# Searching for Dark Matter in the Galactic Halo with a Wide Field-of-View TeV Gamma-ray Observatory in the Southern Hemisphere

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**Abstract.** Despite mounting evidence that astrophysical dark matter exists in the Universe, its fundamental nature remains unknown. In this paper, we present the prospects to detect and identify dark matter particles through the observation of very-high-energy ( $\gtrsim$  TeV) gamma-rays coming from the annihilation or decay of these particles in the Galactic halo. The observation of the the Galactic Center and a large fraction of the halo by a future wide field-of-view gamma-ray observatory located in the southern hemisphere would reach unprecedented sensitivity to dark matter particles in the mass range of ~500 GeV to ~2 PeV. Combined with other gamma-ray observatories (present and future) a thermal relic annihilation cross-section could be probed for all particle masses from ~80 TeV down to the GeV range in most annihilation channels.

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# 1 Introduction

The nature of Dark Matter (DM) is one of the most fundamental open questions in physics, with numerous astrophysical evidence – from galactic rotation curves [1], galaxy cluster dynamics [2], the cosmic microwave background fluctuations [3], and others – no DM particle signal has ever detected.

The most promising candidates are called Weakly Interacting Massive Particles (WIMPs). These are particles with masses in the GeV-TeV range and weak-scale interaction strength, although related models have expanded the mass range to include PeV masses and stronger interactions or even decaying DM (e.g. dark glueballs [4–10] and hidden sector DM [11, 12]).

Human made collider experiments (see ref. [13] and references therein) and large passive calorimeters (see ref [14] and references therein) are probing the DM mass range up to hundreds of GeV. However, if the DM has a mass well above the TeV scale, the only discovery space may be astrophysical. This is because the current generation of colliders does not have enough maximum energy to produce >TeV DM and the naturally produced flux of DM above the TeV mass scale is not detectable by the current volume and technology of the calorimeters.

With the high-dark-matter-density regions observed in astrophysical objects and the high-energy reach of astrophysical experiments, DM masses much greater than 1 TeV can be identified through their annihilation or decay products. Several experiments are currently searching for these particles [15–24] and several more are planned [25–27]. Nothing have been found yet but the parameter space for discovery is shrinking with time.

In particular, gamma-ray observatories can be tuned to have peak sensitivity and fine angular resolution at energies above 1 TeV, thus becoming effective probes for DM signals at this mass scale. Given its large DM density and relative proximity, the Galactic Center (GC) region is expected to be the brightest source of gamma rays from DM annihilation or decay in the sky by several orders of magnitude. Even considering possible signal contamination from other astrophysical sources, it is one of the most promising targets to detect the presence of new massive DM particles.

An experiment designed for the observation of extended sources of gamma-rays at the TeV scale and above, constructed in the southern hemisphere would be highly sensitive to these DM gamma-ray signals due to the GC transiting close to directly overhead the experiment. Such an experiment has been proposed to be built in South America under the exploratory name of the Southern Gamma-ray Survey Observatory (SGSO) [28]. The highest energies (> 10 TeV) are only achievable with a large detection area  $(> 50000 \,\mathrm{m}^2)$  and a long exposure. This implies the need for non-expensive detector of particles instead of directional telescopes, like Imaging Atmospheric Cherenkov Telescopes (IACTs). This observatory needs to have an unprecedented sensitivity in the multi-TeV energy-scale, large field of view (FOV)  $(45^{\circ})$ , long exposure to the GC and good angular resolution ( $< 0.5^{\circ}$ ). The large FOV of the observatory would allow the observation of a large fraction of the Galactic DM halo and therefore reduces the dependence of the detection on the DM radial profile, allowing for a more robust and model free measurement. Also, above the TeV scale, where SGSO would be most sensitive, background from other astrophysical sources is expected to be small and allows for the detection of very faint DM signals.

In this paper we investigate in detail the potential of an experiment such as SGSO to measure a DM signal. Based on a "straw man" detector design of SGSO, we derive sensitivity limits to the annihilation and decay of DM particles in the Galactic halo. We show that, together with other contemporaneous gamma-ray observatories, SGSO would allow the detection of DM particles with thermal relic cross-sections and masses up to 80 TeV. We also investigate the impact of different assumptions of DM halo density profiles on the sensitivity limits, as well as how electroweak (EW) radiative corrections improve the sensitivity of SGSO to DM annihilation/decay signals.

# 2 A Straw Man Design for a Southern Gamma-ray Survey Observatory

#### 2.1 Instrumental Context

A wide-field of view very high energy gamma-ray detector in the southern hemisphere is now being discussed [28] to complement the existing northern hemisphere instruments HAWC and LHAASO and the extremely powerful, but narrower field of view, CTA Observatory. A southern hemisphere location is essential for targeting the most promising (i.e. by far the largest astrophysical J-factor 3.3) DM annihilation target: the halo of our own Galaxy. The Fermi-LAT instrument has very limited capabilities for WIMP masses beyond ~100 GeV due to its limited collection area. CTA will have excellent performance up to at least a few TeV, from deep, targeted observations of the region around the Galactic Center (GC) [26]. However, CTA's limited field of view does imply limitations to the performance in the case of a rather flat central DM density profile, and/or the case of DM decay rather than annihilation. At the highest energies, beyond ~10 TeV in gamma-rays, the performance of SGSO is expected to surpass that of CTA for steady point-like sources after a few years of operation [28]. For emission extended on degree scales the cross-over point in sensitivity occurs at lower energies, due to the more limited spatial resolution expected for SGSO in the <TeV range with respect to CTA. The combination of a very wide field of view and excellent performance at multi-TeV energies make an SGSO-like detector an excellent prospect for heavy WIMP detection, in particular for the case of Galactic halo emission.

#### 2.2 Simulations Results

The detector model of a potential SGSO-like observatory design is used to assess the sensitivity to DM searches. For this purpose, publicly available<sup>1</sup> instrument response functions were used, which have been produced for the science case studies presented in [28]. This observatory design can be regarded as a scaled-up version of the current generation of its type, like High Altitude Water Cherenkov gamma-ray observatory (HAWC) [29]. In our calculation a latitude of 25°S is assumed, giving close to optimal exposure to the GC.

While the response of a single detector unit has been kept roughly similar to HAWC, the size of the array, the ground coverage (80%), and elevation  $(5 \,\mathrm{km})$  have been significantly increased with respect to HAWC. To estimate realistic instrument response functions, published performance figures from HAWC [29] (like angular resolution and gamma and hadron cut passing rate) are used as a baseline. To these we relate the instrument response functions of the straw man design by assuming that the performance stays the same when the shower deposits the same amount of energy on the array. The energy deposited on the array is estimated for a HAWC-like detector and the straw man design using a toy detector together with air shower simulations generated by CORSIKA [30] (more details can be found in [28]). With the beefed up array parameters for the straw man design, a similar performance will be reached at a comparable lower gammaray energy than HAWC. For the study of DM signals from the GC, the DM mass regime beyond the energy range of CTA provides a unique opportunity for an air shower array. To probe this regime, a sufficiently large effective area is of key importance. The effective area of the straw man design, after the application of gamma-ray selection cuts, is shown in Figure 1. Another important factor is the energy migration matrix (relation between true and reconstructed gamma-ray energy), which is summarized by the bias and resolution of the difference between true and reconstructed energy in the right panel of Figure 1. The obtainable resolution becomes especially relevant in the case where

<sup>&</sup>lt;sup>1</sup>https://github.com/harmscho/SGSOSensitivity



Figure 1. Left: Effective area for a source at 20° from zenith as a function of energy of the primary particle (gamma ray or proton) after applying gamma-hadron separation and trigger multiplicity cuts. Right: Energy bias and resolution, where bias is defined as mean value of  $\Delta = (\log_{10} E_{\rm R} - \log_{10} E_{\rm T})$  (with reconstructed energy  $E_{\rm R}$  and true energy  $E_{\rm T}$ ), while the resolution in taken as the root mean square of  $\Delta$ .

there are pronounced spectral features in the gamma-ray DM annihilation spectrum that might provide a unique signature. The expected energy resolution is below 40% above a gamma-ray energy of 10 TeV. Since a very simplistic energy assignment was used, this should be considered as an upper-limit on the energy resolution of a future observatory. The angular resolution needs to be sufficient to resolve the angular scales of the emission, but with an anticipated angular resolution of less than  $0.3^{\circ}$  above 10 TeV this should not be a limiting factor.

#### 3 Gamma-ray Fluxes from Dark Matter towards the Galactic Center

# 3.1 Annihilation and Decay of Dark Matter Particles

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

$$\frac{\mathrm{d}\Phi_{\mathrm{Ann}}(\Delta\Omega, E_{\gamma})}{\mathrm{d}E_{\gamma}} = \left(\frac{1}{2}\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{M_{\mathrm{DM}}^2}\frac{\mathrm{d}N}{\mathrm{d}E_{\gamma}}\right) \times \left(J(\Delta\Omega)\right), \qquad (3.1)$$

and

$$\frac{\mathrm{d}\Phi_{\mathrm{Dec}}(\Delta\Omega, E_{\gamma})}{\mathrm{d}E_{\gamma}} = \left(\frac{1}{4\pi} \frac{1}{\tau_{\mathrm{DM}} M_{\mathrm{DM}}} \frac{\mathrm{d}N}{\mathrm{d}E_{\gamma}}\right) \times \left(D(\Delta\Omega)\right) \,. \tag{3.2}$$

The astrophysical factors, also called *J*-factor for annihilations and *D*-factor for decays, are integrated over a given region of interest (ROI) of solid angle size  $\Delta\Omega$  along the line of sight (l.o.s.). They are defined as

$$J(\Delta\Omega) = \int_{\Delta\Omega} \int_{\text{l.o.s.}} d\Omega \, \mathrm{d}s \, \rho_{\rm DM}^2[r(s,\Omega)] \,, \tag{3.3}$$

and

$$D(\Delta\Omega) = \int_{\Delta\Omega} \int_{\text{l.o.s.}} d\Omega \, \mathrm{d}s \, \rho_{\text{DM}}[r(s,\Omega)] \,, \tag{3.4}$$

where  $\rho_{\rm DM}$  is the DM density distribution.

The particle physics term contains the DM particle mass  $M_{\rm DM}$ , the velocity-weighted annihilation cross section  $\langle \sigma v \rangle$ , DM lifetime  $\tau_{\rm DM}$ , and the differential spectrum of gamma rays in a specific annihilation or decay channel  $dN/dE_{\gamma}$ . We take a model-independent approach by considering DM particles annihilating/decaying with a 100% branching ratio into different single channels. As representatives of different types of Standard Model (SM) particles, we compute our limits for annihilations/decays into pairs of gauge bosons, W<sup>+</sup>W<sup>-</sup>, quarks,  $b\bar{b}$ , and leptons,  $\tau^+\tau^-$ . In the cases where positrons and electrons are produced in the final states, an additional contribution to the gamma-ray flux can come from Inverse Compton (IC) up-scattering of ambient photons, such as those of the cosmic microwave background (CMB). However, this additional contribution is sub-dominant at the TeV energies. Thus, here we only consider the prompt gamma-ray emission, which leads to a slightly conservative estimate of the SGSO sensitivity to a DM signal. In Figure 2 the gamma-ray energy distributions are compared for the three annihilation channels with a dark matter of 10 TeV.

Usually, searches for DM annihilation focus on particle masses below a few 100 TeV. Within this mass range, most models of DM particles will produce the DM thermal relic abundance without being in violation of the unitarity bound [31–33] (for some exceptions, see for e.g. ref. [11, 12]). Thus, for the case of DM annihilation we limit ourselves to masses between 500 GeV and 100 TeV. There is, however, no theoretical limit to DM particle masses for the case of decaying DM, so in this case we extend our limits to DM particles as massive as  $\sim 2$  PeV.

#### 3.2 Galactic halo density profiles and regions of interest

One of the main difficulties when searching for DM signals from the Milky Way is that the DM density distribution of the Galactic halo is poorly constrained. As shown in Fig. 2, the expected DM density varies greatly between possibly functional forms, with the Einasto and NFW ("cuspy") profiles peaking sharply, and the Burkert ("cored") profile levelling off. This creates substantial uncertainty in the J and D-factors and therefore on the corresponding sensitivity, especially for searches close to the center of the halo.

Thus, in order to estimate the predicted DM flux, it is important to consider different classes of halos. Here two models are assumed: a peaked Einasto profile [34] and a cored Burkert profile [35], parametrised as

$$\rho_E(r) = \rho_0 \exp\left\{\frac{-2}{\alpha} \left[\left(\frac{r}{r_s}\right)^{\alpha} - 1\right]\right\}$$
(3.5)

and

$$\rho_B(r) = \frac{\rho_c r_c^3}{(r+r_c)(r^2+r_c^2)},$$
(3.6)

respectively. Here  $r_s$  and  $\rho_0$  are the radius and density at which the logarithmic slope of the density is -2, respectively,  $\alpha$  is a parameter describing the degree of curvature of the profile,  $\rho_c$  is the central density, and  $r_c$  the core radius. We take explicitly  $r_s = 20$  kpc,  $\alpha = 0.17$  [34] and  $r_c = 12.67$  kpc [36].  $\rho_0$  and  $\rho_c$  are chosen so that the local DM density  $\rho_{\rm DM}(r_{\odot}) = 0.39$  GeV/cm<sup>3</sup>, where  $r_{\odot}$  is the distance from the Sun to the GC [37, 38].



Figure 2. Left: Comparison of the gamma-ray energy density distribution of three annihilation channels for  $M_{\rm DM} = 10 \,\text{TeV}$  (and  $x = E_{\gamma}/M_{\rm DM}$ ) [36]. Right: Behavior of three physically motivated density profiles as a function of radial distance from the center.

We focus our searches for DM signals to the inner 10° of the Galaxy. The spatial ROIs are defined as circular concentric regions of  $0.2^{\circ}$  width each, centered at the GC, excluding a  $\pm 0.3^{\circ}$  band in Galactic latitude to avoid the above-mentioned standard astrophysical background. In Table 1 we present the solid angle sizes  $\Delta \Omega_i$ , *J*-factors and *D*-factors calculated for these ROIs.

<i>i</i> -th ROI	Solid Angle	$J(\Delta\Omega_i)$ [1	$10^{19} \text{ GeV}^2 \text{ cm}^{-5}$	$D(\Delta\Omega_i)$ [1	$0^{19} \text{ GeV cm}^{-2}$
$\Delta \theta_i = [\theta_{\min}, \theta_{\max}]$	$\Delta\Omega_i \ [10^{-4} \ {\rm sr}]$	Einasto	Burkert	Einasto	Burkert
$\Delta \theta_1 = [0.3^\circ, 0.5^\circ]$	0.68	75.78	0.17	1.91	0.31
$\Delta \theta_2 = [0.5^\circ, 0.7^\circ]$	1.53	129.11	0.38	4.06	0.70
$\Delta \theta_3 = [0.7^\circ, 0.9^\circ]$	2.31	154.19	0.58	5.83	1.06
$\Delta \theta_4 = [0.9^\circ, 1.1^\circ]$	3.08	168.57	0.78	7.43	1.41
	:	:	÷	:	:
$\Delta \theta_{45} = [9.1^{\circ}, 9.3^{\circ}]$	34.33	110.84	8.10	36.86	15.33
$\Delta \theta_{46} = [9.3^{\circ}, 9.5^{\circ}]$	35.09	109.28	8.25	37.23	15.65
$\Delta \theta_{47} = [9.5^{\circ}, 9.7^{\circ}]$	35.84	107.76	8.41	37.59	15.97
$\Delta \theta_{48} = [9.7^{\circ}, 9.9^{\circ}]$	36.60	106.27	8.46	37.94	16.29
$\Delta\theta_{\rm total} = [0.3^{\circ}, 9.9^{\circ}]$	899.5	7032.9	218.3	1190.0	405.7

**Table 1.** Definitions of the ROIs with their corresponding inner  $(\theta_{\min})$  and outer  $(\theta_{\max})$  radii, the solid angle of each ROI, and values of *J*-factors and *D*-factors calculated for both Einasto and Burkert profiles. Only the first and last 4 ROIs out of the 48 are presented here.

#### 3.3 Analysis methodology

The sensitivity of SGSO to DM annihilations/decays can be found by comparing the number of observable gamma rays with the expected background (see [39]). The statistical tool used to derive limits is a 2D (energy and space) joint-likelihood method, where the comparisons between DM and background fluxes are performed in different energy and spatial intervals (or bins) [18]. Hereafter, we divide the energy range between 100 GeV and 100 TeV into 40 logarithmically-spaced bins. The number of observable gamma-ray events by a detector is computed by folding the considered gamma-ray flux with the instrument response functions. The expected signal in a spatial ROI i and energy bin j is given by

$$N_{ij} = T_{\rm obs} \int_{\Delta E_j} dE_{\gamma}^r \int_0^\infty dE_{\gamma}^t \frac{\mathrm{d}\Phi_{\gamma}(\Delta\Omega_i, E_{\gamma}^t)}{\mathrm{d}E_{\gamma}^t} \times A_{\rm eff}(E_{\gamma}^t) \times \mathrm{PDF}(E_{\gamma}^t, E_{\gamma}^r)$$
(3.7)

where  $T_{\text{obs}}$  is the observation time,  $E_{\gamma}^{t}$  is the true primary energy,  $A_{\text{eff}}$  is the effective collection area as function of the true energy (Fig. 1 right), and  $\text{PDF}(E_{\gamma}^{t}, E_{\gamma}^{r})$  is the representation of the energy resolution as the probability density function  $P(E_{\gamma}^{r}|E_{\gamma}^{t})$ , of observing an event at the reconstructed energy  $E_{\gamma}^{r}$  for a given true energy  $E_{\gamma}^{t}$ .

Assuming that the number of detected events follows a Poisson distribution, the likelihood functions are calculated in each individual bin and combined into a joint-likelihood function from which we derive the limits at different confidence levels. This method takes full advantage of differences on the energy and spatial distribution between the expected DM signal and the background. For instance, the former is supposed to follow the J-factor (D-factor), whereas the latter is isotropic on the sky.

# 4 Results

# 4.1 Sensitivity to Dark Matter Annihilation

Figure 3 shows the the 95% C.L. sensitivity upper-limits on  $\langle \sigma v \rangle$  versus  $M_{\rm DM}$  for DM particles annihilating into W<sup>+</sup>W<sup>-</sup>,  $b\bar{b}$  and  $\tau^+\tau^-$  assuming an Einasto profile for the GC halo. The final state gamma-ray spectra are provided by the PPPC 4 DM ID [36]. The sensitivities are shown for 10 yrs of observations with SGSO. They are compared to the sensitivity of CTA [26], an Einasto profile and 500 hours of observation in the inner 1° of the Galaxy. The current most-stringent Fermi-LAT limits using 15 dwarf spheroidal galaxies (dSphs) are also plotted [24], as well as the projected sensitivities assuming a total 15 years of observations and a projected sample of 60 dSphs<sup>2</sup> [40].

A sensitivity to values of  $\langle \sigma v \rangle$  smaller than the nominal thermal relic cross-section  $(\sim 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1})$  is reachable for SGSO in the mass range of ~500 GeV to ~80 TeV for the W<sup>+</sup>W<sup>-</sup> and  $\tau^+\tau^-$  channels, and in the range of ~700 GeV to ~20 TeV for the  $b\bar{b}$  channel. SGSO will be more sensitive than CTA for DM particles masses above 700 GeV in the  $\tau^+\tau^-$  channel, and above ~2.5 TeV in the  $b\bar{b}$  channel, and it will have a

<sup>&</sup>lt;sup>2</sup>Here we assumed that the Fermi-LAT  $W^+W^-$  projected sensitivity scales similar to the  $b\bar{b}$  sensitivity.



Figure 3. 95% C.L. sensitivity upper-limit on the velocity weighted cross section for DM self-annihilation into W<sup>+</sup>W<sup>-</sup>,  $b\bar{b}$  and  $\tau^+\tau^-$  as a function of  $M_{\rm DM}$ , for SGSO and CTA [26]. Current Fermi-LAT limits [24] towards dwarf galaxies as well as projected sensitivities are also plotted [24].

similar sensitivity to CTA in the mass range of ~500 GeV to ~20 TeV, and better above 10 TeV. But most importantly, the combined sensitivity of SGSO with Fermi-LAT and CTA will be able to probe a thermal relic cross-section for all WIMP masses  $\leq 80$  TeV in most annihilation channels ( $\leq 20$  TeV for  $b\bar{b}$ ).

# 4.2 Sensitivity to Dark Matter Decay

Figure 3 shows the 95% C.L. sensitivity upper-limits on the decay lifetime  $\tau$  versus  $M_{\rm DM}$  for DM particles decaying into W<sup>+</sup>W<sup>-</sup>,  $b\bar{b}$  and  $\tau^+\tau^-$  assuming both an Einasto and a Burkert profile for the GC halo. Here, final state gamma-ray spectra are produced using the PYTHIA 8.219 software [41, 42] with electroweak corrections enable [43]. Sensitivities are shown for 10 yrs of observations with SGSO. CTA sensitivity curves are also shown

for 500 hours of observation of an Einasto profile, and decays into  $b\bar{b}$  and  $\tau^+\tau^-$  [44]. The current most-stringent Fermi-LAT limits based on the modelling of the isotropic gamma-ray background (IGRB) [6] are also plotted.



**Figure 4.** 95% C.L. sensitivity lower-limits on the DM decay lifetime into W<sup>+</sup>W<sup>-</sup>,  $b\bar{b}$  and  $\tau^+\tau^-$  as a function of  $M_{\rm DM}$ , for SGSO, CTA [44] and Fermi-LAT [6].

SGSO will reach an unprecedented sensitivity in the TeV mass range, being more sensitive than CTA for all DM particle masses above  $\sim 600$  GeV. A sensitivity to decaying lifetimes larger than  $10^{27}$  seconds will be attained for all channels and masses above 1 TeV.

# 4.3 Density profile effects

In order to estimate the impact of different Galactic halo profiles in the sensitivity estimates of different instruments, the sensitivity assuming a Burkert profile is compared to an Einasto profile in Fig. 5 for annihilation into  $\tau^+\tau^-$  and in Fig. 4 for decays into all three channels. The sensitivity of CTA is also plotted for comparison [26, 44] in both cases. Note that the signal extraction region of CTA was limited to the inner 1° of the Galaxy due to its smaller field-of-view. As already shown before, SGSO would be more sensitive to DM annihilations than CTA for all DM masses above 700 GeV assuming an Einasto profile, and this difference in sensitivity becomes even more pronounced in the case of the cored Burkert profile. As one can see, limits on WIMP annihilation are highly sensitive to the assumed behavior of the DM halo towards the center. If the DM density profile flattens toward the center, the expected flux from this region becomes much smaller and the limits become much less constraining. However, a survey-style instrument would be able to consider a more extended region surrounding the central halo and thus recover some of the integrated flux .



Figure 5. (left) 95% C.L. sensitivity upper-limit on the velocity weighted cross section for DM annihilation into  $\tau^+\tau^-$  as a function of  $M_{\rm DM}$ , for both an Einasto (less conservative) and Burkert (more conservative) profile of the Galactic halo. The sensitivity of SGSO is calculated in the inner 10°, and CTA in the inner 1° of the Galaxy, excluding a ±0.3° band in Galactic latitude.

Indeed, cored profiles are best of observed using a wide field-of-view instrument. In addition to the increased sensitivity, a wide field-of-view allows for a robust estimate of the hadronic background. Since the DM flux from a cored profile is roughly constant over space near the center, backgrounds estimated from off regions too close to the region of interest would be highly contaminated by signal. Wide field of view instruments are able to simultaneously observe regions far enough away from the halo center to eliminate signal contamination, allowing them to resolve emission even in the case of a cored profile.

An example of the power of simultaneous observation of background estimates for highly extended sources is the TeV emission from the Geminga pulsar. This emission has only been observed by wide field of view instruments such as Milagro, and the contemporary HAWC experiment [45], while observations from IACTs such as the contemporary VERITAS experiment have shown no significant excess [46]. The power of these wide field of view observations when applied the Galactic halo is shown in Fig. 5, comparing the expected sensitivity of SGSO to that of CTA.

#### 4.4 Importance of electroweak corrections at TeV mass-scale

Over the last decade, it has been shown that electroweak (EW) radiative corrections significantly modify the energy spectra of annihilation/decay of DM particles with masses larger than the electroweak scale [47]. At energies much higher than the weak scale, the highly energetic initial products of the DM annihilation/decay soft radiate electroweak gauge bosons W/Z, which then decay into many other SM particles. Most notably, the effect of these EW-corrections are particularly relevant for large DM masses (above a TeV).



Figure 6. (left) DM annihilation spectra into  $W^+W^-$  with and without taking into account electroweak corrections. (right) SGSO and CTA flux sensitivity curves as a function of reconstructed gamma-ray energy, for 5 years and 50 hours of observation of the Galactic halo, respectively. Also plotted are the DM annihilation rate into  $W^+W^-$  per reconstructed energy bin (E<sub>r</sub>) for different DM particle masses in arbitrary units, but keeping  $\langle \sigma v \rangle$  and the *J*-factor the same for all masses.

The typical modifications to the spectra of TeV-scale DM particles are: (i) they enhance the low energy part of the spectrum, as a small number of highly energetic particles is converted into a great number of low energy particles; (ii) since they open new channels in the final states which otherwise would be forbidden, all stable particles will be present in the final spectrum, independently of the primary annihilation channel considered; (*iii*) in the case of an annihilations/decay into  $W^+W^-$ , a strong peak close in energy to the value of the DM mass arises (see Fig. 6). In Fig. 7, we estimate the impact of such additional features for the SGSO sensitivity. For annihilations into  $W^+W^-$ , EW-corrections improve the sensitivity by a factor of ~1.3 for masses  $\leq 10$  TeV, and as much as a factor of ~2 for masses between 20-80 TeV.



Figure 7. Comparison of SGSO sensitivity upper-limit for DM particles annihilating into  $W^+W^-$  with and without taking into account electroweak corrections.

#### 4.5 Complementarity between gamma-ray observatories

The combination of deep observations of the GC region by SGSO with other gamma-ray observatories would provide independent results, which would increase the confidence in a detection if it were found in both. Observing the cutoff of the spectrum at the DM mass would be one of the strongest indications that an observed gamma ray source originates from DM interactions and is the source hypothesis used to constrain DM interactions. As shown in Fig. 6, SGSO would achieves peak sensitivity at the energy

scale where these cutoffs would be apparent for multi-TeV mass DM. In the case of a DM particle in the mass range 10 - 80 TeV annihilating into  $W^+W^-$ , such an instrument would provide the WIMP mass measurement by probing the spectral cut-off, with CTA helping to constrain the morphology. We note that this mass range has also considerable advantages to the GeV range in terms of astrophysical foreground, with a much shorter list of objects capable of accelerating particles to these energies and in particular avoiding the magnetospheric emission of pulsars whose spectra can mimic an annihilation spectrum in the GeV range [48, 49].

# 5 Conclusion

The GC is one of most promising regions for detecting gamma-ray signals from DM annihilation or decay. Its close proximity and high DM content yield one of the highest expected fluxes from DM interactions. A survey-style instrument with a wide field-ofview in the southern hemisphere, such as SGSO, will be an important tool in searching for such emissions from multi-TeV mass DM. Here we proposed a design of SGSO that would be sensitive enough to probe thermal DM for a large range of multi-TeV DM masses and interaction channels. In addition, the large region-of-interest would allow for strong constraints on DM annihilation and decay even for assumed density profiles that have large flat cores, mitigating the systematic uncertainties on DM limits originating from uncertainties in the density profile. We also highlighted the impact of EW-corrections for the detection of DM particles with masses in the mulit-TeV-scale. A wide field-of-view experiment would also be able to work in tandem with CTA to confirm and identify any potential detection of DM emission through independent observations. With all of these advantages available, a Southern wide field-of-view gamma-ray observatory promises to shed new light on the still unknown nature of DM, allowing it to be a critical tool towards a better understanding of this diverse topic in the coming decade.

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