Superdense dark matter clumps from superheavy particle

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Abstract

In this report we describe some specific but reasonable conditions for the formation of superdense clumps (or minihalos) of DM. Such clumps can be produced by several mechanisms, most notably by spiky features in the spectrum of density perturbations. Being produced very early during the radiation dominated epoch, these clumps 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. If the clumps are constituted of superheavy DM particles, the evolution of their central part can lead to a "gravithermal catastrophe", increasing the central density and thus the annihilation signal. As a result annihilations of superheavy neutralinos in dense clumps may lead to observable fluxes of annihilation products in the form of ultrahigh energy particles.

1 Superheavy dark matter particles

Let us begin from superheavy particles. The masses of thermal relics are limited by about $m_\chi \sim 100\,\mathrm{TeV}$ [1]. But the assumption that the DM particle was in chemical equilibrium is not necessary and does not hold for sufficiently heavy particles. Superheavy particles can be produced at the end of inflation and they can play the role of DM particles [2, 3]. Gravitational production in the nonstationary gravitational field provides the natural mechanism for the origin of superheavy dark matter [4]. Their decays can result in UHE gamma-rays [2, 3] but this scenario is very restricted now.

We shall use as candidate for superheavy DM particles the neutralino with masses 10^{11} GeV in the model of superheavy supersymmetry, as suggested in [5].

The possibility of indirect detection of stable SHDM depends on their annihilation rate, that scales roughly as $\dot{N}_{\rm ann} \propto m_\chi^{-4}$. Since backgrounds like cosmic rays from astrophysical sources or the diffuse photon flux decrease only as $1/E^\alpha$ with $\alpha \leq 3$, indirect detection of DM seems to become more and more difficult for increasing DM masses. The possibility which overcomes this difficulty is the annihilation in the superdense central region of DM clumps [6], but one needs the realistic scenario for the very high density of DM. The 2nd possibility is the formation of superdense clumps [7], [8] with very high mean density.

Aim of our work is to study the detection prospects for stable superheavy particles through their annihilation in superdense clumps.

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2 Kinetic decoupling of superheavy DM particles

The mass spectrum of DM clumps has a low-mass cutoff $M_{\rm min}$ due to the leakage of particles from a clump. This mass is strongly model dependent. The mass spectrum of DM clumps formed by standard ~ 100 GeV neutralinos has a cutoff near the Earth mass. The cutoff can be diminished significantly in the case of superheavy particles.

The kinetic decoupling for bino and higgsino occurs at the temperatures ($M_{\rm SUSY} = 10^{12}$ GeV):

$$T_d \simeq \begin{cases} 2\times 10^{11}\,{\rm GeV}\,, & \text{bino} \\ 2\,{\rm GeV}\,, & \text{higgsino,} \end{cases} \tag{1}$$

and the mass of DM inside the horizon in these cases are

$$M_d \simeq \begin{cases} 6\times 10^{-12}\,{\rm g}\,, & \text{bino} \\ 6\times 10^{21}\,{\rm g}\,, & \text{higgsino.} \end{cases} \tag{2}$$

The mass M_d corresponds to the possible cutof of the mass spectrum. For a bino, the mass M_d is only 34 times greater than the particle mass $m_\chi \sim 10^{11}$ GeV$= 1.78\times 10^{-13}$ g. In the case of bino the free streaming mass defines the 2nd cutoff. Formally, all clump masses are possible beginning from $M_{fs} \simeq 260 m_\chi$. In the case of a higgsino, the free-streaming mass is negligibly small, and free-streaming plays no role for the evolutions of perturbations.

3 Non-standard spiky density perturbation spectrum

The mean fluctuation of the CMB normalized power-law spectrum at the horizon scale during the RD stage was expressed as

$$\sigma_H(M) \simeq 9.5\times 10^{-5}\left(\frac{M}{10^{56}\ {\rm g}}\right)^{\frac{1-n_p}{4}}. \tag{3}$$

The simplest inflation models give approximately scale-invariant spectrum. The 7-year WMAP data, $n_p = 0.963 \pm 0.014$, favour clearly $n_s < 1$. In view of these observations the variance $\sigma_H(M)$ is too small for the formation of clumps at the RD stage. Such clumps can be produced effectively only from non-standard spectra containing spikes.

A sharp peak emerges in the fluctuation spectrum if an inflationary potential $V(\phi)$ has a flat segment because the derivative $V' = dV(\phi)/d\phi \to 0$. A peak emerges in the perturbation spectrum on the corresponding scale. A similar effect can arise in inflationary models with several scalar fields [9], [10]. In both types of models, the spectrum outside the peak can have an ordinary shape. In particular, it can be approximately Harrison–Zel'dovich spectrum, and can give rise to galaxies, clusters and superclusters according to the standard scenario.

Dark matter clumps are formed in a wide range of masses, if the spectrum of primordial density perturbations has a power-law form. If on the contrary the spectrum has a peak on some scale, then clumps are formed mostly in a narrow range of masses, near the peak.

4 Formation of superdense DM clumps at the RD epoch

Let us consider the formation of superdense clumps. In spherical model, the evolution of perturbations after the horizon crossing is described by the Equation [7]

$$y(y+1)\frac{d^2b}{dy^2} + \left[1+\frac{3}{2}y\right]\frac{db}{dy} + \frac{1}{2}\left[\frac{1+\Phi}{b^2} - b\right] = 0\,, \tag{4}$$

This equation is applicable for the evolution of both entropy and adiabatic perturbations, but has to be used with different initial conditions.

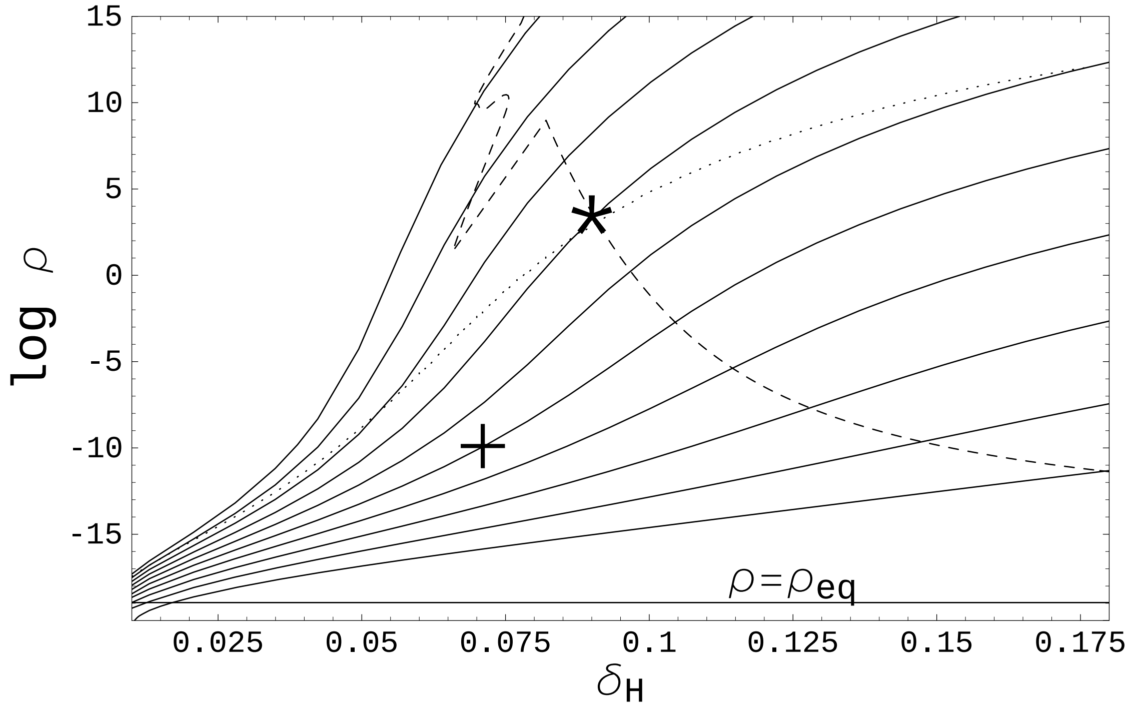

Figure 1: The mean density ρ (in g cm^{-3}) of DM clumps as function of the perturbation $\delta_{\rm H}$ in the radiation density on the horizon scale; solid lines from top to bottom are for for clump masses $M = 10^{-10}$, 10^{-5}, ..., 10^{35} g. The dashed line is the bound on the clump density from primordial black holes overproduction with threshold $\delta_c = 0.7$. The time of two-body gravitational relaxation inside the clump cores is less then the age of the Universe for clumps above the dotted lines for DM particles masses $m_\chi = 10^{11}$ GeV. The star marks favourable parameters for annihilations, and the cross marks a typical example considered for comparison.

The formation of clumps from entropy perturbations was considered in [7]. In this case, the initial velocity of spherical shells in co-moving space is zero. The object formed has the density

$$\rho \simeq 140\Phi^3(\Phi+1)\rho_{\rm eq}, \tag{5}$$

which depends on the value of perturbations Φ. Axion miniclusters are the possible example of such clumps.

Now we consider the method for the evolution of adiabatic perturbations during the radiation dominated epoch. For adiabatic perturbations $\Phi = 0$, but the initial velocity db/dt is non-zero and is defined by the known analytic solution for linear stage [11]

$$\delta = \frac{3A_{\rm in}}{2}\left[\ln\left(\frac{x}{\sqrt{3}}\right) + \gamma_E - \frac{1}{2}\right]. \tag{6}$$

where the variable x is related to the co-moving wave-vector k. It is suitable to connect the analytic solution of the linear theory with the numerical solution of the nonlinear Eqation at the moment corresponding to the "transition" value $\delta = 0.2$.

After decoupling from the cosmological expansion, the object contracts by a factor two and virializes. Within the above formalism, we found the density of the clump $\rho = \rho(M, \delta_{\rm H})$ as function of its mass M and the radiation perturbation value on the horizon scale $\delta_{\rm H}$. Clump's density is displayed in the Fig. 1 for several masses of the clumps. One observes the convergence of curves to $\rho \sim \rho_{\rm eq} \sim 10^{-19}$ g cm^{-3}, i.e. for clumps formed near matter-radiation equality, as it must be.

Note that superdense clumps from a spike in the spectrum are not destroyed by tidal forces and their mass function peaks near a definite mass. Therefore the fraction of DM in the form of such clumps is of the order of unity. Half of the volume is in the form of over-densities (clumps), and the remaining mass is in the voids.

Restriction on the spectrum of the adiabatic perturbations comes from limits on primordial black holes, which can form from the same spectrum of perturbation. In the case of entropy perturbations PBHs do not form. The corresponding restrictions are shown in Fig. 1 by the dashed curve. The local minimum on the curve corresponds to the Hawking evaporation of PBHs. The allowed region of parameters is under the dashed curve.

5 Relaxation in clumps, "gravithermal catastrophe"

The first stage of clumps evolution is the ordinary gravitational contraction. Other processes can become important at the second stage: (i) two-body gravitational scattering and (ii) some limiting effect like Fermi degeneracy or the intensive annihilation of particles. How can it be that the gravitational two-body scattering becomes the dominant process for elementary particles? It occurs for the superheavy particles because the gravitational scattering is proportional to m^2, while EW scattering of these particles is inversely proportional to m^2.

The large particles masses and very high clump density provides the relaxation time

$$t_{\rm rel,gr} \simeq \frac{1}{4\pi}\frac{v^3}{G^2 m_\chi^2 n \ln(0.4N)}, \tag{7}$$

to be shorter than the age of the universe t_0. This leads to the "gravithermal catastrophe", which results in an isothermal density profile $\rho(r) \propto r^{-2}$. These parameters are shown by dotted line in the Figure 1. In this regime the evaporation of particles from the core becomes the main process, which responsible for the evolution of the clumps. .

Do any physical processes exist that prevent the extremely large densities in the clump center? The first candidate for such process is given by the Electroweak elastic scattering of particles or self-interaction. The calculations show that the self-interactions cannot stop the gravitational collapse, because the core remains transparent for superheavy neutralinos down to extremely small radii. Another effect is the particle annihilation. This effect was studied in [12], [13]. The core radius is found from the balance of annihilation and hydrodynamical flow. The corresponding dimensionless core radius $x_c \equiv R_c/R$ is given by the equation

$$x_c^2 \simeq \frac{\langle\sigma_{\rm ann} v\rangle \rho^{1/2}}{G^{1/2} m}. \tag{8}$$

If superheavy DM particles are fermions like in the case of neutralinos, there is quite different effect which stops the core contraction at much larger radius. This effect is the pressure of Fermi degenerated gas. The maximum density of the core can be derived from equality of the Fermi momentum and the virial momentum of particles:

$$p_F = (3\pi^2)^{1/3}(\rho_c/m_\chi)^{1/3} = m_\chi V_c. \tag{9}$$

We obtain the corresponding relative core radius

$$x_c^2 = \pi^2 \frac{\bar\rho}{m_\chi^4}\left(\frac{GM}{R}\right)^{-3/2}. \tag{10}$$

Therefore the gravithermal instability is limited by the Fermi degeneracy in the central core.

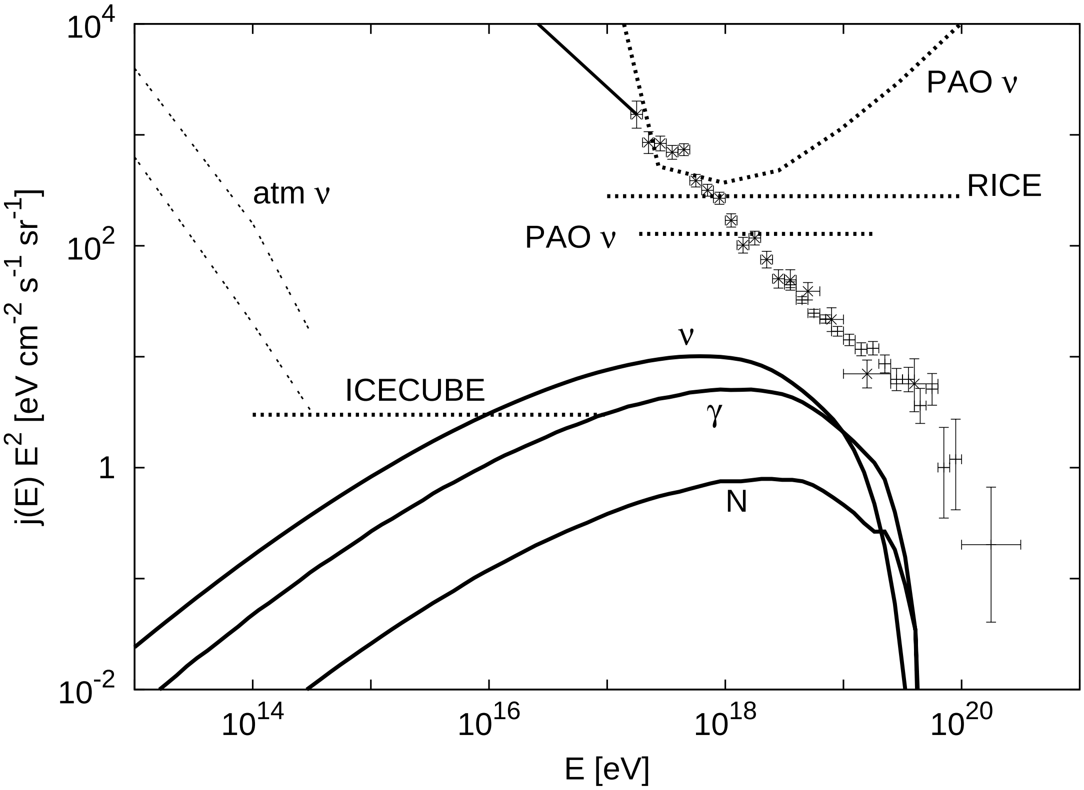

Figure 2: The maximal fluxes $I_i(E)$ of photons, nucleons and neutrinos from neutralino annihilations in Galactic halo together with experimental data for a neutralino with 10^{11} GeV.

6 Annihiation signals

Superdense clumps cannot be composed of standard 100 GeV neutralinos, since their annihilations would overproduce the diffuse gamma radiation. Let us consider the superheavy neutralino. We calculate the rate of annihilation in a single clump and the resulting flux of different particles:

$$I_i(E) = \frac{1}{2}\,\dot{N}_{\rm ann}F\,\frac{1}{m_\chi}\,\frac{dN_i}{dx}\,, \tag{11}$$

where F is the astrophysical factor, it contains the information about DM distribution in the Galactic halo. As the distributions we use the Navarro-Frenk-White density profile. We take spectra and fragmentation functions from [14]. In the case of a higgsino, the annihilation signal is additionally enhanced by the Sommerfeld effect.

The maximal fluxes of photons, nucleons and neutrinos allowed by cosmic ray data are shown in Fig. 2 together with upper limits from different experiments. At present, annihilations of superheavy particles are mainly restricted by experimental limits on the photon fraction, but in the future neutrino searches at lower energies by the km^3 neutrino telescope IceCube may become competitive. For the optimistic parameters of clumps and for a superheavy bino as DM particle, the flux must be rescaled and it is several orders higher in comparison with the upper limits. For the pessimistic choice of parameters the flux is several orders lower. Therefore the annihilation rate of stable superheavy neutralinos may be large enough to be detectable, if primordial density perturbations are spiky.

7 Search for clumps by gravitational waves' detectors

It has been already suggested that interferometric detectors for gravitational waves like LISA have the capability to detect the tiny variation of the gravitational field, when a compact object passes near the detector. It has been suggested for primordial black holes [15], asteroids [16], or compact DM objects of unknown nature [17]. Superdense clumps may be included into this list. The observable signal is caused by the gravitational tidal force which changes the interferometer arm length and produces correspondingly a phase shift.

LISA will have the capability to search for compact objects in the mass interval 10^{16} g$\leq M \leq 10^{20}$ g according to [15] and 10^{14} g$\leq M \leq 10^{20}$ g according to [17]. The signal will be in the form of single pulses with characteristic frequency at the lower end of the expected LISA sensitivity curve and a rate $\sim$ a few per decade, if the objects constitute the major part of DM.

Clumps formed from the standard power-law spectrum have a rather small density, and the radii of the clumps generally exceed LISA's arm length $L \simeq 5 \cdot 10^{11}$ cm. So, the detection of the ordinary clumps by LISA seems unlikely. Superdense clumps can easy satisfy the condition of compactness for the mass intervals and therefore they are observable in principle by the LISA detector.

8 Conclusions

Superdense clumps can be produced from isothermal perturbations in the model of E.W. Kolb and I.I. Tkachev [7] or from spikes in the spectrum of adiabatic perturbations. Clumps are produced in the very early universe during the RD epoch. In principle, the perturbation spectrum may include both a scale-invariant power-law component and spikes. The superdense clumps are limited by primordial black holes which originated from the same spectrum of perturbations. For supermassive constituent particles a "gravithermal catastrophe" may develop in the superdense clumps. The large initial core can transform into the very dense new core restricted by Fermi degeneracy. Gamma radiation from the superdense clumps can be detectable even in the case of superheavy DM particles. These clumps can be observed by the future gravitational wave detectors, like LISA space interferometer. The details of this work can be found in [18].

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References

[1] K. Griest and M. Kamionkowski, Phys. Rev. Lett. **64**, 615 (1990); L. Hui, Phys. Rev. Lett. **86**, 3467 (2001).

[2] V. Berezinsky, M. Kachelrieß and A. Vilenkin, Phys. Rev. Lett. **79**, 4302 (1997).

[3] V.A. Kuzmin and V.A. Rubakov, Phys. Atom. Nucl. **61**, 1028 (1998) [Yad. Fiz. **61**, 1122 (1998)].

[4] D.J.H. Chung, E.W. Kolb and A. Riotto, Phys. Rev. D **59**, 023501 (1999); V. Kuzmin and I. Tkachev, JETP Lett. **68**, 271 (1998); see also D.H. Lyth and D. Roberts, Phys. Rev. D **57**, 7120 (1998).

[5] V. Berezinsky, M. Kachelrieß and M. A. Solberg, Phys. Rev. D **78**, 123535 (2008).

[6] P. Blasi, R. Dick, E.W. Kolb, Astropart. Phys. **18**, 57 (2002).

[7] E.W. Kolb and I.I. Tkachev, Phys. Rev. D **50**, 769 (1994).

[8] P. Scott and S. Sivertsson, Phys. Rev. Lett. **103**, 211301 (2009).

[9] J. Yokoyama, Astron. Astrophys. **318**, 673 (1997).

[10] J. Garcia-Bellido, A.D. Linde and D. Wands, Phys. Rev. D **54**, 6040 (1996).

[11] C. Schmid, D.J. Schwarz and P. Widerin, Phys. Rev. D **59**, 043517 (1999).

[12] V.S. Berezinsky, A.V. Gurevich and K.P. Zybin, Phys. Lett. B **294**, 221 (1992).

[13] V. Berezinsky, A. Bottino and G. Mignola, Phys. Lett. B **391**, 355 (1997).

[14] R. Aloisio, V. Berezinsky and M. Kachelrieß, Phys. Rev. D **69**, 094023 (2004).

[15] N. Seto and A. Cooray, Phys. Rev. D **70**, 063512 (2004).

[16] P. Tricarico, Class. Quantum Grav. **26**, 085003 (2009).

[17] A. W. Adams and J. S. Bloom, arXiv:astro-ph/0405266v2.

[18] V. Berezinsky, V. Dokuchaev, Yu. Eroshenko, M. Kachelrieß and M. A. Solberg, arXiv:1002.3444v2 and arXiv:1002.3445v2.