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Remnants of small-scale dark matter clumps

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The small-scale dark matter clumps are efficiently disrupted at early stages of hierarchical structure formation and later in the Galaxy by tidal interactions with stars. It is demonstrated that a substantial fraction of clump remnants survive through the tidal destruction during the lifetime of the Galaxy if a clump core radius is rather small. The resulting mass spectrum of survived clumps is extended down to the core mass of a minimal mass clump. These survived dense remnants of tidally destructed clumps provide a suitable contribution to the amplification (boosting) of dark matter annihilation signal in the Galaxy.

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Results of numerical simulations and theoretical models of Dark Matter (DM) clustering at the scales of subhalos and smaller heavily depend on the (unknown) form of initial perturbation spectrum. The form of perturbation spectrum at small scales cannot be recovered from the nowadays and future cosmic microwave background observations. In the lack of unique fundamental theory of cosmological inflation, the only possible chance to obtain information on the perturbation spectrum at small scales is the observation of annihilation boosting produced by the clumpy DM structures in the Galaxy.

The cold DM component is gravitationally unstable and is expected to form the gravitationally bounded clumpy structures from the scale of superclusters of galaxies and down to very small clumps of DM. The minimum mass of clumps (the cutoff of the mass spectrum), $M_{\rm min}$ is determined by the collisional and collisionless damping processes (see e. g. [1] and references therein). Recent calculations [2] show that the cutoff mass is related to friction between DM particles and cosmic plasma similar to the Silk damping. In the case of the Harrison-Zeldovich spectrum of primordial fluctuations with CMB normalization the first small-scale DM clumps are formed at redshift $z \sim 60$ with a mean density 7×10^{-22} g cm^{-3}, virial radius 6×10^{-3} pc and internal velocity dispersion 80 cm s^{-1} respectively. Only very small fraction of these clumps survives the early stage of tidal destruction during the hierarchial clustering [3]. Nevertheless these survived clumps may provide the major contribution to the annihilation signal in the Galaxy [3, 4, 5, 6, 7].

The unresolved problem of DM clumps is a value of the central density or core radius. Numerical simulations give a nearly power density profile of DM clumps. Both the Navarro-Frenk-White (NFW) and Moore profiles give formally a divergent density in the clump center. A theoretical modelling of the solitary clump formation [8] predicts a power-law profile of the internal density of clumps

$$\rho_{\rm int}(r) = \frac{3-\beta}{3}\,\bar{\rho}\left(\frac{r}{R}\right)^{-\beta}, \qquad (1)$$

where $\bar{\rho}$ and R are the mean internal density and a radius of clump, respectively, $\beta \simeq 1.8-2$ and $\rho_{\rm int}(r) = 0$ at $r > R$. A near isothermal power-law profile (1) with $\beta \simeq 2$ has been recently obtained in numerical simulations of small-scale clump formation [9]. Additional indication that mergers do not play a pivotal role in establishing the universal internal clump density profile comes from the recent numerical simulation [10]. We consider the relative core radius $x_c = R_c/R$ of DM clumps as a free parameter in the range $0.001-0.1$ and investigate the dependence of the probability of clump survival in the Galaxy on this parameter under the action of tidal forces from galactic disk and stars.

It must be noted that density profiles of small-scale DM clumps and large-scale DM halos may be quite different. The galactic halos are well approximated by the Navarro-Frenk-White profile outside the central core where dynamical resolution of numerical simulations becomes insufficient. The theoretical estimation of the relative core radius of DM clump $x_c = R_c/R$ was obtained in [8] from the energy criterion, $x_c \equiv R_c/R \simeq \delta_{eq}^3$, where δ_{eq} is a value of density fluctuation at the beginning of matter-dominated stage. A similar estimate for DM clumps with the minimal mass $\sim 10^{-6} M_\odot$ originated from 2σ fluctuation peaks gives $\delta_{eq} \simeq 0.013$ and $R_c/R \simeq 1.8 \times 10^{-5}$ respectively. The other possibility is that a real core radius is determined by the relaxation of small-scale perturbations inside the forming clump [11].

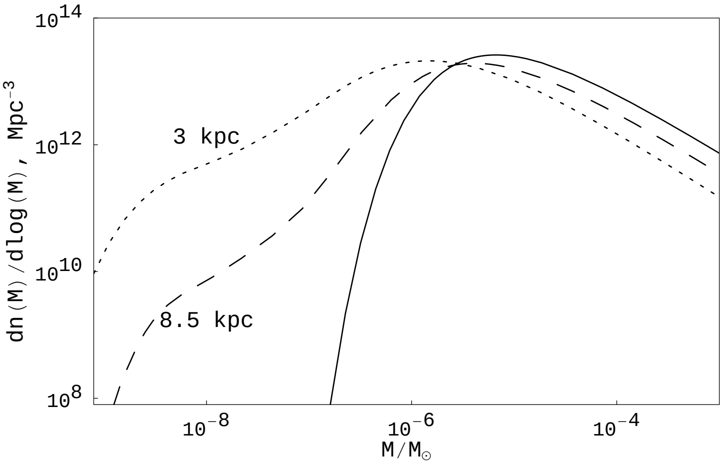

Figure 1: Numerically calculated modified mass function of clump remnants for galactocentric distances 3 and 8.5 kpc. The solid curve shows the initial mass function.

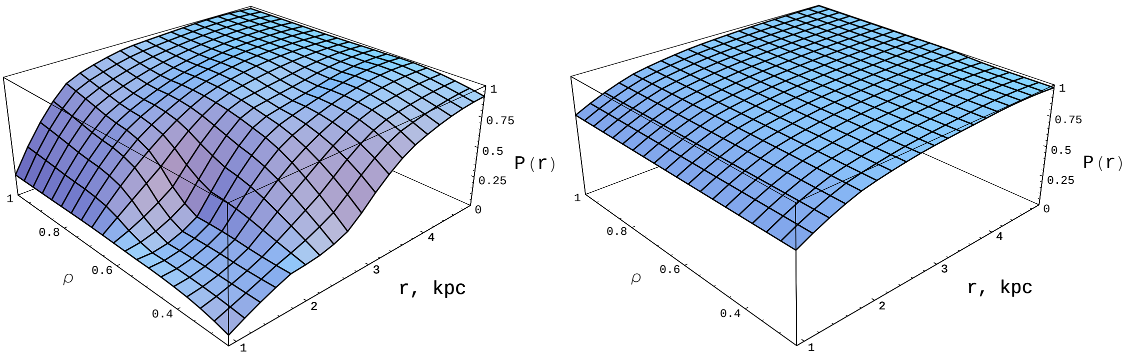

Figure 2: The survival probability $P(r,\rho)$ for clumps, which survives the tidal destruction by the stellar disk and the halo stars, plotted as as a function of distance from the galactic center r and a mean internal clump density ρ in the case $x_c = 0.1$ (left panel) and $x_c = 0.05$ (right panel). The density of clumps is normalized to the density 7.3×10^{-23} g cm^{-3} valid for clumps with mass $M = 10^{-6}\mathrm{M}_{\odot}$.

We describe a gradual mass loss of small-scale DM clumps assuming that only the outer layers of clumps are involved and influenced by the tidal stripping. In this approximation we calculate a continues diminishing of the clump mass and radius during the successive galactic disk crossings and encounters with the stars. An effective time of mass loss for DM clump remains nearly the same as in our previous calculations [3, 12]. However the clump destruction time has now quite different physical meaning: it provides now a characteristic time-scale for diminishing of clump mass and size instead of the total clump destruction. This means that small remnants of clumps may survive in the Galaxy. See details in [13] In Fig. 1 is shown the final mass function of small-scale in the halo at the present epoch for two distances from the Galactic center [13]. We supposed in numerical calculations that a core radius is very small and all masses of remnants are admissible. With a finite core size the final mass function has a cut-off near the cores mass of clump with a minimal mass $M_{\min}$. One can see from in Fig. 1 that clump remnants exist below the $M_{\min}$. Deep

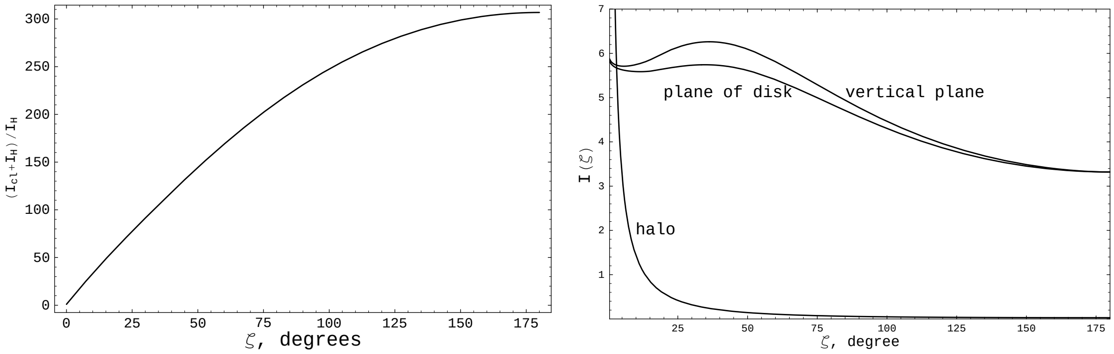

Figure 3: Left panel: the amplification (boosting) of the annihilation signal $(I_{\rm cl}+I_{\rm H})/I_{\rm H}$ as function of the angle between the line of observation and the direction to the Galactic center. Right panel: the annihilation signal in the Galactic disk plane, in the vertical plane crossing the Galaxy rotation axis and from the diffuse DM halo.

in the bulge (very near to the Galactic center) the clump remnants are more numerous because of intensive destructions of clumps in the dense stellar environment in comparison with the rarefied one in the halo. The main contribution to the low-mass tail of the mass function of remnants comes from the clumps with the near-disk orbits where the destructions are more efficient.

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