Astro2020 Science White Paper

Searching for TeV Dark Matter in the Milky Way Galactic Center

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: Despite mounting evidence that astrophysical dark matter exists in the Universe, its fundamental nature remains unknown. In this white 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 $\sim$500 GeV to $\sim$80 TeV. Combined with other gamma-ray observatories (present and future) a thermal relic cross-section could be probed for all particle masses from $\sim$80 TeV down to the GeV range in most annihilation channels. 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* [1]. If you'd like to cite results presented in this white paper, please cite the original paper.

1 Introduction

Although the evidence for astrophysical dark matter (DM) is plentiful—from galactic rotation curves [2], galaxy cluster dynamics [3], the cosmic microwave background [4], and others—the nature of the DM is undetermined. One primary direction for DM searches are for 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 [5, 6, 7, 8, 9, 10, 11, 12], and hidden sector DM [13, 14]).
If the DM 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 DM 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, DM masses much greater than 1 TeV can be identified through their annihilation or decay. In particular, the Galactic Center (GC) region is the most interesting location to look for gamma rays from DM interactions. This region is expected to be the brightest source of DM annihilations in the gamma-ray sky by several orders of magnitude due to its large DM density and relative proximity to Earth. Even considering possible signal contamination from other astrophysical sources, it is one of the most promising targets to detect the presence of new massive particles. An experiment constructed in the Southern Hemisphere, designed for the observation of extended sources of gamma rays at the TeV scale and above, would be highly sensitive to these DM gamma-ray signals due to the GC transiting close to directly overhead in relation to the experiment. One example of such an experiment would be a next-generation observatory analogous to the present High Altitude Water Cherenkov (HAWC) detector [15].
So far, the search for a DM-induced signal toward the GC at GeV energies has been inconclusive; partly impeded by the detection of multiple emissions due to particle accelerators [16, 17, 18, 19]. However, above the TeV scale, where a HAWC-like detector would be most sensitive, astrophysical gamma-ray backgrounds are expected to be small and allow for detection of very faint DM signals. Such an observatory would also be able to take advantage of its wide field-of-view to observe regions relatively far from the GC, allowing for backgrounds which minimize contamination from gamma-ray sources, thus increasing its sensitivity to emission from the wider DM halo. This ability to observe a more extended region makes the sensitivity less dependent on the assumed behavior of the DM density profile than pointed instruments such as the next generation of Imaging Atmospheric Cherenkov Telescopes (IACTs), the Cherenkov Telescope Array (CTA) [20].

2 Sensitivity to Dark Matter Annihilation and Decay

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

$$\frac{\mathrm{d}\Phi_{\mathrm{Ann}}(\Delta\Omega, E_\gamma)}{\mathrm{d}E_\gamma} = \left(\frac{1}{2}\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{M_{\mathrm{DM}}^2}\frac{\mathrm{d}N}{\mathrm{d}E_\gamma}\right) \times \left(\int_{\Delta\Omega}\int_{\mathrm{l.o.s.}} \mathrm{d}\Omega\,\mathrm{d}s\,\rho_{\mathrm{DM}}^2[r(s,\Omega)]\right), \qquad (1)$$

and

$$\frac{\mathrm{d}\Phi_{\mathrm{Dec}}(\Delta\Omega, E_\gamma)}{\mathrm{d}E_\gamma} = \left(\frac{1}{4\pi}\frac{1}{\tau_{\mathrm{DM}}M_{\mathrm{DM}}}\frac{\mathrm{d}N}{\mathrm{d}E_\gamma}\right) \times \left(\int_{\Delta\Omega}\int_{\mathrm{l.o.s.}} \mathrm{d}\Omega\,\mathrm{d}s\,\rho_{\mathrm{DM}}[r(s,\Omega)]\right), \quad (2)$$

where M_{DM} is the DM particle mass, $\langle\sigma v\rangle$ is the velocity-weighted annihilation cross section, τ_{DM} is the DM lifetime, $\mathrm{d}N/\mathrm{d}E_\gamma$ is the differential spectrum of gamma rays in a specific annihilation or decay channel, and ρ_{DM} is the DM density distribution. The astrophysical factors, also called J-factor for annihilations and D-factor for decays, consist of an integral along the line-of-sight (l.o.s.) and over the solid angle $\Delta\Omega$. The DM density distribution of the Galactic halo is poorly constrained. As shown in Fig. 1, the expected DM density varies greatly between possible functional forms, with the Einasto and NFW (”cuspy”) profiles peaking sharply, and the Burkert (”cored”) profile leveling off toward the GC. This creates substantial uncertainty in the J- and D-factors and therefore on the corresponding sensitivity for searches close to the center of a DM halo. Thus, in order to estimate the predicted DM flux, it is important to consider different possibilities for halos. Here two models are considered: a peaked Einasto profile [21] and a cored Burkert profile [22]. For the purposes of this paper, we use the estimated sensitivity from Fig. 3.3 of Ref. [1] as a characteristic estimate of Southern Hemisphere survey instruments.

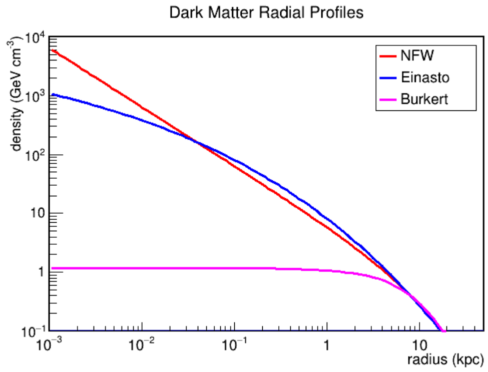

Figure 1: Behavior of three physically motivated density profiles as a function of radial distance from the center.

3 Dark Matter Annihilation Searches Towards the Galactic Center

3.1 Sensitivity to Different Annihilation Channels

We focus our searches for DM signals to the inner 10° of the Galaxy. The spatial regions of interest are defined as circular concentric regions of 0.2° width, excluding a ±0.3° band in Galactic latitude to avoid the above-mentioned standard astrophysical background. We initially assume an Einasto profile and calculate the expected sensitivity for a DM particle annihilating into $\mathrm{W}^+\mathrm{W}^-$, $b\bar{b}$ and $\tau^+\tau^-$.
Figure 2 shows the 95% C.L. sensitivity upper limits on $\langle\sigma v\rangle$ versus M_{DM} for the three annihilation channels from 10 years of observation with a next-generation Southern observatory, here modeled as a 200,000 m^2 water Cherenkov detector (WCD; 10 times the HAWC area). A sensitivity smaller than the nominal thermal relic cross-section $\langle\sigma v\rangle \lesssim 3\times10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$ is reachable in the mass range of ∼500 GeV to ∼80 TeV.

3.2 Density Profile Effects

In order to estimate the impact of different Galactic halo profiles, the sensitivity assuming a Burkert profile is compared to an Einasto profile in Figure 3. The sensitivity of a future IACT

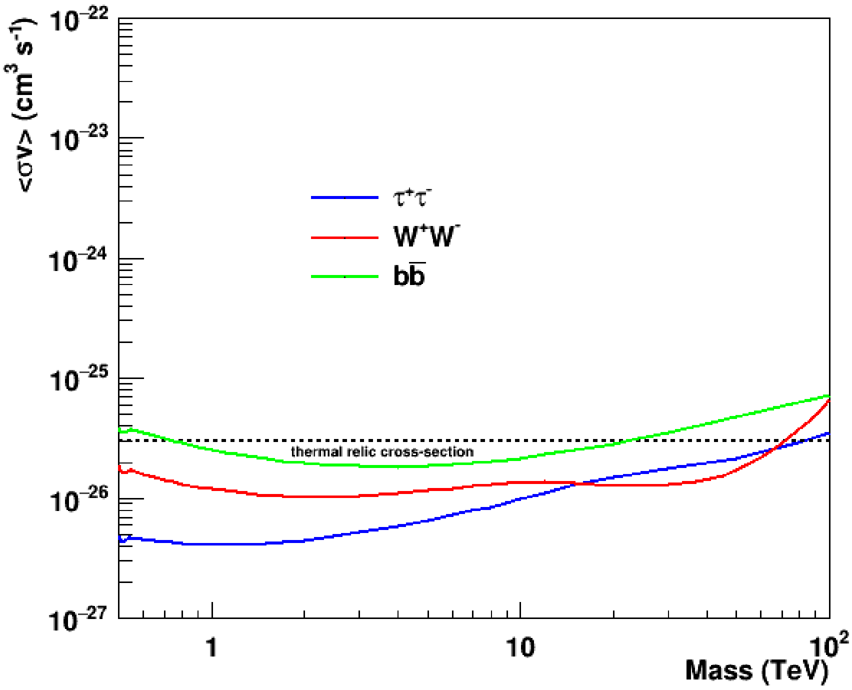

Figure 2: (left) 95% C.L. sensitivity upper-limit on the velocity weighted cross section for DM self-annihilation into W^+W^-, $b\bar{b}$ and $\tau^+\tau^-$ as a function of $M_{\rm DM}$, for an Einasto profile of the Galactic halo.

(CTA), calculated for 500 hours of observation, is also plotted for comparison [23]. Due to the smaller field-of-view of CTA, the signal extraction region was limited to the inner 1° of the Galaxy. A wide field-of-view observatory would be more sensitive to DM annihilations than CTA for all DM masses above 700 GeV, especially 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 GC. 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 recover some of the lost sensitivity by increasing the expected integrated flux.

Indeed, cored profiles are best if 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 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 minimize signal contamination, allowing them to resolve emission even in the case of a cored profile.

A non-DM 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 current HAWC experiment [24], while observations from air Cherenkov telescopes such as the current VERITAS experiment have shown no significant excess [25]. The power of these wide field-of-view observations when applied the Galactic Halo is shown in Fig. 3, which compares the expected sensitivity of a potential wide field-of-view experiment (a 200,000 m^2 WCD) to that of CTA.

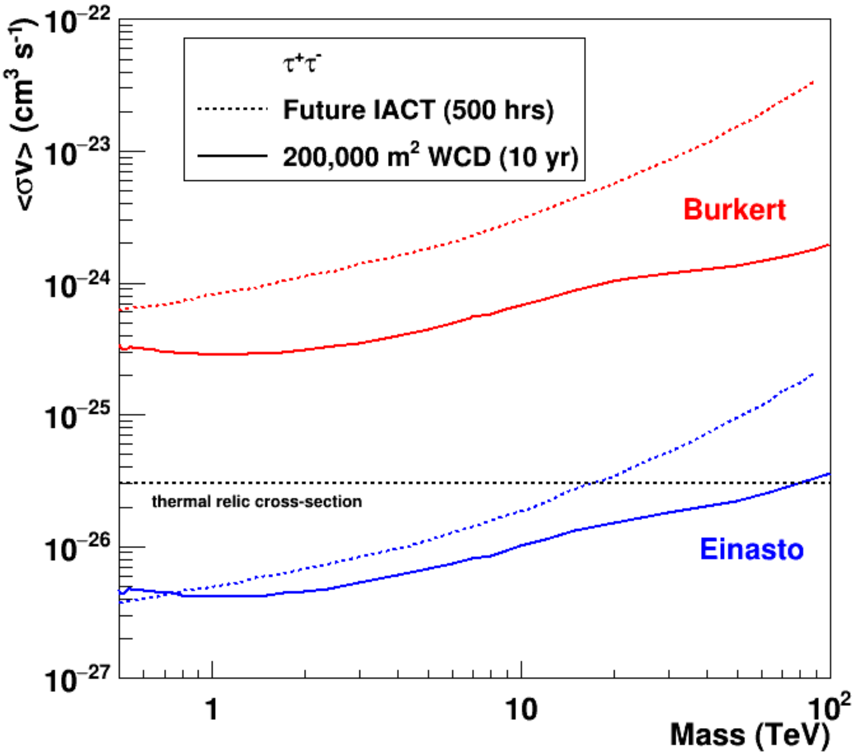

Figure 3: (left) 95% C.L. sensitivity upper limit on the velocity weighted cross section for DM annihilation into $\tau^+\tau^-$ as a function of $M_{\rm DM}$, for both an Einasto (less conservative) and Burkert (more conservative) profile of the Galactic halo. The sensitivity is modeled by Ref. [1], calculated for 10 years of observation in the inner 10°. 500h of observation with CTA in the inner 1° of the Galaxy, excluding a ±0.3° band in Galactic latitude, is shown for comparison.

3.3 Complementarity Between Gamma-ray Observatories

By combining deep observations of the GC region by a ground-based gamma-ray survey observatory with other gamma-ray observatories, such as Fermi-LAT and CTA, a thermal relic cross-section could be probed for all WIMP masses $\lesssim$ 80 TeV in most annihilation channels (see Fig. 2 and Refs. [23, 26]). For masses close to the overlap region with CTA, greatly increased confidence in a detection could be achieved by measurements in both detectors. The DM flux spectra are characterized by a hard cutoff at the DM mass; observing such a cutoff would be one of the strongest indications that an observed gamma-ray source originates from DM interactions. As shown in Fig. 4, a Southern survey-style instrument 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 $\tau^+\tau^-$, such an instrument would provide the WIMP mass measurement by probing the spectral cutoff, with CTA helping to constrain the morphology. We note that this mass range also has considerable foreground advantages over 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 a DM annihilation spectrum in the GeV [27, 19].

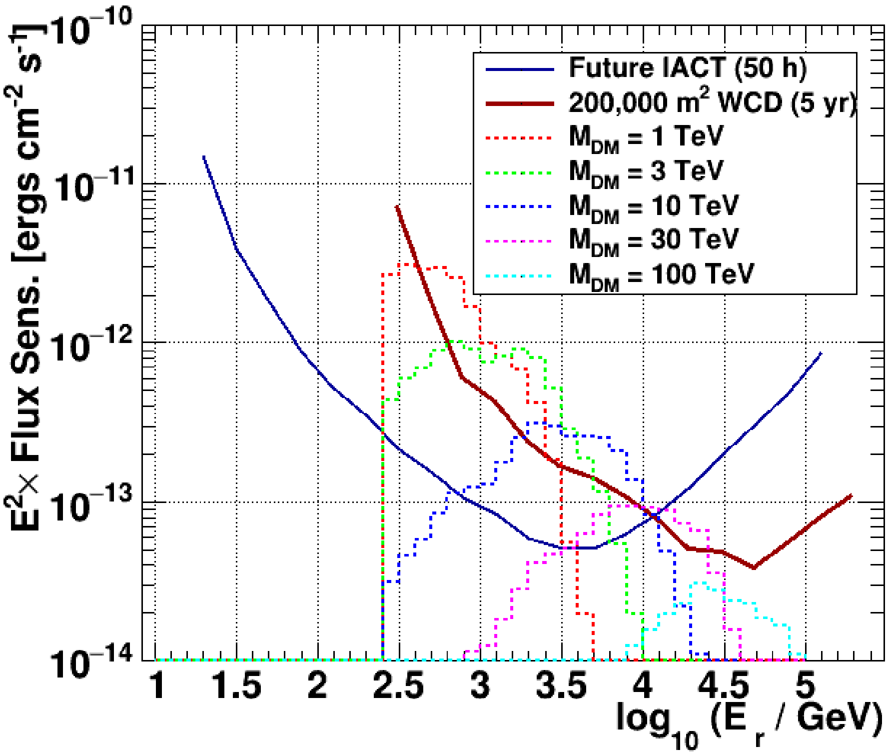

Figure 4: Flux sensitivity curves of a possible next-generation ground-based gamma-ray survey observatory (200,000 m^2 WCD) and of CTA as a function of reconstructed gamma-ray energy, for 5 years and 50 hours of observation of the Galactic halo, respectively. Also plotted are the DM annihilation rate into $\tau^+\tau^-$ per reconstructed energy bin (E_r) for different DM particle masses in arbitrary units, but keeping $\langle\sigma v\rangle$ and the J-factor the same for all masses.

4 Conclusion

The GC is one of most promising regions for detecting gamma-ray signals from WIMP DM. Its close proximity and high DM content yield one of the highest expected fluxes from WIMP interactions. A survey-style instrument with a wide field-of-view in the Southern Hemisphere is an important tool in searching for such emissions from multi-TeV mass DM. Such an instrument 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 WIMP 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. 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 observation. 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 dark matter, allowing it to be a critical tool towards a better understanding of this diverse topic in the coming decade.

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