Small-scale dark matter clumps in the Galactic halo

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Abstract: A mass function of small-scale dark matter clumps is calculated by taking into account the tidal destruction of clumps at early stages of structure formation. The surviving clumps can be disrupted further in the Galaxy by tidal interactions with stars. A corresponding annihilation of dark matter particles in clumps produces the anisotropic gamma-ray signal on the level $\approx 9\%$ with respect to the Galaxy plane. It is demonstrated that a substantial fraction of clump remnants may survive the tidal destruction during the lifetime of the Galaxy if a clump core radius is rather small. The dense part of clump core produces the dominating input into the annihilation signal from a single clump. For this reason the survived dense remnants of tidally destructed dark matter clumps may provide the major contribution to annihilation signal from the Galactic halo.

1. Introduction: Dark matter clumps

About 30% of mass of the Universe is in a form of cold dark matter (DM), but the nature of DM particles is still unknown. The cold DM component is gravitationally unstable and forms the gravitationally bounded clumpy structures from the scale of superclusters of galaxies and down to very small clumps of DM. The cutoff of the mass spectrum, M_{min} is determined by the collisional and collisionless damping processes and typical values $M_{min} \approx (10^{-8}\text{-}10^{-6})M_{\odot}$ for neutralino DM. Due to uncertainties in the SUSY parameters, a numerical value of M_{min} is not exactly predicted. Theoretical study of DM clumps are important for understanding the properties of DM particles, because annihilation of DM particles in small dense clumps may result in observable signals. The cosmological formation and evolution in early Universe and properties of small-scale DM clumps have been studied in many works [1-9]. Only very small fraction of these clumps survives the early stage of tidal destruction during the hierarchial clustering. Nevertheless these survived clumps will provide the major contribution to the annihilation signal in the Galaxy [9]. One of 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 and Moore profiles give formally a divergent density in the clump center. A theoretical modelling of the clump formation [10] predicts a power-law profile of the internal density of clumps A near isothermal power-law profile has been recently obtained in numerical simulations of small-scale clump formation [11].

2. Cosmological distribution function of clumps

The first gravitationally bound objects in the Universe are the DM clumps of the minimum mass M_{min}. In the case of the Harrison-Zeldovich spectrum of primordial fluctuations with CMB normalization the first small-scale DM clumps are formed at redshift $z \approx 60$ (for 2σ fluctuations) 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. The clumps of larger scales are formed later. During its lifetime a small-scale clump can stay in many host clumps of larger mass. After tidal disruption of the first lightest host, a small-scale clump becomes a constituent part of a larger one, etc. The process of hierarchical transition of a small-scale clump from one host to another occurs almost continuously in time up to the final host formation, where the tidal interaction becomes inefficient. The first host provides a major contribution to the tidal destruction of the considered small-scale clump, especially if the first host density is close to the clump density. Using the Press-Schechter formalism we obtained in [12] the following distribution function of clumps (mass fraction):

$$\xi \; \frac{dM}{M} d\nu \approx \frac{\nu d\nu}{M\sqrt{2\pi}} \exp(-\nu^2/2)\, f_1(\gamma) \frac{d\log\sigma(M)}{dM} dM \qquad (1)$$

where $\sigma(M)$ is a r.m.s. fluctuation on a mass-scale M at the time of matter-radiation equality, ν is the peak high and one may use $f_1(\gamma) \approx 0.2\text{-}0.3$. Integrating Eq.(1) over ν, we obtain

$$\xi \frac{dM}{M} \approx 0.02(n+3) \frac{dM}{M}. \qquad (2)$$

An effective power-law index n in Eq.(2) of power-spectrum depends very weakly on M. The simple M^{-1} shape of the mass function (2) is in a very good agreement with the corresponding numerical simulations [11], but our normalization factor is a two times smaller.

3. Tidal destruction of clumps

Crossing the Galactic disk, a DM clump can be tidally destructed by the collective gravitational field of stars in the disk. This phenomenon is similar to the destruction of globular clusters. In [12] 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. Additionally we assume that inner layers of a clump are not affected by tidal forces due to adiabatic correction [13]. 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. As a criterium of a clump destruction we accept now the approaching of the radius of tidally stripped clump down to the core radius. Then we calculate the tidal mass loss by clumps using a distribution of their orbits in the standard Navarro-Frank-White Galactic halo. The simplification in calculation of follows from the fact that a velocity of orbit precession is constant. For this reason the points of successive odd crossings are separated by the same angles and the same is also true for successive even crossings. By the similar formalizm we calculate the diminishing of a clump mass due to a tidal heating by stars in the halo and bulge. Combining together the rates of mass losses due to the tidal stripping of a clump by the disk and stars we obtain the evolution equation for a clump mass:

$$\frac{dM}{dt} = \left(\frac{dM}{dt}\right)_{\rm d} + \left(\frac{dM}{dt}\right)_{\rm s} \qquad (3)$$

We solve this equation numerically starting from the time of Galaxy formation at up to the present moment and calculate the probability P of the survival of clump remnant during the lifetime of the Galaxy.

4.Modified distribution function of clumps

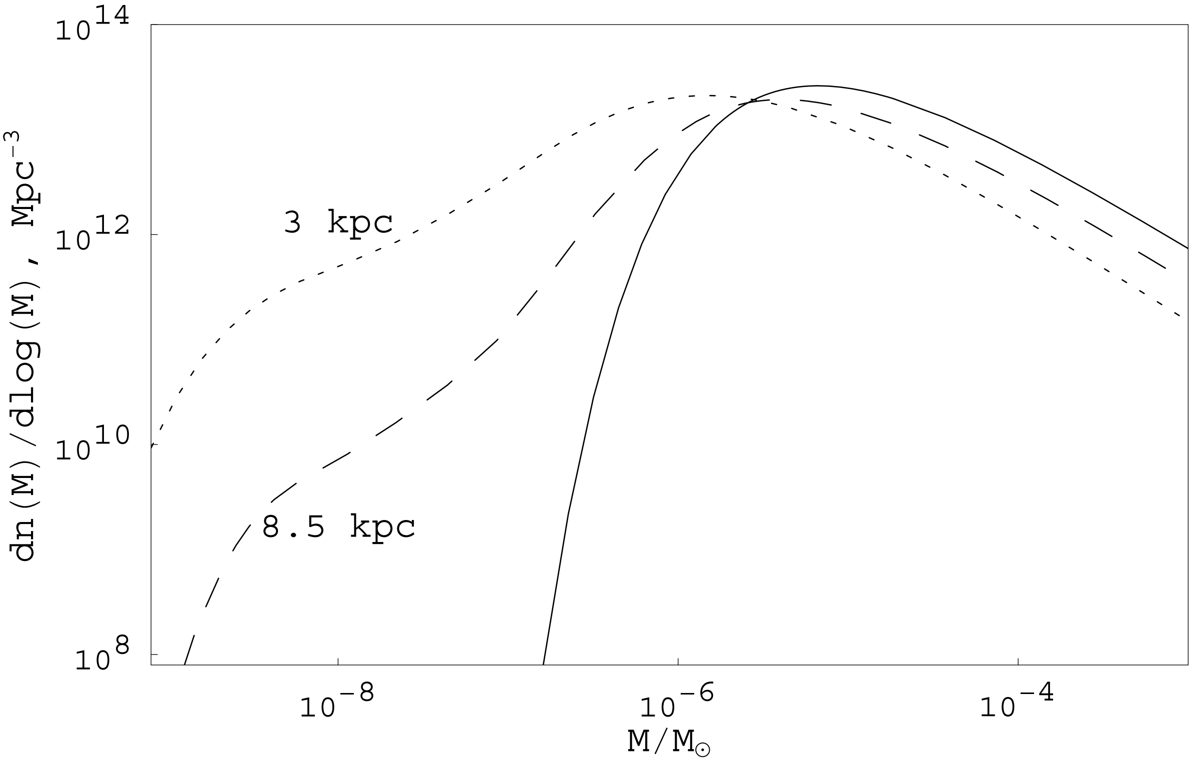

Fig. 1 Numerically calculated modified mass function of clump remnants for galactocentric distances 3 and 8.5 kpc. The solid curve shows initial mass function.

We calculated (see details in [12]) the modified mass function for the small-scale clumps in Galaxy taking into account clump mass loss instead of clump destruction considered in [9]. One can see in the Fig. 1 that clump remnants exist below the M_{min}. Deep in the bulge (very near to the Galactic center) the clump remnants are more numerous because of intensive clump destructions in the dense stellar environment in comparison with the rarefied one in the halo. In [14] it was found that almost all small-scale clumps in Galaxy are destructed by tidal interactions with stars and transformed into "ministreams" of DM. The properties of these ministreams may be important for the direct detection of DM particles because DM particles in streams arrive anisotropically from several discrete directions. We demonstrate that the cores of clumps (or clump remnants) survive in general during the tidal destruction by stars in the Galaxy. Although their outer shells are stripped and produce the ministreams of DM, the central cores are protected by the adiabatic invariant and survived as the sources of annihilation signals.

5. Annihilation of dark matter in clumps

A local annihilation rate is proportional to the square of DM particle number density. A number density of DM particles in clump is much large than a corresponding number density of the diffuse (not clumped) component of DM. For this reason an annihilation signal from even a small fraction of DM clumps can dominate over an annihilation signal from the diffuse component of DM in the halo. This amplification of an annihilation signal is often called a 'boost factor'. A boost factor of the order of 10 is required for interpretation of the observed EGRET gamma-ray excess as a possible signature of DM neutralino annihilation [15].

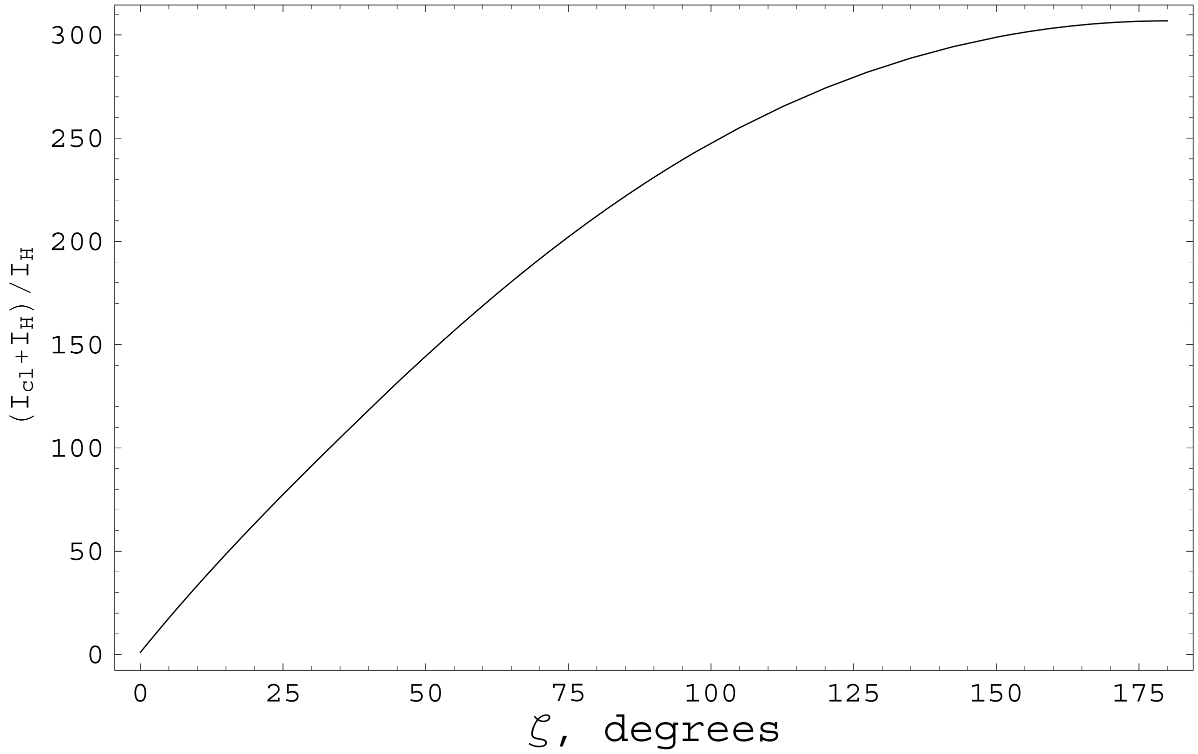

Fig. 2 The amplification of the annihilation signal $(I_{cl}+I_H)/I_H$ as function of the angle between the line of observation and the direction to the Galactic center.

The usual assumption in calculations of DM annihilation is a spherical symmetry of the Galactic halo. In this case an anisotropy of annihilation gamma-radiation is only due to off-center position of the Sun in the Galaxy. Nevertheless, in [14] the anisotropy with respect to the Galactic disk was discussed. A tidal heating and final destruction of clumps by the gravitational field of the Galactic disk depends on the inclination angle of a clump orbit to the disk.

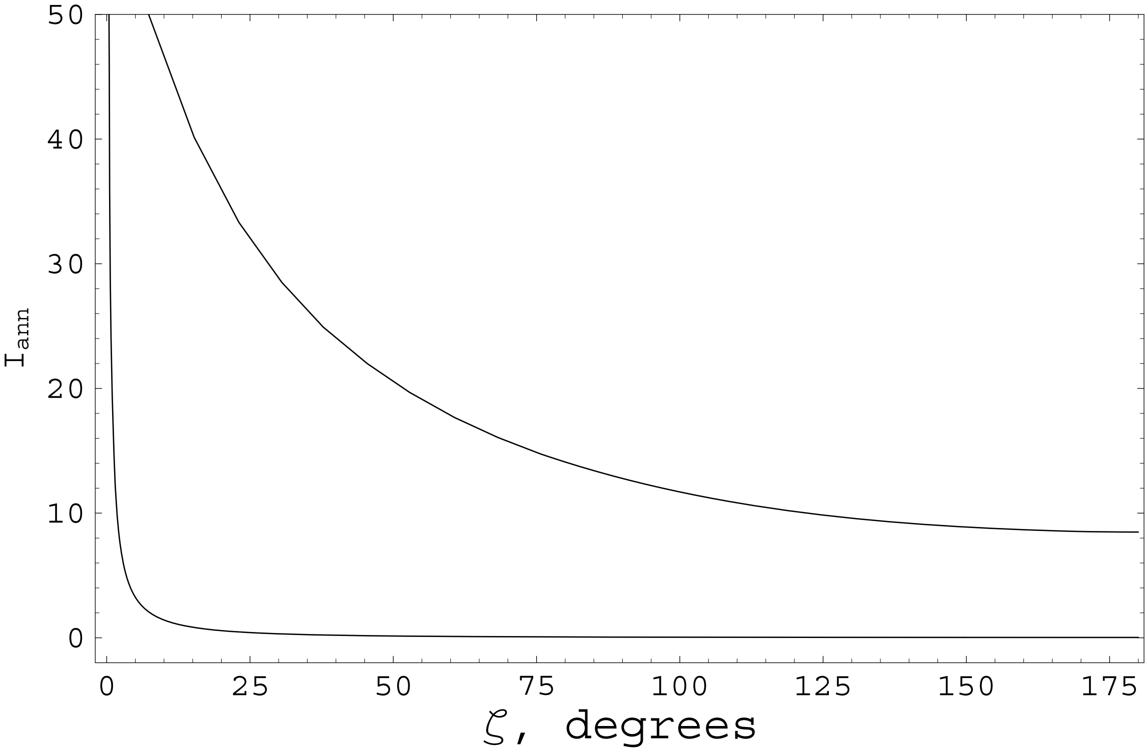

Fig. 2 The annihilation signal in the Galactic disk plane and in vertical plane.

In the Fig. 3 the annihilation signal is shown for the Galactic disk plane and for the orthogonal vertical plane (passing through the Galactic center) as function of angle ζ between the observation direction and the direction to the Galactic center. For comparison in the Fig. 3 is also shown the signal from the spherically symmetric Galactic halo without the DM clumps. The later signal is the same in the in the Galactic disk plane and in vertical plane and therefore can be principally extracted from the observations. The difference of the signals in two orthogonal planes at the same ζ can be considered as an anisotropy measure. Defined as $\delta=(I_2-I_1)/I_1$, it has a maximum value $\delta\approx0.09$ at $\zeta\approx39°$. This anisotropy provides a possibility to discriminate dark matter annihilation from the diffuse gamma-ray backgrounds of other origin.

6.Acknowledgments

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