CAN DARK MATTER BE SELF-INTERACTING?

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Abstract. Self-interacting dark matter could bring simulations of galaxy formation into better agreement with observations. However, the resulting energy transfer from the hotter to colder systems would tend to evaporate the dark matter halos of galaxies in clusters and dwarf galaxies within larger halos. Fundamental plane relations require that the halos survive for a Hubble time and appear to exclude the range of the cross-section thought to be optimal for reducing the central density, $0.3 < \sigma_p/m_p < 10^4$ cm^2 g^{-1}. These astrophysical considerations strongly constrain the properties of self-interacting dark matter particles.

1 Elliptical galaxies in clusters

Collisionless cold dark matter simulations seem to predict too many small halos and too steep central density profiles (Moore et al. 1999), in conflict with observations. To alleviate these problems, it has been recently suggested that dark matter particles can be self-interacting (Spergel & Steinhardt 2000). In a system of size r and density ρ, they would have the "optical depth" to scattering $\tau = (\sigma_p/m_p)\rho\, r$. For the right value of the scattering cross-section per unit particle mass, σ_p/m_p, the central cusps of large halos expand and form flat cores, while small halos evaporate. *However, the desired effects on one scale lead to undesired consequences on other scales* (Gnedin & Ostriker 2001).

In clusters of galaxies, heat conduction from the hot cluster halo leads to evaporation of the relatively cooler galactic halos. Depending on the cross-section, dark matter particles can behave either as a fluid ($\tau \gg 1$) or as a rarefied gas ($\tau \ll 1$). In the fluid regime, the mean free path of the particles is short and the heat diffuses from the hot cluster into the galaxy. We have solved the equations of hydrostatic equilibrium and heat transport for this case in the spherically-symmetric approximation.

As an example, we consider the heat diffusion into the halo of the elliptical galaxy NGC 4869 in the Coma cluster. The galaxy halo is initially a Hernquist model with virial mass $M = 3 \times 10^{11}\, M_\odot$ and radius $R = 28$ kpc, the cluster is similar to an isothermal sphere. In the fluid regime, the evolution proceeds on the conduction timescale, $t_0 = 6.5 \times 10^4\, (\sigma_p/m_p)\, (M/3 \times 10^{11}\, M_\odot)^{1/2}\, (R/28\,\mathrm{kpc})^{-1/2}$ yr. As the heat propagates from the cluster halo into the galaxy, the tidal boundary between the relatively hot and cold regions moves inward and the halo expands. As a result, the confining pressure drops and the temperature decreases in the middle part of the galactic halo that remains self-gravitating. At $t \approx 10\, t_0$ the whole galaxy becomes isothermal, but at $t = 14\, t_0$ the remains of the galaxy halo quickly evaporate and the temperature jumps to match the cluster profile.

Note, that the difference between forming a central core and evaporating the whole halo is no more than a factor of two in time. In order to achieve the desired result (core formation) but avoid the consequences (evaporation), the cross-section of self-interaction must be finely tuned for each system. In the fluid regime, the larger the cross-section the longer is the evaporation time, $t_{ev} \propto \sigma_p/m_p$.

In the optically-thin regime, direct collisions with much hotter cluster particles would unbind the galactic particles. The number of collisions is proportional to the cross-section, and therefore now $t_{ev} \propto (\sigma_p/m_p)^{-1}$. The two regimes match when the optical depth at the tidal radius is of order unity, $\tau_t \approx 1$ at $\sigma_p/m_p = 50$ cm^2 g^{-1}.

Figure 1 shows the range of the cross-section that appears to be excluded by the requirement that the galactic halos survive for a Hubble time. (Large elliptical galaxies must retain their halos in order to satisfy the same fundamental plane relation as the field ellipticals, as the left panel of Figure 1 demonstrates). This range includes the values $\sigma_p/m_p \sim 1 - 10$ cm^2 g^{-1} that might lead to a desired reduction of the central density in the Milky Way-type halo (see Wandelt et al. 2001).

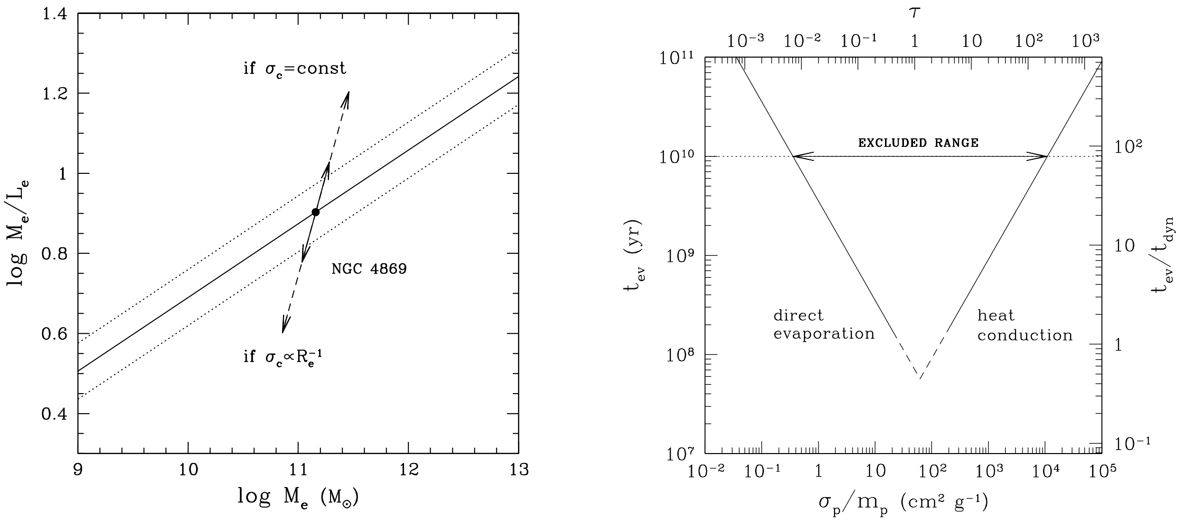

Figure 1: *Left panel:* Fundamental plane relation for the elliptical galaxies (solid line) and its scatter (dots). The half-light mass-to-light ratio M_e/L_e is in solar units. If NGC 4869 loses its dark matter halo, the stellar profile would expand and deviate from the plane either upward (if the core velocity dispersion stays constant as the effective radius increases) or downward (if $\sigma_c \propto R_e^{-1}$). The length of solid arrows is calculated using $f_{dm} = 0.25$, a minimum dark matter fraction within R_e determined from X-ray data (Loewenstein & White 1999), while dashed arrows are for the best-fitting model, $f_{dm} = 0.5$. *Right panel:* Evaporation time of the dark matter halos of elliptical galaxies in clusters in the fluid ($\tau_t > 1$) and scattering ($\tau_t < 1$) regimes. The lines broke into dashes in the marginal range, for the optical depth at the tidal radius $1/3 < \tau_t < 3$. The arrows indicate the range of the cross-section excluded by the requirement that the halos survive for 10^{10} yr.

2 Dwarf galaxies in the Local Group

If the cross-section varies with the relative velocity of dark matter particles, $\sigma = \sigma_p\,(v/v_p)^{-2\delta}$, dwarf galaxies can evaporate even when large galaxies are safe. Suppose we fix the parameters for the large elliptical NGC 4869, $\sigma_p/m_p = 0.1$ cm^2 g^{-1} and $v_p = 1000$ km s^{-1}. In the optically-thin regime, the relative velocity is dominated by the velocity dispersion of the hotter particles. The cross-section would remain the same for the cluster galaxies, but would increase sharply for the dwarf spheroidals in the Milky Way halo. These galaxies are entirely dark matter-dominated and must retain their halos. This limits the slope δ.

If the cores of the dwarf galaxies become optically-thick, the cross-section soars by another factor $(v_{\rm hot}/v_{\rm cold})^{2\delta}$. In this case, heat conduction may become unimportant for a very large δ. Combining the two regimes seems to exclude $1.1 < \delta < 1.8$. (The lower limit is further reduced for a larger normalization σ_p/m_p.) However note, that Hennawi & Ostriker (2001) find the case $\delta = 0 - 0.5$ interesting for growing supermassive black holes by accretion of dark matter particles.

References

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