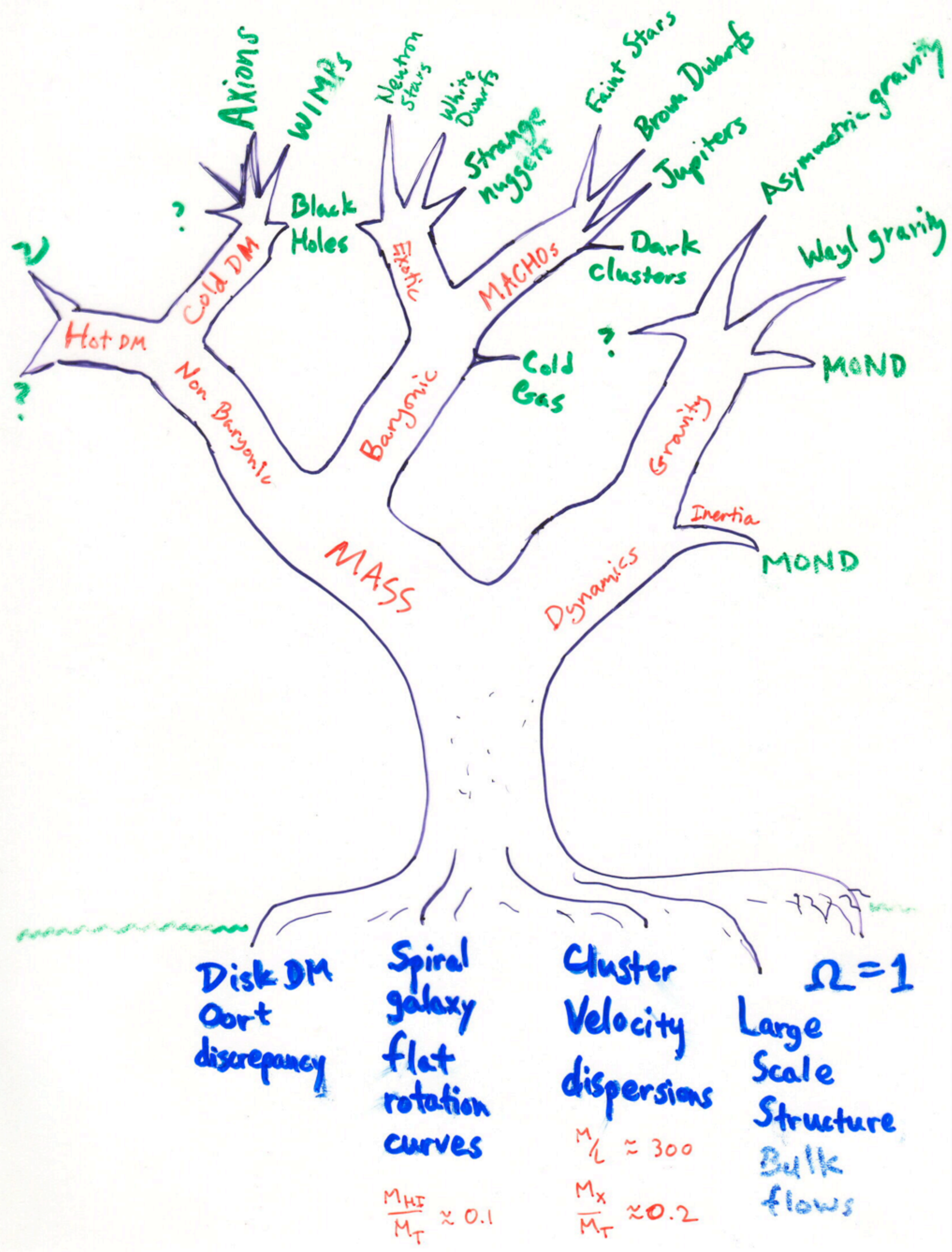
Dark Matter

ASTR 333/433

TODAY

Galactic Rotation

Homework 1
Due Now



Empirical Laws of Galactic Rotation

- Flat rotation curves (Rubin-Bosma Law)

  Rotation curves tend asymptotically towards a constant rotation velocity that persists to indefinitely large radii: $V(R \to \infty) \to V_f$

- Tully-Fisher relation (Luminous, Stellar Mass, and Baryonic TF relations)

  The baryonic mass of galaxies scales as the fourth power of the flat rotation velocity: $M_b = AV_f^4$

- Central density relation (lower surface brightness galaxies exhibit larger mass discrepancies)

  The central dynamical surface densities of galaxies is related to their central surface brightnesses: $\Sigma_{dyn}(R \to 0) = f[\Sigma_*(R \to 0)]$

- Renzo's rule (Sancisi's Law)

  "For any feature in the luminosity profile there is a corresponding feature in the rotation curve and vice versa." (Sancisi 2004).

- Radial acceleration relation

  The observed centripetal acceleration is related to that predicted by the observed distribution of baryons: $\mathrm{g_{obs}} = \mathcal{F}(\mathrm{g_{bar}})$

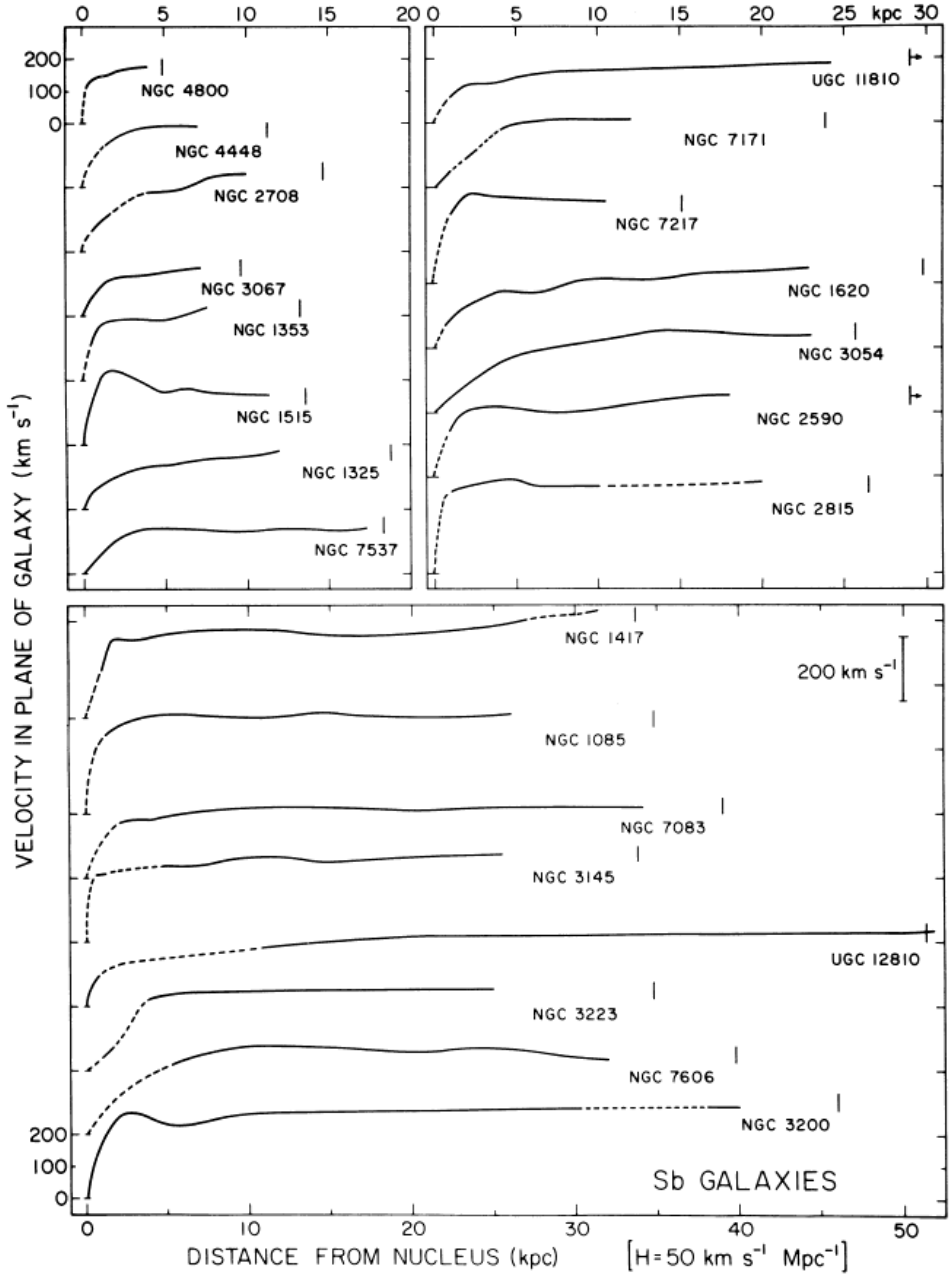


FIG. 3.—Mean velocities in the plane of the galaxy, as a function of linear radius for 23 Sb galaxies, arranged approximately according to increasing luminosity. Adopted curve is rotation curve formed from the mean of velocities on both sides of the major axis. Vertical bar marks the location of R_{25}, 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.

Rotation curves tend to become flat at large radii

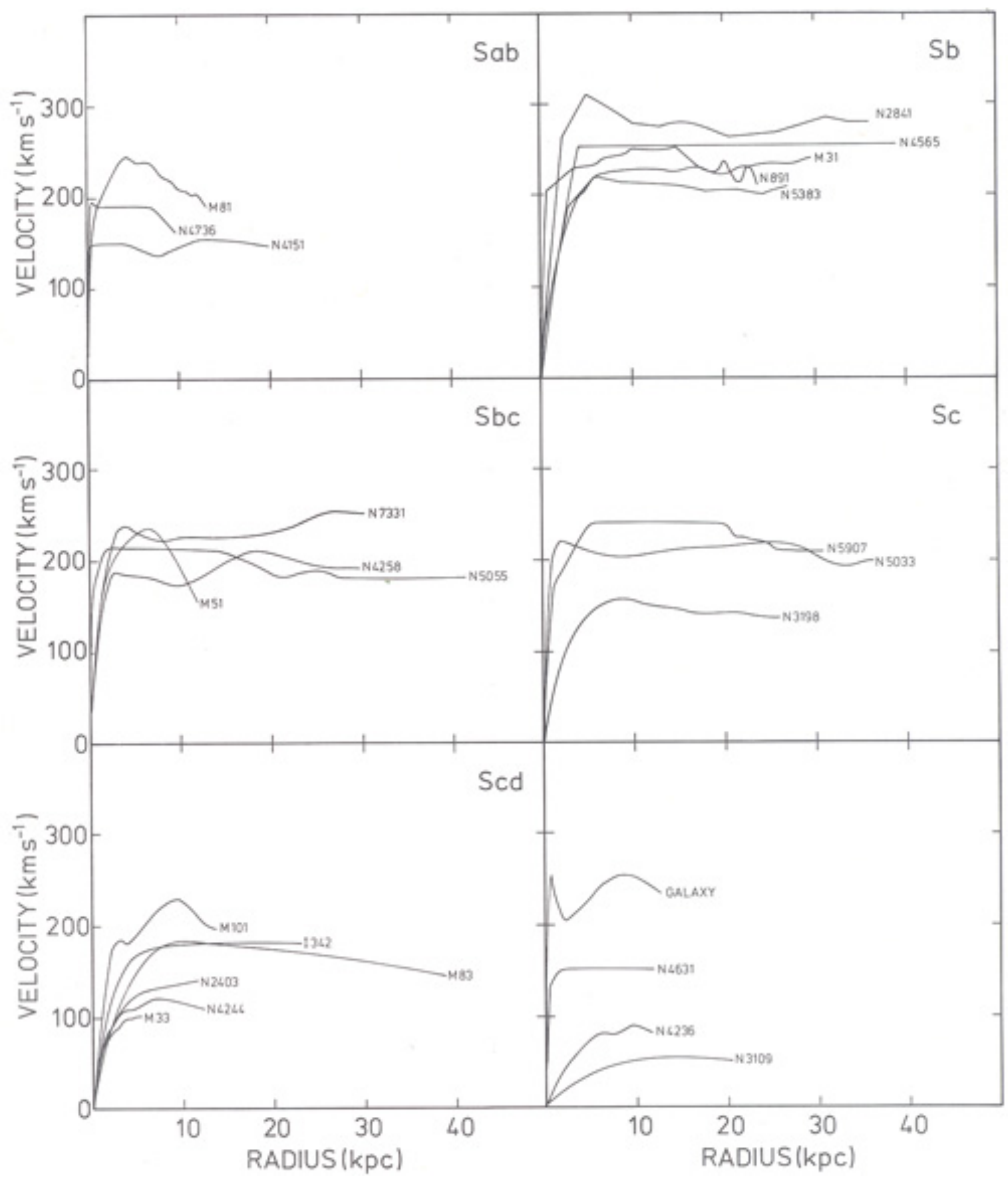
$$V \propto \text{const}$$

$$M \propto R$$

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

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

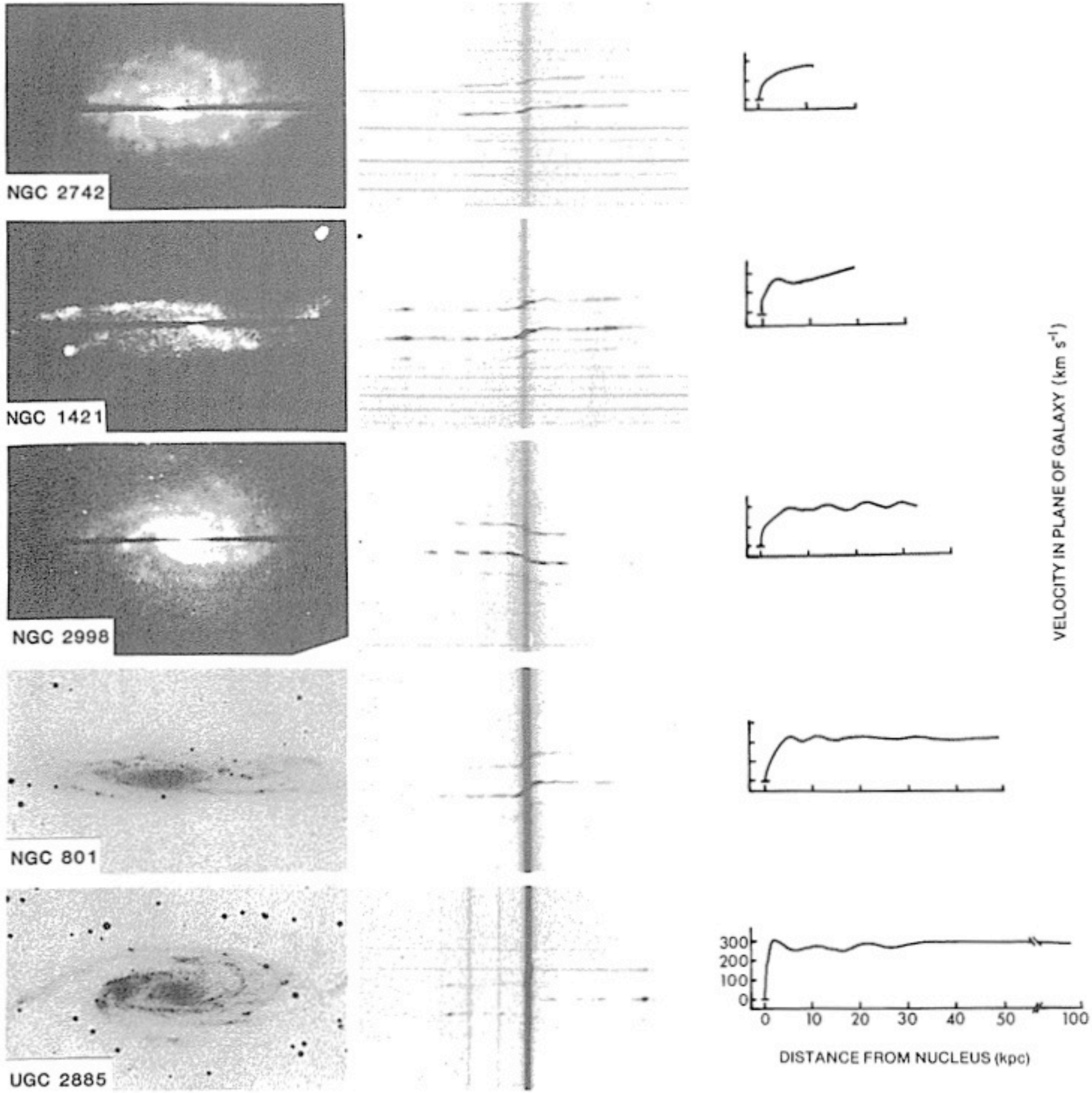
Radio data from
Bosma 1981, *AJ*, **86**, 1825

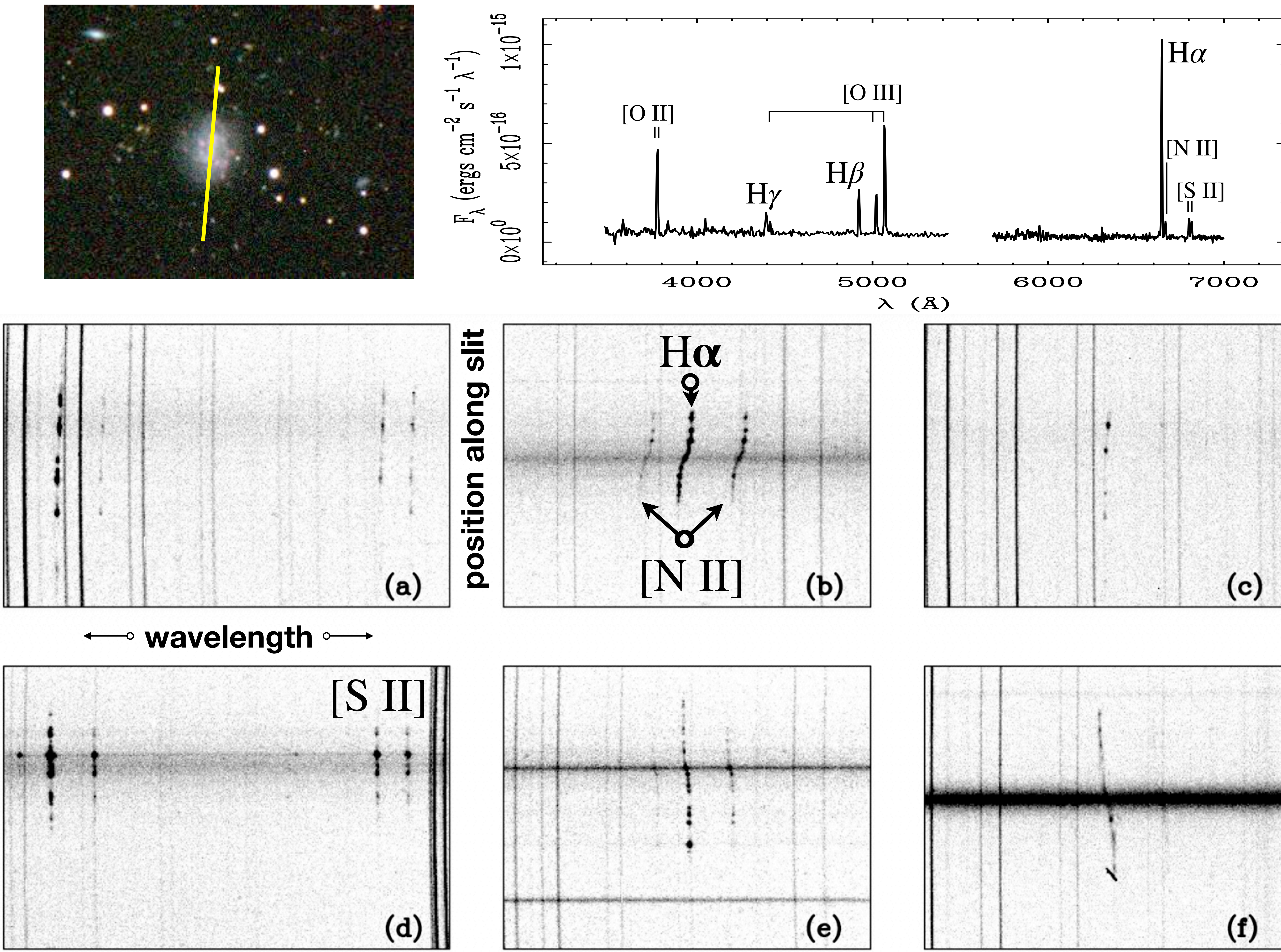


...and stay pretty flat to the largest radii probed

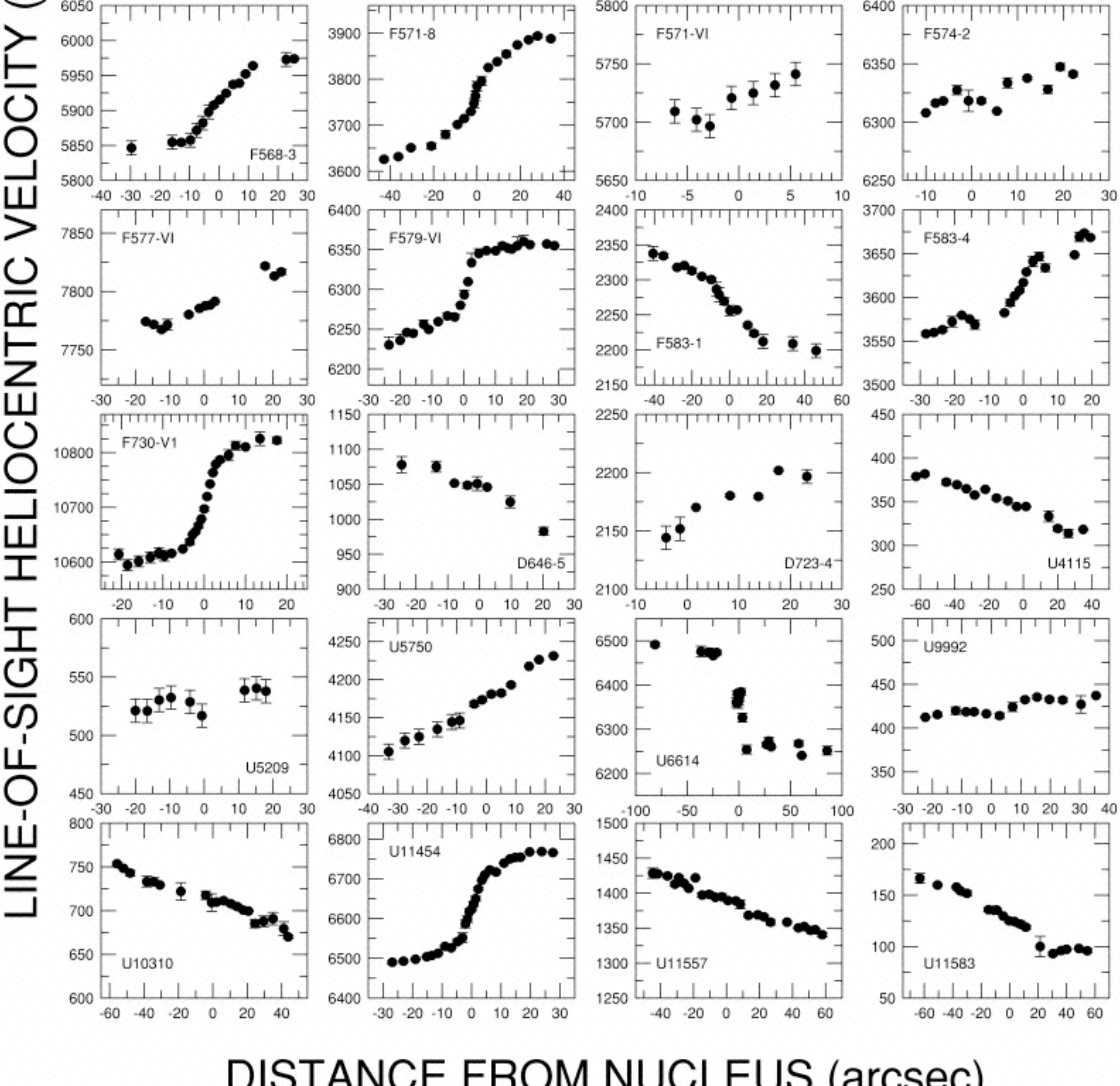
Historically, 21cm data were an important independent validation that flat rotation curves persisted to much larger radii than could be explained by the observed luminous mass.

See IAU Symposium 100 pp. 87-88
(Kalnajs on mass models)

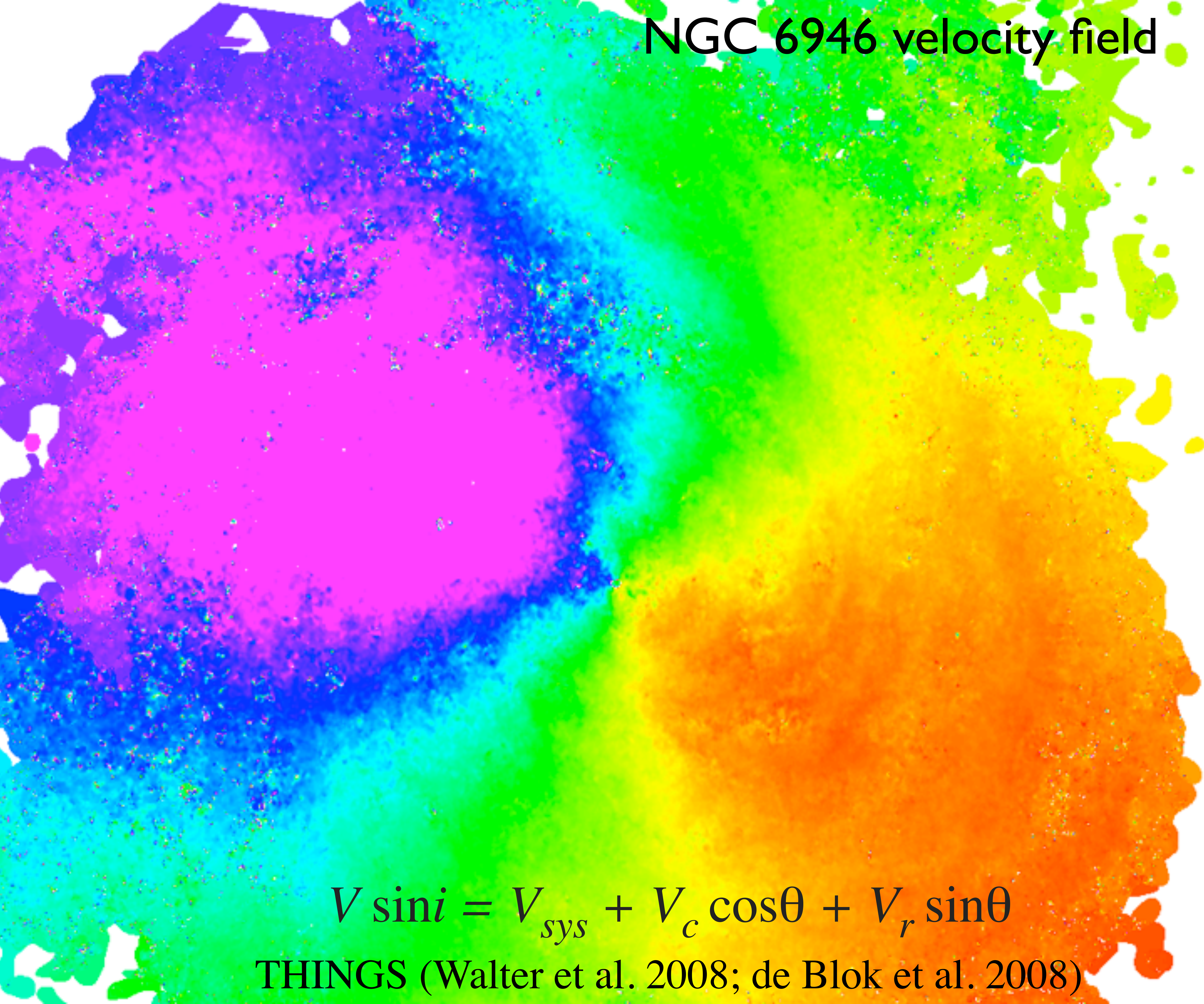

NGC 2742
NGC 1421
NGC 2998
NGC 801
UGC 2885
VELOCITY IN PLANE OF GALAXY (km s⁻¹)
300
200
100
0
0
10
20
30
40
50
100
DISTANCE FROM NUCLEUS (kpc)



Hα
[N II]
[S II]
[O II]
[O III]
Hγ
Hβ
F_λ (ergs cm^{-2} s^{-1} λ^{-1})
λ (Å)
position along slit
wavelength
(a)
(b)
(c)
(d)
(e)
(f)


LINE-OF-SIGHT HELIOCENTRIC VELOCITY (
DISTANCE FROM NUCLEUS (arcsec)
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

NGC 6946 velocity field



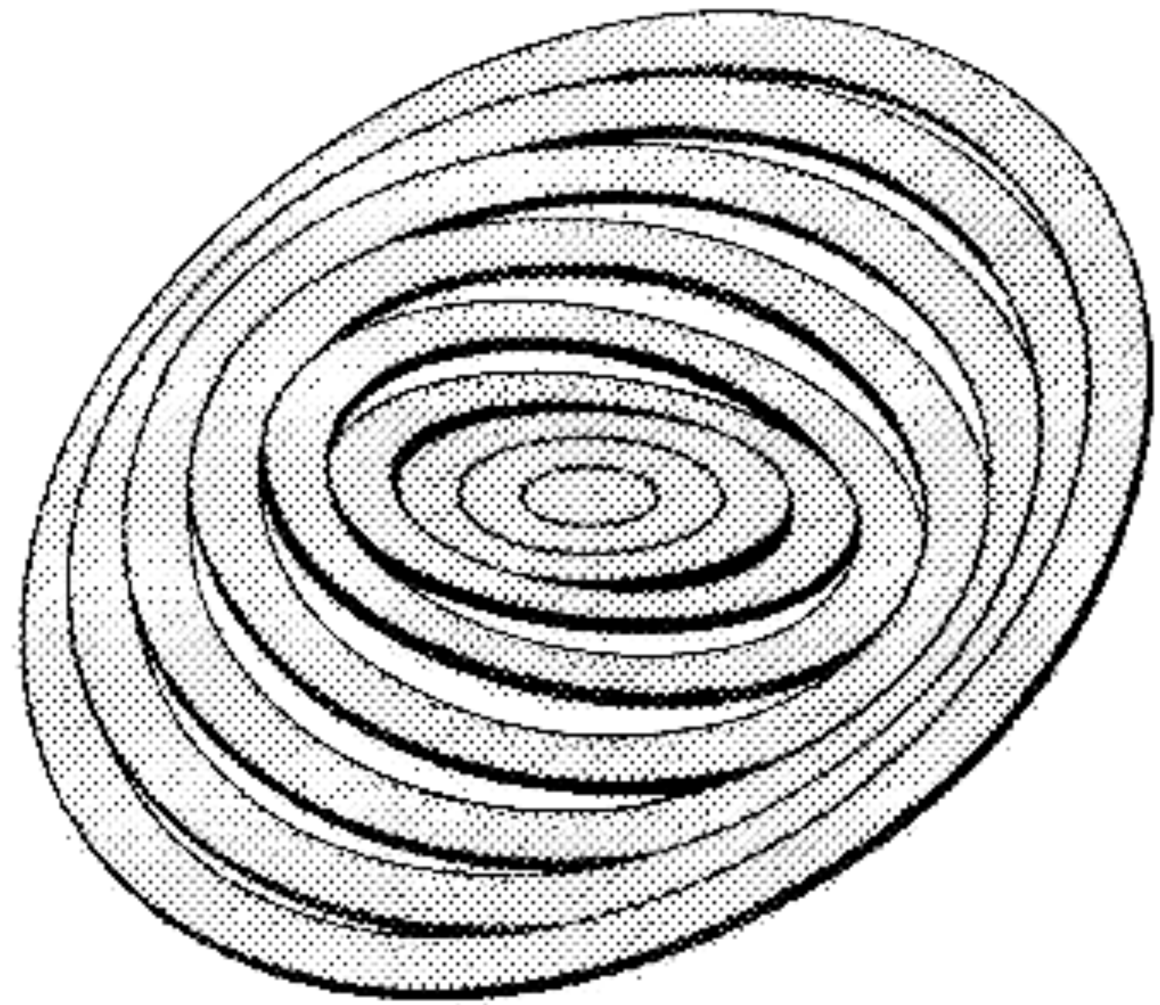
$$V \sin i = V_{sys} + V_c \cos\theta + V_r \sin\theta$$

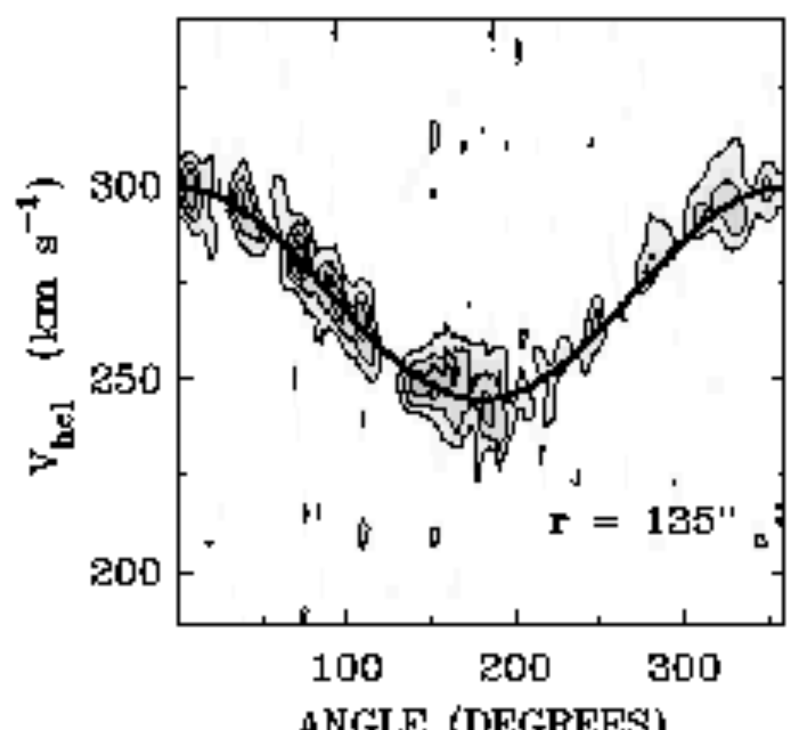
THINGS (Walter et al. 2008; de Blok et al. 2008)

Rotation curves extracted using "tilted ring" fits

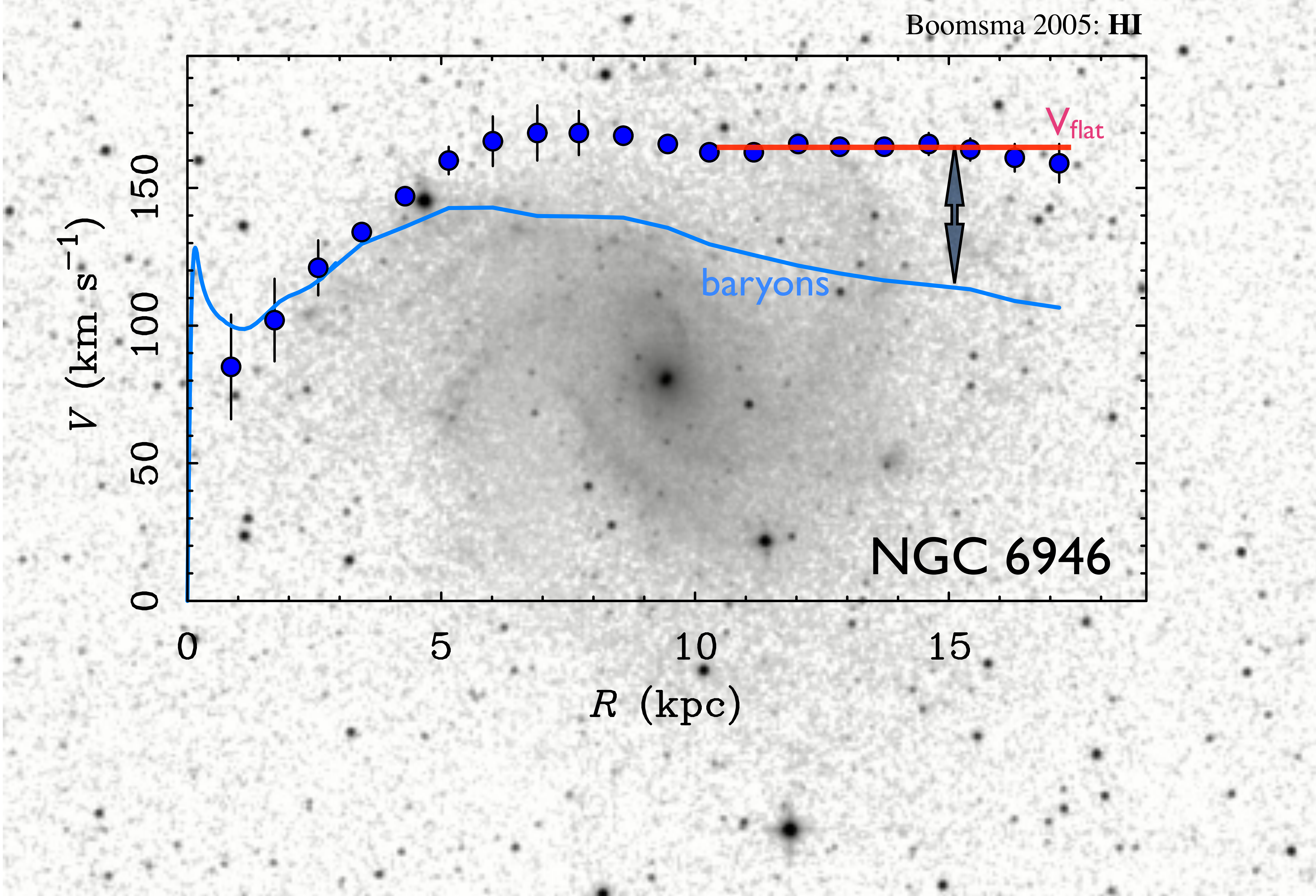
Fit ellipses that most closely match the circular velocity at a given radius. In principle, get ellipse center, position angle, axis ratio, inclination, and rotation velocity. In practice, usually have to fix some of these parameters.

titled ring model



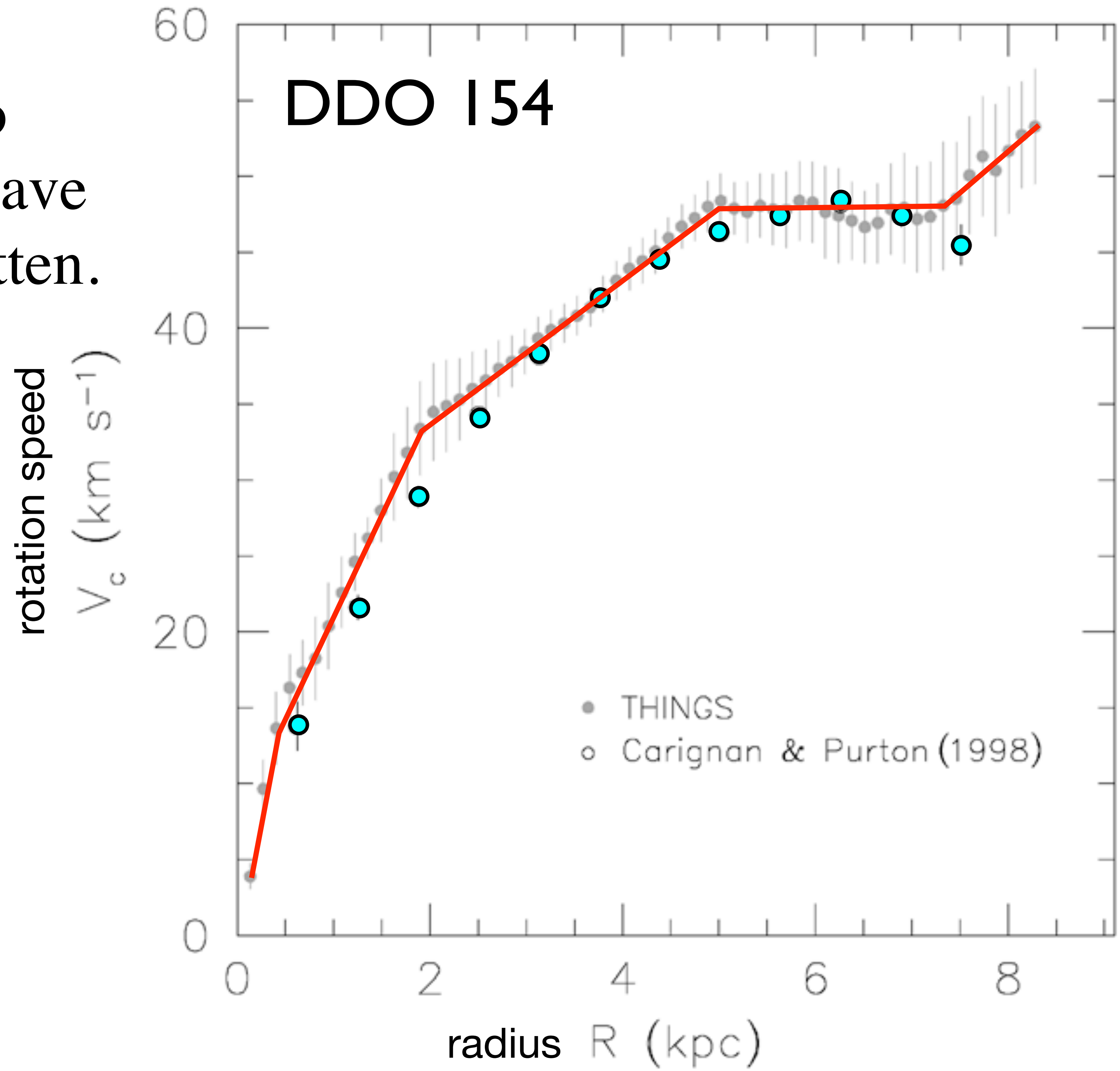


velocity variation along ring



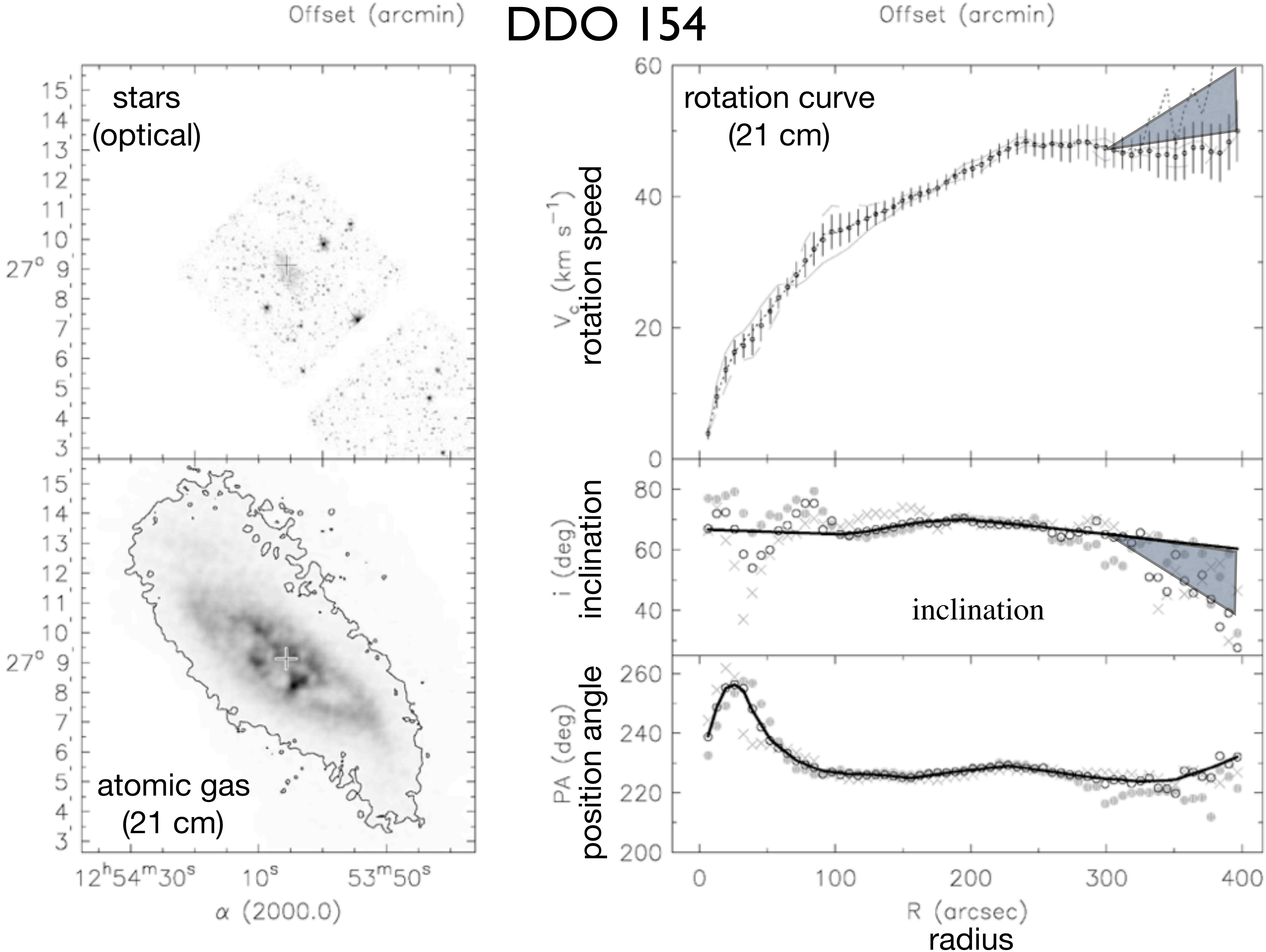
Boomsma 2005: **HI**
V_{flat}
baryons
NGC 6946
V (km s^{-1})
R (kpc)
0
50
100
150
0
5
10
15

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

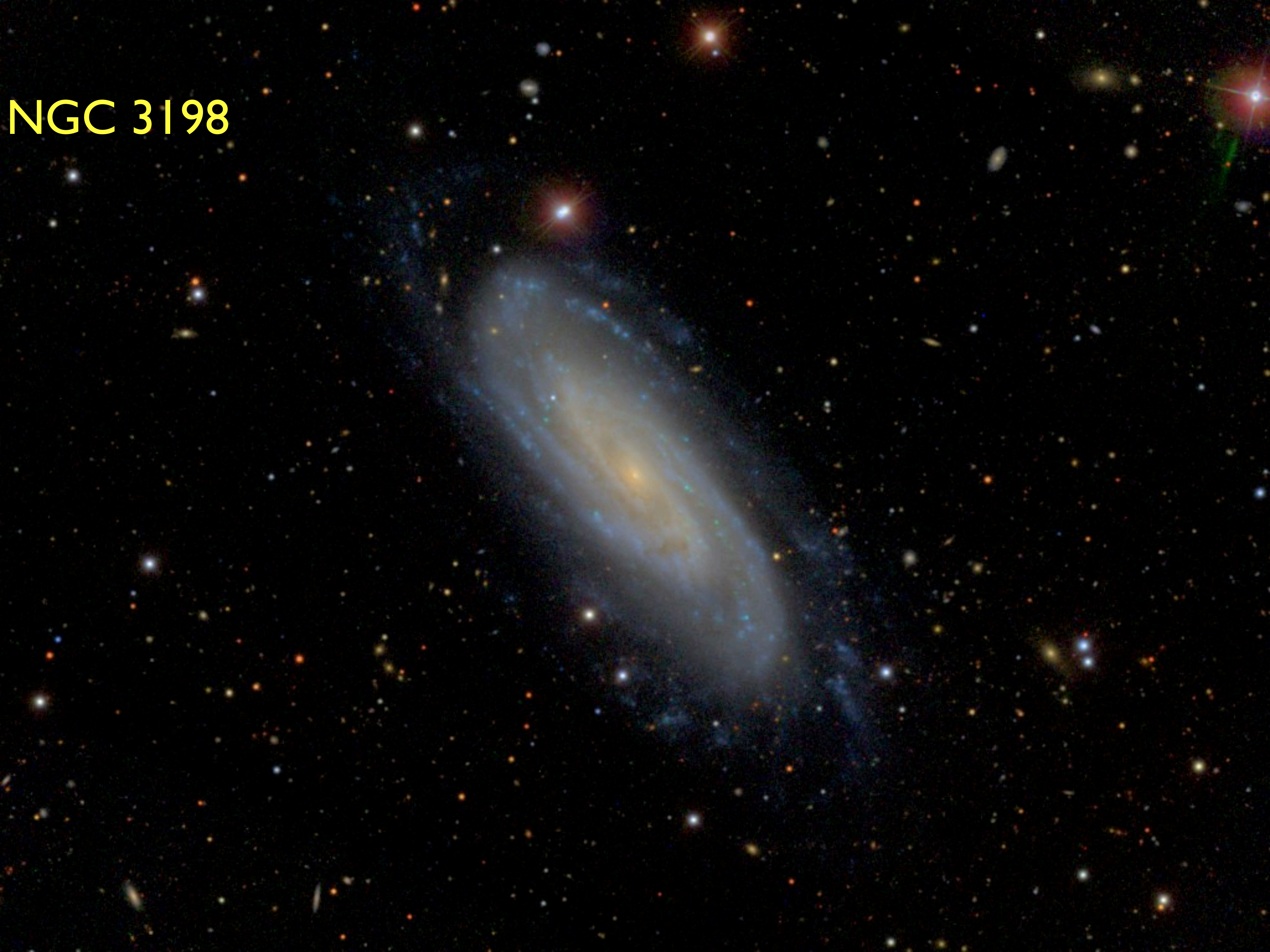


de Blok et al. (2008 [THINGS]):
"We do not find steep declines in velocity in the outer rotation curves of NGC 3521, NGC 7793, DDO 154, and NGC 2366. Where declines are observed, they are gentler, and (within the uncertainties in rotation velocity and inclination) consistent with flat rotation curves."

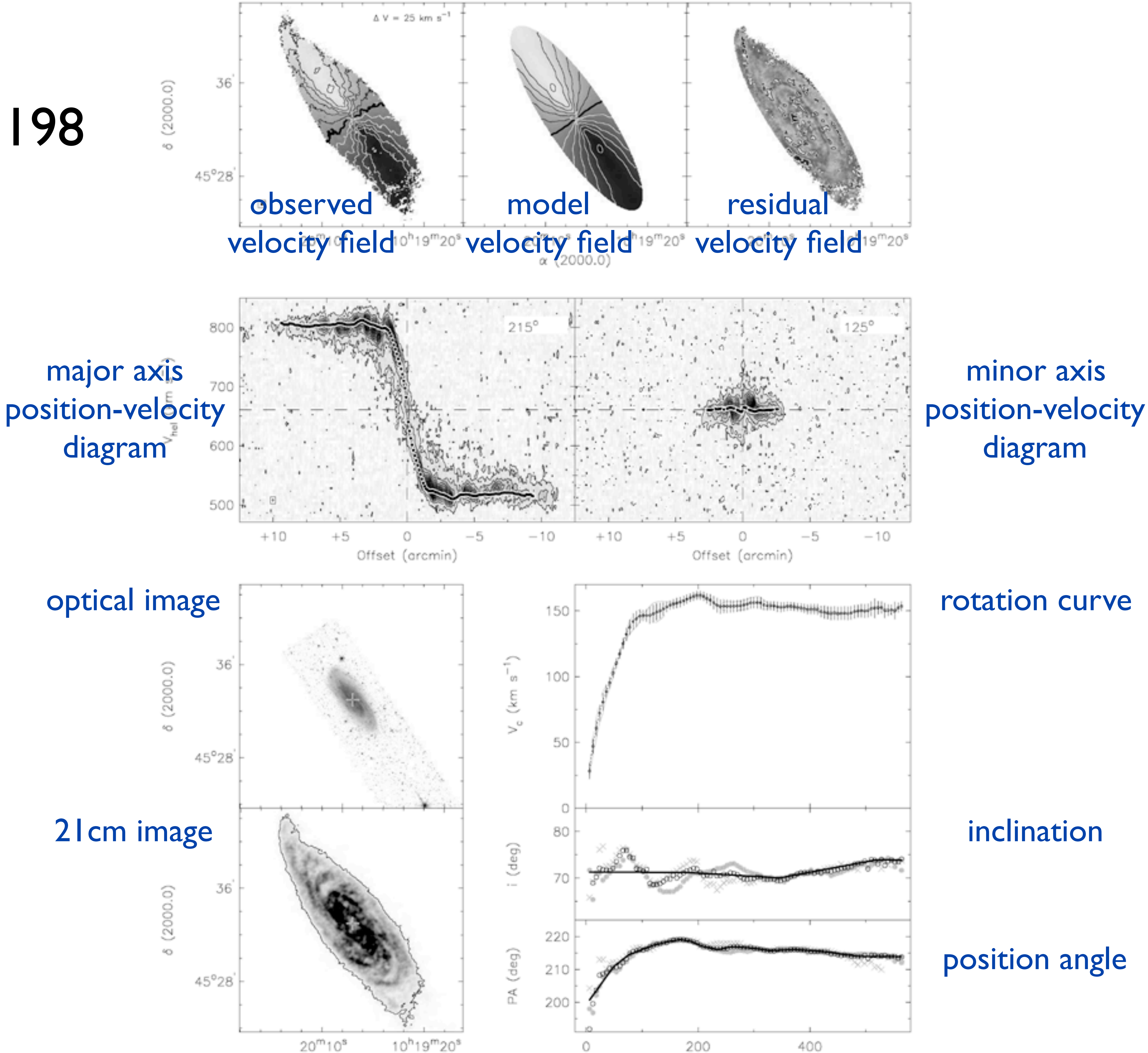
DDO 154



Offset (arcmin)
stars
(optical)
atomic gas
(21 cm)
27°
12h54m30s
10s
53m50s
α (2000.0)
Offset (arcmin)
rotation curve
(21 cm)
Vc (km s−1)
rotation speed
i (deg)
inclination
inclination
PA (deg)
position angle
R (arcsec)
radius


NGC 3198

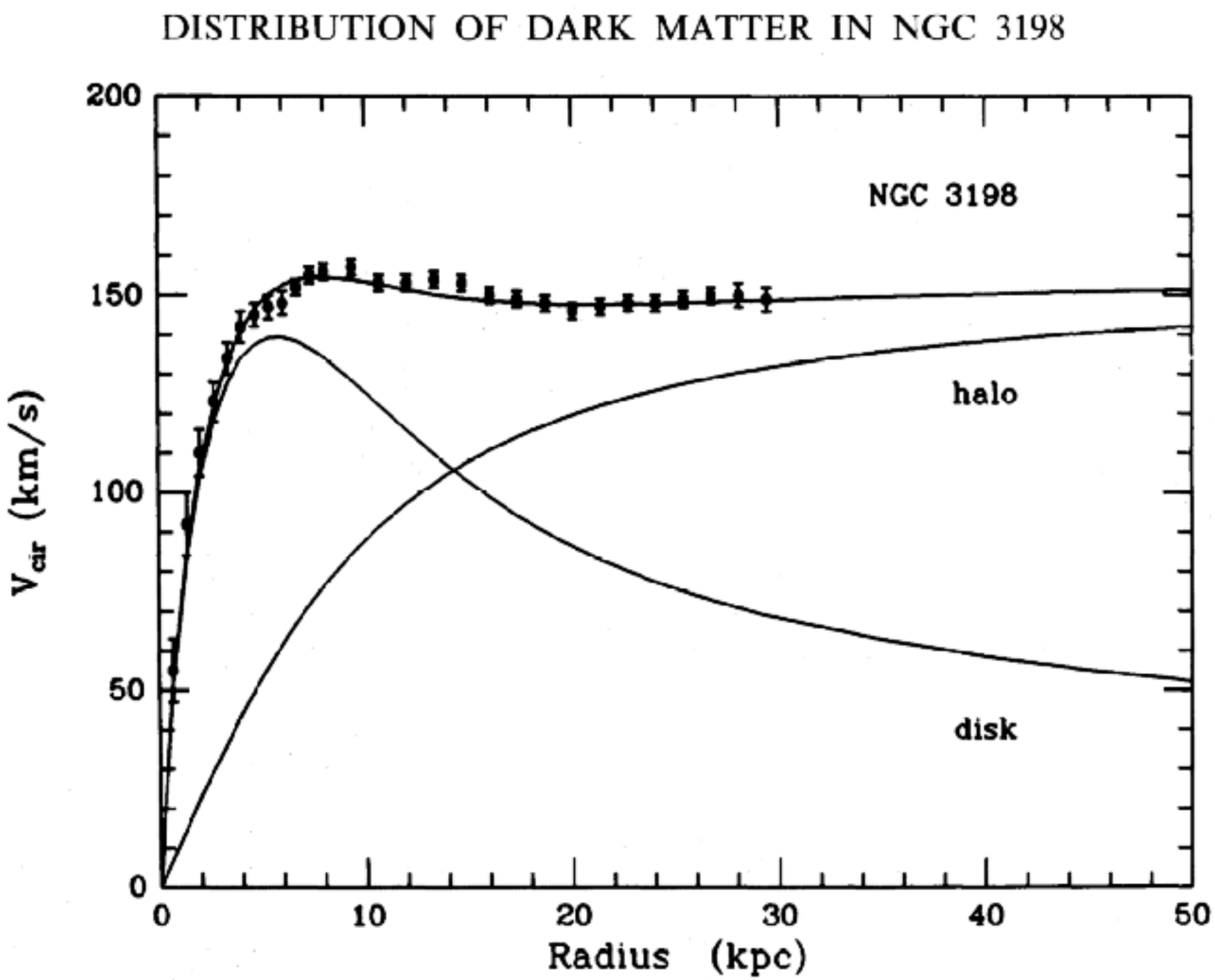
NGC 3198



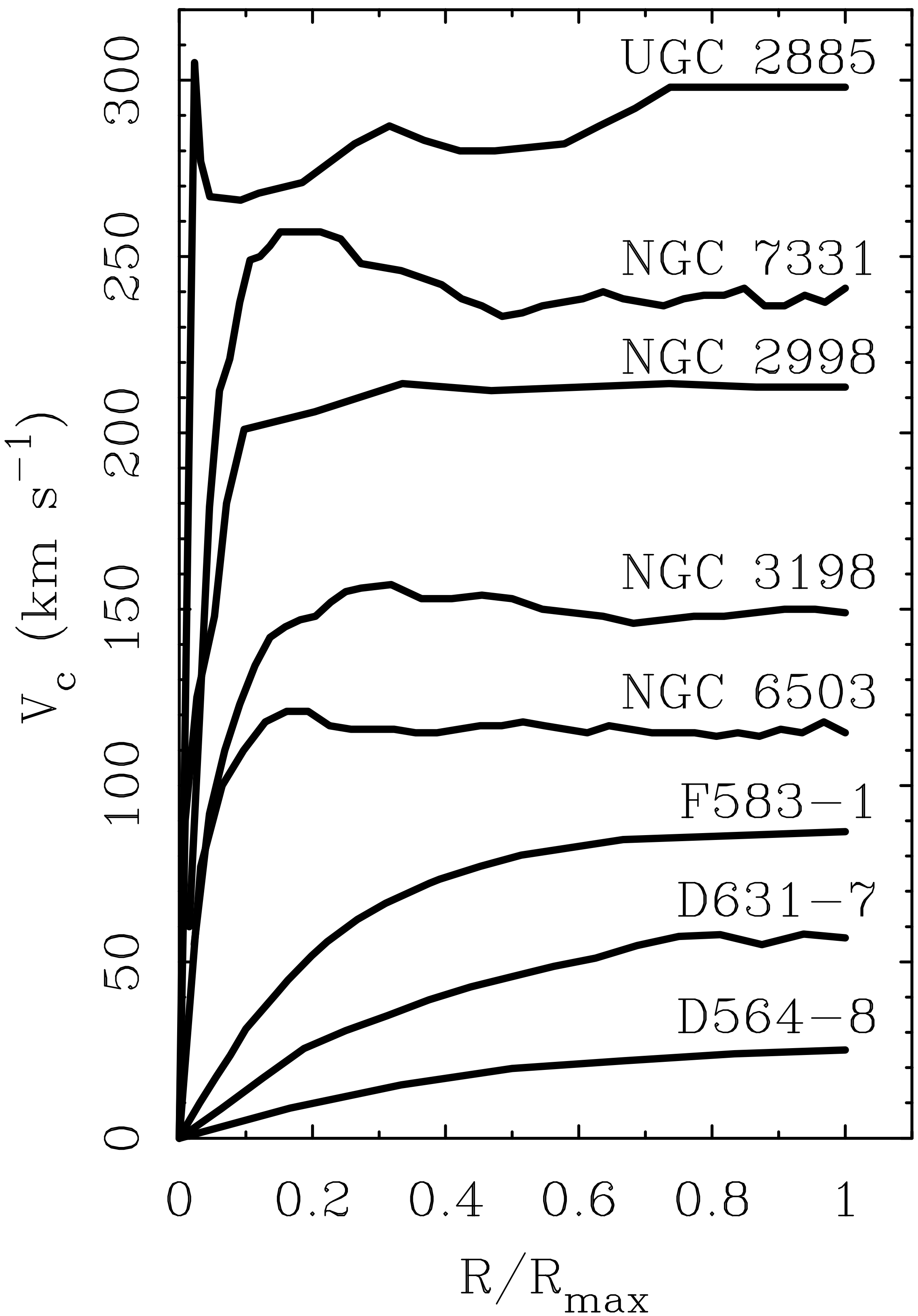
observed velocity field
model velocity field
residual velocity field
ΔV = 25 km s⁻¹
36′
45°28′
δ (2000.0)
10ʰ19ᵐ20ˢ
α (2000.0)
major axis position-velocity diagram
minor axis position-velocity diagram
215°
125°
800
700
600
500
+10
+5
0
−5
−10
Offset (arcmin)
optical image
21cm image
20ᵐ10ˢ
rotation curve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

van Albada et al. (1985)

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



Tully-Fisher: Rotation curve amplitude correlates with observed mass:

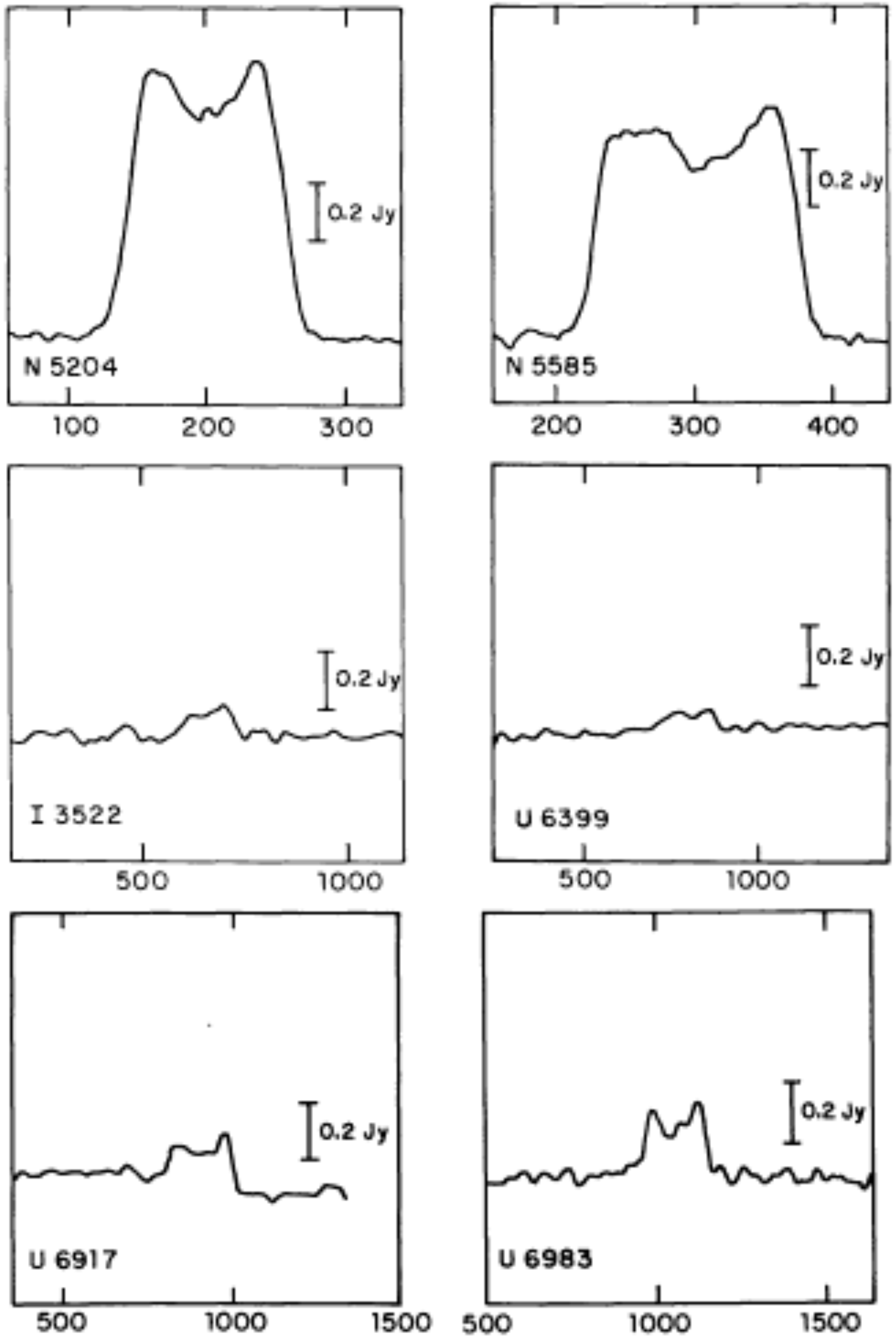


star dominated HSB

gas dominated LSBs

Flat rotation curves continue to occur in quite small systems (e.g., Leo P with V_f ~ 15 km/s)

Tully & Fisher (1977)
Great for distance scale work.
But why does it happen?



R. B. Tully and J. R. Fisher: Distances to Galaxies

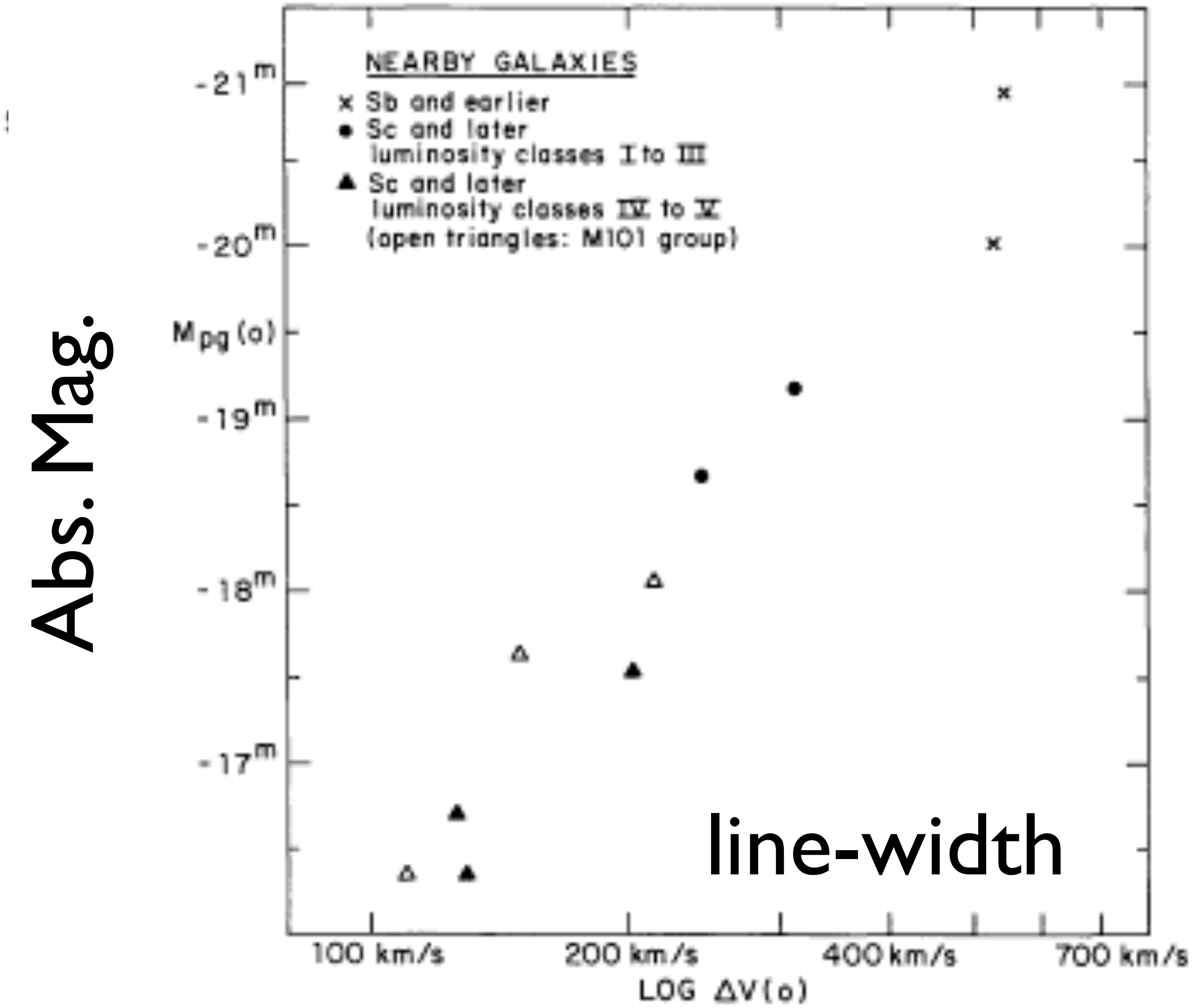


Fig. 1. Absolute magnitude – global profile width relation for nearby galaxies with previously well-determined distances. Crosses are M31 and M81, dots are M33 and NGC 2403, filled triangles are smaller systems in the M81 group and open triangles are smaller systems in the M101 group

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

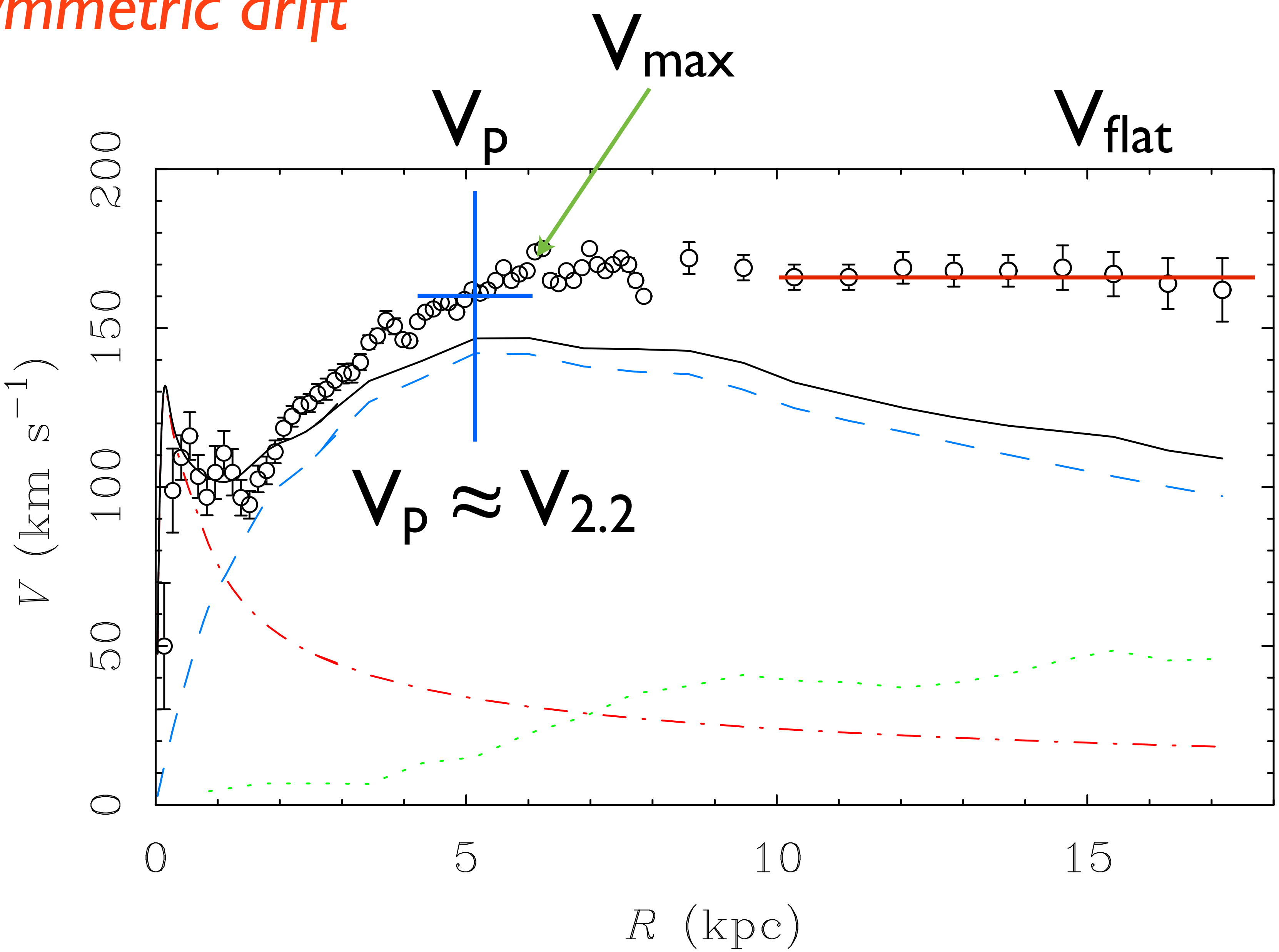
What we measure
- Luminosity
  - Stellar Mass
  - Gas: HI, H_2
- Rotation speed
  - line-width
  - rotation curve

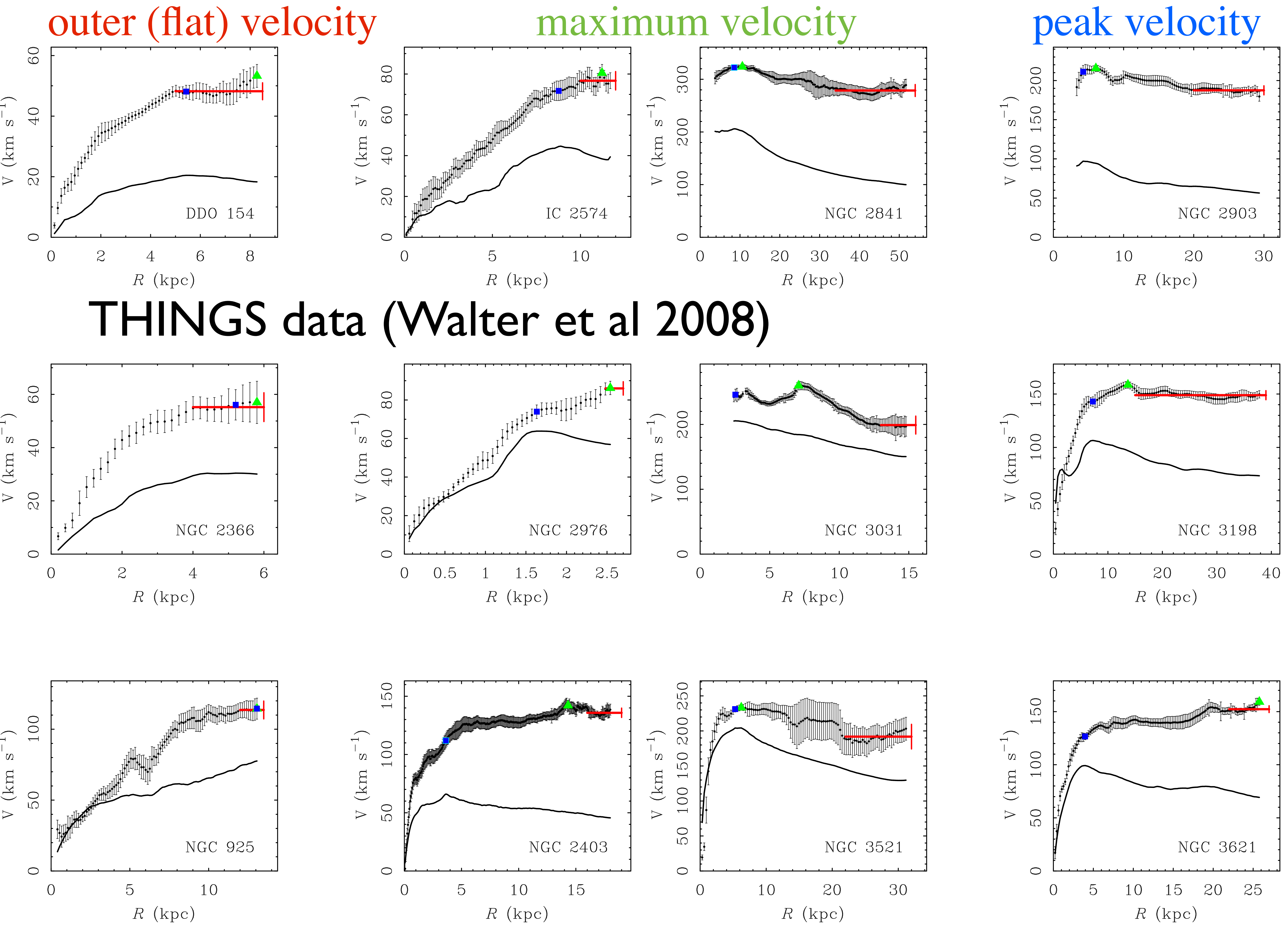
Uncertainties
- Distance
  - Stellar M_*/L
  - HI flux, X-factor
  - velocity dispersion
  - *inclination*
  - *asymmetric drift*

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



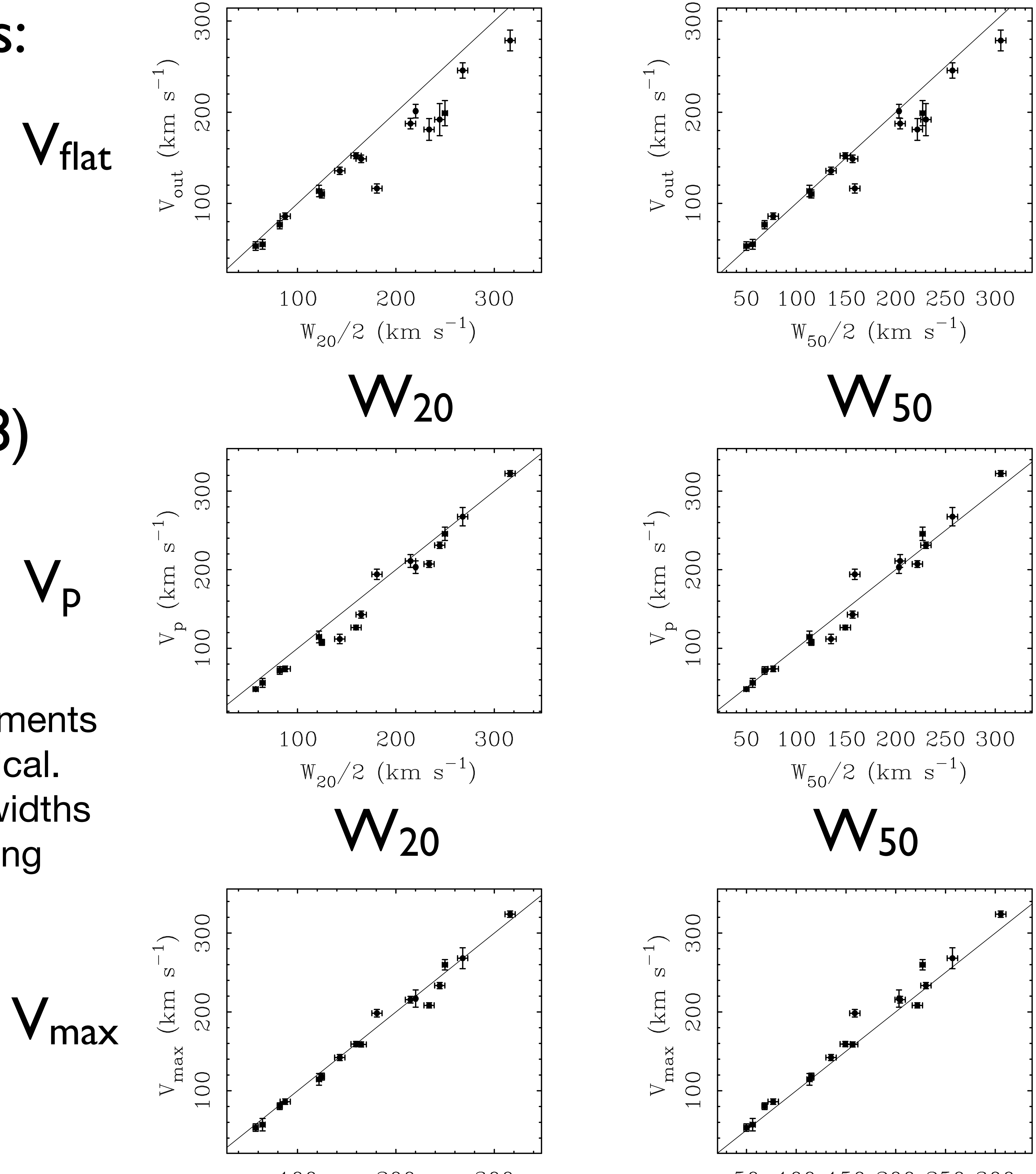


outer (flat) velocity
maximum velocity
peak velocity
THINGS data (Walter et al 2008)
DDO 154
IC 2574
NGC 2841
NGC 2903
NGC 2366
NGC 2976
NGC 3031
NGC 3198
NGC 925
NGC 2403
NGC 3521
NGC 3621
V (km s^-1)
R (kpc)

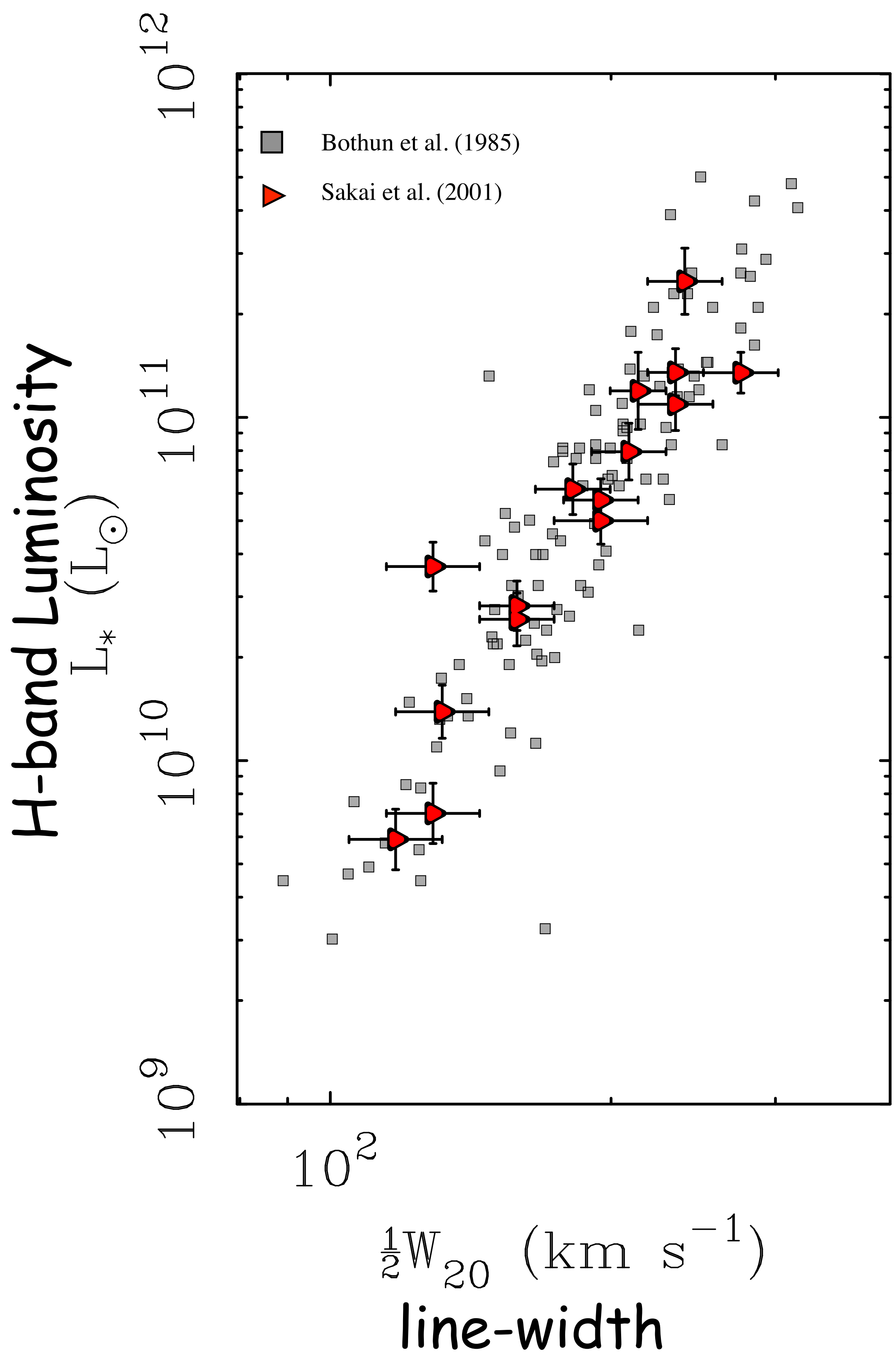
Velocity estimators:

THINGS data (Walter et al 2008)

Different velocity measurements correlate but are not identical. TF relations fit using line-widths will differ from those fit using resolved rotation curves.



Tully-Fisher relation



Luminosity and line-width are presumably proxies for stellar mass and rotation velocity.