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JHEP08(2009)052

(http://iopscience.iop.org/1126-6708/2009/08/052)

Published by IOP Publishing for SISSA

Received: *June 12, 2009*
Accepted: *August 1, 2009*
Published: *August 13, 2009*

Neutralino dark matter stars can not exist

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Abstract: Motivated by the recent "Cosmos Project" observation of dark-matter concentrations with no ordinary matter in the same place, we study the question of the existence of compact objects made of pure dark matter. We assume that the dark matter is neutralino, and compare its elastic and annihilation cross sections. We find that the two cross sections are of the same order of magnitude. This result has a straightforward and important consequence that neutralinos comprising a compact object can not achieve thermal equilibrium. To substantiate our arguments, by solving Oppenheimer-Volkoff equation we constructed a model of the star made of pure neutralinos. We explicitly showed that the condition for the thermal equilibrium supported by the Fermi pressure is never fulfilled inside the star. This neutralino state can not be described by the Fermi-Dirac distribution. Thus, a stable neutralino star, which is supported by the Fermi pressure, can not exist. We also estimated that a stable star can not contain more than a few percents of neutralinos, most of the mass must be in the form of the standard model particles.

Keywords: Supersymmetry Phenomenology

doi:10.1088/1126-6708/2009/08/052

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1 Introduction

Recent observational data [1–3] indicate that the universe contains a significant fraction (22%) of dark matter whose origin is still unclear. A possible solution to this problem comes from supersymmetric (SUSY) models in the form of neutralino [4]. Neutralino is the lightest supersymmetric partner in SUSY, with the mass of about 100 GeV, and is stable. It interacts with the gravitational and weak interactions only, which indicates that it is "dark". Weak interactions and neutralino mass are sufficient to satisfy the relic density needed to explain the observed portion of the dark matter in the universe.

In a remarkable recent study [5], a detailed distribution of dark matter as a function of the redshift in a part of our universe was obtained. These observations indicate that dark matter plays a role of a scaffolding upon which ordinary matter builds structures. However, the observations show that large pockets with only dark matter (and no ordinary matter) also exist. Then a natural question arises whether compact objects like planets, stars or maybe even larger structures made exclusively of dark matter can exist.

Recent study discussed the existence of stars powered by annihilation of neutralinos [6]. However, these objects contain mostly baryons and only several percents of dark matter. Compact objects made of pure dark matter were discussed in [7–10]. There it was assumed that the equilibrium of these stars was supported by the Fermi pressure. It was argued that the size of such a dark matter star is less than 1m with the mass less than $10^{-4} M_{\odot}$, if neutralino mass is around 100 GeV [8]. Since the density inside a neutralino star is very high, neutralinos collide frequently. These earlier studies used the estimate that identical non-interacting fermions have elastic cross section of about $\pi\lambda^2$, where λ is de Broglie thermal wavelength [11]. With this assumption, non-relativistic neutralinos have the elastic cross section which is much larger than the weak interaction cross section. If this claim is indeed correct, than a thermal neutralino star could exist, since neutralino annihilation can be neglected in this case. However, it is unlikely that the neutralino elastic cross section is as large as $\pi\lambda^2$. For example, the large elastic cross section would directly contradict the recent "bullet cluster" observations [12]. It is therefore very important to explicitly check this fact.

In order to achieve a thermal distribution, the lifetime of a particle has to be much longer than the characteristic interaction time. Stable neutralinos could in principle achieve thermal state in cosmological context. However, at high densities annihilation can not be neglected. A necessary condition for the thermal equilibrium among neutralinos (at densities smaller than $(100\,\mathrm{GeV})^4$) is that the neutralino-neutralino elastic cross section is much larger than the neutralino-neutralino annihilation cross section.

2 Neutralino elastic and annihilation cross sections

In this section, we will explicitly calculate and compare the neutralino-neutralino elastic and annihilation cross sections. We will show that they are comparable, i.e. of the same order of magnitude. This implies that neutralinos can not be in a thermal equilibrium in a compact object. After several encounters they will annihilate and be converted into the standard model particles. The thermal state of neutralions can not be reached. Thus, the neutralinos can not be described by the the Fermi-Dirac distribution. This then indicates that compact objects made only of neutralinos and supported by the Fermi pressure can not exist.

In SUSY, the neutralinos χ_i^0 are the mixed states of the neutral higgsinos, $\Psi^1_{H_1}$ and $\Psi^2_{H_2}$, and the neutral gauginos, binos (λ_B) and winos (λ^3_A) [13]. The mixing and mass matrices are given by

$$Z_N^T \begin{pmatrix} M_1 & 0 & \frac{-ev_1}{2c_W} & \frac{ev_2}{2c_W} \\ 0 & M_2 & \frac{ev_1}{2s_W} & \frac{-ev_2}{2s_W} \\ \frac{-ev_1}{2c_W} & \frac{ev_1}{2s_W} & 0 & -\mu \\ \frac{ev_2}{2c_W} & \frac{-ev_2}{2s_W} & -\mu & 0 \end{pmatrix} Z_N = \begin{pmatrix} M_{\chi_1^0} & 0 & 0 & 0 \\ 0 & M_{\chi_2^0} & 0 & 0 \\ 0 & 0 & M_{\chi_3^0} & 0 \\ 0 & 0 & 0 & M_{\chi_4^0} \end{pmatrix} \tag{2.1}$$

where Z_N is the matrix that diagonalizes the mass matrix. Parameters M_1, M_2 and μ are mass parameters in the potential, v_1 and v_2 are the vacuum expectation values of the two higgsions, s_W and c_W are sinus and cosinus of the weak angle, while e is the electron charge. The matrix Z_N also defines the mixing between the states

$$\begin{aligned} \lambda_B &= iZ_N^{1i}\kappa_i^0 \\ \lambda_A^3 &= iZ_N^{2i}\kappa_i^0 \\ \Psi^1_{H_1} &= iZ_N^{3i}\kappa_i^0 \\ \Psi^2_{H_2} &= iZ_N^{4i}\kappa_i^0 \end{aligned} \tag{2.2}$$

$$\chi_i^0 = \begin{pmatrix} \kappa_i^0 \\ \bar{\kappa}_i^0 \end{pmatrix} \tag{2.3}$$

Here, $M_{\chi_1^0} < M_{\chi_2^0} < M_{\chi_3^0} < M_{\chi_4^0}$.

Neutralino χ_1^0 is presumably the lightest supersymmetric particle, and can not decay into other supersymmetric particles. Because of the R-parity conservation, it can not decay into the standard model particles either. Therefore, neutralino is stable. The only way to destroy neutralinos is annihilation.

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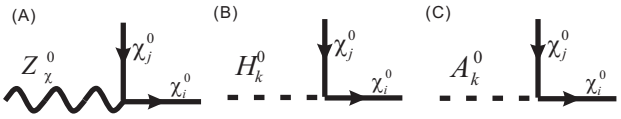

Figure 1. The possible vertices of neutralino-neutralino interaction.

The cross section for the two-particle final state is

$$\frac{d\sigma}{d\Omega} = \frac{|P_1|}{16\pi^2 E_A E_B |v_A - v_B| E_{cm}} |M(P_A, P_B \to P_1, P2)|^2 \tag{2.4}$$

In our case, both particle A and particle B are neutralinos. In an elastic collision, particles 1 and 2 are neutralinos. In an annihilation process, particles 1 and 2 are the standard model particles. P_1 is a momentum of the particle 1. v_A and v_B are velocities of particles A and B respectively. E_A and E_B are energies of particles A and B respectively. M is the scattering amplitude. If the two incoming neutralinos have non-relativistic velocities, say $v \sim 100$km/s, then the momentum P_1 of the light standard model particle (except maybe for the top quark) in an annihilation process is about $v/c \sim 1000$ times larger than the momentum P_1 of the neutralino in an elastic collision. Thus, only for highly relativistic incoming neutralinos elastic collisions will have P_1 of the same order of magnitude as an annihilation process. Since for various different channels all of the parameters are fixed, except for the amplitude, in what follows we compare the amplitudes only.

We now look for the possible neutralino-neutralino elastic interactions. The possible neutralino-neutralino-something vertices can be found in [13] and are shown in figure 1. The values of the vertices are

$$(A) : \frac{ie}{2s_W c_W} \gamma^\mu \left[(Z_N^{4i*} Z_N^{4j} - Z_N^{3i*} Z_N^{3j}) P_L - (Z_N^{4i} Z_N^{4j*} - Z_N^{3i} Z_N^{3j*}) P_R \right] \tag{2.5}$$

$$\begin{aligned}(B) : \frac{ie}{2s_W c_W} \Big\{ & \Big[(Z_R^{1k} Z_N^{3j} - Z_R^{2k} Z_N^{4j})(Z_N^{1i} s_W - Z_N^{2i} c_W) \\ & + (Z_R^{1k} Z_N^{3i} - Z_R^{2k} Z_N^{4i})(Z_N^{1j} s_W - Z_N^{2j} c_W) \Big] P_L \\ & + \Big[(Z_R^{1k} Z_N^{3i*} - Z_R^{2k} Z_N^{4i*})(Z_N^{1j*} s_W - Z_N^{2j*} c_W) \\ & + (Z_R^{1k} Z_N^{3j*} - Z_R^{2k} Z_N^{4j*})(Z_N^{1i*} s_W - Z_N^{2i*} c_W) \Big] P_R \Big\}\end{aligned} \tag{2.6}$$

$$\begin{aligned}(C) : \frac{e}{2s_W c_W} \Big\{ & \Big[(Z_H^{1k} Z_N^{3j} - Z_H^{2k} Z_N^{4j})(Z_N^{1i} s_W - Z_N^{2i} c_W) \\ & + (Z_H^{1k} Z_N^{3i} - Z_H^{2k} Z_N^{4i})(Z_N^{1j} S_W - Z_N^{2j} c_W) \Big] P_L \\ & + \Big[(Z_H^{1k} Z_N^{3i*} - Z_H^{2k} Z_N^{4i*})(Z_N^{1j*} S_W - Z_N^{2j*} c_W) \\ & + (Z_H^{1k} Z_N^{3j*} - Z_H^{2k} Z_N^{4j*})(Z_N^{1i*} S_W - Z_N^{2i*} c_W) \Big] P_R \Big\}\end{aligned} \tag{2.7}$$

Here, $m_Z = \frac{e}{2s_W c_W}(v_1^2 + v_2^2)^{0.5}$ and $m_W = \frac{e}{2s_W}(v_1^2 + v_2^2)^{0.5}$. The masses of the Z and W bosons are m_Z and m_W respectively. From these vertices, the possible Feynman diagrams for elastic neutralino-neutralino interactions are shown in figure 2. Consider now

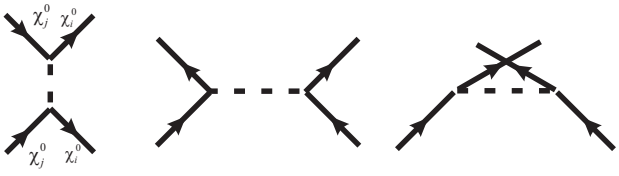

Figure 2. The neutralino-neutralino elastic collisions: The dashed line can be Z_μ^0, H_k^0, and A_k^0. From the top down are s-, t- and u-channel respectively.

non-relativistic neutralino-neutralino elastic collision. The amplitude in the s-channel is approximately

$$M^{(s)}_{el\, Z^0_\mu} \sim \left(\frac{e}{s_W c_W}\right)^2 \bar{\chi}^0_1 \gamma^\mu \chi^0_1 \frac{1}{s - m_Z^2} \bar{\chi}^0_1 \gamma_\mu \chi^0_1 \tag{2.8}$$

$$M^{(s)}_{el\, H^0_k, A^0_k} \sim \left(\frac{e}{s_W c_W}\right)^2 \bar{\chi}^0_1 \chi^0_1 \frac{1}{s - m_H^2} \bar{\chi}^0_1 \chi^0_1 \tag{2.9}$$

To simplify these equations, omit writing the projectors P_L and P_R, since they will not affect the order or magnitude estimate. Here, $s \sim 2M^2_{\chi^0_1}$, while m is the mass of H_k^0 and A_k^0. $M^{(s)}_{el\, H^0_k, A^0_k}$ is the amplitude if H_k^0 or A_k^0 are the mediators, while $M^{(s)}_{el\, Z^0_\mu}$ is the amplitude if Z_μ^0 is the mediator. The t- and u-channel elastic amplitudes are

$$M^{(t,u)}_{el\, H^0_k, A^0_k} \sim \left(\frac{e}{s_W c_W}\right)^2 \bar{\chi}^0_1 \chi^0_1 \frac{1}{v^{t,u} - m_H^2} \bar{\chi}^0_1 \chi^0_1 \tag{2.10}$$

$$M^{(t,u)}_{el\, Z^0_\mu} \sim \left(\frac{e}{s_W c_W}\right)^2 \bar{\chi}^0_1 \gamma^\mu \chi^0_1 \frac{1}{v^{t,u} - m_Z^2} \bar{\chi}^0_1 \gamma_\mu \chi^0_1 \tag{2.11}$$

$v^{t,u}$ can be t or u. In this case $v^{t,u} \sim 0$. If masses of H_k^0, A_k^0 and Z_μ^0 are comparable to $M_{\chi^0_1}$ (and the energies are not tuned to be in the resonant channel), then all the channels are of the same order of magnitude.

We now compare the s-channel elastic scattering amplitude with the s-channel annihilation amplitude (shown in figure 3). For the simple order of magnitude estimate we ignored the production of Z and W bosons. We note that this a conservative approximation since these channels will only enhance conversion of neutralinos into standard model particles. In order to find the annihilation amplitude we need to calculate the three vertices in figure 4. The values are

$$(A) : D\frac{ie}{2s_W c_W}\gamma^\mu(P_L - Es_W^2) \tag{2.12}$$

$$(B) : \frac{i}{\sqrt{2}} Y_f Z_R^{jk} \tag{2.13}$$

$$(C) : \frac{1}{\sqrt{2}} Y_f Z_H^{jk} \gamma_5 \tag{2.14}$$

Parameters D, E, Y_f and j have different values for different fermions. For u-quark we have $D = -1$, $E = \frac{4}{3}$, $Y_f = \sqrt{2}m_f/v_2$ and $j = 2$. For d-quark we have $D = 1$, $E = \frac{2}{3}$,

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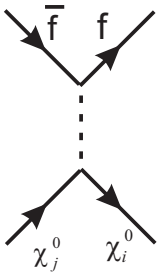

Figure 3. The neutralino-neutralino s-channel annihilation: The dashed line represents Z^0_μ, H^0_k, and A^0_k.

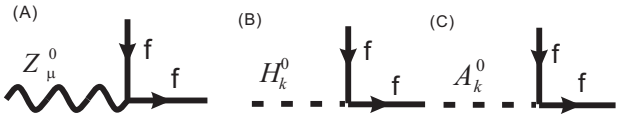

Figure 4. The s-channel annihilation vertices.

$Y_f = \sqrt{2}m_f/v_1$ and $j = 1$. For e we have $D = 1$, $E = 2$, $Y_f = \sqrt{2}m_f/v_1$ and $j = 1$. For ν we have $D = -1$, $E = 0$, $Y_f = 0$ and $j = 2$. The amplitudes are

$$M^{(s)}_{ann\, Z^0_\mu} \sim \left(\frac{e}{s_W c_W}\right)^2 \bar{f}\gamma_\mu f \frac{1}{s - m_Z^2} \bar{\chi}^0_1 \gamma_\mu \chi^0_1 \tag{2.15}$$

$$M^{(s)}_{ann\, H^0_k, A^0_k} \sim \left(\frac{e}{s_W c_W}\right) \bar{f}^c f Y_f \frac{1}{s - m_H^2} \bar{\chi}^0_1 \chi^0_1 \tag{2.16}$$

where f^c is antiparticle of f. Again we omit writing P_L and P_R. Eq. (2.15) gives the amplitude if the mediator is Z^0_μ, while eq. (2.16) gives the amplitude if the mediators are H^0_k and A^0_k. The amplitude in eq. (2.15) is of the same order of magnitude as the amplitude for the elastic scattering in eq. (2.8). The amplitude in eq. (2.16) is roughly (m_f/M_Z) times the amplitude for the elastic scattering in eq. (2.9). If m_f is of the same order of magnitude as M_Z, we can conclude that the elastic and annihilation scattering amplitude are also of the same order of magnitude. The only case when this may not happen is when the neutralino is lighter than the top quark and its initial energy is very low. In that case top quark can not be in the final state for kinematic reasons. However, as mentioned earlier, the cross section also includes the momentum of the emitted particle. Since the next particle in the mass hierarchy is b-quark, which is much lighter than neutralino, the final state particle will have a large momentum. Then the annihilation cross section will be enhanced by a large factor as explained after eq. (2.4). Also, there are more branches in the annihilation process than in an elastic collision since the fermion f in figure 3 stands for several species of particles. This is more than enough to overcome the mass suppression factor if the neutralino is lighter than the top quark. Finally, for our argument to work, it is enough that there exists only one annihilation channel which is comparable to the elastic cross section. As we will show, t- and u- annihilation channels have no mass suppression factors regardless of the sign of the neutralino-top quark mass difference.

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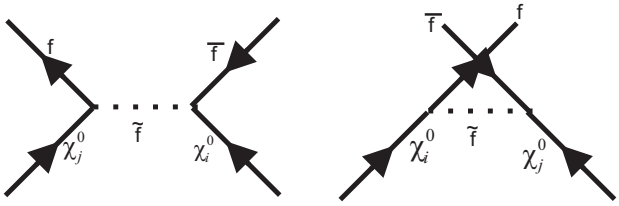

Figure 5. The neutralino-neutralino t- and u-channel annihilation: The dashed line represents a sfermion.

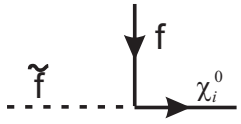

Figure 6. The vertices of fermion-neutralino interaction.

We now compare the t- and u-channels elastic scattering amplitude with the corresponding annihilation amplitude (shown in figure 5). In this case, the mediators are sfermions. The vertices needed for these diagrams are shown in figure 6. The values are

$$i\left(\frac{e}{s_W c_W}A_f P_L + \frac{e}{c_W}B_f P_R\right) \tag{2.17}$$

where A_f and B_f are constants, which are different for different species [13]. The amplitude is

$$M_{ann}^{(t,u)} \sim \left(\frac{e}{s_W c_W}\right)^2 \bar{f}^c \chi_1^0 \frac{1}{v^{t,u} - m_{\tilde{f}}^2} \bar{f} \chi_1^0 \tag{2.18}$$

Again we omitted writing P_L and P_R. Here, $v^{t,u}$ is the square of the momentum transfer, while $m_{\tilde{f}}$ is the mass of sfermion $\tilde{f}$. If $m_{\tilde{f}}$ is not much different from the mass of Z_μ^0, H_k^0, and A_k^0, then the t- and u-channel annihilation amplitudes are of the same order as the t- and u-channel elastic amplitude in (2.10).

This analysis indicates that the neutralino annihilation amplitude is at least of the same order as the neutralino elastic amplitude. The annihilation cross section can be much larger than elastic cross section, when one includes the momentum difference between the light standard model quarks and heavier neutralinos in the final state, as explained after eq. (2.4).

3 Model of the star made of pure neutralinos

In this section we quantify our arguments about the non-existence of the star made of pure neutralinos by treating the Pauli exclusion force as a real interaction between the fermions (different than the weak interaction).

First we will show that the mean free path for the interaction caused by the Pauli exclusion force must be shorter than the distance between fermions if the Fermi pressure is to provide stability. To show this, we consider a general setup like in figure 7. A wall with an area A is embedded in a group of particles (either fermions or bosons). The number

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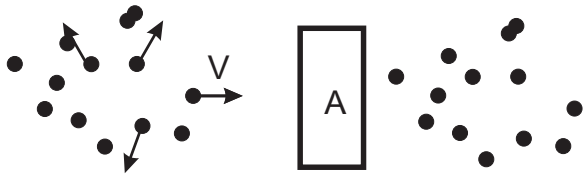

Figure 7. The black dots are particles moving with velocity $\vec{v}(E)$. A small wall of area A is embedded inside the particle distribution.

density of particles with energy E is $n(E)$. The particles move with velocity $\vec{v}(E)$. The total particle number density, N, and energy density, ρ, are

$$N = \int n(E)dE \tag{3.1}$$

$$\rho = \int n(E)EdE \tag{3.2}$$

The pressure can be calculated from the momentum transfer of particles that hit the area A. In a three-dimensional space, about 1/6 of the particles move toward one side of the wall and bounce back. The momentum transfer, $\mathcal{P}$, in the time interval Δt is

$$\Delta\mathcal{P}(E) = \frac{n(E)AEv^2\Delta t}{3} \tag{3.3}$$

The pressure is

$$P = \int \frac{\Delta\mathcal{P}(E)}{A\Delta t}dE = \int \frac{nEv^2}{3} \tag{3.4}$$

This is a common result in statistical mechanics. Note that the crucial assumption in eq. (3.3) is that every particle that arrives at the wall A is bounced back. In other words, the efficiency of the interaction between the wall and particles is 100%. If the wall bounces back only $\gamma(E)$ of the incoming particles (i.e. $1-\gamma(E)$ of the particles pass through the wall) eq. (3.3) must be rewritten as

$$\Delta\mathcal{P}(E) = \gamma(E)\frac{n(E)AEv^2\Delta t}{3} \tag{3.5}$$

In this case, the pressure must be rewritten as

$$P = \int \frac{\Delta\mathcal{P}(E)}{A\Delta t}dE = \int \frac{\gamma(E)nEv^2}{3} \tag{3.6}$$

The factor $\gamma(E)$ then measures the departure from the thermal pressure ($\gamma(E) = 1$ means the pressure is equal to the thermal pressure).

Now consider the wall made of particles themselves. From the number density, the size of a particle is $l = n^{-1/3}$. The crucial factor $\gamma(E)$ can be estimated from the ratio between the interaction cross section between the particles, $\sigma(E)$, and the area l^2:

$$\gamma(E) = \frac{\sigma(E)}{l^2} = \frac{l}{\lambda(E)} \tag{3.7}$$

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Here, $\lambda = 1/(n\sigma) = l^3/\sigma$ is the mean free path of the particles. If $\lambda < l$, i.e. the mean free path is shorter than the distance between the particles, then we need to set $\gamma(E) = 1$. However, if the mean free path is larger than the distance between the particles, $\gamma(E) < 1$. In that case, the pressure is smaller than the thermal pressure. In the extreme case when $\lambda \gg l$ the particles practically do not interact with each other, i.e. $\gamma(E) \approx 0$, and the pressure can not be built up at all. These arguments are true both for bosons and fermions. For fermions, the Pauli exclusion force builds up the Fermi pressure between the fermions. However, for this to happen, the mean free path for fermions must be smaller than (or at most equal to) the distance between the fermions. We will use this result in what follows.

We now model the structure of the star made of pure dark matter. The relativistic mean field approximation [15] implies that the density, pressure and number density of neutralinos can be written as (for details see [10])

$$\begin{aligned} \rho &= \int_0^{k_F} \frac{\sqrt{k^2+m^{*2}}k^2dk}{\pi^2} + \frac{m_H^2H^2}{2} + \frac{m_h^2h^2}{2} + \frac{m_z^2Z^2}{2} \\ P &= \int_0^{k_F} \frac{k^4dk}{3\pi^2\sqrt{k^2+m^{*2}}} - \frac{m_H^2H^2}{2} - \frac{m_h^2h^2}{2} + \frac{m_z^2Z^2}{2} \\ N &= \frac{k_F^3}{3\pi^2} \end{aligned} \tag{3.8}$$

Here, k_F is the Fermi momentum. Also

$$\begin{aligned} H &= \frac{-g_H}{m_H^2\pi^2}\int_0^{k_F} \frac{m^{*2}}{\sqrt{k^2+m^{*2}}}k^2dk \\ h &= \frac{-g_h}{m_h^2\pi^2}\int_0^{k_F} \frac{m^{*2}}{\sqrt{k^2+m^{*2}}}k^2dk \\ Z &= \frac{g_z}{3m_z^2\pi^2}k_F^3 \\ m^* &= m_\chi + g_H H + g_h h \end{aligned} \tag{3.9}$$

The numerical values of the relevant parameters are $m_\chi = 1.01679763 \times 10^6\, MeV$, $m_H = 7.5336438 \times 10^5\, MeV$, $m_h = 1.18760345 \times 10^5\, MeV$, $m_z = 9.1187 \times 10^4\, MeV$, $g_H = 3.131 \times 10^{-1}$, $g_h = -2.705 \times 10^{-2}$, and $g_z = 1.43 \times 10^{-3}$.

The neutralino annihilation cross section is $\sigma_a \sim 1 \times 10^{-10} MeV^{-2}$. The mean free path for annihilations is $\lambda_a = 1/(N\sigma_a)$. As we showed above, the mean free path of the Pauli exclusion force is about the distance between fermions, i.e. $\lambda_p = N^{-1/3}$. To keep neutralinos in thermal equilibrium, we need

$$\frac{\lambda_p}{\lambda_a} = N^{2/3}\sigma_a \ll 1 \tag{3.10}$$

From figure 8, we see that the condition (3.10) can not hold at high k_F (i.e. high densities).

We now write the Oppenheimer-Volkoff equation [16]

$$\begin{aligned} \frac{dP}{dr} &= -\frac{(\rho+P)(M+4\pi Pr^3)}{r^2(1-2M/r)}, \\ \frac{dM}{dr} &= 4\pi\rho r^2. \end{aligned} \tag{3.11}$$

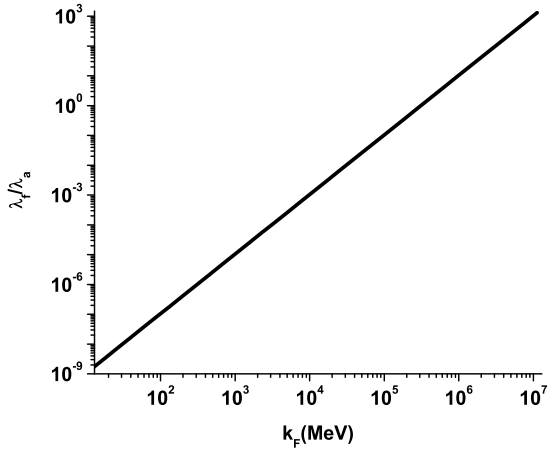

Figure 8. The dependence of the ratio between the mean free paths for the Pauli exclusion force and annihilations λ_p/λ_a on the Fermi momentum k_F. The condition (3.10) breaks down for high k_F (high densities).

Combining eqs. (3.11) with the equation of state given by eqs. (3.8), we can find the structure of the neutralino star. We need to setup the boundary condition for k_F, so we choose $k_F = 0.5m_\chi$ at the center of the compact object. We then numerically integrate eqs. (3.11). The radius of the star is the distance from the center at which the pressure drops to zero (in this case the radius of the star is 1.2cm). This gives us the structure of the star, i.e. energy density, pressure and neutralino number density as functions of the distance from the center of the star.

Figure 9 shows the ratio of λ_p/λ_a vs. radius. Clearly, the ratio is about 1 throughout the star. The ratio drops sharply only at the surface of the star. This indicates that the Pauli exclusion force is not sufficient to overcome annihilation. The neutralinos decay into the standard model particles before the star becomes thermal.

One may roughly estimate the ratio between the standard model particles and neutralinos which is needed to stabilize the star. This ratio will depend on the mean free path for neutralino annihilation and that of the standard model particles. For a condition (3.10) to hold, the mean free path of the standard model particles can not be greater than several percents of the mean free path for neutralino annihilation. This implies that the neutralino content in the star can not be greater than a few percents.

Finally, we comment on the interplay between gravity and annihilations. Gravity brings neutralinos together, but annihilations put an upper limit to the density of (pure) dark matter clumps. Even without detailed numerical simulations we can perform a simple order of magnitude estimate. Consider for example a neutralino clump that was presumably created when the galaxy was formed, and survived till now. The density of the clump can be calculated from the condition

$$\Delta T < \frac{\lambda_a}{v_\chi} = \frac{1}{\sigma_a N v_\chi} \tag{3.12}$$

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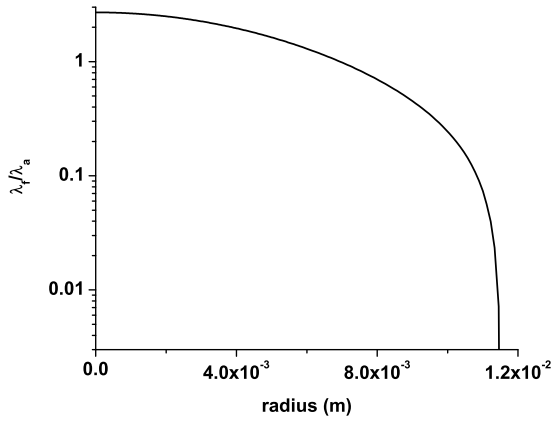

Figure 9. The dependence of the ratio between the mean free paths for the Pauli exclusion force and annihilations λ_p/λ_a on the distance from the center of the compact object made of pure dark matter. Throughout the star the condition (3.10) is violated. The ratio λ_p/λ_a drops sharply only near the surface of the star.

where ΔT is the lifetime of a galaxy — about 10 Gyrs, while the velocity of dark matter is assumed to be 100 km/s. N is the total number density of neutralinos and the neutralino annihilation cross section is $\sigma_a \sim 1 \times 10^{-10} MeV^{-2}$. From this condition we find that the number density of the clump must be lower than $N \sim 6.2 \times 10^{-35}\,\mathrm{GeV}^3 \approx 8.2 \times 10^{12}\ \mathrm{m}^{-3}$, which for a 100 GeV neutralino gives the mass density of $10^{-13}\mathrm{g/cm}^3$. For more general constraints, one would need to perform detailed numerical simulations of the gravitational collapse with annihilations included.

4 Conclusions

In conclusions, we studied here whether pure dark mater can make compact objects like stars. The study was motivated by the remarkable recent observations [5] that there are regions in our universe with pure dark matter distribution without the visible presence of the ordinary matter. We explicitly calculated and compared the neutralino elastic cross section with the annihilation cross section and found them to be comparable. This means that, in each encounter, neutralinos have about the same chance to annihilate into the standard model particle or to be scattered. If they are scattered, they exchange energy and momentum and after many repeated encounters will reach the thermal equilibrium. However, annihilation will prevent this scenario from happening. Once neutralions get converted into the standard model particles they can not come back. This situation can not be described by the Fermi-Dirac equation of state. This implies that a stable neutralino star supported by the Fermi pressure can not exists.

To substantiate our arguments, by solving Oppenheimer-Volkoff equation we constructed a model of the star made of pure neutralinos. We explicitly showed that the

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condition for the thermal equilibrium supported by the Fermi pressure is never fulfilled inside the star. We also estimated that a stable star can not contain more than a few percents of neutralinos, most of the mass must be in the form of the standard model particles. This may have implications for the question why we are made of the standard model particles if most of the matter in the universe comes in the form of dark matter. For intelligent observers like us to evolve, structures like stars and planets are (perhaps) necessary.

One of the possibilities to have neutralinos in thermal equilibrium is an environment with enormous densities, of the order of $(100\,\mathrm{GeV})^4$. If such an environment is thermalized, then its temperature is of the order of the rest mass of the neutralino. In this case neutralinos can be produced thermally. This can only happen in early universe or in the central core of a very dense star. In the case of the central core of a star, this region must be very tiny, with the radius smaller than 1cm [14]. Again, such an object can not be supported by the Fermi pressure. The annihilation process would be so quick that the star could not exist long enough to be observed.

The other possibility to have neutralinos in thermal equilibrium is an environment with very low densities. In an environment where the neutralino density is so low that neutralinos barely collide with each other, their effective lifetime is much longer than the weak-scale characteristic collision time. In such conditions, gravitational cooling may bring neutralinos to equilibrium. This is the mechanism behind dark matter halo formation. However, these are rather low density dark matter distributions and can not be called compact objects. At higher densities gravitational scattering can not compete with weak interactions. Therefore, gravitational cooling may bring neutralinos together but can not play an important role in the subsequent evolution of the compact object.

We assumed here that the dark matter is comprised of neutralinos. However, any particle with the mass around the weak energy scale and weak scale interaction cross section (such is neutralino) automatically has a relic density which satisfies observational constraints. Thus, we expect that the same conclusions will hold for more general models. Therefore, despite the fact that regions in our universe with the pure dark matter distribution were observed, compact objects like planets, stars and larger systems like galaxies made of dark matter are unlike to exist.

We also note that we used the dark matter models in their most standard form. In some exotic models, dark matter particles with an extra self-interaction [17–24] were considered to solve the problems with subhaloes [25, 26], cuspy cores [27–30] and recent apparent PAMELA [31], ATIC [32] and FERMI [33] observations. In the context of these models, this extra self-interaction has to be properly included.

Acknowledgments

The authors are grateful to D. Wackeroth, A. Scharf, Y.C. Lee, G. Starkman and H. Mathur for very useful conversations. DS acknowledges the financial support from NSF.

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References

[1] Supernova Search Team collaboration, A.G. Riess et al., *Type Ia supernova discoveries at $z > 1$ from the Hubble space telescope: evidence for past deceleration and constraints on dark energy evolution*, *Astrophys. J.* **607** (2004) 665 [astro-ph/0402512] [SPIRES].

[2] WMAP collaboration, H.V. Peiris et al., *First year Wilkinson Microwave Anisotropy Probe (WMAP) observations: implications for inflation*, *Astrophys. J. Suppl.* **148** (2003) 213 [astro-ph/0302225] [SPIRES].

[3] WMAP collaboration, D.N. Spergel et al., *Wilkinson Microwave Anisotropy Probe (WMAP) three year results: implications for cosmology*, *Astrophys. J. Suppl.* **170** (2007) 377 [astro-ph/0603449] [SPIRES].

[4] H.E. Haber and G.L. Kane, *The search for supersymmetry: probing physics beyond the standard model*, *Phys. Rept.* **117** (1985) 75 [SPIRES].

[5] R. Massey et al., *Dark matter maps reveal cosmic scaffolding*, *Nature* **445** (2007) 286 [astro-ph/0701594] [SPIRES].

[6] D. Spolyar, K. Freese and P. Gondolo, *Dark matter and the first stars: a new phase of stellar evolution*, *Phys. Rev. Lett.* **100** (2008) 051101 [arXiv:0705.0521] [SPIRES].

[7] L. Clavelli, *Gravitational collapse of a SUSY star*, *High Energy Dens. Phys.* **0606** (2006) 002 [*High Energy Dens. Phys.* **2** (2006) 97] [hep-ph/0602024] [SPIRES].

[8] G. Narain, J. Schaffner-Bielich and I.N. Mishustin, *Compact stars made of fermionic dark matter*, *Phys. Rev.* **D 74** (2006) 063003 [astro-ph/0605724] [SPIRES].

[9] N. Bilic, F. Munyaneza and R.D. Viollier, *Stars and halos of degenerate relativistic heavy neutrino and neutralino matter*, *Phys. Rev.* **D 59** (1999) 024003 [astro-ph/9801262] [SPIRES].

[10] J. Ren, X.-Q. Li and H. Shen, *Equation of state for neutralino star as a form of cold dark matter*, *Commun. Theor. Phys.* **49** (2008) 212 [hep-ph/0604227] [SPIRES].

[11] D. Pfenniger and V.M.G. Observatory, *Cosmological neutrino entanglement and quantum pressure*, astro-ph/0605354 [SPIRES].

[12] D. Clowe et al., *A direct empirical proof of the existence of dark matter*, *Astrophys. J.* **648** (2006) L109 [astro-ph/0608407] [SPIRES].

[13] J. Rosiek, *Complete set of Feynman rules for the MSSM — erratum*, hep-ph/9511250 [SPIRES].

[14] D. Dai, A. Lue, G.D. Starkman and D. Stojkovic, *Electroweak stars*, in preparation.

[15] B.D. Serot and J.D. Walecka, *The relativistic nuclear many body problem*, *Adv. Nucl. Phys.* **16** (1986) 1 [SPIRES].

[16] J.R. Oppenheimer and G.M. Volkoff, *On massive neutron cores*, *Phys. Rev.* **55** (1939) 374 [SPIRES].

[17] D.N. Spergel and P.J. Steinhardt, *Observational evidence for self-interacting cold dark matter*, *Phys. Rev. Lett.* **84** (2000) 3760 [astro-ph/9909386] [SPIRES].

[18] A. Burkert, *The structure and evolution of weakly self-interacting cold dark matter halos*, astro-ph/0002409 [SPIRES].

[19] L. Ackerman, M.R. Buckley, S.M. Carroll and M. Kamionkowski, *Dark matter and dark radiation*, *Phys. Rev.* **D 79** (2009) 023519 [arXiv:0810.5126] [SPIRES].

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[20] J.L. Feng and J. Kumar, *Dark-matter particles without weak-scale masses or weak interactions*, *Phys. Rev. Lett.* **101** (2008) 231301 [arXiv:0803.4196] [SPIRES].

[21] D. Hooper and K.M. Zurek, *A natural supersymmetric model with MeV dark matter*, *Phys. Rev.* **D 77** (2008) 087302 [arXiv:0801.3686] [SPIRES].

[22] Y.G. Kim, K.Y. Lee and S. Shin, *Singlet fermionic dark matter*, *JHEP* **05** (2008) 100 [arXiv:0803.2932] [SPIRES].

[23] J.-H. Huh, J.E. Kim, J.-C. Park and S.C. Park, *Galactic 511 keV line from MeV milli-charged dark matter*, *Phys. Rev.* **D 77** (2008) 123503 [arXiv:0711.3528] [SPIRES].

[24] D.-C. Dai, K. Freese and D. Stojkovic, *Constraints on dark matter particles charged under a hidden gauge group from primordial black holes*, *JCAP* **06** (2009) 023 [arXiv:0904.3331] [SPIRES].

[25] B. Moore et al., *Dark matter substructure in galactic halos*, astro-ph/9907411 [SPIRES].

[26] S. Ghigna et al., *Density profiles and substructure of dark matter halos: converging results at ultra-high numerical resolution*, *Astrophys. J.* **544** (2000) 616 [astro-ph/9910166] [SPIRES].

[27] J.F. Navarro, C.S. Frenk and S.D.M. White, *The structure of cold dark matter halos*, *Astrophys. J.* **462** (1996) 563 [astro-ph/9508025] [SPIRES].

[28] B. Moore, *Evidence against dissipationless dark matter from observations of galaxy haloes*, *Nature* **370** (1994) 629 [SPIRES].

[29] R.A. Flores and J.R. Primack, *Observational and theoretical constraints on singular dark matter halos*, *Astrophys. J.* **427** (1994) L1 [astro-ph/9402004] [SPIRES].

[30] W.J.G. de Blok and S.S. McGaugh, *The dark and baryonic matter content of low surface brightness disk galaxies*, *Mon. Not. Roy. Astron. Soc.* **290** (1997) 533 [astro-ph/9704274] [SPIRES].

[31] PAMELA collaboration, O. Adriani et al., *An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV*, *Nature* **458** (2009) 607 [arXiv:0810.4995] [SPIRES].

[32] J. Chang et al., *An excess of cosmic ray electrons at energies of 300–800 GeV*, *Nature* **456** (2008) 362 [SPIRES].

[33] The Fermi LAT collaboration, A.A. Abdo et al., *Measurement of the cosmic ray $e^+ + e^-$ spectrum from 20 GeV to 1 TeV with the Fermi Large Area Telescope*, *Phys. Rev. Lett.* **102** (2009) 181101 [arXiv:0905.0025] [SPIRES].

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