

Detecting dark matter subhalos in the Galactic plane with the Cherenkov Telescope Array Observatory

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Numerous observations confirm the existence of dark matter (DM) at astrophysical and cosmological scales, yet the fundamental nature of this elusive component of our Universe remains unknown. Theory and simulations of Galaxy formation predict that DM should cluster on small scales in bound structures called subhalos or DM clumps. While the most massive DM subhalos host baryonic matter and are observed as dwarf galaxies of the Milky Way (MW), less massive, unpopulated subhalos could be abundant in the Galaxy as well and yield high-energy gamma rays as final products of DM annihilation. Recently, it has been highlighted that the brightest halos should also have a sizeable extension in the sky. In this study, we examine the prospects offered by the Cherenkov Telescope Array Observatory (CTAO), a next-generation gamma-ray instrument, for detecting and characterizing such objects. Previous studies have primarily focused on high-latitude observations; here, we assess the potential impact of the CTAO's Galactic Plane Survey, which will provide unprecedentedly deep survey data for the inner five degrees of the Galactic plane. Our modeling accounts for tidal effects on the subhalo population, examining the conditions under which DM subhalos can be detected and distinguished from conventional astrophysical sources. We find that regions a few degrees above or below the Galactic plane offer the highest likelihood for DM subhalo detection. For an individual subhalo—the brightest from among various realizations of the MW subhalo population—we find that detection at the 5σ level is achievable for an annihilation cross section of $\langle\sigma v\rangle \sim 3 \times 10^{-25} \text{ cm}^3/\text{s}$ for TeV-scale DM annihilating into $b\bar{b}$. For a full population study, depending on the distribution and luminosity model of Galactic subhalos, still unconstrained cross sections in the range $\langle\sigma v\rangle \sim 10^{-23}\text{--}10^{-22} \text{ cm}^3/\text{s}$ for TeV DM candidates are necessary for the brightest subhalos to be detected.

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I. INTRODUCTION

A. Weak-scale particle dark matter indirect detection

The composition of the Universe remains one of the most intriguing puzzles in the realm of astrophysics and cosmology. While visible baryonic matter constitutes only a small fraction of the total matter-energy density of the Universe, a significant amount ($\sim 25\%$) of the total matter-energy density exists in the form of dark matter (DM), a non-baryonic matter component, whose nature is still unknown [1]. Yet, we observe that its gravitational influence shapes the Universe on a variety of scales, all the way from large-scale structure formation to dynamics within galaxies [2].

There are many different theoretical models proposing particle DM candidates, with some of the most popular candidates being the weakly interacting massive particles (WIMPs) [3,4]. The WIMP hypothesis, in the context of the

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Λ -cold DM (Λ CDM) model of cosmology, assumes that in the early thermal history of the Universe, all particles, including the DM ones, coexisted in thermal equilibrium in the primordial hot plasma (also called the thermal bath). A species of particles remains in a thermal equilibrium with other particles, as long as the interaction rate of the species with other particles in the thermal bath remains larger than the expansion rate of the Universe. As the expansion rate became similar to the interaction rate of that species with other particles, that species decoupled from the thermal equilibrium, and their interaction with the thermal bath eventually stopped altogether, leaving their total number of particles of the same species constant until the present time. This way, the WIMP DM abundance freezes out. From a quantum field theoretical point of view, the simplest particle models of WIMP DM may feature particles of masses up to ~ 140 TeV [5] (the unitarity bound). However, in more refined models allowing for Sommerfeld enhancement, resonances or bound-state formation, this upper mass bound can be pushed beyond this zero-order estimate from unitarity (see, e.g., [6]). The WIMP hypothesis entails a rather simple mechanism to generate the observed cosmological DM abundance for GeV- to TeV-scale particles with $2 \rightarrow 2$ cross sections of WIMPs and Standard Model particles at the level of the electroweak force [7] (the so-called “thermal” cross section). In addition, the WIMP hypothesis allows for testing the predicted cross section with experiments that can achieve a sufficiently good sensitivity to the DM signal.

WIMPs have been priority targets for both astrophysical and particle physics experiments in the last decade and several different approaches to the search for DM signals have been actively pursued [8]. Direct searches for DM aim at detecting the scattering of DM particles on nuclei [9], particle accelerator experiments look for DM signatures in the collision debris [10], and indirect searches scrutinize astronomical and astrophysical observations for the annihilation or decay signal of DM particles in the Universe [11].

Particle physics models predict that DM particles annihilate or decay into SM final states. Those final states may be unstable in nature and further decay into lighter and more stable SM particles that can traverse large distances from their place of origin to the Earth. Out of the three types of potential particle messengers, namely neutrinos, charged cosmic rays (CRs), and gamma rays, the latter represent the most prominent candidate for indirect searches. They are electrically neutral and are subject to comparatively low attenuation, which allows them to travel large distances undeflected and unabsorbed, pointing back to their origin [12]. While this is also true for neutrinos, gamma rays interact more strongly with baryonic matter enabling a larger variety of methods to detect them in experiments. So far many gamma-ray telescopes have been utilized for the search of DM signals, observing various promising DM targets.

Over the years, a wide array of promising sources of DM annihilation or decay signals have been studied, such as the Galactic center (GC) [13–18], the Galactic ridge [19], Milky Way (MW) satellites like dwarf galaxies [20–26], the M31 galaxy [27,28], galaxy clusters [29–31], globular clusters [32–35] and dark subhalos within the MW [36–40], to name a few. Due to the absence of a robustly detected signal, only upper limits and constraints on the parameter space have been derived (see [41–44] for comprehensive overviews). The current situation with gamma-ray observations is that for WIMP particles of masses up to a few hundreds of GeV, the most constraining limits have been obtained from observations of dwarf spheroidal galaxies (dSphs), using space-borne and ground-based instruments, such as Fermi-LAT, H.E.S.S., MAGIC, VERITAS, and HAWC, recently combined to derive joint upper limits on the DM annihilation cross section as a function of the DM particle mass [25]. These limits are 2–3 times stronger than for individual telescopes in the multi-TeV mass range, with limits for masses below ~ 500 GeV dominated by Fermi-LAT, and higher mass limits above ~ 10 TeV dominated by ground-based experiments. For heavier WIMP DM with masses around the TeV scale, the leading constraints are derived from H.E.S.S. observations of the GC within the innermost $\sim 3^\circ$ [45]. For example, assuming a peaked DM density in the GC and $\tau^+\tau^-$ annihilation final states, the thermal cross section can already be ruled out for masses around 1 TeV given the statistical and systematic uncertainties of the study.

B. Dark matter subhalos as indirect detection targets

Complementary targets in gamma-ray searches are dark subhalos, which represent DM overdensities predominantly devoid of any luminous matter. They are bound to their parent DM halo and have masses between $10^{-11} - 10^{-3} M_\odot$ and $10^{10} M_\odot$, depending on the particle physics model [46].¹ They are theoretically predicted by N-body and galaxy formation simulations, implementing the bottom-up hierarchical structure formation scenario expected in the concordance cosmological model [49,50]. In such models, a large number of subhalos are present in the vicinity of the Solar System.

DM subhalos bound to galaxies undergo a complex evolution from the initial merger event to their present-day state. On the one hand, massive subhalos may capture a sizable amount of baryonic matter that is sufficiently large to initiate star formation, leading to electromagnetic radiation over a wide range of wavelengths. On the other hand, the gravitational pull of the MW causes tidal effects on the

¹This statement is true mostly for “vanilla” WIMPs, where TeV-scale particles would most likely produce a cutoff closer to the lower bound. As soon as more elaborate WIMP models are considered, the cutoff scale can become sizeably larger (see, e.g., [47,48]).

subhalo, leading to a change in its matter density profile and mass stripping. Therefore, it is necessary to distinguish the respective subhalo's preinfall virial mass from its current bound mass. Regarding a potential luminous counterpart in DM subhalos, it is the preinfall mass that largely determines the baryon–DM connection. While tidal stripping due to the MW's gravitational potential can reduce a subhalo's bound mass by orders of magnitude, its stellar content is mostly left intact [51–55]. Cosmological hydrodynamical simulations quantitatively demonstrate that star formation is strongly suppressed in subhalos with infall masses below $\sim 5 \times 10^8 M_\odot$ [56,57]. Noteworthy examples of the impact of tidal forces on DM subhalo evolution after infall are Segue I [58] and Reticulum II [59], known ultrafaint dwarf spheroidal galaxies of the MW. These ultrafaint dwarfs exhibit present-day bound masses between 10^5 and $10^6 M_\odot$. This observation is shown to be consistent with having originated in halos above this threshold for star formation and subsequently losing most of their dark matter through tidal evolution [60].

The majority of the subhalo population is yet too light to produce considerable astrophysical emissions. This truly dark part of the population holds an advantage in the indirect search for DM, as there is no astrophysical foreground to obscure the putative DM emission. Moreover, DM-only N-body simulations predict that subhalos contain high concentrations of DM [61,62], potentially exhibiting DM densities that are high enough to produce a bright gamma-ray emission from DM annihilation or decay within the sensitivity reach of gamma-ray instruments [63–65]. Thus, they represent potentially promising DM targets. However, one of the main challenges when looking for signals from dark subhalos is the fact that, in this type of search, we lack information on their exact distribution within the MW. Besides, the limited resolution of N-body simulations limits the precise determination of subhalo properties (their inner structure, abundance, etc.).

Searches for dark subhalo signatures do not have to hinge on the WIMP hypothesis. Their gravitational influence on baryonic matter already yields viable methods to look for their presence. One approach concerns galactic stellar streams, the tidal vestiges of dwarf galaxies and globular clusters. Dynamically cooled stellar streams may be perturbed by dark subhalos leaving, e.g., gaps, spurs and breaks in the stream [66] depending on the stream's density. A spur candidate was identified in the GD-1 stellar stream [67], which was used to infer the properties of the potential perturbing object [68,69]. In contrast, indications for a stream break joining the seemingly disconnected ATLAS and Aliqa Uma streams were identified in [70]. Besides individual events, the cumulative effect of multiple encounters with the Galactic dark subhalo population on stellar streams can be studied statistically to explore the subhalo mass function down to masses around $10^5 M_\odot$ [71] leveraging future datasets of the *Gaia* mission or the Vera Rubin Observatory [72].

A different pure gravitational search channel is looking for distortions in Einstein rings of strongly lensed objects. The idea is that the dark substructure along the line-of-sight to the lensed object induces a magnification of the image on small scales. With this technique, subhalos with masses around $10^{8-9} M_\odot$ could be identified in data of the Hubble Space Telescope, Keck adaptive optics, and ALMA interferometric data [73–76]. Machine learning methods have been employed in this context and it was shown that they are capable of pushing the sensitivity of this method to less massive subhalos, rendering it possible to constrain the particle nature of DM based on the inferred subhalo mass function [77–79].

Coming back to the WIMP hypothesis, several gamma-ray searches for dark subhalos leveraged data of current generation gamma-ray instruments, such as unidentified sources in the *Fermi*-LAT catalogs [26,40,65,80–86], HAWC [87,88], and H.E.S.S. observations [89]. While *Fermi*-LAT and current ground-based gamma-ray instruments provide stringent constraints on the DM mass and annihilation cross section, no subhalo detection has been confirmed. A future generation of ground-based gamma-ray telescopes, the Cherenkov Telescope Array Observatory (CTAO), represents a promising next step for the discovery of dark subhalos, by widening the reachable DM parameter space and opening the possibility of setting even more stringent constraints on DM properties. The potential of the CTAO for the detection of Galactic DM subhalos has recently been assessed for the planned extra-Galactic survey. The extra-Galactic survey is envisaged to cover one-quarter of the sky focusing on the northern hemisphere with a mean sensitivity to pointlike sources of about 6 mCrab over the entire area covered [90]. The authors of [91] looked at the prospects of serendipitous discovery of dark subhalos at higher latitudes, where source confusion has a less pronounced impact (see also [40,92]).

C. Motivation for a dedicated study with CTAO

CTAO will consist of more than 60 imaging atmospheric Cherenkov telescopes (IACTs) in the northern (CTAO-North) and southern (CTAO-South) hemispheres, making it the world's largest and most sensitive high-energy gamma-ray observatory [90].

CTAO surveys are expected to reach two orders of magnitude deeper exposure than the currently performed surveys using IACTs, mostly thanks to the improved sensitivity and wider field of view (FoV) [90]. Surveys are part of CTAO's Key Science Projects which form the core scientific program of CTAO. This ensures that the surveys will receive dedicated observation time early on in the observation schedule of CTAO. The CTAO is well suited to survey the entire Galactic plane due to its large FoV (reaching $> 8^\circ$ diameter at the highest energies) and an angular resolution of a few arcminutes. The Galactic Plane Survey (GPS) is planned to be performed in the energy

range between 20 GeV and 300 TeV with unprecedented depth and spectral coverage, using both CTAO-North and CTAO-South arrays.²

Several surveys of the Galactic plane have been performed with IACTs in the last decades [94,95], with the largest survey performed by H.E.S.S., covering the $-110^\circ < \ell < 65^\circ$ and $|b| \leq 3^\circ$ range and detecting a total of 78 sources [96]. With a target (point-source) sensitivity of the GPS at the level of a few mCrab, CTAO is expected to detect a factor of 2–7 times as many astrophysical TeV sources as there are in the current catalogs [93], offering a unique opportunity to perform population studies of Galactic very high energy gamma-ray emitters.

Past studies have suggested different strategies for searching for Galactic subhalos [91,92], as stated before, focusing on the envisaged extra-Galactic survey of CTAO. The authors of [91], as well as most of the sensitivity predictions for DM subhalo detectability and searches for DM subhalos in unidentified sources, assume all DM subhalos to be point sources. Nevertheless, N-body cosmological simulations predict possible large angular sizes for some dark subhalos, even reaching several degrees in extension depending on their mass profile and distance, exposing the need for a dedicated study of sensitivity to extended DM subhalos. The investigation of the detection of DM subhalos as extended sources with *Fermi*-LAT has recently been performed [97]. We focus our study on the sensitivity of the CTAO to extended DM subhalos, assuming the technical specifications of the GPS, which provides a deeper exposure with respect to the planned extra-Galactic survey. The targeted (pointlike) sensitivity of the GPS is around 1.8 mCrab in the inner Galaxy region, which outperforms the extra-Galactic survey by more than a factor of three. In addition, the prospects of the GPS for DM subhalo searches are yet unexplored, even though a sizeable number of these objects will be present in the vicinity of the Galactic plane. Although the Galactic plane contains higher levels of astrophysical background and an increased probability of source confusion, we will show that the GPS will be competitive in the search for dark subhalos. In Sec. VII, we therefore provide an *a posteriori* argument for why the GPS is a suitable CTAO survey for the subhalo search.

The assessment of the sensitivity of the planned GPS to a DM subhalo signal presented in this paper is a proof of principle, aimed to show that the GPS is complementary to previously suggested strategies for subhalo detection. In case of no DM subhalo detection, the sensitivity of the GPS to constrain the DM annihilation cross section is comparable to that of other targets, for example, dSphs [98,99]. Yet, DM subhalos are less promising targets than the signal from DM annihilation in the GC (see Sec. VI). However, if

the DM profile at the GC has an extended (kpc-scale) core, the sensitivity to the DM GC signal deteriorates and depending on the extension of the density core, it could become comparable to that of satellites of the MW-like Large Magellanic Cloud [100] or the stacked limits from dSphs.

The study of the GPS sensitivity to extended sources has been performed in our paper on prospects for the detection of pulsar halos [101]. In this work, we adopt a similar analysis framework and follow the same approach with a focus on dark subhalos.

The paper is organized as follows: Sec. I introduces the topic of indirect searches for DM and Galactic DM subhalos. In Sec. II, we list and describe the assumed background components of instrumental and astrophysical nature. We also outline the derivation of our subhalo model and templates. The subsequent Sec. III outlines the data simulation scheme and adopted statistical framework. Section IV reports our results for a single DM subhalo where we obtain the detection sensitivity and discuss the impact of systematic uncertainties. The following Sec. V sheds light on the question of how well we can access a subset of subhalos of the full population, and what is the contribution of the population to the overall Galactic diffuse emission. Section VI discusses what are the prospects for detection of the MW's main halo in the GPS. We conclude the paper in Sec. VII.

II. MODELING THE SKY COMPONENTS

Following our objective to estimate the sensitivity of the CTAO GPS to DM subhalos, we first define the sky model we employ to describe the dominant gamma-ray emission components along the Galactic plane. The main contribution to the gamma-ray emission in this region comes from the Galactic diffuse emission, whose modeling we describe first. On top of the diffuse emission, we consider different benchmark subhalo models extracted from mock populations of Galactic subhalos.

A. Large-scale diffuse backgrounds

Our analyses include the large-scale interstellar emission (IE) and examine its effects on the GPS sensitivity to DM subhalos. Coming from the interaction of the Galactic CR population with the interstellar medium, the IE is a significant contribution to the gamma-ray sky. It runs predominantly along the Galactic plane and has been well mapped at the GeV energies with the *Fermi* LAT (see [102] for a review). As the IE extends over large angular scales, measuring its TeV-range emission using the IACTs with very limited fields of view has been challenging. Recent advances have been made in measuring the IE at high energies using water-Cherenkov detectors (MILAGRO, HAWC, and LHAASO), thanks to their large effective area, field of view, and high duty cycles.

²The current plan for the GPS is outlined in detail in [93], which differs from the original description of the GPS in [90].

To model this component, we use a recent study by Luque *et al.* [103], that takes the available GeV to PeV gamma-ray data from *Fermi* LAT, Tibet AS γ , LHAASO, and ARGO-YBJ, and measurements of the local charged CR performed with AMS-02, DAMPE, CALET, ATIC-2, CREAM-III, and NUCLEON. The study uses two physical frameworks to distinguish the different assumptions on diffusion coefficient variability: the so-called “Base” scenario models the diffusion coefficient as constant throughout the Galaxy, while the “ γ -optimized” scenario allows for a radial variability of the diffusion coefficient. In our analyses, we utilize the “Base” framework. Both frameworks offer two spectral setups, dubbed “Min” and “Max,” describing different behaviors in the CR proton and helium source spectra at high energies (see [103] for more details), with the “Base-Max” setup selected as our benchmark. This model predicts the largest gamma-ray emission along most parts of the Galactic plane (except for the Galactic center region). It was also the benchmark choice for [101], in which a more detailed study of the impact of these models on searches for extended sources is given.

B. Gamma rays from Galactic dark matter subhalos

1. Gamma-ray DM signal

The signal coming from DM particle annihilation within a subhalo³ depends on the density and distribution of DM and the assumed particle physics model of the interaction of DM particles with the SM. The expected flux of photons coming from DM annihilation in a given energy range is therefore

$$\mathcal{F}(E_{\min}, E_{\max}) = \frac{\langle \sigma v \rangle}{8\pi M_\chi^2} \mathcal{J} \int_{E_{\min}}^{E_{\max}} \frac{dN_\chi}{dE} dE, \quad (1)$$

where $\langle \sigma v \rangle$ is the thermally averaged annihilation cross section, M_χ is the mass of the DM particle, $\mathcal{J}$ is the $\mathcal{J}$ -factor corresponding to the DM subhalo spatial density ρ_χ , and dN_χ/dE is the gamma-ray spectrum of a single DM annihilation process. In our calculations, we adopt the spectral model from [41], assuming the $b\bar{b}$ annihilation channel and a varying DM particle mass, M_χ , ranging between 100 GeV and 100 TeV. Given the distribution of DM within the subhalo, the $\mathcal{J}$ factor for annihilating DM is calculated by integrating the square of the spatial density, ρ_χ , over a solid angle $\Delta\Omega$ and along the line of sight (LOS) l ,

$$\mathcal{J}(\Delta\Omega) = \int_0^{\Delta\Omega} \int_{1.o.s.} dl d\Omega \rho_\chi^2(l, \Omega). \quad (2)$$

In practice, the integration over the solid angle $\Delta\Omega$ and LOS is performed numerically via the publicly available software

package CLUMPY⁴ [104–106]. To account for the angular resolution of the CTAO, which depends on the reconstructed gamma-ray energy and to some degree also on the utilized CTAO array (CTAO-North or CTAO-South), we pixelized the $\mathcal{J}$ -factor skymap using a HEALPix map with $N_{\text{side}} = 2048$, corresponding to an angular resolution of $\sim 0.0286^\circ$ and a value of $\Delta\Omega = 2.5 \times 10^{-7}$ sr. This value is in good agreement with the spatial resolution that CTAO will reach at the highest energies, $\mathcal{O}(100 \text{ TeV})$, where its spatial resolution is best [90]. Over most of CTAO’s energy range, this resolution is finer than the point-spread function (PSF) size (see also Sec. III A for further descriptions). Note that we do not take into account any further level of substructure boosting the J factor of the MW subhalos since even subhalos may host subhalos themselves as indicated by the results of N -body simulations (see for example [64] for the modeling of the boost factor).

2. Subhalo modeling: Single subhalo with optimal properties

Most information on the properties of Galactic subhalo populations in the literature that take into account the baryonic effects on DM substructure is either extracted from numerical simulations of galaxy formation [65,107–109] or derived as a result of analytical or semianalytical methods [110–113]. In our study, we focus on a specific semianalytical model of Galactic subhalos by Stref and Lavalley (SL17) [113], with the goal of providing a proof-of-principle calculation of the sensitivity of CTAO’s GPS to dark subhalos.

The SL17 subhalo population model relies on a realistic description of the MW [114] and takes into consideration the tidal and shocking effects in the Galactic disc. All subhalos in the SL17 model are assumed to have a Navarro-Frenk-White (NFW) density profile [115] parametrized as,

$$\rho_{\text{SH}}(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right) \left(1 + \frac{r}{r_s}\right)^2}, \quad (3)$$

where r_s is the so-called scale radius, defining the radius at which the steep cuspy profile transitions to a more gradual decrease, and ρ_s is the characteristic density that depends on the concentration of the subhalo.

The resilience of DM subhalos to tidal disruption is still under debate as the effects and strength of disruption vary significantly in different studies. Recent studies suggest that dark subhalos are relatively resilient to tidal forces, maintaining their structures and gravitational integrity even when subject to strong gravitational potentials in their surroundings, causing significant mass loss [116,117]. These subhalos can possess dense, cuspy cores, which enhance their

³This is the very same DM signal expected from subhalos regardless of whether they host stars or not.

⁴The full online documentation is hosted at: <https://clumpy.gitlab.io/CLUMPY/v3.1.1/>.

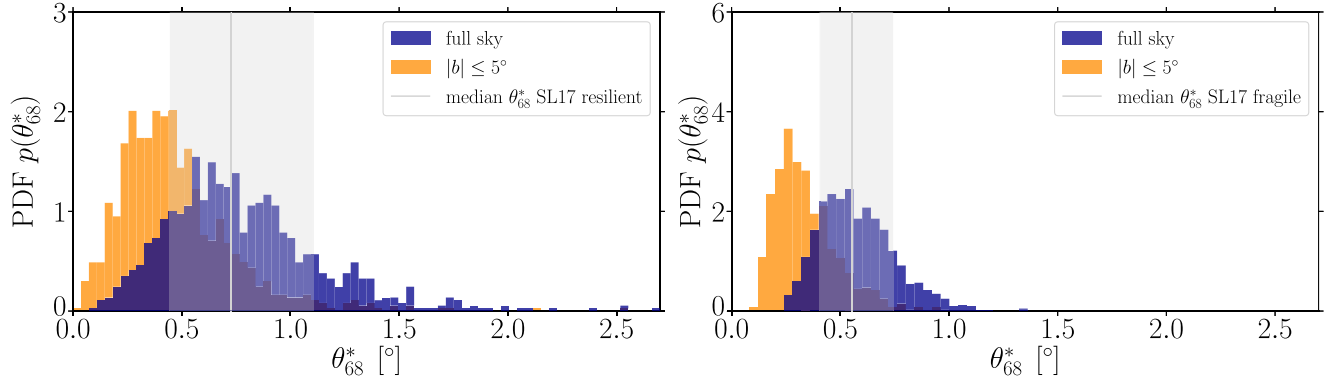


FIG. 1. PDF of brightest subhalo extensions derived from all 1010 realizations of the SL17 resilient (left) and SL17 fragile (right) populations (for details on the population modeling see [113,118]). On the x axis, the angle θ_{68}^* denotes the angle in which 68% of the total $\mathcal{J}$ factor is contained. The gray lines mark the median extension of the brightest subhalos over all the generated populations, with the contours marking the band between the 16% and 84% quantiles. For comparison, we present the PDFs for selecting the brightest subhalo from the entire sky (blue) as well as limited to the Galactic plane within $|b| \leq 5^\circ$ (orange). Note that in contrast to [97], the displayed full-sky histograms only include subhalos up to $M_\Delta = 10^8 M_\odot$.

resistance to tidal disruption. On the other hand, cosmological N-body simulations suggest that dark subhalos are efficiently disrupted in the inner region of the Galaxy, indicating that tidal forces can significantly affect the abundance and distribution of DM subhalos [61,62].

To account for uncertainties caused by the tidal effects, we investigate two variants of the model, dubbed “SL17 fragile” and “SL17 resilient,” originally defined in [118]. In the SL17 fragile model, the disruption of the subhalo occurs when $r_t < r_s$, with r_t being the tidal radius, i.e., the radius beyond which the gravitational tidal forces from the surrounding matter in the Galaxy become stronger than the self-gravity of the subhalo. For SL17 resilient, the disruption occurs instead when $r_t < 0.01 r_s$. As the names suggest, the SL17 fragile scenario predicts efficient disruption of dark subhalos, while the SL17 resilient case leaves many more objects resistant to tidal disruption. For each of the two SL17 scenarios, we generated 1010 realizations of the subhalo populations.

The results of previous works [40,97] suggest a correlation between the $\mathcal{J}$ factor and the subhalo mass and $\mathcal{J}$ factor and the angular extension, respectively. Based on these results, we expect the (present-day) mass of the brightest subhalos to lie between 10^6 and $10^8 M_\odot$. As a matter of fact, the terminology “brightest” and “largest $\mathcal{J}$ -factor” can be used interchangeably in this context since the expected gamma-ray signal strength is directly proportional to the $\mathcal{J}$ factor [see Eq. (1)].

We investigate CTAO’s potential to detect a single DM subhalo in the most optimistic scenario. The brightest subhalos should provide the best sensitivity. To study CTAO’s sensitivity to an ideal subhalo, we focus on subhalos up to $10^8 M_\odot$ with high DM density, yielding large $\mathcal{J}$ factors. By browsing all of our realizations and SL17 scenarios, we find the most optimistic subhalo with $r_s = 2.36$ kpc,

$\rho_s = 3.4 \times 10^6 M_\odot/\text{kpc}^3$, $M_\Delta = 4.8 \times 10^6 M_\odot$ and $r_\Delta = 0.162$ kpc at a distance of $d = 0.92$ kpc.⁵ For us, the quantity r_Δ of a DM subhalo defines its total extent. It is the radius up to which the overall subhalo mass equals the tidal mass M_Δ , i.e., the mass associated with the subhalo after evolving it in the MW’s gravitational potential and accounting for tidal stripping and shocking effects.

Since we set out to determine CTAO’s sensitivity to *extended* subhalos, we define the total angular extension of a subhalo as $\arctan(r_\Delta/d)$. The extension depends, on one hand, on the evolution of the subhalo within the MW since it determines r_Δ and, on the other hand, on the distance of the subhalo d to the observer. A second useful quantity providing information about the subhalo’s extent is θ_{68} defined as the radius or angular size that contains 68% of the subhalo’s total $\mathcal{J}$ factor. We adopt θ_{68} as the benchmark quantity when referring to the angular size of a subhalo following the approach in [97].

In our search for the most optimistic subhalo, we browsed the available set of population realizations for the subhalo with the largest $\mathcal{J}$ factor. We observe a certain scatter of the associated angular extent for both SL17 scenarios. In Fig. 1, we show the probability distribution function (PDF) for the sample of θ_{68} obtained from the brightest subhalo of each realization, i.e., θ_{68}^* , searching in the full sky (blue) and only in the Galactic plane at $|b| \leq 5^\circ$ (orange). Focusing first on the distributions we derive for the entire sky, the brightest subhalos of the resilient scenario exhibit generally larger extensions than their

⁵We stress that this is a study case for the most optimistic scenario and, as such, it is meant to develop some intuition on the reach of CTAO to such objects. Eventually, the same argument and analysis can be applied to dwarf spheroidal galaxies, with very little modification of our analysis pipeline.

counterparts in the fragile scenario. This observation is caused by the fact that resilient subhalos are on average closer to Earth than subhalos of the fragile scenario since the former may survive the gravitational forces present in the inner parts of the MW. Therefore, their apparent size in the sky is larger while their overall size r_Δ is typically smaller than found in fragile populations. Moreover, the PDF for the SL17 resilient model exhibits a substantial tail with extensions up to 2.5° that is absent in the SL17 fragile case. This tail is, again, caused by the ability of resilient subhalos to survive as bound objects at smaller distances from the GC than fragile subhalos. In comparison, the brightest subhalos specifically localized in the Galactic plane region show a smaller extension on average. This observation is in line with the intuition that the fraction of surviving subhalos was more severely affected by the baryonic gravitational potential of the Galactic disc; thus, inducing stronger tidal stripping or shocking effects. The tail of the PDFs can reach extensions similar to the maximal extensions over the entire sky, though. These findings also imply that, on average, dark subhalos in the Galactic plane will appear more pointlike than subhalos found at higher latitudes. Therefore, the GPS can naturally complement⁶ the search for Galactic subhalos in data of CTAO's extra-Galactic survey and provide competitive constraints as we will derive in what follows.

Additionally, we display in Fig. 1 the median extension of the brightest subhalos over the entire sky as a vertical gray line while the 16% and 84% quantiles are visualized as gray bands. We later use subhalo templates representing these median cases as references to infer the sensitivity to the SL17 resilient and SL17 fragile populations as a whole as outlined in Sec. III E. We chose the full-sky samples and their median for this study because we aim to gauge our method against larger extensions, which are still plausible even for subhalos in the Galactic plane given the wide tails of the orange distributions.

III. DATA SIMULATION AND ANALYSIS

A. Simulation of GPS observations

We adopt the approach described in [93] to simulate the GPS observations. The planned observation schedule consists of an early-phase program (480 hours of observation time in the first two years of observations) and a long-term program (1140 hours of observation time over the following eight years). The planned pointing strategy for the GPS adopts a double-row pattern of equally spaced pointing directions, observations during the dark time (moonless nights), and optimizations regarding minimal zenith angles of each observation. The exposure of different regions of the Galactic plane will differ depending on the expected

number of sources and objects of interest in each region. The Galactic plane is divided into five respective regions, namely the Inner Galaxy, which is planned to receive more observation time and with that deeper exposure, as it is most densely populated with sources; the Cygnus/Perseus region; the Vela/Carina region; the outer South region; and the Anticenter region. Therefore, each region's point- and extended-source sensitivity will differ, which is considered when performing our population study.

To simulate GPS observations, we utilize the most recent instrument response functions (IRF) provided by the CTAO,⁷ dubbed PROD5-v0.1.⁸ The IRFs correspond to the anticipated configuration of the CTAO arrays, consisting of four large- and nine middle-sized telescopes (STs) in the Northern site and 14 middle- and 37 small-STs in the Southern site. These represent the instruments that will be built in the initial construction phase. Among other properties, the IRFs contain information about CTAO's PSF and energy dispersion. Simulations and analyses were performed using the publicly available gamma-ray analysis software GAMMAPY⁹ [120,121]. We selected the set of IRFs corresponding to background cuts appropriate for studies of extended sources. These cuts were optimized based on Monte Carlo simulations of 50 h of observations. The largest fraction of events detected by ground-based observatories comes from air showers triggered by CR particles that enter the atmosphere. These can be misidentified as gamma rays in the event reconstruction process and represent the irreducible CR background component. This CR component is modeled from extensive Monte-Carlo simulations of CR air showers, detection of the associated Cherenkov radiation, and subsequent event reconstruction. The rate and distribution of misidentified CR events are provided by the IRF suite and depend on the given observing conditions, such as the duration of observations and the zenith angle. This component is fitted to the data, together with the astrophysical emission models (cf. Sec. II), in the case of a real data analysis. In the spatial-spectral likelihood analysis introduced in the next section, the overall normalization of the CR background is left free to account for the uncertainties or biases in this component.

B. Statistical analysis framework

We adopt the statistical inference framework of Ref. [18] and adapt it to our needs, as it was done in our previous work on detecting and characterizing pulsar halos [101]. Consequently, we are conducting binned template-based fits of gamma-ray emission models to simulated CTAO mock data. Given a specific region of interest, we devise a

⁶Of course, this statement depends on the observer's distance to the bright part of the Galactic dark subhalos population.

⁷See <https://www.ctao.org/for-scientists/performance/> for more details.

⁸The IRF files are publicly available at [119].

⁹<https://gammapy.org>.

gamma-ray emission model as a linear combination of templates encompassing the expected CR background B , taken from the adopted CTAO IRF instance, and astrophysical signal components $\{S_k\}_{k \in K}$. The latter set of templates $\{S_k\}_{k \in K}$ is comprised of components describing conventional astrophysical gamma-ray emission like the diffuse emission originating in CR interactions with the interstellar medium as well as exotic contributions linked to DM annihilation in subhalos of the MW's parent halo. All statistical inference is based on the Poisson likelihood function,

$$\mathcal{L}(\boldsymbol{\mu}|\mathbf{n}) = \prod_{i,j} \frac{\mu_{ij}^{n_{ij}}}{(n_{ij})!} e^{-\mu_{ij}}, \quad (4)$$

where $\boldsymbol{\mu}$ represents the gamma-ray emission model (cf. Sec. II) used to fit $\mathbf{n}$, the CTAO experimental mock data. The index i enumerates the energy bins while the index j labels the spatial pixels of the employed templates.

Our gamma-ray emission model is then generally given by,

$$\boldsymbol{\mu} = \sum_{k \in K} S_k(\boldsymbol{\theta}_k^S) + B(\boldsymbol{\theta}^B), \quad (5)$$

where $\{\boldsymbol{\theta}_k^S\}_{k \in K}$ and $\{\boldsymbol{\theta}^B\}$ represent generic model parameters adjusting the spectral and angular dependence of the signal and CR background templates. For all practical matters, we consider linear models assigning renormalization parameters (global or per energy bin) to our employed templates, i.e., spelled out explicitly

$$\mu_{ij} = \sum_{k \in K} \theta_{k,i}^S S_{k,ij} + \theta_i^B B_{ij}. \quad (6)$$

We derive CTAO sensitivity projections based on the log-likelihood ratio test statistic (TS). This approach allows us to statistically quantify the evidence for detecting a new signal above a given background or to distinguish between alternative hypotheses regarding the nature of a measured signal. The TS is generically expressed as:

$$\text{TS} = 2 \left(\ln \left[\frac{\mathcal{L}(\boldsymbol{\mu}(\hat{\boldsymbol{\theta}}_k^{S_{\text{test}}}, \hat{\boldsymbol{\theta}}^B) | \mathbf{n})}{\mathcal{L}(\boldsymbol{\mu}(\hat{\boldsymbol{\theta}}_k^{S_{\text{null}}}, \hat{\boldsymbol{\theta}}^B) | \mathbf{n})} \right] \right), \quad (7)$$

where the hatted quantities refer to the best-fitting values for all model parameters. The model composition in the null and test hypotheses depends on the task at hand. It will be specified for each analysis individually.

C. General analysis definitions

In the case that we analyze single subhalos (cf. Sec. II B 2 for the description of the brightest subhalo

candidate), the template-based likelihood analysis is performed using the following specifications:

- (i) The subhalo is positioned at the reference location $(l, b) = (40^\circ, 0^\circ)$ of our region of interest (ROI), represented by $6^\circ \times 6^\circ$ regions around the subhalo positions. We will use this location in the Inner Galaxy region of the GPS, which is characterized by the highest exposure (an illustration of the exposure across the GPS band can be found in [101]). This position is far from the rather complex GC, which allows us to reduce the amount of background component modeling for this sensitivity forecast.
- (ii) Simulations are performed on a $0.02^\circ \times 0.02^\circ$ pixel grid unless stated otherwise. The simulated templates are later rebinned to a larger, $0.12^\circ \times 0.12^\circ$ grid before performing the sensitivity analysis to ensure that the chosen bin size corresponds to the characteristic length scale of CTAO PSF (see Sec. IV A 2 for more details).¹⁰
- (iii) To properly sample the IRFs and in particular the energy dispersion of the array, the energy binning is done with 15 logarithmically spaced energy bins per decade. The energy range we consider is between 10 GeV and 100 TeV. The finer energy bins are rebinned to 5 log-spaced energy bins per decade before the likelihood analysis. However, not all energy bins will contain statistically significant numbers of events (at lower energies due to exceeding the low limit of the CTAO's energy range and at high energies due to a DM mass cutoff in the spectra).

Considering single DM subhalos, we will perform several analyses that apply Eq. (7). In what follows, we provide a brief description of how this equation is specified and approached in each of these cases.

D. Deriving the differential flux sensitivity to single subhalos

This analysis part revolves around the most optimistic scenario for a dark subhalo detection based on the brightest subhalo candidate identified in our population realizations. However, the selected optimal DM subhalo yields a single sensitivity estimate for CTAO that does not capture the dependence on all the parameters that enter the value of θ_{68} . To study the CTAO sensitivity to extended subhalos in a broader sense, we vary the distance of the optimal subhalo keeping the radius r_Δ constant. Besides its nominal

¹⁰Spatial bin size for the sensitivity analysis does not strongly impact the forecast when no systematic uncertainties are included. Otherwise, our treatment of systematic uncertainties introduces a dependence on the spatial bin size and, thus, our results should be understood in this sense. A more detailed study of the impact of the spatial bin size on sensitivity forecasts with CTAO is given in [18] in the context of searches for DM annihilation from the Milky Way main halo in the Galactic center.

TABLE I. Table of selected subhalos simulated with CLUMPY and considered in the assessment of the GPS sensitivity, listing in consecutive columns the final (after tidal stripping) subhalo mass M_Δ , its distance from Earth, its scale radius r_s , the total $\mathcal{J}_{\text{tot}}$ -factor values, representing the $\mathcal{J}$ factor of the subhalo across its full extent (up to r_Δ), and the $\mathcal{J}_{\text{FoV}}$ -factor values, representing the fraction of the $\mathcal{J}_{\text{tot}}$ -factor observed within the telescope's FoV, the total radial size r_Δ , and the angular size θ_{68} of the subhalo. The first four rows list different instances of the overall brightest subhalo found across all realizations and population scenarios at increasing distances from Earth. The first entry corresponds to the original dark subhalo from the SL17 resilient scenario. The last two entries list the parameters of the median SL17 resilient and fragile representatives marked by grey lines in Fig. 1.

Subhalo mass M_Δ	Distance (kpc)	r_s (kpc)	$\mathcal{J}_{\text{tot}}$ ($\text{GeV}^2 \text{ cm}^{-5}$)	r_Δ (kpc)	θ_{68} ($^\circ$)
$4.8 \times 10^6 M_\odot$	0.92	2.36	9.56×10^{21} (6.44×10^{21} in FoV)	0.162	1.54
$4.8 \times 10^6 M_\odot$	5.0	2.36	3.21×10^{20}	0.162	0.46
$4.8 \times 10^6 M_\odot$	10.0	2.36	8.02×10^{19}	0.162	0.23
$4.8 \times 10^6 M_\odot$	30.0	2.36	8.94×10^{18}	0.162	0.08
$7.7 \times 10^7 M_\odot$	12.3	1.26	8.94×10^{19}	1.02	0.7
$1.1 \times 10^7 M_\odot$	11.6	0.529	1.59×10^{19}	0.54	0.54

distance $d \sim 1$ kpc, we simulate the subhalo for three additional distances $d = 5, 10, 30$ kpc.

The sensitivity of CTAO depends on the location of the subhalo as well since the GPS consists of regions with varying exposure as mentioned in Sec. III A. Since we find subhalos all along the Galactic plane in our simulations, we consider the single benchmark location given in the previous section, at which we place the center of our selected DM subhalo templates. The sensitivity to subhalos in the other regions of the GPS can easily be derived by rescaling the sensitivity we obtain for the Inner Galaxy. Since the pointing pattern of the GPS is designed to achieve a relatively uniform exposure in the different GPS domains, the difference in exposure is typically a factor of a few following from the total observation time t so that the sensitivity will scale with $\sqrt{t}$.

A list of all considered single subhalo benchmarks and their properties is given in Table I. The obtained results for the sensitivity to the different subhalos described above and listed in the table are discussed in Sec. IV. The differential sensitivity and the constraining power to the DM annihilation cross section for different subhalos are displayed in Sec. IV A.

Having defined the cases to consider for this analysis, we derive the GPS $\text{TS} = 25$ (5σ) detection sensitivity per energy bin stated in units of flux (differential flux sensitivity) in complete analogy to [101] with the only difference being the employed spatial template, i.e., the respective DM subhalo profile. For details, for instance, on how we effectively include systematic uncertainties, we refer the reader to this publication.

E. Assessing the sensitivity to the entire subhalo population

While the analysis outlined in the previous section was dedicated to the CTAO prospects in an optimistic scenario, we now aim for an assessment of the CTAO's sensitivity to a dark subhalo population within the GPS as a whole.

We derive a statement about the number of detectable sources as a function of the annihilation cross section incorporating the statistical scatter of their properties and positions according to the expectations following from the 1010 realizations of the SL17 resilient and fragile populations.

We design a dedicated analysis approach that allows us to estimate the detection sensitivity to objects exhibiting a certain angular extension. The exposure of the GPS is not uniform in latitude and longitude; hence, the guiding idea is to consider the integrated energy band from 70 GeV to 100 TeV and to derive the *integrated sensitivity* to a certain source type for a selected number of representative positions in the GPS band. To this end, we define a coarse tiling of the GPS ROI at 60 different locations given by five latitude bins with edges at $b = [-5^\circ, -3^\circ, -1^\circ, 1^\circ, 3^\circ, 5^\circ]$, and 13 longitude bins with edges at $l = [-180^\circ, -155^\circ, -115^\circ, -85^\circ, -60^\circ, -40^\circ, -15^\circ, 15^\circ, 40^\circ, 60^\circ, 85^\circ, 115^\circ, 155^\circ, 180^\circ]$. The nonuniform longitude bin size is motivated by the nonuniform exposure pattern of the GPS. We avoid large overlaps between regions of strongly different exposure (cf. Fig. 5). At each position, we compute the integrated sensitivity for three source types: (i) a pointlike source, (ii) the median representative of the SL17 fragile population, and (iii) the median representative of the SL17 resilient population. The selection of the median representative of the subhalo populations is based on θ_{68}^* of the brightest subhalo per realization as shown in Fig. 1. In that sense and to be precise, they are the median representations of the ensemble of brightest subhalos. The gray vertical line indicates the median extension, which reads $\theta_{68, \text{fragile}}^* = 0.54^\circ$ for SL17 fragile and $\theta_{68, \text{resilient}}^* = 0.7^\circ$ for SL17 resilient. The other subhalo parameters characterizing these subhalos are stated in Table I.

To obtain a better visual impression of these subhalos' extensions, we compare in Fig. 2 the appearance of the resilient and fragile populations' representative subhalos to typical profiles encountered for astrophysical sources

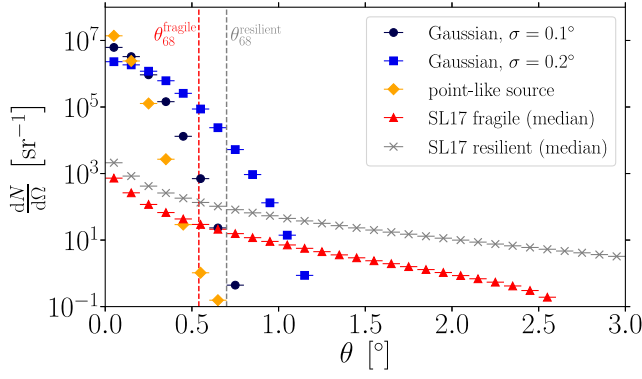


FIG. 2. Comparison of the surface brightness angular profile (concentric annuli of width 0.1°) of two DM subhalo templates, SL17 resilient (gray) and fragile (red), corresponding to the median angular extension marked with a vertical gray line in Fig. 1. The angular extension θ_{68} of SL17 fragile amounts to 0.54° while the resilient subhalo exhibits an extension of 0.7° . Both angular sizes are marked with vertical dashed lines in their respective colors. For reference, we show the surface brightness profile of a pointlike source and two extended sources following a Gaussian profile of a width of 0.1° and 0.2° , respectively. The profiles are convolved with the CTAO IRFs and extracted from a simulation between 100 GeV and 1 TeV. We assume $M_\chi = 100$ TeV and annihilation into $b\bar{b}$ final states.

including pointlike objects. The displayed surface brightness angular profiles have been obtained from simulated data featuring a convolution with CTAO’s IRFs in the energy range from 100 GeV and 1 TeV. For definiteness, we assumed the gamma-ray spectrum of DM annihilating into $b\bar{b}$ pairs with a mass of 100 TeV for all shown sources. We also added two Gaussian-like sources with widths 0.1° and 0.2° , respectively, to this figure to emphasize the morphological differences between DM subhalos and spatial profiles typically employed in gamma-ray analyses of extended astrophysical sources. These extensions are, e.g., common for astrophysical objects like pulsar wind nebulae (PWNe) [93]. While the angular profile of the astrophysical sources exhibits a rapid drop of brightness in agreement with their extension (and additional PSF size), the DM subhalo profiles display a much shallower profile, which continues this trend even beyond what is shown in the figure. Nonetheless, the central part of the subhalo is about an order of magnitude brighter than its remainder. The stated angular extension of the subhalos θ_{68} is, thus, not to be understood as a sharp boundary but rather the region from which the majority of the gamma-ray emission originates.

Figure 2 illustrates why it is necessary to derive extension-dependent integrated sensitivities for the population study: Extended objects like the displayed DM subhalos are much harder to discern from the CR background of the instrument due to their shallow emission profile being degenerate with this background component. Only the very central part produces more concentrated photon counts. Here, the integrated sensitivity represents

the sensitivity to a signal integrated over a selected energy range, conveying information on the minimal integrated flux that must be emitted by the source under study for it to be detected with a $TS \geq 25$. The evaluation of the integrated sensitivity is done by performing the same approach as in the case of the differential sensitivity assessment, i.e., calculating the likelihoods of the two fits (for the test and the null hypothesis) in each energy bin, but instead of iteratively assessing the normalization of the source in each energy bin, the likelihoods over all energy bins in the considered energy range are summed, and the normalization of the source is determined as the source normalization value at which the newly obtained “integrated” likelihood reaches $TS = 25$. The obtained source normalization is then used as the renormalization factor on the initial source spectra that entered the simulations of the source template, and the integrated sensitivity, i.e., the flux that needs to be achieved for source detection, is equal to the renormalized source spectrum integrated over the selected energy range.

Eventually, we obtain three grids of flux values that mark the threshold for the detection of our three targeted source classes at specific positions in the GPS band. Finding the required flux for claiming a significant detection regarding all three considered sources provides us with the evolution of the CTAO sensitivity to extended sources as a function of their angular extent. Of course, the subhalos in our population realizations are of different angular extents to what we selected as test cases. To inter- and extrapolate from these three benchmark cases, we adopt and slightly modify the approach applied in the H.E.S.S. Galactic plane survey publication [96]. In each probed tile of the GPS ROI, we parametrize the dependence of the flux sensitivity F for detection as

$$F(\theta_{68}) = A(\mathbf{x}) \sqrt{\alpha \theta_{68}^2 + \sigma_{\text{PSF}}^2}. \quad (8)$$

The quantity σ_{PSF} refers to the energy-averaged PSF of the CTAO, which is $\sim 0.05^\circ$ for the chosen energy band. Having derived the required flux for detecting pointlike sources, we calculate the position-dependent normalization $A(\mathbf{x})$ for $\theta_{68} = 0$. With the flux sensitivities for $\theta_{68, \text{fragile}}^*$ and $\theta_{68, \text{resilient}}^*$, we optimize this rescaling equation by varying α such that it minimizes the error margin at each individual position. Eventually, the minimal error we can achieve with this method is of the order of 15%, corresponding to a position-independent value of $\alpha = 0.06$. We derive the flux sensitivity with this rescaling function for any subhalo of our realizations and translate it to an annihilation cross section based on the respective $\mathcal{J}$ factor.

IV. GPS SENSITIVITY TO INDIVIDUAL DARK MATTER SUBHALOS

In this section, we discuss the obtained results on the sensitivity of the CTAO’s GPS to the most optimistic

scenario with the brightest subhalos found across our simulations being located in the Galactic plane as described in Sec. II B 2. An exploration of the prospects for the full population follows in Sec. V.

A. Sensitivity to subhalos from a spectral analysis

1. Flux sensitivity for GPS conditions

The spectral sensitivities, shown in the left panel of Fig. 3, correspond to the benchmark brightest subhalo in the simulated populations of subhalos positioned at different distances from Earth (the first section of the subhalo list shown in Table I). The sensitivity degrades with decreasing distance to the subhalo, which corresponds to a larger source extension (see the last column in Tab. I for the angular size of subhalos positioned at various distances).

Figure 3 displays the flux levels of our reference single subhalo model (dotted lines) scaled to higher values by two orders of magnitude to allow the flux to fall within the plotted flux range for the obtained sensitivities. The fluxes are computed assuming the thermal cross section for DM annihilation, $\langle\sigma v\rangle = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$. We note while this numerical value for the thermal cross section is commonly taken as a reference, there are various particle physics models of DM in which the current annihilation rate can be larger than in the early Universe. Such scenarios may occur in the presence of resonances [122–126] or they may be related to the so-called Sommerfeld effect [127]. The expected annihilation cross section can reach levels more than one order of magnitude above the vanilla WIMP value.

To explore the cross sections that would be within the reach of the GPS, we analyze the spectra of annihilating DM with masses ranging from 0.1–100 TeV. The results for the brightest subhalo positioned at various distances, shown in the right panel of Fig. 3, suggest that GPS will achieve the best sensitivity to DM masses in the 0.5–3 TeV range, and for sources positioned closest to the observer, reaching the $\langle\sigma v\rangle$ values down to $\sim 3 \times 10^{-25} \text{ cm}^3 \text{ s}^{-1}$. This is, however, only true in case no systematic uncertainty is considered in the analysis. The added systematic uncertainty significantly modifies the CTAO reach in the range where it is most sensitive, leading to significantly different results (see Sec. IV A 2 for further discussion). Another important thing to note is that the flux sensitivity estimate is also annihilation channel dependent. Here, as mentioned before, we only consider the annihilation into $b\bar{b}$ final states.

We emphasize the striking fact that the ordering of lines in the left and right panels of Fig. 3 are inverted. The brightest subhalo at $\sim 1 \text{ kpc}$ distance requires the lowest annihilation cross section for detection while it requires the highest differential flux among all probed subhalos for a detection. The reason for this observation is the $\mathcal{J}$ factor, which compensates for the loss in differential sensitivity caused by the large angular extension of the subhalo. In general, the ordering of sensitivity in Fig. 3 is driven by the angular size of the subhalo since it is easier to detect a pointlike source (far distant subhalo) than an extended (close) one. The $\mathcal{J}$ factor is suppressed by a factor of $1/d^2$ so that subhalos with large $\mathcal{J}$ factor are typically closer to the observer.

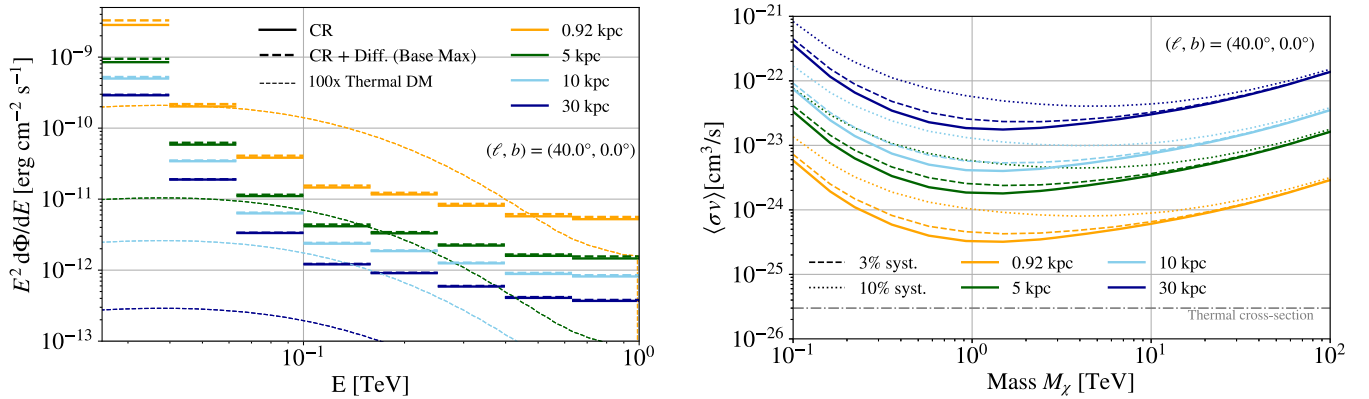


FIG. 3. (Left:) Differential sensitivity, defined as the minimum flux needed to obtain a 5σ detection of the benchmark subhalos positioned at four different distances from the observer and at the reference positions $(l, b) = (40.0^\circ, 0.0^\circ)$. The sensitivity does not simply scale with the inverse of the distance squared due to substantial angular extensions for subhalos that exceed the latitude extension of the GPS, which causes only a fraction of the total flux to be contained within the ROI. The sensitivities are calculated with (dashed lines) and without the IE (solid lines). The thermal DM spectra for each subhalo are overlaid and enhanced by two orders of magnitude to fit within the plotted flux range (following the same color code as the sensitivity lines). The $\mathcal{J}$ -factor values for each subhalo position and distance are listed in Table I. (Right:) Sensitivity of the CTAO GPS to the brightest DM subhalo candidate found among all realizations, described in Sec. II and listed in Table I, with respect to the DM particle mass M_χ . Sensitivity to the brightest subhalo positioned at four distances from Earth, assuming no systematic uncertainty (solid lines) or various levels of added systematics (dashed and dotted lines). The benchmark subhalos are positioned at the reference location within the planned GPS at $(l, b) = (40.0^\circ, 0.0^\circ)$.

From the presented results, and as we will see in Sec. V, the reach of GPS allows for the detection of subhalos when cross sections are at best one order of magnitude above the thermal cross section.

2. Impact of IE and systematic uncertainties

From the results presented in Fig. 3, we can assess the impact of the IE and systematics, respectively. While including the IE in our analysis does not significantly affect the derived sensitivities, the same cannot be said about the effect of systematics, which is most significant precisely at the energies where CTAO would probe the lowest $\langle\sigma v\rangle$ values. The degree to which the systematic uncertainty worsens the derived sensitivity strongly depends on the overall systematic error amplitude included in the model. We explore three different levels of systematic uncertainty: 1%, 3%, and 10%. While the 1% added systematics do not significantly modify the conclusions that we can emanate from the results that do not consider systematic uncertainty, the effects become noticeable at the 3% level, and cause the obtained sensitivities at energies below few TeV to be dominated by systematics at the 10% level. There is no benchmark model for systematic uncertainty for CTAO at this time, however, we consider in our selection of the explored systematic errors that the target level of systematic uncertainty for CTAO is expected to be at the level of a few percent.

As another way to look at these results and to facilitate the comparison of different levels of systematic uncertainty, we display their relative impact in Fig. 4 for two cases of DM subhalo templates from Fig. 3, located at a distance of either $d = 0.92$ kpc or $d = 30$ kpc. The impact is shown

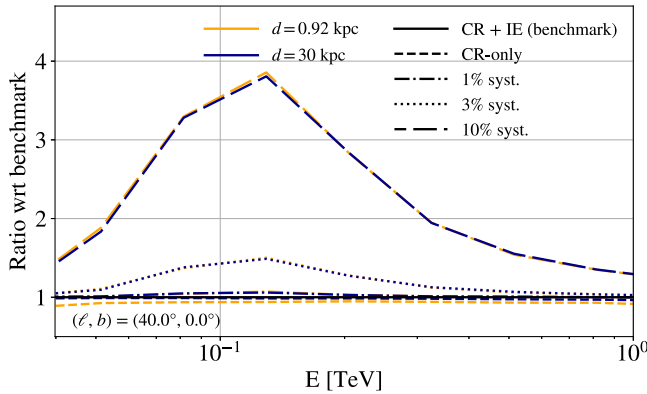


FIG. 4. Differential sensitivity ratio with respect to the benchmark model, showing the effect of the IE (dashed lines) and two different levels of systematic uncertainty (1%, 3%, and 10% levels are shown with dash-dotted, dotted, and wide-dashed lines, respectively) on derived sensitivities to subhalos positioned at 920 pc and 30 kpc distance in yellow and blue colors, respectively. The benchmark model takes into consideration the instrumental (CR) and the IE, without added systematics.

relative to the differential flux sensitivity without systematic uncertainties and a background comprised of CR and IE. We see that the inclusion of IE has the strongest impact on a nearby source since it will appear as a very extended object that can be affected by the structure of the IE. A distant subhalo rather classified as a PLS stays nearly unaffected by this additional background component. It becomes likewise evident that systematic uncertainties at the level of 3% already deteriorate the expected sensitivity by more than 40% for energies around 100 GeV. Note that this energy range dominates the sensitivity to DM particles of masses around 1 TeV.

V. GPS SENSITIVITY TO A POPULATION OF DARK MATTER SUBHALOS

A. Accessible fraction of the subhalo population

As outlined in Sec. III E, we analyze the accessible fraction of a subhalo population via position-dependent integrated sensitivities for the GPS band. These sensitivity maps are obtained for fragile, resilient, and point source templates and displayed in Fig. 5. To identify whether a subhalo is detectable or not, we compute the total integrated flux of the subhalo using Eq. (1). Based on the location of the subhalo in the GPS region as found in our population realizations, its total integrated flux is compared with the expected CTAO sensitivity at that location from applying the rescaling formula in Eq. (8) taking into account its angular extent θ_{68} . We interpolate to any intermediate position of the entire GPS region using the cubic-kind 2D-interpolation. If the total integrated flux is greater than the derived sensitivity at this position then the subhalo is classified as detected.

We apply this formula to all subhalos in the 1010 realizations of SL17 resilient and fragile, respectively. However, we limit the considered set of subhalos to those falling into the Galactic plane with $|b| \leq 5^\circ$. As a function of annihilation cross section, our approach yields a quantitative estimate of how many subhalos of each population can be detected. The results are visualized in Fig. 6. The solid lines indicate the mean evolution of the number of detected objects for SL17 resilient (red) and SL17 fragile (blue). We also provide the scatter of these quantities displayed as colored shaded bands where the high opacity band denotes the 68% containment and the lighter band the 95% containment.

As a general trend, we confirm that the SL17 resilient population produces more subhalos within the GPS ROI due to their resilience to tidal shocks and stripping. To detect at least one subhalo of this population, the annihilation cross section for a WIMP particle of mass $M_\chi = 1$ TeV needs to amount to $\langle\sigma v\rangle = 3.3 \times 10^{-23} \text{ cm}^3/\text{s}$ on average. The SL17 fragile population is fainter on average requiring a cross section value of $\langle\sigma v\rangle = 9.7 \times 10^{-23} \text{ cm}^3/\text{s}$ to allow for a single detected subhalo. However, the scatter of $\mathcal{J}$ factors for

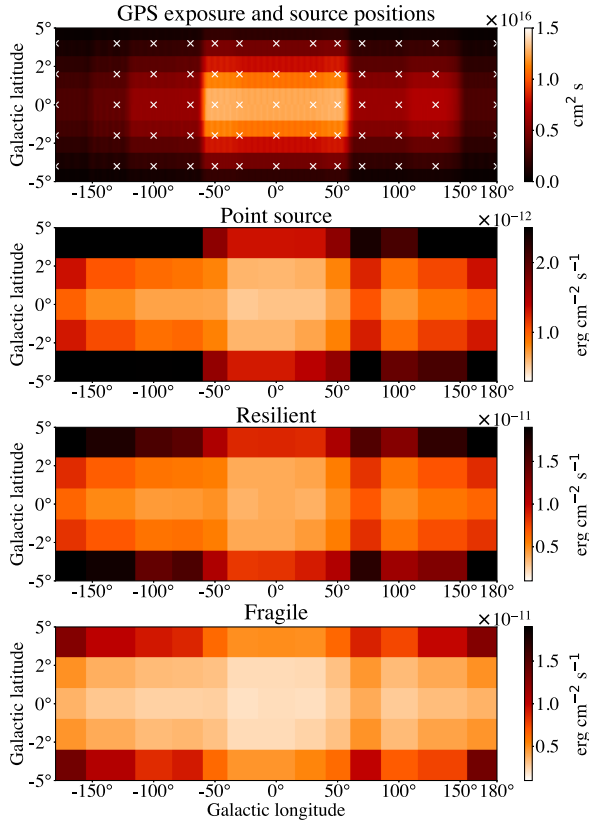


FIG. 5. Integrated sensitivity to subhalo models with various extensions, integrated over the energy range 0.07–100 TeV. The positions of the subhalos are shown in the upper panel with white marks, and their distribution is overlaid with the exposure map of the CTAO Galactic plane survey region. The lower three panels show the integrated sensitivity to a point source, a subhalo with a mean extension of the subhalos in SL17 resilient populations, and a subhalo with a mean extension of the subhalos in SL17 fragile populations, in this order.

the resilient population is more pronounced than for the fragile one. There are realizations in SL17 resilient simulations where a cross section close to 10^{-24} cm³/s is already sufficient for detection. Thus, we are closer to the findings in Sec. IV that examine the most optimistic scenario for CTAO.

What do these results imply for the real MW? The most optimistic case has, given the available number of resilient realizations we have at hand, at least a 0.1% probability of occurring in our Galaxy, that is, finding a quite massive subhalo of $\sim 5 \times 10^6 M_\odot$ at about 920 pc from Earth. By browsing the subhalo realizations for similar brightest-per-population subhalo cases regarding the distance to Earth, we find around 90 (SL17 resilient) candidates between 500 pc and 1.5 kpc with varying total $\mathcal{J}$ factors. We checked numerically with our statistical analysis approach that the required flux for a 5σ detection of these subhalos is up to an order of magnitude higher than for the most optimistic case when located within the GPS ROI. Hence, there is about a 9% chance of finding a DM subhalo in our proximity with properties that may lead to an annihilation

signal that is not yet excluded by present-day indirect searches (see Fig. 8).

B. Imprint of the unresolved subhalo population

A DM subhalo population in the MW generates a certain level of gamma-ray emission irrespective of the potential detectability of individual subhalos. Their cumulative emission is part of the diffuse Galactic emission whose main components are IE and the part of gamma-ray source class populations too dim to be resolved individually. In fact, DM subhalos may be considered an exotic contribution to the latter component. To estimate the importance of this exotic diffuse contribution we compare the cumulative flux of our two DM subhalo population scenarios with expectations for TeV-bright astrophysical sources in the GPS.

We analyze the synthetic population of PWNe generated for the CTAO consortium publication on the prospects of characterizing source populations with GPS data [93]. As shown by the authors of this work, PWNe make up the largest fraction of TeV gamma-ray sources along the Galactic plane such that restricting ourselves to them does not limit our qualitative comparison. The results are shown in the top panel of Fig. 7, which divides the synthetic population of PWNe into a detected and subthreshold part. The detection threshold follows the quantitative estimate reported in [93] of 8×10^{-14} ph cm⁻² s⁻¹ (for energies > 1 TeV). On top of the synthetic sources, we include in the left panel all already known TeV-bright sources also considered in [93]. Note that the authors of this work made sure that bright synthetic sources that have a detected analog in the real sky were removed from the catalog to avoid double counting. The cumulative emission of the astrophysical source population follows the spatial binning defined in Fig. 5. The results clearly show an increase of gamma-ray emission toward the GC and a Galactic latitude of 0°. This observation is a natural consequence of the formation mechanisms of PWNe, which are remnants of massive stars and supernova explosions at the end of their lifecycle. Thus, their location in the sky is ultimately tied to regions rich in gas and featuring active star formation, for instance, the GC and the MW’s spiral arms.

In contrast to most astrophysical source populations, DM subhalos are not predominantly present along the Galactic plane but may occur throughout the entire Galaxy. In particular, the three-dimensional distribution of the subhalos follows the NFW profile of the Milky Way’s main DM halo assumed for the simulations. We report the cumulative gamma-ray emission arising from DM pair annihilation into $b\bar{b}$ final states in the bottom row of Fig. 7, which shows one realization of the resilient (left) and fragile (right) subhalo scenarios. In accordance with the parameter choices adopted in Fig. 6, we fix the DM mass to $M_\chi = 1$ TeV and calculate the gamma-ray intensity for a cross section of $\langle\sigma v\rangle = 3.3^{+1.7}_{-1.9} \times 10^{-23}$ ($9.3^{+4.4}_{-4.8} \times 10^{-23}$) cm³ s⁻¹ for the resilient (fragile) population. The stated

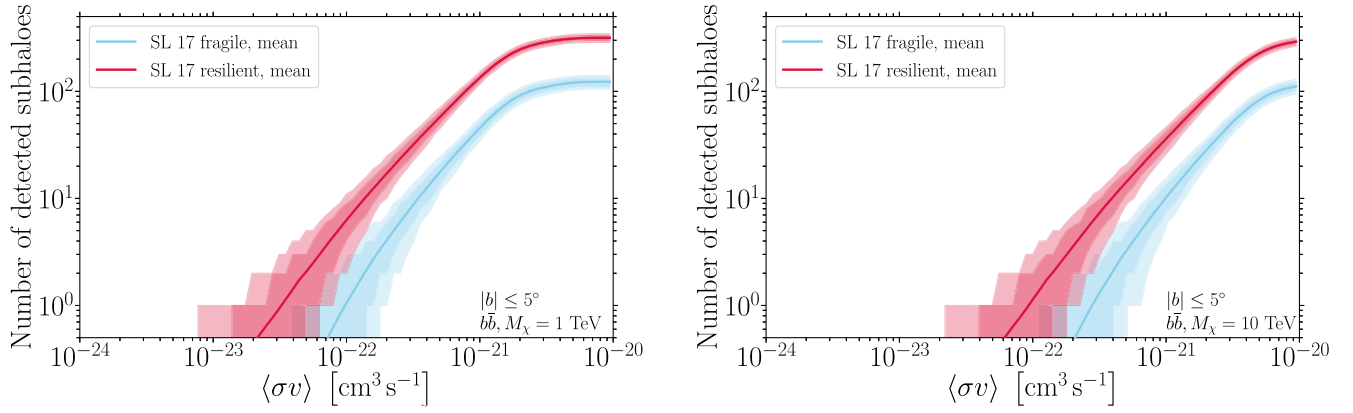


FIG. 6. Number of detectable DM subhaloes for the two population models SL17 resilient (red) and SL17 fragile (blue). The sensitivity derives from the integrated sensitivity in Fig. 5 rescaled via Eq. (8) to the angular extent of each probed subhalo accounting for the position-dependent threshold flux of the GPS assuming a DM particle of mass $M_\chi = 1 \text{ TeV}$ (left) or $M_\chi = 10 \text{ TeV}$ (right) annihilating into $b\bar{b}$ final states. The mean numbers are derived from the 1010 realizations for each population scenario selecting only subhalos at Galactic latitudes $|b| \leq 5^\circ$. The colored shaded bands indicate the 1σ and 2σ containment bands reflecting the scatter of the numerical simulations. The mean cross section to detect at least one subhalo is $\langle\sigma v\rangle = 3.3^{+1.7}_{-1.9}(9.3^{+4.4}_{-4.8}) \times 10^{-23} \text{ cm}^3/\text{s}$ for SL17 resilient and $\langle\sigma v\rangle = 9.7^{+4.9}_{-5.4}(28^{+14}_{-13}) \times 10^{-23} \text{ cm}^3/\text{s}$ for SL17 fragile at $M_\chi = 1(10) \text{ TeV}$. The stated numerical uncertainties refer to the 1σ containment band.

uncertainties are at the 1σ level. These cross section values quantify the required annihilation strength to guarantee the detection of at least one DM subhalo. Thus, the reported cumulative intensities are quantifying the truly diffuse part of the DM subhalo population. Both realizations illustrate

the formerly mentioned spatial distribution of subhalos. However, the fragile DM subhalo population is less represented toward the central Galaxy reflecting the fact that the increasing tidal forces deplete this part of the MW from “fragile” DM subhalos.

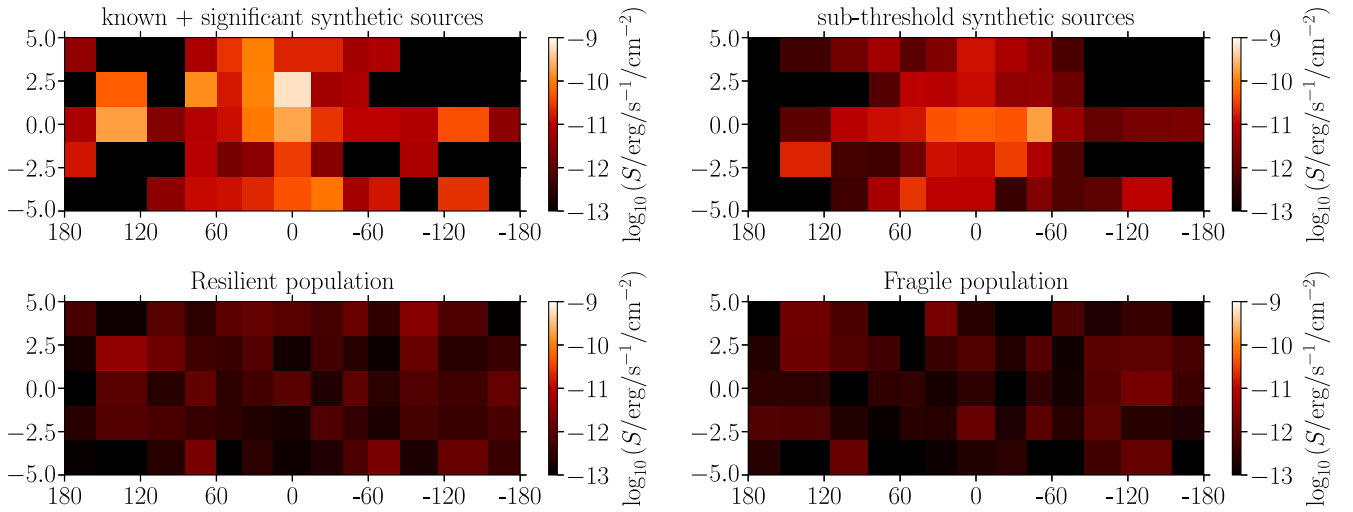


FIG. 7. (Top row:) Cumulative intensity S of the source population comprised of known and synthetic PWNe sources simulated and employed in CTAO’s GPS publication [93]. The intensity map follows the spatial binning of Fig. 5 and has been calculated per source from 70 GeV to 100 TeV. The left panel displays the cumulative emission expected from the resolved part of the population where we assume the most pessimistic CTAO detection sensitivity target of $8 \times 10^{-14} \text{ ph cm}^{-2} \text{ s}^{-1}$ (for energies $> 1 \text{ TeV}$) reported in [93]. This maximizes the expected cumulative intensity of the unresolved part of the population shown in the right panel. (Bottom row:) Cumulative intensity S of the resilient (left) and fragile (right) DM subhalo populations for a realization matching the median conditions of all simulated realizations, respectively. For definiteness, the intensity is computed for a DM mass of $M_\chi = 1 \text{ TeV}$ assuming annihilation into $b\bar{b}$. The annihilation cross section coincides with the mean values to detect at least one subhalo for the respective population scenario as reported in Fig. 6. The displayed intensity maps reflect the subthreshold contribution associated with the MW DM subhalo population.

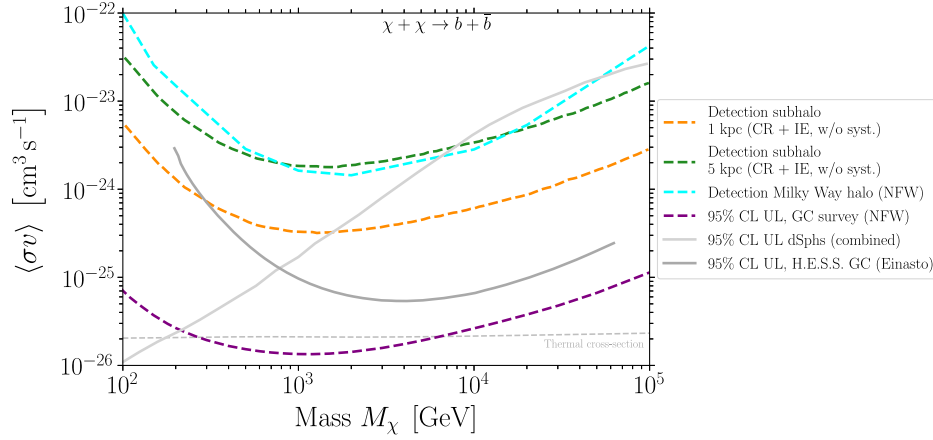


FIG. 8. Sensitivity to the MW DM parent halo modeled with an NFW profile and representative parameters ($r_s = 20.5$ kpc, $r_\odot = 8.3$ kpc and $\rho_\odot = 0.41$ GeV/cm³) adopted from [114] derived in a simultaneous fit to simulated GPS data excluding the region $l \in [-12^\circ, 12^\circ]$. The GPS mock data is comprised of the irreducible CR background and interstellar emission. No systematic uncertainties are included. In addition, the prospects of CTAO's GC survey to constrain the Galactic halo (same NFW profile setup) are stated as 95% CL UL as dotted purple line [18]. For comparison, we plot the most optimistic prospects for detecting the brightest DM subhalo of the MW population within the GPS for two distances taken from the right panel of Fig. 3. In addition, we show in light gray the 95% CL UL on the DM annihilation cross section obtained from a combined analysis of 45 dSphs observed by *Fermi*-LAT, HAWC, H.E.S.S., MAGIC, and VERITAS [25,128]. The current 95% CL UL including instrumental systematic uncertainties on DM annihilation in the GC, assuming an Einasto profile, from more than 500h of observation time with the H.E.S.S. telescope are shown as dark gray line [45].

These figures demonstrate qualitatively and quantitatively that the diffuse emission from the full DM subhalo population can reach values comparable to or even higher than the diffuse emission expected from the presence of astrophysical gamma-ray emitters. In particular at latitudes above $|b| > 1^\circ$ DM subhalos might dominate the diffuse emission in the resilient case and to a lesser extent in the fragile scenario. For example, in the region $1^\circ < b < 5^\circ$ and $85^\circ < \ell < 265^\circ$ the cumulative emission from the resilient population shown in the left panel of Fig. 7 reaches a value of 1.2×10^{-11} erg/cm²/s, which is about five times larger than the expected cumulative flux of the subthreshold part of the synthetic astrophysical source population. Seen from a different point of view, this implies that these latitudes are less contaminated by astrophysical sources and, hence, they bear a higher potential to detect the brightest part of the DM subhalo population (which is not featured in both figures). To restate our earlier results, the brightest subhalo of the population may be detected at an annihilation cross section about an order of magnitude lower than the cross section applied in this figure. As a side note, these figures show that the presence of astrophysical sources and the thereby caused obstacle of source confusion do not heavily deteriorate the potential to detect individual objects of the population slightly above or below the plane.

VI. GPS SENSITIVITY TO THE MAIN DARK MATTER HALO

Since the GPS sweeps the Galaxy all along the Galactic plane, it can potentially detect DM pair annihilation in the

MW's main DM halo. In fact, this signal might even be stronger than any emission from its substructure. We examine it in a simplified setup: We perform a simultaneous fit of the GPS region of interest without the innermost part ($l \in [-12^\circ, 12^\circ]$) around the GC. We exclude the central part because it would require special treatment due to the complex astrophysical emission and rather uncertain DM density profile (see [18] for details). Next, we assume CR and IE as the only background components. We model the MW parent halo with an NFW profile and parameters taken from the Bayesian characterization in [114] where we adopt a realization compatible with the reported posteriors' centers: $r_s = 20.5$ kpc, $r_\odot = 8.3$ kpc and $\rho_\odot = 0.41$ GeV/cm³. While the background components' normalization may vary per energy bin, we assign a single parameter to the DM template that is directly related to the strength of the annihilation cross section. We derive the 5σ detection sensitivity and associated cross section in the framework discussed in Sec. III B.

The result for $b\bar{b}$ final states is displayed in cyan as a function of the DM mass M_χ in Fig. 8. Additionally, we plot the results for the brightest DM subhalo from the right panel of Fig. 3 for direct comparison. As expected, the MW parent halo constitutes a bright extended gamma-ray source in the GPS. Depending on the position of the brightest DM subhalo, the main halo may even be the most prominent target in the GPS. However, our analysis is meant to show a rather simplified scenario with only two background components and no further complications. In reality, it is necessary to include all resolved, localized gamma-ray

emitters in the GPS (or to mask them) in order to search for such a substantially extended component. Realistically speaking, detecting the MW parent halo would require an even larger annihilation cross section.

We stress, however, that the GC and the planned GC survey proposed by the CTAO consortium have a much better sensitivity to the annihilation signal of the main halo as indicated by the purple line in Fig. 8 taken from [18]. The quoted sensitivity is stated in terms of a 95% CL upper limit (UL) for the same NFW profile—in contrast to the 5σ discovery reach presented in this work. Yet, the DM density profile toward the GC is rather unconstrained as concerns the results of parameter estimation from data on stellar kinematics [129,130]. Consequently, DM density profiles with extensive cores in the MW’s center are not excluded and would drastically weaken the sensitivity of CTAO by orders of magnitude (cf. [18]).

VII. CONCLUSIONS

In this work, we examined the prospects of CTAO’s GPS to characterize the substructure of the MW’s parent DM halo. The presence of subhalos within the MW is a natural consequence of the cold DM paradigm. Yet, the number and distribution of DM subhalos are subject to tidal forces acting on them due to the MW’s and its components’ gravitational potential. Hence, we investigated these objects relying on two benchmark scenarios quantifying the survival probability of DM subhalos inside the Galactic halo (see [113]); an optimistic case—the resilient population—which withstands stronger tidal forces and thereby evades total disruption to a larger extent than subhalos of the more pessimistic scenario—the fragile population. Beyond these scenarios for DM substructures other formation mechanisms and models have been proposed that yield more aggressive predictions in number and density, for example, in the series of works [131–134]. Here, highly concentrated and low-mass cusps may form in the early Universe that are very different from the typical DM subhalos predicted by N -body simulations of structure formation.

Assuming that the particle nature of DM is a form of WIMP, DM subhalos may efficiently produce (very) high-energy gamma-ray emission due to DM pair annihilation in their innermost region boosted by the expected high DM densities. Depending on the distance to the observer and the subhalo’s mass, subhalos could appear as pointlike or extended gamma-ray sources enriching the zoology of known gamma-ray emitters. Gamma-ray telescopes like CTAO with their high sensitivity and good angular resolution are thus suitable to detect a signal from these objects. Previous sensitivities forecasts have focused on the CTAO consortium’s proposed extra-Galactic survey (covering about one quarter of the sky) as well as serendipitous signals in the entirety of CTAO’s legacy data [91,92]. Our work investigates the potential of the GPS—a large-scale

survey of the CTAO consortium not yet considered in the context of searches for DM subhalos—to detect these objects. While the extra-Galactic survey is less “polluted” with conventional astrophysical gamma-ray emitters and comprises a more considerable fraction of the sky, thus facilitating a DM subhalo detection, the GPS is characterized by a larger exposure time, which improves the sensitivity to pointlike and slightly extended sources. Concerning the brightest subhalo of the population, we find that GPS prospects may be about a factor of three better than similar considerations for the extra-Galactic survey [92] depending on the position of the subhalo.

We investigated the impact of several sources of systematic uncertainty that may be of relevance to our inferred 5σ discovery reach of the brightest subhalo of $\langle\sigma v\rangle\sim\mathcal{O}(10^{-25}\text{--}10^{-24})\text{ cm}^3/\text{s}$. We recall from our discussions above that such cross-section values, despite being certainly larger than the canonical thermal annihilation cross section, can be sufficient to generate the observed DM abundance in the Universe if effects like Sommerfeld enhancement or resonances are present. Additionally, our results can potentially be relaxed when accounting for the additional boost of the subhalos’ J -factor due to subsubstructure.

Based on the subhalo extensions and $\mathcal{J}$ factors derived from many realizations of the assumed population scenarios, we find that the prospect of detecting at least one member of the population requires $\langle\sigma v\rangle\sim\mathcal{O}(10^{-23})\text{ cm}^3/\text{s}$ (see Sec. VA). In this section, we also motivated in Fig. 7 that the search for DM subhalos slightly above and below the Galactic equator is less impacted by conventional astrophysical sources.

As reported in Sec. IVA 2, diffuse interstellar emission on top of the irreducible CR background weakens our prospect at the level of tens of percent in case of perfect knowledge about its spatial morphology. Imperfect knowledge—a scenario encountered at the GeV scale with *Fermi*-LAT—introduces uncertainties as large as a factor of two around TeV energies (see [101]). Considering the effect of instrumental systematic uncertainties of around 3% (CTAO’s instrumentation goal) yields a deterioration of the expected sensitivity around a factor of two. More pessimistic assumptions around 10% increase detectable annihilation cross section by an order of magnitude.

Current generation space-borne and ground-based gamma-ray instruments are already somewhat constraining the viable parameter space of TeV-scale DM. We illustrate the current landscape of 95% CL upper limits on $\langle\sigma v\rangle$ in Fig. 8, which includes results from the combined observations of Galactic dSphs with *Fermi*-LAT, H.E.S.S., MAGIC, VERITAS, and HAWC [25,128] and H.E.S.S. observations of the GC for more than 500h [45]. All these observations, of course, come with their own assumptions, data selection, quality cuts, and systematic uncertainties. In particular, the very stringent H.E.S.S. limits from the GC are subject to large uncertainties of the MW’s innermost

DM profile. Currently, a peaked profile like the shown Einasto distribution is as likely as a more extended/cored profile, which heavily deteriorates the sensitivity of H.E.S.S. to a DM signal in the GC by orders of magnitude. Therefore, the combined limits from dSphs are the more reliable observational constraint. In light of these, the brightest part of the subhalo population may provide complementary insight into the WIMP parameter space should it fall into the CTAO's GPS band. Thus, CTAO's GPS has sufficiently good sensitivity to search for the dark substructure of the MW's main halo and to set bounds on the annihilation cross section in case of no detections.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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