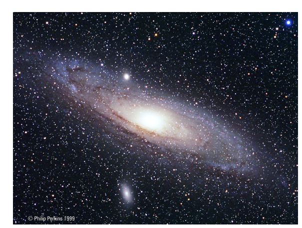
ASTR 303
Spiral Galaxies

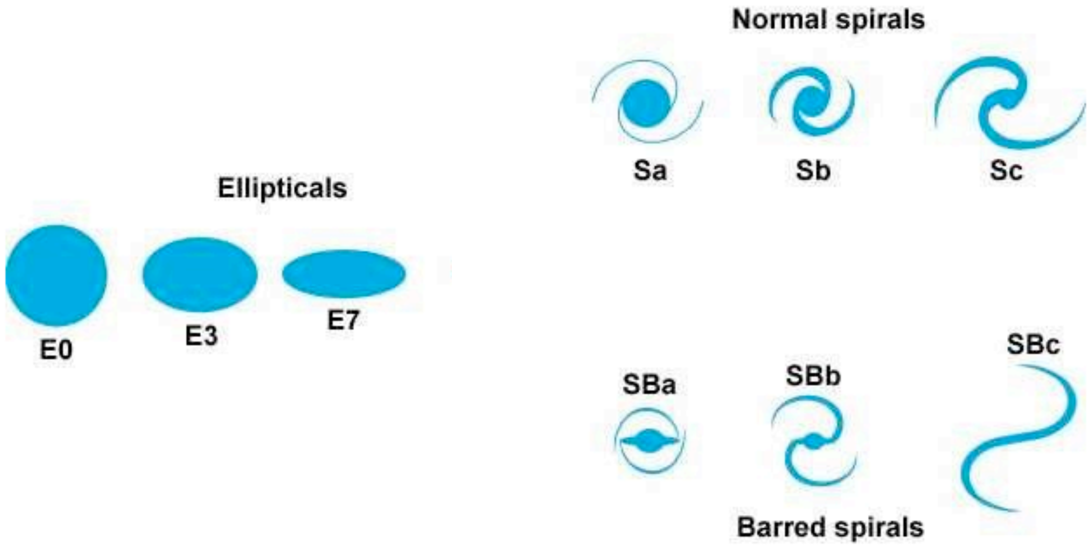
1. The Hubble Sequence
2. Spirals
3. Ellipticals
4. High Redshift Morphology
5. Disk Rotation Curves
6. The Tully-Fisher relation



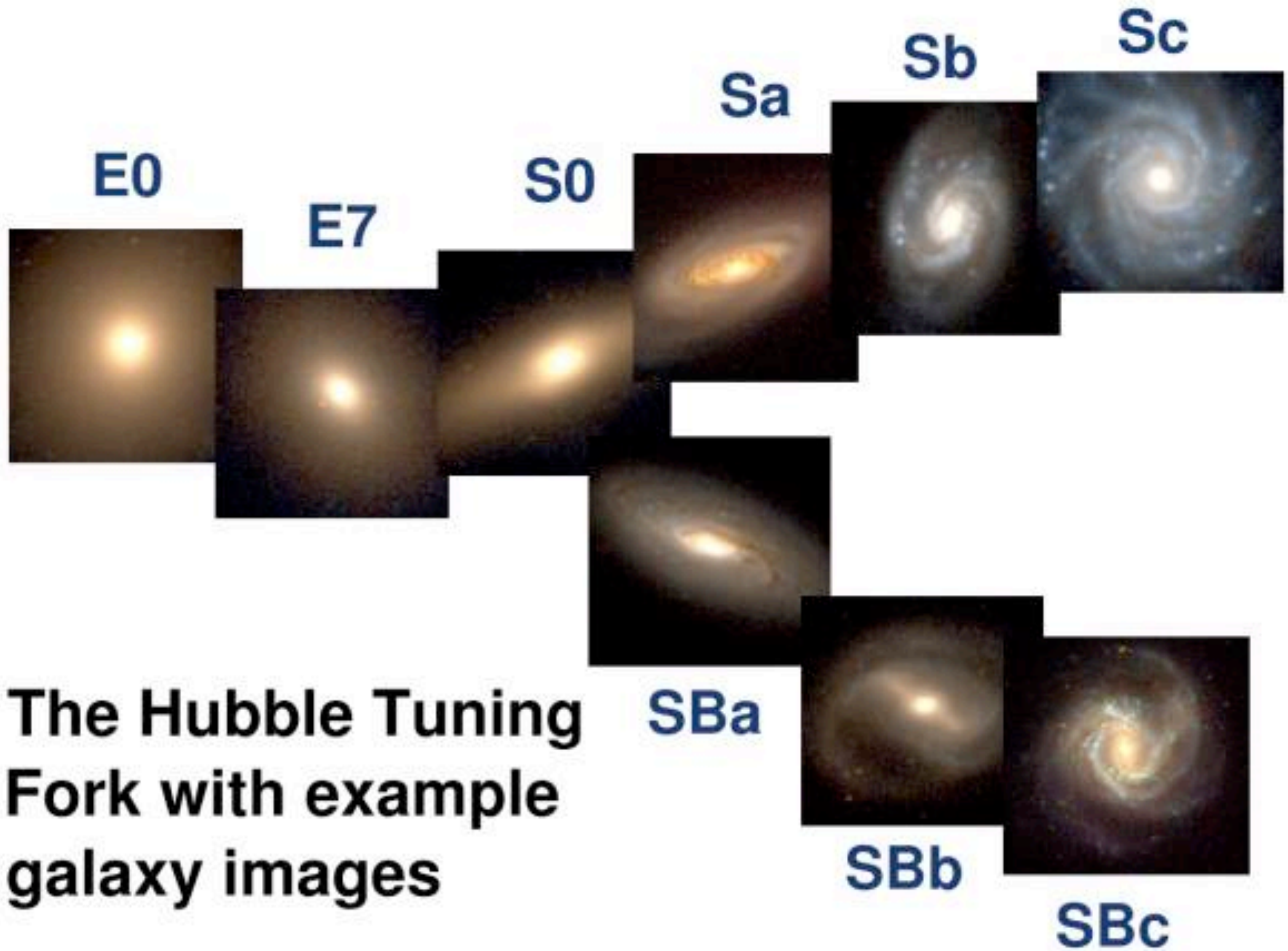



The Hubble Tuning Fork (1926)

- Morphology is first step in understanding a discipline
  - Hope is that morphology yields insight into nature, origin, evolution - not always true
  - Hubble sequence is **not** an evolutionary sequence!
  - http://nedwww.ipac.caltech.edu/level5/Shapley_Ames/RSA5.html for details
- S0 added 1936

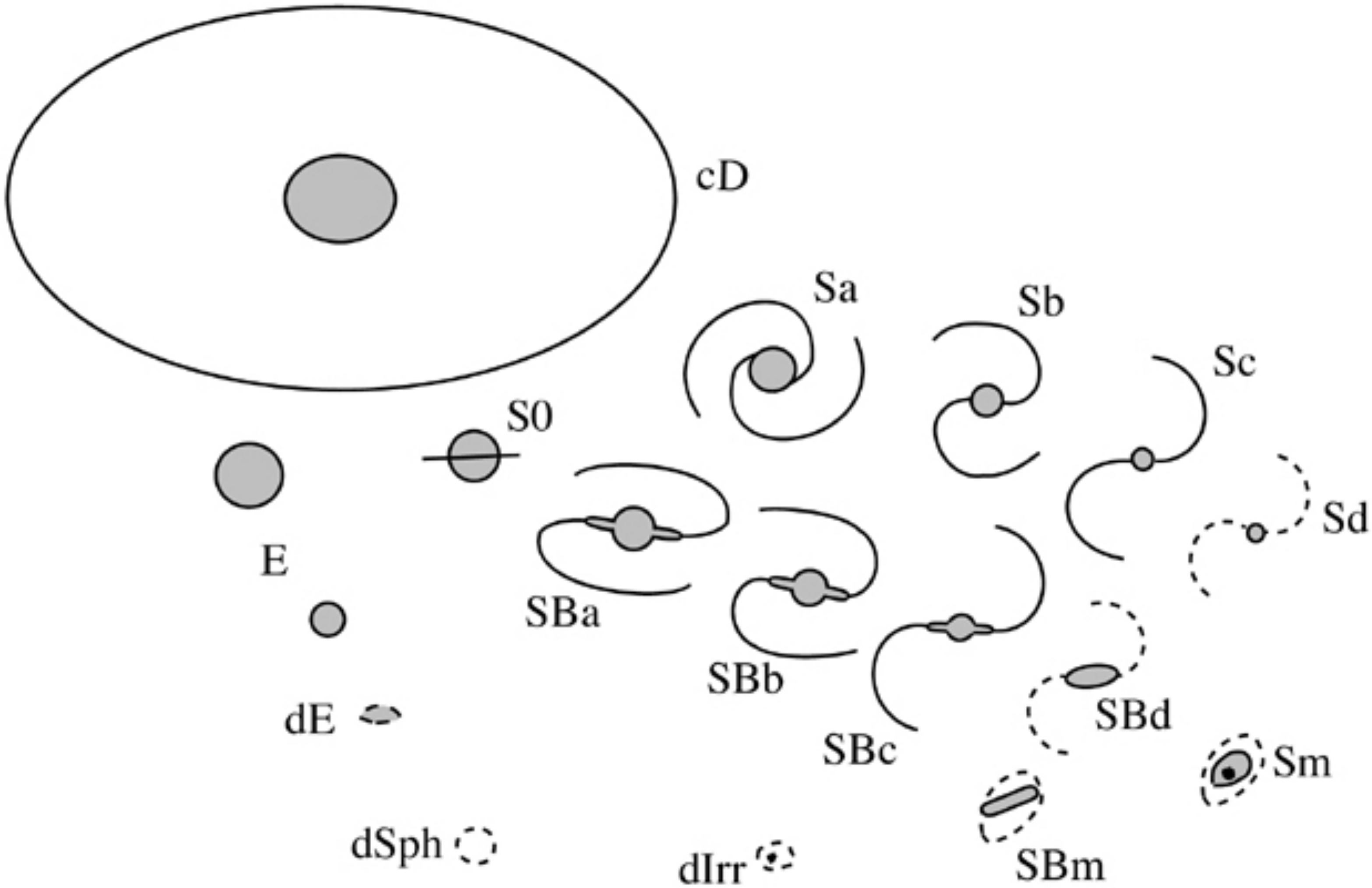


A Schematic Diagram of the Hubble Tuning Fork



The Hubble Tuning Fork with example galaxy images

- A revised “Hubble Sequence”

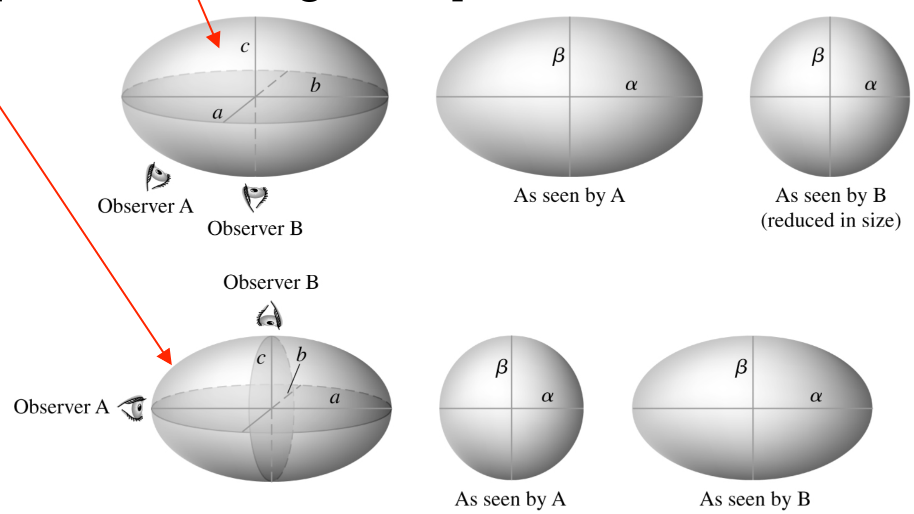


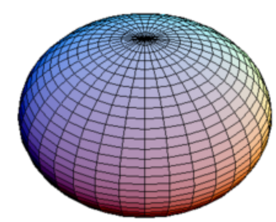
Ellipticals

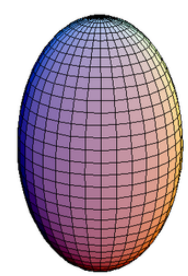
- Classification is based on ellipticity:

En galaxy: $n = 10(1 - \beta / \alpha)$, where β / α is axial ratio.

- Not an intrinsic property; depends on:
    - Viewing angle
    - Prolate vs oblate vs triaxial
        - [how to distinguish?]

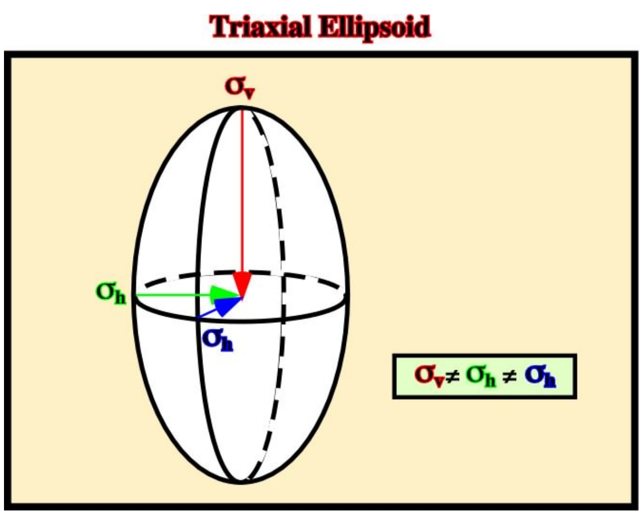


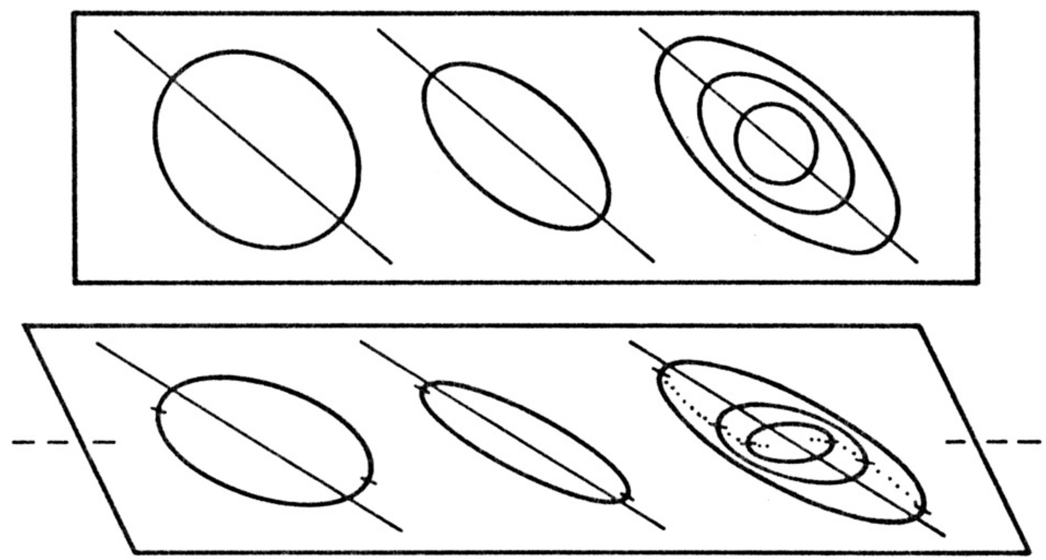




Ellipticals

- Triaxial ellipsoids in projection show “isophotal twists”: i.e., changes in the ellipticity and position angle of the isophotes as a function of radius





Ellipticals

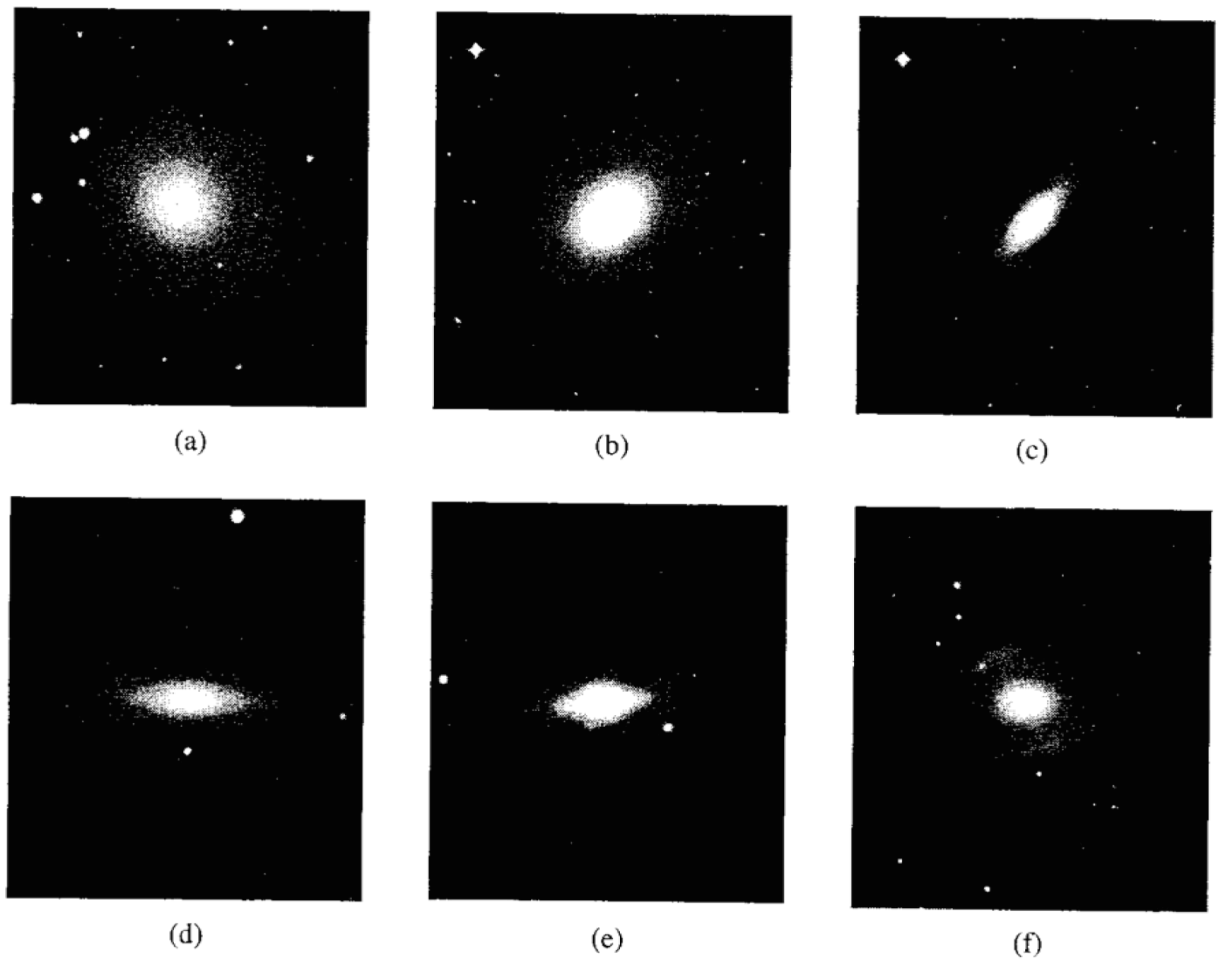


FIGURE 25.4 Typical early-type galaxies. (a) IC 4296 (E0), (b) NGC 4365 (E3), (c) NGC 4564 (E6), (d) NGC 4623 (E7), (e) NGC 4251 (S0), (f) NGC 4340 (RSB0). (Images from Sandage and Bedke, *The Carnegie Atlas of Galaxies*, Carnegie Institution of Washington, Washington, D.C., 1994.)

cD galaxies

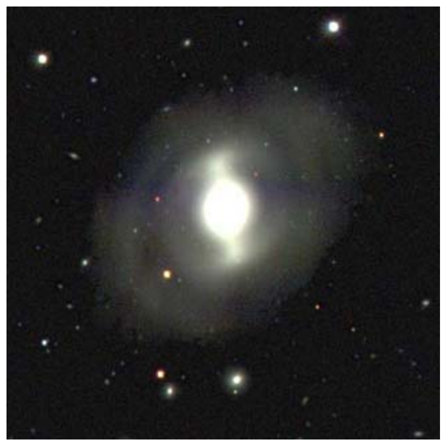
- Central dominant
  - Centre of cluster
  - Most luminous galaxy in cluster
  - Extended envelope, multiple nuclei
  - Velocity dispersion rises outwards

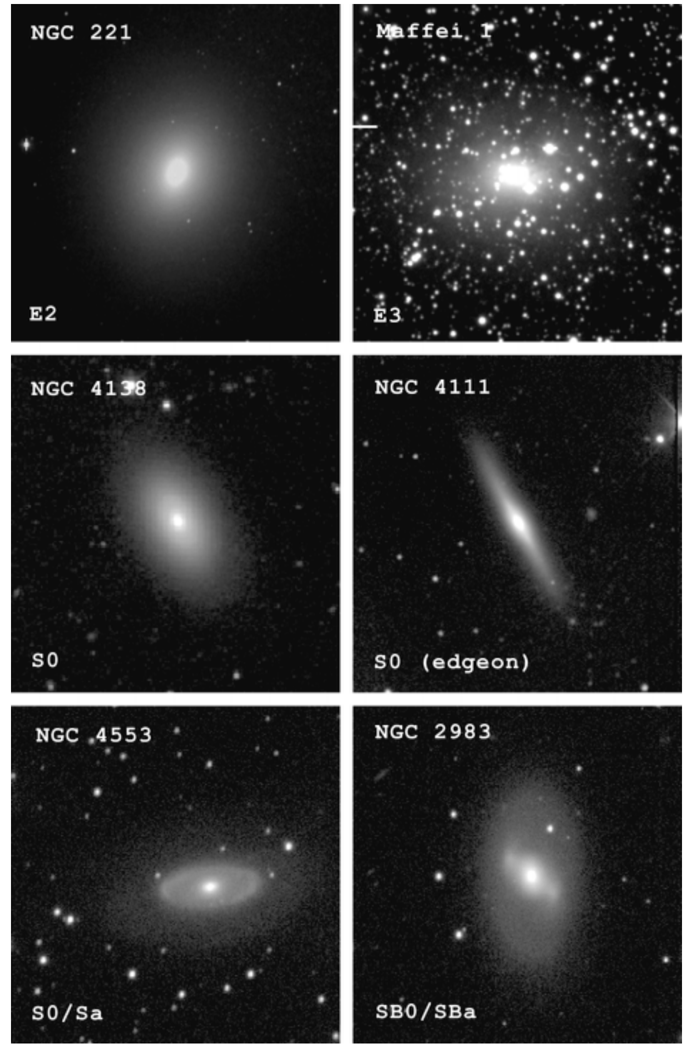
  - NGC 6166 in Abell 2199 (right - SDSS)

  - cD sometimes just means brightest cluster galaxy - e.g. M87

S0 (Hubble 1936)

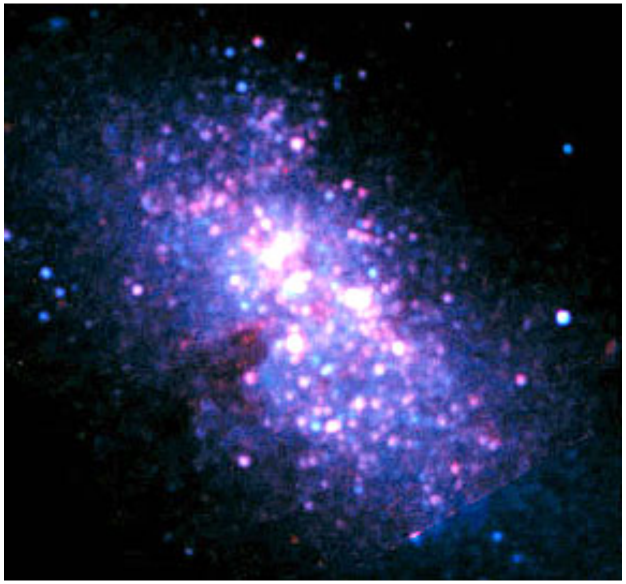
- Contrast edge-on and face-on
- Disk plus spheroid
  - Little or no star formation

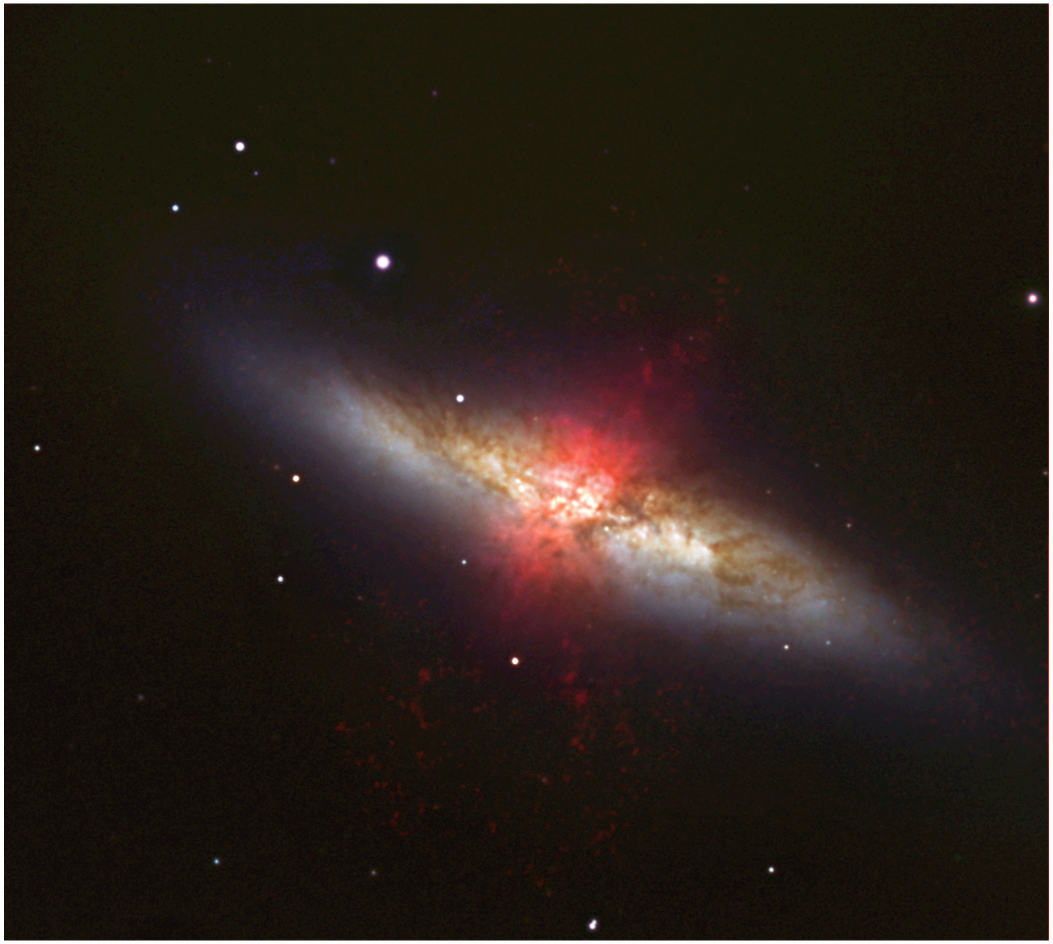




Amorphous Irr (I0)

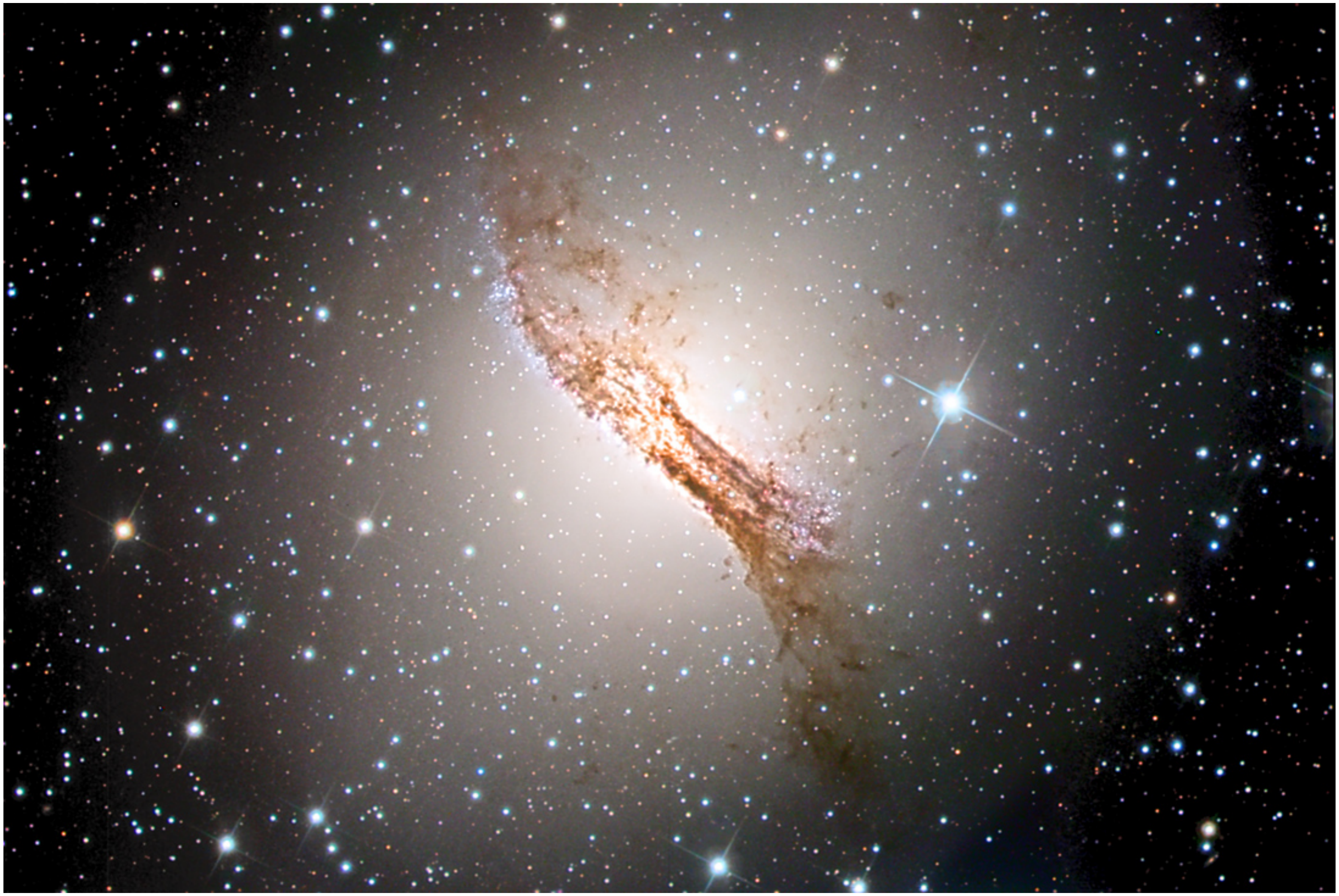
- Right: 2 views of NGC 5253
- Below: M82





Peculiar

- NGC 5128 (Cen A)



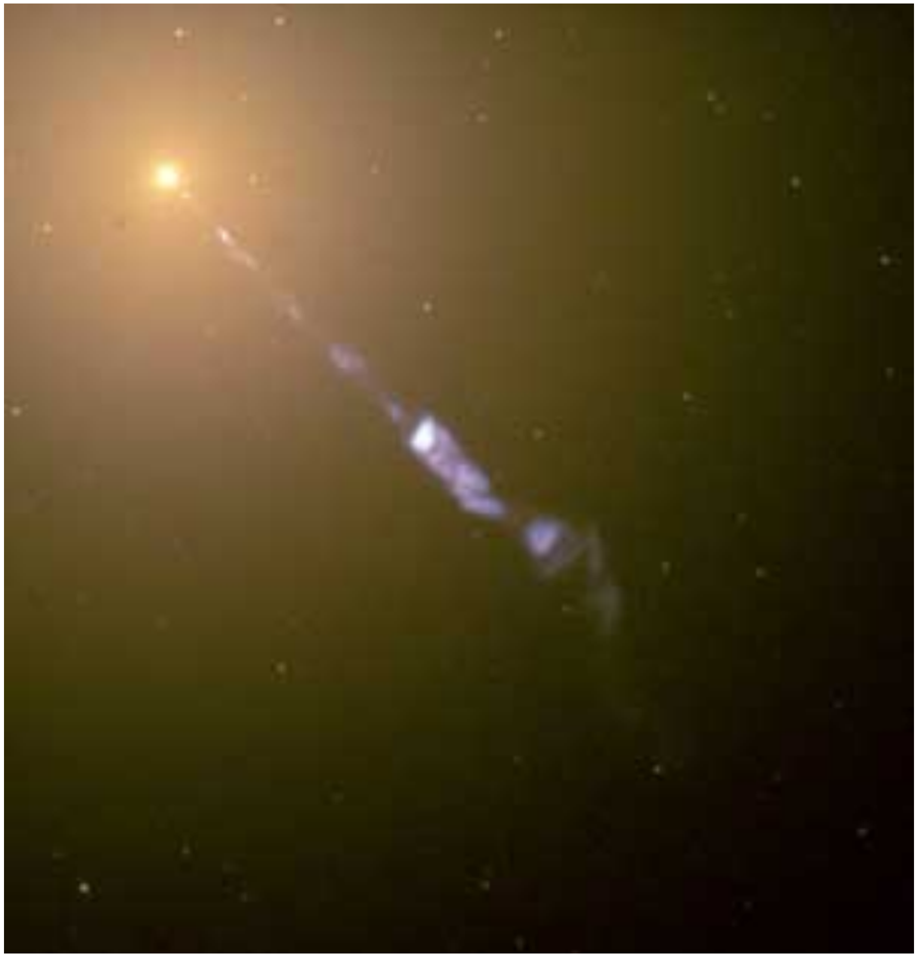
- NGC1316

Billows of cosmic dust in galaxy NGC 1316
Photograph courtesy NASA, ESA, and the Hubble Heritage Team (STScI/AURA)

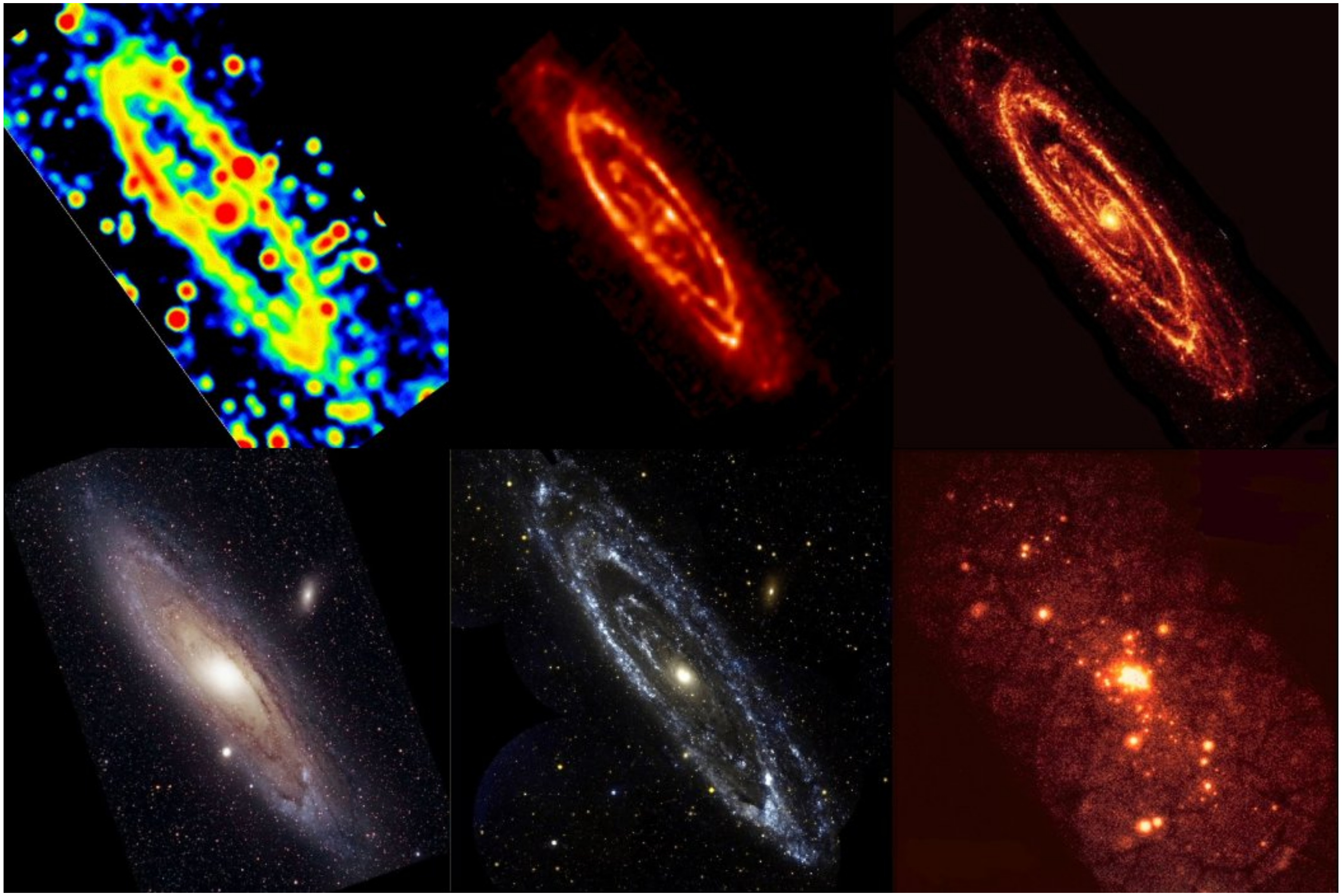
NATIONAL GEOGRAPHIC

- NGC 4038+4039 (The “Antennae”)

- Jets - e.g. M87



Wavelength effects on morphology



Next let's look at something more exotic but still familiar, the Andromeda Galaxy. Also called M31, this is closest neighbouring galaxy in the wider universe and is just about visible from a good site. We are seeing this in the radio, microwave, infrared, visible, ultraviolet and x-ray.

Wavelength and Morphology

These are, left to right: a ROSAT image, from data archived at HEASARC; a color-mapped UV image from GALEX; an optical color image, from data provided by G. Bothun; a near-IR image from the 2MASS atlas [Atlas Image obtained as part of the Two Micron All Sky Survey (2MASS), a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by NASA and the NSF], and a 70-μ image from Spitzer.

Higher redshift (z) morphology

Size of the expanding universe=1/(1+z)

- Difficulties:
  - Fewer pixels (resolution elements)
  - $(1+z)^4$ dimming
  - Bandpass shifting due to redshift
  - Universe denser, more mergers

- Basic results
  - Few or no bars
  - Few grand-design spirals
  - Many more irregulars, mergers
    - z=1: 30% "strongly peculiar/merging" vs 5% locally
    - z=1: another 30% "fall outside conventional framework"

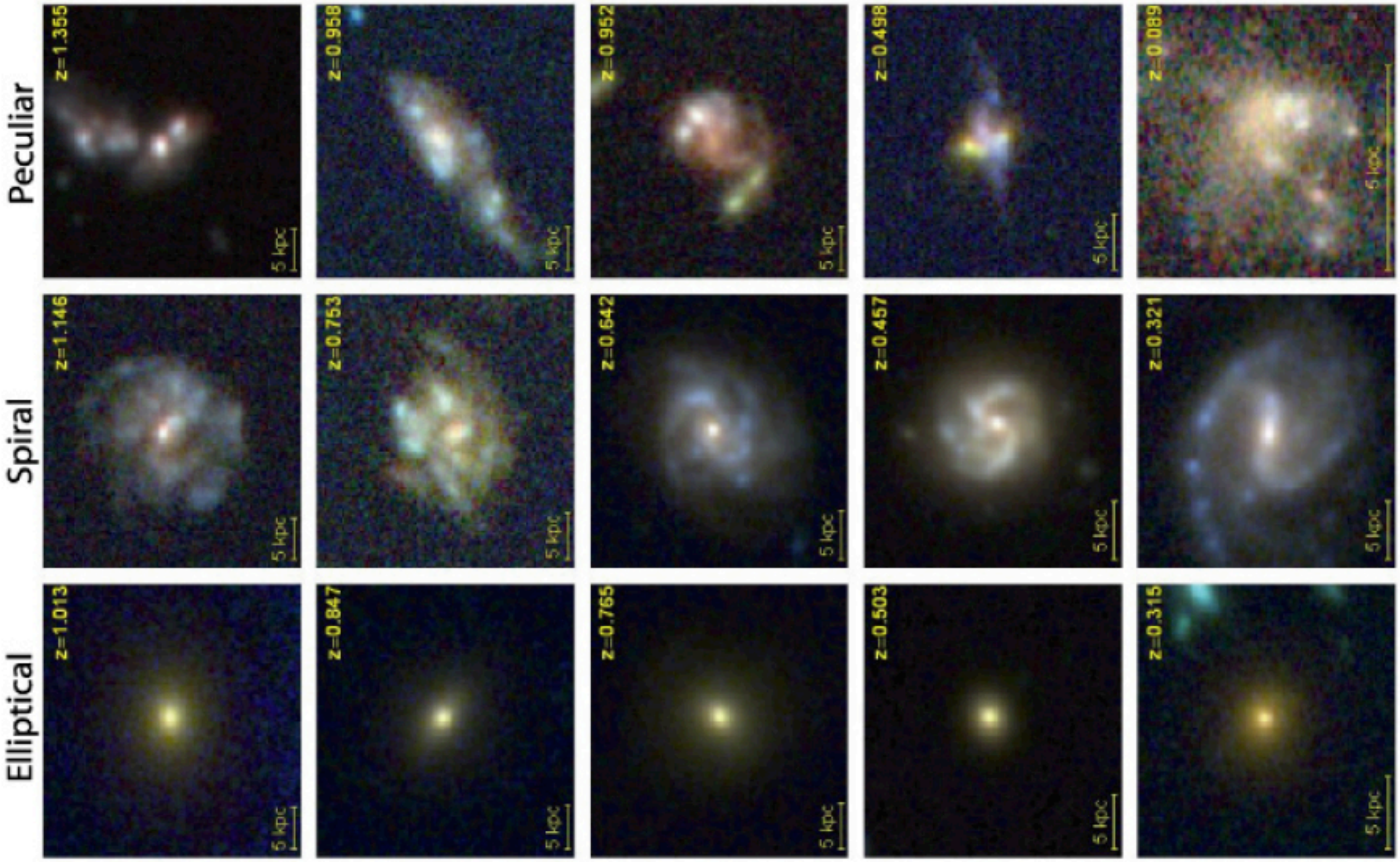


Figure 2: Montage of typical elliptical (left column), spiral (middle column), and peculiar (right column) galaxies in the Northern and Southern Hubble Deep Fields, imaged by the Hubble Space Telescope. The images are sorted by redshift (local galaxies at bottom, distant galaxies at top). Color images were constructed by stacking images obtained through blue, yellow, and near-infrared filters. Note the gradual loss in the organization (and the increase in the fragmentation) of spiral arms in the spirals. Barred spirals (such as the example shown in bottom row) become rare beyond z=0.5. The physical nature of most of the peculiar galaxies in the far right column is poorly understood. The exception is the object at the bottom-right corner, which is a dwarf irregular, a class of objects common in the local Universe. In Figure 4 we speculate on the possible nature of two other galaxies in the far-right column.

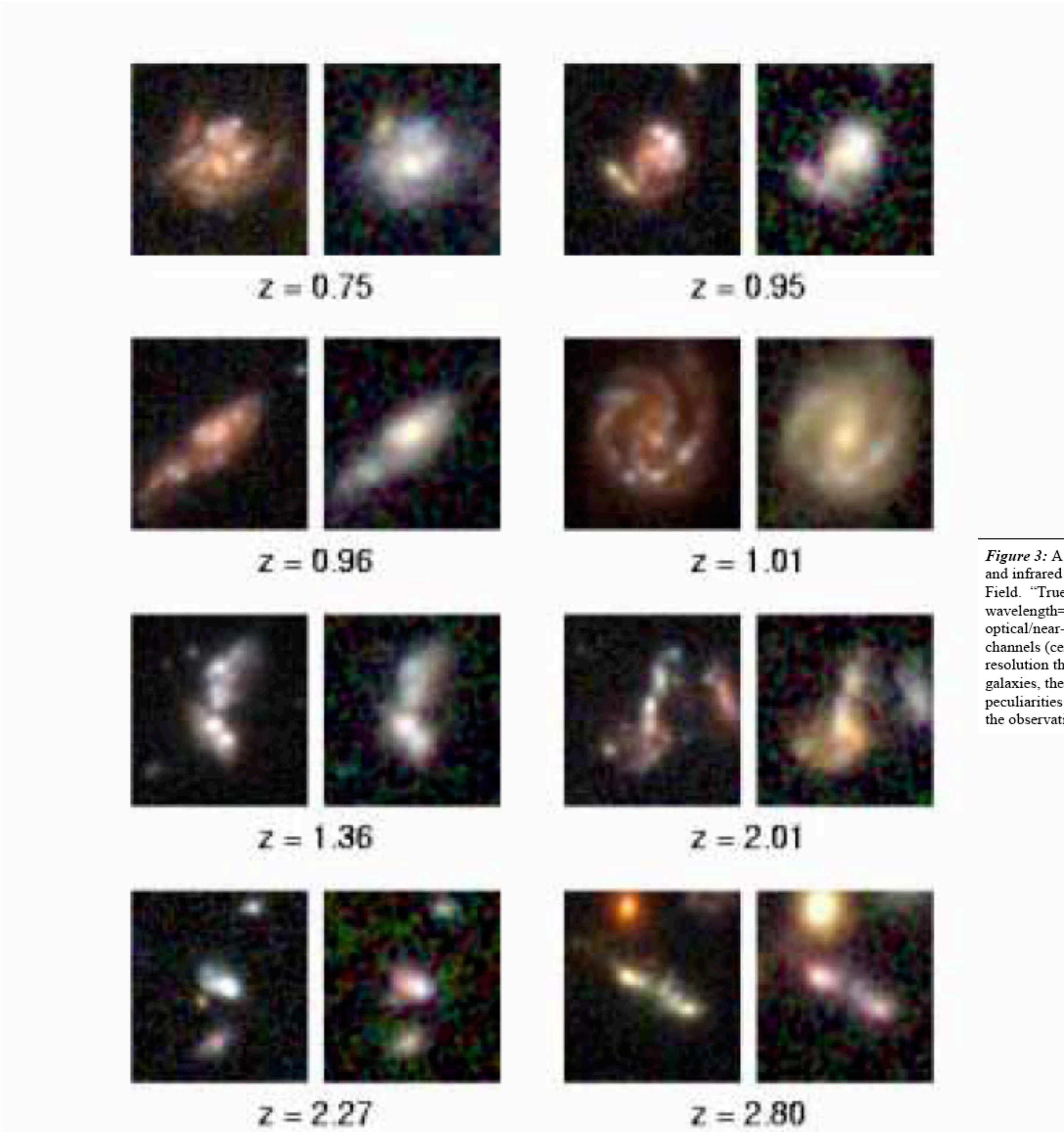


Figure 3: A montage, taken from Ferguson, Dickinson and Williams (2000), comparing the optical and infrared morphologies of selected galaxies at various redshifts from the northern Hubble Deep Field. "True color" composites in the left-hand panels are made using a blue channel (central wavelength=450nm), a "visual" channel (central wavelength=606nm), and a channel straddling the optical/near-IR border (central wavelength=814nm). The right hand panels are constructed using IR channels (central wavelengths of 814nm, 1100nm, and 1600nm), and have slightly poorer resolution than the corresponding images at left. For most objects, including the most distant galaxies, the optical and near-IR morphologies are similar, indicating that the morphological peculiarities are intrinsic to the galaxies, and are not the result of the changing rest-wavelength of the observations. [Courtesy H. Ferguson, M. Dickinson, R. Williams, STScI and NASA].

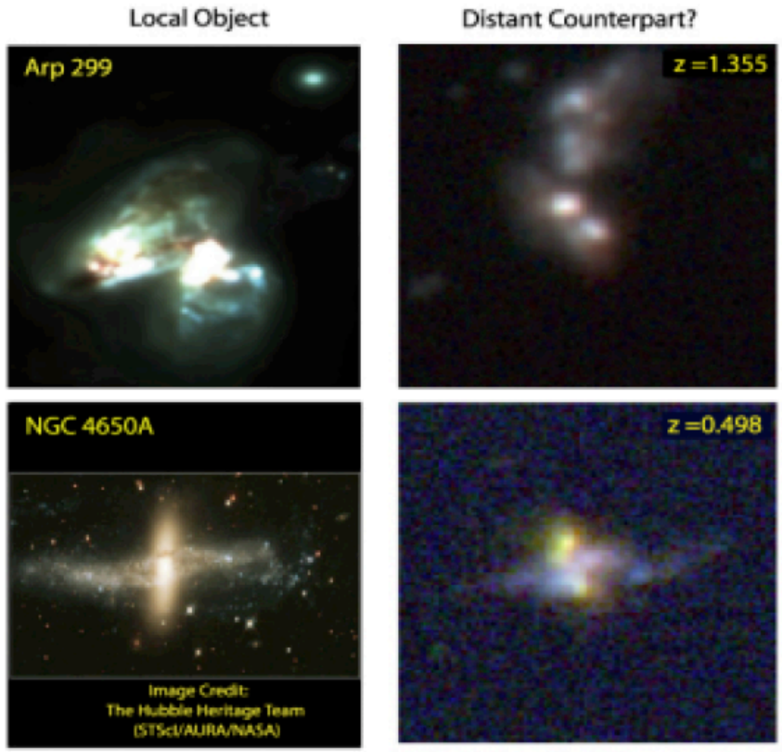


Figure 4: Some speculations on the nature of high-redshift peculiar galaxies. [Top row] As pointed out by Hibbard & Vacca (1997), the nearby local merging starburst galaxy Arp 299 shares many of the morphological and star-formation of characteristics of "chain-like" peculiar galaxies, such as the example (HDFN_J123652.78+621354.3) shown at right. While the correspondence is not exact (chain-like peculiars exhibit more components than is typical seen in local starbursts, and sometimes show a curious synchronization of internal colors), local starbursts remain the closest match to many distant systems. [Bottom row] Classes of merging galaxies that are exceedingly rare in the local Universe may be responsible for some of the oddest systems seen in the Hubble Deep Fields. For example, the "polar ring" galaxy NGC 4650A bears a close resemblance (both in terms of morphology and in terms of relative color) to the distant galaxy (HDFN_J123652.88 + 621404.8) shown at bottom right. Galaxy collisions can produce a rich variety of morphologically peculiar galaxies, many of which do not resemble "textbook" mergers, i.e. a pair of objects with obvious tidal tails.

Table 1: Summary of key ages in galaxy morphology to z=1

Redshift	**Look-back Time**	**Key Developments in Galaxy Morphology**
z<0.3	<~3.5 Gyr	Grand-design spirals exist. Hubble scheme applies in full detail.
z~0.5	~5 Gyr	Barred spirals become rare. Spiral arms are underdeveloped. The bifurcated "tines" of the Hubble tuning fork begin to evaporate.
z>0.6	>6 Gyr	Fraction of mergers and peculiar galaxies increases rapidly. By z=1 around 30% of luminous galaxies are off the Hubble sequence.

Spiral structure

- Density waves
- Bar instabilities sheared by rotation
- SSPSF ("Stochastic Self-propagating Star Formation")
- Companions - tidal effects

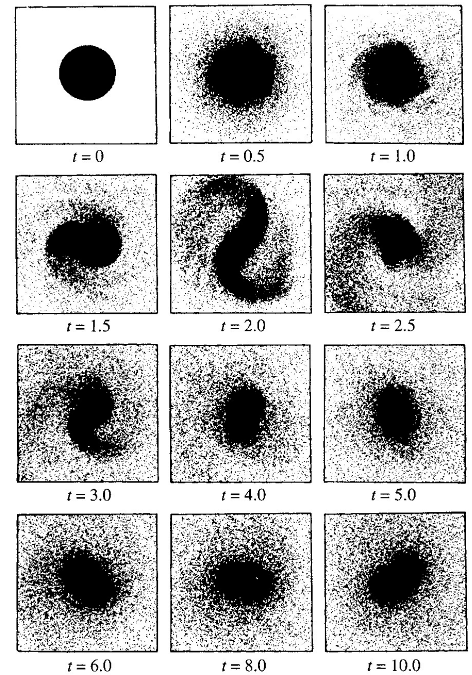
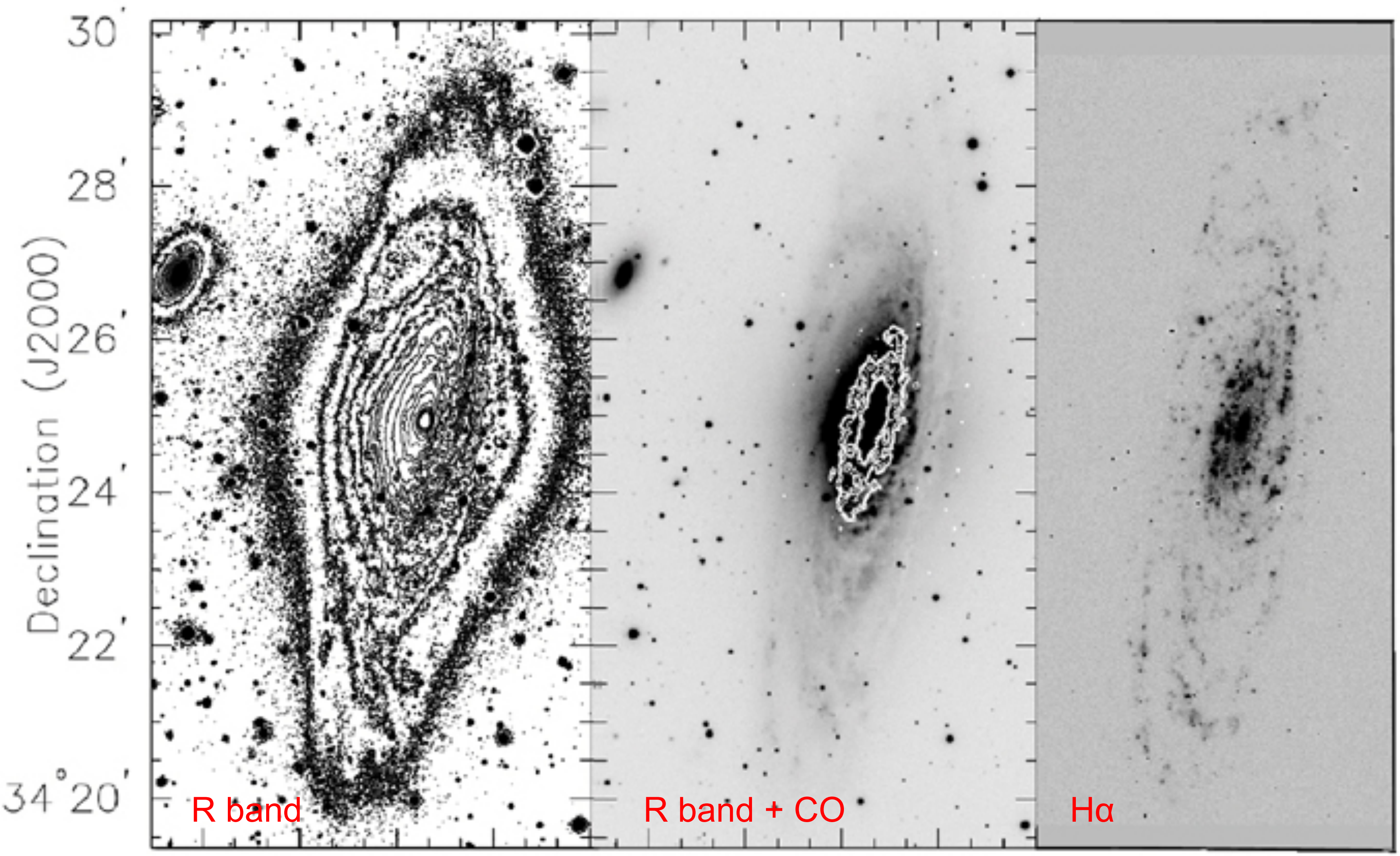


FIGURE 25.31 An early study of a rotating disk with an N-body simulation using 10^5 stars. The disk began with complete axial symmetry and quickly developed an $m = 2$ mode instability. Eventually the disk "heated up," destroying the spiral arms but leaving a long-lived bar. (Figure from Hohl, *Ap. J.*, *168*, 343, 1971.)

Surface brightness profiles: NGC7331



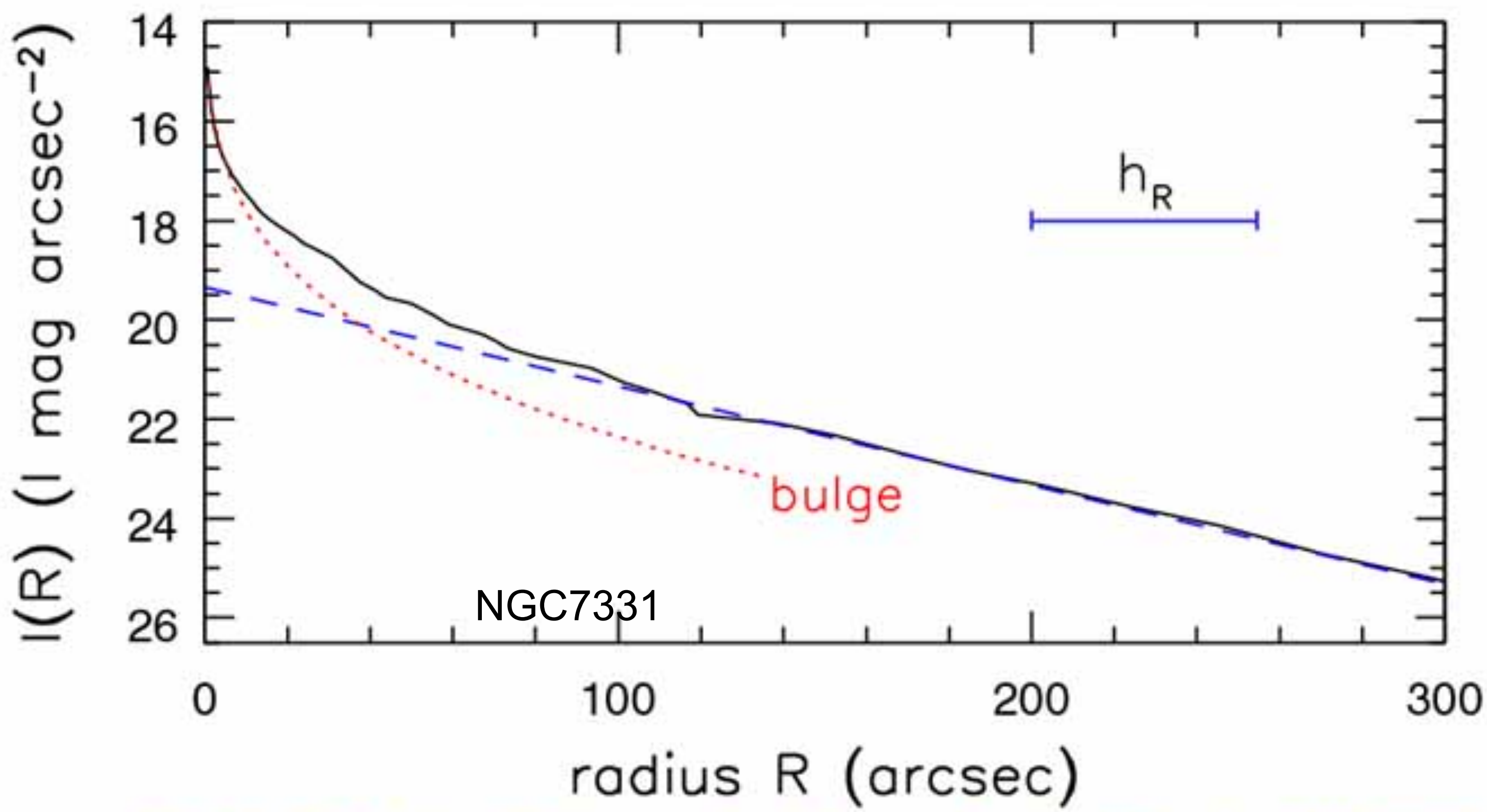
Surface brightness profiles

- Inclination-corrected surface brightness profiles are typically *exponential* (in Lsun/kpc^2 or mag/asec^2)

$$I(R) = I(0)\exp(-R/h_R),$$

$$\mu(r) = \mu_0 + 1.09(r/h_r),$$

where h_r = scale length = 1/e-folding length, and 1.09 comes from conversion to mags



The 25 mag/asec^2 isophote in the B-band is usually adopted to define the "radius" of a galaxy

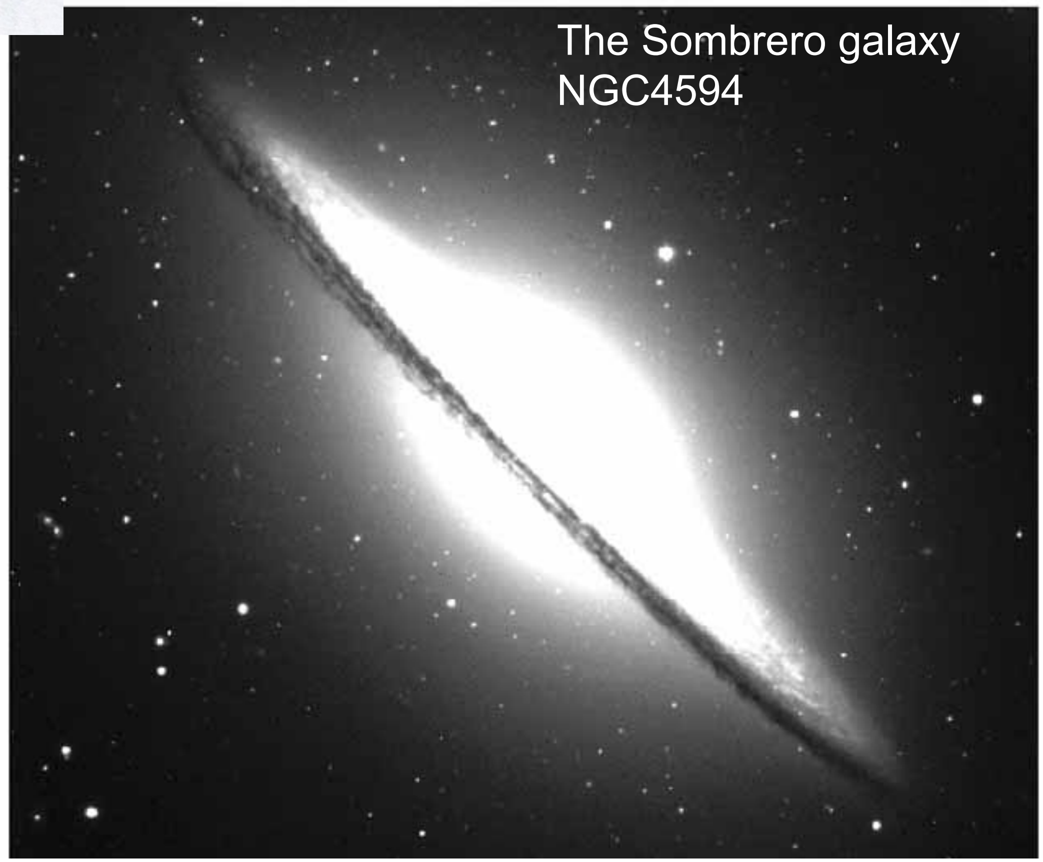
Bulges

- Surface brightness profile of bulges is usually approximated by “Sersic’s law”

$$I(R) = I(0)\exp[-(R/R_0)^{1/n}].$$

- n~4 OK for bulges
- n~ 1 for disks

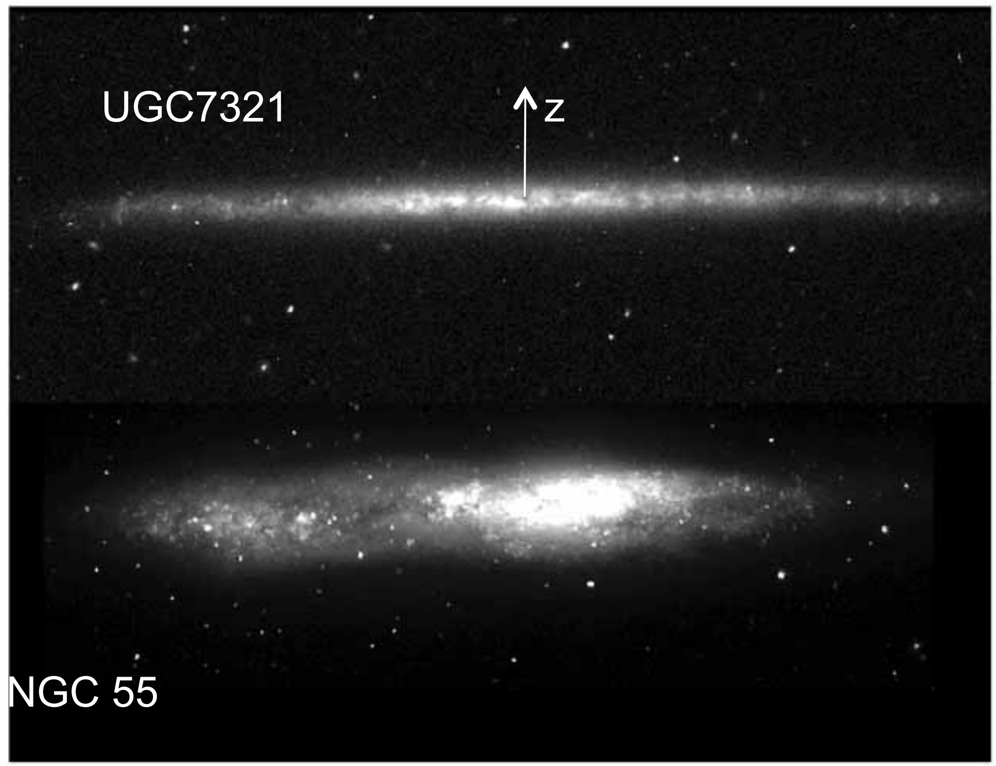
José Luis Sérsic



Vertical disk structure

- Vertical profiles are also usually approximated with exponential laws
- "Bulgeless" galaxies exist!
- About 20% of disks are bulgeless, a challenge to theory?

$$I(R, z) = I(R)\exp(-|z|/h_z).$$



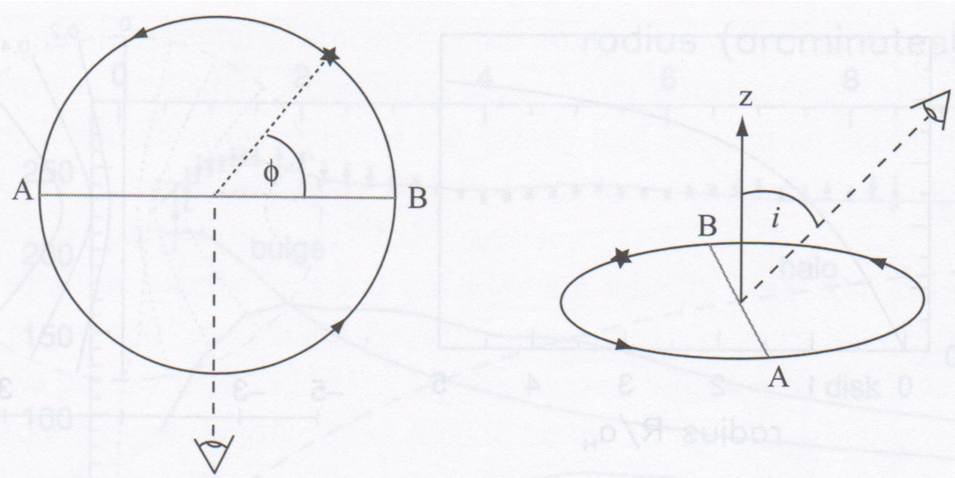
Rotation Curves

- Since gas is "*dissipative*" it tends to settle into nearly circular orbits in thin disks.
- This may then be used to measure the mass of disk galaxies.
- Although strictly true only for spherically-symmetric systems, the *interior* mass to radius R is well approximated by the "centripetal acceleration" equation:

$$\frac{V^2(R)}{R} = \frac{G\mathcal{M}(<R)}{R^2}$$

Rotation Curves

- For gas in circular motion the line-of-sight ("radial") velocity depends on the rotation curve, *V(R)* through:
  - Azimuthal angle, ϕ
  - Distance to the center of the galaxy, *R*
  - Galaxy inclination, *i*
  - The systemic velocity of the galaxy, V_{sys}

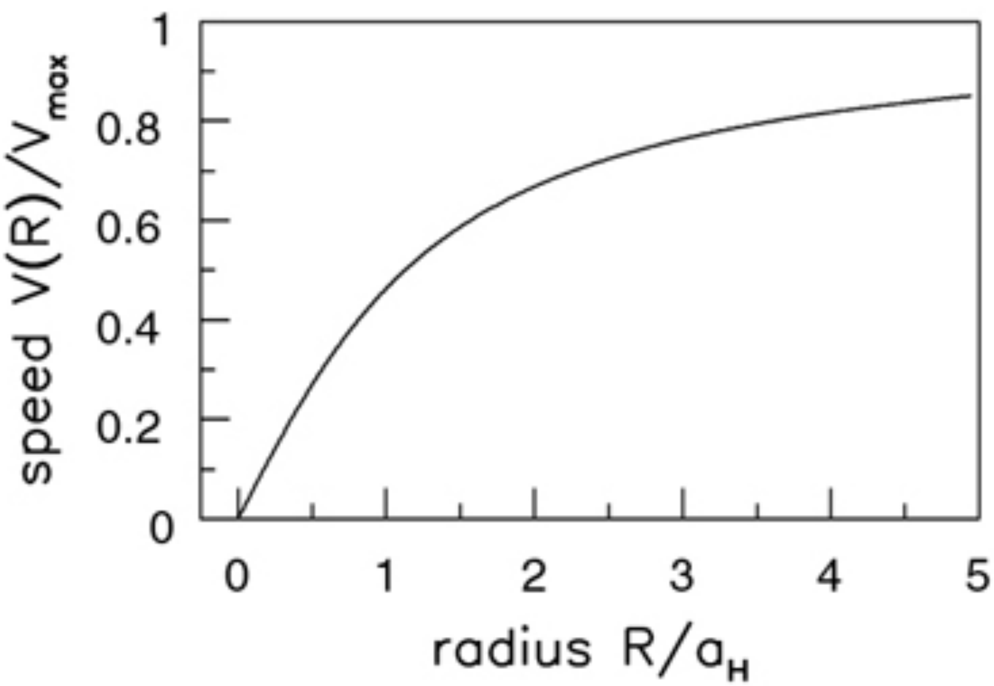


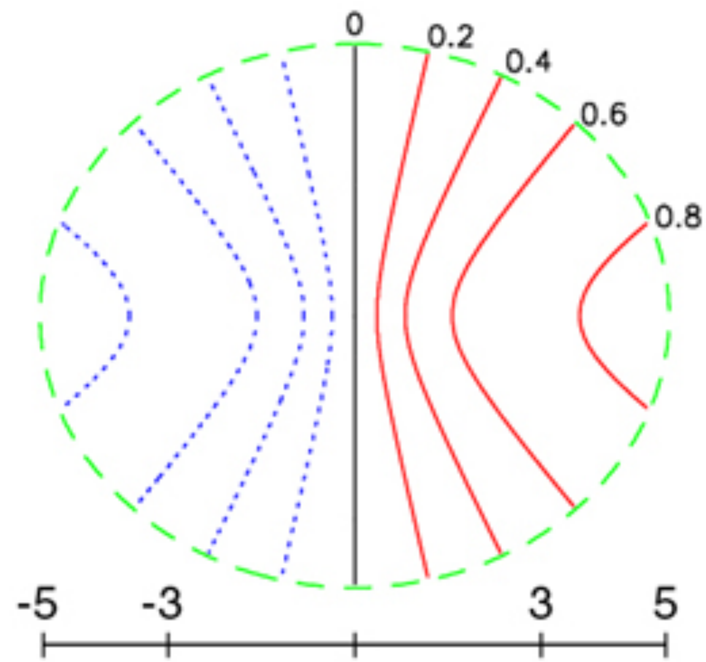
$$V_r(R, i) = V_{sys} + V(R) \sin i \cos \phi.$$

Fig. 5.18. Left, a rotating disk viewed from above. Azimuth ϕ, measured in the disk plane, gives a star's position in its orbit; an observer looks from above the disk, perpendicular to diameter AB. Right, the observer's line of sight makes angle i with the disk's rotation axis z.

Rotation Curves

- The line AB in the previous figure is the kinematic major axis (the location where te observed velocity deviates most from V_{sys})
- Contours of constant line-of-sight velocity form a "spider diagram" in 2D velocity maps.

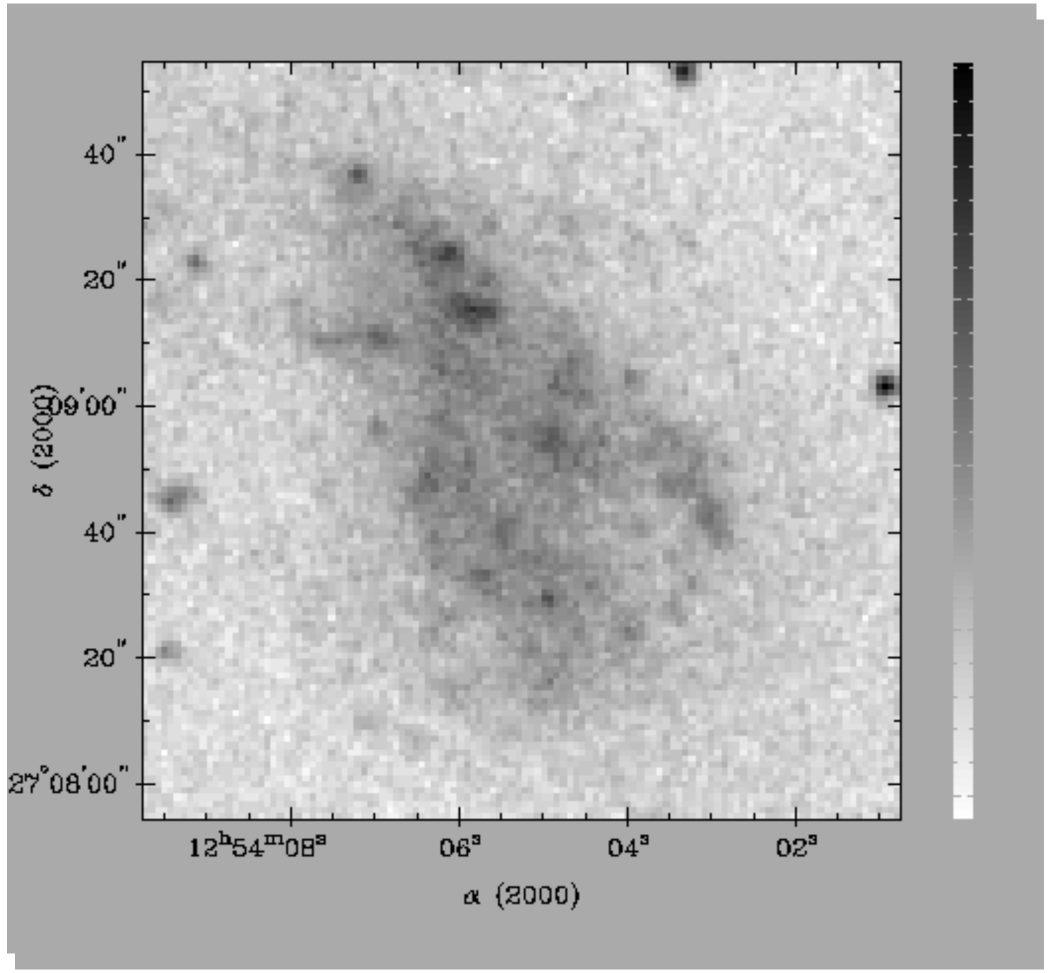




Problems with rotation curve measurements

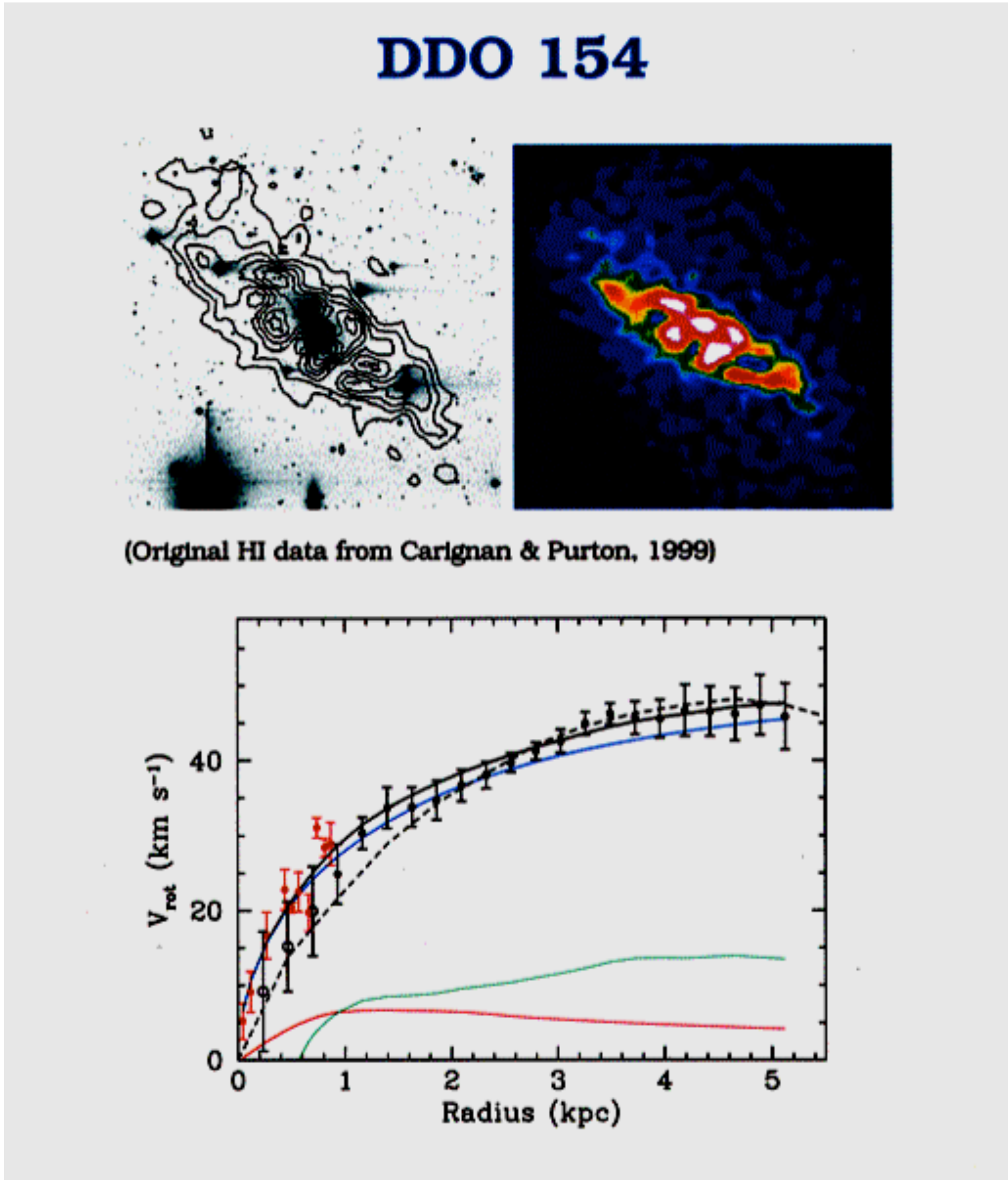
- Sometimes only the velocity along *one* direction in the sky is available (*long-slit* spectroscopy). This leads to systematic effects that are hard to correct for:
  - Kinematic major axis?
    - Usually assumed to coincide with the optical major axis
  - Inclination?
    - Usually guessed from the shape of the optical isophotes
  - Circular orbits?

DDO154



A difficult case: where is the optical/ kinematic axis?

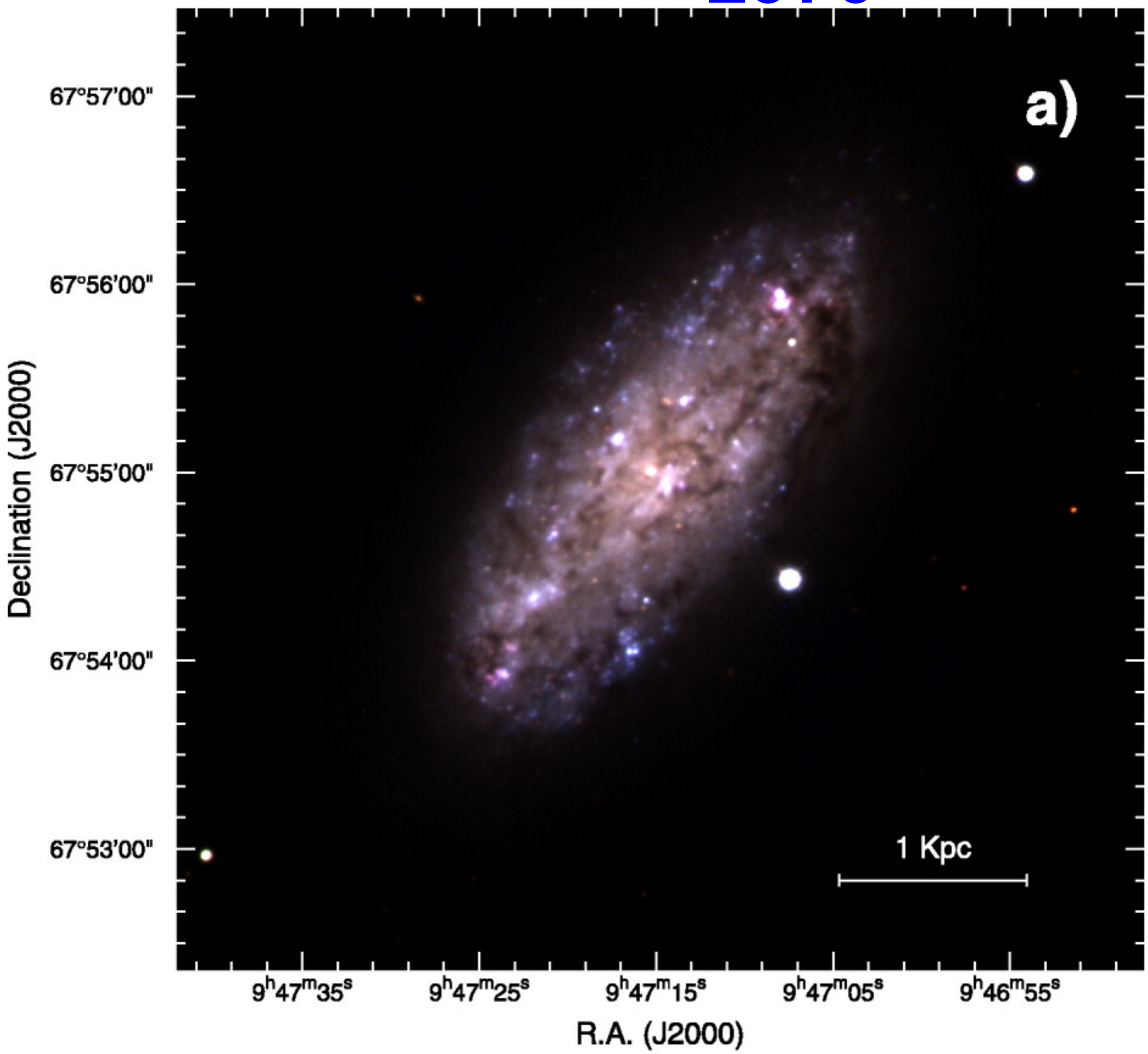
The cuspy dark halo of DDO154



Rotation curve measurements near the center of a galaxy can put constraints on the distribution of dark matter near the center of halos

van den Bosch & Swaters (2000)

LSBs with 2D Velocity Field Data: NGC 2976

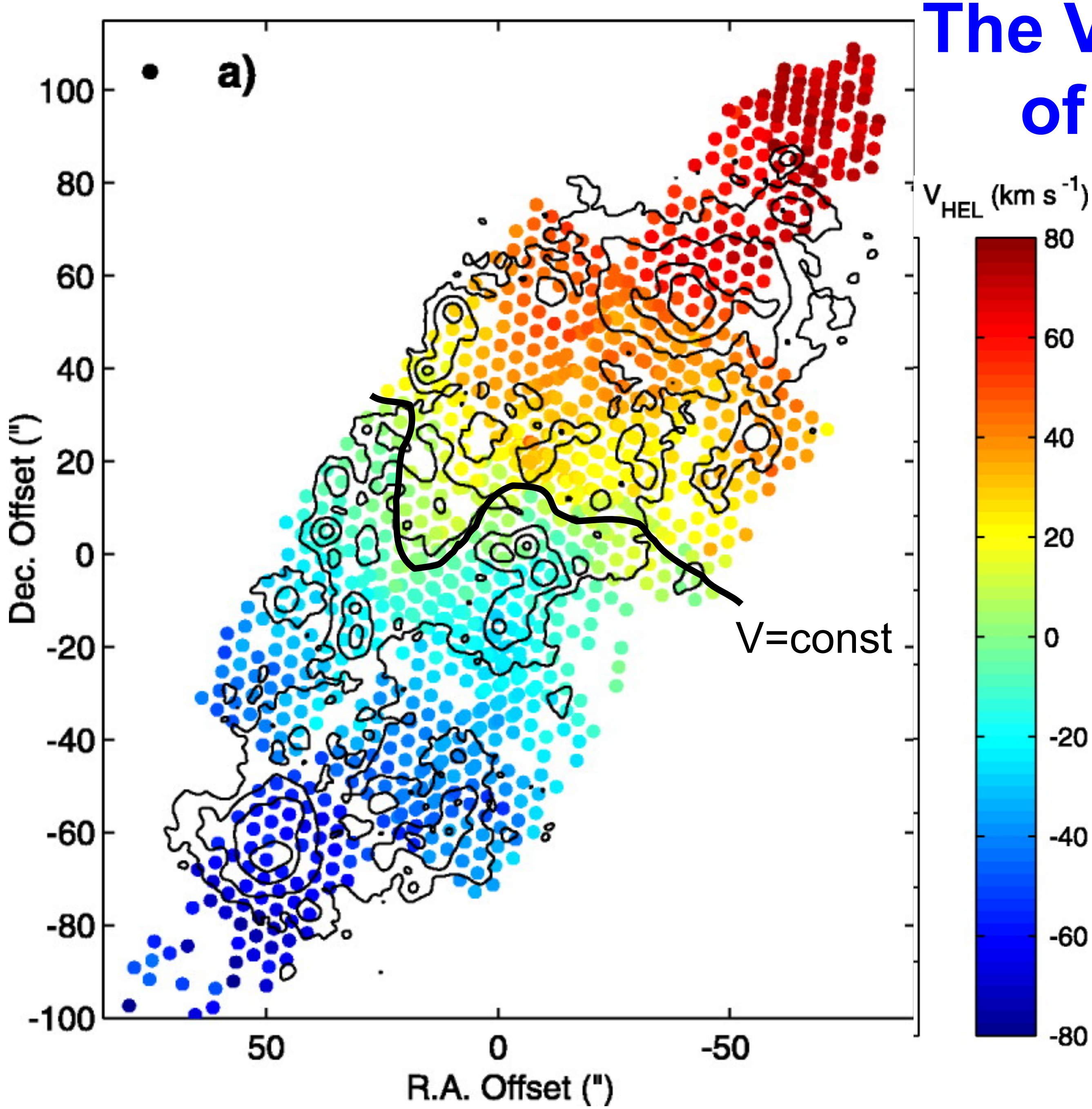


NGC 2976:
an LSB disk without obvious bulge or bar components.

"…independent of any assumptions about the stellar disk or the functional form of the density profile, NGC 2976 does not contain a cuspy dark matter halo"

Simon et al 2004

The Velocity Field of NGC 2976

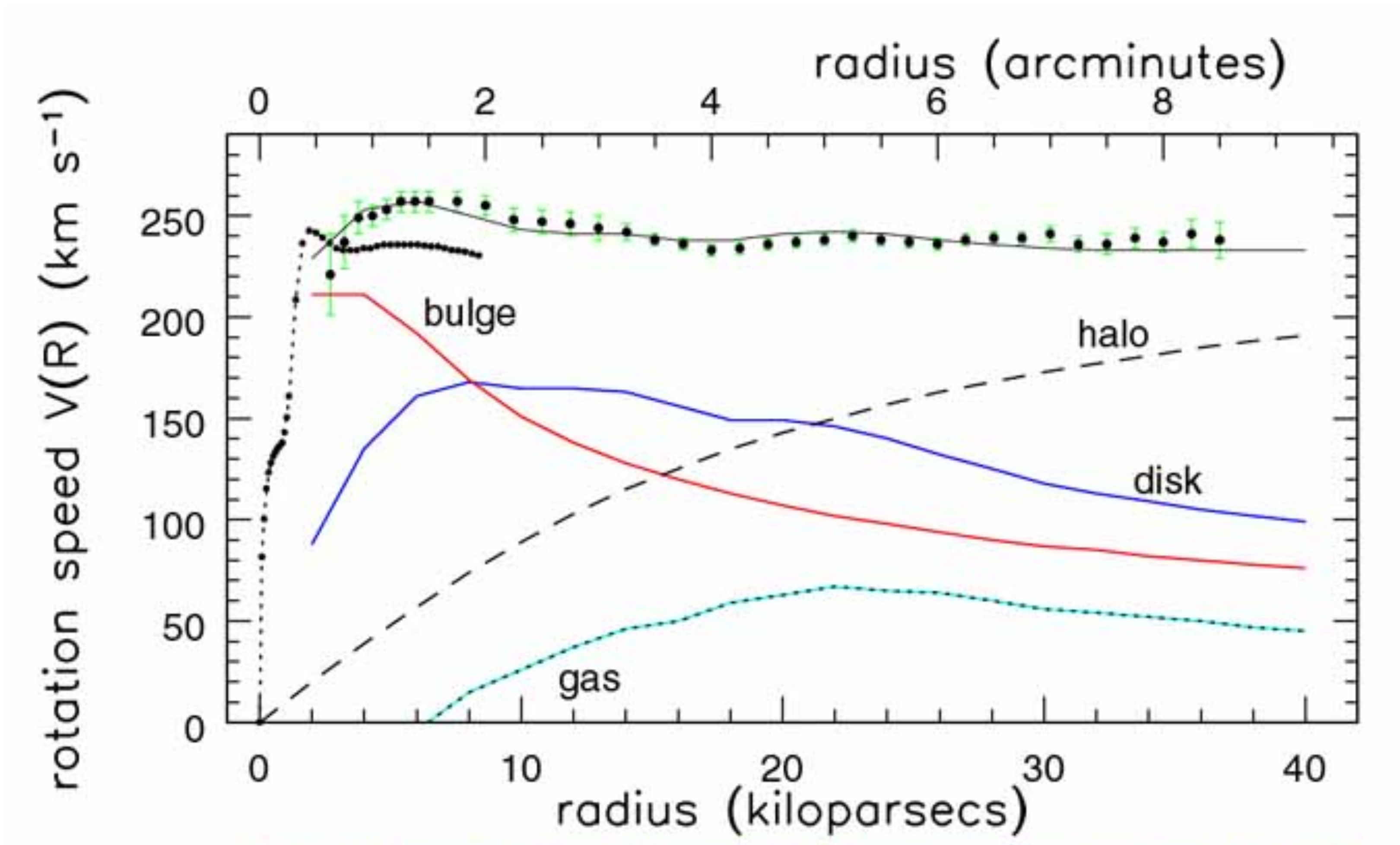


Velocity field is quite asymmetric, with "kinks" similar to those seen in projection for disks in triaxial halos. Difficult!

Simon et al 2004

The rotation curve of NGC 7331

- A simpler case: one of the best studied spiral galaxy rotation curves.
- Clear evidence for a dark matter halo.



Rotation Curves

- The shape of rotation curves correlates with morphological type/luminosity

Chapter 25 The Nature of Galaxies

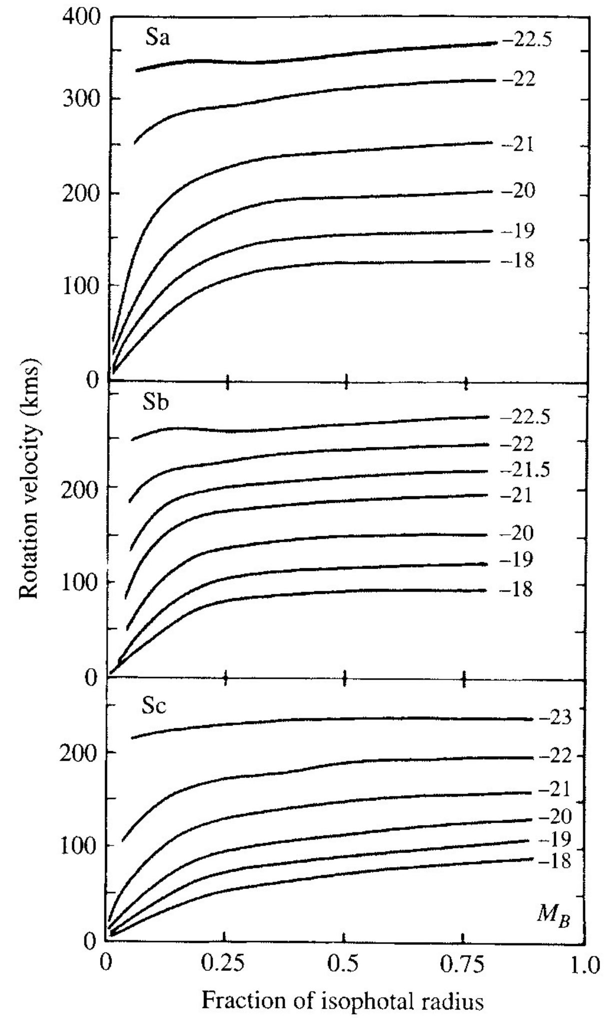


FIGURE 25.8 Variations in the average rotation curves of Sa, Sb, and Sc galaxies for various values of absolute magnitude in the *B* band. (Figure adapted from Rubin et al., *Ap. J.*, *289*, 81, 1985.)

Rotation Curves

- At times only a global measurement of the velocity is available
  - This happens typically when a radio telescope cannot “resolve” the angular size of the galaxy.
    - Recall that the diffraction limit is ~λ/D (wavelength/ telescope diameter)
    - In this case a “velocity profile is all that is available. Note that still in this case a “characteristic” rotation velocity for a galaxy may be measured.

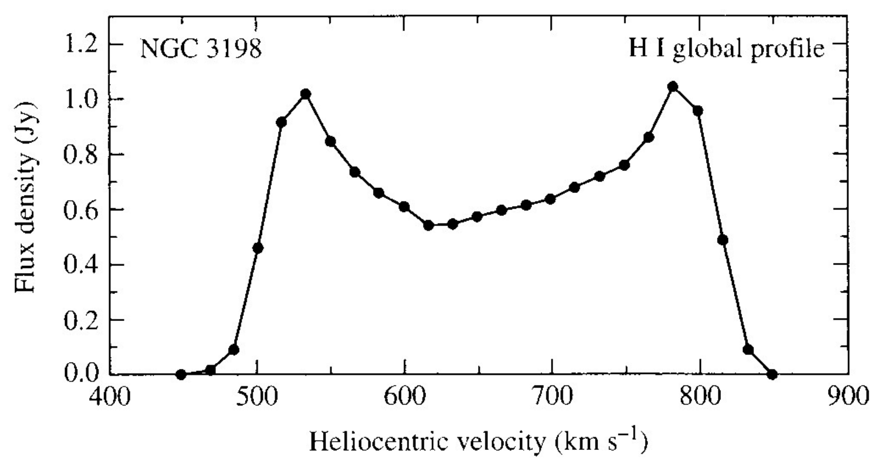
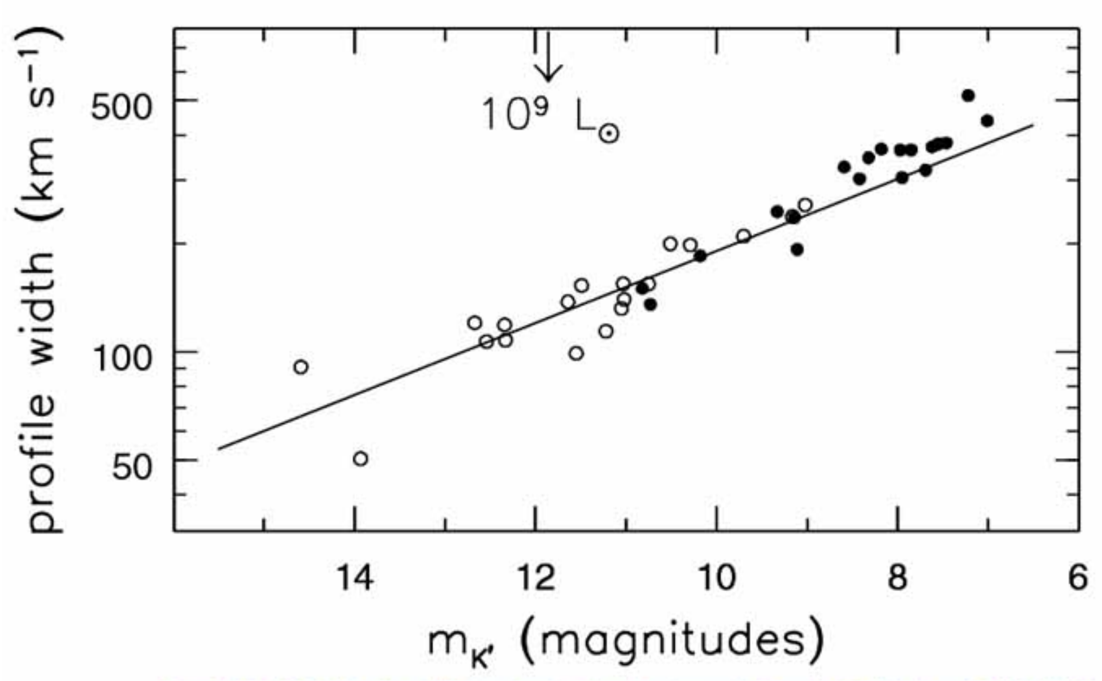


FIGURE 25.9 The global H I profile for NGC 3198. (Data from Begeman, *Astron. Astrophys.*, *223*, 81, 1991.)

The Tully-Fisher relation

- The rotation speed of a galaxy is a well-defined quantity (especially if the rotation curve is flat)
- V_{rot} correlates extremely well with the total luminosity of a galaxy---this is known as the "Tully-Fisher relation"
  - This is a very useful *secondary distance indicator*



•In the I-band: $L_I/L_{sun} \sim 4\times10^{10}*(V_{rot}/200\ km/s)^4$

• The relation is tighter in the redder bands, where starlight is less affected by dust absorption

- Origin of Tully-Fisher:

Flat rotation curves: $M = V_{max}^2 R / G$

Assume M/L is the same for all galaxies.

$$L = \frac{1}{(M/L)_0} \frac{V_{max}^2 R}{G}.$$

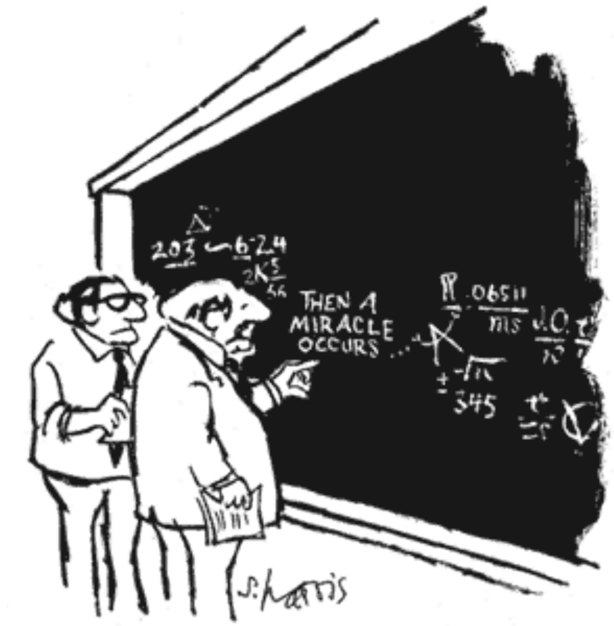
Also *assume* all galaxies have about the same mean surface brightness: $L/R^2 = c_{sb}$. Some algebra, a miracle happens ...

$$L = cV_{max}^4$$

or, in mags:

$$M_B = c' - 10 \log_{10} V_{max}$$

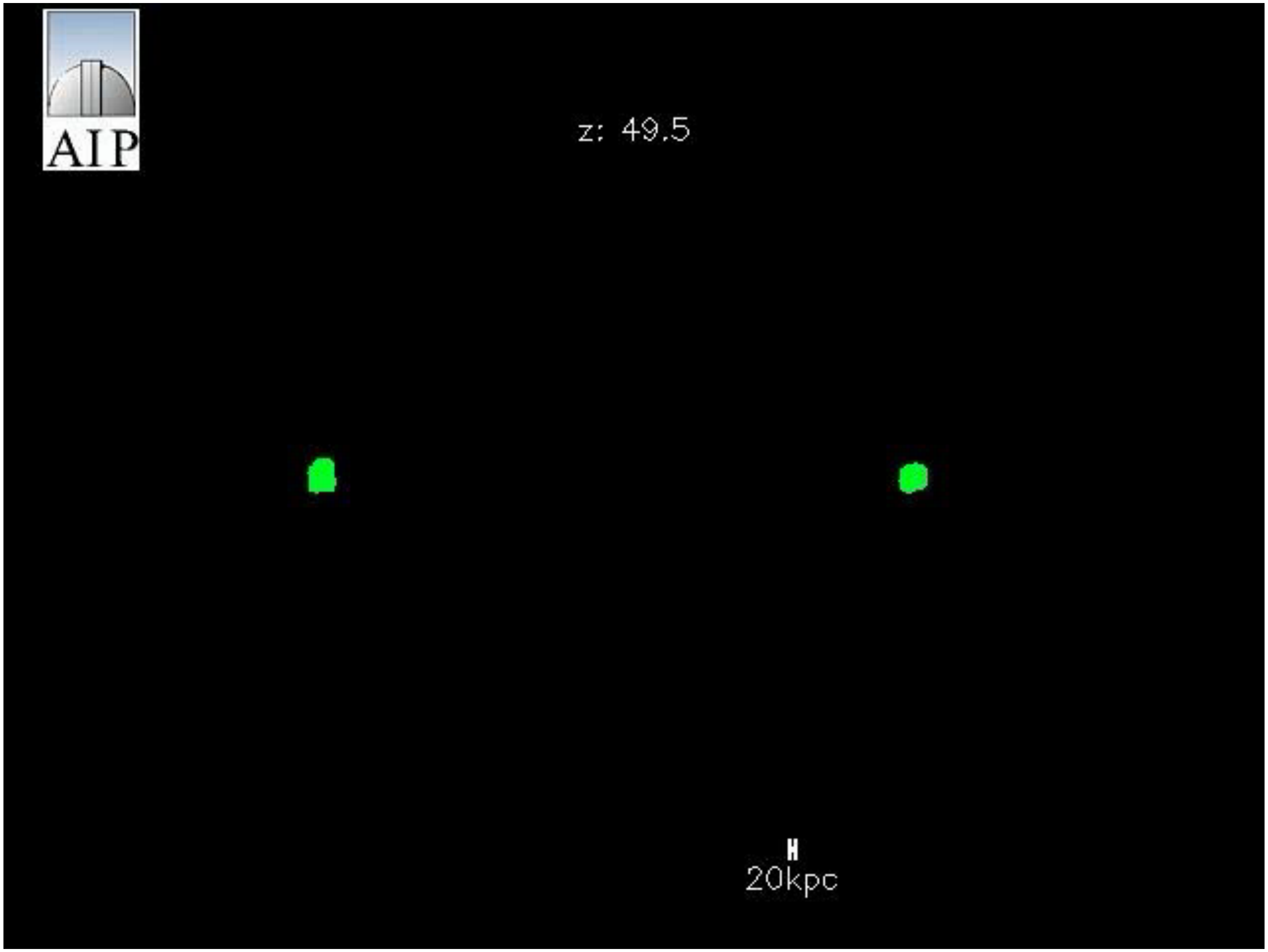
as observed!



"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

- Not thought to be the real reason. Probably something to do with the properties of the dark halos, but what exactly?

The Hierarchical Formation of a Disk Galaxy



•Stellar disks form after the dissipative collapse of gas onto thin, centrifugally supported structures.

• Spheroids form subsequently as a consequence of mergers.

•Galaxy morphology is a transient, evolving feature in the lifetime of a galaxy.

Steinmetz & Navarro 2000