Evidences for Collisional Dark Matter In Galaxies?

P Salucci 1,2⋆ N. Turini 3,4†

1SISSA/ISAS, International School for Advanced Studies, Via Bonomea 265, 34136, Trieste, Italy
2INFN, Sezione di Trieste, Via Valerio 2, 34127, Trieste, Italy
3University of Siena, Dipartimento DSFTA, Strada Laterina 2, 53100, Siena, Italy
4INFN, Gruppo collegato di Siena, Via Roma 56, 53100, Siena, Italy

Accepted .., Received ..., in original form ...

ABSTRACT

The more we go deep into the knowledge of the dark component which embeds the stellar component of galaxies, the more we realize the profound interconnection between them. We show that the scaling laws among the structural properties of the dark and luminous matter in galaxies are too complex to derive from two inert components that just share the same gravitational field. In this paper we review the 30 years old paradigm of collisionless dark matter in galaxies. We found that their dynamical properties show strong indications that the dark and luminous components have interacted in a more direct way over a Hubble Time. The proofs for this are the presence of central cored regions with constant DM density in which their size is related with the disk lengthscales. Moreover we find that the quantity \( \rho_{DM}(r, L, R_D)\rho_\star(r, L, R_D) \) shows, in all objects, peculiarities very hardly explained in a collisionless DM scenario.

1 INTRODUCTION

The mass distribution in Spirals (and in any other galaxy) is largely dominated by a dark component. This comes from their kinematics and from weak and strong lensing effects that arise only in gravitational potentials dominated by such a component (Rubin (1983); Bosma (1981); Schneider (1996)). Moreover, the analysis of the CMB fluctuations spectrum and a number of cosmological measurements unavoidably point to a scenario in which a Dark Massive Particle is the responsible for the mass discrepancy phenomenon in Galaxies.
and Clusters of Galaxies (Planck Collaboration (2016)). Alternative scenarios to the Dark Matter do exist (e.g. Milgrom (1983)), but, in the light of the evidences reported above and of their inability to address the crucial issue of how galaxies did form, they are far less convincing than the DMP scenario. We associate, as usual, the huge local mass discrepancy in galaxies with the presence of surrounding halos made by a massive elementary particle that lays outside the HEP Standard Model (e.g.: see Bertone et al. (2010)). This particle also does not interact significantly with atoms, photons and with itself, through strong, weak and electromagnetic force. This does not strictly require that DMP must interact with the rest of the Universe only through gravitational force, but that, such eventual interaction must be much weaker with respect to the ordinary baryonic matter vs baryonic matter interaction. Moreover, no current observation prevents the existence of interactions between the dark and the luminous sector of elementary particles that result relevant in the galaxy formation context. However, so far, the simplest dark matter scenario has been routinely adopted, according to which the DM halos are made by WIMP particles, more precisely by collisionless cold dark massive particles that interact very feebly with themselves and atoms. These particles are thought to emerge in SuperSymmetric extensions of the Standard Model of Elementary Particles (e.g. Bertone et al. (2010)).

Although large scale observations are in agreement with the predictions of this scenario, recently serious reservations are mounting against it. In fact, at the galactic scale masses of \(M < 10^{11-12} M_\odot\), the predicted WIMP/ΛCDM dark matter halos are much more numerous than those detected and show very different structural properties with respect to those inferred by the internal motions of galaxies (e.g. see Salucci, F.-Martins & Lapi (2011)). The questioning issues for the WIMP particle are well known as the “missing satellites” (Klypin et al. (1999)), the “too big too fail” (Boylan-Kolchin et al. (2011)) and the lack of a cuspy central density profiles in the DM halos (Gentile et al. (2004); Spano et al. (2008); Oh et al. (2011) and reference therein). There are proposals in which astrophysical processes could modify the predictions of the N-body ΛCDM models and the related density profiles to fit the observations (e.g. Vogelsberger et al. (2014); Pontzen & Governato (2012); Di Cintio et al. (2014); Read, Agertz, & Collins (2016)). However, this modelizations are growing in number and in diversity (Karukes & Salucci (2016)) and the cores formation via hypothetical strong baryonic feedbacks requires ad hoc fine tuning. Let us also remind that WIMP particles have not convincingly been detected in underground experiments (see e.g. Freese (2017)) and they have not emerged even in the most energetic LHC proton-
proton collisions (e.g. [CMS collaboration (2017)]. Finally, the X and gamma ray radiation coming from annihilating WIMP particles at the center of our and nearby galaxies has not unambiguously been detected ([Freese (2017], e.g. [Albert et al. (2016); Lovell et al. (2016)]. Thus, to claim that ΛCDM is not anymore the forefront cosmological scenario for dark matter will bring no surprise.

Recent alternative scenarios for dark matter point to a sort of significant self-interactions between the dark particles which seems suitable to explain the observational evidence which has created the ΛCDM crisis. Among those, the Warm Dark Matter, the axion as a Bose-Einstein condensate and the self-interacting massive particles scenario (e.g. [Freese (2017); Krishna et al] (2017); Suarez et al.] (2014); de Vega, Salucci, & Sanchez (2014)) are the most promising. Their common characteristic is that, at galactic scales, dark matter stops to be collisionless and it starts to behave in a way which could make it compatible with observations. However, also these scenarios hardly explain the fact that we continue to find that in galaxies, dark and luminous matter are extremely well correlated (e.g. [Gentile et al. (2009)]. Thus, we have to envisage the possibility of a direct interaction between the dark particles and the galaxy atoms and photons leading to major cosmological/astrophysical consequences. In fact, the dark-luminous coupling that emerge in spirals is so intricate that it is extremely difficult to frame it in a scenario in which the dark and the luminous galactic components are completely separated but through their gravitational interaction.

In this paper, just by varying the I magnitude, we will investigate the whole family of normal spirals, i.e. all disk systems of Sb-Im Hubble types and with I-magnitudes in the range \(-17.5 \leq M_I \leq -24\), whose corresponding 1) halo masses range between \(10^{11} M_{\odot}\) and \(10^{13} M_{\odot}\), 2) disk masses between \(10^9 M_{\odot}\) and \(10^{12} M_{\odot}\), 3) optical radii between 3 kpc and 30 kpc and 4) optical velocities between 80 km/s and 300 km/s.

In detail, the matter in these galaxies has two different components: a luminous one, with its sub components (stellar disk, stellar bulge, HI disk) proportional to the corresponding luminosity densities, and a dark one, which results distributed in a very different way. In detail, the HI disk is somewhat dynamically important in regions well outside those considered in this paper and, by selection, the galaxies we consider here have a negligible bulge.

The stars in late type spiral galaxies are the main baryonic component in the inner regions and are settled in thin disks with an exponential surface density distribution ([Freeman (1970))
\[ \mu(r) = \Sigma_0 e^{-r/R_D}, \]  

(1)

where \( \Sigma_0 = (M_d/L)I_0 \) is the central surface mass density, with \( I_0 \) the central luminosity density, \( L \) is the total luminosity in the I band. The uncertainties in the measurement of the lengthscales \( R_D \) are reasonably between 5\% and 10\%.

Given the aim of this work \( \rho_\star(r, L, R_D) \) is derived by assuming the 3D geometry of the spiral disks as cylinders with circles of radius 3 \( R_D \) as bases and, inspired by spirals of our Local Group, 0.1\( R_D \) high on the rotational plane. We also assume no dependence of the stellar density with the \( z \) cylindrical coordinate. Then:

\[ \rho_\star(r) = \mu(r, L)/(0.1R_D) \]  

(2)

We have also considered other reasonable modelization for the 3D stellar distribution (see Appendix A), but the results found in this paper are independent of this choice.

A detailed investigation of the inner combined kinematics of thousands of spirals (Persic, Salucci & Stel (1996) hereafter PSS, Yegorova & Salucci (2007); Catinella, Giovanelli & Haynes (2006)) allows us to determine the distributions of their dark and luminous components which show an universal behavior, namely, specific functions of 1) the disk mass \( M_D \), (or equivalently of the disk luminosity or of the halo mass) and of 2) the disk size \( R_{opt} \equiv 3.2 R_D \) (Persic & Salucci (1991); Persic, Salucci & Stel (1996); Karukes & Salucci (2016)). This picture was confirmed also by the mass decomposition of hundredths individual RCs (e.g. Spano et al. (2008); Kormendy & Freeman (2004) and it will allow us to investigate the coupling of dark and luminous matter in spirals of all luminosities.

Let us notice that in this paper the DM halo density has a cored inner distribution, rather than the cuspy NFW profile. This originates by the results in Persic, Salucci & Stel (1996); Yegorova & Salucci (2007) but is is also further well justified in literature? and it will not be discussed here.

The outcome of this study call for a new dark sector as a portal for a direct DM/LM interaction capable to modify the galaxy mass distribution on a Hubble time scale.

In the second section we will present the evidences of the tight dark-luminous coupling in spirals and the resulting scaling laws of the structural parameters of the luminous and dark matter that call for a collisional nature of the dark matter particle. In the third section we show the direct imprint of such a process in spirals.

In the next section we start to investigate its underlying physics.

Radii are in kpc, velocities in km/s
2 THE COUPLING OF DARK AND LUMINOUS MATTER IN SPIRALS

In this section we will present new and old evidence for the existence of a peculiar coupling between the dark and luminous components of spirals. Let us recall that, in this work the DM density distribution is represented by the well known Burkert profile, that very successfully performs in fitting the RCs of spirals (Salucci & Burkert (2000); Salucci et al. (2007); Burkert (2015))

\[ \rho_{DM}(r) = \frac{\rho_0 r_0^3}{(r + r_0)(r^2 + r_0^2)} \]  

(3)

The core radius \( r_0 \) is a fundamental DM structural quantity which defines the inner halo dark region of almost constant density \( \rho_0 \).

The analysis of the coadded (and of the individual) kinematics of a large number of spirals shows that the distributions of dark and luminous matter are very well represented by the above discussed URC mass model (see fig 2 of PSS), more precisely by the Eqs (4)-(8) of Salucci et al. (2007)). This set of equations provides, for the entire family of spirals: \( \rho_{DM}(r, M_I R_D) \) and \( \rho_*(r, M_I, R_D) \), i.e. the dark matter and stellar density profiles as function of their I-Band luminosity and disk length scale.

In order to estimate the error budget in the determinations of the densities we should recall that: 1) the cosmic variance of the spirals mass distributions is quite small Yegorova & Salucci. (2007)) while 2) the best-fitting 1\( \sigma \) uncertainties of the three free parameters of the URC velocity model are (see Appendix B and Persic, Salucci & Stel (1996); Salucci et al. (2007) ):

\[ \Delta \rho_0/\rho_0 = 0.2, \Delta r_0/r_0 = 0.2, \Delta M_d/M_d = 0.15 \]  

(4)

Noticeably, these fractional uncertainties are small and independent of the halo mass, so that they affect the log-log scaling laws in Eqs (4)-(8) of Salucci et al. (2007)) only by small random values.

We find that the core radius \( r_0 \) tightly correlates with \( R_D \), the stellar disk lenght-scale (see Fig. 1), data are from Persic, Salucci & Stel (1996) and Karukes & Salucci (2016)):

\[ \log r_0 = 1.38 \log R_D + 0.47 \]  

(5)

The error budget of eq (5) is enough low to make it statistically relevant. In fact, first let us notice that the quantities involved (\( r_0 \) and \( R_D \)) are derived in totally independent ways, moreover a) the measurement errors in \( R_D \) are negligible in that we use coadded values and
b) the range of variation of $r_0$ among Spirals is about 1.1 dex, while its fitting uncertainty is only 0.04 dex.

This correlation is confirmed by Donato, Gentile & Salucci (2004); Kormendy & Freeman (2004); Spano et al. (2008) and it extends over several orders of magnitudes and to different Hubble Types as dwarfs spiral Karukes & Salucci (2016) and ellipticals Memola, Salucci, & Babic (2011). The scaling law of eq (5) has no straightforward explanation. In fact, while the origin and the values of the disk lenght-scales $R_D$ can be traced to the angular momentum per mass unit owed by their HI proto- components (Mo, Mao & White (2008)), the halo core radii have certainly a different (and yet unknown) origin. Eq (5) is a tight relationship between two structural quantities of spirals that, in collision less DM scenario, are thought to arise from totally different physical processes.

The analysis of the URC brings up a second intriguing coupling between the dark and luminous matter in Spirals: (Salucci et al. (2007)):

$$\log \frac{\rho_0}{\text{g cm}^{-3}} = -(23.5 \pm 0.2)(0.96 \pm 0.1), \left( \frac{M_D}{10^{11} \text{M}_\odot} \right)^{(0.3\pm0.03)}$$  \hspace{1cm} (6)

Noticeably, a similar result is obtained in individual objects Kormendy & Freeman (2004)). Eq (6) is statistically relevant: the relationship is monotonically decreasing and, in spirals, the ranges of ($\log M_D$, $\log \rho_0$) are (2.9, 1.6) dex, while their fitting uncertainties are only (0.2,0.2) dex. Within the collisionless DM halos scenario, the standard process of the formation of the spiral disks within DM halos, unlikely, would make the stellar disk masses and the DM halos central densities partners in any tight relationship.
Furthermore, let us recall that spirals show other intriguing relationships with no straightforward explanation in the scenario in which the DM halos are made by collisionless dark particles 1) at $r_0$, the baryonic component of the acceleration relates with the galaxy luminosity (see Gentile et al. (2009) for details) and 2) in dwarf Spirals the concentrations of dark and the luminous matter are directly correlated (see Karukes & Salucci (2016) for details).

Then, the structural properties of the spiral stellar disks correlate with those of the surrounding DM halos in ways that, within the collisionless WIMP scenario, have not a clear physical justification. In fact, the direct interactions between dark and luminous matter are absent. The indirect ones, instead, to reproduce the observational evidence require that the baryons largely modify, with fine tuned models, the total gravitational field that, back reacting, act in a very precise way on the dark matter distribution (e.g. Di Cintio et al. (2014)).

In this work, we take the view that the straightforward relationships presented in this section are beacon of a different scenario.

3 A DIFFERENT PARADIGM

We have seen in the previous section that in galaxies, physical quantities, deep rooted in the Dark World, correlate with the most important quantities of the Luminous World. Let us stress that this lack of a direct explanation emerges when we strictly follow the view according to which dark and luminous matter interact only through the gravitational force. Everything changes if we consider the possibility for which halo dark particles, over the Hubble time, exchange a fraction of their kinetic energy with ordinary matter. This opens a talking line between dark and luminous matter which can have a dynamical role in the galaxy formation process, and it explains the above relations as a straight dynamical outcome of the above new interactions.

We, therefore, propose a different paradigm which abandons the assumption that the interactions between DM and LM are only of gravitational nature, and we postulate the existence of a collisional Dark Matter Particle. Namely, a particle that directly interacts, in a Hubble Time, with the ordinary matter in an astrophysically relevant way.

Let us stress that such an idea is not new, in fact, it has has proposed and discussed in
the literature in a number of works Hochberg et al. (2014) What it is absolutely new here is the observational support that we claim we provide at support.

This interaction, in competition with the gravitational force that acts on the much shorter time scale of the galaxy free-fall time, is able to modify the DM halos distribution around galaxies, namely in their central regions. One of the many possible schemes that ensues this, depicts that the dark particle interacts with components of ordinary matter and then it decays into light, hot, high momentum products that escape from the gravitational field of galaxies. Such type of particle, evidently, does not exist in the Standard Model, neither in its most popular extensions such SUSY. So, in view of the above, we are thinking on a (new) dark Sector interacting with ordinary particles such as photons, nuclei and electrons in the galaxies. We expect, in this case, that the DM mass should be large enough \( \sim 10^2 \text{ GeV} \) to have easily escaped detection until now.

Respect to previous works, we are not postulating a specific new type of particle and checking it with crucial observations, but we are instead claiming that the latter require that the DM particle should have certain exotic properties.

Without entering a very complex issue we have to stress that such particle interaction with the ordinary matter can be detected. In fact it could produce excesses in cosmic positrons or/and antiprotons and then be a component of the PAMELA and AMS detected excess. In addition, it could produce diffuse VHE photons. Moreover, this collisional particle, if created in accelerators, could be detected as missing momentum or missing masses in the particle flow of the interaction. It is worth to notice that LEP data doesn’t show such signature, while hadronic colliders data are more difficult to be interpreted. However, more powerful missing masses searches and event symmetry studies are currently performed at LHC and there is a chance that these particles, if produced, will be detected. Data mining of old experiments could indeed even give us useful hints on the issue. Moreover, non accelerator searches for DM, eg, LUX and Xenon1T, that play a decisive role for a WIMP searches, are currently not tuned for such detection. Furthermore, after the lack of detection of “favorite” SUSY particles, this new scenario opens up a huge field of possibilities for the actual nature of this collisional particles, whose precise individuation is beyond the aim of this work.

Finally, although we are unable to imagine it now, we cannot exclude the existence of some weird scheme of transferring energy from baryons to WIMP particles, whose effect on the above scaling laws would mimic the presence of collisional interactions. However, as the
information on the DM distributions gathers, also new evidences for a direct coupling with the baryonic components do.

4 EVIDENCES OF AN INTERACTION BETWEEN DARK PARTICLES AND ATOMS

In section (2) we have presented a number of relationships that provide motivations for abandoning the framework of collisionless Dark matter halos. In this section, we will investigate other special properties and relationships of Spirals that will direct us towards different framework featuring the existence of direct interactions between the dark and luminous components.

Let us assume spherical symmetry and introduce the DM particle pseudo pressure

\[ P(r) = \frac{1}{3} \rho_{DM} V(r)^2 \]  \hspace{1cm} (7)

whose radial variation balances, on a dark particle at radius \( r \), the gravitational attraction of all the matter inside \( r \). For halos around spirals we derive this quantity from the mass modelling of the Universal rotation curve which, for any Spiral of halo mass \( M_H \), endows us with the corresponding values of \( \rho_0, r_0, M_D, R_D \) and their uncertainties (see section

Figure 2. The pseudo pressure in Spirals as function of halo mass (in solar masses) and radius (in kpc). The uncertainties on \( \log P(r) \), propagated from those of mass model fitting, are 0.2 dex
Figure 3. The relationship between $R_{cp}$ and $M_H$ (blue). The red lines are its 2σ uncertainty contour.

3). Notice that due to the term $V(r)^2 = V_{DM}^2 + V_b^2$ inside the pseudo pressure, $P(r)$ is a hybrid dark-luminous matter quantity. It behaves as it follows (see Fig. 2). Its value is zero at the center, it rises out to the radius $R_{cp}$ and it slowly declines outward. Thus, in spirals, the length scale $R_{cp}$ emerges. We derive this quantity by computing the radius at which $dP(r)/dr = 0$. $R_{cp}$ is found to tightly correlate with the galaxy halo mass (see Fig. 3).

$P(R_{cp})$ varies less than a factor 1.5 in all galaxies, that might also suggests that the DM particles have been subjected to some form of direct interaction with baryon. Looking at the Fig (2) the radius $R_{cp}$ can be seen as that at which there is a dynamical equilibrium between the number of DM particles that, inside this radius, get destroyed during a Hubble Time and the number of the ones that, in the same period, enter into such a volume, driven by the gravitational unbalance inside it. Notice that $R_{cp}$ is finite since the rate of DM particle destruction by interacting with baryons, for $r > R_{cp}$, strongly declines with radius because the latter do so. Therefore, we envisage that, in each galaxy, inside a volume of radius $R_{cp}$, the DM density has dynamically evolved in a Hubble time, leading to $T_H d\rho_{DM}/dt/\rho_{DM}(10^{10}y) \simeq 1$. Notice that the zero-pressure gradient line above, if not due to the proposed radial time variation of the number of particles, has to be originated by a huge radial variation of their anisotropy, which we have no explanation of.

$R_{cp}$ tightly relates also with the core radius $r_0$ (see Fig. (4)). This may suggest that the physics behind the former quantity is connected with the existence of cored DM cored distributions. In any case, this relationship is not explained by the collisionless DM models, in which the two correlating quantities do not even exist.

As in the self-annihilating dark matter case, in which the well known kernel of the
Figure 4. The relationship between $R_{cp}$ and $r_0$ in spirals (thick line). The thinner lines are the $2\sigma$ uncertainty contour.

The astrophysical term is $K_{SA} = \rho_{DM}^2(r)$, in the present collisional dark matter case, we have that

$$K_C(r) = \rho_{DM}(r)\rho_\star(r)$$

is the kernel of the (collisional) astrophysical term of the proposed DM-baryons interaction. Notice that the term $K_C$ can consider also the interaction between dark particles and the photons and neutrinos emitted by stars and supernovae, whose numbers density is, on large scales, proportional to $\rho_\star(r)$.

Finally, in the case of collisionless dark matter, $K_C(r)$ has little physical sense, the quantity that matters, in this scenario, is instead the sum of the two densities: $\rho_{DM}(r) + \rho_\star(r)$ that get related via the gravitational potential of the galaxy from the Poisson Equation.

Of course across spirals $K_C(r) = K_C(r, M_I)$, by varying the galaxy magnitude $M_I$ in Eqs (4)-(8) of Salucci et al. (2007), we derive $K_C(r, M_I)$ and so $K_C(R_{cp}(M_I), M_I)$ for the whole family of Spirals. Remarkably, we find, see Fig. (5), that, $K_C(R_{cp}) \simeq const = 10^{-47.5} g^2 cm^{-6}$, within a factor of about 2. As a comparison, at the same radius, $K_{SA}(R_{cp})$ varies by two order of magnitude with the galaxy halo mass. This result in no way is affected by the uncertainties on log $K_C(R_{cp}$ derived from fitting the URC). In fact, these are small ($< 0.2 dex$) and, above all, independent of halo mass.

Therefore, in each object, the radius $R_{cp}$ emerge as an intriguing lengthscale which 1) marks the radius of a remarkable feature in the DM pseudo-pressure distribution 2) it is related to the core radii $r_0$, 3) it is almost constant in all galaxies. It is impressing to realize in Fig. 6 that $K_C(r, M_h))$ varies hugely among galaxies and at different radii and only
at $R_{cp}$ it takes a similar value for all objects indicating a sort of a threshold value for the densities in order to have a significant interaction between the two components.

The two relationships above may well call for a general time evolution of the DM density of spirals $\rho_{DM}(r,t,M_H)$ triggered by a collisional dark-luminous component interaction, proportional to $K_C$. In this scenario, inside $\sim R_{cp}$ of the size of the core radius $r_0$, the value of the product of the two densities $K_C$ is larger than the above reference value and enough collisional interactions have occurred over a time of $\sim 10$ Gyr, to flatten the DM density distribution. Instead, outside $\sim R_{cp}$, $K_C$ decreases rapidly with radius and collisions get soon suppressed in any object.

5 FORMATIONS OF CORES IN THE DM DENSITY

In the collisional DM scenario, such kind of interaction, may play an important role in shaping the structural properties of the Spiral mass distribution and therefore in the creation of DM density cores. This idea also finds support by the fact that $r_0$ is related to $R_{cp}$, the length-scale of the ‘collisional’ process (see Fig. 4) and to $R_D$ (see Fig. 1), the length scales of the stellar distribution.

The next step is to derive, galaxy by galaxy, how much dark mass has been involved in the process, i.e. how many dark particles have interacted with ordinary matter particles. Let us guess the original density distribution of the DM halos, formed in a free fall time of
Figure 6. $K_C$ as function of $\log \left(M_H/10^{11} \, M_\odot\right)$ and radius $r/kpc$. The full range of the values plus/minus their 1-σ uncertainties of $\sim 0.2 \, \text{dex}$ of the quantity $K_C(R_{cp})$ lies between the two parallel planes.

about $10^{7-8}$ years, well before that the collisional interactions, in a time scale of $10^{10}$ years, removed a great fraction of the dark mass inside $R_{cp}$.

Noticeably, the DM halo density around Spirals, i.e. outside the region inside which the collisional interactions took place, is well reproduced by a NFW profile with concentration: $c = 13(M/(10^{12} \, M_\odot))^{-0.13}$ (see Salucci et al. (2007)), so that in Spirals, for $r > R_{cp}$ we have:

$$
\rho_{\text{cusp}}(M, r) = \frac{1.65 \times 10^{-24} \times M^{0.073}}{r \left(\frac{k_1}{M^{0.12}} r + 1\right)^2 \left(\log \left(\frac{k_2}{M^{0.12}} + 1\right) - \frac{k_2}{(k_2^{0.12} + 1) M^{0.13}}\right)}
$$

with $k_1 = 1.82 \times 10^4$ and $k_2 = 4.72 \times 10^2$ and $M$ the halo mass in solar masses. Notice that, in this work, we consider the latter distribution just as an empirical one, survival of the LM-DM interaction occurred at smaller radii. Extrapolating this density back in time and to the center of the galaxies, we recover $\rho_{\text{cusp}}$ the originally (cuspy) profile of the just formed DM halos. In Fig (7) we show the primordial and the actual DM density profiles.

For a present day spiral of mass $M_H$ the amount of removed DM over the Hubble time is:

$$
\Delta M_H = 4\pi \int_0^{R_{cp}} (\rho_{\text{cusp}}(r, M_H) - \rho(r, M_H)) r^2 dr
$$

The results are in fig (9). We see that in a galaxy of halo mass $10^{11} M_\odot \leq M \leq 10^{13} M_\odot$, the full range of the values plus/minus their 1-σ uncertainties of $\sim 0.2 \, \text{dex}$ of the quantity $K_C(R_{cp})$ lies between the two parallel planes.
Figure 7. Primodia (red) and present-day (blue) DM density profile around galaxies as a function of radius (in kpc) and halo mass (in units of $10^{11} M_\odot$).

Figure 8. Removed -to -primordial dark mass inside $R_{cp}$, as function of halo mass (blue line). The thinner lines indicate the 1-sigma uncertainty propagated by those of the URC mass model.

the amount of mass removed by the dark-luminous collisional interactions is from 40% to 90%, the original dark matter mass inside the cored radius.

However, let us notice that such mass, likely removed during the formation of the cores in the DM density, is only 1/100 the present day halo mass. see Fig (9)

All the intriguing features in the mass distribution in spirals could be created with the complicity of a minuscule fraction of the whole dark halo mass. This is in contradiction with
the current view according to which, each particle in the halo DM has participates to the formation of the galaxy through the processes of bottom-up collapse and merging.

6 COLLISIONAL DM AND DM HALOS AT Z=1

We have direct support for an evolution of DM halos over the Hubble time as result of the interactive process we have claimed for. We know the structural properties of four disc galaxies located at $z = 1$ ([Salucci et al. (2007)]) from high spatial resolution measurements due to large boosts in their apparent angular sizes that are caused by strong gravitational lensing from foreground massive galaxy clusters. This provided us with proper photometry and kinematics of spirals at cosmological distances, well outside the possibility of direct measurements. The stellar surface photometry of these galaxies shows that they, at those early times, had already grown Freeman stellar disks of sizes not much different from those of local galaxies with the same $V_{opt}$. Their RCs are consistent with the local ones and we modeled them by means of a Freeman disk and Burkert halo, whose free parameters, the core radius, the central DM density and the disk mass are derived by standard best-fitting method. [Salucci et al. (2007)]. We find that the core radii $r_0$ of the 4 objects are about $1/3$ those of local spirals with the same $V_{opt}$. Specifying, at $z = 1$, galaxies have a core radius three time smaller that those of the $z = 0$ objects with the same size and angular momentum per unit mass of local ones (see Fig. 6). These 4 galaxies must be formed at $z_f \sim 2 - 3$, so the ratio between their age at $z = 1$ and at $z = 0$ results to be $1/3$, a value which we claim that it is not a coincidence.
Figure 10. The relationship $r_0-R_D$ today (lines) and that for objects at $z=1$ (points).

This result, although found in a yet limited sample, indicates a linear increase of the size of the core radii with time, a characteristic of secular processes like the one we have proposed. In the meantime, it puts strong constraints on the idea that the creation of DM density cores may be related to supernovae explosions: these have an exponential evolution with time so that DM density cores created by baryonic feedback should already have been almost fully developed at $z=1$.

7 THE CROSS SECTION OF THE COLLISIONAL DM -LM INTERACTIONS

We are now in a completely new territory of physics, and, while it is relatively easy to point out the existence of new phenomena, it is instead very difficult to frame them in a proper scenario. We have given evidence that collisional interactions may have been occurred in Spirals. Given all this, the kernel of the collisional interactions is the product $\rho(r) \rho_*(r)$. Notwithstanding the evidence of this interaction, its cross section can be estimated only very roughly. All the action occurs within $R_{cp}$. The DM is removed from this region, e.g. by absorption (and emission) onto baryonic matter. DM particles traverses the region of size $2R_{cp}$ in a time twice the free fall time $t_{ff} = 2.1 \times 10^3 [\langle \rho \rangle / (g/cm^3)]^{-1/2}$ s. Now, we select a galaxy with $M = 10^{12} M_\odot$, then from Salucci et al. (2007) and from the previous section: $R_{cp} = 6 \text{ kpc}$, $M_*(R_{cp}) = 4 \times 10^{10} M_\odot$, $\rho_* = 2.9 \times 10^{-24} g/cm^3$, $\rho > = 4/3 \pi M_{cusp}(R_{cp})/R_{cp}^3 = 1.4 \times 10^{-24} g/cm^3$. The number density of the absorbers inside $R_{cp}$ is $n_* = 3/(\pi 4) M_*(R_{cp})/(R_{cp}^3 m_H)$ where we have assumed that stars are entirely made by hydrogen. The flux attenuation of DM particles, over $10^{10}$ yr, is 0.5 (see Fig (5)). The number of cycles is $10^{10}/(2t_{ff}) = 10^{10}/10^8 \sim 100$. 

Putting together all these data we roughly estimate the absorption cross section of DM vs LM interaction as:

\[ \sigma \sim 10^{-42} \text{ cm}^{-2} \text{ mGeV} \] (11)

8 CONCLUSION

Rotation curves studies on a large sample of spiral and dwarf galaxies show an extraordinary correlation between Dark and Luminous matter over many order of magnitude in halo masses. The idea of a dynamical evolution of galaxies, in the Hubble time period, driven only by gravity is failing the explanation of such a deep-rooted correlation. Moreover, the large discrepancy of DM densities in the inner part of the galaxies from the outcome of NBody ΛCDM simulations and the actual measured data cannot be explained only by astrophysical phenomena without a fine tuned modelization, that very likely could not account for the mounting scenario of universal correlations. Warm Dark Matter models are certainly nearer to the latter, however they cannot account easily of the universality of its internal structure. In this paper we also show that the quantity \( \rho(r)\rho_*(r) \) tend to be almost the same on all the galaxies as the DM pseudo pressure reaches the maximum close to the Core Radius. The same Pressure has the same value no matter the galaxy dimension. This density product in fact is proportional to the interaction probability of the the two components, Luminous and Dark matter, and account for a direct interaction between them. This is hardly a coincidence, in that, the quantity like \( K_{SA} = \rho_{DM}^2(r) \) which is proportional to the self interaction of the DM component is varying all over in galaxies and among galaxies.

Therefore, we claim that the structure of the inner parts of the galaxies is driven by a direct interaction between Dark and Luminous components. The DM central cusp, foreseen...
for any heavy collisionless DM dark matter particle and also in many other cases, with an increase of DM pressure at lower radius, gets, as time goes by, progressively eaten up/absorbed by the dominant luminous component. The interaction flattens the density of DM and drops the pressure towards the center of the galaxy.

SuSy, if ever appears, has a large energy scale that could in principle lead to neutralino masses in the TeV region. We estimated an absorption cross section for a heavy DM particle from the luminous component to be from 3 to 5 order of magnitude larger than foreseen by SuSy prediction. Current prediction for a minimal Dark Sector zoology based on a (U1) symmetry, with heavy Dark Fermions and a mediator Dark Photon, (e.g. Marciano (2015); Ringwald (2014); Alexander et al. (2016); Harigaya & Nomura (1996)) cannot address the full phenomenology described in this paper. A direct coupling between Dark Fermions and SM particles, in presence of luminous matter, should take place allowing the decay of the heavy Dark Matter particles into light ones, SM or other. Heavy Axion Like Particles (ALP) are another DM candidate. Finally There can be in principle also be mediators between the two sectors, such as the Higgs.

The estimated absorption cross section is low enough to make direct DM detection experiments based on nucleus recoil fail, the recoil could not happen at all and the experiments should see large energy showers, that if they are initiated by electrons or photons can be confused with high energy neutrino showers. On the contrary, exotic searches at LHC, with the integrated luminosity already taken and foreseen in the next years, can confirm such picture. Production cross section at high energy should be big enough to have the DM particles produced in detectable quantity. Moreover, the positron excess in our galaxy, if from DM interaction, points to a TeV scale mass particle that might be related with our proposal. LHC searches are not calibrated to detect such type of invisible particles, the method based on missing transverse energy and momentum asymmetry, is not very sensitive if the production cross section is of the femtobarn order of magnitude. The large QCD background is masking all the events. Missing mass detection done with more sophisticated apparatus such as the forward spectrometers CT-PPS and AFP, respectively in CMS and Atlas, can enhance the detection probability if the production is initiated by photon-photon interaction. Also triggering algorithms can be optimized for such a search, right now they are focused on SuSy production and exotics searches are done with low efficiency.

The DM scenario that arises from this picture points to a DM sector different from any predicted so far. Neutralino interaction cross sections foreseen by SuSy cannot account
for the absorption rate we measure. So a new DMP or a more complex DM sector should appear. We yet don’t have any hint on how the coupling with matter is, surely nothing yet envisaged in the present DM theoretical panorama. Model independent searches have to be pursued in LHC. While in direct searches underground the detection could be made looking to the appearance of particle showers in large mass detectors as neutrino telescopes (Ice Cube, Antares...). A diffuse gamma ray signal with large energy, above 100GeV, with a cutoff spectrum, could be correlated to DMP absorption.

9 ACKNOWLEDGMENTS

We thank the referee for important help in presenting the results of this paper.

10 APPENDIX A

Other used 3D modelization of the stellar disk intrinsically 2D distribution different from that adopted in this paper are: i) to make spherical the stellar disk mass profile. This, in cylindrical coordinates is given, for the Freeman disk, by $M_D(r) = M_D(1-(1+r/R_D)e^{-r/(R_D)})$ the 3D density is obtained by substituting the cylindrical coordinate $R$ with the spherical $r$ so that: $\rho_*(r) = 1/(4\pi r^2) dM_D(r)/dr$, ii) By solving the Poisson equation one finds that a Freeman disk mimics a sphere of effective density $\rho_*(r) = GM_D/R_D^3 H(r/R_D)$ where the latter function is given in Eq. (9) of Salucci et al. (2010).

11 APPENDIX B

We show, by means of fig a) the very great number of objects and of individual velocity measurements that have concurred in the derivation of the 11 coadded rotation curves representing the whole kinematics of spirals. b) the smoothness and the very small internal rms $\delta v/v = 0.02 - 0.05$ of these latter c) the goodness of the DM halo + disk best fit velocity model to data, which leads to the small fitting uncertainties of Eq(4) and in turn, to the existence of the URC in Spirals.
Figure 12. Number of objects and data, the 11 coadded RCs and their velocity modelling.

REFERENCES

Alexander J., et al., 2016, arXiv, arXiv:1608.08632
Fermi-LAT, DES collaborations Albert, A. et al 2016 arXiv:1611.03184
Bertone, G.F. 2010, Particle Dark Matter: Observations, Models and Searches, Cambridge Univ. Press
Bertone, G. and Hooper, D. and Silk, J., 2005, PhR, 405, 279
Bosma A., 1981, AJ, 86, 1791
Boylan-Kolchin, M. and Bullock, J. S. and Kaplinghat, M, 2011, MNRAS.415L..40B
Burkert A., 2015, ApJ, 808, 158
Catinella, B, Giovanelli R and Haynes M.P., 2006 Apj .640, 751.
Cirelli, M., Corcella, G., Hektor, A., et al 2011, JCAP 1103, 051
CMS collaboration 2017, Submitted to Eur. Phys. J. C arXiv:1701.06940 [hep-ex]
de Vega H. J., Salucci P., Sanchez N. G., 2014, MNRAS, 442, 2717
de Blok W. J. G., 2010, AdAst, 2010, 789293
de Laurentis, M, Salucci, P, Invited Review at VIII Inter. Workshop on the Dark Side of the Universe, 2012, PoS(DSU 2012) 012
Di Cintio, A. Brook C. B., Macciò, et al. 2014 MNRA, 437, 415
Donato, F., Gentile, G., Salucci, P., 2004, MNRAS, 353L, 17
Donato, F., Gentile, G. Salucci, P., et al, 2009, MNRAS, Vol. 397, 1169.

Evoli, C., Salucci, P., Lapi, A., & Danese, L. 2011, ApJ, 743, 45

Freese, K. 2017 Proceedings of 14th Marcel Grossman Meeting, MG14, Rome, arXiv 170101840

Freeman, K. C. 1970, ApJ, 160, 811

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

Gentile G., Famaey B., Zhao H., Salucci P., 2009, Natur, 461, 627

Jungman, G., Kamionkowski, Griest, K. 1996, PhR...267..195J

Harigaya K. & Nomura Y., 2016, Phys. Rev. D 94, 035013

Hochberg Y., Kuffik E., Volansky T., Wacker J. G., 2014, PhRvL, 113, 171301

Karukes, E. V., & Salucci, P. 2016, arXiv:1609.06903

Klypin, A. and Kravtsov, A. V. and Valenzuela, O. Prada F.,1999,ApJ...522...82

Kormendy, J., Freeman, K. C. 2004, IAUS, 220, 377K

Krishna C. P; Das, S 2017, arXiv:1702.01882

Lovell, M. R.; Gonzalez-Perez, V; Bose, S et al 2016 arXiv:1611.00005

Marciano W. J., 2015, Phys. Rev. D 92, 035008

Memola E., Salucci P., Babić A., 2011, A&A, 534, A50

Milgrom, M., 1983, ApJ 270, 365

Mo, H. J., Mao S., White, S. D. M. 2008 AJ, 136, 2761

Navarro, J. F., Frenk, C. S., & White, S. D. M. 1997, ApJ, 490, 493

Oh S.-H., de Blok W. J. G., Brinks E., Walter F., Kennicutt R. C., Jr., 2011, AJ, 141, 193

Planck Collaboration, 2016A & A...594, 13

Persic, M., Salucci, P. 1991, ApJ, 368, 60

Persic, M., Salucci, P., Stel, F., 1996, MNRAS 281, 27

Pontzen, A., Governato, F. 2012, MNRAS, 421, 3464

Read J. I., Agertz O., Collins M. L. M., 2016, MNRAS, 459, 2573

Ringwald, 2014, arXiv:1407.0546 [hep-ph]

Rubin V. C., 1983, Sci, 220, 1339

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

Salucci, P., Burkert, A .2000, ApJ, 5379

P. Salucci, C. F. Martins and A. Lapi, 2011, DMAW 2010 arXiv:1102.1184v1, 2011.

Salucci, P.; Swinbank, A. M.; Lapi, A. et al 2007 MNRAS, 382, 652

Schneider, P.,1996. MNRAS.283, 837
Salucci P., Nesti F., Gentile G., Frigerio Martins C., 2010, A&A, 523, A83
Spano M., Marcelin M., Amram P., etal 2008, MNRAS, 383, 297
Surez, A; Robles, V H.; Matos, T. 2014 Astrophysics and Space Science Proceedings, 38, 107
Tonini, C.; Lapi, A.; Shankar, F.; Salucci, P. 2006, ApJ, 638, 13
Vogelsberger, M., Zavala, J., Simpson C. Jenkins, A. 2014, MNRAS, 444, 3684
Yegorova, I, Salucci., P. 2007, MNRAS.377, 507
White, S. D. M.,1988 ASPC, 5, 197