# DARK MATTER

**ASTR 333/433**
**SPRING 2024**
**TR 11:30AM-12:45PM**
**SEARS 552**

http://astroweb.case.edu/ssm/ASTR333/


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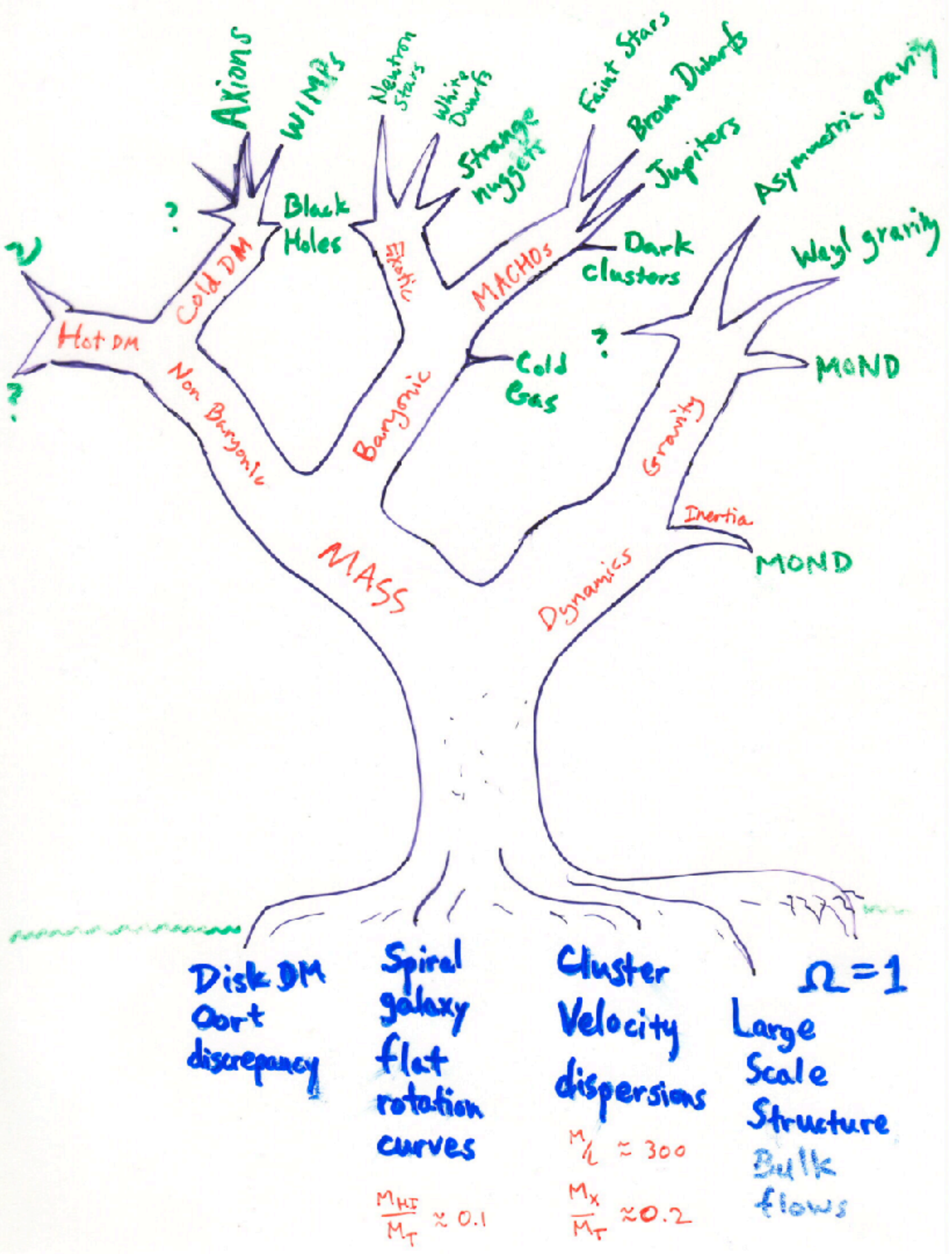
**HOMEWORK DUE NEXT TIME**

CASE WESTERN RESERVE
UNIVERSITY EST. 1826



## Basic Picture:

**Dark Matter Halo**

**Luminous Galaxy**
stars, gas, dust, etc.

Galaxies are embedded in extended,
quasi-spherical halos of dark matter

$R_{vir} \gg R_*$

The virial radius of the dark matter halo is much larger than the luminous galaxy

# Dark Matter Halo models

## pseudo-isothermal

*older*

*empirically motivated*

$\rho(r) \sim r^{-2}$ gives a flat rotation curve

3D density profiles

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

*theoretically reminiscent of an isothermal distribution*

Both models have 2 parameters - a characteristic density and scale radius

## NFW

*now old new normal*

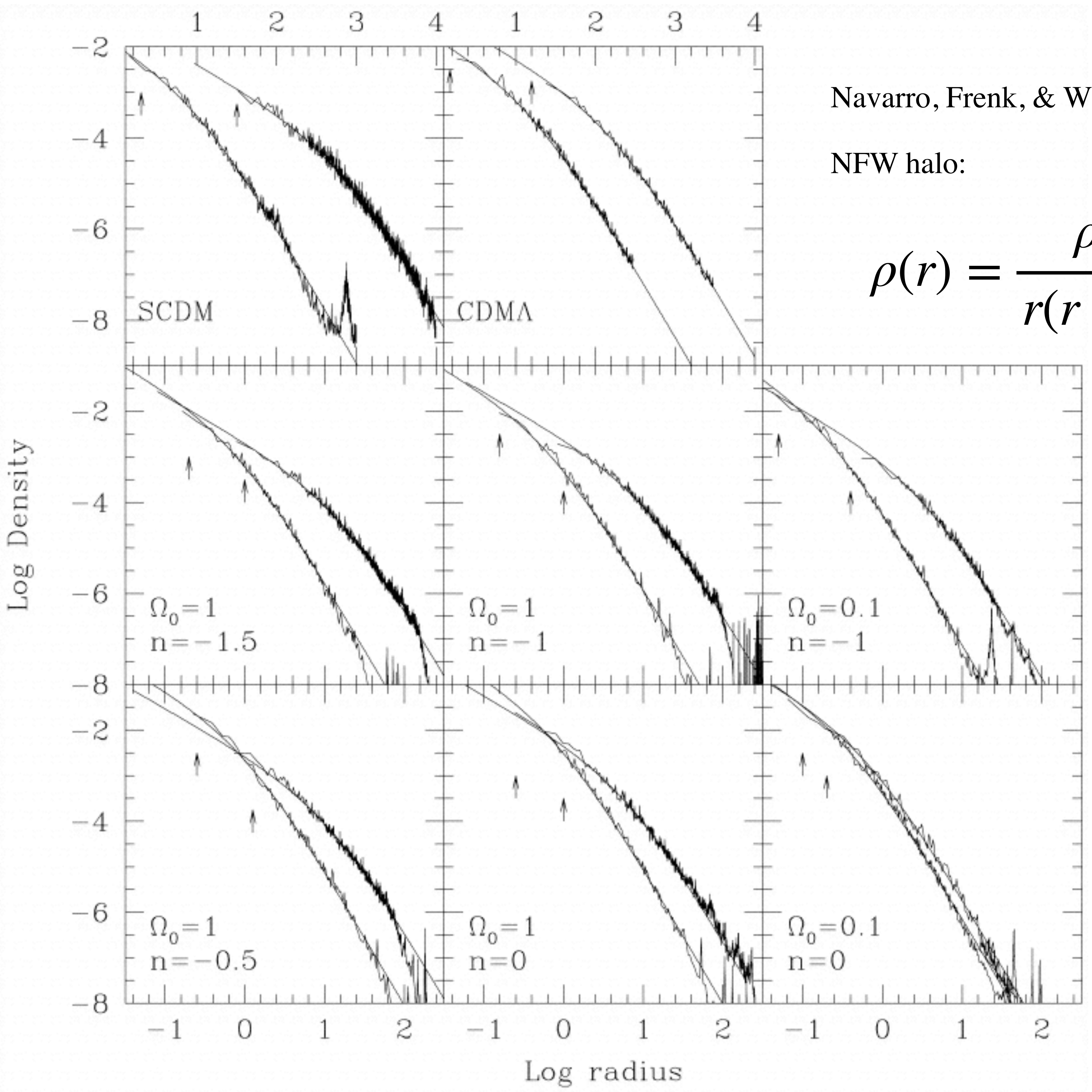
*theoretically motivated*

NFW arises in pure, dark matter only (DMO) simulations

$$\rho(r) = \frac{\rho_s r_s^3}{r(r + r_s)^2}$$

*an analytic approximation to the results of numerical simulations*

Density profiles of simulated dark matter halos




Navarro, Frenk, & White (1997)

NFW halo:

$$\rho(r) = \frac{\rho_s r_s^3}{r(r + r_s)^2}$$

# Mass models

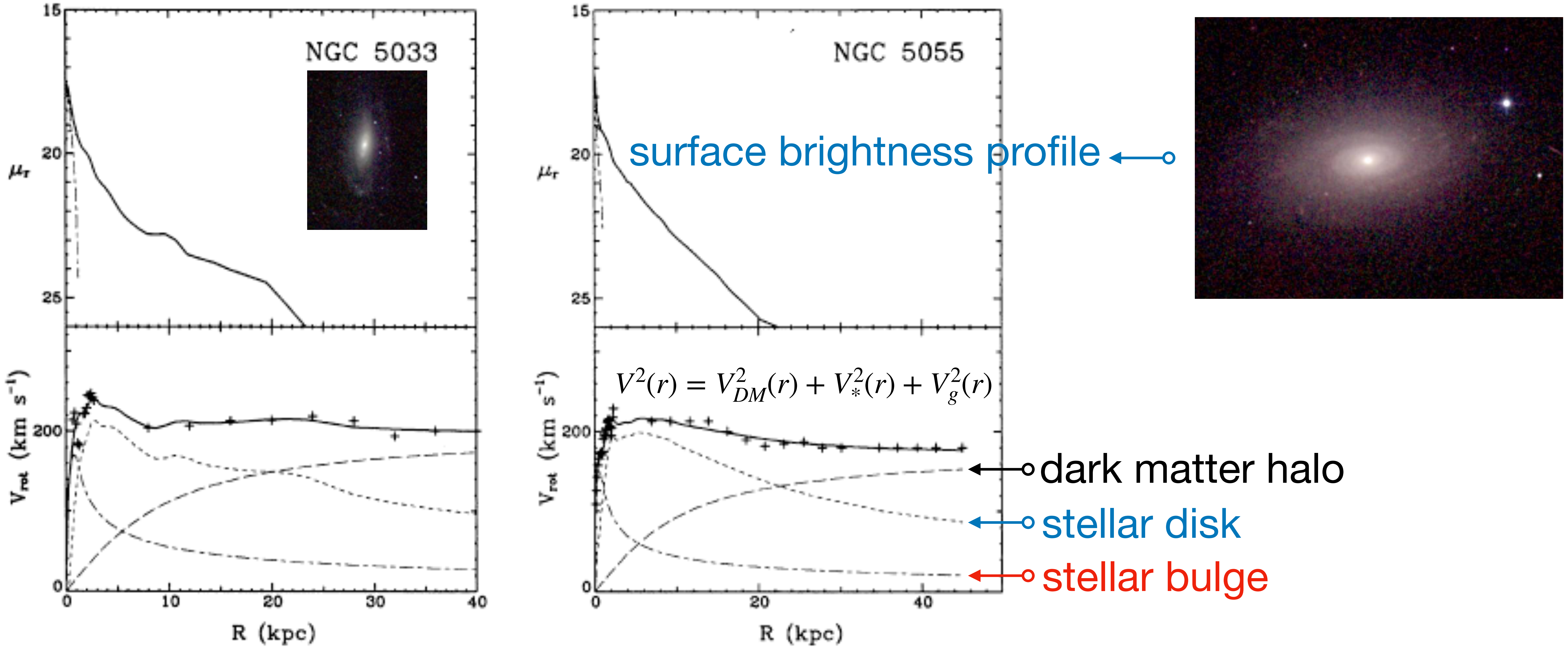
Kent (1987)

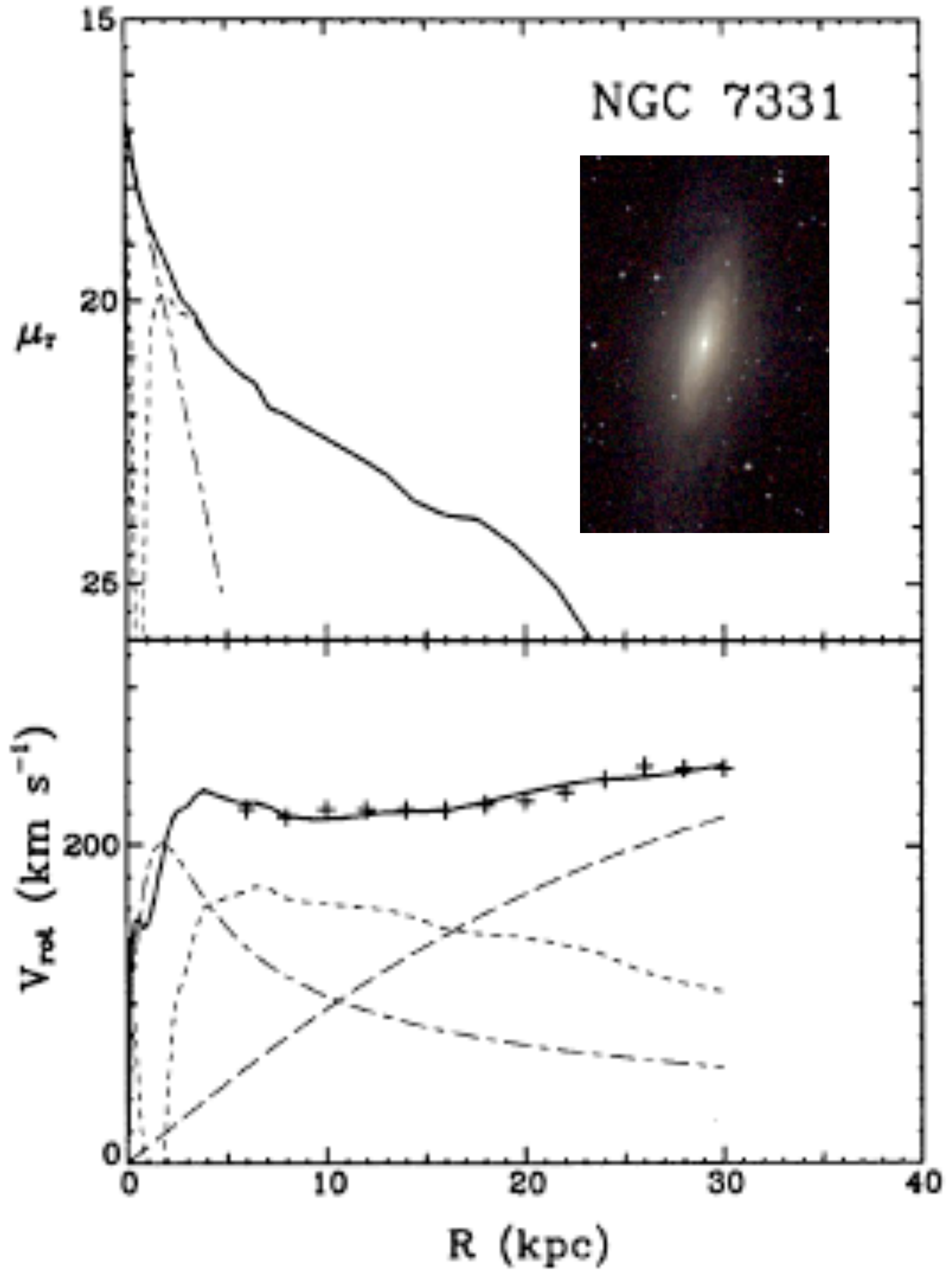
Rotation curves fit with pseudo-isothermal halos

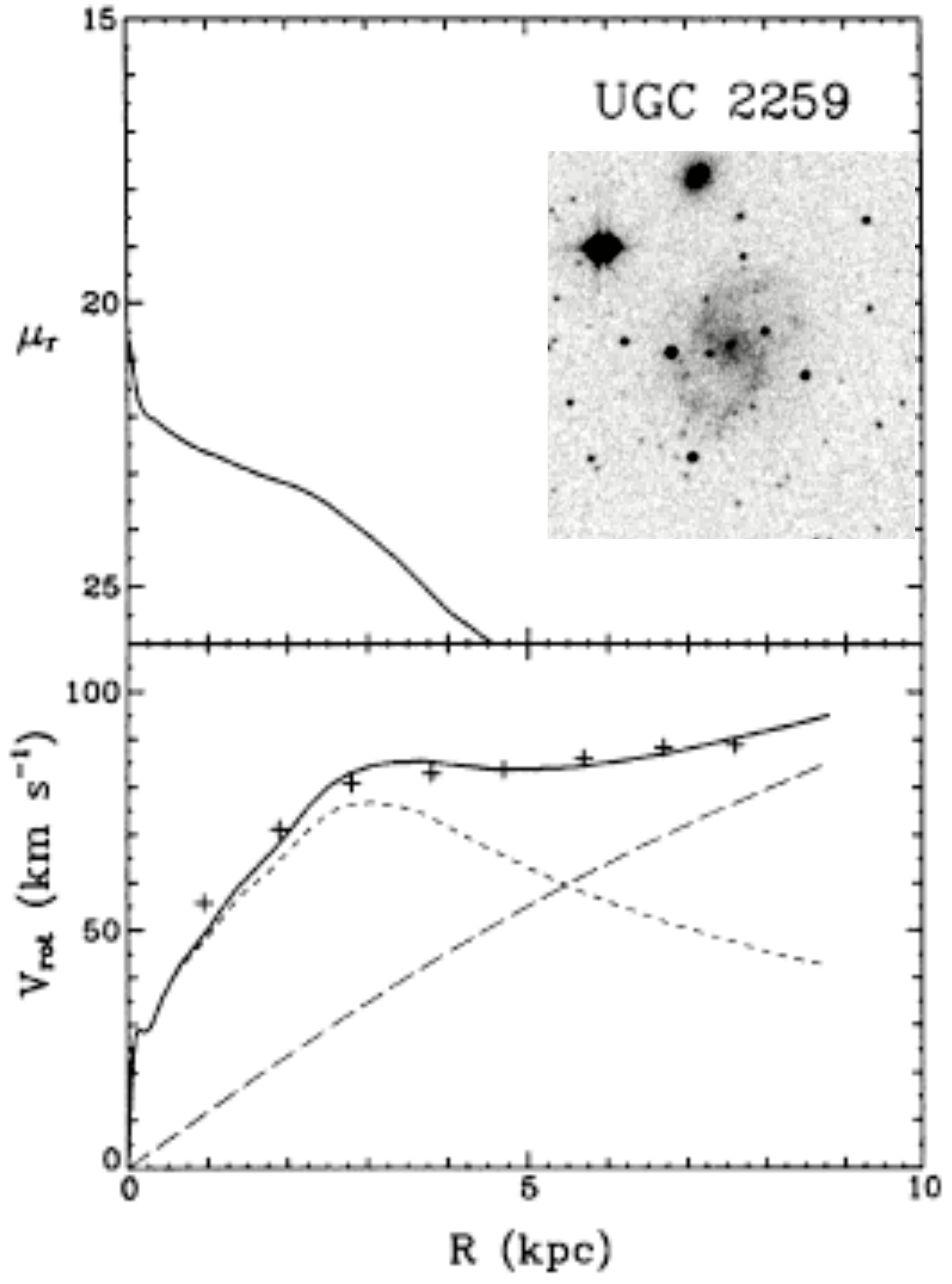
$$\rho(r) = \frac{\rho_0}{1 + (r/R_c)^2}$$

$$V_{\rm iso}(r) = V_\infty \sqrt{1 - \frac{R_c}{r} \tan^{-1}\left(\frac{r}{R_c}\right)}$$

$$V_\infty = \sqrt{4\pi G \rho_0 R_c^2}$$




$$V^2(r) = V_{DM}^2(r) + V_*^2(r) + V_g^2(r)$$

velocities sum in quadrature since $V^2 \sim \frac{M}{r}$

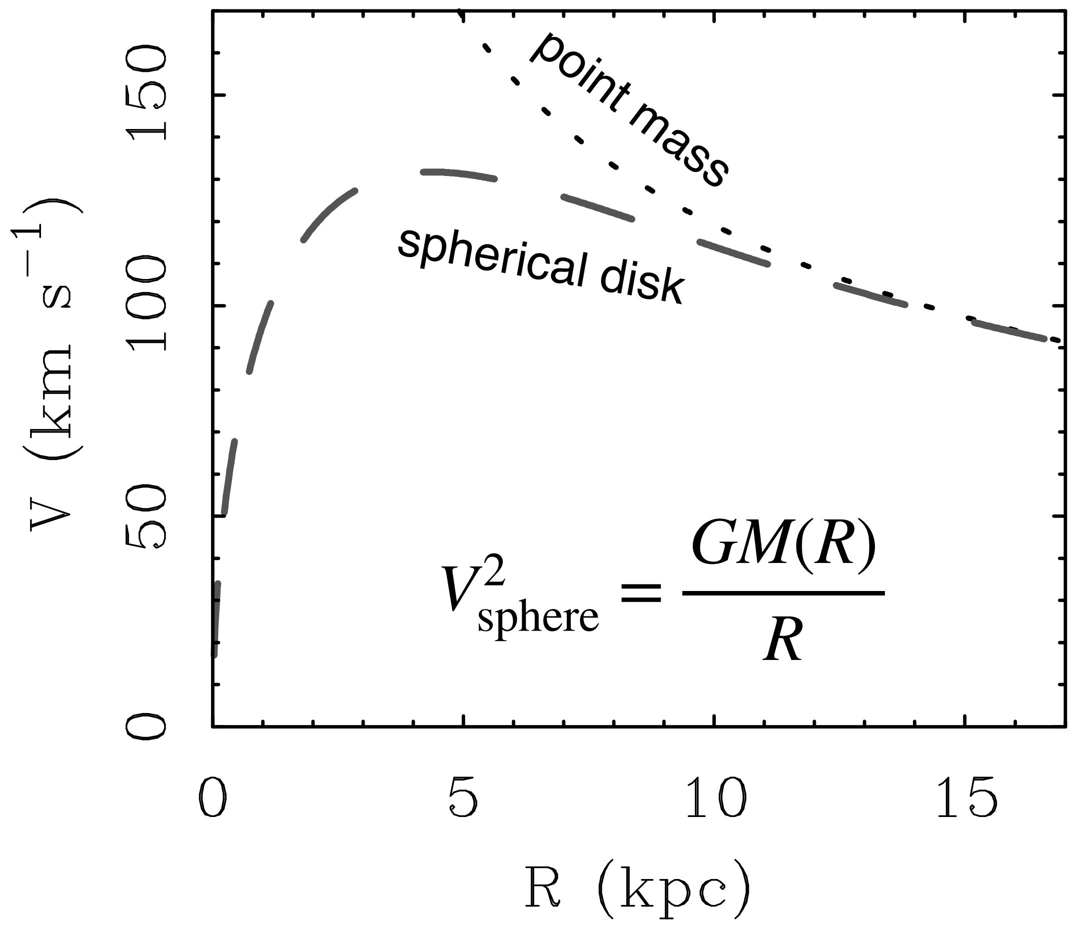
Examples for the size and mass of NGC 6946

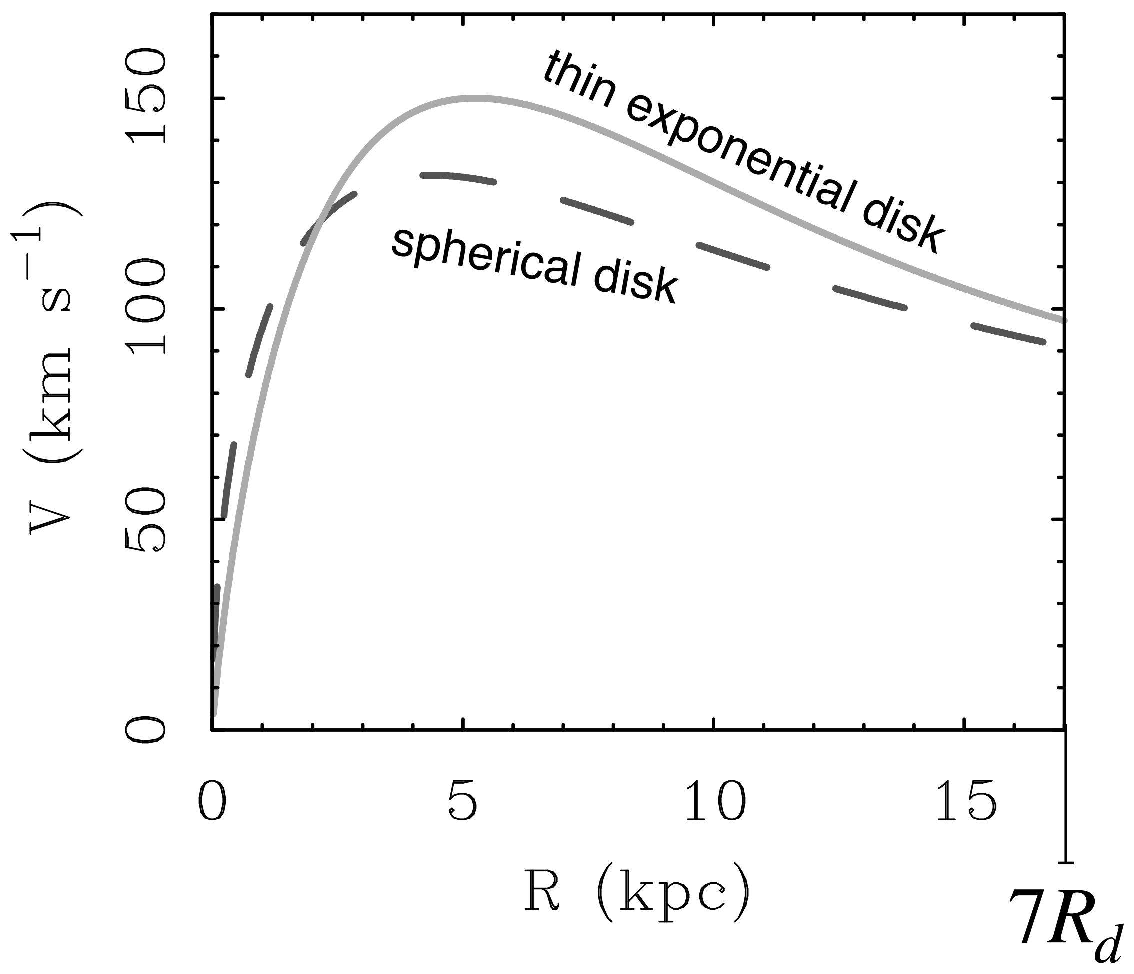
$$M_* = 3.3 \times 10^{10}\ M_\odot$$
$$R_d = 2.44\ \text{kpc}$$

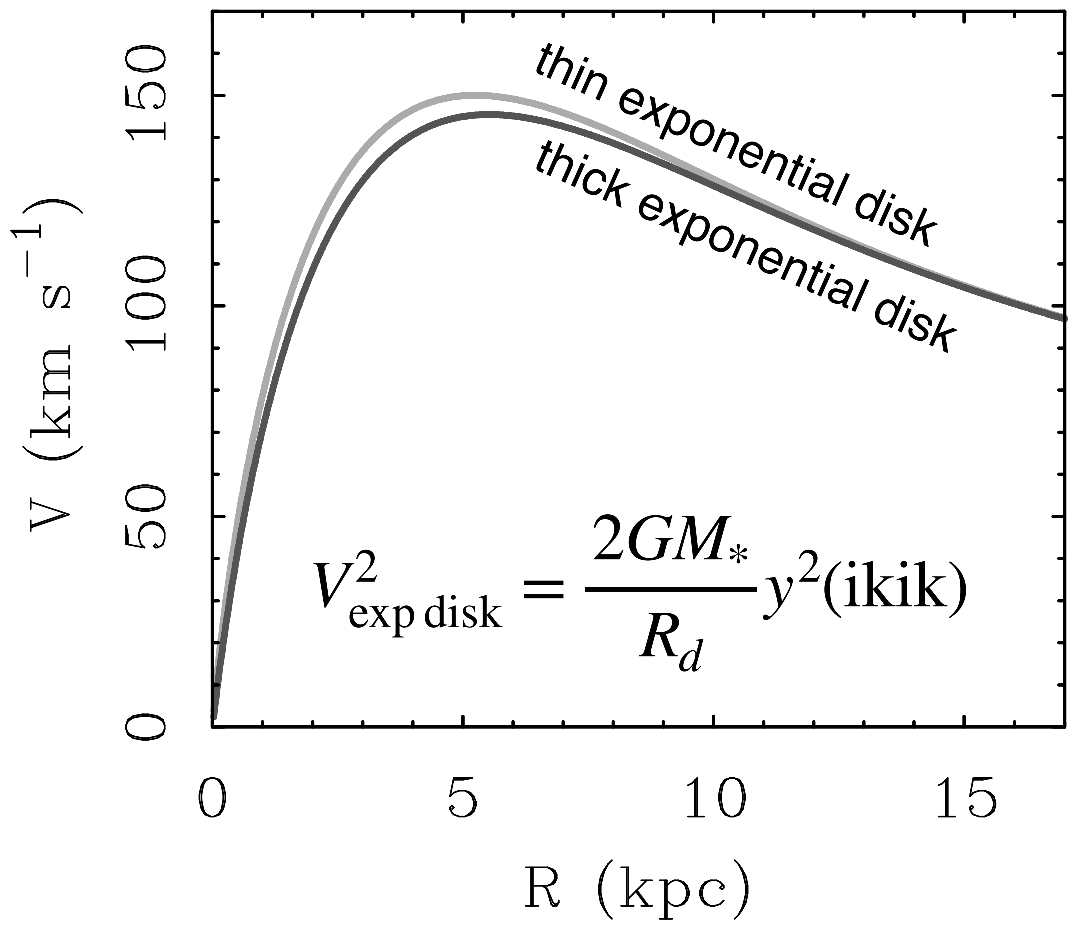
## Progressive approximations
in mass modeling

Appear in homework:

- Point Mass
- "spherical" disk
- thin exponential disk
- thick exponential disk
- surface density $\Sigma(R)$
- 2D $\Sigma(R, \phi)$ [e.g., bars]
- 3D $\rho(R, \phi, z)$
- 3D + non-equilibrium



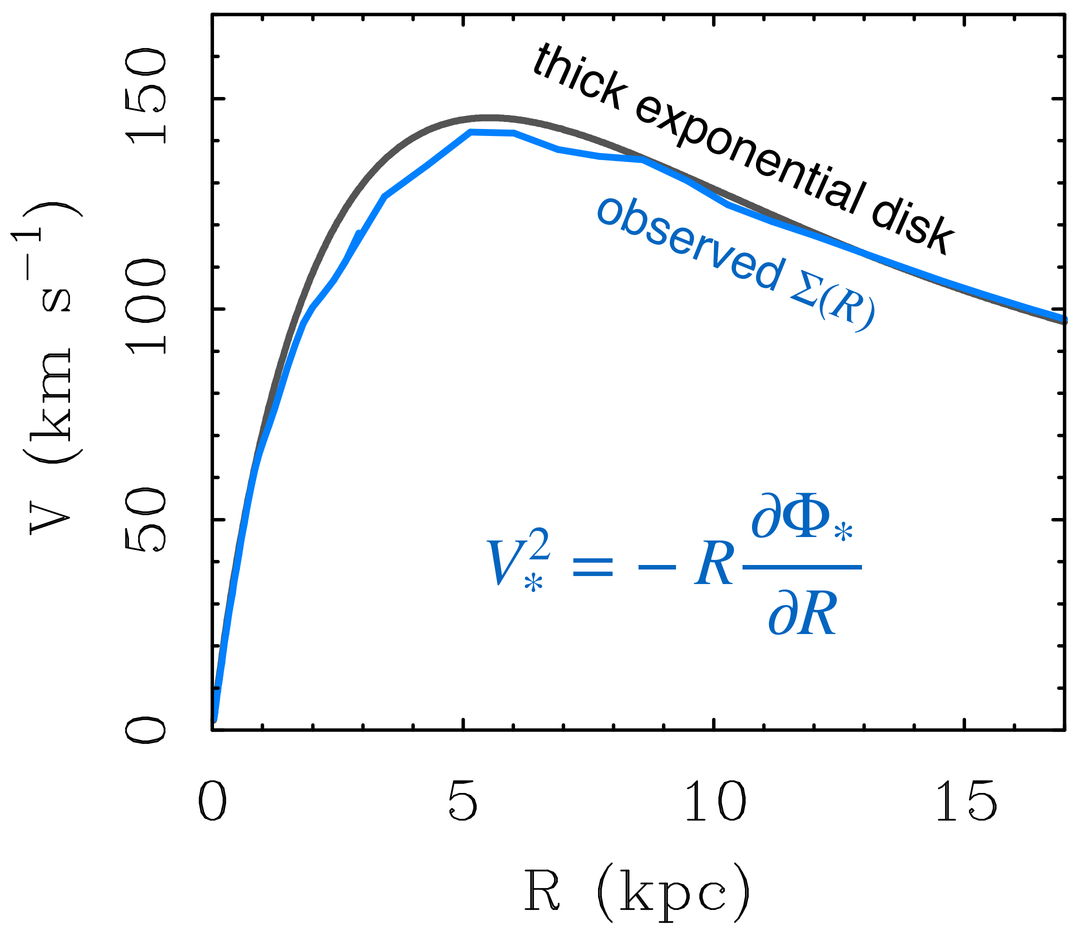



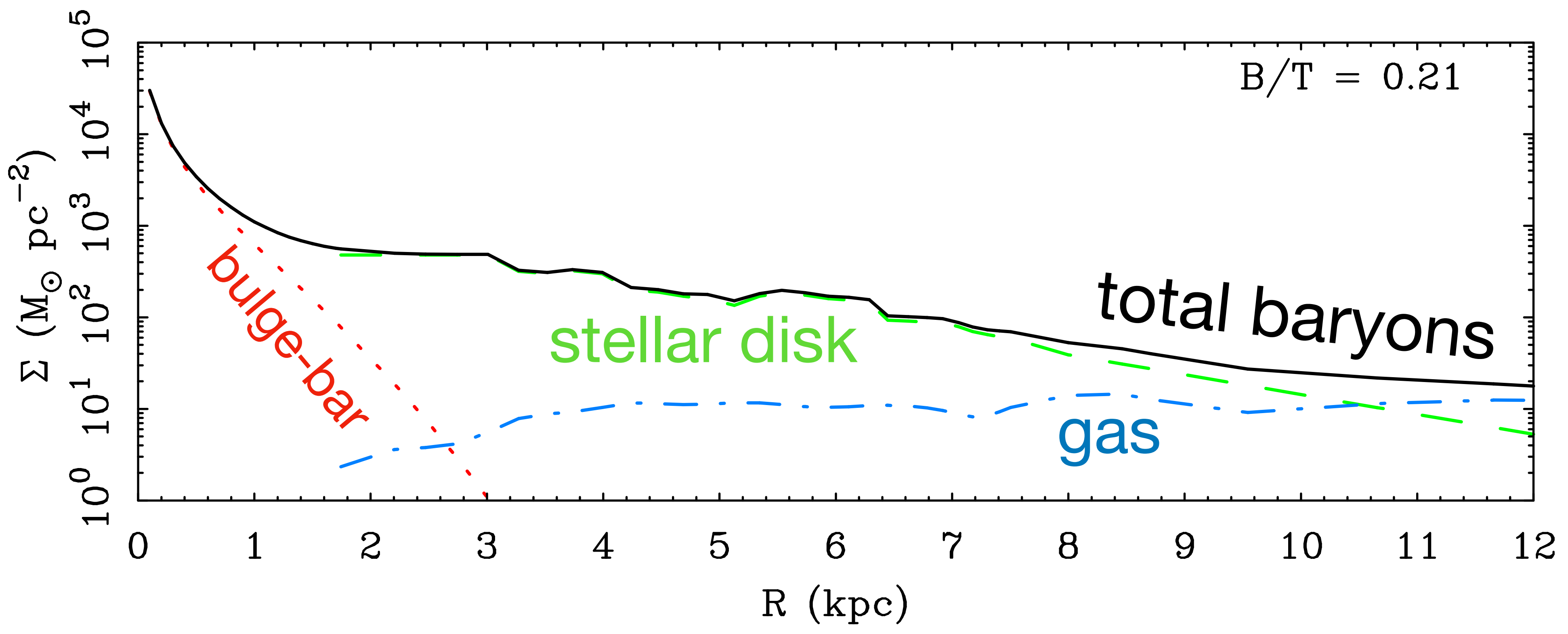

$$\text{ikik} = [I_0(y)K_0(y) - I_1(y)K_1(y)]$$

$$y = \frac{R}{2R_d}$$

We numerically solve the Poisson equation to obtain the gravitational potential $\Phi_*$ from the observed surface density $\Sigma_*(R)$



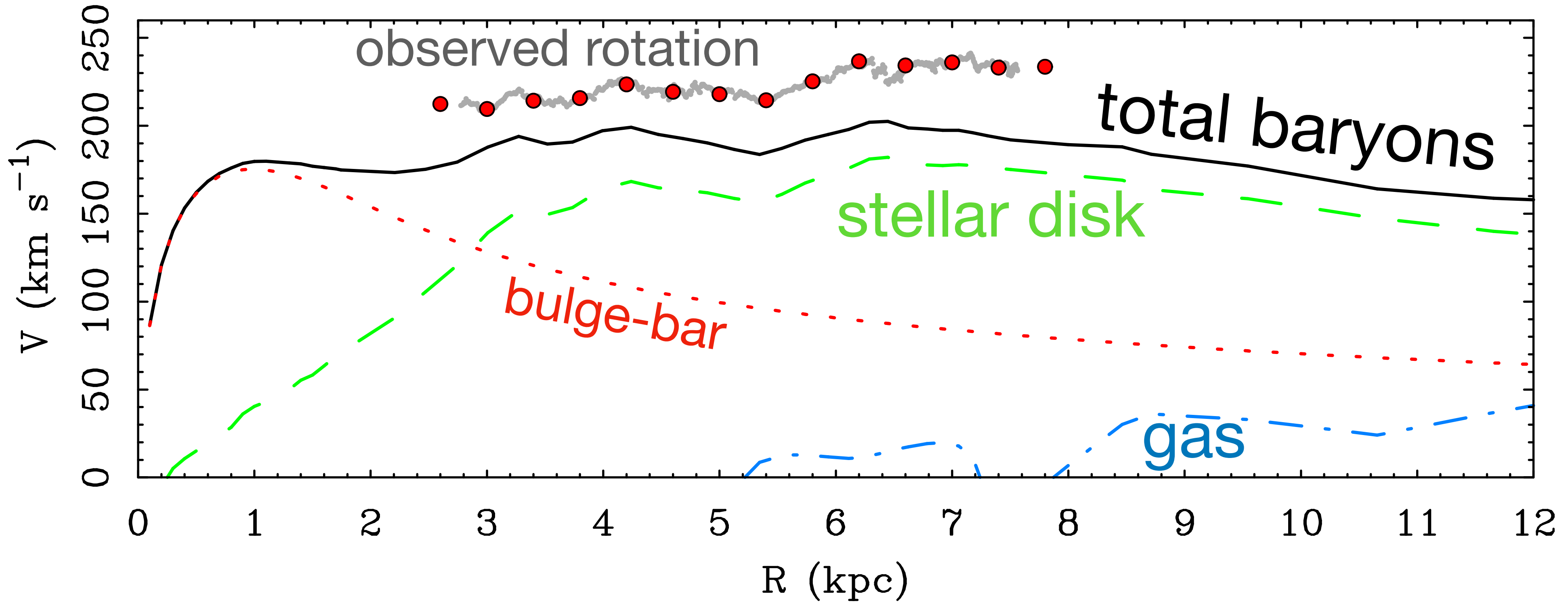
# Mass modeling - Milky Way example




**Surface density profile**

$\Sigma(R)$ *from observed surface brightness profile*

*The main uncertainty is the mass-to-light ratio of the stars.*

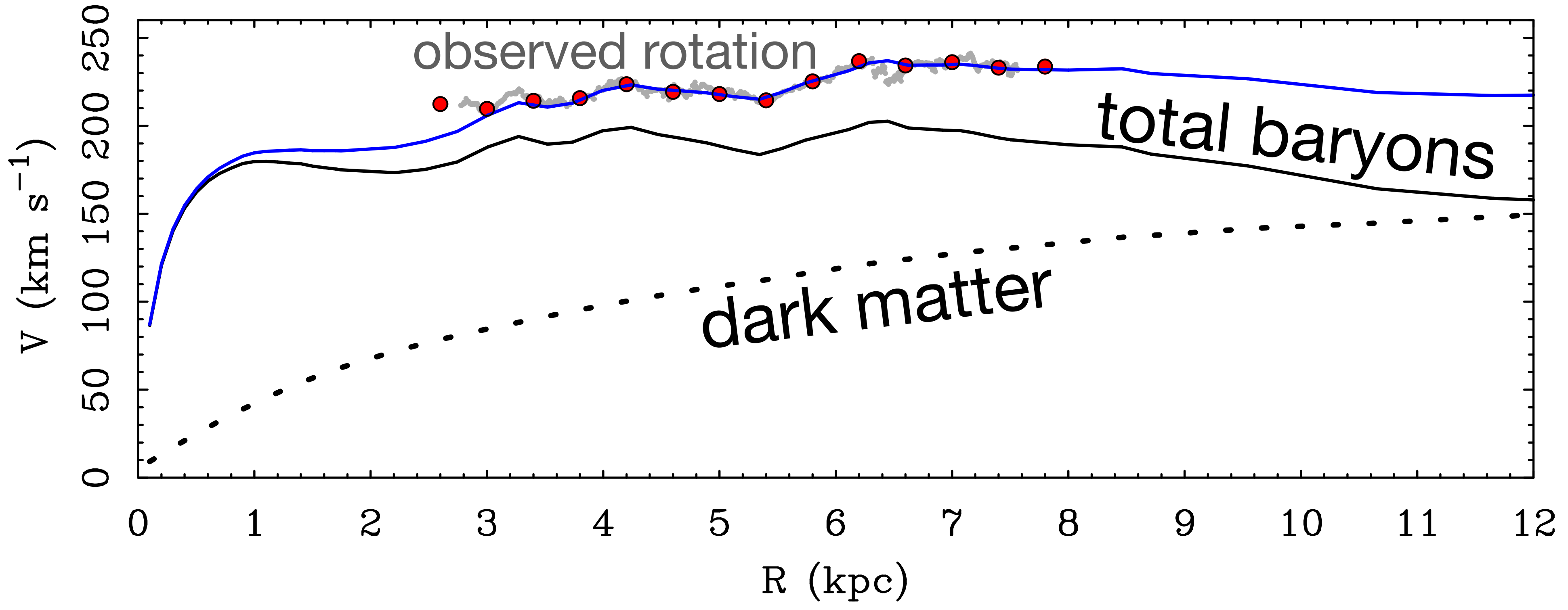



**Mass model**

$$\frac{V^2}{R} = -\frac{\partial \Phi}{\partial R} = 2\pi G \Sigma(R)$$

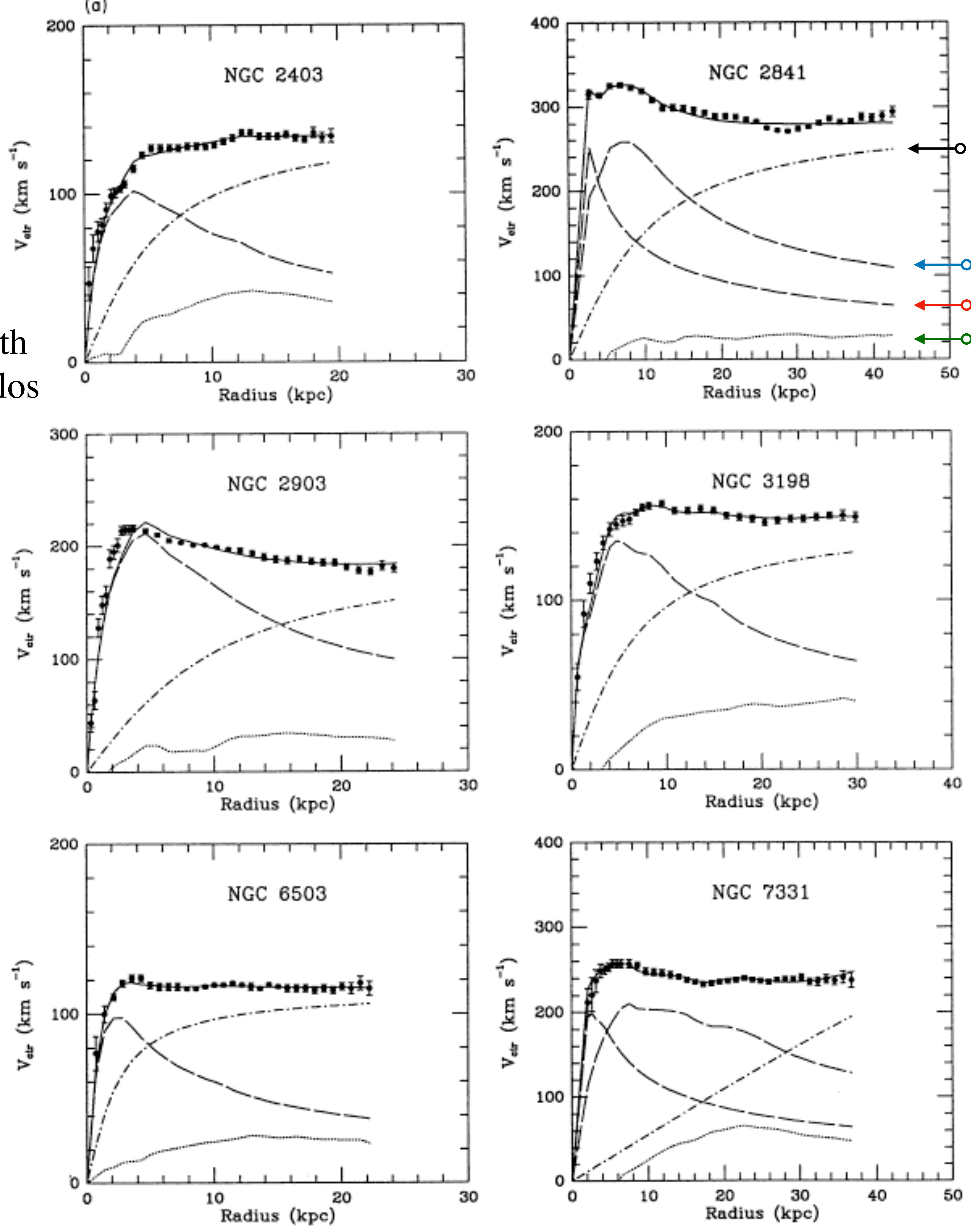
$$V_{DM}^2 = V_{obs}^2 - V_{bar}^2$$

**Mass model with DM halo**




**Total rotation decomposed into baryonic and dark components**

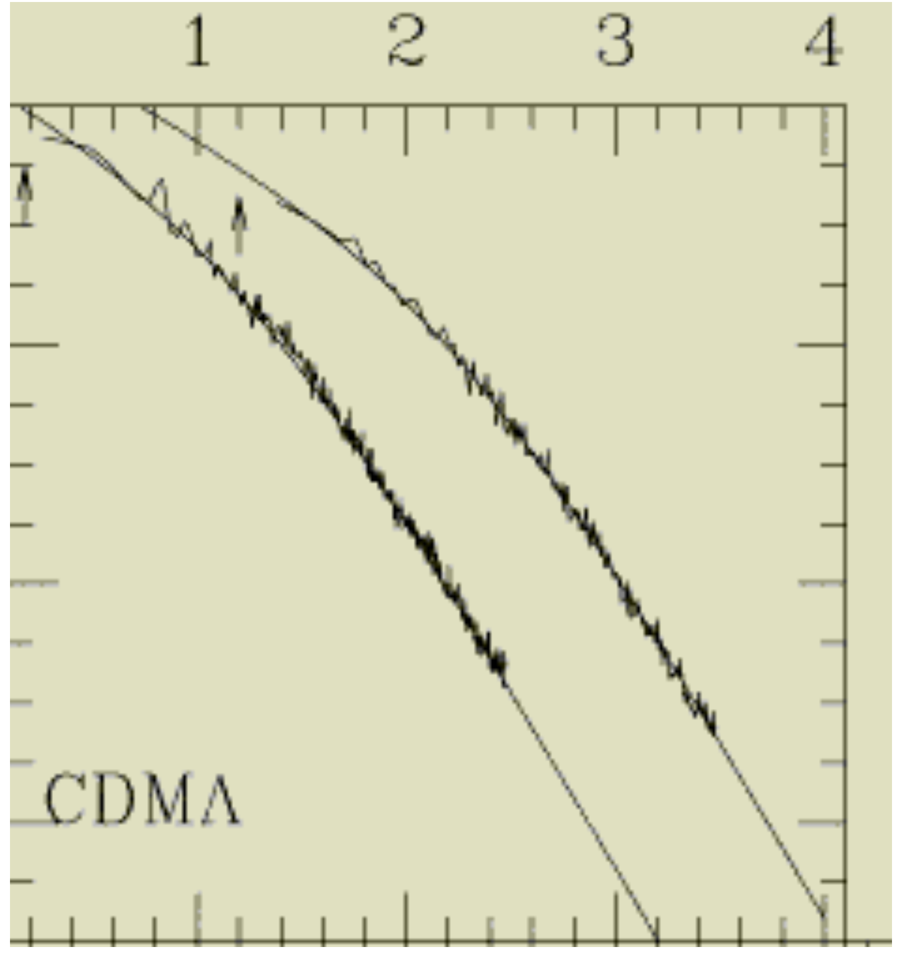
Rotation curves fit with pseudo-isothermal halos



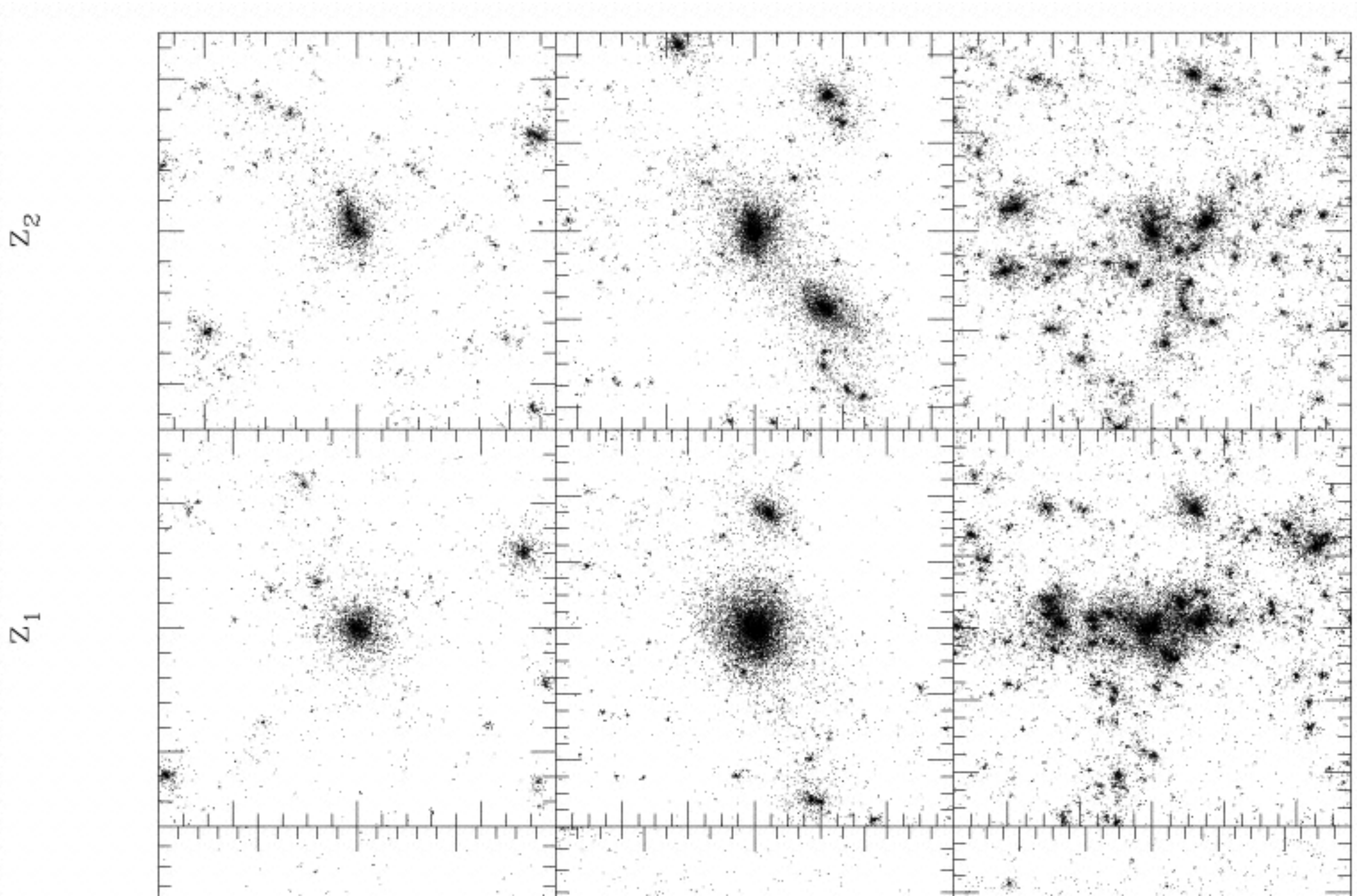

Begeman, Broeils, & Sanders (1991)

It is often assumed that $V_\infty = V_f$ but typically we only observe the rising part of the DM rotation curve

NFW




Simulation output (Navarro, Frenk, & White 1997)




NFW halo

$$\rho(r) = \frac{\rho_s r_s^3}{r(r + r_s)^2}$$

Can also define an overdensity $\Delta$

$$M_\Delta = \frac{4\pi\Delta}{3}\,\rho_{crit}\,r_\Delta^3$$

Conventionally take `virial' $\Delta = 200$

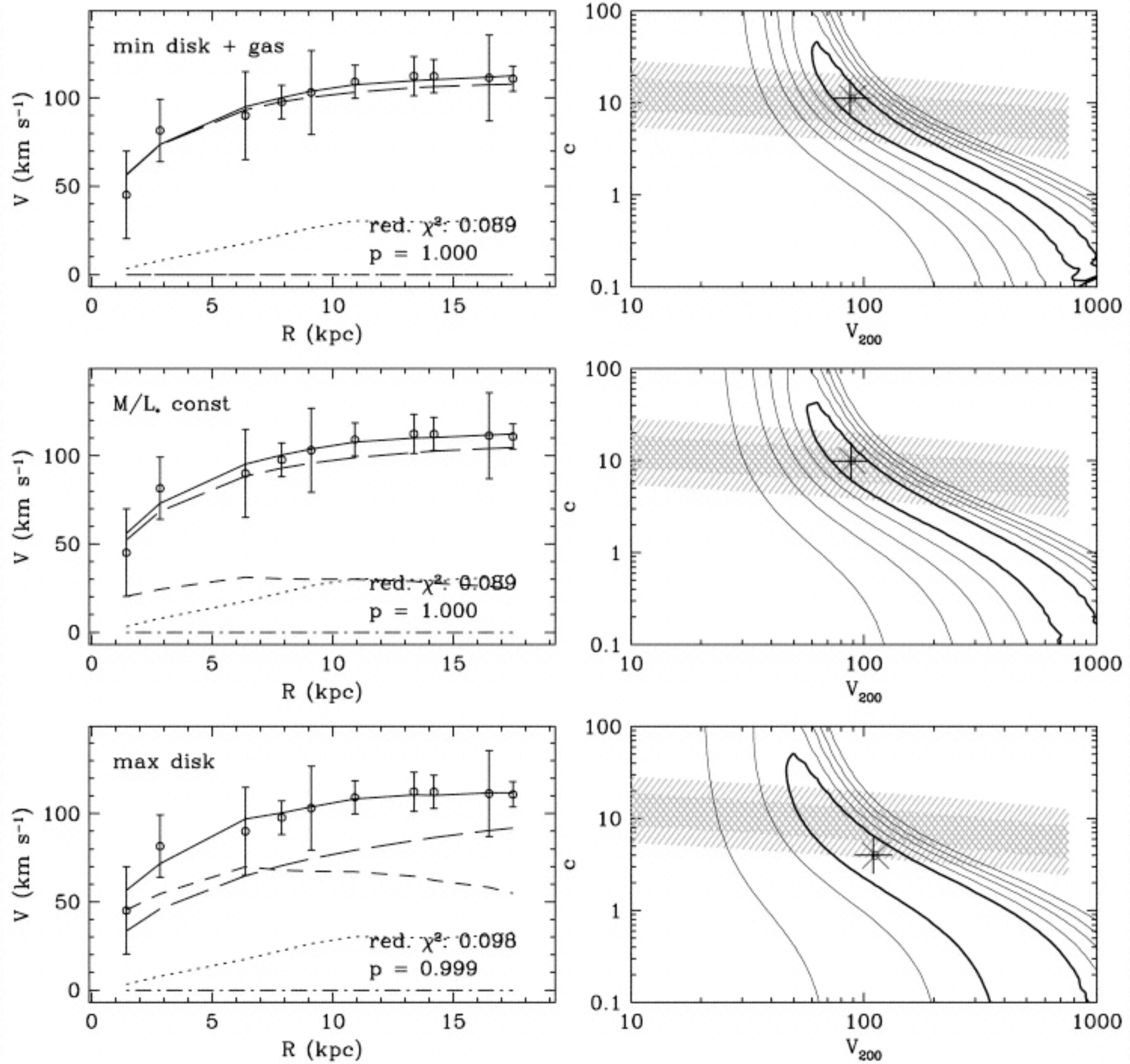
$$V_{200}^2 = \frac{G\,M_{200}}{r_{200}}$$

halo mass $\quad M_{200} = (3.3 \times 10^5\ \mathrm{M_\odot\,km^{-3}\,s^3})\,V_{200}^3$

concentration $\quad c = \frac{r_{200}}{r_s}$

NFW
fits

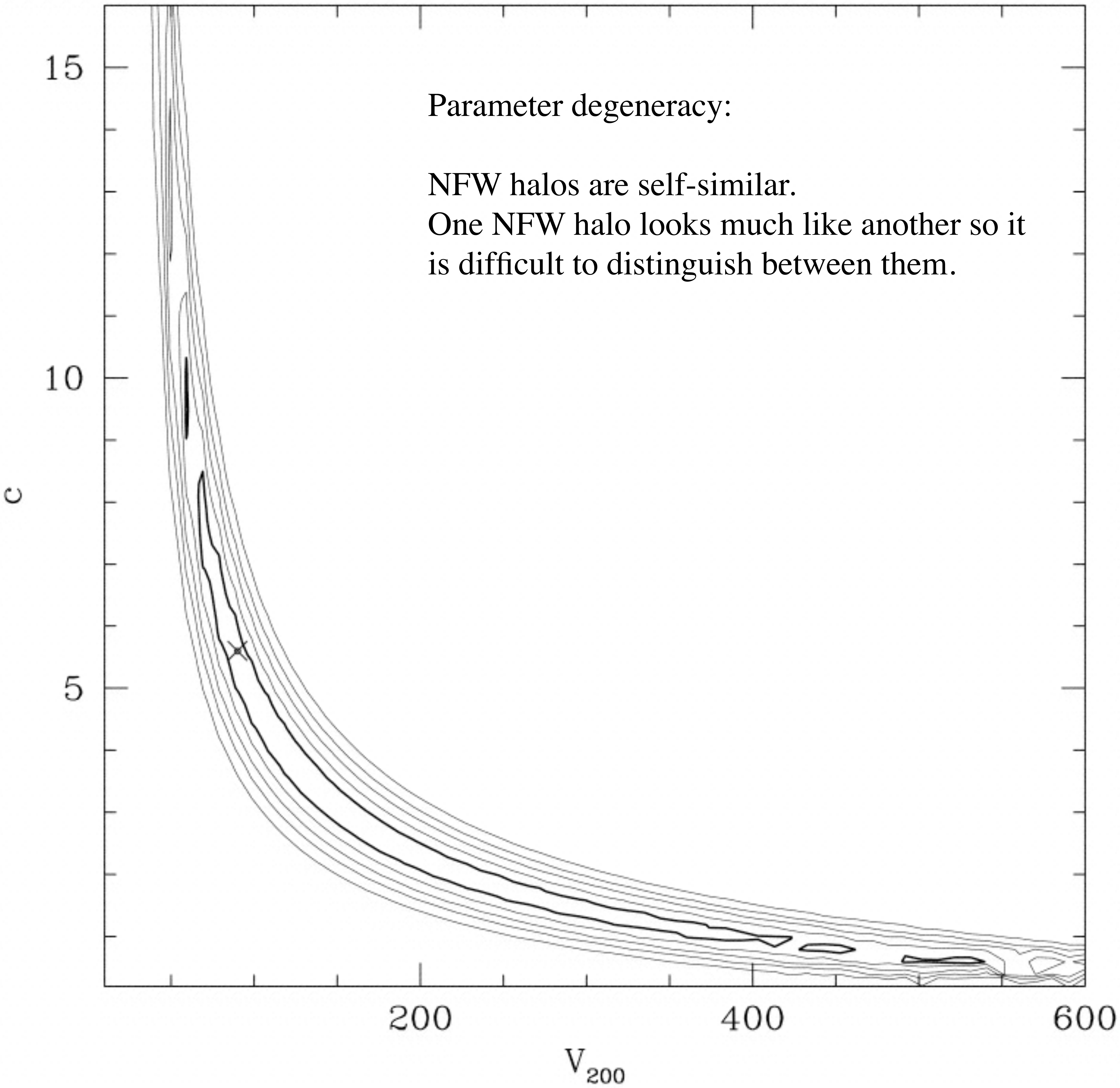
LSB
F563-1




considerable parameter degeneracy!

NFW
fits

LSB
F583-4



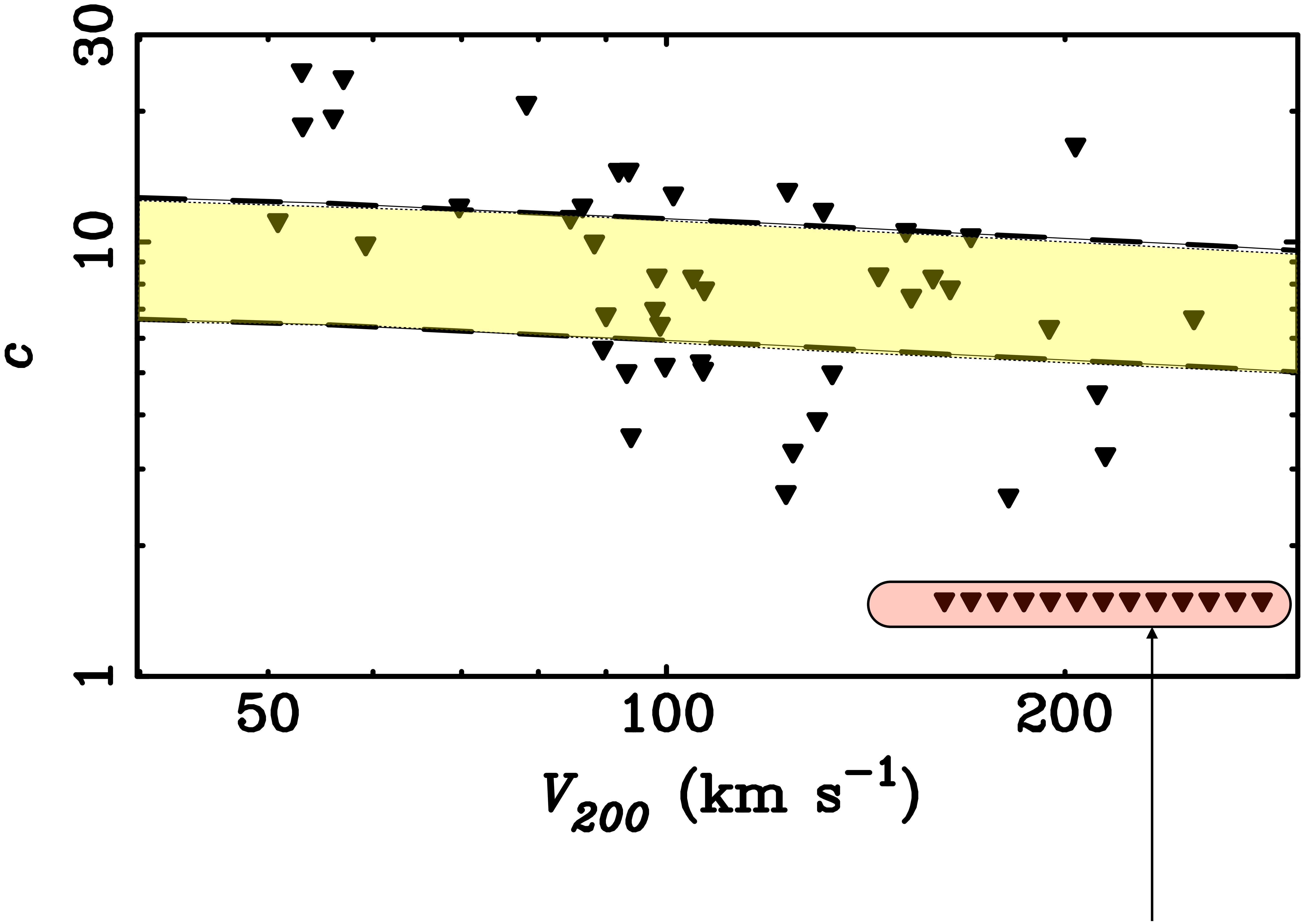

Parameter degeneracy:

NFW halos are self-similar.
One NFW halo looks much like another so it is difficult to distinguish between them.

considerable parameter degeneracy!

NFW
c-V200
relation

NFW halos are a one parameter family with some scatter

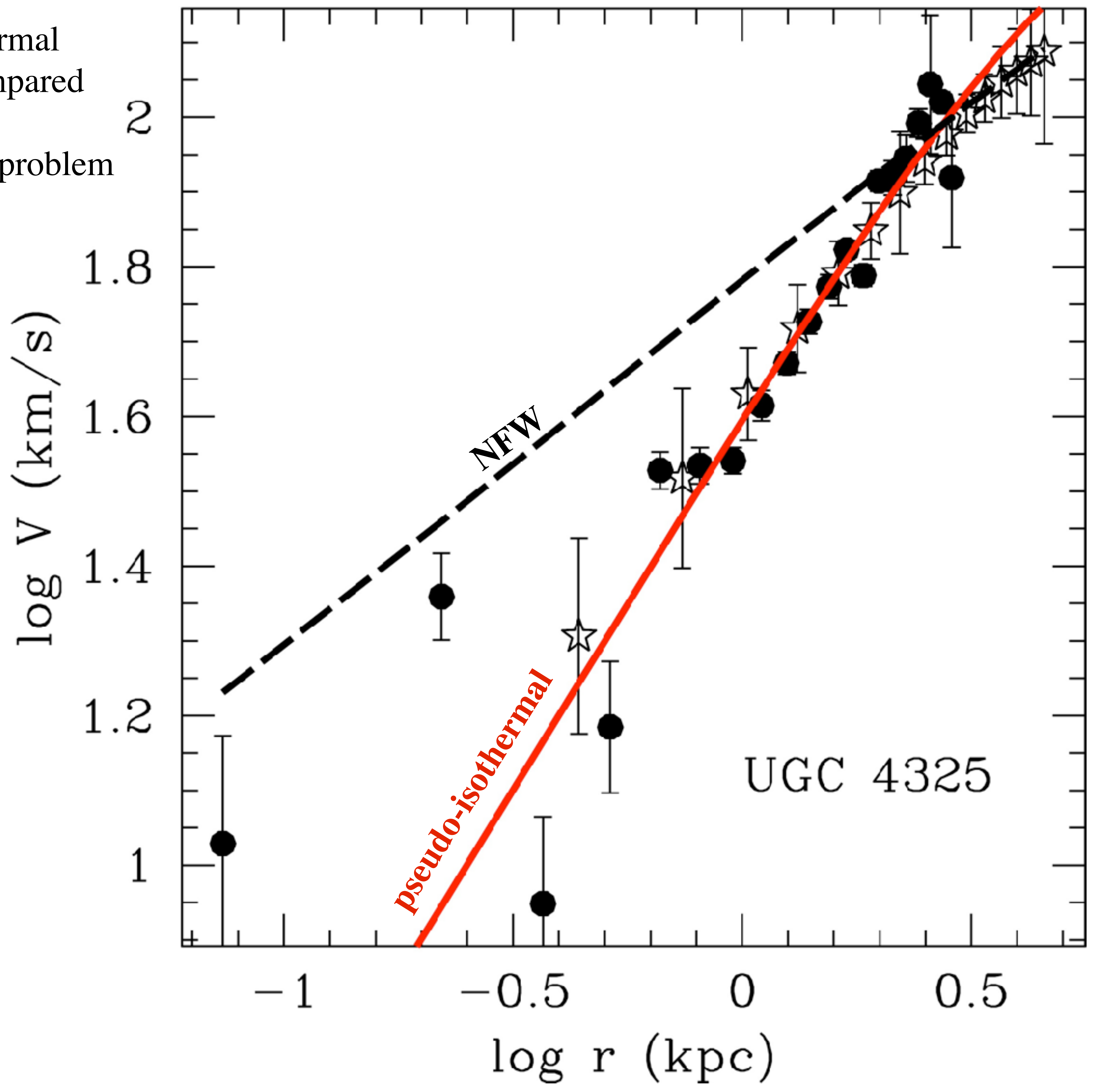



Many galaxies - especially LSBs - have upper limits on c that are unacceptably low.
This is one indication of the “**cusp-core problem**.”

The central “cuspy” profiles predicted for dark matter halos are not always observed; much of the data prefer a nearly constant density core (like a pseudo-isothermal halo).

pseudo-isothermal
and NFW compared

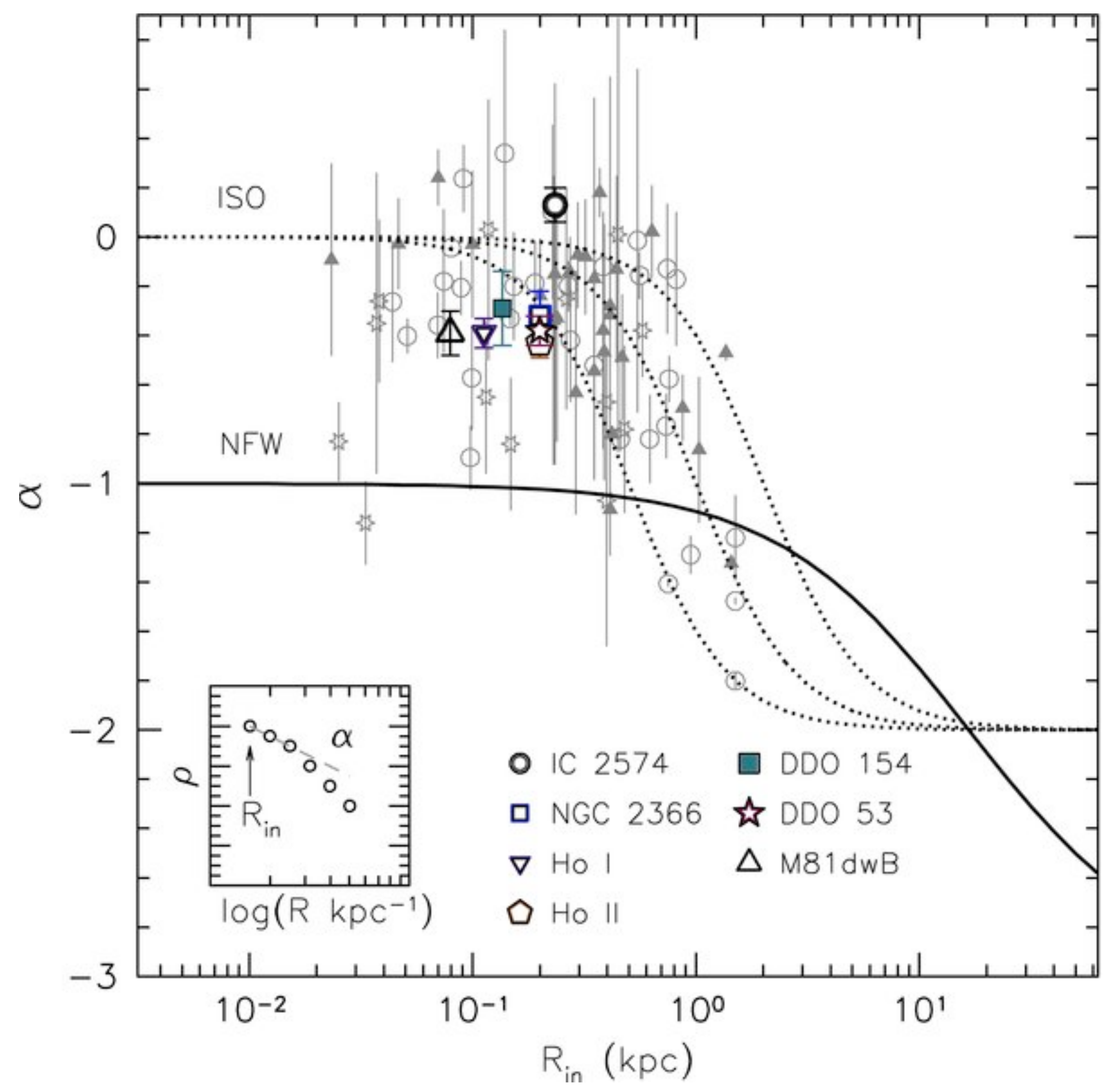
the cusp-core problem




Kuzio de Naray et al. (2008)

Inner density profiles of dark matter halos

$$\rho \sim r^{\alpha}$$




Oh et al (2011) AJ, 141, 193

# DM HALO MODELS

## many flavors have ben suggested

- pseudo-isothermal - empirically motivated
- NFW - DMO simulations
- Burkert - merges pISO inner core and NFW outer profile
- Einasto - NFW with an extra parameter to tweak the profile shape
- DC14 - from simulations with baryons
- coreNFW - from other simulations with baryons
- generic alpha-beta-gamma (inner-middle-outer power law density profiles)

NFW shape

NFW halos **triaxial**. More massive halos less round

perhaps because they are still building up hierarchically ?

Maccio et al (2007)

*Concentration, spin and shape of dark haloes* 63

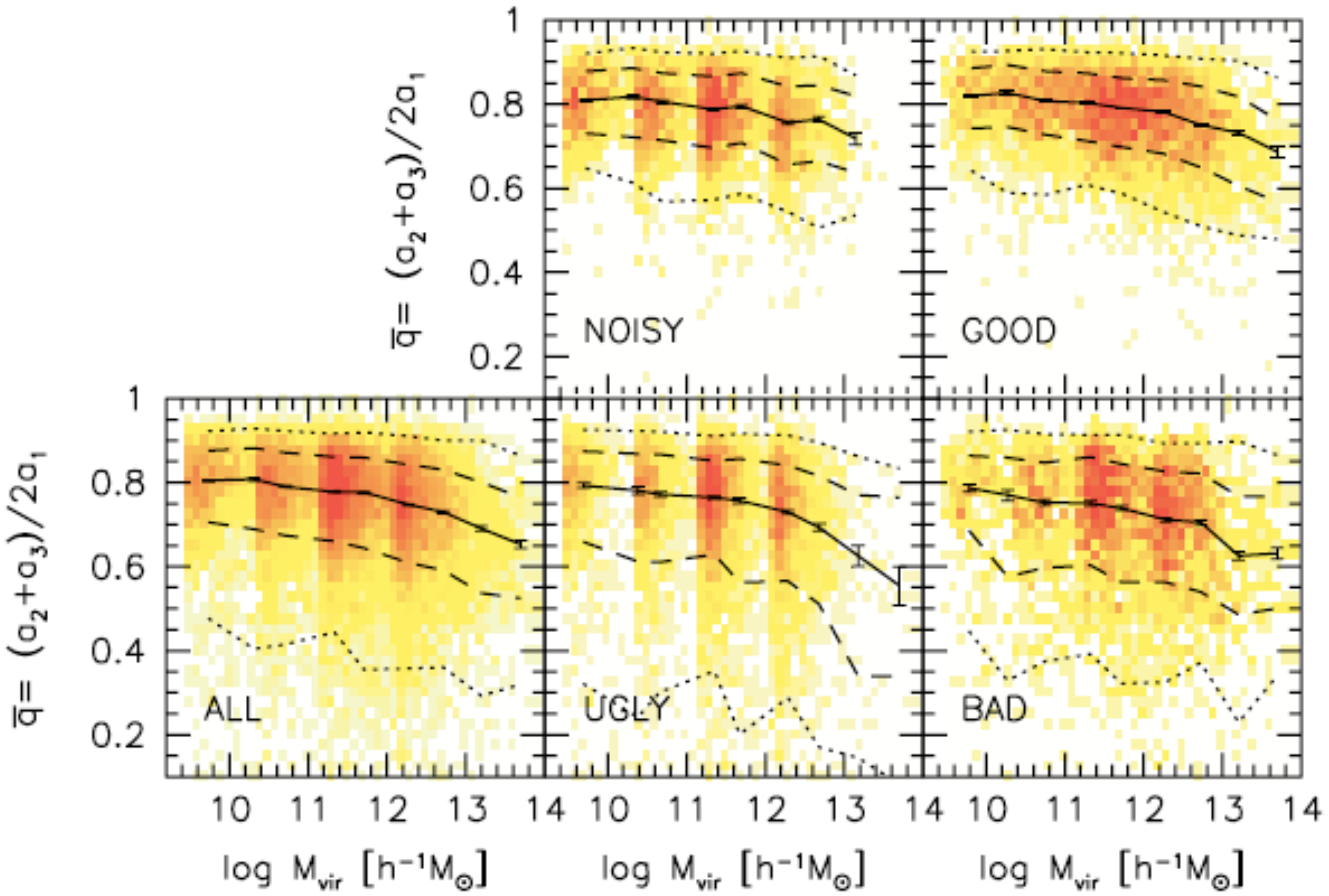
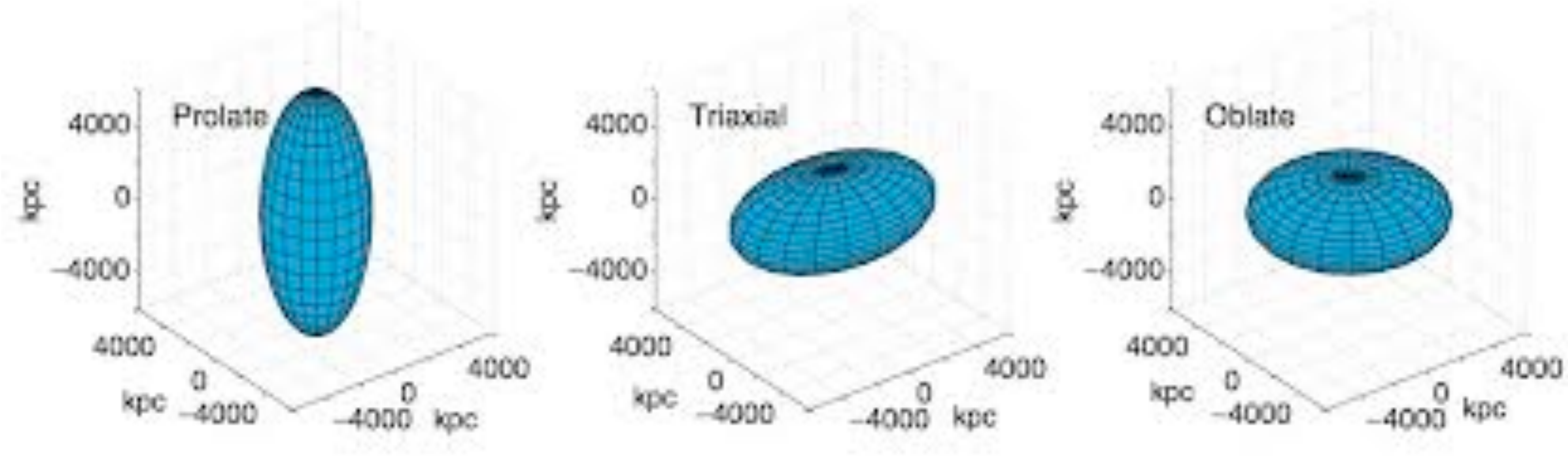



**Figure 6.** Relation between $\bar{q}$ and $M_{vir}$ for different subsamples of haloes. The solid lines show the 50th percentile, dashed lines show the 16th and 84th percentiles, and the dotted lines show the 2.5th and 97.5th percentiles. The error bar gives the Poisson error on the median.

As well as the average density profile, there is also the 3D shape

shape

prolate triaxial oblate



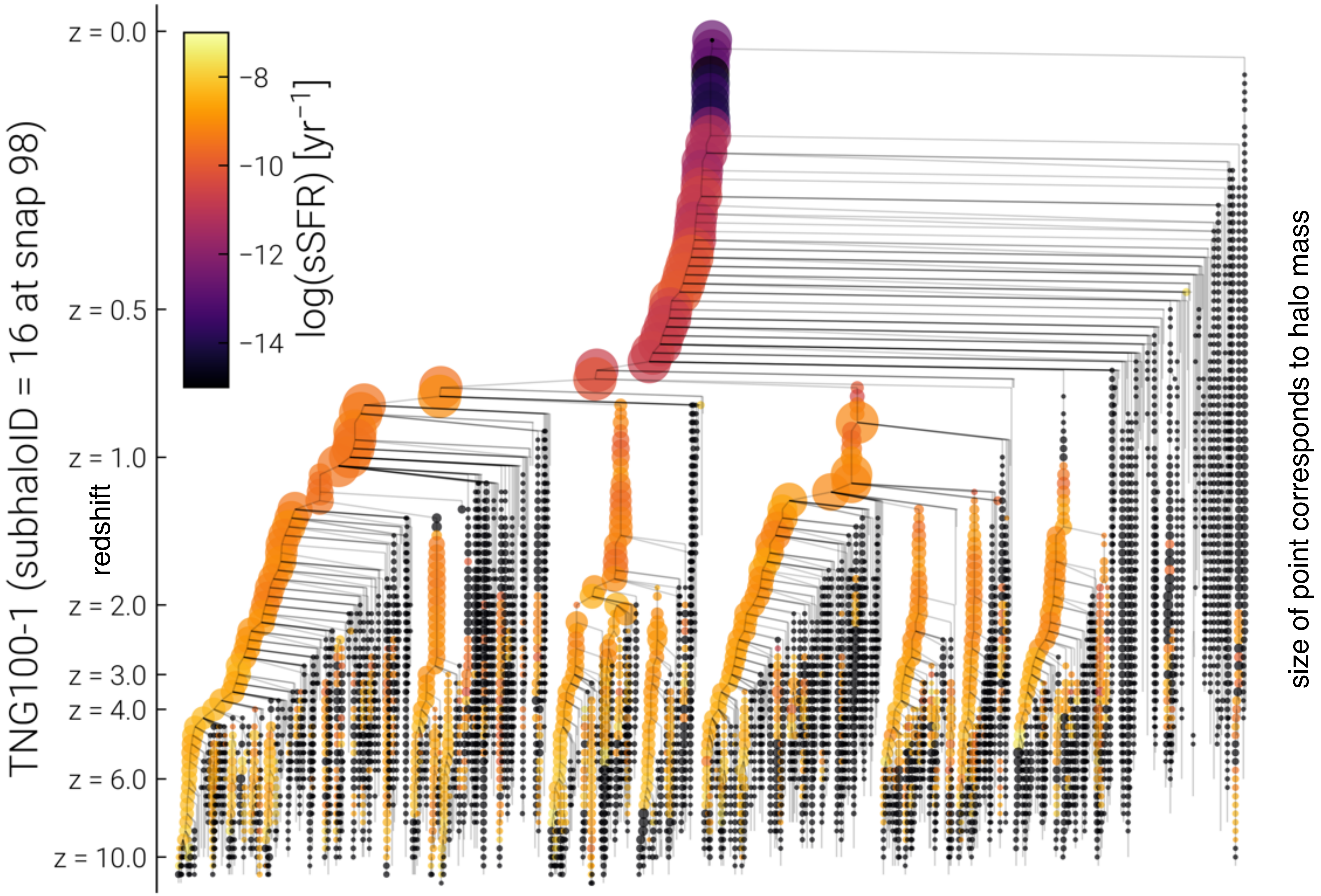

$a > b = c$ $a > b > c$ $a = b > c$

Simulations blobby and even more complicated

Galaxy formation is *hierarchical* in [L]CDM (*not* monolithic)

Small objects conglomerate to make big ones

## Merger tree from Illustris simulation



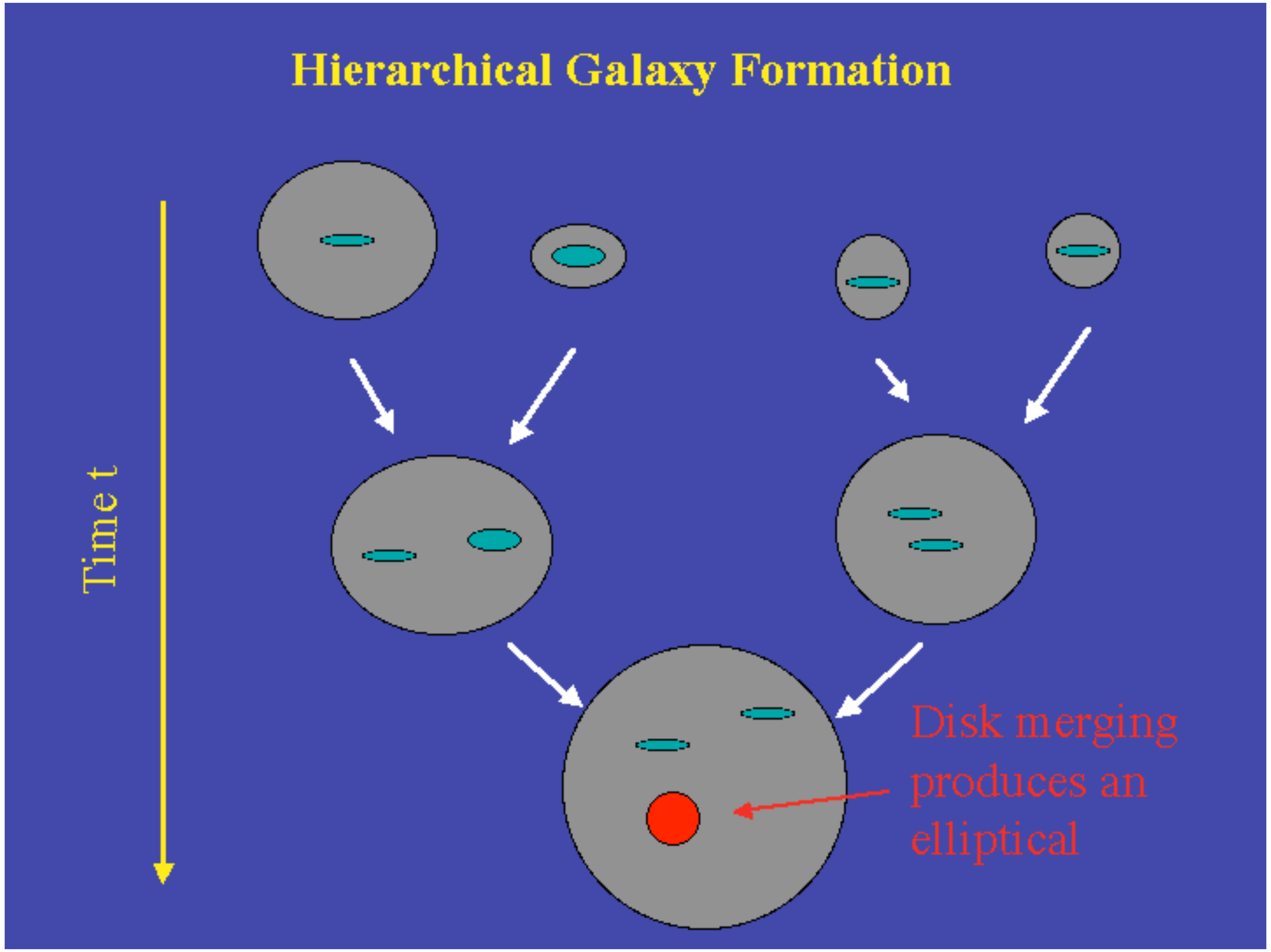

Small halos form first, then merge to make ever bigger halos

Gray: dark matter halos

Blue: gas rich disks

Red: elliptical merger remnant

Sometimes it is imagined that a disk re-forms around an elliptical to form a bulge+disk system. The newly formed disk will only contain stars dating from this epoch.




But: remember limits from Toth & Ostriker (1992)

# Baryonic effects

## Effects that might alter halo structure

- Pristine NFW halos form in DMO simulations
- Baryons fall into DM halos
  - some baryons cool & condense
    - Adiabatic contraction: DM halo adjusts to sinking of baryonic component
    - makes DM halos more centrally concentrated, making cusp/core problem worse
  - star formation
    - Feedback from SF injects energy into surrounding gas via winds & SN (etc.)
      - might make DM halo less concentrated