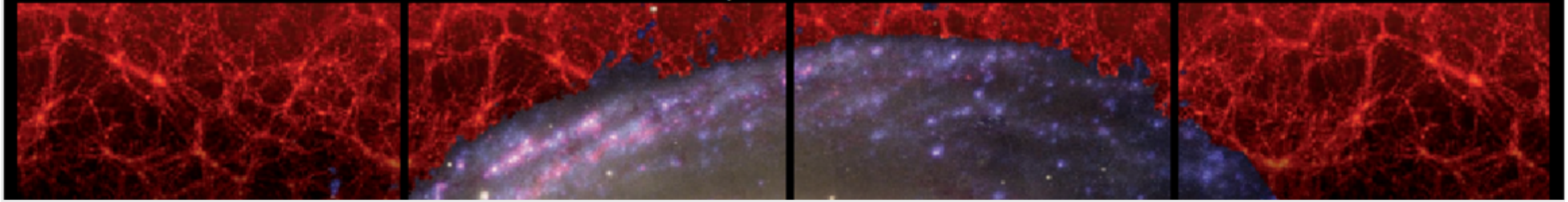
Dark Matter Awareness Week, 1-8 December 2010



DARK MATTER IN GALAXIES

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Dark Matter in Galaxies - A journal club seminar at your institute

DMAW2010

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Overview

The concept of Dark Matter

Dark Matter in Spirals, Ellipticals, dSphs

Dark and Luminous Matter. Global properties.

What is Dark Matter?

In a galaxy, the radial profile of the gravitating matter M(r) and that of the sum of all luminous components $M_L(r)$ do not match.

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

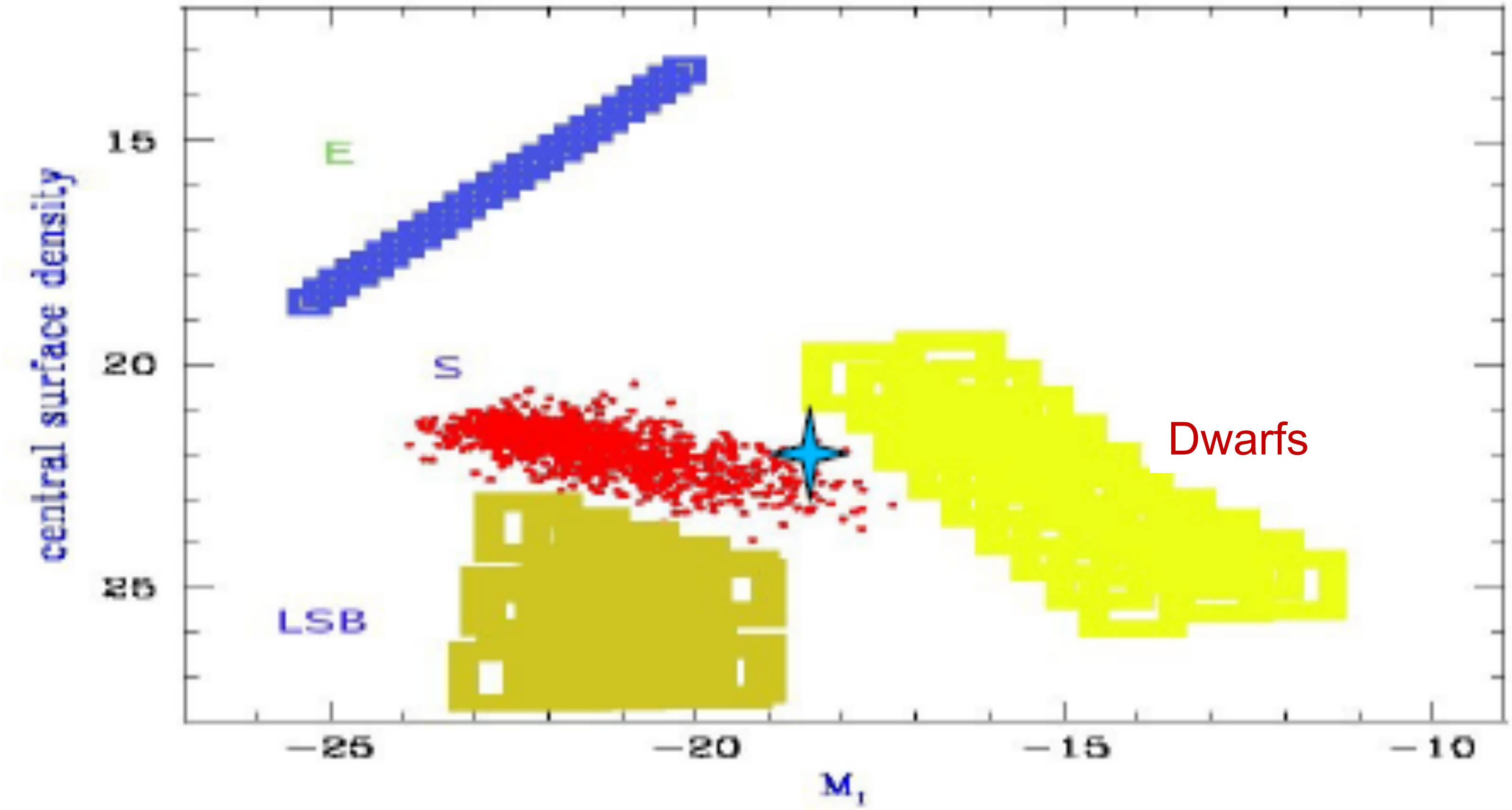
The DM phenomenon can be investigated only if we accurately meausure the distribution of:

Luminous matter.
Gravitating matter.

The Realm of Galaxies

The range of galaxies in magnitude, types and central surface density : 15 mag, 4 types, 16 mag arsec^2

Central surface brightness vs galaxy magnitude

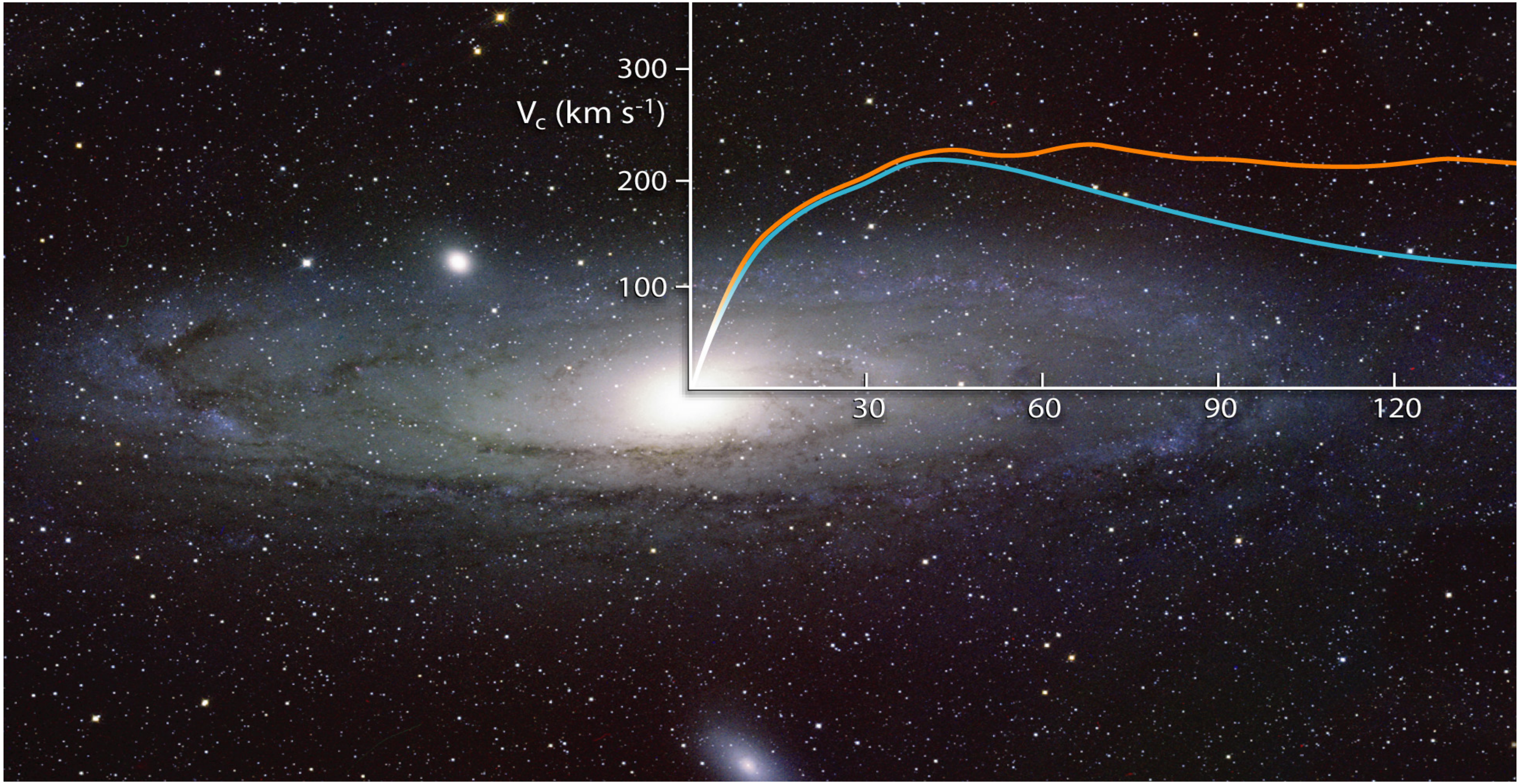


The distribution of luminous matter :

Spirals : stellar disk +bulge +HI disk

Ellipticals & dSph: stellar spheroid

SPIRALS

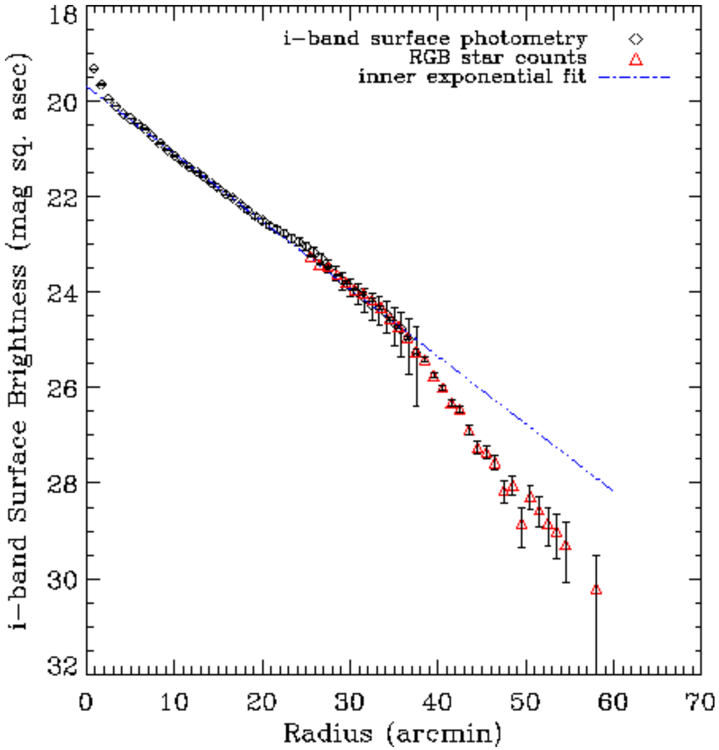


Stellar Disks

M33 very smooth structure

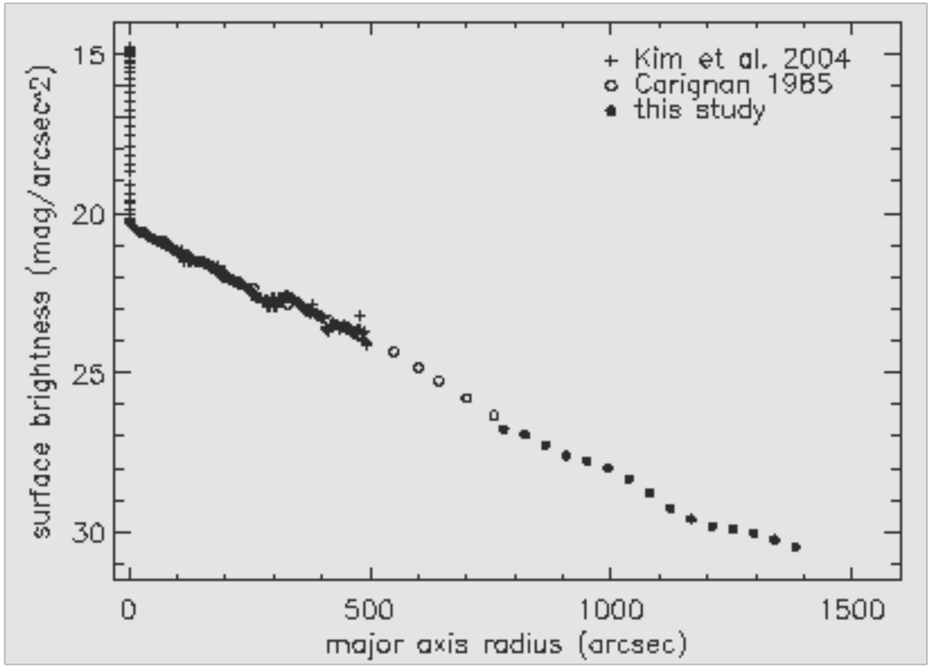
NGC 300 - exponential disk goes for at least 10 scale-lengths

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



Ferguson et al 2003

scale radius



Bland-Hawthorn et al 2005

Gas surface densities

GAS DISTRIBUTION

HI

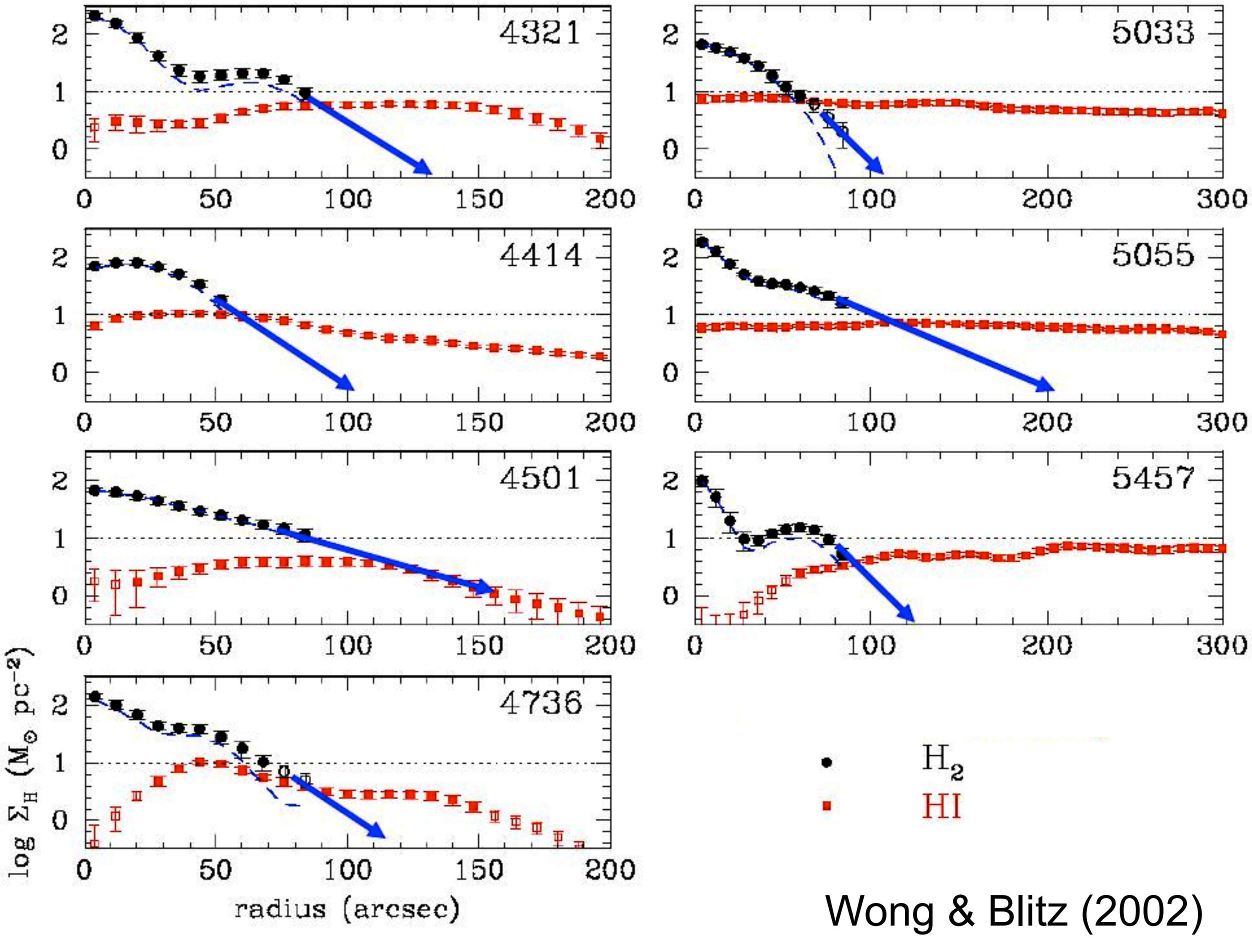
Flattish radial distribution

Deficiency in the centre

CO and H$_2$

Roughly exponential

Negligible mass



Wong & Blitz (2002)

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}

ROTATION CURVES (RC)

Symmetric circular rotation of a disk characterized by

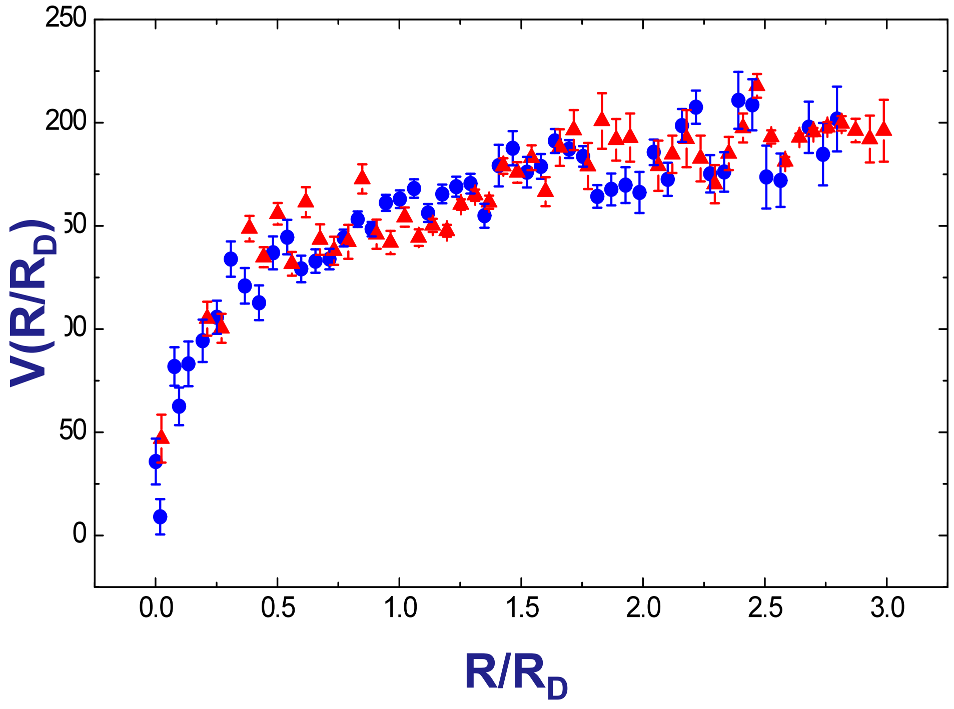
- Sky coordinates of the galaxy centre
- Systemic velocity V_{sys}
- Circular velocity $V(R)$
- Inclination angle

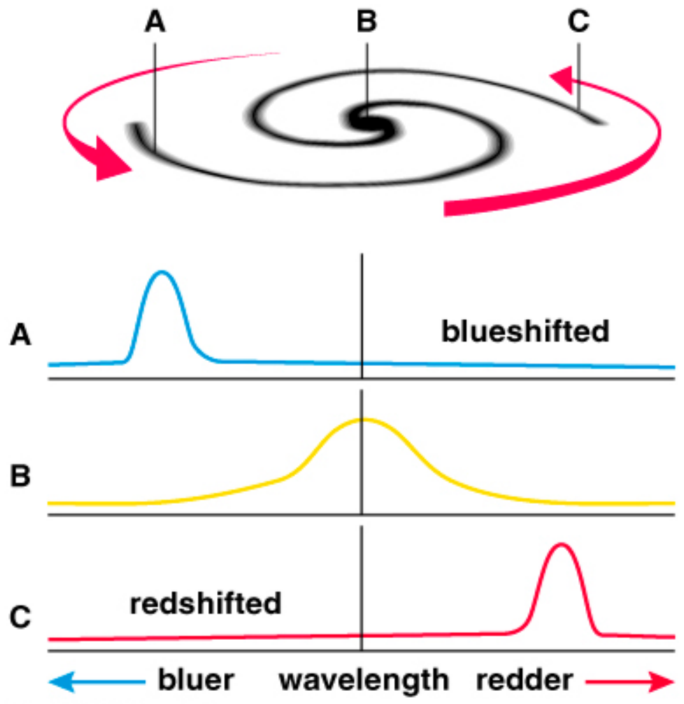
$$V_{obs}(\xi,\eta) = V_{sys} + V(R)\cos\theta \sin i$$

$$i = \arccos\left(\frac{a}{b}\right)$$

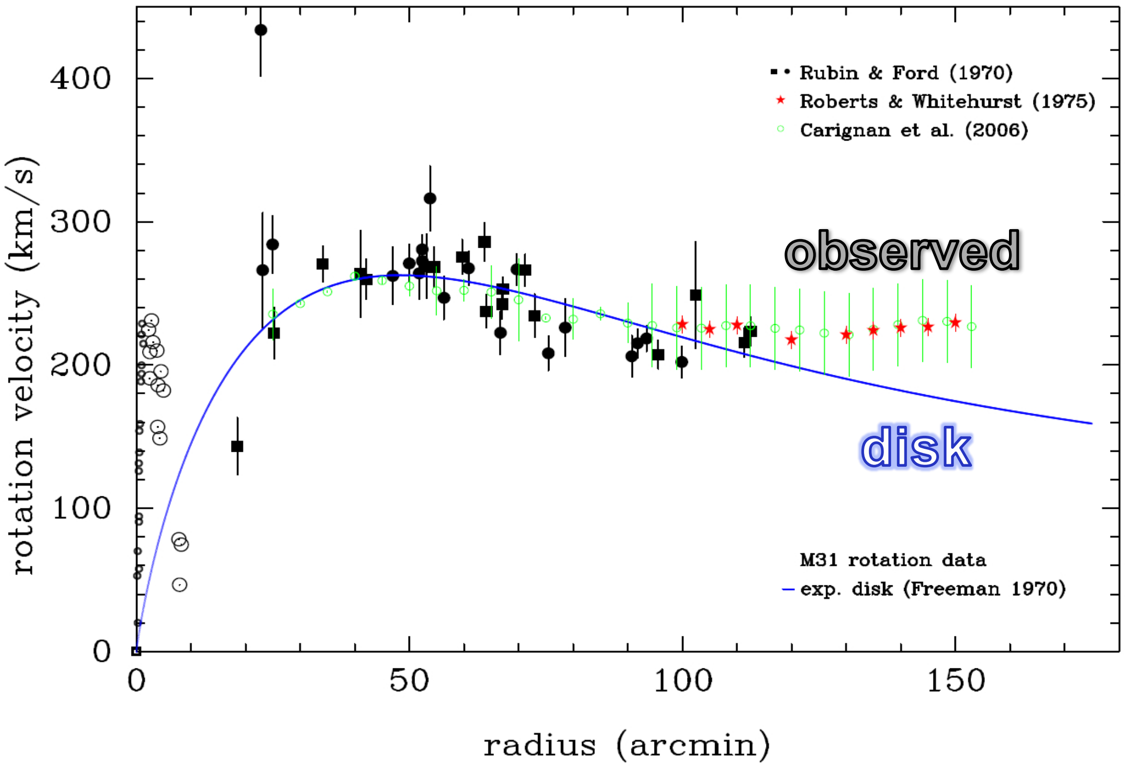
θ = azimuthal angle

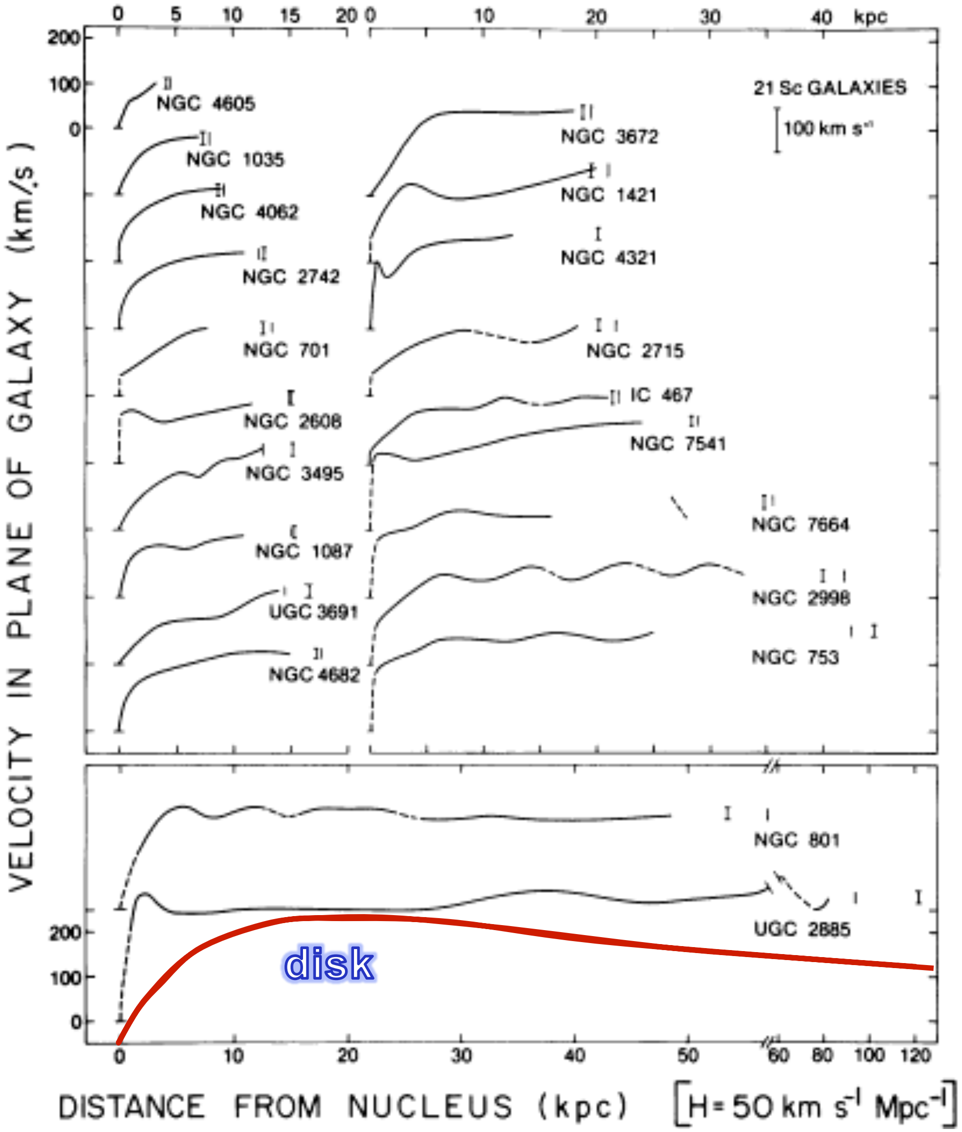
UGC2405 EXEMPLE OF HIGH QUALITY RC





Early discovery from optical and HI rotation curves



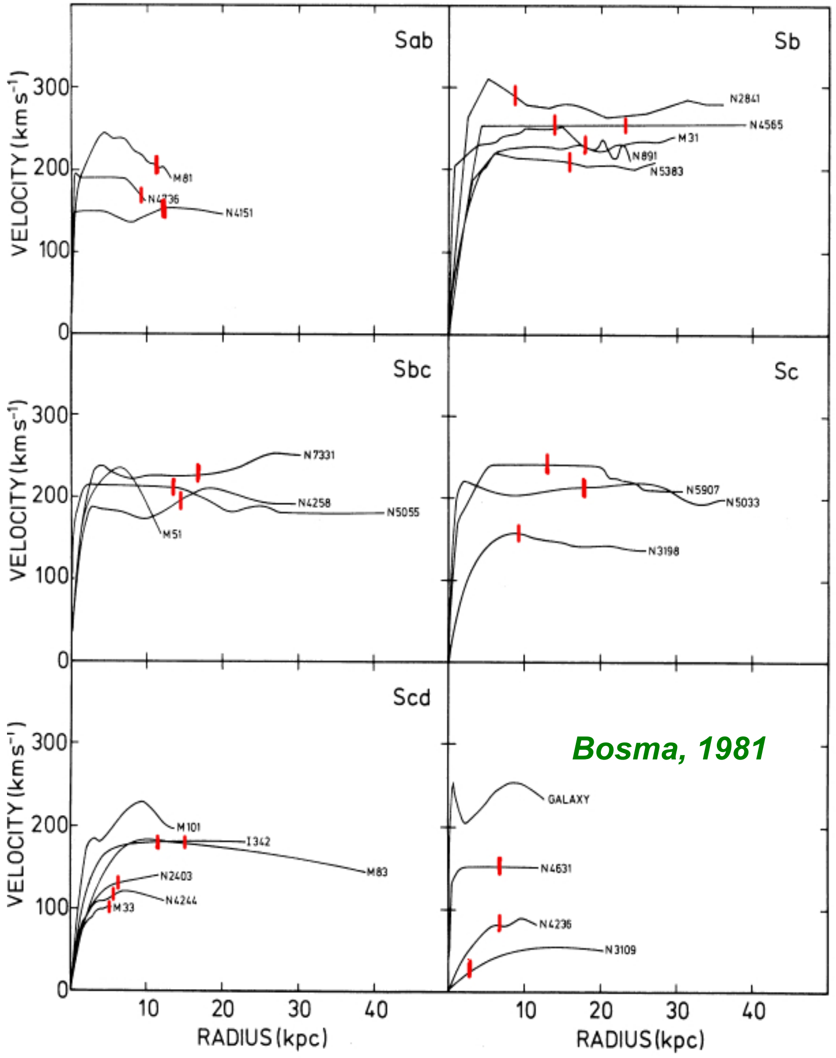


Rubin et al 1980

NO ROTATION CURVE FOLLOWS THE DISK VELOCITY PROFILE

MASS DISCREPANCY AT OUTER RADII

Extended HI kinematics traces dark matter



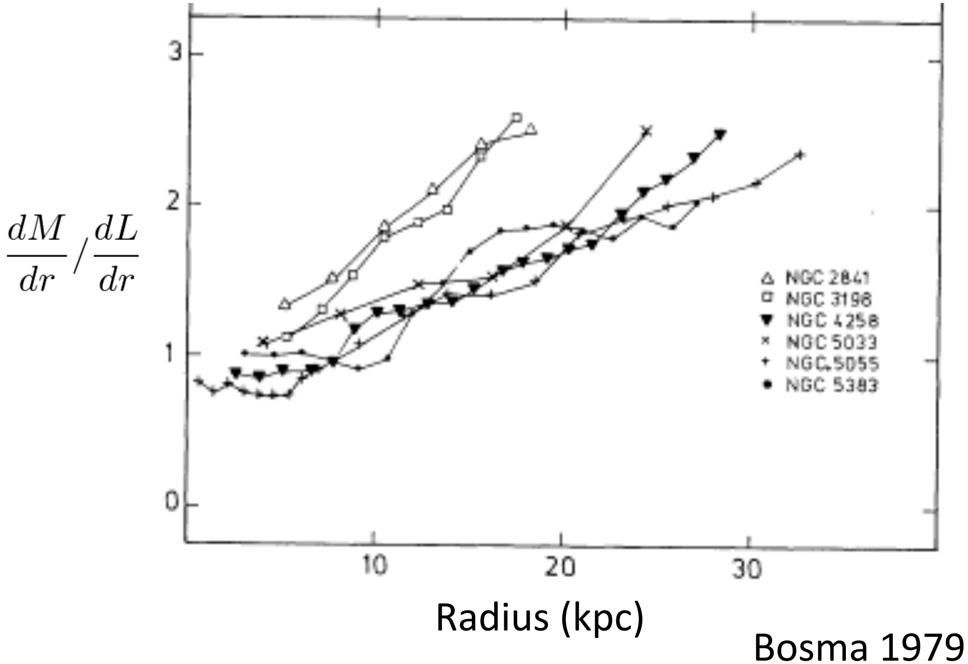
Bosma, 1981

FIG. 3. Rotation curves of 25 galaxies of various Hubble types.

HI velocity field

Light (SDSS)

NGC 5055



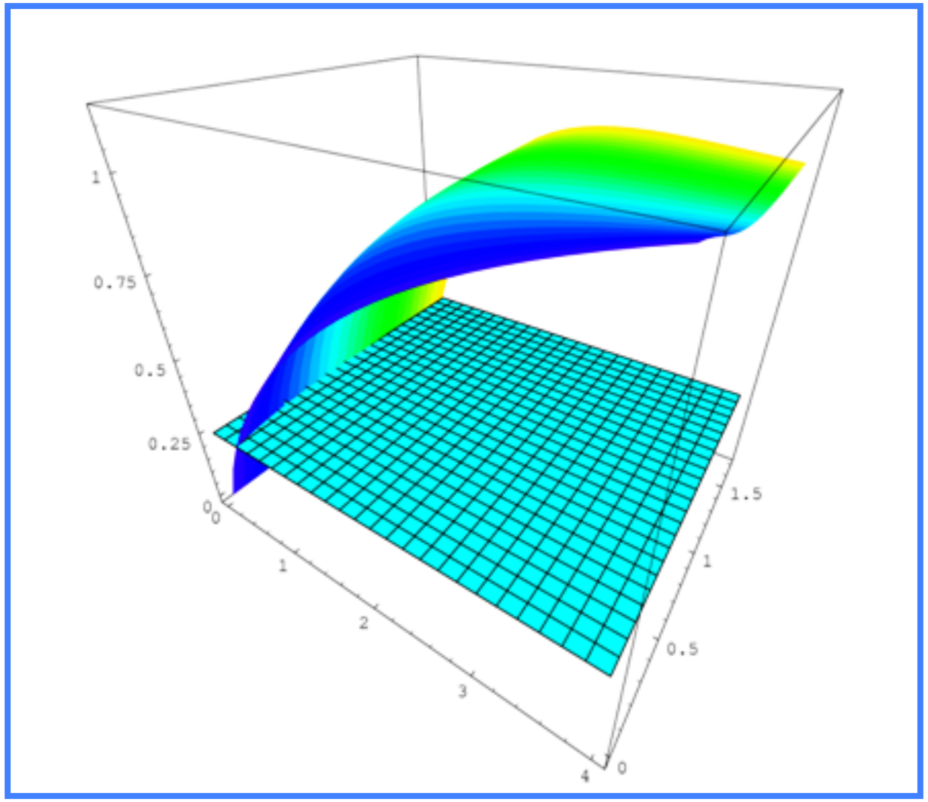
Bosma 1979

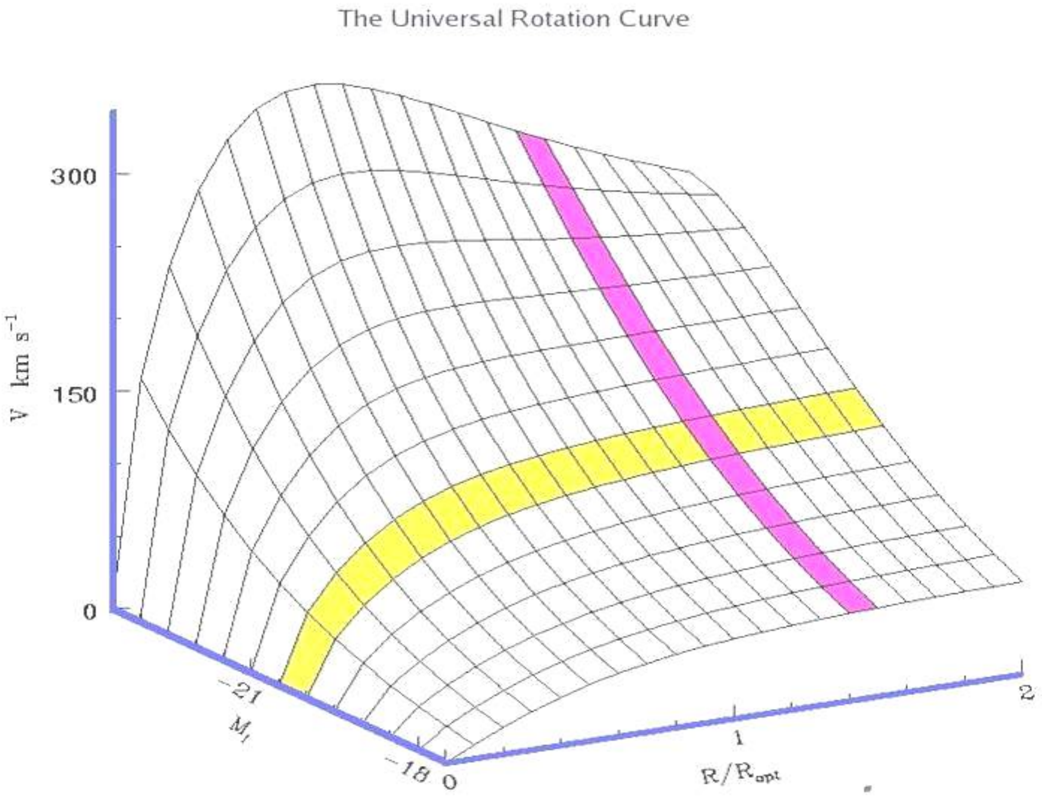
The mass discrepancy emerges as a disagreement between light and mass distributions

$$\frac{dM}{dr} \Big/ \frac{dL}{dr} \neq const = \left(\frac{M}{L}\right)_{\star}$$

The Concept of the Universal Rotation Curve (URC)

Parametrization V(R,L) of rotation curves as a function of radius and luminosity. Accurate for vast majority of spiral galaxies.





Persic et al. 1996, Salucci et al. 2009

Rotation curve analysis

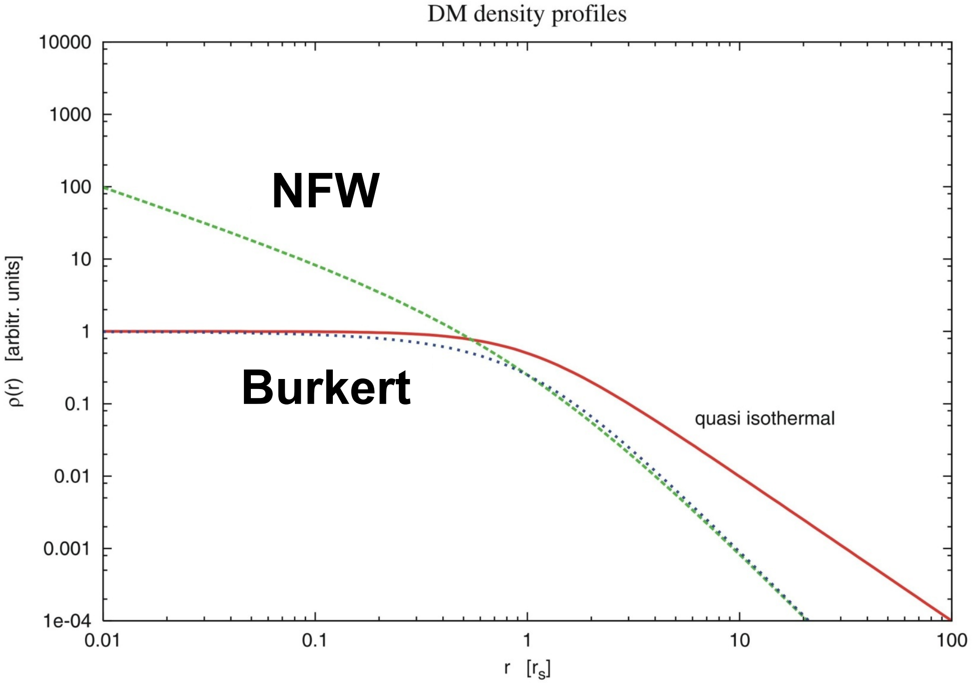
From data to mass models

$$V_{tot}^2 = V_{DM}^2 + V_{disk}^2 + V_{gas}^2$$

- V_{disk}^2 **from I-band photometry**
- V_{HI}^2 **from HI observations**
- V_{halo}^2

Dark halos with constant density cores (Burkert) $\rho(r) = \dfrac{\rho_0}{(1 + r/r_0)(1 + (r/r_0)^2)}$

Dark halos with cusps (NFW, Einasto)



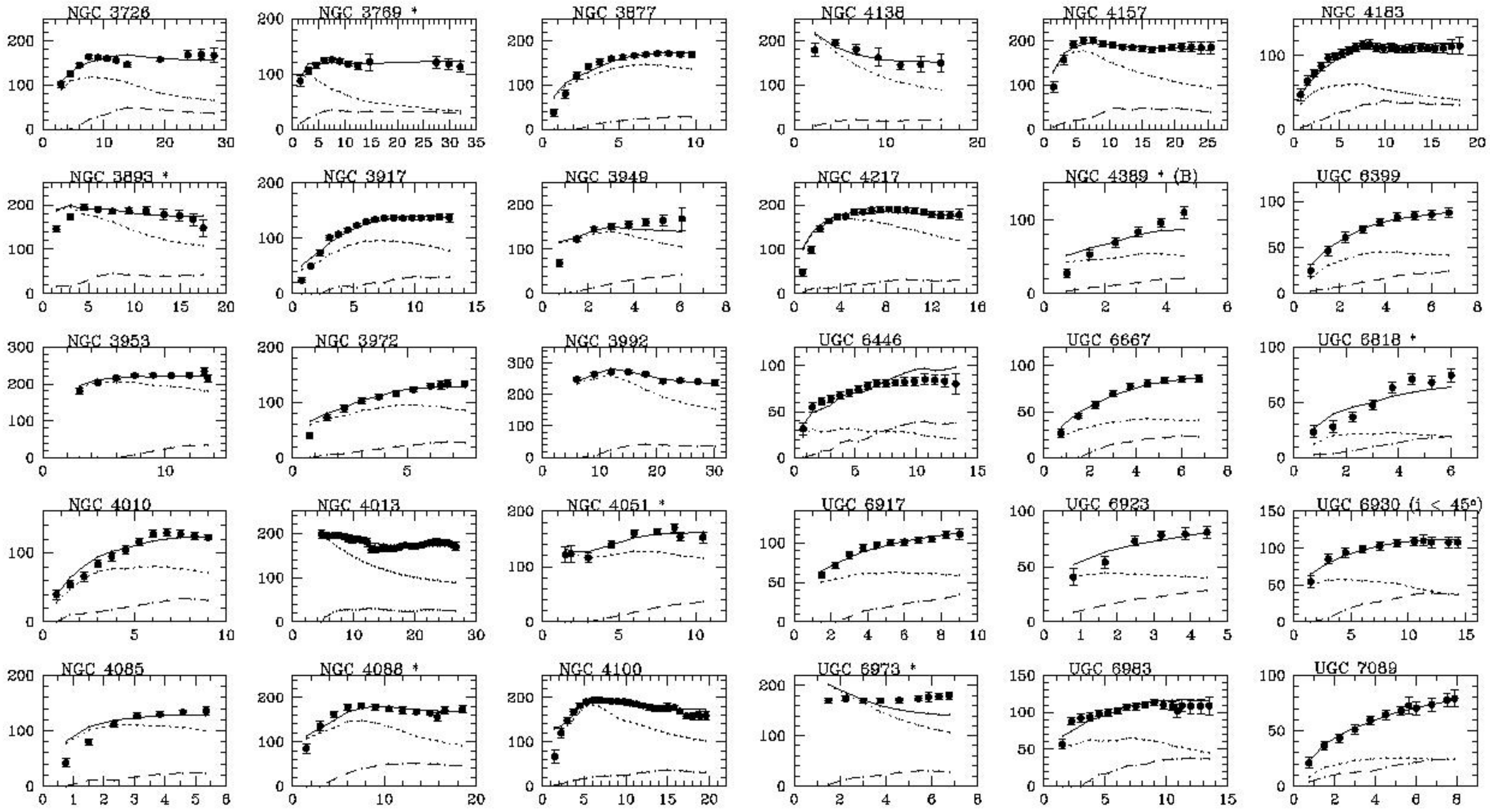
The mass model has 3 free parameters: mass, halo central density and core radius (halo length-scale).

Rotation curve analysis

From data to mass models

Also good mass modelling results with MOND
(Modified Newtonian Dynamics, Milgrom 1983).

In MOND: - no dark matter in galaxies
- gravity is “boosted” below $a_0 \approx 10^{-8}\ \mathrm{cm\ s^{-2}} \approx cH_0 / 2\pi$



Sanders & Verheijen 1998

Rotation curve analysis

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(Modified Newtonia

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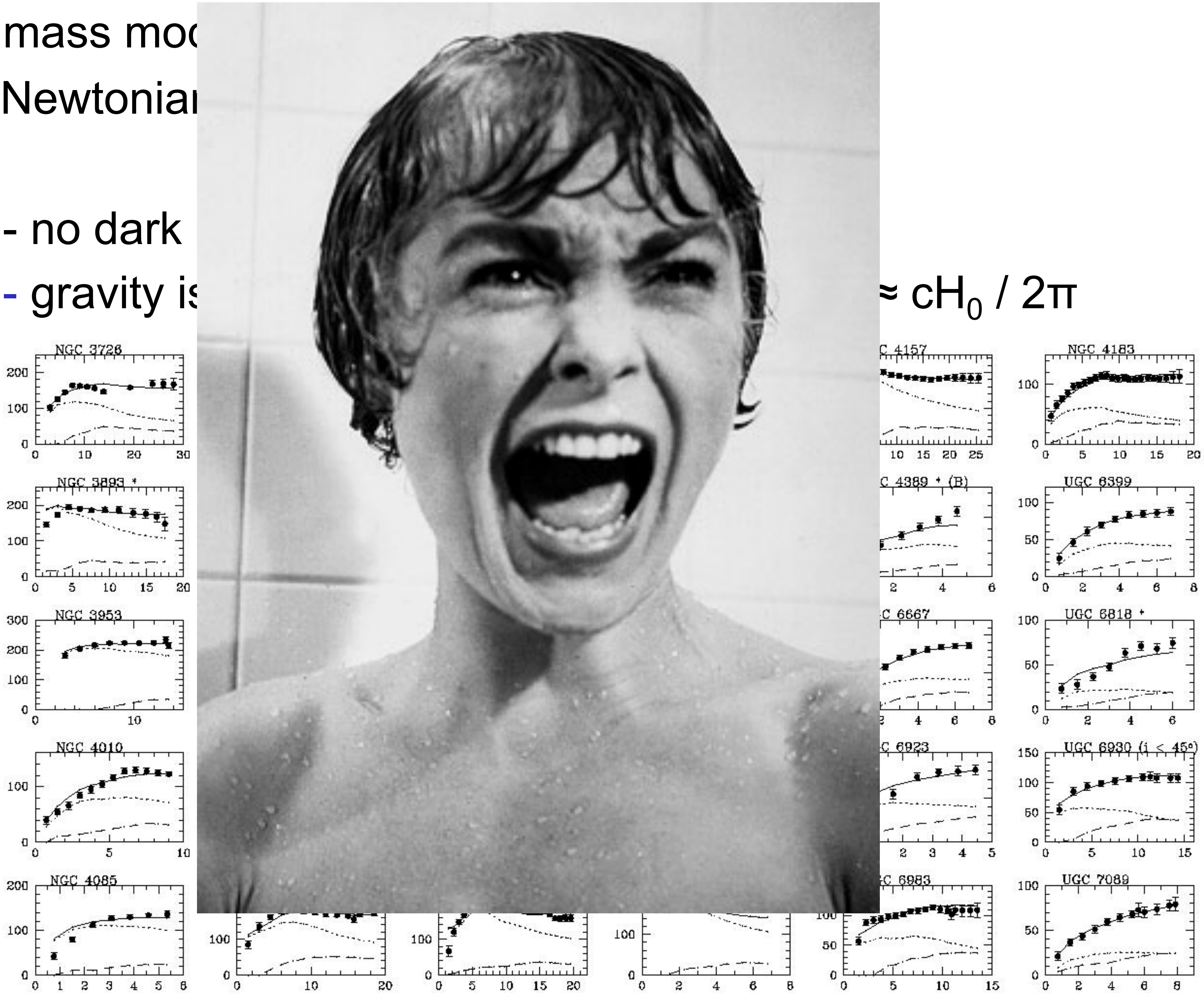
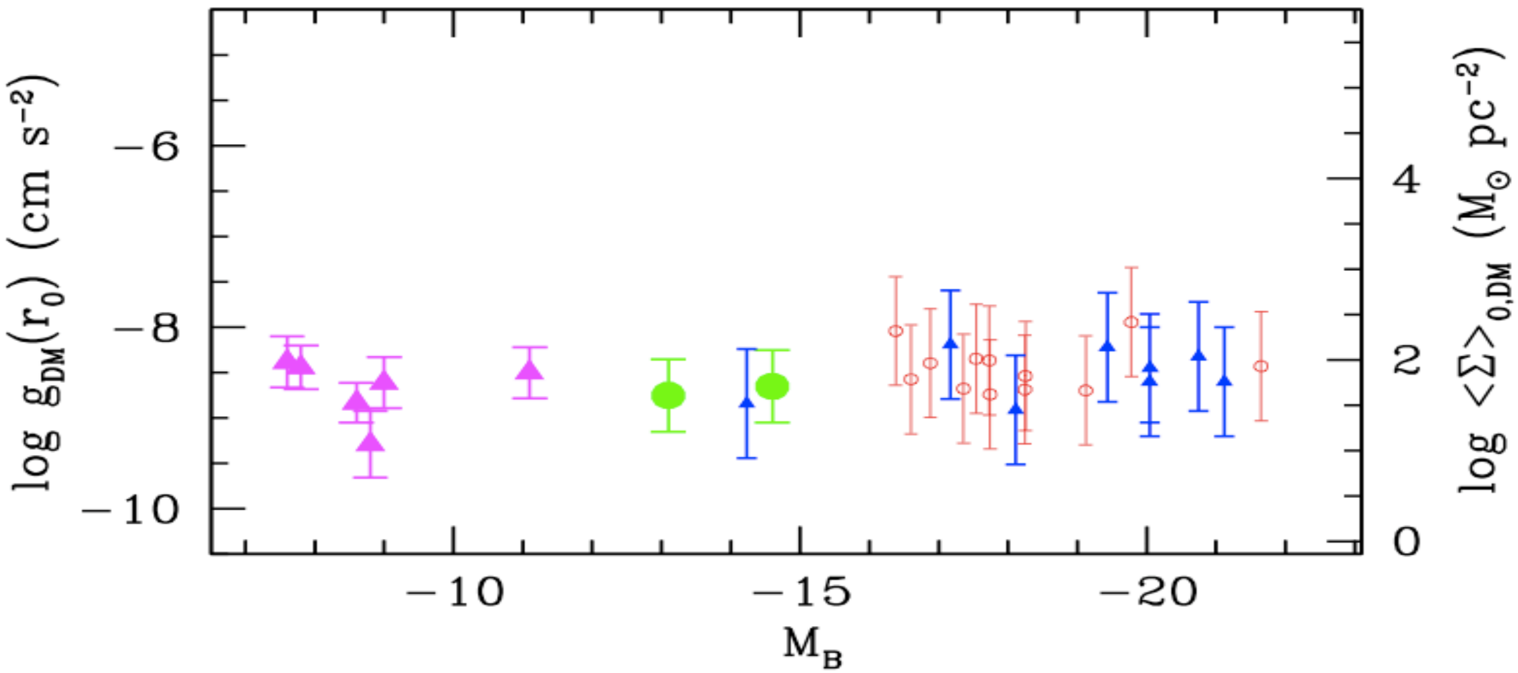
- gravity is ≈ cH_0 / 2π

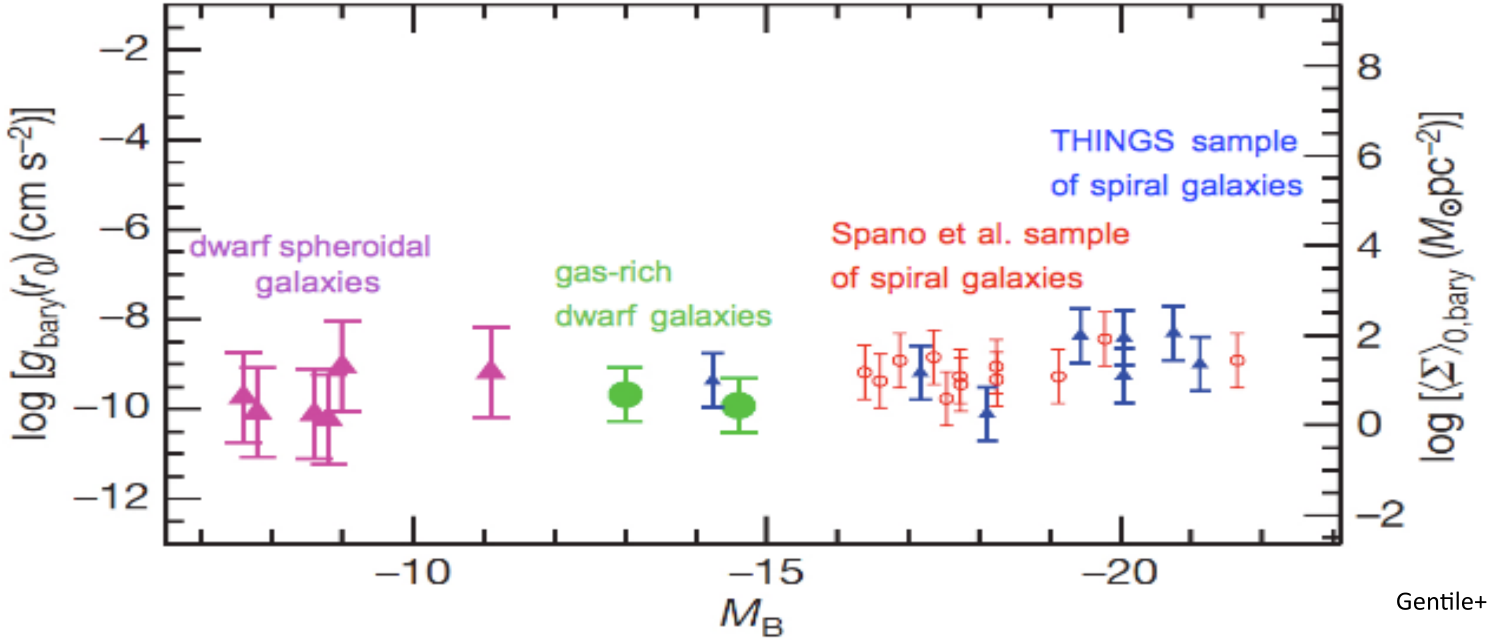


Sanders & Verheijen 1998

Dark matter - baryons scaling laws



Donato+09, MNRAS



Gentile+09, Nature

Dark matter - baryons scaling laws

Mean dark matter surface density within r_0 of a Burkert halo is:

$$\langle \Sigma \rangle_{0,\,\mathrm{dark}} = M_{<r_0} / \pi r_0^2 \approx \boxed{0.51 \rho_0 r_0} = 72^{+42}_{-27}\ M_{\odot} \mathrm{pc}^{-2}$$

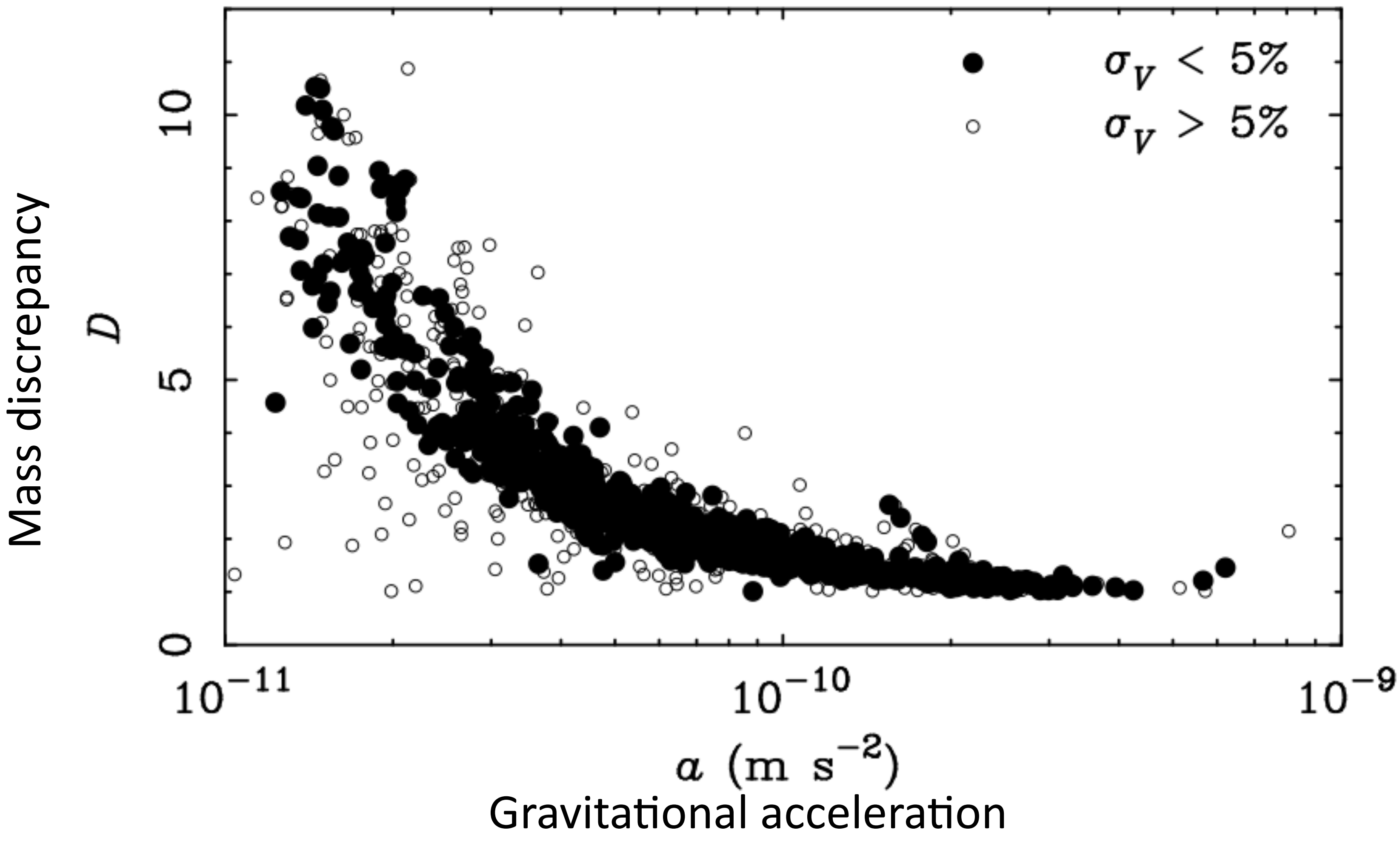
where $M_{<r0}$ is the enclosed dark matter mass within r_0

This is equivalent to:

$$g_{\mathrm{dark}}(r_0) = \boxed{G\pi \langle \Sigma \rangle_{0,\,\mathrm{dark}}} = 3.2^{+1.8}_{-1.2}\ 10^{-9}\,\mathrm{cm\ s}^{-2}$$

the **gravitational acceleration generated by dark matter at r_0**
is also universal

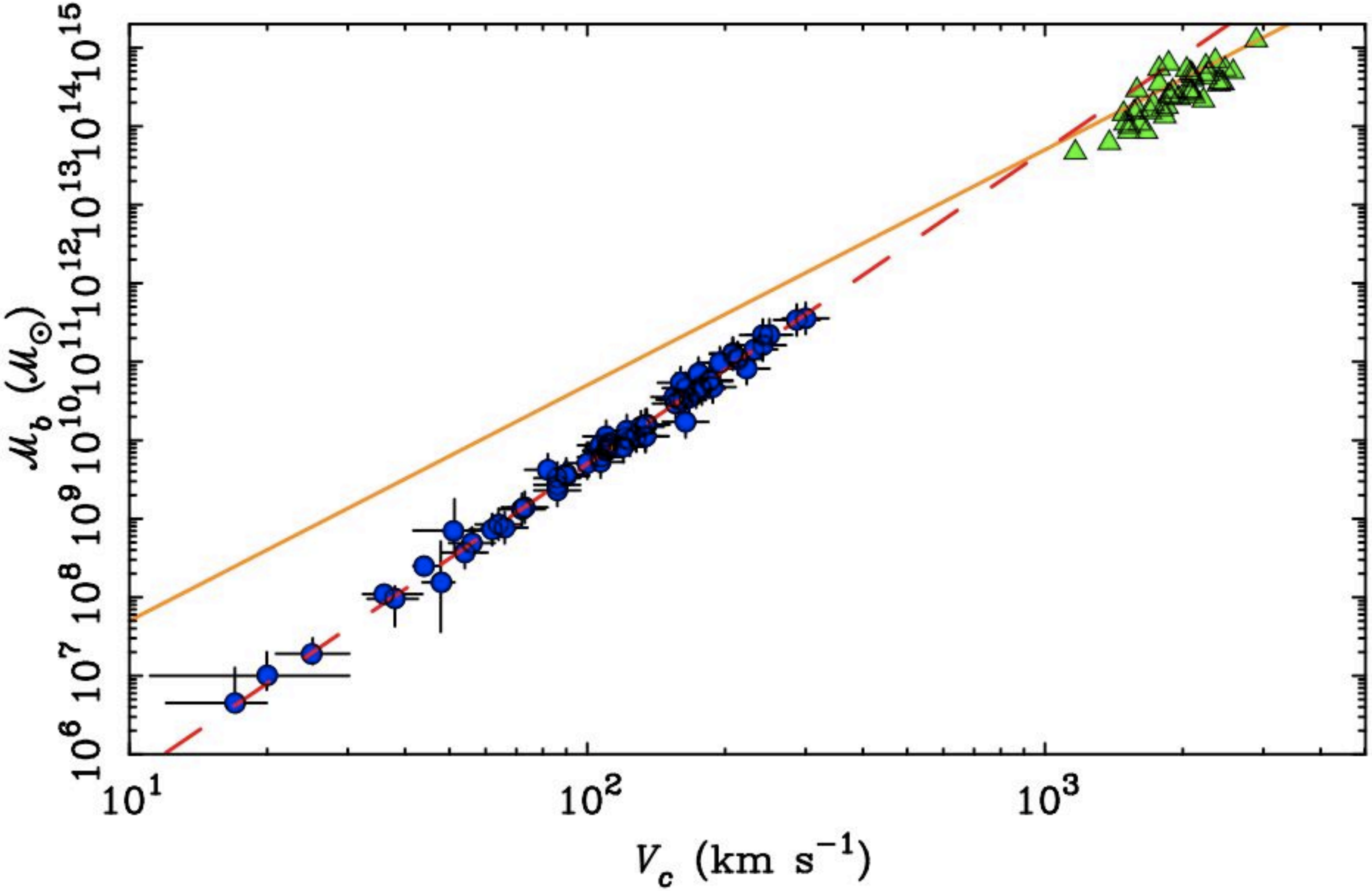
Dark matter - baryons scaling laws
Mass discrepancy - acceleration relation



McGaugh 2004

Dark matter - baryons scaling laws
Baryonic Tully-Fisher relation

Baryonic mass



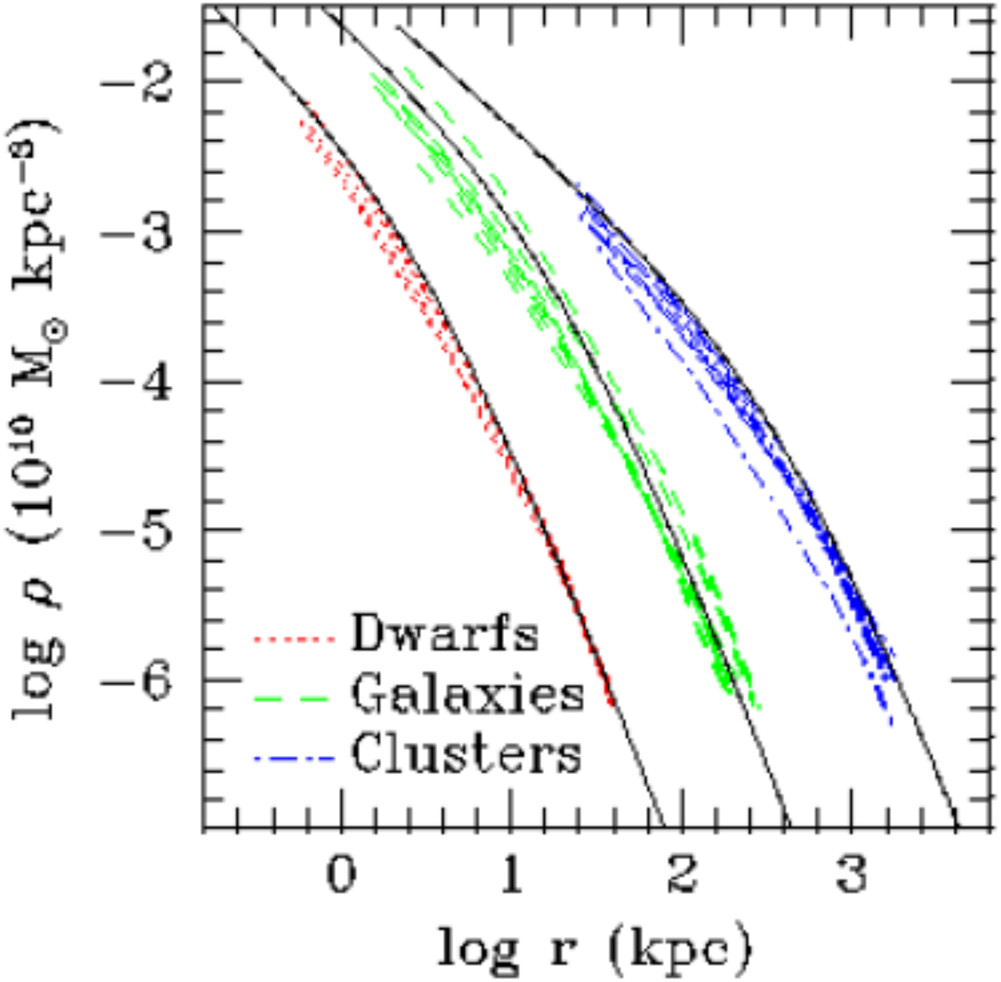
Rotation velocity

McGaugh 2005

Dark Matter Profiles from N-body simulations

In ΛCDM scenario the density profile for virialized DM halos of all masses is empirically described at all times by the universal (NFW) profile (Navarro+96,97).

$$\rho(r)/\rho_{crit} \approx \delta\, r_s / r(1 + r/r_s)^2$$



Object today virialized:

mean halo density inside R_{vir} = 100 ϱ_c

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

Concentration $c = R_{vir} / r_s$

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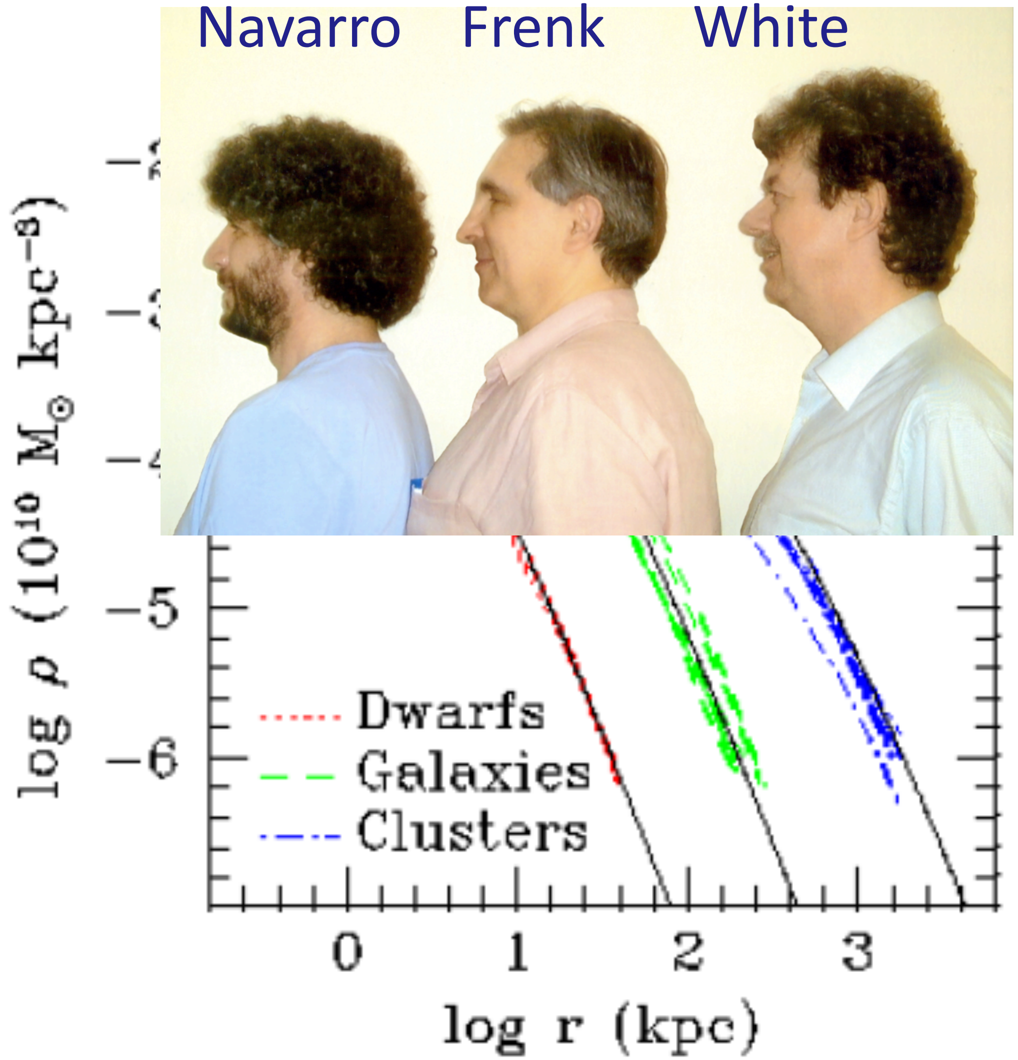

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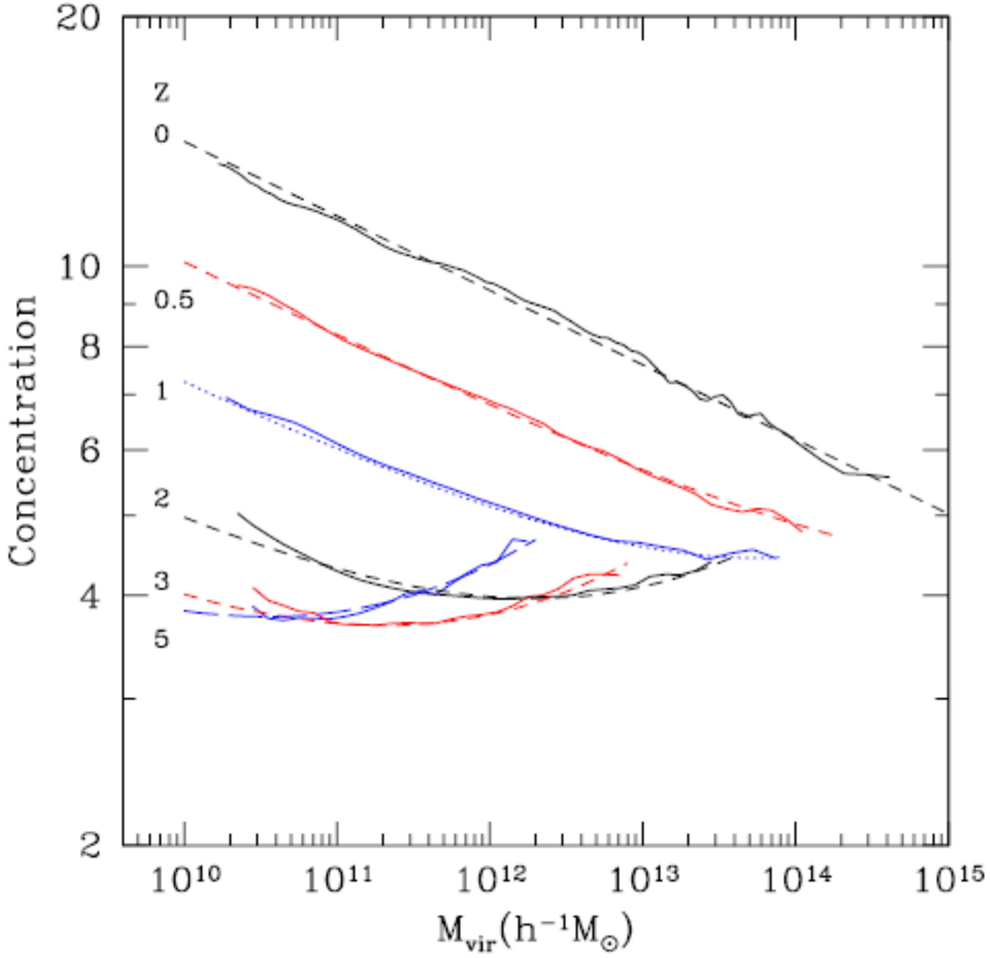
Concentration $c = R_{vir} / r_s$

The concentration scales with mass and redshift (Zhao+03,08; Gao+08, Klypin +10):

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

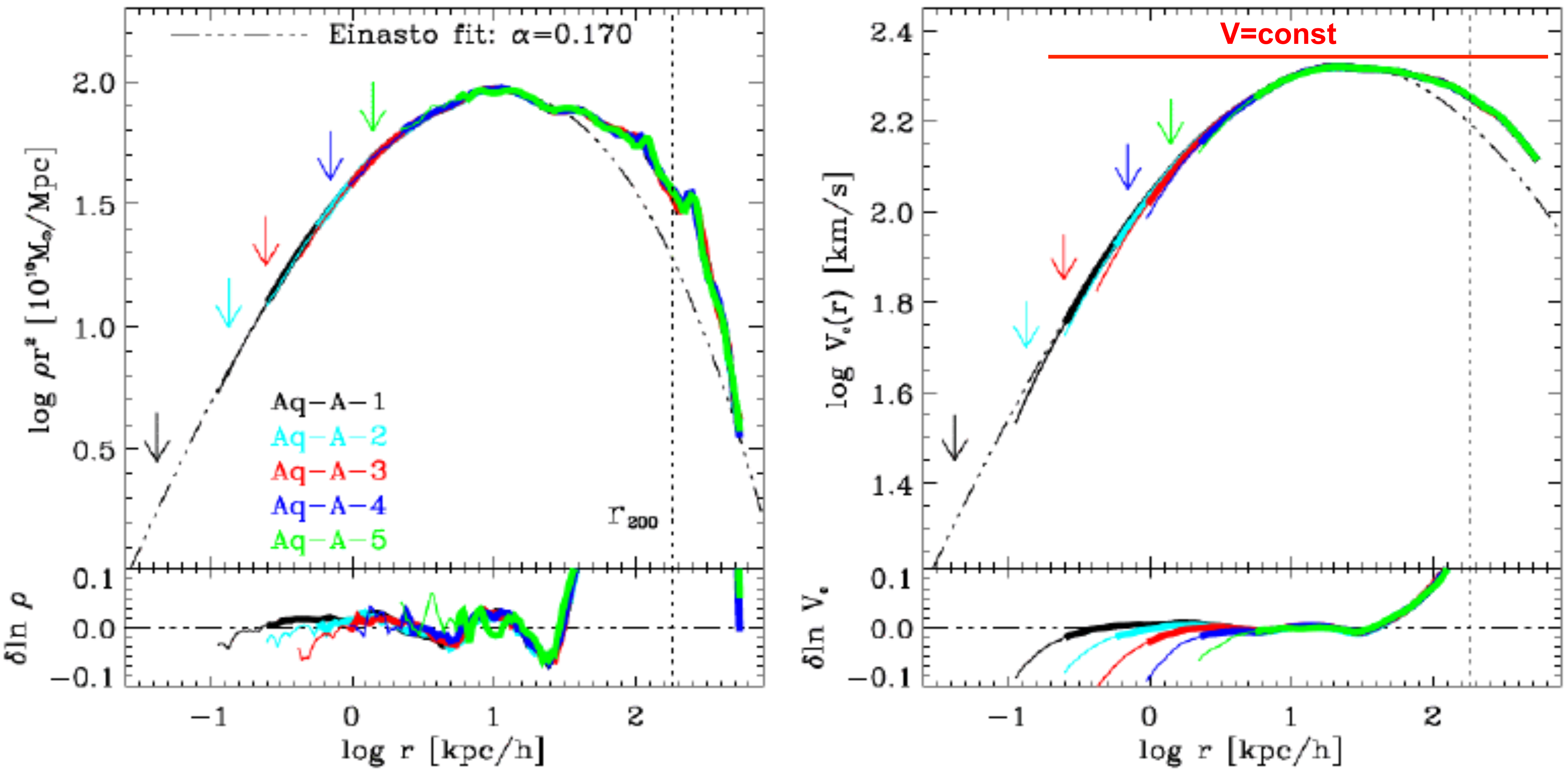
At z=0, c decreases with mass.



Aquarius simulations, highest mass resolution to date.

Density distribution: still a cuspy profile but similar to the Einasto Law Navarro+10
No difference, for mass modelling, with the NFW one.

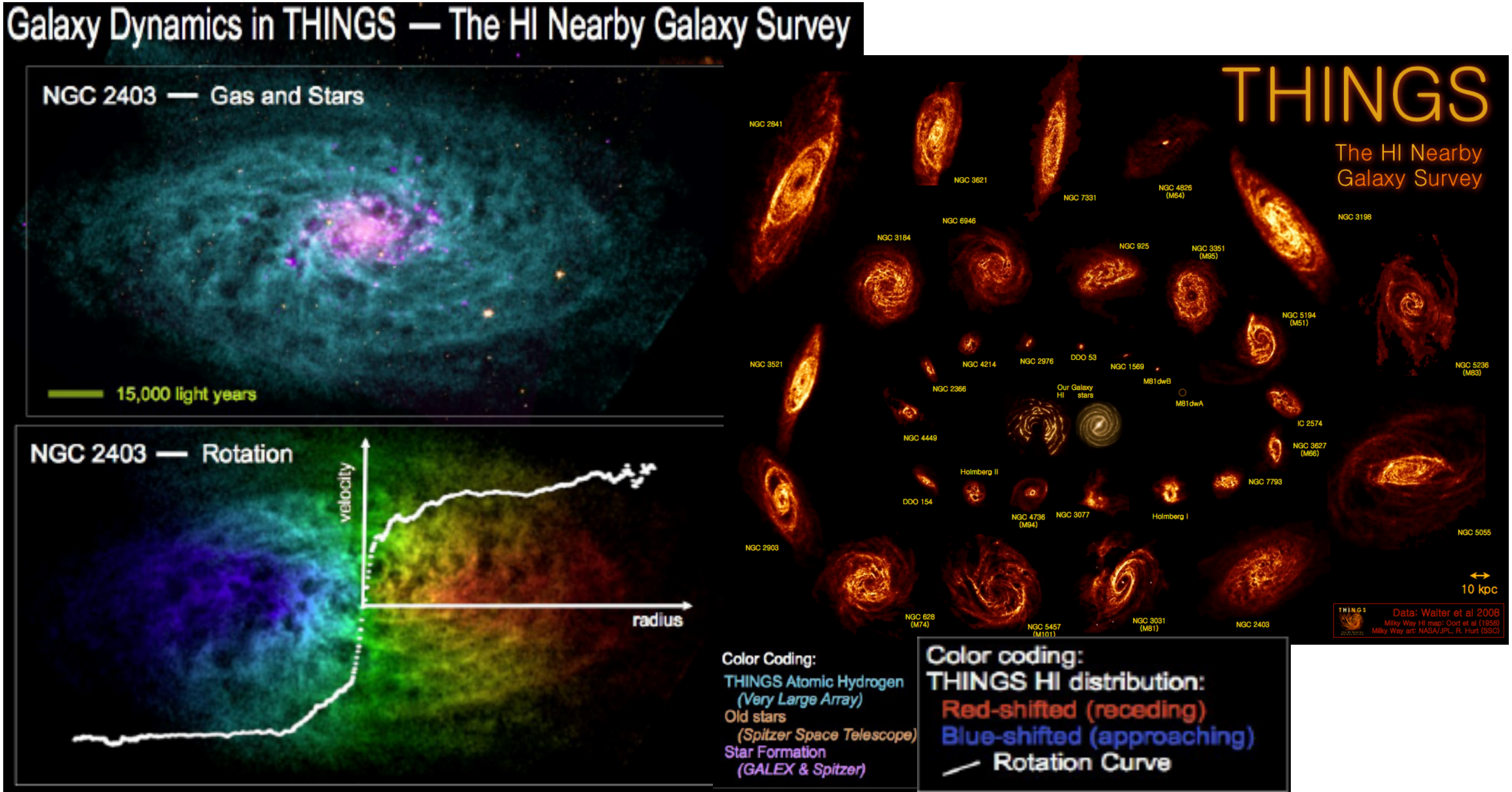
density and circular velocity for an halo of 10^{12} M_{SUN}

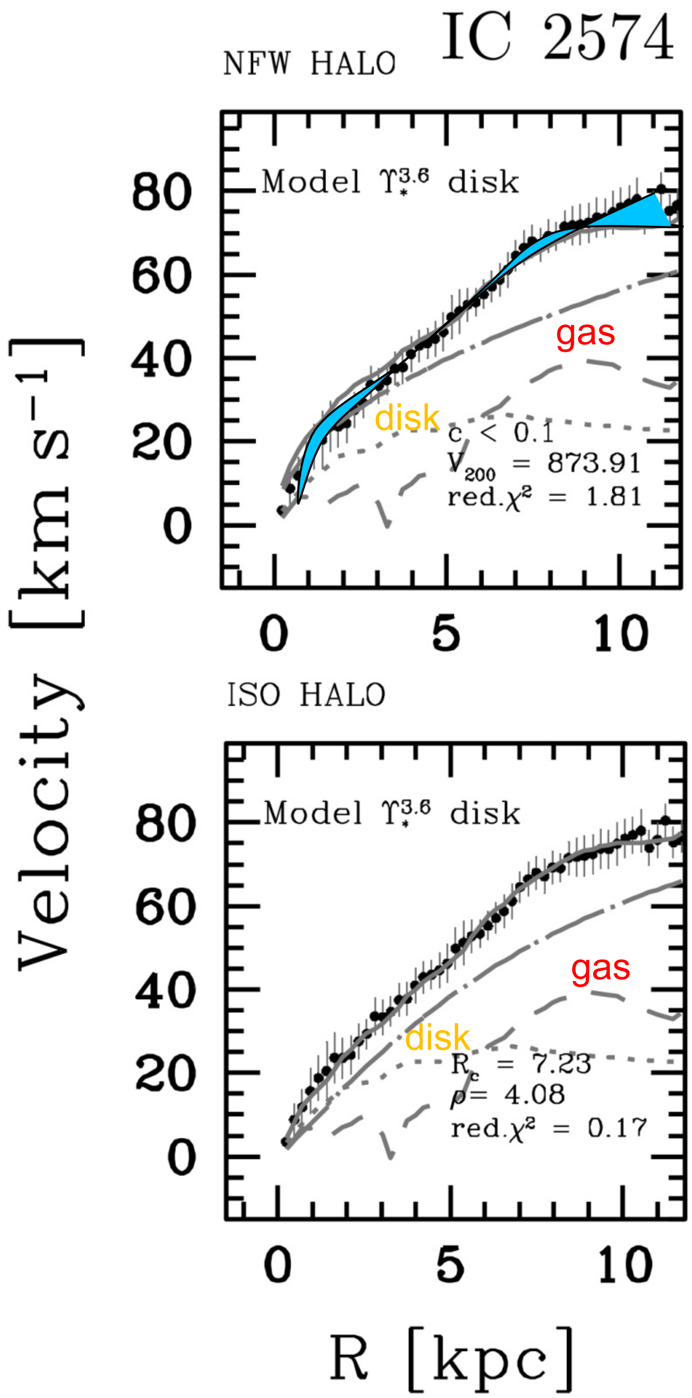


Comparing observations and simulations

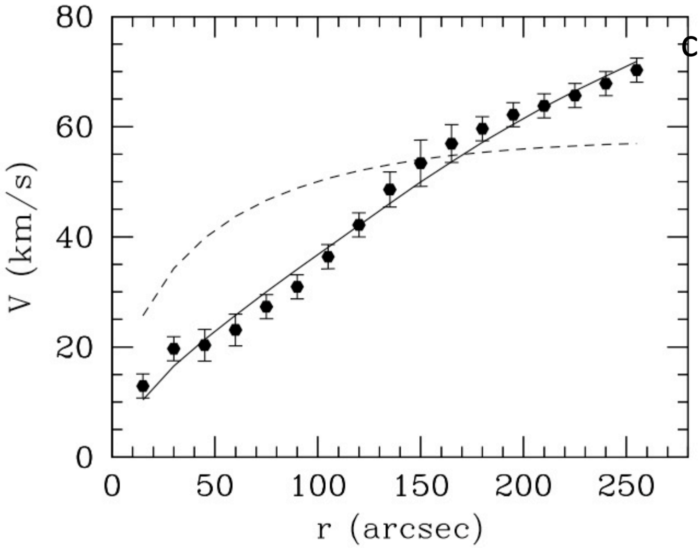
Using individual galaxies Gentile+ 2004, de Blok+ 2008 Kuzio de Naray+ 2008, Oh+ 2008, Spano + 2008, Trachternach+ 2008, Donato+,2009

A detailed investigation: high quality data and model independent analysis





DDO 47



cored halo

cuspy halo (NFW)

Gentile+05

General results from several samples including THINGS, HI survey of uniform and high quality data

- Non-circular motions are small.
- No DM halo elongation
- ISO/Burkert halos preferred over NFW

- **Tri-axiality and non-circular motions cannot explain the CDM/NFW cusp/core discrepancy**

ELLIPTICALS

M87 © Anglo-Australian Observatory
Photo by David Malin

The Stellar Spheroid

Surface brightness of ellipticals follows a Sersic (de Vaucouleurs) law

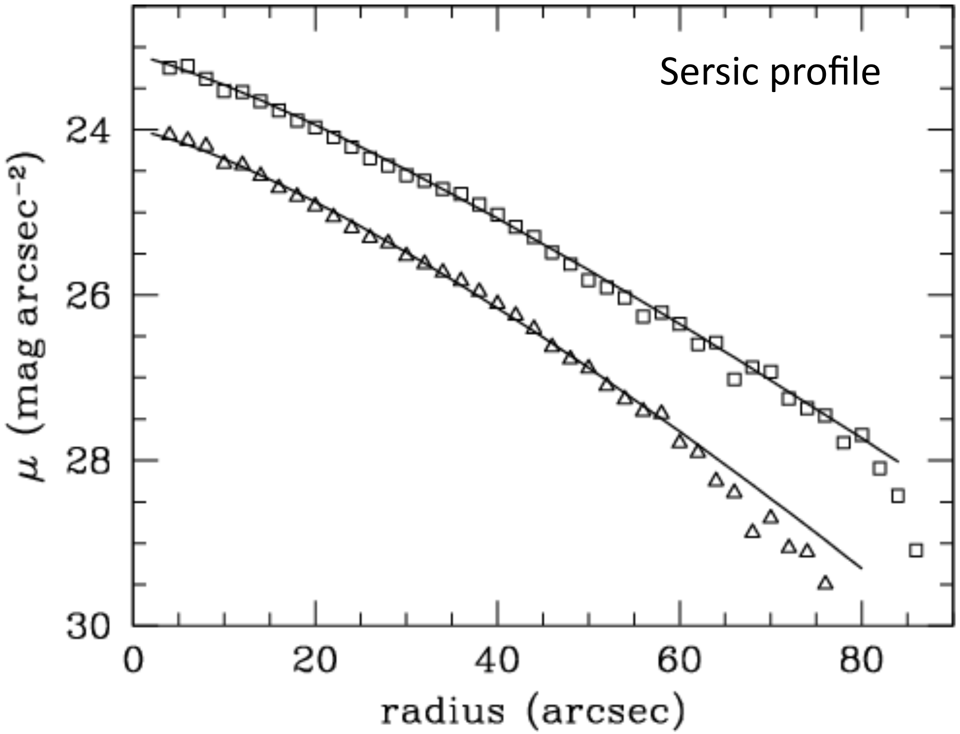
$$I(R) = I_e e^{-b_n[(R/R_e)^{1/n} - 1]}$$

R_e : the effective radius

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

$$I(R) = \int_{-\infty}^{+\infty} j(r)\,dz = 2\int_{R}^{+\infty} \frac{j(r)\,r\,dr}{\sqrt{r^2 - R^2}} \qquad \rho_{sph}(r) = (M/L)_\star\, j(r)$$

ESO 540 -032



Modelling Ellipticals

Measure the light profile

Derive the total mass profile from

- Dispersion velocities of stars or Planetary Nebulae
- X-ray properties of the emitting hot gas
- Combining weak and strong lensing data

Disentangle the dark and the stellar components

Line-of-sight, projected Velocity Dispersions, 2-D kinematics

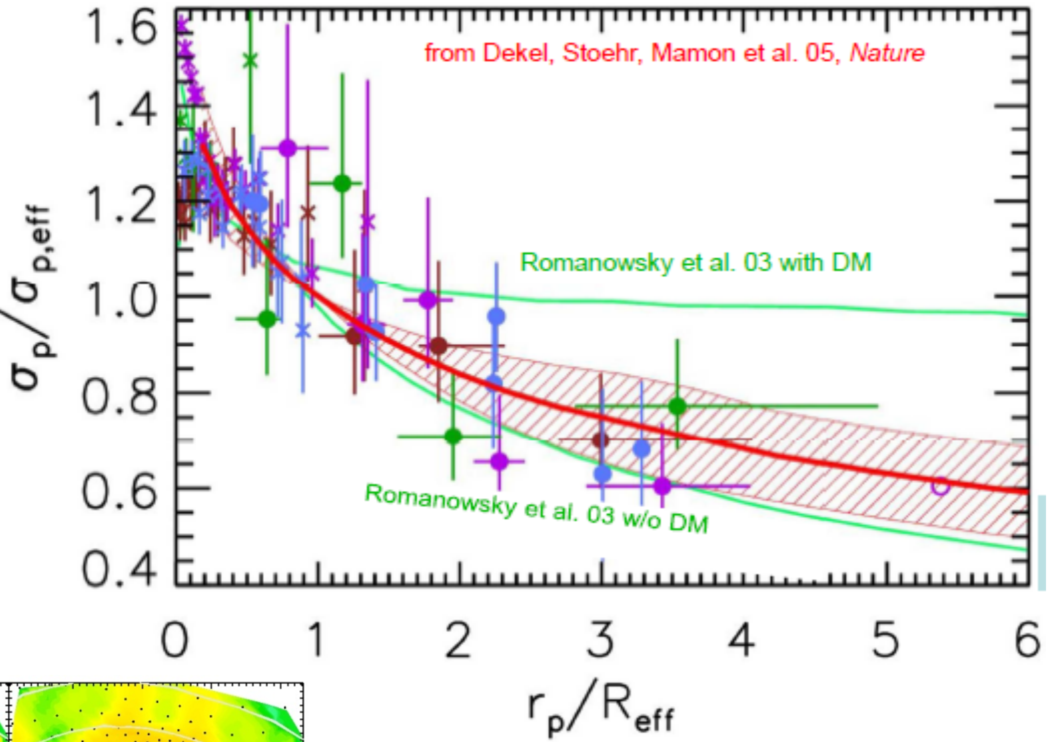
$$M(r) = M_{sph}(r) + M_h(r).$$

$$\sigma_r^2(r) = \frac{G}{\rho_{sph}(r)} \int_r^\infty \frac{\rho_{sph}(r') M(r')}{r'^2}\, dr'$$

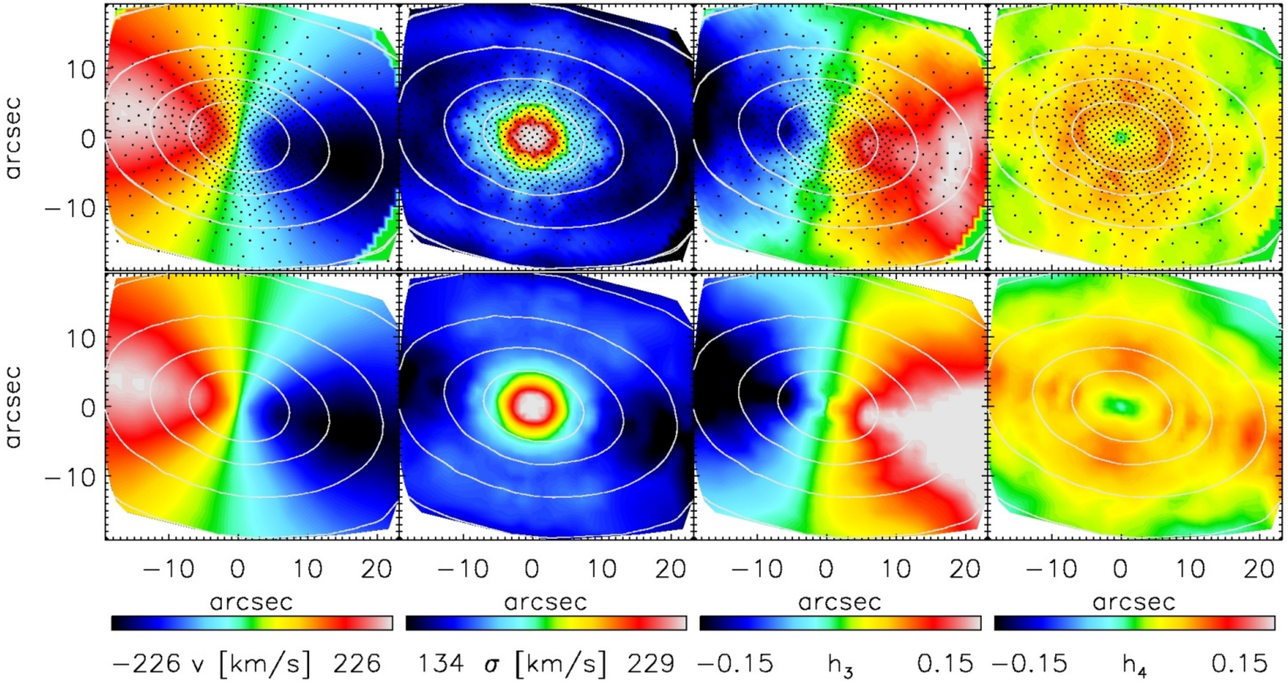
$$\sigma_P^2(R) = \frac{2}{I(R)} \int_R^\infty \frac{\rho_{sph}(r)\ \sigma_r^2(r)\ r}{\sqrt{r^2 - R^2}}\, dr$$

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

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



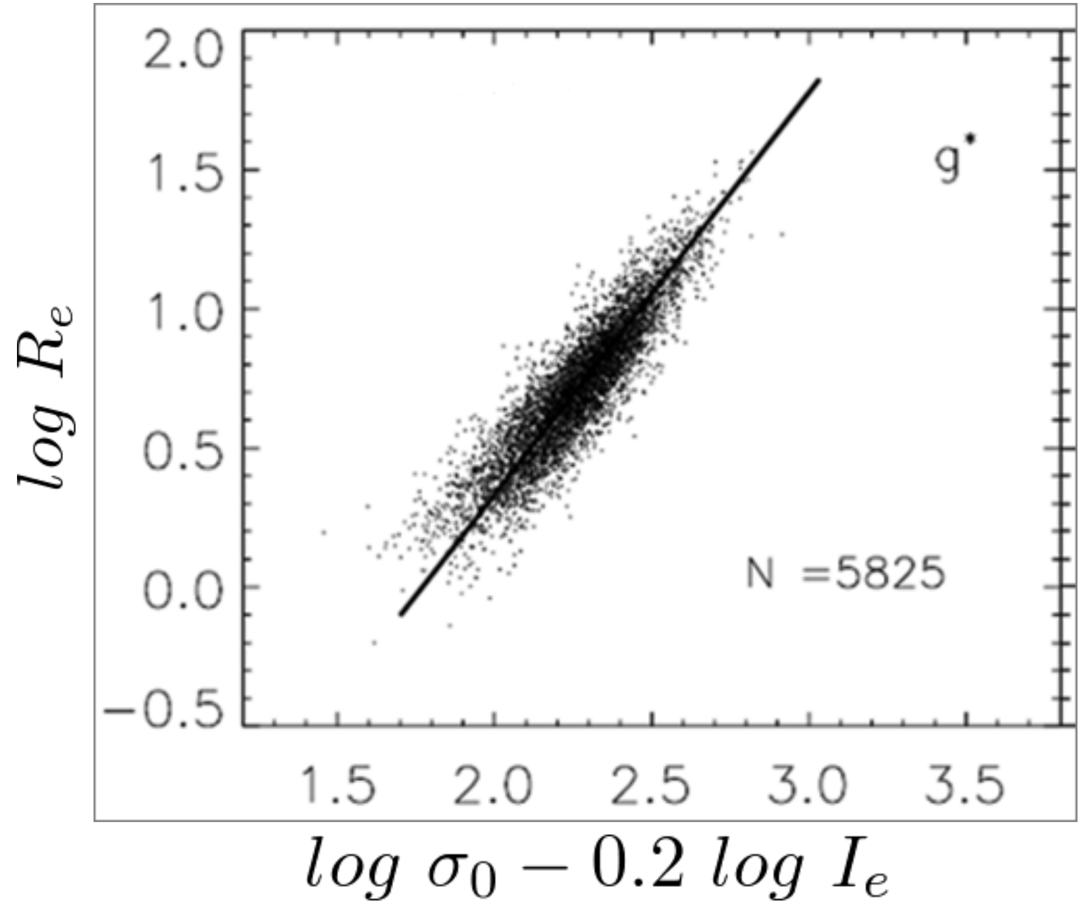
SAURON data of N 2974



The Fundamental Plane: central dispersion velocity, half light radius and central surface brightness are related

SDSS early-type galaxies

Bernardi et al. 2003



From virial theorem

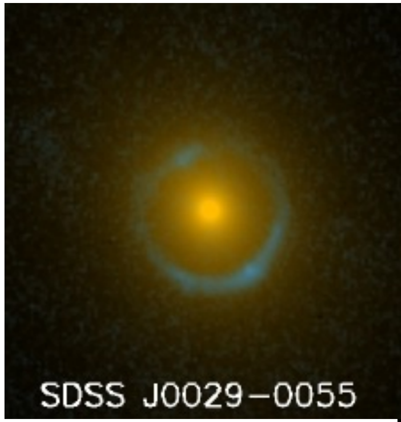
$$\sigma^2 \propto \frac{M}{r} \propto \left(\frac{M}{L}\right)\left(\frac{L}{r}\right) \propto \left(\frac{M}{L}\right)\left(\frac{L}{r^2}\right) r$$

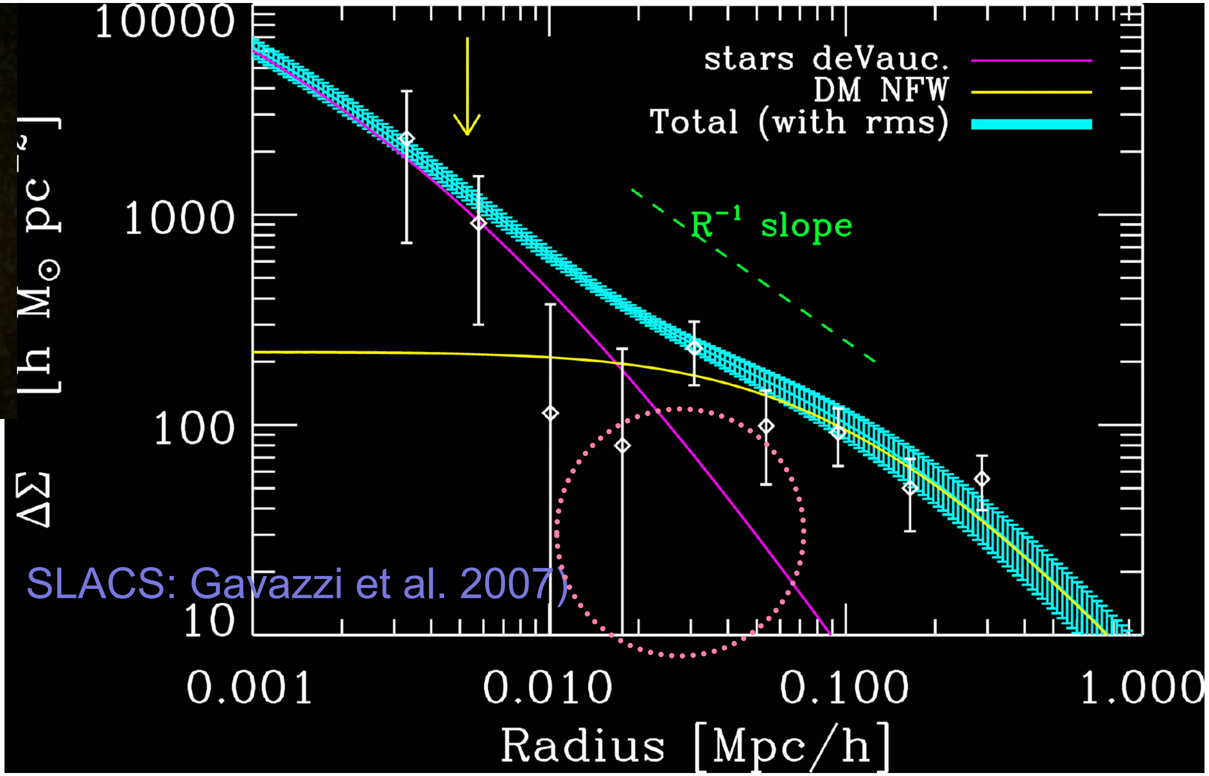
Hyde & Bernardi 2009

Fitting $R_e \propto \sigma_0^a I_e^b$

gives: a=1.8 , b~0.8
then:

Weak and strong lensing

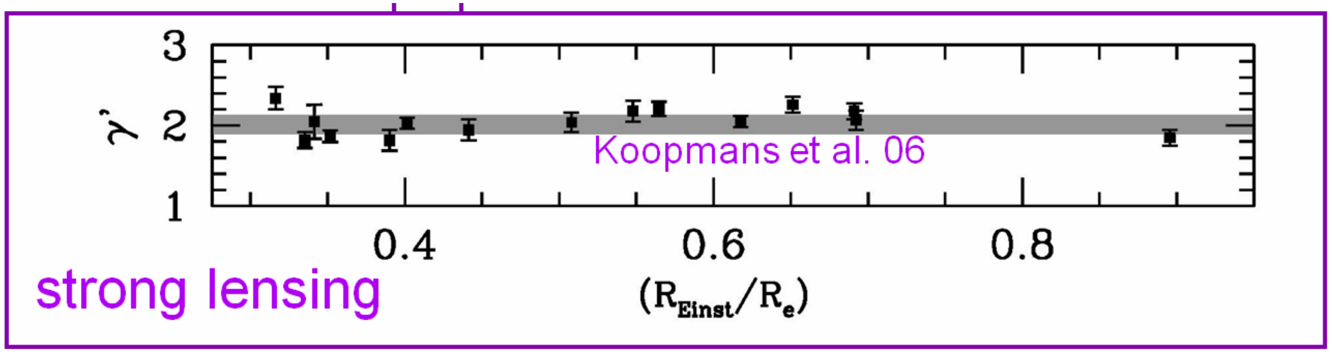




SLACS: Gavazzi et al. 2007

Gavazzi et al 2007

Inside R_e, the total (spheroid + dark halo) mass increases proportionally to the radius



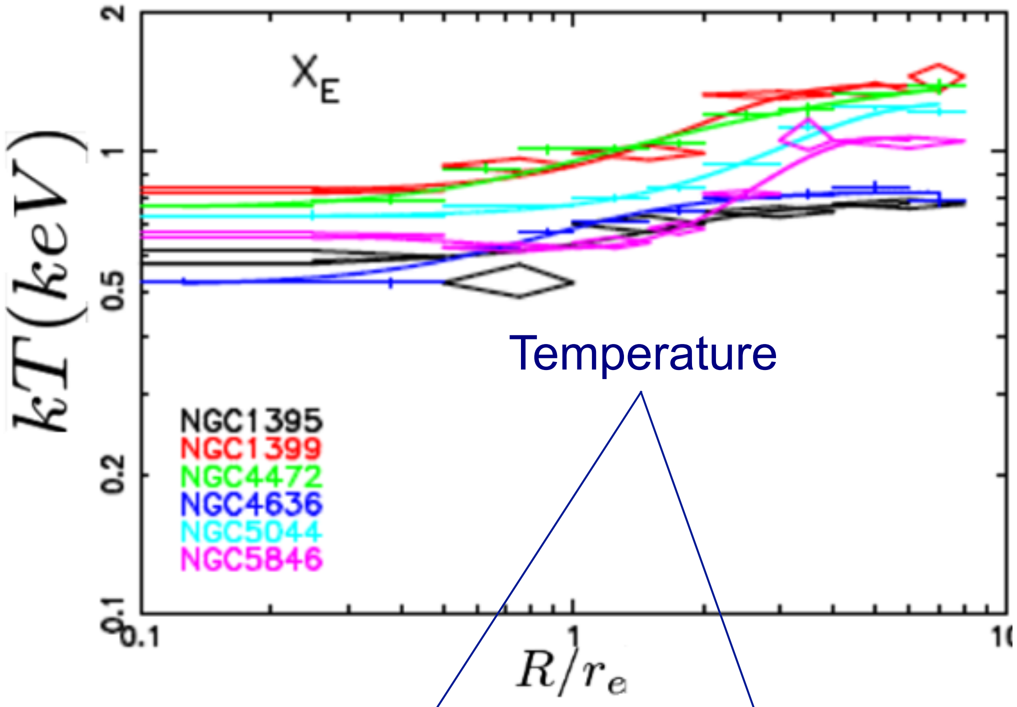
Koopmans et al. 06

strong lensing

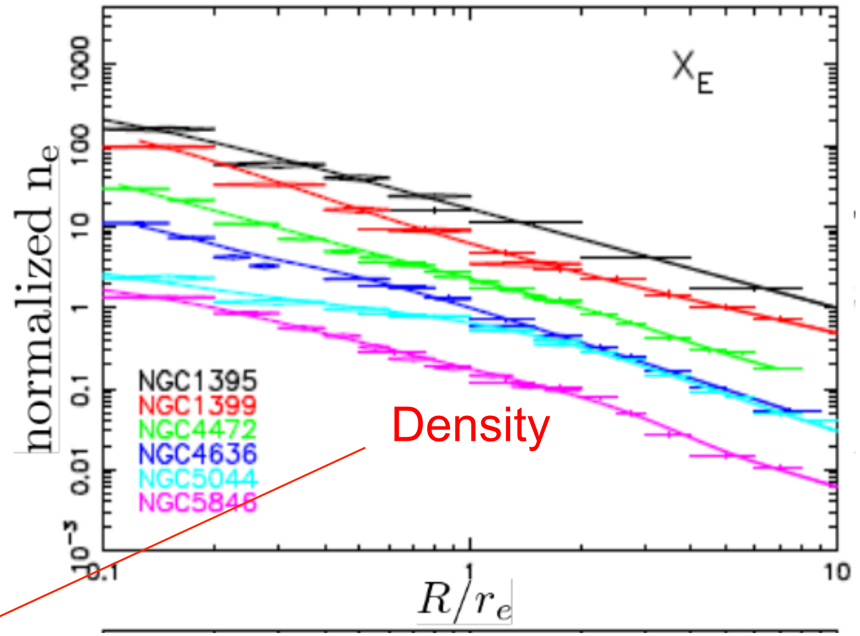
UNCERTAIN DM DENSITY PROFILE

Mass Profiles from X-ray

Nigishita et al 2009



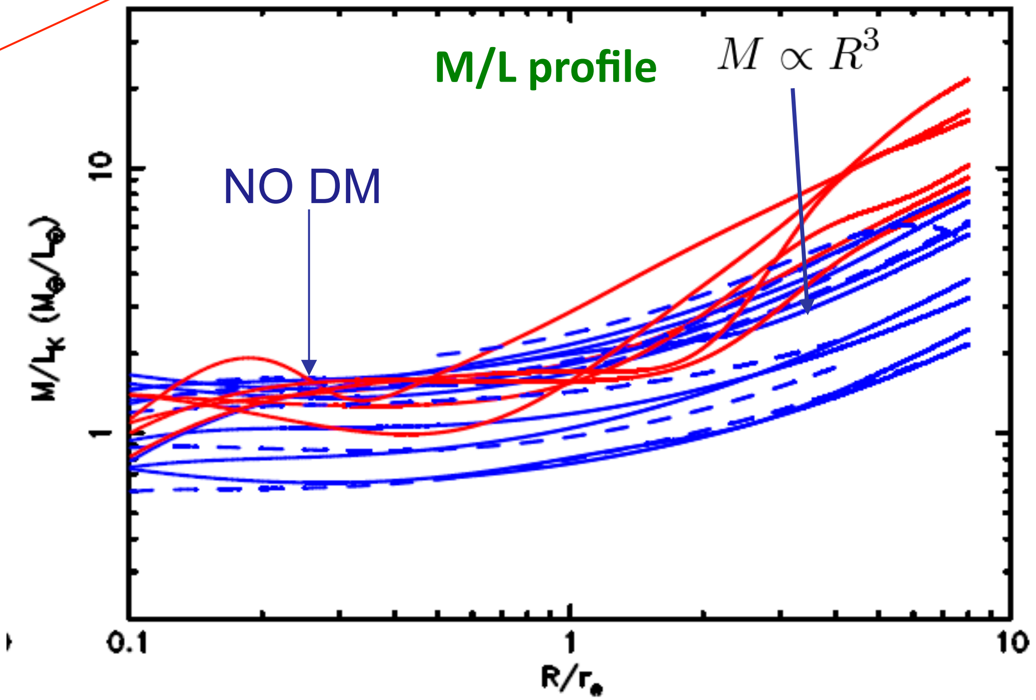
Temperature



Density

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

Hydrostatic Equilibrium

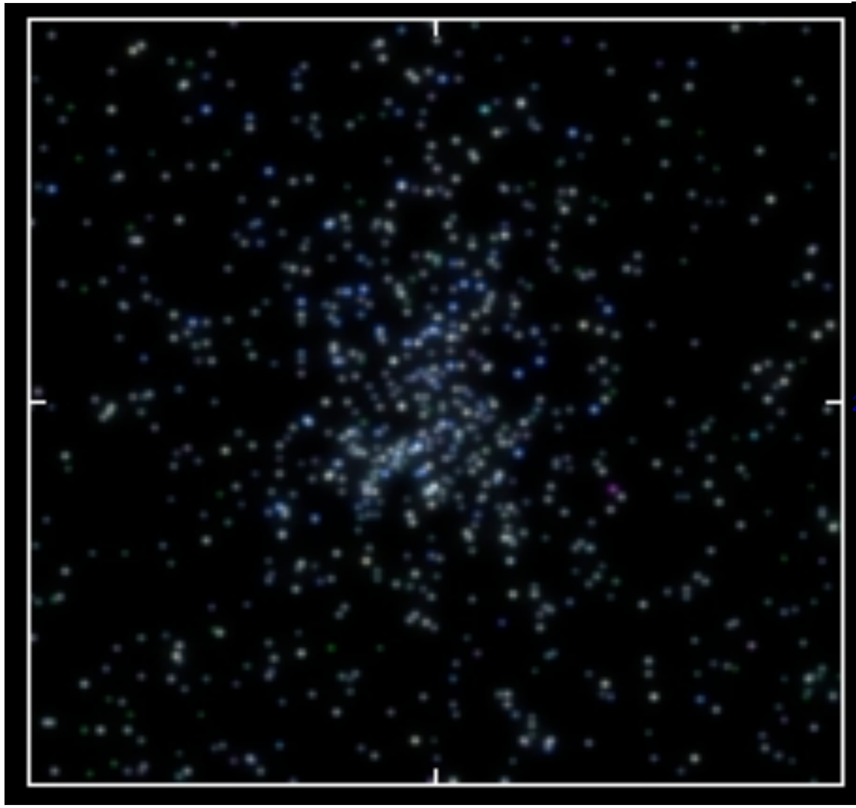


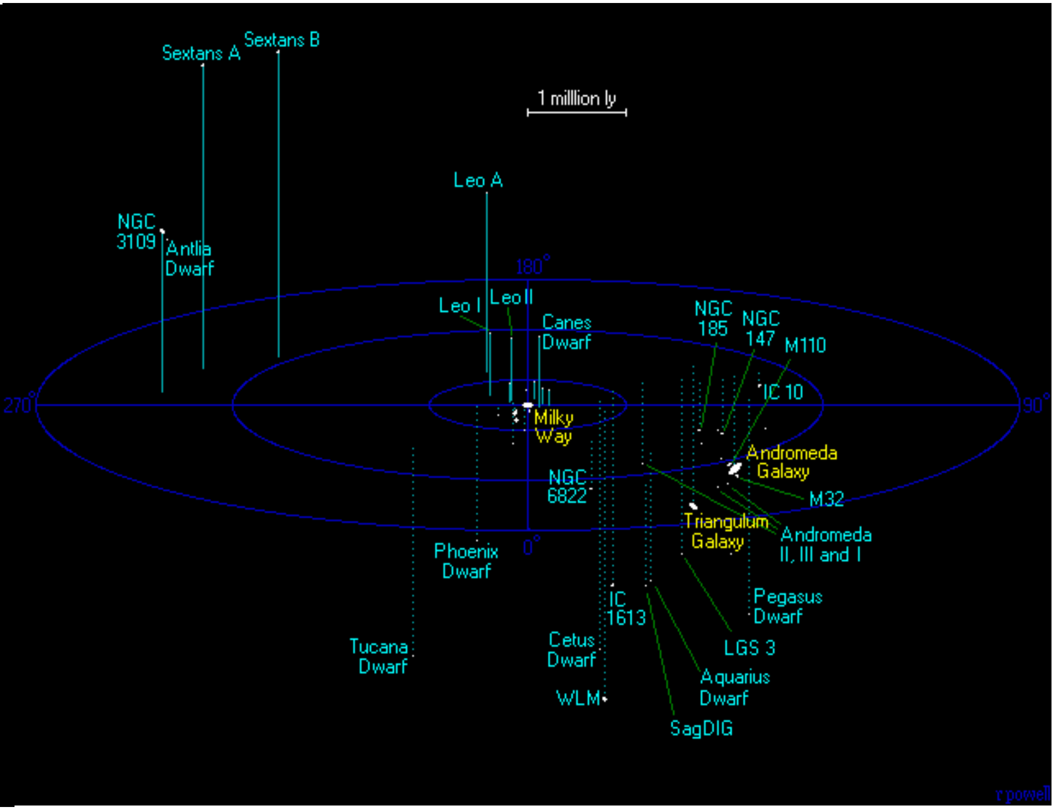
M/L profile

$M \propto R^3$

NO DM

dwarf Spheroidals



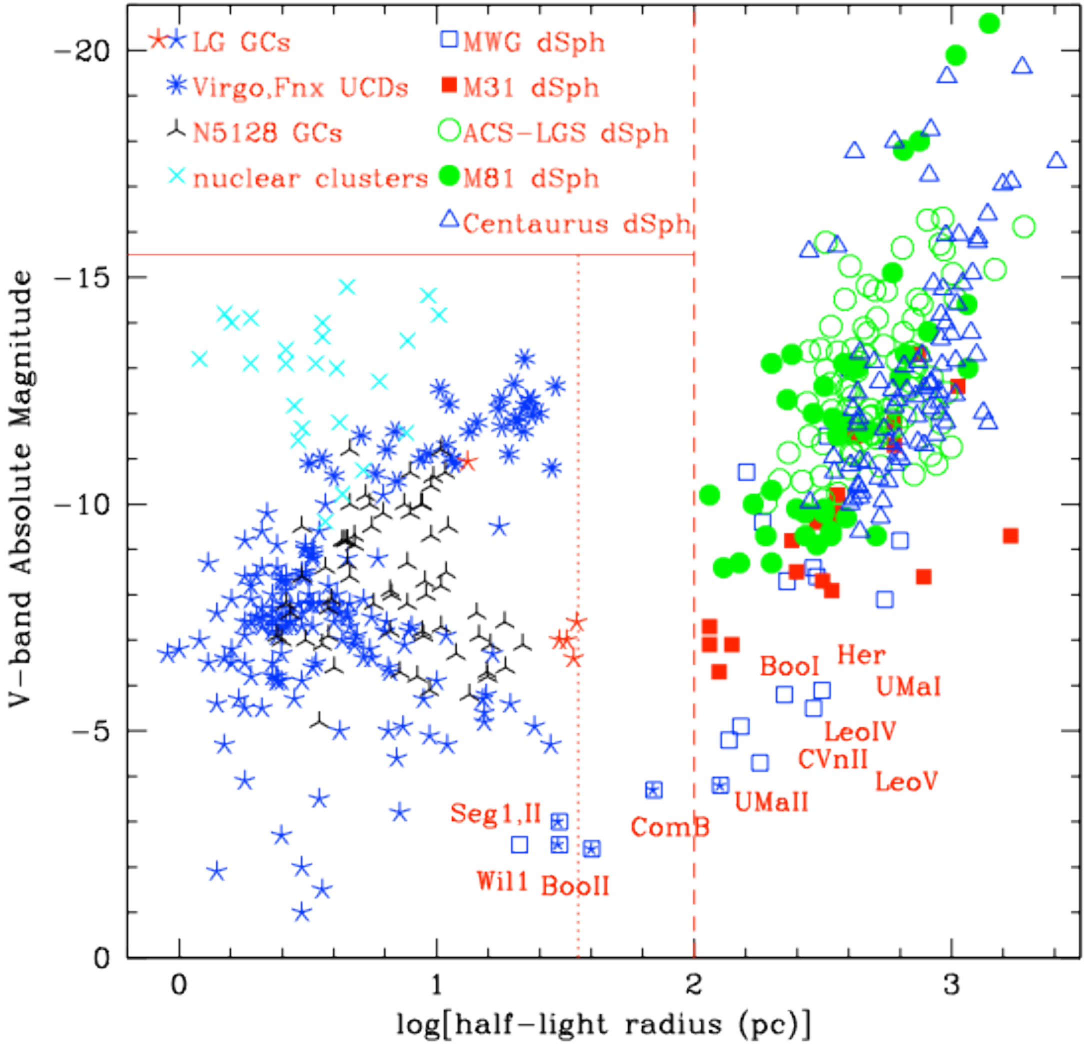


Dwarf spheroidals: basic properties

$$L = 2\times 10^{3} L_{\odot} - 2\times 10^{7} L_{\odot} \quad \sigma_0 \sim 7-12\,\mathrm{km\,s^{-1}} \quad r_0 \approx 130-500\,\mathrm{pc}$$

Low luminosity, gas-free satellites of Milky Way and M31

Large mass-to-light ratios (10 to 100), smallest stellar systems containing dark matter



Luminosities and sizes of Globular Clusters and dSph

Gilmore et al 2009

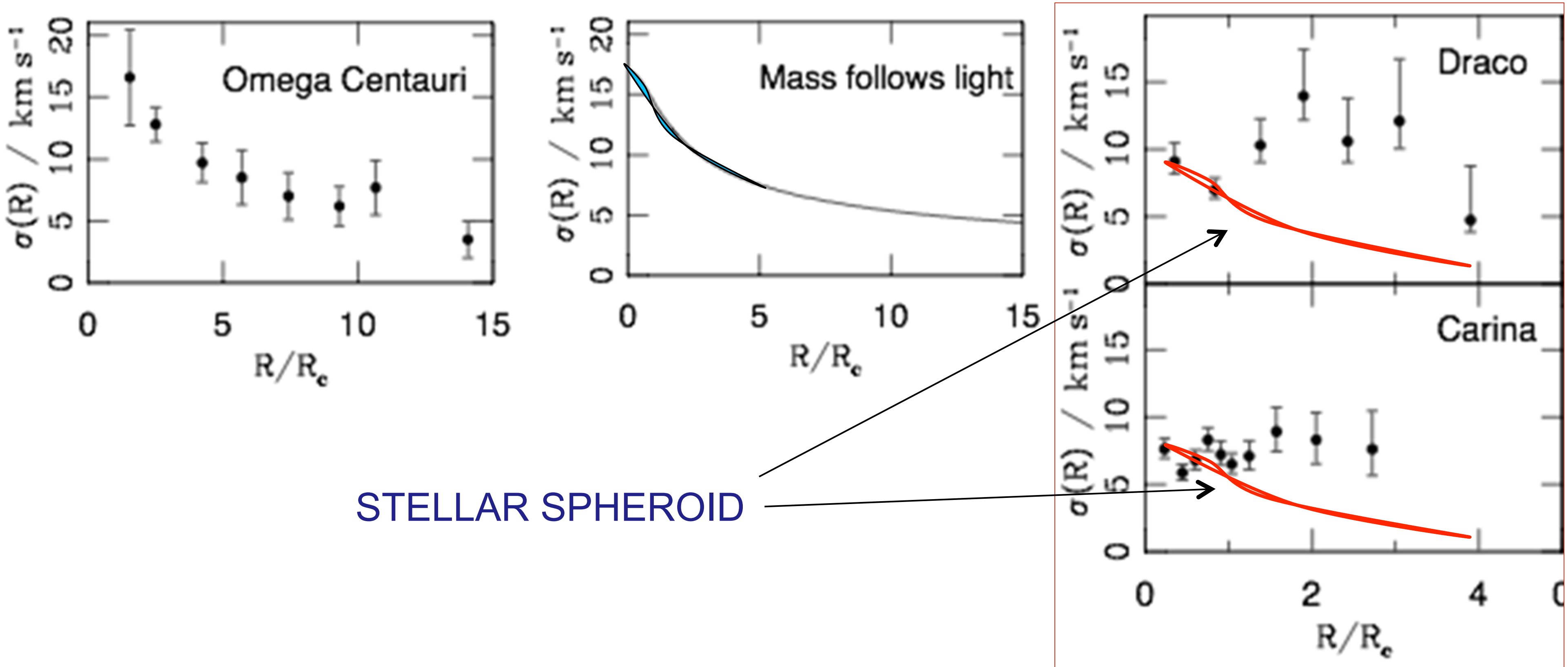
Kinematics of dSph

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

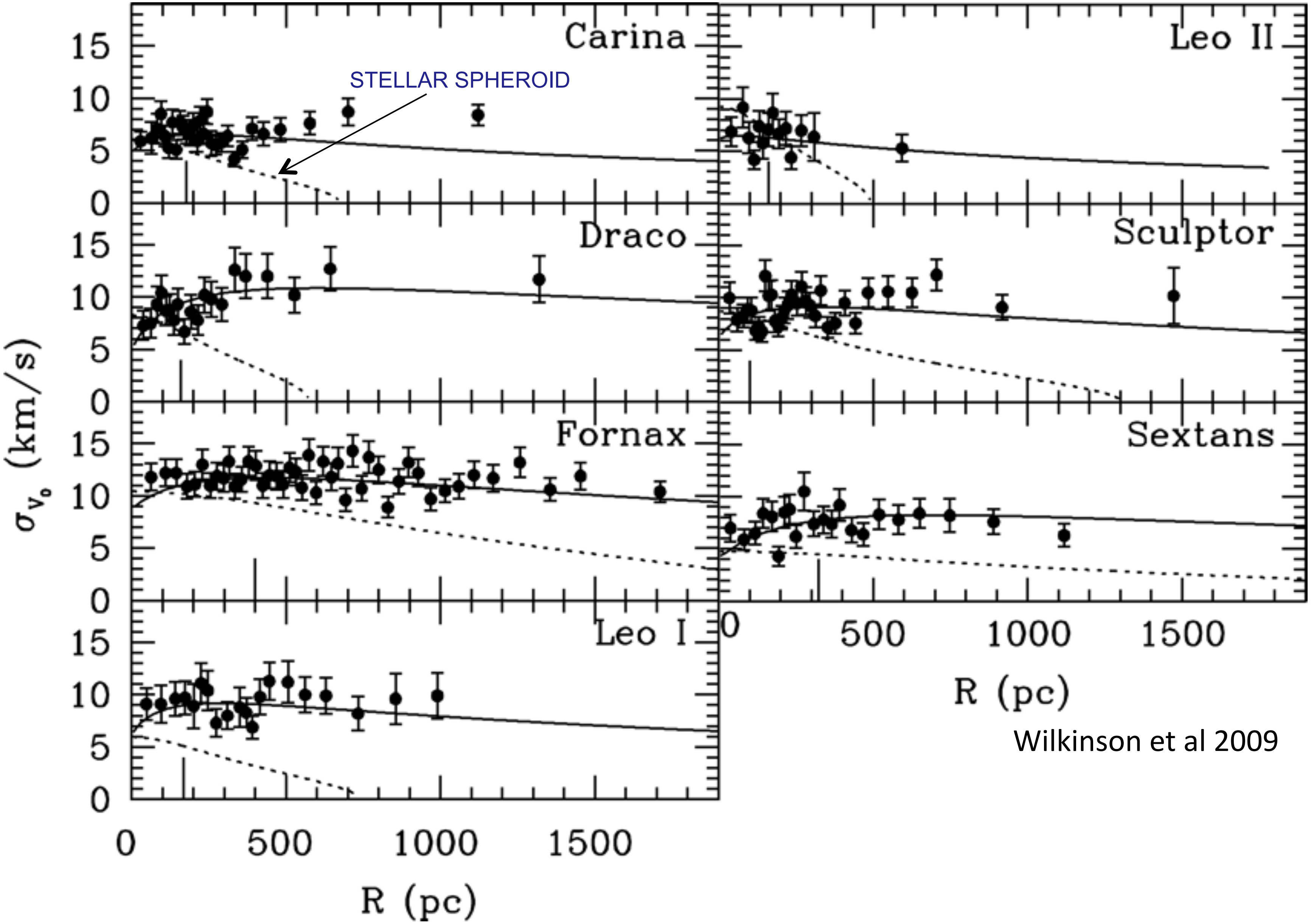
1997: First dispersion velocity profile of Fornax (Mateo)

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



Wilkinson et al 2009

dSph dispersion profiles generally remain flat to large radii

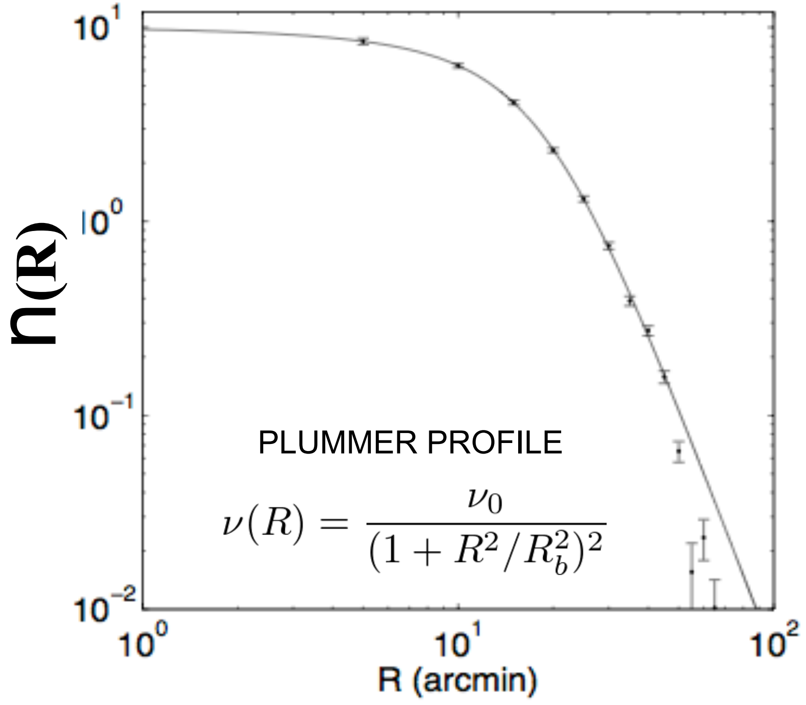
Mass profiles of dSphs

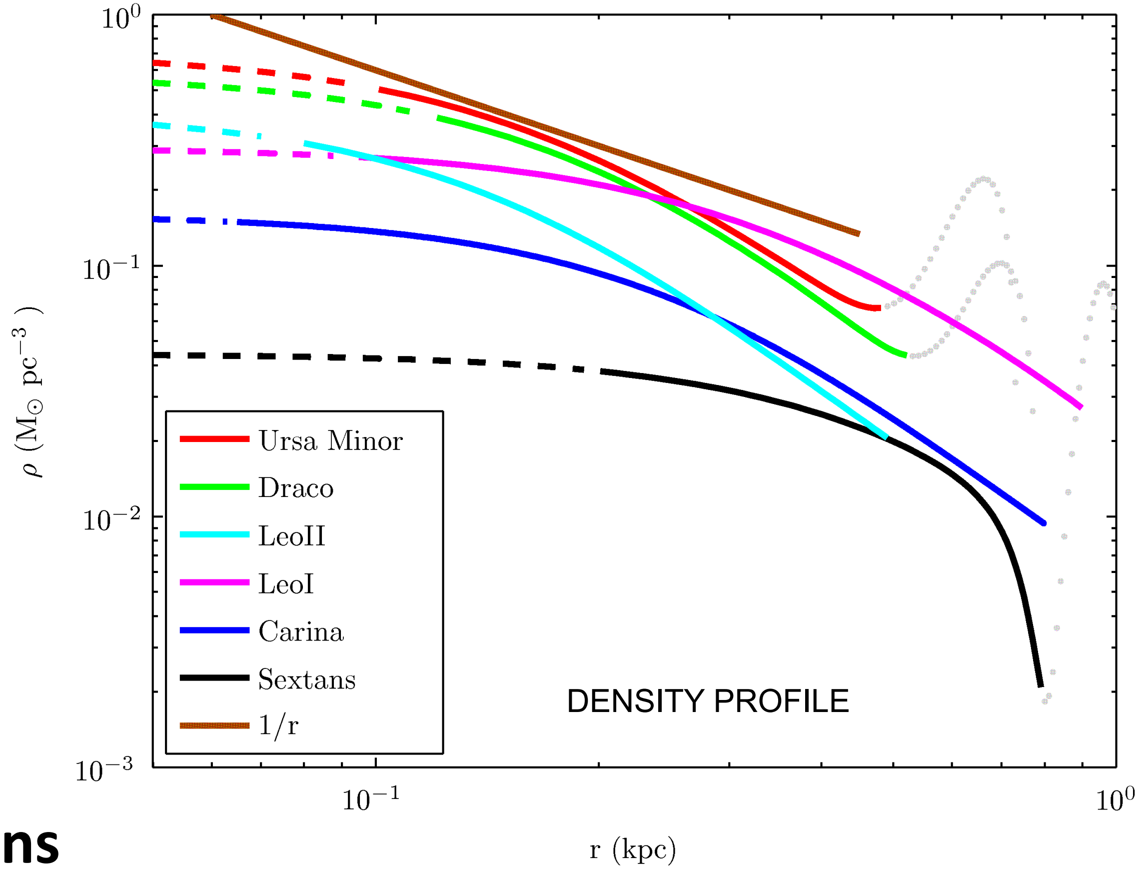
$$M(r) = -\frac{r^2}{G}\left(\frac{1}{\nu}\frac{\mathrm{d}\,\nu\sigma_r^2}{\mathrm{d}\,r} + 2\,\frac{\beta\sigma_r^2}{r}\right)$$

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



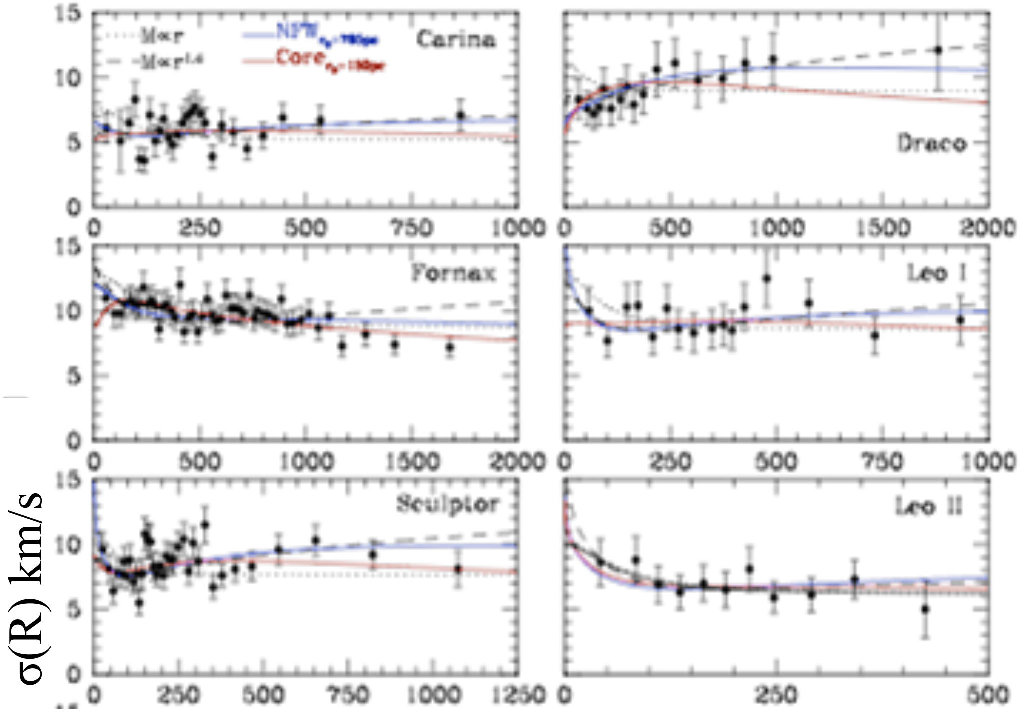


Results point to cored distributions

Gilmore et al 2007

Degeneracy between DM mass profile and velocity anisotropy

Cusped and cored mass models fit dispersion profiles equally well



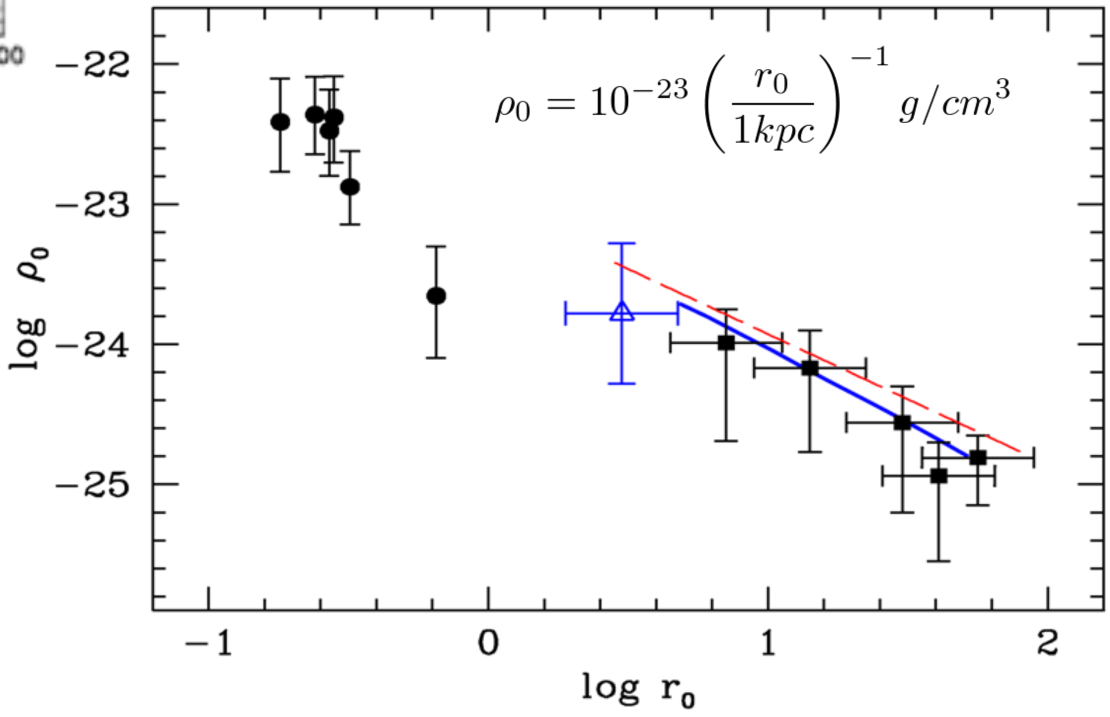
Walker et al 2009

NFW+anisotropy = CORED

However:

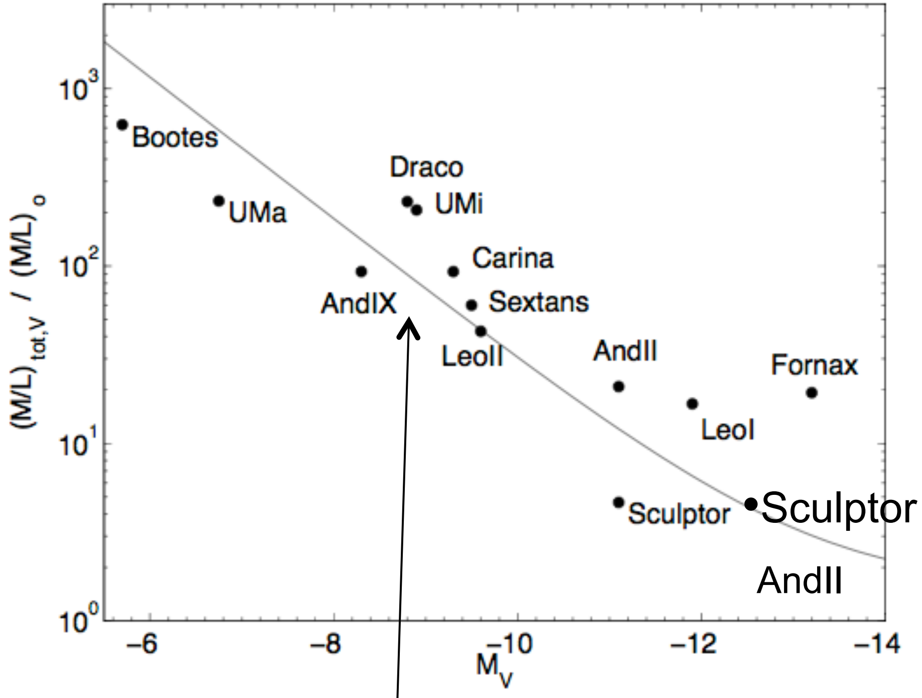
dSphs cored model structural parameters agree with those of Spirals and Ellipticals

Halo central density vs core radius



Donato et al 2009

Global trend of dSph haloes



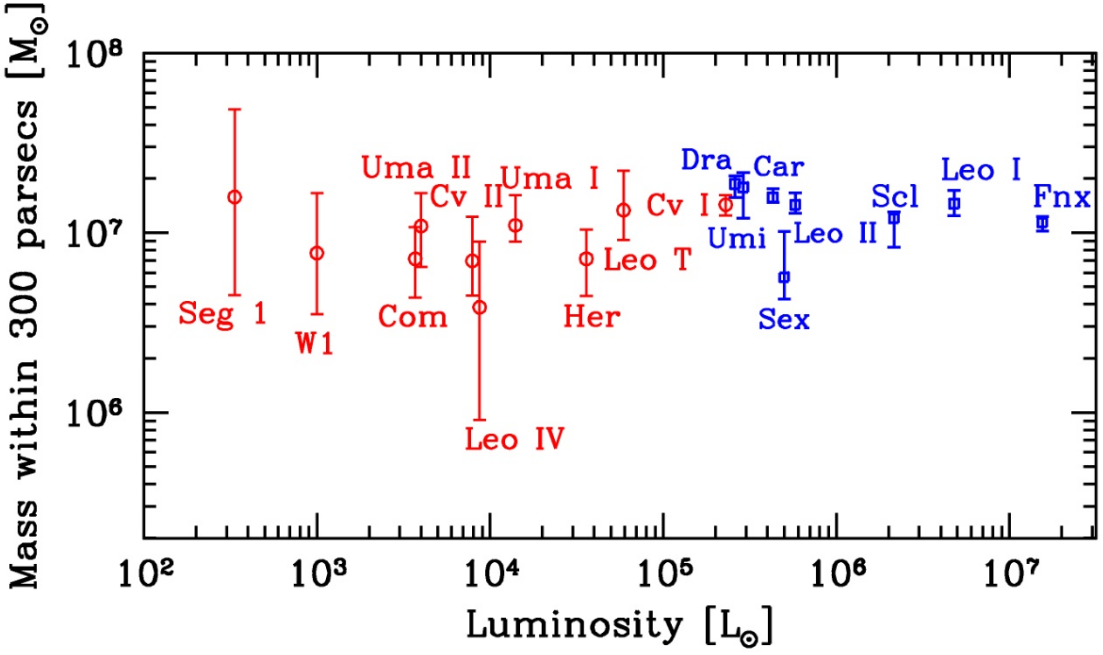
UNIQUE MASS PROFILE in dSph?

Gilmore et al 2007

Mateo et al 1998

M ~ THE SAME IN ALL DWARF SPHEROIDALS

Strigari et al 2008



CONCLUSIONS

The distribution of DM halos around galaxies shows a striking and complex phenomenology This leads to essential information on:

the very nature of dark matter; the galaxy formation process

Baryon +DM Simulations should reproduce:

Shallow DM inner distribution, the observed relationships between the halo mass and 1) central halo density, 2) baryonic mass, 3) half-mass baryonic radius and 4) baryonic central surface density, a constant central halo surface density.

Theory, phenomenology, simulations, experiments should all play a role in the search for dark matter.

Observations suggest that the mass discrepancy in galaxies is intimately related to the distribution of visible matter.