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A constant dark matter halo surface density in galaxies

F. Donato,[1★] G. Gentile,[2,3] P. Salucci,[4] C. Frigerio Martins,[5] M. I. Wilkinson,[6]
G. Gilmore,[7] E. K. Grebel,[8] A. Koch[9] and R. Wyse[10]

[1] *Università degli Studi di Torino and INFN, via Giuria 1, 10125 Torino, Italy*
[2] *Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles, CP 226, Boulevard du Triomphe, B-1050 Bruxelles, Belgium*
[3] *Sterrenkundig Observatorium, Ghent University, Krijgslaan 281, S9, B-9000 Ghent, Belgium*
[4] *Department of Astrophysics, SISSA, via Beirut, 2-4, 34014 Trieste, Italy*
[5] *Universidade Federal do ABC, Rua Catequese 242, 09090-400 Santo André, Brazil*
[6] *Department of Physics and Astronomy, University of Leicester, University Road, Leicester LE1 7RH*
[7] *Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 OHA*
[8] *Astronomisches Rechen-Institut, Zentrum für Astronomie der Universität Heidelberg, Mönchhofstr 12-14, D-69120 Heidelberg, Germany*
[9] *Department of Physics and Astronomy, UCLA, 430 Portola Plaza, Los Angeles, CA 90095-1547, USA*
[10] *Johns Hopkins University, 366 Bloomberg Center, 3400 North Charles Street, Baltimore, MD 21218, USA*

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ABSTRACT

We confirm and extend the recent finding that the central surface density $\mu_{0D} \equiv r_0\rho_0$ of galaxy dark matter haloes, where r_0 and ρ_0 are the halo core radius and central density, is nearly constant and independent of galaxy luminosity. Based on the co-added rotation curves (RCs) of ∼1000 spiral galaxies, the mass models of individual dwarf irregular and spiral galaxies of late and early types with high-quality RCs, and the galaxy–galaxy weak-lensing signals from a sample of spiral and elliptical galaxies, we find that $\log \mu_{0D} = 2.15 \pm 0.2$ in units of $\log(\mathrm{M}_\odot\ \mathrm{pc}^{-2})$. We also show that the observed kinematics of Local Group dwarf spheroidal galaxies are consistent with this value. Our results are obtained for galactic systems spanning over 14 mag, belonging to different Hubble types and whose mass profiles have been determined by several independent methods. In the same objects, the approximate constancy of μ_{0D} is in sharp contrast to the systematical variations, by several orders of magnitude, of galaxy properties, including ρ_0 and central stellar surface density.

Key words: galaxies: kinematics and dynamics – galaxies: spiral – dark matter.

1 INTRODUCTION

It has been known for several decades that the kinematics of disc galaxies exhibit a mass discrepancy (e.g. Bosma 1978; Bosma & van der Kruit 1979; Rubin, Thonnard & Ford 1980). More precisely, spirals show an inner baryon dominance region (e.g. Athanassoula, Bosma & Papaioannou 1987; Persic & Salucci 1988; Palunas & Williams 2000), whose size ranges between 1 and 3 disc exponential length-scales according to the galaxy luminosity (Salucci & Persic 1999), inside which the observed ordinary baryonic matter accounts for the rotation curve (RC), but outside which, the distribution of the baryonic components cannot justify the observed *profiles* and sometimes the *amplitudes* of the measured circular velocities (Bosma 1981, see also Gentile et al. 2007a,b). This is usually solved by adding an extra mass component, the dark matter (DM) halo. RCs have been used to assess the existence, the amount and the distribution of this dark component. Recent debate in the literature has focused on the 'cuspiness' of the DM density profile in the centres of galaxy haloes that emerges in cold dark matter (CDM) simulations of structure formation (Navarro, Frenk & White 1996, NFW hereafter; Moore et al. 1999; Navarro et al. 2004; Neto et al. 2007), but is not seen in observed data (e.g. de Blok, McGaugh & Rubin 2001; de Blok & Bosma 2002; Marchesini et al. 2002; Gentile et al. 2004, 2005, 2007a), as well as in the various systematics of the DM distribution (see Salucci et al. 2007).

An intriguing general property of DM haloes was noted by Kormendy & Freeman (2004), based on halo parameters obtained by mass modelling 55 spiral galaxy rotation curves within the framework of the maximum disc hypothesis (MDH), whose validity has been much debated (Salucci & Persic 1999; Palunas & Williams 2000; Bosma 2004). Among other relations between the halo parameters, they found that the quantity $\mu_{0D} \equiv \rho_0 r_0$, proportional to the halo central surface density for any cored halo distributions, is nearly independent of the galaxy blue magnitude. Here, ρ_0 and r_0 are, respectively, the central density and core radius of the adopted pseudo-isothermal cored DM density profile $\rho(r) = \rho_0 r_0^2/(r^2 + r_0^2)$. In particular, they found that this quantity takes a value of $\sim 100\,\mathrm{M}_\odot\ \mathrm{pc}^{-2}$. The Kormendy and Freeman analysis relies on the MDH, which fixes the value of the disc mass at its maximum

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★E-mail: donato@to.infn.it

compatible with the observed rotation curve, under the reasonable hypothesis that mass follows light in the disc and that the halo is not hollow. From the value of the disc mass, RC fitting yields the values of the two structural DM parameters (i.e. r_0 and ρ_0). As a matter of fact, MDH allows to *uniquely* decompose the RCs – also those that, in terms of extension, spatial resolution, rms errors, non-axisymmetric motions, cannot be *successfully* analysed by χ^2 method assuming mass models with also the disc mass as a free parameter. The MDH, on the other hand, may strongly bias the determination of the halo properties in the case in which stars do not dominate the inner parts of a galaxy.

More recently, Spano et al. (2008) χ^2 fitted the RCs of 36 spiral galaxies by using a mass model with a stellar disc and a cored dark sphere of density

$$\rho(r) = \frac{\rho_0}{\left[1 + \left(\frac{r}{r_0}\right)^2\right]^{3/2}}. \qquad (1)$$

The *R*-band surface brightness, via the assumption of a constant mass-to-light ratio for the stellar component, provided the *profile* of the stellar contribution to the circular velocity. They showed that

$$\log \frac{\mu_{0\mathrm{D}}}{\mathrm{M}_\odot\,\mathrm{pc}^{-2}} = 2.2 \pm 0.25 \qquad (2)$$

or $\mu_{0\mathrm{D}} = 150^{+100}_{-70}\,\mathrm{M}_\odot\,\mathrm{pc}^{-2}$, consistent with the findings of Kormendy & Freeman 2004.

In this paper, we will investigate the $\mu_{0\mathrm{D}}$ versus magnitude relationship for objects whose central densities and core radii vary by several orders of magnitude. We aim to investigate the above galaxy relationship by applying a number of unbiased techniques of DM decomposition to new large samples of galaxies of different Hubble type and magnitudes. Given the wide-ranging nature of the data and of the mass modelling involved in the present investigation, there is very little likelihood of obtaining a false-positive result due to systematic errors and biases in the analysis or in the data.

We will investigate: (i) a large sample of spiral galaxies, analysed by χ^2 fitting their universal rotation curve (URC; Persic, Salucci & Stel 1996, hereafter as PSS); (ii) NGC 3741, the most DM dominated spiral in the local Universe and DDO 47, a very well studied dwarf spiral (Gentile et al. 2005) by χ^2 modelling their kinematics; (iii) the H I Nearby Galaxy Survey (THINGS) sample (Walter et al. 2008): disc galaxies with high quality RCs that have been mass modelled in *two* independent ways, (a) by the standard χ^2 technique and (b) by assuming the value of the stellar disc mass from the galaxy colour according to the prescription of spectro-photometric galaxy models; (iv) a sample of Sa galaxies by χ^2 modelling their kinematics; and (v) a large sample of spiral and elliptical galaxies, by χ^2 mass-modelling the available weak-lensing shear measurements. We, therefore, investigate equation (2) in a much wider range of Hubble types and magnitudes and by exploiting a larger number of techniques than previous works. Finally, we test the value of $\mu_{0\mathrm{D}}$ with the kinematics of six dwarf spheroidal (dSph) satellite galaxies of the Milky Way for which extensive stellar kinematic data sets are available.

In all cases, a cored DM halo provides a very satisfactory fit to the observed data, generally superior to that obtained by assuming a NFW profile for the DM halo. The success of the simple stellar disc + Burkert cored halo + H I disc model in accounting for the available kinematics (both in absolute terms and with respect to different halo models) is a strong support for the reliability of the derived halo structural parameters. It is not an aim of this paper to directly test the NFW halo profile, and we will exclusively work in the alternative framework of the cored halo profiles.

With the exception of the weak-lensing analysis and of dSph galaxies, the mass models used in this paper have been obtained elsewhere, in papers to which we redirect the reader for further information.

In Section 2, we compute the quantity $\mu_{0\mathrm{D}}$ for different families of galaxies, work out its relation with galaxy magnitude. A discussion of our result is given in Section 3.

2 THE $\rho_0 r_0$ VERSUS MAGNITUDE RELATIONSHIP

In this paper, we assume that the DM halo in each galaxy follows the Burkert profile (Burkert 1995):

$$\rho(r) = \frac{\rho_0\, r_0^3}{(r + r_0)\left(r^2 + r_0^2\right)}. \qquad (3)$$

This profile, when combined with the appropriate baryonic gaseous and stellar components, is found to reproduce very well the available kinematics of disc systems (Salucci & Burkert 2000; Salucci, Walter & Borriello 2003; Gentile et al. 2004; see Gentile et al. 2007a for the case of the most extended RC). Moreover, it leads to estimates of the disc mass in good agreement with the expectations from stellar population synthesis models (e.g. Gentile et al. 2004; Salucci, Yegorova & Drory 2008; Spano et al. 2008; see also Frigerio Martins & Salucci 2007). The existence of a constant central surface density of DM in galaxies does not depend on which specific (cored) density profile is assumed for the DM, i.e. whether we adopt any of the following: Spano et al. (2008; labelled as S hereafter), Donato et al. (2004; D) or the present one (B). Different *cored* mass models provide equally good fits to the same kinematical data sets (e.g. Gentile et al. 2004). All of them can describe the actual halo mass profile $M_\mathrm{h}(r, act)$ in the core region by tuning the values of the central density and of core radius. The relations $M_\mathrm{h}(r, act) = M_\mathrm{h}(r, B) = M_\mathrm{h}(r, S) = M_\mathrm{h}(r, D)$ must hold, thus providing us with the proportionality factors between the corresponding parameters (core radius and central density) of different profiles. We find: $\log \mu_{0\mathrm{D}}(B) = \log \mu_{0\mathrm{D}}(D) + 0.24 = \log \mu_{0\mathrm{D}}(S) + 0.1$. We use this small corrections to compare the values of $\mu_{0\mathrm{D}}$ relative to different halo profiles. Of course, at outer radii – outside the core region and often outside the last measured point – each cored model has a different well distinct velocity behaviour.

One of the advantages of the adopted Burkert halo profile is that, at small radii and for appropriate values of the parameter r_0, it can reproduce the NFW velocity profiles to which, in any case, it converges for $r > 0.3 R_\mathrm{vir}$. Therefore, with the adopted profile, the RC data themselves discriminate, by determining the value of the best-fit parameter r_0, the actual level of cuspiness of the halo.

Donato, Gentile & Salucci (2004) analysed the mass profiles of 25 spiral and low-surface brightness (LSB) galaxies obtained by χ^2 modelling their RCs. The successful models had cored DM halo profiles whose core radii correlated strongly with the exponential disc scale length R_D of their stellar distributions. In Fig. 1, we plot $\mu_{0\mathrm{D}}$ as a function of R_D for the Donato et al. (2004) sample. We see that the derived values for $\mu_{0\mathrm{D}}$ are almost constant, although R_D varies by more than one order of magnitude, consistently with the findings of Spano et al. (2008) and Kormendy & Freeman (2004). In addition, there is no obvious difference between the results from high-surface brightness (HSB) galaxies and LSB galaxies. While this result is in good agreement with equation (2), it is important to note that the two samples are similar, with five objects in common, and the analysis employed is essentially the same.

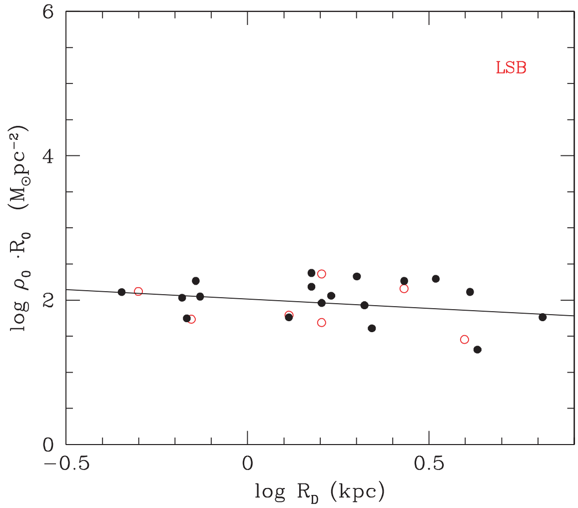

Figure 1. The central halo surface density $\rho_0 r_0$ as a function of disc scale-length R_D for the Donato et al. (2004) sample of galaxies. Open and filled circles refer to LSB and HSB galaxies, respectively. The solid line is our best fit to the data.

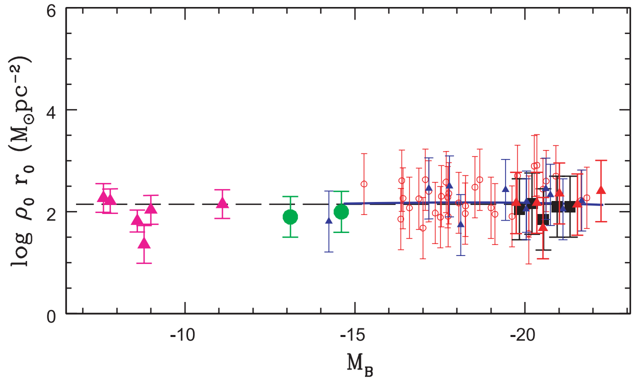

Figure 2. $\rho_0 r_0$ in units of $\mathrm{M}_\odot$ pc^{-2} as a function of galaxy magnitude for different galaxies and Hubble types. The original Spano et al. (2008) data (empty small red circles) are shown as a reference of previous work. The new results come from: the URC (solid blue line), the dwarf irregulars (full green circles) N 3741 ($M_B = -13.1$) and DDO 47 ($M_B = -14.6$), spirals and ellipticals investigated by weak lensing (black squares), dSphs (pink triangles), nearby spirals in THINGS (small blue triangles), and early-type spirals (full red triangles). The long-dashed line is the result of this work.

Before adding new crucial evidences for a relationship like equation (2), we would like to stress again that this will come from mass modelling techniques that are unbiased towards any particular DM profile, and unable to artificially create spurious relationship between the DM mass parameters.

It is useful to recall the evidence from which we start (see Fig. 2): the relation found by Spano et al. (2008) for 36 spirals and the above $\mu_0 D$ versus R_D relationship for the 25 spirals of the Donato et al. (2004) sample, both in qualitative agreement with Kormendy & Freeman (2004).

We now calculate the central surface density μ_{0D} for the family of spirals by means of their URC (PSS). This curve, *on average*, reproduces well the RCs of late-type (Sb-Im) spirals out to their virial radii $R_{\rm vir}$ (PSS; Salucci et al. 2007). The URC is built from (i) the co-added kinematical data of a large number of spirals (PSS; see also Catinella, Giovanelli & Haynes 2006) and (ii) the disc mass versus halo virial mass relationship of Shankar et al. (2006). By χ^2 fitting the URC with a Burkert halo + a Freeman disc velocity model, with no assumptions on the amount of baryonic matter, we obtain ρ_0 and r_0 as the best-fit values (see equations 6a, 7 and 10 of Salucci et al. 2007). The corresponding μ_{0D} values are plotted versus M_B as a solid line in Fig. 2. The URC, derived from co-added rotation curves of objects with the same luminosity, traces their ensemble-averaged gravitational potential. This is extremely useful: the consequent mass model is free from the particularities (internal rms, non-axisymmetric motions, observational errors) that affect, at different levels, almost every *individual* rotation curve and the ensuing mass model; these particularities, in fact, get averaged out in the URC construction.

On the other hand, for the task of determining the DM structure parameters, the co-added RCs are not sufficient in that, at a fixed luminosity, there could be a cosmic variance around 'the average galaxy'. Then, in order to assess the universality of equation (2), we will investigate the DM mass structure in individual objects supplementing new observational data to those of Kormendy & Freeman (2004), Spano et al. (2008) and of Donato et al. (2004).

de Blok et al. (2008) measured high-resolution rotation curves for a sample of late spirals belonging to THINGS. We select from this sample the objects in which the mass modelling yields reliable estimates of the DM structural parameters. We have rejected objects in which (i) the kinematics is clearly affected by non-circular motions, (ii) the stellar mass component strongly dominates the galaxy potential out to the last measured point, preventing us from determining the properties of the underlying DM halo or (iii) very different models are found to equally fit the RC. With these selection criteria, we rejected six galaxies out of 17. This selection, though mandatory to successfully probe the DM potential (e.g. Lake & Feinswog 1989), limits the investigation of the DM distribution of galaxies by means of their kinematics and photometry. For instance, we can use only objects in which (i) *both* dark component and the stellar components *of known distribution* affect (at different radii) the available kinematics in a clear way (ii) non-circular motions are modest.

The rotation curves in the Blok et al.'s THINGS sample were modelled with a spherical pseudo-isothermal dark halo plus an H I disc and a stellar disc whose free mass parameters are obtained by χ^2 fits. In addition to the standard method in which the stellar mass-to-light ratio is a free parameter, they also modelled their RCs by assuming for the latter quantity the values obtained from the galaxy colours as predicted by spectro-photometric models with a (i) diet-Salpeter or a (ii) Kroupa initial mass function (IMF). For each object, we take their results in the following way: we average the value of $\rho_0 r_0$ obtained by the latter two methods, and then we average the result with the value obtained by the unconstrained mass model. Note that we take also the values of $\rho_0 r_0$ coming from the spectro-photometric method of mass modelling, although the latter may be less accurate than the χ^2 one (e.g. Salucci et al. 2008), because we want an independent check on the mass modelling procedure. In any case, the values obtained by χ^2 fits are within the shown error bars.

We found that the galaxies DDO 154, N 925, N 2366, N 2403, I 2574, N 2976, N 3198, N 3621, N 5055, N 6946, N 7331 satisfy the above discussed selection criteria. The resulting mass models well reproduce the RCs, and the relative halo parameters are derived within a reasonable uncertainty ($\leq$50 per cent). The resulting values of μ_{0D} are plotted in Fig. 2.

We extend the relationship down to the lowest luminosities of disc systems by means of the nearby dwarf galaxy NGC 3741 ($M_B = -13.1$): it represents the very numerous dwarf disc objects which are DM dominated down to one disc length-scale or less, and in which the H I gaseous disc is the main baryonic component. In addition, this galaxy has an extremely extended H I disc, which allowed Gentile, Tonini & Salucci (2007b) to carefully trace the RC and, therefore, its gravitational potential out to unprecedented distances, relative to the extent of the optical disc. The data probe a region out of 7 kpc (equivalent to 42 B-band exponential scale-lengths) with several independent measures within the estimated halo core radius. By standard χ^2 fitting, the RC was decomposed into its stellar, gaseous and dark (Burkert halo) components. The resulting best-fit mass model very well reproduces the observed RC (Gentile et al. 2007b): the corresponding $\mu_{0\mathrm{D}}$ is plotted in Fig. 2 as a filled green circle. This result is seconded by DDO 47, another faint dwarf spiral. Gentile et al. (2005) have mass modelled its RC in the same way as described above. We plot the relevant quantities in Fig. 2 as another filled green circle, at $M_\mathrm{B} = -14.6$. The relatively large error bars of both estimates are due to uncertainties in the distance, that affects any nearby object, and not by the mass model itself, which is virtually free from the uncertainties in the estimate of the mass of the stellar disc (which for these object is negligible).

It is worth to note that Burkert (1995), in his pioneering study on the DM structure in galaxies, for a handful of dwarfs with absolute blue magnitudes ranging between -14.5 and -17.0 and modelling their low spatial resolution H I RCs, found values of r_0 and ρ_0 that lead, in these objects, to $90 \le \mu_{0\mathrm{D}}/(\mathrm{M}_\odot\ \mathrm{pc}^{-2}) \le 140$ in agreement with our results.

To investigate the opposite end of Hubble spiral sequence, i.e. the Sa galaxies, disc systems embedded in a relevant spheroidal stellar component, we resort to the mass models that have become recently available (Noordermeer 2006; Noordermeer et al. 2007). From this sample, using to the selection criteria discussed above, we take the following galaxies: N 2487, N 2916, N 2953, N 3546, UGC 8699, UGC 11852.

We reject 11 galaxies out of 17. Note that, only for a small fraction of the rejected objects in the THINGS and Noordermeer sample, the failure of the mass modelling is due to poor kinematics. In most of the cases, it originates from the presence of a strong inner dominance on the galaxy dynamics of *two* baryonic components (the disc and the bulge), and it may reflect an intrinsically complex inner mass distribution. On the other hand, systems with a multicomponent strong central baryonic mass concentration likely underwent secular physical processes that may have affected the original distribution of the DM halo (Heller, Shlosman & Athanassoula 2007; Athanassoula 2008) making them complex systems that must be investigated more accurately by future studies.

The mass models are based on RC χ^2 decompositions that include a stellar bulge, a stellar disc, a neutral gas disc and a pseudo-isothermal (cored) DM halo. The resulting $\mu_{0\mathrm{D}}$ are plotted in Fig. 2.

We now derive the galaxy mass distribution by measuring their gravitational potential in a different way from that employed so far. This will test both the observational data and the fundamental assumptions underlying the results shown above. From the galaxy–galaxy weak-lensing signals of a large sample of spiral and elliptical galaxies, we determine their DM distribution. The basic data are the azimuthally-averaged tangential shear $\gamma(r)$ recently measured for a sample containing about 10^5 isolated objects split into five luminosity bins (Hoekstra et al. 2005), as a function of the galactocentric radius. The sample spans a good luminosity range of spirals, while the most luminous bins are likely dominated by the biggest ellipticals in the local Universe. Data extend from $R_i = 70$ kpc out to $R_f = 560$ kpc from the centre of the lenses. In this radial range, the galaxy stellar component (a Freeman disc for spirals, a Sersic spheroid for ellipticals) contributes negligibly to the shear: the spheroid half-light radius does not reach 10 kpc, a distance $\ll R_i$. The mass model, therefore, includes only a (Burkert) dark halo. Note, however, that, while we need kinematical data at radii well inside r_0 to detect in a RC a Burkert core (of size r_0), in the tangential shear, instead, the effect of a Burkert profile extends further out, up to $2\,r_0$, i.e. for the most luminous objects, it extends out to $\sim R_i$. The present weak-lensing data are (marginally) able to measure the values of ρ_0 and r_0. Formally these are obtained by χ^2 modelling $\gamma(r)$ with a Burkert mass profile. The details are presented in Appendix A and the resulting $\mu_{0\mathrm{D}}$ are plotted in Fig. 2 (as solid squares). Thus, we applied the same technique to the same kind of data both for spirals (all luminosity bins but the last) and for ellipticals (the last bin). We found no difference in the DM profile systematics and in particular in the value of $\mu_{0\mathrm{D}}$. Then, from our collection of values, at the level of 0.2 dex, no substantial differences emerge between the values of $\mu_{0\mathrm{D}}$ estimated from different types of data or between spiral and elliptical galaxies. It thus appears that the central surface density of DM haloes assumes a nearly constant value with respect to galaxy luminosity, over a range of at least 9 mag.

For illustrative purposes, we compare our results with those of Spano et al. (2008). We plot their data in Fig. 2. Let us remark that their data are not included in our present sample: indeed, because we want to raise our claim in an independent way from their work, and their data are used as a consistency check. However, we remove two objects with an enormous uncertainty (i.e. greater than a factor of 10) on the best-fit value of one of the two parameters r_0, ρ_0 (private communication, UGC 3876 and UGC 4456).

2.1 Milky Way satellites

This result can be extended to lower magnitudes by means of the Milky Way satellite dwarf spheroidal (dSph) galaxies, the smallest and most DM dominated systems known in the universe (see e.g. Mateo 1998; Gilmore et al. 2007, and references therein). Their low H I gas content is another property that sets them apart as a galaxy class (e.g. Grebel, Gallagher & Harbeck 2003). In a recent study of six dSphs Gilmore et al. (2007) showed by χ^2 techniques that, assuming spherical symmetry and velocity isotropy, the stellar kinematics and photometry of dSphs are consistent with their occupying cored DM haloes. Our current lack of knowledge about the anisotropy of the stellar velocity distribution makes their density profiles not uniquely constrained by the data. Cusped models can also reproduce the dispersion velocity data in most dSphs (Gilmore et al. 2007; Koch et al. 2007; Battaglia et al. 2008), modulus an appropriate run with radius of the anisotropy parameter. Bearing this caveat in mind, we will assume spherical symmetry and velocity isotropy in estimating $\mu_{0\mathrm{D}}$. The observed stellar density $\nu(r)$ distribution is well represented by a Plummer sphere: $\nu(r) \propto [1 + (r/a)^2]^{-5/2}$ with a the half light radius. This stellar spheroid is tracer of but a negligible source for the gravitational potential: its mass is only 10^{-3} times the dark mass inside a (Gilmore et al. 2007). The full mass modelling of these objects are given in Salucci et al. (2009). Here, we compute the relevant structural parameters with a simplified approach. We realize that the one-dimensional stellar velocity dispersions $\sigma(r)$ are radially very slowly varying and we assume, for the purpose of this work, that is constant: $\sigma(r) = \sigma_0$. Therefore, within the above assumptions, from the Jeans equation the halo mass can be computed by: $G^{-1}\,\frac{r^2}{\nu(r)}\,\frac{\mathrm{d}\nu(r)}{\mathrm{d}r}\,\sigma_0^2$ that leads to $5G^{-1}\,\frac{r^3}{a^2(\frac{r^2}{a^2}+1)}\ \sigma_0^2$ with the values of σ_0 and a given in Gilmore et al. (2007). The r^3 dependence at small radii indicates the presence of a core. Indeed, the above mass distribution can be successfully fit by a Burkert profile with a $r_0 \simeq a$ and $\rho_0 \simeq 2.7\, G^{-1}\sigma_0^2/a^2$. The corresponding $\mu_{0\mathrm{D}}$ are plotted in Fig. 2 as triangles with the error bars reflecting the statistical errors in the estimation of the parameters from the observed data.

As a result, the values $\mu_{0\mathrm{D}}$ keep constant around $\simeq 100\,\mathrm{M}_{\odot}\,\mathrm{pc}^{-2}$ also for this sample of dwarf galaxies. This outcome is far from trivial. In dSphs, both the central halo density and the core radius take much higher and much smaller values with respect to those of the faintest spirals, which are objects 5 mag brighter. Such variations are nevertheless fine-tuned so that the product $\rho_0 r_0$ remains almost constant, despite the strong discontinuity of the two separate quantities (and of any other galaxy property).

Finally, the 'well noted curiosity' that all dSph haloes contain roughly equal masses interior to about 0.3–1.0 kpc (Mateo et al. 1998; Gilmore et al. 2007; Strigari et al. 2008) can be understood. For a Burkert profile, the constancy of $\mu_{0\mathrm{D}}$ implies the mass constancy inside any fixed physical radii and vice versa.

3 RESULTS

We have assembled and discussed data on the DM halo mass distribution for many galactic systems of different Hubble type including dwarf discs and spheroidals, spirals, ellipticals, spanning almost the whole galaxy magnitude range $-8 \geq M_{\mathrm{B}} \geq -22$ and gaseous-to-stellar mass fraction range (wide as many orders of magnitude). The mass modelling of such objects has been carried out by using different and independent techniques, none of them capable to bias the resulting DM distribution towards an artificial relationship.

Then, our current knowledge of the distribution of DM in dSphs suggests that the relation $\rho_0 r_0 \approx$ constant may extend to the faintest galaxy systems, and then we can claim valid over a range of 14 mag in luminosity and for all Hubble types:

$$\log(\mu_{0\mathrm{D}}/\mathrm{M}_{\odot}\,\mathrm{pc}^{-2}) = 2.15 \pm 0.2 \qquad (4)$$

or

$$\mu_{0\mathrm{D}} = 140^{+80}_{-30}\,\mathrm{M}_{\odot}\,\mathrm{pc}^{-2}.$$

The observed galaxy kinematics are well reproduced by a Burkert cored halo profiles with two structural parameters: a central halo density ρ_0 and a core radius r_0, whose respective values span several orders of magnitude: $6 \times 10^{-23}\,\mathrm{g\,cm}^{-3} \geq \rho_0 \geq 10^{-25}\,\mathrm{g\,cm}^{-3}$ and $0.3 \leq r_0 \leq 30$ kpc. In spite of dealing with spirals/ellipticals with such different DM physical properties, that parallels the large systematical variations of properties of the luminous counterparts, we have found that their DM surface densities $\mu_{0\mathrm{D}} \equiv \rho_0 r_0$ remain almost constant. Our finding indicates that the DM central surface density in galaxies is essentially independent of their luminosity (mass).

Our result crucially strengthens and enlarges the earlier findings by Kormendy & Freeman (2004) and Spano et al. (2008) of a constant ($\sim 100\,\mathrm{M}_{\odot}\,\mathrm{pc}^{-2}$) value for the surface density among some classes of galaxies, a result obtained by extracting DM halo parameters from the galaxy kinematics of relatively small samples of galaxies within, for the first case, an assumed theoretical framework. Equation (4) relies on a much larger number of objects across more Hubble types and a much wider luminosity range. Furthermore, they are obtained from mass modelling performed by *model independent* techniques of both *individual* and *co-added* galaxy kinematics/shear. While the URC/shear analysis has provided reliable estimates of the average value of $\mu_{0\mathrm{D}}$ for galaxies of a given luminosity, the detailed studies of individual objects have detected the small cosmic variance around this average.

We cannot presently exclude that $\mu_{0\mathrm{D}}$ has systematical or object by object variations at the level smaller than 30 per cent of its value, neither that equation (4) be a byproduct of some more fundamental relationship, however, we can claim that Fig. 2 and equation (4), alongside the support of previous work, points to an (unexpected) DM property that it is not a spurious effect due to adopted selection criteria, observational errors and/or incorrect assumptions in the galaxy modelling.

4 THE INTRIGUING RELATION BETWEEN $\mu_{0\mathrm{D}}$ AND THE STELLAR CENTRAL SURFACE DENSITY

The constancy of $\mu_{0\mathrm{D}}$ is particularly relevant also because in stark contrast to the observed variations of *stellar* central surface density Σ_* of galaxies of different Hubble type and magnitudes, i.e. of its luminous counterpart. Σ_* (the details on the following estimates can be found in the papers cited above) shows a strong luminosity dependence, as illustrated in Fig. 3. In spirals, PSS find that Σ_* increases with luminosity: $\Sigma_* \sim 800\,\mathrm{M}_{\odot}\,\mathrm{pc}^{-2}$ at about $M_{\mathrm{B}} = -22.5$ and $\Sigma_* \sim 50\,\mathrm{M}_{\odot}\,\mathrm{pc}^{-2}$ at $M_{\mathrm{B}} = -17$; in dSphs, obtained by the central surface photometry and by assuming $M/L_V = 1$ Σ_* takes extremely low values: (1–10) $\mathrm{M}_{\odot}\,\mathrm{pc}^{-2}$; when computed in ellipticals by the central surface photometry and by assuming $M/L_{\mathrm{B}} = 5$, it easily exceeds values of $10\,000\,\mathrm{M}_{\odot}\,\mathrm{pc}^{-2}$. Given these very large variations with galaxy luminosity, the uncertainties related to the estimate of Σ_*, of the order of 30 per cent, are irrelevant here. We can draw the following consequences: (i) the central surface density is the only DM quantity which is not correlated with its stellar analogous, differently from any other (core radius, central spatial density, mass, etc.), (ii) the stellar component dominates the centre of all galaxies, except that in dwarfs where it is surprisingly very subdominant.

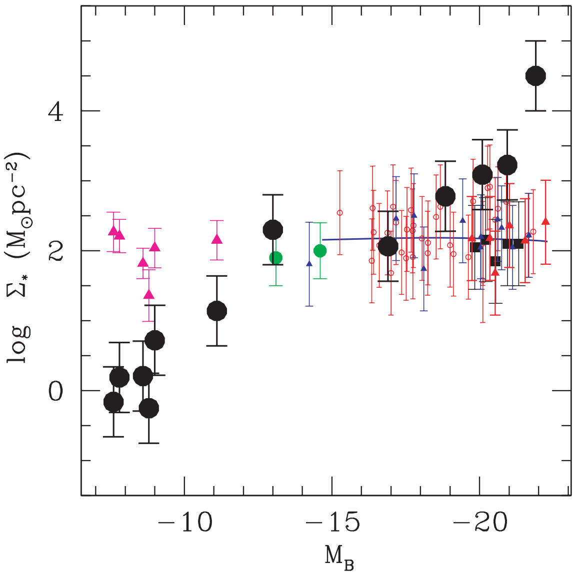

Figure 3. Stellar central surface density Σ_{*0} in units of $\mathrm{M}_{\odot}\,\mathrm{pc}^{-2}$ (full black circles) as a function of galaxy magnitude for different galaxies and Hubble types. As comparison, the values of $\mu_{0\mathrm{D}}$ are also shown with the same coding of Fig. 2.

5 DISCUSSION AND CONCLUSIONS

Let us consider how the approximate constancy of μ_{0D} with M_B is related to the correlation between r_0 and ρ_0,

$$\log r_0 = A \log \rho_0 + C, \qquad (5)$$

found in spiral galaxies (e.g Burkert 1995). Clearly, if μ_{0D} were exactly constant, this would imply that $\rho_0 \propto r_0^{-1}$ and vice versa. However, the variations in equation (4), as well as the observational uncertainties irrelevant for the run of μ_{0D} with luminosity, are substantial if one wants to invert relation (4) to obtain a $\rho_0 - r_0$ relation. In fact, the propagated uncertainties from equation (4) would make the estimate of r_0 from ρ_0 uncertain within a factor not less than $2 \times 10^{0.2}$ and occasionally as big as $2 \times 10^{0.5}$, i.e. useless for mass modelling aims. Furthermore, given the large range of the values of ρ_0 and r_0 in galaxies, equation (4) cannot make any claim beyond to confirm a general trend between the two structural halo quantities, with $A \sim 1$. The relationship between ρ_0 and r_0 must be worked out separately from the study of equation (4), from a properly selected observational data and with suitably performing methods of mass modelling.

It is remarkable that the constancy of μ_{0D} can be related to well-known scaling laws of spirals. Let us define M_{h0} and V_{h0} is the enclosed halo mass inside r_0 and the halo circular velocity at r_0. Since for a Burkert halo $M_{h0} \propto \rho_0 r_0^3$, equation (4) implies $M_{h0} \propto V_{h0}^4$ which immediately reminds a sort of Tully–Fisher relation (e.g. Freeman 2004; McGaugh 2005).

Moreover, we can estimate the ratio between the contribution to the circular velocity from the disc and the dark halo at r_0. From $\mu_{0D} =$ const one has, for a Burkert halo: $V_{h0} \propto r_0^{0.5}$. From the relationship in equation (3) of Tonini et al. (2006), that relates in spirals R_D with M_D and from the relation $r_0 \propto R_D^{1.05}$ (Donato et al. 2004), one can compute the disc contribution at r_0: $V_{d0} \propto r_0^{0.8}$. From these dependencies, we get that the velocity contribution fraction is proportional to $R_D^{-0.6} \propto L_B^{-0.3}$, in good agreement with a main scaling law of spirals (Persic & Salucci 1988, PSS). The constancy of μ_{0D} seems, therefore, related to the fact that less luminous objects have, in proportion, more DM.

Considering that DM haloes are (almost) spherical systems, it is surprising that their central surface density plays a role in galaxy structure. One could wonder whether the physics we witness in μ_{0D} is instead stored separately in the quantities r_0 and ρ_0. This reasonable interpretation has, however, a problem: r_0 and ρ_0 do correlate with the luminous counterparts (the disc length-scale and stellar central surface density) while μ_{0D} does not.

The evidence that the DM halo central surface density $\rho_0 r_0$ remains constant within less than a factor of 2 over at least nine (and possibly up to fourteen) galaxy magnitudes, and across several Hubble types (we note, however, that for early-type spirals we have limited information), obviously indicates that this quantity may hide an important physical meaning in the DM distribution of galaxies. Presently, this finding is surprising, as it is difficult to envisage how such a relation can be achieved across galaxies which range from DM-dominated to baryon-dominated in the inner regions. In addition, these galaxies have experienced significantly different evolutionary histories (e.g. number of mergers, significance of baryon cooling, stellar feedback, etc.).

Finally, let us spend a few words of caution about the result we claim in this paper. Further investigation is still needed before we can correctly frame it in a cosmological context. In fact, although the number of objects for which a reliable DM mass distribution has been obtained is impressive, it is still quite limited with respect to the cosmic variance of present day galaxies. Moreover, some types of objects, such as those with distorted kinematics or those in which a bicomponent stellar distribution has a strong central concentration, still escape a satisfactory analysis.

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APPENDIX A

Recent developments in weak gravitational lensing have made it possible to probe the ensemble-averaged mass distribution around galaxies out to large projected distances providing crucial information, complementary to that obtained from kinematics. The tidal gravitational field of the DM haloes generates weak-lensing signals, by introducing small coherent distortions in the images of distant background galaxies, which can be detected in current large imaging surveys. We can measure, from the centre of the lenses out to large distances (much greater than the distances probed by the kinematic measurements), the azimuthally-averaged tangential shear γ_t:

$$\langle\gamma_t\rangle \equiv \frac{\overline{\Sigma}(R) - \Sigma(R)}{\Sigma_c}, \tag{A1}$$

where $\Sigma(R) = 2\int_0^\infty \rho(R, z)\,\mathrm{d}z$ is the projected mass density of the object distorting the galaxy image, at projected radius R and $\overline{\Sigma}(R) = (2/R^2)\int_0^R x\,\Sigma(x)\,\mathrm{d}x$ is the mean projected mass density interior to the radius R. The critical density Σ_c is given by $\Sigma_c \equiv \frac{c^2}{4\pi G}\frac{D_s}{D_l D_{ls}}$, where D_s and D_l are the distances from the observer to the source and lens, respectively, and D_{ls} is the source–lens distance. The above relations directly relate observed signals with the underlying DM halo density. For our analysis, we use the weak-lensing measurements from Hoekstra et al. (2005) available out to a projected source–lens distance of 530 kpc. The sample, which contains about 10^5 isolated objects and spans the whole luminosity range of spirals, is split into five luminosity bins whose B magnitudes (taken from their Table 1) are given in Table A1. By adopting a density profile, we model γ_t (see Fig. A1) and obtain the structural parameters ρ_0 and r_0 by means of standard best-fitting techniques. The Burkert profile given by equation (5) provides an excellent fit to the tangential shear (see Fig. A1 and Table A1).

Although testing the NFW density profile is not an aim of this paper, let us note that it provides a fit marginally sufficient for the shear data, but less satisfactory than the Burkert profile, especially around the most luminous objects ($M_B = -21.4$) (Fig. A1; see also fig. 6 of Hoekstra et al. 2005) we found $M_{\mathrm{vir}} = 4.2 \times 10^{12}$ where we found a reduced χ^2 of 2. The region mapped by weak lensing is much more extended with respect to that probed by internal kinematics; it is, therefore, not surprising that a NFW halo does not show the same variance with observations found at smaller radii

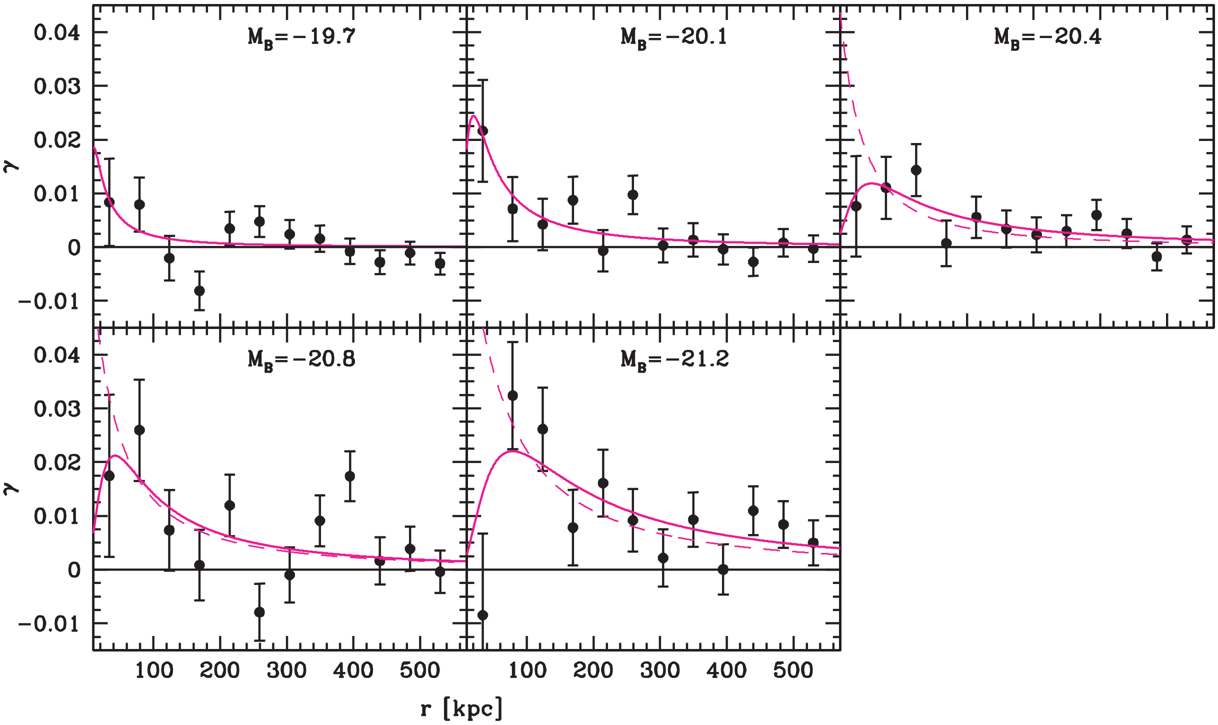

Figure A1. Tangential shear measurements from Hoekstra et al. (2005) as a function of projected distance from the lens in five *R*-band luminosity bins. In this sample, the lenses are at a mean redshift $z \sim 0.32$ and the background sources are, in practice, at $z = \infty$. The solid (dashed) magenta line indicates the Burkert (NFW) model fit to the data. At low luminosities they agree.

Table A1. Structural parameters and goodness of fit for a Burkert profile to the weak-lensing signals of Hoekstra et al. (2005); the corresponding B magnitudes come from their Table 1.

M_B	r_0 (kpc)	$\rho_0 (10^6\ \mathrm{M}_\odot\ \mathrm{kpc}^{-3})$	χ^2_{red}
-19.7	7^{+3}_{-6}	15^{+15}_{-7}	1.6
-20.1	14^{+6}_{-10}	10^{+10}_{-5}	1
-20.4	40.4^{+20}_{-20}	$1.7^{+1.5}_{-0.7}$	0.7
-20.8	30^{+10}_{-20}	4.1^{+4}_{-2}	2.2
-21.1	56^{+20}_{-20}	$2.3^{+1.2}_{-0.6}$	1.1

in which the densities of actual DM haloes around galaxies seem to converge, for $R > 1/3\ R_{\mathrm{vir}}$ to NFW profile (see Salucci et al. 2008).

Note that at low luminosities ($M_{\mathrm{B}} > -20.1$), the signal-to-noise ratio is too low to discriminate between mass models, so, differently from the other estimates in this paper, in these cases we cannot prove a posteriori that the Burkert profile is superior over the cuspy one.

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