A constant dark matter halo surface density in galaxies

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ABSTRACT
We confirm and extend the recent finding that the central surface density $\mu_D \equiv r_0 \rho_0$ of galaxy dark matter halos, where $r_0$ and $\rho_0$ are the halo core radius and central density, is nearly constant and independent of galaxy luminosity. Based on the co-added rotation curves of $\sim 1000$ spiral galaxies, mass models of individual dwarf irregular and spiral galaxies of late and early types with high-quality rotation curves and, galaxy-galaxy weak lensing signals from a sample of spiral and elliptical galaxies, we find that $\log \mu_D = 2.15 \pm 0.2$, in units of $\log(M_\odot \text{ pc}^{-2})$. 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 magnitudes, belonging to different Hubble Types, and whose mass profiles have been determined by several independent methods. In the same objects, the approximate constancy of $\mu_D$ is in sharp contrast to the systematical variations, by several orders of magnitude, of galaxy properties, including $\rho_0$ 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 disk 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 et al. 1987, Persic & Salucci, 1988, Palunas & Williams 2000), whose size ranges between 1 and 3 disk exponential lengthscales according to the galaxy luminosity (Salucci and Persic, 1999), inside which the observed ordinary baryonic matter accounts for the rotation curve, but outside which, the distribution of the baryonic components cannot justify the observed profiles and sometimes amplitudes of the measured circular velocities (Bosma 1981, see also Gentile et al. 2007). This is usually solved by adding an extra mass component, the dark matter (DM) halo. Rotation Curves (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 “cuspsiness” of the dark matter density profile in the centers of galaxy halos 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 on the various systematics of the DM distribution (see Salucci et al., 2007).

An intriguing general property of dark matter haloes was noted by Kormendy & Freeman (2004, proceedings of IAU meeting), based on halo parameters obtained by mass modelling 55 spiral galaxy rotation curves within the framework of the Maximum Disk Hypothesis (MDH), whose validity has been much debated (Bosma 2004, Palunas and...
Williams 2000, Salucci and Persic 1999). 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 $\rho_0$ and $r_0$ are, respectively, the central density and core radius of the adopted pseudo-isothermal cored dark matter 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 $\sim 100 M_\odot pc^{-2}$. The Kormendy and Freeman analysis relies on the MDH, which fixes the value of the disk mass at its maximum compatible with the observed rotation curve, under the reasonable hypothesis that mass follows light in the disk and that the halo is not hollow. From the value of the disk mass RC fitting yield the values of the two structural DM parameters (i.e. $r_0$ and $\rho_0$).

As matter of fact, MDH allows to uniquely decompose the RCs - also those that, in term of extension, spatial resolution, r.m.s errors, non-axisymmetric motions, cannot be successfully analyzed by $\chi^2$ method assuming mass models with also the disk 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) $\chi^2$ fitted the RCs of 36 spiral galaxies by using a mass model with a stellar disk and a cored dark sphere of density

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

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

$$\log \frac{\mu_{0D}}{M_\odot pc^{-2}} = 2.2 \pm 0.25 \quad (2)$$

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

In this paper, we will investigate the $\mu_{0D}$ vs 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: (a) a large sample of Spiral galaxies, analyzed by $\chi^2$ fitting their Universal Rotation Curve (URC, PSS); (b) NGC3741, the most dark matter dominated Spiral in the local Universe and DDO 47, a very well studied dwarf spiral (Gentile et al. 2005) by $\chi^2$ modelling their kinematics; (c) the THINGS sample (Walter et al. 2008): disk galaxies with high quality RCs that have been mass modelled in two independent ways, 1) by the standard $\chi^2$ technique and 2) by assuming the value of the stellar disk mass from the galaxy color according to the prescription of spectro-photometric galaxy models; (d) a sample of Sa galaxies by $\chi^2$ modelling their kinematics; (e) a large sample of Spiral and Elliptical galaxies, by $\chi^2$ mass-modelling the available weak-lensing shear measurements. We therefore investigate Eq. 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 $\mu_{0D}$ with the kinematics of six dwarf spheroidal satellite galaxies of the Milky Way for which extensive stellar kinematic data sets are available.

In all cases a cored dark matter 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 disk + Burkert cored halo + HI disk 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 $\mu_{0D}$ for different families of galaxies, work out its relation with galaxy magnitude. A discussion of our result is given in Section 3.

2 THE $\rho_0 r_0$ VS MAGNITUDE RELATIONSHIP

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

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

This profile, when combined with the appropriate baryonic gaseous and stellar components, is found to reproduce very well the available kinematics of disk systems (Gentile et al., 2004; Salucci et al., 2003; Salucci & Burkert, 2000; see Gentile et al., 2007a for the case of the most extended RC). Moreover, it leads to estimates of the disk mass in good agreement with the expectations from stellar population

Figure 1. The central halo surface density $\rho_0 r_0$ as a function of disk 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.
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Figure 2. $\rho_0 r_0$ in units of $M_\odot$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.

Donato et al. (2004) analyzed the mass profiles of 25 spiral and LSB galaxies obtained by $\chi^2$ modelling their RCs. The successful models had cored dark matter halo profiles whose core radii correlated strongly with the exponential disk scale length $R_D$ of their stellar distributions. In Figure 1 we plot $\mu_0D$ as a function of $R_D$ for the Donato et al. (2004) sample. We see that the derived values for $\mu_0D$ 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 Low Surface Brightness (LSB) galaxies. While this result is in good agreement with Eq. 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.

Before adding new crucial evidences for a relationship like Eq. 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 Figure 2): the relation found by Spano et al. (2008) for 36 spirals and the above $\mu_0D$ vs $R_D$ 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 $\mu_0D$ for the family of Spirals by means of their Universal Rotation Curve (URC) (Persic, Salucci & Stel, 1996, PSS hereafter).
This curve, on average, reproduces well the RCs of late type (Sb-Im) Spirals out to their virial radii $R_{\text{vir}}$ (PSS; Salucci et al., 2007). The URC is built from (a) the co-added kinematical data of a large number of Spirals (PSS; see also Catinella et al., 2006) and (b) the disk mass versus halo virial mass relationship of Shankar et al. (2006). By $\chi^2$ fitting the URC with a Burkert halo + a Freeman disk velocity model, with no assumptions on the amount of baryonic matter, we obtain $\rho_0$ and $r_0$ as the best-fit values (see equations 6a, 7 and 10 of Salucci et al., 2007). The corresponding $\mu_D^2$ values are plotted vs. $M_B$ as a solid line in Figure 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 r.m.s., non-axisymmetric motions, observational errors) that affect, at different levels, almost every individual rotation curve and the ensuing mass model; this particularities, in fact, get averaged out in the URC construction.

On the other hand, for the task of determining the DM structure parameters, the coadded 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 Eq. 2, we will investigate the DM mass structure in individual objects supplementing new observational data to those of Kormendy and Freeman 2004, Sano et al. 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 (The HI Nearby Galaxy Survey). We select from this sample the objects in which the mass modelling yields reliable estimates of the dark matter structural parameters. We have rejected objects in which a) the kinematics is clearly affected by non-circular motions, b) the stellar mass component strongly dominates the galaxy potential out to the last measured point, preventing us from determining the properties of the underlying dark matter halo, or c) very different models are found to equally fit the RC. With these selection criteria, we rejected 6 galaxies out of 17. This selection, though mandatory to successfully probe the DM potential (e.g. Lake & Feinswig 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 a) neatly both dark component and the stellar components of known distribution affect (at different radii) the available kinematics b) non-circular motions are modest.

The rotation curves in the Blok el al.’s THINGS sample were modelled with a spherical pseudo-isothermal dark halo plus an HI disk and a stellar disk whose free mass parameters are obtained by $\chi^2$ fits. In addition to the standard method in which the stellar mass-to-light ratio is a free parameter, they also modelled their RC’s by assuming for the latter quantity the values obtained from the galaxy colors as predicted by spectro-photometric models with a 1) diet-Salpeter or a 2) Kroupa IMF. For each object we take their results in the following way: we average the value of $\rho r_0$ obtained by the latter two methods, and then we average the result with the value obtained by the un-constrained mass model. Notice that we take also the values of $\rho r_0$ coming from the spectro-photometric method of mass modelling, although the latter may be less accurate than the $\chi^2$ 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 $\chi^2$ fits are within the shown errorbars.

We found that the galaxies DDO 154, N 925, N 2366, N 2403, 12574, N 2976, N 3198, N 3621, N 5055, N 6946, N 7331 satisfy the above discussed selection criteria. The resulting mass models well reproduces the RCs and the relative halo parameters are derived within a reasonable uncertainty ($\leq 50\%$). The resulting values of $\mu_D^2$ are plotted in Figure (2).

We extend the relationship down to the lowest luminosities of disk systems by means of the nearby dwarf galaxy NGC 3741 ($M_B = -13.1$): it represents the very numerous dwarf disk objects which are dark matter dominated down to one disk length-scale or less, and in which the HI gaseous disk is the main baryonic component. In addition, this galaxy has an extremely extended HI disk, which allowed Gentile et al. (2007b) to carefully trace the RC and therefore its gravitational potential out to unprecedented distances, relative to the extent of the optical disk. The data probe out of 7 kpc (equivalent to 42 B-band exponential scale lengths) with several independent measures within the estimated halo core radius. By standard $\chi^2$ 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 $\mu_D^2$ 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 $M_B = -14.6$. The relatively large error-bars of both estimates is 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 disk (which for these object is negligible).

It is worth to notice 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 HI RCs, found values of $r_0$ and $\rho_0$ that lead, in these objects, to $90 \leq \mu_D^2/(M_0\text{pc}^{-2}) \leq 140$ in agreement with our results.

To investigate the opposite end of Hubble Spiral Sequence, i.e. the Sa galaxies, disk 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 6899, UGC 11852.

We reject 11 galaxies out of 17. Notice 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 disk and the bulge), and it may reflect an intrinsically complex inner mass distribution. On the other hand, systems with a multi-component strong central baryonic mass concentration likely underwent secular physical processes that may have affected the original distribution of the dark matter halo (Heller et al. 2007, Athanassoula, 2008) making them complex systems that must be investigated more accurately by future studies.
The mass models are based on RC $\chi^2$ decompositions that include a stellar bulge, a stellar disk, a neutral gas disk and a pseudo-isothermal (cored) dark matter halo. The resulting $\mu_{OD}$ 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 is the azimuthally-averaged tangential shear $\gamma(r)$ recently measured for a sample containing about $10^5$ isolated objects split into 5 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 bin is 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 center of the lenses. In this radial range, the galaxy stellar component (a Freeman disk for spirals, a Sersic spheroid for ellipticals) contributes negligibly to the shear: the spheroid half-light radius does not reach 10 kpc a distance $< R_e$. The mass model, therefore, includes only a (Burkert) dark halo. Notice, 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 $2r_0$, i.e. for the most luminous objects, it extends out to $\sim R_e$. The present weak lensing data are (marginally) able to to measure the values of $r_0$ and $r_0$. Formally these are obtained by $\chi^2$ modeling $\gamma(r)$ with a Burkert mass profile. The details are presented in Appendix A and the resulting $\mu_{OD}$ 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 $\mu_{OD}$. Then, from our collection of values, at the level of 0.2 dex, no substantial differences emerge between the values of $\mu_{OD}$ estimated from different types of data or between Spiral and Elliptical galaxies. It thus appears that the central surface density of DM halos assumes a nearly constant value with respect to galaxy luminosity, over a range of at least nine magnitudes.

For illustrative purposes, we compare our results with those of Spano et al. (2008). We plot their data in Figure 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. > than a factor 10) on the best fit value of one of the two parameters $r_0$, $\rho_0$ (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 dark matter dominated systems known in the universe (see e.g. Mateo, 1998; Gilmore et al. 2007, and references therein). Their low HI 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 $\chi^2$ 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, make 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 $\mu_{OD}$. 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 1-D stellar velocity dispersion $\sigma(r)$ 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:

$$G^{-1} \frac{\rho}{\nu(r)} \frac{d\nu}{dr} \rho_0^2 \sigma_0^4 \frac{r}{a^3} \propto \frac{\rho_0}{a^2} \sigma_0^3$$

with the values of $\sigma_0$ 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 $\sigma_0 \approx 0.25 \rho_0 \approx 2.7 G^{-1} \sigma_0^3/a^2$. The corresponding $\mu_{OD}$ are plotted in Figure 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 $\mu_{OD}$ keep constant around $\approx 100 \ M_\odot$ 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 magnitudes brighter. Such variations are nevertheless fine-tuned so that the product $\rho_0 a$ 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 halos 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 $\mu_{OD}$ implies the mass constancy inside any fixed physical radii and viceversa.

3 RESULTS

We have assembled and discussed data on the DM halo mass distribution for many galactic systems of different Hubble Type including dwarf disks and spheroidals, spirals, ellipticals, spanning almost the whole galaxy magnitude range $-8 < M_B < -22$ and gaseous-to-stellar mass fraction range (wide as many orders of magnitude). The mass modeling 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 fourteen magnitudes in luminosity and for all Hubble Types:

\[
\log(\mu_{0D}/M_\odot \text{pc}^{-2}) = 2.15 \pm 0.2
\]

or \( \mu_{0D} = 140^{+80}_{-30} M_\odot \text{pc}^{-2} \)

The observed galaxy kinematics are well reproduced by a Burkert cored halo profiles with two structural parameters: a central halo density \( \rho_0 \) and a core radius \( r_0 \), whose respective values span several orders of magnitude: \( 6 \times 10^{-21} \text{g/cm}^3 \leq \rho_0 \leq 10^{-25} \text{g/cm}^3 \) and \( 0.3 \text{ kpc} \leq r_0 \leq 30 \text{ kpc} \). 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 \( \mu_{0D} \equiv \rho_0 r_0 \) 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 \( \sim 100 M_\odot \text{pc}^{-2} \) 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. Eq. 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 have provided reliable estimates of the average value of \( \mu_{0D} \) for galaxies of a given luminosity, the detailed studies of individual objects have detected small the cosmic variance around this average.

We cannot presently exclude that \( \mu_{0D} \) has systematical or object by object variations at the level smaller than 30\% of its value, neither that Eq. 4 be a byproduct of some more fundamental relationship, however, we can claim that Fig. 2 and Eq. 4, alongside with 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.

\[ r_0 = A \log \rho_0 + C \]

found in spiral galaxies (e.g Burkert, 1995). Clearly, if \( \mu_{0D} \) were exactly constant, this would imply that \( \rho_0 \propto r_0^{-1} \) and viceversa. However, the variations in Eq. 4, as well as the observational uncertainties irrelevant for the run of \( \mu_{0D} \) 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 Eq. 4 would make the estimate of \( r_0 \) from \( \rho_0 \) uncertain by 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 \( \rho_0 \) and \( r_0 \) in galaxies, eq (4) cannot make any claim beyond to confirm a general trend between the two structural halo quantities, with \( A \sim 1 \). The relationship between \( \rho_0 \) and \( r_0 \) must be worked out separately from the study of Eq. 4, from a properly selected observational data and with suitably performing methods of mass modelling.

It is remarkable that the constancy of \( \mu_{0D} \) can be related to well-known scaling laws of spirals. Let us define \( M_{10} \) and \( V_{10} \) is the enclosed halo mass inside \( r_0 \) and the halo circular velocity at \( r_0 \). Since for a Burkert halo \( M_{10} \propto r_0^{4} \rho_0^{2} \), then eq (4) implies \( M_{10} \propto V_{10}^{4.2} \) 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 disk and the dark halo at \( r_0 \). From \( \mu_{0D} = \) const one has, for a Burkert halo: \( V_{10} \propto r_0^{0.5} \). By means of the relationship in eq(3) of Tonini et al. (2006) that relates in Spirals \( R_D \) with \( M_{10} \) and from the relation \( r_0 \propto R_D^{1.1} \) (Donato et al. 2004), one can compute the disk contribution \( r_0 \) : \( V_{10} \propto r_0^{0.8} \). From these dependencies we get that the velocity contributions fraction is proportional to \( R_D^{0.6} \propto L_B^{-0.3} \), in good agreement with a main scaling law of spirals (Persic and Salucci, 1988, PSS). The constancy of \( \mu_{0D} \) seems therefore related to the fact that less luminous objects have, in proportion, more dark matter.

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 \( \mu_{0D} \) is instead stored separately in the quantities \( r_0 \) and \( \rho_0 \). This reasonable interpretation has however a problem: \( r_0 \) and \( \rho_0 \) do correlate with the luminous counterparts (the disk length-scale and stellar central surface density) while \( \mu_{0D} \) does not.

The evidence that the DM halo central surface density \( \rho_0 r_0 \) remains constant to within less than a factor of
two 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 dark-matter-dominated to baryon-dominated in the inner regions. In addition, these galaxies have experienced significantly different evolutionary histories (e.g. numbers 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 that 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 bi-component 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 halos 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 $\gamma_t$.

| $M_B$ | $r_0$ (kpc) | $\rho_0$ ($10^6 M_\odot$/kpc$^3$) | $\chi^2_{red}$ |
|-------|-------------|-------------------------------|---------------|
| -19.7 | $7^{+4}_{-6}$ | $15^{+15}_{-10}$ | 1.6 |
| -20.1 | $14^{+6}_{-10}$ | $10^{+10}_{-7}$ | 1 |
| -20.4 | $40^{+4}_{-10}$ | $1.7^{+0.7}_{-0.5}$ | 0.7 |
| -20.8 | $30^{+6}_{-10}$ | $4.1^{+0.5}_{-0.4}$ | 2.2 |
| -21.1 | $56^{+6}_{-20}$ | $2.3^{+0.6}_{-1.0}$ | 1.1 |

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.

$\gamma_t > = \frac{\Sigma(R) - \Sigma(R)}{\Sigma_c},$ (A1)

where $\Sigma(R) = 2 \int_R^\infty \rho(R, z) dz$ is the projected mass density of the object distorting the galaxy image, at projected radius $R$ and $\Sigma_c(R) = (2/R^2) \int_0^R x \Sigma(x) dx$ is the mean projected mass density interior to the radius $R$. The critical density $\Sigma_c$ is given by $\Sigma_c \equiv \frac{c^2}{4\pi G D_\text{s} D_\text{l}}$, 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 5 luminosity bins whose B magnitudes (taken from their Table 1) are given in Table A1. By adopting a density profile, we model $\gamma_t$ (see Figure A1) and obtain the structural parameters $\rho_0$ 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 Figure A1 and Table A1).

Although testing the NFW density profile is not an aim of this paper, we let us notice that it provides a fit marginally sufficient for the shear data, but less satisfactory than the Burkert profile especially around the most luminous objects ($M_B = -21.4$) (Figure A1; see also Figure 6 of Hoekstra et al. 2005) we found $M_{vir} = 4.2 \times 10^{12}$ where we found a reduced $\chi^2$ 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 in that the densities of actual DM halos around galaxies seem to converge, for $R > 1/3R_{vir}$ to NFW profile (see Salucci et al. 2008).

Notice that at low luminosities ($M_B > -20.1$) the signal-to-noise 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.
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.