaxy clusters are one of the best targets for dark matter decay. For example, dark matter decay lifetime limits from a search for gamma rays in the Virgo Cluster by HAWC [26] produce the most constraining decay limits above 1 TeV mass (Fig. 2). For very heavy dark matter ( $M_{DM} > 10$  TeV), decay would be the only way to detect particle dark matter.

Therefore, searches for TeV and higher gamma ray energies from galaxy clusters probe an important class of heavy dark matter models.

## 5 Dark matter searches toward the Magellanic Clouds

Two other promising Southern Hemisphere dark matter targets are the Large (LMC) and Small (SMC) Magellanic Clouds. The LMC is the largest Milky Way satellite and rich in dark matter. It also is likely on its first in-fall, meaning it has not been tidally stripped by the galaxy

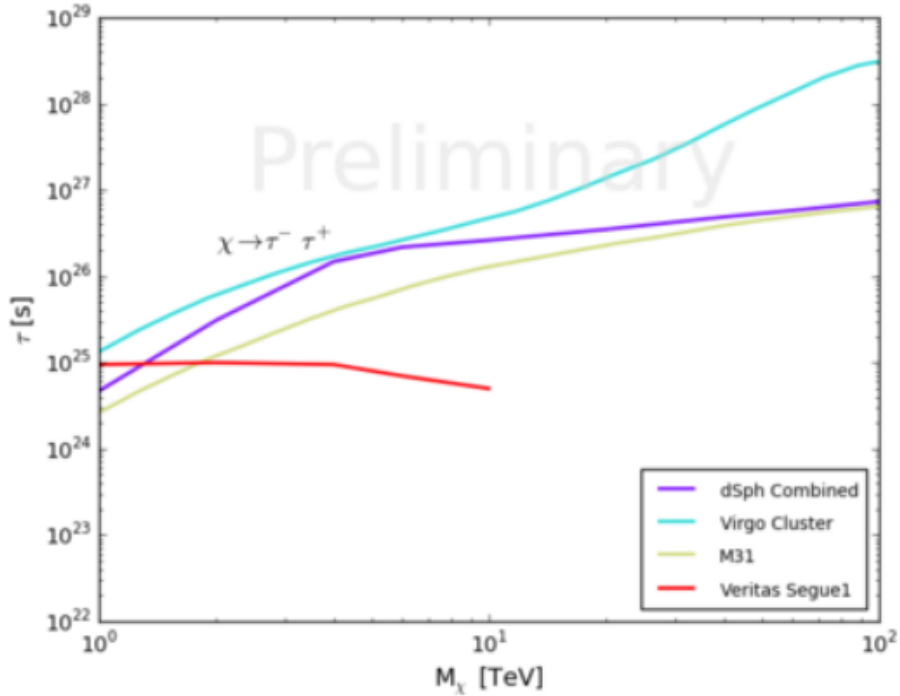


Figure 2: Dark matter decay lifetime lower limits from several TeV searches, including the HAWC analysis of the Virgo Cluster [26]

and still contains most of its initial dark matter density. The SMC is in a complicated orbit around the LMC, but also likely on its first in-fall and therefore not tidally stripped. Though its dynamics are more complicated than the LMC, the SMC's rotation curves show that it is dark matter dominated.

Both the LMC and SMC are nearby, dark matter dominated systems, making them excellent targets for searches for gamma rays from dark matter annihilation or decay. The H.E.S.S. Observatory has detected several TeV sources in the LMC, but has not performed a dedicated dark matter search there [4]. Dark matter searches have been performed in the LMC and SMC by the Fermi Large Area Telescope, a GeV gamma ray observatory [18, 20]. Though no dark matter signal is seen, they have produced competitive limits.

Since it is extended by 10 degrees, a wide field-of-view observatory would uniquely observe the entire LMC dark matter subhalo at TeV energies.

## 6 Conclusion

There are several key dark matter targets in the Southern Hemisphere that won't be fully explored by current or future IACTs. These include searches in multiple dwarf galaxies, extended gamma-ray signals in galaxy clusters, and the Magellanic clouds. A wide field-of-view TeV gamma ray observatory would be well suited to search for gamma rays from particle dark matter annihilation or decay in these targets. It would also be able to search for signals from relatively heavy particle dark matter ( $100 \text{ GeV} < M_{\text{DM}} < 1 \text{ PeV}$ ), which can only be probed astrophysically.

A future wide field of view observatory would be able to obtain an unbiased survey containing

several dark matter targets each day. Particularly in the case of a positive signal in one of these targets, it would be important to have observed many dark matter-rich regions to look for correlated signals. Dark matter is expected to exist in all of these targets, so seeing a signal in multiple targets would give more confidence to a potential detection. Additionally, an observatory with a wide field-of-view would allow unique observations in extended targets like galaxy clusters and the LMC with unprecedented sensitivity.

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