Constraints on Interacting Dark Matter from small scale structure

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Abstract

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 investigate 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 a theoretical model as to how self-interacting dark matter may arise. We implement this form in simulations of self-interacting dark matter in models for galaxy formation and evolution. Constraints on this form of self-interacting dark matter will be summarized.

Introduction

The nature of most of the matter in the universe remains as one of the challenging questions in modern physics. Cosmological models with a mixture of roughly 25% collisionless cold dark matter as axions, WIMPs, etc. interacting through the weak and gravitational forces only, and 70% vacuum energy or quintessence match current observations of the cosmic microwave background and large scale structure with remarkable accuracy. It is known that only a fraction of the present total matter can be made of ordinary baryons has an unknown, non-baryon origin. Observational evidence from the Cosmic Microwave Background, galaxies cluster, weakly lensing, and the Lyman alpha agree with the predictions of the Λ CDM model. This model satisfies observational cosmology, for a spectrum of density fluctuations that is nearly scale-invariant and adiabatic. However, in recent years it has been pointed out 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 ($\gg 1Mpc$). Also, N-body simulations in these models result in a central singularity of the galactic halos and a large number of sub-halos than observed.

The models for Self Interacting Dark Matter

The 3-3-1 model with RH neutrinos furnishes a good candidate for (self-interacting) dark matter. The main properties that a good dark matter candidate must satisfy are stability and neutrality. Therefore, we go to the scalar sector of the model, more specifically to the neutral scalars, and we examine whether any of them can be stable and in addition whether they can satisfy the self-interacting dark matter. In addition, one should notice that such dark matter particle must not overpopulate the Universe.

To get the interaction of dark matter to the SM Higgs boson, we consider the following relevant parts

$$L(\sigma,\zeta_\eta)_{int} = \frac{1}{4}[v^2+2v\xi_\eta+\xi_\eta^2+\zeta_\eta^2+\xi'^2_\eta+\zeta'^2_\eta+2\eta^+\eta^-]^2+\frac{1}{4}\lambda_4[v^2+2v\xi_\eta+\xi_\eta^2+\zeta_\eta^2+\xi'^2_\eta+\zeta'^2_\eta+2\eta^+\eta^-]... \quad (1)$$

the couplings of SIDM with the SM Higgs boson σ

$$L = \left(\frac{\sigma(x)}{\sqrt{\lambda_5^2v^2+\lambda_6^2u^2}}(\lambda_1\lambda_5v^2+\frac{\lambda_4\lambda_6}{2}u^2)+\frac{H_1(x)\sigma(x)}{(\lambda_5^2v^2+\lambda_6^2u^2)}(\lambda_1-\frac{\lambda_4}{2})\lambda_5\lambda_6uv+\frac{\sigma^2(x)}{2\lambda_5^2v^2+\frac{\lambda_6^2u^2}{2}}\right)(\eta'^2+\zeta'^2). \quad (2)$$

The decay of the h_0 scalar is automatically forbidden in all orders of perturbative expansion. This is because of the following features:

- this scalar comes from the triplet χ, the one 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 .
- the h^0 scalar comes from the imaginary part of the Higgs triplet χ. As we mentioned above, the imaginary parts of η and ρ are pure massless Goldstone bosons.

Therefore, there is not physical scalar fields which can mix with h^0. So, the only interactions of h^0 come from the scalar potential and they are $H_3^0h^0h^0$ and $H_1^0h^0h^0$ and h^0 does not interact with other exotic particle.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 $h^0h^0h^0h^0$. Other quartic interactions evolving h^0 and other neutral scalars are proportional to $\frac{1}{w}$ and so we neglect them. The cross section of the process $h^0h^0 - h^0h^0$ via the quartic interaction is $\sigma = \frac{a_3^2}{64\pi m_h^2}$. The contribution of the trilinear interactions via H_1^0 and H_3^0 exchange are negligible. There is no other contribution to the process involving the exchange of vector or scalar bosons. Dark matter particle in this model is non-relativistic in the decoupling era and, it is produced by a thermal equilibrium density of the standard Higgs scalar to h^0h^0 pairs . The density of the h^0 scalar from the H^0 decay can be obtained following the standard procedure

$$\frac{dn_h}{dt}+3Hn_h =<\Gamma_H> n_H, \quad (3)$$

where n_h is the number density of the h^0scale at the time t, H is the Hubble expansion rate, Γ_H is the decay rate for the H_1^0 with energy E and

$$n_H = \frac{1}{2\pi^2}\int_{m1}^{\infty}\frac{E\sqrt{E^2-m^2}}{e^{E/T}-1} \quad (4)$$

is the thermal equilibrium density of the standard H_1^0 at temperature T. The thermal average of the decay rate is given by

$$\Gamma = \frac{\alpha(\Theta T)^2}{8\pi^3 n_H}e^{m_1/T} \quad (5)$$

where α is an integration parameter. We define $\beta = \frac{n_h}{T^3}$ and in the radiation dominated era we write the evolution Boltzmann Equation as

$$\frac{d\beta}{dT} = -\frac{\Gamma\beta}{KT^3} = -\frac{\alpha}{8\pi^3Ke^{m_1/T}}(\frac{\Theta}{T^2})^2 \quad (6)$$

where $K^2 = \frac{4\pi^3g(T)}{45m_{Pl}^2}$ $\beta = \frac{n_h}{T^3}$ is the parameter in the thermal equilibrium, $m_{Pl} = 1.2\times10^{19}$ GeV is the Planck mass and $g(T) = g_B + 7\frac{g_F}{8} = 136.25$ (Kob and Turner, 1990) Cosmic density of the scalar particles h is:

$$\Omega_h = 2g(T_\Gamma)T_\gamma^3\frac{m_h\beta}{\rho_c g(T)} \quad (7)$$

A self interacting dark matter candidate have mean free path $\frac{1}{n_\sigma}$ in the range of Kpc, this range less than Mpc. We know that the number density of the scalar particles h_0 is $n = \frac{\rho}{m_h}$, where ρ is the density at the solar radius. Since that we obtain the mass for the scalar particles is from 4.7 MeV to 29 MeV and density of the scalar particles is from 0.14 to 0.3 and cross section is

$$3.7cm^2g^{-1} \leqslant \frac{\sigma}{m_{dm}} \leqslant 5.2cm^2g^{-1} \quad (8)$$

Constraint with Galaxy simulation

We now consider the relation between the dark matter density and galactic radius. The model for self interacting dark matter should have a core size less than 2kpc on the scale of dwarf galaxies.

$$\Omega_{SIDM} = \frac{\rho_{SIDM}}{\rho_0} = 2.g.2.(2,4.10^{-4})^3eV.\frac{4.7MeV.\beta}{7.5} \quad (9)$$

We study the galaxy formation with stellar masses in self interacting dark matter (SIDM) with cross section over mass in the range from 3.7 to 5.2 cm^2g^{-1}, the ΛCDM model consider that DM is non relativistic and collisioness.

For simulations, we set the initial conditions for the ENZO code using cosmological parameters from the WMAP9 data $\Omega_\Lambda = 0.734, \Omega_m = 0.266, \Omega_b = 0.0449, n_s = 0.963, h = 0.71, \sigma_8 = 0.801$ (Komatsu et al.2011). We start with isolated halo galaxies with a stellar mass of $M_{star} = 1.4\times10^{11}M_\odot$ and temperature $T = 10^4$K with in a box size of $50Mpc.h^{-1}$

Simulations in this paper

Name	Volume ($h^{-1}Mpc$)	Number of particles N_p	Cross section $\frac{\sigma}{m}(cm^2g^{-1})$
CDM	50	512^3	0
SIDM-3.5	50	512^3	3.7
SIDM-5.5	50	512^3	5.2

For the Cold Dark Matter run we use the initial radial density profile (Navarro et al. 1997)

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\sigma_c}{(\frac{r}{r_0})(1+\frac{r}{r_0})^2}, \quad (10)$$

where r_0 is a scale radius, σ_c is a density, and critical density ρ_{crit}

The density of the galaxy core should constant at the small radii, so the profile for the cores is from (Burkert 1995)

$$\rho(r) = \frac{\rho_0 r_0^3}{(r+r_0)(r^2+r_0^2)} \quad (11)$$

where ρ_0 is central density and r_0 scale radius

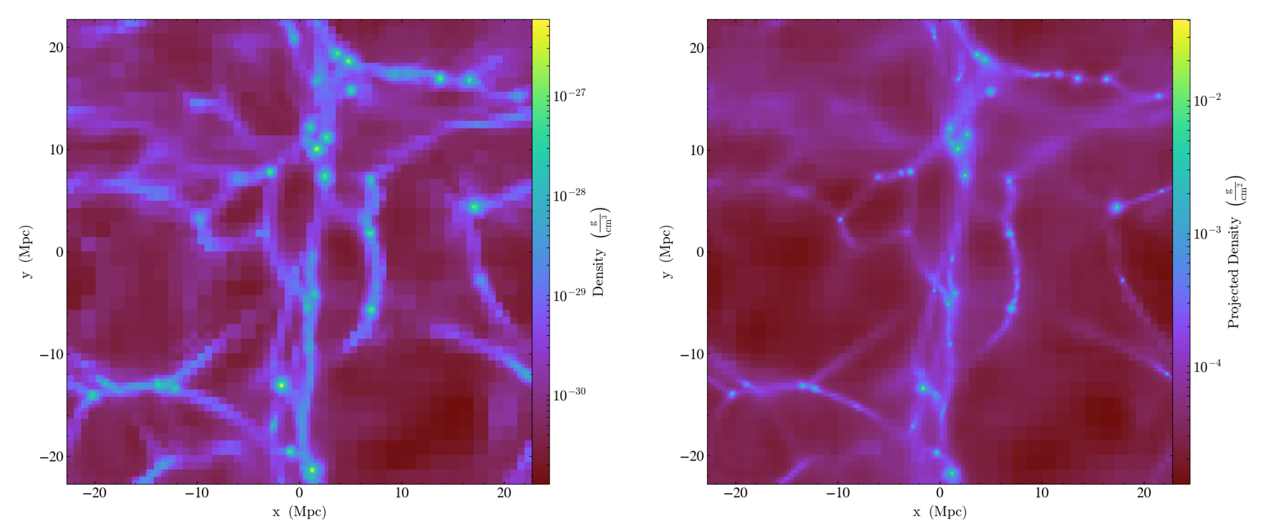

Figure 1: Density distribution

Conclusions

- Self-Interacting Dark Matter is a viable solution to the Core-Cusp Problem.
- SIDM may provide insight into physics beyond the standard model.
- 3-3-1 models are the gauge theories of SIDM.
- Future work will include a detailed analysis of constraints on properties of interacting dark matter from observations of Galaxy cores and CMB

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