Dark matter annihilation in the Galaxy

V Berezinsky\textsuperscript{1}, V Dokuchaev\textsuperscript{2} and Yu Eroshenko\textsuperscript{2}

\textsuperscript{1}Laboratori Nazionali del Gran Sasso; Center for Astroparticle Physics at LNGS, Italy
\textsuperscript{2}Institute for Nuclear Research RAS, Russia
E-mail: eroshenko@inr.ac.ru

Abstract. The formation and evolution of superdense clumps of dark matter (DM) is studied. DM clumps (DMC) can be observed via gamma-radiation from DM particles annihilations. Annihilation signal from the dark matter could be greatly increased due to the small-scale clumpiness. It provides the additional possibilities for the indirect DM particle identification. The superdense DMCs can be produced from the spiky features in the spectrum of inflationary perturbations or around cosmic strings loops. Being produced very early during the radiation-dominated epoch, superdense DMCs evolve as isolated objects. They do not belong to hierarchical structures for a long time after production, and therefore they are not destroyed by tidal interactions during the formation of larger structures. Superdense DMC can also be observed by the gravitational wave detectors.

1. Superdense clumps

According to observations, about quarter of the mass in the Universe is in a form of cold DM, but the nature of DM particles is still unknown. The DM is gravitationally unstable and it forms the gravitationally bounded objects from the scale of the superclusters of galaxies and down to small clumps. Studies of clumps are important for understanding the nature of DM because particles annihilation in the small dense clumps may result in observable signals.

DMC formation usually considered at the matter-dominated stage from the flat spectrum of density perturbations. However, it have been suggested that DMCs can form at the radiation-dominated stage from isothermal \cite{1}, \cite{2} or adiabatic \cite{3}, \cite{4}, \cite{5} perturbations. According to the WMAP data, in the case of a power-law perturbation spectrum, the mean magnitude of the perturbations diminishes to the small scales, and the perturbations are too small for DMC formation before the matter-radiation equality. They could only be formed early in the case of nonstandard spectra, e.g., with additional peaks. The peaks are possible if the inflationary potential has a flat segment \cite{6, 7}. Peaks at minimum scales correspond to DMCs which would be the most dense DM objects in the Universe. An experimental discovery of such DMCs would give information about the inflationary potential. Another class of inflationary models producing peaks in the spectra are models with multiple scalar fields \cite{8}. Generation of high entropy perturbations is possible at cosmological phase transitions \cite{9} and around topological defects, such as cosmic string loops \cite{1}.

Let us consider a nonlinear evolution of density perturbations at the radiation-dominated stage. The spherical layer evolves according to the equation \cite{1}

\[
y(y+1)b'' + \left(1 + \frac{3}{2}y\right)b' + \frac{1}{2} \left(\frac{1 + \Phi}{b^2} - b\right) = 0,
\]

(1)
where $y = a(t)/a_{eq}$, $a_{eq}$ is the scale factor value at the transition to the dust-dominated stage, $\Phi$ is the density perturbation and the prime denotes the derivative over $y$. The radius of the perturbed region is parametrised as $r = ab\xi$, where $\xi$ is the comoving coordinate of the layer while $b$ accounts for expansion in the perturbed region. After detachment from the Hubble flow, the object contracts approximately twice in radius and virializes.

In the models with entropy perturbations, the initial conditions for (1) have the form $\Phi = \delta_{DM}/\rho_{DM}$ and $db/dt = 0$, and the density of DMC is approximated by the expression $\rho \approx 140\Phi^3(\Phi + 1)\rho_{eq}$ [1] with good precision.

In the case of adiabatic perturbations, $\Phi = 0$, the initial velocity $db/dt \neq 0$ is determined by the linear theory. The initial conditions in (1) are chosen from the correspondence with the linear solution $\delta \ll 1$ at sub-horizon scales [9], $\delta \propto \ln(t) + \text{const}$. Solving (1) numerically, we get the density of DMC $\rho$ as a function of its mass $M$ and the perturbation value at the horizon scale $\delta_H$, the results are shown at Fig. 1.

![Figure 1](image)

**Figure 1.** The mean density of DMC $\rho$ (in g cm$^{-3}$) as a function of the perturbation $\delta_H$ at the horizon scale. The solid lines correspond to the DMC masses (upside down): $M = 10^{-10}$, $10^{-9}$, $1$, $10^5$, $10^{10}$, $10^{15}$, $10^{20}$, $10^{25}$, $10^{30}$, $10^{35}$ g. The dashed line shows the upper limit due to primordial black holes over-production [3]. The two-body relaxation time for particle masses $m_\chi = 10^{11}$ 1011 GeV is smaller than the Hubble time for the DMCs above the dotted curve. The star marks the parameters favourable for annihilation, and the cross corresponds to the typical parameters.

2. **Superheavy particles as DM**

In this section we will consider neutralino DM in the superheavy supersymmetry model [10]. In very dense DMCs, in the “gravothermal catastrophe” regime, particles evaporate from the DMC core due to mutual gravitational scattering. Electroweak particle scatterings cannot stop the contraction of the core, because the core is transparent for the neutralinos, up to extremely high densities [5]. In [11] and [12], the central core radius has been calculated from the balance
between the particle flow towards the core and the annihilation rate inside the core. For supermassive neutralinos the main effect that constrains the core radius is the Fermi degeneracy. The maximum density of the core is defined by the equality of the Fermi momentums and the virial momentums of a particles [5].

In the case of ultracold WIMPs the minimum DMC mass is extremely small [13]. It is defined by the kinetic splitting of supermassive particles from the cosmic plasma. The annihilation cross-section of the supermassive neutralino has been found in [10]. For an “optimistic” set of DMC parameters, the calculated signal exceeds the observational data by several orders. At smaller DMC density, the signals decrease and become smaller than the observational constraints. Therefore the model of annihilation in superdense DMCs can correspond to the observations in intermediate cases.

3. Formation of clumps around cosmic string loops

Loops of cosmic strings that form at the time instant \( t_i \) have a length \( l \sim 0.1ct_i \) in the scaling regime [14]. A main parameter of a cosmic string the mass per unit length \( \mu \equiv M_l/l \). The strongest constraint \( G\mu/c^2 \leq 4 \times 10^{-9} \) has been obtained from pulsar timing in the work [15]. The fraction \( P_{lv} \sim 10^{-7} \) of loops with small velocities are able to produce DMCs [2]. The DMC evolution around a slowly moving loop is also described by (1), but unlike [1], we allow the variation of \( \Phi \): steady decrease in the continual evaporation approximation and a stepwise

![Figure 2](image-url)

**Figure 2.** The solid line shows the upper allowed limit on the neutralino annihilation cross-section \( \langle \sigma v \rangle \) (in the units of \( 10^{-26} \text{ cm}^3 \text{ s}^{-1} \)) as a function of \( \mu_{-8} = G\mu/(10^{-8}c^2) \) in the approximation of a rapid decay of cosmic string loops. The restriction has been obtained by a comparison of the calculated signal with the Fermi-LAT observational data. The dotted curve shows the same upper limit in the approximation of continual evaporation. The upper and lower dashed curves show the typical \( \langle \sigma v \rangle \simeq 3 \times 10^{-26} \text{ cm}^3\text{s}^{-1} \) and minimum possible \( \langle \sigma v \rangle = 1.7 \times 10^{-30} \text{ cm}^3\text{s}^{-1} \) annihilation cross-sections, respectively.
change in the rapid decay approximation. After the loop full decay, the DMC contracts only due to self-gravity and due to velocities towards the DMC center which had been obtained before the decay. Due to the velocity boost the perturbations grow even after a complete decay of the seed loop. A limit on the maximum DMC density [1] from the conservation of adiabatic invariants is not applicable in the case where the loop decay before the DMC virialization [2].

From the loop size distribution calculated in [16] we obtain a distribution of forming DMCs. Now we consider the annihilation of “standard” neutralinos with masses $m_{\chi} \sim 100$ GeV in DMCs formed around string loops. We take into account the annihilation channel with $\pi^0$ creation and the decays $\pi^0 \rightarrow 2\gamma$. Comparison of the calculated signal with the Fermi-LAT data on the diffuse extragalactic gamma-ray background in the galactic anti-center direction leads to the upper bound on $\langle \sigma v \rangle$ depending on $\mu_{-8} = G\mu/(10^{-8}c^2)$. These results are shown in Fig. 2. In the case of a typical annihilation cross-section, $\langle \sigma v \rangle \simeq 3 \times 10^{-26}$ cm$^3$s$^{-1}$, the range $0.05 < \mu_{-8} < 0.51$ is excluded in the rapid decay approximation, and $0.1 < \mu_{-8} < 1.16$ in the steady evaporation approximation. If we take the minimum possible cross-section $\langle \sigma v \rangle = 1.7 \times 10^{-30}$ cm$^3$s$^{-1}$ [12], the ranges $0.16 < \mu_{-8} < 0.43$ and $0.27 < \mu_{-8} < 1.07$ are excluded.

4. LISA detection of superdense clumps
The projected large gravitational-wave space interferometers will have an opportunity to detect small gravitational tidal variations from compact objects passing by. With the help of LISA, it has been suggested to seek PBHs [17], asteroids [18] and compact objects of unknown nature [19]. The superdense DMCs can also be targets of the search. The tidal signal is produced by a gravitational force which changes the length of the interferometer leg and creates a phase shift. A DMC signal will have the form of separate pulses with specific delays in the legs at the characteristic frequency near the lower frequency of LISAs sensitivity curve. The rate of these events is predicted to be about one per decade.

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References
[1] Kolb E W and Tkachev I I 1994 Phys. Rev. D 50 769
[2] Berezinsky V S, V I Dokuchaev, Eroshenko Yu N 2011 JCAP 12 007
[3] Dokuchaev V I and Eroshenko Yu N 2002 J. Exp. Theor. Phys. 94 1
[4] Berezinsky V, Dokuchaev V, Eroshenko Yu, Kachelriess M, Solberg M Aa 2010 Phys. Rev. D 81 103529
[5] Berezinsky V, Dokuchaev V, Eroshenko Yu, Kachelriess M, Solberg M Aa 2010 Phys. Rev. D 81 103530
[6] Starobinsky A A 1992 JETP Lett. 55 489
[7] Ivanov P, Naselsky P and Novikov I 1994 Phys. Rev. D 50 7173
[8] Yokoyama J 1997, Astron. Astrophys. 318 673
[9] Schmid C, Schwarz D J and Widerin P 1999 Phys. Rev. D 59 043517
[10] Berezinsky V, Kachelriess M and Solberg M A 2008 Phys. Rev. D 78 123535
[11] Berezinsky V S, Gurevich A V and Zybin K P 1992 Phys. Lett. B 294 221
[12] Berezinsky V, Bottino A and Miglioli G 1997 Phys. Lett. B 391 355
[13] Gelmini G B and Gondolo P 2008 JCAP 0810 002
[14] Vanchurin V, Olum K D and Vilenkin A 2006 Phys. Rev. D 74 063527
[15] van Haasteren R et. al. 2011, arXiv:1103.0576 [astro-ph].
[16] Olum K D and Vilenkin A 2006 Phys. Rev. D 74 063516
[17] Seto N and Cooray A 2004 Phys. Rev. D 70 063512
[18] Tricarico P 2009 Class. Quantum Grav. 26 085003
[19] Adams A W and Bloom J S 2004 arXiv:astro-ph/0405206v2