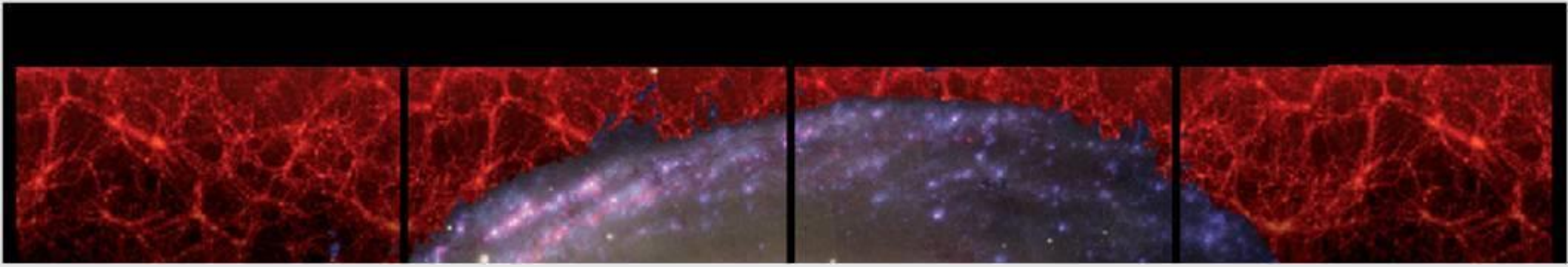


Galaxies properties lead to WDM

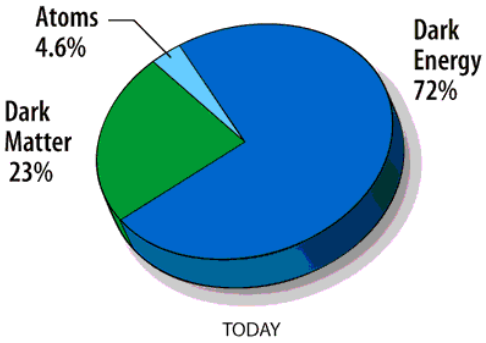
PAOLO SALUCCI
E. Karukes, R. Aversa

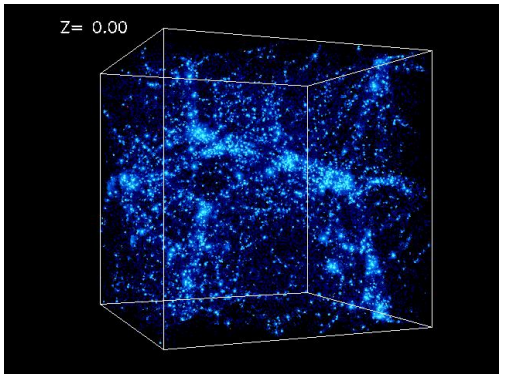
SISSA

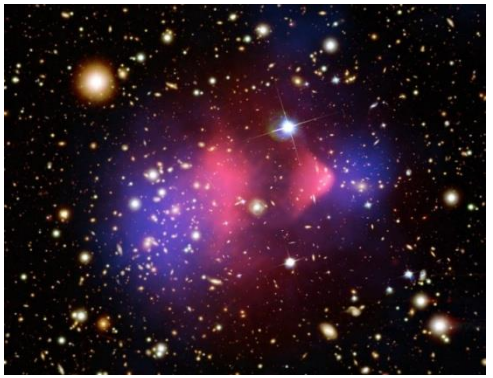
Dedicated to my friend Hector

Outline

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





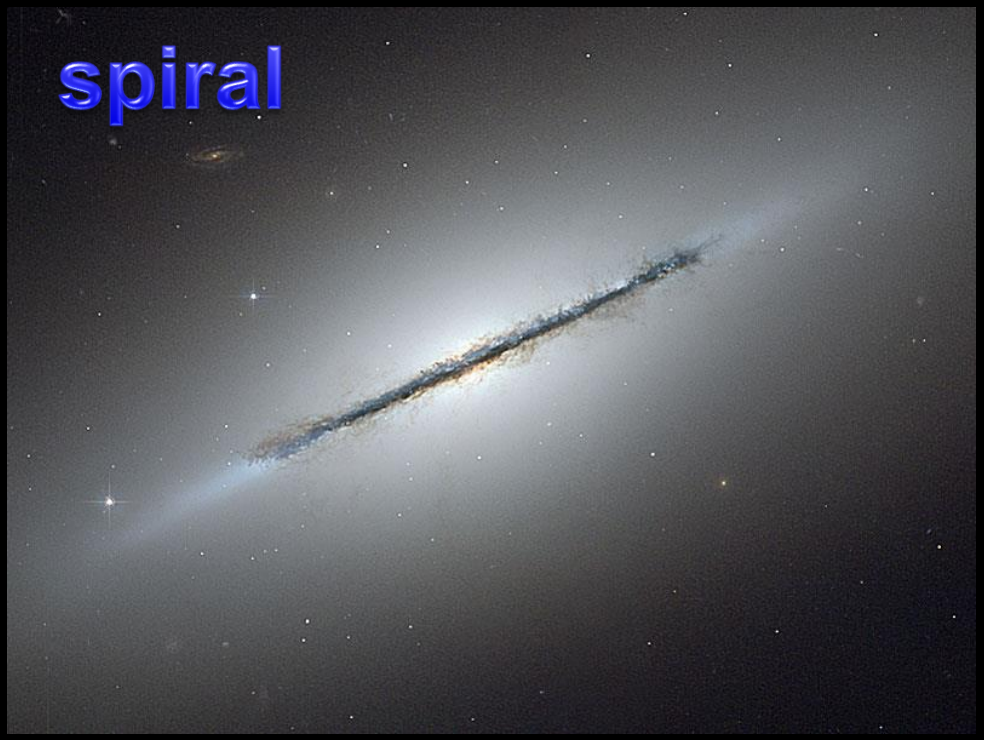


We weigh the mass of the Universe in several independent ways

Atoms alone cannot cosmologically develop the structures

In these structures we detect in several independent ways a dark massive component

Standard Model of Elementary particles requires an extension involving a dark particle

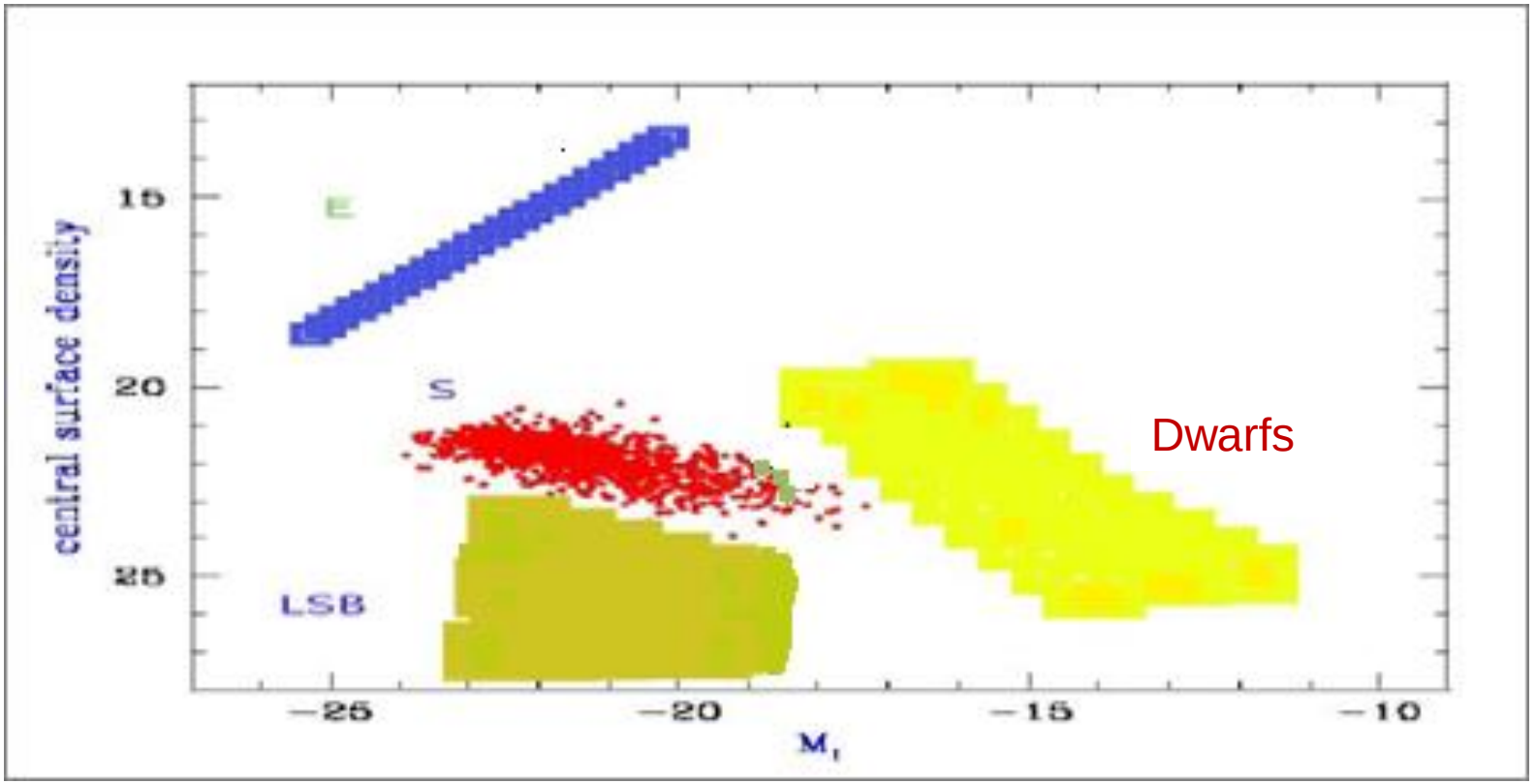


3 TYPES OF GALAXIES

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

What is Dark Matter ?

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

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

Its profile $M_H(r)$ must obey:

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

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

)

THEORY AND SIMULATIONS
CDM: the simplest theory

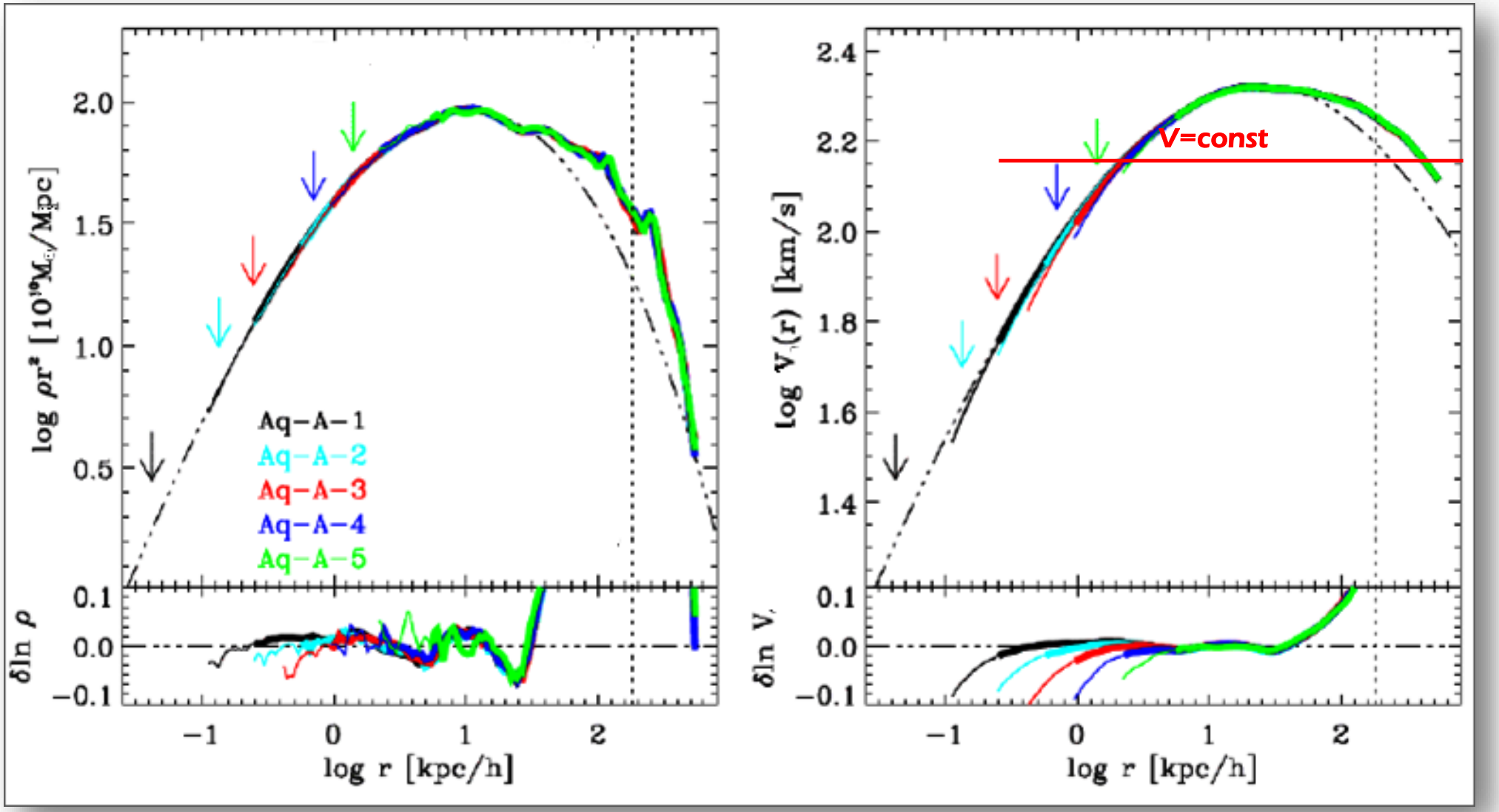
Straighforward predictions

Aquarius N-Body simulations

Navarro et al +10

density

circular velocity



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).

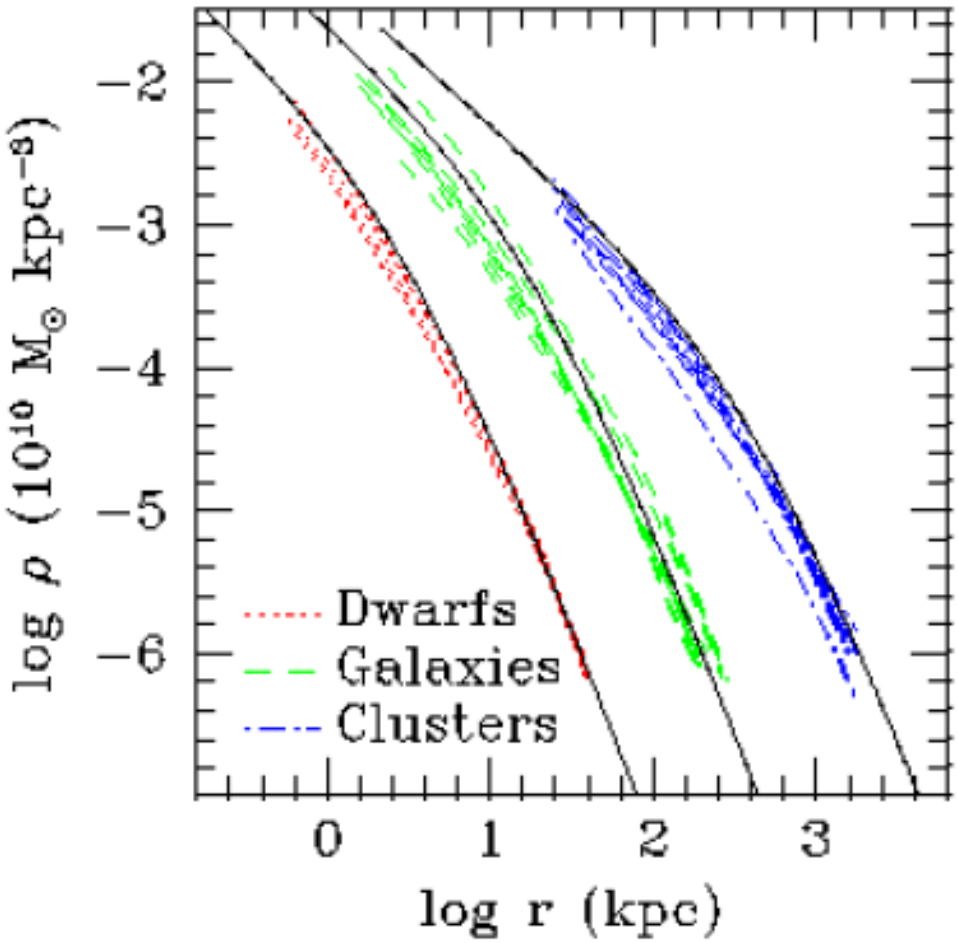
$$\rho_{NFW}(r) = \delta\rho_c \frac{r_s}{r} \frac{1}{(1+r/r_s)^2}$$

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

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

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

Klypin, 2010



Pure DM LCDM -> Occam razor

Stellar Disks

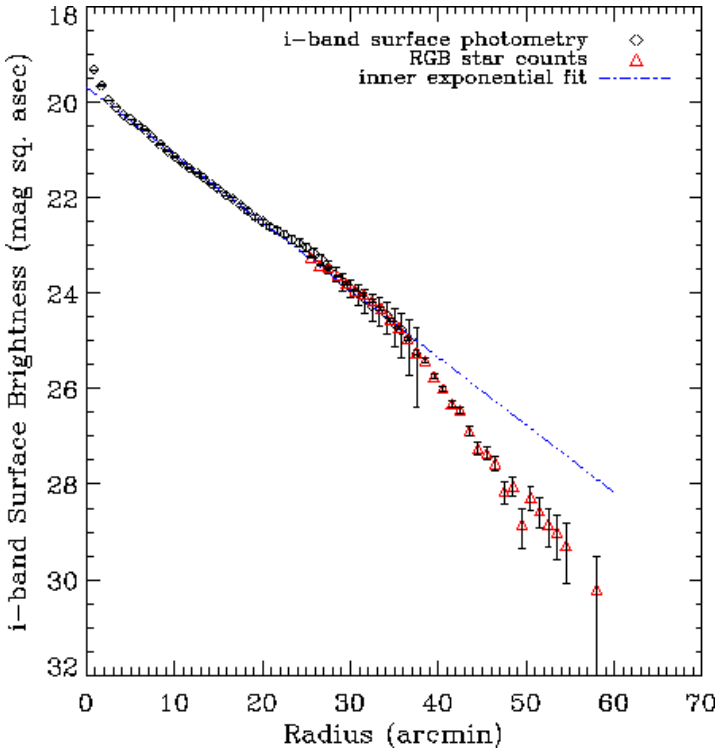
M33 disk very smooth,
truncated at 4 scale-lengths

NGC 300 exponential disk
for at least 10 scale-lengths

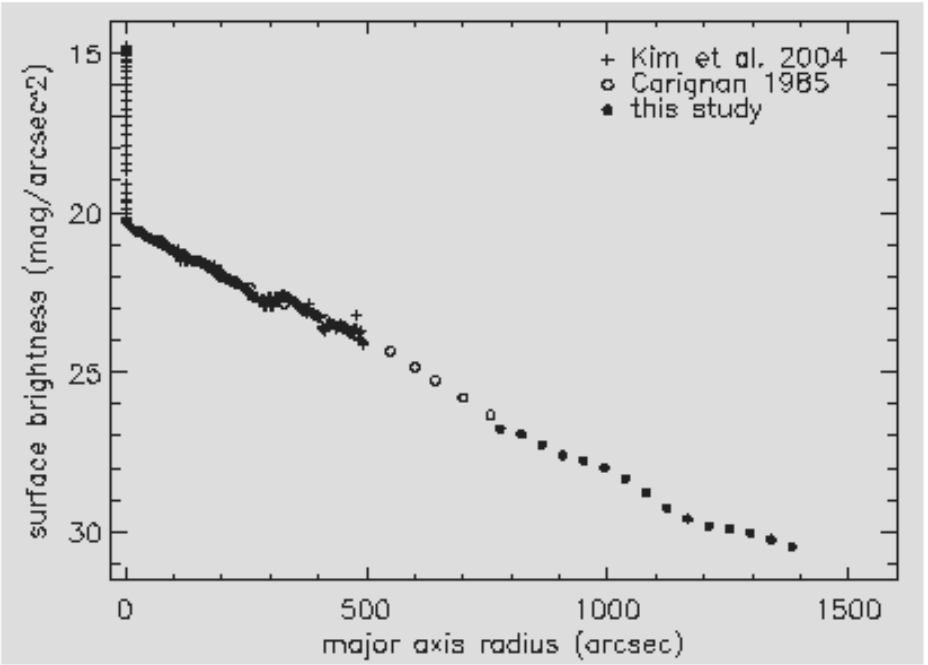
$$I(r) = I_0 e^{-r/R_D}$$

R_D lenght scale of the disk

Freeman, 1970



Ferguson et al 2003

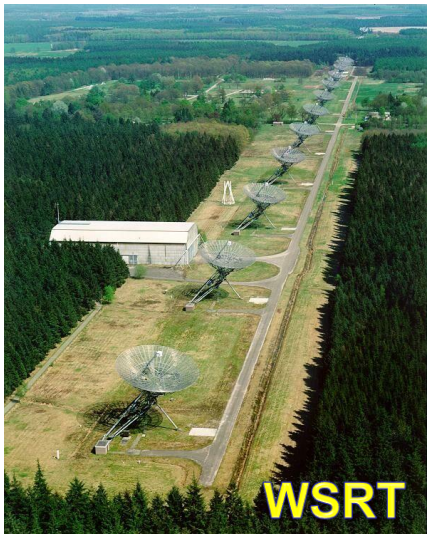


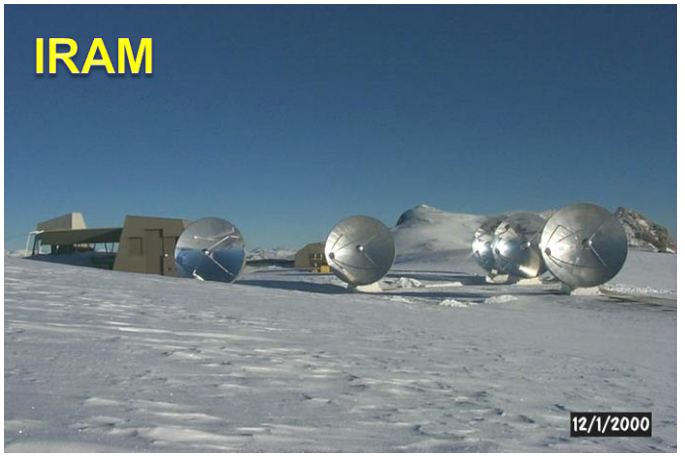
Bland-Hawthorn et al 2005

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}

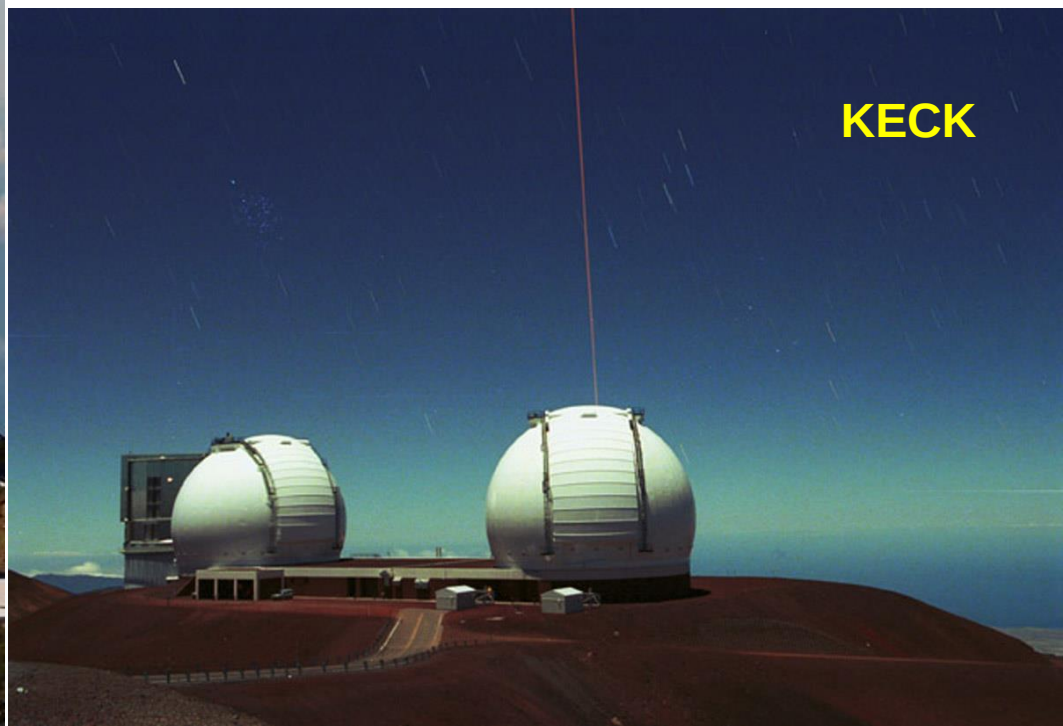





VLT

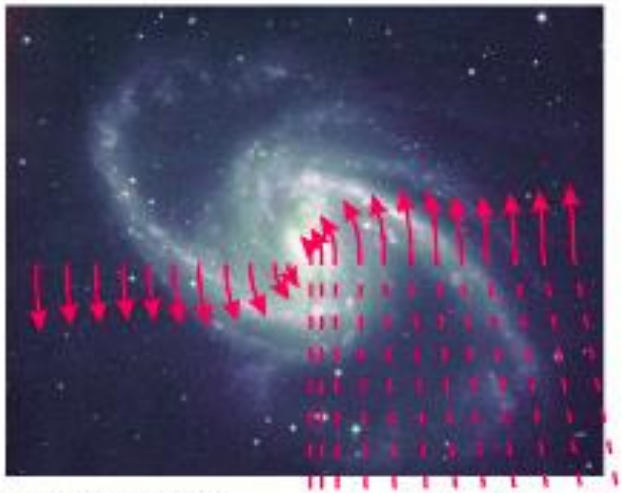

LBT


GTC

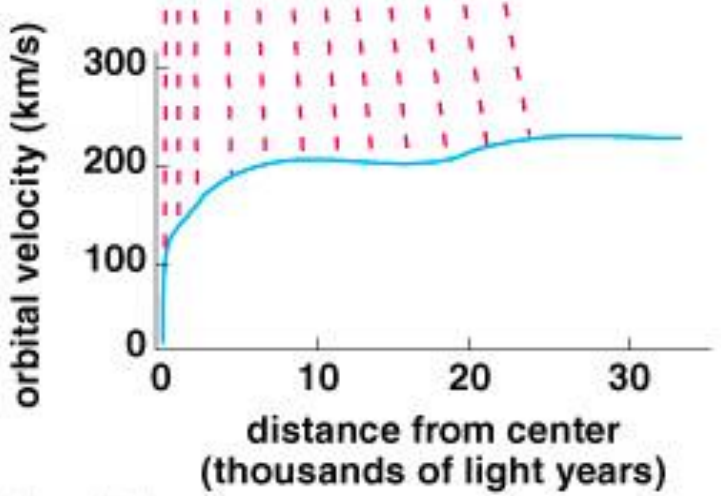

KECK

ROTATION CURVES

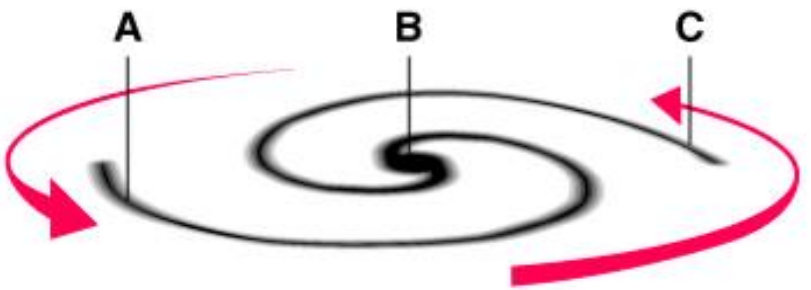
artist impression

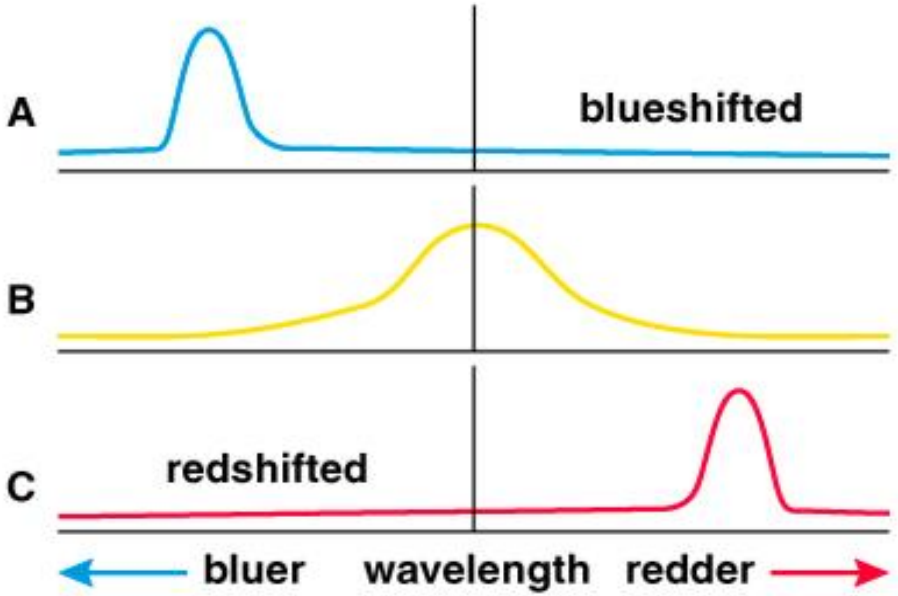


Longer arrows represent larger orbital velocities.



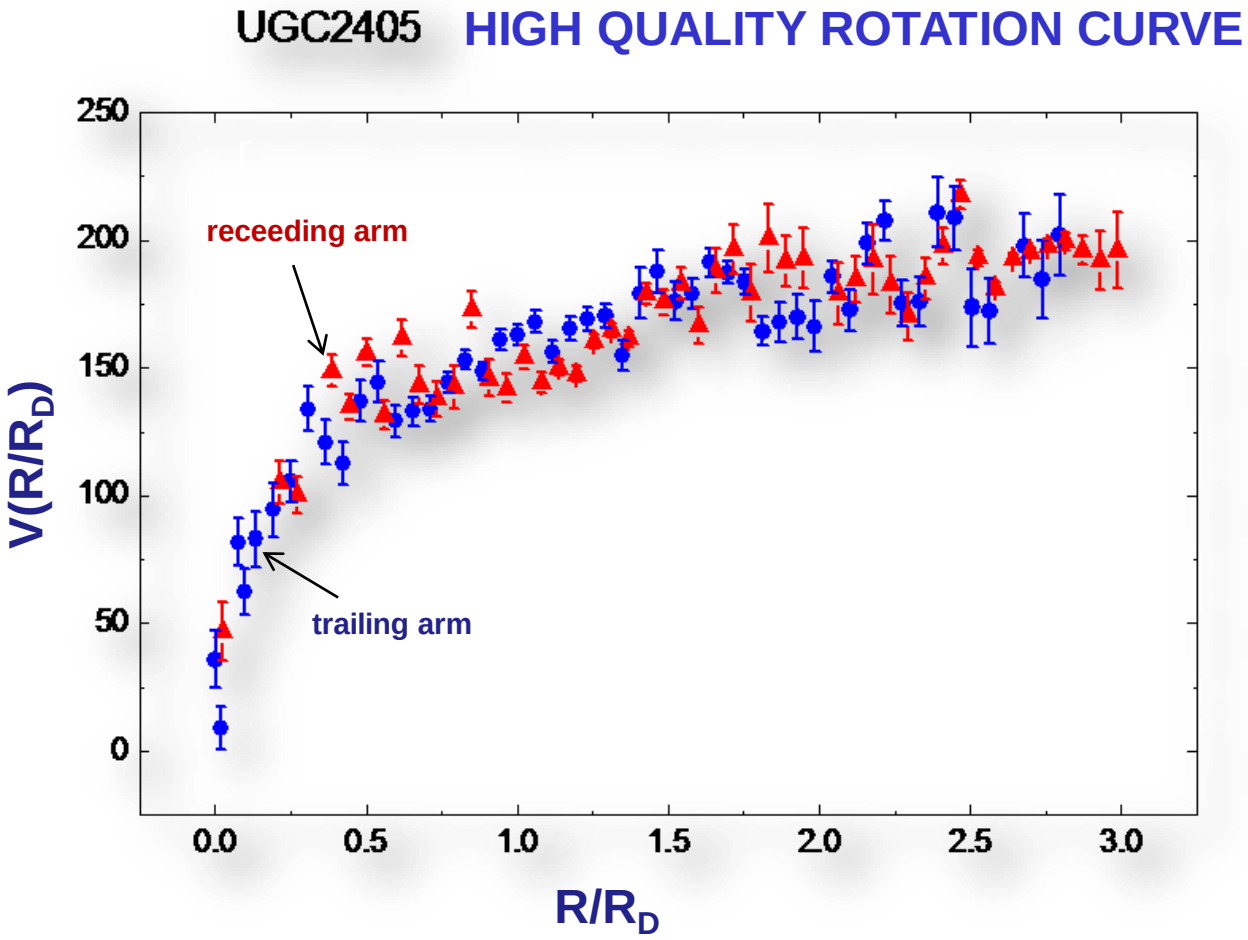
artist impression





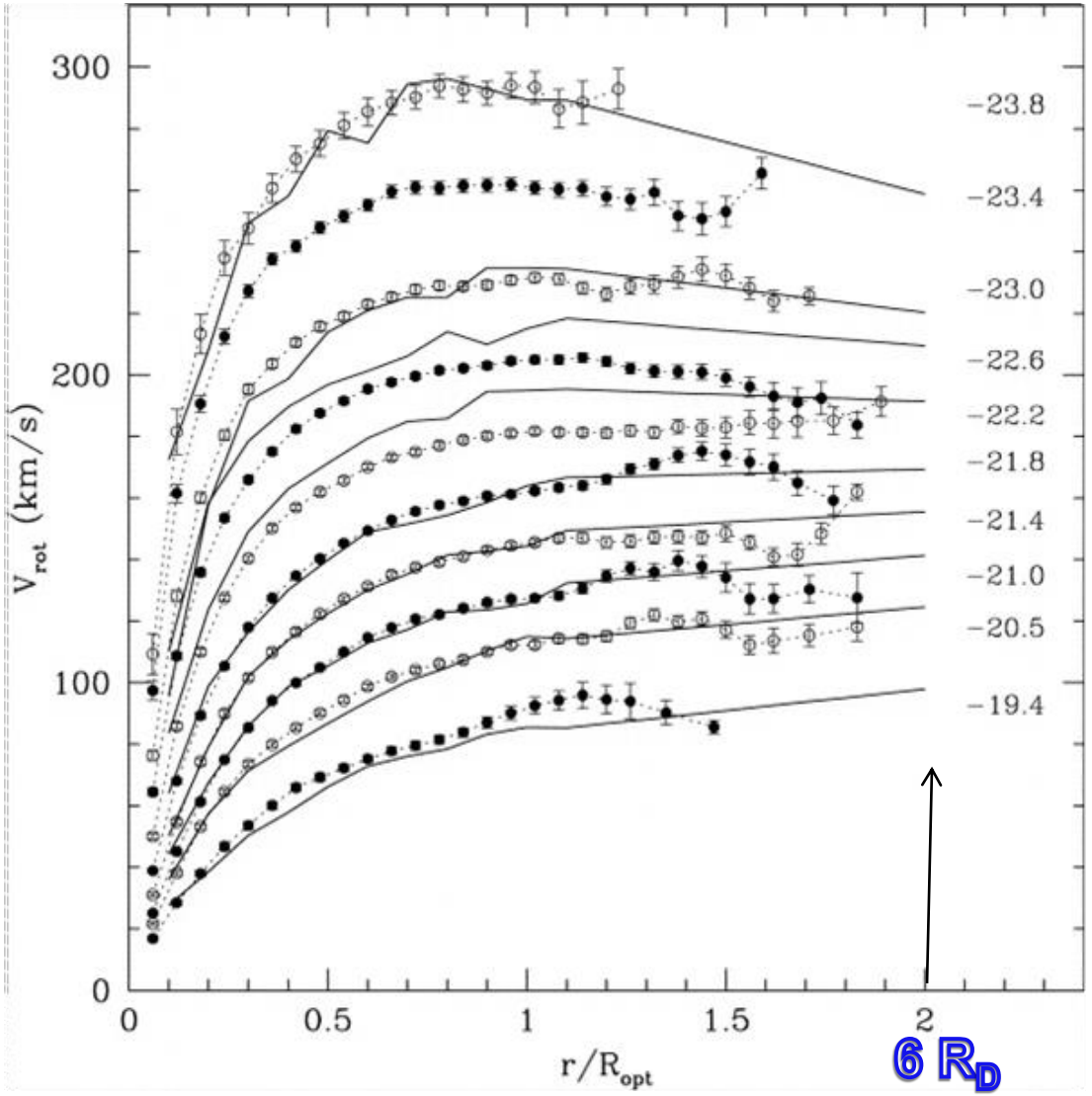
Symmetric circular rotation of a disk characterized by

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

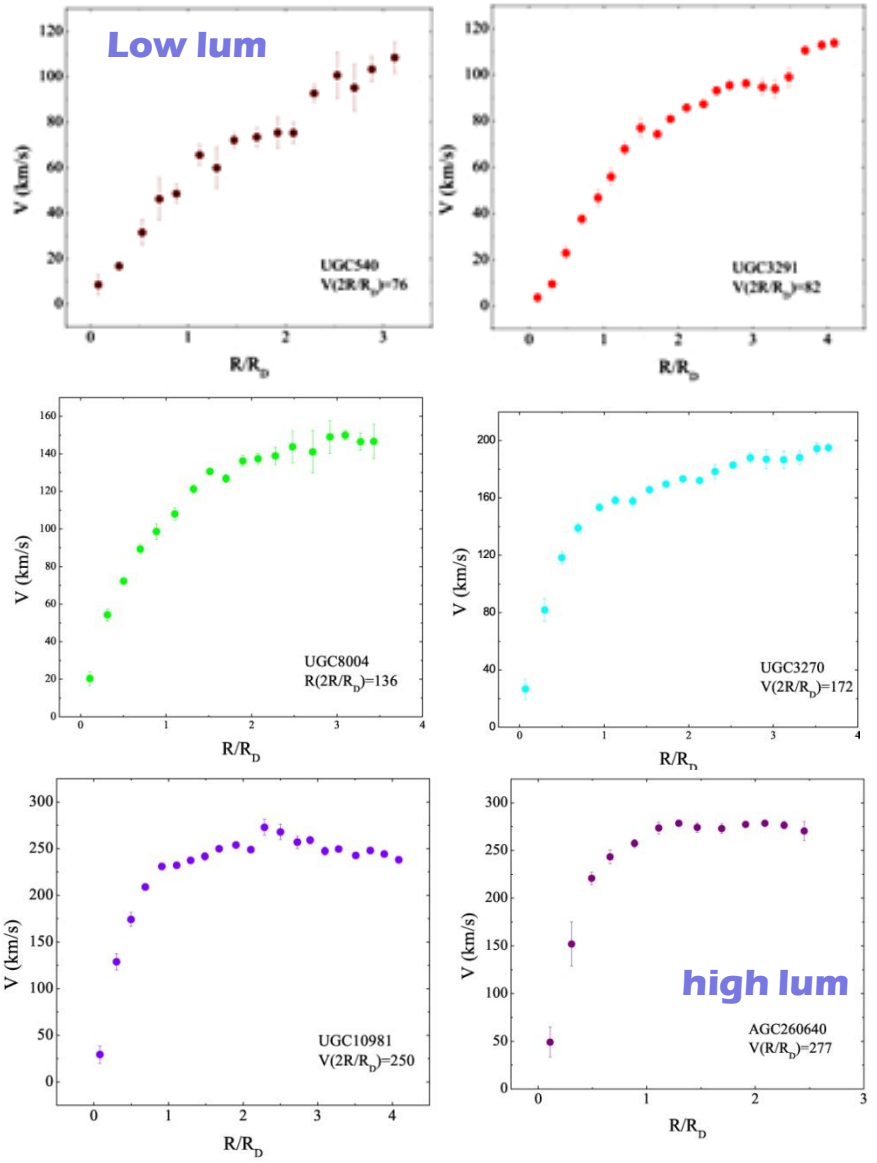


Rotation Curves

Coadded from 3200 individual RCs

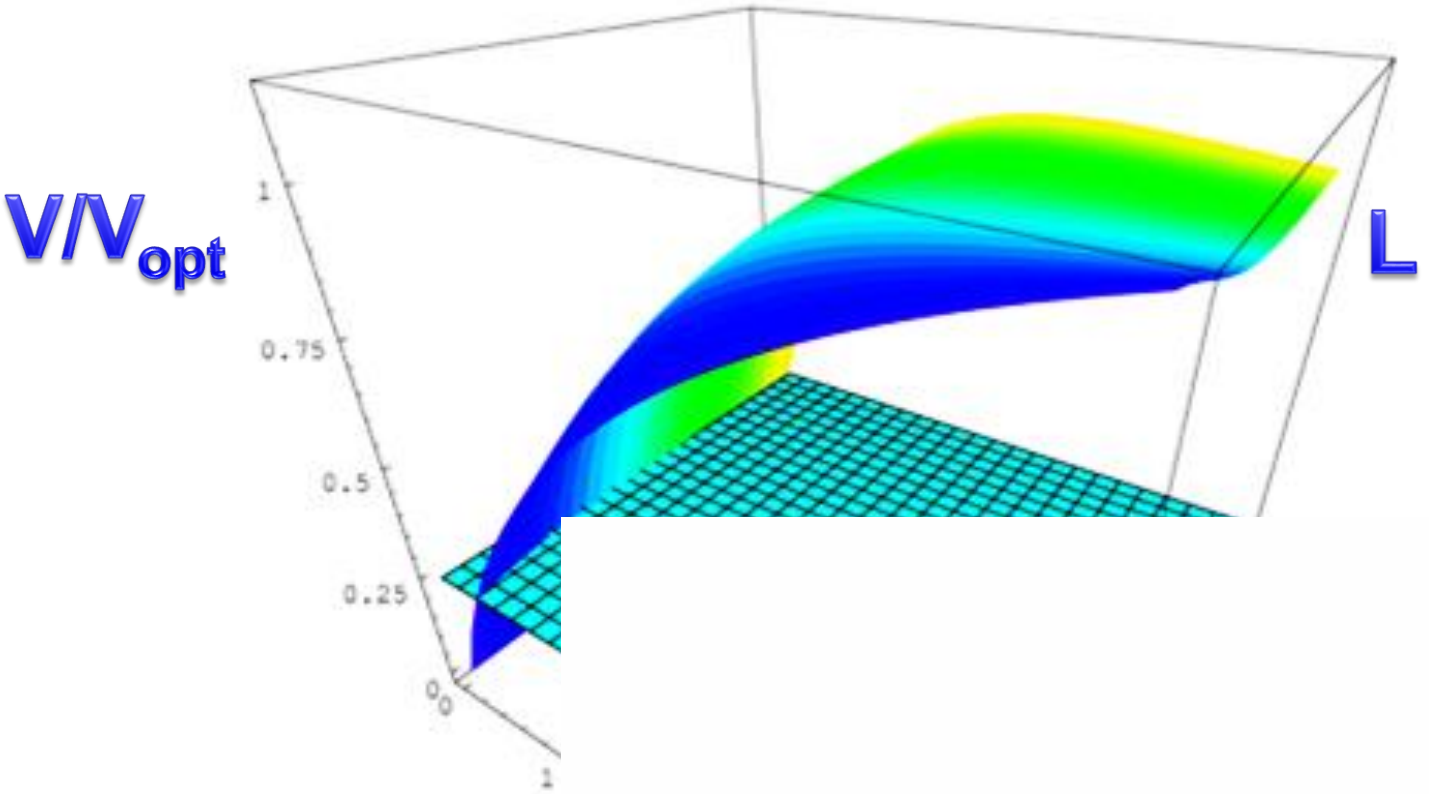


TYPICAL INDIVIDUAL RCs OF INCREASING LUMINOSITY



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

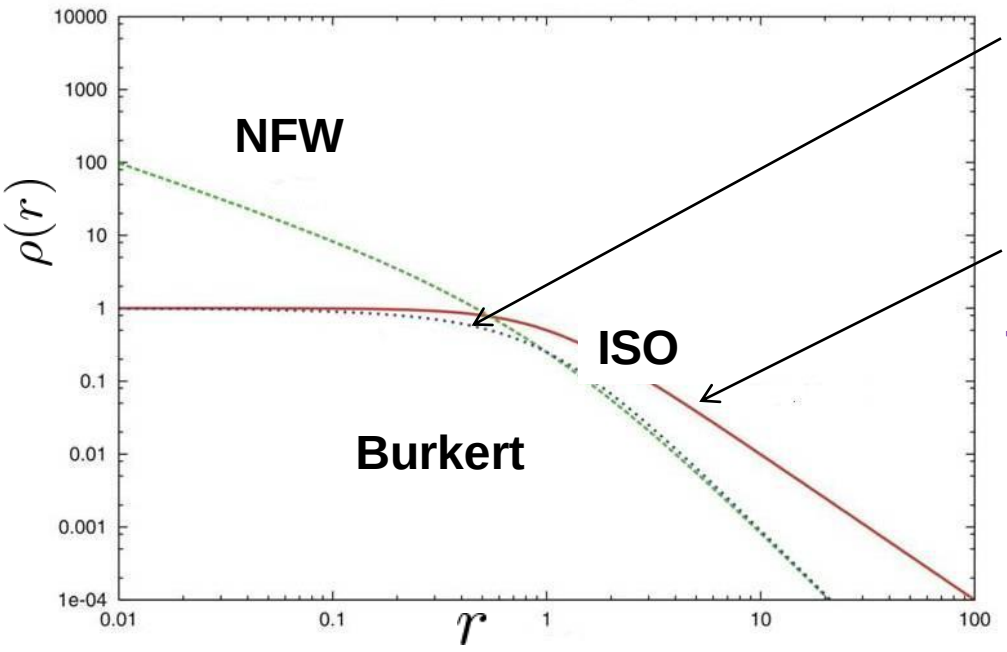
$$V^2(R) = V^2_{halo}(R) + V^2_{HI}(R) + V^2_{disk}(R)$$

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)

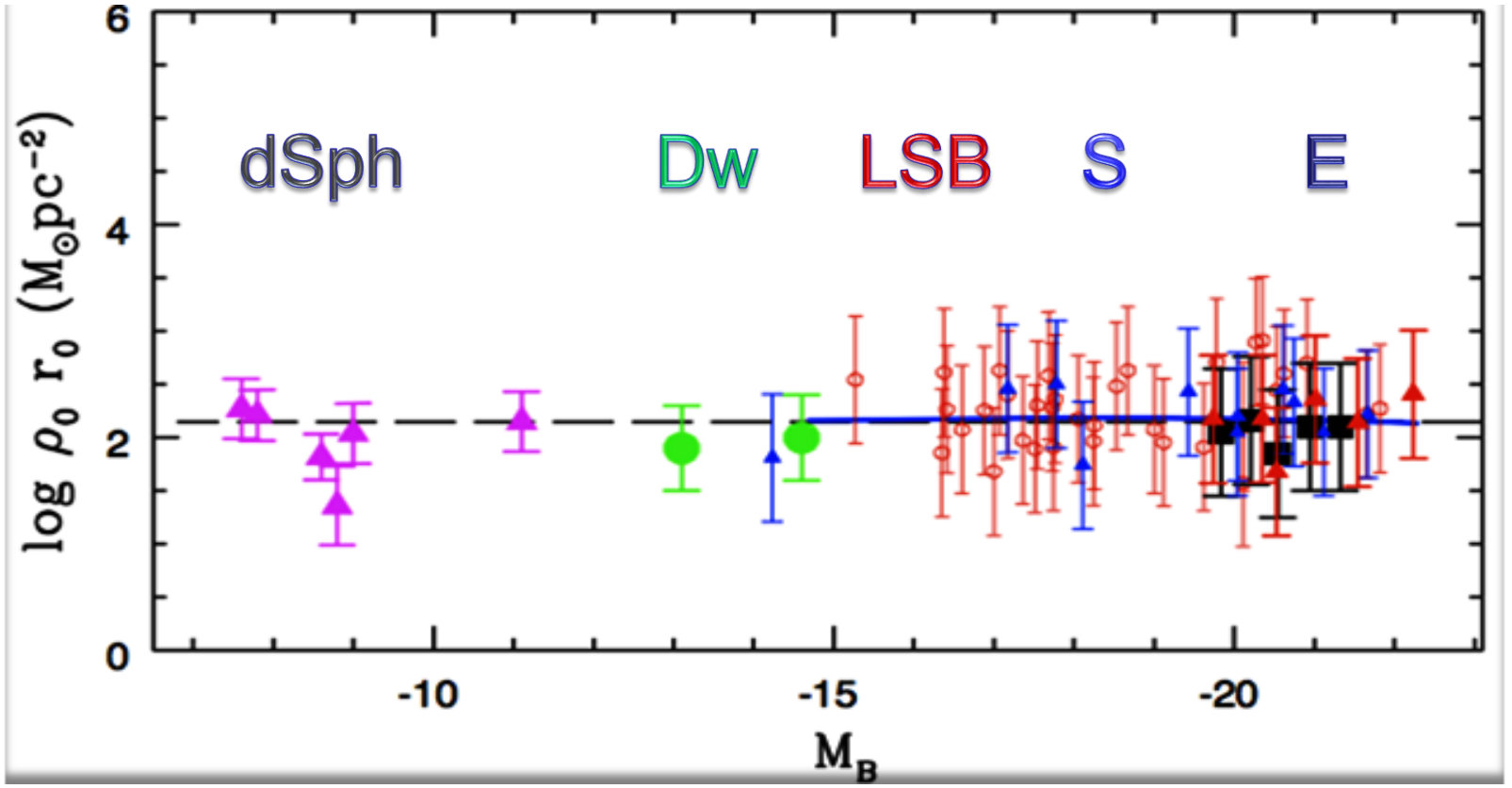


$$\rho(r) = \frac{\rho_0}{(1 + r/r_0)(1 + (r/r_0)^2)}$$

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

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

GALAXY HALOS: AN UNIFIED VISION

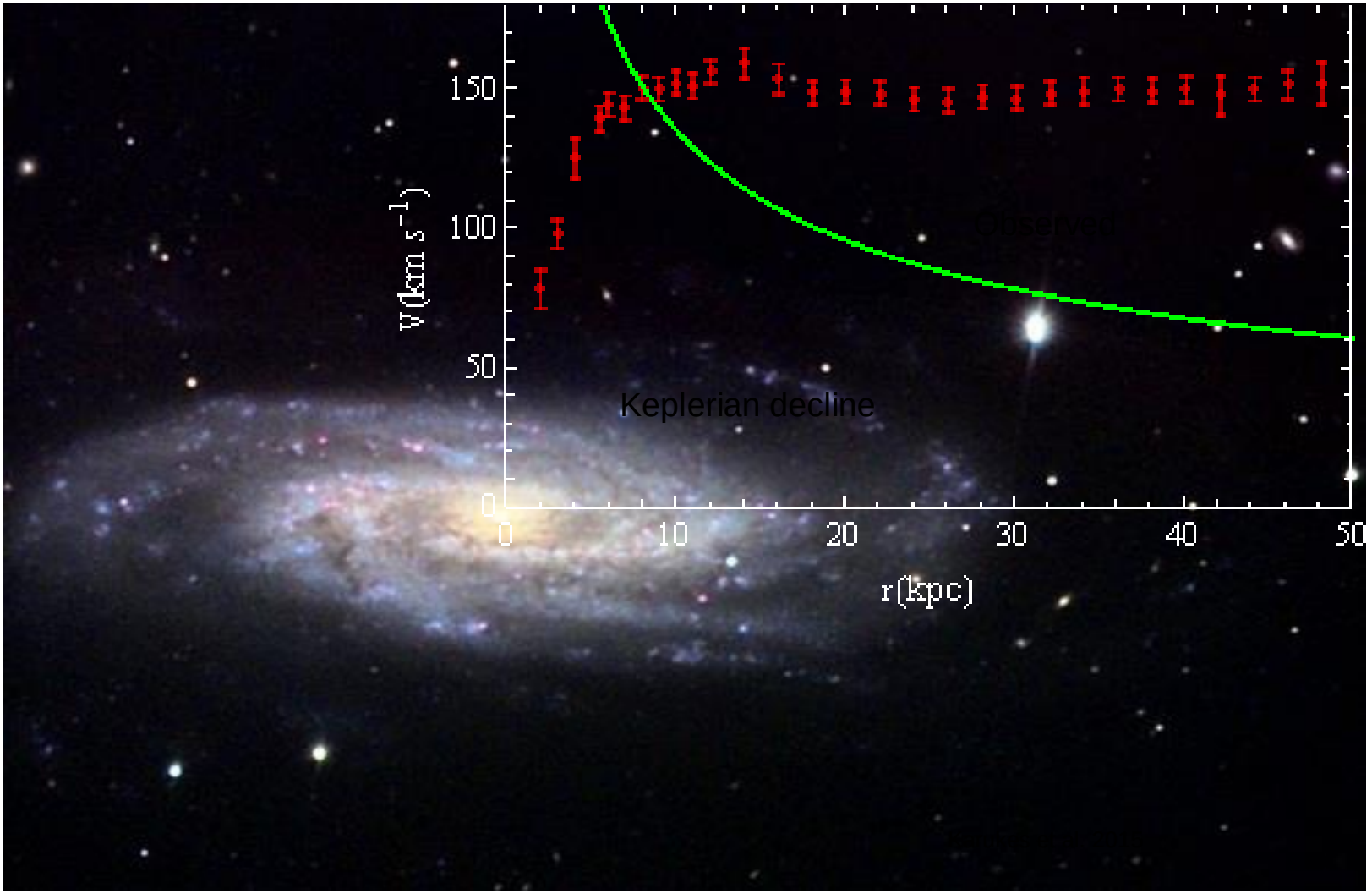


Core radii between 0.1 kpc to 100 kpc

Small scale LCDM problems
New recently obtained galaxy properties go further
Clear lead to WDM

1-Objects in which NFW seem to work.
2-The smallest galaxies of the Universe.
3-Outer DM density profiles.

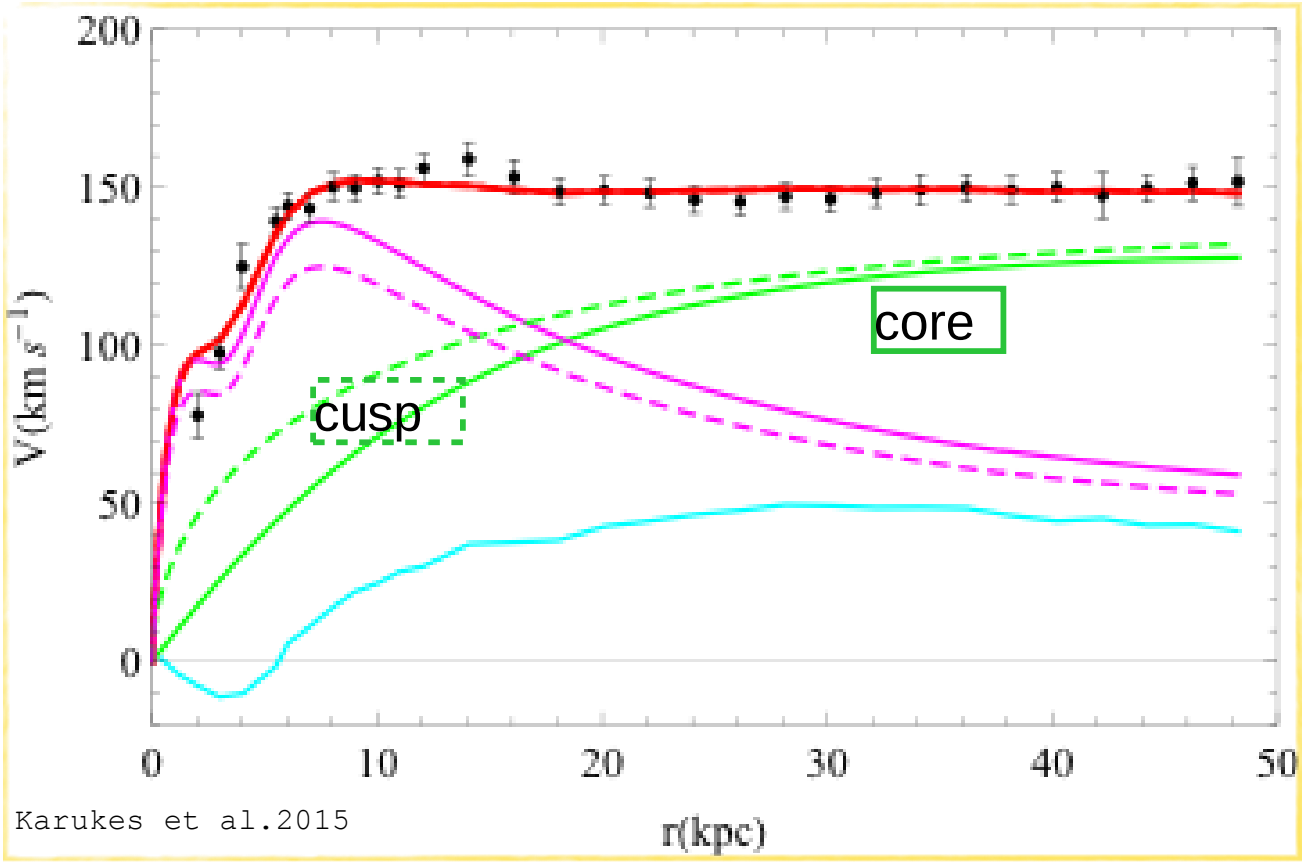
The DM distribution in NGC 3198,a crucial test case



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

NGC 3198

NGC 3198: most extended flat RC



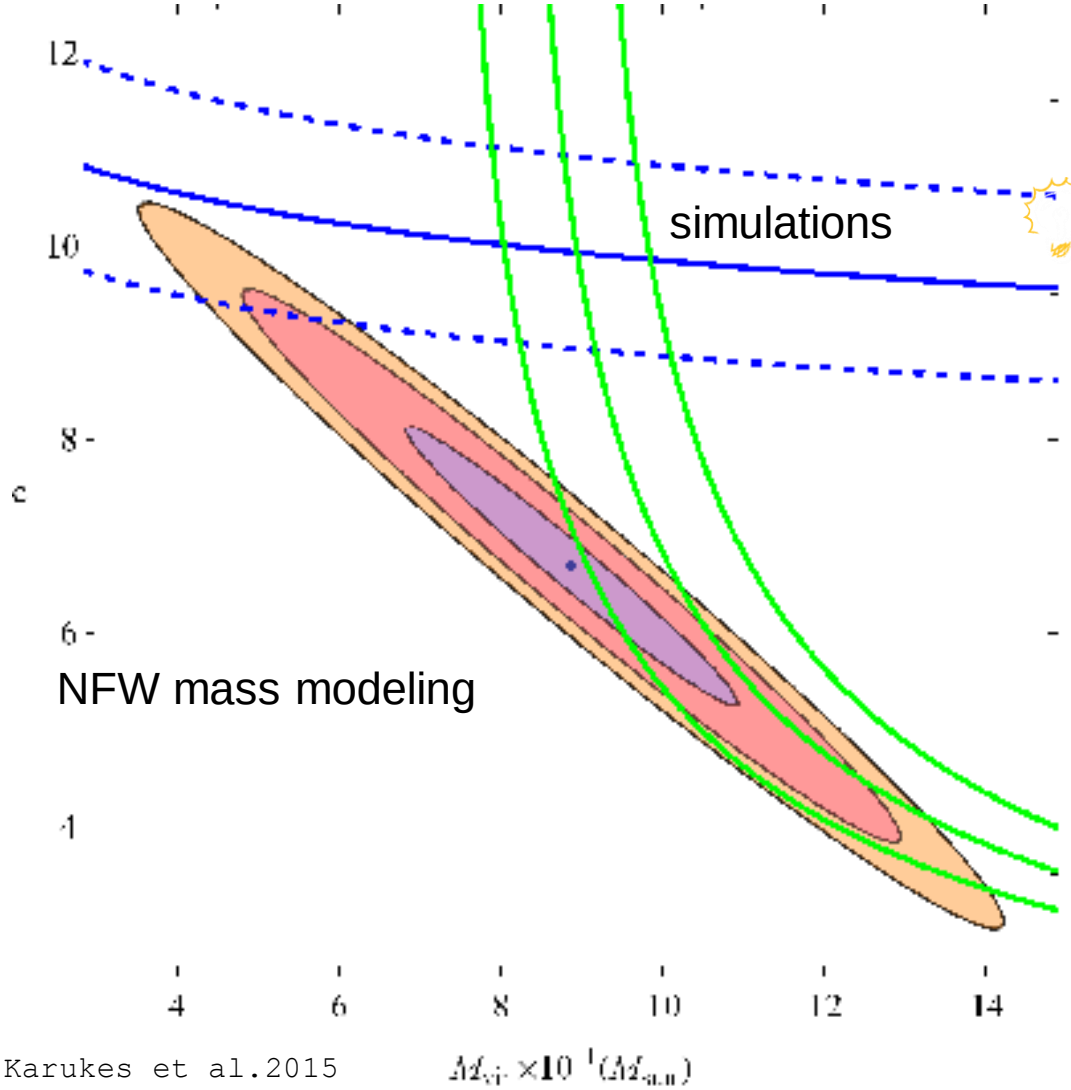
Two DM models:

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

$$\rho_{Bur}(r) = \frac{\rho_0 r_{core}^3}{\left(r+r_{core}\right)\left(r^2+r_{core}^2\right)} \qquad \rho \sim r^{-3}$$

Not possible to discriminate between the two DM profiles ?!

NGC 3198



simulations

NFW mass modeling

c-M_{vir}

Non-cosmological values

Karukes et al.2015

e 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.

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

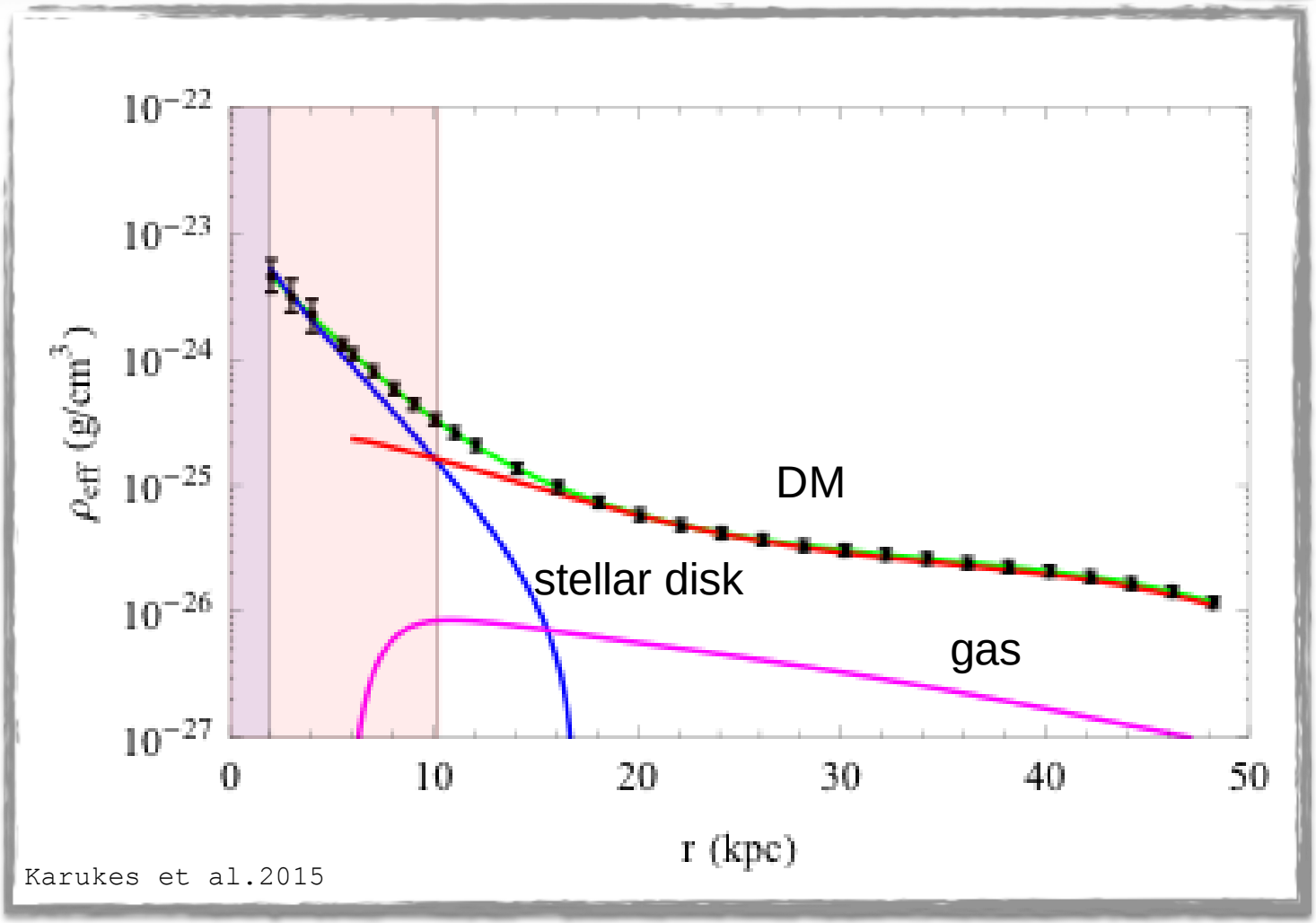
spherical DM halo

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

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

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

NFW profile in terms of $c\text{-}M_{vir}$:

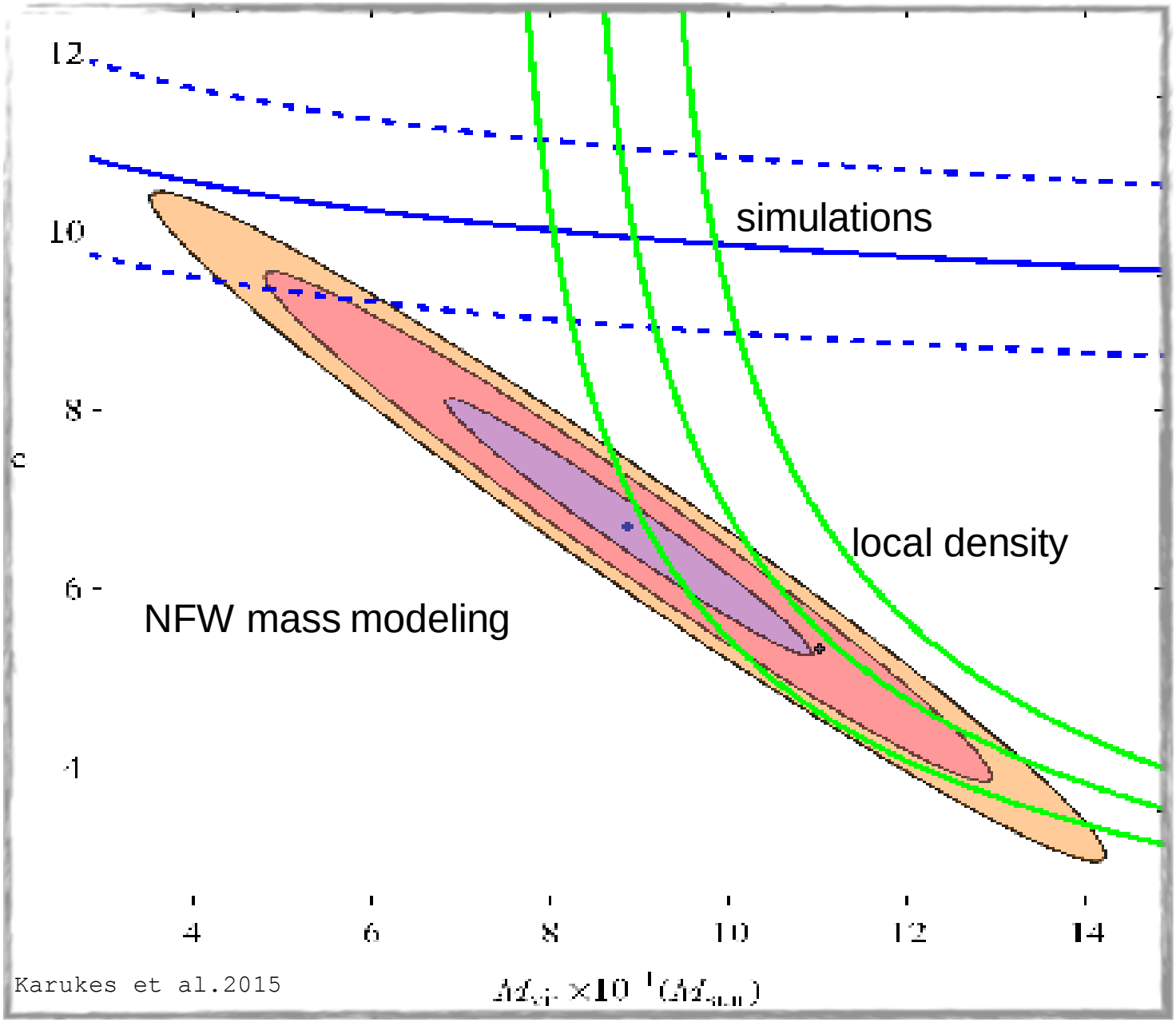
$$\rho_s = \frac{100}{3} \frac{c^3}{\log(1+c) - \left(\frac{c}{1+c}\right)} \rho_{crit}$$

$$r_s = \frac{1}{c} \left(\frac{3 \times M_{vir}}{4\pi 100 \rho_{crit}} \right)^{\frac{1}{3}}$$

From Klypin et al. 2011

$$c \simeq 9.6 \left(\frac{M_{vir}}{10^{12} (0.71)^{-1} M_{\odot}} \right)^{-0.075}$$

The DM density at large radii



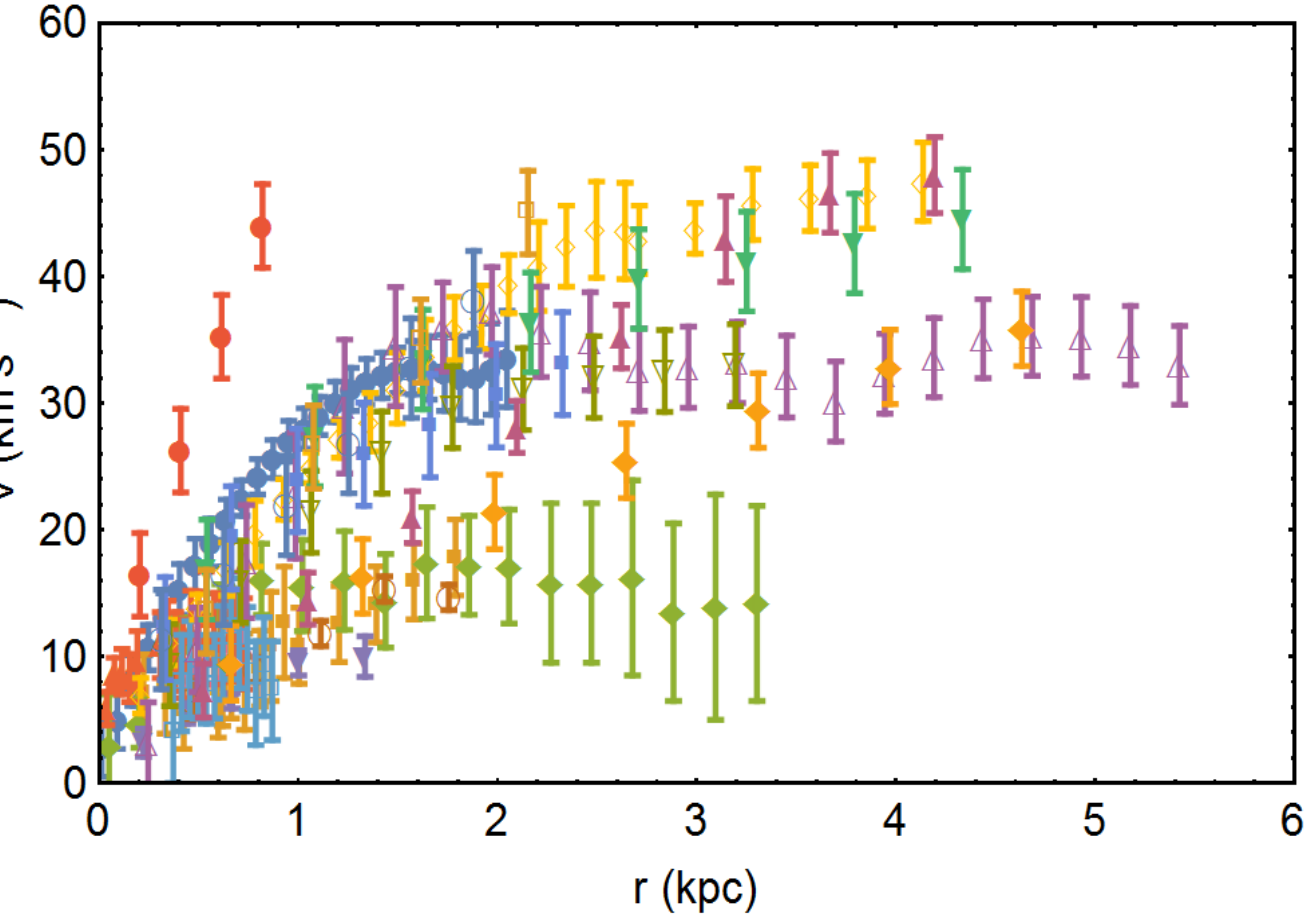
Karukes et al.2015

NFW mass model must accomplish:

-**reduced chisquare <1**
-disk mass inside physical values
-halo mass inside physical values
-concentration-mass relation as from simulations

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

RCs of the smallest spirals

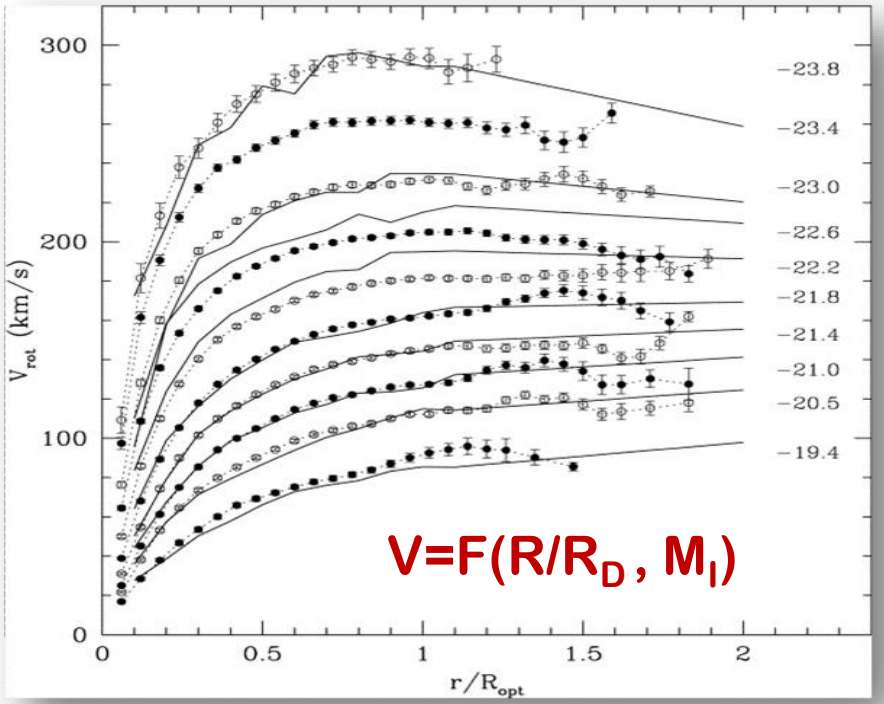


- UGC8508
- DDO125
- DDO53
- DDO99
- CGCG269−049
- UGC6456
- UGC8638
- UGC11583
- UGC4305
- UGC7559
- UGC7232
- UGC7866
- UGC7916
- UGC8837
- UGC5918
- UGC7047
- UGC5272

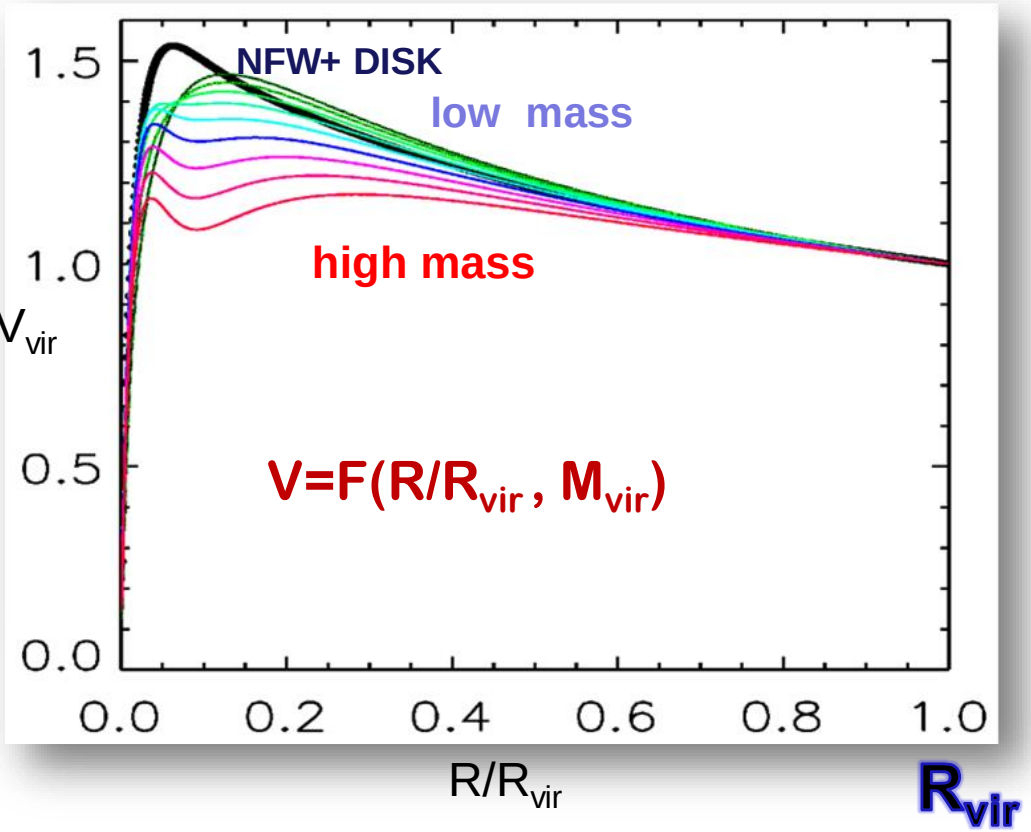
inside 10 Mpc

Universal Mass Distribution

URC



URC out to R_{vir} and ΛCDM model



The URC 07 and new data

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

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

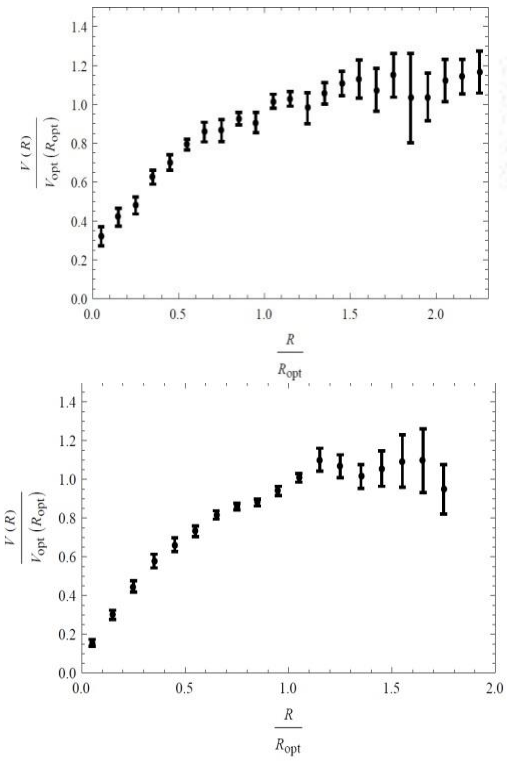
$$\log\left(\frac{\rho_0}{g/cm^3}\right) = -22.515-0.964\left(\frac{M_D}{10^{11}M_{sun}}\right)$$

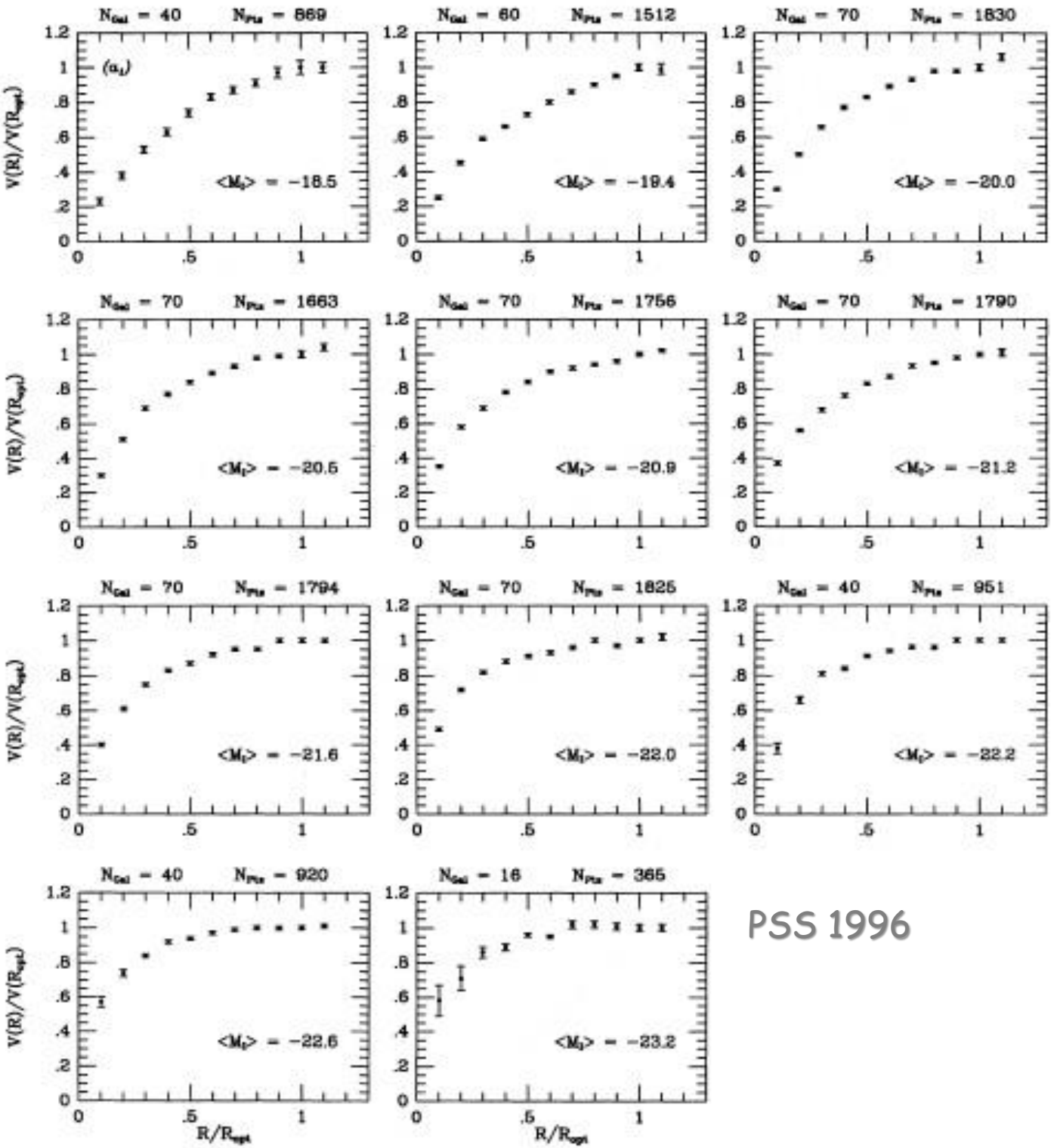
$$M_D = 2.3\times10^{10}M_{sun}\frac{\left[M_{vir}/\left(3\times10^{11}M_{sun}\right)\right]^{3.1}}{1+\left[M_{vir}/\left(3\times10^{11}M_{sun}\right)\right]^{2.2}}$$

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



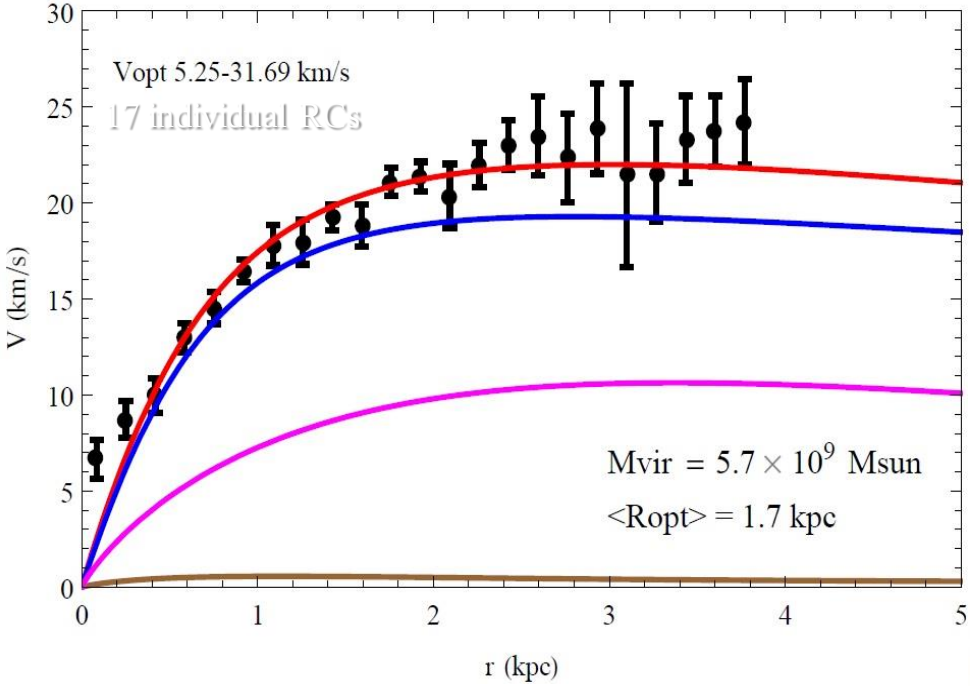


URC 2015

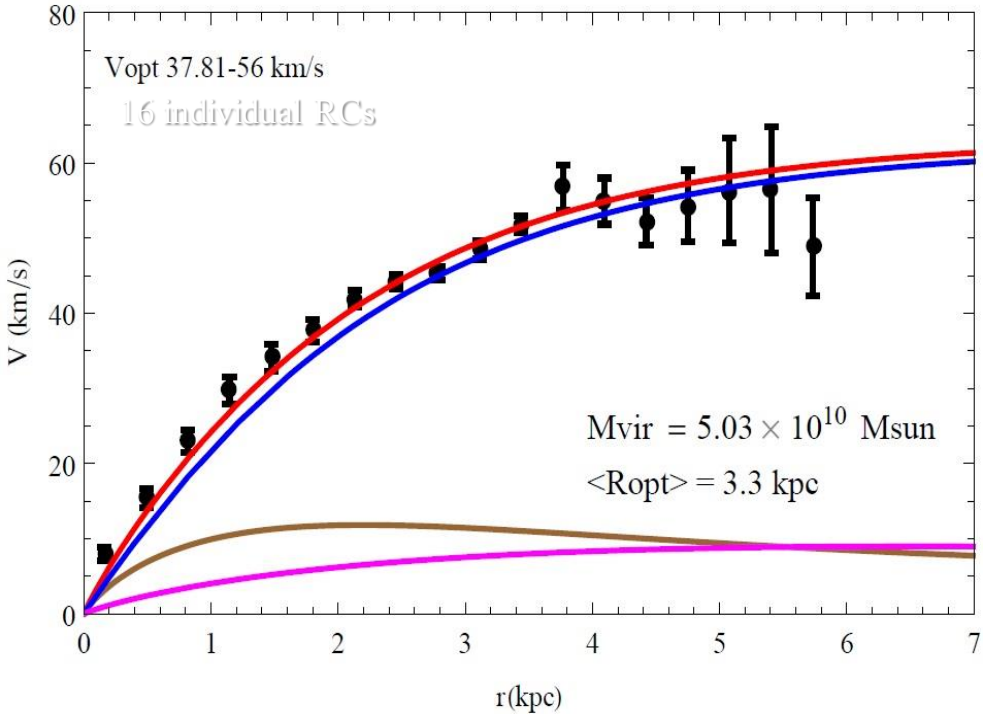
PSS 1996

Late-Type Dwarf

Best three-component fits to the URC



dark matter dominates

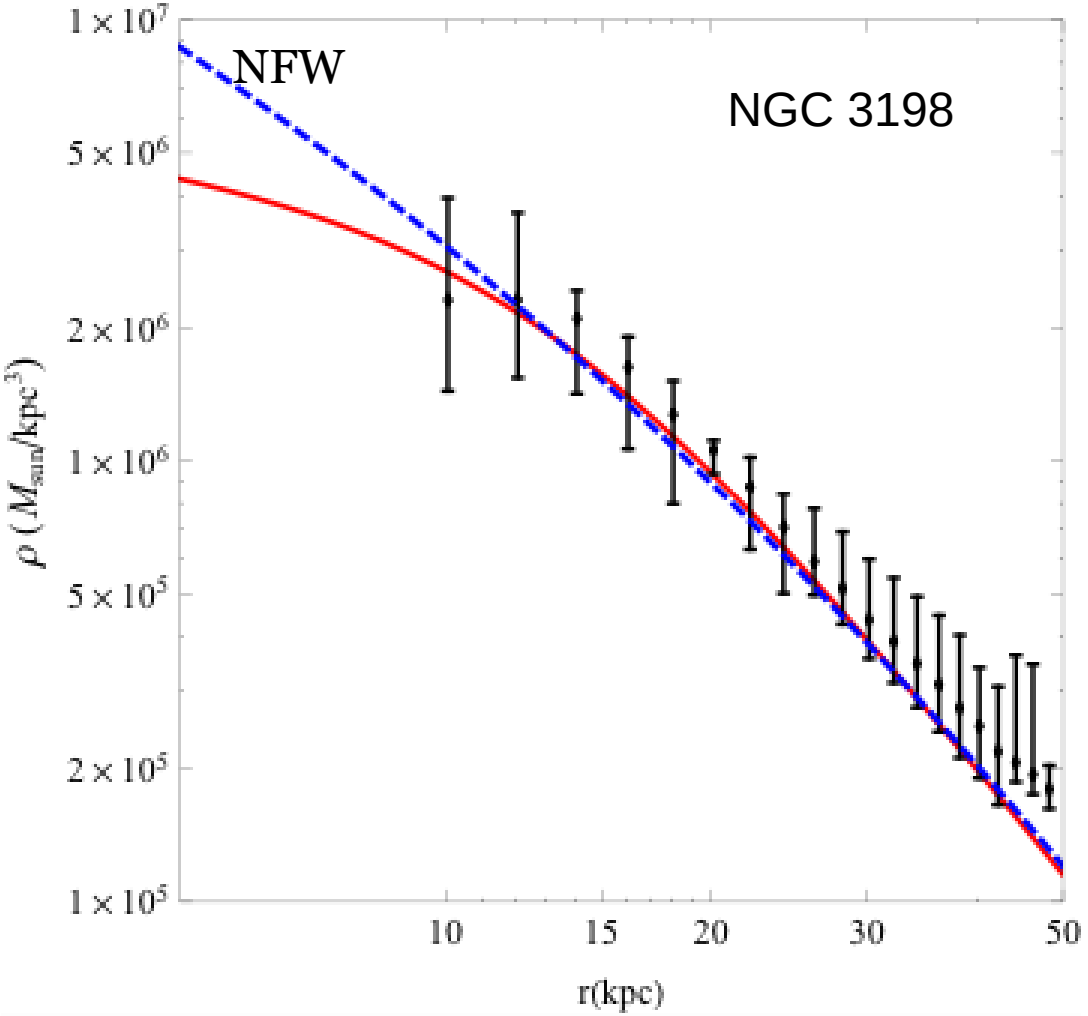


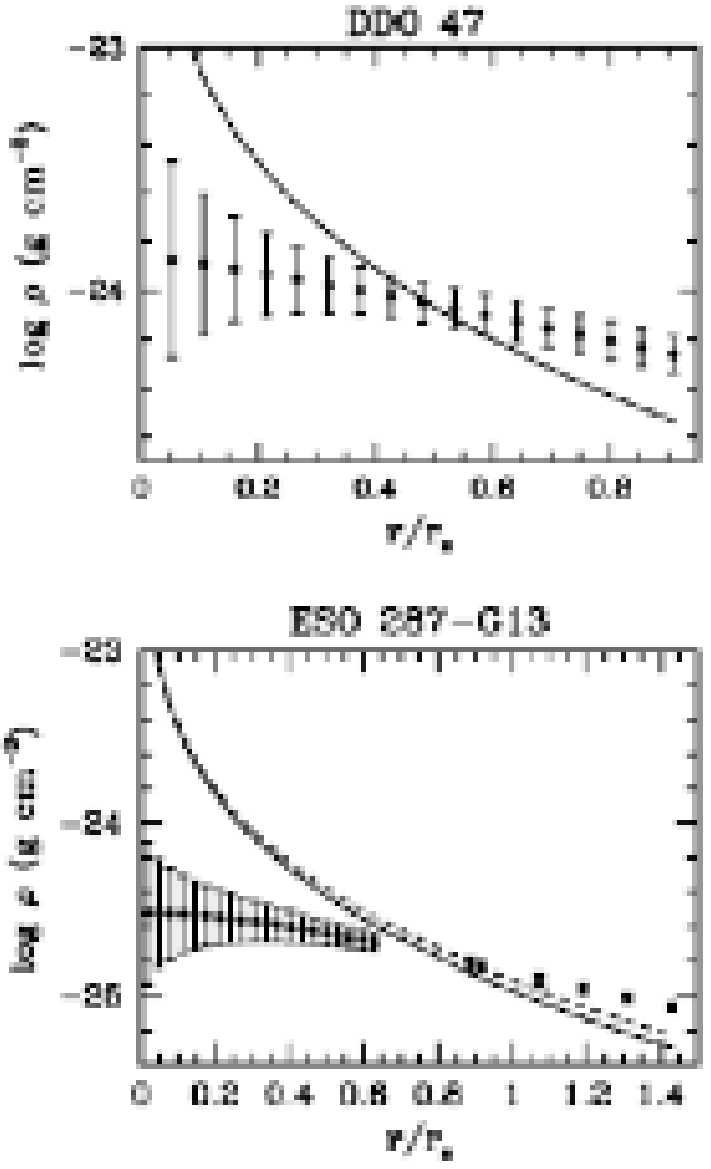
In progress

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

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

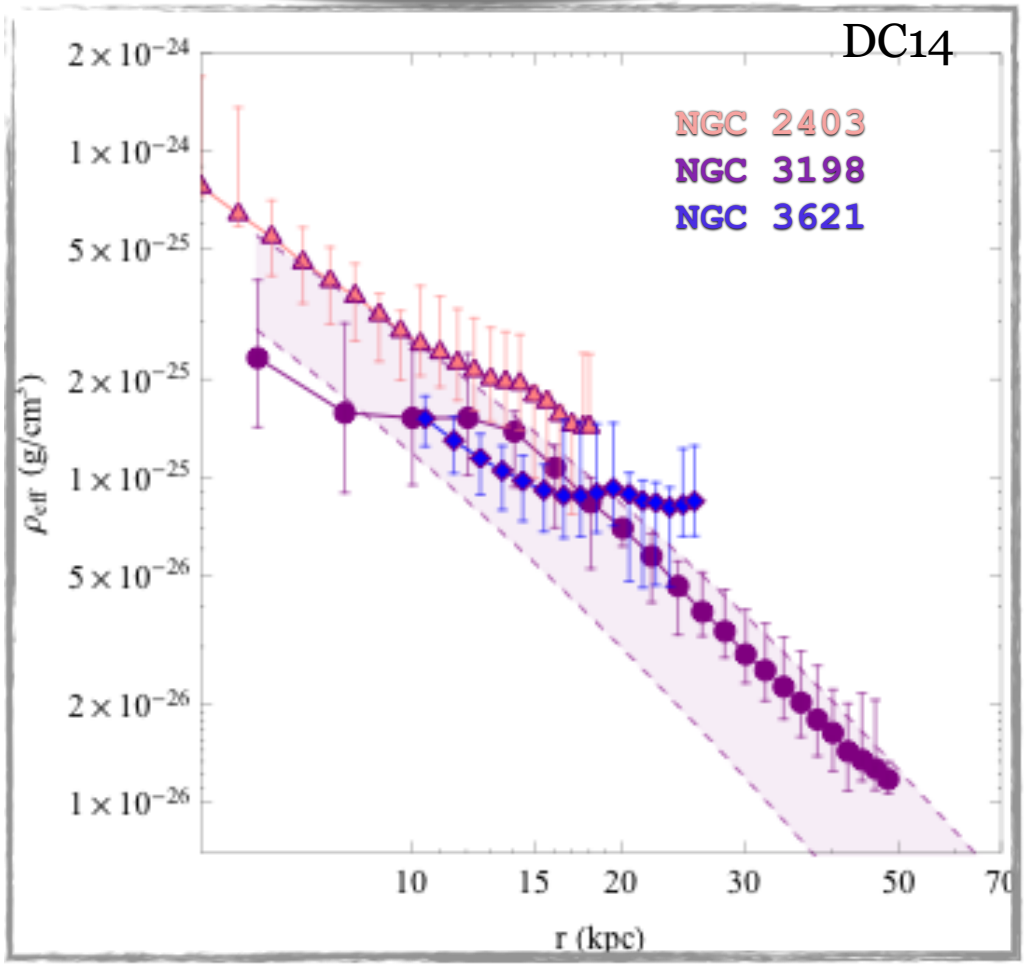
lazy densities



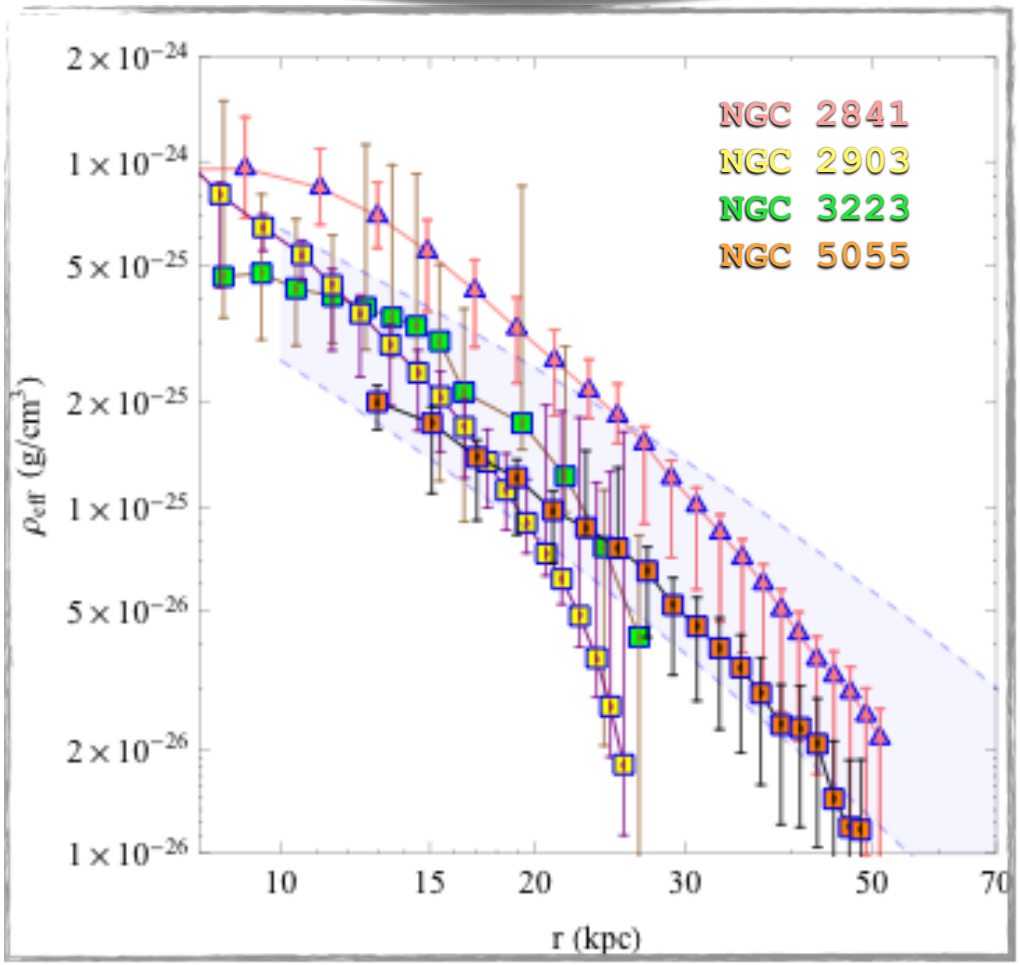


Gentile et al. 2007

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



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



Outer DM log densities profiles

NFW =LCDM = -2.4

OBSERVATIONS = -1.7,-3

WDM= ?

CONCLUSIONS

facts:

ALL *SPIRALS SHOW A FLAT CENTRAL DM DENSITY PROFILE*

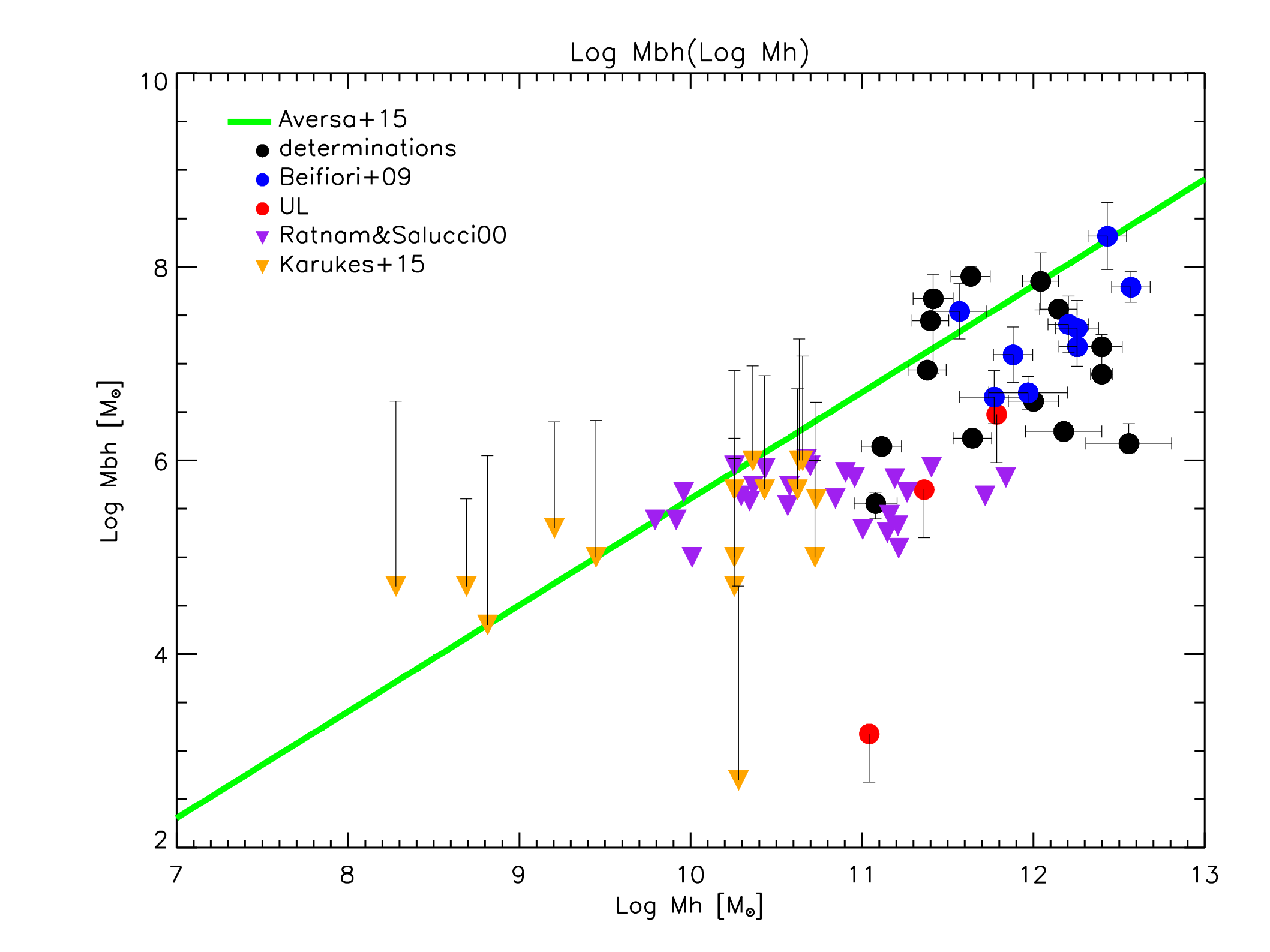
NFW MASS MODELS FAIL IN EVERY SPIRAL

WDM MASS MODELS OK

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

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).


Log Mbh(Log Mh)
Aversa+15
determinations
Beifiori+09
UL
Ratnam&Salucci00
Karukes+15
Log Mbh [M⊙]
Log Mh [M⊙]
10
8
6
4
2
7
8
9
10
11
12
13