PROCEEDINGS OF SCIENCE

On the small scale problems of the ΛCDM model

A. Del Popolo∗†
Dipartimento di Fisica e Astronomia, Universitá di Catania,
Viale Andrea Doria 6, 95125 Catania, Italy;
INFN sezione di Catania,
Via S. Sofia 64, I-95123 Catania, Italy
International Institute of Physics, Universidade Federal do Rio Grande do Norte,
59012-970 Natal, Brazil
E-mail: adelpopolo@oact.inaf.it

We study, the effect of baryon physics on the small scale problems of the CDM model by means of the model proposed in Del Popolo (2009). The cusp/core problem, the missing satellite problem (MSP), the Too Big to Fail (TBTF) problem, and the angular momentum catastrophe can be reconciled with observations. Concerning the cusp/core problem, the interaction among dark matter (DM) and baryonic clumps, through dynamical friction (DF), is able to flatten the inner cusp of the density profiles. Concerning the MSP and TBTF problem, applying to the Via Lactea II (VL2) subhaloes a series of corrections similar to those of Brooks et al. (2013) obtained with our model, and further correcting for the UV heating and tidal stripping, we obtain that the number of massive, luminous satellites is in agreement with the number observed in the MW. The model also produces an angular momentum distribution in agreement with observations. In conclusion, the small scale problems of the CDM model can all be solved by introducing baryon physics :.

XI Multifrequency Behaviour of High Energy Cosmic Sources Workshop,
25-30 May 2015
Palermo, Italy

∗Speaker.
†A footnote may follow.

PoS(MULTIF15)013

1. Introduction

Despite the ΛCDM model being highly successful in describing the observations of the Universe, its large scale structure and evolution (Spergel et al. 2003, Komatsu et al. 2011; Del Popolo 2007, 2013, 2014), it has some problems in describing structures at small scales (e.g., Moore 1994; Boylan-Kolchin, Bullock, and Kaplinghat 2011; Oh et al. 2011)[1]. The main problems are the a) cusp-core problem (CCP) (Moore 1994; Flores & Primak 1994), namely the discrepancy between the flat density profiles of dwarf galaxies and LSBs and the cuspy profile predicted by dissipationless N-body simulations (Navarro, Frenk & White 1996; Navarro 2010). b) The "missing satellite problem" (MSP), namely the discrepancy between the number of predicted subhalos in N-body simulations (Moore et al. 1999) and the one observed[2]. c) The Too-Big-To-Fail problem, namely the discrepancy between the large number of subhaloes with $V_{max} > 25$ km/s predicted by simulations, and observations (Boylan-Kolchin, Bullock, and Kaplinghat 2011). d) The angular momentum catastrophe (AMC) (van den Bosch, Burkert,& Swaters, 2001 (VBS)) namely the angular momentum loss in Smooth Particle Hydrodynamics (SPH) simulations of galaxy formation, giving rise to disks (of dwarf galaxies) having angular momentum distributions different than those of cold dark matter haloes, and disc size of simulated galaxies much smaller than the real ones.

The astrophysical solutions to the previous problems are based on the idea that some "heating" mechanism produces an expansion of the DM component of the galaxy, reducing the inner density. In this group, the main categories are: "supernova-driven flattening" (Navarro et al. 1996; Mashchenko et al. 2006; Governato et al. 2010), and dynamical friction from baryonic clumps (El-Zant et al. 2001; Romano-Diaz et al. 2009; Del Popolo 2009 (DP09); Cole et al. 2011).

A trial to find a unifying baryon solutions to the small scale problems is that of Zolotov et al. (2012) (Z12), and Brooks et al. (2013) (B13). Z12 showed that the same model can solve the TBTF. Z12 found a correction to the velocity in the central kpc of galaxies to mimic the flattening of the cusp due to SF, and the enhancement of tidal stripping produced by a baryonic disc. This correction together with destruction effects produced by the tidal field of the baryonic disc, and the identification of subhaloes that remain dark because of inefficiency in forming stars due to UV heating, were applied by B13 to the VL2 subhaloes of the VL2 simulation (Diemand et al. 2008). As a result the number of massive subhaloes in the VL2 were in agreement with the number of satellites of MW and M31.

In the present paper, we study if the CCP, the AMC, the MSP, and the TBTF problem can be simultaneously solved using baryon physics, through the model of DP09.

The paper is organized as follows. In Sect. 2, we describe the results and discussion. Sect. 3 is devoted to conclusions.

2. Results and discussion

In this section, we show how using DP09 and its improvements (Del Popolo, Pace, Lima 2013a,b; Del Popolo et al. 2013; Hiotelis & Del Popolo 2006, 2013), we can find similarly to Z12,

[1] Other problems of the ΛCDM model are the cosmological constant problem (Weinberg 1989; Astashenok, & Del Popolo 2012), and the "cosmic coincidence problem".

[2] For the Milky Way (MW) the difference is larger than an order of magnitude.

PoS(MULTIF15)013

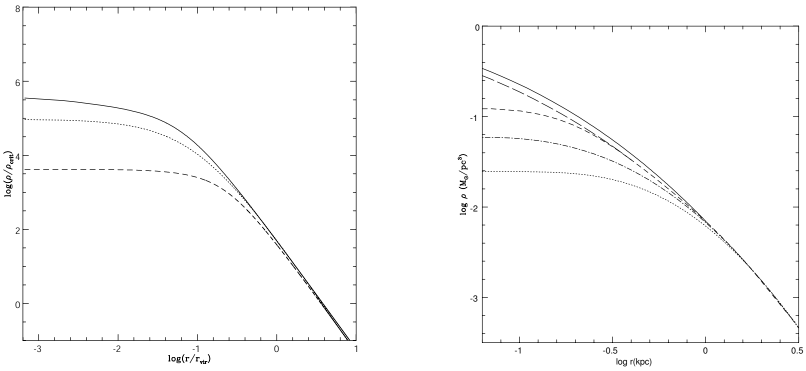

Figure 1: Left panel: density profiles of galaxies (see the text). Right panel: density profile evolution of a $10^9 M_\odot$ halo (see the text).

an analytical correction to apply to the center of the haloes which mimics the effect of flattening of the cusp, and finally similarly to B13, we apply the previous correction together with the tidal destruction and UV heating effects on subhaloes, to the VL2, as done by B13.

2.1 The CCP

In Fig. 1a, we plot the density profile of a galaxy with $M = 10^8 M_\odot$ (dashed line), $10^9 M_\odot$ (dotted line), and $M = 10^{10} M_\odot$. The specific angular momentum was chosen similar to one of the van den Bosch et al. (2001) galaxies, namely UGC 6446, to be having $h \simeq 400$ kpc km /s (or soin parameter $\lambda \simeq 0.05$), and the baryon fraction $f_d \simeq 0.04$. The final density profile is well described by a Burkert profile.

As Fig. 1a shows, the density profile shape is dependent on mass. The slight steepening of the density profile with mass was explained in DP09, Del Popolo (2010) (DP10), Del Popolo (2012a) (DP12a), and is in agreement with the density profiles of THINGS galaxies (de Blok et al. 2008), and with simulations (e.g., Governato et al. 2010).

Fig. 1b, shows the evolution of a $10^9 M_\odot$ halo starting from the redshift of virialization $z = 10$ (solid line). The density profile at $z = 3$, 2, 1, and 0, is represented by the long-dashed line, short-dashed line, dot-dashed line, and dotted-line, respectively. Theoretical results in agreement with the previous ones are those of Ma & Boylan-Kolchin (2004); Romano-Diaz et al. (2009)); Cole et al. (2011).

2.2 The AMC

In Fig. 2, left panel, we plotted the λ' distribution. The solid line represents the DM spin parameter distribution (Bullock et al. 2000), while the dashed curve, the spin parameter distribution for the baryons in the 14 VBS galaxies obtained by Maller & Dekel (2002). The solid histogram is the spin distribution obtained from the 14 VBS galaxies (see Maller & Dekel 2002), and the dashed histogram is the spin parameter distribution obtained from the 14 VBS galaxies, using the method of this paper, in good agreement with the Maller & Dekel (2002) feedback model.

In Fig. 2, center and right panel, we plot the specific angular momentum j profile for UGC 6446 obtained by VBS (Fig. 2, right panel), and the one calculated by us (Fig. 2, ceneter panel).

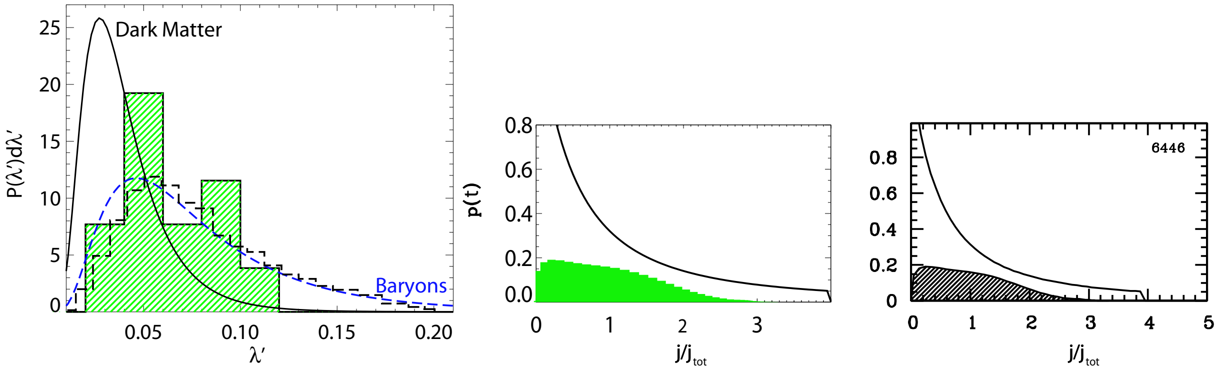

Figure 2: Left panel: the distribution of λ' (see text). Central and right panels: the AMDs (see the text).

In the figure, the solid line is the Bullock et al. (2001) average DM j-profile ($\mu = 1.25$), while the shaded area represent the angular momentum distribution (AMD) for UCG 6446.

The figure shows the angular-momentum profile mismatch. The dwarf angular momentum shows a deficit of angular momentum, at the high and low end of the distribution, with respect to the DM distribution, as in observed galaxies.

2.3 The Too Big to Fail and the Missing Satellites problems

B13, proposed an interesting baryonic solution to the MSP and the TBTF problem. Namely, instead of running SPH simulations of different galaxies, they tried to introduce the baryons effect in large N-body dissipationless simulations, like the VL2, showing that the result obtained is in agreement with observations of MW and M31 satellites.

In the following, we will partly follow their steps to obtain the corrected circular velocities and distribution of VL2 satellites in the framework of DP09.

In summary the method is based on the following ideas and is divided into two main phases.

Initially the attention is directed to the isolated satellites, before accretion to the main system. As noticed by several authors (e.g., Mashchenko et al 2006, 2008; Peñarrubia et al. 2010) the effects of the tidal forces of the main halo on a satellite depends fundamentally on its shape. If the satellite has a cuspy profile, its structure will not suffer big changes, when it will enter the main halo. If the satellite has a cored profile, the tidal field of the main halo can strip easily its gas and in some cases even destroy it (Peñarrubia et al. 2010). So, this first phase, defining the shape of the satellite is of fundamental importance. This first phase and the flattening of the satellites density profiles will be studied through DP09.

The correction that we obtained is close to that obtained by Z12, accounting mainly for the reduction of the subhaloes central mass produced by SF, and given by

$$\begin{aligned}\Delta(v_{1kpc}) &= 0.2\mathrm{v_{infall}} - 0.26\mathrm{km/s} \\ &\quad 20\mathrm{km/s} < \mathrm{v_{infall}} < 50\mathrm{km/s}\end{aligned} \tag{2.1}$$

The last equation gives the difference between DM and SPH runs, and then the corrections to apply to satellites in N-body simulations that take account of the missing piece of baryonic physics.

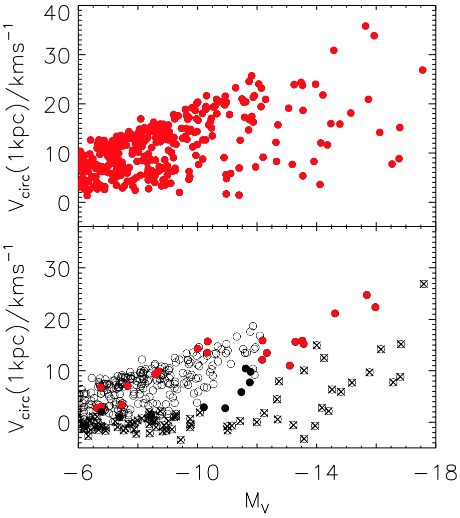

Figure 3: Plot of v_{1kpc} vs M_V for the VL2 simulation subhaloes (see the text).

Then comes the second phase, when the satellite is no longer considered isolated, it is subject to the tidal field of the main halo, and finally it is accreted to the main halo. In this phase, we consider the effetcts of tidal stripping, tidal heating, and photo-heating (see Del Popolo et al. 2014 for a wider discussion).

The result of the previously corrections are plotted in Fig. 6. The top panel of this figure represents the results from VL2 at $z = 0$. The bottom panel represents the same satellites after the previous discussed corrections (heating, destruction, and velocity corrections) were applied. The red filled symbols are the object “observable" in VL2. Dark objects are marked by empty circles. Objects marked with a circle and a “x" through them, represent subhaloes that do not survive to the baryonic effects (e.g., baryonic disc, etc). Empty circles have a mass smaller than the minimum to retain baryon and form stars. Finally, filled black circles are satellites that lose 90% of their mass since infall, but do not satisfy the destruction criteria previously described.

In our model, the solution to the previous quoted problems is connected to the complex interaction between DM and baryons mediated by DF. Our study is similar to those of El-Zant et al. (2001), Romano-Diaz et al. (2009), Cole et al. (2011), in the sense that like them in our study DF plays an important role. However, differently from the previous studies, we consider the joint effect of several other effects (e.g., random angular momentum, angular momentum generated by tidal torques, adiabatic contraction, cooling, star formation), that in the quoted studies were not considered.

3. Conclusions

In the present paper, we studied the small scale problems of the ΛCDM by means of the model presented in DP09 (see also DP12a, b).

The model had already shown in DP09, DP12a,b, that the CCP can be solved by baryonic clumps-DM interaction. Here we showed that the AMC, the MSP and TBTF problem can be solved in the same framework, as shown in Del Popolo et al. (2014).

PoS(MULTIF15)013

References

[1] Adams J. J., et al. 2014, ApJ, 789, 63

[2] Astashenok, A. V., and Del Popolo, A., 2012, Class. Quantum Grav. 29, 085014 (doi:10.1088/0264-9381/29/8/085014)

[3] Boyarsky A., Ruchayskiy O., Iakubovskyi D., Maccio A. V., Malyshev D., 2009, preprint (arXiv:0911.1774)

[4] Boylan-Kolchin, M., Bullock, J. S., Kaplinghat, M, 2011, MNRAS 415L, 40

[5] Brooks, Alyson M.; Kuhlen, Michael; Zolotov, Adi; Hooper, Dan, 2013, ApJ 765, 22

[6] Bullock, J. S., Kravtsov, A. V., & Weinberg, D. H. 2000, ApJ, 539, 517

[7] Cardone V. F., Tortora C., 2010, MNRAS, 409, 1570

[8] Cardone V. F., Del Popolo A., 2012, MNRAS, 427, 3176

[9] Cardone, V.F., del Popolo, A., Tortora, C., Napolitano, N.R., 2011, MNRAS 416 (3), pp. 1822-1835

[10] Cole, D. R., Dehnen,W., & Wilkinson, M. I. 2011, MNRAS, 416, 1118

[11] de Blok W. J. G., et al. 2008, AJ 136, 2648

[12] Del Popolo, A., Gambera, M., 1997, A&A 321, 691

[13] Del Popolo, A., 2007, Astronomy Reports, Volume 51, 169

[14] Del Popolo, A., 2009, ApJ 698, 2093

[15] Del Popolo, A., 2010, MNRAS 408, 1808

[16] Del Popolo, A., & Cardone, V., 2012, MNRAS 423, 1060

[17] Del Popolo, A., 2012a, MNRAS 424, 38

[18] Del Popolo, A., 2012b, MNRAS 419, 971

[19] Del Popolo A., Cardone V. F., Belvedere G., 2013, MNRAS, 429, 1080

[20] Del Popolo, A., 2013, AIP Conference Proceedings 1548 , pp. 2-63

[21] Del Popolo, A., Pace, F., Lima, J.A.S., 2013, MNARS 430 (1), pp. 628-637

[22] Del Popolo, A., Pace, F., Lima, J.A.S., 2013, IJMPD 22 (8), 1350038

[23] Del Popolo, A., Pace, F., Maydanyuk, S.P., Lima, J.A.S., Jesus, J.F., 2013, Physical Review D - Particles, Fields, Gravitation and Cosmology 87 (4), 043527

[24] Del Popolo, A., 2014, IJMPD 23, No. 3, 1430005

[25] Del Popolo A., et al. 2014, JCAP 04, 021

[26] Diemand, J., et al. 2008, Nature 454, 735

[27] Flores, R., Primack, J. R., Blumenthal, G. R., Faber, S. M., 1993, ApJ 412, 443-454

[28] Governato et al. 2010, Nature 463, 203

[29] Graham A. W., 2013, Elliptical and Disk Galaxy Structure and Modern Scaling Laws, Berlin, Springer, p. 91

[30] Hiotelis, N., Del Popolo, A., 2006, Astrophysics and Space Science 301 (1-4), pp. 167-177

[31] Hiotelis, N., del Popolo, A., 2013, MNRAS 436 (1), pp. 163-178

[32] Komatsu, E., et al. 2009, ApJS, 180, 330

[33] Komatsu, E., Smith, K. M., Dunkley, J., et al. 2011, ApJS, 192, 18

[34] El-Zant, A., Shlosman, I., & Hoffman, Y. 2001, ApJ, 560, 636

[35] Maller A. H., & Dekel A., 2002, MNRAS 335, 487

[36] Merritt D., Graham A.W., Moore B., Diemand J., Terzit'c B., 2006, AJ, 132, 2685

[37] Oh, S-H, de Blok, W. J. G., Brinks, E., Fabian, W., Kennicutt, R. C., Jr., 2011 AJ 141, 193

[38] Moore B., 1994, Nat, 370, 629

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

[40] Navarro J. F., Frenk C. S., White S. D. M., 1996, ApJ, 462, 563

[41] Navarro J. F. et al., 2010, MNRAS, 402, 21

[42] Navarro J. F., Frenk C. S., White S. D. M., 1996, ApJ, 462, 563

[43] Mashchenko, S., Couchman, H. M. P., & Wadsley, J. 2006, Nature, 442, 539

[44] Napolitano N. R., Romanowsky A. J., Tortora C., 2010, MNRAS, 405, 2351

[45] Oh S.-H., Brook C., Governato F., Brinks E., Mayer L., de Blok W. J. G., Brooks A., Walter F., 2011b, AJ, 142, 24

[46] Oman, K. A., et al. 2015, arXiv:1504.01437

[47] Peñarrubia et al., 2010, MNRAS 406, 1290

[48] Romano-Diaz, E., Shlosman, I., Heller, C., & Hoffman, Y. 2009, ApJ, 702, 1250

[49] Saburova, A., Del Popolo, A., 2014, MNRAS 445, 3512Ű3524

[50] Simon J. D., Bolatto A. D., Leroy A., Blitz L., Gates E. L., 2005, ApJ, 621, 757

[51] Simon J. D., Bolatto A. D., Leroy A., Blitz L., 2003, ApJ, 596, 957

[52] Spano M., Marcelin M., Amram P., Carignan C., Epinat B., Hernandez O., 2008, MNRAS, 383, 297

[53] Spergel, D. N., Verde, L., Peiris, H. V., et al. 2003, ApJS, 148, 175

[54] van den Bosch F. C., Burkert A., Swaters R. A., 2001, MNRAS, 326, 1205 (VBS)

[55] Weinberg, S., Rev. Mod. Phys., 1989, 61, 1

[56] Zolotov, A., Brooks, A. M., Willman, B., Governato, F., Pontzen, A., Christensen, C., Dekel, A., Quinn, T., Shen, S., Wadsley, J., 2012, ApJ 761, 71

DISCUSSION

P. L. BIERMANN's Comment: Can you reproduce the regularities in galaxy structure found by Paolo Salucci?

ANTONINO DEL POPOLO:

Your question is linked to the oldest and most stubborn small scale problem of the ΛCDM model, the already mentioned cusp-core problem.

According to some researchers (e.g. Salucci), a. rotation curves (or density ptofiles) of all galaxies, from dwarves to giant ellipticals can be described by the so-called URC (universal Rotation Curve). b. When the density profile of galaxies is fitted by that function (or a cored density profile) the central column density is constant.

Now, issue a (URC) is refuted by observations, and simulations.

After two decades of studies, from Flores & Primack (1994) paper, it is becoming clear that the statement of the cored nature of the inner density profile of all galaxies, is not at all obvious. While according to Spano et al. (2008) high-surface brightness galaxies are cored, other authors (e.g., Simon et al. 2005; de Blok et al. 2008; Del Popolo & Cardone 2012) conclude differently. The THINGS sample shows a tendency to have profiles better described by isothermal (ISO) profiles for low luminosity galaxies, $M_B >$ -19 and the profiles are equally well described by cuspy or cored profiles for $M_B <$ -19. Even dwarfs do not always have flat slopes, as shown by Simon et al. (2005). In the case of NGC 2976, 4605, 5949, 5693, 6689, the authors showed that the profiles range from 0 (NGC2976) to -1.28 (NGC5963). Different results have been obtained even using similar techniques for the same object. For example, in the case of NGC2976 the dark matter profile slope is bracketed by $-0.17 < \alpha < -0.01$, according to Simon et al. (2003), while $\alpha = -0.90 \pm 0.15$ for Adams et al. (2012), $\alpha = -0.53 \pm 0.14$ according to Adams et al. (2014), considering stars as tracers, or $\alpha = -0.30 \pm 0.18$ (Adams et al. 2014), considering gas as tracer. The situation is very unclear in the case of the local group dSphs. Different authors found different inner profiles for Fornax, and Sculptor. The previous results show that in reality there is no accepted conclusion on the inner structures of dSphs. The result from the previous studies and several others is that exists a range of profiles, and even with the improvements of nowaday's kinematic maps there is no agreement on the exact dark matter slopes distribution (Simon et al. 2005; Oh et al. 2011b; Adams et al. 2014). To reinforce the non universality of rotation curves or similar, comes the recent high resolution simulation of Oman et al. (2015), in line with previous results of Del Popolo (2010, 2012b), showing that the high diversity in rotation curves of dwarves. In the case of ellipticals many studies (e.g., Merrit et al. 2006; Graham et al. 2013) converge to the idea that the density profile is fitted by a Sersic-Einasto profile.

The previous discussion also undermines the claim b, namely the constancy of the central density. The claimed constancy is obtained assuming assuming that all galaxies, from dwarfs to ellipticals, are fitted by a Burkert DM halo density profile. Several authors, (e.g., Boyarsky et al. 2009; Napolitano, Romanowsky & Tortora 2010; Cardone & Tortora 2010; Napolitano et al. 2010; Cardone et al. 2011; Cardone & Del Popolo 2012; Del Popolo, Cardone, & Belvedere (2013); Saburova & Del Popolo 2014; Adams et al. 2014), clearly showed that the surface density is not constant. We refer the interested reader to the detailed studies Cardone & Del Popolo (2012), Del Popolo, Cardone, & Belvedere (2013); Saburova & Del Popolo (2014).