Observational evidence for self-interacting cold dark matter

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Cosmological models with cold dark matter composed of weakly interacting particles predict overly dense cores in the centers of galaxies and clusters and an overly large number of halos within the Local Group compared to actual observations. We propose that the conflict can be resolved if the cold dark matter particles are self-interacting with a large scattering cross-section but negligible annihilation or dissipation. In this scenario, astronomical observations may enable us to study dark matter properties that are inaccessible in the laboratory.

Flat cosmological models with a mixture of ordinary baryonic matter, cold matter, and cosmological constant (or quintessence) and a nearly scale-invariant, adiabatic spectrum of density fluctuations are consistent with standard inflationary cosmology and provide an excellent fit to current observations on large scales ($\gg 1$ Mpc).\(^1\) However, an array of observations on galactic and subgalactic scales ($\lesssim$ few Mpc) appears to conflict with the structure formation predicted by analytical calculations and numerical simulations. The predictions are based on the standard view of cold dark matter as consisting of particles with weak self-interactions, as well as weak interactions with ordinary matter.

A generic prediction for weakly self-interacting dark matter, independent of other details of the cosmological model, is that cold dark matter forms triaxial halos with dense cores and significant dense substructures within the halo. Yet, lensing observations of clusters\(^2\) reveal central regions (roughly galactic scale) with nearly spherical low density cores. Dwarf irregular galaxies appear to have low density cores\(^3,4\) with much shallower profiles than predicted in numerical simulations.\(^7,8\) The persistence of bars in high surface brightness galaxies imply that galaxies like our own Milky Way also have low density cores.\(^9\) Observations of the Local Group reveal less than one hundred galaxies,\(^10\) while numerical simulations\(^11,12\) and analytical theory\(^13,14\) predict that there should be roughly one thousand discrete dark matter halos within the Local Group.

In this paper, we propose that the inconsistencies with the standard picture may be alleviated if the cold dark matter is self-interacting with a large scattering cross-section but negligible annihilation or dissipation. The key feature is that the mean free path should be in the range 1 kpc to 1 Mpc. The large scattering cross-section may be due strong, short-range interactions, similar to neutron-neutron scattering at low-energies, or weak interactions mediated by the exchange of light particles (although not so light as to produce a long-range force). For the purposes of our proposal, only two-body scattering effects are important so either repulsive or attractive interactions are possible. Exchanged particles should be massive enough that they are not radiated by the scattering of dark matter particle in the halo.

We are led to consider self-interactions because ordinary astrophysical processes are unlikely to resolve the problems with standard, weakly interacting dark matter. Consider the dwarf galaxy problem. One might suppose that supernova explosions\(^15\) could cause the galactic core density to be made smoother; but, while the explosions suppress star formation in dwarf galaxies, numerical simulations\(^16\) find that starbursts in dwarfs are very inefficient at removing gas or matter from the core. One might also consider whether the apparent overabundance of halos found in simulations can be explained if the low velocity halos form primarily low surface brightness galaxies,\(^17\) which are difficult to find. However, while low brightness galaxy surveys suggest a steeper luminosity function outside of groups,\(^18\) even these surveys do not find enough small galaxies to eliminate the discrepancy between theory and observations. If star formation in dwarfs is sufficiently suppressed,\(^19\) then they should have been detected as gas clouds in the local group\(^20\) or external systems. HI surveys do not find large numbers of small isolated gas clouds.\(^21\) Even if any of the processes were successful in reducing the number of visible dwarfs, the dense small halos would still persist. When these halos fall onto galactic disks, they will heat the stellar disks and destroy them.\(^12,22,23\) These dense halos will also settle to the centers of the central halo and produce a high density core in galaxies and clusters. Since the baryon fraction in the centers of low surface brightness galaxies is low,\(^17\) hydrodynamic processes are not likely to alter their dark matter profiles.\(^3,4\)

The success of the cold dark matter model large scales suggests that a modification of the dark matter properties may be the best approach for resolving the problems on small scales. If the dark matter is not cold, but warm (moderately relativistic), this alleviates some of these discrepancies.\(^24\) If the mass of the dark matter is $\sim$ 1 keV, then its initial thermal motion suppresses the formation of low mass halos and reduces the central density in more massive halos. Warm dark matter; however, may be too effective in its suppression of small scale power. In warm dark matter models, galaxies form primarily in clusters and there would not be any Lyman $\alpha$ clouds in low den-
sity regions. The remarkably good agreement between standard cold dark matter (CDM) models and the observed power spectrum of Lyman $\alpha$ absorbers suggests that cold, non-dissipative, but self-interacting dark matter candidates.

We propose that a better resolution is dark matter that is cold, non-dissipative, and self-interacting. There are stringent constraints on the interactions between dark matter and ordinary matter and on long range forces between dark matter particles. However, as long as the dark matter annihilation cross-section is much smaller than the scattering cross-section, there are relatively few constraints on short-range dark matter self-interactions. Carlson, Machacek & Hall suggested a self-interacting dark matter model in which the dark matter particle is warm rather than cold. Their model assumed that the dark matter plus ordinary matter sum to the critical density predicted by inflationary cosmology. Their purpose was to alter the shape of the dark matter power spectrum on large scales to address the problem that the standard CDM model and matches well the current large scale structure data. Because we do not require that the dark matter properties affect the large scale structure on the 10 Mpc scale but only on the 1 kpc scale, our model satisfies the constraints raised by de Laix et al.

To be more specific, we suggest that the dark matter particles should have a mean free path between $\sim 1$ kpc to 1 Mpc in a typical galaxy (mean density 0.4 GeV/cm$^3$), for reasons to be explained below. For a particle of mass $m_x$, this implies an elastic scattering cross-section of

$$\sigma_{XX} = 8.1 \times 10^{-25} \text{cm}^2 \left(\frac{m_x}{\text{GeV}}\right) \left(\frac{\lambda}{1\text{Mpc}}\right)^{-1}. \quad (1)$$

If the dark matter particles scatter through strong interactions similar to low-energy neutron-neutron scattering, then the cross-section is $\sigma = 4\pi a^2$, where $a$ is the scattering length. For neutrons, the scattering length is more than 100 times its Compton wavelength. Using the estimate $a \approx 100 f m_x^{-1}$, we obtain

$$m_x = 4 \left(\frac{\lambda}{1\text{Mpc}}\right)^{1/3} f^{2/3} \text{GeV}. \quad (2)$$

Alternatively, the self-interaction may be weak but longer-range, as in the case of the exchange of a light intermediate vector boson of mass $m_y$, in which case the cross-section is $\sigma \approx \alpha_y m_y^2/m_x^4$. The mass of the vector boson must large enough that there is no dissipation when dark matter particles scatter; this requires that $m_y > 450 \text{eV} (m_x/\text{GeV}) (v/200 \text{km/s})^2$, where $v$ is the typical velocity of dark matter particles in the halo. This mass scale for $m_y$ corresponds to a force that is short-range compared to the dark matter interparticle spacing (about 1 cm in the halo). Hence, we need only consider two-body interactions in our analysis. If $m_y = g m_x$ and $\alpha_y = O(1)$, then the maximum dark matter mass is

$$m_x < 80 \left(\frac{\lambda}{1\text{Mpc}}\right)^{1/3} f^{-4/3} \text{MeV}. \quad (3)$$

The strong self-interaction might occur if the dark matter consists of particles with a conserved global charge (such as a hidden baryon number) interacting through a hidden gauge group (e.g., hidden color). If the gauge group is unbroken, the particles experience strong interactions which can be non-dissipative but the particle number is conserved. M-theory and superstrings, for example, suggest the possibility that dark matter fields reside on domain walls with gauge fields separated from ordinary matter by an extra (small) dimension. Similar scenarios can be constructed in purely four-dimensional supergravity models. Note that, if the sum of the hidden baryon number and the ordinary sector baryon number is zero, then $\Omega_x = (m_x/m_{proton})\Omega_b \approx 0.19 (m_x/4 \text{GeV})$ (using $\Omega_b h^2 = 0.02$ and $h = 0.65$). More generally, the particles we suggest correspond to light versions of the WIMPZILLAS discussed by Kolb et al. (Beyond what is expressed in the relations above, there is no significant constraint on how light the dark matter particles can be; for example, particles produced initially as a cold Bose condensate, similar to axions, can have masses of order microelectron volts or smaller.)

How does the mean free path of the dark matter particles affect astrophysics? Since interactions only alter the evolution of cold dark matter when the density inhomogeneities are large, the cosmic microwave background (CMB) and large-scale power spectrum measurements are not sensitive to the self-interactions. So long as the dark matter is cold ($T_x/m_x < \Phi$, where $\Phi$ is the depth of the gravitational potential), the dark matter will collapse to form a bound halo regardless of its collisional properties. If the dark matter mean free path were much longer than $\sim 1$ Mpc, the typical dark matter particle would not experience any interactions as it moves through a halo. In this regime, the usual, triaxial cold dark matter halo with dense core forms through gravitational collapse. On the other hand, if the dark matter mean free path is much smaller than 1 kpc, then the dark matter behaves as a collisional gas and this alters the halo evolution significantly. The dark matter will shock: this will heat up the low entropy material that would usually
collapse to form a core and produce a shallower density profile. Since collisions tend to make the dark matter velocity distribution isotropic, the halo can not be triaxial and will only be elliptical if flattened by significant rotation. Since dark halos form with little angular momentum, if the dark matter is not dissipative, then all halos will be nearly spherical. X-ray observations of clusters reveal that most halos are moderately ellipsoidal. This implies that the collision time scale for dark matter near the half-mass radius of clusters must be longer than the Hubble time: one of the strongest constraints on this model. Studies suggest that polar ring galaxies are nearly isothermal spheres on the scale of one collision time, $t_c; \text{for a } 1 \text{kpc core and particle velocity of } 200 \text{ km/s, } t_c \approx 5 \times 10^9 (\lambda/1 \text{Mpc}) (v/200 \text{km/s})^{-1} \text{yr. Then, the time for core collapse is } \sim 300 \tau_r; \text{where the } \tau_r \text{ is the relaxation time for energy transport. To transport energy several kiloparsecs via self-interactions with mean free path of } 1 \text{kpc, say, the relaxation time is given approximately by the diffusion limit } \tau_r = t_d^2/t_c, \text{ where } t_d \approx R \text{ kpc}/(200 \text{km/s}) \text{ is the dynamical time at radius } R \text{ kpc from the core. Hence, the time for core collapse is approximately } 300 R^2 t_c, \text{ which is greater than a Hubble time. (If the mean free path, } \lambda, \text{ exceeds } R, \text{ then the diffusion limit does not apply and } \tau_r \approx t_c. \text{ A similar conclusion holds.)}

It should be emphasized that our proposal explores an intermediate regime in which the mean free path is longer than length scale of the smallest dwarfs but shorter than the length scale for the largest halos and comparable to structures in between. Hence, our estimates of ram pressure drag, core collapse, and the like can only be used as a rough guide. Detailed numerical simulations are essential to refine the estimates and perhaps to constrain further the viable range of self-interactions.

Even without numerical simulations, we can already make a number of predictions for the properties of galaxies in a self-interacting dark matter cosmology: (1) the centers of halos are spherical; (2) dark matter halos will have cores; and (3) substructure in the inner regions of groups and galaxies will be suppressed more rapidly than predicted in models with only tidal forces. The suppression of substructure will lead to fewer dwarf galaxies in groups, but the persistence of dwarfs in lower density environments. Intriguingly, current observations appear to be consistent with all of these predictions.

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[24] halo and satellite companion