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The mass of the dark matter particle: Theory and galaxy observations

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ABSTRACT

In order to determine as best as possible the nature of the dark matter (DM) particle (mass and decoupling temperature) we compute analytically the DM galaxy properties as the halo density profile, halo radius and surface density and compare them to their observed values. We match the theoretically computed surface density to its observed value in order to obtain: (i) the decreasing of the phase-space density since equilibration till today (ii) the mass of the dark matter particle and the decoupling temperature T_d (iii) the kind of the halo density profile (core or cusp). The dark matter particle mass turns to be between 1 and 2 keV and the decoupling temperature T_d turns to be above 100 GeV. keV dark matter particles necessarily produce cored density profiles while WIMPS ($m \sim 100$ GeV, $T_d \sim 5$ GeV) inevitably produce cusped profiles at scales about 0.003 pc. We compute in addition the halo radius r_0, the halo central density ρ_0 and the halo particle r.m.s. velocity $\overline{v^2}^{1/2}_{\rm halo}$ they all reproduce the observed values within one order of magnitude. These results are independent of the particle physics model and vary very little with the statistics of the dark matter particle. The framework presented here applies to any kind of DM particles: when applied to typical CDM GeV WIMPS, our results are in agreement with CDM simulations. keV scale DM particles reproduce all observed galaxy magnitudes within one order of magnitude while GeV DM mass particles disagree with observations in up to eleven orders of magnitude.

1. Introduction

Since several years and more recently (Persic et al., 1996; Disney et al., 2008; Garcia-Appadoo et al., 2009; van den Bergh, 2008) it has been stressed that basic galaxy parameters as mass, size, baryon-fraction, central density, are not independent from each other but in fact all of them do depend on one parameter that works as a galaxy identifier. In fact there exist functional relations that constrain the different galaxy parameters in such a way that the galaxy structure depends essentially on one parameter (Salucci et al., 2007 and references therein).

These functional relations may play for galaxies the rôle that the equations of state play in thermodynamical systems.

First, let us remind that the density of DM in galaxies is usually well reproduced by dark halos with a cored distribution (de Blok, 2010; Salucci and Frigerio Martins, 2009), where r_0 is the core radius, ρ_0 is the central density $\lim_{r\to 0}\rho(r) = \rho_0$ and $\rho(r)$ for $r < r_0$ is approximately constant. Recent findings highlight the quantity $\mu_0 \equiv r_0\rho_0$ proportional to the halo central surface density defined as

$$2\int_0^\infty \rho(0,0,x_3)\,dx_3 \quad \text{where } \vec{r} = (x_1,x_2,x_3)$$

where x_3 goes along the line of sight. The quantity μ_0 is found nearly *constant* and independent of luminosity in different galactic systems (spirals, dwarf irregular and spheroidals, elliptics) spanning over 14 magnitudes in luminosity and over different Hubble types. More precisely, all galaxies seem to have the same value for μ_0, namely $\mu_0 \simeq 120 M_\odot/\text{pc}^2$ (Kormendy and Freeman, 2004; Donato et al., 2009; Spano et al., 2008). It is remarkable that at the same time other important structural quantities as r_0, ρ_0, the baryon-fraction and the galaxy mass vary orders of magnitude from one galaxy to another.

The constancy of μ_0 is unlikely to be a coincidence and probably has a deep physical meaning in the process of galaxy formation. It must be stressed that μ_0 is the only dimensionful quantity which is constant among galaxies.

By analogy with the theory of phase transitions in statistical physics we find useful to call 'universal' those quantities which take the same value for a large set of galaxies while non-universal quantities vary orders of magnitude from one galaxy to another. In

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this context the quantities called universal take the same value up to ±20% for different galaxies.

Other known universal quantity in the above sense is the shape of the density profile when expressed as a function of r/r_0 and normalized to unit at $r = 0$.

In order to understand the above observations, we compute here from the Boltzmann–Vlasov equation (Dodelson, 2003; Kolb and Turner, 1990) the DM density profile and the surface density μ_0 for different types of DM.

In this paper, we follow the evolution of the gravitational collapse of a perturbation of mass $M \sim 3 \times 10^{12} M_\odot$ and derive the resulting linear halo density profile. This reproduces the phase of fast accretion found in *N*-body simulations. As a result, we obtain robust predictions for the properties of DM halos.

In the case of ΛCDM our results agree with the *N*-body ΛCDM simulations and in the case of ΛWDM our results agree with the observations.

We obtain a very good fit of the computed profile to the Burkert profile. This determines the relation between r_0 and the free-streaming length.

We also compute non-universal galaxy quantities as the halo radius, galaxy mass, halo central density and squared halo velocity. We find that the linear approximation provides halo central densities smaller than or in the range of the observations, and halo velocities larger than the observed ones by a factor between 1 and 10. We thoroughly analyze in our paper the validity of the linear approximation to study galaxy properties and its limitations. Notice that our determination of the DM particle mass does not relay to these non-universal galaxy quantities.

We combine the observed properties of galaxies as the effective core density and the core radius with the theoretical evolution of density fluctuations computed from first principles.

We consider in this paper the whole range of galaxy virial masses going from 5 to $300 \times 10^{11} M_\odot$.

The theoretical treatment presented here captures many essential features of dark matter, allowing to determine its nature.

Our treatment also applies to CDM: if we use the CDM surface density value obtained from CDM simulations (Hoffman et al., 2007), we determine (Section 9) a dark matter particle mass in the WIMPS mass scale (GeV), fully consistent with CDM simulations.

This paper is organized as follows: Section 2 presents galaxy data and empirical formulas relating basic galaxy parameters; Section 3 deals with the phase-space density; Section 4 contains our theoretical results for the density profile from the linearized Boltzmann–Vlasov equation. In Section 5 we derive the DM particle mass and the decoupling temperature from the theoretical and observed galaxy surface density, in Section 6 we compute non-universal galaxy properties and in Section 7 we derive the profiles for keV scale DM particles and for WIMPS (cored vs. cusped profiles). In Section 8 we present our conclusions.

2. DM halos around galaxies: the observational framework

The kinematics of about several thousands disk galaxies, described by the Universal Rotation Curves of Spirals, and the information obtained from other tracers of the gravitational field of galaxies, including the dispersion velocities of spheroidals and the weak lensing measurements (Salucci et al., 2007 and references therein) found that the density of the dark matter halos around galaxies of different kinds, different luminosity and Hubble types is well represented, out to the galaxy virial radius, by a Burkert profile

$$\rho(r) = \rho_0 F_B\left(\frac{r}{r_0}\right), \quad F_B(x) = \frac{1}{(1+x)(1+x^2)}, \quad x \equiv \frac{r}{r_0}, \tag{1}$$

where ρ_0 stands for the effective core density and r_0 for the core radius. The Burkert profile satisfactorily fits the astronomical observations and we use the observed values of ρ_0 vs. r_0 for DM dominated spiral galaxies given in Salucci et al. (2007).

The structural halo parameters ρ_0 and r_0 are found to be related, it is worth to compute from them the virial mass $M_{\rm vir}$ in terms of the core radius r_0 (Salucci et al., 2007 and references therein)

$$m_v \equiv \frac{M_{\rm vir}}{10^{11} M_\odot} = 0.320 \left(\frac{r_0}{\rm kpc}\right)^{1.72}. \tag{2}$$

The surface density μ_0 is defined as:

$$\mu_0 \equiv \rho_0 r_0 \tag{3}$$

We display in Table 1 the values of the observed surface density $\mu_{0\,\rm obs}$ in $({\rm MeV})^3/(\hbar^2 c^4)$ and the corresponding core radius r_0. We plot in Fig. 1 the observed surface density $\mu_{0\,\rm obs}$ in $({\rm MeV})^3/(\hbar^2 c^4)$ vs. the core radius r_0.

Notice that in galaxies both r_0 and ρ_0 vary by a factor 10^3 while μ_0 varies only by less than ±20%. 5 kpc $\lesssim r_0 \lesssim$ 50 kpc for normal spiral galaxies. Therefore, as stressed by Kormendy and Freeman (2004), Donato et al. (2009), Spano et al. (2008) the surface density is a constant over a large number of galaxies of different kinds.

Notice that the surface density of ordinary matter in luminous galaxies is about a factor 4 larger than the surface density value for dark matter (Gentile et al., 2009). Clusters of galaxies, exhibit

Table 1
The observed core radius r_0 and the observed surface density $\mu_{0\,\rm obs}$.

r_0 (kpc)	$\mu_{0\,\rm obs}$ (MeV^3)
4.8	0.63×10^4
6.1	0.64×10^4
7.9	0.63×10^4
10.2	0.62×10^4
13.3	0.61×10^4
17.3	0.60×10^4
22.6	0.60×10^4
29.4	0.59×10^4
38.7	0.57×10^4
51.8	0.55×10^4

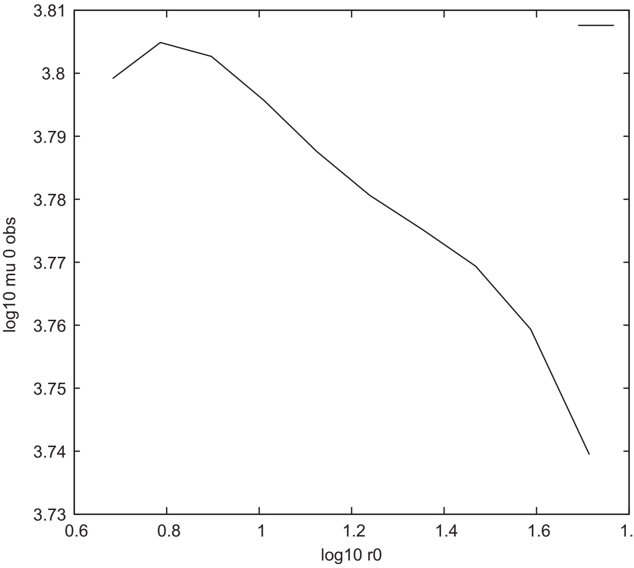

Fig. 1. The common logarithm of the observed surface density $\mu_{0\,\rm obs}$ in $({\rm MeV})^3/(\hbar^2 c^4)$ vs. the common logarithm of the core radius r_0 in kpc. Notice that in galaxies both r_0 and ρ_0 vary by a factor of thousand while μ_0 varies only by about ±20%.