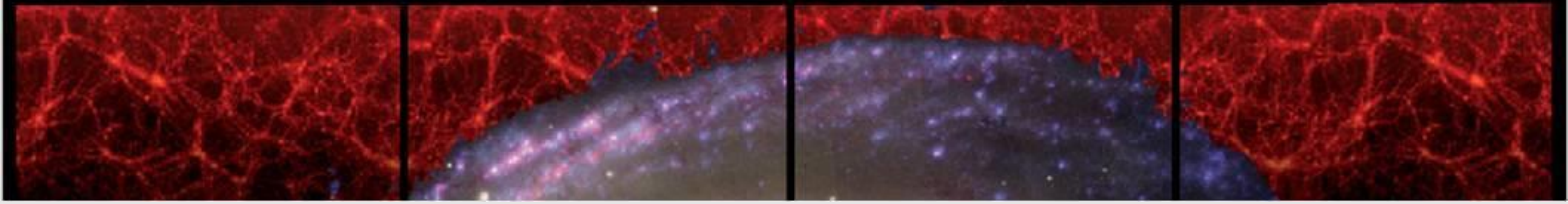


Galaxies properties lead to ΛWDM

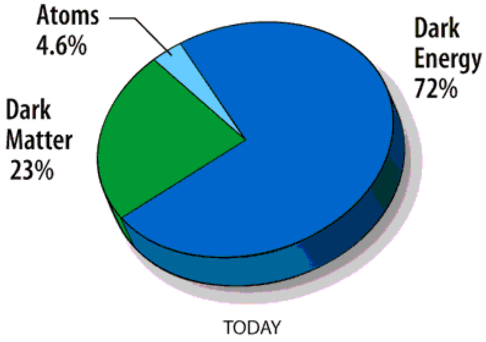
PAOLO SALUCCI

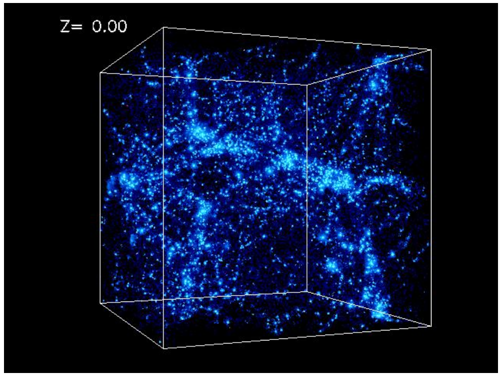
SISSA, GSSI

Dedicated to my friend Hector

Outline

Dark Matter is a main **protagonist** in the Universe





In the mass distribution of the structures of the Universe we detect a dark massive component

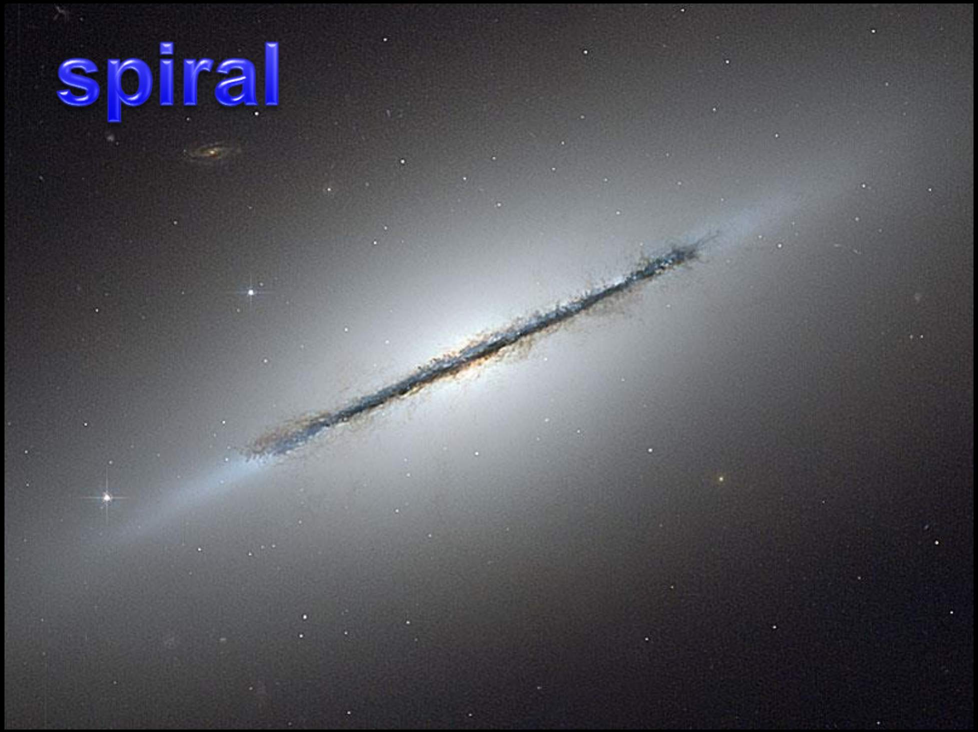
Atoms cannot develop these structures neither be responsable of this component

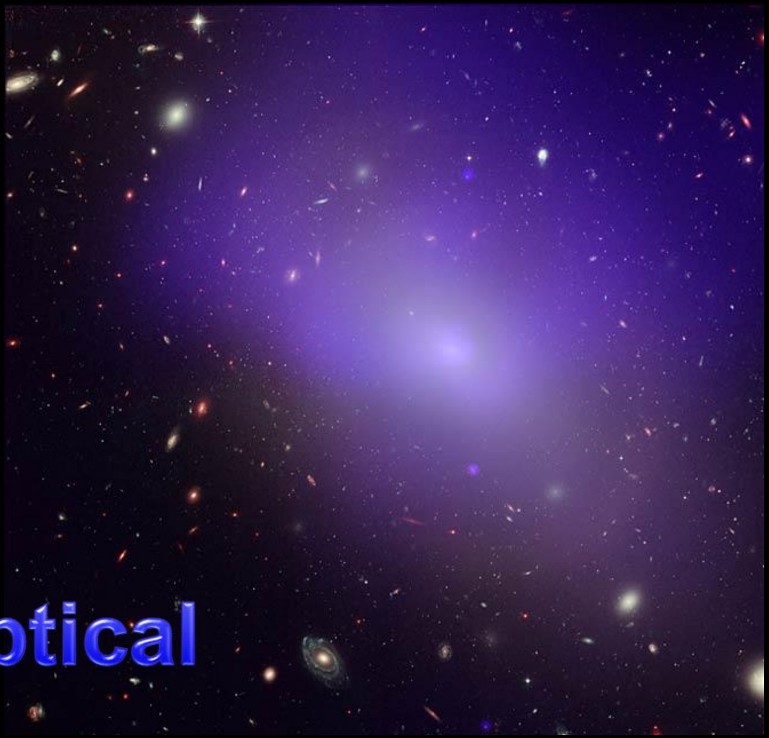
Standard Model of Elementary particles has reasonable extensions in which the required dark particle is naturally created

Details of the In the mass distribution in galaxies play today a new role

-were often found incompatible with all-DM LCDM predictions (1996-2014)
-lead to a LWDM scenario and falsify the baryonically fine-tuned LCDM scenario (2014 -)

3 TYPES OF GALAXIES: DIFFERENT DISTRIBUTION OF BARYONS

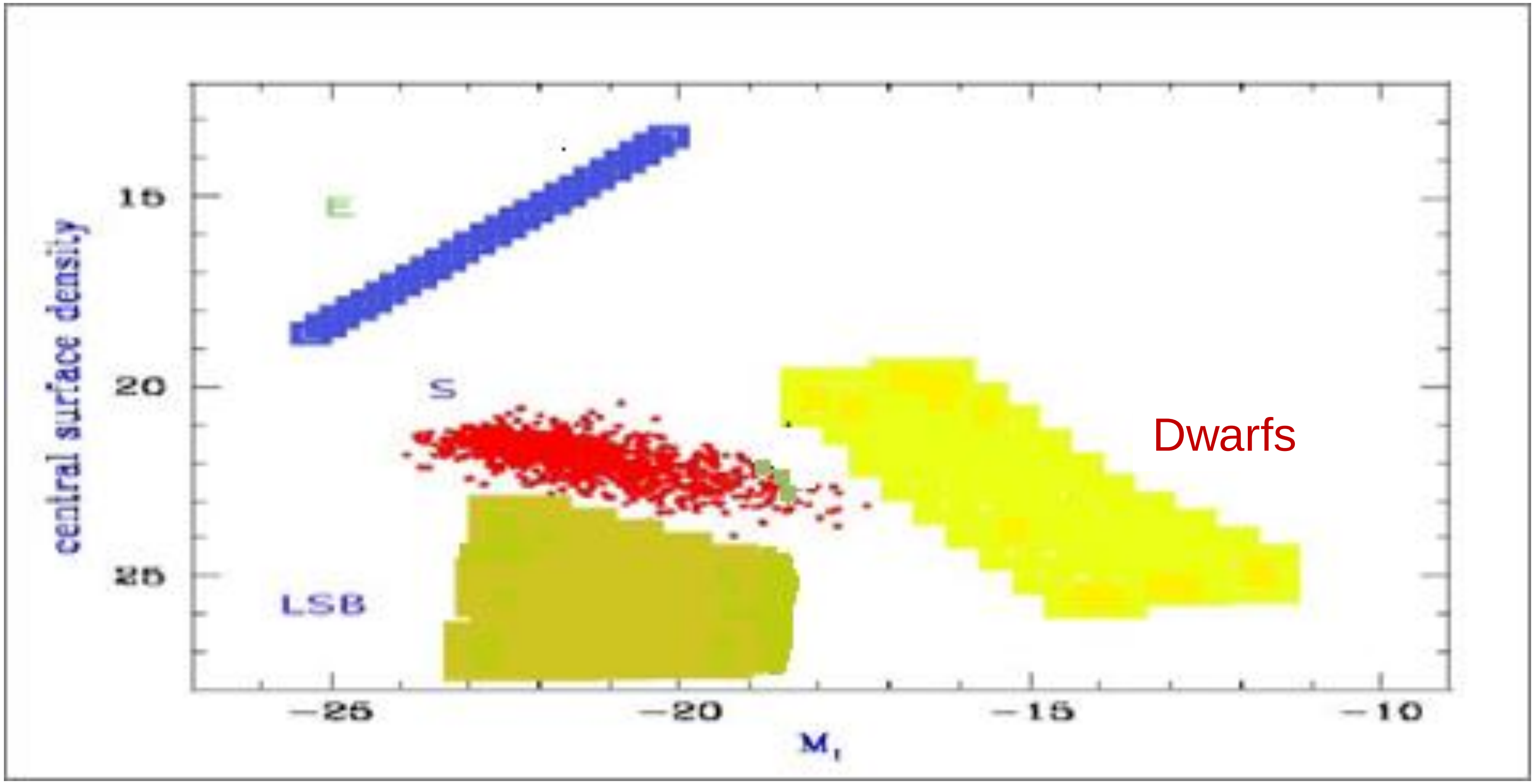




The Realm of Galaxies

The range of galaxies in magnitudes, types and central surface densities : 15 mag, 4 types, 16 mag arsec^{-2}

Central surface brightness vs galaxy magnitude



The distribution of luminous matter :

Spirals : stellar disk +bulge +HI disk

Ellipticals & dwarfs E: stellar spheroid

How do we detect Dark Matter ?

$M(r)$, $M_L(r)$, dlog $M_L(r)$/dlog r, dlog $M(r)$/dlog r **observed**

In a galaxy, the radial profile of the gravitating matter $M(r)$ does not match that of the luminous component $M_L(r)$.

:

$$\frac{d\log M(r)}{d\log r} = \frac{M_L(r)}{M(r)}\,\frac{d\log M_L(r)}{d\log r} + \frac{M_H(r)}{M(r)}\,\frac{d\log M_H(r)}{d\log r}$$

A MASSIVE DARK COMPONENT is then introduced to account for the disagreement

$$M_H(R) = \int_0^R \frac{M(R)}{R}\ \left(\alpha(R) - \frac{\alpha_L(R)\, M_L(R)}{M(R)}\right) dR$$

CDM:

the simplest cosmological and EP scenario
the simplest simulations

Straighforward predictions

ΛCDM Dark Matter Density Profiles from N-body simulations

The density of virialized DM halos of any mass is empirically described at all times by an Universal profile (Navarro+96, 97, NFW).

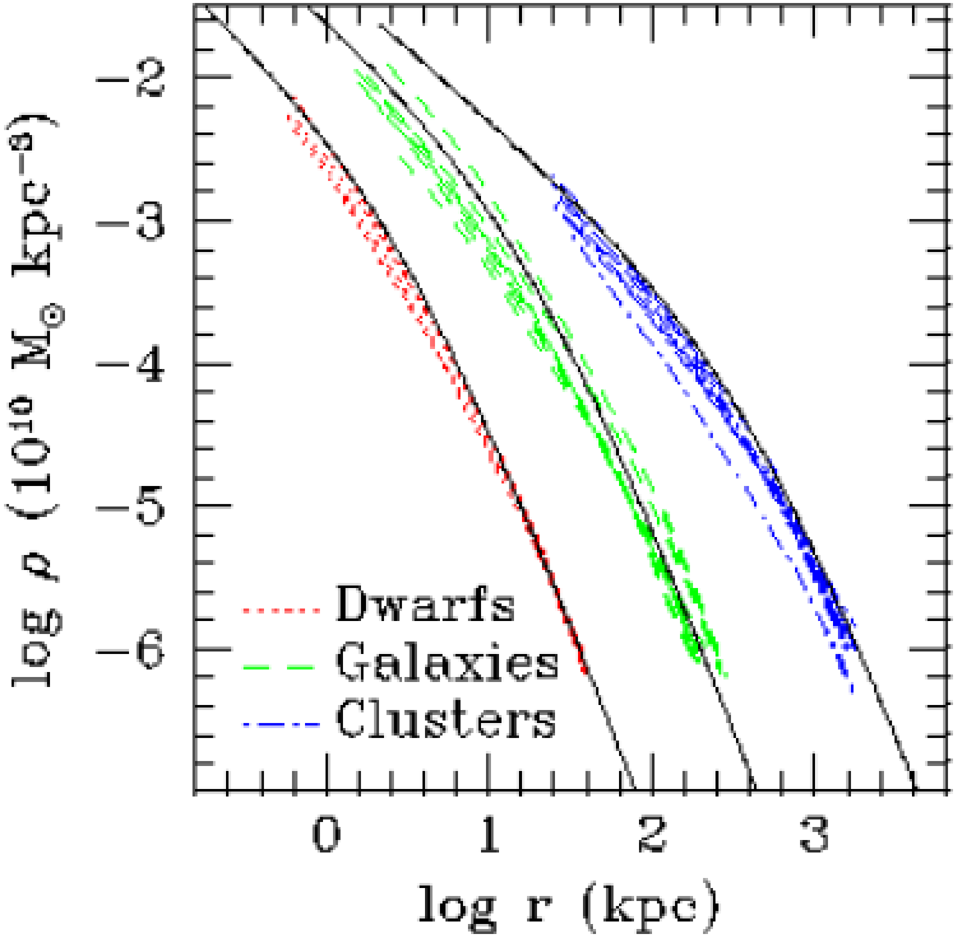
$$\rho_{NFW}(r) = \delta\rho_c \frac{r_s}{r} \frac{1}{(1+r/r_s)^2}$$

$$c = \frac{R_{vir}}{r_s}$$

$$R_{vir} = 260 \left(\frac{M_{vir}}{10^{12}\ M_\odot}\right)^{1/3} kpc$$

$$c(M_{vir}) = 9.35 \left(\frac{M_{vir}}{10^{12}\, M_\odot}\right)^{-0.09}$$

Klypin, 2010



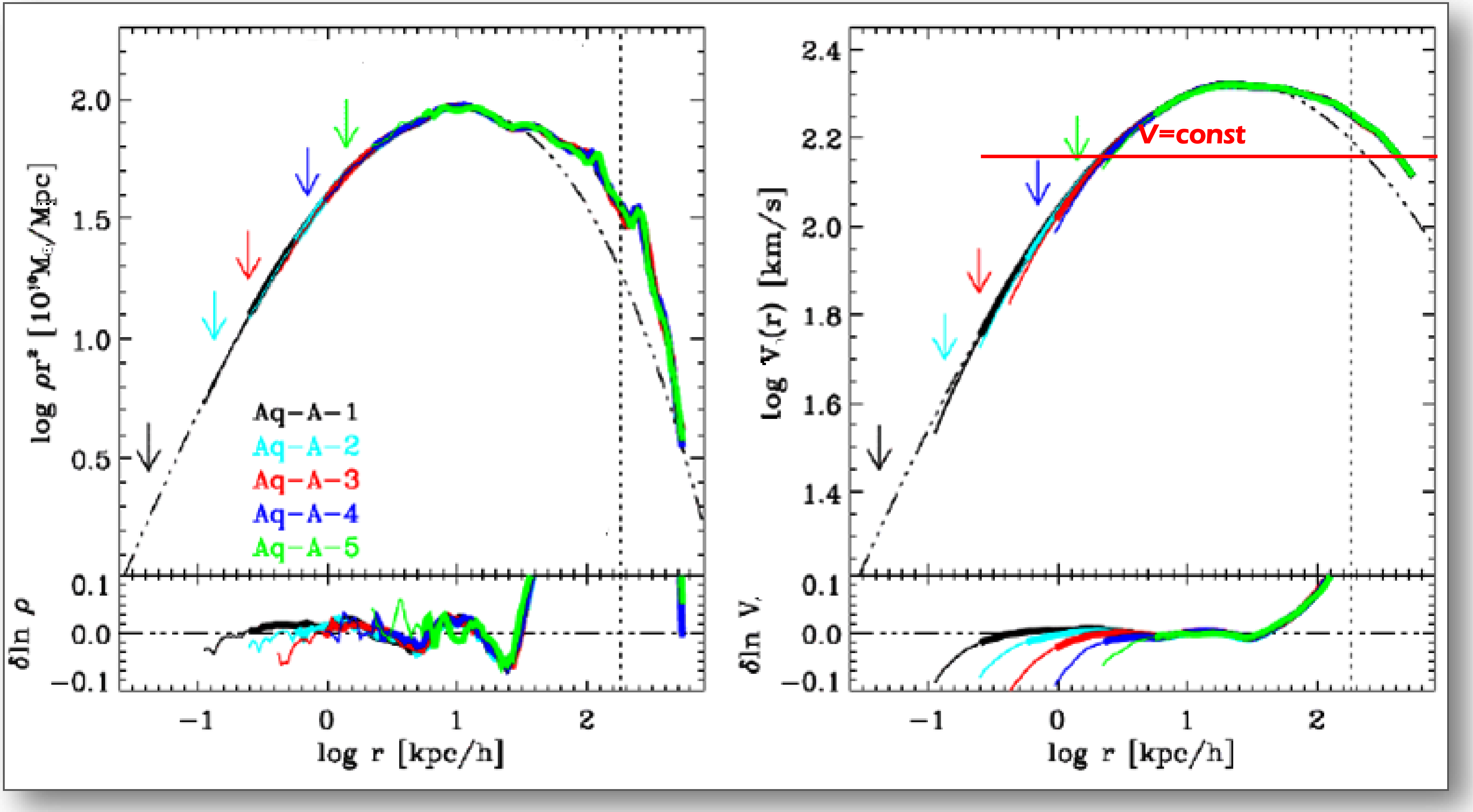
Pure DM LCDM -> Occam razor

Aquarius N-Body simulations

Navarro et al +10

density

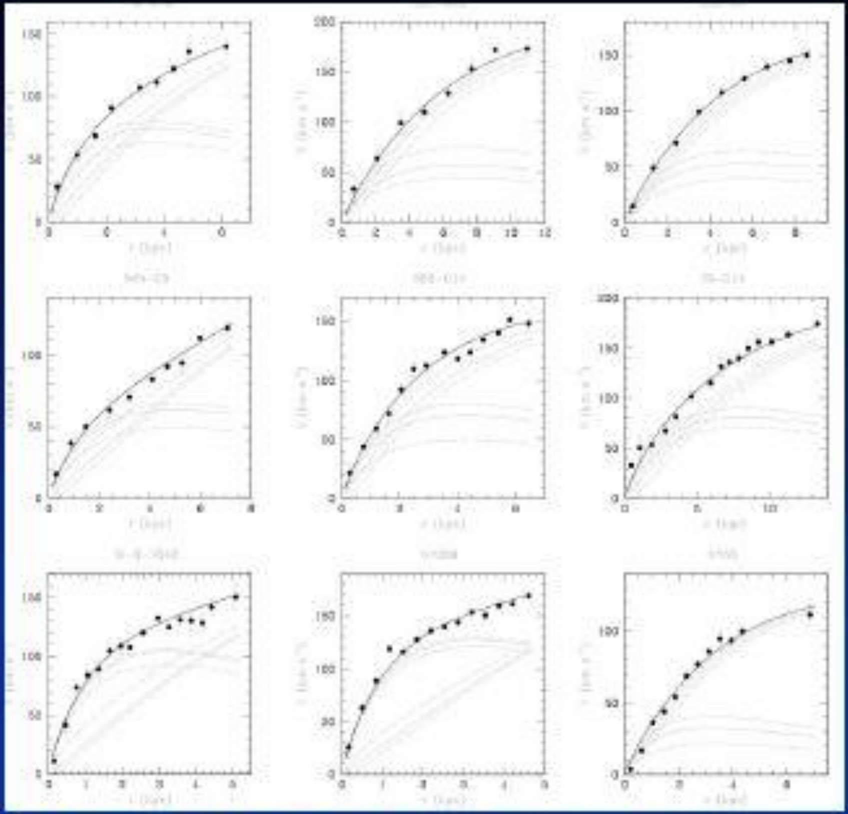
circular velocity

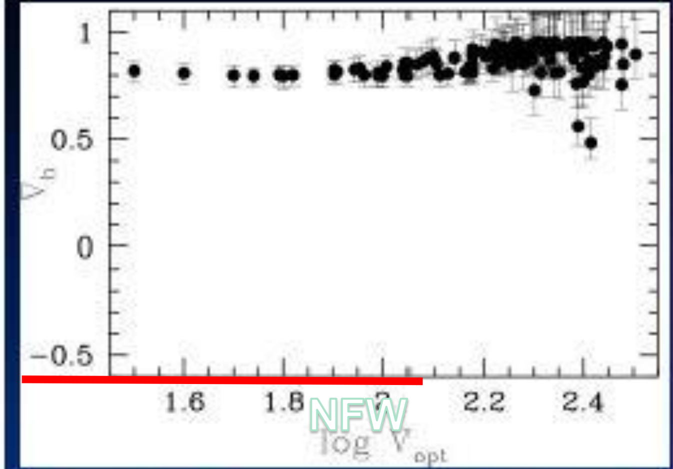


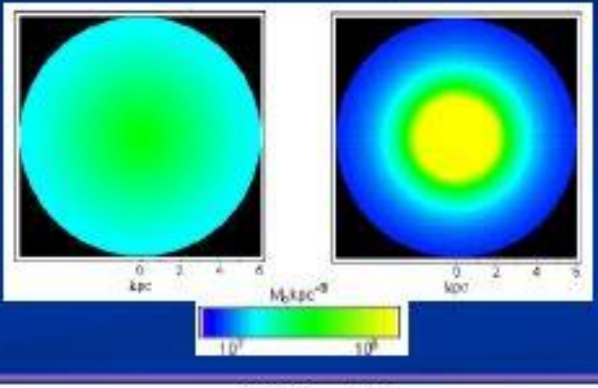
Results from Trieste: analysis of high quality RCs

URC fits to RCs

PROOFS
OF CORES
DISPROOF
OF CUSPS

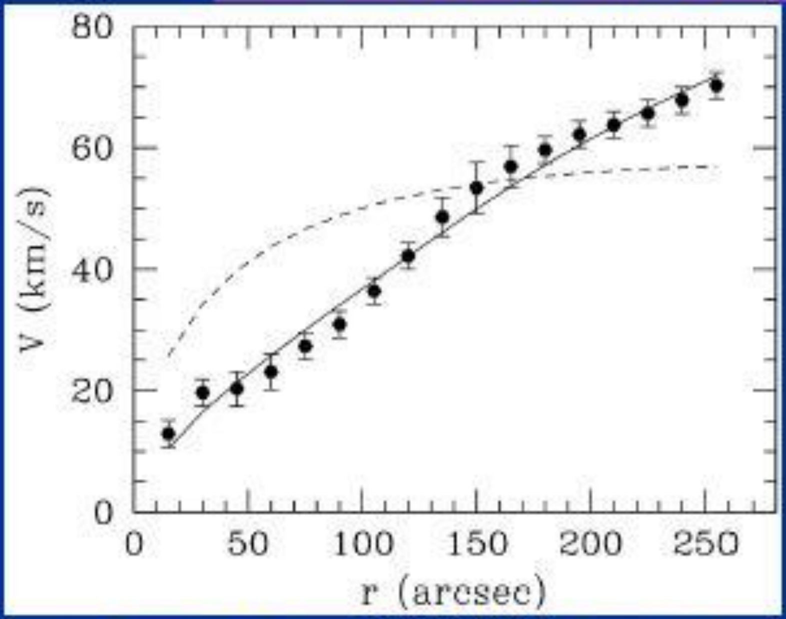




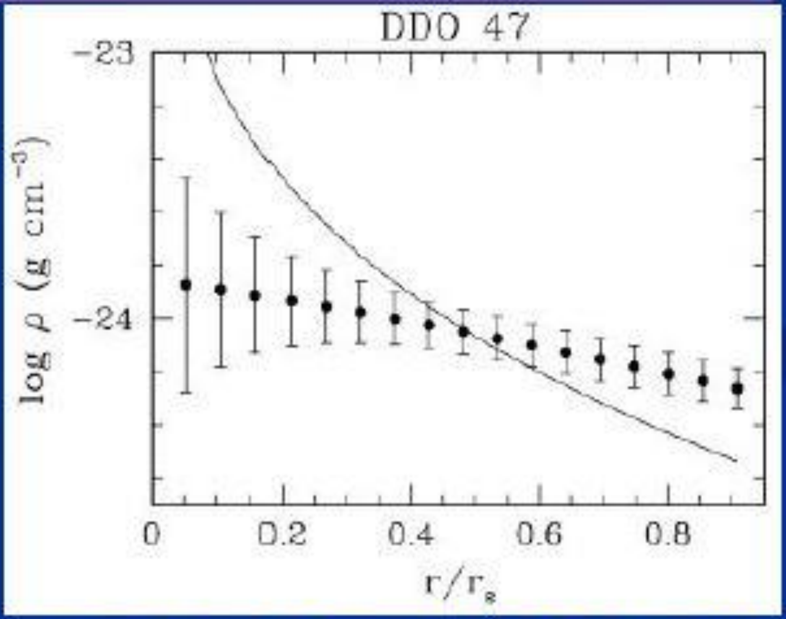


Borriello & Salucci, MNRAS 323, 285 (2001)

DDO 47



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



Gentile, Tonini & Salucci, A&A 467, 925 (2007)

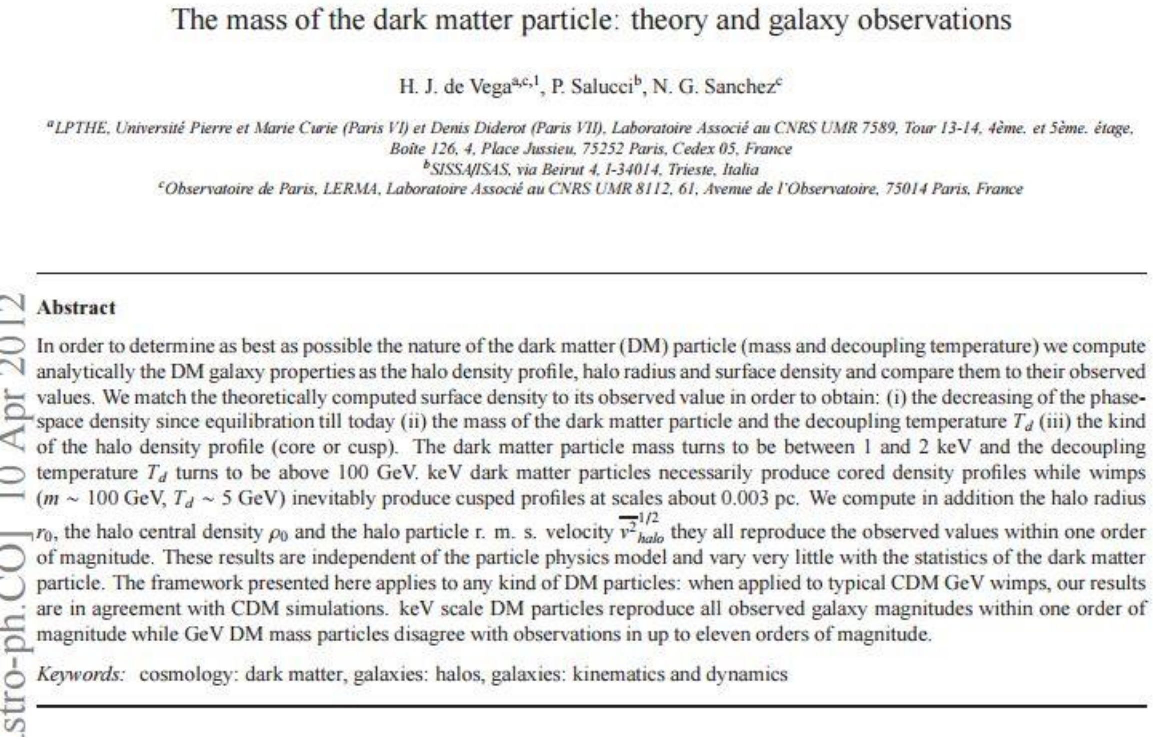
-halo mass inside a physical range of values
-concentration-mass relation as from simulations

No spiral with suitable kinematics passes the test. NFW always fails

NFW+Baryon mass model must accomplish all the above

People started to serioulsy investigate WDM, Chalonge School being a major attractor of these studies)

Hector, Norma, Peter, Claudio,Sinziana, Alessandro, P., Anastasia,
KATRIN, Casey, Christopher +many others



The mass of the dark matter particle: theory and galaxy observations

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Abstract

In order to determine as best as possible the nature of the dark matter (DM) particle (mass and decoupling temperature) we compute analytically the DM galaxy properties as the halo density profile, halo radius and surface density and compare them to their observed values. We match the theoretically computed surface density to its observed value in order to obtain: (i) the decreasing of the phase-space density since equilibration till today (ii) the mass of the dark matter particle and the decoupling temperature T_d (iii) the kind of the halo density profile (core or cusp). The dark matter particle mass turns to be between 1 and 2 keV and the decoupling temperature T_d turns to be above 100 GeV. keV dark matter particles necessarily produce cored density profiles while wimps ($m \sim 100$ GeV, $T_d \sim 5$ GeV) inevitably produce cusped profiles at scales about 0.003 pc. We compute in addition the halo radius r_0, the halo central density ρ_0 and the halo particle r. m. s. velocity $\overline{v^2}^{1/2}_{halo}$ they all reproduce the observed values within one order of magnitude. These results are independent of the particle physics model and vary very little with the statistics of the dark matter particle. The framework presented here applies to any kind of DM particles: when applied to typical CDM GeV wimps, our results are in agreement with CDM simulations. keV scale DM particles reproduce all observed galaxy magnitudes within one order of magnitude while GeV DM mass particles disagree with observations in up to eleven orders of magnitude.

Keywords: cosmology: dark matter, galaxies: halos, galaxies: kinematics and dynamics

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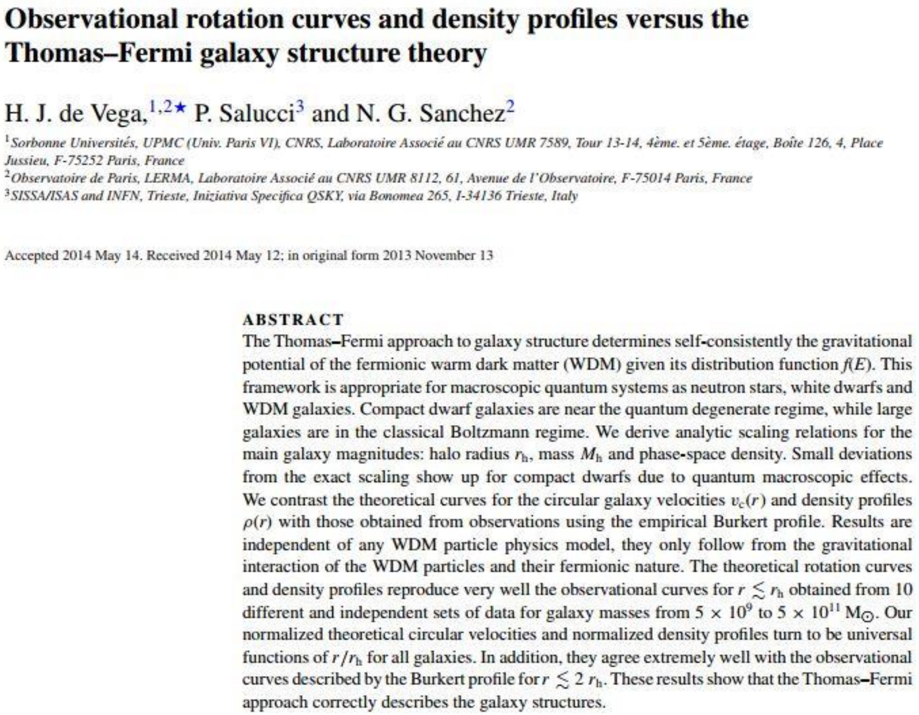

Observational rotation curves and density profiles versus the Thomas–Fermi galaxy structure theory

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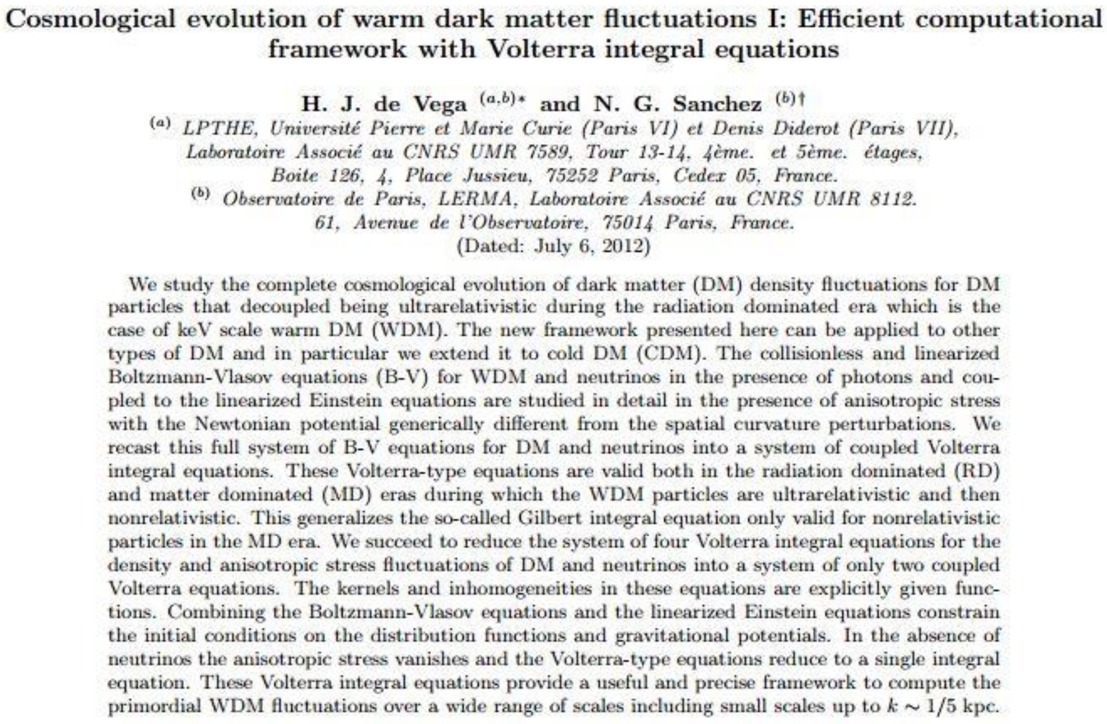
ABSTRACT

The Thomas–Fermi approach to galaxy structure determines self-consistently the gravitational potential of the fermionic warm dark matter (WDM) given its distribution function $f(E)$. This framework is appropriate for macroscopic quantum systems as neutron stars, white dwarfs and WDM galaxies. Compact dwarf galaxies are near the quantum degenerate regime, while large galaxies are in the classical Boltzmann regime. We derive analytic scaling relations for the main galaxy magnitudes: halo radius r_h, mass M_h and phase-space density. Small deviations from the exact scaling show up for compact dwarfs due to quantum macroscopic effects. We contrast the theoretical curves for the circular galaxy velocities $v_c(r)$ and density profiles $\rho(r)$ with those obtained from observations using the empirical Burkert profile. Results are independent of any WDM particle physics model, they only follow from the gravitational interaction of the WDM particles and their fermionic nature. The theoretical rotation curves and density profiles reproduce very well the observational curves for $r \lesssim r_h$ obtained from 10 different and independent sets of data for galaxy masses from 5×10^9 to 5×10^{11} $M_\odot$. Our normalized theoretical circular velocities and normalized density profiles turn to be universal functions of r/r_h for all galaxies. In addition, they agree extremely well with the observational curves described by the Burkert profile for $r \lesssim 2\ r_h$. These results show that the Thomas–Fermi approach correctly describes the galaxy structures.



Cosmological evolution of warm dark matter fluctuations I: Efficient computational framework with Volterra integral equations

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(a) *LPTHE, Université Pierre et Marie Curie (Paris VI) et Denis Diderot (Paris VII),*
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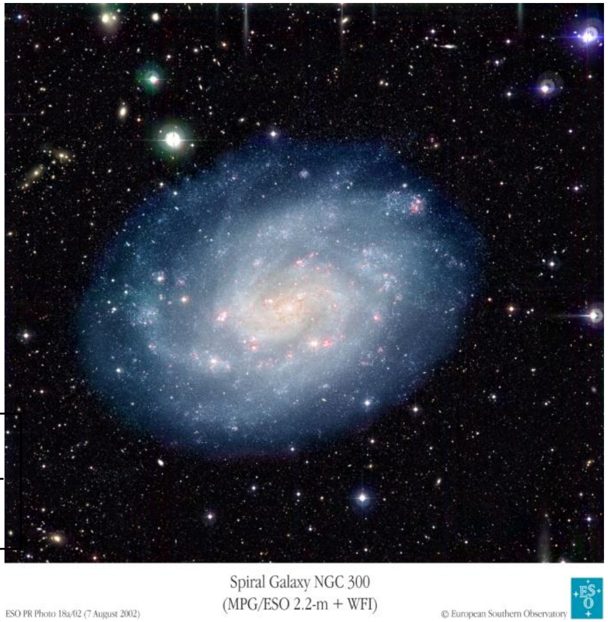
61, Avenue de l'Observatoire, 75014 Paris, France.
(Dated: July 6, 2012)

We study the complete cosmological evolution of dark matter (DM) density fluctuations for DM particles that decoupled being ultrarelativistic during the radiation dominated era which is the case of keV scale warm DM (WDM). The new framework presented here can be applied to other types of DM and in particular we extend it to cold DM (CDM). The collisionless and linearized Boltzmann-Vlasov equations (B-V) for WDM and neutrinos in the presence of photons and coupled to the linearized Einstein equations are studied in detail in the presence of anisotropic stress with the Newtonian potential generically different from the spatial curvature perturbations. We recast this full system of B-V equations for DM and neutrinos into a system of coupled Volterra integral equations. These Volterra-type equations are valid both in the radiation dominated (RD) and matter dominated (MD) eras during which the WDM particles are ultrarelativistic and then nonrelativistic. This generalizes the so-called Gilbert integral equation only valid for nonrelativistic particles in the MD era. We succeed to reduce the system of four Volterra integral equations for the density and anisotropic stress fluctuations of DM and neutrinos into a system of only two coupled Volterra equations. The kernels and inhomogeneities in these equations are explicitly given functions. Combining the Boltzmann-Vlasov equations and the linearized Einstein equations constrain the initial conditions on the distribution functions and gravitational potentials. In the absence of neutrinos the anisotropic stress vanishes and the Volterra-type equations reduce to a single integral equation. These Volterra integral equations provide a useful and precise framework to compute the primordial WDM fluctuations over a wide range of scales including small scales up to $k \sim 1/5$ kpc.

Spirals best place to investigate DM

M33 disk very smooth,
truncated at 4 scale-lengths

NGC 300 exponential disk
for at least 10 scale-lengths



Spiral Galaxy NGC 300
(MPG/ESO 2.2-m + WFI)

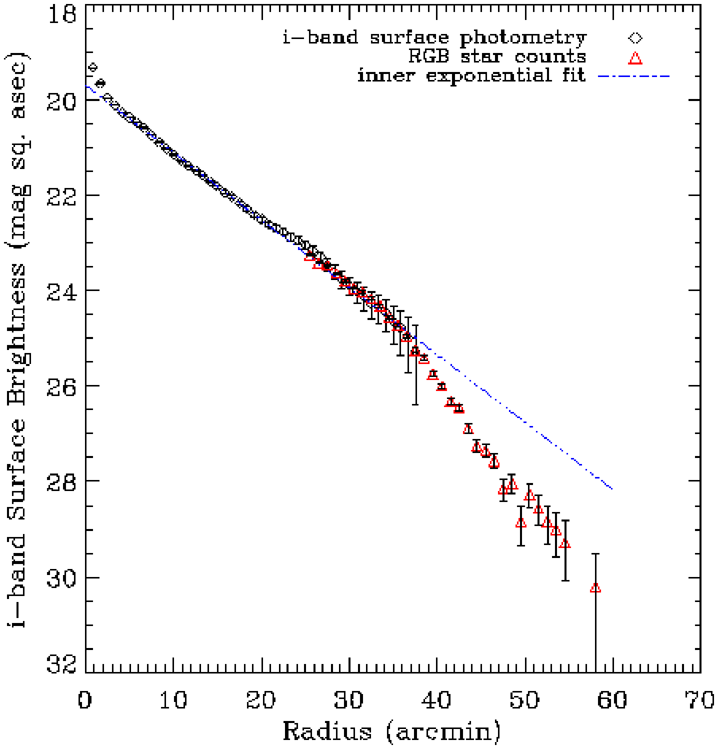
ESO PR Photo 18a/02 (7 August 2002)

© European Southern Observatory

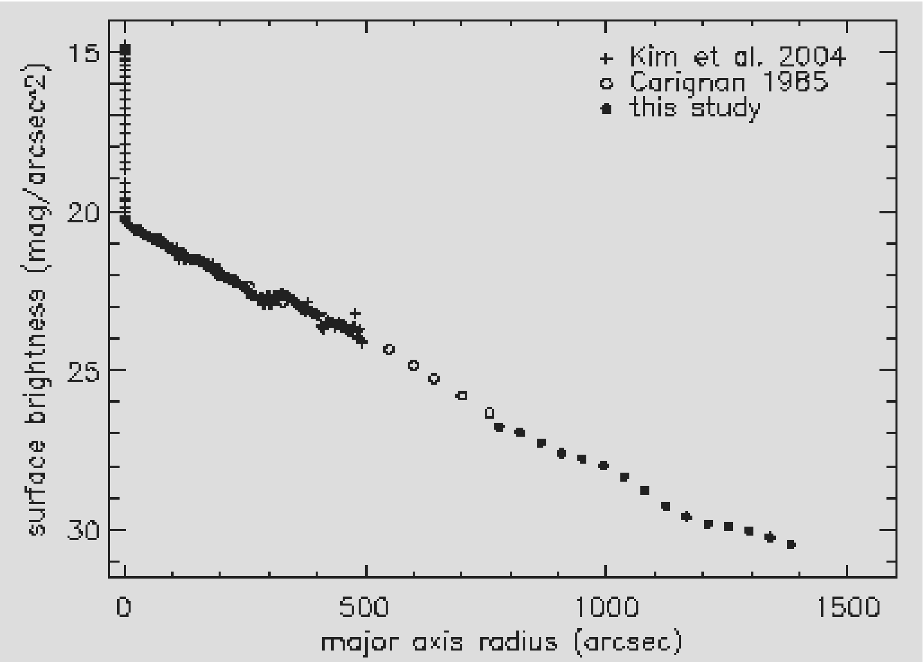
$$I(r) = I_0 e^{-r/R_D}$$

R_D lenght scale of the disk

Freeman, 1970



Ferguson et al 2003

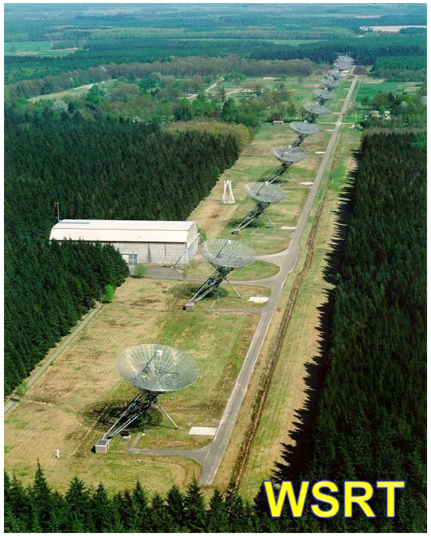


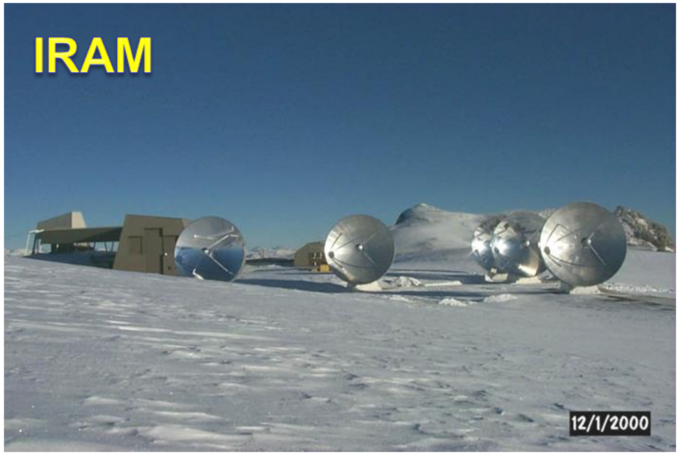
Bland-Hawthorn et al 2005

Circular velocities from spectroscopy

- Optical emission lines (Hα, Na)
- Neutral hydrogen (HI)-carbon monoxide (CO)

Tracer	angular resolution	spectral resolution
HI	7" … 30"	2 … 10 km s^{-1}
CO	1.5" … 8"	2 … 10 km s^{-1}
Hα, …	0.5" … 1.5"	10 … 30 km s^{-1}

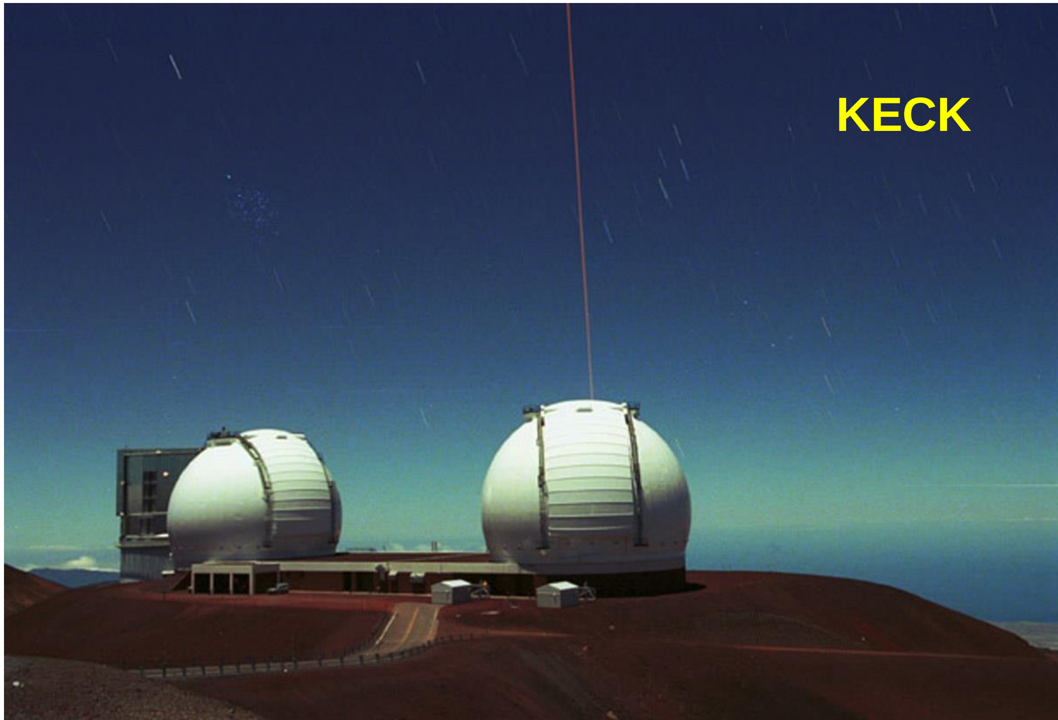




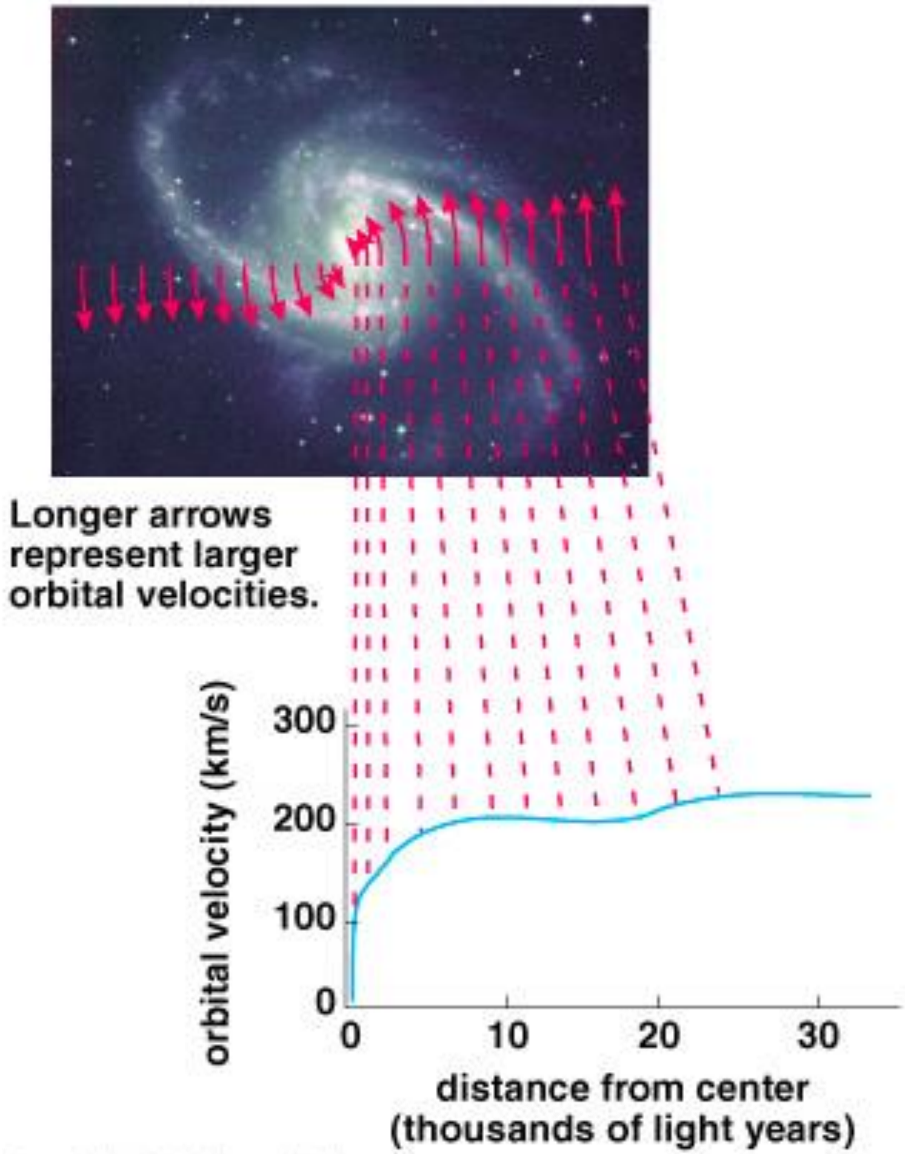

VLT


LBT


GTC

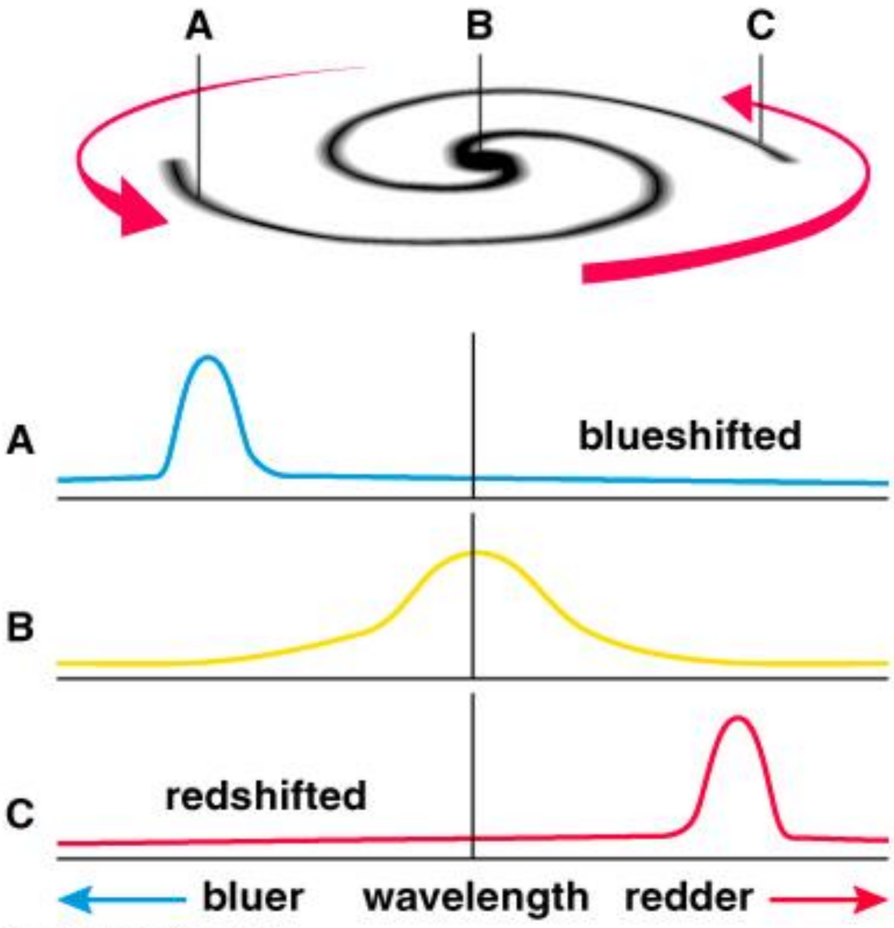

KECK

ROTATION CURVES



artist impression

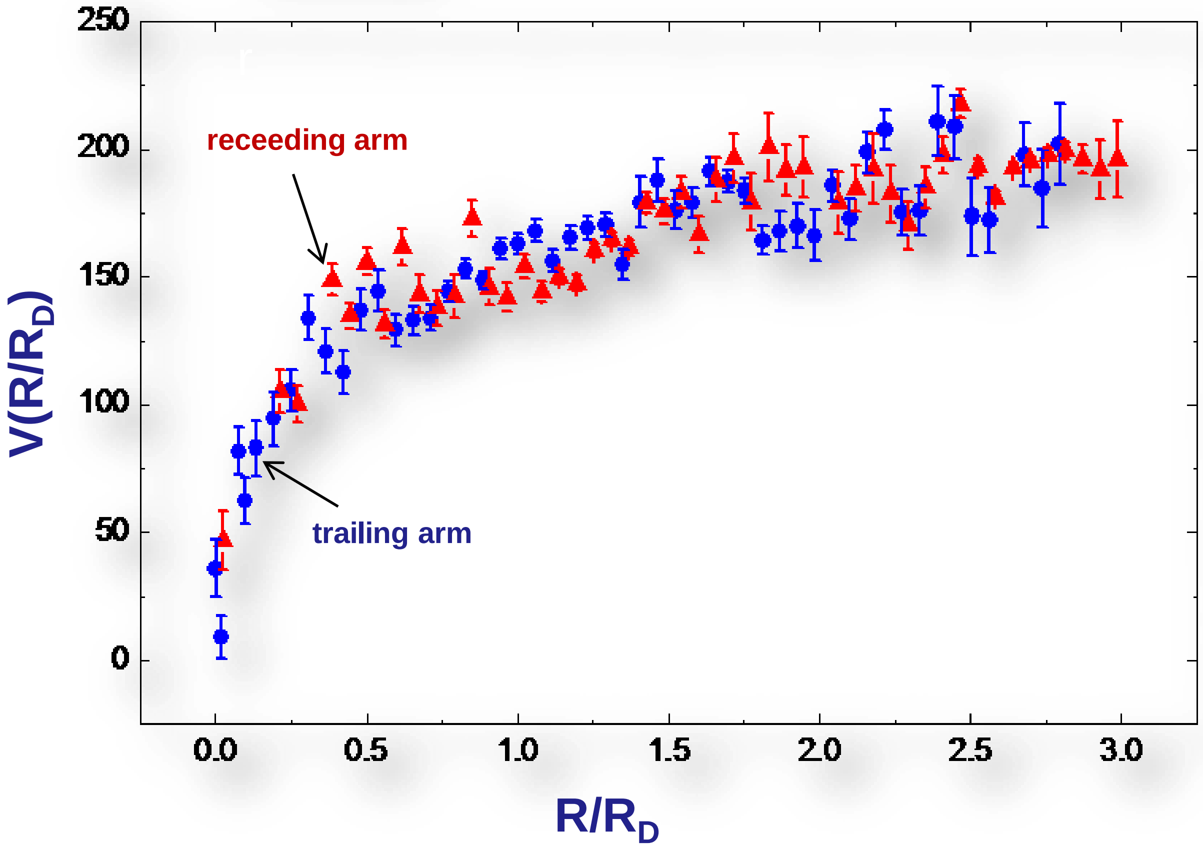
artist impression



Symmetric circular rotation of a disk characterized by

- Sky coordinates of the galaxy centre
- Systemic velocity **V_{sys}**
- Circular velocity **$V(R)$**
- Inclination angle

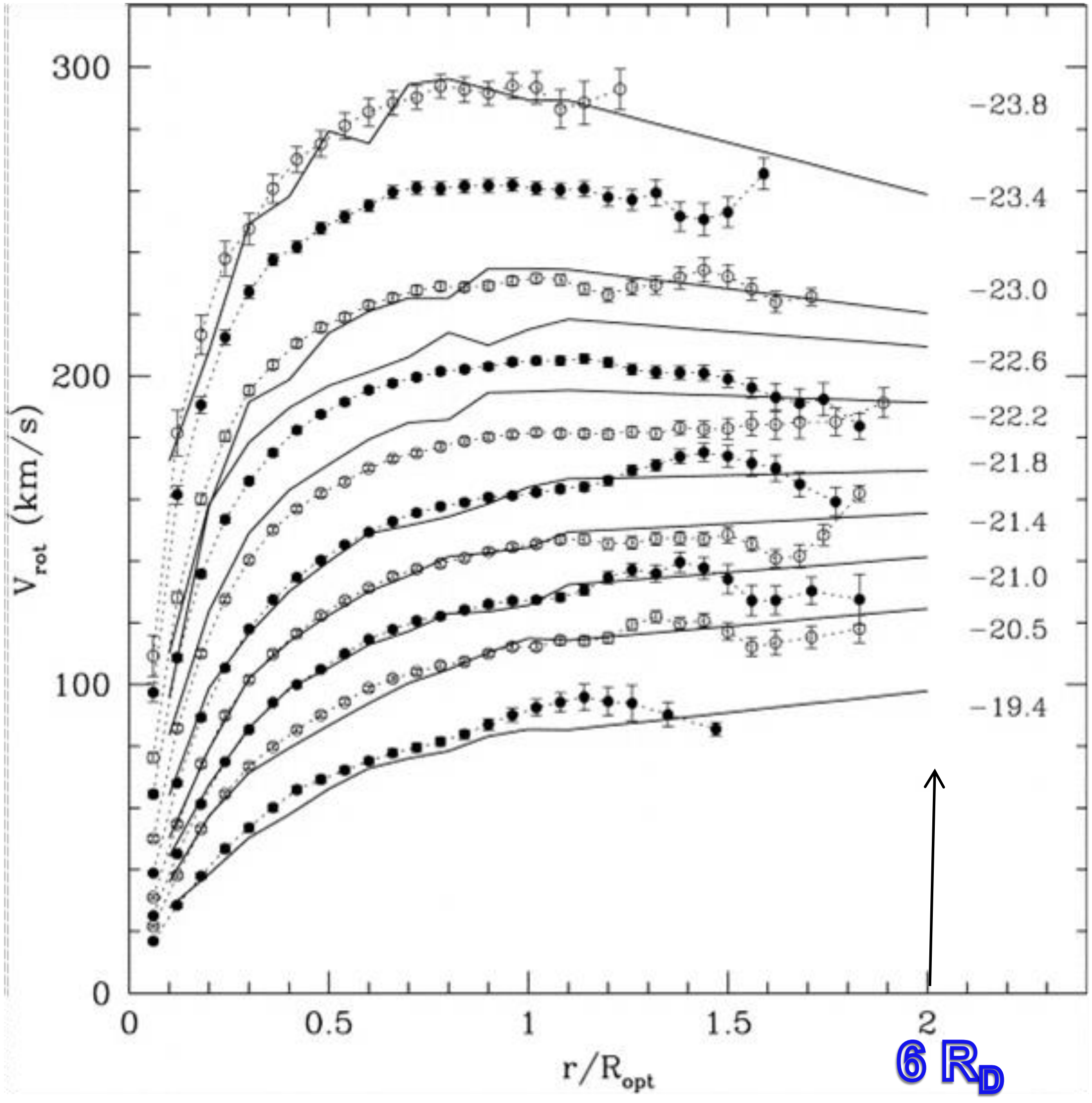
UGC2405 **HIGH QUALITY ROTATION CURVE**

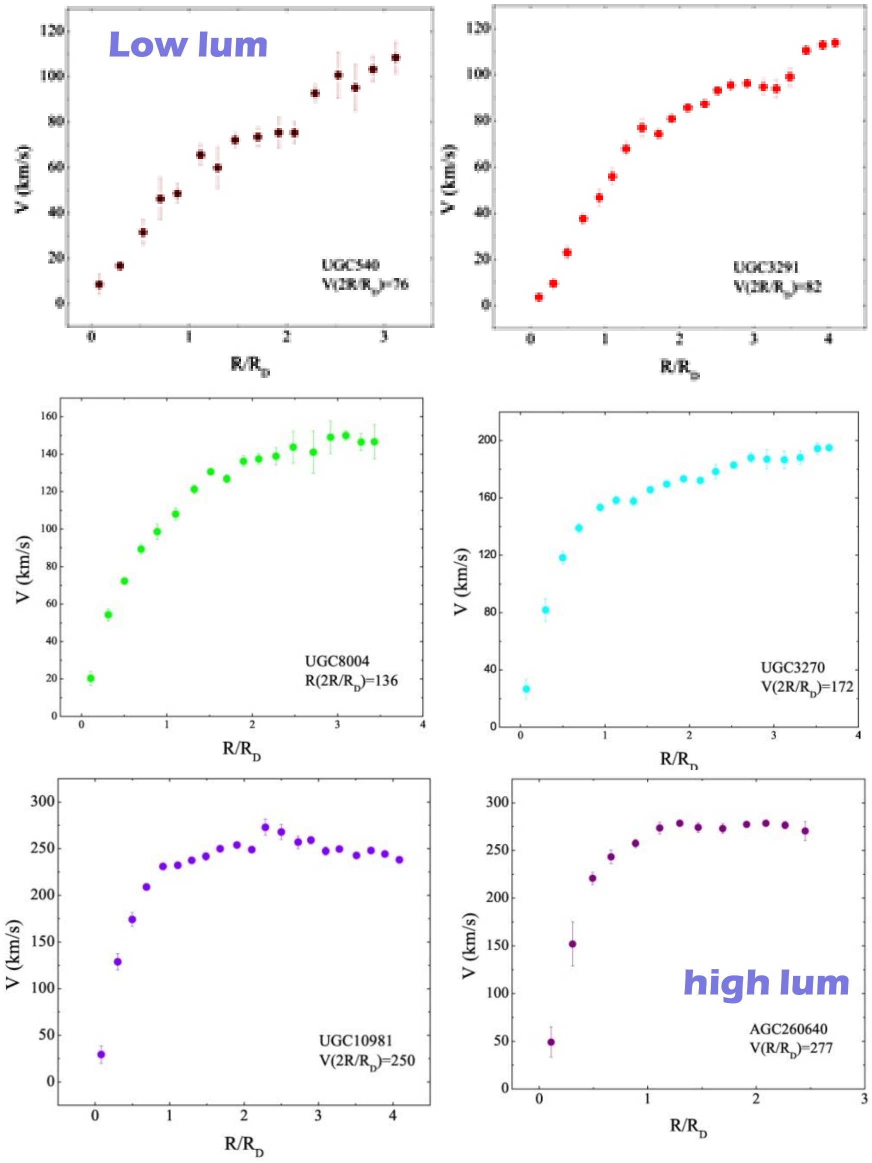


Rotation Curves (1991-2007)

TYPICAL INDIVIDUAL RCs OF INCREASING LUMINOSITY

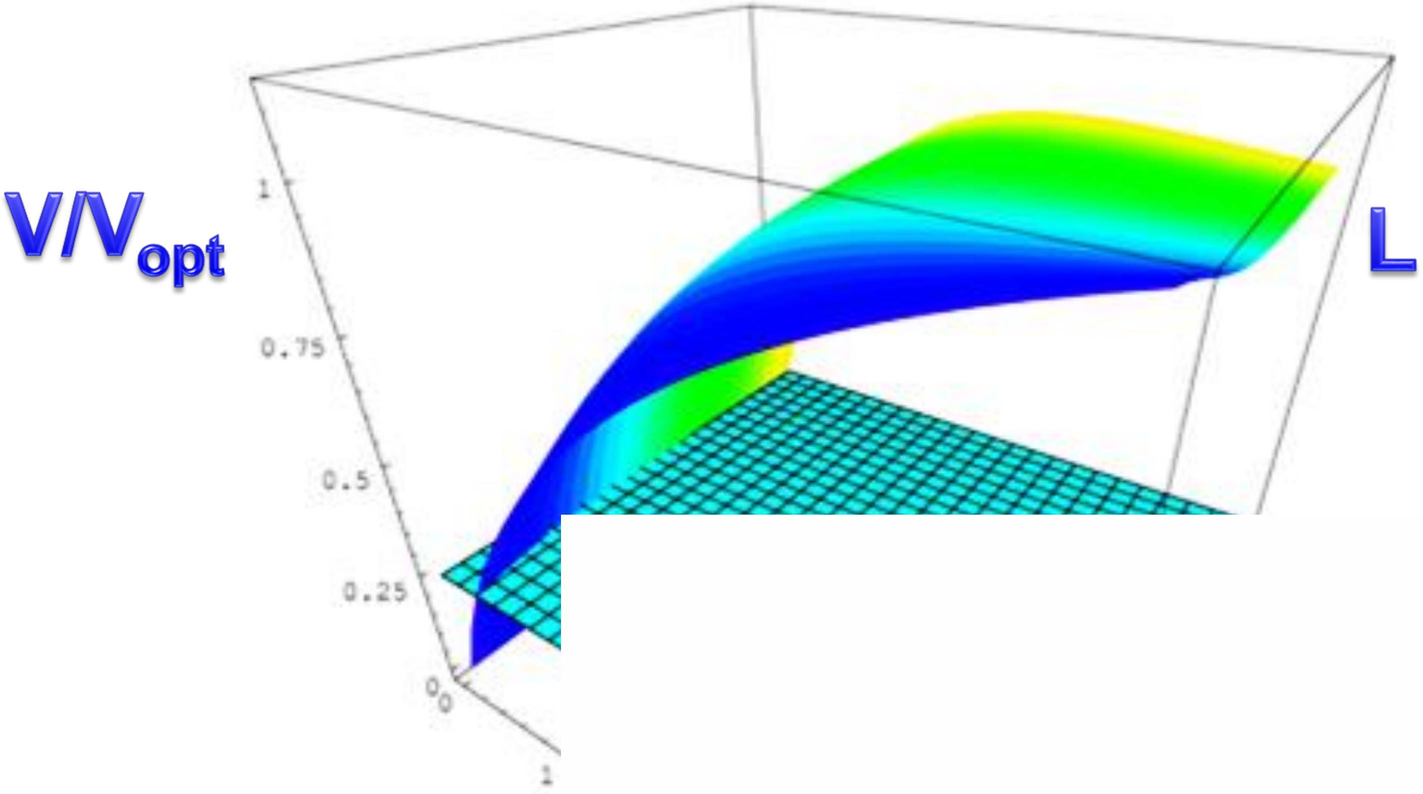
Coadded from 3200 individual RCs





The Concept of the Universal Rotation Curve (URC)

Every RC can be represented by: V(x,L) $x=R/R_D$



The URC out to 6 R_D is derived di

Rotation curve analysis

From data to mass models

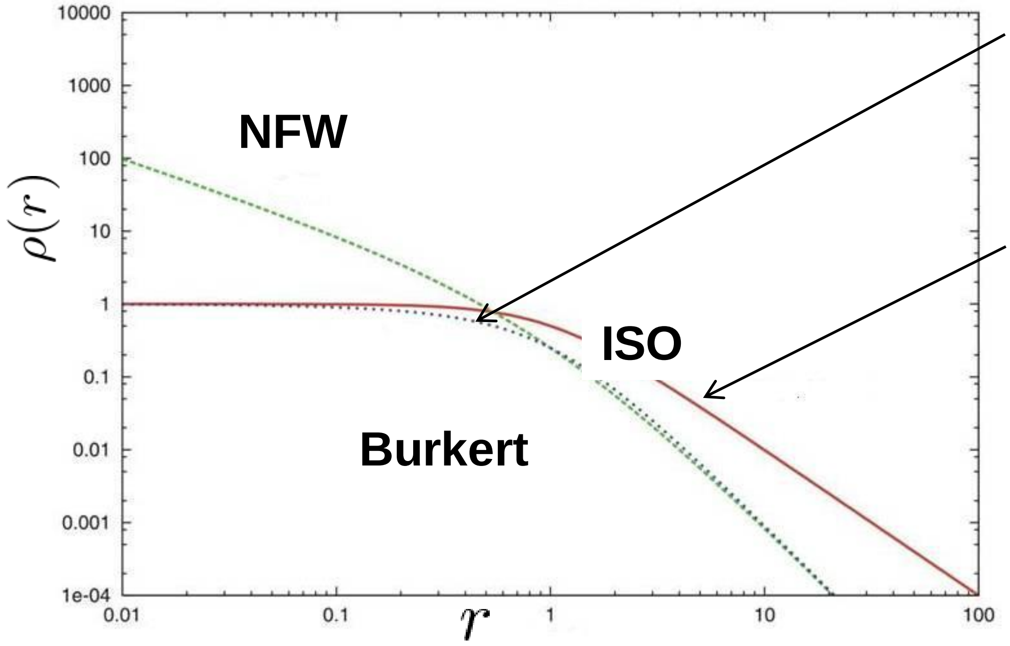
$$V^2(R) = V^2_{halo}(R) + V^2_{HI}(R) + V^2_{disk}(R)$$

observations = model

- V^2_{disk} **from I-band photometry**
- V^2_{HI} **from HI observations**
- V^2_{halo} **different choices for the DM halo density**

Dark halos with central constant density (Burkert, Isothermal)

Dark halos with central cusps (NFW, Einasto)

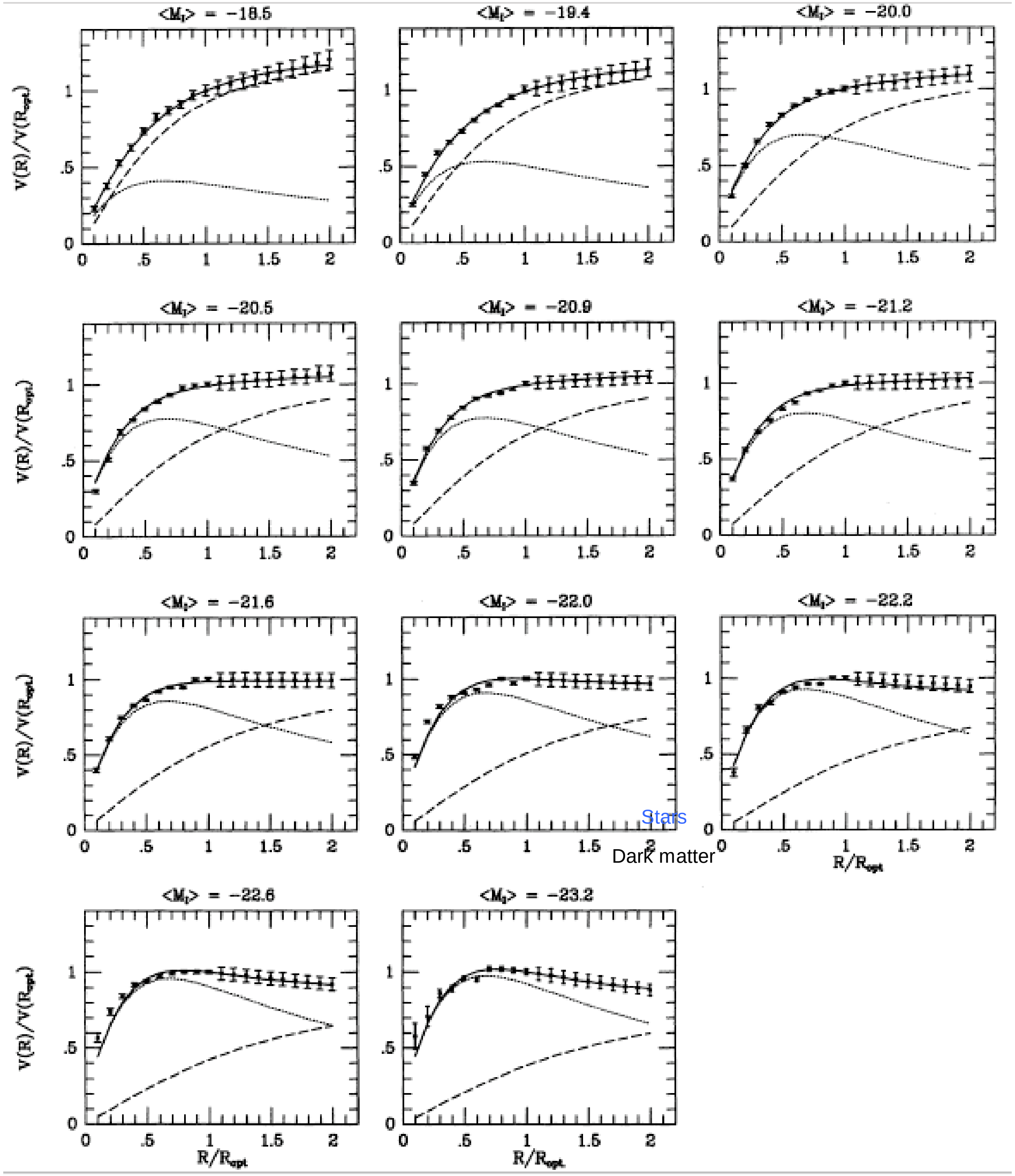


$$\rho(r) = \frac{\rho_0}{(1 + r/r_0)(1 + (r/r_0)^2)}$$

$$\rho(r) = \frac{\rho_0}{1 + (r/r_0)^2}$$

The mass model has 3 free parameters:
disk mass
halo central density
Halo core radius (length-scale)
Obtained by best fitting method

Modelling the Universal Rotation Curve



*M*_B < -17.5

Rotation Velocity

Stellar contribution

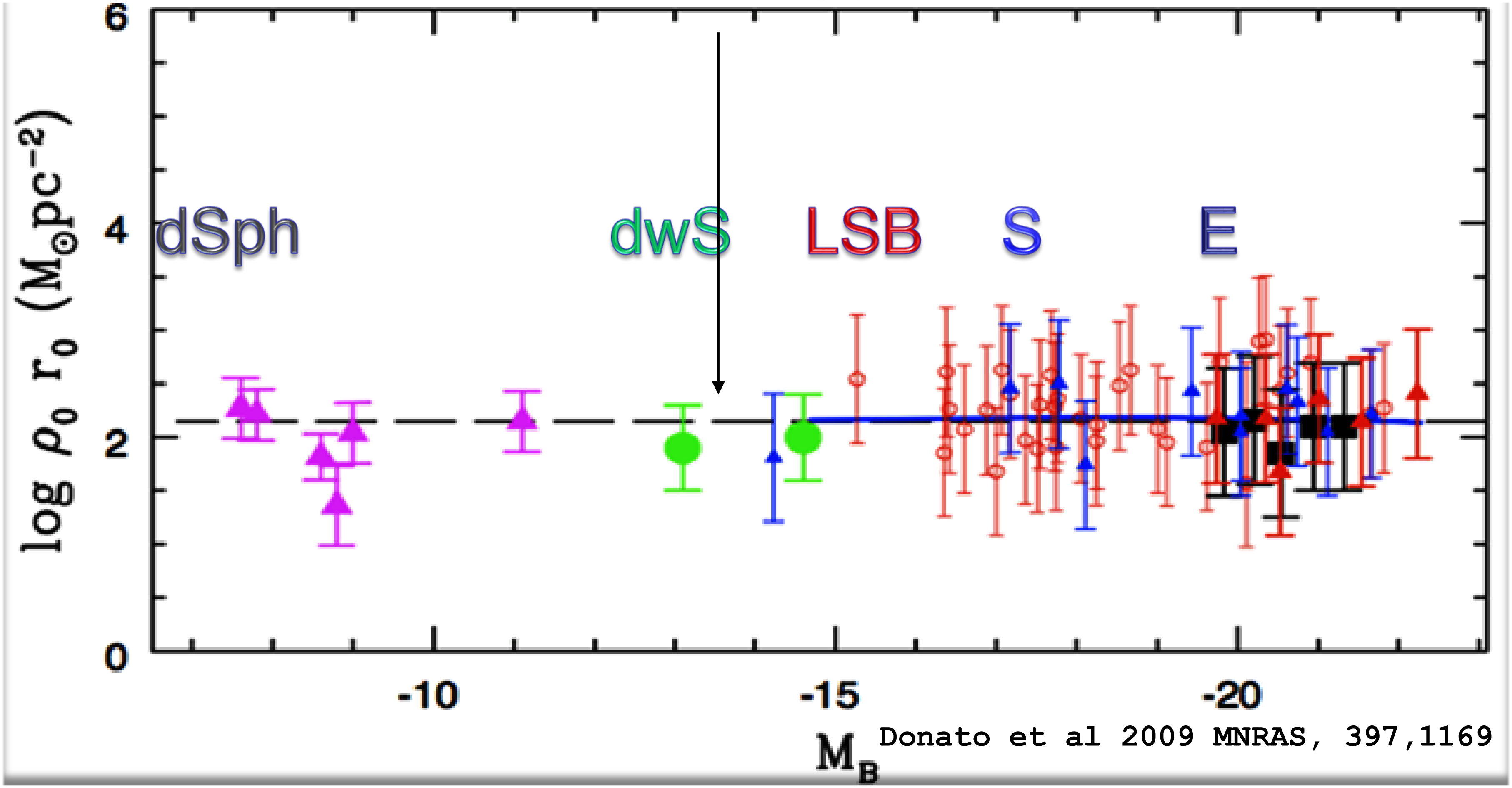
$$V_{\rm URC}\left(\frac{R}{R_{\rm opt}}\right)=V(R_{\rm opt})\left\{\left(0.72+0.44\log\frac{L}{L_*}\right)\frac{1.97x^{1.22}}{(x^2+0.78^2)^{1.43}}+1.6\exp\left[-0.4(L/L_*)\right]\frac{x^2}{x^2+1.5^2\left(\frac{L}{L_*}\right)^{0.4}}\right\}^{1/2}\ \mathrm{km\ s^{-1}}$$

Dark matter halo contribution

GALAXY HALOS STRUCTURAL PARAMETRES

ΛCDM → heavy ΛBCDM regime

eg (di Cintio 15, Frenk 15)



Donato et al 2009 MNRAS, 397,1169

Core radii between 0.1 kpc to 100 kpc

Recently obtained galaxy properties go further Clear lead to WDM

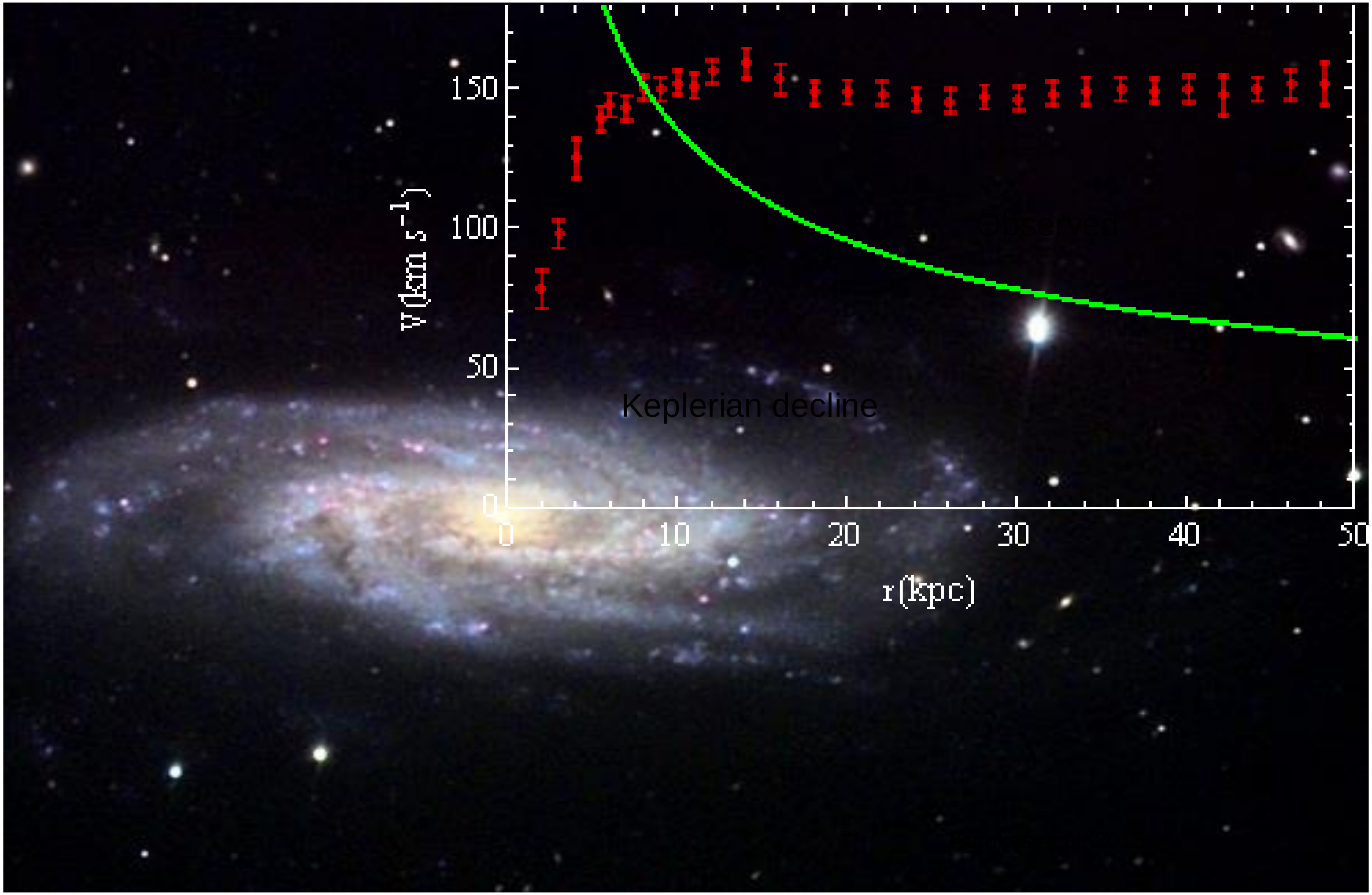
We do not know the actual WDM power spectrum

We do not know the WDM particle

Changes mass limits from Lya AND our dynamical mass

1-The smallest galaxies of the Universe.
2-Outer DM density profiles.
3-Formation by merging?

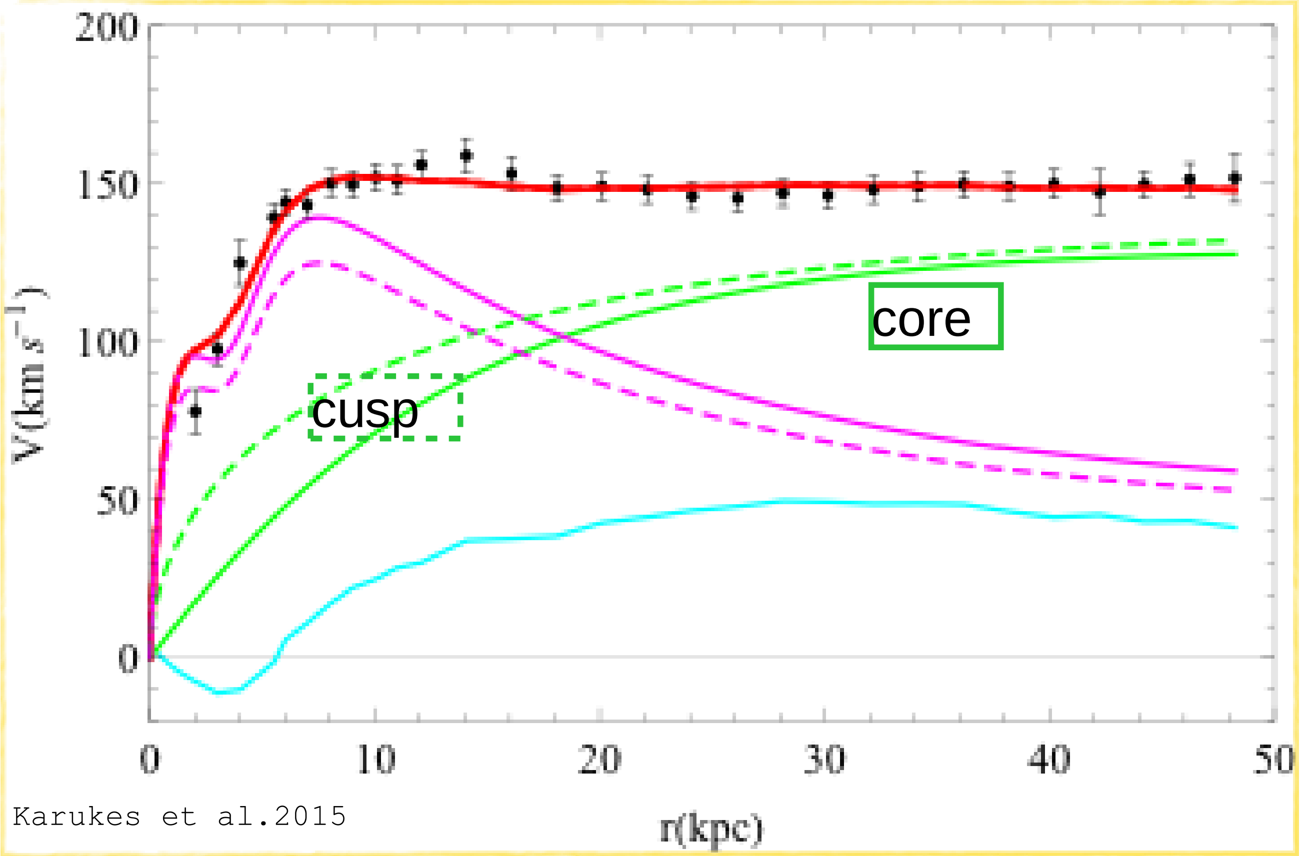
The DM distribution in NGC 3198,a crucial test case



$$\boxed{V \sim \frac{1}{\sqrt{R}}}$$

NGC 3198

NGC 3198: most extended flat RC



Karukes et al.2015

Two DM models:

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

$$\rho\sim r^{-1}$$

$$\rho_{Bur}(r)=\frac{\rho_0\, r_{core}^3}{(r+r_{core})(r^2+r_{core}^2)}$$

$$\rho\sim r^{-3}$$

Not possible to discriminate between the two DM profiles ?!

The DM density at large radii

- The local density at large radii feels no influence of the stellar disk and the HI disk

The equation of centrifugal equilibrium holding in spiral arms is (see Fall & Efstathiou 1980):

$$\frac{V^2}{r} = a_H + a_D + a_{HI}$$

where a_H, a_D and a_{HI} are the radial acceleration, generated, respectively, by the halo, stellar disk and HI disk mass distribution.

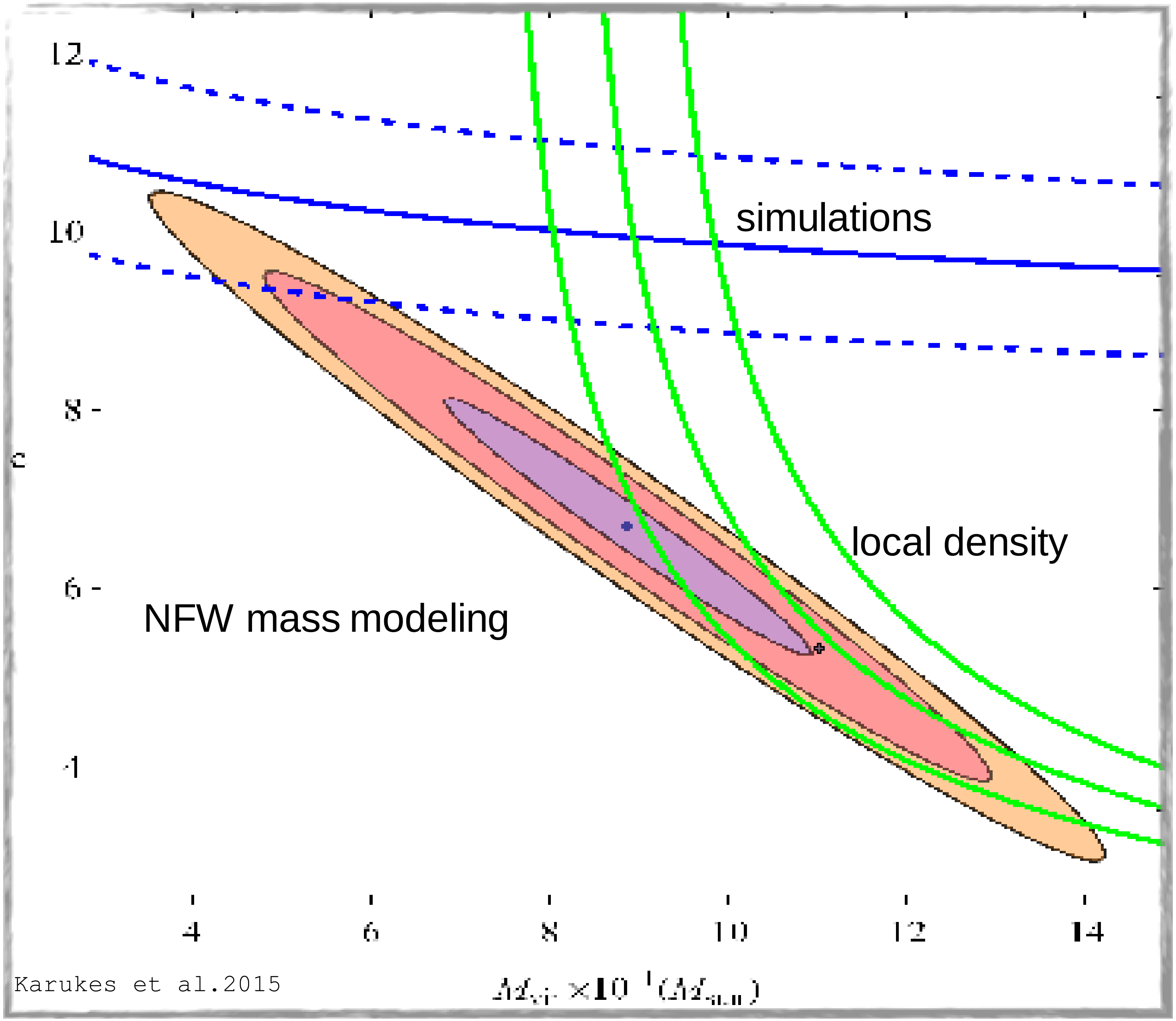
$$a_H = 4\pi G r^{-2} \int_0^r \rho_H(R) R^2 dR$$

spherical DM halo

$$\rho_H(r) = \frac{X_q}{4\pi G r^2} \frac{d}{dr}\left[r^2 \left(\frac{V^2(r)}{r} - a_D(r) - \frac{V_{HI}^2}{r} \right) \right]$$

where Xq a factor correcting the spherical Gauss low. We assume $Xq=1$

The DM density at large radii



simulations

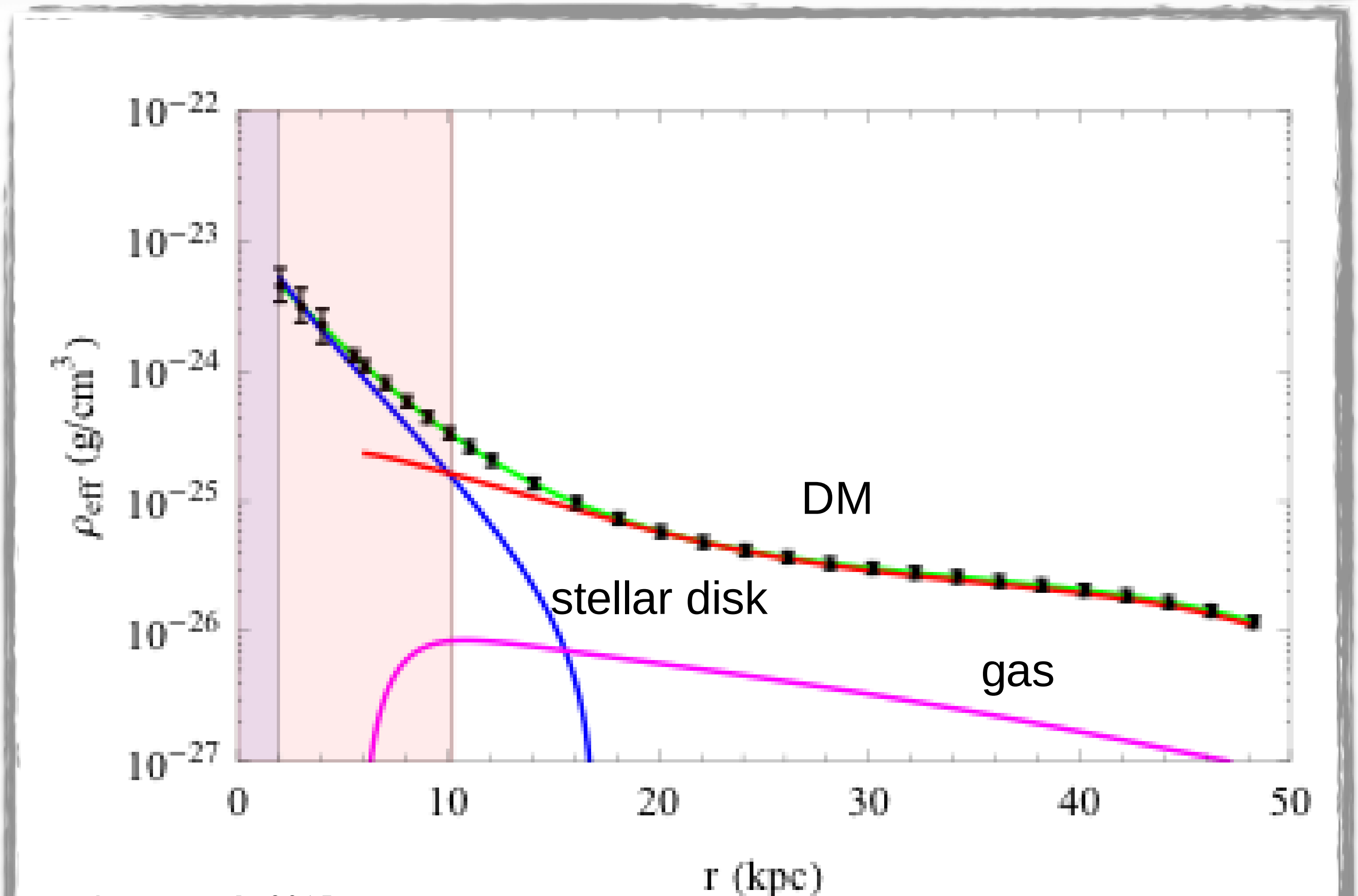
local density

NFW mass modeling

Karukes et al.2015

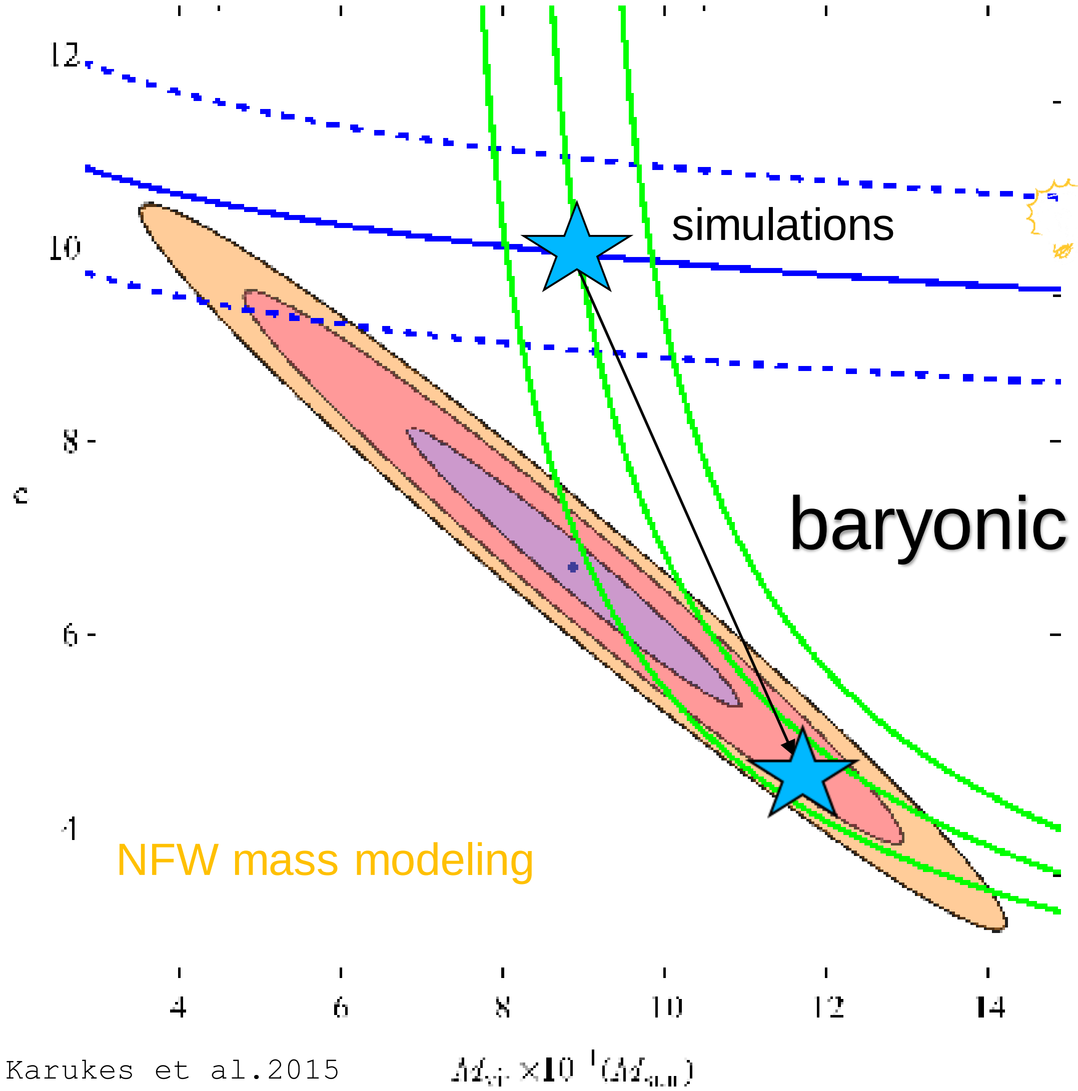
The Halo Dark Matter density at large radii

$$\rho_H(r)=\frac{1}{4\pi G}\left[\frac{V^2(r)}{r^2}(1+2\alpha)-\frac{GM_D}{R_D^3}H\left(\frac{r}{R_D}\right)-\frac{V_{HI}^2(r)}{r^2}(1+2\gamma)\right]$$



Karukes et al.2015

NGC 3198



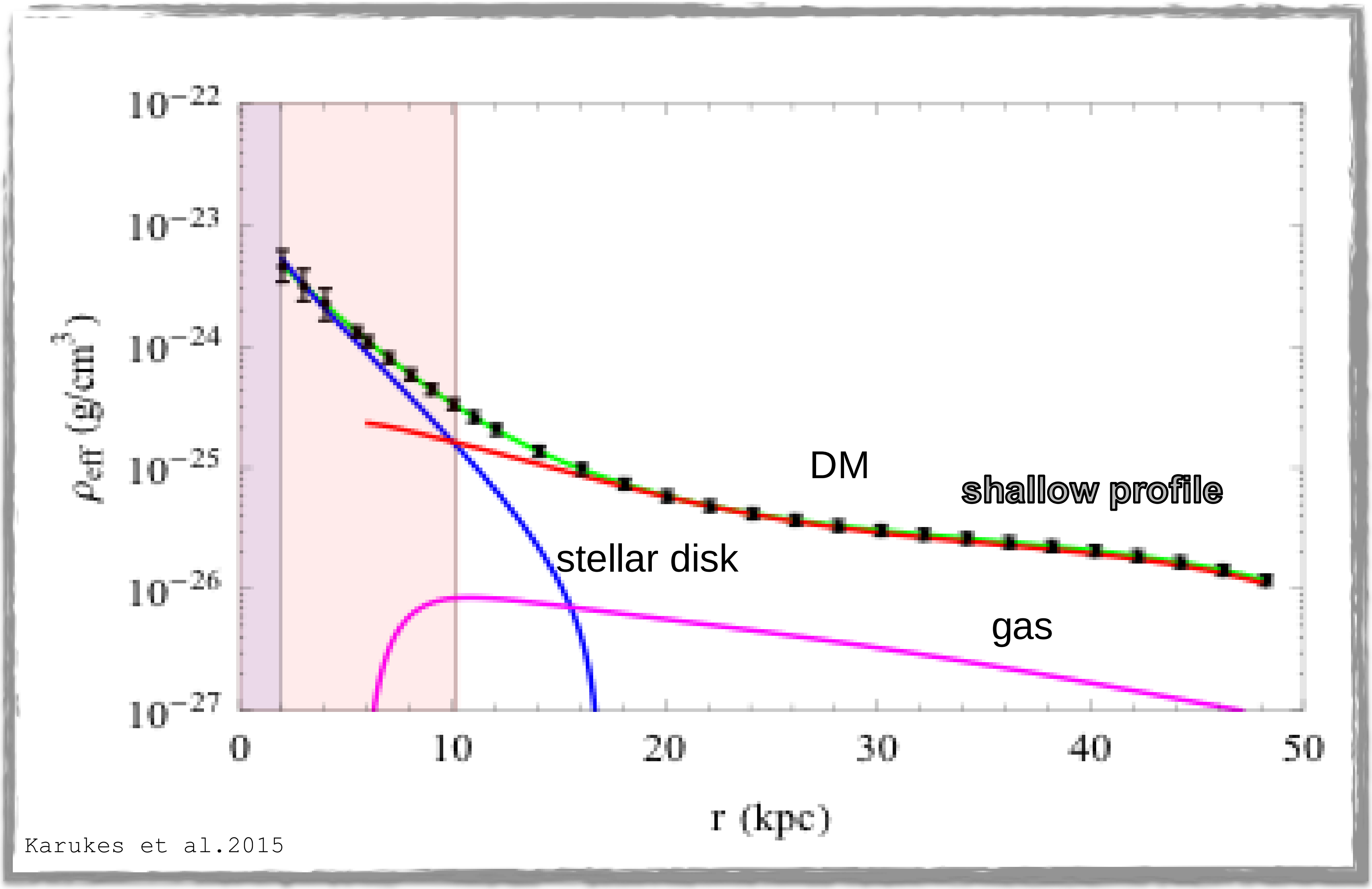
Karukes et al.2015

$c\text{-}M_{vir}$

Non-cosmological values

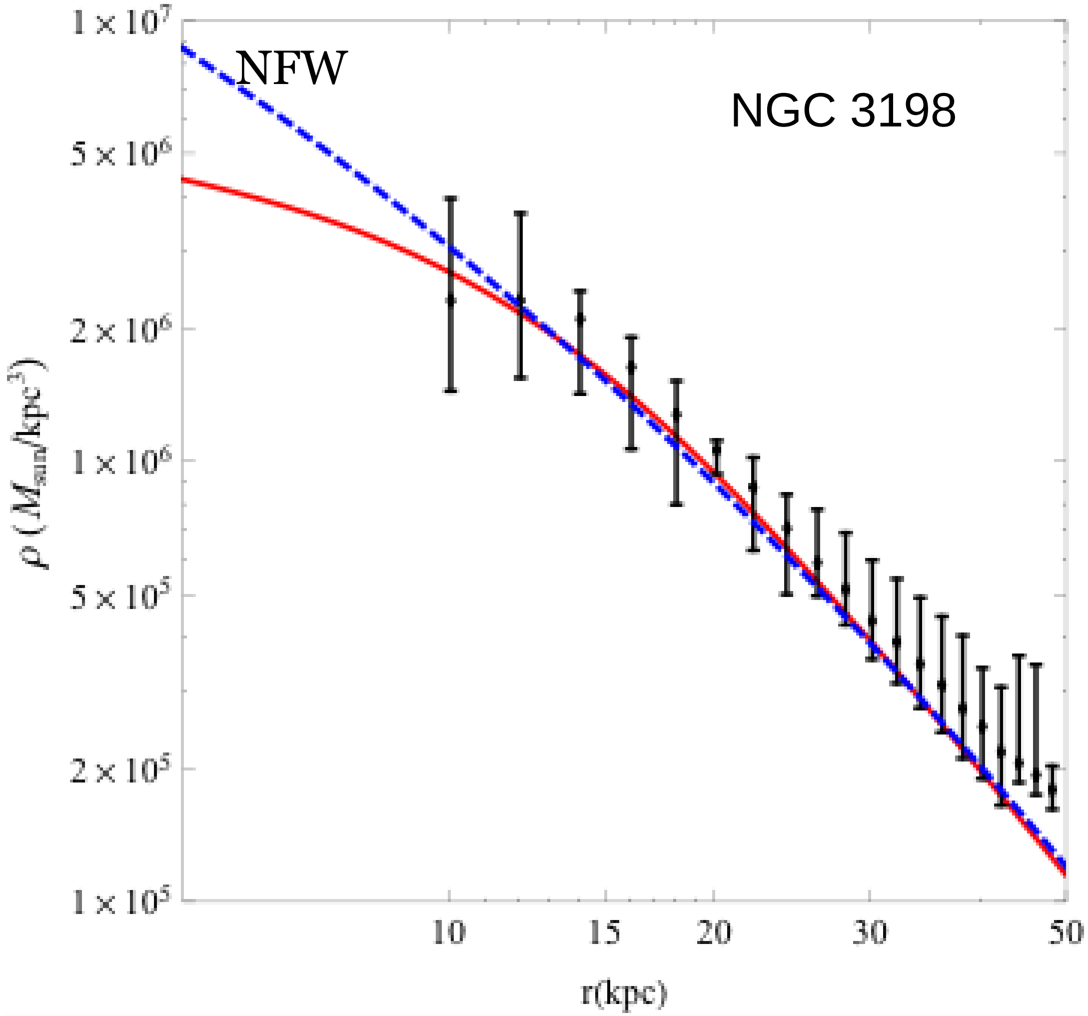
baryonic effect

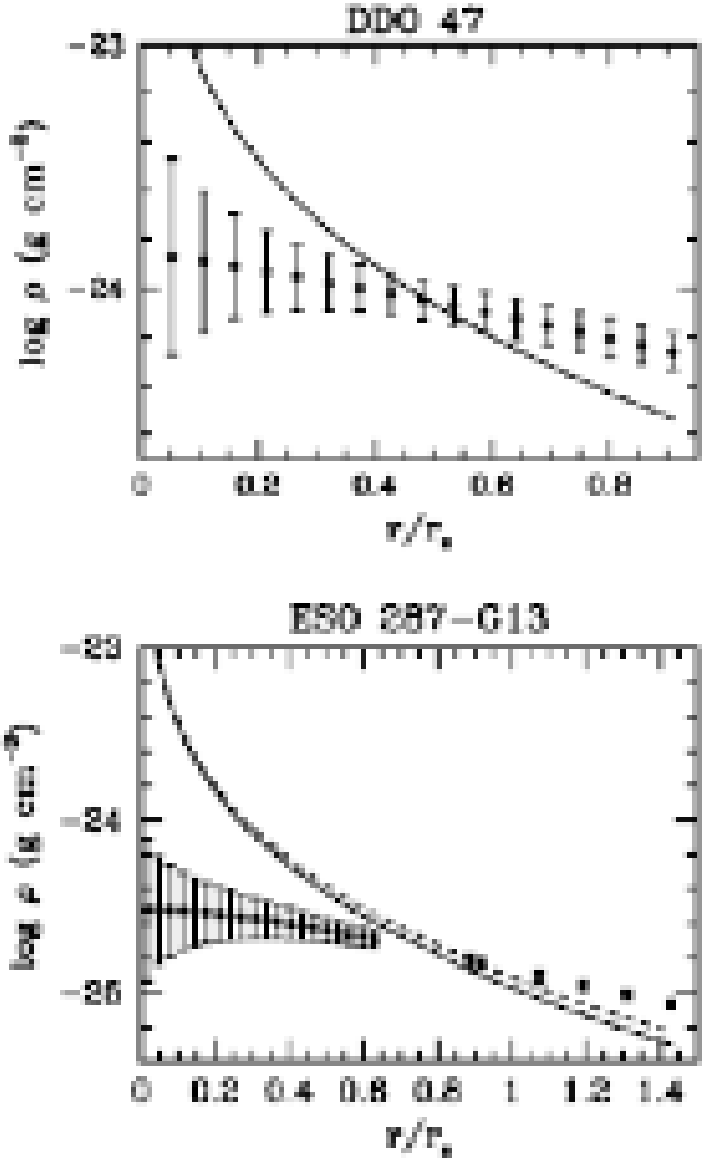
The Halo Dark Matter density at large radii



Karukes et al.2015

lazy densities

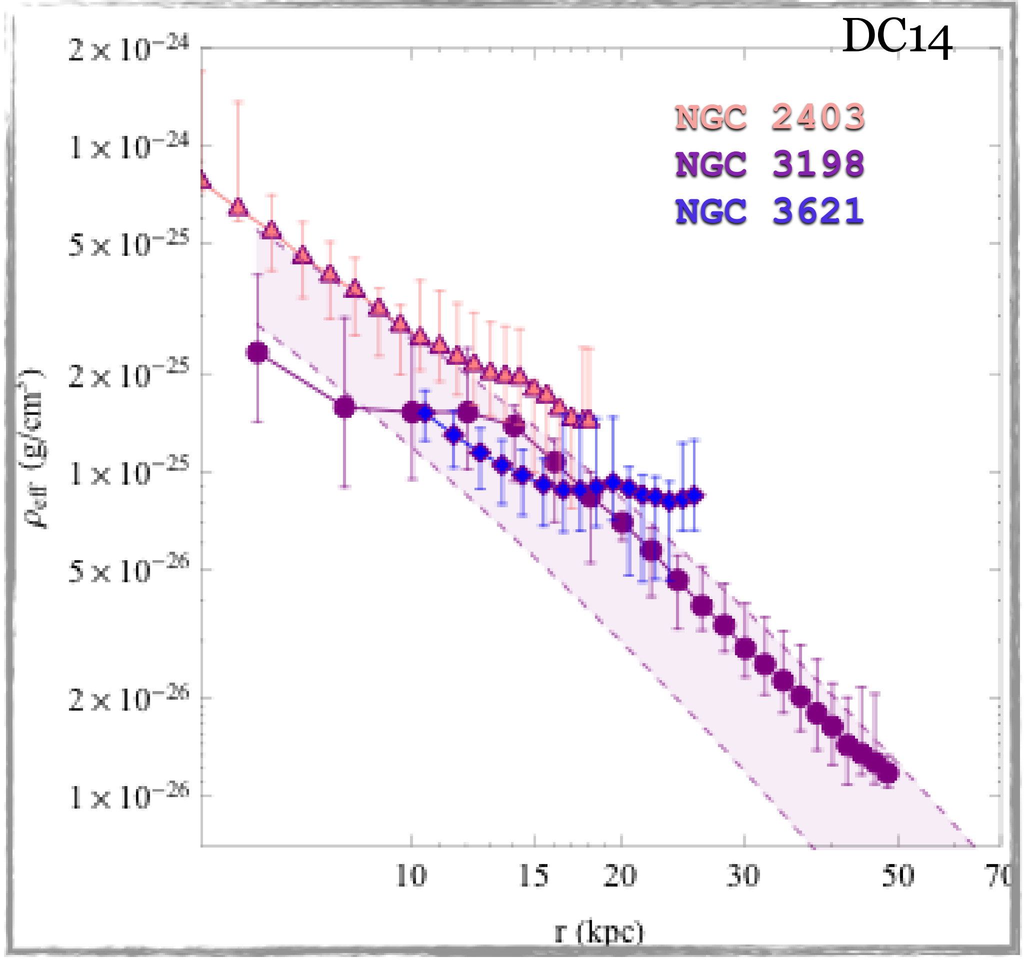




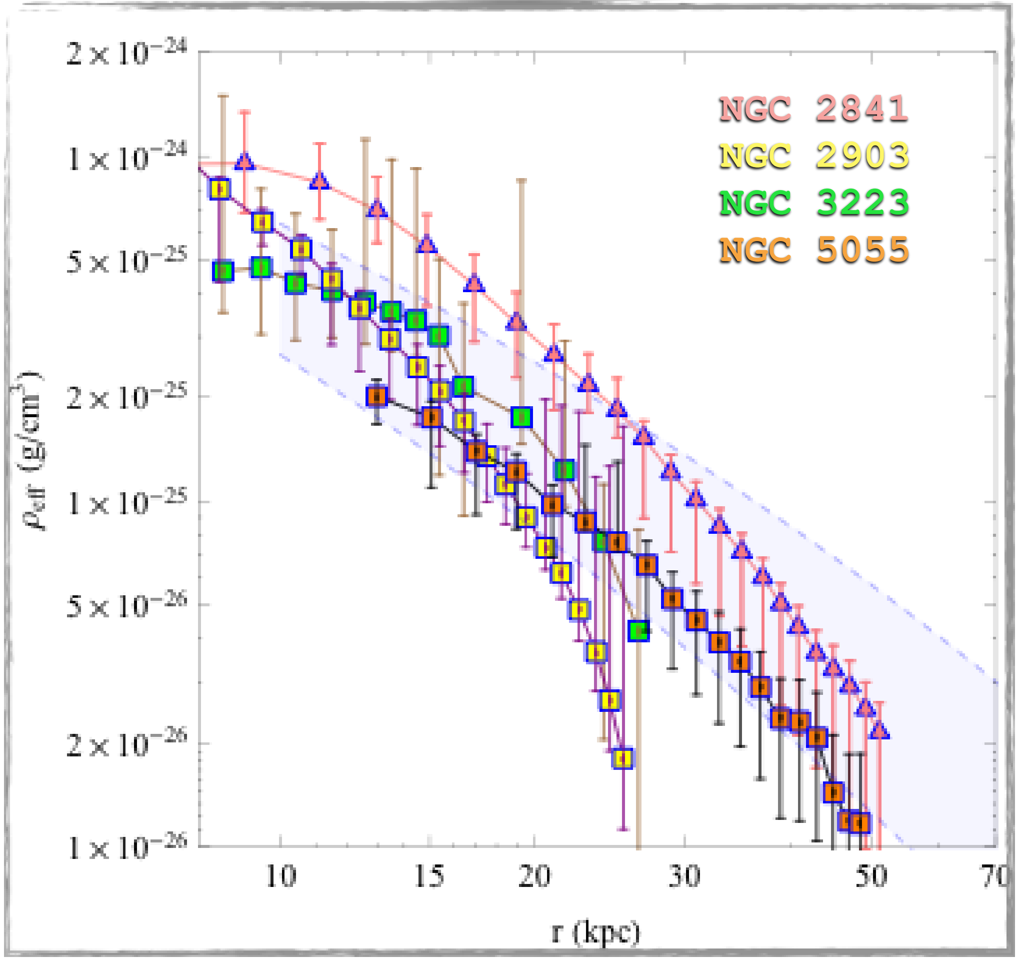
Gentile et al. 2007

DM density profiles

$M_{vir} = 2\times10^{11} - 10^{12} M_\odot$



$M_{vir} = 10^{12} - 10^{13} M_\odot$



Outer DM log densities profiles

NFW =LCDM = -2.4

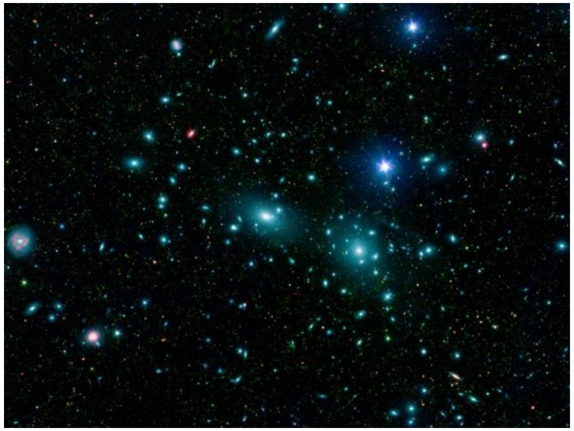
OBSERVATIONS = -1.7,-3

WDM= ?

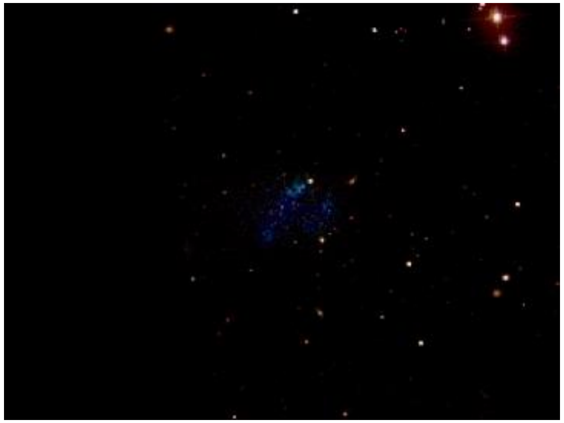
SMALLEST GALAXIES

the most numerous ones
the more DM dominated
the densest objects
the first born
immune by LBCDM

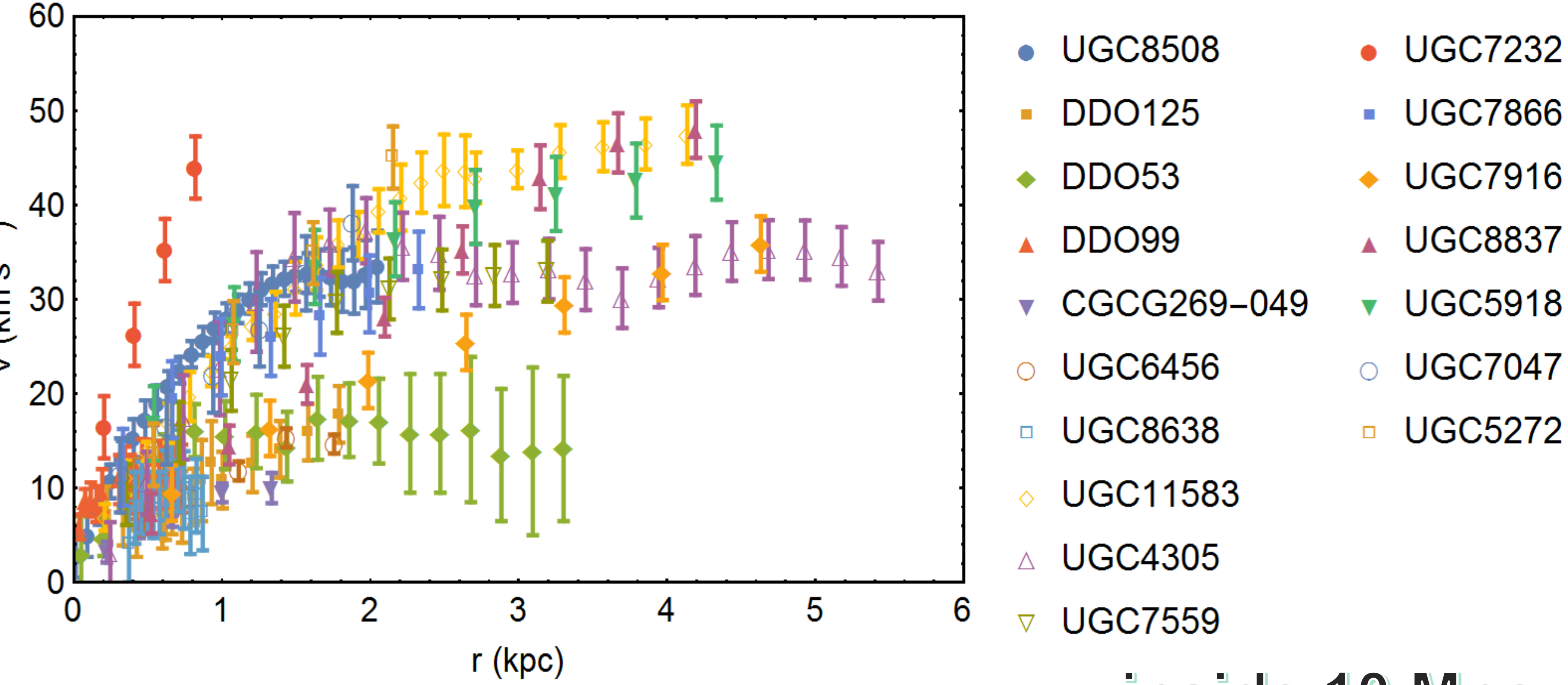
dSph
complex dynamics



dwS
simple dynamics



RCs of dwarf spirals (new data)



inside 10 Mpc

The URC 07 and new data

The Universal Velocity profile $V^2(r, Mvir)=Vg^2(r,Mvir)+ VURCH^2(r,Mvir)+ VD^2(r,Mvir)$

$$V^2_{URCH}(r) = 6.4G\frac{\rho_0 r_0^3}{r}\left(\ln\left(1+\frac{r}{r_0}\right)-\tan^{-1}\left(\frac{r}{r_0}\right)+\frac{1}{2}\ln\left[1+\left(\frac{r}{r_0}\right)^2\right]\right)$$

$$\log\left(\frac{\rho_0}{g/cm^3}\right) = -22.515 - 0.964\left(\frac{M_D}{10^{11}M_{sun}}\right)$$

$$M_D = 2.3\times10^{10}M_{sun}\frac{\left[M_{vir}/\left(3\times10^{11}M_{sun}\right)\right]^{3.1}}{1+\left[M_{vir}/\left(3\times10^{11}M_{sun}\right)\right]^{2.2}}$$

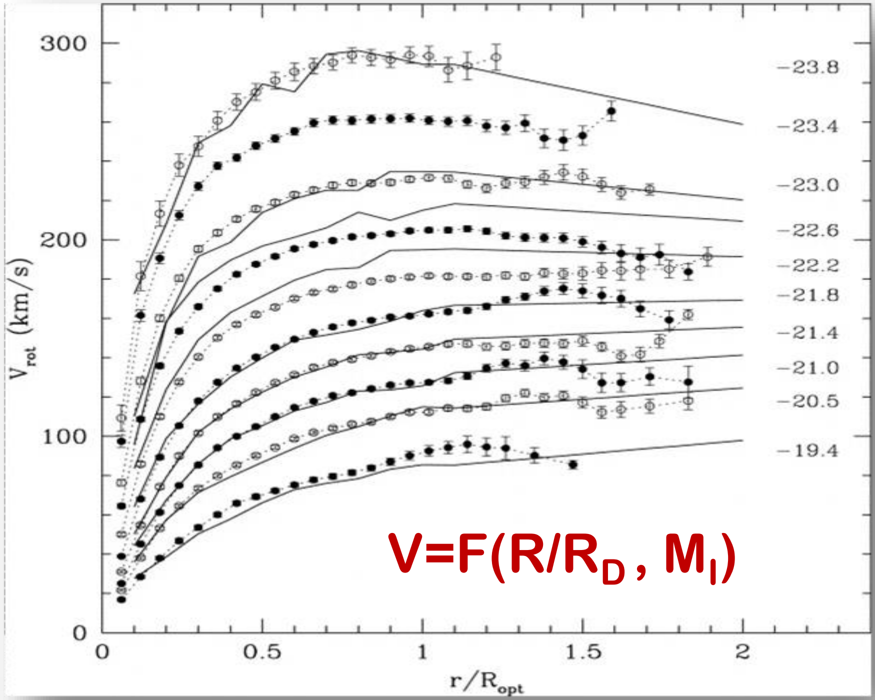
Shankar et al. 2006

$$\log\left(\frac{r_0}{kpc}\right) \approx 0.66 + 0.58\log\left(\frac{M_{vir}}{10^{11}M_{sun}}\right)$$

For more details see
P. Salucci et al. 2007

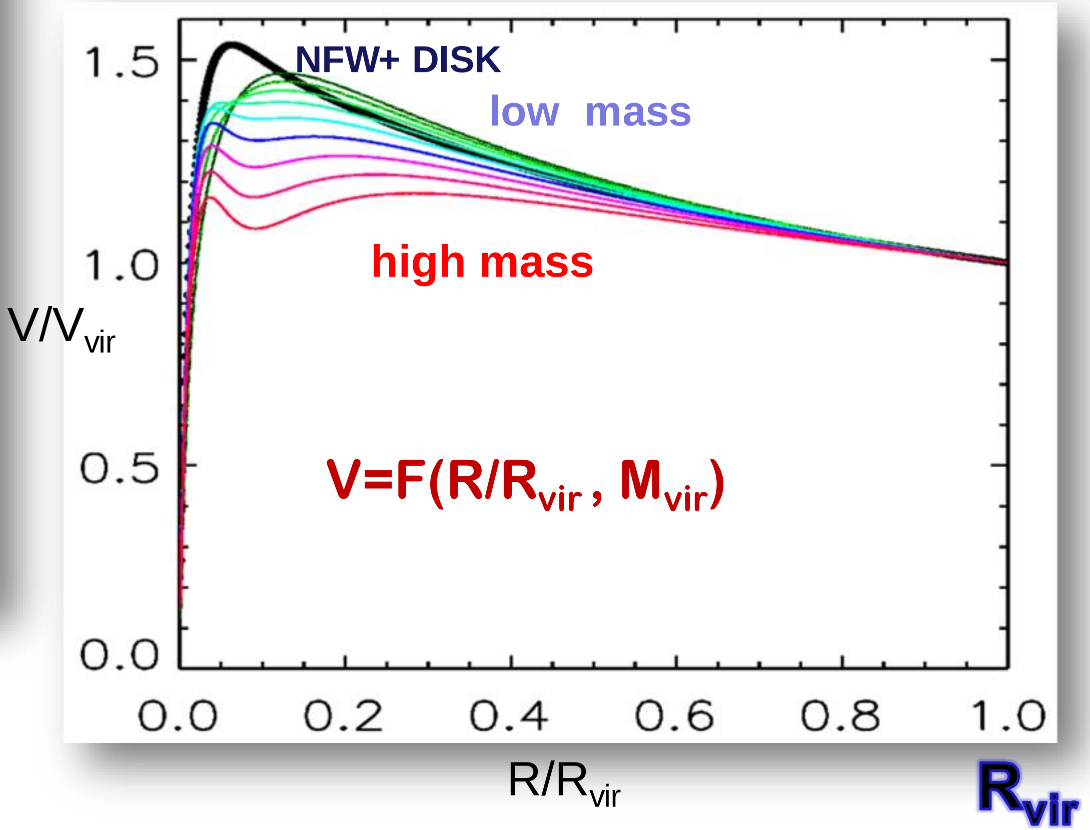
Universal Mass Distribution

URC



$V=F(R/R_D\,, M_I)$

URC out to R_{vir} and ΛCDM model



NFW+ DISK

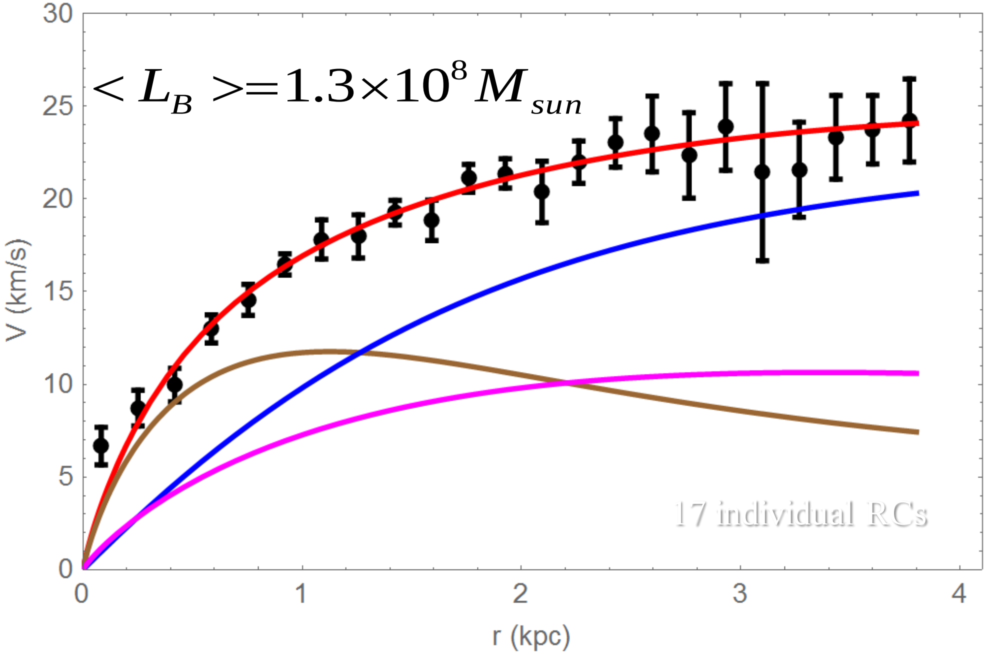
low mass

high mass

$V=F(R/R_{vir}\,, M_{vir})$

R_{vir}

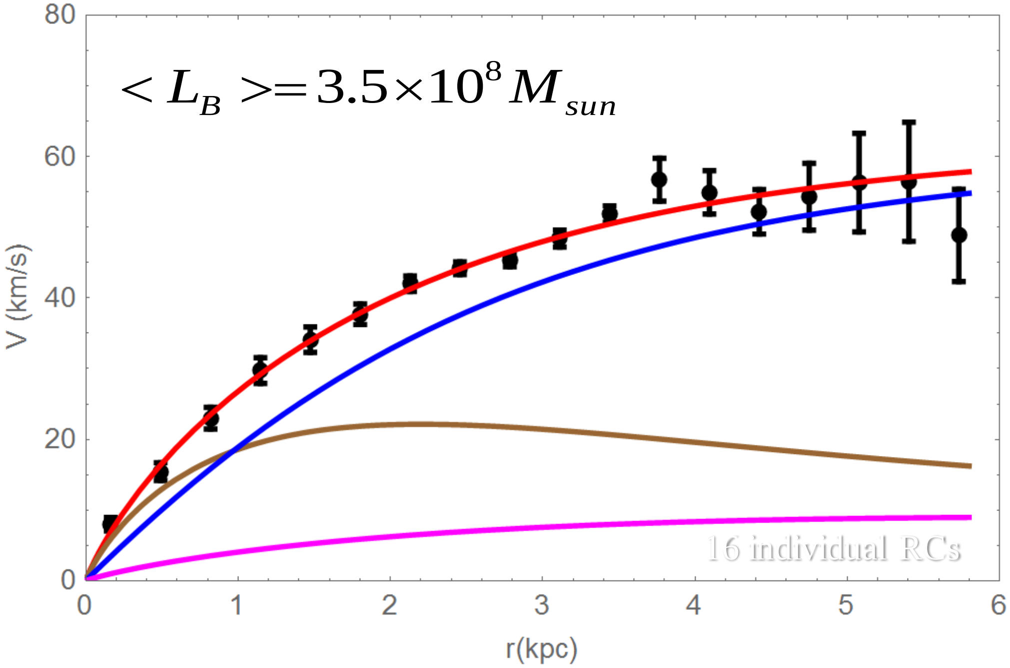
THE UNIVERSAL ROTATION CURVE (URC)



Vopt 5.25-31.69 km/s
<Ropt>=1.7 kpc

Best-fit parameters:

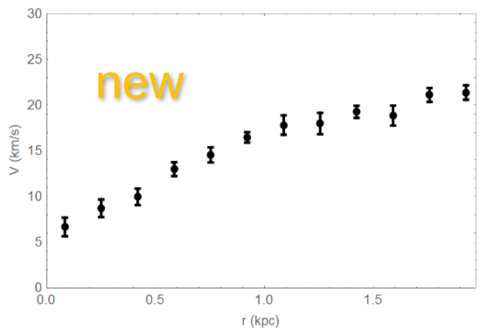
$$M_d = 4.5\times10^7 M_{sun}$$
$$\rho_0 = 7.9\times10^6 M_{sun}/kpc^3$$
$$r_0 = 2.3 kpc$$
$$M_{vir} = 2.4\times10^9 M_{sun}$$

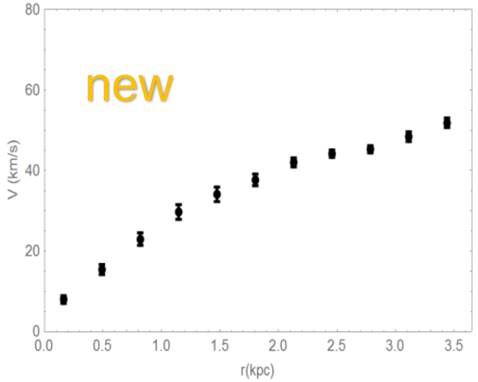


Vopt 37.81-56 km/s
<Ropt>=3.3 kpc

Best-fit parameters:

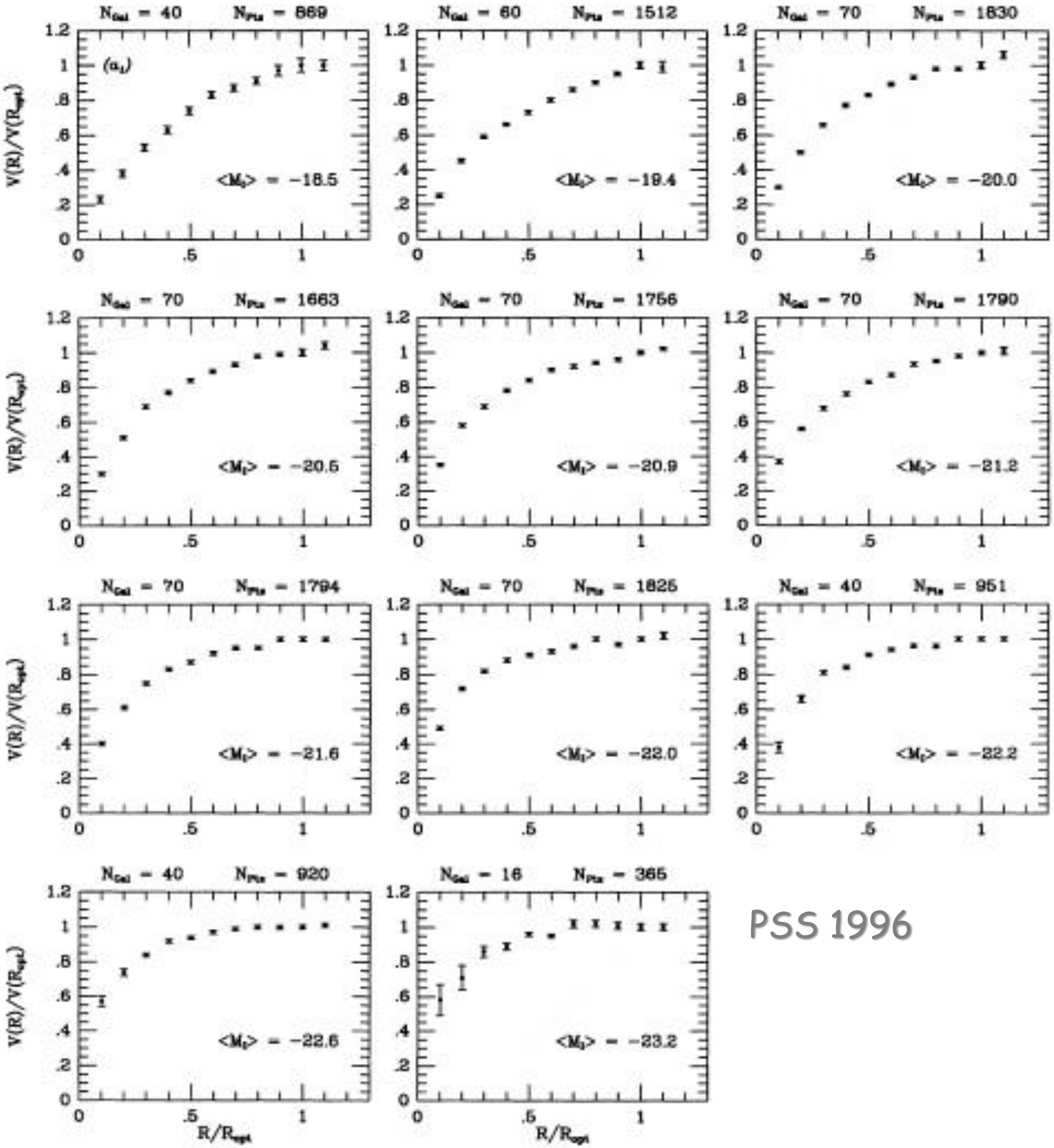
$$M_d = 3.1\times10^8 M_{sun}$$
$$\rho_0 = 2.6\times10^7 M_{sun}/kpc^3$$
$$r_0 = 3.5 kpc$$
$$M_{vir} = 3.2\times10^{10} M_{sun}$$





URC 2015

Late-Type Dwarf

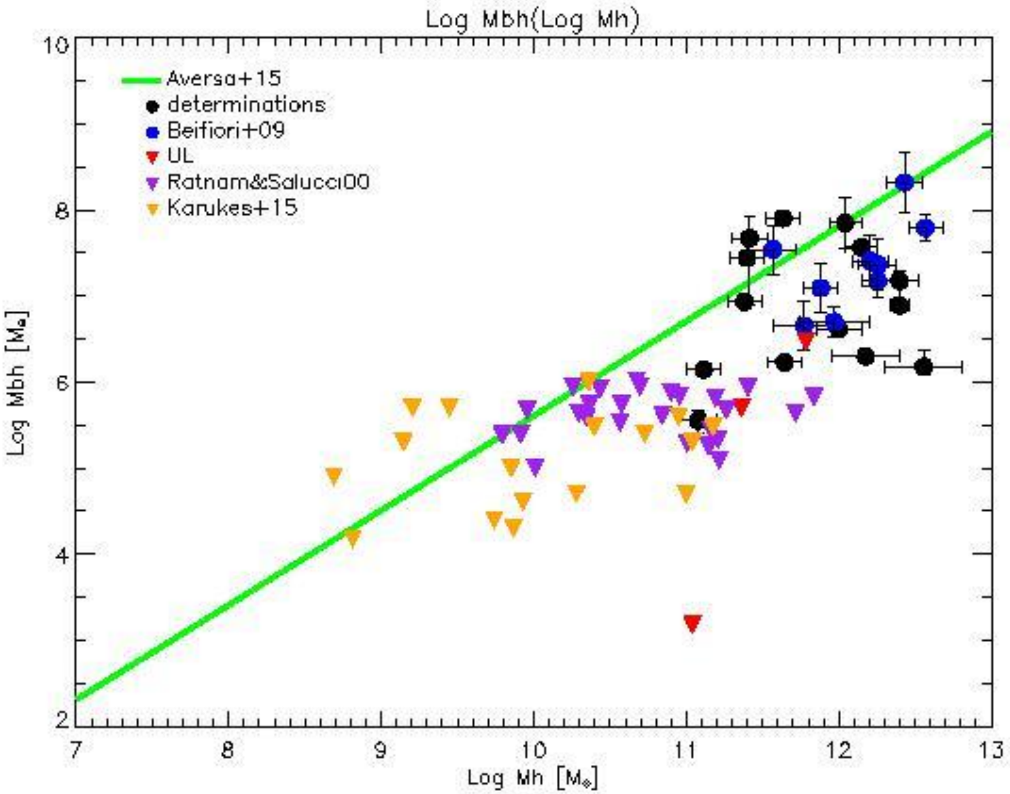


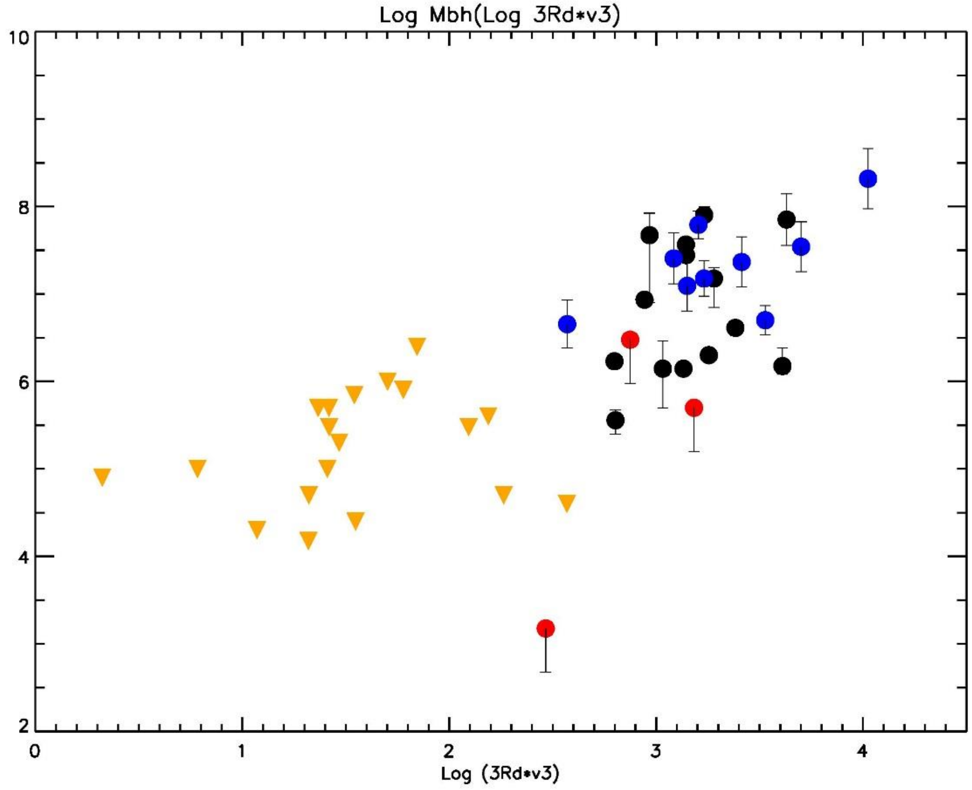
PSS 1996

The URC holds for halo masses from 6×10^9 M_{sun} to 3×10^{12} M_{sun}

Small masses, large number of objects, RC profiles directly incompatible with NFW, ΛBCDM must enter

Ellipticals from Spirals ?





the answer is in the…black holes

CONCLUSIONS

facts:

ALL *SPIRALS SHOW A FLAT CENTRAL DM DENSITY PROFILE*

NFW MASS MODELS FAIL IN EVERY SPIRAL

CDM must repair its bad predictions in every single object. It loses the status of the simplest theory. It requires fine tunig

WDM MASS MODELS OK

WDM is much MORE than CDM with a finite free streeming lenght.

Next step: lead -> imply. Requirement: study Ellipticals (1 PhD student), Low Surface Brightness galaxies (1 PhD student), dSph, Giant spirals (1 PhD student), Baryonic Effects (1 PhD student).