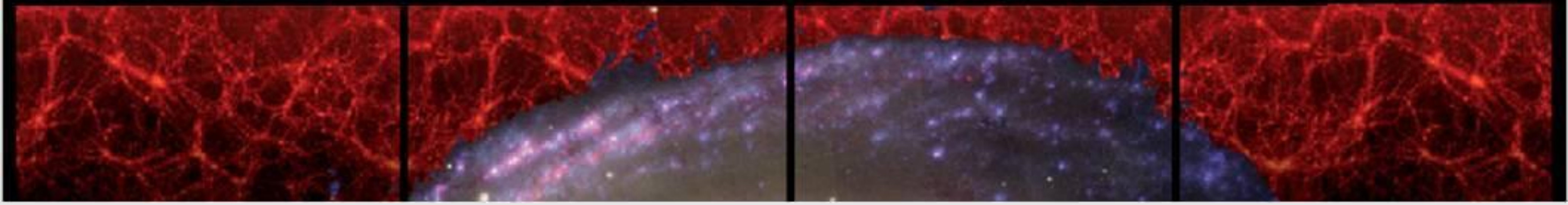


Structural properties of Galaxies and Cored Density Profiles from Galaxy Observations

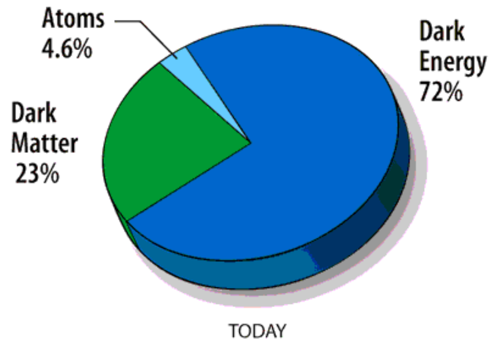
PAOLO SALUCCI

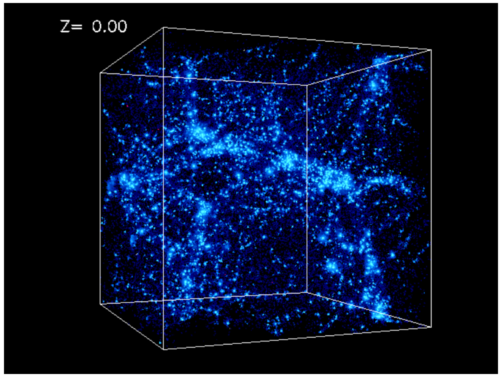
SISSA

Ecole Internationale Daniel Chalonge
Workshop CIAS Meudon 8-10/6/2011

Outline

Dark Matter: main protagonist in Cosmology, change of paradigm?



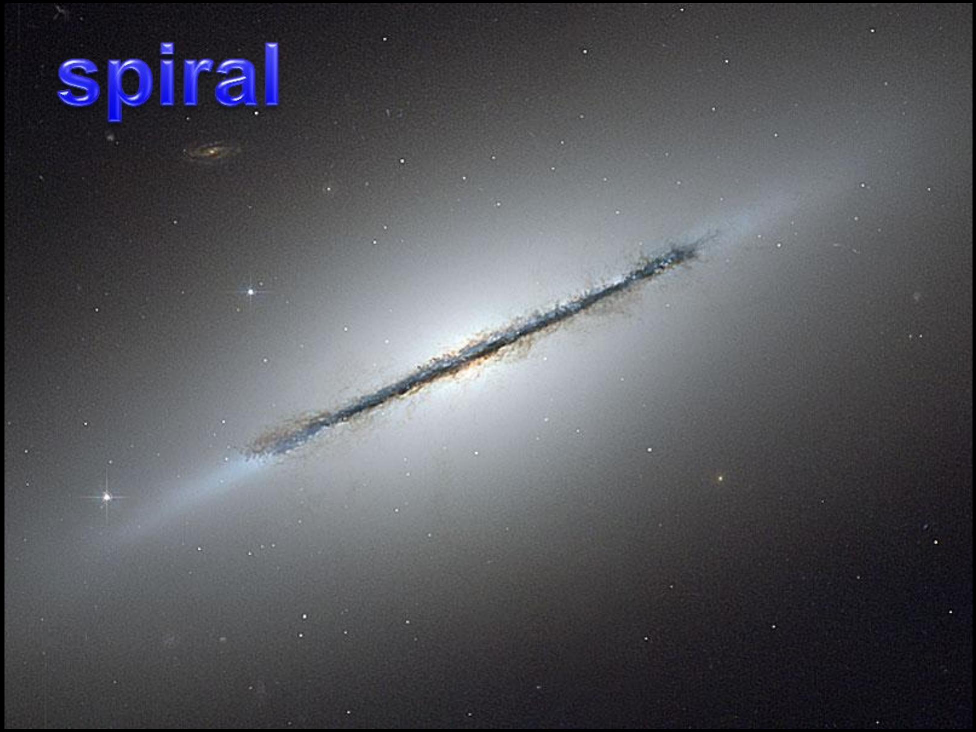


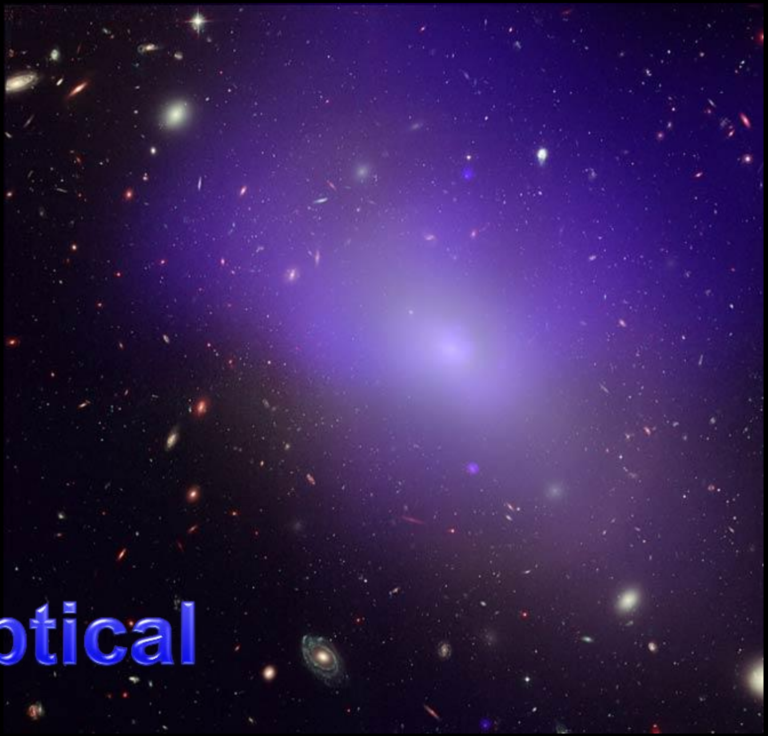
This lecture focus: Dark Matter distribution in Galaxies

The concept of Dark Matter in virialized objects

Dark Matter in Spirals, Ellipticals, dSph

Phenomenology of the mass distribution in Galaxies and theorethical predictions



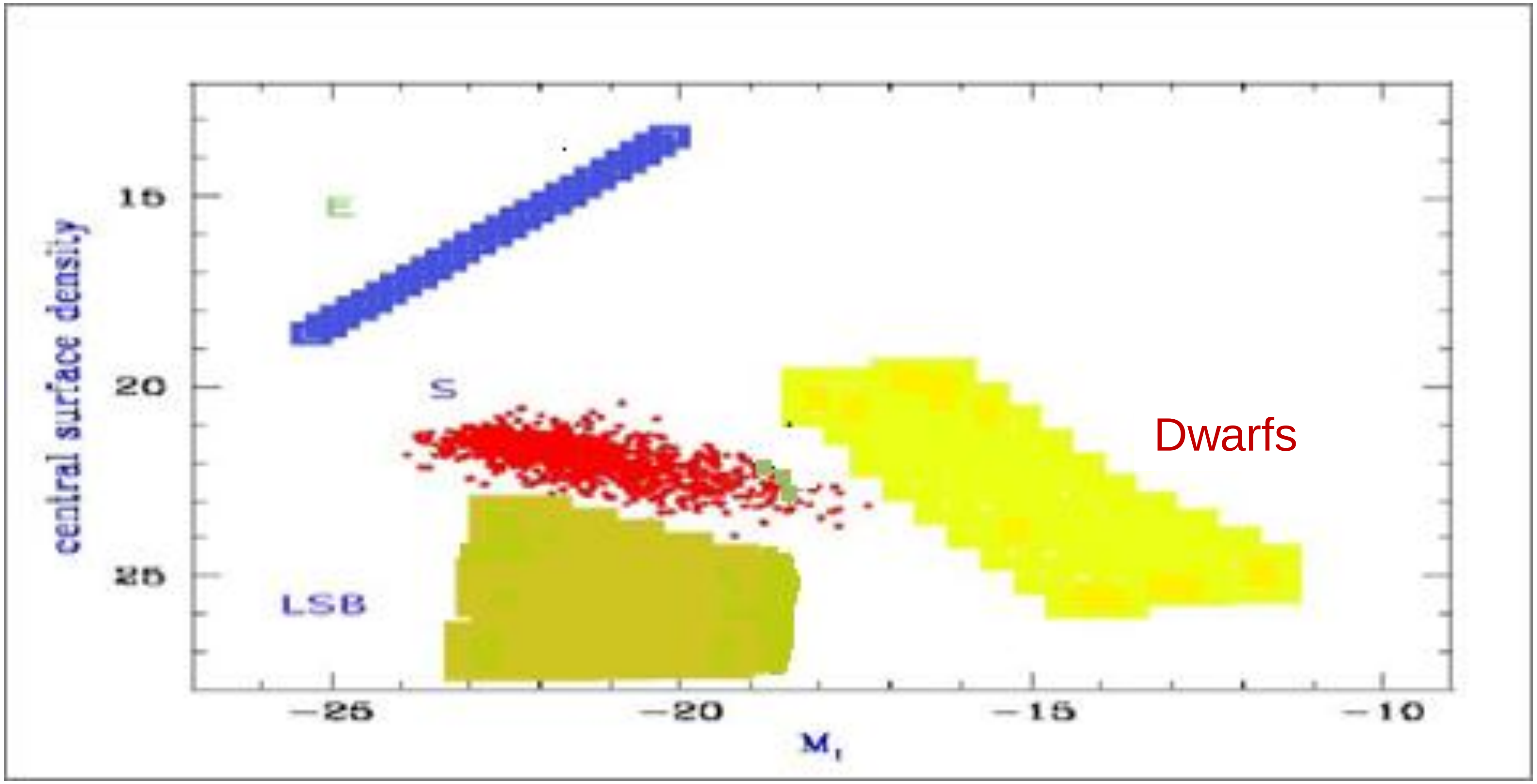


3 MAJOR TYPES OF GALAXIES

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 **observed**

The DM phenomenon can be investigated only if we **accurately** meausure the distribution of:

Luminous matter $M_L(r)$.
Gravitating matter M(r)

THEORY AND SIMULATIONS

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).

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

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

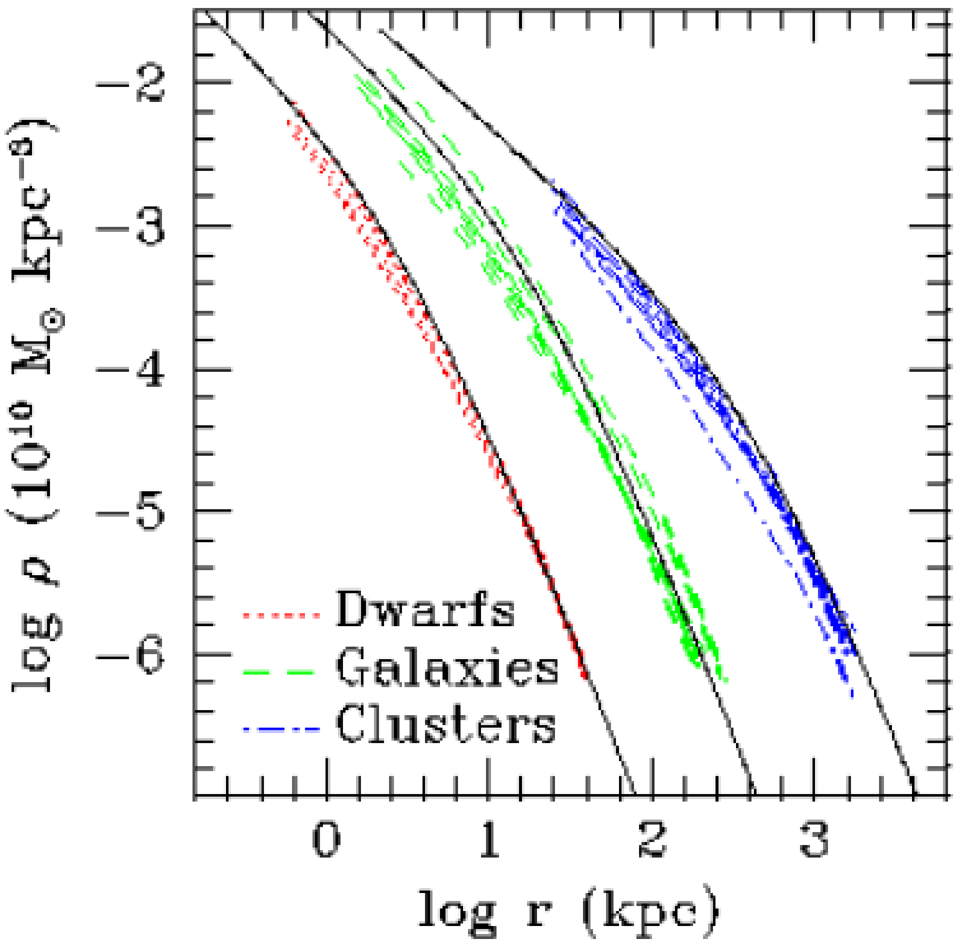
More massive halos and those formed earlier have larger overdensities

Today mean halo density inside

R_{vir} = 100 ϱ_c

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

Klypin, 2010

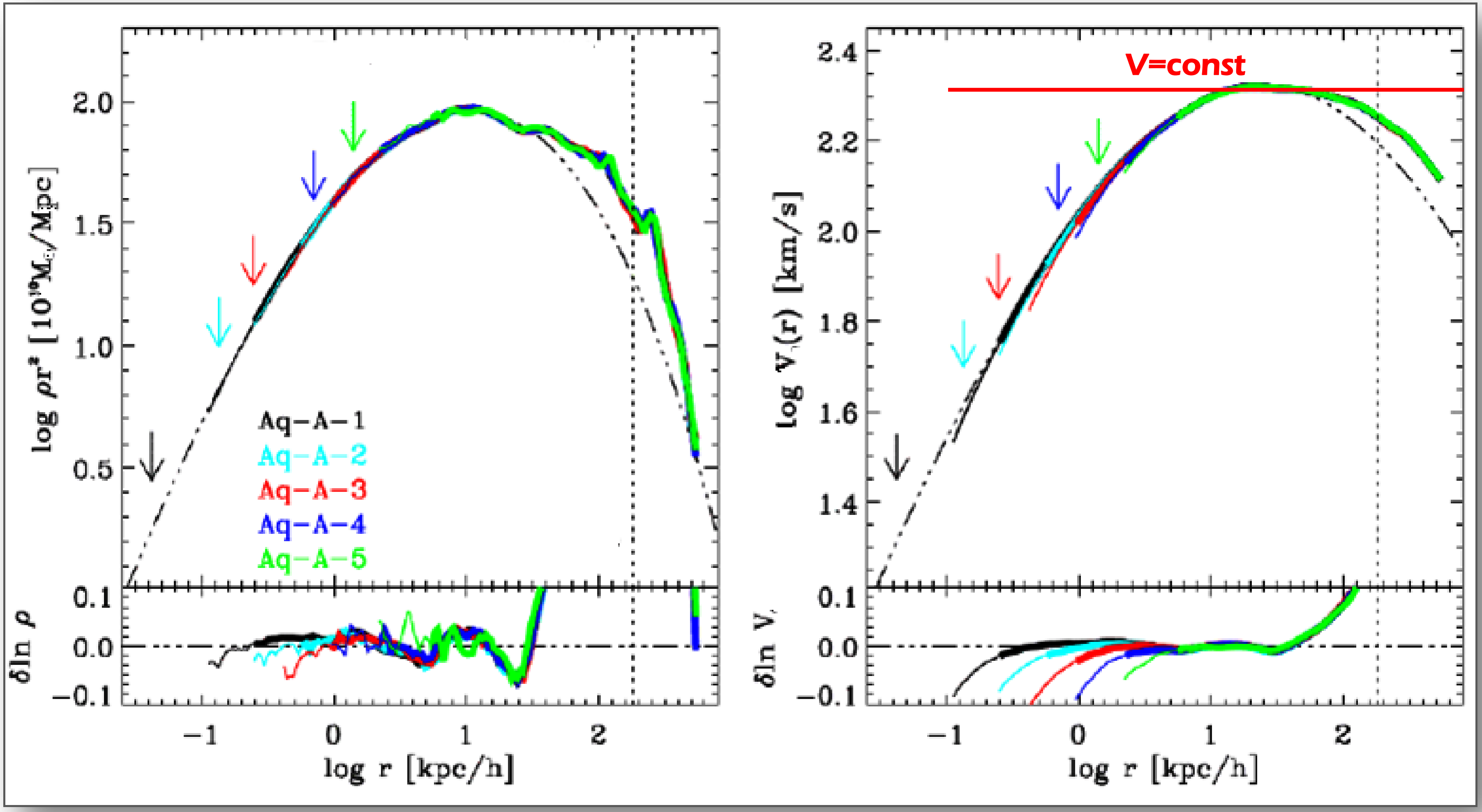


Aquarius N-Body simulations, highest mass resolution to date.

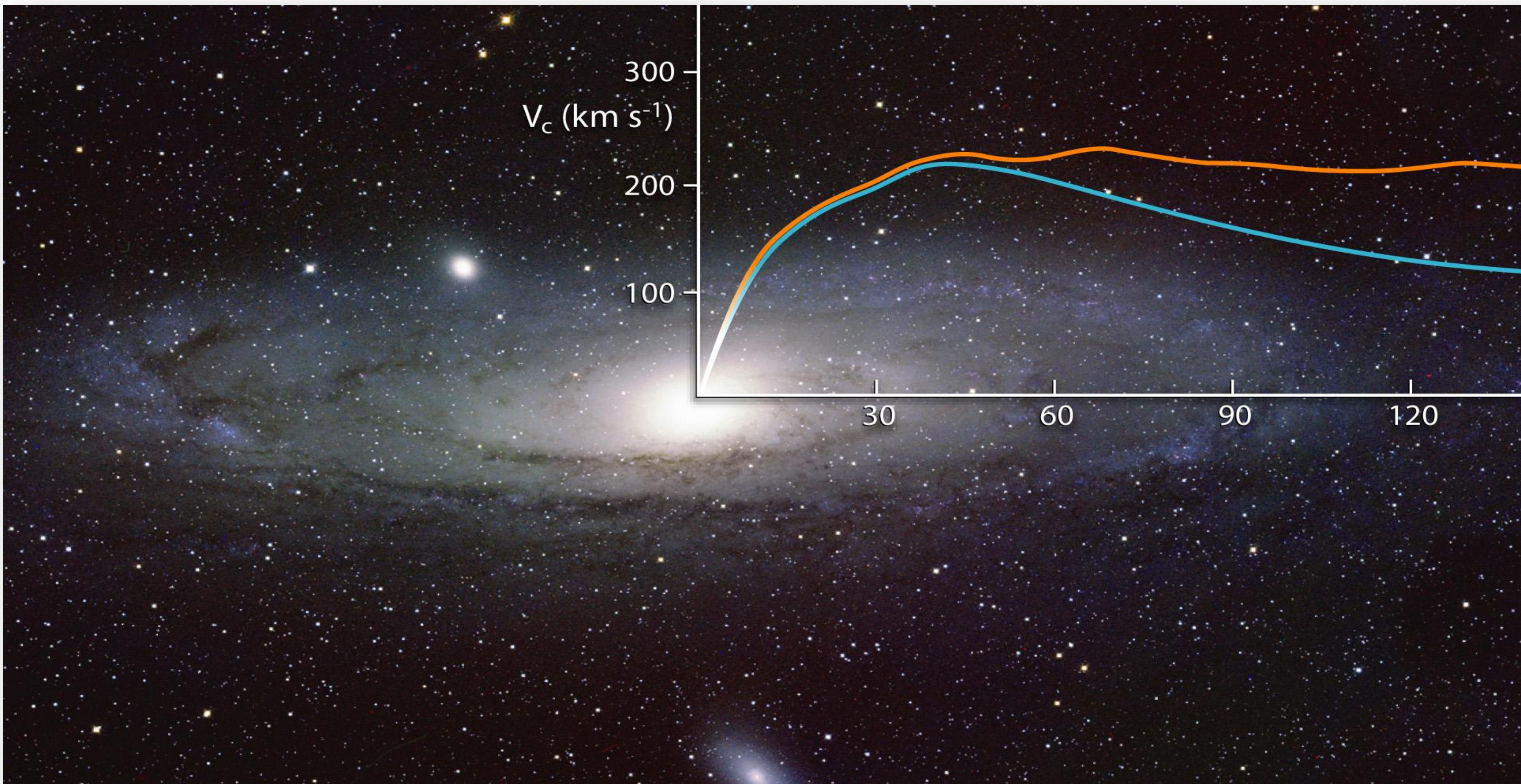
Density: central cusp $\rho \approx r^{-1}$, *asymptotically*: $\rho \approx r^{-2.5}$

Navarro et al +10

density circular velocity



SPIRALS



Stellar Disks

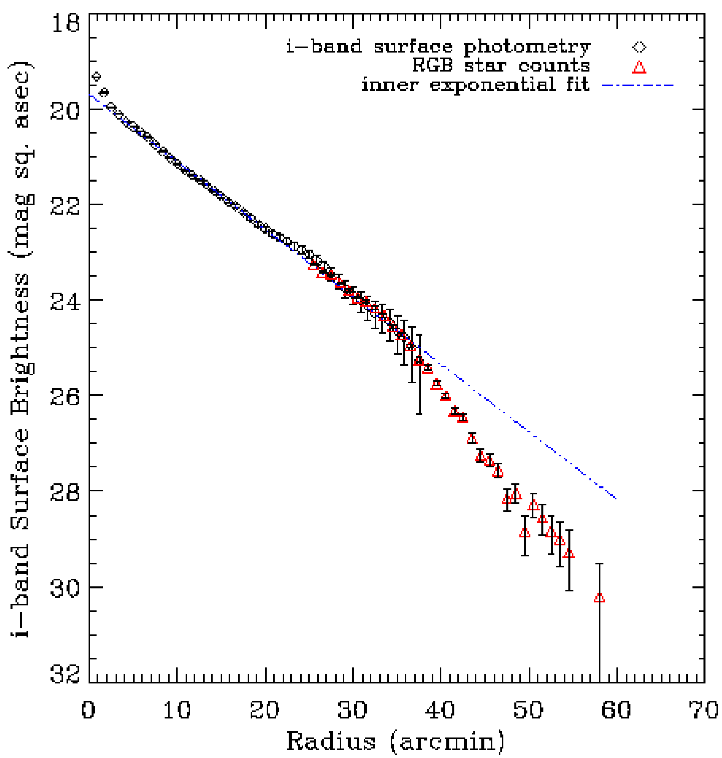
M33 disk very smooth,
truncated at 4 scale-lengths

NGC 300 exponential disk
for at least 10 scale-lengths

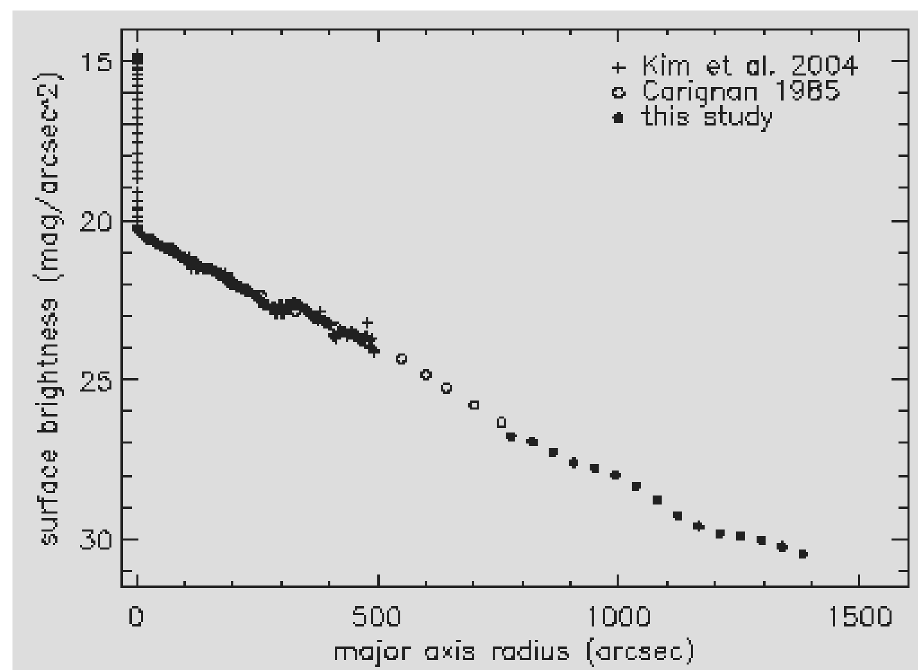
$$I(r) = I_0 e^{-r/R_D}$$

R_D lenght scale of the disk

Freeman, 1970



Ferguson et al 2003



Bland-Hawthorn et al 2005

Gas surface densities

HI

Flattish radial distribution

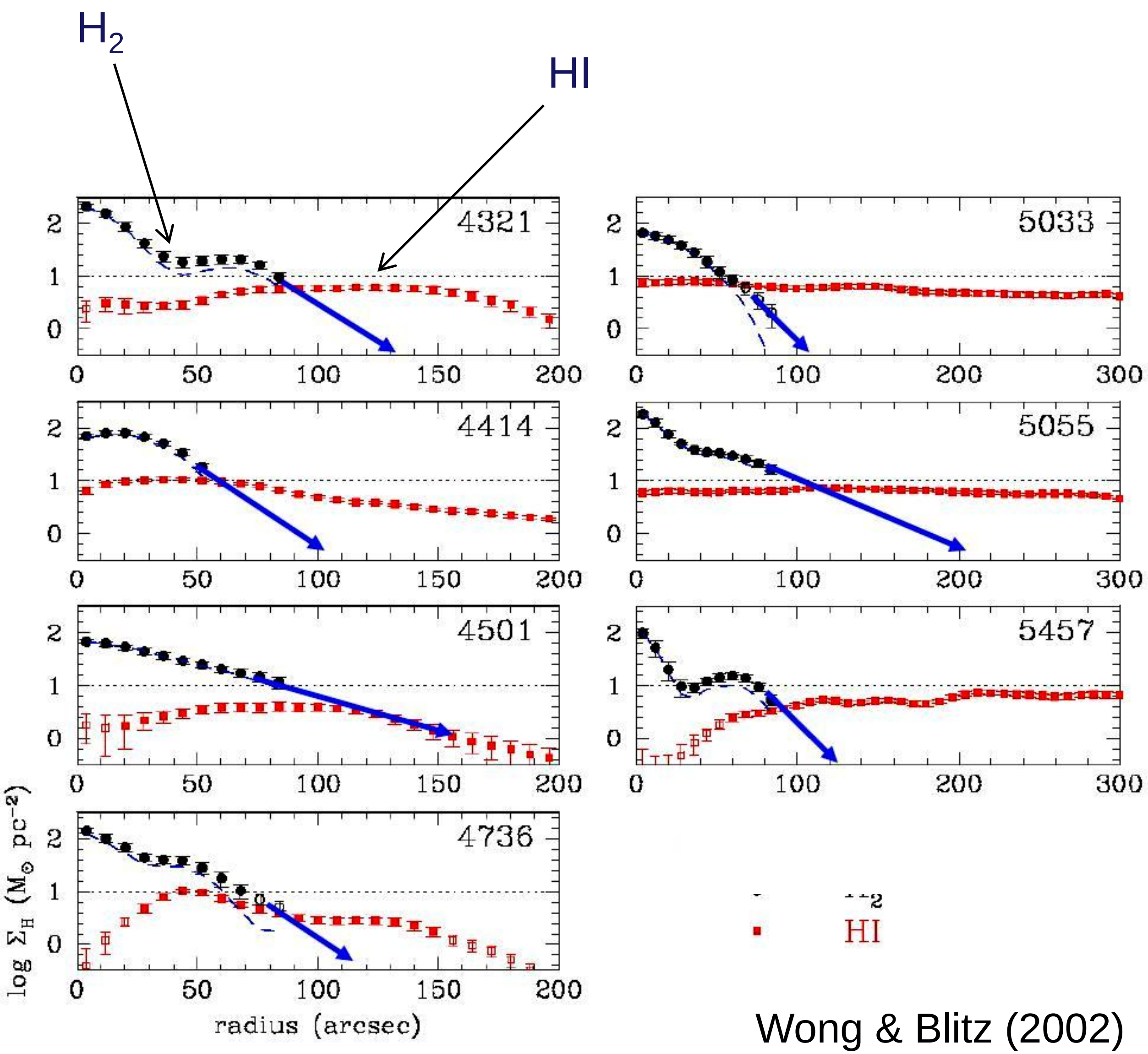
Deficiency in the centre

Extended to (8 – 40) R_D

H_2

Follows the stellar disk

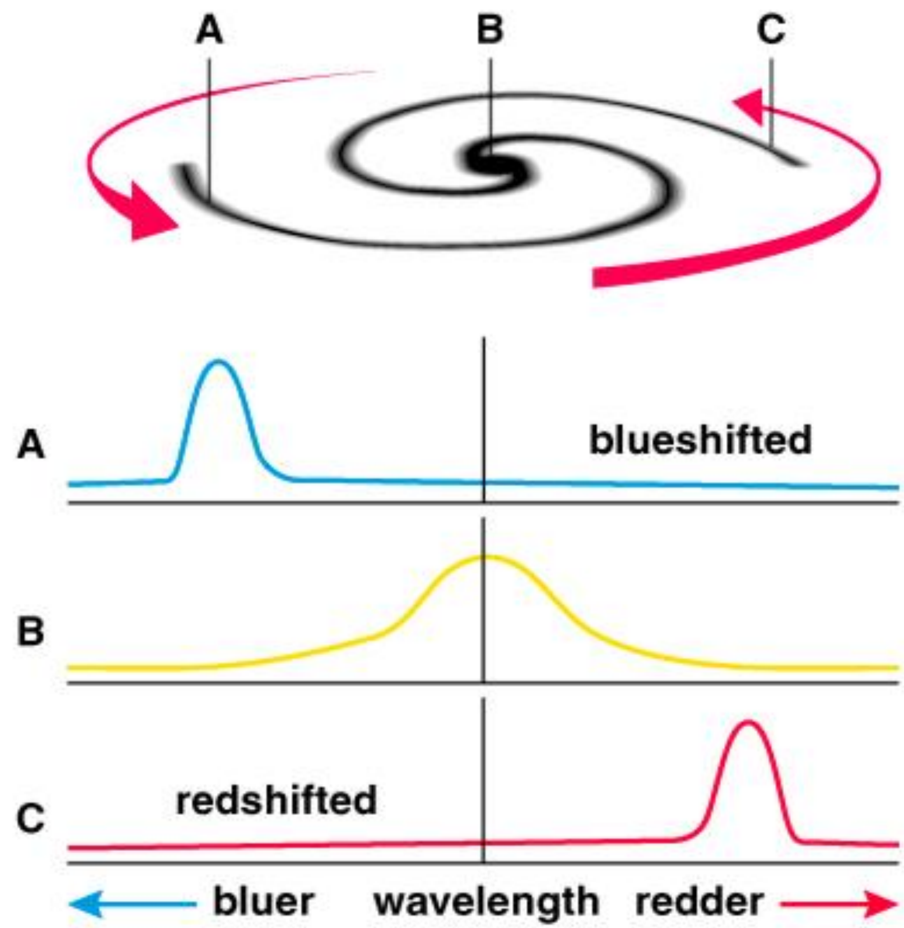
Negligible

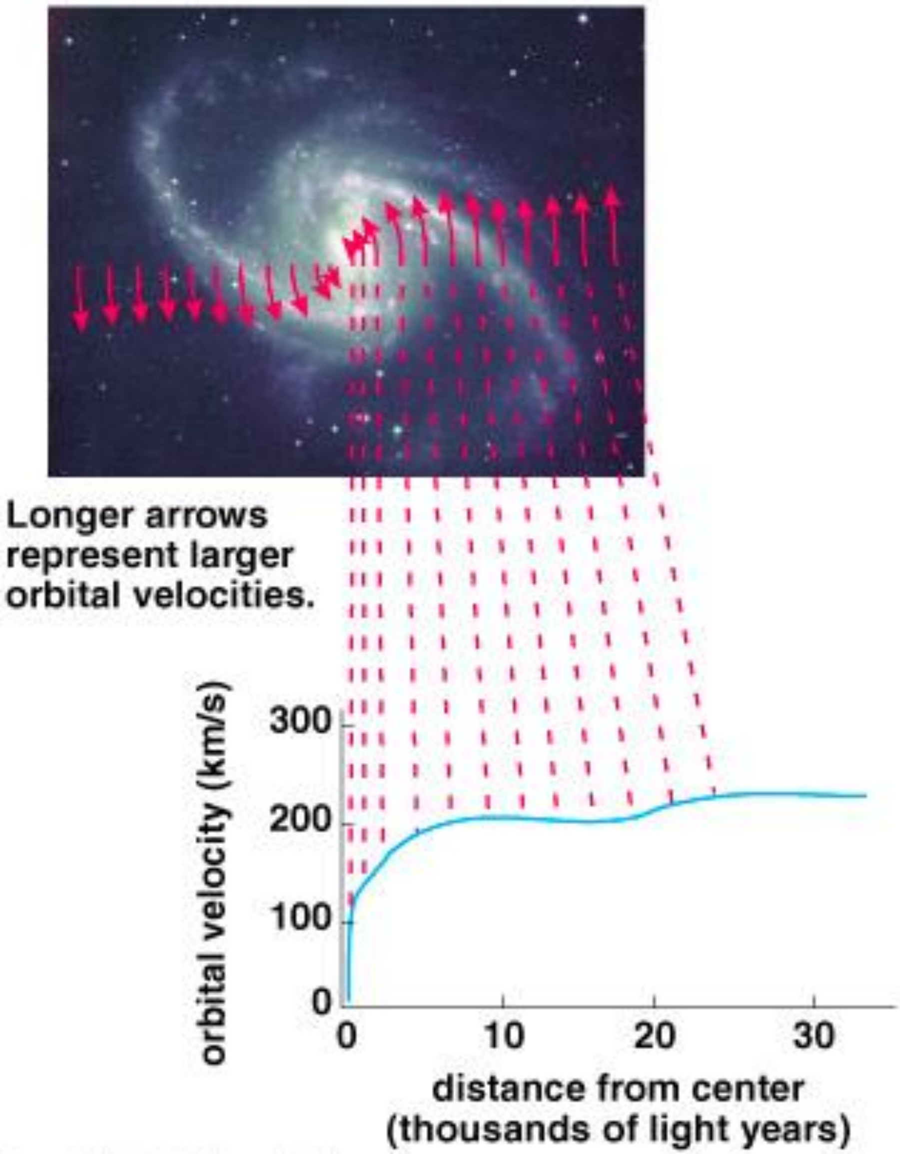


Wong & Blitz (2002)

ROTATION CURVES

artist impression

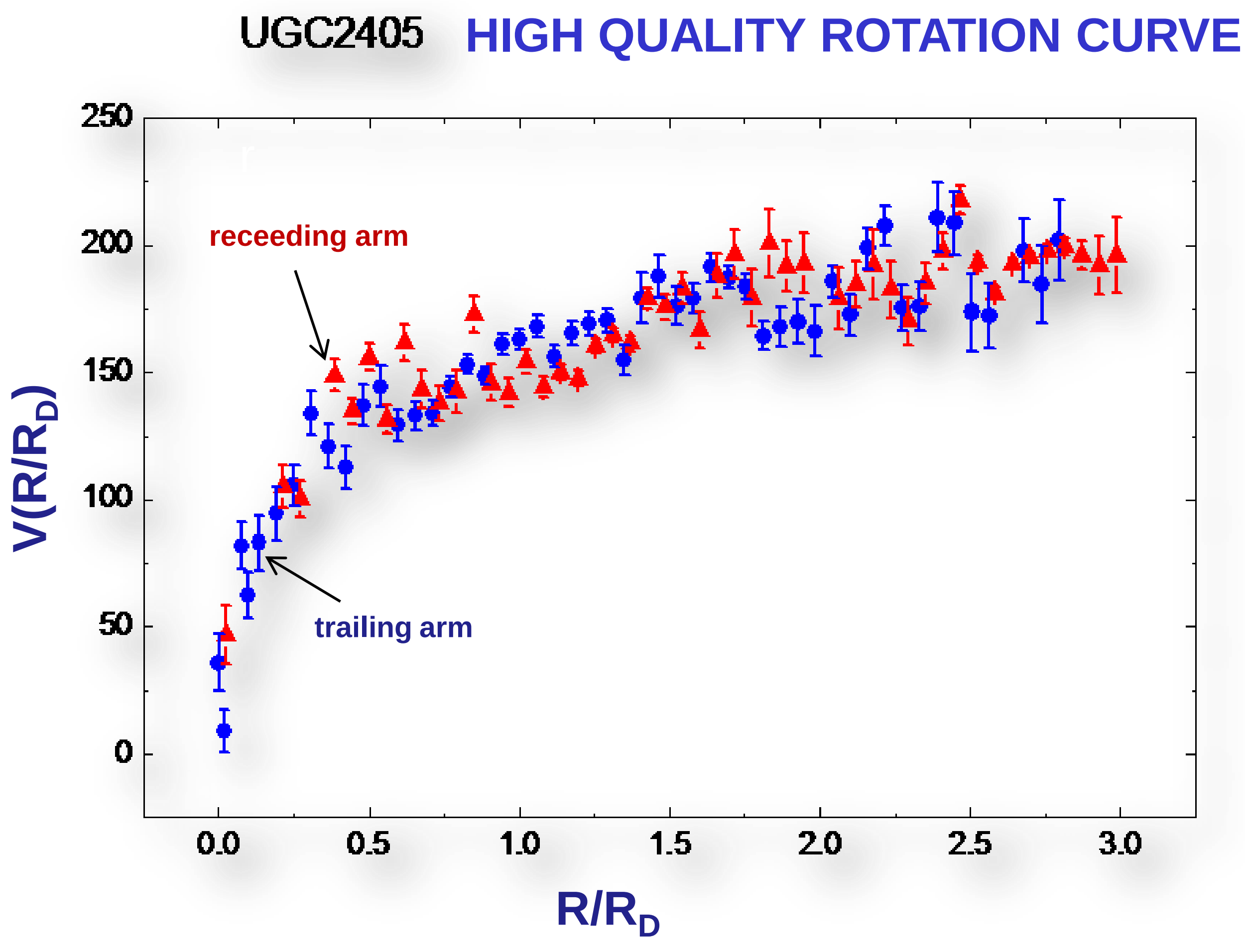




artist impression

Symmetric circular rotation of a disk characterized by

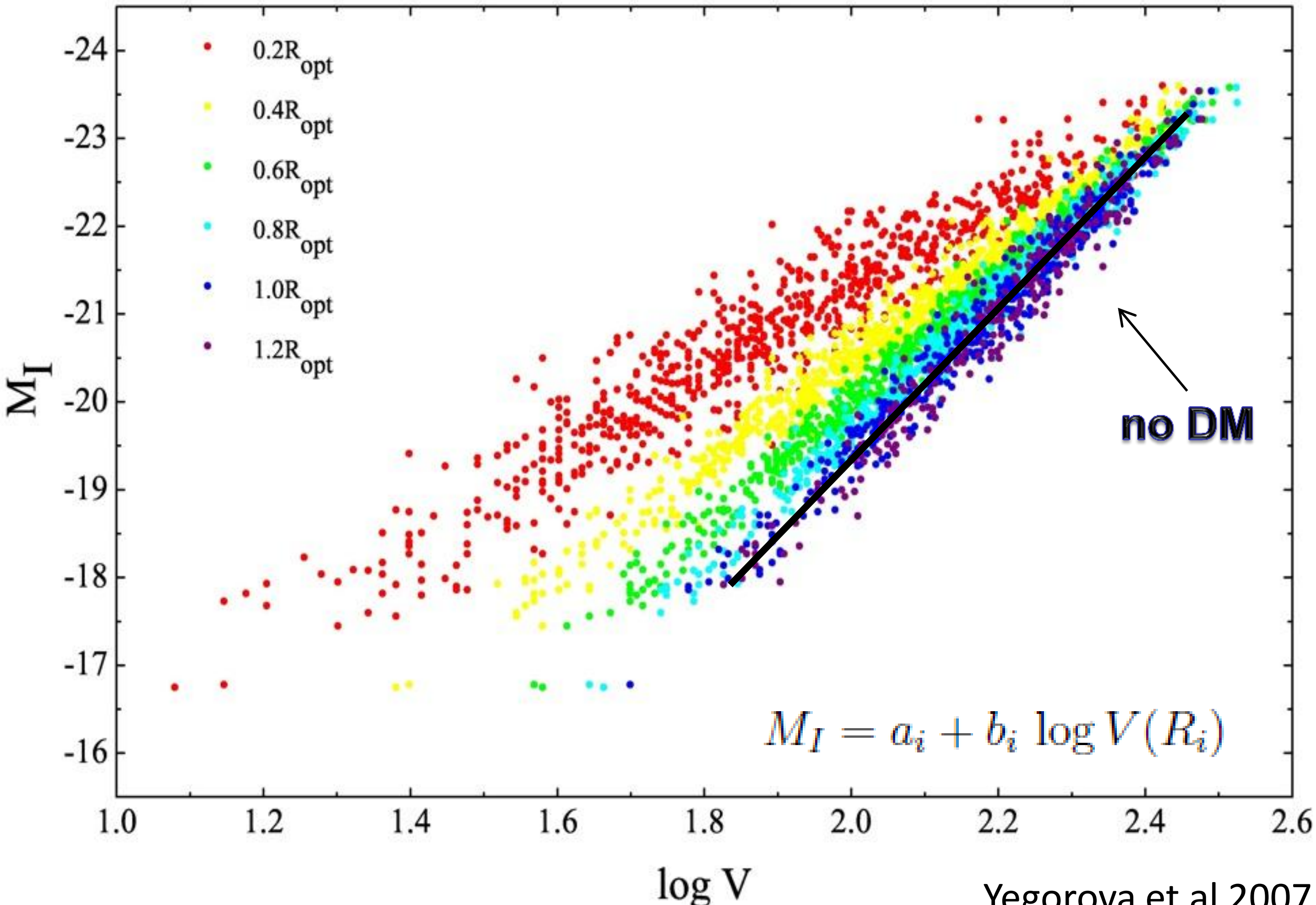
- Sky coordinates of the galaxy centre
- Systemic velocity $\boldsymbol{V_{sys}}$
- Circular velocity ***V(R)***
- Inclination angle



Evidence for a Mass Discrepancy in Galaxies

The distribution of gravitating matter, unlike the luminous one, is luminosity dependent.

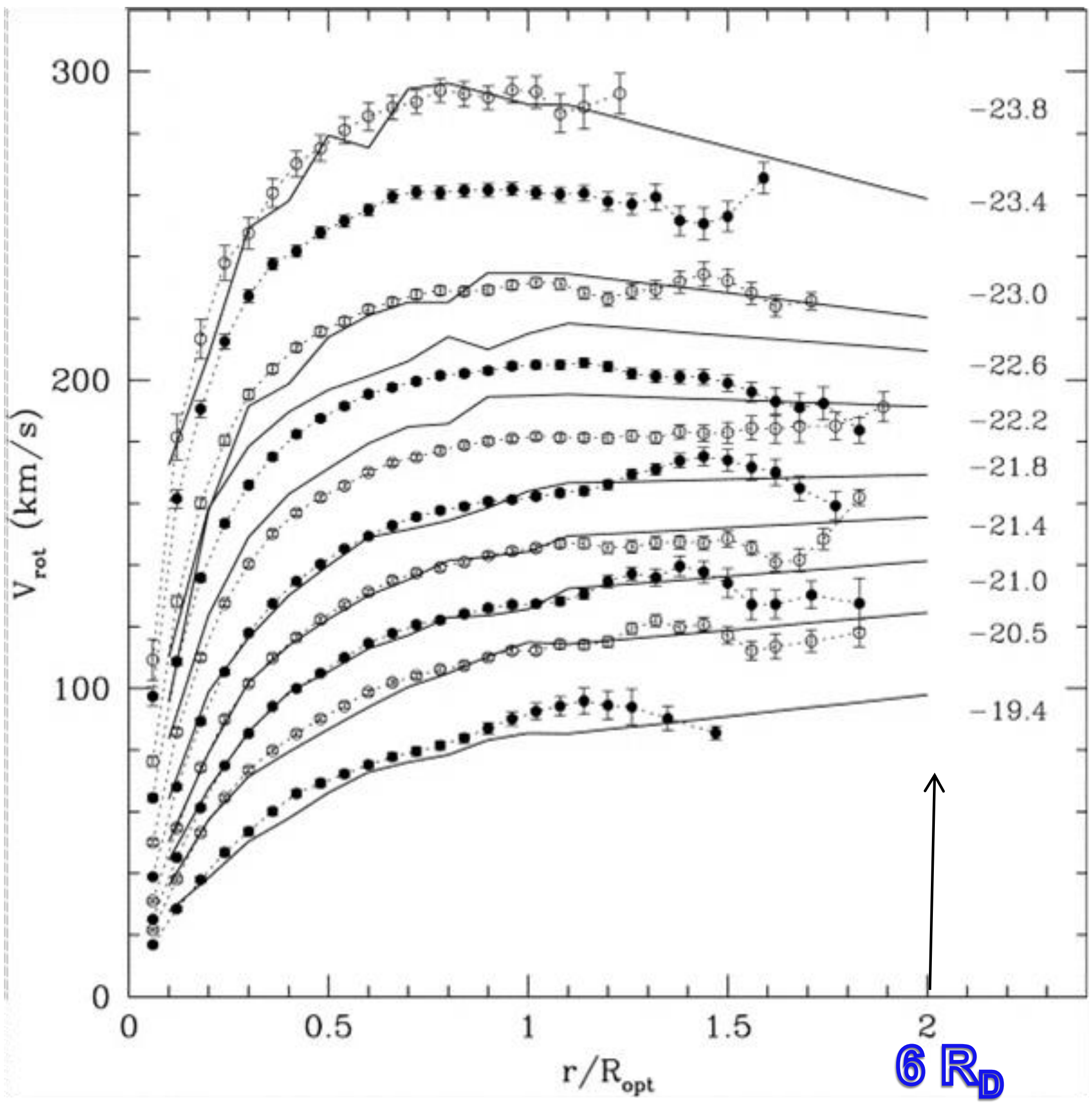
Tully-Fisher relation exists at local level (radii R_i)



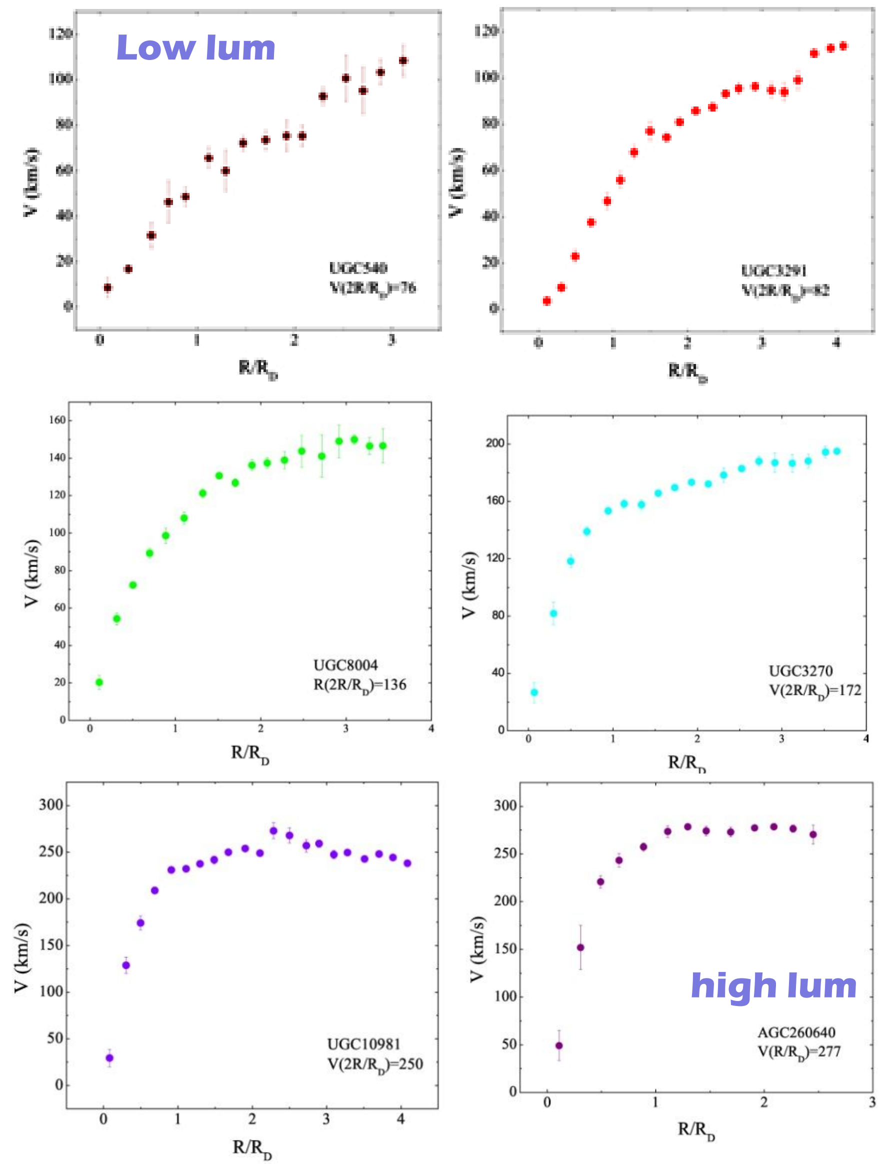
Yegorova et al 2007

Rotation Curves

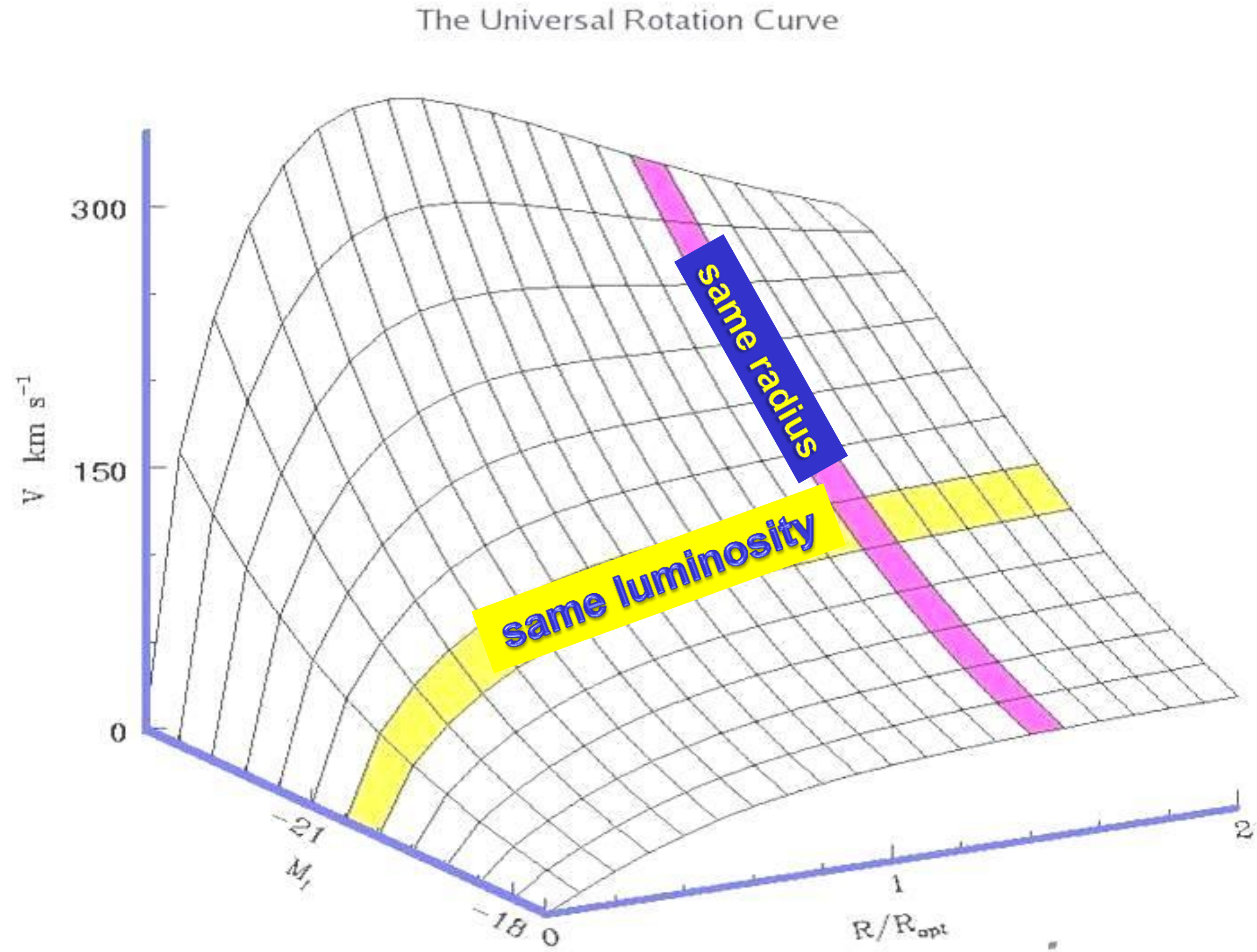
Coadded from 3200 individual RCs



TYPICAL INDIVIDUAL RCs SHOWN BY INCREASING LUMINOSITY

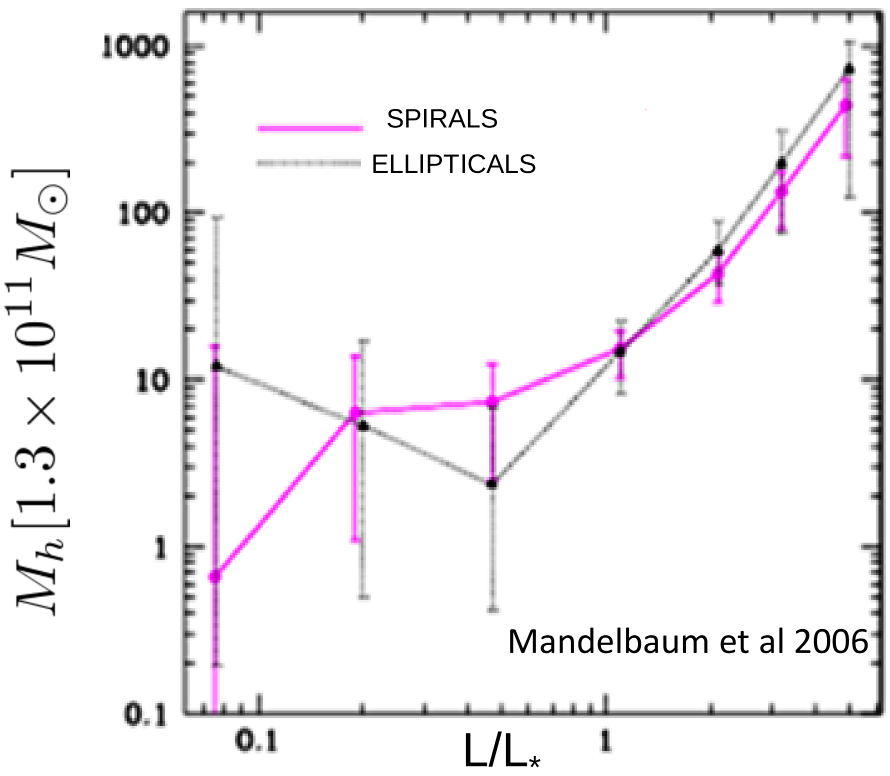


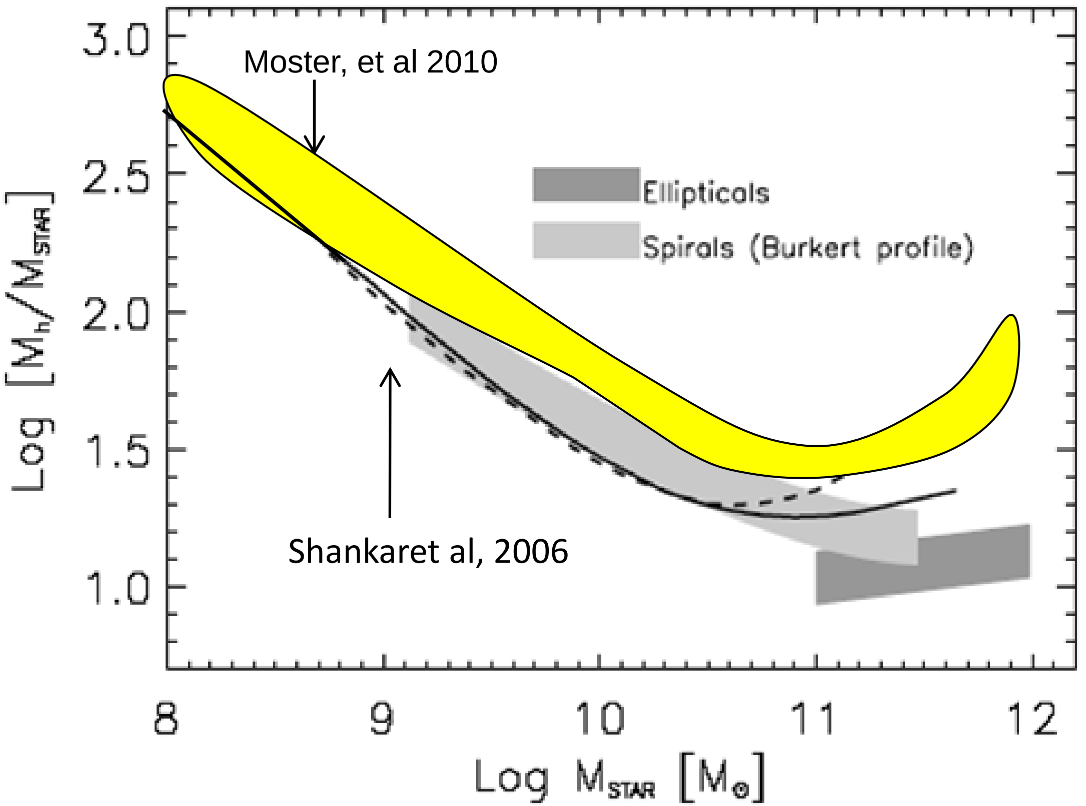
The Cosmic Variance of V measured in galaxies of same luminosity L at the same radius x=R/R_D is negligible compared to the variations that V shows as x and L varies.



Universal Rotation Curve out to the Virial Radius

Method: inner kinematics + independent determinations of halo virial masses



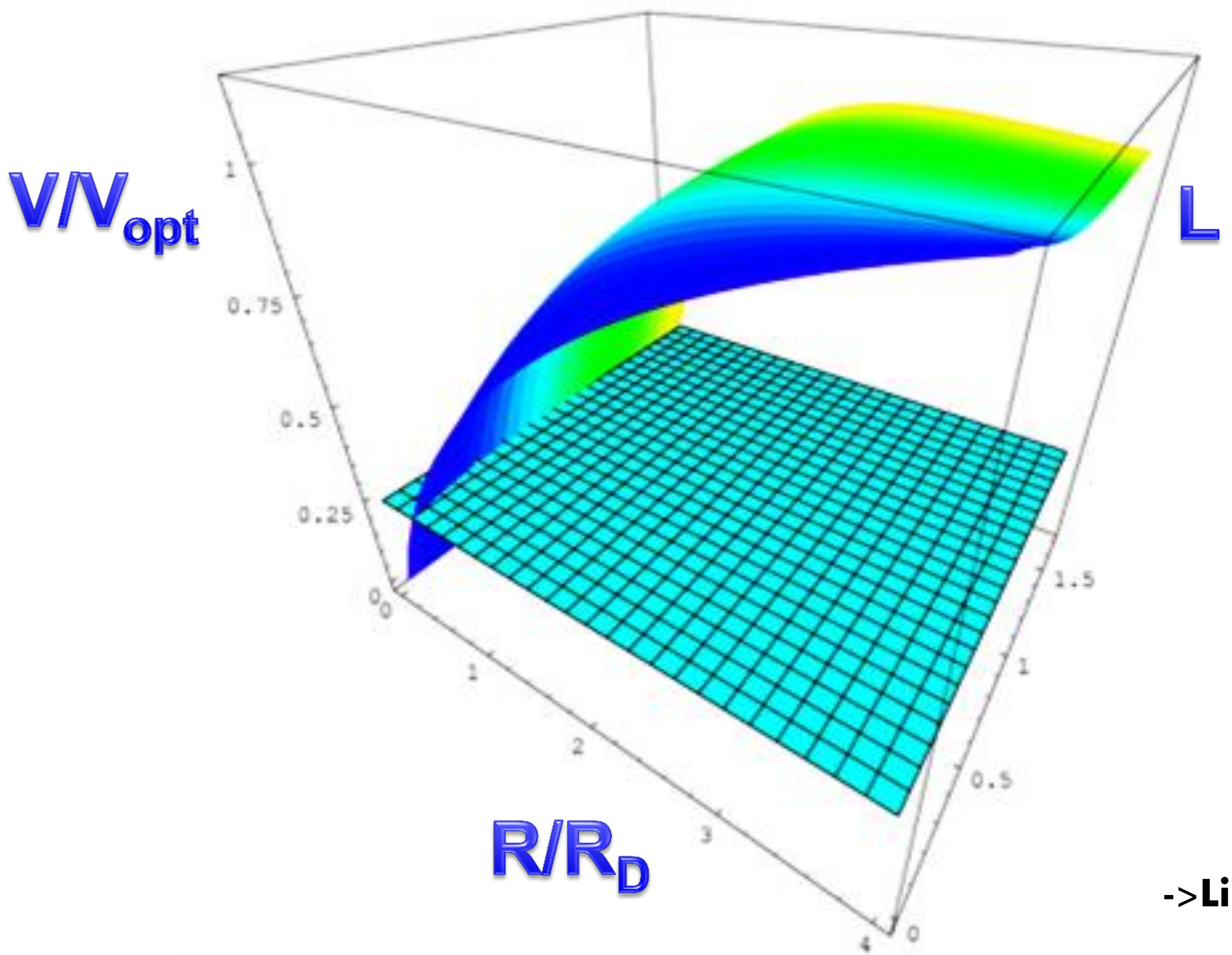


Virial masses M_h of halos around galaxies with stellar mass M_{STAR} (or luminosity L) are obtained

- directly by weak-lensing analysis *(left)*
- indirectly by correlating *dN/dL* with theoretical DM halo *dN/dM (right)*

The Concept of the Universal Rotation Curve (URC)

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



->Link to Movie 2

The URC out to 6 R_D is derived directly from observations
Extrapolation of URC out to virial radius by using V(R_{vir})

Rotation curve analysis

From data to mass models

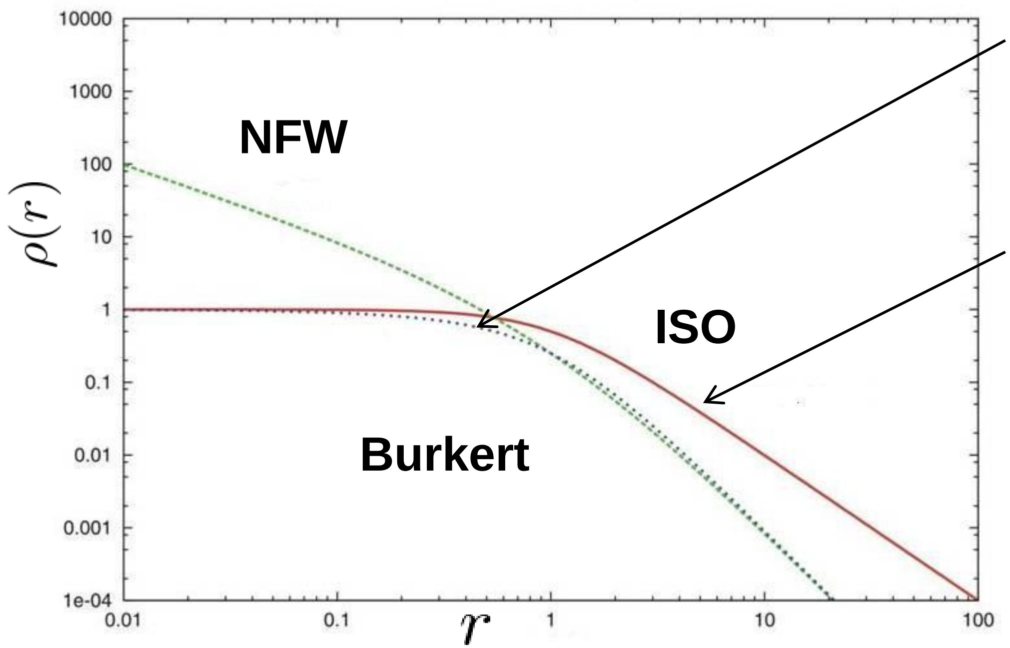
$$V^2(R) = V^2_{halo}(R) + V^2_{HI}(R) + V^2_{disk}(R)$$

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)

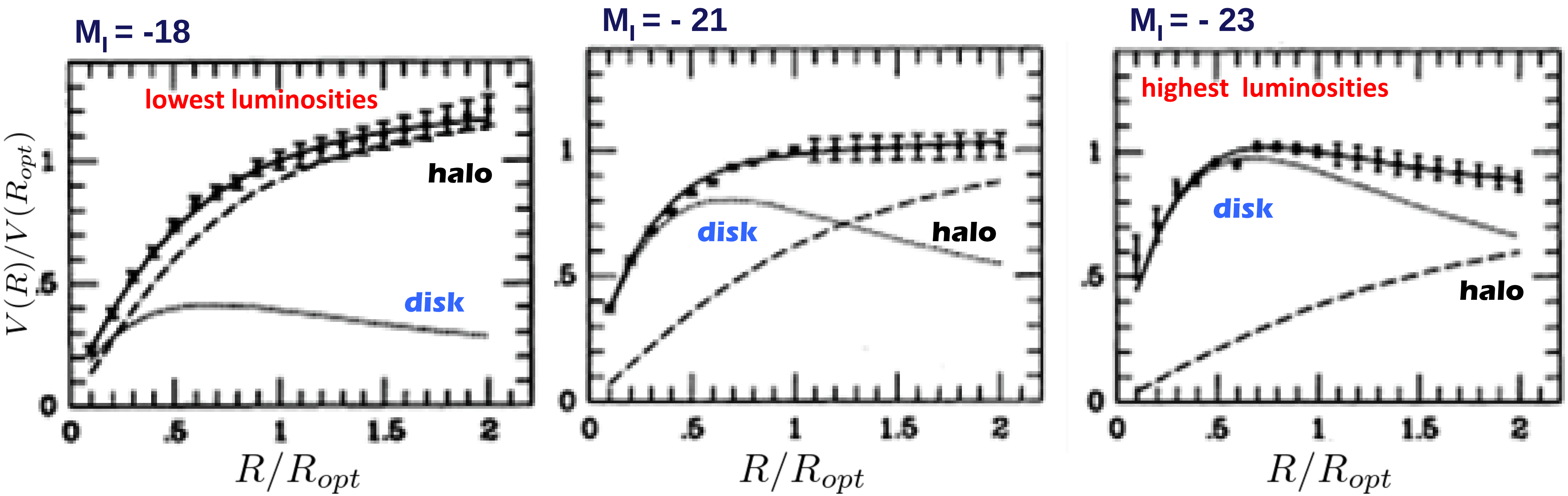


$$\rho(r) = \frac{\rho_0}{(1 + r/r_0)(1 + (r/r_0)^2)}$$

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

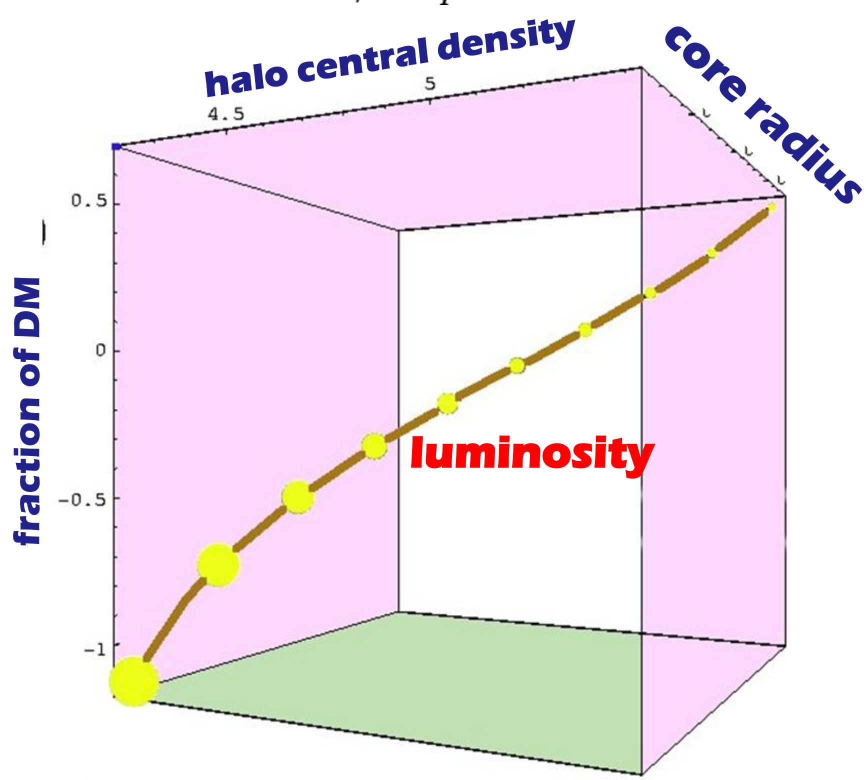
The mass model has 3 free parameters:
disk mass
halo central density
Halo core radius (length-scale)
Obtained by best fitting method

MASS MODELLING RESULTS



All structural DM and LM parameters are related with luminosity.

Smaller galaxies are denser and have a higher proportion of dark matter.

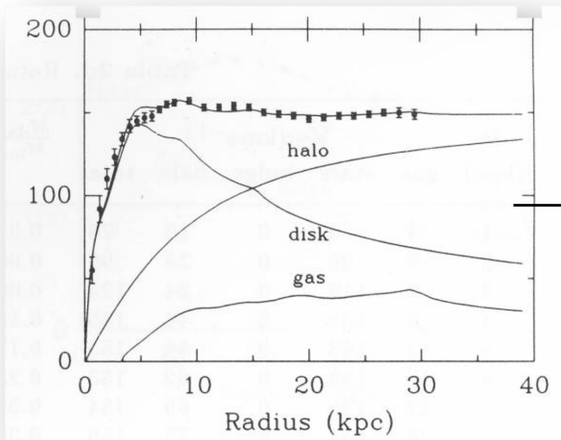


MASS MODELLING INDIVIDUAL OBJECTS

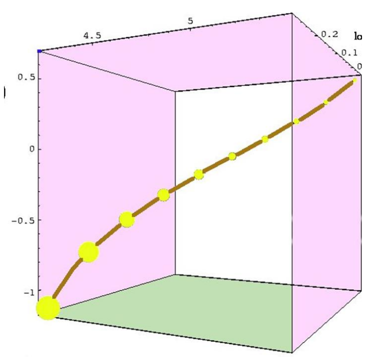
Dark Halo Scaling Laws in Spirals

Careful derivation of halo structural parameters (ρ_0, r_0)

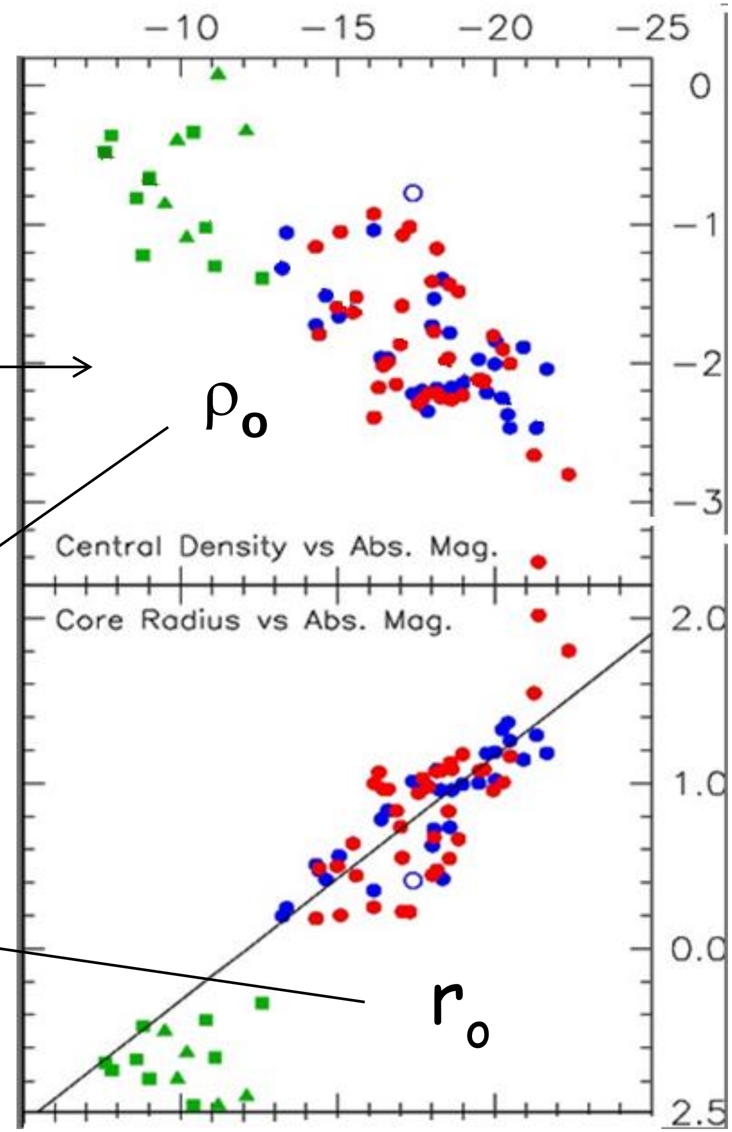
- **Assumption: Maximun Disk**
- **the <u>slope</u> of the halo contribution gives the halo central density**
- **extended RC provides the estimate of halo core radius r_0**



URC



$$\rho_o \sim L_I^{-0.7} \qquad \rho_o \sim L_B^{-0.6}$$
$$r_o \sim L_I^{0.7} \qquad r_o \sim L_B^{0.6}$$

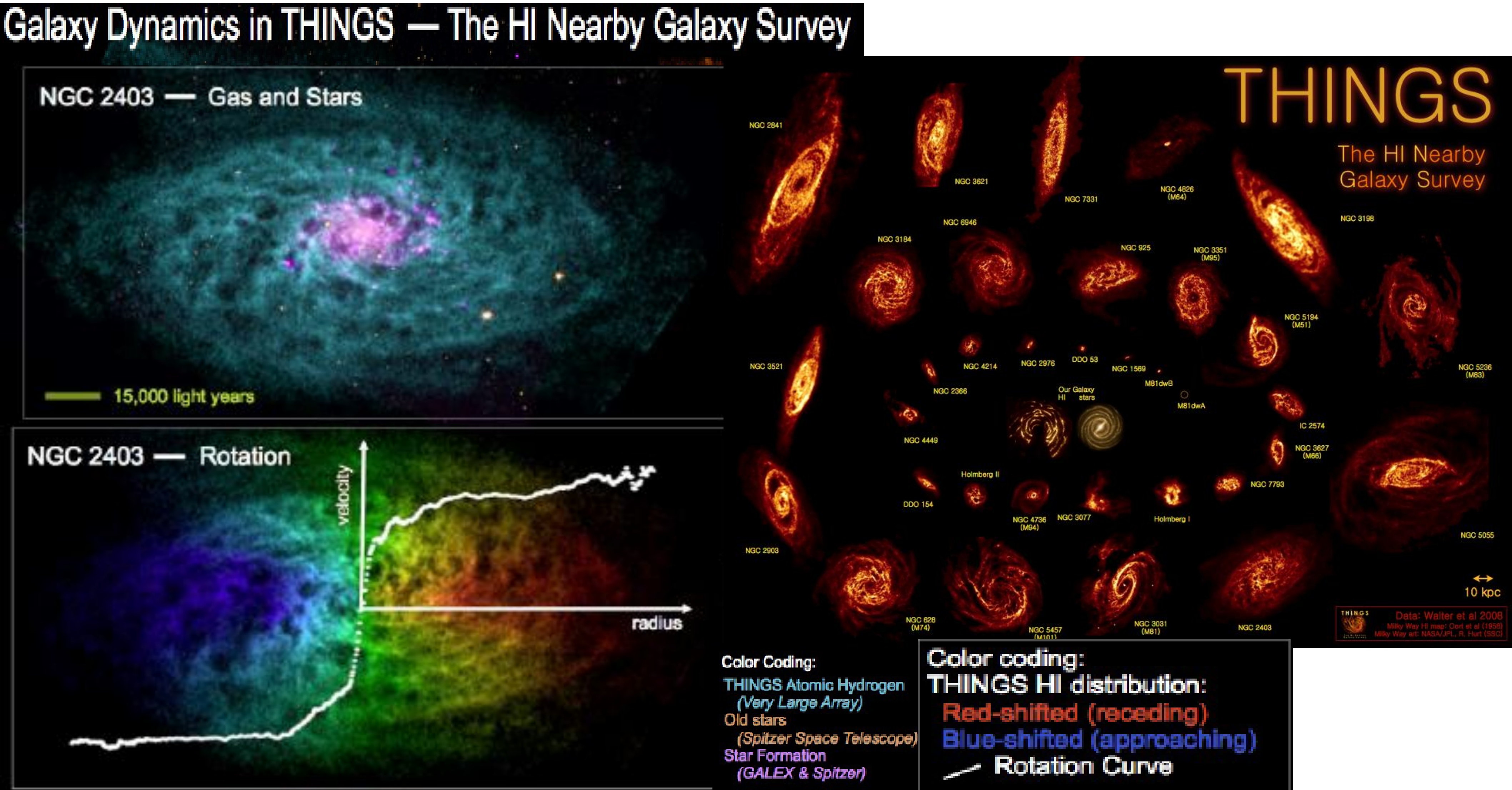


Kormendy & Freeman (2004)

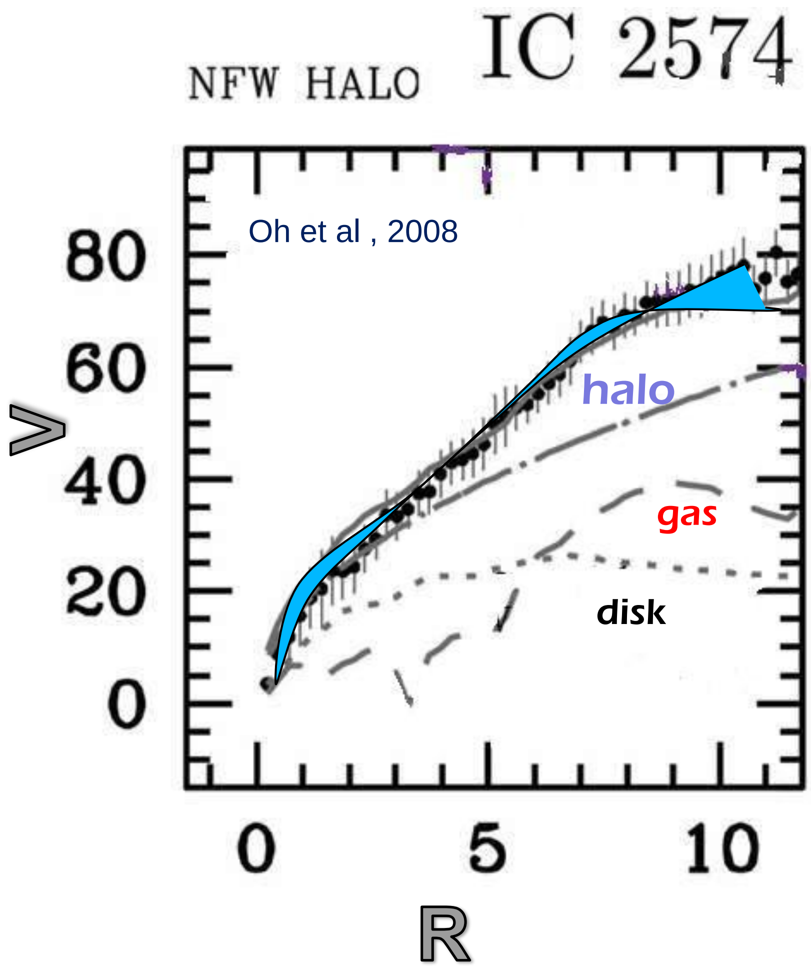
The distribution of DM around spirals

Individual objects **Gentile+ 2004, de Blok+ 2008 Kuzio de Naray+ 2008, Oh+ 2008, Spano+ 2008, Trachternach+ 2008, Donato+,2009**

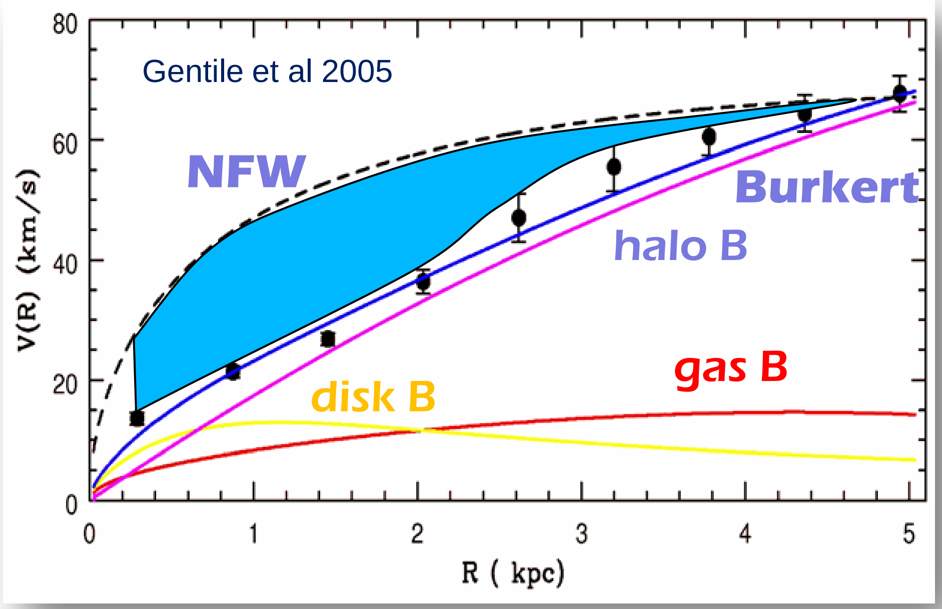
A detailed investigation: high quality data and model independent analysis



COUNTEREXAMPLES FOR NFW



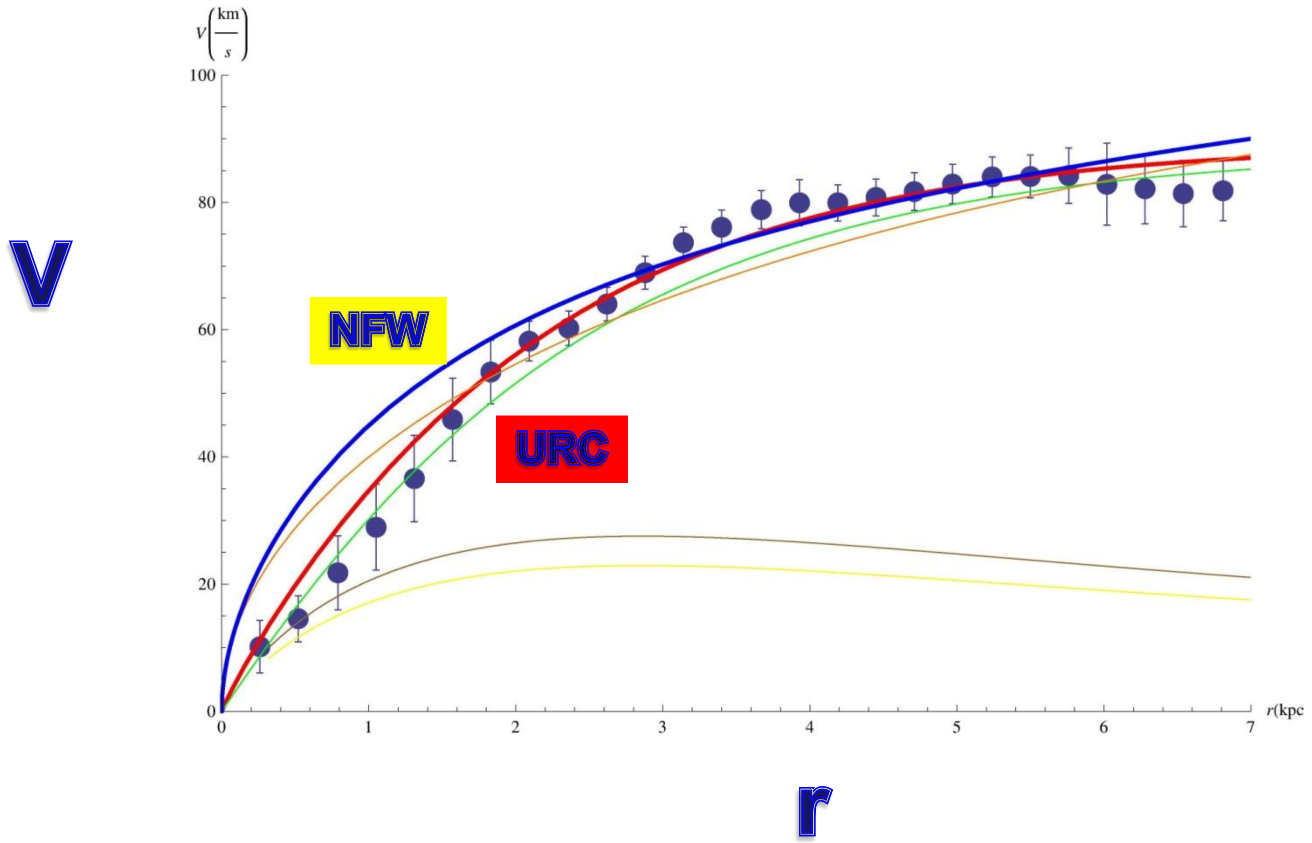
DDO 47



General results from several samples e.g. THINGS

- ***Non-circular motions are small.***
- ***DM halo spherical***
- ***ISO/Burkert halos much more preferred over NFW***
- **Tri-axiality and non-circular motions cannot explain the CDM/NFW cusp/core discrepancy**

ORION DWARF



SPIRALS: WHAT WE KNOW

AN UNIVERSAL CURVE REPRESENTS ALL INDIVIDUAL RCs
MORE PROPORTION OF DARK MATTER IN SMALLER SYSTEMS
THE RADIUS IN WHICH THE DM SETS IN IS A FUNCTION OF LUMINOSITY
THE MASS PROFILE AT LARGER RADII IS COMPATIBLE WITH NFW
DARK HALO DENSITY SHOWS A CENTRAL CORE OF SIZE 2 R_D

ELLIPTICALS

The Stellar Spheroid

Surface brightness of ellipticals follows a Sersic

$$I(R) = I_e \; dex[-b_n \left(\frac{R}{R_e}\right)^{1/n} - 1]$$

$$b_n = 0.868 \; n - 0.142$$

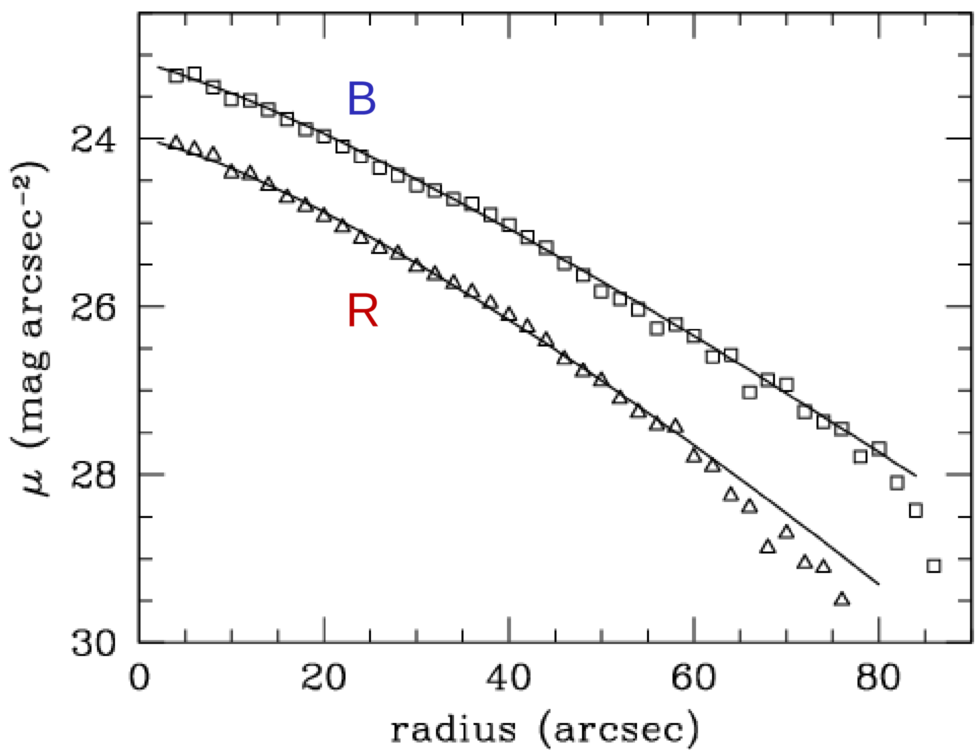
R_e the radius enclosing half of the projected light.

By deprojecting I(R) we obtain the luminosity density *j(r)*:

$$I(R) = \int_{-\infty}^{+\infty} j(r)\, dz = 2\int_{R}^{+\infty} \frac{j(r)\, r\, dr}{\sqrt{r^2 - R^2}}$$

$$\rho_{sph}(r) = (M/L)_\star \; j(r)$$

ESO 540-032 Sersic profile



Modelling Ellipticals

Measure the light profile = stellar mass profile $(M_*/L)^{-1}$

Derive the total mass profile M(r)

Dispersion velocities of stars or of Planetary Nebulae

X-ray properties of the emitting hot gas

Weak and/or strong lensing data

Disentangle M(r) into its dark and the stellar components

In ellipticals gravity is balanced by pressure gradients -> Jeans Equation

anisotropy of the orbits

$$\frac{\mathrm{d}}{\mathrm{d}r}(j\sigma_r^2) + \frac{2\beta}{r} j\sigma_r^2 = -j\frac{\mathrm{d}\Phi}{\mathrm{d}r}$$

grav. potential

dispersion velocities

Kinematics of ellipticals: Isotropic Jeans modelling of velocity dispersions

$$M(r) = M_{sph}(r) + M_h(r).$$

$$\sigma_r^2(r) = \frac{G}{\rho_{sph}(r)} \int_r^\infty \frac{\rho_{sph}(r')M(r')}{r'^2}\, dr'$$ **radial** **not observable**

$$\sigma_P^2(R) = \frac{2}{I(R)} \int_R^\infty \frac{\rho_{sph}(r)\ \sigma_r^2(r)\ r}{\sqrt{r^2 - R^2}}\, dr$$ **projected**

$$\sigma_A^2(R_A) = \frac{2\pi}{L(R_A)} \int_0^{R_A} \sigma_P^2(R)\ I(R)\ R\, dR$$ **aperture**

$$L(R) = 2\pi \int I(R)\ R\, dR$$

measure I(R), $\sigma_P(R)$

derive $M_h(r)$, $M_{sph}(r)$

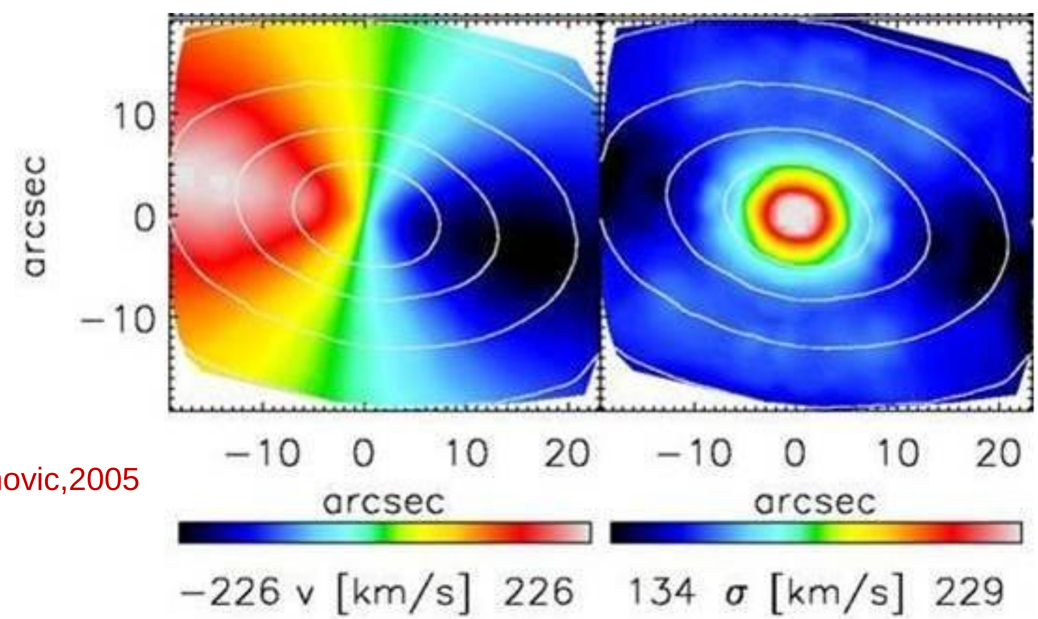
Anisotropic Jeans equations

$$\frac{\partial(\nu\overline{v_R^2})}{\partial R} + \frac{\partial(\nu\overline{v_R v_z})}{\partial z} + \nu\left(\frac{\overline{v_R^2} - \overline{v_\phi^2}}{R} + \frac{\partial\Phi}{\partial R}\right) = 0,$$

$$\frac{\partial(\nu\overline{v_R v_z})}{\partial R} + \frac{\partial(\nu\overline{v_z^2})}{\partial z} + \frac{\nu\overline{v_R v_z}}{R} + \nu\frac{\partial\Phi}{\partial z} = 0.$$

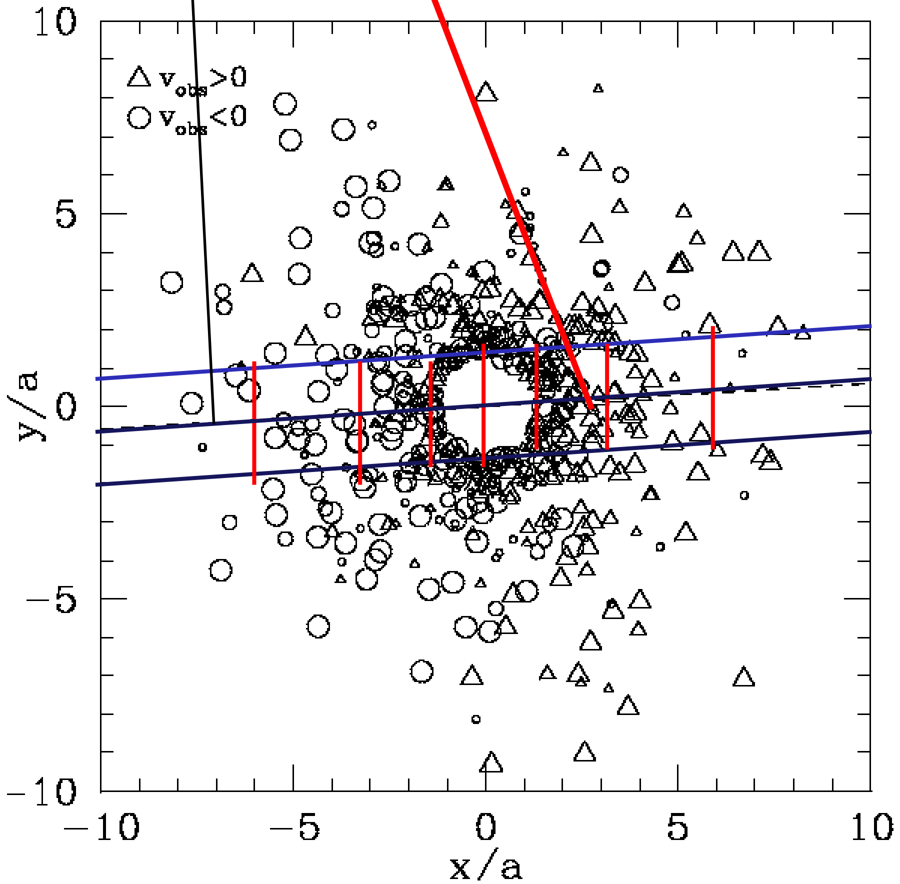
Cappellari,2008

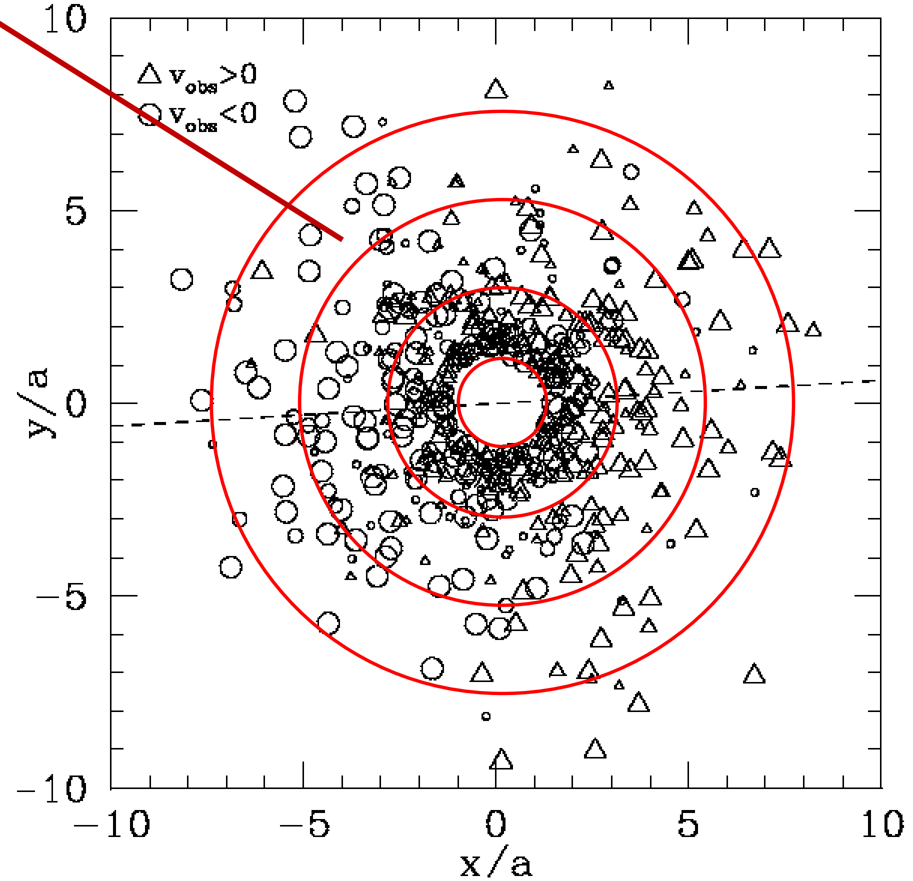
V SAURON data of N 2974 σ_P



Krajnovic,2005

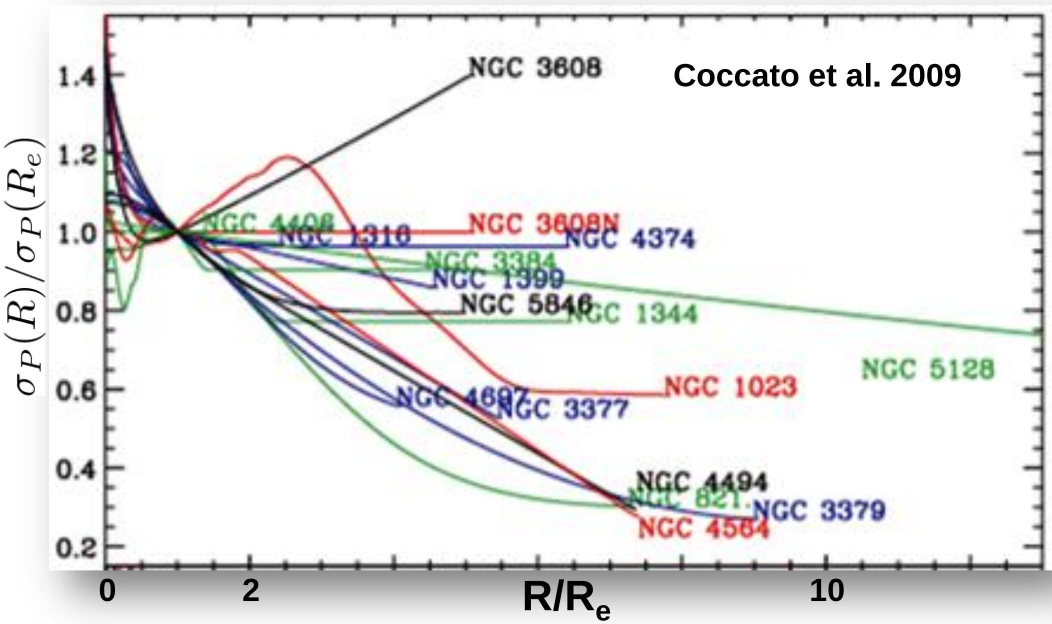
PN : Major/minor axis or radial binning of the data

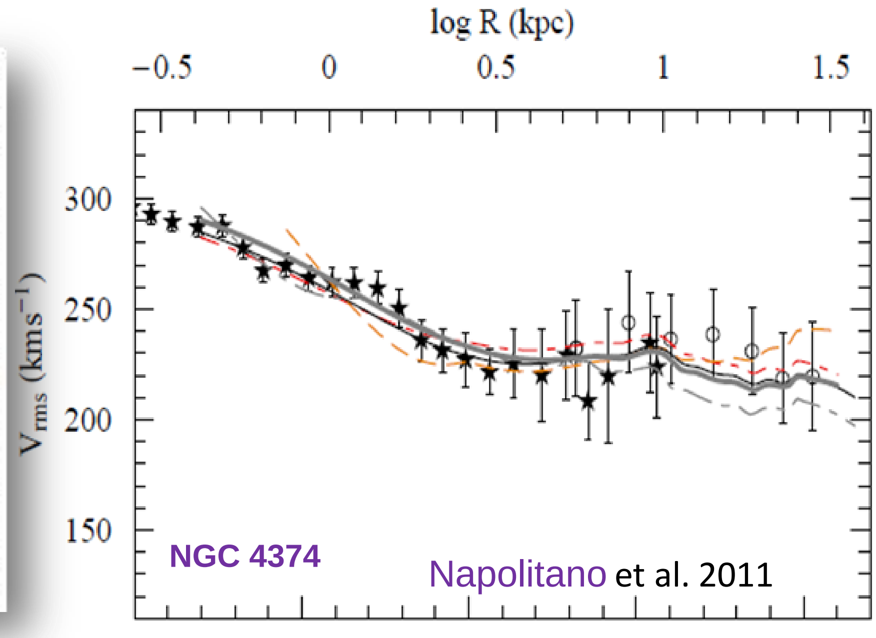




PN data

Jeans modelling of PN data with a stellar spheroid + NFW dark halo





Velocity dispersion are flat or strongly decreasing outside ~2R_e

JEANS ANALYSIS

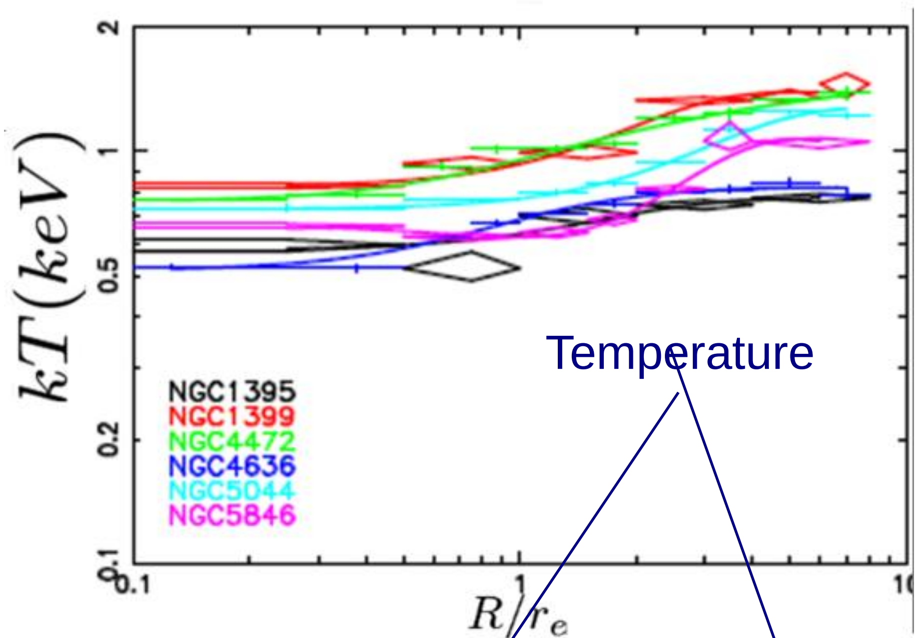
$$M(r) = -\frac{\sigma_r^2\, r}{G}\left(\frac{d\ln j_*}{d\ln r} + \frac{d\ln \sigma_r^2}{d\ln r} + 2\beta\right)$$

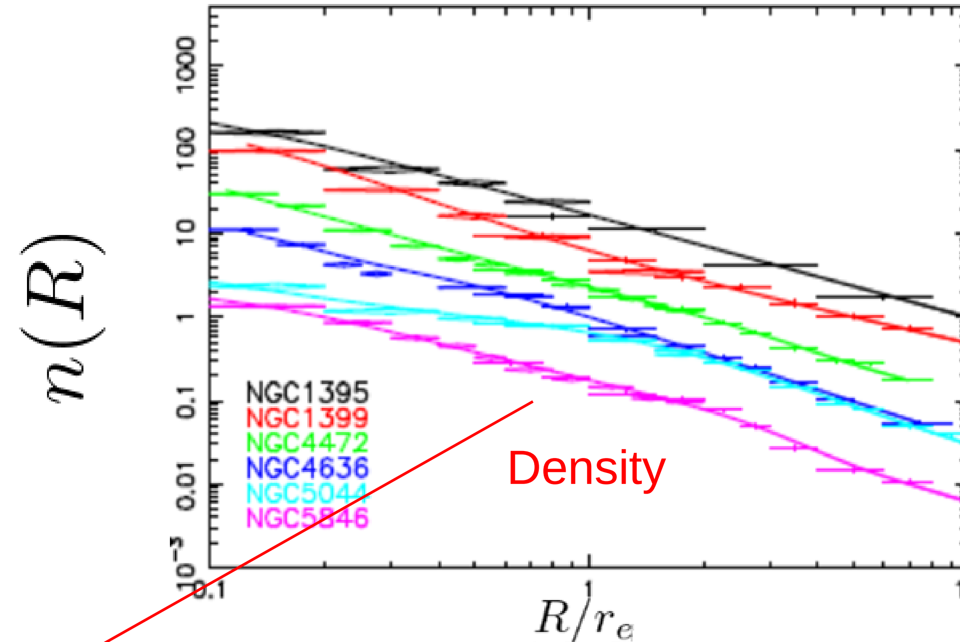
There exist big DM halos around Ellipticals,

Cored and cuspy DM profiles are both possible.

Mass Profiles from X-ray

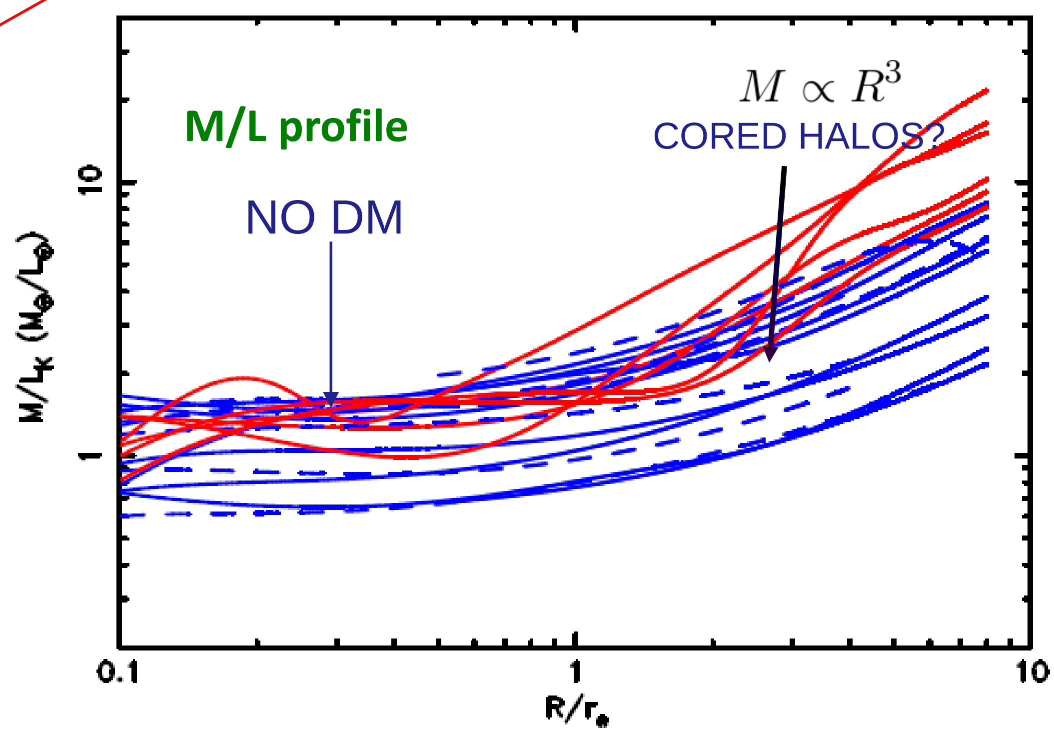
Nigishita et al 2009





$$M(R) = -\frac{kT(R)\cdot R}{G\mu m_p}\left(\frac{d\ln n(R)}{d\ln R} + \frac{d\ln T(R)}{d\ln R}\right)$$

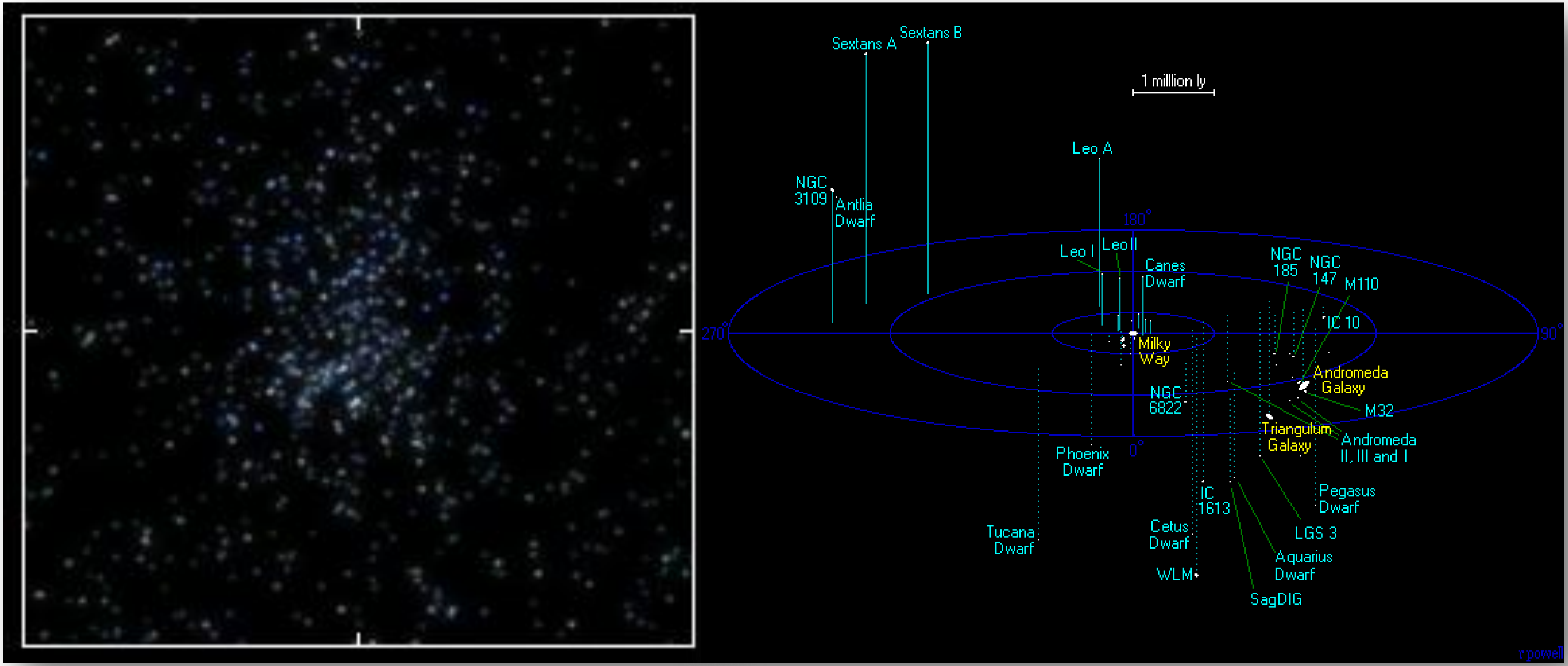
Hydrostatic Equilibrium



ELLIPTICALS: WHAT WE KNOW

A LINK AMONG THE STRUCTURAL PROPERTIES OF STELLAR SPHEROID
SMALL AMOUNT OF DM INSIDE R_E
MASS PROFILE COMPATIBLE WITH NFW AND BURKERT
DARK MATTER DIRECTLY TRACED OUT TO R_{VIR}

dSphs


Sextans A
Sextans B
1 milllion ly
Leo A
NGC 3109
Antlia Dwarf
180°
Leo I
Leo II
Canes Dwarf
NGC 185
NGC 147
M110
IC 10
270°
90°
Milky Way
Andromeda Galaxy
NGC 6822
M32
Triangulum Galaxy
Andromeda II, III and I
0°
Phoenix Dwarf
IC 1613
Pegasus Dwarf
Tucana Dwarf
Cetus Dwarf
LGS 3
Aquarius Dwarf
WLM
SagDIG

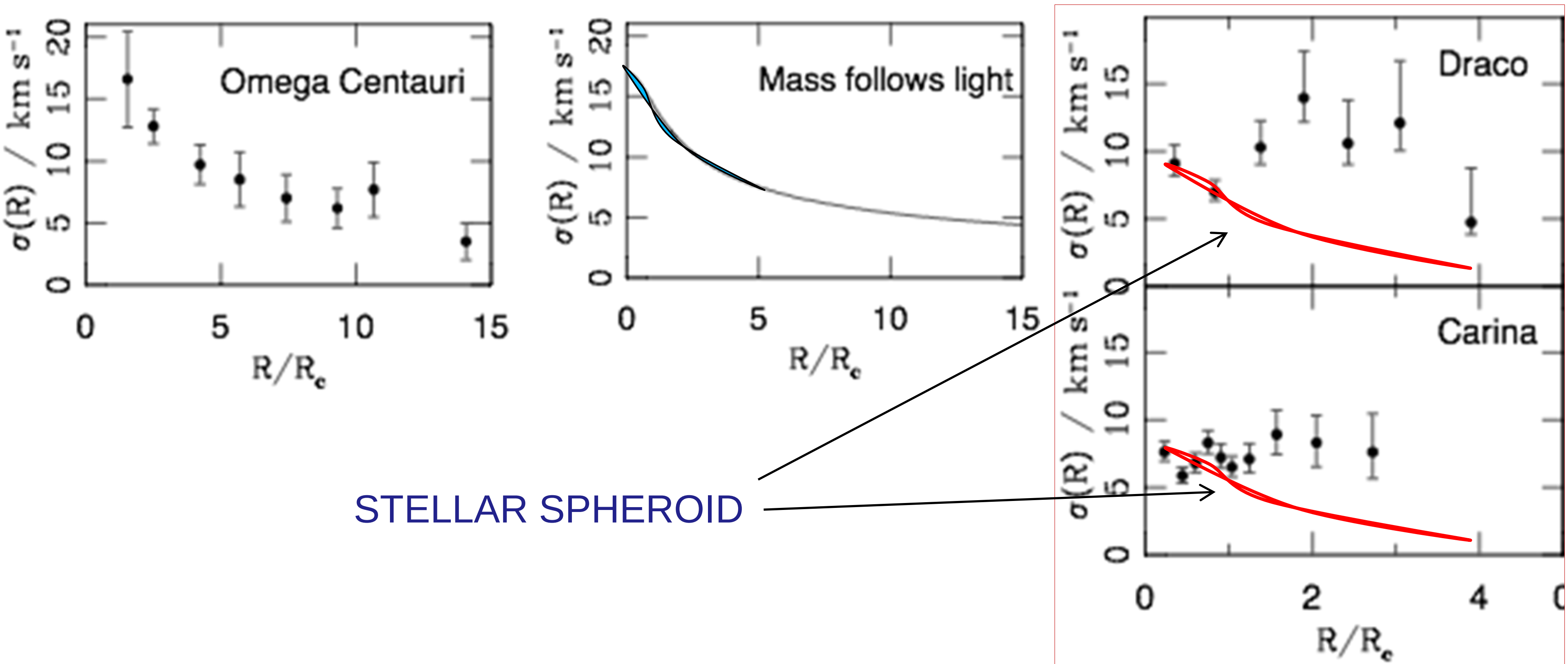
Kinematics of dSph

1983: Aaronson measured velocity dispersion of Draco based on observations of 3 carbon stars - M/L ~ 30

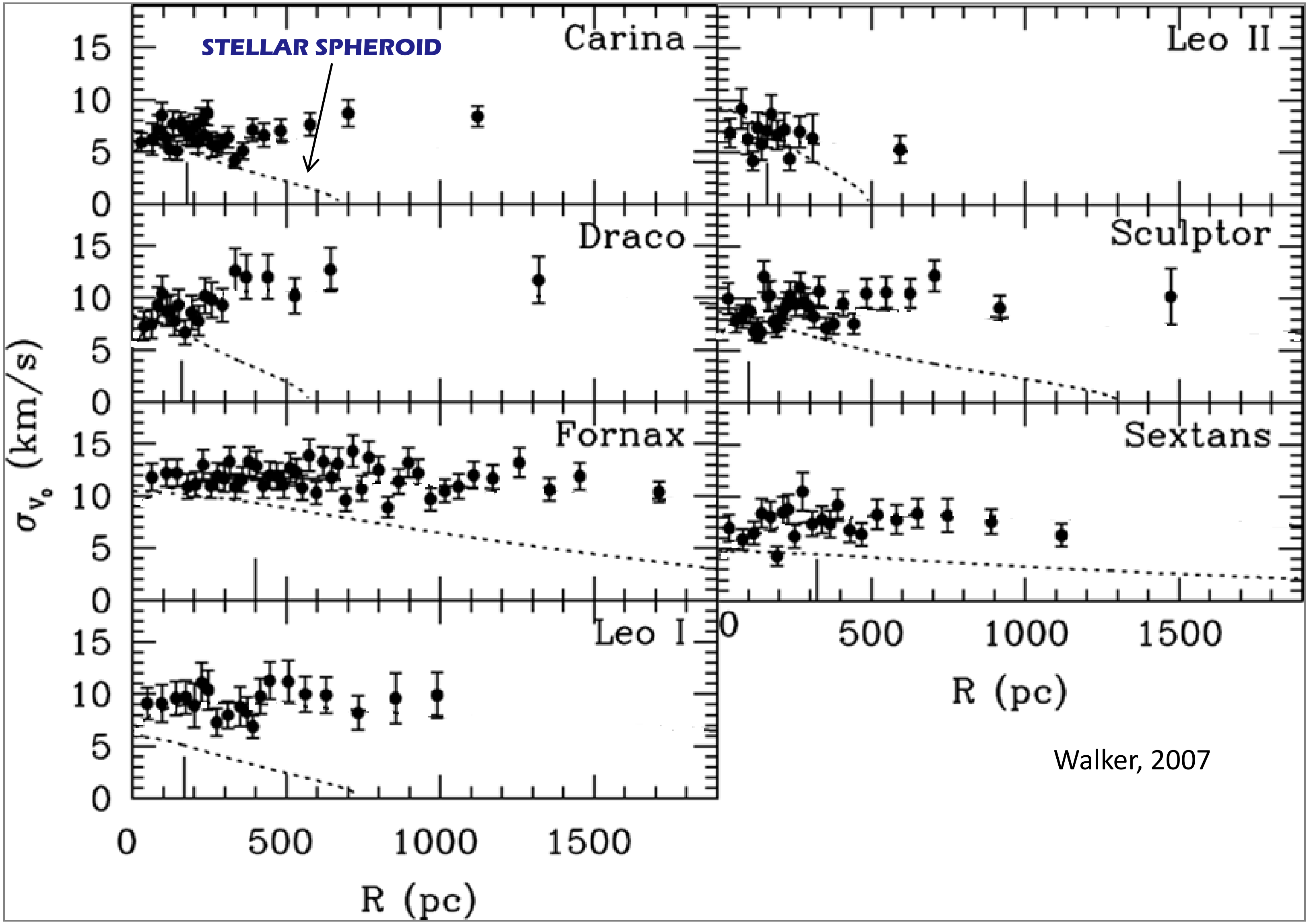
1997: First dispersion velocity profile of Fornax (Mateo)

2000+: Dispersion profiles of all dSphs measured using multi-object spectrographs

2010: full radial coverage in each dSph, with 1000 stars per galaxy



Dispersion velocity profiles



dSph dispersion profiles generally remain flat to large radii
Huge model-independent evidence of mass-to-light discrepancy

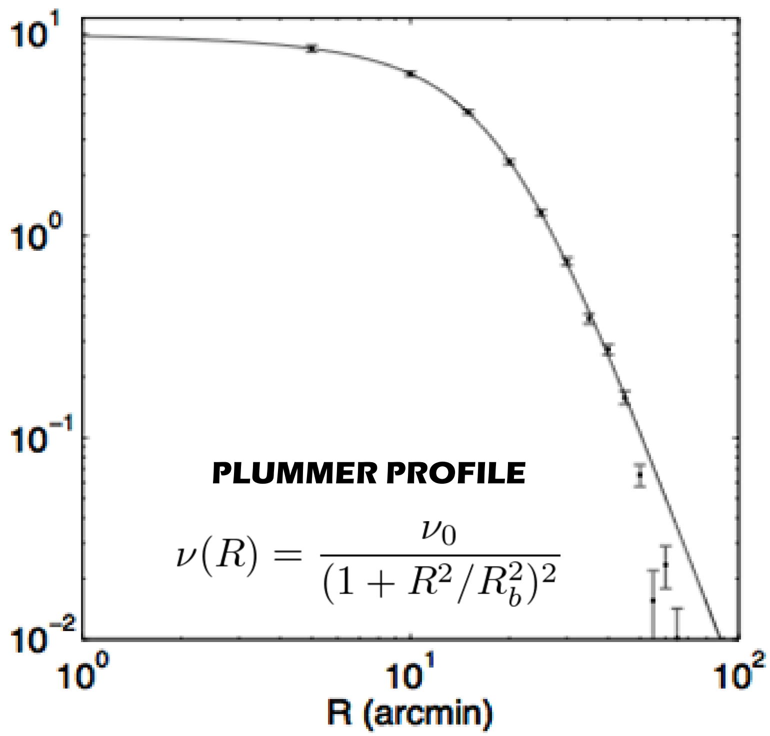
Mass profiles of dSphs

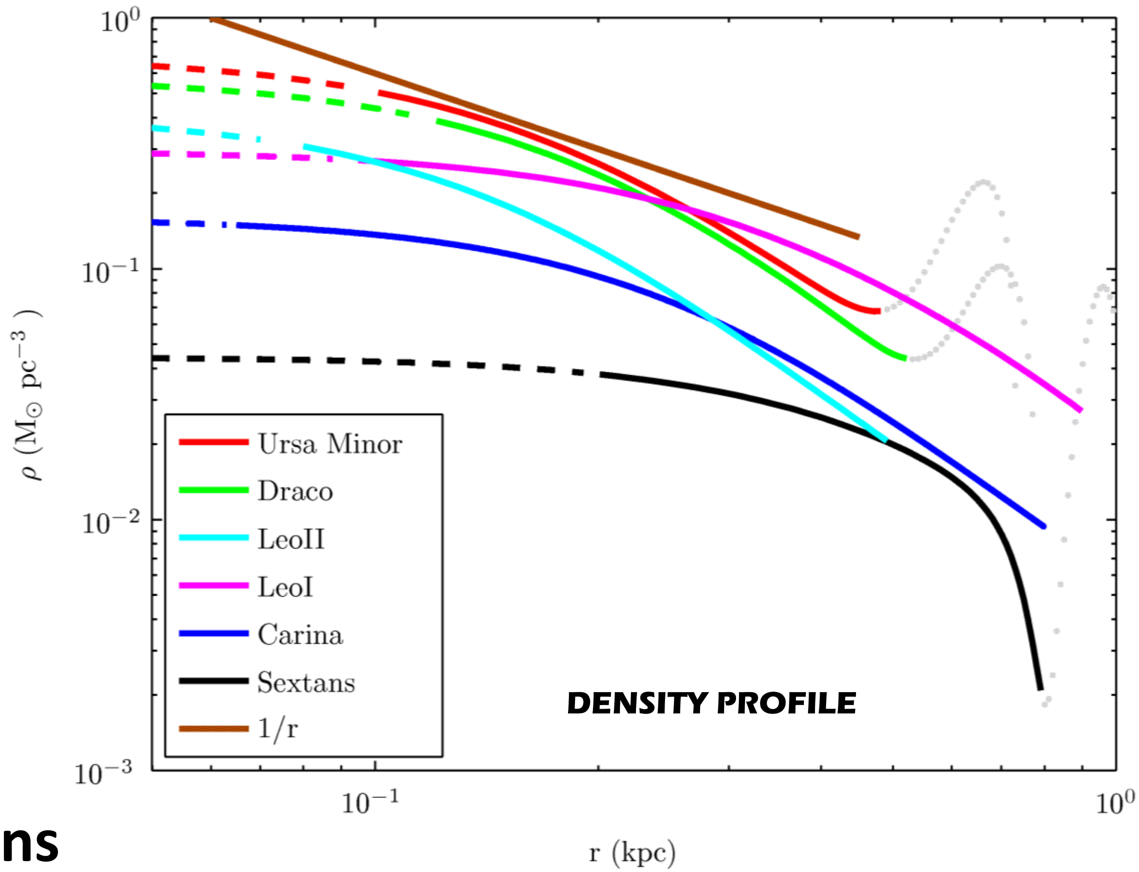
$$M(r) = -\frac{r^2}{G}\left(\frac{1}{\nu}\frac{\mathrm{d}\,\nu\sigma_r^2}{\mathrm{d}\,r} + 2\,\frac{\beta\sigma_r^2}{r}\right)$$

Jeans' models provide the most objective sample comparison

Jeans equation relates kinematics, light and underlying mass distribution

Make assumptions on the velocity anisotropy and then fit the dispersion profile

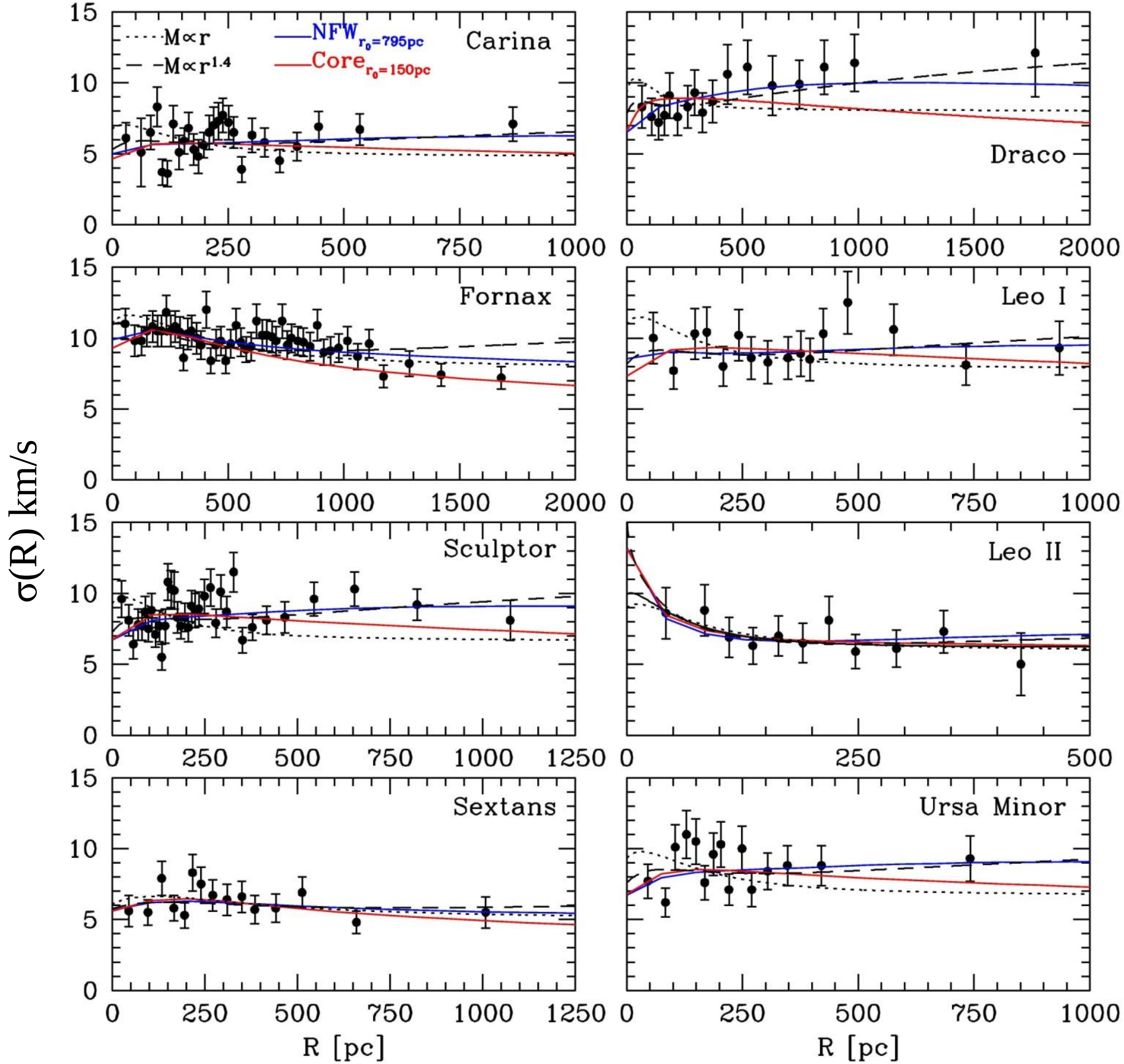




Results point to cored distributions

Gilmore et al 2007

Cored and (lesser cusped halos) fit dispersion velocity profiles

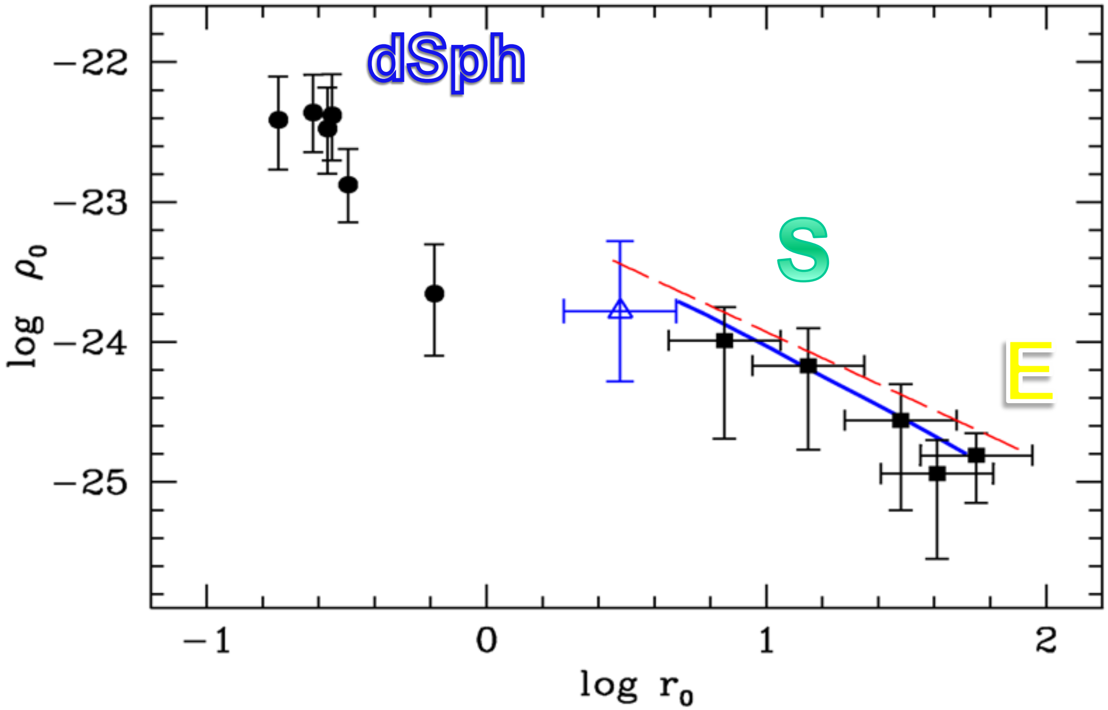


Walker et al 2009
Donato et al 2009

dSphs cored halo model

halo central densities correlate with core radius in the same way as Spirals and Ellipticals

$$\rho_0 = 10^{-23} \left(\frac{r_0}{1kpc} \right)^{-1} g/cm^3$$

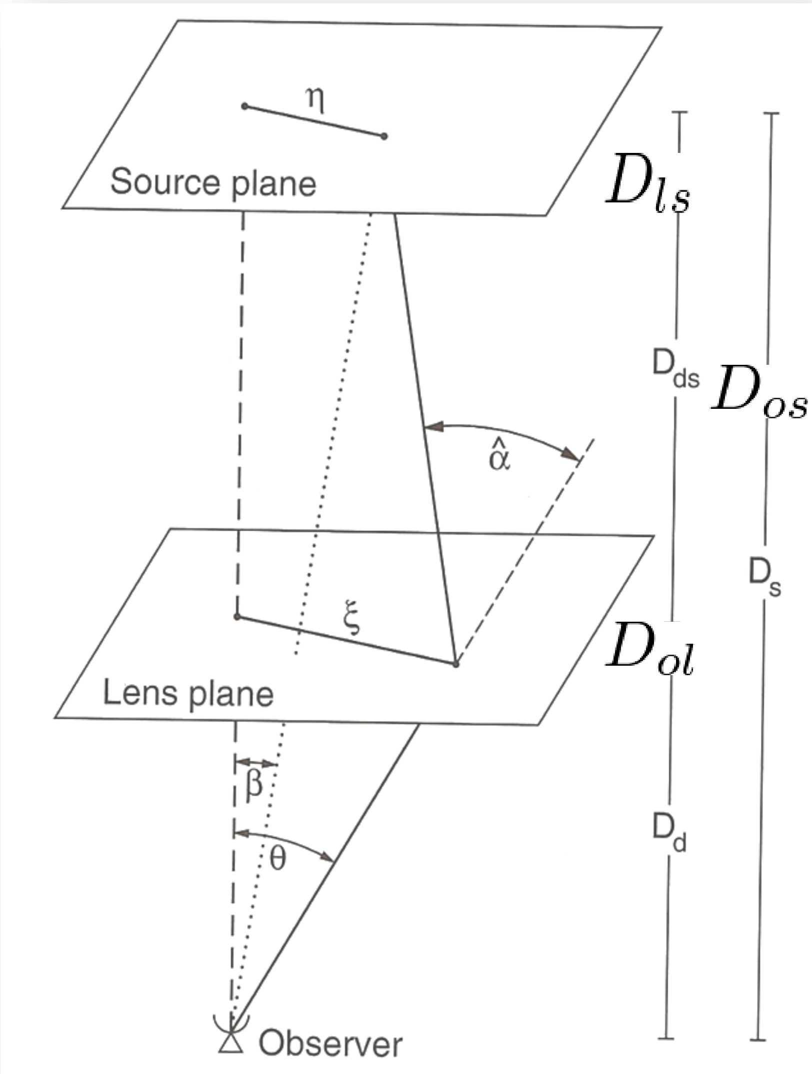


Donato et al 2009

DSPH: WHAT WE KNOW

PROVE THE EXISTENCE OF DM HALOS OF 10^{10} M_{SUN} AND ρ_0 =10^{-21} g/cm^3
DOMINATED BY DARK MATTER AT ANY RADIUS
MASS PROFILE CONSISTENT WITH THE EXTRAPOLATION OF THE URC
HINTS FOR THE PRESENCE OF A DENSITY CORE

Mass profiles from weak lensing



Lensing equation for the observed tangential shear

e.g. Schneider,1996

$$\langle \gamma_t \rangle \equiv \frac{\overline{\Sigma}(R) - \Sigma(R)}{\Sigma_c(R)}$$

$$\bar{\Sigma} = \frac{M(R)}{4\pi R^2}$$

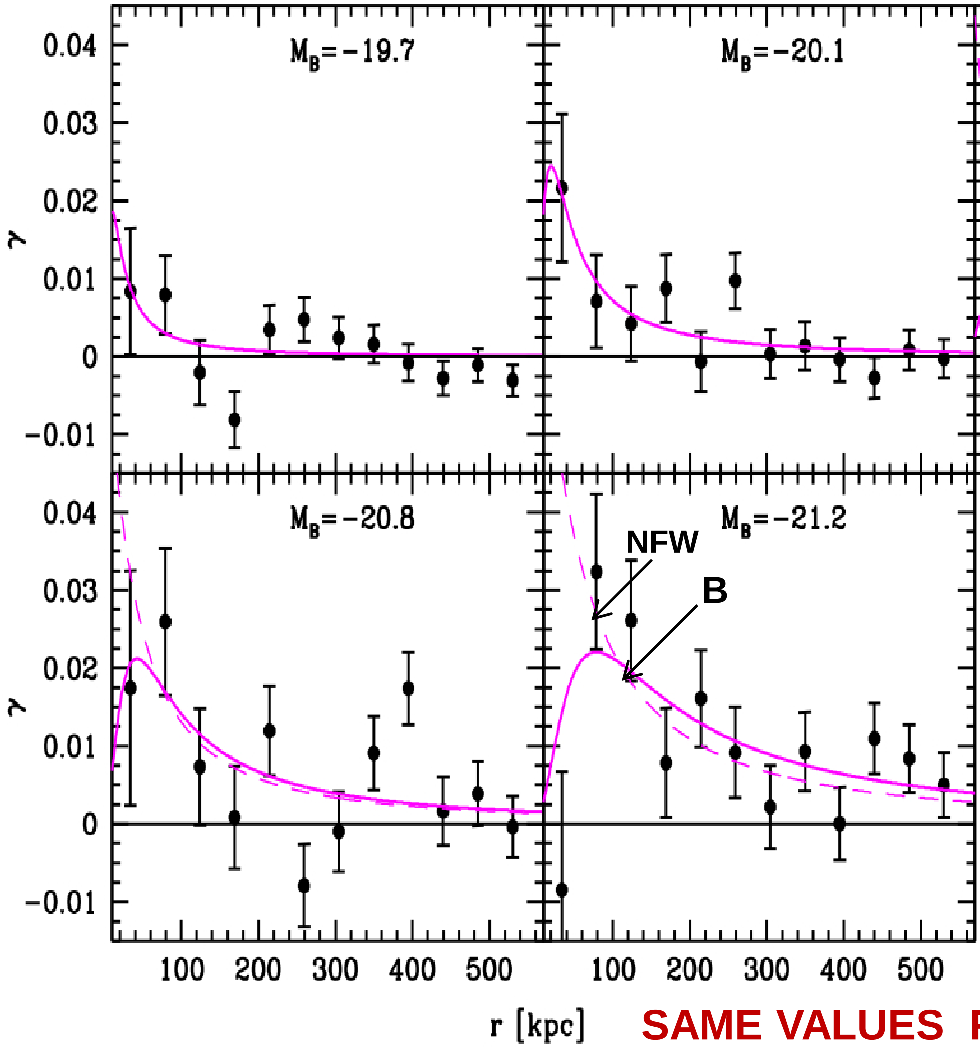
$$R = \theta D_{ol}$$

$$\Sigma_c = \frac{c^2}{4\pi G} \frac{D_{os}}{D_{ol} D_{ls}}$$

OUTER DM HALOS: NFW/BURKERT PROFILE

Lenses: 170 000 isolated galaxies, sources: 3 10^7 SDSS galaxies

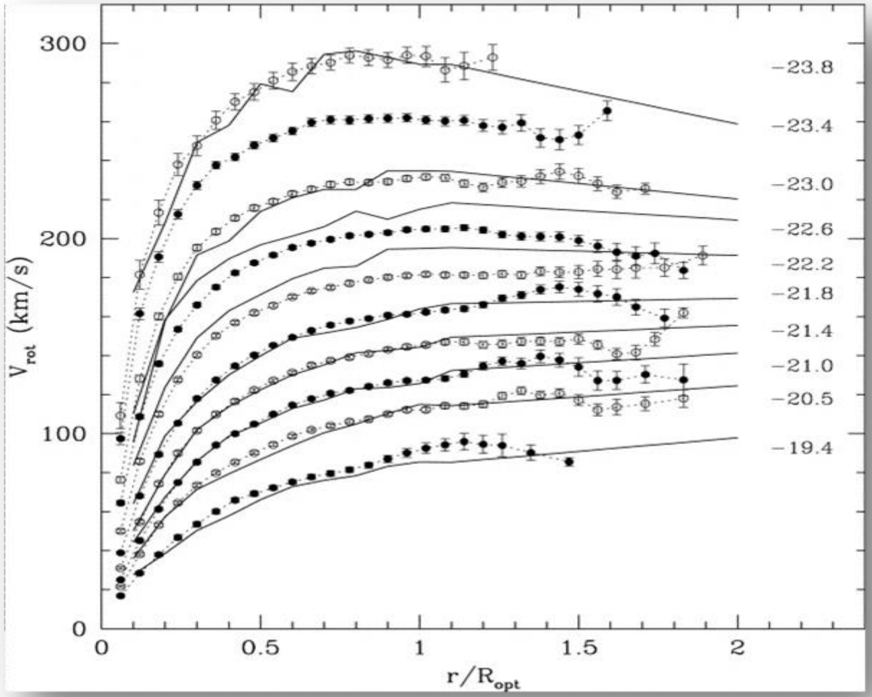
Donato et al 2009



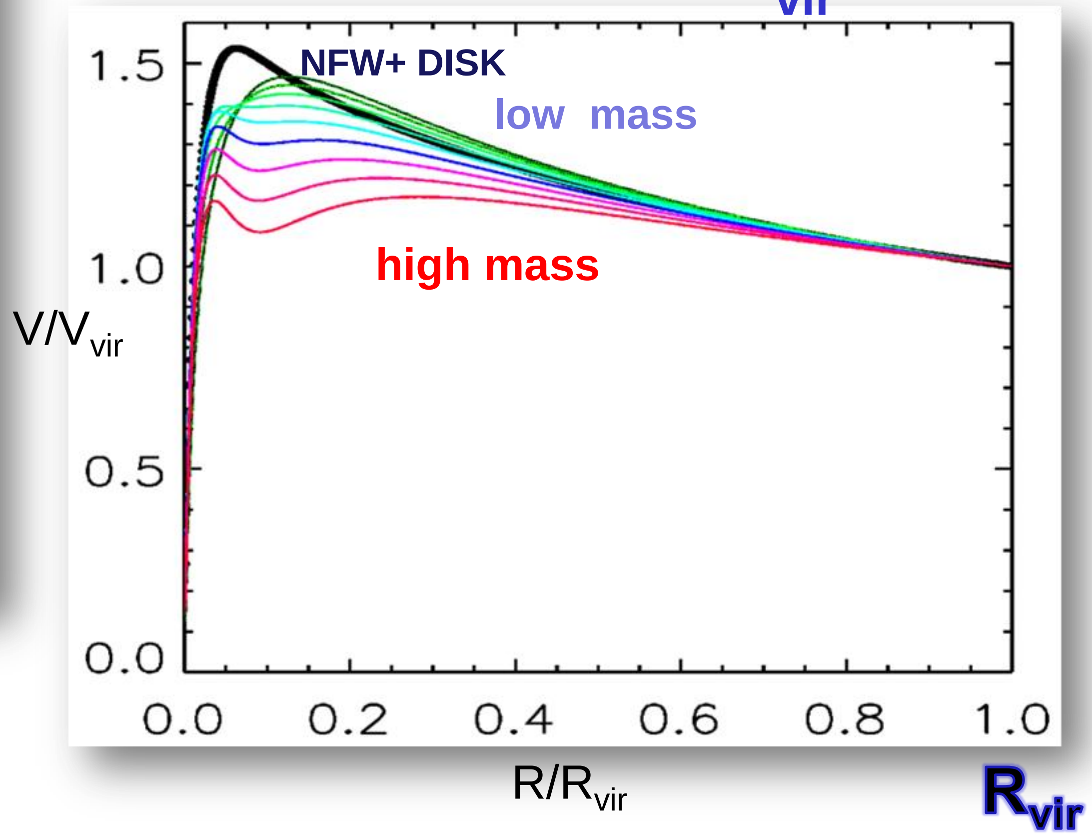
r_0 (kpc)	ρ_0 ($10^6 M_\odot/kpc^3$)
7^{+3}_{-6}	15^{+15}_{-15}
14^{+6}_{-10}	10^{+10}_{-10}
40.4^{+20}_{-20}	$1.7^{+1.5}_{-1.5}$
30^{+10}_{-20}	4.1^{+4}_{-4}
56^{+20}_{-20}	$2.3^{+1.2}_{-1.2}$

SAME VALUES FOUND BY MASS MODELLING THE URC

URC



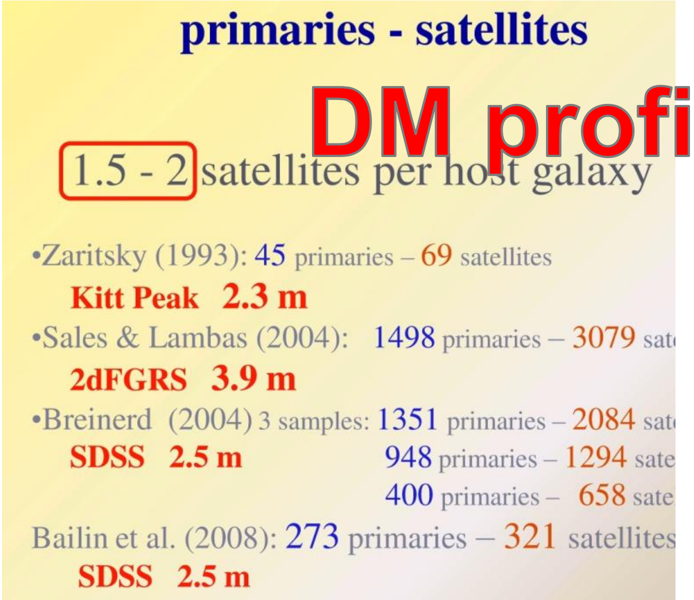
URC out to R_{vir}

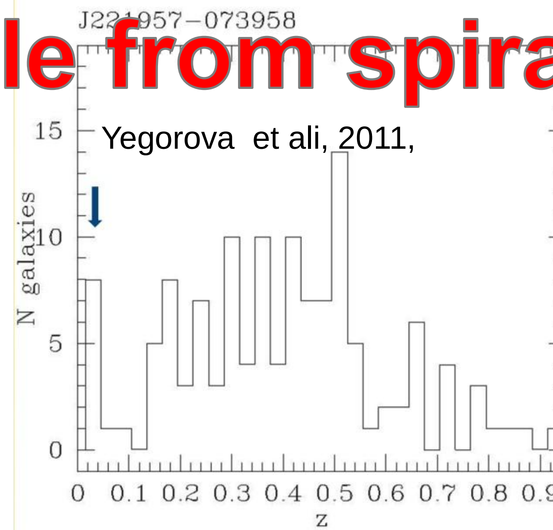


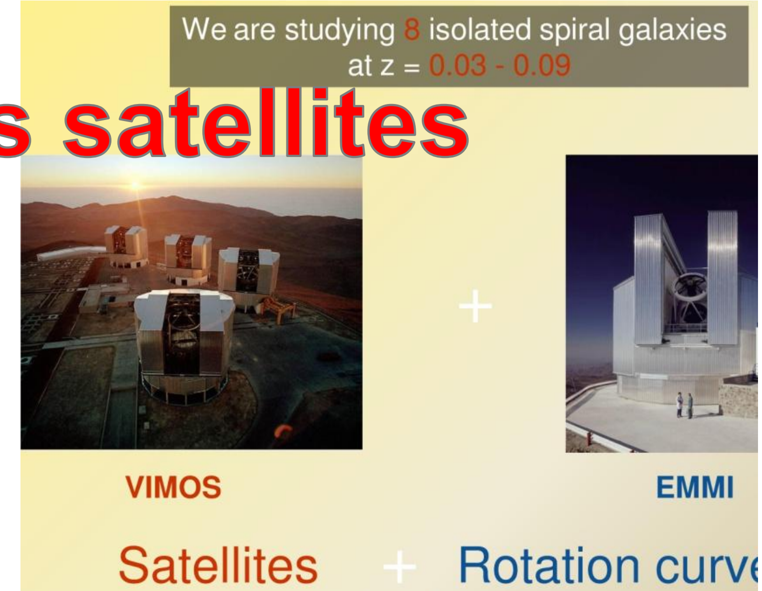
$V=F(R/R_D, M_I)$

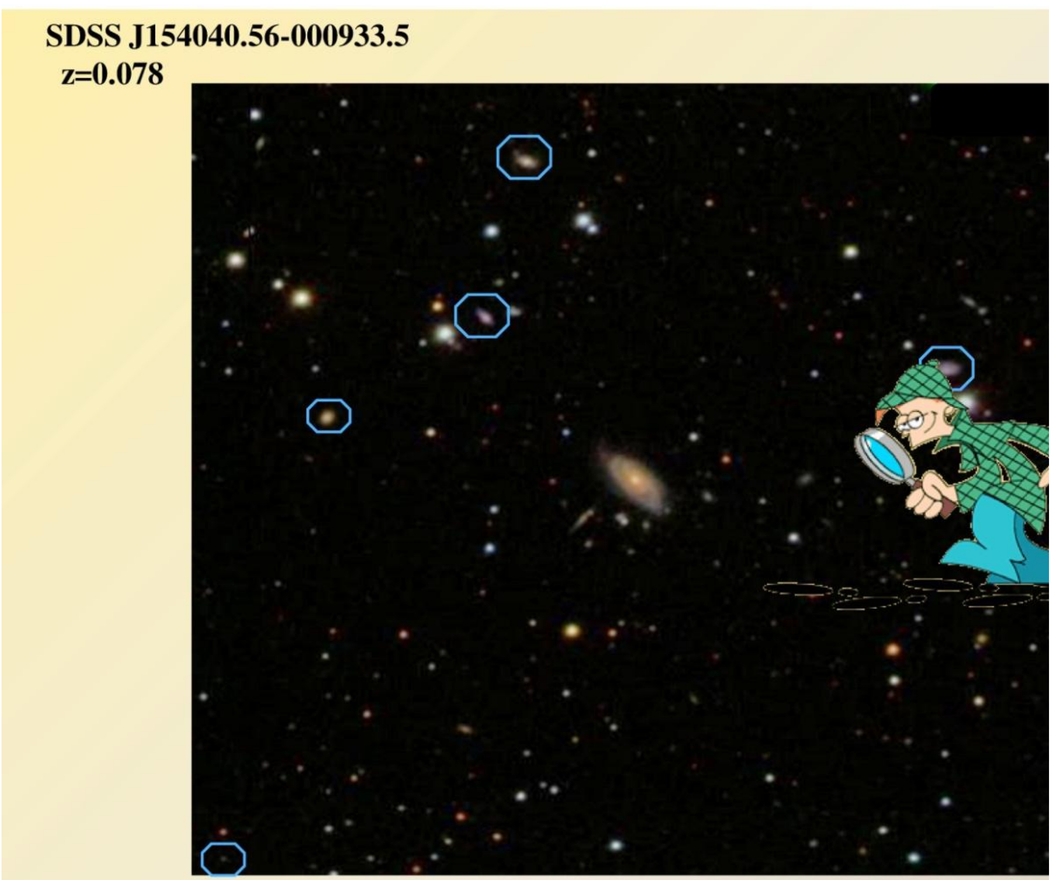
$V=G(R/R_{vir}, M_{vir})$

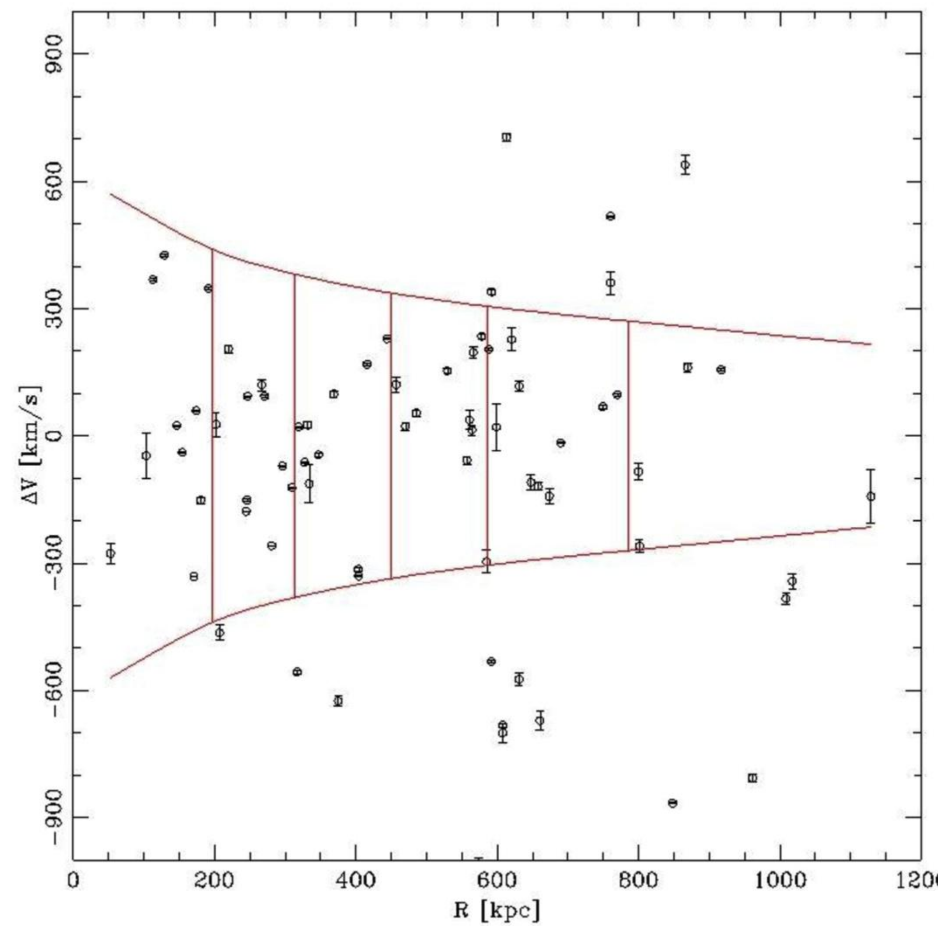
DM profile from spiral's satellites



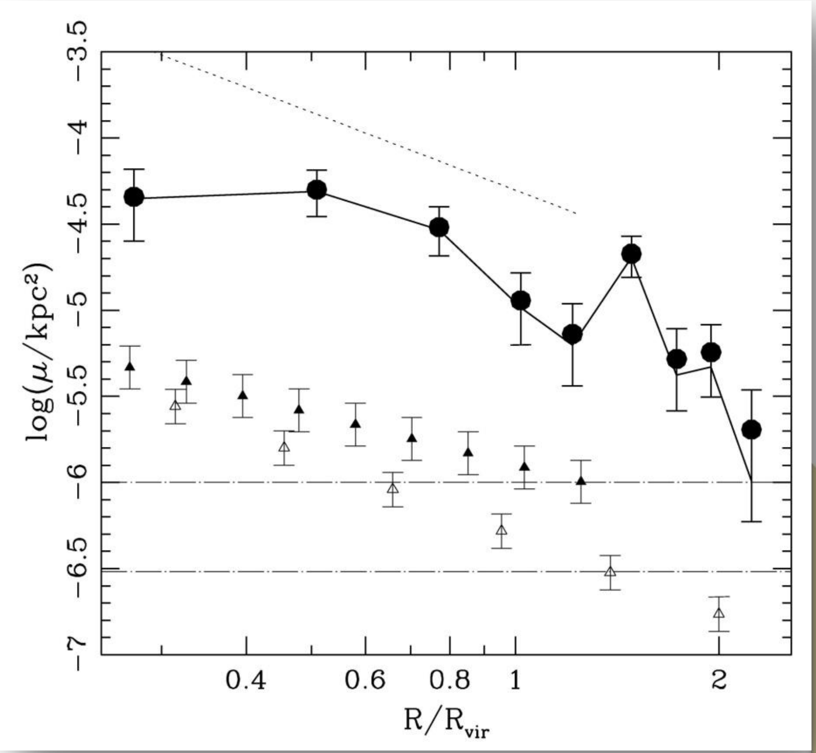




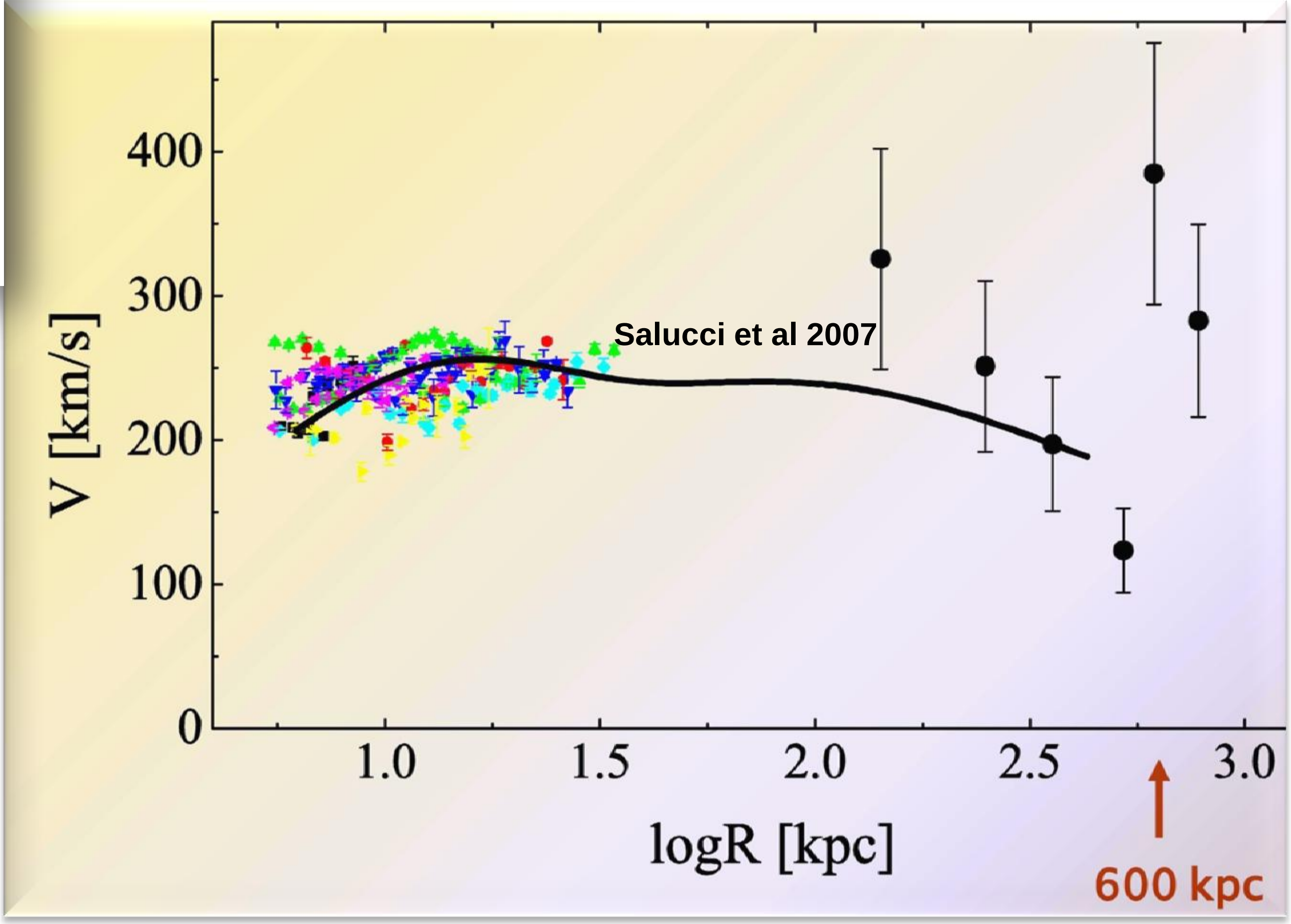




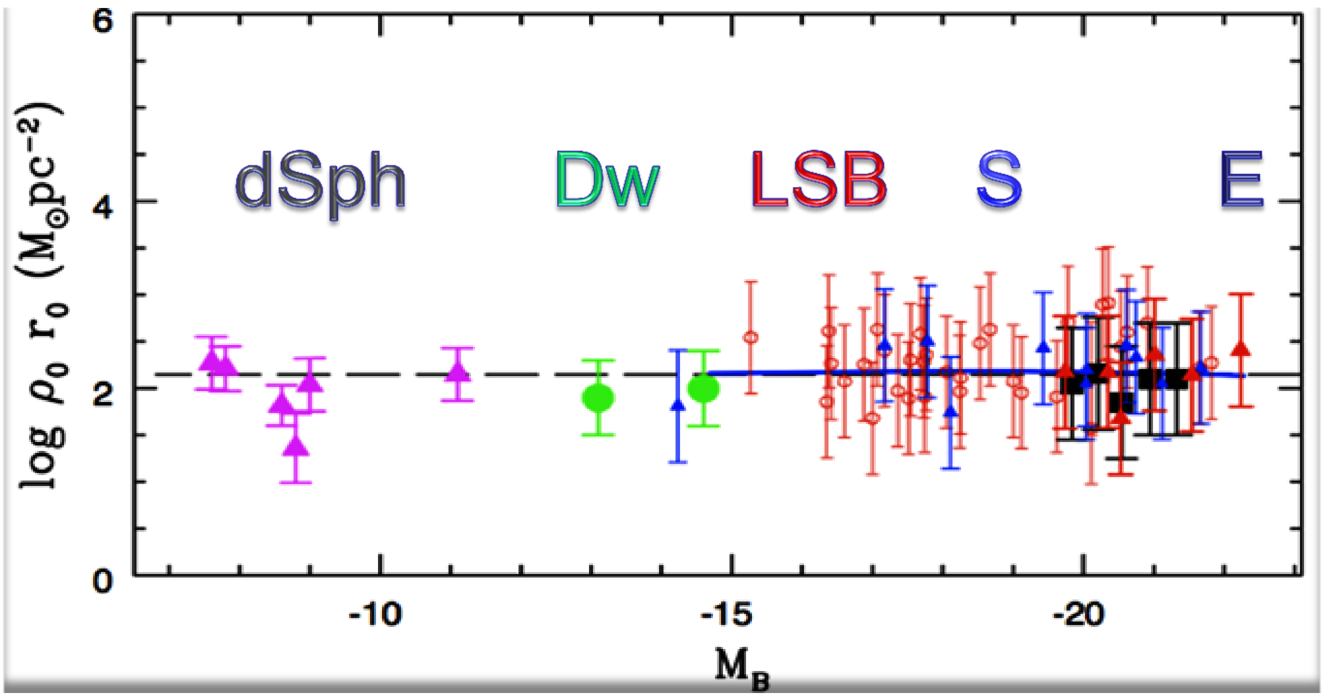
Surface density of satellites around 8 primaries



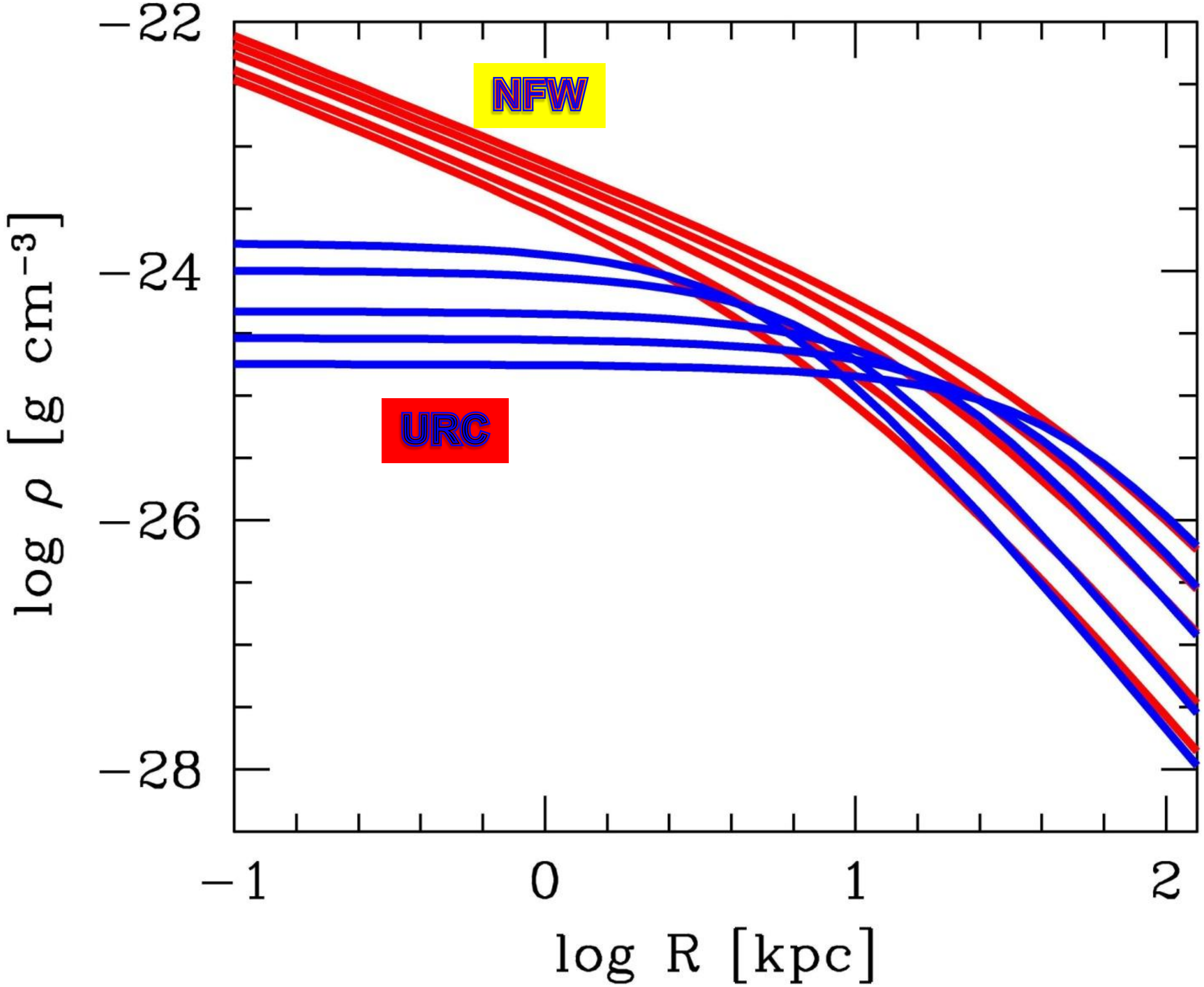
averaged circular velocity



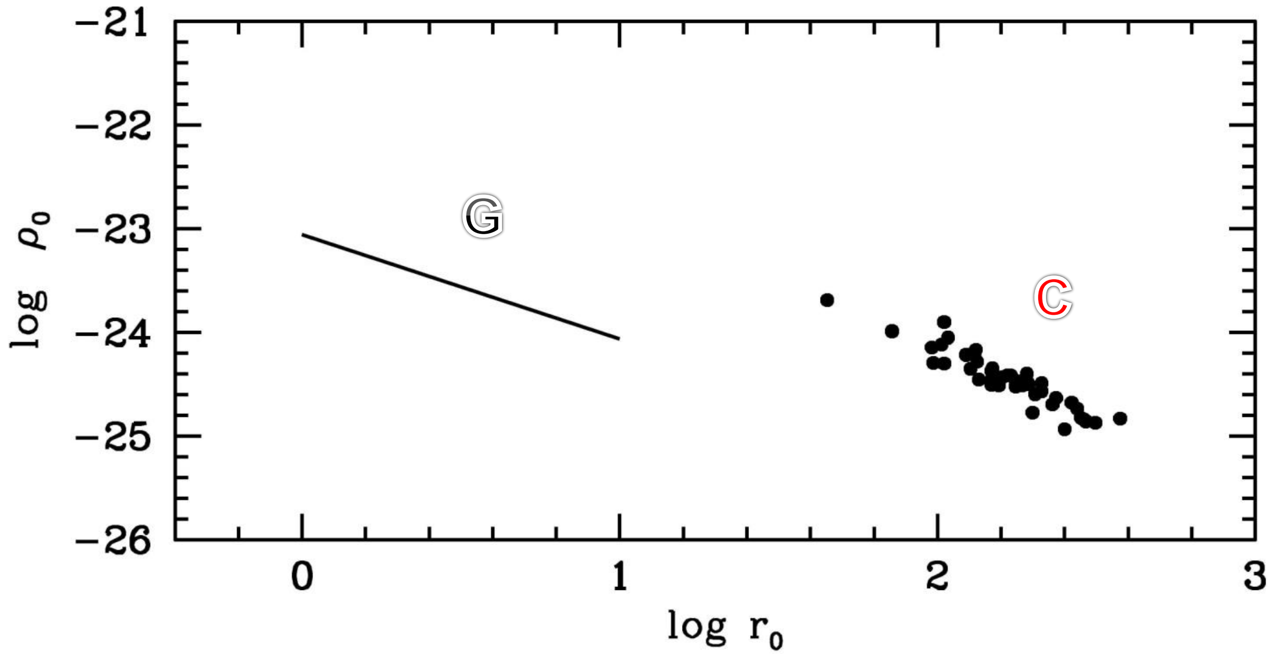
GALAXY HALOS: UDP

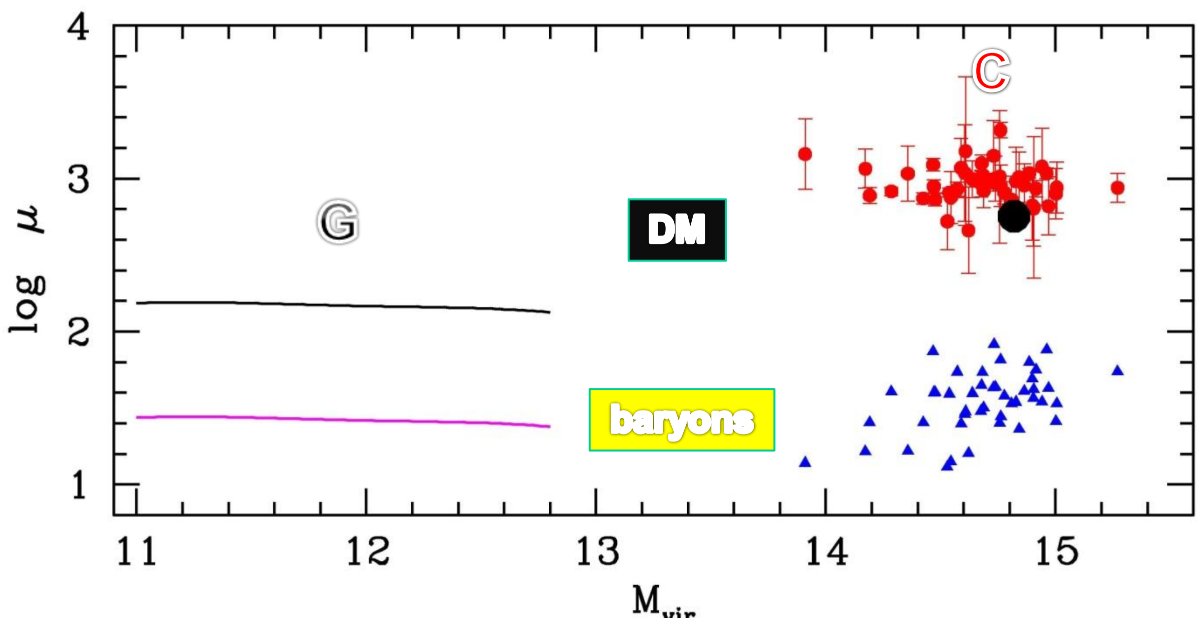


Universal Density Profile



CLUSTERS: $M(R) = -\frac{kT(R) \cdot R}{G\mu m_p}\left(\frac{d\ln n(R)}{d\ln R} + \frac{d\ln T(R)}{d\ln R}\right)$





CONCLUSIONS

The distribution of DM in halos around galaxies shows a striking and complex phenomenology

At play: the nature of dark matter and the galaxy formation process

We find a centrally shallow, Universal DM density profile**.**

Unlikely that all this masks a new law of Gravity, rather it points to a warm particle with a characteristic scale

Innovative review on DM in galaxies

http://people.sissa.it/~salucci/DMAW2010

DMAW20101.pptx