ANISOTROPY OF DARK MATTER ANNIHILATION IN THE GALAXY

V.S. BEREZINSKY[1,2], V.I. DOKUCHAEV[2] AND YU.N. EROSHENKO[2]
[1] *INFN, Laboratori Nazionali del Gran Sasso, I-67010 Assergi (AQ), Italy*
[2] *Institute for Nuclear Research of the Russian Academy of Sciences, 60th October Anniversary Prospect 7a, 117312 Moscow, Russia*

Dark matter (DM) annihilation in the Galactic halo is strongly enhanced (boosted) with respect to a diffuse DM annihilation by the presence of small-scale DM clumps. The distribution of clumps in the Galactic halo is described in the framework of standard cosmology and hierarchical structure formation by taking into account a tidal destruction of clumps by stars. A tidal destruction of clumps in the Galactic disk results in an anisotropy in clump distribution. A corresponding annihilation of dark matter particles in small-scale clumps produces the anisotropic gamma-ray signal with respect to the Galactic disk. This anisotropy is rather small, $\sim 9\%$, and superimposed on that due to off-centering position of the Sun in the Galaxy. The anisotropy of annihilation signal with respect to the Galactic disk provides a possibility to discriminate DM annihilation from the diffuse gamma-ray backgrounds of other origin

1 Introduction

A primordial power-law spectrum of density fluctuations in the Dark Matter (DM) ranges from the largest scales above the scales of superclusters of galaxies to the smallest sub-stellar scales according to prediction of inflation models. This permits to predict the properties of smallest DM structures from the known CMB fluctuations at large scales. Substructures of DM in the galactic haloes with a rather large mass, $\geq 10^7 M_\odot$, were extensively discussed in early works, see for example [1]. The nonlinear dynamics and mechanism of hierarchical clustering of these large DM clumps were analyzed in both analytical calculations [2,3,4] and numerical simulations [5,6,7]. At sub-stellar mass-scales of DM fluctuations, a principal new phenomenon arise — the cutoff of mass spectrum due to collisional and collisionless (free streaming) damping processes of DM particles in the forming clumps. The resulting smallest mass of DM clumps is determined by the properties of DM particles, in particular, by their elastic scattering. See e. g.[8] and references therein for detailed calculations of this cutoff. Additionally the cutoff of mass spectrum is influenced by the acoustic absorption [9] at the time of kinetic decoupling of DM particles [10] and also by the horizon-scale perturbation modes [11]. The kinetic equations for DM phase space density were solved in [12] for the case of perturbed cosmological background by taking into account the acoustic absorption, horizon-scale modes and gravitational perturbations. A corresponding value of the smallest clump mass for neutralino DM is of the order of the Moon or Earth mass. The formation of small-scale DM clumps with a mass larger than the Earth mass, $M_{\rm min} \sim 10^{-6}M_{\odot}$, have been explored in numerical simulations [13,14]. A resulting differential number density of small-scale clumps, $n(M)\,dM \propto dM/M^2$, turns out very close to that obtained in the numerical simulations of large-scale clumps with mass $M \geq 10^6 M_{\odot}$. The other important result obtained in numerical simulations [13] is determination of the internal density profile in the isolated clump of minimal mass. The resulting density profile is approximately a power-law, $\propto r^{-\beta}$, with $\beta = 1.5 - 2.0$, which is in a good agreement with theoretically predicted value $\beta = 1.7 - 1.8$ according to [2].

The number density of small-scale DM clumps existing nowadays in the Galactic halo is determined by their tidal destruction during hierarchical structure formation [15] and also by tidal interactions with stars in the Galaxy [13,16,17,18,19,20,21]. Annihilation of DM particles in small-scale clumps [14,22,23,24,25,26,27,28,29] enhances the total DM annihilation signals in our Galaxy and thus boosts a chance for indirect detection of DM.

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, a principal significance of the halo nonsphericity for the observed annihilation signal was demonstrated in [30]. According to observations, the axes of the Galactic halo ellipsoid differ most probably no more than $10 - 20\%$, but even a much more larger difference of axes, up to a factor 2, can not be excluded [31,32]. This leads to more than an order of magnitude uncertainty in the predicted annihilation flux from the Galactic anti-center direction [30]. It must be noted also the "intrinsic" annihilation anisotropy caused by the small-scale DM clustering itself. A corresponding angular power spectrum of annihilation signal at small scales is connected with a power spectrum of DM clumping [33]. In principle, the DM clumps may be seen as point sources at the gamma-sky [30]. Another minor source of annihilation anisotropy is a dipole anisotropy due to proper motion of the Sun in the Galaxy [34].

In [18] the anisotropy with respect to the Galactic disk was discussed basing on the numerical calculations of the destruction of DM clumps by stars in the disk and taking into account the influence of gravitational potential of the disk on the clump orbits. It was also shown [15,19] that (i) small-scale DM clumps dominate in the generation of annihilation signal and (ii) the Galactic stellar disk provides the main contribution to the tidal destruction of clumps at $r > 3$ kpc, i. e. outside the central bulge region. A process of clump destruction in the halo is anisotropic in general (e. g. it depends on the inclination of clump orbit with respect to the disk plane). Respectively, the DM annihilation in the halo is also anisotropic. In this work we estimate the value of this anisotropy. It must be stressed that with a present state of art it is impossible to separate this source of anisotropy from that produced by the halo nonsphericity. More detailed investigation is required to constrain the shape of the halo and to search the distinctive features of annihilation anisotropy due to non-spherical halo clumpinesss. The detectors at the GLAST satellite will be sensitive to anisotropy up to 0.1% level [34]. This will provide a hope to discriminate the anisotropic DM annihilation signal from the diffuse gamma-ray backgrounds.

2 Anisotropic destruction of clumps by disk

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 by the "tidal shocking" in the Galactic disk [35]. The corresponding energy gain per unit mass of a clump at one disk crossing[35] is

$$\Delta\tilde{E} = \frac{2g_m^2(\Delta z)^2}{v_{z,c}^2}, \tag{1}$$

where g_m is the maximum gravitational acceleration of the clump moving through the disk, Δz is a vertical (perpendicular to the disk plane) distance of a DM particle from the clump center, $v_{z,c}$ is a vertical component of velocity at disk crossing. The dependence of $v_{z,c}$ on the inclination of orbit relative to the disk plane is the origin of the discussed anisotropy in the clump destruction, and, as a result, the origin of the anisotropy in annihilation signal.

The surface mass of the Galactic disk can be approximated as

$$\sigma_s(r) = \frac{M_{\rm d}}{2\pi r_0^2}\, e^{-r/r_0}, \tag{2}$$

with $M_{\rm d} = 8 \times 10^{10} M_\odot$ and $r_0 = 4.5$ kpc, and therefore

$$g_m(r) = 2\pi G\sigma_s(r). \tag{3}$$

We use the power-law parametrization[2,3,4,13] of the internal density of a clump

$$\rho_{\rm int}(r) = \frac{3-\beta}{3}\,\rho\left(\frac{r}{R}\right)^{-\beta}, \tag{4}$$

where ρ and R are the mean internal density and a radius of clump, respectively, $\beta = 1.8$ and $\rho_{\rm int}(r) = 0$ at $r > R$. The total (kinetic plus potential) internal energy of a clump for density profile (4) is given by

$$|E| = \frac{3-\beta}{2(5-2\beta)}\frac{GM^2}{R}, \tag{5}$$

where M is the mass of the clump. Integrating (1) over a clump volume and using the density profile (4), one obtains an energy gain for the whole clump as

$$\frac{\Delta E}{|E|} = \frac{(5-2\beta)}{\pi(5-\beta)}\frac{g_m^2}{G\rho v_{z,c}^2}. \tag{6}$$

We will use the following criterium for a tidal destruction of clump: a clump is destructed if a total energy gain $\sum \Delta E_i$ after several disk crossings exceeds the initial internal energy $|E|$ of a clump.

Let us consider now some particular orbit of a clump in the halo with an "inclination" angle γ between the normal vectors of the disk plane and orbit plane. The orbit angular velocity at a distance r from the Galactic center is $d\phi/dt = J/(mr^2)$, where J is an orbital angular momentum of a clump. A vertical velocity of a clump crossing the disk is

$$v_{z,c} = \frac{J}{mr_c}\sin\gamma, \tag{7}$$

where r_c is a distance of crossing point from the Galaxy center. There are two crossing points (with different values of r_c) during the one orbital period. The momentum approximation used here for calculations of the tidal heating is violated at small inclination angles, $\gamma \ll 1$. Nevertheless the resultant anisotropy is a cumulative quantity. It results from an integration over all clump orbits, and orbits with $\gamma \ll 1$ provide only small input into the anisotropy value.

A tidal heating and final destruction of clumps by the gravitational field of the Galactic disk depends on the inclination angle γ of a clump orbit to the disk according to (1). This is a cause of the anisotropic clump number density decreasing during the lifetime of the Galaxy. The numerically calculated survival probability of DM clumps in the halo[36] is shown in the Fig. 1. The annihilation anisotropy is artificially enhanced in the Fig. 1 for better visualization for three chosen radial distances from the Galactic center, $r = 3$, 8.5 and 20 kpc respectively by using the different multiplication factors.

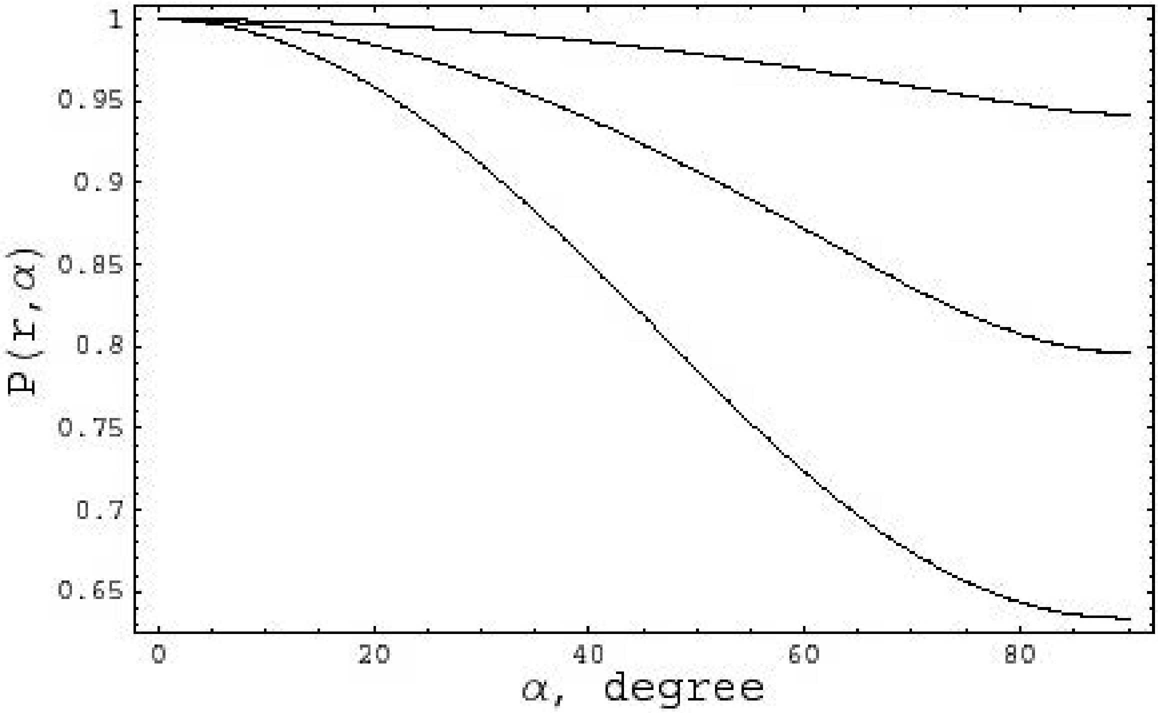

Figure 1: A survival probability of DM clumps in the halo $P(r,\alpha)$ as a function of angle α between a radius-vector $\vec{r}$ and the disk polar axis. The plots are shown for radial distances from the Galactic center $r=3$, 8.5 and 20 kpc from the bottom to the top. These curves must be multiplied by factors 0.04, 0.4 and 0.9 respectively to reproduce the actual values.

3 Annihilation anisotropy

For the diffuse distribution of DM in the halo, the annihilation signal (e. g. gamma-ray or neutrino flux per unit solid angle) is proportional to

$$I_{\rm H} = \int\limits_{0}^{r_{\rm max}(\zeta)} \rho_{\rm H}^2(\xi)\, dx, \qquad (8)$$

where $x = r/L$ and integration over r goes along the line of sight, $\xi(\zeta,r) = (r^2 + r_{\odot}^2 - 2rr_{\odot}\cos\zeta)^{1/2}$ is the distance to the Galactic center, $r_{\rm max}(\zeta) = (R_{\rm H}^2 - r_{\odot}^2\sin^2\zeta)^{1/2} + r_{\odot}\cos\zeta$ is the distance to the external halo border, ζ is an angle between the line of observation and the direction to the Galactic center, $R_{\rm H}$ is a virial radius of the Galactic halo, $r_{\odot} = 8.5$ kpc is the distance between the Sun and Galactic center. The corresponding signal from annihilations in DM clumps is proportional to the quantity [15]

$$I_{\rm cl} = \mu S \rho \int\limits_{0}^{r_{\rm max}(\zeta)} \rho_{\rm H}(\xi) P(\xi,\alpha) P_{\rm sp}(\xi)\, dx, \qquad (9)$$

where $\mu \simeq 0.05$ is a fraction of the DM mass in the form of clumps, $P_{\rm sp}$ is a survival probability of clumps due to their tidal destructions by stars in the halo and bulge from [19]. The function S depends on the clump density profile and core radius of clump [15] and we use $S \simeq 14.5$. Here for simplicity we do not take into account the distribution of DM clumps over their internal densities. As a representative example we consider the Earth-mass clumps $M = 10^{-6} M_{\odot}$ originated from 2σ density peaks in the case of power-law index of primordial spectrum of perturbations $n_{\rm p} = 1$. The mean internal density of these clumps is $\rho \simeq 7\times10^{-23}$ g cm^{-3}. The values of μ and S, as

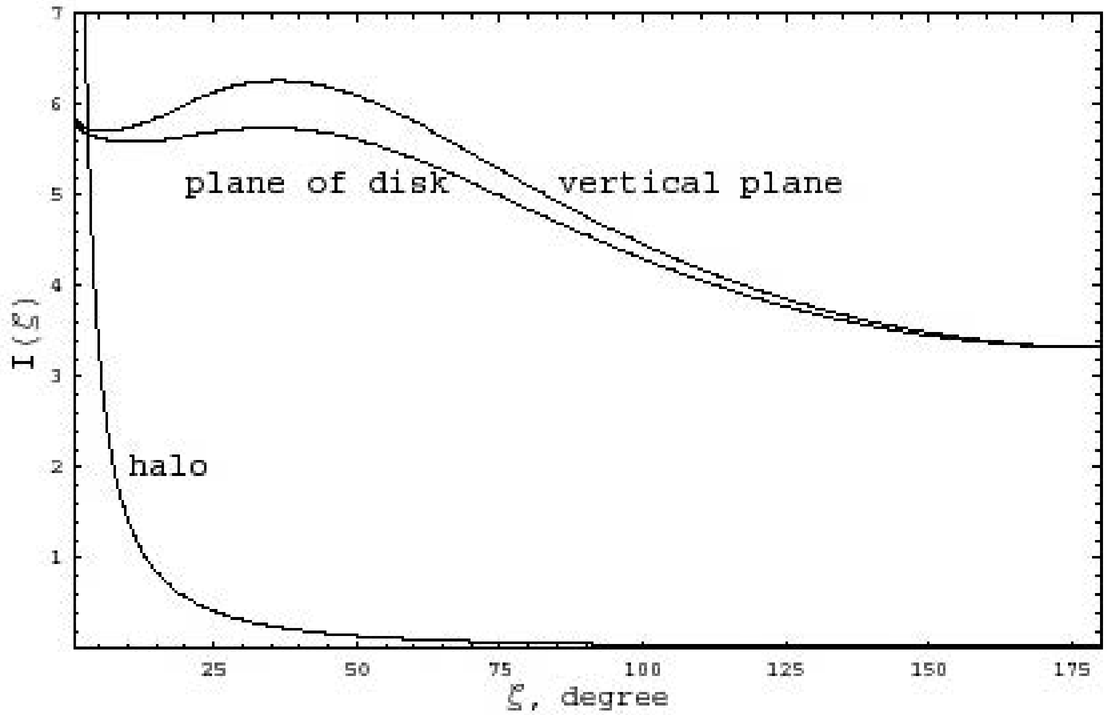

Figure 2: The annihilation signal (9) in the Galactic disk plane and in vertical plane as a function of the angle ζ between the line of observation and the direction to the Galactic center. For comparison it is shown also the annihilation signal from the Galactic halo without DM clumps (8). The values of both integrals (9) and (8) are multiplied by factor 10^{48}.

well as the distribution of the clumps over various parameters influence the annihilation signal but only weakly affect the predicted anisotropy.

In the Fig. 2 the annihilation signal calculated according to (9) 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. 2 is also shown the signal from the spherically symmetric Galactic halo without the DM clumps (8). 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 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 $\delta \simeq 0.09$ at $\zeta \simeq 39°$.

4 Discussions

A total anisotropy of DM annihilation signal is determined in general by the Sun off-centering in the Galaxy and by the halo nonsphericity. The small-scale DM clumps are completely destructed inside the Galactic stellar bulge region. The "gamma-rings" are predicted in other galaxies due to the absence of clumps in their centers [18]. The unknown nonsphericity of the halo is a main source of anisotropy uncertainty. The value of anisotropy due to nonsphericity of the halo may be several times larger than one caused by the discussed in this paper effect of tidal destruction of DM clumps by the disk. More detailed analysis is required to separate these two sources of anisotropy. A nonsphericity (oblateness) of the halo due to the angular momentum can be easily estimated. It is natural to assume that the DM halo and disk have the same value of specific angular momentum (i. e. an angular momentum per unit mass). In this case the model of the Maclaurin spheroid for the halo gives only $\sim 0.5\%$ difference for the halo axes. Therefore, the nonsphericity of the halo due to the angular momentum produces a negligible anisotropy. The anisotropy with respect to disk plane in the Galaxy was pointed out in[18]. As it is seen from our calculations (see Fig. 2) this anisotropy of annihilation signal from the DM clumps with respect to the disk is rather small, $\sim 9\%$, but far exceeds the anticipated GLAST resolution, $\sim 0.1\%$. Therefore, the discussed anisotropy may be used in future detailed gamma-ray observations for discrimination of the annihilation signals from the DM clumps, diffuse DM in the Galactic halo and diffuse gamma-ray backgrounds.

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