Galaxy–Scale Challenges for Cosmology

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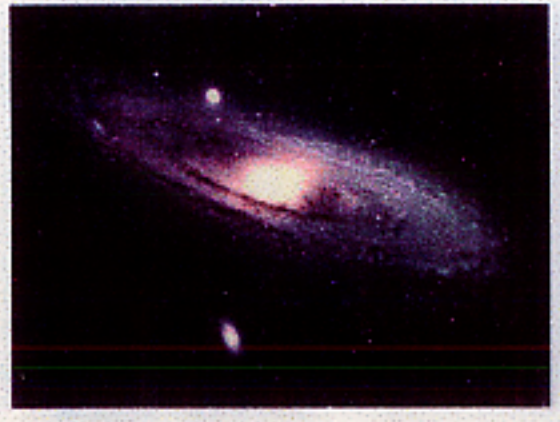
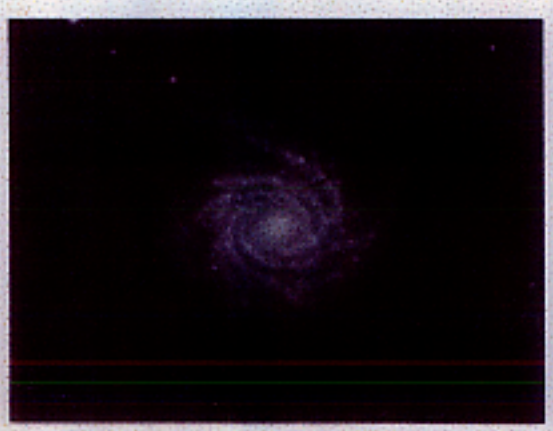
Standard cosmological model successful on scales from horizon down to galaxy clusters

Microwave background properties	Initial conditions
Large–scale structure properties	Present epoch
Evolution history	In between

Galaxies are not a comfortable match. Is this important?
Galaxies are complex objects.





Problems on Galaxy Scales

Sellwood & Kosowsky 2000
Tasitsiomi 2002

1. Galaxy ensemble properties

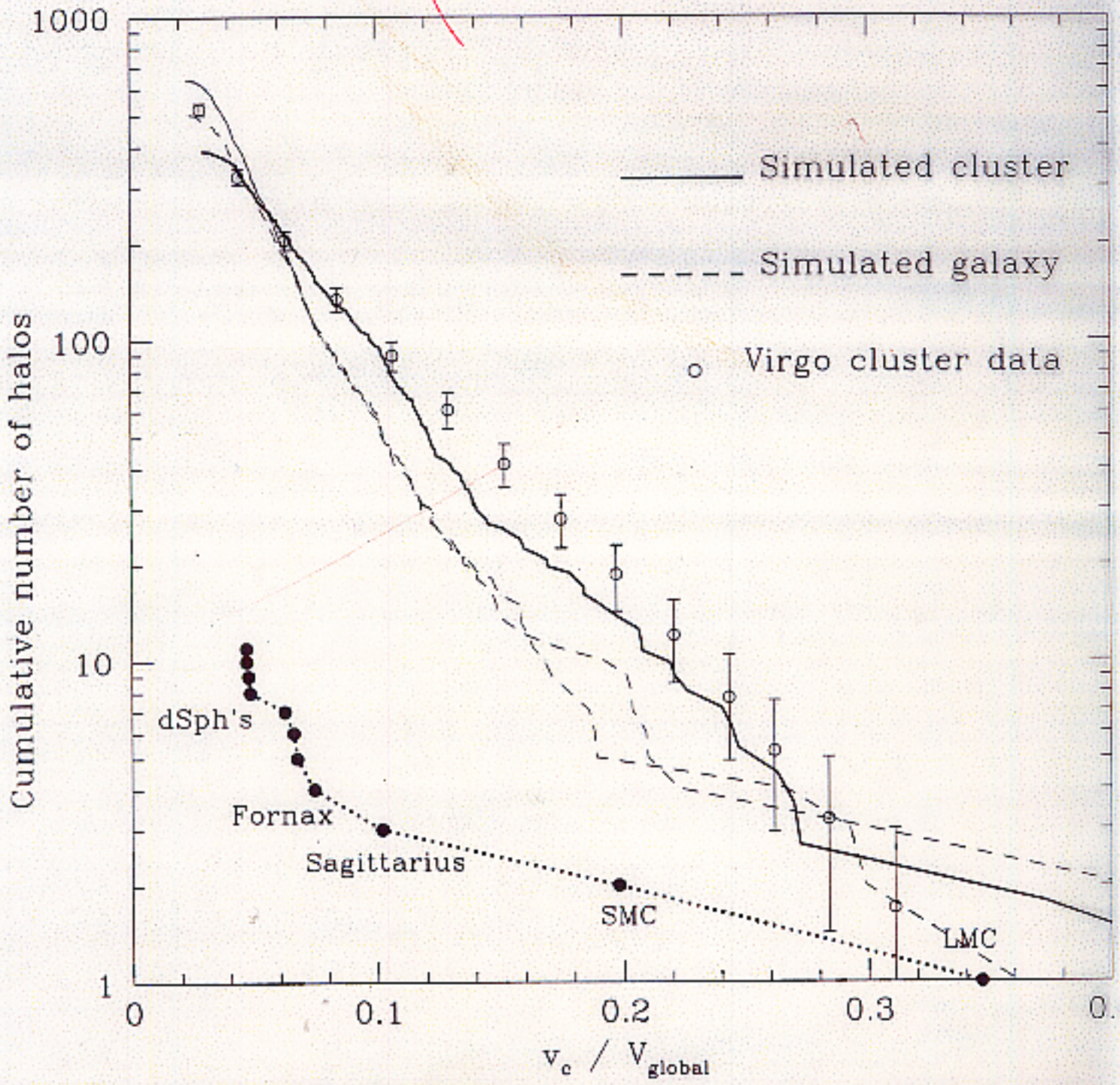
   Substructure ; Angular Momentum

2. Halo shapes

   Cusps vs. cores; Central concentration

3. Disk / Halo mass distributions

   Rotation curve from disk only ; related problems



B. Moore et al. 1999

Bullock, Kravtsov & Weinberg 2000: Accretion onto small dark matter clumps inefficient after reionization. Disk heating a problem

Angular Momentum Problem

- Realistic disks: baryons must retain angular momentum as disk forms

  White & Rees 1978
  Burkert 2000

- Little angular momentum lost, either radiatively or via dynamical friction

Most simulations give disks which are too small, have too little angular momentum (factor of 10)

Navarro & White 1994

Governato et al. (2002) claim problem is solved with better resolution ($N \simeq 10^5$) and better gas physics but few details so far.

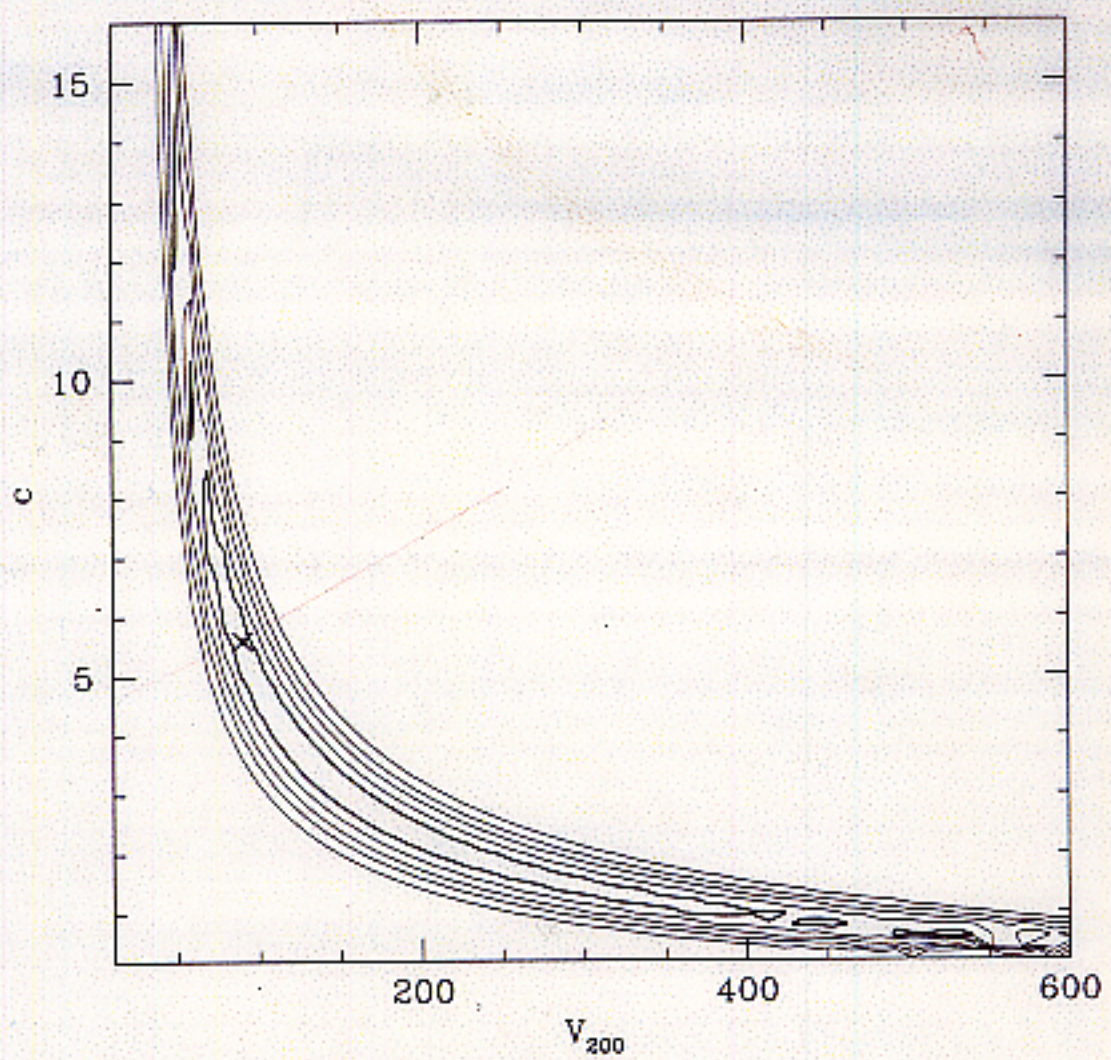


FIG. 4.— The error contours for the minimum disk NFW fit of F583-4 drawn in linear $c - V_{200}$ space. Contour values are as in Fig. 3.

de Blok, McGaugh & Rubin 2001

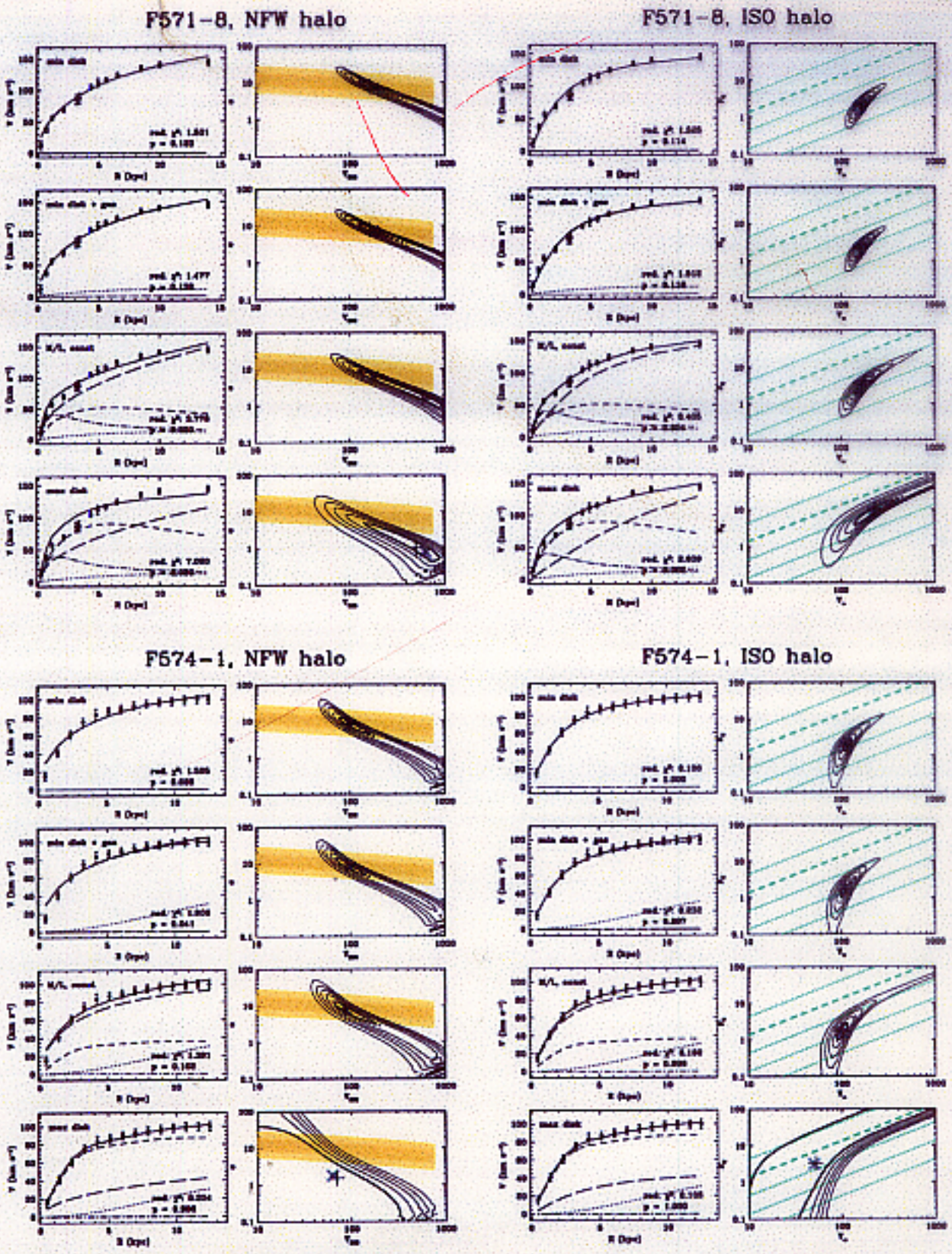
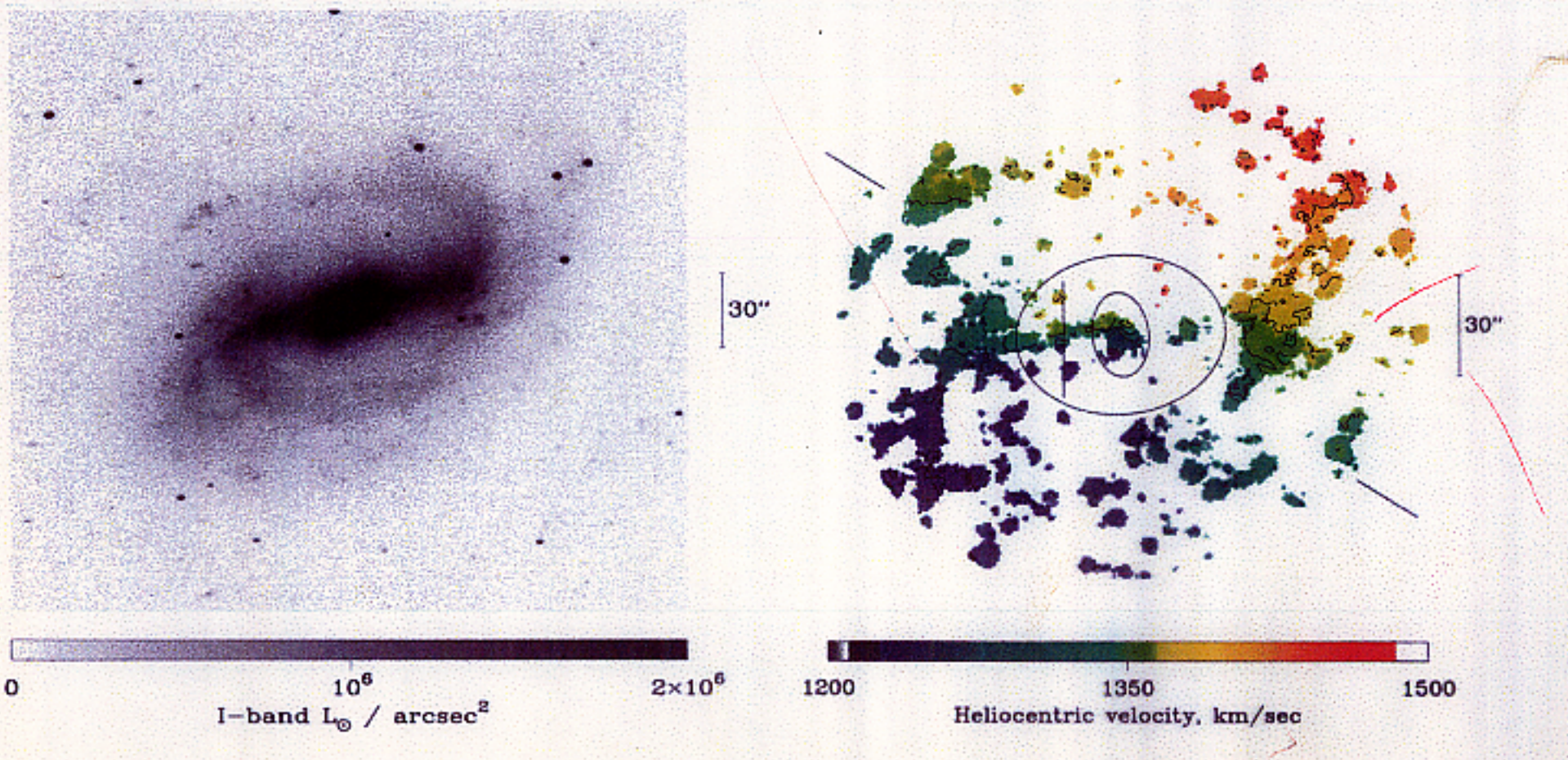


FIG. 3.— Mass models assuming NFW halo (left) and pseudo-isothermal halo (right). Within each panel the left column shows the best fitting model, the right column shows the probability distribution of the halo parameters. For a full description see text (Sect. 4).

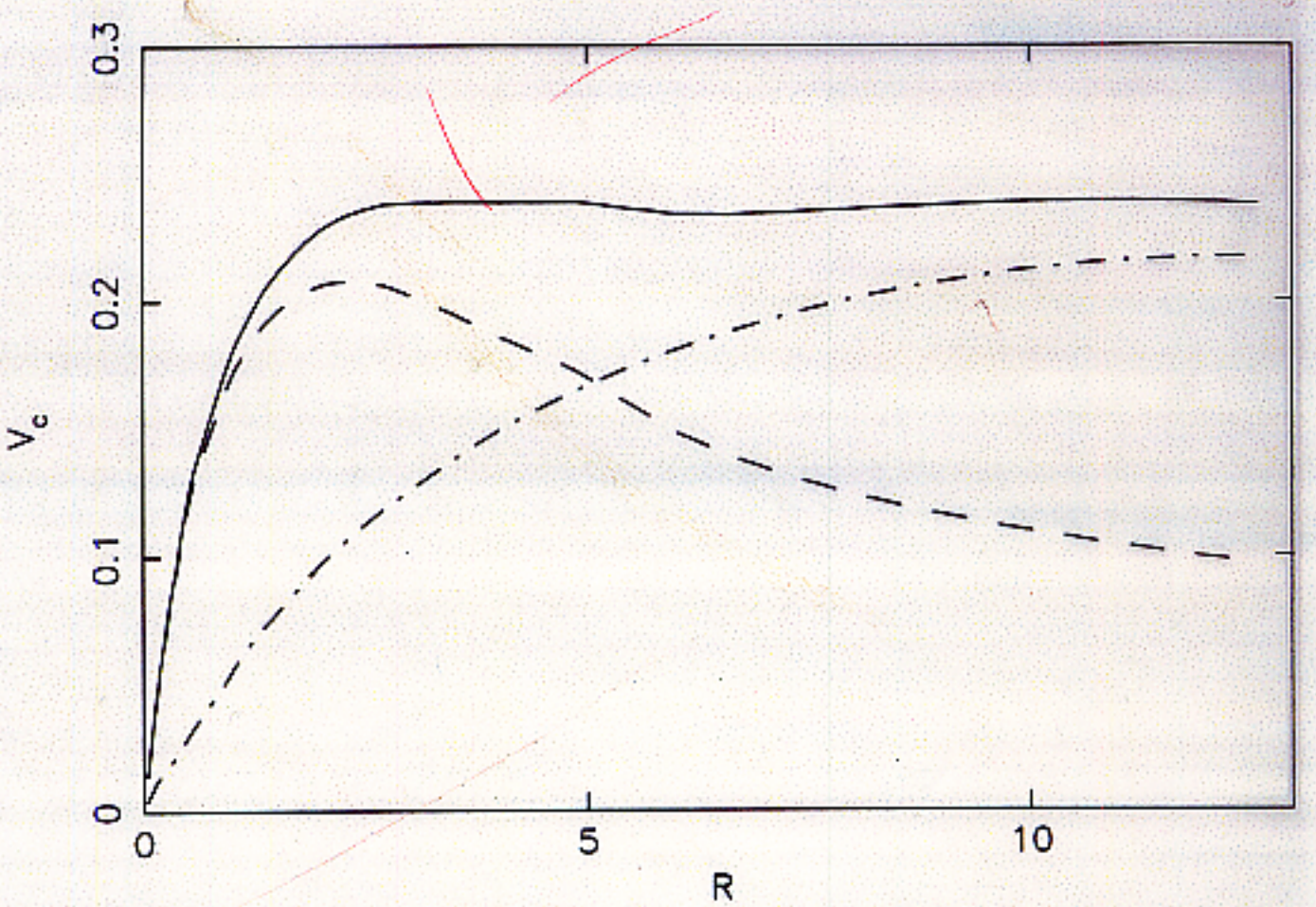
de Blok, McGaugh & Rubin 2001

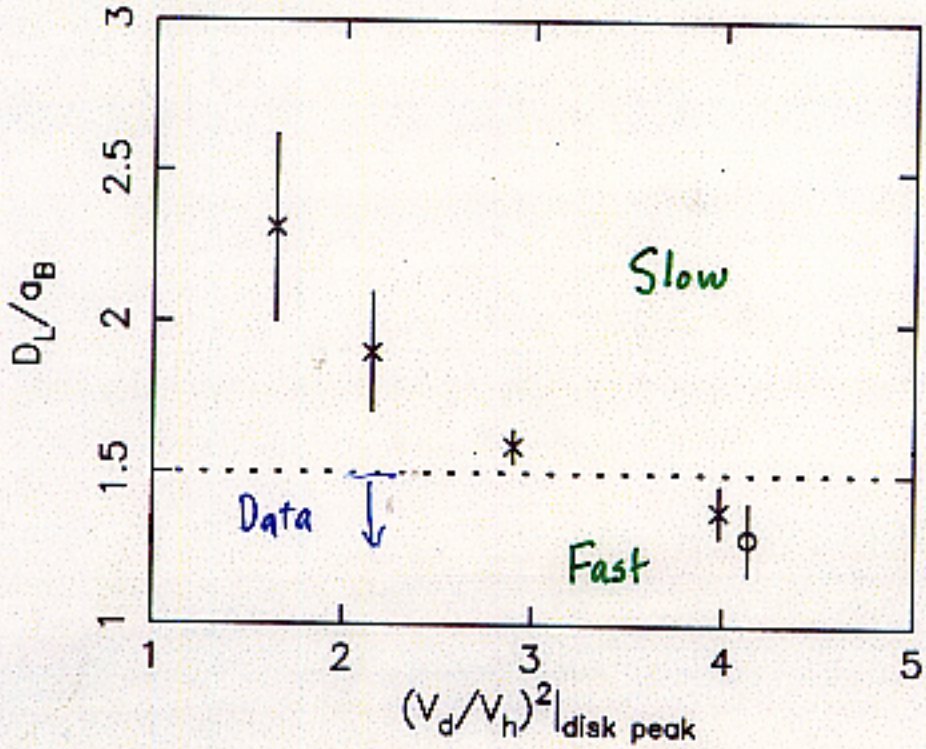
Radial motions in NGC4123 give visible mass estimate

Weiner, Sellwood and Williams 2000



I–band M/L about 2.25, gives "maximum disk" fit





Debattista & Sellwood 1997

Observed bar pattern speeds are fast, so central halo densities must be low

- Low surface-brightness rotation curves favor

$$\rho(R) \propto \frac{1}{1+\left(\frac{R}{R_s}\right)^2} \qquad \text{"pseudo-isothermal"}$$

instead of

$$\rho(R) \propto \frac{1}{\left(\frac{R}{R_s}\right)\left(1+\left(\frac{R}{R_s}\right)^2\right)} \qquad \text{NFW}$$

- Dynamical evidence shows low central densities
  (→ small NFW concentration $c = R_{200}/R_s$)

Weiner et al. 2000
Debattista et al. 2000
Binney & Evans 2001

How can we make low-density cores?

Zentner & Bullock 2002 Primordial $n \simeq 0.8$ helps
Eke, Navarro & Steinmetz 2001
Weinberg & Katz 2002 Dramatic dynamical effects of satellites or bars? (Not seen in other simulations)

Spergel & Steinhardt 2000 Modified dark matter properties

Disk-Halo Mass Distribution

Full rotation curve can be predicted from only the disk mass

Disk luminosity vs. R
M/L ratio
Distance
} → Rotation curve

Note M/L ratio constrained by spectrum

Distances estimated via distance ladder; cepheids; SNIA
Distance the same for galaxies in clusters or groups

Corollaries:

Tully-Fisher relation (slope, zero point, surface brightness independence)

Disk-Halo conspiracy

Acceleration scale

"Milgrom Relation" Milgrom 1984

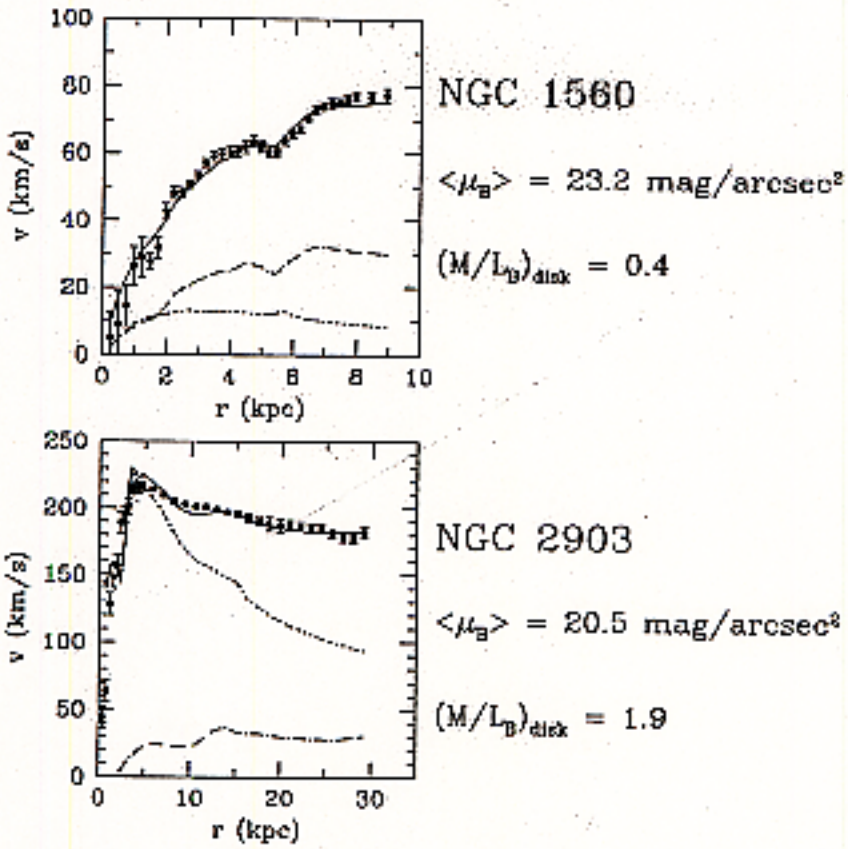


Figure 3: The points show the observed 21 cm line rotation curves of a low surface brightness galaxy, NGC 1650 (Broeils 1992) and a high surface brightness galaxy, NGC 2903 (Begeman 1987). The dotted and dashed lines are the Newtonian rotation curves of the visible and gaseous components of the disk and the solid line is the MOND rotation curve with $a_o = 1.2\times10^{-8}$ cm/s^2– the value derived from the rotation curves of 10 nearby galaxies (Begeman et al. 1991). The only free parameter is the mass-to-light ratio of the visible component.

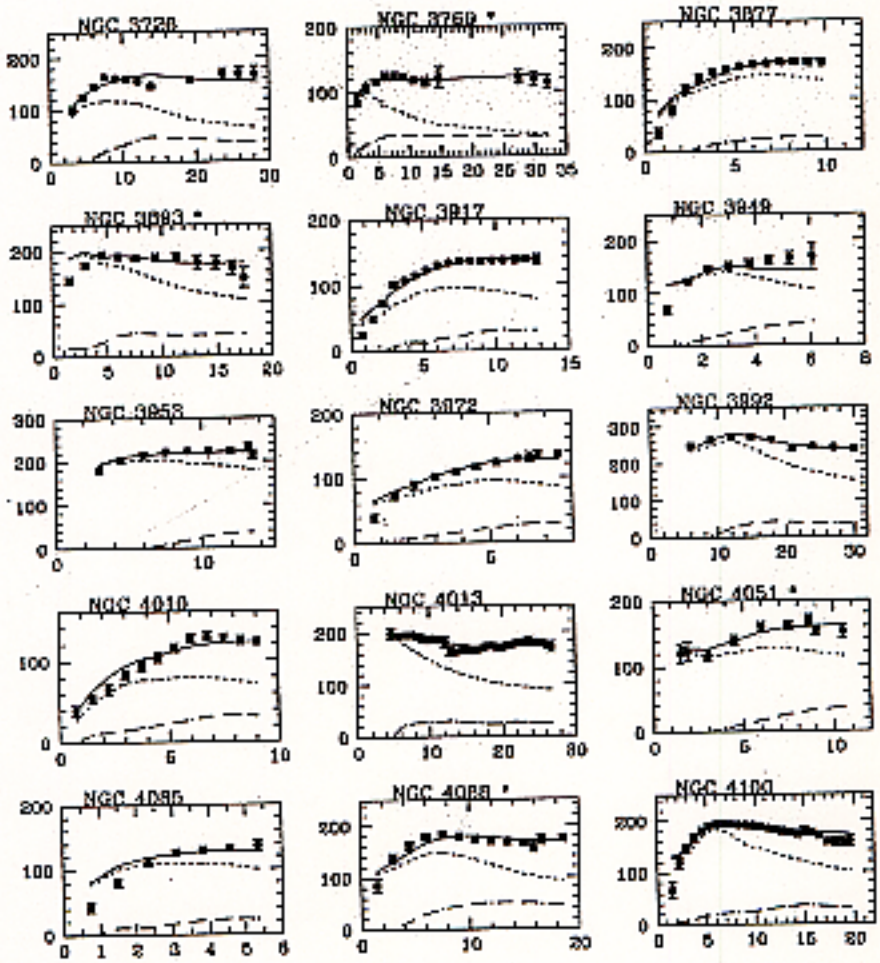

NGC 3198
NGC 3769 *
NGC 3877
NGC 3893 *
NGC 3917
NGC 3949
NGC 3953
NGC 3972
NGC 3992
NGC 4010
NGC 4013
NGC 4051 *
NGC 4085
NGC 4088 *
NGC 4100

Figure 4:

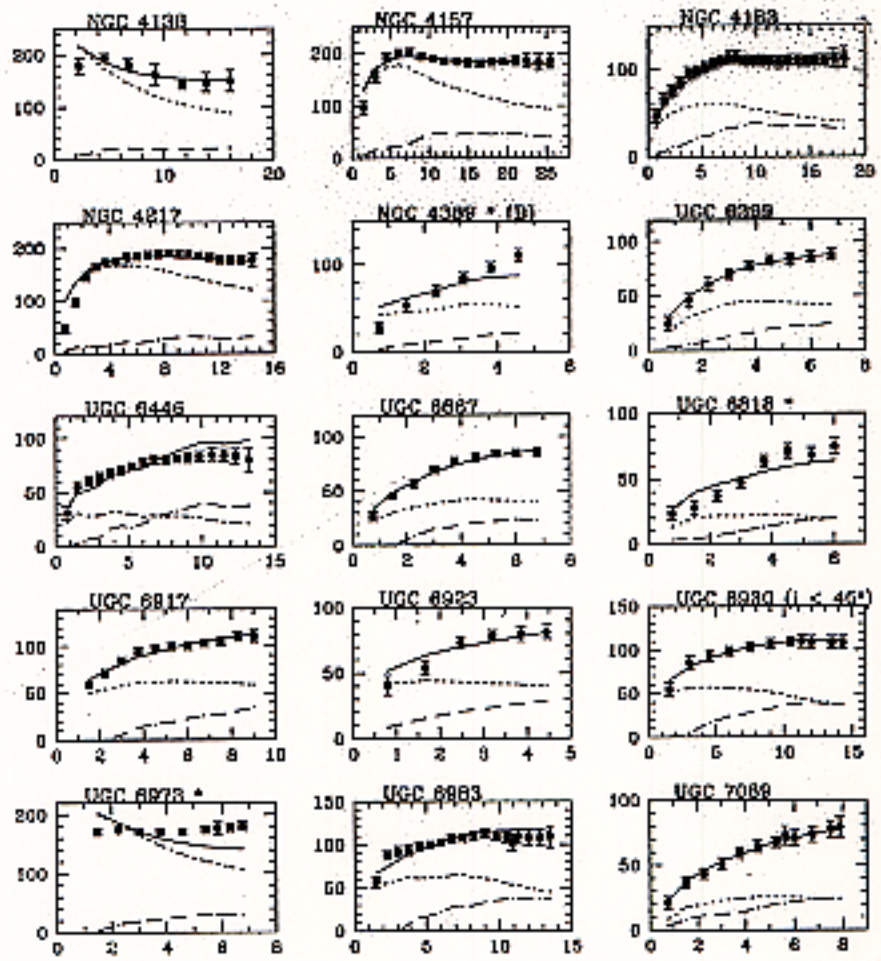


Figure 4: MOND fits to the rotation curves of the Ursa Major galaxies (Sanders & Verheijen 1998). The radius (horizontal axis) is given in kiloparsecs and in all cases the rotation velocity is in kilometers/second. The points and curves have the same meaning as in Fig. 3. The distance to all galaxies is assumed to be 15.5 Mpc and a_o is the Begeman et al. (1991) value of 1.2×10^{-8} cm/s^2. The free parameter of the fitted curve is the mass of the stellar disk. If the distance to UMa is taken to be 18.6 Mpc, as suggested by the Cepheid-based re-calibration of the Tully-Fisher relation (Sakai et al. 2000), then a_o must be reduced to 10^{-8} cm/s^2.

Disk mass profile $\longrightarrow$ halo mass profile

For exponential disk, $\rho \propto \begin{cases} r^{-1} & \text{small } r \\ r^{-2} & \text{large } r \end{cases}$

AK 2002

Of more interest to modellers,

halo mass profile restricts acceptable disk mass profiles

If disk, halo each described by 2 parameters (mass, length), only 2 are independent

$\longrightarrow$ Evolution must possess dynamical attractors in this 4-parameter space

What causes this?

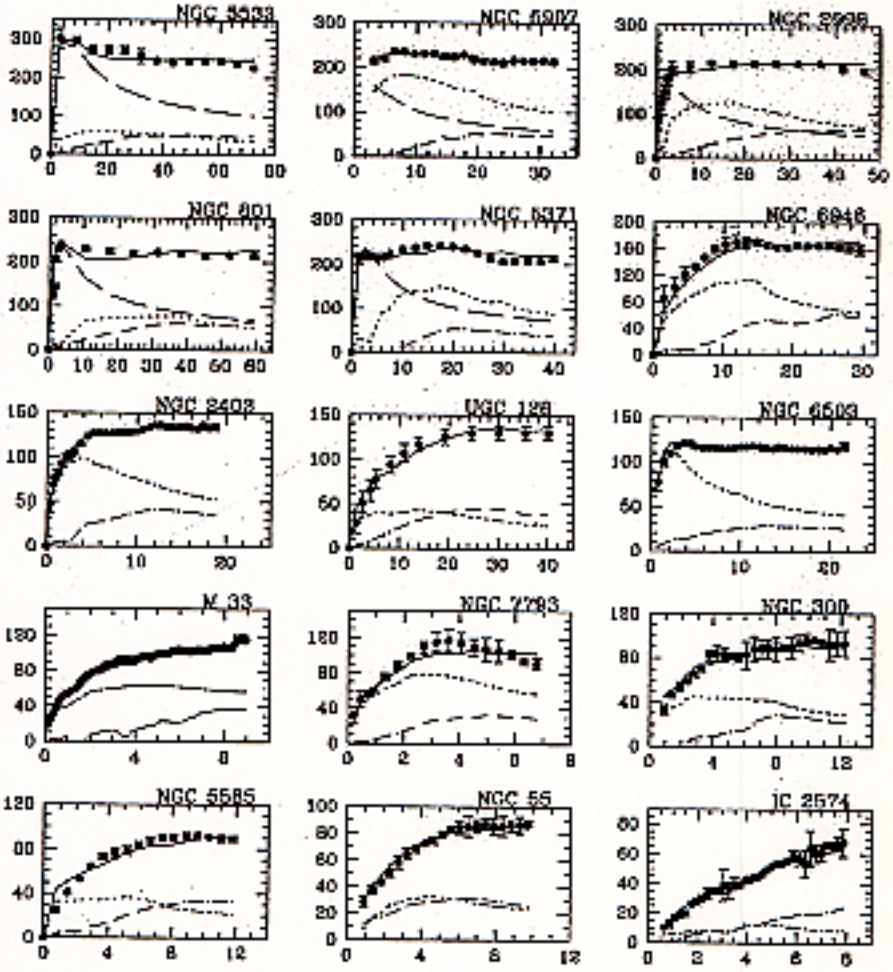
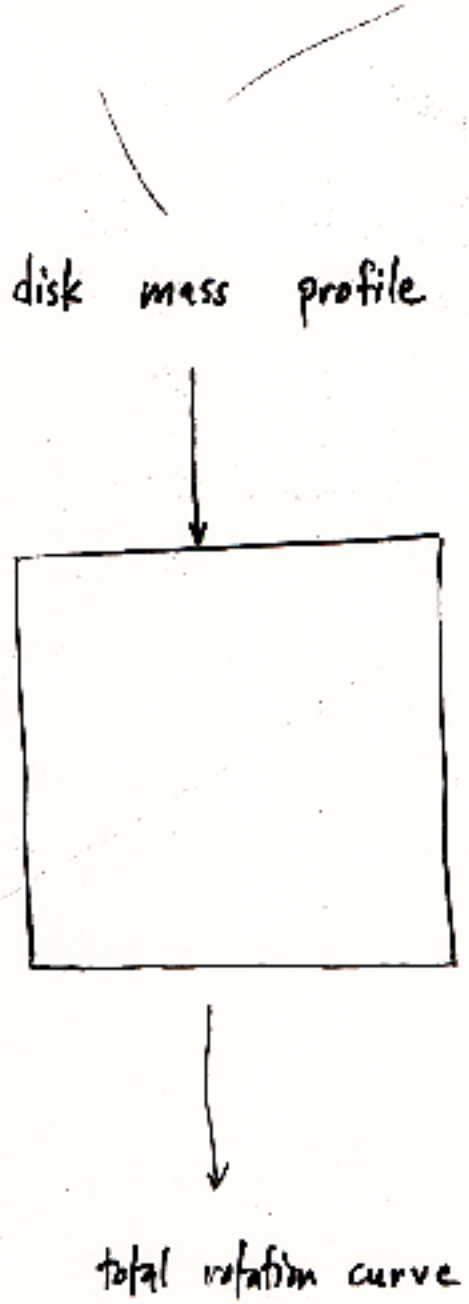


Figure 5: MOND fits to the rotation curves of spiral galaxies with published data, from Sanders (1996) and de Blok & McGaugh (1998). The symbols and curves are as in Fig. 4.


disk mass profile
total rotation curve

$$g \propto \begin{cases} r^{-2}, & g > a_0 \\ r^{-1}, & g < a_0 \end{cases}$$

$$a_0 \simeq 1.0 \times 10^{-8} \ \mathrm{cm/s^2}$$

This is the effective force law for baryonic matter in disk galaxies!