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Searches for Dark Matter Subhaloes with Cherenkov Telescopes Wide-Field Surveys

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The presence of substructures in dark matter haloes is an unavoidable consequence of the cold dark matter paradigm. Indirect signals from these objects have been extensively searched for with cosmic rays and γ-rays. At first sight, Cherenkov telescopes seem not very well suited for such searches, due to their small fields of view and the random nature of the possible dark matter substructure positions in the sky. However, with long enough exposure and an adequate observation strategy, the very good sensitivity of this experimental technique allows to constrain particle dark matter models. We confront here the sensitivity map of the HESS experiment built out of their Galactic scan survey to the state-of-the-art cosmological N-body simulation Via Lactea II. We obtain competitive constraints on the annihilation cross-section, at the level of 10^{-24}–10^{-23} cm^3 s^{-1}. The results are extrapolated to the future Cherenkov Telescope Array (CTA), in the cases of a Galactic plane survey and of an even wider extragalactic survey. In the latter case, it is shown that the sensitivity of the CTA will be sufficient to reach the most natural particle dark matter models.

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I. INTRODUCTION

In the current cosmological paradigm, cold dark matter (CDM) dominates structure formation. The haloes of galaxies and clusters of galaxies are assembled through the merging of a huge number of smaller structures. Most mergers are incomplete and large CDM halos, *e.g.* the one around the Milky Way, harbor an enormous population of subhaloes, which are a record of its assembly history. Some particle physics models beyond the Standard Model predict the existence of these new weakly interacting massive particles (WIMPs) that could well form the cosmological dark matter (DM). Should these particles be thermally produced in the early Universe, their co-moving density would have been regulated by self-annihilations. The freeze-out of this reaction in the early Universe leads to the establishment of the nowadays observed CDM density. In dense enough structures, the very same annihilation process can efficiently convert particle DM mass energy into high energy Standard Model particles. The CDM structures represent at least one tenth of the total halo mass and are priviledged targets of searches for DM particles annihilations. The dense regions worth considering are the Galactic center and galactic subhaloes, including a small subset of them which harbors the dwarf satellite galaxies of the milky way. The principle of indirect searches for DM through γ-rays is to search for the γ-ray emission following the hadronization and/or decays of these exotically produced Standard Model particles.

Strategies for searching this dim radiation include targeted searches or wide-field surveys. Thanks to their very large collection area, imaging atmospheric Cherenkov telescopes (IACT) are very well suited for deep observations of selected sources. Constraints on particle DM models have been obtained by the HESS experiment from the observation of the Galactic center [1], the Sagittarius dwarf galaxy [2], the Canis Major overdensity [3], and by MAGIC from the observation of the Perseus galaxy cluster [4] and Miky Way satellites Draco [5] and Wilman-1 [6]. Alternatively, space-based instruments such as the Fermi satellite can much more easily perform blind searches for DM subhaloes with a regular scanning of the entire sky thanks to their large field of view [7]. In [8], HESS data from the Galactic plane survey has been used to perform for the first time a blind search for DM substructures with a wide-field survey with IACTs (the structures were DM spikes around intermediate-mass black holes (IMBHs)). However, this substructure scenario is rather optimistic since the abundance and the properties of IMBHs and of the DM spikes around them remain practically unconstrained. Here we investigate constraints derived using the HESS Galactic survey and the conventional CDM subhalo distribution obtained by the cosmological N-body simulation Via Lactea II (VL-II) [9] . As we shall see in the following, the outcome of this study is based only on the numerically well resolved distribution of CDM structures in the Galactic halo, it is thus quite robust. Also, it does not rely on further density enhancements such as *e.g.* the possible formation of IMBHs. This results in weaker but safer constraints on the particle physics models than those of [8]. To go beyond these contraints, it is interesting to consider extended surveys that will certainly be performed by the next generation of IACT such as the Cherenkov Telescope Array (CTA) [10] as high priority observations. We thus extend the study by extrapolating the current constraints to the sensitivity of CTA, the future observatory in this range of energy.

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The paper is structured as follows. In Section II we present the results of the VL-II simulation regarding the subhalo population which we are interested in. Section III is devoted to the description of the HESS sensitivity map and how the extrapolation to CTA is done. The results inferred from the HESS survey are presented in Section IV. Finally, Section V presents the prospects with CTA and section VI is devoted to the conclusion.

II. PREDICTIONS FOR THE SUBHALO CONTENT OF THE MILKY WAY

The CDM subhalo distribution is taken directly from the VL-II simulation [9], one of the largest, most accurate cosmological N-body simulations of the Galactic CDM halo. The particle mass of 4,100 $M_\odot$ allows to resolve small subhaloes ($> 10^5 M_\odot$) throughout the Galactic halo and even as close to the Galactic center as the solar neighbourhood. Much smaller CDM subhaloes are expected to survive as well [11], but we will show now that for the purposes of this analysis it is not necessary to include CDM clumps below the VL-II resolution limit. The smallest clumps, which are still well enough resolved in VL-II, have peak circular velocities of $V_{\rm max} = 3\ {\rm km\,s^{-1}}$, luminosities of $L = 1.7 \times 10^5\ {\rm M_\odot pc^{-3}}$ and a local mean separation of $\langle d \rangle = 5.8$ kpc, i.e. in a random realization they are found at a median distance of $D_0 \simeq 0.5\langle d \rangle \simeq 2.9$ kpc from the observer [12]. Under the assumption of point-like sources, the predicted flux is expressed as

$$\Phi(> E_{\rm th}) \;=\; \frac{1}{8\pi D^2}\;\frac{\sigma v}{m^2}\;L\;\; N_\gamma(> E_{\rm th})\;\;, \qquad (1)$$

N_γ being the integrated number of γ-rays produced in a WIMP collision above a given energy threshold $E_{\rm th}$, and σv the velocity-weighted annihilation cross section. With $D = 2.9$ kpc, one gets the reference flux of $\Phi_0 = 7 \times 10^{-14}\ {\rm cm^{-2}s^{-1}}$ from such a small, but still well resolved, VL-II clump . This value is obtained for $\sigma v = 3 \times 10^{-26}\ {\rm cm^3s^{-1}}$, $m = 500$ GeV in the case of an annihilation into τ pairs. As we shall see in the following, the observable flux for HESS is roughly $\Phi_{\rm HESS} = 10^{-12}\ {\rm cm^{-2}s^{-1}} = 14 \times \Phi_0$ and in the best case for CTA is $\sim 3 \times 10^{-13}\ {\rm cm^{-2}s^{-1}}$, which is still larger than Φ_0. This means that the smallest clumps which the VL-II simulation is able to resolve are already too faint to be observed by HESS or CTA for most random realizations. They would need to fall unusually close to the observer to be detected ($D < 1.8$ kpc), which happens in only 18 percent of all realizations. A HESS detection of a smaller CDM clump, below the numerical resolution of our simulation is even less likely : in CDM the distance $D_{\rm n}$ to the nearest subhalo of above given luminosity scales roughly like $D_{\rm n} \propto L^{1/3}$(see for instance [12]). The flux $\Phi \propto L/D^2$ therefore goes like $\Phi \propto L^{1/3}$, i.e. the flux from the nearest subhalo in a given bin in log L (or log subhalo mass) increases with subhalo mass and we can safely ignore small subhaloes below the VL-II numerical resolution for the present analysis.

III. FLUX SENSITIVITY MAPS

Data from the Galactic plane survey conducted by the HESS experiment allowed to obtain maps of flux sensitivity to DM annihilations [8]. The γ-ray flux sensitivity map which is used here is extracted from [8]. The HESS Galactic plane survey allowed to detect a large population of unidentified sources [13, 14]. None of them exhibit an energy cut-off in the covered energy range. Each γ-ray source is best-characterized by a power-law spectrum, as expected for γ-ray emission from standard acceleration astrophysical processes. Consequently it excludes them to be relevant candidates for DM subhaloes. The upper panel of Fig. 1 shows the HESS flux sensitivity map to DM annihilation for a 500 GeV DM particle annihilating into $b\bar{b}$. In the following, when other annihilation channels or masses are considered, the flux sensitivity is properly rescaled. The map contains hints of the presence of all the discovered sources by HESS : as expected, the flux sensitivity decreases at the position of the detected sources. The flux sensitivity map can be easily understood as follows : if a γ-ray source at a given Galactic position gave a larger flux than the value quoted in the corresponding bin, it would have been detected. Consequently, any model predicting a statistically significant number of sources with fluxes above these values is excluded.

The next generation of IACT will consist of a large telescope array (CTA). The current effort on its design should allow to improve significantly the global performance of the present generation. The goal is to extend the accessible energy range both towards the low and the high energies, and gain at least a factor of ten in flux sensitivity. To extrapolate the current results to future observatories, different assumptions are made regarding the foreseen CTA characteristics. A conservative value of 50 GeV for the energy threshold is assumed. The effective area of the instrument is improved by a factor of 10 and the hadron rejection by a factor of 2. The overall improved capabilities of CTA will presumably allow to detect a number of new γ-ray sources. The construction of the CTA-extrapolated map follows the procedure described in [15]. Assuming a SNR source model for the γ-ray emission [16] and a radial source distribution [17], the distance and the γ-ray flux are calculated. The Galactic plane is then randomly populated according to the spatial distribution of sources observed by the HESS survey [13, 14]. So the HESS γ-ray flux source distribution is extrapolated to CTA performance. This extrapolation results in the prediction for the discovery of a few hundreds of new sources in the survey field of view. The presence of these new sources deteriorates the DM flux sensitivity accordingly. The resulting projected CTA sensitivity map is shown on the lower panel of Fig. 1 for a DM particle mass of 500 GeV annihilating into $b\bar{b}$. A flat exposure of 10 h in each position of the map is assumed. This value allows to match the total amount of time for the CTA survey to the ~ 400 hours which were needed by HESS to survey this region of the sky. The flux sensitivity for

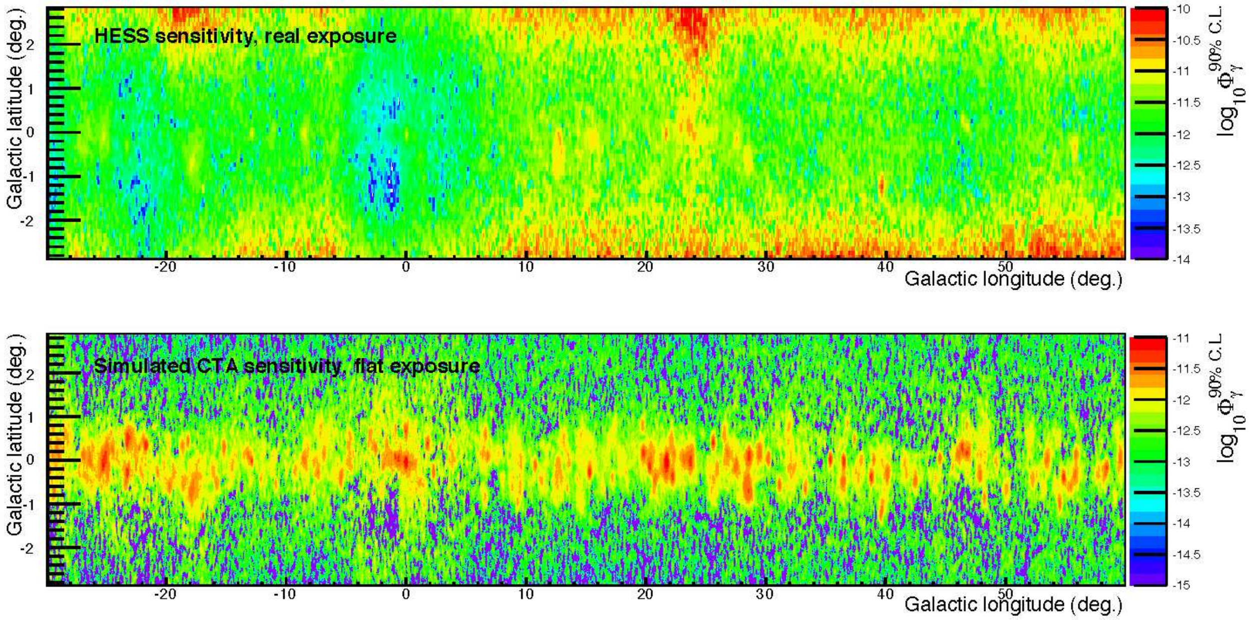

FIG. 1: Flux sensitivity maps at 90% C.L. for HESS and a CTA-like array. The maps are calculated here for a 500 GeV DM particle annihilating with 100% BR into $b\bar{b}$. Top : The HESS sensitivity map is calculated with real exposure. Bottom : The simulated flux sensitivity map for CTA-like array is obtained for a flat exposure of 10h.

CTA ranges from $\sim 10^{-12}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in the region where the new sources are present and a few $10^{-13}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ on average at higher latitudes.

IV. CURRENT EXCLUSION LIMITS

The question to be adressed in this section is –for a fixed set of particle physics parameters– what is the probability for a clump to lie in the survey region with a flux larger than the HESS sensitivity at its position in the sky. To answer this question, we generate 10^3 different Monte-Carlo realizations of the Milky-Way halo. Independent realizations are obtained by randomly placing the observer at a distance of 8.5 kpc from the Galactic center. Over our realizations, the total number of subhaloes inside the field of view shown on Fig.1 is 168 ± 44, out of the $\sim 10^4$ resolved subhaloes contained in the Milky Way. The distribution obtained after these 10^3 virtual experiments is displayed on Fig. 2. The probability to find no subhalo in the field of view is less than 10^{-3}. The spatial distribution of clumps is slightly triaxial, with an unknown orientation which is not expected to be correlated with the baryonic distribution. For that reason, the distribution is wider than what is expected from a purely spherical distribution. To scan the (DM particle mass,σv) plane, the mass of the DM particle is kept fixed and the value of the cross-section for which 2.3 subhaloes are visible *on average* is searched. This corresponds to a 90% C.L. limit on σv.

A fraction ($\sim 50\%$) of the clumps that are found to be

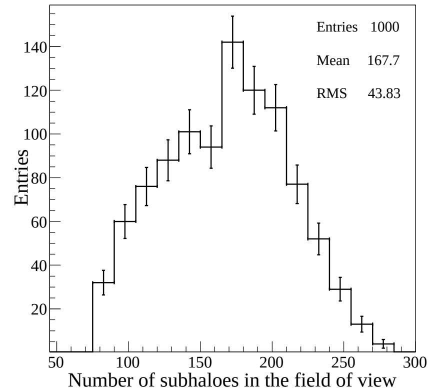

FIG. 2: Distribution of the number of suhaloes between $\pm 3°$ in Galactic latitude and from -30° to 60° in Galactic longitude. The distribution is obtained from 1000 stochastic realizations of the Milky Way-like halo from VL-II. The mean of the distribution is 168 with a rms of 44.

above the HESS sensitivity are slightly extended. This has to be handled as the sensitivity map is built assuming point-like sources. In that case, we make the conservative choice to rescale the flux by lowering it to the value enclosed in the instrument angular resolution. Because the flux sensitivity concerns the integrated flux above some threshold, its value depends on an assumed spectrum. Depending on the considered annihilation channel (hereafter $\chi\chi \to b\bar{b}$ or $\tau^+\tau^-$) and on the DM particle mass, the values of the HESS sensitivity in each bin of the map

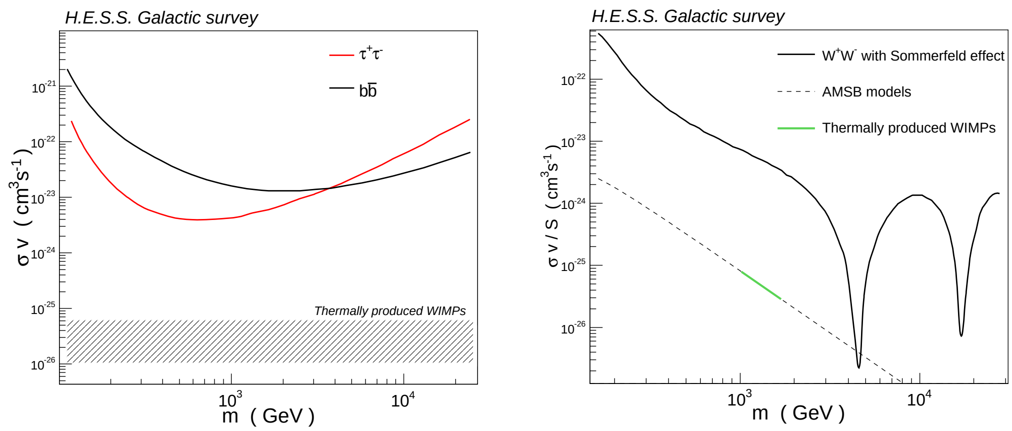

FIG. 3: Left : Exclusion curves on σv versus the DM particle mass m for HESS. The limit is calculated at the 90% C. L. for the DM clumps provided by the VL-II simulation. The DM particle is assumed to annihilate into purely $b\bar{b}$ and $\tau^+\tau^-$ pairs respectively. The region of natural values of the velocity-weighted annihilation cross section of thermally produced WIMPs is also plotted. Right : Exclusion curves on σv versus the DM particle mass m for HESS including the Sommerfeld enhancement effect.

are then properly rescaled.

The left hand side of Fig. 3 shows the 90% C.L. exclusion limit on σv as a function of the DM particle mass. Two annihilation spectra are considered : 100% BR annihilation channel in $b\bar{b}$ and $\tau^+\tau^-$ respectively, in order to somehow encompass all possible annihilation spectra for DM particle. The limits on the annihilation cross section reach a few 10^{-24} cm^{3}s^{-1} at 1 TeV for the $\tau^+\tau^-$ spectrum. The dashed region corresponds to cosmologically relevant values for the annihilation cross-section. The constraints obtained are 2 orders of magnitude above this region. For the sake of comparison, the best current constraints obtained from targeted searches are from the Galactic center with HESS (of the order $10^{-24} - 10^{-23}$ cm^{3}s^{-1} [1]) and Sagittarius dwarf galaxy (from 10^{-25} to 10^{-23} cm^{3}s^{-1}, depending on the modeling of the source [2]). The constraints obtained here from VL-II subhaloes are based on canonical assumptions and reach $10^{-24} - 10^{-23}$ cm^{3}s^{-1}, they are thus among the most competitive to date obtained with γ-rays in this range of mass.

In the case of an annihilation into gauge boson pairs (here W^+W^-), it could happen that the cross section is significantly increased by the mean of the so-called Sommerfeld effect [18, 19]. The enhancement factor S depends on the mass of the DM particle and on the relative velocity of the colliding particles, it ranges from a few percents up to very large values of $\sim 10^4$. For $V_{\rm max} \ll c$, the enhancement goes approximately as $V_{\rm max}^{-1}$ before S reaches a plateau due the finite range of the Yukawa interaction. When m is close to a WIMP almost-bound state, the annihilation process becomes resonant with $S \propto V_{\rm max}^{-2}$. The Sommerfeld effect has been modelled here in the case of an annihilation into W pairs, with an annihilation proceeding towards the exchange of a 90 GeV bosons and a coupling constant of $g = 1/30$. In the HESS sensitivity range, the resonances are obtained for $m \sim 4.5$ TeV and $m \sim 17.6$ TeV. In the specific case of annihilations within substructures, the enhancement can become very large, because the colder the subhalo, the larger the enhancement factor [20]. In the subhaloes considered in VL-II, the maximal velocity $V_{\rm max}$ ranges from 0.5 km s^{-1} to 20 km s^{-1}. Having $S \propto V_{\rm max}^{-1}$, the boost factor can indeed be large [21]. In our Monte-Carlo realizations, a Sommerfeld boost is assigned to each subhalo depending on its specific $V_{\rm max}$. The constraints obtained are displayed on the right panel of Fig. 3. Some predictions from supersymmetric models with annihilation into W bosons, extracted from [22] (in the anomaly-mediated susy breaking scenario (AMSB)), are also shown. These predictions do not include the S factor, so constraints on the unboosted cross section $\sigma v/S$ are shown. Outside resonances, the limit is less that 2 orders of magnitude above the annihilation cross section expected for thermally produced WIMPS, but –thanks to the resonant Sommerfeld effect– a small region around 4.5 TeV is excluded.

V. PROSPECTS FOR CTA OBSERVATIONS PROGRAMS

A. HESS-like Galactic plane survey

The projected map for CTA is used as in the previous analysis of the HESS galactic survey to make a prediction for the sensitivity of the future array. As a first step, the same field of view as HESS is used. We consider that a scan of the Galactic plane will for sure be performed by CTA, so that this region of the sky is somehow the minimal guaranteed field of view. The results for the projection to CTA is presented in Fig. 4. The exclusion li-

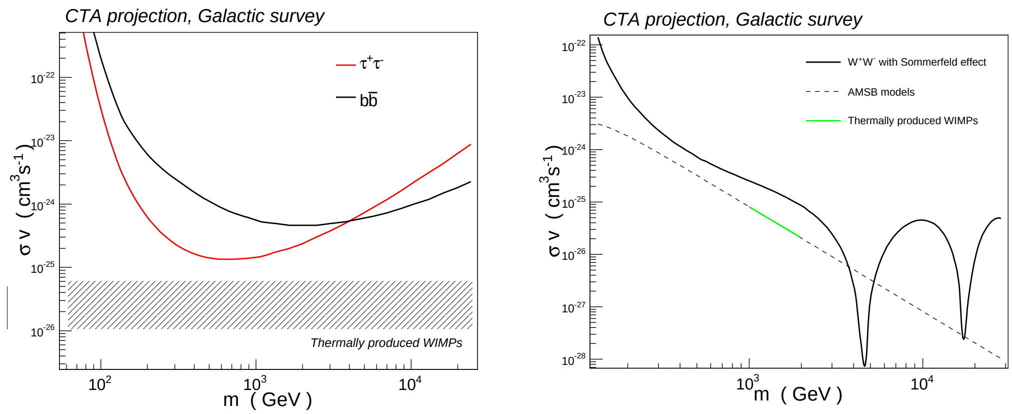

FIG. 4: Left : The projected sensitivity curves on σv versus the DM particle mass m for a CTA Galactic plane survey. The limit is calculated at the 90% C. L. for the DM clumps provided by the VL-II simulation. The DM particle is assumed to annihilate into purely $b\bar{b}$ and $\tau^+\tau^-$ pairs respectively. The region of natural values of the velocity-weighted annihilation cross section of thermally produced WIMPS is also plotted. Right : Exclusion curves on σv versus the DM particle mass m for CTA-like including the Sommerfeld enhancement effect.

mits are a lower by factor of ∼10 than those obtained with HESS. In the conventional case ($b\bar{b}$ and $\tau^+\tau^-$, without Sommerfeld enhancement), they are reaching σv values of a few 10^{-25}cm^{3}s^{-1}. In the case of Sommerfeld enhanced annihilations, some regions of the parameter space for the model could be excluded, since a large array of telescopes would have enough sensitivity to detect WIMPs in the mass range from ∼3 TeV to 6 TeV and close to the second resonance.

We conclude from Fig. 4 that using this field of view, CTA will not be able to reach signals from the most natural WIMPs. One order of magnitude is gained with respect to HESS, but a factor of 2 to 10 is still necessary to reach the natural DM annihilation cross sections. An homogeneous increase of the exposure time will only improve the exclusion limits as the square root of exposure time in the background-limited regime, so one has to enlarge the field of view instead of using longer exposure. In addition, the flux sensitivity along the Galactic Plane will be limited by the population of newly detected sources at a flux level of 10^{-12} cm^{-2}s^{-1}. The Galactic plane might also not be the best place to look for subhaloes since they could have been tidally affected by the disk. For those reasons, an observing strategy focusing on fields with absolute Galactic Latitude of at least 0.5° should be preferred for DM subhalo searches, as it clearly appears on the lower panel of Fig. 1. This is precisely the point developed in the next subsection.

B. CTA survey of one quarter of the sky

To go further, one can note that larger scans of the sky will most likely be conducted by CTA. In particular a more extended survey of the order of a quarter-sky size can be foreseen. In this section, the CTA sensitivity to DM annihilations is computed in the context of such an ambitious program. A large survey increases the probability to find bright subhaloes in the field of view, which thus translates in better constraints. Such a survey should not include the Galactic plane where numerous sources are expected to shine and therefore decrease the sensitivity to DM clumps. On the other hand, the central region of the Milky Way is attractive since the VL-II subhalo distribution is peaked towards the center. For this study, the survey region is chosen to be from -90° to +90° in Galactic longitude and from from -45° to +45° in Galactic latitude, excluding the Galactic plane between ±1.5°. Inside this region, the distribution of the number of subhaloes from the simulation is similar to the one of Fig. 2, but with an average value of 3907, and a RMS of 324. The sensitivity is taken to be constant on the entire field of view. Its value is calculated from the previous CTA sensitivity map averaged for Galactic latitudes above 1.5° and corrected for a shorter exposure leading to a flux sensitivity of the order of 5×10^{-13}cm^{-2}s^{-1} for a 5h exposure time in each pixel and a WIMP mass of 500 GeV. As in previous sections, the value of the sensitivity is renormalized for each DM particle mass. To a very good approximation, the decrease of the sensitivity due to the new population of extragalactic sources such as *e.g.* AGNs is negligible. The quoted value of the sensitivity is reached by pointing the whole array in the same direction, which is quite time consuming. Assuming a duty cycle of 1000 h of observation per year, this quarter-of-the-sky survey can be completed within about 6 years of operation. An implicit assumption is that all unidentified sources do not present the required features of DM source candidates. Notice however that should a couple of plausible DM sources be detected, additional dedicated observation time would be devoted for deeper studies.

Fig. 5 shows the 90% C.L. exclusion limit on σv as a function of the DM particle mass. Annihilation cross

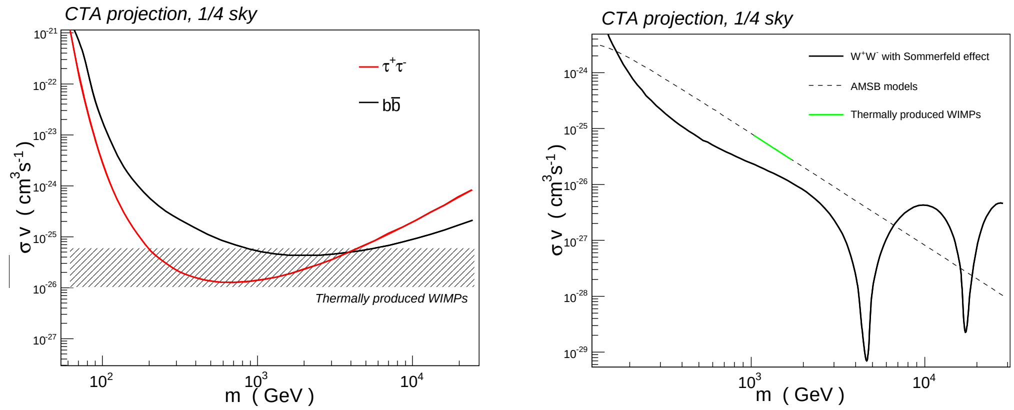

FIG. 5: Left : Exclusion curves on σv versus the DM particle mass m for a CTA survey of a one fourth of the sky. The limit is calculated at 90% C. L. for the DM clumps provided by the VL-II simulation. The DM particle is assumed to annihilate into purely $b\bar{b}$ and $\tau^+\tau^-$ pairs respectively. The region of natural values of the velocity-weighted annihilation cross section of thermally produced WIMPs is also plotted. Right : Exclusion curves on σv versus the DM particle mass m for CTA including the Sommerfeld enhancement effect.

sections of a few 10^{-26} cm^{3}s^{-1} are reached in the 200 GeV - 3 TeV mass range in the case of annihilation into τ pairs. In the scenario of an annihilation into W bosons pairs with Sommerfeld enhancement, all WIMPs from AMSB with masses from 200 GeV to 6 TeV are within the reach of CTA.

VI. CONCLUSIONS

We used for the first time a wide field survey from Cherenkov telescopes to constrain conventional DM substructure scenarios. Unlike the case when DM annihilations are searched for towards selected sources, the constraints from this blind search do not rely crucially on the modeling of the DM distribution in the source. The constraints obtained out of the HESS Galactic plane survey are still 2 orders of magnitude higher than the thermal WIMP region. Thus most natural models for WIMPs as dark matter are out of the reach of current generation ground-based Cherenkov telescopes with wide field surveys and realistic observing time. However, the limits reachable in the $\sigma v - m$ plane are very competitive compared to other strategies such as targeted searches. By using the same Galactic Plane field of view, we show that the discovery of particle DM in the form of WIMPs is unlikely to be accessible for the next generation of Cherenkov telescopes such as CTA. However, by considering an ambitious but realistic quarter-of-the-sky survey with CTA, it is shown that the thermal WIMP promised land can be hit. Note that such a survey will likely be conducted by CTA independently of particle DM considerations. This search for DM subhaloes will therefore not be in conflict with other physics programs.

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