Dark Matter

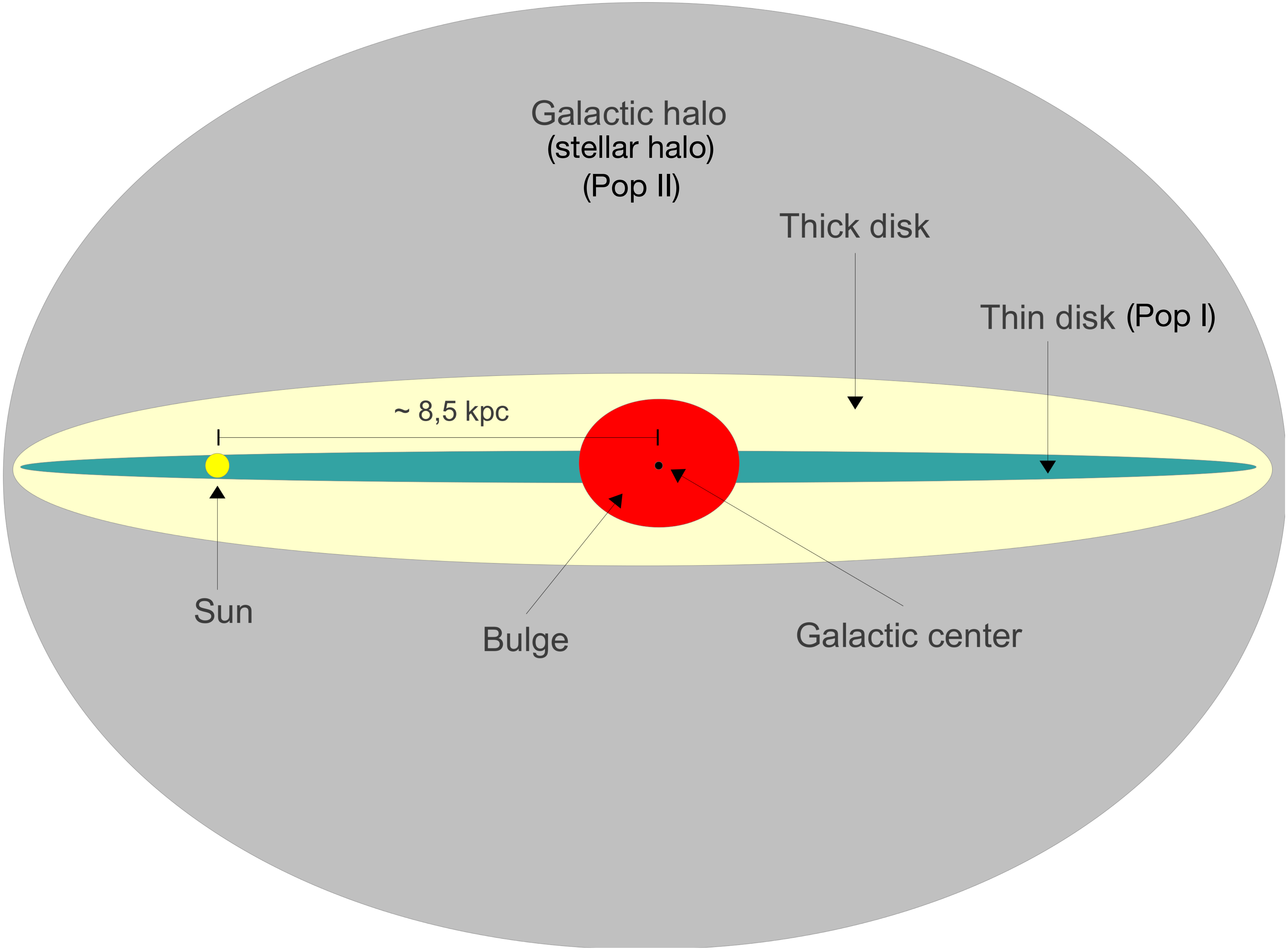
ASTR 333/433
Spring 2018
T R 4:00-5:15pm
Sears 552

"You sly dog! You got me monologuing!"

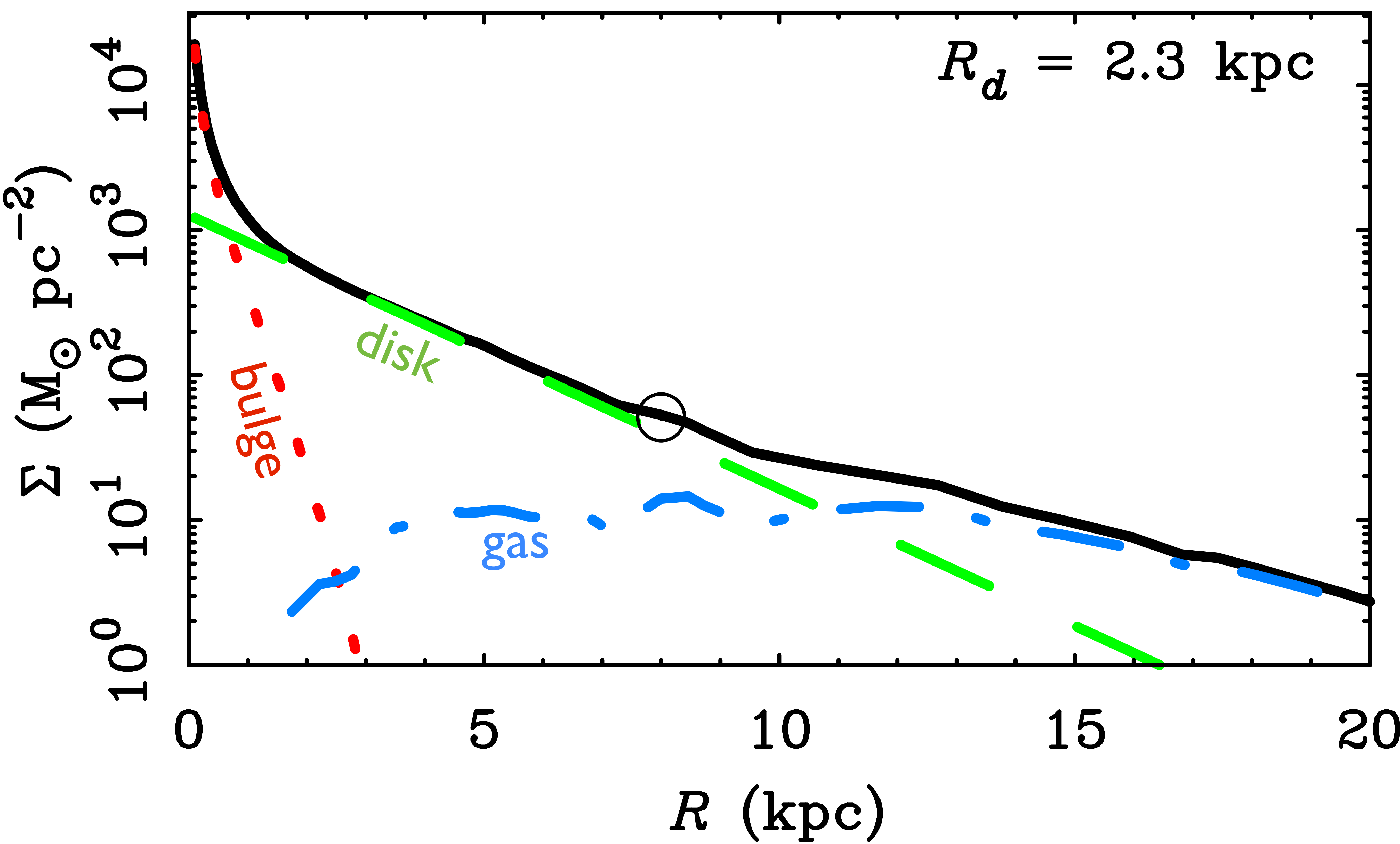
TODAY

- Galactic Structure
  - Thick Disk
- Dynamical Friction

- Laws of Galactic Rotation
  - Flat rotation curves
  - Tully-Fisher
  - Radial acceleration relation


Galactic halo
(stellar halo)
(Pop II)
Thick disk
Thin disk (Pop I)
~ 8,5 kpc
Sun
Bulge
Galactic center

radial direction



Exponential disks in 3 dimensions

$$\rho(R, Z) = \rho_0 e^{-R/R_d} e^{-|z|/h_z}$$

R_d Radial scale length $R_d \approx 2 \text{ to } 3 \text{ kpc}$

h_z vertical scale height $h_z \approx 300 \text{ pc}$

for thin disk

for external galaxies, typically $R_d/h_z \approx 6 \text{ to } 10$

other models possible, e.g., $\text{sech}(|z|/z_0)$

also exponential in vertical direction; scale height depends on the population

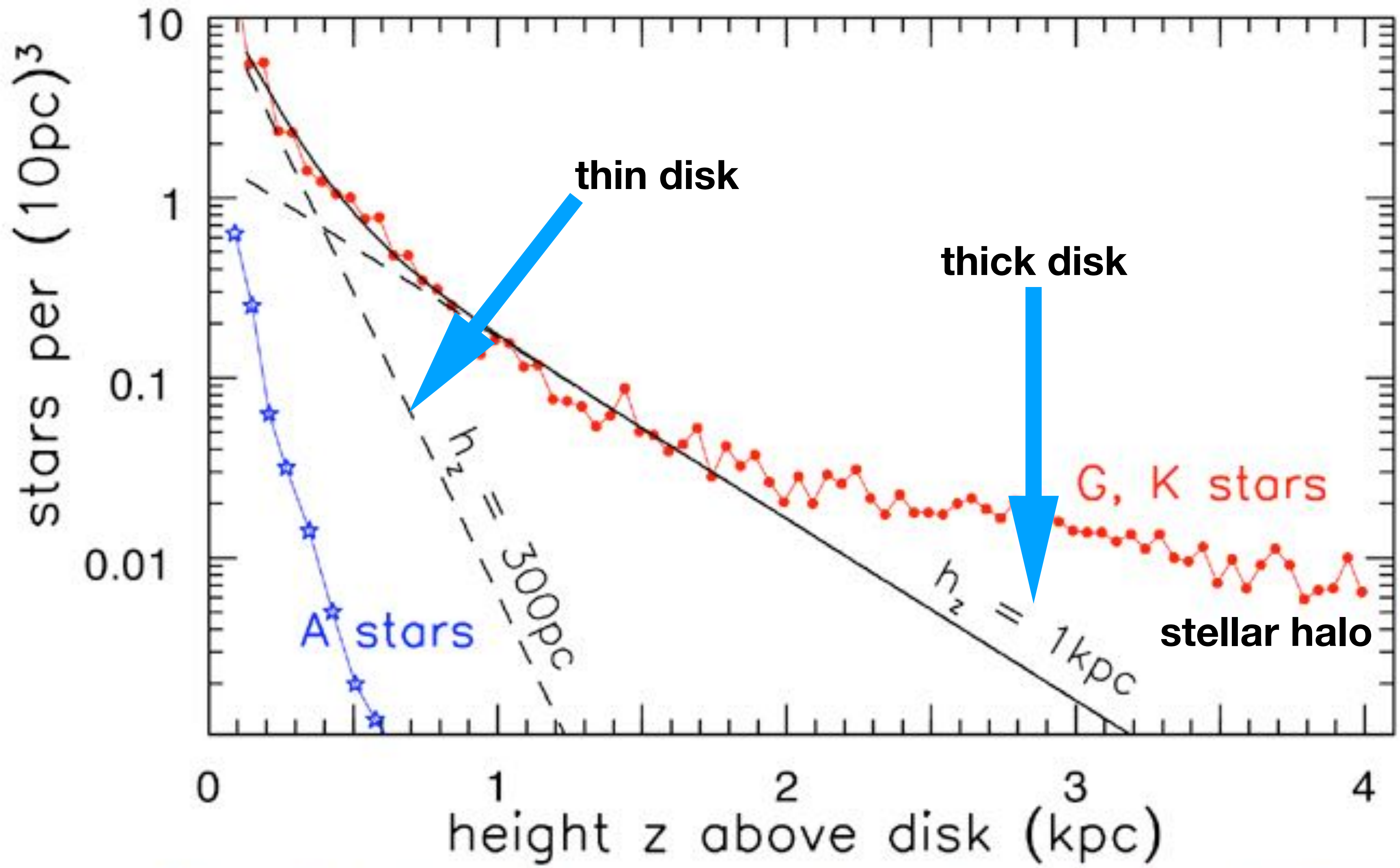


Fig 2.8 (Reid, Knude) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

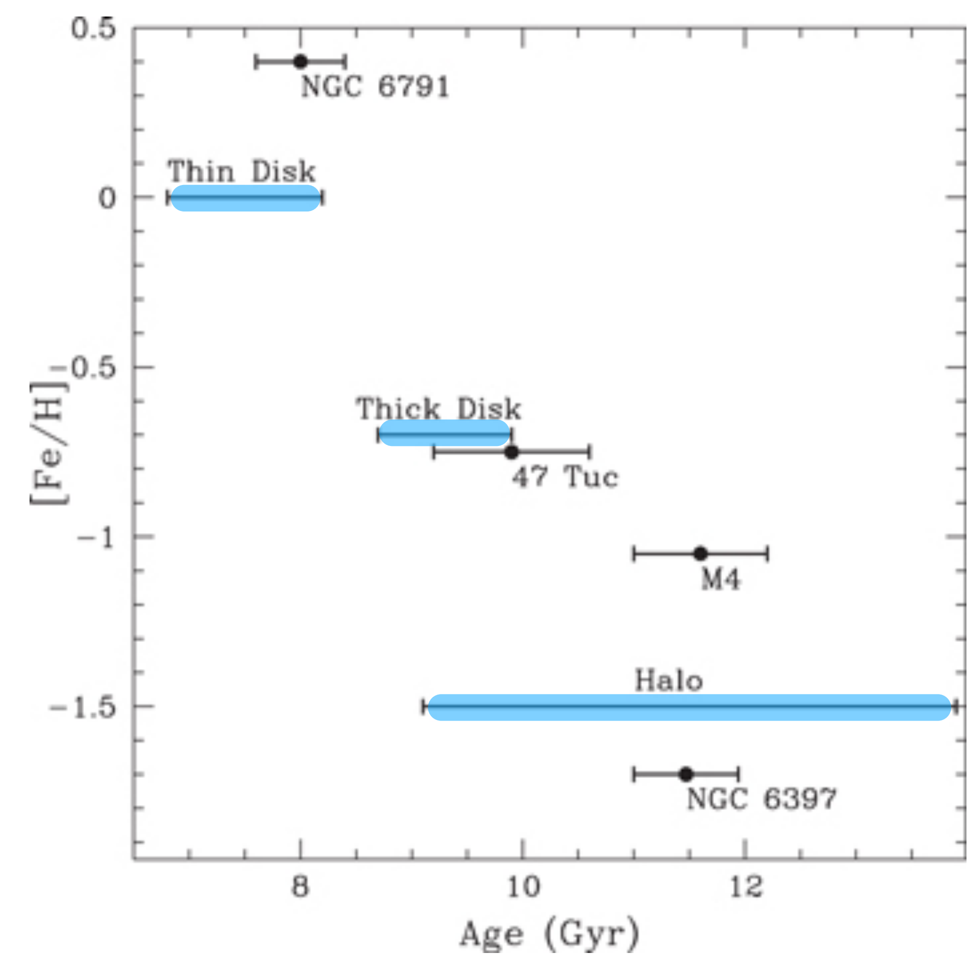
Stars in the thin disk, thick disk, and stellar halo are chemically distinct (different $[\alpha/\mathrm{Fe}]$)

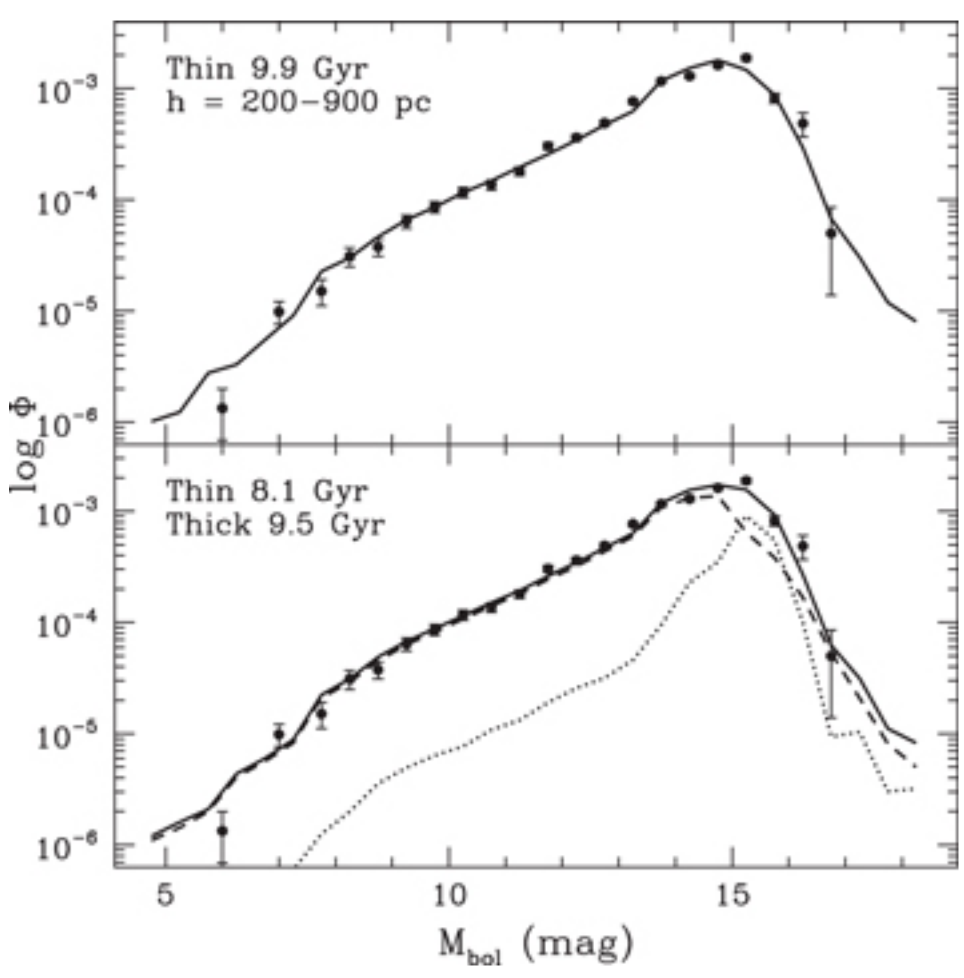
Thin disk
Age: 8 Gyr

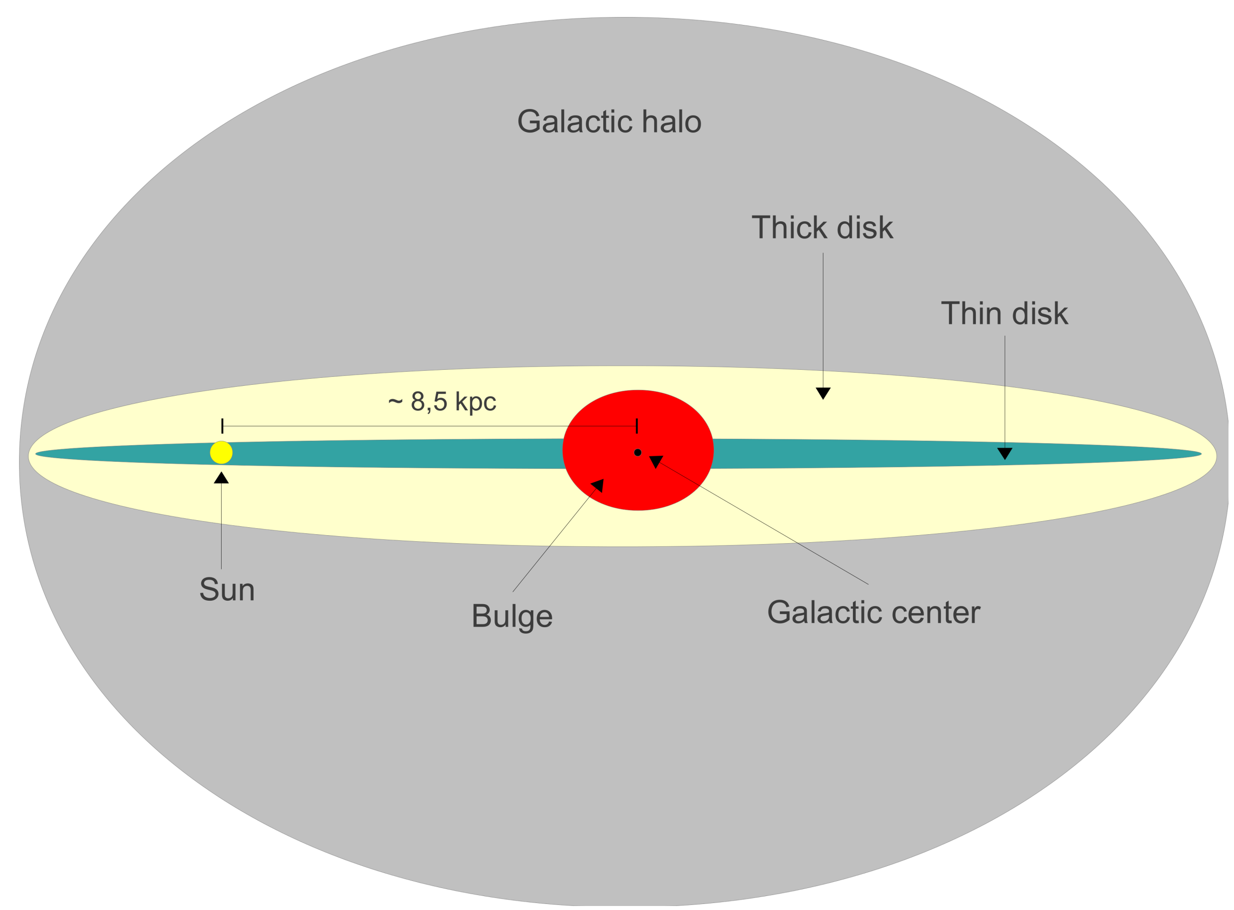
Thick disk
Age: 9.5 Gyr
mass fraction: ~20%

Stellar Halo
Age: 12.5 Gyr
mass fraction ~1%

Ages from oldest white dwarfs
(Mukremin et al. 2017)

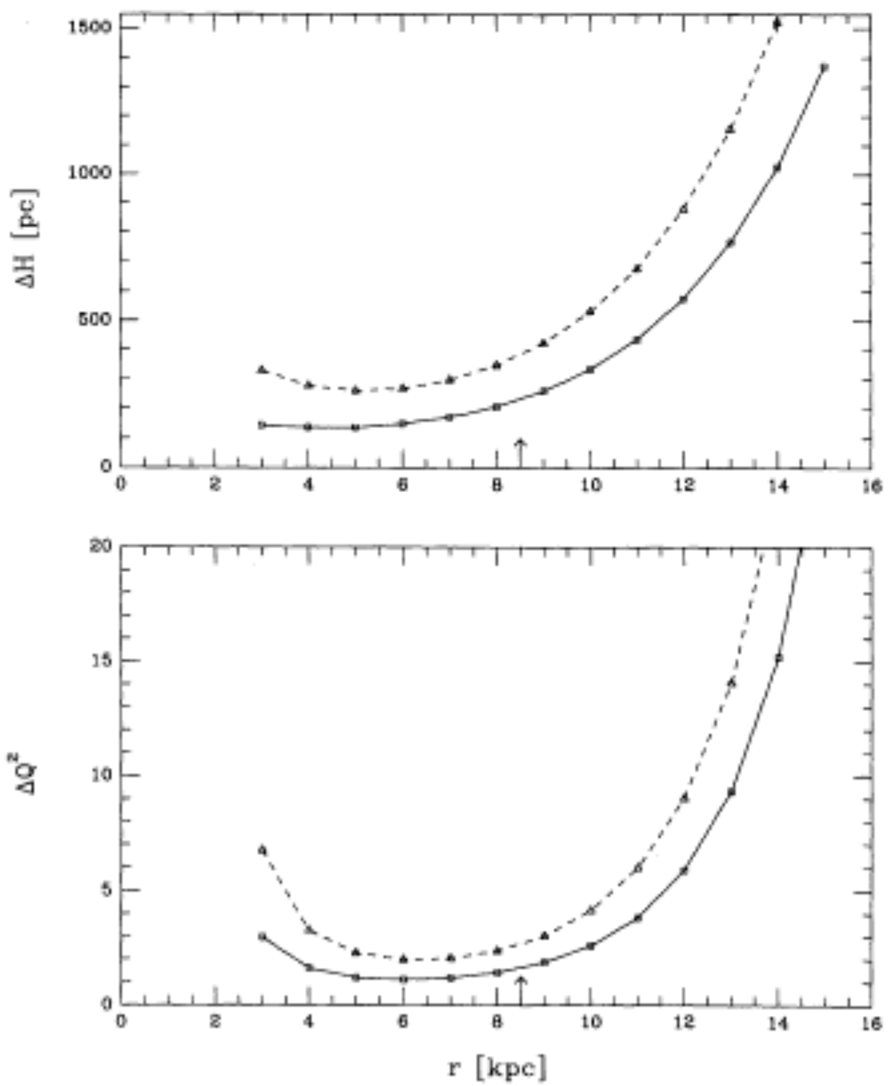






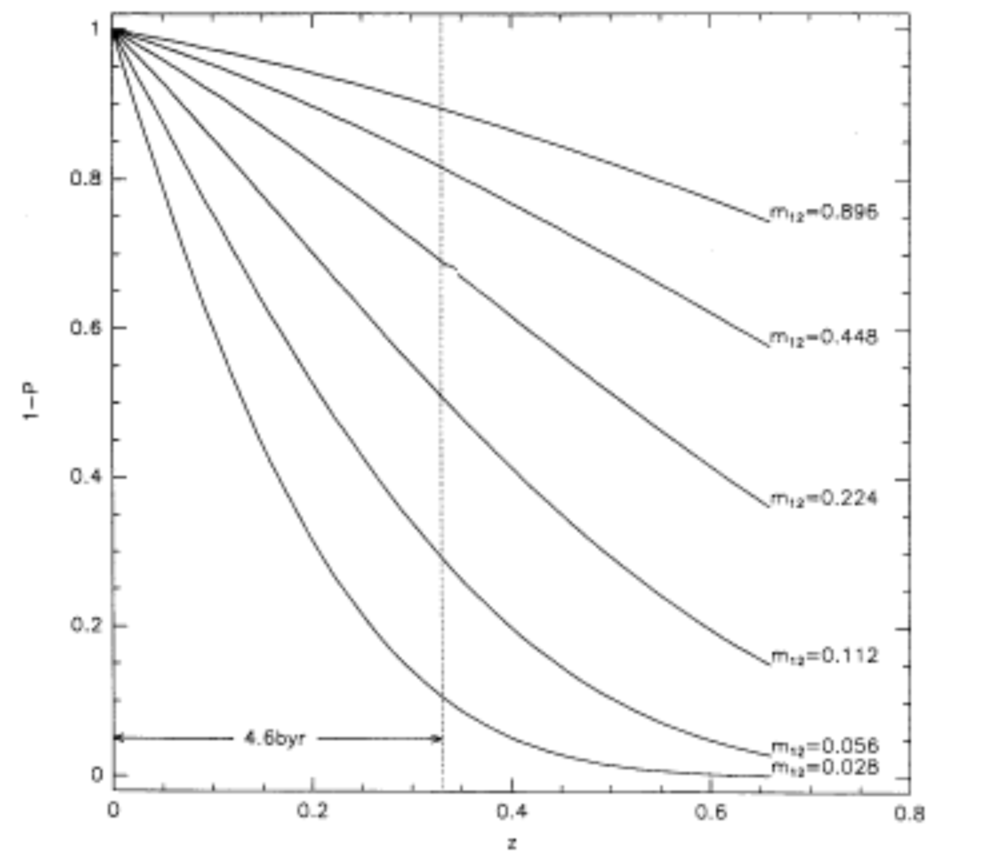
Toth & Ostriker (1992)

Mergers thicken and heat disks. The existence of cold, thin disks (spiral galaxies) limits the mass of mergers to < 1:10 (crudely speaking).



ght and Toomre's Q in the Caldwell-Ostriker galaxy model. The infalling satellites are modeled by Jaffe spheres with a total mass of the solar circle ($=4.3 \times 10^9\ M_\odot$) and scale lengths of 1 kpc (*solid lines*) or 0.1 kpc (*dashed lines*). They are assumed to spiral in along distribution of orientations. See § 4 for details. In the top panel the scale-height increase ΔH is plotted against the Galactocentric he change in Toomre's Q^2 is shown.

odds of dodging a major merger are small

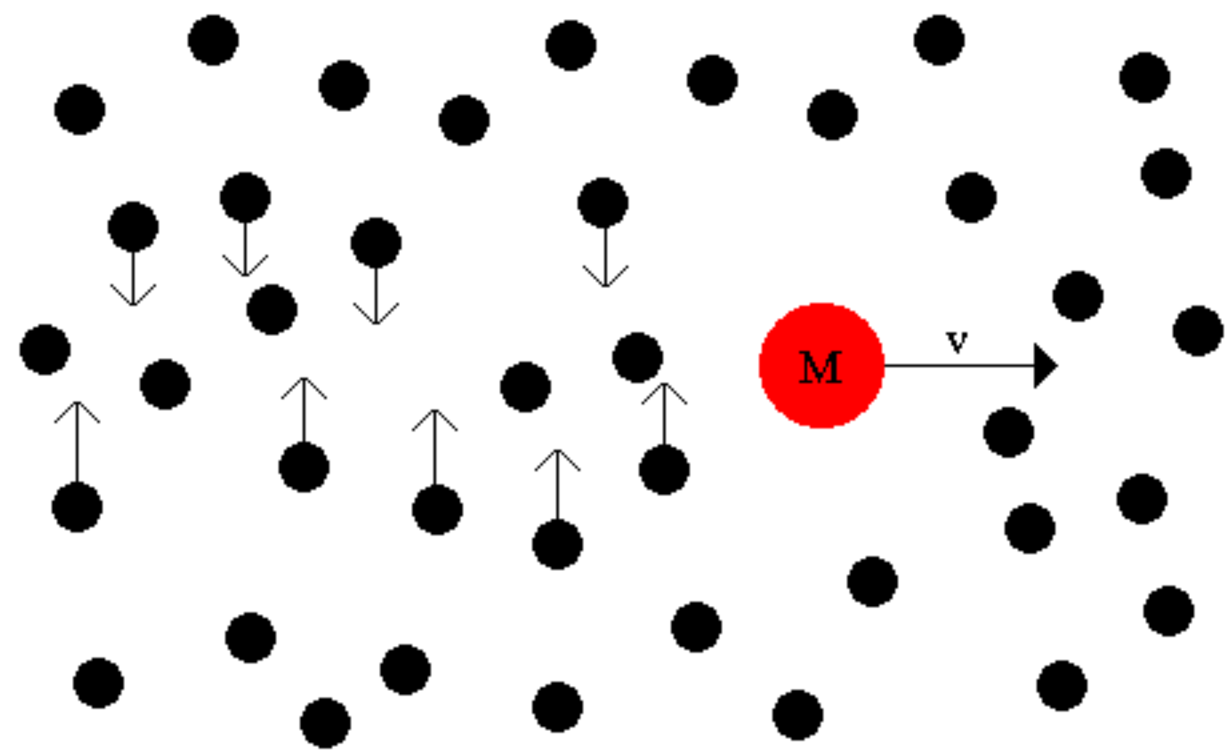


rs, after Carlberg (1990b), as a function of look-back time. The typical (L_*) galaxy would have hance of a merger with one of mass $3 \times 10^{10}\ M_\odot$ within the lifetime of the Sun.

The Milky Way has an old (~9 Gyr) thick disk, that is a modest fraction of the total stellar disk mass. Perhaps a sizable merger thickened the disk long ago, but not much has happened since.

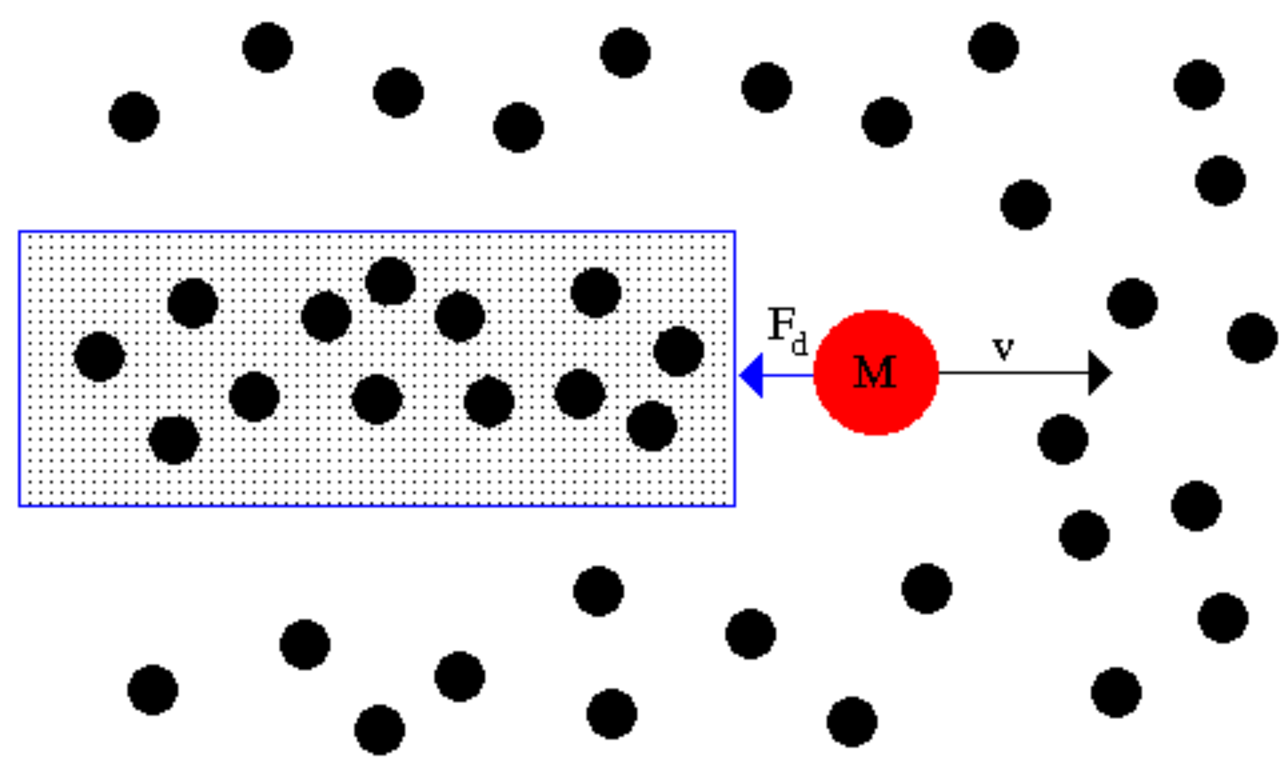
Dynamical friction acts to slow a particle of mass M and velocity v_M traversing a medium of N gravitationally attractive particles each of mass m.

consider a mass, M, moving through a uniform sea of stars. Stars in the wake are displaced inward.



Dynamical friction arises when the passage of an object pulls particles towards it, creating a density enhancement in its wake. This density enhancement pulls back against the motion of the object.

this results in an enhanced region of density behind the mass, with a drag force, F_d known as dynamical friction



Dynamical friction acts to slow a particle of mass M and velocity v_M traversing a medium of N gravitationally attractive particles each of mass m.

Chandrasekhar formula for dynamical friction (BT eqn 8.3)

$$\frac{d\vec{v_M}}{dt} = -16\pi^2 G^2 M m \ln\Lambda \frac{\vec{v_M}}{v_M^3} \int_0^{v_M} f(v) v^2 dv$$

net frictional force

Coulomb logarithm

distribution fcn of background particles (N of mass m and velocity v)

The Coulomb logarithm measures the “extent” of the system and is a complete kludge

$$\Lambda \approx \frac{b_{max}}{b_{min}} \approx \frac{NmR}{M\mathcal{R}}$$

orbital radius of mass M

extent of N masses m

e.g., the radius of a dark matter halo

Examples where dynamical friction is important

- Dynamical friction acts to slow the pattern speed of bars embedded in dark matter halos.

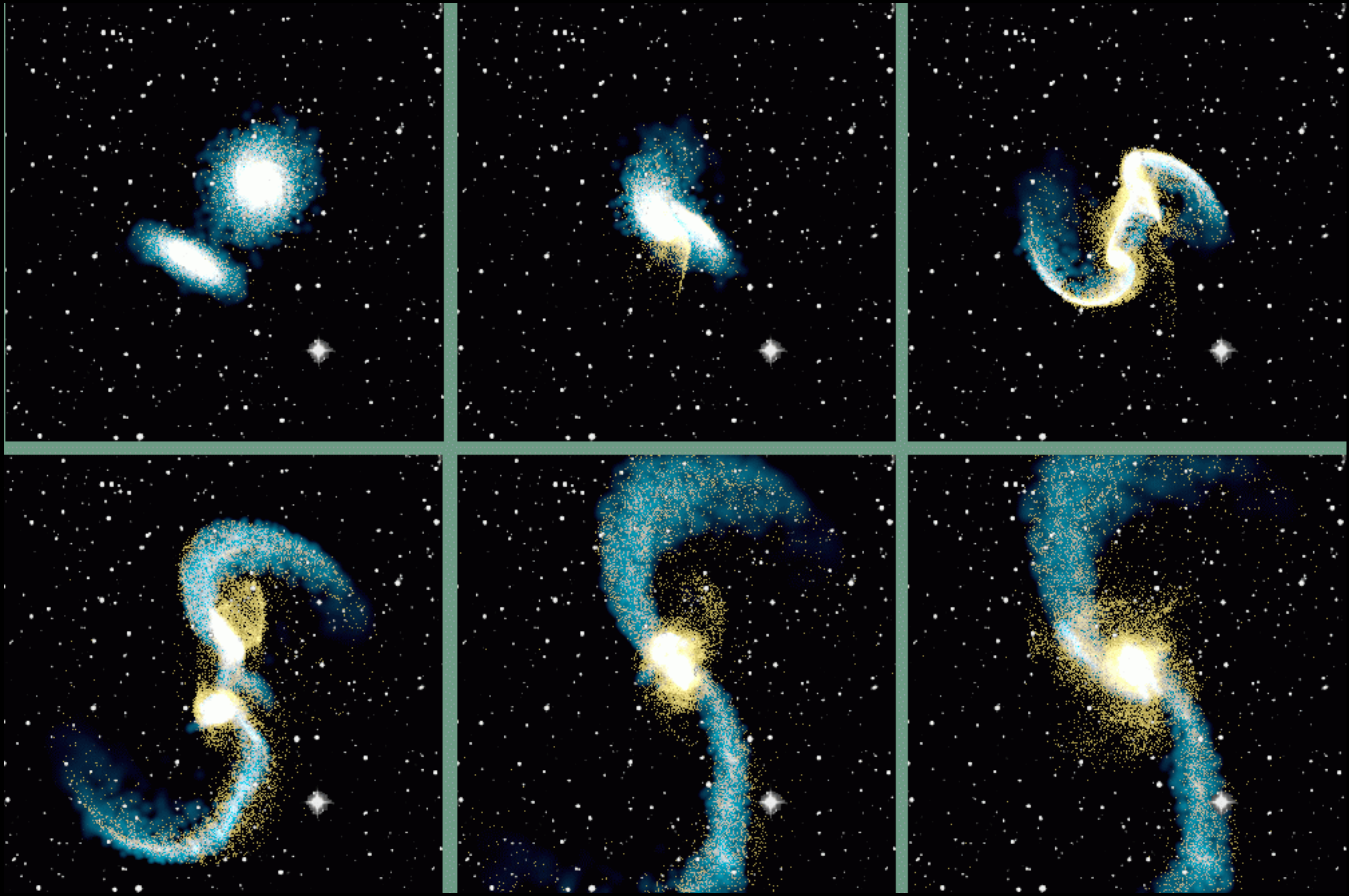
Mostly. We think.
Some configurations of live halos can amplify rather than suppress bars!

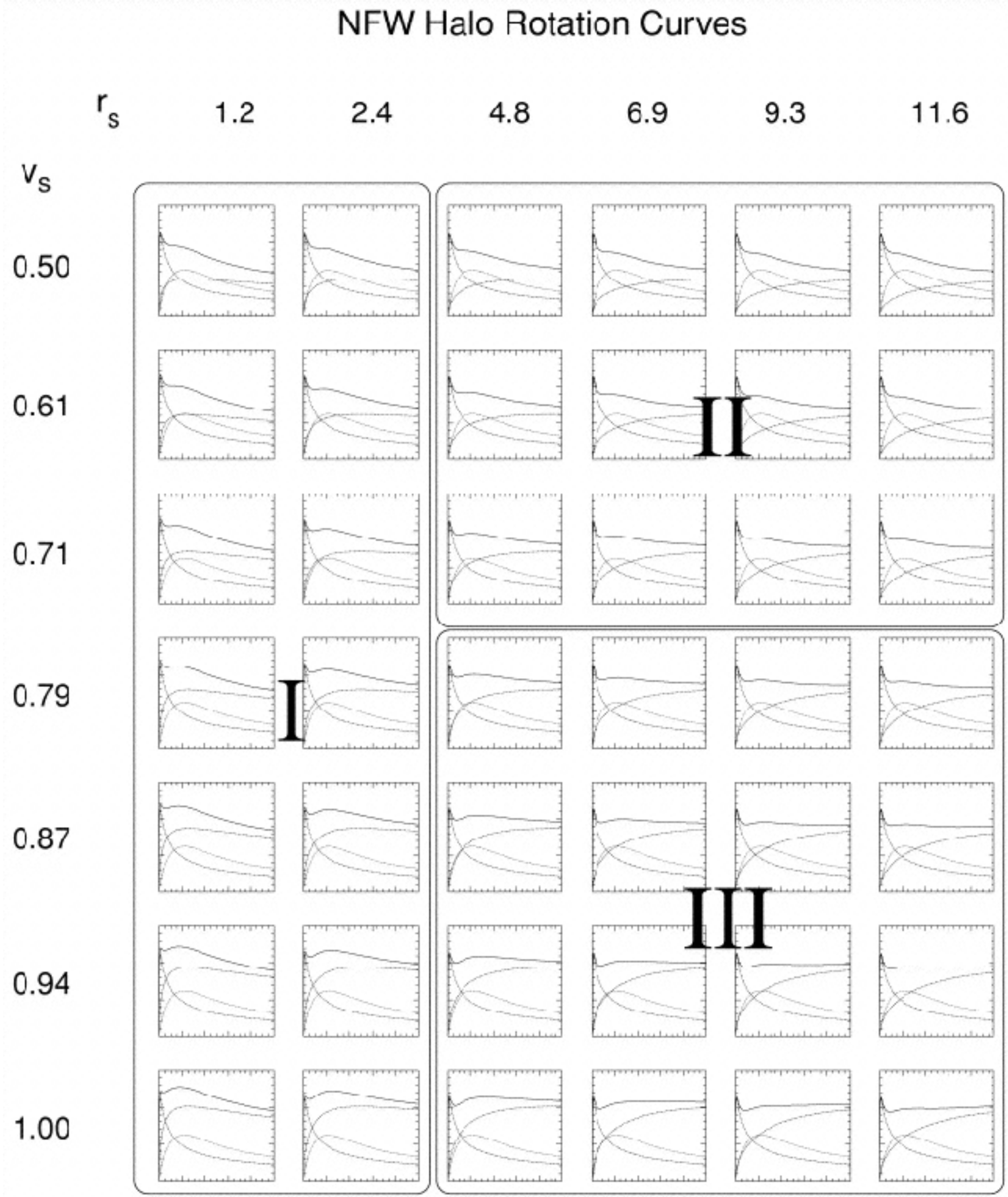
- Plays a role in the orbits of satellite galaxies and their incorporation into larger dark matter halos.

- Also required for merging galaxies - orbital energy and angular momentum gets transferred to the dark matter halo, which acts like a big catchers mitt to make galaxies merge that would otherwise just fly past each other.

The Antennae [merger of NGC 4038 and NGC 4039]

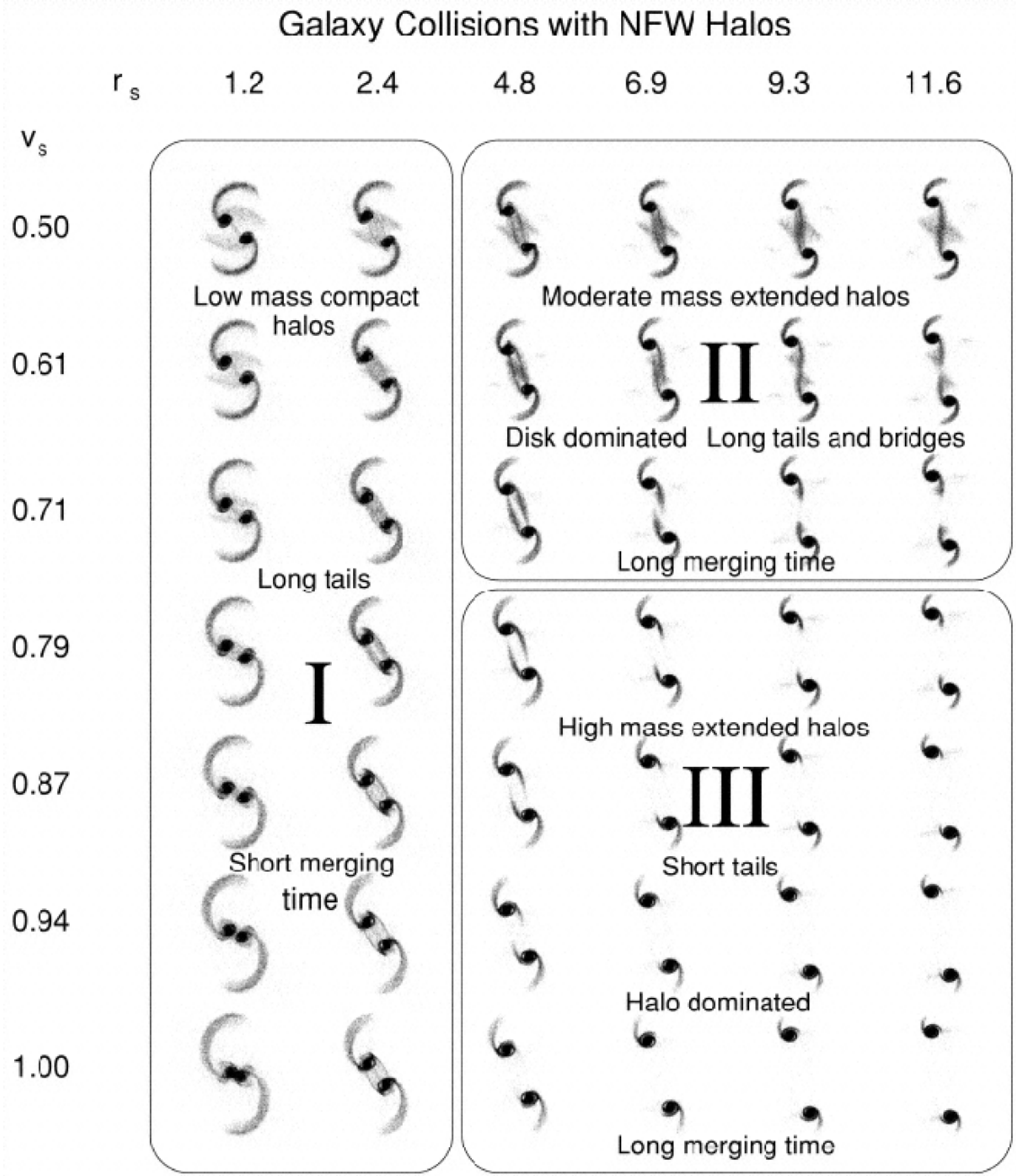
Merging galaxies simulation by Prof. Mihos





Merging galaxy models
initial rotation curves

Dubinski, Mihos & Hernquist (1999)



Merging galaxy models

morphology of merger models

Dubinski, Mihos & Hernquist (1999)

Zone II gives the most realistic tidal tail morphologies.

Zone III has more realistic rotation curves.

small contradiction, that.

The potential well of the DM halo needs to be deep enough to cause a merger, but not so deep that it inhibits the formation of tidal tails.

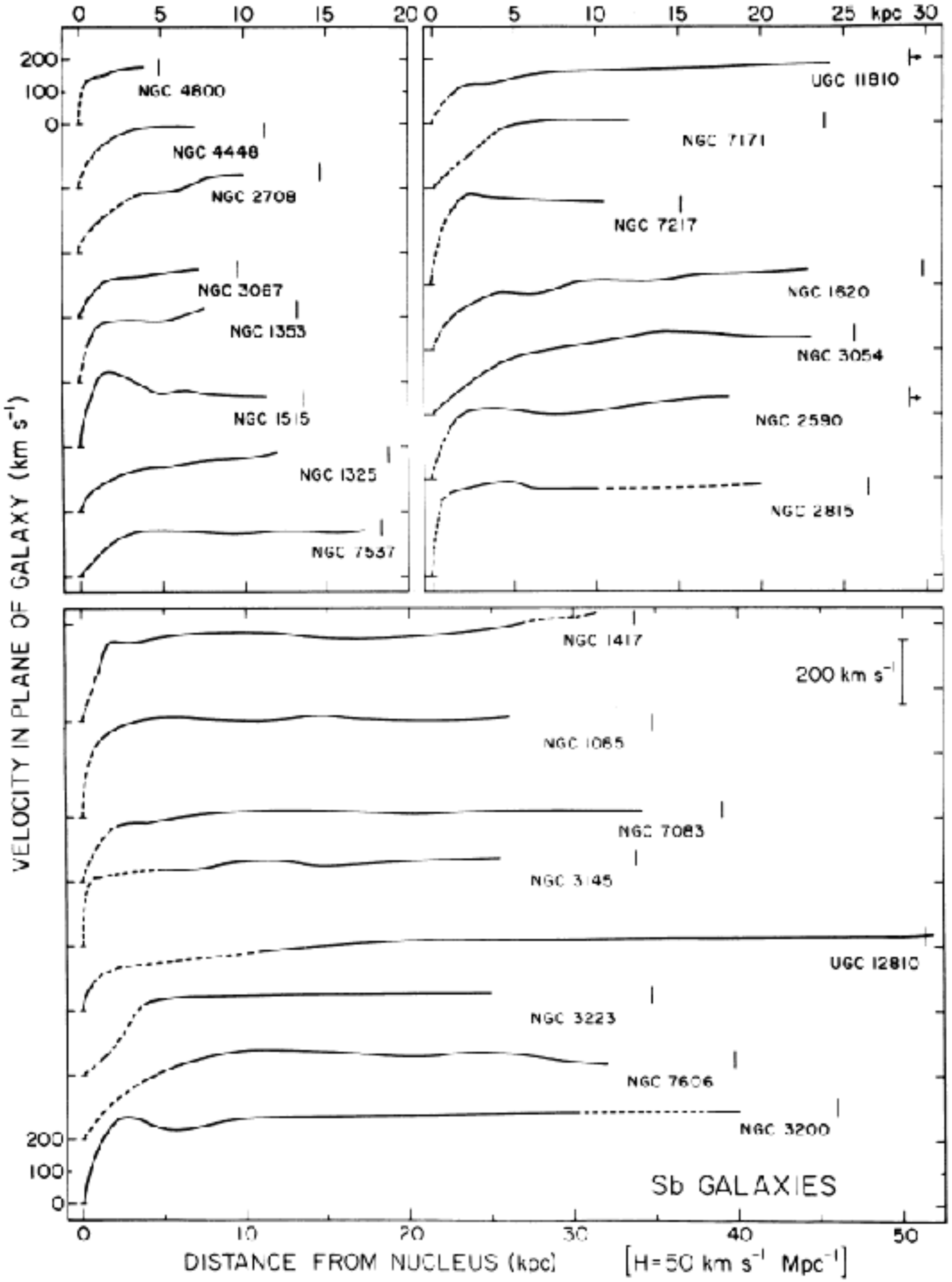


FIG. 3.—Mean velocities in the plane of the galaxy, as a function of linear radius for 23 Sb galaxies, arranged approximately according to increasing luminosity. Adopted curve is rotation curve formed from the mean of velocities on both sides of the major axis. Vertical bar marks the location of R_{25},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

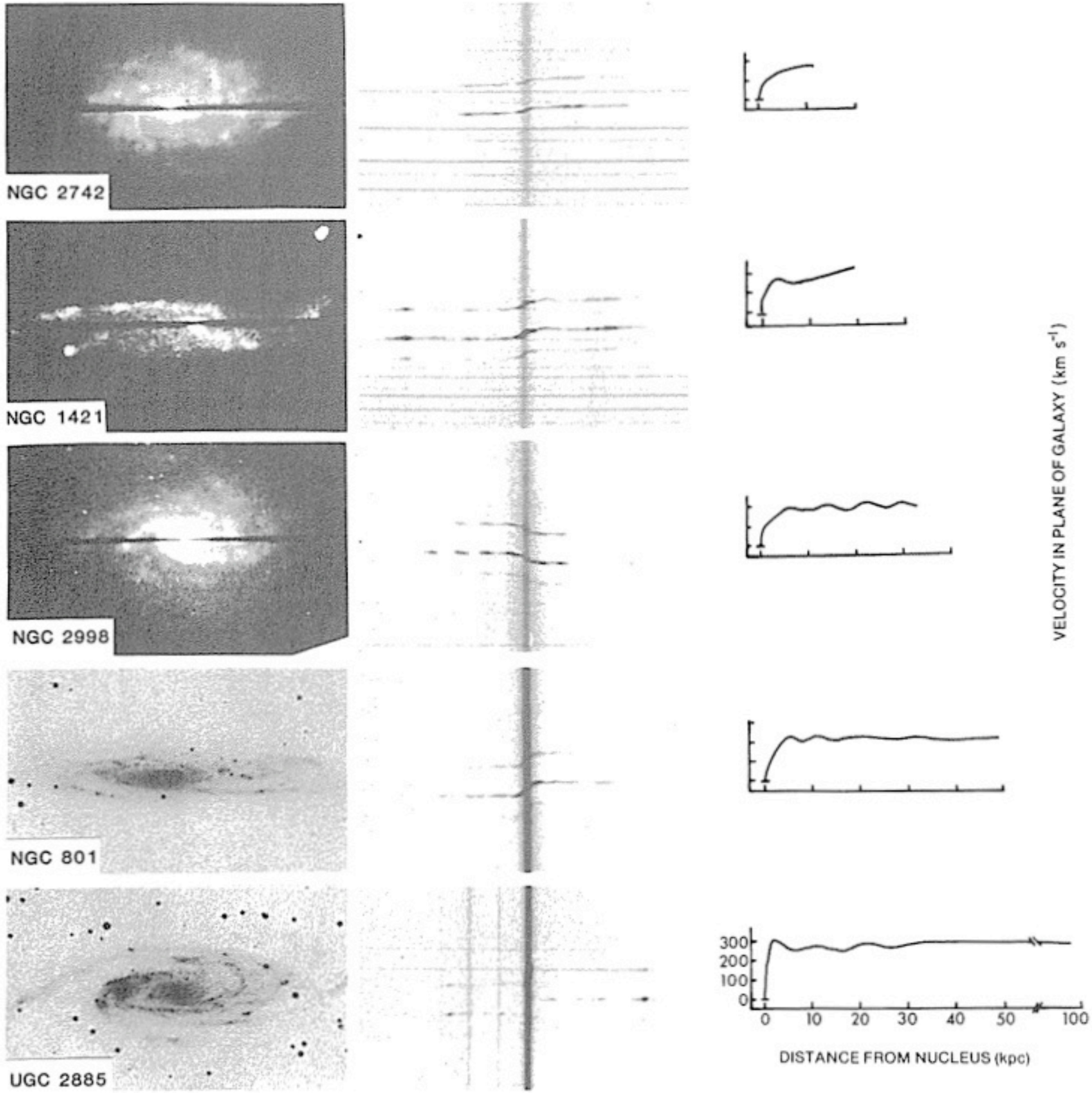
Rotation curves tend to become flat at large radii

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

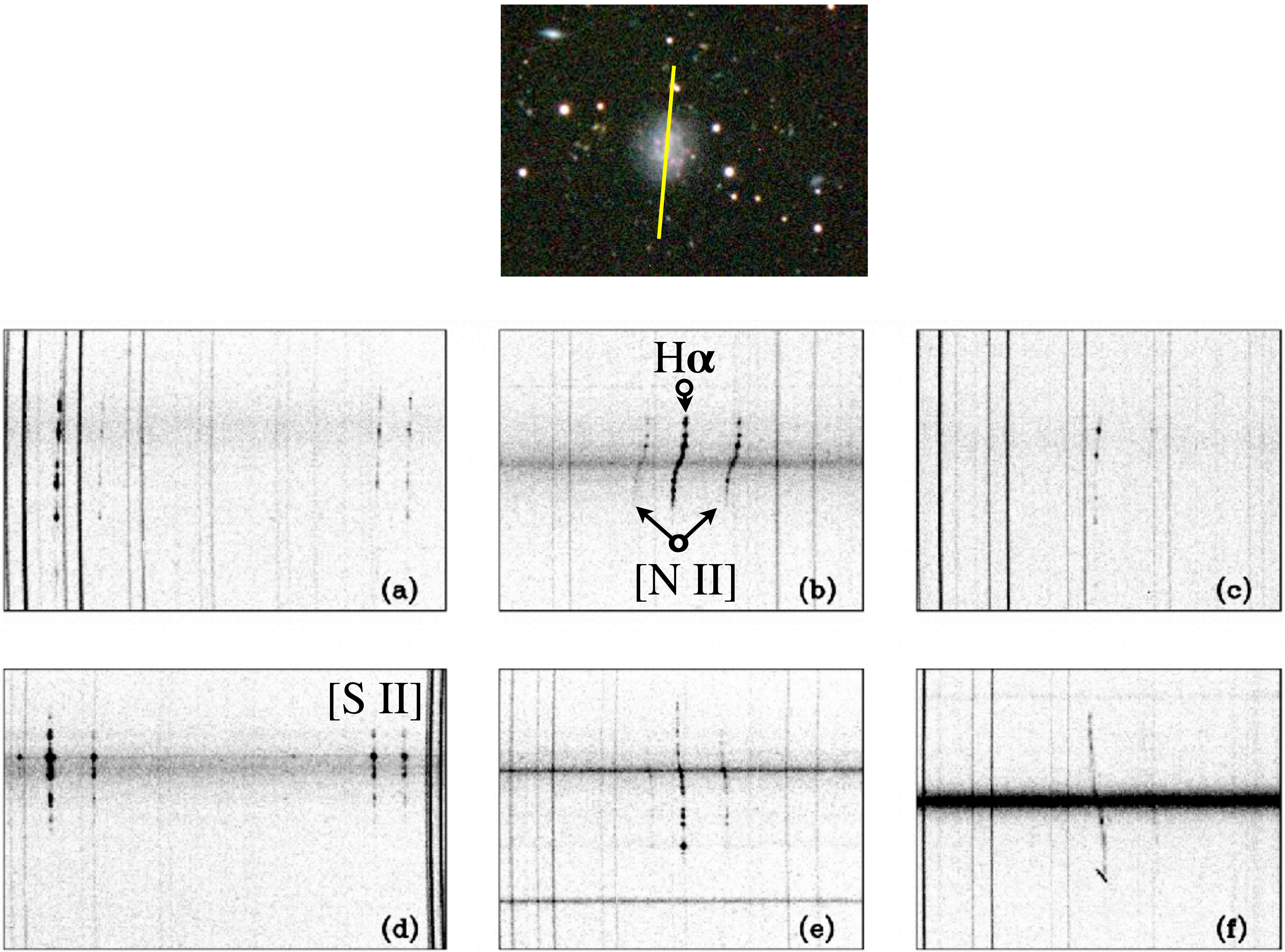
$$M \propto R$$

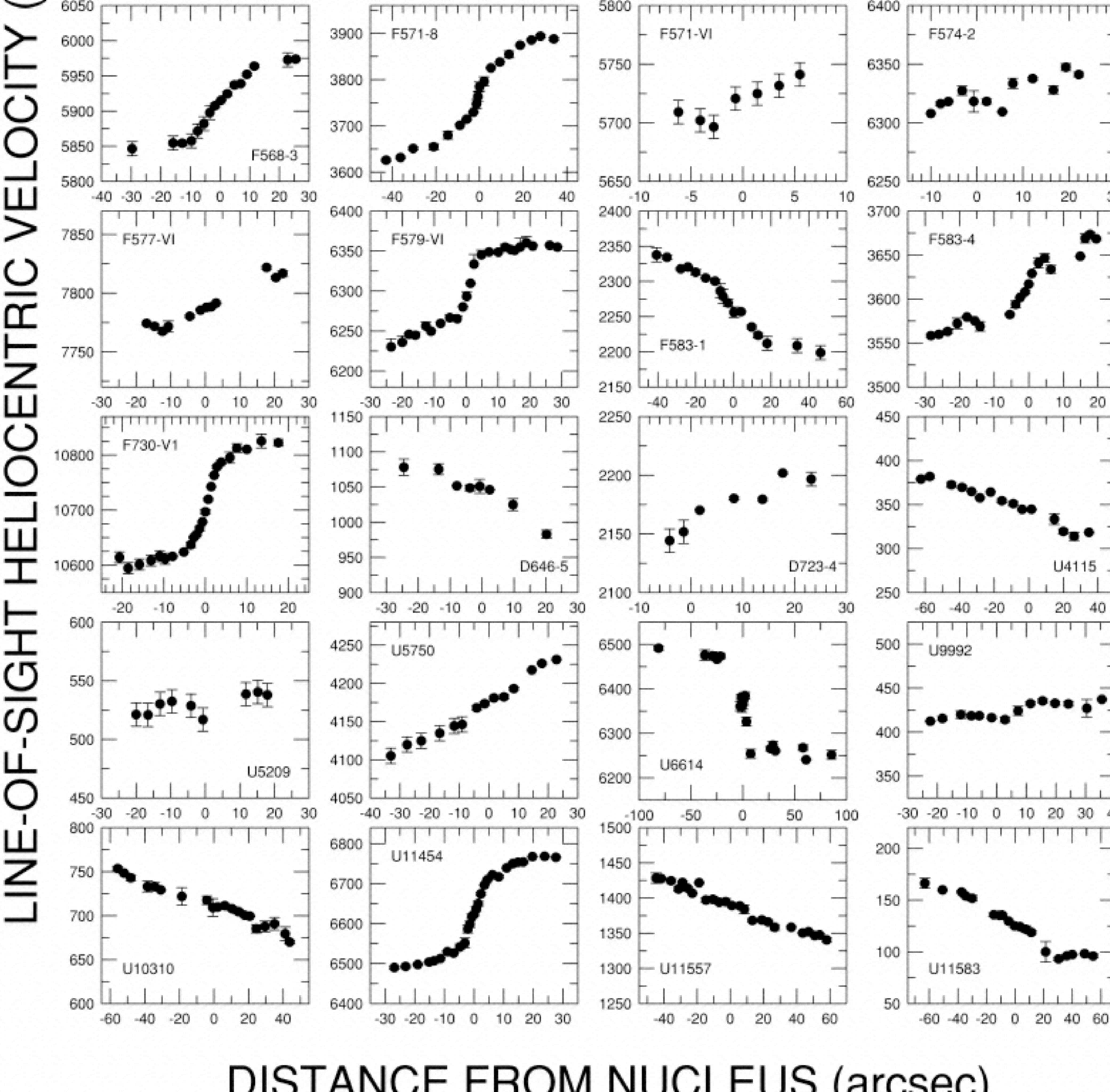
$$\rho \propto R^{-2}$$

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

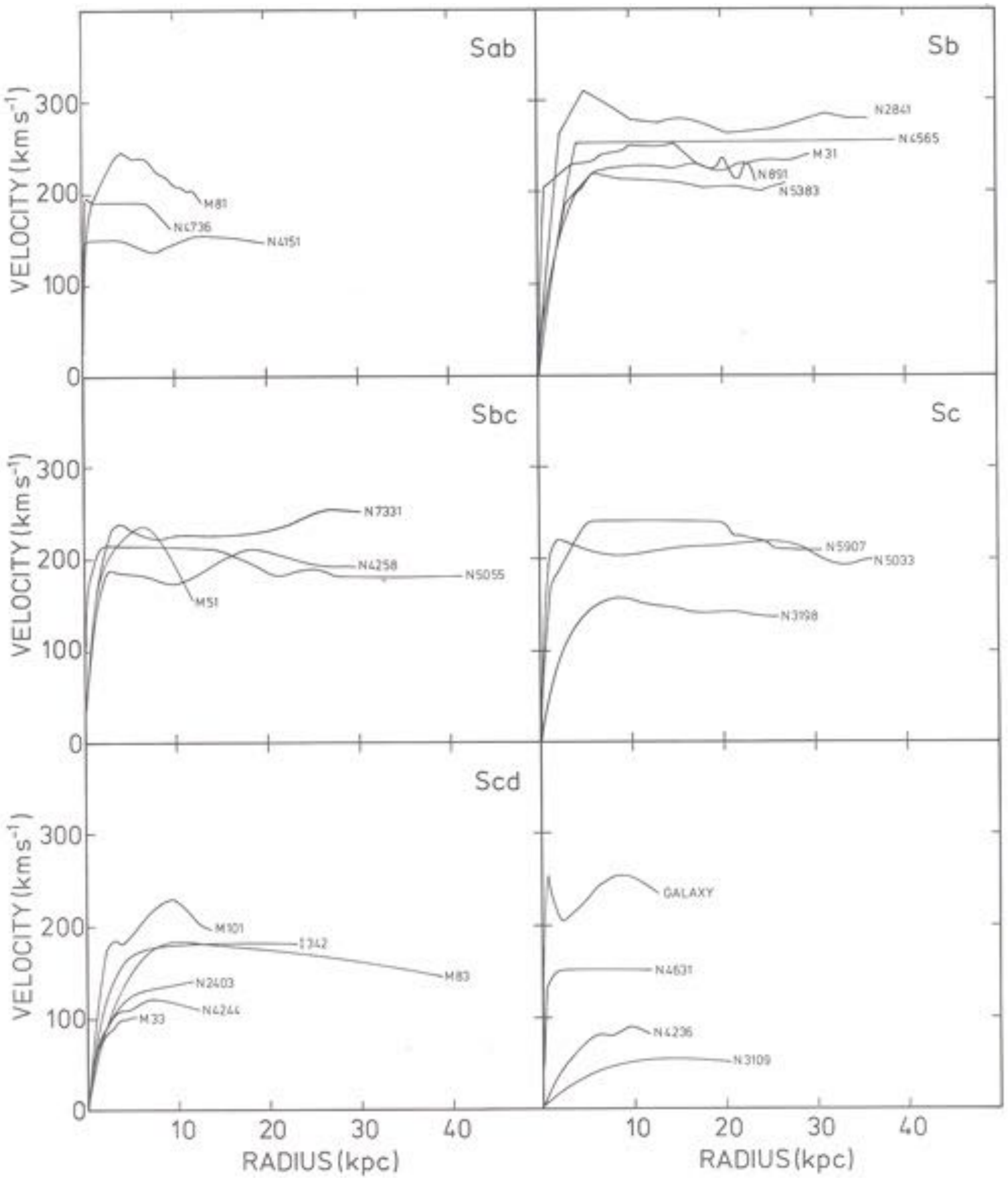


NGC 2742
NGC 1421
NGC 2998
NGC 801
UGC 2885
VELOCITY IN PLANE OF GALAXY (km s^{-1})
300
200
100
0
0
10
20
30
40
50
100
DISTANCE FROM NUCLEUS (kpc)


Hα
[N II]
(a)
(b)
(c)
[S II]
(d)
(e)
(f)


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

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)