Self interacting dark matter and small scale structure

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The core-cusp problem remains as one of the unresolved challenges between observation and simulations in the standard ΛCDM model for the formation of galaxies. Basically, the problem is that ΛCDM simulations predict that the center of galactic dark matter halos contain a steep power-law mass density profile. However, observations of dwarf galaxies in the Local Group reveal a density profile consistent with a nearly flat distribution of dark matter near the center. A number of solutions to this dilemma have been proposed. We summarize investigations the possibility that the dark matter particles themselves self interact and scatter. The scattering of dark matter particles then can smooth out their profile in high-density regions. We also summarize theoretical theoretical models as to how self- interacting dark matter may arise. We summarize our own implementation this form in simulations of self-interacting dark matter in models for galaxy formation and evolution. Constraints on self-interacting dark matter are then summarized.

Keywords: Interacting Dark Matter; Dwarf Galaxies; Galactic Structure.

1. Introduction

The nature of most of the matter in the universe remains as one of the most challenging questions in modern physics.[1] Nevertheless, observational evidence from the Cosmic Microwave Background, galaxies cluster, weakly lensing, and the Lyman-α forest agree with the predictions of the ΛCDM model. Such models contain a mixture of roughly 25% collisionless cold dark matter such as WIMPs, axions, etc. interacting through the weak and gravitational forces only, and 70% vacuum energy or quintessence.[2,3] Only a fraction of the present total matter can be made of ordinary baryons has an unknown, nonbaryonic origin[4].

However, it is now appreciated (e.g. Ref. [5] and refs. therein) that conventional models of collisionless cold dark matter lead to problems with regard to galactic structure. They are only able to fit the observations on large scales ($\gg 1Mpc$). In particular, high-resolution N-body simulations in these models result in a central singularity of the galactic halos[6] and a large number of sub-halos[7] than observed. This is called the *Core-Cusp Problem.* A number of other inconsistencies are discussed in Refs. [5, 8, 9, 10]. In particular, the mass density profile for CDM halos increases toward the center, scaling approximately as $\rho_{\rm dm} \sim r^{-1}$. However, many observed rotation curves of disk and dwarf spheroidal galaxies prefer[11–13] a constant density profile $\rho_{\rm dm} \sim r^0$, as evidenced by a linearly rising circular velocity in the inner regions. This is most evident in dwarf and low surface brightness (LSB) galaxies since they are highly DM-dominated.

A possible way to avoid these problems is to hypothesize *self-interacting dark matter*[14] (SIDM). [Although self-interacting models lead to spherical halo centers in clusters. This is not in agreement with the inferred ellipsoidal centers indicated by gravitational lensing[15] and by Chandra observations[16].]

Self-interacting dark matter models are well motivated as a model for particle dark matter. The key property of dark-matter particles is that they are non-relativistic and have have a weak scattering cross-section. The Spergel-Steinhard model[14] has motivated many follow-up studies[4,17,18] to identify a dark matter particle with self interactions. Here we constrain one particular model[19] with right-handed (RH) neutrinos for self-interacting dark matter based upon simulations of galactic structure. We deduce that the mass of the SIDM in this model in about an MeV. We compare numerical simulations to the observations.

The range of mass for SIDM is from $\sim$MeV with a mean free path and total cross section over mass from 0.1 cm^2 g^{-}1 to 100 cm^2 g^{-1} can solve the core-cusp and the missing satellite problems of the ΛCDM model. In our model the cross section over mass σ/m is in the range of 4 to 5 cm^2 g^{-1}. In large scale structure there is no difference between that of normal CDM and SIDM. However, on small scales galactic cores are consistent with all of the observational constraints. We analyze the small scale structure of the dark matter based upon the hydrodynamic simulations described in this work.

2. Model for self-interaction dark matter

The SM offers no options for dark matter. The first gauge model[20] for SIDM was found in the 3-3-1 model. To keep the Higgs sector with three triplets in that model the existence of *exotic leptons* was proposed. The 3-3-1 models were proposed with an independent motivation[21–23]. These models have the intriguing features that they are anomaly free only if the number of families N is a multiple of three. If one adds the condition of QCD asymptotic freedom, which is valid only if the number of families of quarks is to be less than five, it follows that N is equal to 3.

I this work we summarize the argument that the 3-3-1 model with right-handed (RH) neutrinos[24] contains such self-interacting dark matter.

The main properties that a good dark matter candidate must satisfy are stability and neutrality. Therefore, one should consider the scalar sector of the model, more specifically, the neutral scalars.[14]. In addition, such dark matter particles must not overpopulate the Universe. On the other hand, since our dark matter particle is not imposed arbitrarily to solve this specific problem, one must check that the necessary values of the parameters do not spoil the other bounds of the model.

Under the assumption of discrete symmetry $\chi \to -\chi$, the most general potential can then be written in the following form,[25]

$$\begin{aligned} V(\eta,\rho,\chi) = {} & \mu_1^2\eta^+\eta + \mu_2^2\rho^+\rho + \mu_3^2\chi^+\chi + \lambda_1(\eta^+\eta)^2 + \lambda_2(\rho^+\rho)^2 + \lambda_3(\chi^+\chi)^2 \\ & + (\eta^+\eta)[\lambda_4(\rho^+\rho) + \lambda_5(\chi^+\chi)] + \lambda_6(\rho^+\rho)(\chi^+\chi) + \lambda_7(\rho^+\eta)(\eta^+\rho) \\ & + \lambda_8(\chi^+\eta)(\eta^+\chi) + \lambda_9(\rho^+\chi)(\chi^+\rho) + \lambda_{10}(\chi^+\eta + \eta^+\chi)^2. \end{aligned} \tag{1}$$

Next one can write the expansion of the scalar fields which acquire a VEV:

$$\eta^o = \frac{1}{\sqrt{2}}\left(v + \xi_\eta + i\zeta_\eta\right);\ \rho^o = \frac{1}{\sqrt{2}}\left(u + \xi_\rho + i\zeta_\rho\right);\ \chi^o = \frac{1}{\sqrt{2}}\left(w + \xi_\chi + i\zeta_\chi\right). \tag{2}$$

For the prime neutral fields which do not have a VEV, one finds analogously:

$$\eta'^{o} = \frac{1}{\sqrt{2}}\left(\xi'_{\eta} + i\zeta'_{\eta}\right);\ \chi'^{o} = \frac{1}{\sqrt{2}}\left(\xi'_{\chi} + i\zeta'_{\chi}\right). \tag{3}$$

To satisfy the requirements of stability and neutrality, one can go to the scalar sector of the model, more specifically to the neutral scalars. One must then whether any of them can be stable and are self-interacting.[14] In addition, such a dark matter particle must freeze out at the correct cosmic abundance. One can check through a direct calculation by employing the relevant Lagrangians that the Higgs scalar h_0 and H_3^0 can, satisfy these criteriona. Remarkably, they do not interact directly with any SM field except for the standard Higgs H_1^0. However, h_0 must be favored, since it is easier to obtain a large scattering cross section.

In contrast to the singlet models of Refs. 4, 18, 28, 29, 26, 27, where an extra symmetry must be imposed to account the stability of the dark matter, the decay of the h_0 scalar is automatically forbidden in all orders of perturbative expansion. This is because this scalar comes from the triplet χ, that induces the spontaneous symmetry breaking of the 3-3-1 model to the standard model. Therefore, the SM fermions and the standard gauge bosons cannot couple with h^0. Also, the h^0 scalar comes from the imaginary part of the Higgs triplet χ.The imaginary parts of η and ρ are pure massless Goldstone bosons. Thus, there are no physical scalar fields which can mix with h^0 and the only interactions of h^0 come from the scalar potential. They are $H_3^0 h^0 h^0$ and $H_1^0 h^0 h^0$. If $v \sim u \sim (100 \sim 200)$ GeV and $-1 \leqslant a_5 \sim a_6 \leqslant 1$, the h^0 can interact only weakly with ordinary matter through the Higgs boson of the standard model H_1^0. The relevant quartic interaction for scattering is thus $h^0 h^0 h^0 h^0$.

3. Structure formation in a SIDM Universe

In the work of Lan and Long,[19] it was deduced that the mass range for the dark matter is from 4.7MeV to 29 MeV. Our dark matter is non-relativistic with decoupling temperature $\sim$ 1eV. Dark matter does not interact with any particles in the standard model except Higgs Boson, so one need not deal with any collision terms. The self-interacting dark matter in the 3-3-1 model of Ref. [19] is non-relativistic driving the decoupling era with a decoupling temperature about 1eV. So we have $g_{\mu\nu}P^{\mu}P^{\nu} = m^2$, where m is the mass of the dark matter particles, $g_{\mu\nu}$ is the full metric tensor, and $P^0 = \sqrt{q^2 + m^2 a^2}(1-\phi)$. We can define the energy $q = \sqrt{(p^2 + m^2)}$, where p the is magnitude of momentum.

If one defines $\beta = n_h/T^3$ in the radiation dominated era one write the evolution Boltzmann Equation as

$$\frac{d\beta}{dT} = -\frac{\Gamma\beta}{KT^3} = -\frac{\alpha}{8\pi^3 K e^{m_1/T}}\left(\frac{\Theta}{T^2}\right)^2 \tag{4}$$

where $K^2 = 4\pi^3 g(T)/45 m_{Pl}^2$ and $\beta = \frac{n_h}{T^3}$ are parameters of thermal equilibrium and m_{PL} is the Planck mass. We take $T = m_1$ so that the cosmic density of the h_0

scalar is

$$\Omega_h = 2g(T_\Gamma)T_\gamma^3 \frac{m_h \beta}{\rho_c g(T)} \tag{5}$$

where $T_\gamma = 2.4 \times 10^{-4}$ eV is the present photon temperature, $g(T_\gamma) = 2$ is the photon degree of freedom and $\rho_c = 7.5 \times 10^{-47} h^2$, with h = 0.71, being the critical density of the Universe. Let us take $m_h = 7.75$ MeV, v = 174 GeV, $a_5 = 0.65$, -$a_6 = 0.38$ (actually in our calculations, we have used a better precision for a_5 and a_6) and $m_1 = 150$ GeV. Thus, from we obtain $\Omega_h = 0.3$. Therefore, without imposing any new fields or symmetries, the 3-3-1 model possesses a scalar field that can satisfy all the properties required for the self-interacting dark matter and does not overpopulate the Universe.

4. Constraint with CMB and galaxy simulation

We have simulated of the formation of a dwarf galaxy of $10^{10} M_\odot$ halos of self interacting dark matter (SIDM) with cross section over mass in the range $\sigma/m = 3.7$ to 5.2 cm^2 g^{-1}. We used a cosmological model with parameters $\Omega_\Lambda = 0.734$, $\Omega_m = 0.266, \Omega_b = 0.0449, n_s = 0.963, h = 0.71, \sigma_8 = 0.801$ (Komatsu et al. 2011). We start with isolated halo galaxies with a stellar mass of $M_{star} = 1.4 \times 10^{11} M_\odot$ and temperature $T = 10^4$K with in a box size of $50 Mpch^{-1}$.

Figure 1 shows an example of our inferred SIDM radial profile for a best fit of $\sigma/m = 4$ cm^2 g^{-1}. It shows a flattening toward the center as required by observation.

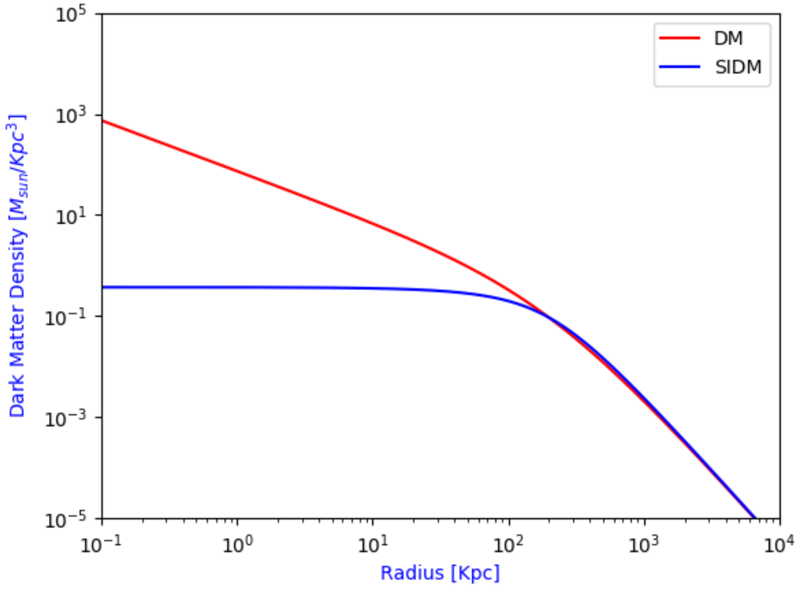

Fig. 1. Galaxy profile calculated with (blue line) and without (red line) SIDM from a fit to the numerical simulations.

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