Dynamically constrained model of galactic subhalos and impact on dark matter searches

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Abstract. The interaction properties of cold dark matter particles candidates are known to lead to the structuring of dark matter on scales much smaller than typical galaxies. This translates into a large population of dark matter subhalos inside our Galaxy, which impacts the predictions for direct and indirect searches. We present a model for this subhalo population that accounts for the gravitational effects experienced by those structures (tidal stripping and disk shocking) while remaining consistent with dynamical constraints. The subhalos mass density and annihilation profiles are derived. The impact of subhalos on indirect searches with cosmic rays antiprotons is evaluated using the latest data from the AMS-02 experiment.

1. Introduction
The nature of the cold dark matter (DM) is still unknown. However, the parameter space of one of the most well-motivated particle candidates, the WIMP, is currently being probed by Earth-based and spatial experiments. Direct detection experiments [1] and indirect searches [2] are especially constraining. Predictions for those experiments depend crucially on the modelling of the Galaxy and its dynamics. Small-scale structures might be of importance: WIMPs (and other cold dark matter particles) are known to form structures on sub-galactic scales [3] down to masses possibly as small as $10^{-10} M_\odot$. Those galactic subhalos impact predictions for direct [1] and indirect searches [4]. In particular, the presence of inhomogeneities results in a systematic enhancement of the annihilation rate of DM particles in galaxies, which in turn boosts the expected flux of primary cosmic rays for instance [5] [6]. Here we present a model that consistently describes the galactic subhalo population while remaining consistent with dynamical constraints (more thoroughly described in [7]).

2. Building the model
We start from a dynamically constrained mass model of the Milky Way (e.g. the model of McMillan [8]). The model gives the total mass density profile (dark matter and baryons) at each point in space $\rho(\vec{x}) = \rho_{\text{dm}}(\vec{x}) + \rho_{\text{baryons}}(\vec{x})$ compatible with the observed dynamics. We include the subhalos in that description by splitting the dark matter contribution in two parts: a clumpy part and a smooth part $\rho_{\text{dm}}(\vec{x}) = \rho_{\text{sub}}(\vec{x}) + \rho_{\text{smooth}}(\vec{x})$. This splitting allows, once $\rho_{\text{sub}}$ is computed, to deduce $\rho_{\text{smooth}}$ in a way that ensures the required dynamical consistency. We will further assume spherical symmetry for the DM components. Note that the baryonic
part $\rho_{\text{baryons}}$ will play a crucial role in the modelling of tidal effects (see Sec. 3). In order to compute $\rho_{\text{sub}}$, we first make the assumption that the internal density profile (assumed spherical) of subhalos has a universal functional form (the NFW profile for instance [9]). Once the profile is fixed, a subhalo is entirely characterized by three variables: its position $\vec{x}$ in the Galaxy, its mass $m$ and its concentration $c$, therefore what we need to determine is the subhalo parameter space density (PSD) $F(\vec{x}, m, c)$. Because of tidal effects (see Sec. 3), we expect all three variables to be correlated and the PSD to be complicated. We start by making a guess on how it should look like without tidal effect. First, since in the CDM paradigm subhalos form before the Galaxy, we expect their spatial distribution to follow the host density profile: $dP/dV \propto \rho dm(\vec{x})$. We stress that this probability distribution function (PDF) is not the subhalo PDF today, as this distribution is strongly modified by tidal effects. The mass distribution $dP/dm$ of DM halos can be computed, in the linear regime, using the extended Press-Schechter formalism [10]. At the galactic scale, the resulting mass function behaves as a simple power law with index $\alpha_M \simeq -2$. This behaviour is recovered in the non-linear scales probed by cosmological simulations zooming on galactic scales [11] [12]. Consequently, we extrapolate the power law down to the smallest scale in our model ($M_{\text{min}}$, taken as a free parameter) where we put a sharp cutoff. Finally, we need the initial concentration PDF $dP/dc$. The field subhalo (i.e. subhalos unaffected by tides) concentration PDF is found in simulations to follow a log-normal law. The variance $\sigma_c$ and mass-median concentration relation are taken from numerical studies (see e.g. [13]). The full initial PSD can now be written down as

$$F_{\text{no tides}}(\vec{x}, m, c) = N_{\text{sub}} \frac{dP}{dV}(\vec{x}) \frac{dP}{dm}(m) \frac{dP}{dc}(c, m),$$

where $N_{\text{sub}}$ is the total number of subhalos. We recall that this density only defines the initial conditions for the subhalo population because we did not take into account tidal effects. In particular, in Eq. (1), $m$ and $c$ are completely uncorrelated with $\vec{x}$. We will see that tidal disruption drastically changes that picture.

3. Tidal effects

The competition between the Galactic potential and a subhalo’s potential results in a limited extension of the subhalo. Assuming DM particles follow circular orbits in a subhalo, this extension can be equalled to a tidal radius [14]. A realistic computation can be performed assuming the mass is continuously distributed in the Galaxy, in which case we get

$$r_t(R, m, c) = \left[ \frac{m_{\text{sh}}(r_t)}{3M(R) \left( 1 - \frac{1}{3} \frac{\ln M(R)}{\ln(r_t)} \right)} \right]^{1/3} R.$$

This definition naturally predicts a stronger effect near the center of the Galaxy. The disk shocking effect is different in nature to tidal stripping: here it is the experience of a rapidly changing gravitational potential as a subhalo crosses the disk that causes the mass depletion [15]. Assuming the disk is an infinite slab, the averaged kinetic energy increase per unit of particle’s mass $\langle \delta \epsilon_k \rangle$, for a DM particle orbiting a subhalo crossing the disk can be computed as in [16]. To derive a tidal radius from the kinetic energy variation, we propose the following definition for the subhalo’s radius after crossing

$$\langle \delta \epsilon_k \rangle (r_t) = \phi(r_t^{\text{in}}) - \phi(r_t),$$

where $\phi$ is the gravitational potential of the subhalo cancelling at infinity. Eq. (3) means that particles which get a velocity kick bigger than their escape velocity are removed from the
substructure. In Eq. (3), \( r_t^{{\text{sh}}}(R) \) is the subhalo’s radius before disk crossing, therefore the subhalo’s extension shrinks at each crossing. To get the radius today one needs the total number of disk crossing, which is computed assuming a 10 Gyr-old disk. A criterion is introduced for the complete disruption of a subhalo: if \( r_{t}/r_{s} \leq \epsilon_t \) with \( \epsilon_t \approx 1 \), then the subhalo does not survive tidal effects. This translates into a minimal concentration needed to survive tidal effects: \( r_{t}/r_{s}(R, m, c_{{\text{min}}}) = \epsilon_t \). It is through the minimal concentration \( c_{{\text{min}}} \) that the parameter space density of Eq. (1) is modified by tidal effects:

\[
\mathcal{F}(\vec{x}, m, c) = \frac{N_{{\text{sub}}}}{K} \frac{dP}{dV}(\vec{x}) \frac{dP}{dm}(m) \frac{dP}{dc}(c, m) \theta(c - c_{{\text{min}}}(\vec{x})) ,
\]

where \( K \) is a normalization factor and \( \theta \) is the Heaviside step function. The parameter space is now completely entangled, \( m \) and \( c \) are correlated to \( \vec{x} \), and \( dP/dV \), \( dP/dm \) and \( dP/dc \) can no longer be interpreted as the subhalo PDFs.

4. Subhalos mass density and annihilation profiles

The total number of subhalos \( N_{{\text{sub}}} \) in Eq. (4) is computed by calibrating the DM mass fraction inside subhalos \( f_{{\text{sub}}} \) on the resolved population of cosmological simulations. We choose to calibrate on the Via Lactea II simulation [12]. We obtain a total number of subhalos ranging from \( 10^{15} \) to \( 10^{20} \) depending on the choice of \( \alpha_{{\text{M}}} \) and \( M_{{\text{min}}} \). The subhalo mass density profile can now be computed

\[
\rho_{{\text{sub}}}(\vec{x}) = \frac{N_{{\text{sub}}}}{K} \frac{dP}{dV} \int dm \int dc \frac{dP}{dm} \frac{dP}{dc} \theta(c - c_{{\text{min}}}(\vec{x})) m_{{\text{sh}}}(r_t) ,
\]

where \( r_t \) is the tidal radius taking into account both stripping and shocking. This density is compared to the total DM density \( \rho_{{\text{dm}}} \) on Fig. 1 (left panel). We can see that tidal effects completely destroy most subhalos in the central region of the Galaxy regardless of the chosen definitions for the stripping and shocking radii. Near the center we have \( \rho_{{\text{sub}}} \ll \rho_{{\text{dm}}} \) and therefore \( \rho_{{\text{smooth}}} \approx \rho_{{\text{dm}}} \), i.e., most of the dark matter is smoothly distributed. The impact of disk shocking is also shown to be significant, especially near the Sun’s position \( (R_\odot \sim 10^{-3} R_{{200}}) \) where this effect dominates the disruption. Relevant for DM indirect searches is the annihilation profile \( \mathcal{L}_{{\text{tot}}} = \rho_{{\text{dm}}}^2 \). The total annihilation is the sum of three contributions: DM annihilation inside subhalos, annihilation in the smooth halo, and annihilation of subhalos’ particles on smooth halo’s particles (see [7] for details). The annihilation profiles are plotted in Fig. 1 (right panel). It is interesting to compare the blue curve (\( \mathcal{L}_{{\text{tot}}} / \rho_\odot^2 \) including subhalos) to the black curve (\( \mathcal{L}_{{\text{tot}}} / \rho_\odot^2 \) assuming all the DM is smoothly distributed). One can see that the inclusion of subhalos systematically increases the annihilation: the luminosity profile is boosted by the spatial inhomogeneities. The effect is stronger in the outer part of the Galaxy because subhalos are less depleted by tidal effects there (see left panel). The enhancement in the annihilation signal is often analyzed in term of the boost factor, either local or integrated. Both boosts are plotted on the lower panels of Fig. 1 (right panel). While the local boost is rather small \( (\sim 2) \), it can reach really high values far from the center (up to \( 10^4 \)). The integrated boost for the whole Galaxy is \( \sim 20 \). Note that those values are obtained for \( \alpha_{{\text{M}}} = 2 \) and \( M_{{\text{min}}} = 10^{-10} M_\odot \) (mass function parameters).

5. Impact on indirect searches with antiprotons

We look at the impact of subhalos on indirect searches by investigating a specific channel: cosmic rays antiprotons [17] [18]. This is motivated by the new measurement of the antiproton flux performed by the AMS collaboration [19]. Antiprotons being charged particles, they diffuse on the inhomogeneities of the Galactic magnetic field. Propagation parameters are usually
We have proposed a model of the Galactic subhalo population that consistently accounts for current dynamical constraints. Tidal effects from the Galactic gravitational potential and the disk were both carefully studied. Not only does our model qualitatively reproduce the results of cosmological simulations but it also fully accounts, by construction, for the details of our Galaxy, which can hardly be captured by simulations. It allows to compute, among other things, the subhalo mass density and annihilation profiles relevant for indirect searches. The model was applied to indirect searches with cosmic-ray antiprotons using the latest data from the AMS-02 experiment and competitive limits were derived. A natural extension of this work would be the study of complementary channels like diffuse gamma-ray emission.

Figure 1. left panel: The subhalo and total DM mass densities (upper panel) and the subhalo mass fraction (lower panel). The “smooth host” stripping effects and “differential” disk shocking corresponds to the computations described in the text (the alternatives are detailed in [7]). right panel: The annihilation (upper panel) and boost profiles (lower panel).
Figure 2. Left panel: primary antiproton flux (prop. model of Kappl et al.) expected from DM annihilation compared to the AMS-02 data, for the canonical annihilation cross-section. The multiple curves correspond to different values of the WIMP mass (as indicated in the top left corner), with the curves farthest on the left being associated with the smallest masses. Right panel: exclusion curve for the thermally averaged annihilation cross-section.

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