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Dense DM clumps seeded by cosmic string loops and DM annihilation

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Abstract. The annihilation of the dark matter in clumps around cosmic string loops is studied. These clumps form at the radiation dominated stage and may have densities $\gg \rho_{eq}$. We conclude that 100 GeV neutralino DM is incompatible with the range of the strings' tension $5 \times 10^{-10} < G\mu/c^2 < 5.1 \times 10^{-9}$ because the gamma-ray signal exceeds the Fermi-LAT limit in this case.

Keywords: dark matter, cosmic string, cosmology

Contents

1 Introduction

The linear topological defects — cosmic strings can be formed in the early cosmological phase transitions (see for a review [1], [2]). Along with the infinite strings there is possibility of closed loops formation in the network of curved cosmic strings due to their interconnections. According to numerical simulations, after a long transient stage a true scaling regime sustained, then the typical distances between strings and the coherence length both scale in proportion with the horizon scale [4]. A string loops formed at the cosmological time t_i have the lengths $l \simeq \alpha c t_i$, where in the scaling regime $\alpha \simeq 0.1$ according to [4] and [5].

A fundamental characteristic of string is the mass per unit length $\mu \equiv M_l/l$ or the tension, which is of the order of symmetry breaking energy squared η^2. In dimensionless units, the $G\mu/c^2$ is the measure of the string gravitational potential. For example, the grand-unification-scale strings have $G\mu/c^2 \sim 10^{-6}$, where G is Newton's constant. There are several restrictions on μ. From CMB observations it follows $G\mu/c^2 \leq 2 \times 10^{-7}$ [3]. The bound $G\mu/c^2 \leq 10^{-7}$ was obtained from study of nucleosynthesis [4]. Search for pairs of galaxies images consistent with the gravitational lensing of a cosmic string presents the limit $G\mu/c^2 < 3 \times 10^{-7}$ at 95% confidence level [6]. In [8] the formation of stars in the first DM haloes seeded by the loops was considered. It was found that $G\mu/c^2 < 3 \times 10^{-8}$ to avoid collision with WMAP data on the reionization redshift. Searches for gravitational wave bursts from strings by LIGO provide the joint constraints on strings parameters (μ and interconnection probability) [7], but $G\mu/c^2$ is only weakly restricted in comparison with the constraints above. And finally, the strongest bound $G\mu/c^2 \leq 4 \times 10^{-9}$ was obtained from pulsar timing [9].

In this work we present new constraint on μ which was obtained from the dark matter particles annihilation in the dense clumps seeded by the loops at the cosmological stage of radiation dominance. The direct detections of DM particles are promising but still elusive experimental problems, therefore the search of indirect signature of the DM is important for clarifying the DM origin. The promising indirect signature – DM particles annihilation would proceed more efficiently (it can be boosted by several orders) if the Galactic halo is filled by the dense DM substructures or DM clumps. The cosmic string loops produce very dense clumps due to their early formation. Only low velocity loops can produce the clumps. The probability of the low velocity loop formation is very small, but even tiny fraction of formed loops may produce the dense clump population and significant annihilation signal.

The clumps formation at the RD stage was studied in details by [10]. In the particular case of loops' density perturbation the maximum density of clump is restricted due to adiabatic expansion of already formed clump after the loop gravitational evaporation. We found the modification of this restriction in the case then the loop decays before the clump virialization. In this case the clumps can reach density $\rho_{\rm cl} \gg 140\rho_{\rm eq}$, where $\rho_{\rm eq}$ is the density at equality. The comparison of the resulting annihilation signal with the Fermi-LAT data allows us to obtain the restriction on the string parameter μ. It must be pointed out that our constraints were obtained by supposing that the DM can annihilate, and we take the $\sim$ 100 GeV neutralino as the most promising particle candidate. The constraints will be different for other DM models. In this sense the obtained constraints must be considered as joint constraints on the properties of string loops and DM particles.

2 Initial speed of the loops and rocket effect

Here we consider the influence of the initial velocities of the loops and rocket effect on the evolution of perturbations and clumps formation.

The necessary condition for the clump formation is the low velocity of the loop [10]. Only results for average initial velocity of formed loops were presented in literature but the distribution over velocities is possible. We interested in low velocity end of the distribution, because the clump forms only if the seed loop stays near the center of the clump during its evolution. Loops can be formed by intersecting long string segments or by self-intersection of long strings. We suppose that the probability of velocity components of the loops is simply Gaussian with mean value at the correlation length scale $\langle v_i^2\rangle^{1/2} \simeq 0.15c$ [11], and therefore the probability of full initial velocity is

$$P(v_i)dv_i \simeq \frac{2^{1/2}dv_i v_i^2}{\pi^{1/2}\langle v_i^2\rangle^{3/2}} e^{-v_i^2/2\langle v_i^2\rangle}. \tag{2.1}$$

Even if the process of a loop's formation involves the intersection of two strings with large velocities, it does not necessarily means that the resulting velocity will be high.

The displacement of the loop beginning from its birth moment t_i till the full decay moment t_d is

$$\Delta r = a(t_d)\int\limits_{t_i}^{t_d} \frac{v(t)dt}{a(t)}, \tag{2.2}$$

where the peculiar velocity is $v(t) = v_i a(t_i)/a(t)$. We require that the displacement Δr is smaller in comparison with the loop's radius $l/(2\pi)$. From this condition and (2.2) we obtain the restriction on the loop's velocity

$$v_i t_i \ln(t_d/t_i) < l/(2\pi). \tag{2.3}$$

For the probable parameters of the strings $t_d/t_i \simeq 2\times10^5$ and the dependence in (2.3) is only logarithmical. Therefore, by using (2.1) we can estimate the probability of the low velocity loop formation as

$$P_{\rm lv} \sim \frac{(2/\pi)^{1/2}v_i^3}{3\langle v^2\rangle^{3/2}} \simeq 2\times10^{-7}. \tag{2.4}$$

As we will show below even the tiny fraction (2.4) of the formed loops may produce superdense clumps and observable annihilation signal.

Now we consider the rocket effect. Velocity of the loop grows linearly with time $v_r = 3\Gamma_P G\mu t/(5l)$, where $\Gamma_P \sim 10$ [1]. Turnaround moment of the clump corresponds to $t_{TA}^2 \simeq 500t_i^2$, and the relative displacement of the loop during clump formation is

$$\frac{1}{l}\int\limits_{t_i}^{t_{TA}} v_r dt \simeq 1.5\times10^{-4}\mu_{-8}\alpha_{0.1}^{-1} \ll 1. \tag{2.5}$$

Therefore, for the small loops formed at radiation era the large rocket displacements are not achieved.

3 Evolution of clumps around evaporating loops

We solve the same equation as eq. (2.7) in [10]

$$x(x+1)\frac{d^2b}{dx^2} + \left[1+\frac{3}{2}x\right]\frac{db}{dx} + \frac{1}{2}\left[\frac{1+\Phi}{b^2} - b\right] = 0, \tag{3.1}$$

where $x = a(\eta)/a_{\rm eq}$, $r = a(\eta)b(\eta)\xi$ and ξ is the comoving coordinate. This equation describes the evolution of clump's radius r in terms of function $b(x)$. The only quantity one need to modify is Φ. In difference with [10] we allow the dependence of Φ on time: steady decrease in continuous evaporation approximation and step-like in fast decay approximation. The evolution of clump stops when $dr/dt = 0$ or equivalently $db/dx = -b/x$ [10]. The density and radius of the clump at the moment of maximum expansion are

$$\rho_{\rm max} = \rho_{\rm eq} x_{\rm max}^{-3} b_{\rm max}^{-3}, \quad R_{\rm max} = \left(\frac{3M}{4\pi\rho_{\rm max}}\right)^{1/3}, \tag{3.2}$$

where $b_{\rm max}$ and $y_{\rm max}$ are the values at the moment of the stop. After the turnaround the clump virializes by contracting twice in radius, and the resulting density increases by factor 8 in comparison with (3.2).

Let us name the spherical region with a volume $(4\pi/3)\cdot(l/2\pi)^3$ as a "string volume". Then the fraction of string mass $M_l = \mu l$ to the mass $M_{\rm DM}^l$ of DM inside the string volume at the moment of the string birth $t_i = l/(\alpha c)$ is simply

$$\left.\frac{M_l}{M_{\rm DM}^l}\right|_{t=t_i} = \left(\frac{M_l}{M_\beta}\right)^{-1/2}, \tag{3.3}$$

where $M_\beta = 1.6\times10^3\mu_{-8}^3\alpha_{0.1}^{-3}M_\odot$. The fraction (3.3) gives also the value Φ of density perturbation inside the string volume at the moment of string birth t_i. The strings with $M_l = M_{\rm DM}^l(t=t_i)$ born at the time $t_\beta = 3.9\times10^{-6}\mu_{-8}^2\alpha_{0.1}^{-4}t_{\rm eq}$ ($x_\beta = 2\times10^{-3}\mu_{-8}\alpha_{0.1}^{-2}$). We consider only the most dense central part of the clump inside the string volume, where the annihilation proceeds most effectively. This central region of the clump can be refereed as a clump core. The outer regions of the clump form through the secondary accretion of DM and have the density profile $\rho(r)\propto r^{-9/4}$ at sufficiently high distance from the center of the clump. Therefore the annihilation concentrates near the clump core.

4 Continuous evaporation and fast decay approximations

The characteristic loop lifetime due to gravitational waves emission is $\tau \simeq lc/(G\mu\Gamma)$, where $\Gamma\sim50$ is a numerical coefficient [12]. One possibility is that the loop losses mass continuously according to mean equation $dM_l/dt = -\Gamma G\mu^2/c$, but the more reliable to assume the approximation of sudden decay after the time interval τ from the birth moment t_i. At $t > t_i+\tau$ the loop's configuration substantially changed, so the loop is likely to self intersect. The resulting daughter loops will fly away at high speeds. We use the last approximation henceforth as the main but also present the results for the continuous evaporation approximation for comparison.

DM clumps formation at the RD stage was explored in [10]. In the particular case for the clumps which are seeded by loops of cosmic strings one have $\Phi\simeq M_l/M$, but in many cases the maximum density is only $\rho_{\rm cl} \simeq 140\rho_{\rm eq}$ due to adiabatic expansion of already formed clump during the seed loop gravitational evaporation [10]. Really, the universal Poincare adiabatic invariant conservation $J = \oint \sum p_i dq_i = const$ for the clump with additional loop mass inside implies $M_{\rm tot}R = const$ or $\rho_{\rm cl} \propto M_{\rm tot}^{-3}$, where $M_{\rm tot} = M_l(t) + M_{\rm DM}$ is the total mass of the loop and DM. For the constant mass loop the clump forms with the density $\rho_{\rm cl} \simeq 140\rho_{\rm eq}(M_l/M_{\rm DM})^3$ (see eq. (3.4) in [10])). After the subsequent loop decay the density lowered due to adiabatic invariant in proportion $\simeq (M_{\rm DM}/M_l)^3$ till the value $\rho_{\rm cl} \simeq 140\rho_{\rm eq}$.

We argue that the above mentioned argument of the adiabatic invariant conservation is not applicable, if the loop decay occurs before turnaround moment (detachment from cosmological expansion and clump virialization). Really, in this case DM particles move not at the orbits around loop but along the radial trajectories. The loop's decay leads only to the change of particles acceleration. The evolution of clump slows down but continues under the influence of velocities db/dt obtained before the decay. We can estimate the processes by the following manner. For the clumps under consideration the conditions $x \ll 1$, $\Phi \gg 1$ and $\Phi x \ll 1$ are valid almost all time before turnaround. Initially the evolution goes due to large value of Φ and the initial velocities db/dx at $t = t_i$ are not important. At this stage one can neglect the first term in (3.1) and the approximate solution is $b \simeq 1 - x\Phi/2$ [10]. If the turnaround occurs before t_d the moment of turnaround can be estimated as $x_{\rm TA} \sim 1/\Phi$ [10]. In the opposite case $x_d < x_{\rm TA}$ just after loop decay (at $x = x_d$) we must put $\Phi = 0$ in (3.1) and the velocity at this moment $db/dx = -\Phi/2$ becomes greater then the last term in (3.1). At $x > x_d$ we can neglect the last term but leave the first one. This leads to the red-shifting of velocity as

$$\frac{db}{dx} = -\frac{\Phi x_d}{2x}, \tag{4.1}$$

and corresponding logarithmic decrease of b. From the condition $db/dx = -b/x$ we obtain the new turnaround moment:

$$x_{\rm TA} \sim x_d \exp\left(\frac{2(1-\Phi x_d)}{\Phi x_d}\right). \tag{4.2}$$

We see that at sufficiently small $\Phi x_d \ll 1$ the clump may not forms at all, because the $x_{\rm TA}$ will be exponentially large. For the moderately small values $\Phi x_d \ll 1$ the clump forms but with small density. The value Φx_d can be expressed as

$$\Phi x_d \simeq 0.9\mu_{-8}^{1/2}\alpha_{0.1}^{-3/2}\Gamma_{50}^{-1/2}. \tag{4.3}$$

For the constant mass loop $x_{\rm TA} \sim 1/\Phi$ [10] and (4.3) is $\sim x_d/x_{\rm TA}$. This value is close to unity at $\mu_{-8} \sim 1$ so we expect the change in the character of clump formation process near $\mu_{-8} \sim 1$.

In the continuous evaporation approximation the rate of loop mass evaporation due to gravitational radiation is $dM_l/dt = -\Gamma G\mu^2/c$. After integration we have

$$M_l(t) = M_l(t_i)\left(1 - 5\times 10^{-6}\frac{\mu_{-8}\Gamma_{50}}{\alpha_{0.1}}\left[\frac{t}{t_i} - 1\right]\right), \tag{4.4}$$

where the $M_l(t_i) = \mu\alpha t_i$ is the initial string mass at the moment of its birth t_i. One need to generalize the evolving seed mass as the fuse of fluctuation growth. The only quantity one need to change is Φ. From the known solutions of Fridmann equations one has the

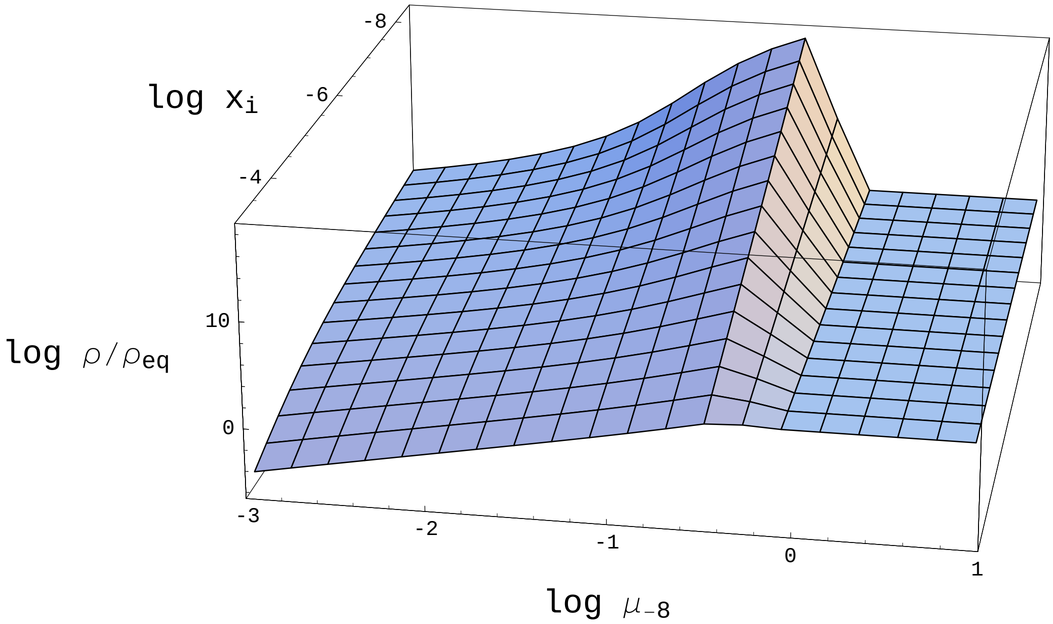

Figure 1. Clump density ρ in the units of density at matter-radiation equality $\rho_{\rm eq}$ in dependence on the loop birth moment x_i and parameter $\mu_{-8} = G\mu/(10^{-8}c^2)$. The break of the surface down to value $\rho = 140\rho_{\rm eq}$ corresponds to the proximity of turnaround and loop decay moments.

dependence $t = \tilde{t}(x)$ and by using (3.3) we finally obtain

$$\Phi(x, x_i) = \frac{2 \times 10^{-3}\mu_{-8}\alpha_{0.1}^{-2}}{x_i} \frac{M_l(\tilde{t}(x))}{M_l(\tilde{t}(x_i))}. \tag{4.5}$$

This expression is valid for $\Phi \geq 0$. If formally $\Phi < 0$ we put $\Phi = 0$ in (3.1). This means that the string had totally evaporated (its mass is zero) and the subsequent clump evolution proceeds only under DM self gravity and due to inward velocity boost which appeared before the string decay. The velocity boost leads to the perturbation growth even after full evaporation of the seed loop. The clump virializes with some density $\rho_{\rm cl}(t_{\rm TA})$. If the string mass goes to zero after the turnaround the adiabatic expansion of the clump occurs only due to loop mass remnant $M_l(t_{\rm TA})$, and the resulting clump density is

$$\rho_{\rm cl} = \rho_{\rm cl}(t_{\rm TA}) \left(\frac{M_{\rm DM}}{M_l(t_{\rm TA}) + M_{\rm DM}} \right)^3 = \frac{\rho_{\rm cl}(t_{\rm TA})}{(1 + \Phi(x_{\rm TA}))^3}. \tag{4.6}$$

In the case $t_d > t_{\rm TA}$ this density is greater in comparison with density $\rho_{\rm cl} \simeq 140\rho_{\rm eq}$ in the fast decay approximation.

5 Numerical results

We solve Eq. (3.1) numerically in the two above approximations. In the approximation of fast decay the loop decay at the moment $t_d = t_i + \tau$. This means that at $t < t_d$ the mass of the string is constant, but at $t > t_d$ the string had totally disappeared (its mass is zero), and the subsequent clump evolution proceeds only under DM self gravity and due to inward velocity boost which appeared before the string decay. The velocity boost leads to the perturbation growth even after full evaporation of the seed loop.

We consider only the most dense central region of clumps, which gives the main contribution to the annihilation signal. These are regions inside the string volumes. As a first approximation we consider these regions as homogenous. We find the density of the clump in dependence of x_i and μ. The turnaround moment is calculated numerically from the condition $db/dx = -b/x$ and solution of (3.1). Clumps density is obtained according to (3.2) and (4.6). If the turnaround moment precedes the loop decay, we put the resulting clump density $\rho = 140\rho_{\rm eq}$ according to adiabatic invariant argument conservation of [10].

The results of calculations for clumps density in the fast decay approximation are shown at figure 1. As it was expected from (4.3), the condition $x_{\rm TA} \simeq x_d$ is satisfied near $\mu_{-8} \sim 1$, and the regime of clump formation changes near $\mu_{-8} \sim 1$ because at larger μ_{-8} the turnaround occurs before the loop decay. The similar figure can be presented for the continuous evaporation approximation, but with smoother surface break and with greater density of clumps.

6 Loops and clumps distributions

The length distribution of cosmic strings' loops in the interconnecting network was obtained in [8] in the form

$$dn_{\rm loop} = \frac{N dl}{c^{3/2} t^{3/2} l^{5/2}}, \tag{6.1}$$

where $N \sim 2$. The evaporating mass cutoff must be superimposed on the distribution (6.1) at the every particular time. If we neglect (temporary) the loop evaporation, then the mass fraction of the universe in the form of loops at the time $t_{\rm eq}$ is

$$\frac{d\rho_l(t_{\rm eq})}{\rho_{\rm eq}} = 0.042\mu_{-8}^{3/2} \left(\frac{M_l}{M_\odot}\right)^{-3/2} \frac{dM_l}{M_\odot} \tag{6.2}$$

In terms of cosmological density of clumps (a fraction of DM mass in the form of clumps) the distribution (6.2) (by using (3.3) can be rewritten as:

$$d\xi_{\rm cl} \simeq \frac{d\rho_l(t_{\rm eq})}{\rho_{\rm eq}} \left(\frac{M_l}{M_\beta}\right)^{1/2} P_{\rm lv}, \tag{6.3}$$

where $P_{\rm lv}$ is given by (2.4). Strings decay but the clumps survive, therefore there is no need to cut of the clumps mass spectrum at the string evaporation scale, and the (6.3) is the real distribution of clumps at MD epoch. The density of these clumps was calculated in the Section 5.

The low mass cut of of the clumps distribution is determined by the process of kinetic decoupling of the DM particles. At earlier times the DM particles strongly frozen in the radiation and do not move toward the loop. In contrast to ordinary inflationary density perturbations the diffusion and free streaming effect are not important for the minimum mass of the clumps. This is because a forming clump mainly subjected by the strong gravitational pull of the central loop and evolve nonlinearly long before the equality moment $t_{\rm eq}$. The kinetic decoupling temperature for ordinary neutralino weakly depends on the particle mass

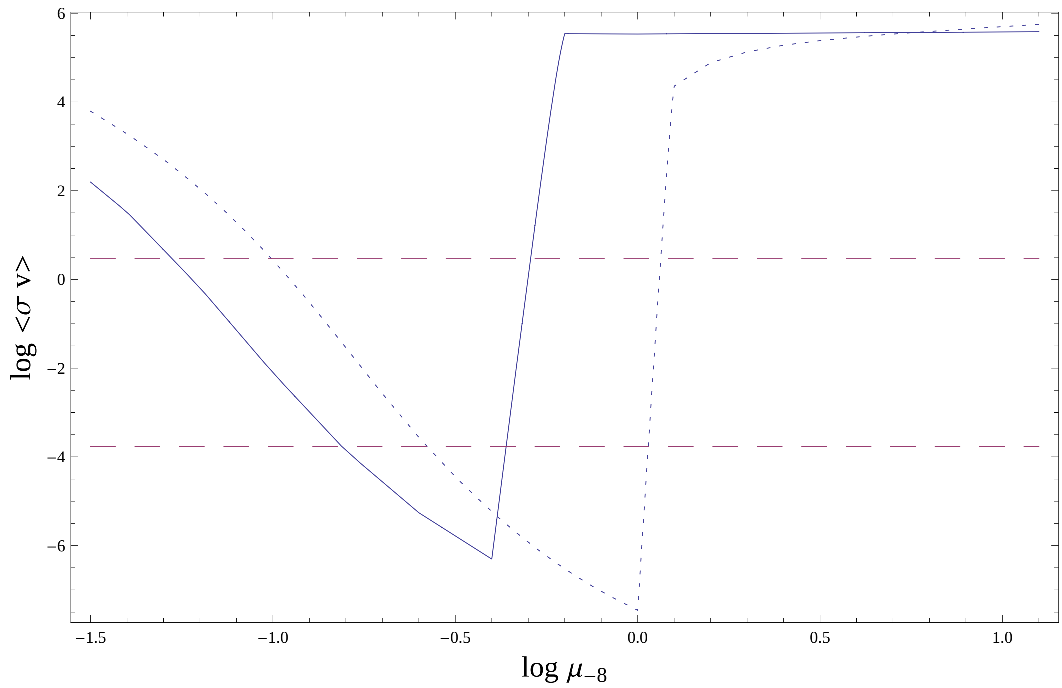

Figure 2. The solid line shows the upper limit on $\langle\sigma v\rangle$ (in units 10^{-26} cm^3 s^{-1}) in dependence of string parameter $\mu_{-8} = G\mu/(10^{-8}c^2)$ in the fast decay approximation. The limit was obtained from the comparison of calculated signal and Fermi-LAT data. The upper and lower horizontal dashed lines show the typical and minimal possible cross-section values, respectively. The dotted line shows the upper limit in the continuous evaporation approximation.

$T_d \propto m_\chi^{1/4}$ and for typical SUSY parameters $T_d \simeq 25$ GeV, with corresponding cosmological time 1.2×10^{-3} s. The loops which formed at this moment have masses $M_{l,\min} = 2.5\times 10^{-7} m_{100}^{-1/2}\mu_{-8}\alpha_{0.1}M_\odot$ and the minimum clump's mass is therefore $M_{\rm cl,min} = M_{l,\min}^{3/2}/M_\beta^{1/2} \simeq 2\times10^{-15} m_{100}^{-3/4}\alpha_{0.1}^3 M_\odot$ according to (3.3). This minimum mass clumps can reach densities $\rho_{\rm cl}\sim 3\times10^{-4}$ g cm^{-3} if $\mu_{-8}\simeq 0.4$ (see figure 1).

7 Annihilation of DM

The clumps under consideration have very large densities and the gamma-ray flux from DM annihilation inside the clumps may exceed the observational limits for some values of string parameter $\mu_{-8} = G\mu/(10^{-8}c^2)$. Let us consider the neutralino (most popular DM candidate) annihilation in the clumps. Annihilation rate of neutralino in a single clump $\dot{N}_{\rm ann} = 2\eta_{\pi^0}4\pi\langle\sigma v\rangle \int\limits_0^R n_\chi^2 r^2 dr$, where $\eta_{\pi^0}\sim 10$ is the neutral pion multiplicity, n_χ is the number density of particles inside clump, $R\simeq(3M/4\pi\rho)^{1/3}$ and $\langle\sigma v\rangle$ is the annihilation cross-section (averaged product with velocity). We consider the annihilation channel with π^0 productions and decays $\pi^0\to2\gamma$. The cumulative gamma-ray signal from the clumps in the angular direction ψ with respect to Galactic center can be expressed as

$$J_\gamma(E>m_{\pi^0}/2,\psi) = 1.9\times10^{-10}\left(\frac{m_\chi}{100\ \text{GeV}}\right)^{-2}\frac{\langle\sigma v\rangle}{10^{-26}\ \text{cm}^3\text{s}^{-1}}\langle J(\psi)\rangle_{\Delta\Omega}, \quad (7.1)$$

where

$$\langle J(\psi)\rangle_{\Delta\Omega} = \int d\xi_{\rm cl}\left(\frac{\rho_{cl}}{0.3~{\rm GeV~cm^{-3}}}\right)\int\limits_{l.o.s.}\frac{dL}{8.5~{\rm kpc}}\left(\frac{\rho_H(r)}{0.3~{\rm GeV~cm^{-3}}}\right), \tag{7.2}$$

and the last integration goes along the line of sight. For halo density profile $\rho_{\rm H}(r)$ we use the NFW profile [14] with scale $a = 20$ kpc, halo mass $M_h = 10^{12}M_\odot$ and virial radius $R_h = 200$ kpc. The lower mass limits in the integration $d\xi_{\rm cl}$ was estimated in the previous section. This limit weakly depends om m_χ through the $T_d(m_\chi)$ dependence. We took $M_{l,\max} \simeq 1.6\times 10^3\mu_{-8}^3 M_\odot$ (this seed mass corresponds to the clump's formation time near $t_{\rm eq}$) as the upper limits of the integration, and the dependence of the final result on $M_{l,\max}$ is weak.

We compare the calculated signals with Fermi-LAT diffuse extragalactic gamma-ray background $J_{\rm obs}(E > m_{\pi^0}/2) = 1.8\times 10^{-5}$ cm^{-2} s^{-1} sr^{-1} [16]. To obtain the most conservative limit we compare $J_{\rm obs}$ with the calculated signal in the anti-center direction $\psi = \pi$. It gives the upper limit on $\langle\sigma v\rangle$ in dependence of $\mu_{-8} = G\mu/(10^{-8}c^2)$. The results are shown at figure 2. We fixed the neutralino mass at the value $m_\chi \simeq 100$ GeV to avoid considering the complicated limits in 3-dimensional space of $\langle\sigma v\rangle$, m_χ and μ_{-8}.

In the case of typical neutralino cross-section $\langle\sigma v\rangle \simeq 3\times 10^{-26}$ cm^{3}s^{-1} the limit excludes the range of parameters $0.05 < \mu_{-8} < 0.51$ in fast decay approximation and $0.1 < \mu_{-8} < 1.16$ in the continuous evaporation approximation. If we take the minimal allowed value $\langle\sigma v\rangle = 1.7\times 10^{-30} m_{100}^{-2}$ cm^{3}s^{-1} [13] and $m_\chi = 100$ GeV the excluded regions are $0.16 < \mu_{-8} < 0.43$ and $0.27 < \mu_{-8} < 1.07$.

8 Conclusion

In this work the combined constraints on the loops parameters (μ and distribution over lengths) and parameters of DM particles were obtained. For the 100 GeV neutralino DM the range $5\times 10^{-10} < G\mu/c^2 < 5.1\times 10^{-9}$ was excluded because of the huge gamma-ray annihilation signal above the Fermi-LAT data.

We calculated the evolution of the clumps around evaporating loops. Only the low-velocity loops result in clumps formation. At the same time, even the low-velocity tail of loop distribution produces DM clumps with the observable signature in the annihilation products. The adiabatic argument conservation doesn't prevent the formation of clumps with densities $\rho_{\rm cl} \gg 140\rho_{\rm eq}$, if the decay of loops occur before the time of clumps virialization. Therefore the DM clumps produced by the loops can be the very dense objects with a high cumulative luminosity in gamma-rays.

In the case of cosmic superstrings, the reconnection probability can be $\ll 1$, resulting in a much higher number density of loops. This could lead to even stronger constraints in comparison with the presented in this paper.

The Fermi-LAT data are used as an upper limit. In principle the annihilation of DM in clumps can explain the observed signal for the particular values, for example $G\mu/c^2 \simeq 5\times 10^{-10}$. The necessity of the DM annihilation can arise if the ordinary astrophysical sources give too small signal in comparison with observations.

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