Dark Matter

ASTR 333/433
Fall 2013
M T 4:00-5:15pm
Sears 552

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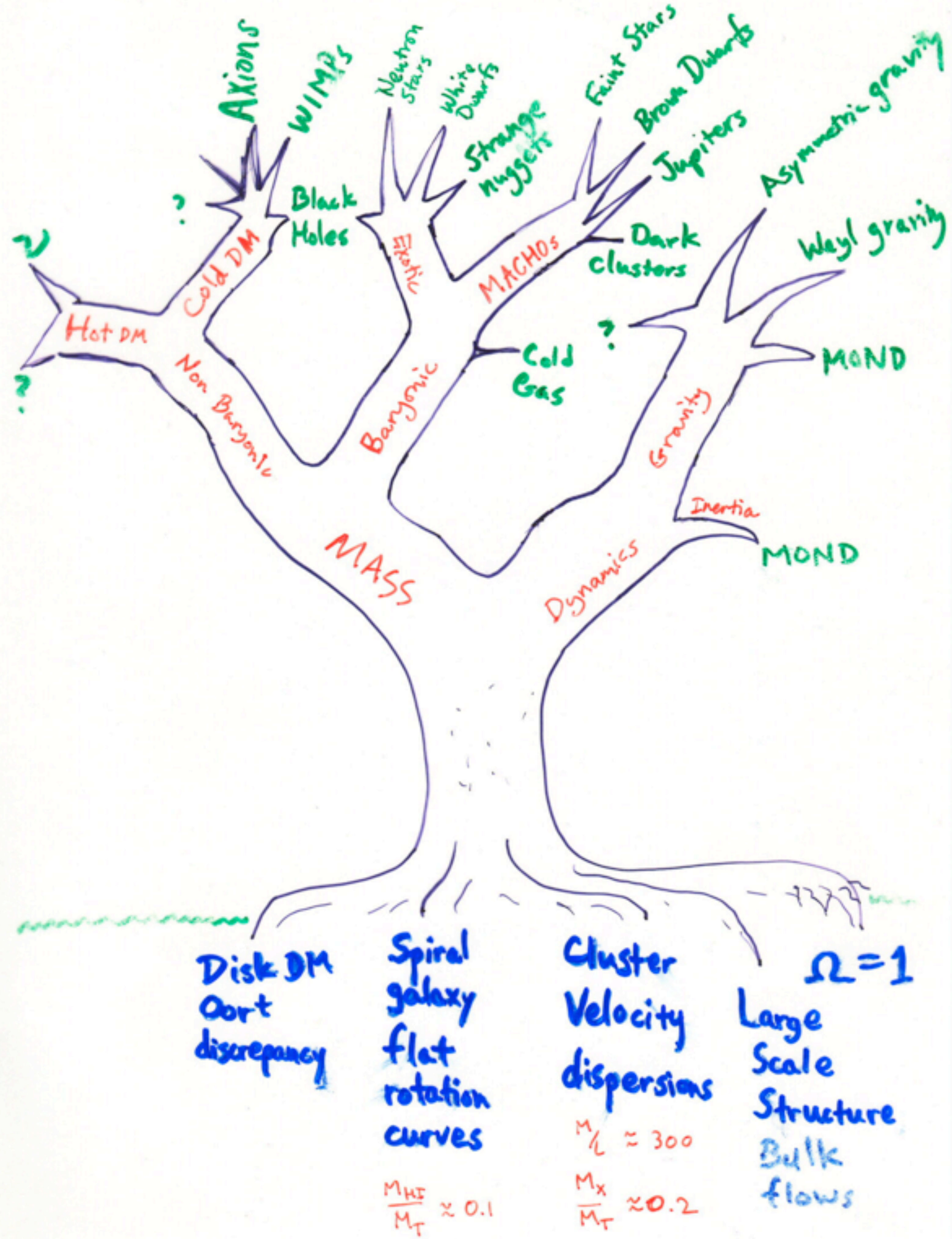


Empirical Laws of Galactic Rotation

Homework 2
due Oct 15

midterm Oct 29

1. Rotation curves tend to become flat at large radii

$$V \propto \text{const}$$

$$M \propto R$$

$$\rho \propto R^{-2}$$

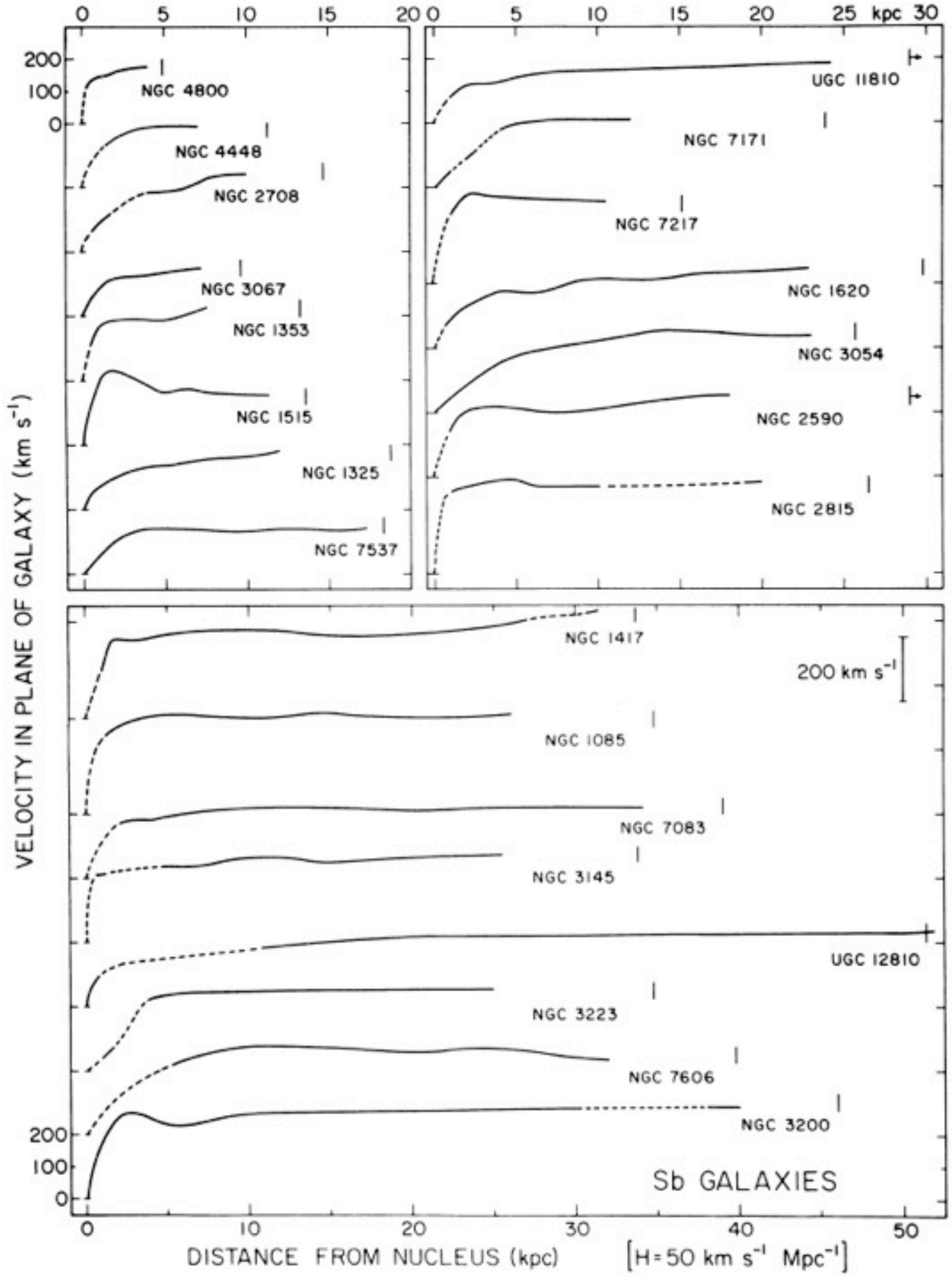
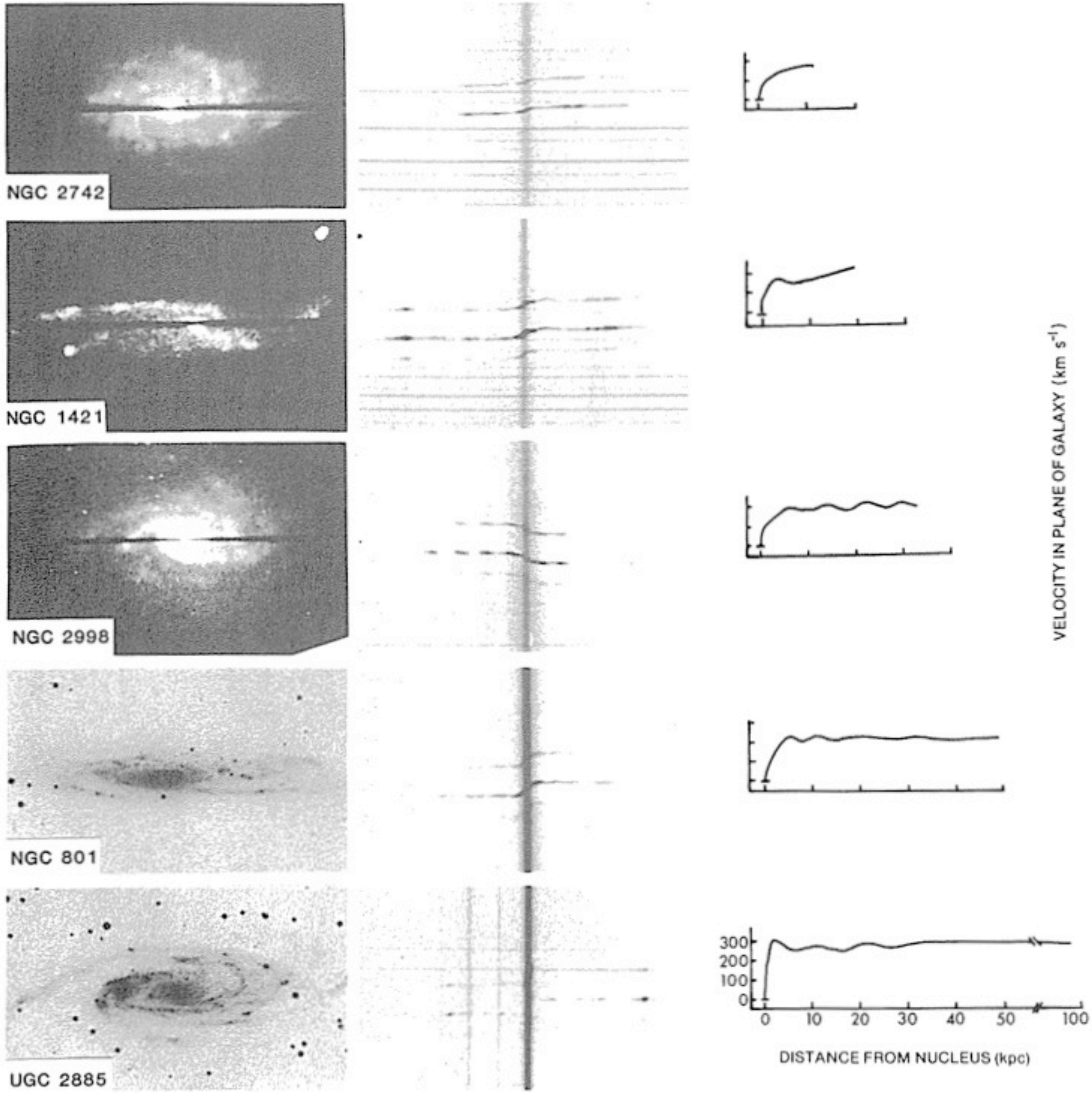
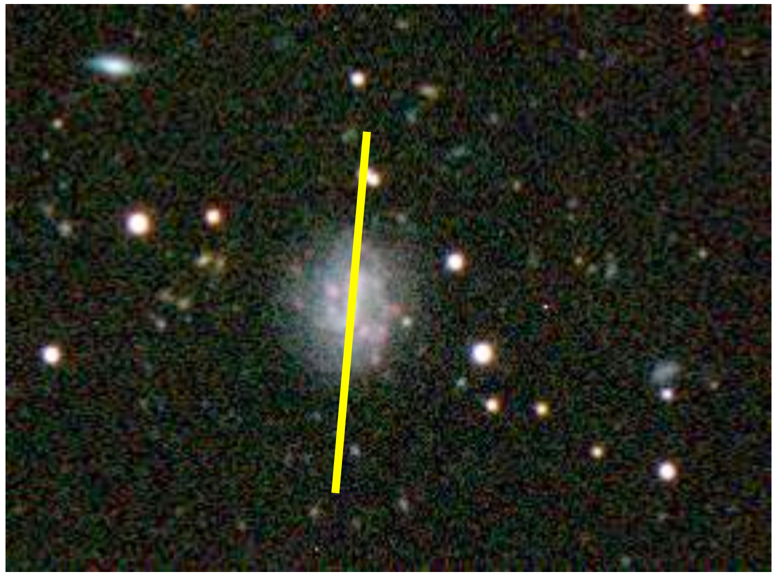


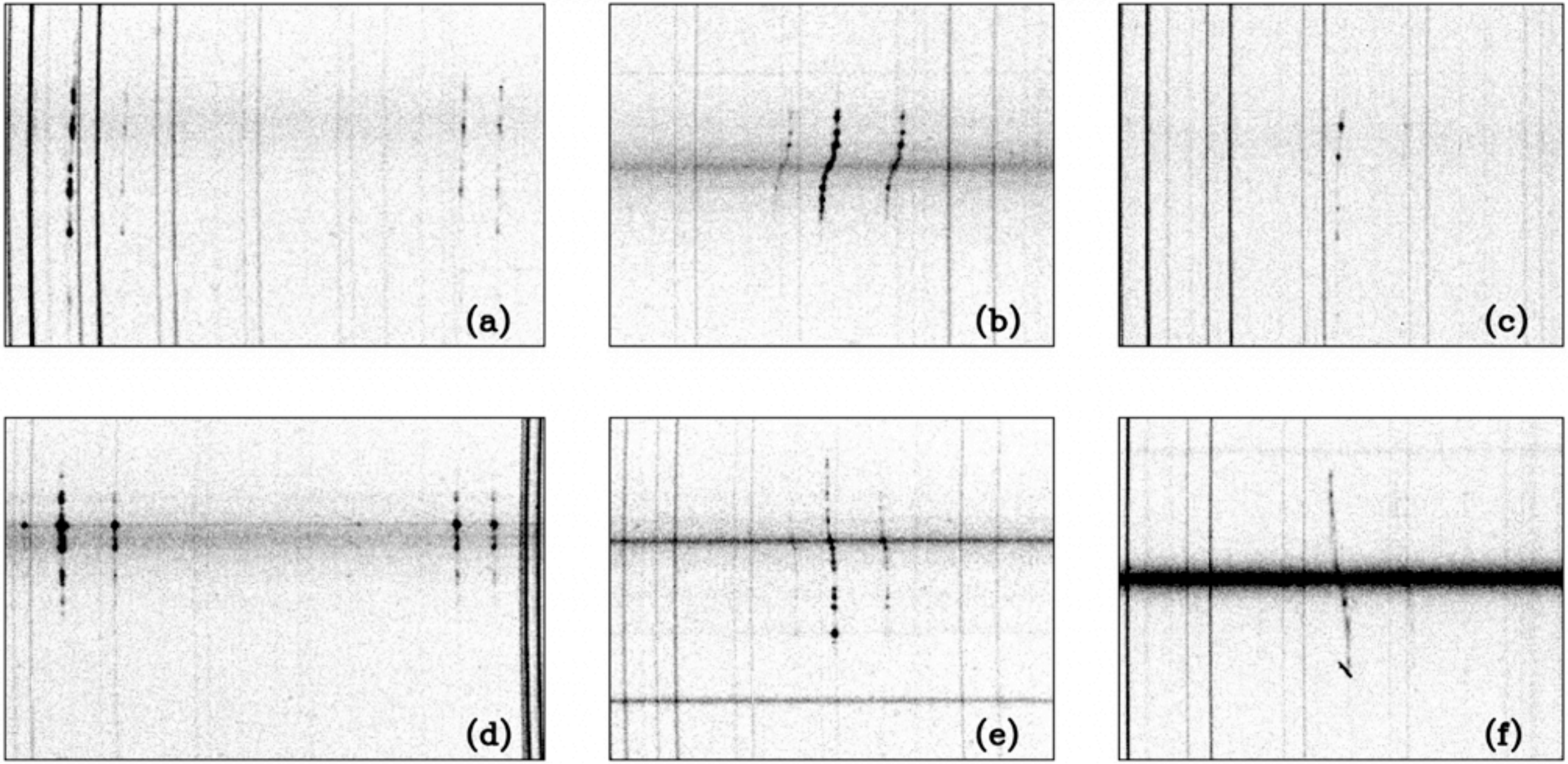
FIG. 3.—Mean velocities in the plane of the galaxy, as a function of linear radius for 23 Sb galaxies, arranged approximately according to increasing luminosity. Adopted curve is rotation curve formed from the mean of velocities on both sides of the major axis. Vertical bar marks the location of R_{25}, the isophote of 25 mag arcsec^{-2}, corrected for effects of internal extinction and inclination. Regions with no measured velocities are indicated by dashed lines.

Optical data from
Rubin, Thonnard, & Ford 1978, *ApJ*, **225**, L107

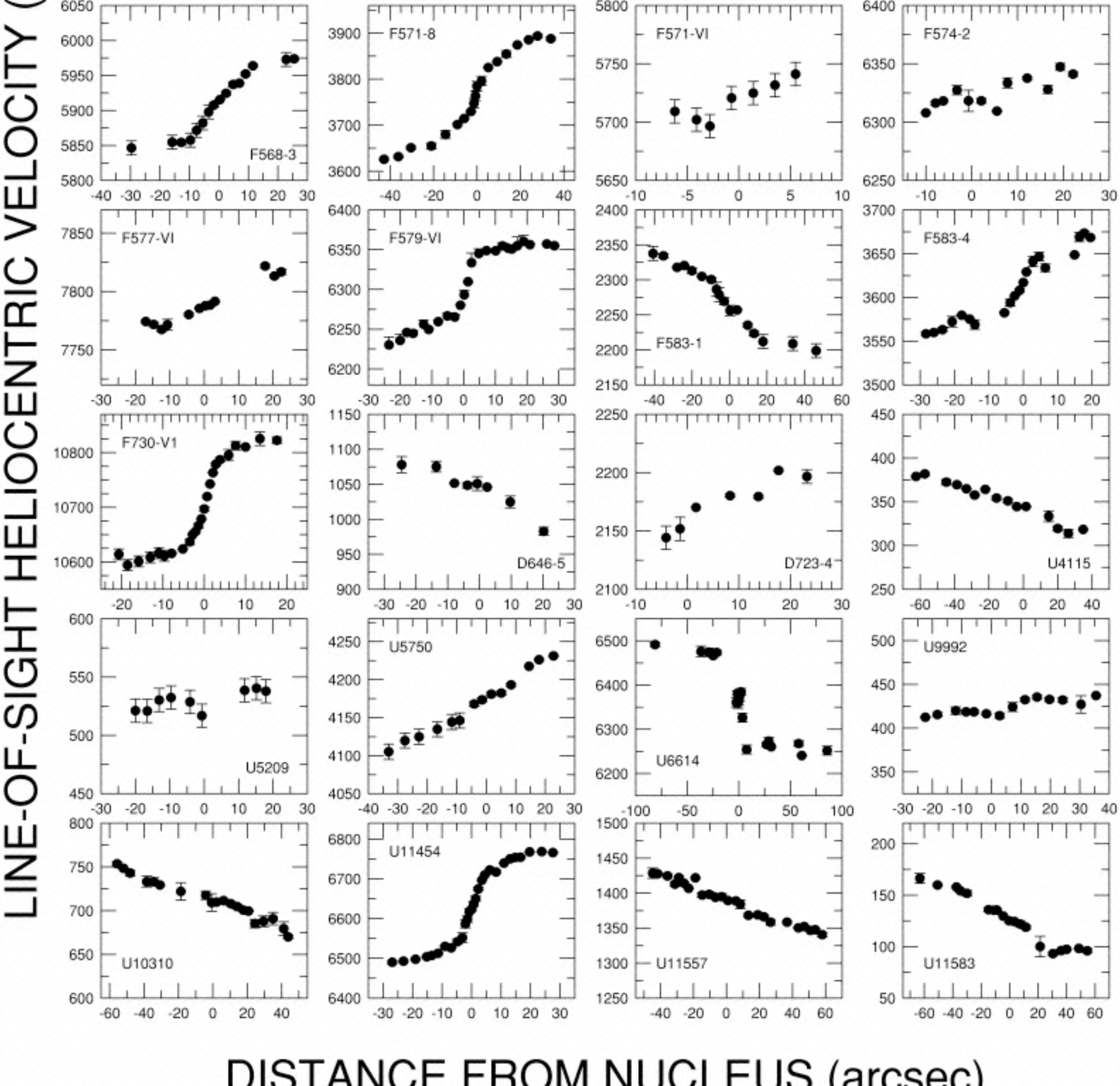


NGC 2742
NGC 1421
NGC 2998
NGC 801
UGC 2885
VELOCITY IN PLANE OF GALAXY (km s⁻¹)
300
200
100
0
0
10
20
30
40
50
100
DISTANCE FROM NUCLEUS (kpc)

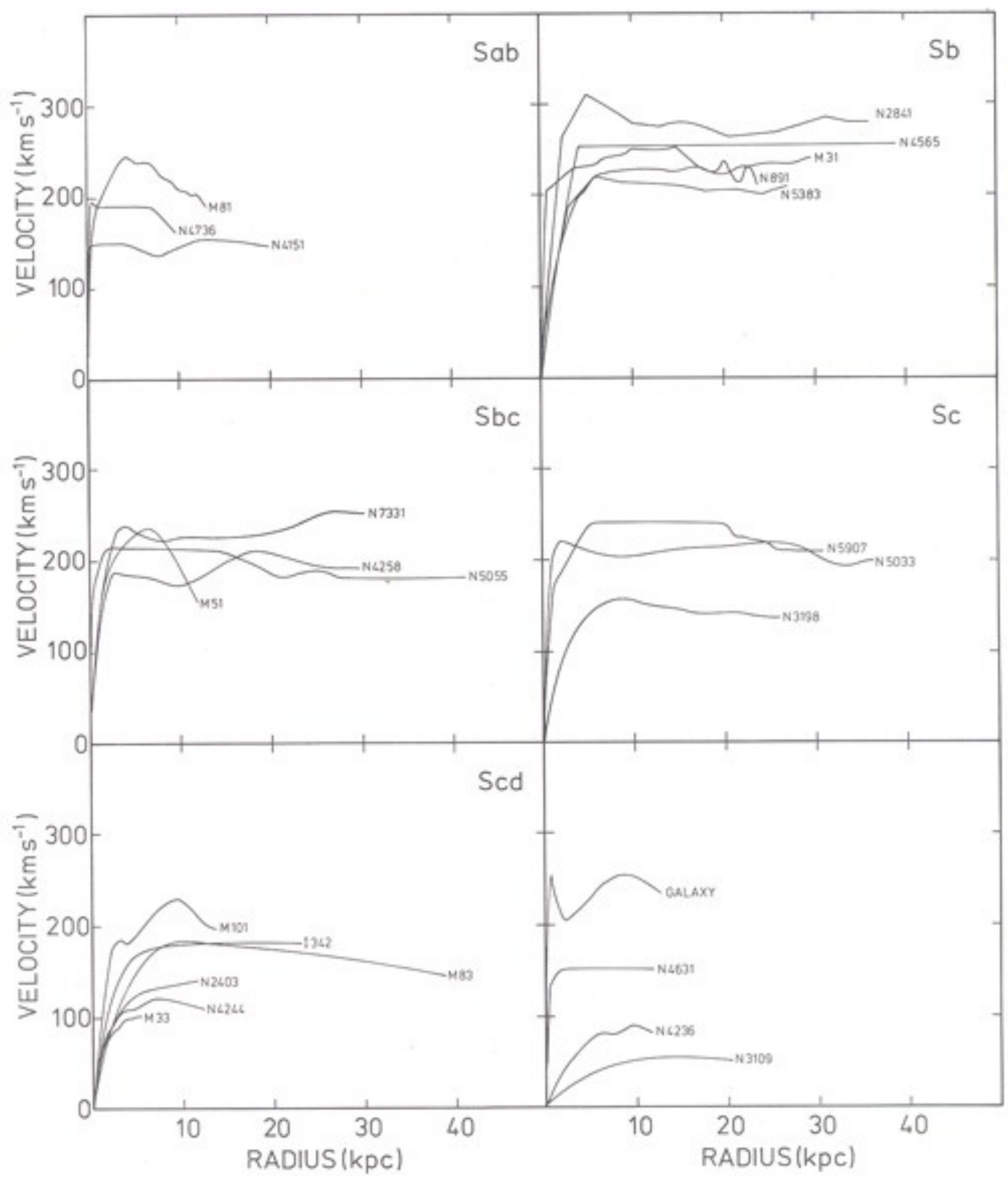




(a)
(b)
(c)
(d)
(e)
(f)

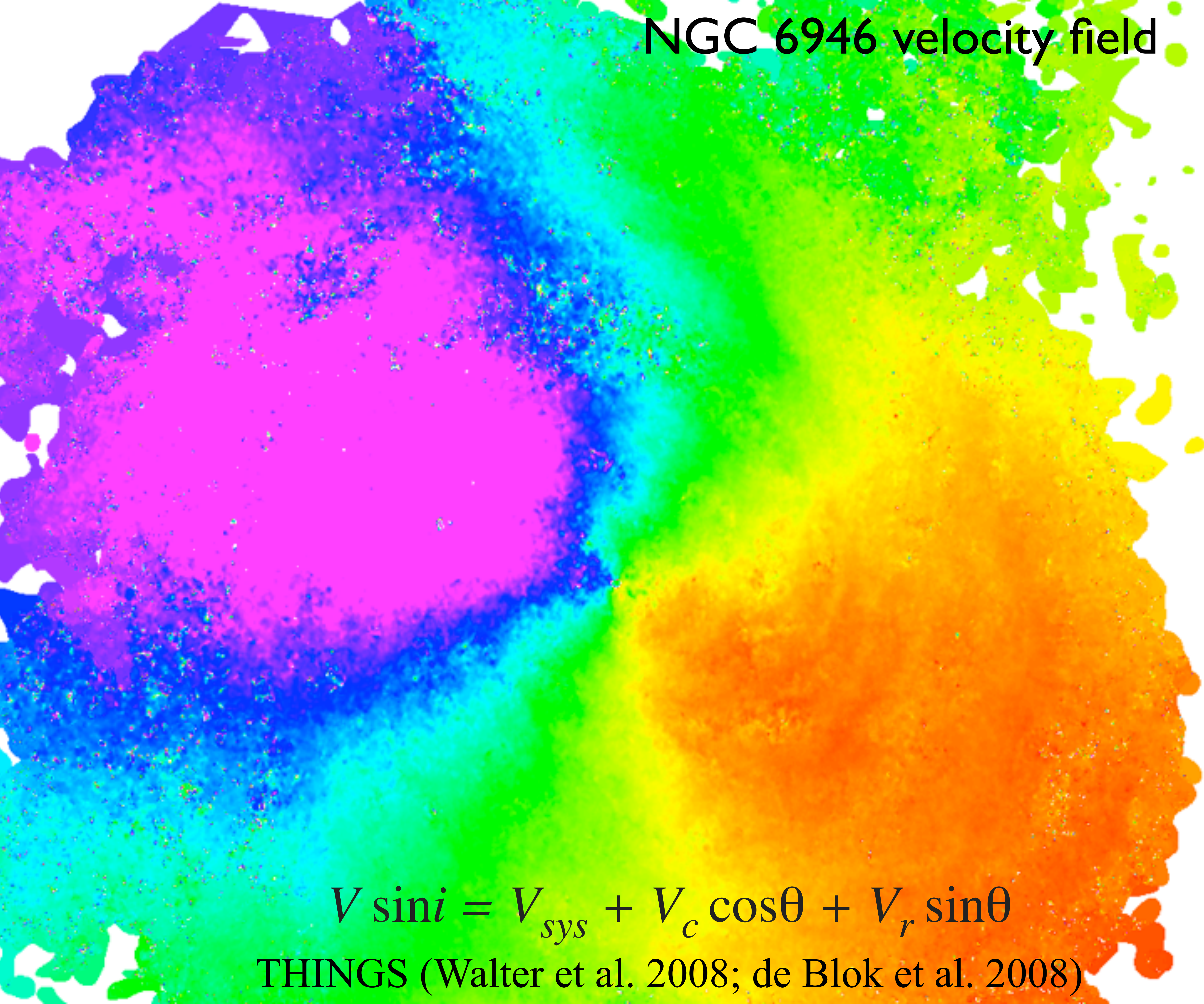

F568-3
F571-8
F571-VI
F574-2
F577-VI
F579-VI
F583-1
F583-4
F730-V1
D646-5
D723-4
U4115
U5209
U5750
U6614
U9992
U10310
U11454
U11557
U11583
LINE-OF-SIGHT HELIOCENTRIC VELOCITY (
DISTANCE FROM NUCLEUS (arcsec)

...and stay flat to the largest radii probed



Radio data from
Bosma 1981, *AJ*, **86**, 1825

NGC 6946 velocity field



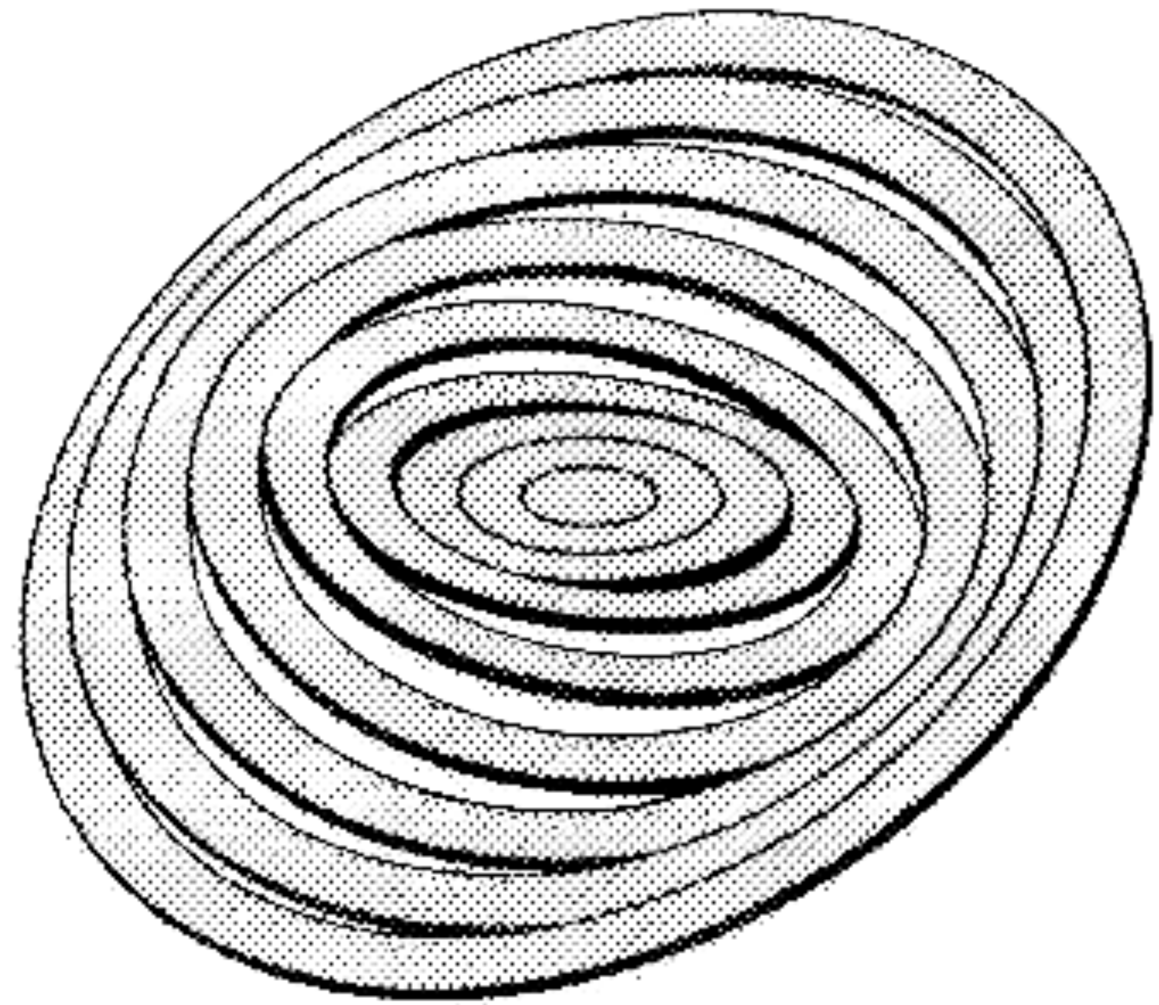
$$V \sin i = V_{sys} + V_c \cos\theta + V_r \sin\theta$$

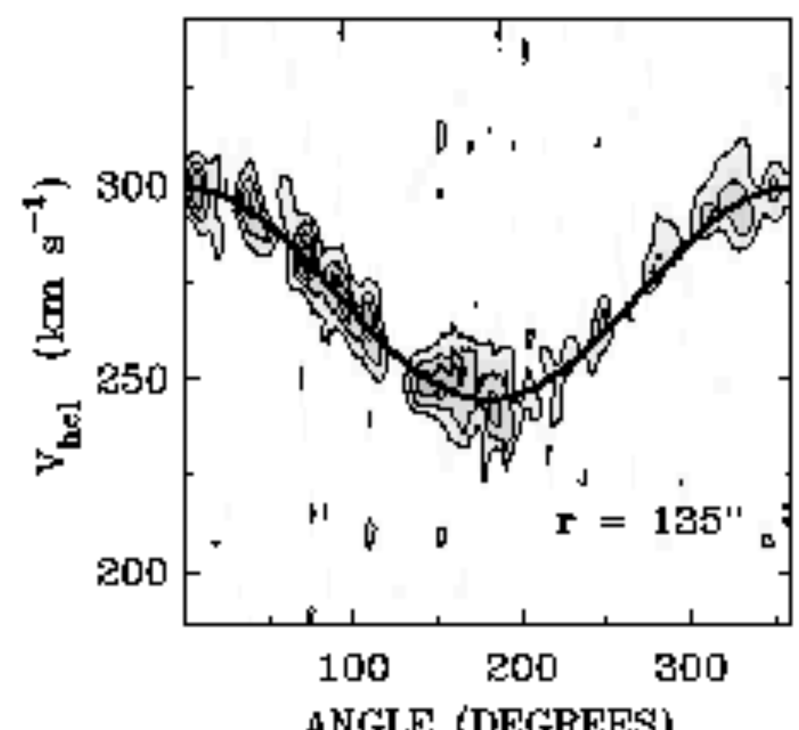
THINGS (Walter et al. 2008; de Blok et al. 2008)

Rotation curves extracted using "tilted ring" fits

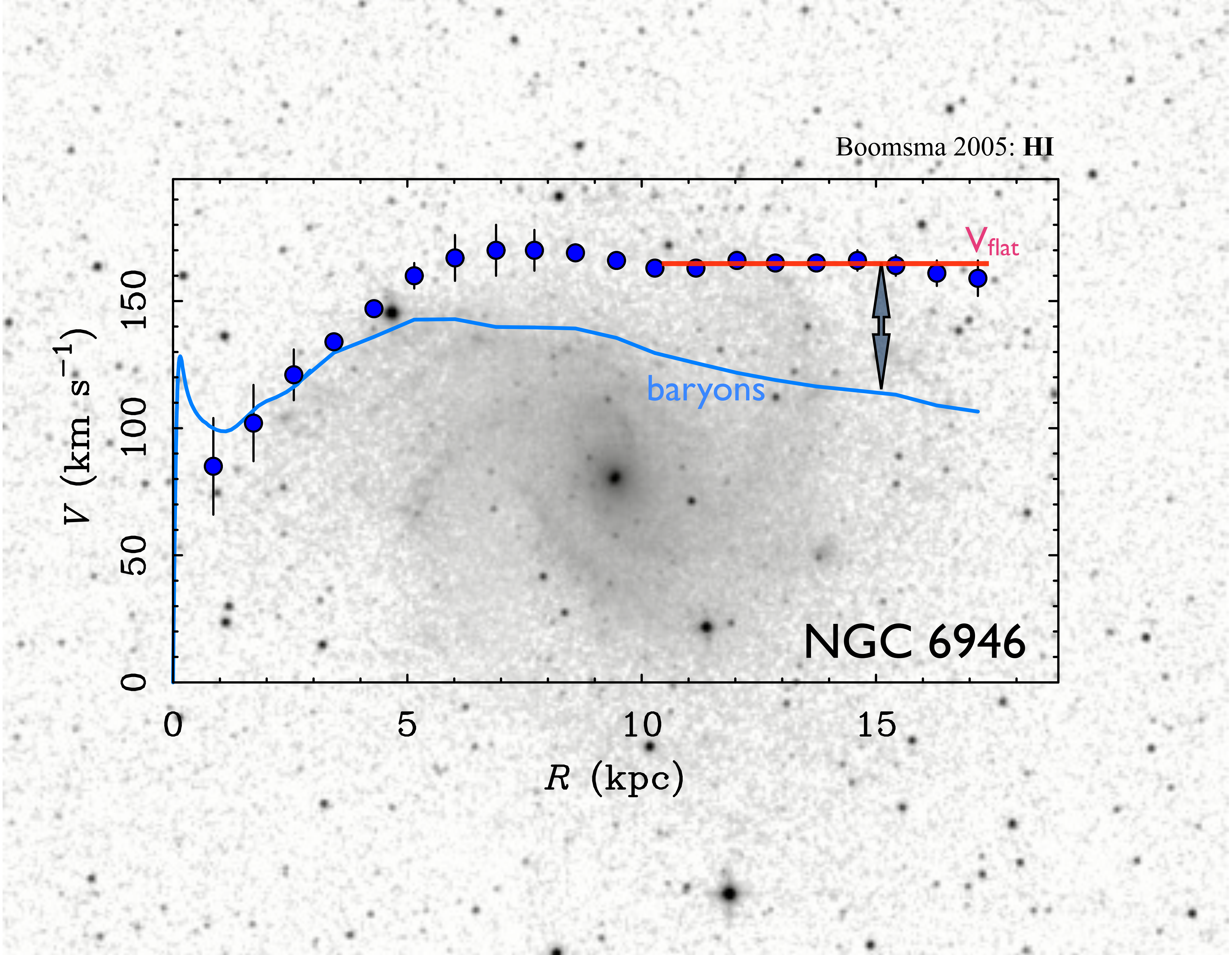
Fit ellipses that most closely match the circular velocity at a given radius. In principle, get ellipse center, position angle, axis ratio, inclination, and rotation velocity. In practice, usually have to fix some of these parameters.

titled ring model

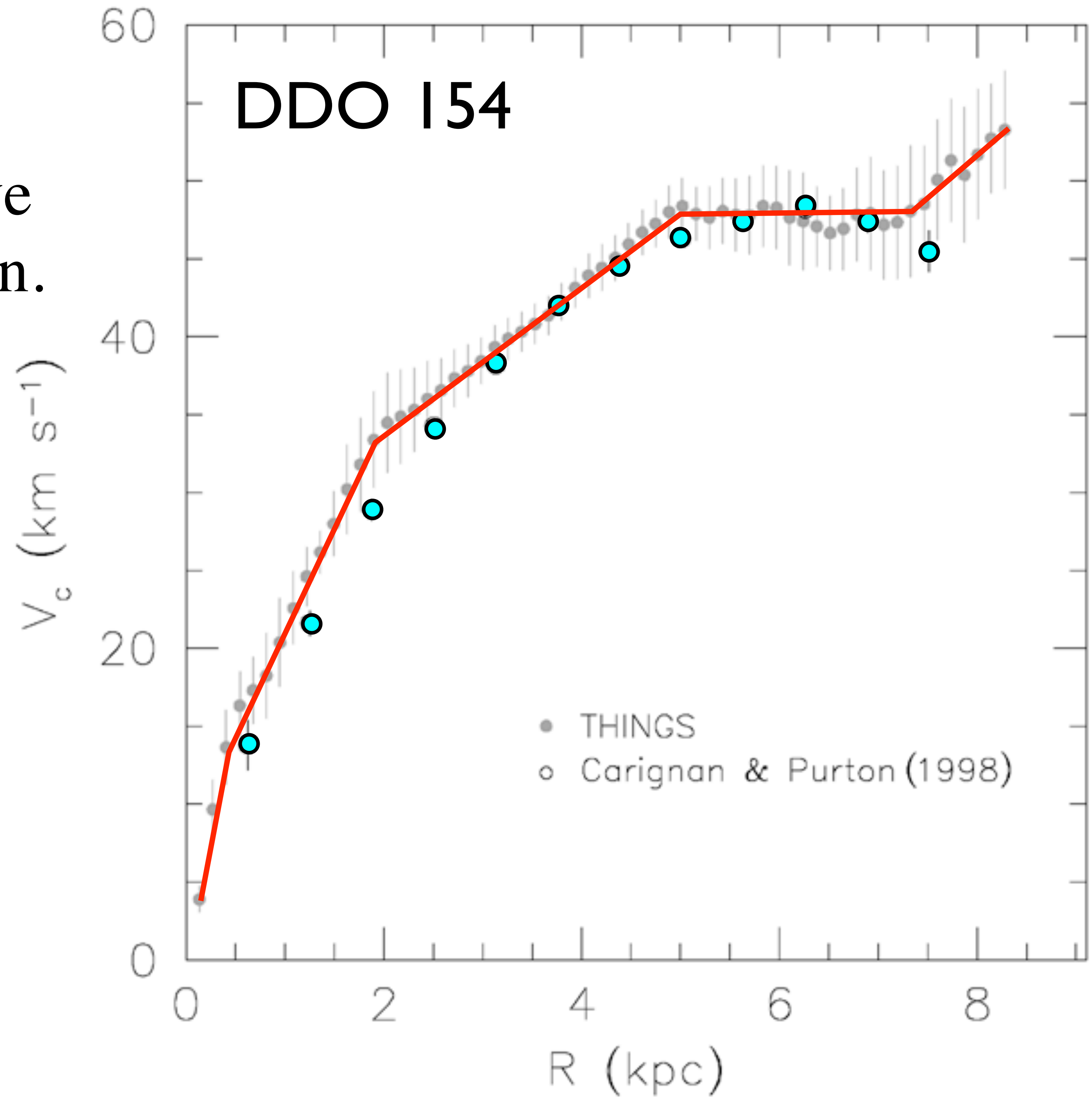




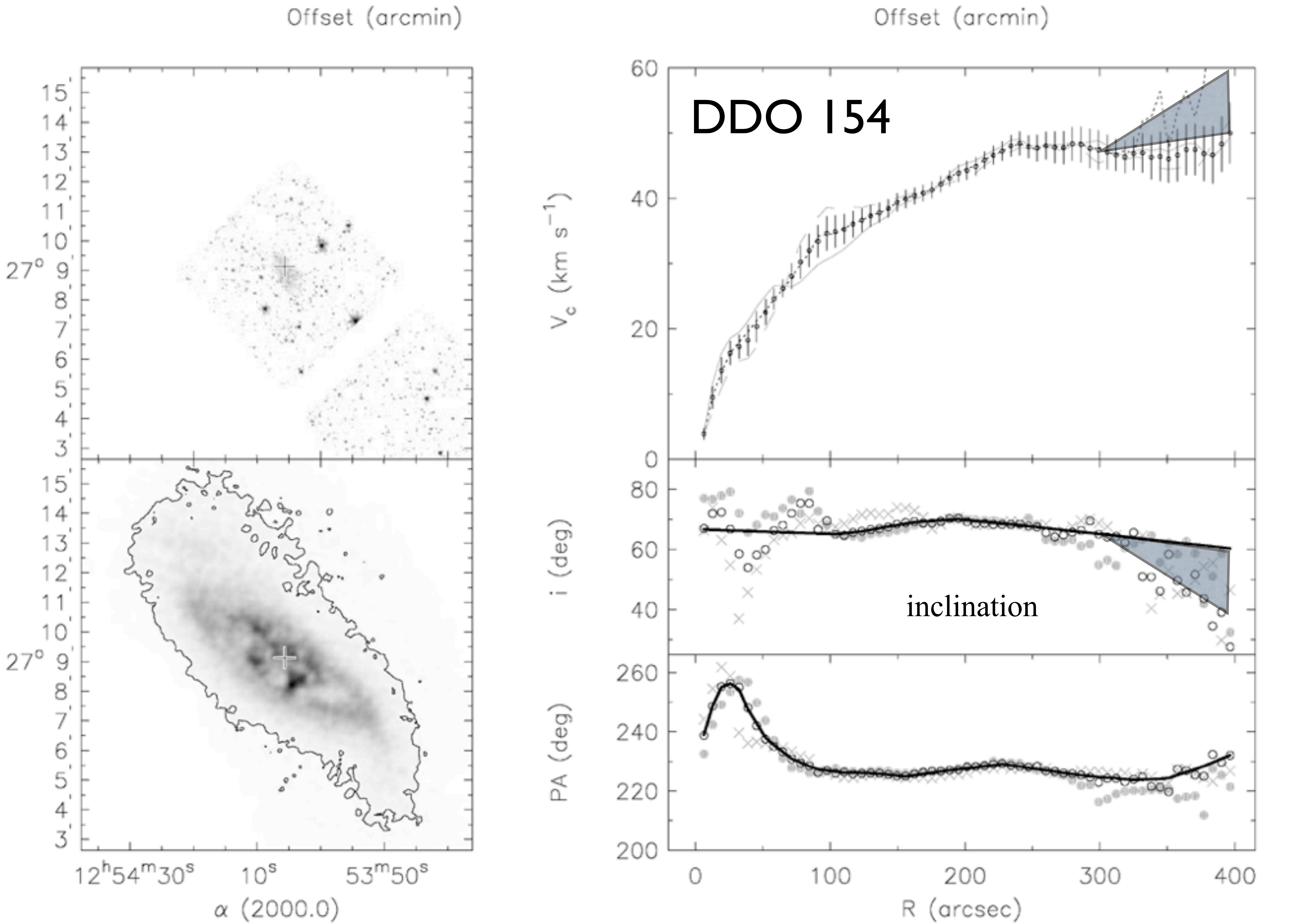
velocity variation along ring

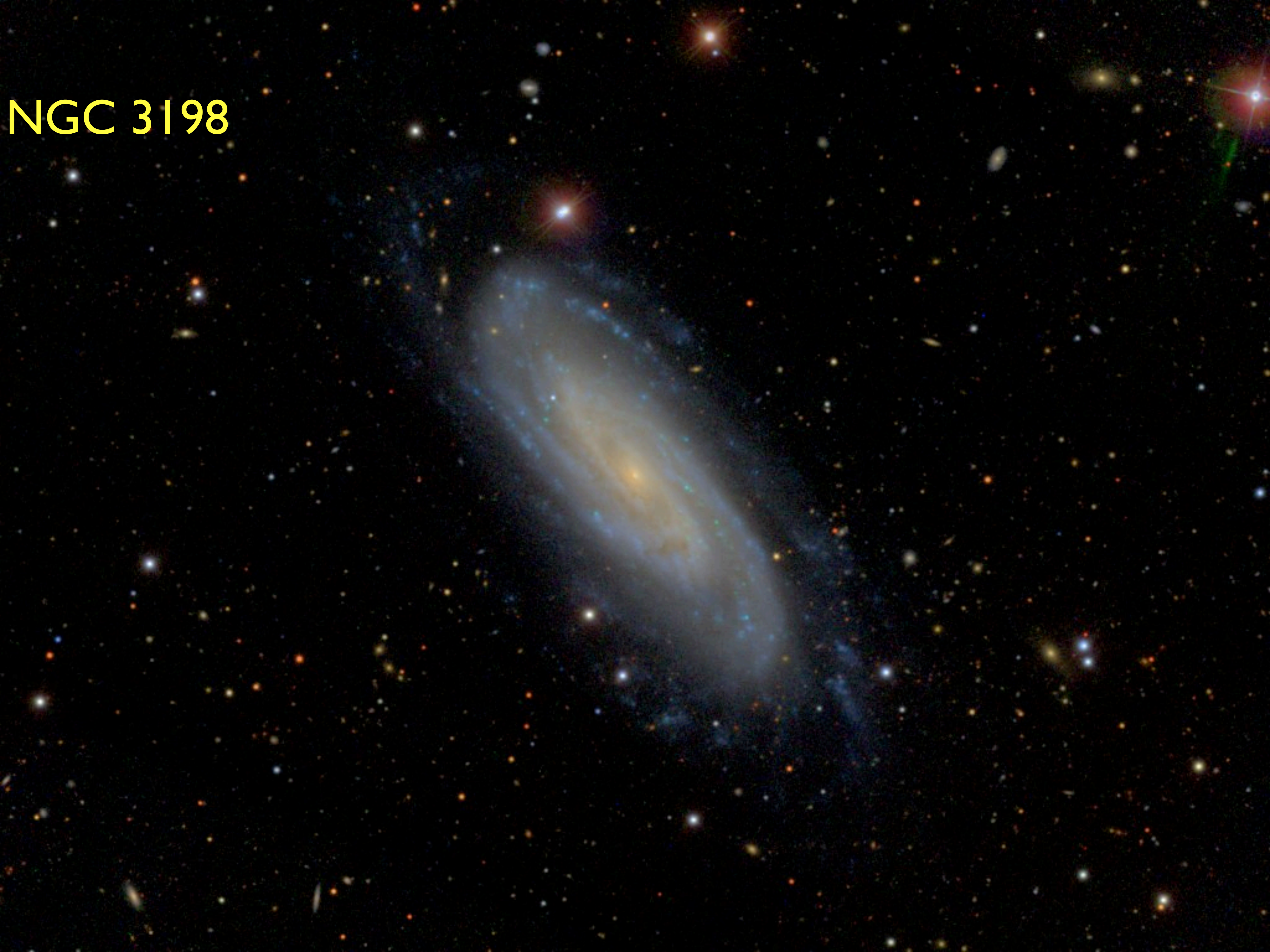

Boomsma 2005: **HI**
V_flat
baryons
NGC 6946
V (km s^-1)
R (kpc)
0
50
100
150
0
5
10
15

Cases where rotation curves were thought to perhaps be declining have so far turned out to flatten.

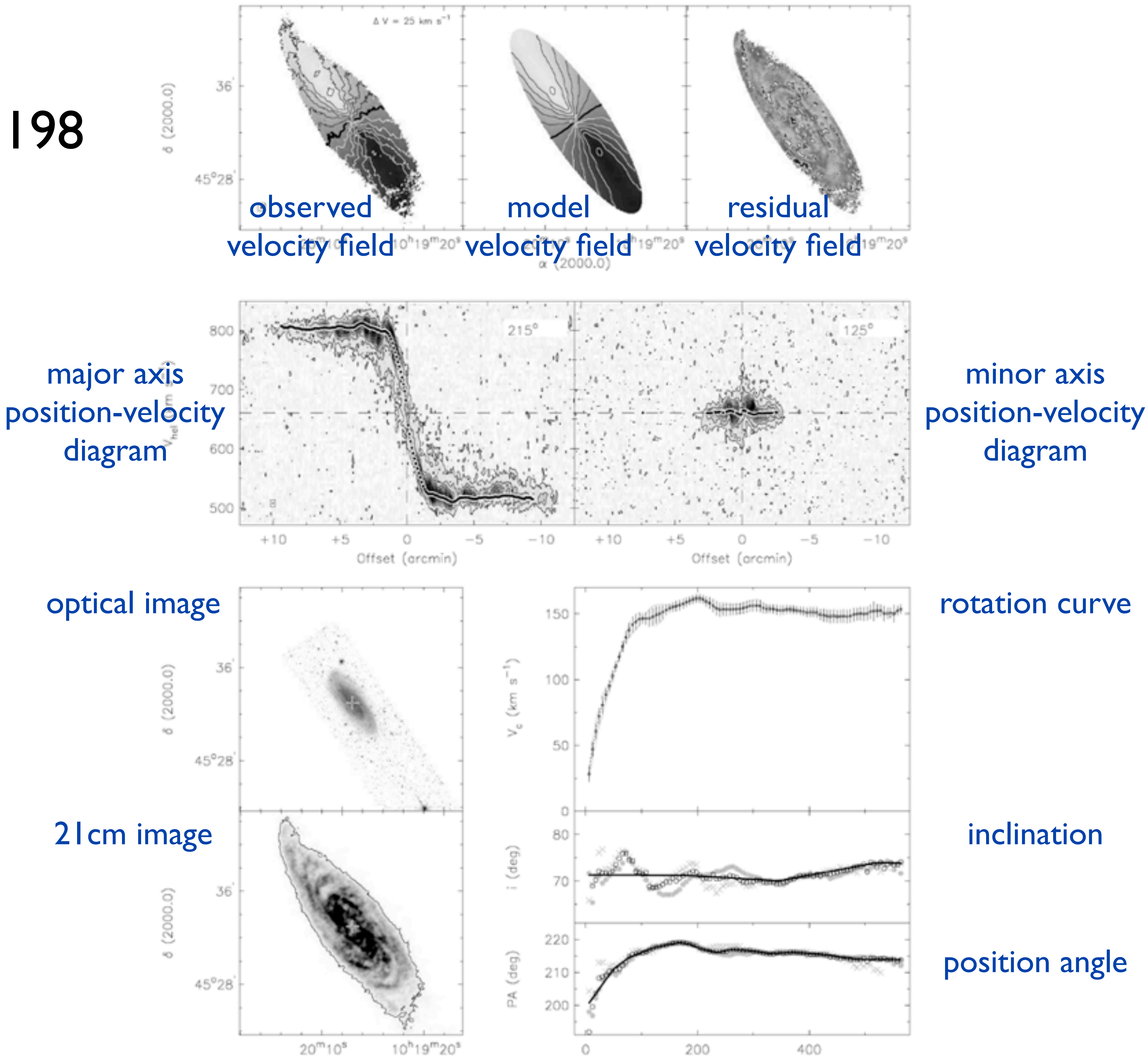


de Blok et al. (2008 [THINGS]):
“We do not find steep declines in velocity in the outer rotation curves of NGC 3521, NGC 7793, DDO 154, and NGC 2366. Where declines are observed, they are gentler, and (within the uncertainties in rotation velocity and inclination) consistent with flat rotation curves.”


Offset (arcmin)
Offset (arcmin)
DDO 154
V_c (km s^{-1})
i (deg)
inclination
PA (deg)
R (arcsec)
α (2000.0)
$12^h54^m30^s$
10^s
53^m50^s
27°

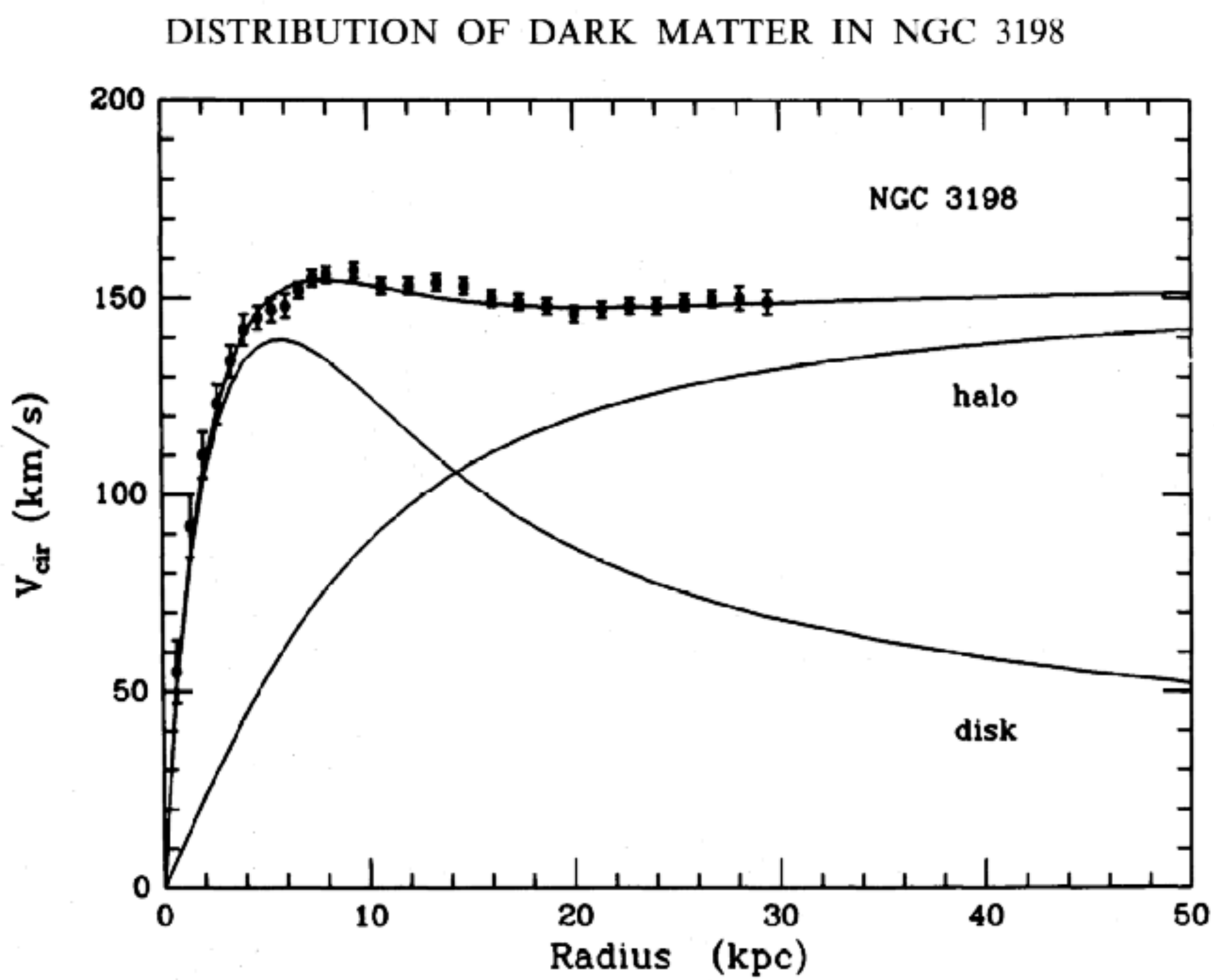

NGC 3198

NGC 3198



observed
velocity field
model
velocity field
residual
velocity field
Δ V = 25 km s⁻¹
δ (2000.0)
36'
45°28'
10ʰ19ᵐ20ˢ
α (2000.0)
major axis
position-velocity
diagram
minor axis
position-velocity
diagram
215°
125°
800
700
600
500
+10
+5
0
-5
-10
Offset (arcmin)
optical image
21cm image
20ᵐ10ˢ
rotation curve
inclination
position angle
Vc (km s⁻¹)
150
100
50
0
i (deg)
80
70
PA (deg)
220
210
200
0
200
400

Mass models



$$V_{tot}^2 = V_{disk}^2 + V_{halo}^2$$

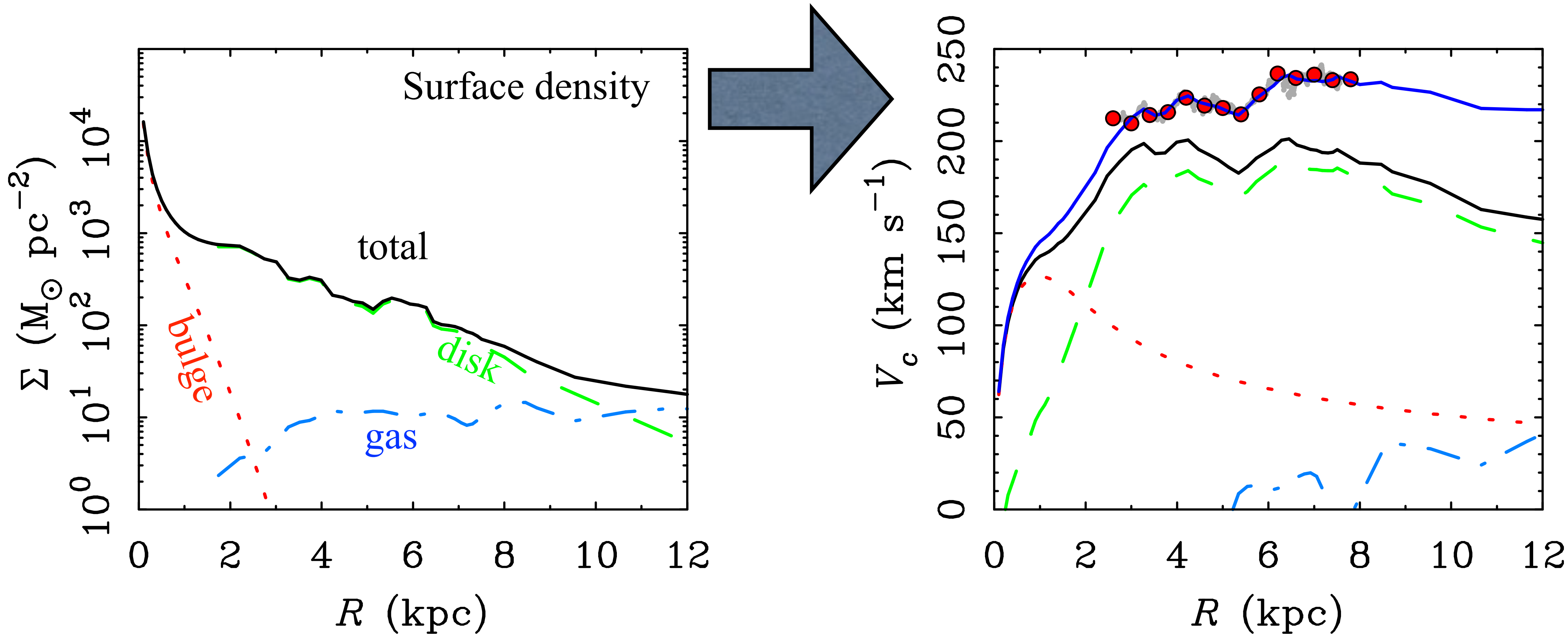
Baryonic models

$$V_b^2(r) = V_{bulge}^2(r) + V_{disk}^2(r) + V_{gas}^2(r)$$

- Bulge
  - not always spherical; sometimes a bar
- Stellar Disk
  - exponential a crude approximation
  - in practice, solve numerically for the observed surface brightness profile with DISKFIT or MASSMOD (in GIPSY)
- Gas disk
  - usually just HI; CO tracks stars

Milky Way structure

Example mass model:



Halo models

pseudo-isothermal

empirically motivated

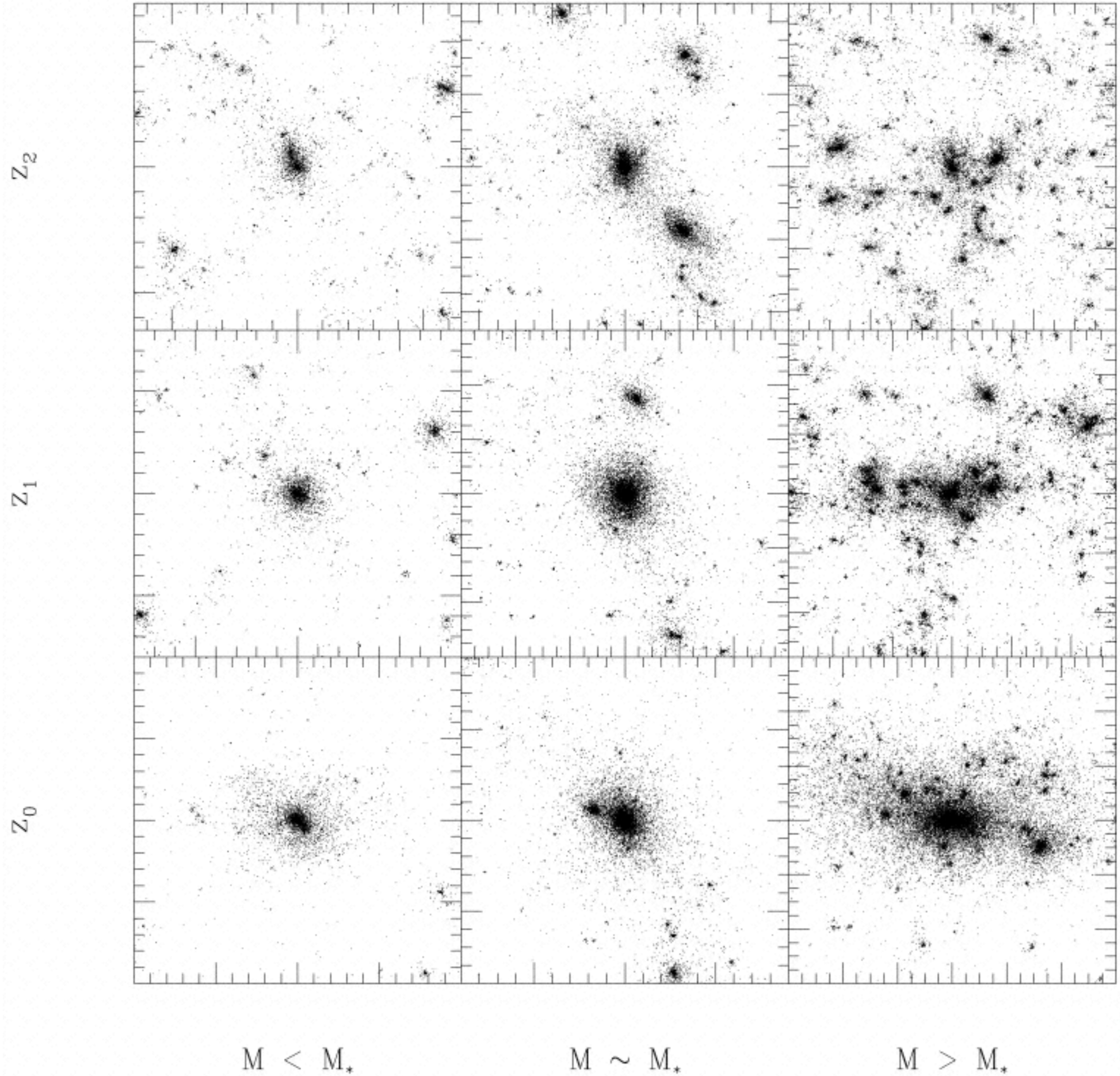
$$\rho(r) = \frac{\rho_0}{1 + (r/R_c)^2}$$

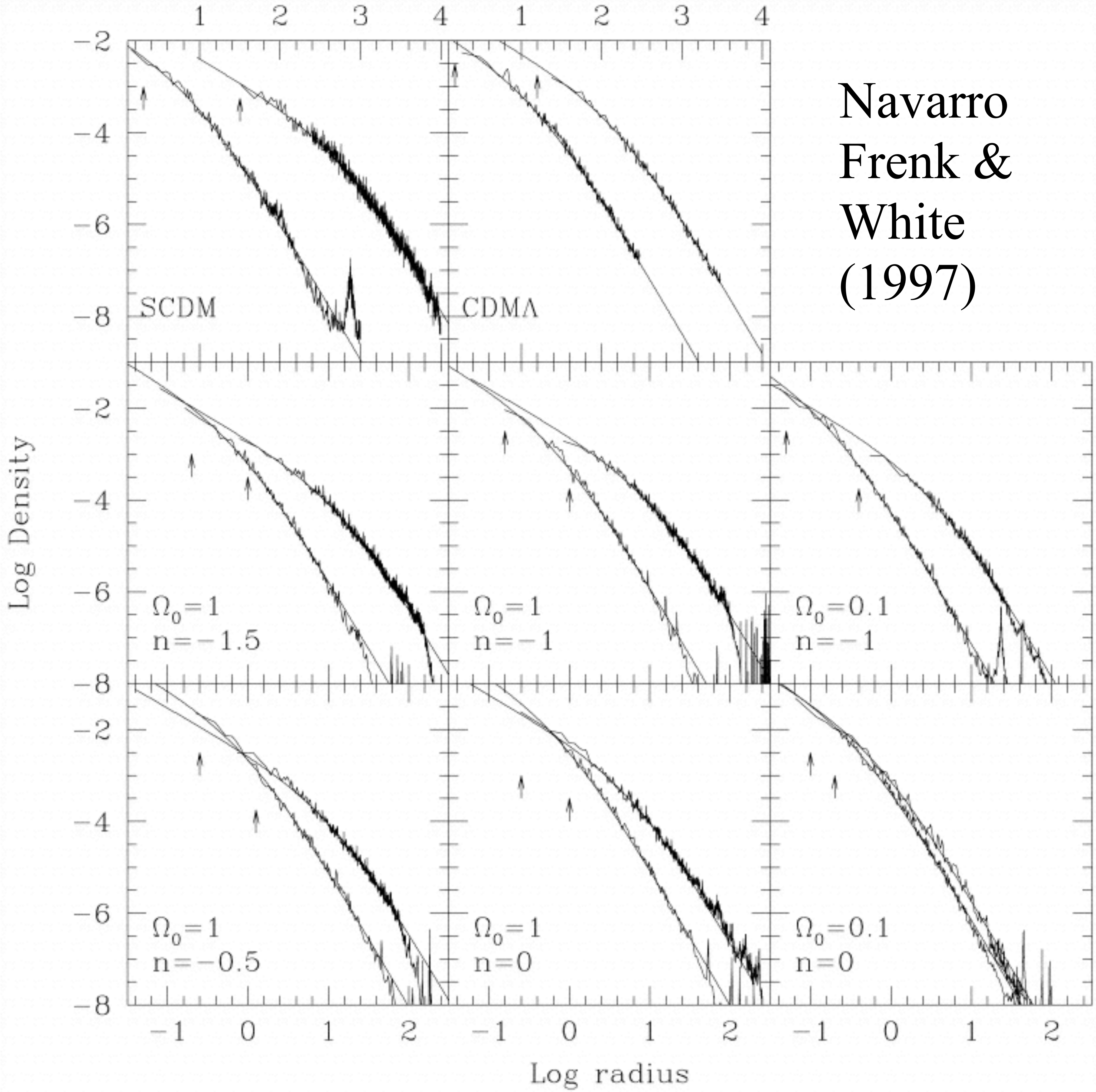
Both models have 2 parameters - a characteristic density and scale radius

NFW

$$\rho(r) = \frac{\rho_i}{(r/r_s)[1 + (r/r_s)^2]}$$

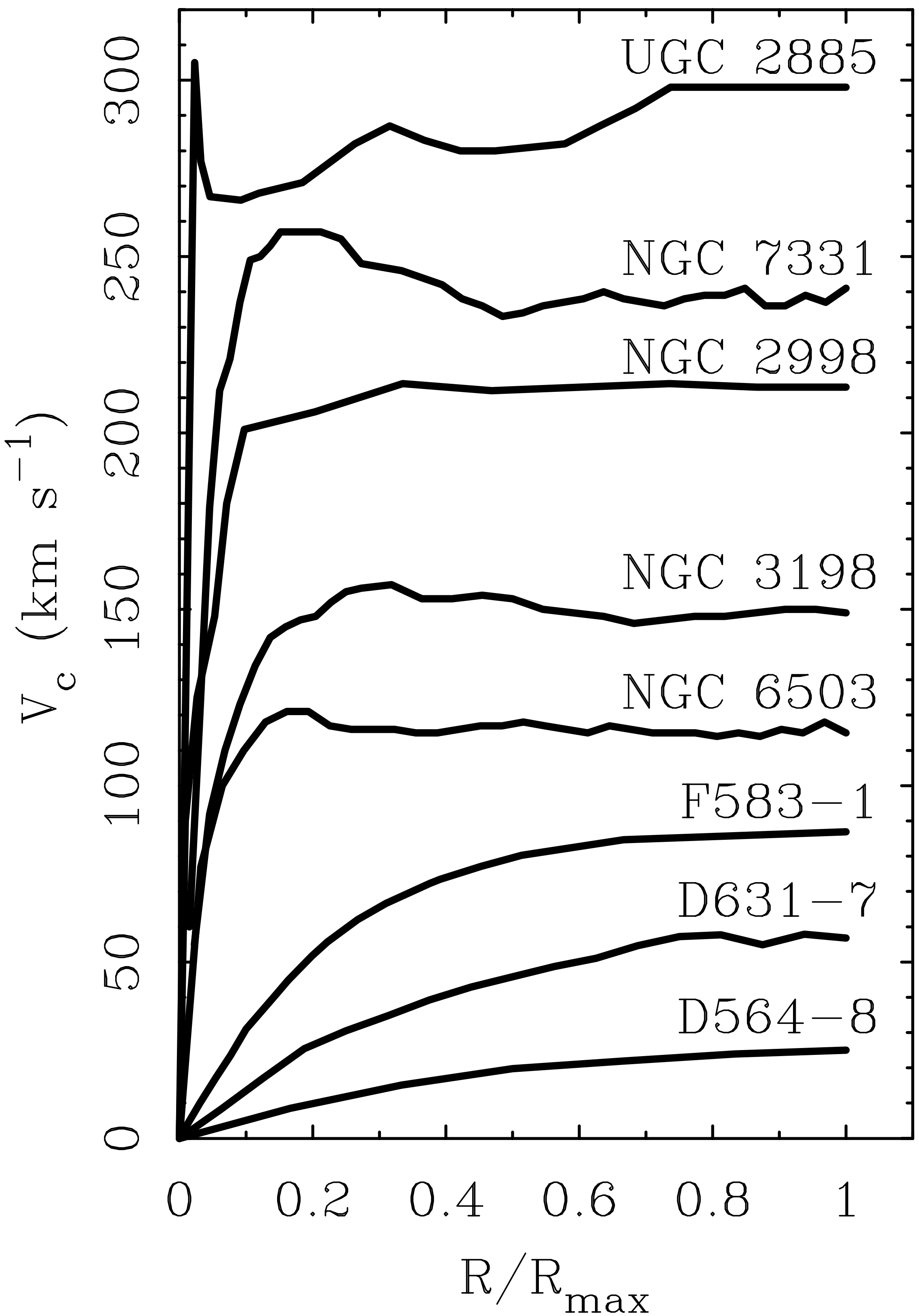
motivated by simulations


z_2
z_1
z_0
$M < M_*$
$M \sim M_*$
$M > M_*$

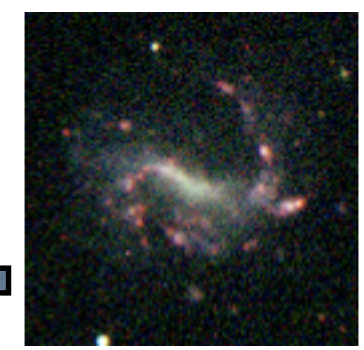


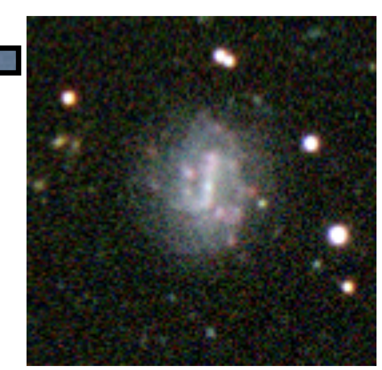
Navarro
Frenk &
White
(1997)

2. Rotation curves amplitude correlates with mass:



star dominated HSB



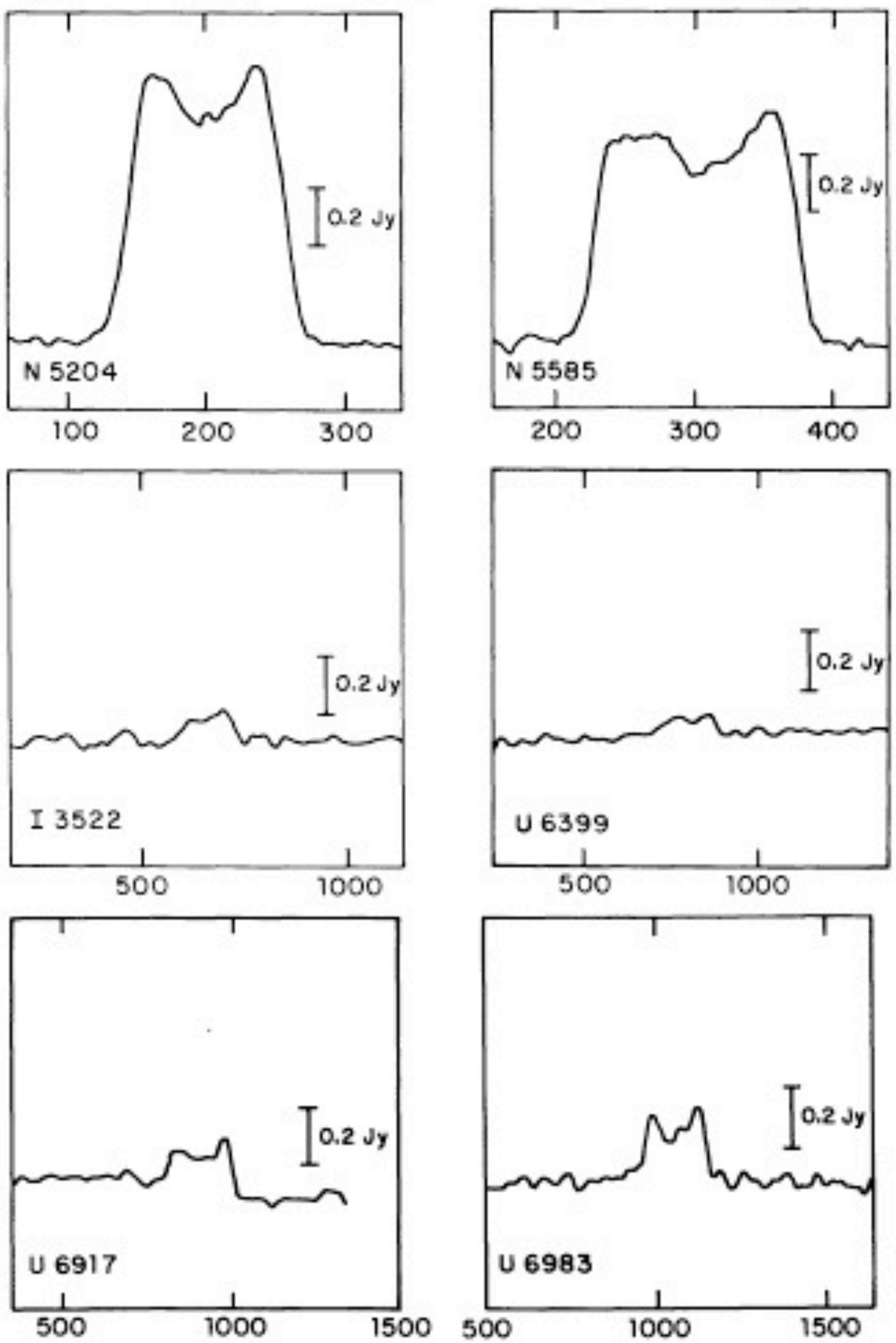


gas dominated LSBs

Flat rotation curves continue to occur in quite small systems ($V_{flat} \sim 20$ km/s)

Tully & Fisher (1977)

Great for distance scale work.
But why does it happen?



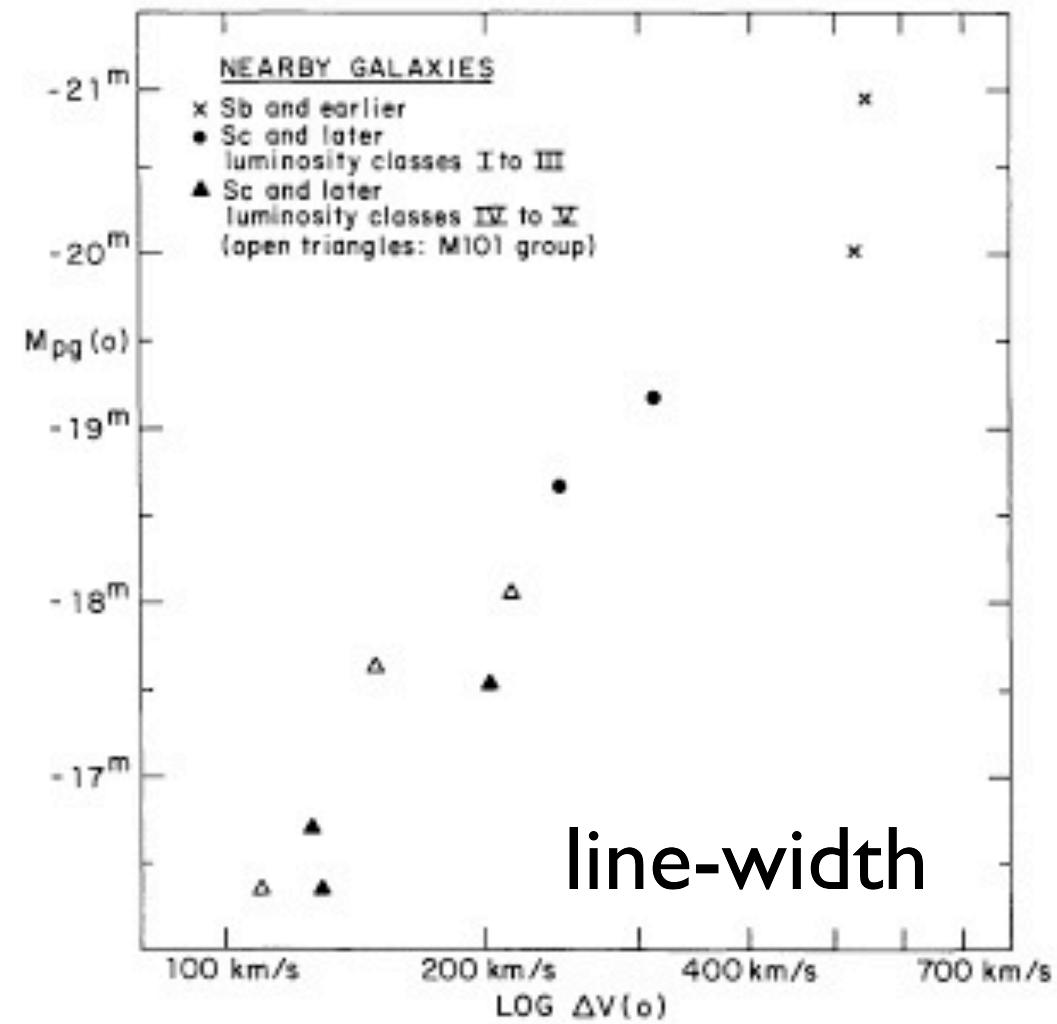


Fig. 1. Absolute magnitude – global profile width relation for nearby galaxies with previously well-determined distances. Crosses are M31 and M81, dots are M33 and NGC 2403, filled triangles are smaller systems in the M81 group and open triangles are smaller systems in the M101 group

others from ST I and ST III]; (4) photographic magnitudes (Holmberg, 1958); (5) magnitude corrections due to galactic extinction according to the precepts in ST I [based on Sandage (1973), except that the source for M31 and M33 is McClure and Racine (1969), and for NGC 2403 is Tammann and Sandage (1968)]; (6) magnitude corrections due to galactic absorption as a function of inclination according to the precepts used by Sandage and Tammann (1974d, hereafter ST IV)

Observables

- Luminosity (must calibrate with known D)
  - Band pass (*BVRIJHK*) [slope varies with band]
  - Mass - stars, gas, stars+gas
- Rotation Velocity
  - line-widths; rotation curves
    - W_{20}, W_{50}; V_{flat}, $V_{2.2}$, V_{max}
  - inclination corrections $1/\sin(i)$
  - turbulence/non-circular motions

Luminosity measures

- Band pass
  - slope becomes steeper from bluer to redder bands (*B I H*)
  - Worry about internal extinction, especially for blue bands and highly inclined galaxies
- Mass
  - Can convert luminosity to stellar mass by estimating the stellar M/L via population modeling.
    - IMF biggest systematic uncertainty

What we measure

- Luminosity
  - Stellar Mass
  - Gas: HI, H_2
- Rotation speed
  - line-width
  - rotation curve

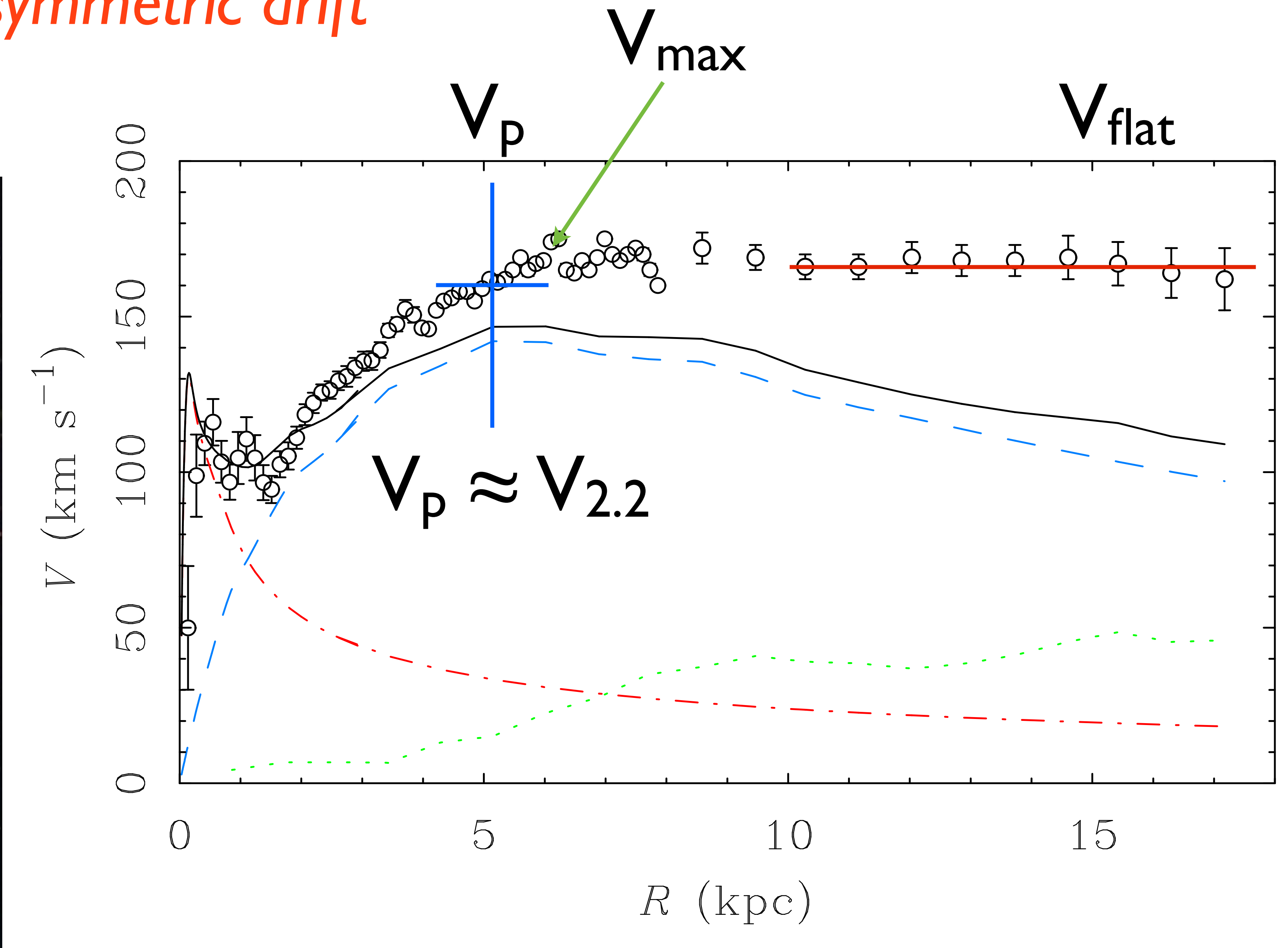
Uncertainties

- Distance
  - Stellar M_*/L
  - HI flux, X-factor
  - velocity dispersion
  - *inclination*
  - *asymmetric drift*

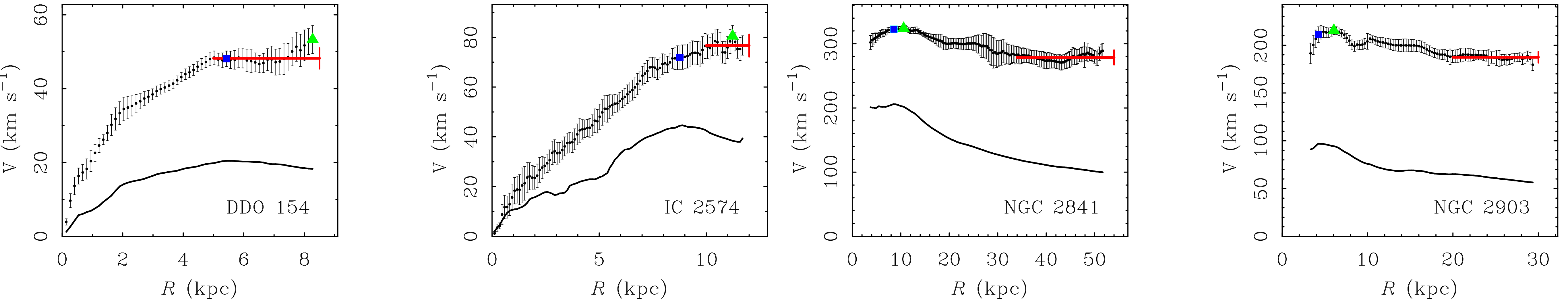
Rotation curve data from
Boomsma et al (2008) [HI]
Daigle et al (2006) [Ha]
Blais-Ouellette et al (2004)

Mass model built from
2MASS K-band data (SSM)

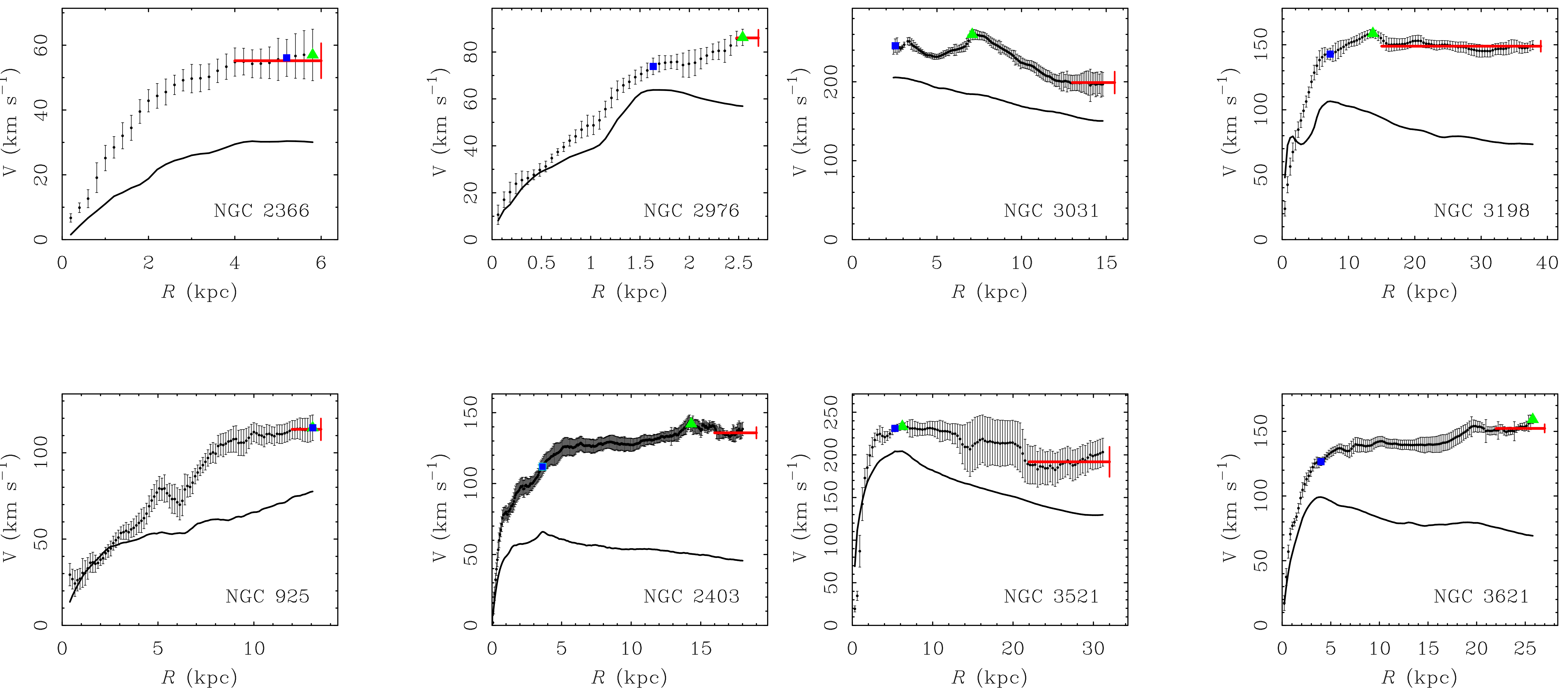
NGC 6946



outer (flat) velocity maximum velocity peak velocity



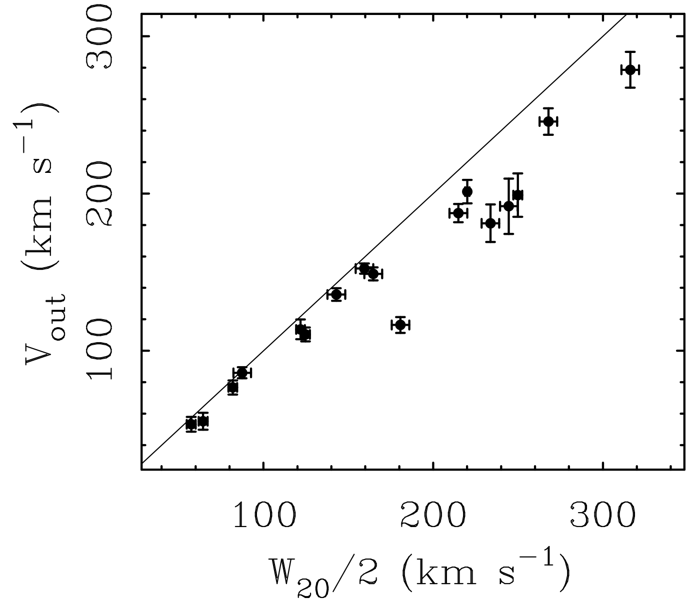
THINGS data (Walter et al 2008)

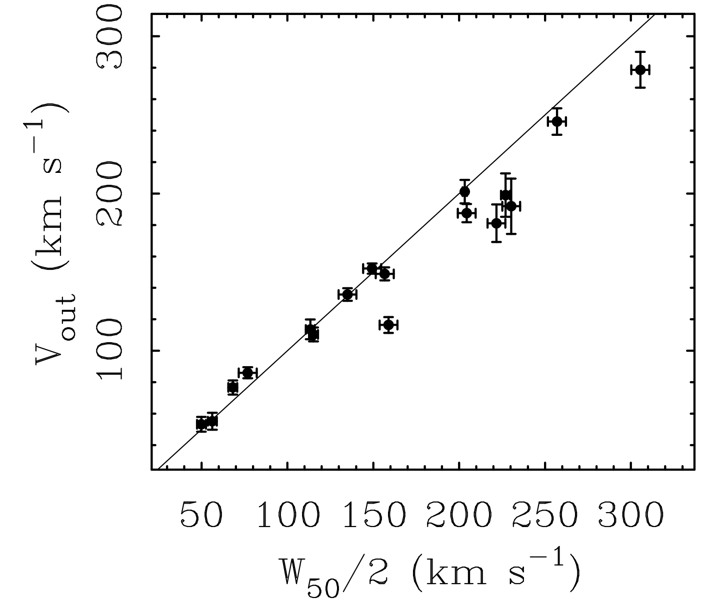


Velocity estimators:

THINGS data
(Walter et al 2008)

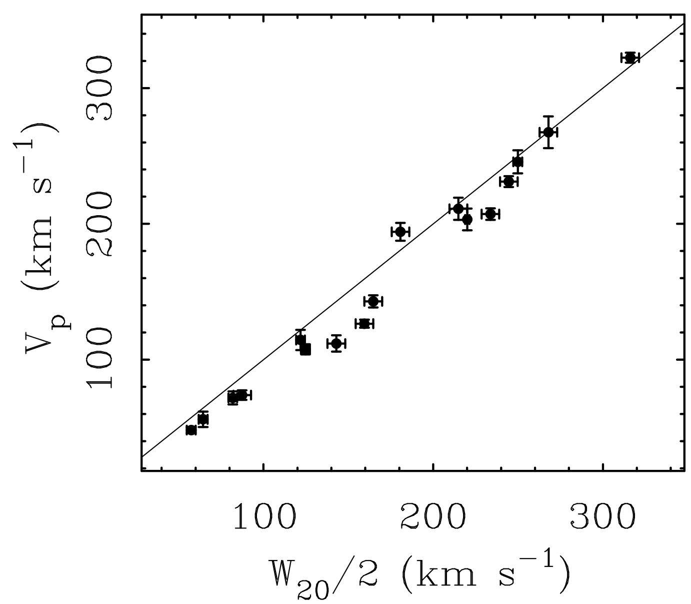
V_{flat}

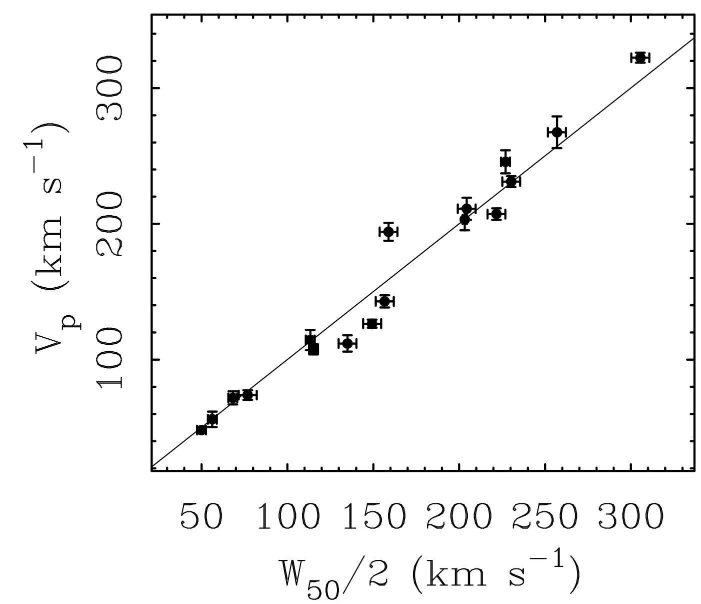




W_{20} W_{50}

V_p





W_{20} W_{50}

V_{max}