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Analytical models of dark matter subhalos for indirect dark matter searches

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We present a semi-analytical model of dark matter subhalos that consistently incorporates (i) the properties of dark matter particles (e.g. kinetic decoupling), (ii) the properties of the primordial power spectrum of density fluctuations, and (iii) mass loss and potential disruption due to tidal stripping in galaxies (for which the detailed content and distributions of baryonic components strongly matter). This model allows to account for changes in the dark matter candidate properties as well as in the cosmological setup. We show applications to indirect dark matter searches for WIMP dark matter, though it could be applied to other observables related to gravitational effects (lensing, kinematics or dynamics) for other dark matter candidates.

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Forewarning: Due to size constraints, citations to relevant or even seminal works have been removed.

Subhalos are expected to play an important role in indirect dark matter searches because they increase the average annihilation rate of dark matter, should it self-annihilate. However, it is difficult to predict their spatial distribution in specific targets like the Milky Way (MW) only based on cosmological simulations because they differ in properties (gas, stellar distributions, etc.) that strongly affect the tidal stripping history of subhalos (not to mention resolution issues). Simulations still provide invaluable information down to their resolution limit, especially on generic properties related to the almost scale-invariant character of hierarchical structure formation, most manifest in dark-matter-only simulations. In their range of validity, they are important to cross-check predictions of analytical models [1, 2]. They can also help better understand tidal processes and therefore develop methods based on physical principles (and not on extrapolations) to better account for or model these effects in arbitrary environments [3–6].

Recently, we proposed a semi-analytical model of subhalo population that accounts for the dynamical impact of all components of the host galaxy as self-consistently as possible [7]. This model implements spatially dependent tidal stripping based on the detailed description of the host, including all baryonic components. Indeed, the latter can be observationally constrained for specific targets like known galaxies, the MW being a particular example. Instead of extrapolating results from cosmological simulations of MW-like galaxies, which usually differ significantly from the MW itself, we rely on physical principles. Beside dynamical consistency at the host level, the subhalo model presented here also incorporates all universal aspects of structure formation theory (mass function inferred from a matter power spectrum itself inferred from a choice of primordial power spectrum, with a cutoff on small scale set by the interaction properties of the dark matter candidate).

The main steps in the building of the model were introduced in [7]. A specific study of tidal stripping was presented in [8]. A comparison of a MW subhalo population model with a MW-like simulation was done in [9], which showed good qualitative agreement (quantitative differences come from the fact that MW-like simulations actually differ substantially from the MW itself).

We assume spherically symmetric dark halos with self-similar shapes, which reduces a subhalo to a two-parameter object, the main parameter being the virial mass m_{200} enclosed in a radius r_{200} over which the average density is 200 times that of the homogeneous cosmological background, and the other one the time-dependent concentration (the background, fluctuations, and formed halos evolve in time). Such a two-parameter model comes with a probability distribution function (pdf) for the concentration, which also depends on the virial mass and time.Formally, the concentration definition that we use in our model is $c = r_{200}/r_{-2}$, where r_{-2} is the radius at which the logarithmic slope of the halo density profile is -2. The virial mass and concentration entirely define any subhalo (and can be traded for the scale density ρ_s and radius r_s). Such a definition of concentration makes physical sense only when the subhalo lives in a low-density environment where m_{200} can be properly defined.Indeed, as tidal stripping operates, r_{200} turns meaningless (so is m_{200}), and leaves the floor to the notion of tidal radius r_t (enclosing a tidal mass m_t). One can actually define a "transfer function" that connects the virial cosmological quantities to the tidally deformed local ones. This transfer function depends on position (orbit) because tidal stripping does, and so do the tidal mass function of subhalos and effective concentration (denser objects are more resilient to

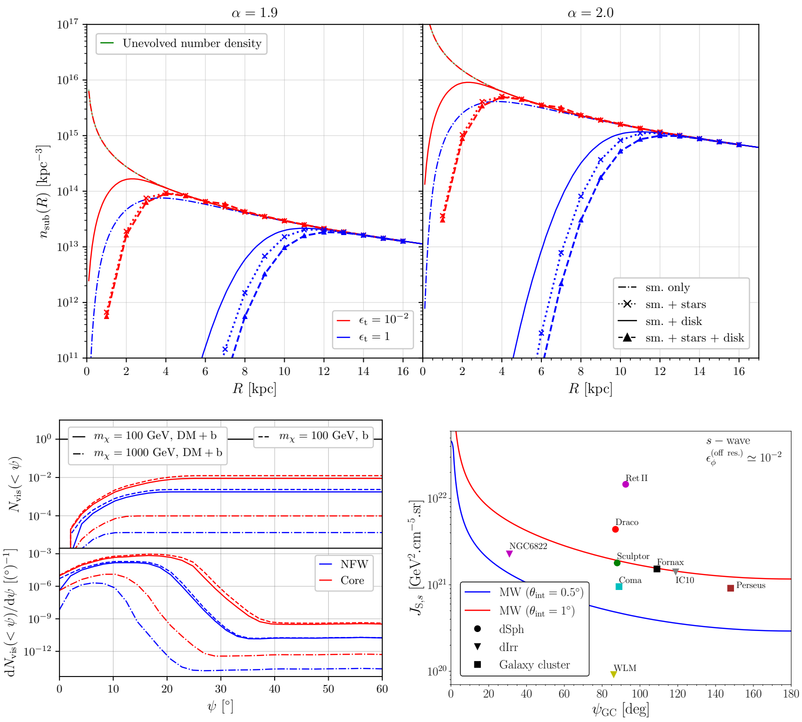

Figure 1: Top panels: subhalo number density profiles obtained for a constrained MW mass model, with the effect of different sources of tidal stripping (the smooth potential, disk shocking, and/or individual encounters with stars), showing the fragile vs. resilient model for tidal disruption (assuming simple power laws of index α for the *initial* mass function); from [8]. Bottom left: angular distribution of subhalos potentially visible with Fermi-LAT for an observation time of 10 years, assuming an annihilation cross section at the limit of exclusion from the non-observation of the smooth halo (annihilation to $\tau^+\tau^-$ is assumed); from [10]. Bottom right: classification of gamma-ray targets after including Sommerfeld-enhancement effects in an s-wave annihilating WIMP model and accounting for the presence of subhalos; from [11].

tides). It further depends on all gravitational components of the system contributing tidal stripping (dark matter, stars, and gas). For known galaxies, visible components are usually constrained by observations, and any realistic model of subhalo population should account for that.

Our model is by construction dynamically consistent with the constrained mass models of the target hosts (galaxies or galaxy clusters).Several studies were performed based on this model, mostly related to indirect dark matter searches with gamma rays and focusing on WIMP-like dark matter candidates. The average annihilation boost factor induced by subhalos in the MW was investigated in [7], based on a kinematically constrained global mass model for the MW. In [10], we investigated the possibility to detect individual subhalos with gamma rays, notably the possibility that some of the unidentified Fermi-LAT point sources could actually be subhalos.Our analytical model allows us to have a dynamically consistent distribution of both the smooth dark matter and the subhalo component. Therefore, we are able not only to determine the probability to detect individual subhalos given our assumptions, but also the probability to detect subhalos before the smooth halo itself (made of the same dark matter and associated annihilation cross section). From a likelihood analysis of Fermi-like Mock data, we could estimate that the probability of detecting a point-like subhalo with Fermi-LAT is vanishingly small, though it slightly increases for extended sources; we could also estimate that the smooth dark matter component is likely to be discovered before individual subhalos (the smooth dark matter component acts as an additional background to the detection of subhalos). Finally, in [11], we classified gamma-ray targets of interest (dwarf galaxies and galaxy clusters) in Sommerfeld-enhanced annihilation scenarios, where the presence of subhalos is crucial owing to the velocity dependence of the signal [12]. In Fig. 1, we illustrate the results discussed just above.

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PoS(TAUP2023)045