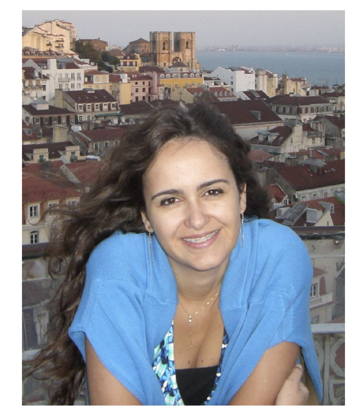
A constant Dark Matter Halo surface density in Galaxies



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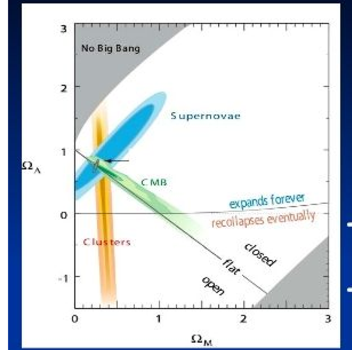
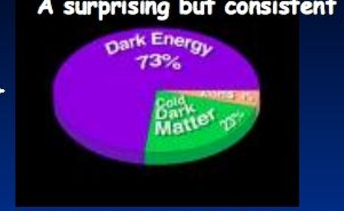
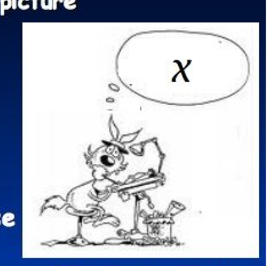
Abstract: We confirm and extend an intriguing recently result by Spano et al. 08: the central surface density μ_{0D} of galaxy DM halos is nearly constant, independent of galaxy luminosity. Based on the co-added RCs of ~1000 spiral galaxies, mass models of individual dwarf irregular and spirals with high-quality RCs, and the galaxy-galaxy weak lensing signals from a sample of spirals and ellipticals, we find that $\log \mu_{0D} = 2.05 \pm 0.15$, in units of $M_\odot pc^{-2}$. We also show that the observed kinematics of Local Group dwarf spheroidals are consistent with this value. Our results are obtained for galactic systems spanning a wide range in magnitude, belonging to different Hubble Types, and whose mass profiles have been determined by independent modeling methods. The constancy of μ_{0D} is in sharp contrast to the variation, by several orders of magnitude, of the halo density and stellar surface density in the same objects.

Introduction 1

A surprising but consistent picture



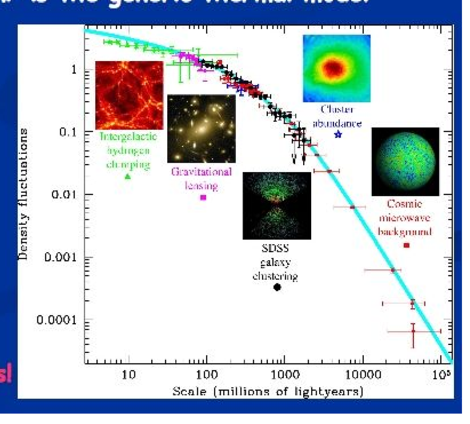




- Cosmological observations: dark Universe
- Dark Matter: cold, neutral, weakly interacting new particles not yet detected: WIMP is the generic thermal model

LCDM scenario

- primordial density perturbations are generated during an inflationary period and become the seeds of the bottom-up structure formation
- accelerated expansion of the universe, temperature fluctuations in the CMB, large scale matter distribution & main aspects of formation and evolution of virialized cosmological objects
- problems in explaining distribution of DM in galaxies!

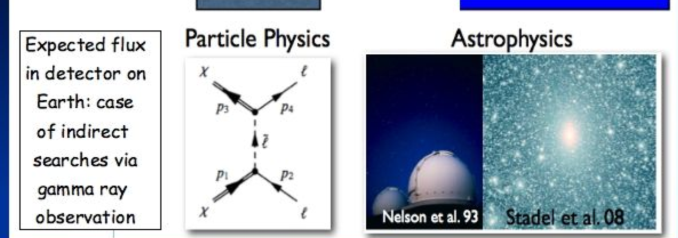


Implications 2

Success of dedicated searches crucially depends on capability of predicting the signal expected for each particle model. Capability relies on knowledge of DM distribution in bound objects.

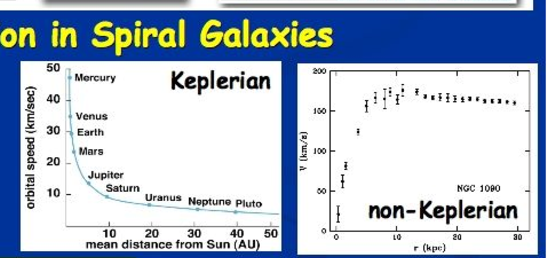
$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\Delta\psi)=\frac{\langle\sigma v\rangle_{ann}}{4\pi m_\chi^2}\Sigma_f B_f \frac{dN_\gamma^f}{dE_\gamma}\times\frac{1}{2}\int_{\Delta\psi}\frac{d\Omega}{\Delta\psi}\int_{l.o.s.} dl(\psi)\rho^2(r)$$

Expected flux in detector on Earth: case of indirect searches via gamma ray observation



The mass distribution in Spiral Galaxies

Presence of large amounts of unseen matter in spirals with a distribution different from that of stars and gas is well established



Crucial steps

- Rubin, Bosma 80: optical, 21cm RCs
- Persic, Salucci 88: scaling relations
- Navarro, Frenk & White 96: numerical simulations
- Persic, Salucci & Stel 96: Universal Rotation Curve
- Salucci et al. 07: URC II

Has DM an universal distribution reflecting its Nature? How and why physical quantities vary in objects of different Hubble type?

Rotation Curves as gravitational field traces 3

The recipe: Analysis of Rotation Curves

Ingredients:

- Total gravitational potential: Stars + Gas + Halo contributions

$$\phi_{total}=\phi_{DM}+\phi_{disk,stars}+\phi_{disk,gas}\rightarrow V_{tot}^2(r)=r\frac{d}{dr}\phi_{tot}=V_{DM}^2+V_{disk,stars}^2+V_{disk,gas}^2$$

- Stellar and gaseous contributions: Available photometry and radio observations show that they are distributed in an infinitesimal thin and circular symmetric disk

$$\phi_{disk}(r)=-G\int_0^\infty dr' r' \Sigma_{disk}(r')\int_0^{2\pi}\frac{d\theta}{|r-r'|}$$

$$\Sigma_{gas}\rightarrow HI\ data \qquad \Sigma_{stars}=\frac{M_D}{2\pi R_D^2}e^{-r/R_D}$$

$$V_{disk,stars}^2=\frac{GM_D}{2R_D}x^2B(x/2) \qquad x\equiv r/R_D;\ B\equiv I_0K_0-I_1K_1$$

Freeman, ApJ 160, 811 (1970)

- Halo contribution: parametrized by theoretical or empirical model
- RCs are chi2 best fitted: free parameters (disk mass & halo parameters)
- Compare data with model: wide sample, from LSB to very luminous galaxies & with accurate and proper kinematics

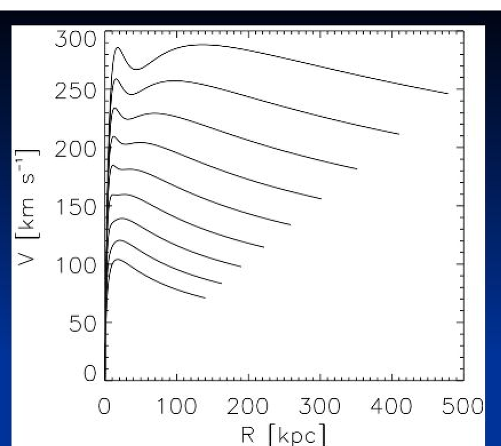
TRIESTE: WE HAVE THE BEST SUITABLE AVAILABLE SAMPLE!

Results from Trieste 4

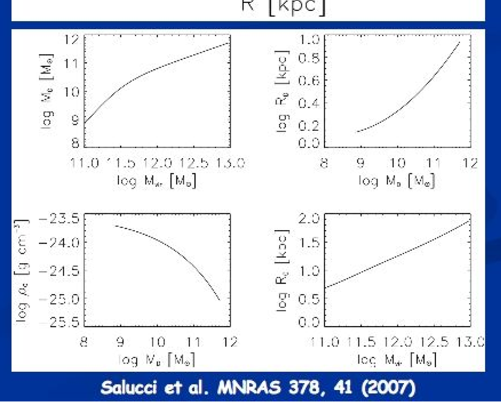
Universal Rotation Curve (URC)

$$V_{URC}^2=V_{URCD}^2+V_{URCH}^2$$

$$\rho_{BURKERT}(r)=\frac{\rho_0 r_0^3}{(R+r_0)(R^2+r_0^2)}$$



- stellar disk dominates inner region
- faint galaxies are more DM dominated
- smaller galaxies are denser
- structural parameters are related
- $0.5\le M_D/L\le 5$

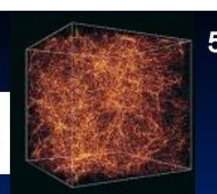


Salucci et al. MNRAS 378, 41 (2007)

Dark halos from simulations 5

Halos form hierarchically bottom-up via gravit. amplification of initial density flucts. Most evident property: CENTRAL CUSP

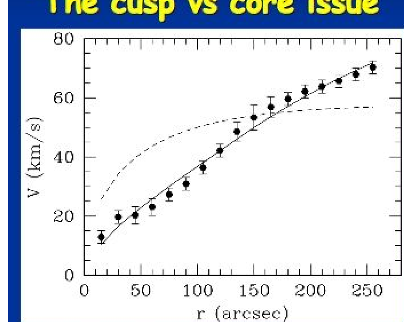
$$\rho_{NFW}(r)=\frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$



$$M_{vir}\equiv\frac{4\pi}{3}\Delta_{vir}\rho_u R_{vir}^3 \qquad V_{vir}^2\equiv GM_{vir}/R_{vir} \qquad c_{vir}\equiv R_{vir}/r_s\simeq 9.7(M_{vir}/10^{12}M_{un})^{-0.09}$$

Navarro, Frenk & White, ApJ 462, 563 (1996)
Bullock et al., MNRAS 321, 559 (2001)

The cusp vs core issue



Gentile et al., ApJ 634, L145 (2005)

Any successful cosmological model must be able to reproduce both observed large and small scale structures. Cuspy NFW density profile disagree with a number of observations.

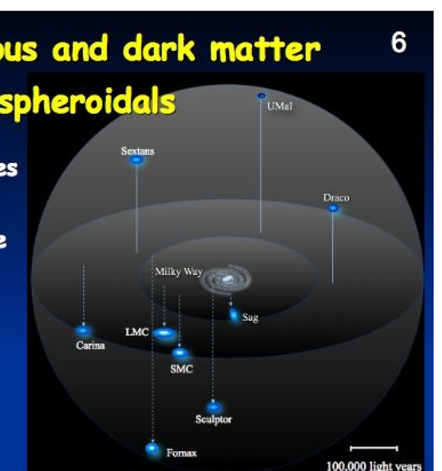
'Galaxy by galaxy' comparison highlights a CDM crisis and has been the main goal of several publications.

- Fits the RCs poorly
- Unphysical too low stellar mass-to-light ratios
- Unphysical too high halo mass

Moore, Nature 370, 629 (1994)
Kravtsov et al., ApJ 502, 48 (1998)
Salucci & Burkert, ApJ 537, L9 (2000)
de Blok, McGaugh & Rubin, AJ 122, 2396 (2000)
Marchesini et al., ApJ 575, 801 (2002)
de Blok & Bosma, A&A 385, 816 (2002)
Salucci, Walter & Borriello, A&A 409, 53 (2003)
Gentile et al., MNRAS 351, 903 (2004)
Kuzio de Naray, McGaugh & de Blok, ApJ 676, 920 (2008)

Universal scaling relations in the luminous and dark matter mass distributions of spirals & dwarfs spheroidals 6

This work: first attempt to investigate whether properties of DM halos at the low end of galaxy luminosity are compatible with structural relations that characterize the 10^4 times more massive halos around Spirals, and its implications for understanding the nature of DM.



MOTIVATIONS:

- DM dominated LG galaxies, at least 2 orders of magnitude less luminous than faintest spirals: ideal test beds for constraining nature of DM that dominates their gravity; dedicated DM searches
- evolutionary histories significantly different from spirals (old, pressure supported, spheroidal systems): indispensable for building up an observational picture of the process of gal. formation

Data & Methodology: Structural DM halo obtained from mass models of

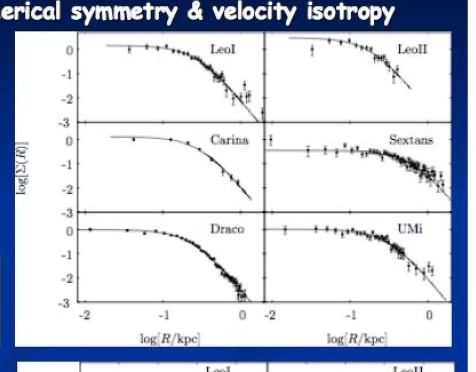
(a) large sample of Spirals, analyzed by means of their URC
(b) darkest Spiral in the local Universe, studied through its kinematics
(c) large sample of Spirals and Ellipticals, for which weak-lensing shear measurements are available
(d) six dSphs satellites of the Milky Way, for which extensive stellar kinematic data are available

Gilmore et al., ApJ 663, 948 (2007)

Dark halos around the Milky Way sattelites 7

- We use the Jeans eqs to determine 3D mass profile corresponding to light distribution & velocity dispersion, under the assumptions of spherical symmetry & velocity isotropy

$$M(r)=-\frac{r^2}{G}\left(\frac{1}{\nu}\frac{d\nu\sigma_r^2}{dr}+2\frac{\beta\sigma_r^2}{r}\right)$$

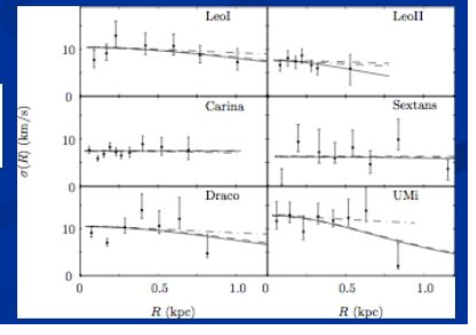


- Fit surface brightness profile with Plummer distribution

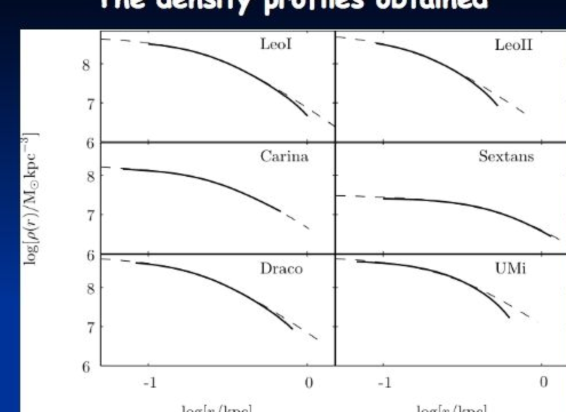
$$\Sigma(R)=\frac{\Sigma_0}{\left(1+R^2/R_b^2\right)^2}$$

- Fit l.o.s. velocity dispersion

$$\sigma(R)=\frac{\sigma_0}{\left(1+R^2/R_s^2\right)^2}$$



The density profiles obtained 8



- Fit a Burkert profile to the density profiles obtained

$$\rho_{BURKERT}(r)=\frac{\rho_0 r_0^3}{(R+r_0)(R^2+r_0^2)}$$

Name	R_b (kpc)	σ_0 (km/s)	R_s (kpc)	ρ_0 ($10^8 M_\odot$ kpc^{-3})	r_0 (kpc)	M_b ($10^5 M_\odot$)	$M(R_{83}/2)$ ($10^7 M_\odot$)
LeoI[1]	0.28 ± 0.01	10.4 ± 1.0	1.9	5.3 ± 1.3	0.27 ± 0.02	48	3.1 ± 0.6
LeoII[1]	0.19 ± 0.01	7.5 ± 0.6	0.9	6.1 ± 1.8	0.18 ± 0.02	5.8	1.1 ± 0.2
Carina[2]	0.31 ± 0.01	7.5 ± 0.4	1.2	2.1 ± 0.3	0.32 ± 0.02	4.3	1.8 ± 0.2
Sextans[1]	0.64 ± 0.04	6.3 ± 1.0	1.9	3.5 ± 1.5	0.65 ± 0.06	5.0	2.6 ± 0.8
Draco[3]	0.247 ± 0.002	10.5 ± 0.8	1.5	6.9 ± 1.2	0.24 ± 0.01	2.6	2.8 ± 0.4
Ursa Minor[1]	0.321 ± 0.014	12.8 ± 1.2	1.1	6.6 ± 1.6	0.28 ± 0.02	2.9	5.2 ± 0.9

Dark halos around galaxies: Weak lensing 9

Recent developments in weak gravitational lensing have made it possible to probe the averaged mass distribution around galaxies out to large projected distances. The gravitational field of 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:

$$\langle\gamma_t\rangle\equiv\frac{\overline{\Sigma}(R)-\Sigma(R)}{\Sigma_c(R)} \qquad \Sigma(R)=2\int_0^\infty \rho(R,z)dz$$

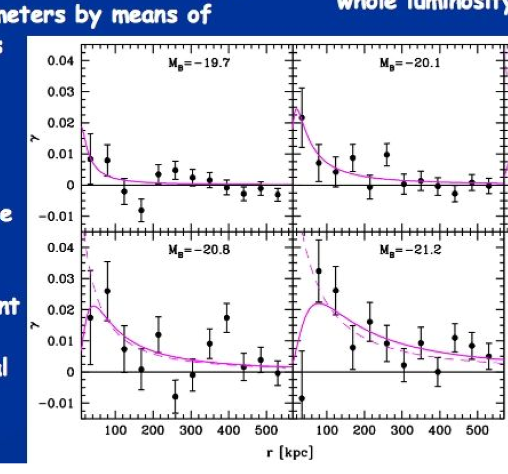
Data: weak lensing measurements from Hoekstra et al. 05 available out to 530 kpc. Sample contains about 10^5 objects and spans whole luminosity range of Spirals.

By adopting a density profile, we model the data and obtain the structural free parameters by means of standard best-fitting techniques

$$\rho_{BURKERT}(r)=\frac{\rho_0 r_0^3}{(R+r_0)(R^2+r_0^2)}$$

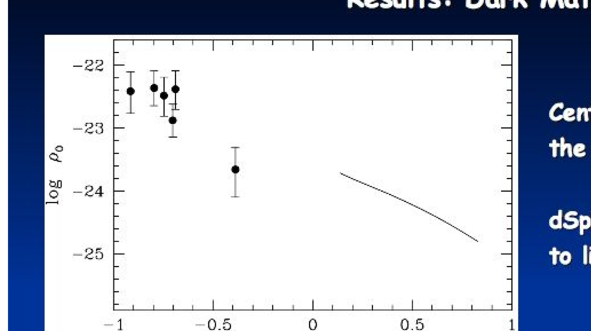
We find same results, in completely different way, as are obtained from RCs.

Burkert profile provides excellent fits. NFW provides less satisfactory fits to gravitational shear around the most luminous objects.



r_0 (kpc)	ρ_0 ($10^6 M_\odot/kpc^3$)
7^{+3}_{-6}	15^{+15}_{-15}
14^{+6}_{-10}	10^{+10}_{-10}
40.4^{+20}_{-20}	$1.7^{+1.5}_{-1.5}$
30^{+10}_{-20}	4.1^{+4}_{-4}
56^{+20}_{-20}	$2.3^{+1.2}_{-1.2}$

Results: Dark Matter properties 10

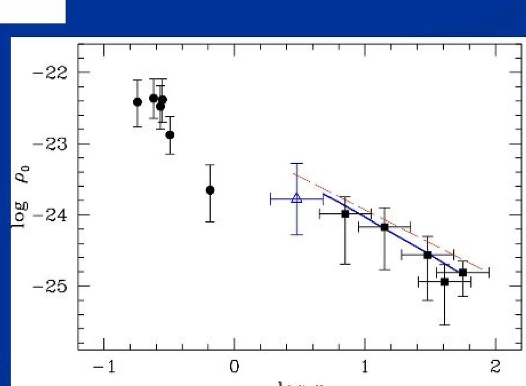


Central DM densities regularly increase as the size of the stellar component decreases.

dSph halos are much denser, they are found to lie on the Spiral relationship.

All these data can be reproduced by

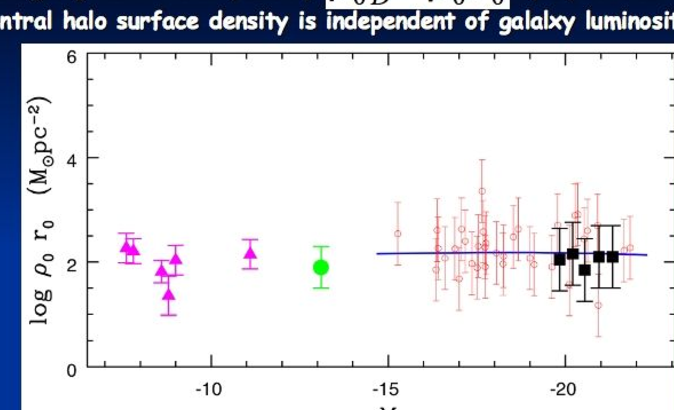
$$\log r_0 = A\log\rho_0 + C$$



Salucci, Wilkinson, Gilmore, Grebel, Koch, Wyse, C.F.M., Gentile [in preparation]

A constant Dark Matter halo surface density in galaxies 11

An intriguing result: the quantity $\mu_{0D}\equiv\rho_0 r_0$ proportional to the central halo surface density is independent of galalxy luminosity:



$$\log\mu_{0D}=2.05\pm0.15\,M_{sun}\,pc^{-2}$$

Donato, Gentile, Salucci, C.F.M., Wilkinson, Gilmore, Grebel, Koch, Wyse [in press]

- DM halo central surface density over at least fourteen galaxy magnitudes and across several Hubble types, remains constant to within less than a factor of two, in contrast to the stellar central surface density in galaxies which shows large variation
- evidence suggests that μ_{0D} may be an important physical quantity in the DM distribution of galaxies

Discussion 12

- halos of the faintest objects have properties scaled down with respect of bigger ones
- suggests a Grand Picture for galaxy formation in which in galaxies of all Hubble Types, DM is "aware" of scale length of luminous matter
- existence of scaling relations between central density and core radius over three orders of magnitude can rule out WDM

Gilmore et al., ApJ 663, 948 (2007)

- DM relations cannot arise due to self-annihilation which would predict narrow range in ρ_0
- results support analysis by Spano $\mu_{0D}=110^{+50}_{-30}M_{sun}\,pc^{-2}$
- surprising finding, difficult to envisage how such a relation can be maintained across galaxies from DM-to baryon-dominated in the inner regions

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