Difficulty of detecting minihalos via $\gamma$-rays from dark matter annihilation

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Analytical calculations and recent numerical experiments have shown that a sizable of the mass in our Galaxy is in a form of clumpy, virialized substructures that, according to \[1\], can be as light as $10^{-6}M_{\odot}$. In this work we estimate the gamma-rays flux expected from dark matter annihilation occurring within these minihalos, under the hypothesis that the bulk of dark matter is composed by neutralinos. We generate mock sky maps showing the angular distribution of the expected gamma-ray signal. We compare them with the sensitivities of satellite-borne experiments such as GLAST and find that a possible detection of minihalos is indeed very challenging.

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Analyses of the anisotropies in the cosmic microwave background radiation \[2\] find that the matter density content of the universe is approximately six times larger than the baryonic one, in agreement with the observed abundance of light elements \[3\] and the matter power spectrum inferred from galaxy redshift surveys. \[4\]. These observations involve very different physics, but unambiguously indicate that the Universe contains a significant amount of non-baryonic cold dark matter (CDM). The nature of CDM is presently unknown. However, weakly interacting massive particles (WIMPs) are regarded as generic particle candidates for CDM, as they naturally arise in extensions of the standard model of particle physics. WIMPs are a particularly attractive CDM candidate, since the average mass density of a stable relic from the electroweak scale is expected to be close to critical \[2\]. A further exciting feature of WIMPs is that they can be investigated in ongoing and future astrophysical direct \[2\] and indirect searches \[2\] and in upcoming laboratory experiments.

Indirect CDM searches focus on measuring the diffuse flux of CDM annihilation products $\Phi_\gamma \equiv \Phi^{\text{SUSY}} \times \Phi^{\text{cosmo}}$. The particle physics dependence embedded in $\Phi^{\text{SUSY}}$ involves the WIMP’s annihilation cross-section and branching ratios as well as the final photon energy spectrum and can be calculated from the underlying WIMP field theory. In this work we assume the nearly mass independent best value for the annihilation cross section of $2 \times 10^{-26} \text{cm}^3\text{s}^{-1}$, which represents an upper bound still allowing the neutralinos to be the dominant CDM component. The geometry dependence of the flux is contained in $\Phi^{\text{cosmo}}$, that is found by integrating the square of the neutralino mass density along the line-of-sight and therefore is very sensitive to the presence of virialized structures representing maxima of the DM density field. In this work we focus on the annihilation signal produced within our Galaxy under the hypothesis, supported by several high resolution numerical experiments, that part of its mass is in the form of subhalos.

CDM models are characterized by their excess power on small scales that leads to a logarithmic divergence of the linear density contrast at large wavenumbers $\Delta \equiv \delta \rho / \rho \propto \ln(k)$. Recent analytical calculations have proved that $\Delta$ shows exponential damping for $k > k_{\text{cut}} = \mathcal{O}(1)/pc$. The cut-off scale $k_{\text{cut}}$ is given by viscus (collisional) processes before and free (collisionless) streaming after kinetic decoupling at $T_{\text{kal}} = \mathcal{O}(10) \text{MeV}$, both leading to exponential damping of the linear CDM density contrast \[2\ [10, 11\]. During the linear regime most of the statistical power typically goes in density contrasts $\Delta$ with $k \sim k_{\text{cut}}$. So $k_{\text{cut}}$ sets also the typical scale for the first halos, that typically form at a redshift $z_{\text{f}} \approx 60 \pm 10$ (for the best fit WMAP matter density) \[10, 11\], when the mass variance $\sigma = 1$ on a comoving length scale $R = \mathcal{O}(1)\text{pc}$.

The fate of these early minihalos in the non linear regime when they typically merge into larger halos, representing higher levels in the hierarchy, can only be followed through numerical experiments. The limited dynamical range explored with currently available N-body codes makes it very challenging to perform numerical experiments with a resolution as high as $k_{\text{cut}}^{-1}$ on a computational box large enough to guarantee statistical significance. Yet, \[10\ have recently simulated hierarchical clustering in CDM cosmologies up to a dynamical resolution $k_{\text{res}} \sim k_{\text{cut}}$ in a small high resolution patch which is nested within a hierarchy of larger low resolution regions. They find a steep halo mass function $dn(M)/dn(M) \propto M^{-1}\exp[-(M/M_{\text{cut}})^{-\frac{1}{2}}]$, with $M_{\text{cut}} = 5.7 \times 10^{-6}h^{-1}M_{\odot} \propto k_{\text{cut}}^{-3}$ in the mass range $[10^{-6}, 10^{-4}]M_{\odot}$ whose extrapolation fits well that of Galactic halos \[12\].
Since [1] stopped their experiment at $z = 26$ and probed a small volume with a limited dynamical range, no general consensus exists on whether these early structures survived within massive galactic halos until today and what their mass function and distribution is. Indeed, although their mass concentration is probably large enough for them to survive the gravitational tides experienced in the external region of the massive host halo (see, however [13]), they could be torn into tidal streams by close encounters with individual stars in the galaxy [14]. These issues could only be settled by simulating the gravitational clustering out to $z = 0$ on a volume large enough to overlap the results with those of other, high resolution numerical experiments of Galaxy size halos ([13] 16), which is beyond current numerical limitations. Yet, [17] have suggested that these minihalos might significantly contribute to the total annihilation flux in our Galaxy.

In this work we compute the expected $\gamma$-ray flux produced by a population of sub-Galactic halos under the optimistic hypotheses of [1] that all minihalos of masses $\geq 10^{-6} M_\odot$ that survived gravitational tides populate the Galactic halo at $z = 0$, trace its mass, share the same self-similar cuspy density profile and have a steep mass function $\propto M^{-1}$ up to $\geq 10^{10} M_\odot$. It is worth stressing that our predictions represent an upper limit to the expected photon flux and to its experimental detectability that we will investigate for the case of a satellite-borne experiment like GLAST [18].

Our analysis extends those of [16] 14 20 21 22 since we consider subhalos much lighter than $10^6 M_\odot$ and since we use Monte Carlo techniques to explicitly account for the contribution of very nearby minihalos to the total annihilation flux. The relevant properties of our minihalo population are: a steep mass function $dn(M)/dln(M) \propto M^{-1}$ in the range $[10^{-6}, 10^{16}] M_\odot$, a spatial distribution that trace the smooth mass component in our Galaxy and a NFW mass density profile [23] for both the MW and for all the subhalos: $\rho_\chi = \rho_s (r/r_s)^{-1} (1 + r/r_s)^{-2}$, where both the scale radius $r_s$ and the scale density $\rho_s$ depend on the concentration parameter $c$ which is a function of mass, redshift and the cosmological model. Since we aim at exploring the most optimistic scenario for neutralino annihilation we do not consider here the results of some recent high resolution N-body experiments, which suggest that halo density profiles near the center have a continuously varying logarithmic slope, and thus are significantly shallower than the cuspy NFW profile. In this work we assume the flat, ACDM “concordance” model and use the numerical routines provided by [24] to compute $c$. The smallest halos of mass $10^{-6} M_\odot$ turn out to have $c \sim O(40)$ at $z = 0$.

The previous assumption allows one to specify the number density of subhalos per unit mass at a distance $r$ from the Galactic Center (GC):

$$\rho_{\text{sh}}(M,r) = AM^{-2} \frac{\theta(r-r_{\text{min}}(M))}{(r/r_{\text{MW}}^2)(1 + r/r_{\text{MW}}^2)^2} M_\odot^{-1} \text{kpc}^{-3}$$

(1)

We set $A$ such that 10% of the MW mass ($M_{\text{MW}} = 10^{12} M_\odot$) is distributed in subhalos with masses greater than $10^7 M_\odot$ to match the results of [12]. As a result about 53% of the dark mass within our galaxy is not smoothly distributed but contained within $\sim 1.5 \times 10^{16}$ subhalos with masses larger than $10^{-6} M_\odot$, corresponding to $\sim 100$ pc$^{-3}$ halos in the solar neighborhood.

The $\theta$ term in Eq. (1) takes into account the effect of gravitational tides which, according to the Roche criterion, disrupt all halos within $r_{\text{min}}(M)$ from the GC [27] in an orbital period. At $z = 0$ $r_{\text{min}}$ is an increasing function of the subhalo mass implying that no subhalos survive within $r_{\text{min}}(10^{-6} M_\odot) \sim 200$ pc.

In this work we wish to predict the annihilation signal expected in a $100^\circ \times 100^\circ$ field of view (f.o.v.) with an angular resolution of $\Delta \Omega = 10^{-5}$ sr, matching those planned for the GLAST experiment, in both the GC and the anticenter (AC) directions. This requires to evaluate the line-of-sight integral:

$$\Phi_{\text{cosmo}}(\psi,\theta) = \int_{\Delta \Omega(\psi,\theta)} d\Omega' \int_{\text{los}} \rho_\chi^2 (r(\lambda,\psi')) d\lambda(r,\psi'),$$

(2)

where $\psi$ is the angle-of-view from the GC, $\theta$ is the angular resolution of the detector, $\rho_\chi(r)$ is the mass density. The distance from the GC $r$ is $r = \sqrt{\lambda^2 + R_\odot^2 - 2 \lambda R_\odot \cos \psi}$, $\lambda$ is the distance from the observer and $R_\odot = 8.5$ kpc is that of the Sun from the GC.

We evaluate of Eq. (2) in two steps. First, we numerically integrate Eq. (2) in which $\rho_\chi(r)$ is the sum of NFW profiles corresponding to all subhalos distributed according to Eq. (1) along the l.o.s.. This gives the average subhalo contribution to the Galactic annihilation flux within $10^{-5}$ sr along the direction $(\psi,\theta)$. We found that the average contribution to $\Phi_{\text{cosmo}}$, in units of GeV$^2$ cm$^{-6}$ kpc sr, of subhalos in the range $10^{-6} M_\odot < M_{\text{sh}} < 10^6 M_\odot$ is $4 \times 10^{-5}$ at the GC, then slowly decreases to $10^{-5}$ at $\psi = 50^\circ$ and to $4 \times 10^{-6}$ at larger angles. For $\phi > 25^\circ$ it dominates over the Galactic foreground accounting for neutralino annihilation in the smooth Galactic halo of $4.7 \times 10^{11} M_\odot$.

To estimate the variance to the average flux we use Eq. (2) to generate several independent Monte Carlo realizations of the closest and brightest minihalos. For each subhalo mass, we only consider objects which are close enough to guarantee $\Phi_{\text{cosmo}} > 10^{-6}$ GeV$^2$ cm$^{-6}$ kpc sr. If no such halo exists then we still Monte Carlo generate the 100 closest objects in that mass range, since we expect the bigger fluxes to come from the closer halos.

The contribution of nearby structures to the annihilation flux can be appreciated from Fig. which shows the sky distribution of the annihilation signal in one of our Monte Carlo realization in the direction of the GC.

To compute the total annihilation signal from all sub-Galactic halos we have followed the same procedure as [20] and have generated several Monte Carlo realizations of subhalos with $10^{5} M_\odot < M_{\text{sh}} < 10^{10} M_\odot$ to compute their contribution to the total flux.
FIG. 1: Sky map of the annihilation signal from nearby subhalos of masses \(10^{-6} \text{ to } 10^6 M_\odot\) contributing more than \(\Phi_{\text{cosmo}} = 10^{-6} \text{ GeV}^2 \text{ cm}^{-6} \text{ kpc sr}\) in a \(100^\circ \times 100^\circ\) f.o.v. centered on the GC in one of our Monte Carlo realizations.

FIG. 2: 3D view of the total \(\Phi_{\text{cosmo}}\) contributed by subhalos and the Galactic foreground, in a \(100^\circ \times 100^\circ\) f.o.v. centered on the GC. The Galactic foreground is cut at the subhalos’ level.

Figs. 2 and 3 show the expected contribution to \(\Phi_{\text{cosmo}}\) accounting for both subhalos and Galactic foreground in the direction of the GC and the AC, respectively. As expected, the Galactic foreground is negligible in Fig. 2, while it is dominating around the GC in Fig. 3. Note that the very prominent peak due to the Galactic foreground at the GC position has been artificially truncated to appreciate the subhalos contribution. We estimate that \(\Phi_{\text{cosmo}} = 0.04 \text{ GeV}^2 \text{ cm}^{-6} \text{ kpc sr}\) at the GC.

Figs. 2 and 3 also show that even the biggest contribution to \(\Phi_{\text{cosmo}}\) from a subhalo is well below the \(\mathcal{O}(1)\) level which, given our best value of \(\Phi_{\text{SUSY}}\), would be required for detection in the GLAST experiment. In fact, in no Monte Carlo realizations we have found that the subhalos contribution to \(\Phi_{\text{cosmo}}\) exceed the value of \(\mathcal{O}(10^{-3})\).

To make this statement more quantitative and to also account for the possibility of detecting the \(\gamma\)-ray annihilation line we have evaluated the sensitivity of GLAST to the differential spectrum of photons expected from DM annihilation, convolved with its energy resolution \(\Delta E = 10\%\). We define the sensitivity \(\sigma(\Delta E)\) as

\[
\sigma(\Delta E) = \sqrt{T_{\delta} \epsilon_{\Delta \Omega}} \int_{\Delta E} A_{\gamma}(E, \theta) \left[ \frac{d\Phi_{\gamma}}{dE d\Omega} \right] dE d\Omega
\]

where \(T_{\delta}\) defines the effective observation time, \(\epsilon_{\Delta \Omega} = 0.7\) is the fraction of signal events within the optimal solid angle \(\Delta \Omega\) corresponding to the angular resolution of 0.1\(^\circ\), and \(A_{\text{eff}} = 10^4 \text{ cm}^2\) is the effective detection area. We optimistically assume that the photon and charged particles’ detection efficiencies \(\epsilon_{\gamma}\) and \(\epsilon_{\text{ch}}\) are 100\%, thus we only consider galactic and extragalactic \(\gamma\)-ray background as it is extrapolated by EGRET data at lower energies. We simulated a continuous 5 years observation of a pixel of our grid located at \(\psi = 55^\circ\), assuming that in that pixel the value of \(\Phi_{\text{cosmo}}\) is the largest value found among all our Monte Carlo realizations.

We chose a neutralino mass of 100 and 300 GeV, whose \(\gamma\)-lines would in principle be observable with GLAST. The results are shown in Fig. The black curves, corresponding to the left y-axis, show the sensitivity \(\sigma(\Delta E)\) of GLAST as a function of E, for two different values of the neutralino mass. The red curves, to be read on the right y-axis, show the expected flux from the same pixel. It is evident that GLAST would hardly detect neither continuum flux nor \(\gamma\)-lines from Galactic subhalos.

Since it seems implausible to significantly increase \(\Phi_{\text{SUSY}}\), our results confirms those of [17, 19, 20, 21] show that currently planned, satellite-borne experiments such
as GLAST will not be able to detect the annihilation signal produced by Galactic subhalos. This is due to the fact that, as pointed out by [15], the total annihilation flux is dominated by massive Galactic subhalos rather than by minihalos. A result which makes our conclusion insensitive to variations in the low-mass density cut-off, in agreement with [22].

All plausible cosmological and astrophysical effects like the existence of a central core in the halo density profile, the various dynamical disturbances that reduce the subhalo survival probability, the possible existence of a cutoff scale $\sim 0.1 k_{\text{cut}}$ found in the CDM power spectrum, generated by acoustic oscillations with wavelength comparable to the size of the horizon at kinetic decoupling, would decrease the expected annihilation signal, making it our conclusions for subhalos more pessimistic. Unless, of course, one adopts steeper density profiles that, however, are not supported by recent numerical experiments. Note that the $\gamma$-ray luminosity of our minihalos, which is designed to match the prediction of [1], is significantly smaller than that of [17]; a difference that traces back to the large internal density of their minihalos.

The presence of a minihalo population like that considered in this work also enhance the $\gamma$-ray flux from nearby objects like M31. We estimate that, for a NFW profile, the total $\Phi^{\text{cosmo}}$ due to both the smooth and the subhalo contribution will not exceed the value of $5 \times 10^{-4}$, making it impossible to detect.

Recently, the HESS telescope has announced the serendipitous discovery of an unidentified extended TeV $\gamma$-ray source, with a total flux above 380 GeV of $\sim 10^{-11} \text{cm}^{-2} \text{s}^{-1}$ [20]. If explained in terms of the annihilation of $O(10 \text{TeV})$ neutralinos, such a large flux could only be accounted for by advocating a central density $r^{-1.5}$, steeper than the NFW model. A prominent central spike might form around a supermassive black hole [31, 52] that, according to hierarchical models of galaxy formation [32], could reside at the center of both massive Galactic and sub-Galactic halos.

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[1] J. Diemand, et al., Nature 433, 389 (2005).
[2] D. N. Spergel, et al., Astrophys. J. Suppl. 148, 175 (2003).
[3] D. Tytler, et al., Phys. Scr. T 85, 12 (2000).
[4] M. Tegmark, et al., Astrophys. J. 606, 702 (2004).
[5] S. Dimopoulos, Phys. Lett. B 246, 347 (1990).
[6] A. K. Drukier, et al., Phys. Rev. D 33, 3495 (1986).
[7] L. Bergström, Rept. Prog. Phys. 63, 793 (2000).
[8] N. Fornengo, et al., Phys. Rev. D 70, 103529 (2004).
[9] S. Hofmann, et al., Phys. Rev. D 64, 083507 (2001).
[10] A. M. Green, et al., MNRAS, 353, L23 (2004).
[11] A. M. Green, et al., JCAP 08, 2005 (2004).
[12] D. Reed, et al., MNRAS, 346, 565 (2003).
[13] V. Berezinsky, et al., Phys. Rev. D 68, 103003 (2003).
[14] H.S. Zhao, et al., astro-ph/0502049.
[15] F. Stoehr, et al., MNRAS, 345, 1313 (2003).
[16] J. Diemand et al., MNRAS, 352, 535 (2004).
[17] T. Oda et al., astro-ph/0504096.
[18] A. Morselli, et al., in Proc. of the 32nd Rencontres de Moriond, (1997).
[19] C. Calcaneo-Roldan and B. Moore, Phys. Rev. D 62, 123005 (2000).
[20] L. Pieri and E. Branchini, Phys. Rev. D 69, 043512 (2004).
[21] S. Peirani, et al., Phys. Rev. D 70, 043503 (2004).
[22] S.M.Koushiappas, et al., Phys. Rev. D 69, 043501 (2004).
[23] J. F. Navarro, et al., Astrophys. J. 490, 493 (1997).
[24] V.R. Eke, et al., Astrophys.J. 554, 114 (2001).
[25] J. F. Navarro, et al., MNRAS 349, 1039 (2004).
[26] D. Merritt, et al., Astrophys.J. 624L, 85 (2005).
[27] E. Hayashi, et al., Astrophys.J. 584, 541 (2003).
[28] L. Bergström, et al., Astroparticle Phys. 9, 137 (1998).
[29] A. Loeb and M. Zaldarriaga, astro-ph/0504112.
[30] F. Aharonian, et al., astro-ph/0505219.
[31] G. Bertone, et al., astro-ph/0501555.
[32] G. Bertone, et al., astro-ph/0504422.
[33] M. Volonteri, et al., Astrophys.J. 582, 559 (2003).