PROCEEDINGS OF SCIENCE

Dark Matter in galaxies: leads to its Nature

Paolo Salucci[*†]
SISSA, Via Bonomea 265, Trieste, Italy
E-mail: salucci@sissa.it

Mariafelicia De Laurentis
Dipartimento di Scienze Fisiche, Universitï£¡ di Napoli "Federico II" and INFN sez. di Napoli, Compl. Univ. di Monte S. Angelo, Edificio G, Via Cinthia, I-80126, Napoli, Italy
E-mail: felicia@na.infn.it

Recent observations have revealed the structural properties of the dark and luminous mass distribution in spirals. These results led to the vision of a new and amazing scenario. The investigation of single and coadded objects has shown that the rotation curves of spirals follow, from their centers out to their virial radii, an universal profile that implies a tuned combination of their stellar disk and dark halo mass distributions. This, alongside with accurate mass modeling of individual galaxies, poses important challenges to the presently theoretically favored ΛCDM Cosmology.

VIII International Workshop on the Dark Side of the Universe,
June 10-15, 2012
Rio de Janeiro, Brazil

[*]Speaker.
[†]

PoS(DSU 2012)012

1. Introduction

The presence of wide content of invisible matter in and around spiral galaxies, distributed differently from stars and gas, is well fixed from optical and 21 cm rotation curves (RCs) which do not show the expected Keplerian fall-off at large radii but remain increasing, flat or only slightly decreasing over their entire observed range [1, 2]. The extra mass component becomes progressively more abundant at outer radii and in the less luminous galaxies [3].

The circular velocity $V(r)$ of spiral galaxies, is the equilibrium velocity due to their mass distribution. The gravitational potentials of the spiral's mass components and namely those of a spherical stellar bulge, a dark matter (DM) halo, a stellar disk and a gaseous disc $\phi_{tot} = \phi_b + \phi_{DM} + \phi_* + \phi_{HI}$ lead to:

$$V_{tot}^2(r) = r\frac{d}{dr}\phi_{tot} = V_b^2 + V_{DM}^2 + V_*^2 + V_{HI}^2. \quad (1.1)$$

with the Poisson equation relating the surface/spatial densities to the corresponding gravitational potentials. The surface stellar density $\Sigma_*(r)$, is assumed proportional to the luminosity surface density [4], so that:

$$\Sigma_*(r) = \frac{M_D}{2\pi R_D^2}\, e^{-r/R_D}, \quad (1.2)$$

where M_D is the disk mass and R_D is the scale length, $\Sigma_{HI}(r)$ is directly derived by HI flux observations. From the above it follows:

$$V_*^2(r) = \frac{GM_D}{2R_D} x^2 B\left(\frac{x}{2}\right) \quad (1.3)$$

where $x \equiv r/R_D$, G is the gravitational constant $B = I_0K_0 - I_1K_1$, a combination of Bessel functions [4].

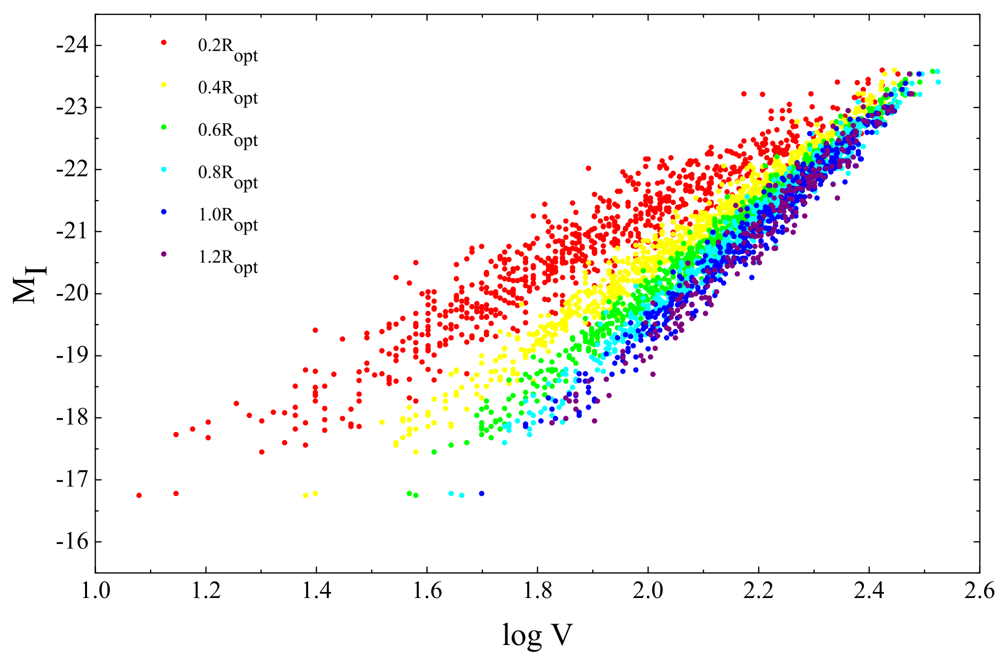

Figure 1: The Radial Tully-Fisher. The relations at different radii are indicated with different colours.

The rotation curve of a spiral is a fair measure of its gravitational potential. In fact:

- in their very inner regions the light well traces the gravitating mass [5] and
- there exists, at any galactocentric radii measured in units of disk length-scale $R_n \equiv (n/5)R_{opt}$, a *radial* Tully-Fisher relation [6] linking, with very low scatter, the local rotation velocity $V_n \equiv V_{rot}(R_n)$ and the total galaxy magnitude M (see Fig. 1).

$$M = a_n \log V_n + b_n, \tag{1.4}$$

(a_n, b_n are the slope and zero-point of the relations) .

In Fig. 2 of [7] it is shown, for a large sample of galaxies, ∇, the logarithmic slope of the circular velocity at R_{opt} as a function of V_{opt} and M_B. One finds: $-0.2 \leq \nabla \leq 1$: at this radius, the RCs slopes take almost all the values allowed by Newtonian gravity, from -0.5 (Keplerian regime) to 1 (solid body regime); furthermore, ∇ strongly correlates with galaxy luminosity and V_{opt} [7]. On the other hand, spirals show an inner baryon dominance region whose size ranges between 1 and 3 disk exponential length-scales according to the galaxy luminosity (see Fig(8) of [7] and [8, 9]). Inside this region, the ordinary baryonic matter fully accounts for the rotation curve; outside it, instead, it cannot justify the observed *profile* and *amplitude*.

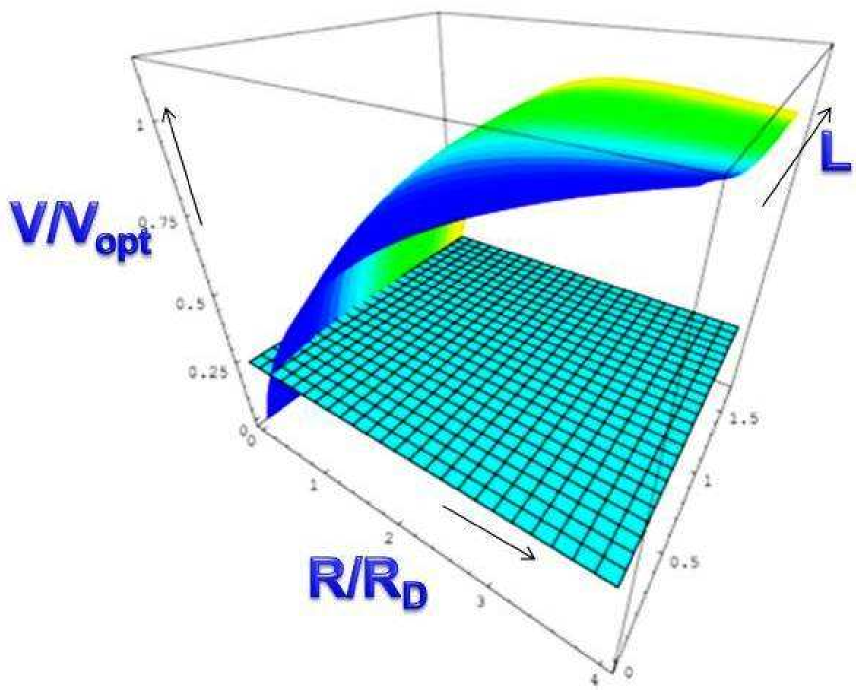

Figure 2: The Universal rotation curve of spiral galaxies.

This riddle is solved by adding an extra mass component, a dark matter (DM) halo, whose existence and properties are assessed by the RC's and whose phenomenology is evident in the 11 coadded rotation curves $V_{coadd}(r/R_{opt}, M_I)$ obtained by binning 1000 RCs of late type spirals extended out to $R_{opt} \equiv 3R_D$. These synthetic RCs correspond to spirals of luminosities spanning their whole I-band range: $-16.3 < \mathrm{M}_I < -23.4$. This led to the Universal Rotation Curve

PoS(DSU 2012)012

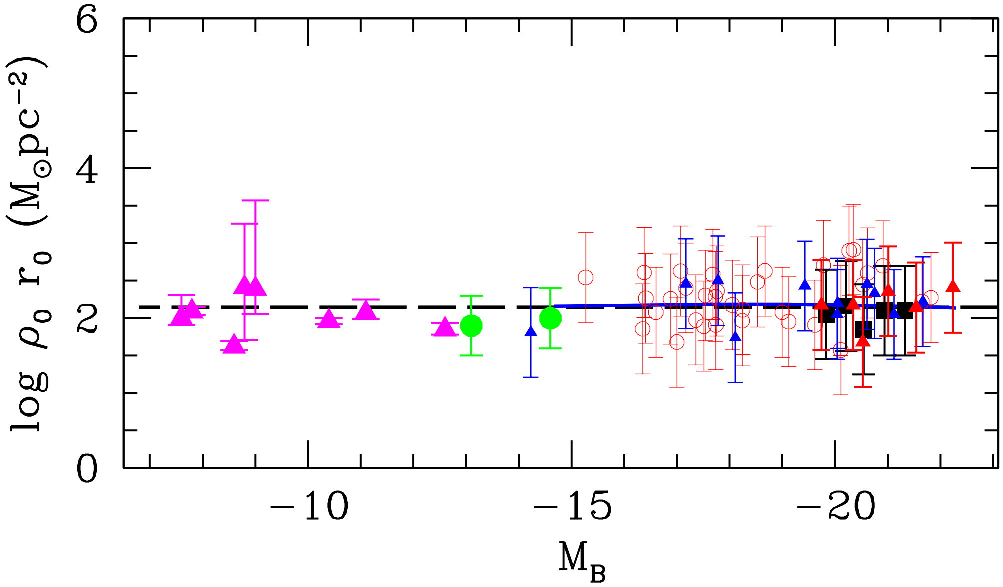

Figure 3: $\rho_0 r_0$ as a function of galaxy magnitude and Hubble type. Data: [10] sample of spiral galaxy data (open red circles); URC relation (solid blue line) [11]; dwarf irregulars N 3741 [12] and DDO 47 ; [13] (green full circles); ellipticals investigated by weak lensing [16] (black squares); Milky Way dSphs (pink triangles); spirals in THINGS sample (blue triangles); [14]; early-type spirals (red triangles); [15]. Long-dashed line shows the [16] result.

(URC) paradigm: there exists a function of radius and luminosity that well fit the RC of any spiral galaxy (see [17] and references therein). Additional kinematics data, including very extended individual RCs and virial velocities $V_{vir} \equiv (GM_{vir}/R_{vir})^{1/2}$ obtained in [11], further support the URC paradigm and accurately determine the Universal velocity function out to the virial radius[17]. Then, $V^2_{URC} = V^2_{URCD} + V^2_{URCH}$ becomes the observational counterpart of the rotation curves of spirals emerging out of cosmological simulations (e.g. [18]).

To model the URC (and any individual RC) we assume the Burkert profile for the DM halo [19] :

$$\rho(r) = \frac{\rho_0\, r_0^3}{(r+r_0)\,(r^2+r_0^2)}\ , \tag{1.5}$$

ρ_0 and r_0 and M_D (see above) are, respectively, the DM central density, its core radius and the galaxy disk mass: these 3 free structural parameters get determined by χ^2 fitting the rotation curves. Remarkably, for all available kinematics of thousands spirals, the above mass model fits data in excellent way [17].

At any radii, objects with lower luminosity have larger dark-to-stellar mass ratio and denser DM halos, with their central values spanning two order of magnitudes over the whole mass sequence of spirals.

Furthermore, a number of scaling laws among the structural mass parameters ρ_0, M_D, M_{vir}, r_0 emerges (see Fig.4 taken from [17]). Among these, we must draw attention on the quantity $\mu_{0D} \equiv \rho_0 r_0$, proportional to the halo central surface density, that it has been found independent of

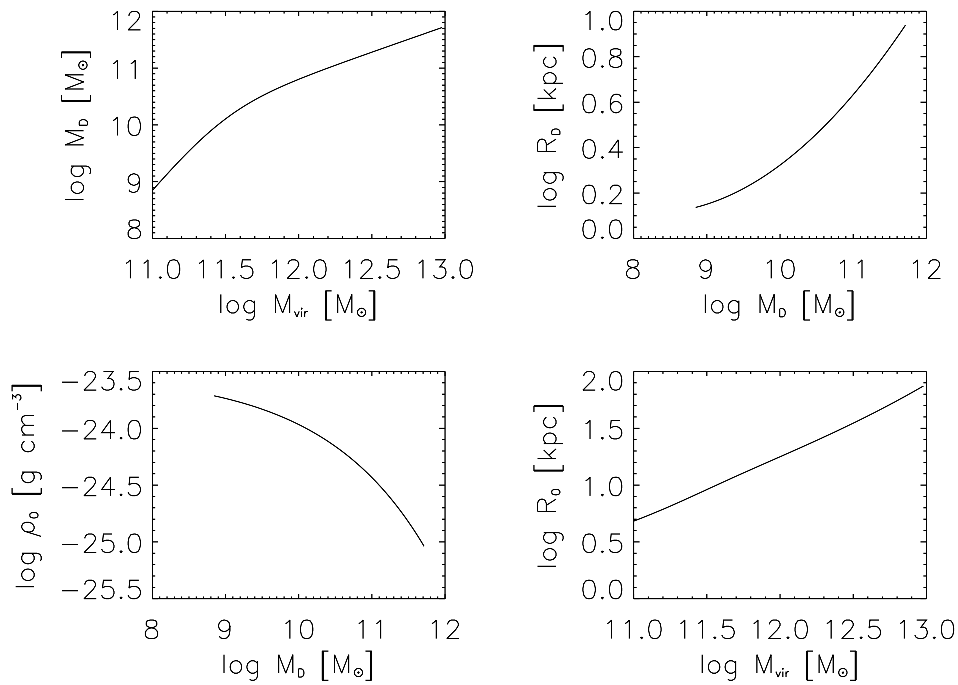

Figure 4: Scaling relations between the structural parameters of spirals.

the galaxy magnitude and Hubble Type

$$\log \frac{\mu_{0D}}{\mathrm{M_\odot pc^{-2}}} = 2.2 \pm 0.25 \tag{1.6}$$

This relationship pioneered in [20], is further supported by [10] and [21].

The relationships between global galaxy quantities are also important. First, the halo mass is the fundamental physical quantity characterizing a spiral galaxy. Its halo mass lies in the range $3 \times 10^{10} M_\odot \leq M_h \leq 3 \times 10^{13} M_\odot$. Halos of very low mass $< \times 10^{10} M_\odot$, hosting disk systems, are not detected. Halos of very large mass $> 3 \times 10^{13} M_\odot$ host groups of galaxies rather than a single object.

[22] by means of abundance matching method derived relations between virial halo masses (M_h) and galaxy properties, including $r*$-band luminosities (L_r) and stellar component masses (M_{star}) .

$$\frac{M_h}{3 \times 10^{11} M_\odot} = \left[\left(\frac{L_r}{1.3 \times 10^{10} L_\odot} \right)^{0.35} + \left(\frac{L_r}{1.3 \times 10^{10} L_\odot} \right)^{1.65} \right] . \tag{1.7}$$

These relationships, i.e. eq (1.7) and eqs. (12)-(14) of [22]), are well represented by double power laws, with a break at $M_{h,break} \approx 3 \times 10^{11} M_\odot$, corresponding to a mass in stars $M_{star} \sim 1.2 \times 10^{10} M_\odot$ and to an $r*$-band luminosity $L_r \sim 5 \times 10^9 L_\odot$.

In [23] the relationship in late-type galaxies between the neutral hydrogen (HI) disk mass and the stellar disk mass has been derived by abundance matching the stellar disk mass function from the Sloan Digital Sky Survey and the HI mass function from the HI Parkes All Sky Survey (HIPASS). As result, the HI mass in late-type galaxies tightly correlates with the stellar mass over three orders of magnitude in stellar disk mass (see eq.(5) in [23]).

Remarkably, the baryonic fraction in a spiral is much smaller than the cosmological value $\Omega_b/\Omega_{matter} \simeq 1/6$, and it ranges between 7×10^{-3} to 5×10^{-2}, (see Fig. 3 in [23]). On the other hand the mass transformed in stars is a strong function of the halo mass suggesting that processes such as Supernovae (SN) explosions must have heated up a very large fraction of the original hydrogen.

The above discussed relations bear the imprint of the processes ruling galaxy formation, and highlight the inefficiency of galaxies both in forming stars below a typical mass $M_{h,break}$ marking the maximum efficiency of the star forming process.

In spirals there is fundamental evidence that dark and luminous matter are well linked together, would this be the imprint of the nature of the DM itself?

2. The DM core-cusp issue

The cuspiness of the DM halos density profiles plays a central role in Cosmology. In fact, a cuspy density profile is predicted by (the simplest version of) the currently favored Cold Dark Matter (CDM) scenario, in detail, from the outcome of high-resolution numerical simulations of the structure formation [18, 24]. Surprisingly, however, such a cusp it is not seen in real kinematical data (e.g. [13, 25, 26, 27, 12]), that, in addition, show unexplained systematics in the DM distribution (see [16]).

Let us recall that in ΛCDM the halo spatial density is found universal and well reproduced by one-parameter radial profile [18]:

$$\rho_{NFW}(r) = \frac{\rho_s}{(r/r_s)\,(1+r/r_s)^2}, \tag{2.1}$$

where r_s is a characteristic inner radius, and ρ_s the corresponding density. The virial radius R_{vir} and halo mass M_{vir} the mean universal density ρ_u are related by: $M_{vir} \simeq 100 \rho_u R_{vir}^3$. Numerical simulations show also that r_s and ρ_s are related within a reasonable scatter: $R_{vir}/r_s \simeq 9.7 \left(\frac{M_{vir}}{10^{12} M_\odot}\right)^{-0.13}$.

Since they were found in numerical simulations, the cuspy NFW density profiles disagreed with the actual profiles of dark matter halo around spirals and LSB [28, 29, 30]. However, strong concerns were raised that this early evidence was biased by observational systematics. The claim that the observed apparent cores rather signaled an hidden cusp was frequently put forward. The solution of this riddle, that lies in the very nature of Dark Matter, was found by properly investigating a number of suitable test-cases. That is, by careful modeling 2D, high quality, extended, regular, free from deviations from axial symmetry rotation curves that were trustable up to their second spatial derivatives. [31, 27]. In addition, a step forward has come from adopting, for the Dark matter halo, the Burkert profile (see eq. (1.5)); this profile is cored at small radii, but it converges to the NFW profile for $r > 0.3 R_{vir}$. As result of this, the RCs data themselves, by determining in an unbiased way the value of r_0, are able to define the actual level of the DM halo cuspiness in Spirals.

About a decade of investigations can be summarized as it follows: in all examined cases, NFW halo predictions and observations are in plain disagreement on *several* aspects: the disk + NFW halo mass model

- fits the RCs poorly and
- implies an implausibly low stellar mass-to-light ratio and in some case
- an unphysical high halo mass

(see e.g. [32, 27, 13, 33]).

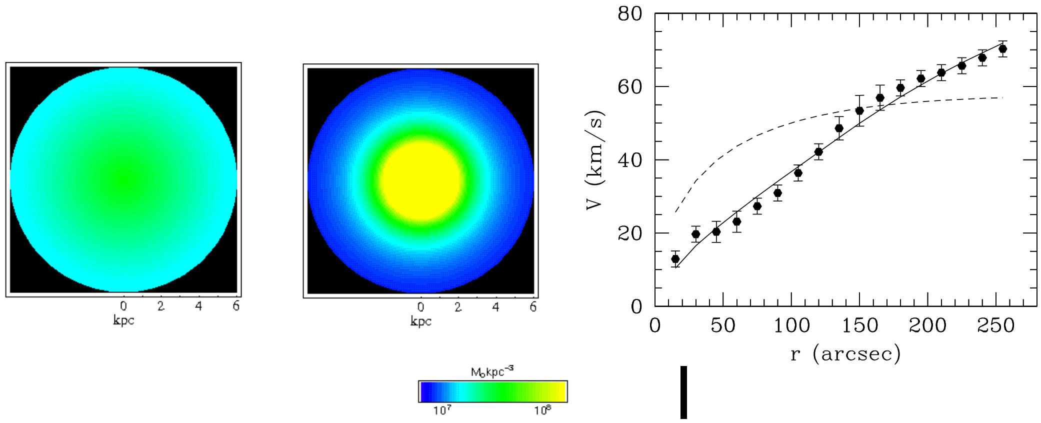

Figure 5: Left: Dark halo density in ESO 116-G12: observations (left) vs. CDM predictions (right) [27]. Right: DDO 47 RC best-fits: URC model (solid line) compared with NFW halo + stellar disk (dashed line) [13]

It is worth illustrating a couple of example of this disagreement: the galaxy ESO 116-G12, see Fig 5 (left) and the nearby spiral dwarf galaxy DDO 47 see Fig 5 (right). For the latter, the RC mass modeling finds that the dark halo density has a core about 7 kpc wide and a central density $\rho_0 = 1.4 \times 10^{-24}$ g cm^{-3}: this density profile is *much* shallower than that predicted by a NFW profile that results totally unable to fit the RC.

Presently, there are about 100 spirals whose RCs cannot be reproduced by a NFW halo + a stellar disk for any value of the model parameters. Furthermore, direct investigation has ruled out that an apparent core may arise from neglecting certain kinematical effects [13].

A complementary evidence comes from [34] who derived, in a model independent way, the logarithmic gradient of the *halo* circular velocity $\nabla_h(r) \equiv \frac{d\log V_h(r)}{d\log r}$ at R_{opt} in 140 spirals of different luminosity (see Fig. 6); their values ~ 1 turned out to independent of galaxy magnitude and inconsistent with NFW halo predictions. For a large sample of LSB a similar result was obtained by [25], see Fig. 6).

Finally, accurate mass modeling of the external regions of 37 spirals with high quality RCs led to the discovery of further disagreement between data and NFW predictions [33]. The DM halos around spirals have, in the inner regions, densities up to one order of magnitude *lower* than the ΛCDM predictions. At about $2.5R_{opt}$ instead, they have densities *higher* by a factor 2-4 than the corresponding NFW profile values (see Fig. 7). DM halos around spirals, at 5 kpc scale, are significantly less dense than the predicted ΛCDM halos, but at 50 kpc scale, they are denser than the latter. The DM density core might be associated to outward mass transfer.

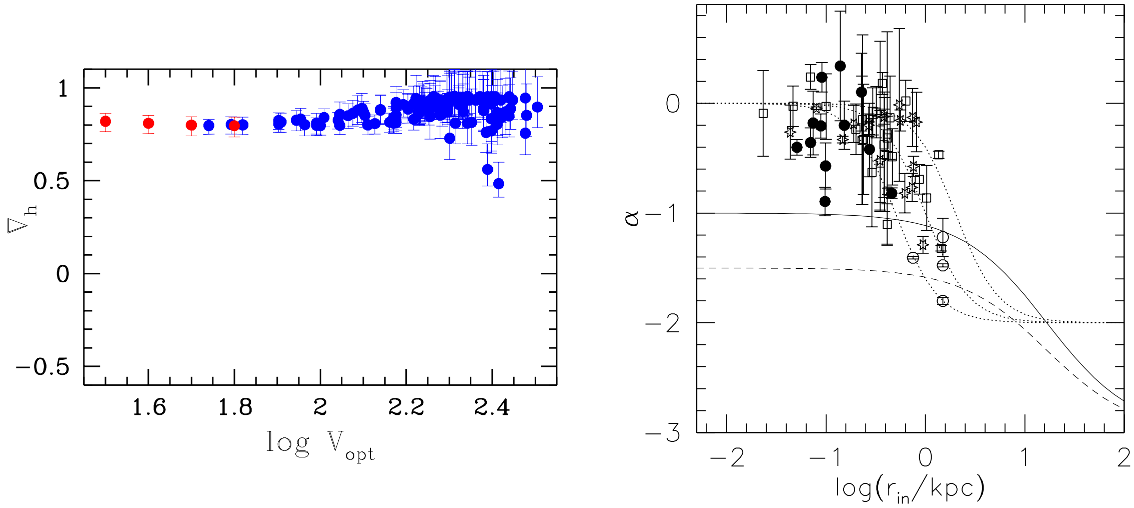

Figure 6: Left: DM halo velocity slope ∇ as a function of V_{opt} [34], remind that: $\nabla_{NFW} \leq 0.3$. Right: Inner slopes of LSB halo density profiles *vs* radii of the innermost data points [25]. Also shown: pseudo-isothermal halo models with core radii of 0.5, 1, 2 kpc (dotted lines) and the NFW profiles (full line)

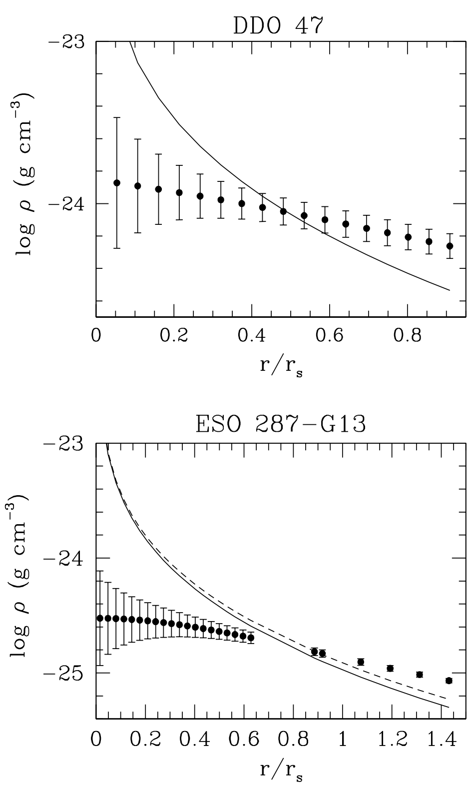

Figure 7: DM halo density of DDO 47 and ESO 287-G13. Solid lines: best fits for the NFW density profiles that, for $0.7 \leq r/r_s \leq 1.3$ result *smaller* than the URC values (circles).

3. Conclusions and Remarks

Considering a large sample of spiral galaxies we found that an Universal Rotation Curve Model, that includes a cored DM halo, provides a very satisfactory fit to their Rotation Curves. Cusped halo profiles, a crucial feature of standard ΛCDM scenario, are inconsistent with available kinematical data. Non standard features in such a scenario might be able to reproduce the above discussed intriguing observations, however, this topic deserves a discussion that is well beyond the goals of the present review.

The success of the simple Universal Rotation Curve model [17] in accounting for the available kinematics is something notable. From a purely empirical point of view, the distribution of luminous and dark matter in galaxies shows amazing properties and a remarkable systematics that are bound to play a decisive role in discovering the nature of "Dark Matter Phenomenon" and in building a successful theory of Galaxy Formation.

A complete review on the topics dealt in this paper can be found at: arxiv.org/abs/1102.1184

References

[1] Rubin, V.C., Ford, W.K., Thonnard, N. 1980, Astrophys. J., 238, 471.

[2] Bosma, A. 1981, AJ, 86, 1825

[3] Persic, M. , Salucci, P. 1991, Astrophys. J. 368, 60.

[4] Freeman K. C., 1970, ApJ, 160, 811

[5] Ratnam, C., Salucci, P. 2000, New Astronomy, 5, 427.

[6] Yegorova, I.A., Salucci, P. 2007, Mon. Not. R. Astron. Soc., 377, 507.

[7] Persic, M., Salucci, P. , Stel, F. 1996, Mon. Not. R. Astron. Soc. 281, 27.

[8] Athanassoula, E., Bosma, A., Papaioannou, S., 1987, A&A, 179, 23

[9] Palunas, P., & Williams, T. B. 2000, AJ, 120, 2884

[10] Spano, M. et al., 2008, MNRAS, 383, 297

[11] Shankar, F. *et al.* 2006, Astrophys. J., 643, 14.

[12] Gentile, G., Tonini, C., Salucci, P., 2007b A&A, 467, 925.

[13] Gentile, G., Burkert, A., Salucci, P., Klein, U., & Walter, F., 2005, ApJ, 634, L145

[14] Walter, F., Brinks, E., de Blok, W. J. G., et al. 2008, AJ, 136, 2563

[15] Noordermeer, E., van der Hulst, J. M., Sancisi, et al. 2007, MNRAS, 376, 1513

[16] Donato F., Gentile, G., Salucci, P., et al., 2009, MNRAS, 397, 1169

[17] Salucci P., Lapi A., Tonini C., Gentile G., Yegorova I., Klein U., 2007, MNRAS, 378, 41

[18] Navarro, J. F., Frenk, C. S., White, S. D. M. 1996, Astrophys. J., 462, 563 (NFW).

[19] Salucci, P., Burkert, A. 2000, Astrophys. J„ 537, L9.

[20] Kormendy, J., Freeman, K. C. 2004, IAU Symposium, Sydney, Astron. Soc. of the Pacific., 220, 377

[21] Donato, F., Gentile, G., Salucci, P., 2004 MNRAS, 353, L17

[22] F. Shankar , A. Lapi , P. Salucci , G. De Zotti , and L. Danese APJ 643, 14, 2006

[23] C. Evoli, P. Salucci, A. Lapi, L. Danese ApJ, 743:45, 2011

[24] Moore, B., Quinn, T:, Governato, F., Stadel, J., Lake, G., 1999 MNRAS, 310, 1147

[25] de Blok, W.J.G., Bosma, A., 2002, A&A, 385, 816

[26] Marchesini, D., et al., 2002, ApJ, 575, 801

[27] Gentile, G., Salucci, P., Klein, U., Vergani, D., Kalberla, P., 2004, MNRAS 351, 903

[28] Moore, B. 1994, Nature 370, 629.

[29] Kravtsov, A.V. *et al.* 1998, Astrophys. J. 502, 48.

[30] McGaugh, S.S., de Blok, W.J.G 1998, Astrophys. J.„ 449, 41.

[31] Salucci, P. , Walter, F., Borriello, A. 2003, Astron. Astrophys., 409, 53.

[32] Spekkens K., Giovanelli R., Haynes M.P. 2005, Astron. J., 129, 2119.

[33] Gentile, G., Salucci, P., Klein, U., & Granato, G. L., 2007a, MNRAS, 375, 199

[34] Salucci, P. 2001, Mon. Not. Roy. Astron. Soc., 320, 1.