Dark matter annihilation in small scale clumps

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Abstract

We study the cosmological origin of small-scale DM clumps in the hierarchical scenario with most conservative assumption of adiabatic gaussian fluctuations. The main included effect (tidal interaction) results in the formation of large core in the center of a clump and in tidal destruction of large fraction of the clumps. The mass distribution of clumps has a cutoff at $M_{\rm min}$ due to diffusion of DM particles out of a fluctuation and free streaming at later stage. $M_{\rm min}$ is a model dependent quantity. In the case the neutralino, considered as a pure bino, is a DM particle, $M_{\rm min} \sim 10^{-8} M_{\odot}$. The enhancement of annihilation signal due to DM clumpiness in the Galactic halo, valid for arbitrary DM particles, is calculated. For observationally preferable value of index or primeval fluctuation spectrum $n_p \approx 1$, the enhancement of annihilation signal is described by factor 2 - 5 for different density profiles in a clump.

1 Introduction

The gravitationally bound structures in the universe are developed from primordial density fluctuations $\delta(\vec{x}, t) = \delta\rho/\rho$. They are produced at inflation from quantum fluctuations. The predicted power spectrum of these fluctuations has a nearly universal form $P(k) \equiv \delta_k^2 \propto k^{n_p}$, with $n_p \simeq 1$. At radiation-dominated epoch the fluctuations grow slowly, $\delta \propto \ln(t/t_i)$. After transition at $t = t_{\rm eq}$ to the matter-dominated epoch, the fluctuations grow as

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$\delta \propto (t/t_{\rm eq})^{2/3}$. The gravitationally bound objects are formed and detached from cosmological expansion when fluctuations enter the non-linear stage $\delta \geq 1$. The non-linear stage of fluctuation growth has been studied both by analytic calculations [1] and in numerical simulations [2, 3, 4] for Large Scale Structure (LSS). The density profile in the inner part of these objects is given by $\rho(r) \propto r^{-\beta}$, with with $\beta \approx 1.7 - 1.9$ in analytic calculations [1], $\beta = 1$ in simulations of NFW [2] and $\beta = 1.5$ in simulations of Moore et al. [3] and Jing and Suto [4]. In this work we apply this approach to the smallest DM objects in the universe, which we shall call *clumps*. The clumps, being the smallest structures, are produced first in the universe, and it makes different our consideration from LSS formation.

The small-scale clumps are formed only if the fluctuation amplitudes in the spectrum are large enough at the corresponding small scales. The inflation models predict the power-law primeval fluctuation spectrum. If the power-law index $n_p \geq 1$, clumps are formed in a wide range of scales. During the universe expansion the small clumps are captured by the larger ones, and the larger clumps consist of the smaller ones and of continuously distributed DM. The convenient analytic formalism, which describes statistically this hierarchical clustering, is the Press-Schechter theory and its extensions, in particular 'excursion set' formalism developed by Bond et al. However, this theory does not include the important process of the tidal destruction of small clumps inside the bigger ones. We take into account this process and obtain the mass function for the small-scale clumps in the Galactic halo. The theoretical observation of this work is that the role of tidal interaction is crucial: the central core in DM distribution is produced and some fluctuations can be fully disrupted. The LSS are produced much later, when the tidal interactions work in the different regime and their role is less essential. In the case of the power-law spectrum only a small fraction of the captured clumps survives, but even this small fraction is enough to dominate the total annihilation rate in the Galactic halo. We use the standard cosmology with WMAP parameters.

2 Tidal Destruction of Clumps

The destruction of clumps by the tidal interaction occurs at the formation of the hierarchical structures, long time before the galaxy formation. The characteristic epoch is roughly $t \sim t_{\rm eq}$. This interaction arises when two clumps pass near each other and when a clump moves in the external gravitational field of the bigger host to which this clump belongs. In both cases a clump is exited by the external gravitational field, i. e. its constituent particles obtain additional velocities in the center of mass system. The clump is destroyed if its internal energy increase ΔE exceeds the corresponding total energy $|E| \sim GM^2/2R$. In [5] we have calculated the rate of excitation energy production by both aforementioned processes. The dominating process is given by tidal interaction in the gravitational field of the host clumps, with the main contribution from the smallest host clump. We use the Press-Schechter formalism for hierarchical clustering.

The differential fraction of mass, M, in the form of clumps which escape the tidal destruction in the hierarchical objects (survival probability) is found as

$$\xi(n,\nu) \simeq (2\pi)^{-1/2} e^{-\nu^2/2} (n+3) y(\nu), \tag{1}$$

where $\nu = \delta/\sigma(M)$ is the peak-height of a fluctuation with δ being the amplitude and σ variance (dispersion), $n \approx -3$ is the effective spectral index at $t \sim t_{\rm eq}$, and function $y(\nu)$ is given numerically in [5]. $\xi(n,\nu)$ depends weakly on index of DM distribution in a clump β. Integrating over ν, we obtain

$$\xi_{\rm int} \simeq 0.01(n+3). \tag{2}$$

Since n is close to -3, only a small fraction of clumps about $0.1 - 0.5\%$ survive the stage of tidal destruction. However, this fraction is enough to dominate the total annihilation rate in the Galactic halo.

3 Core of Dark Matter Clump

The core formation in a fluctuation begins at the linear stage of evolution and continues at the beginning of non-linear stage. The tidal forces diminishes with time as $t^{-4/3}$ (see [5]). Once the core is produced it is not destroyed in the evolution followed. The stage of the core formation continues approximately from $t_{\rm eq}$ to the time of maximal expansion t_s and a little above, when a clump decouples from expansion of universe and contracts in the non-linear regime. Soon after this period, a clump enters the hierarchical stage of evolution, when the tidal forces can destroy it, but surviving clumps retain their cores.

The calculations proceed in the following way (see [5] for details and references). The background gravitational field (including that of the host clumps) is expanded in series in respect to the distance from the point with maximum density in a fluctuation. The motion of a DM particle in this field is studied. The spherically symmetric term of the expansion causes the radial motion of a particle in the oscillation regime. Spherically non-symmetric term describes the tidal interaction. It results in deflection of a particle trajectory from a center (point with maximum density). The average (over statistical ensemble) deflection gives the radius of the core R_c. After statistical averaging, R_c is expressed through the amplitude of the fluctuation $\delta_{\rm eq}$ and the variance $\sigma_{\rm eq}$ (or $\nu = \delta_{\rm eq}/\sigma_{\rm eq}$) as

$$x_c = R_c/R \approx 0.3\nu^{-2} f^2(\delta_{\rm eq}). \quad (3)$$

The fluctuations with $\nu \sim 0.5 - 0.6$ have $x_c \sim 1$, i.e. they are practically destroyed by tidal interactions. Most of galactic clumps are formed from $\nu \sim 1$ peaks, but the main contribution to the annihilation signal is given by the clumps with $\nu \simeq 2.5$ for which $x_c \simeq 0.05$.

4 Clumps of Minimal Mass

The mass spectrum of clumps has a low-mass cutoff at $M = M_{\rm min}$, which value is determined by a leakage of DM particles from the overdense fluctuations in the early universe. CDM particles at high temperature $T > T_f \sim 0.05 m_\chi$ are in the thermodynamical (chemical) equilibrium with cosmic plasma. After freezing at $t > t_f$ and $T < T_f$, the DM particles remain for some time in *kinetic* equilibrium with plasma, when the temperature of CDM particles T_χ is equal to temperature of plasma T. At this stage the CDM particles are not perfectly coupled to the cosmic plasma. Collisions between a CDM particle and fast particles of ambient plasma result in exchange of momenta and a CDM particle diffuses in the space. Due to diffusion the DM particles leak from the small-scale fluctuations and thus their distribution obtain a cutoff at the minimal mass M_D.

When the energy relaxation time for DM particles $\tau_{\rm rel}$ becomes larger than the Hubble time $H^{-1}(t)$, the DM particles get out of the kinetic equilibrium. This conditions determines the time of kinetic decoupling t_d. At $t \geq t_d$ the CDM matter particles are moving in the free streaming regime and all fluctuations on the scale of free-streaming length λ_{fs} and smaller are washed away. The corresponding minimal mass

$$M_{\rm fs} = (4\pi/3)\rho_\chi(t_0)\lambda_{\rm fs}^3, \quad (4)$$

is much larger than M_D and therefore $M_{\rm min} = M_{\rm fs}$. In [5] we have performed the calculations using two methods: the transparent physical method, based on the description of diffusion and free streaming, and more formal method based on solution of kinetic equation for DM particles starting from the period of chemical equilibrium. Both methods agree perfectly. The minimal mass in the mass distribution is given by free-streaming mass and for the case of neutralino (bino) as DM particle it is equal to $M_{\rm min} = 1.5 \times 10^{-8} M_\odot$ for the mass of neutralino $m_\chi = 100$ GeV and the mass of selectron and sneutrino $\tilde{M} = 1$ TeV. Our calculations agree reasonably well with that of [6], while M_{min} from [7] coincides with our value for M_D.

5 Annihilation Signal due to Clumps

We calculate the enhancement of annihilation signal due to presence of small clumps in the Galactic halo as

$$\eta = (I_{\rm cl} + I_{\rm hom})/I_{\rm hom}, \tag{5}$$

where $I_{\rm hom}$ is the flux due to annihilation of unclumpy DM particles homogeneously distributed in halo, and $I_{\rm cl}$ is the flux from the clumps. In calculations we used different density profiles in the clumps, the distribution of DM clumps over their masses M and radii R, and the distribution of clumps in the galactic halo. The enhancement depends on the nature of DM particle only through $M_{\rm min}$. The details of calculations and corresponding plots one can find in [5]. The enhancements η for $n_p = 1$ or less is not large: typically it is not larger than factor 2 -5 for $M_{\rm min} \sim 10^{-8} M_\odot$. For example, $\eta = 5$ for $n_p = 1.0$ and $M_{\rm min} = 2 \cdot 10^{-8} M_\odot$. It strongly increases at smaller $M_{\rm min}$ and larger n_p. For example, for $n_p = 1.1$ and $M_{\rm min} = 2 \cdot 10^{-8} M_\odot$, enhancement becomes very large, $\eta = 130$ and $\eta = 4 \cdot 10^3$, respectively. Our approach is based on the hierarchical clustering model in which smaller mass objects are formed earlier than the larger ones, i. e. $\sigma_{\rm eq}(M)$ diminishes with the growing of M. This condition is satisfied for objects with mass $M > M_{min} \simeq 2 \cdot 10^{-8} M_\odot$ only if the primordial power spectrum has the value of the power index $n_p > 0.84$. In this case the enhancement of the annihilation signal is absent: $\eta \simeq 1$, for $n_p < 0.9$.

Finally, we calculated the enhancement due to large clumps with masses in the range $10^8 - 10^{10} M_\odot$ and the number density distribution $\propto dM/M^2$, which are seen in numerical simulations (see e.g. [3]). This distribution of large accidentally coincides with our derived distribution for small clumps (2). For NFW profile of DM in halo and mass fraction of large clumps 0.15 the calculated enhancement of annihilation signal from typical ($\nu \simeq 1$) large clumps is rather small, $\eta \simeq 1.07$.

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