Lecture 20

Galaxies

Outline of Lecture 20

- Shapley-Curtis debate over the Galactic or extragalactic nature of spiral “nebulae”.
  - “Island universe” versus galaxies in an unimaginably large cosmos
  - Hubble’s determination of the distance to M31 = Andromeda galaxy
- Morphological classification of regular and irregular galaxies
  - Hubble tuning fork diagram
  - Spiral structure as a density wave
- Interacting galaxies
  - Bridges and tails, rings
  - Mergers, starbursts, and the origin of elliptical galaxies
- Extra material: Active Galactic Nuclei (Lecture 20b)

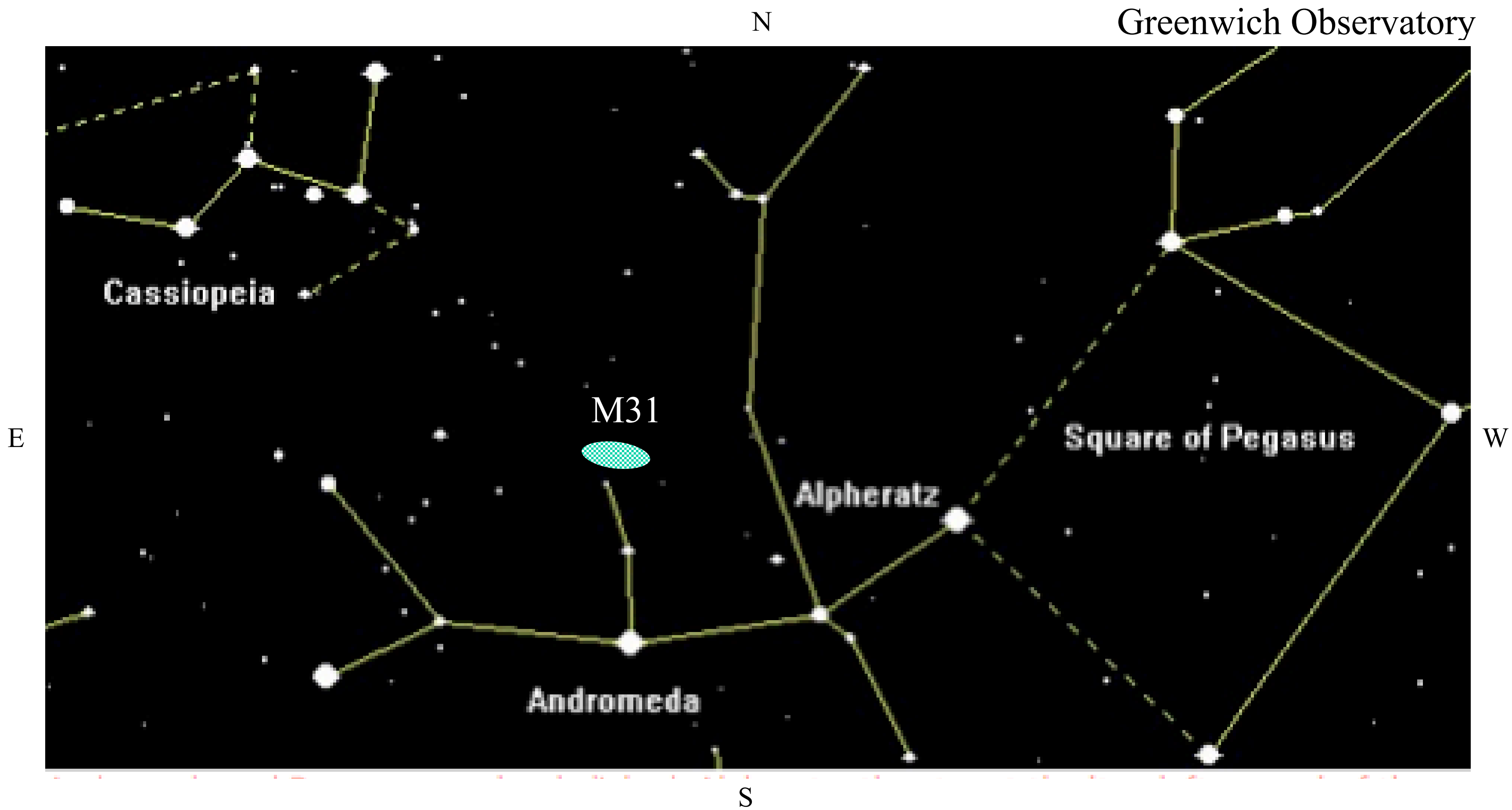
Existence of Nebulous Objects in the Night Sky

Since antiquity, Mayans, Aztecs, Africans, aborigines in Australia, and others who lived in or close to the Southern Hemisphere must have seen the spectacular nebulosities in the night sky that are the Large and Small “Magellanic” Clouds.

In the tenth century, Al Sufi (903-986) also observed and drew a picture of the Andromeda “nebula,” Depicting it as the body (M31) and tail (M110) of a fish.

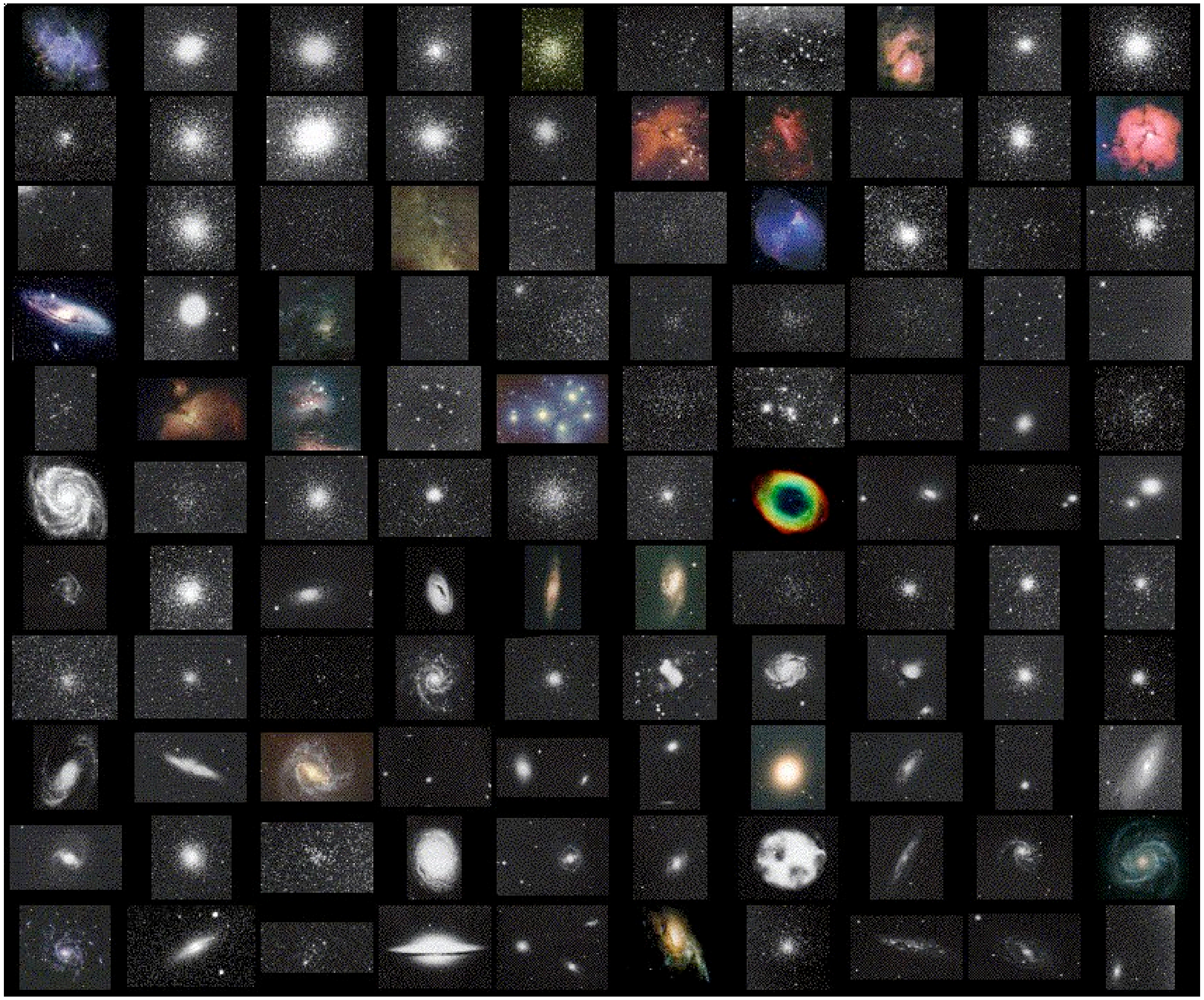
Bill Keil

Finding M31 in Evening (Around 8 pm) Late Fall or Early Winter



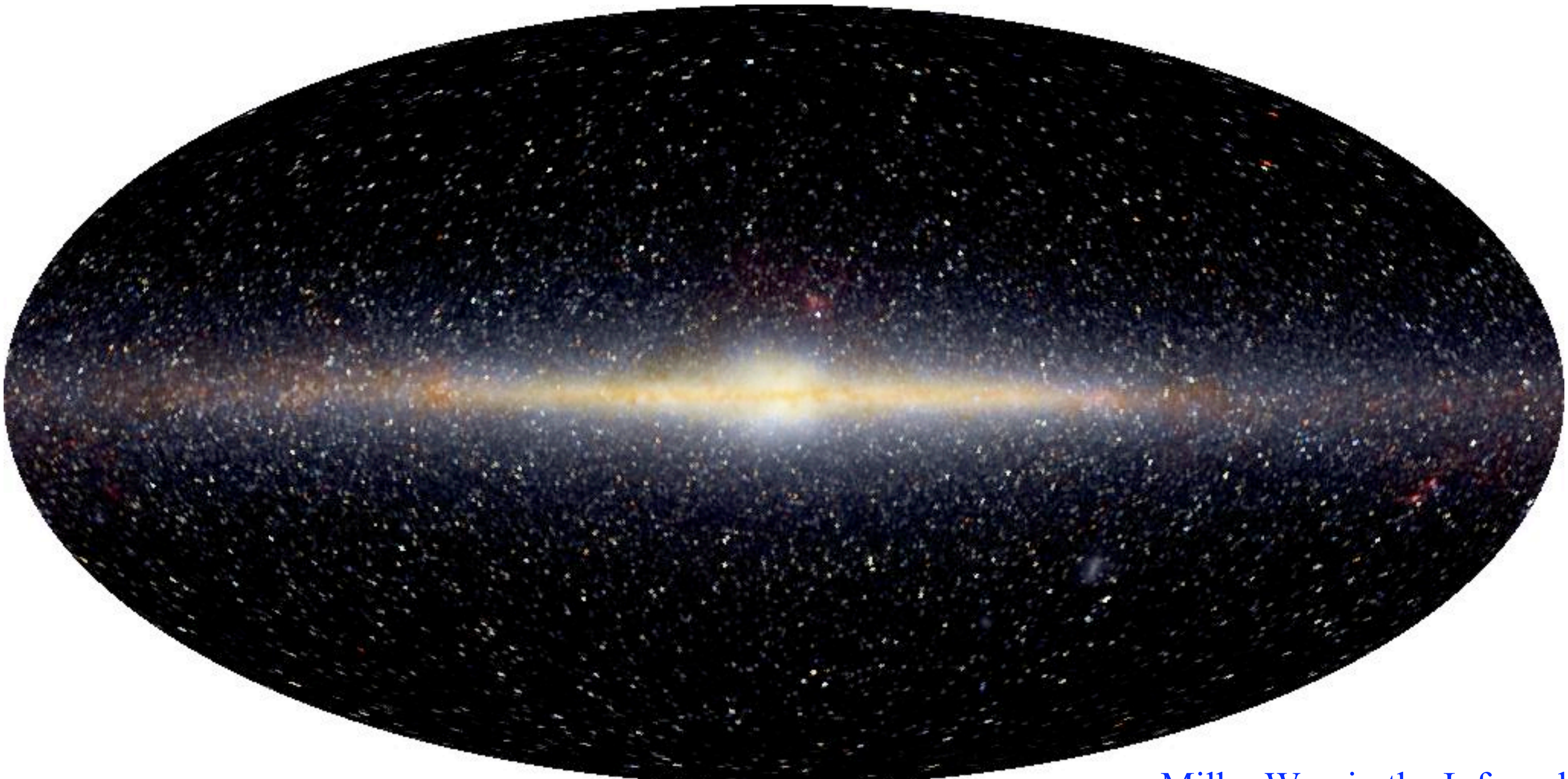
Note E (toward the Chair of Cassiopeia from Pegasus) and W are reversed in astronomical maps (looking up, not down). Start at Alpheratz, the bright star at the East corner of the Square of Pegasus. Move two bright stars to the East to Andromeda, and then North two faint stars. Just above, you will find fuzzy M31, the most distant object that can be seen with the unaided eye. (Use "averted vision" or binoculars.)

Messier Objects -- A Mixed Bag



110 nebulous objects in catalogue of comet hunter Charles Messier (1730-1817)

What Is the Relationship of Such Nebulosities to the Milky Way?



Milky Way in the Infrared:
White = Stars; Red = Dust

Photo Credit: COBE/NASA

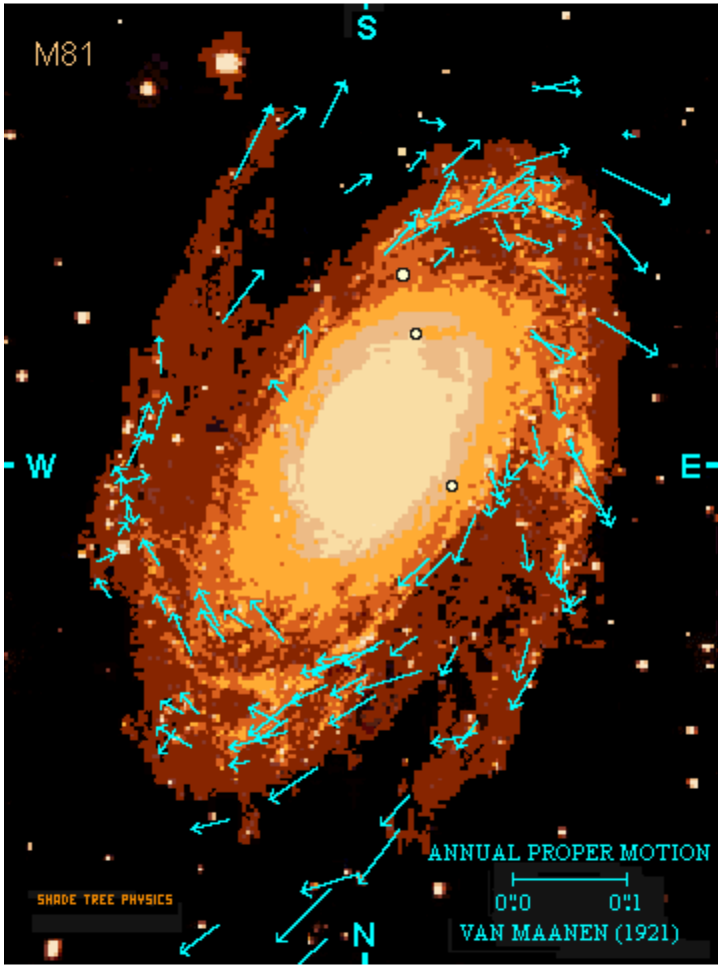
Spirals: Stellar Systems Coequal with Milky Way or Gas Clouds Within It?

A spiral

Orion nebula

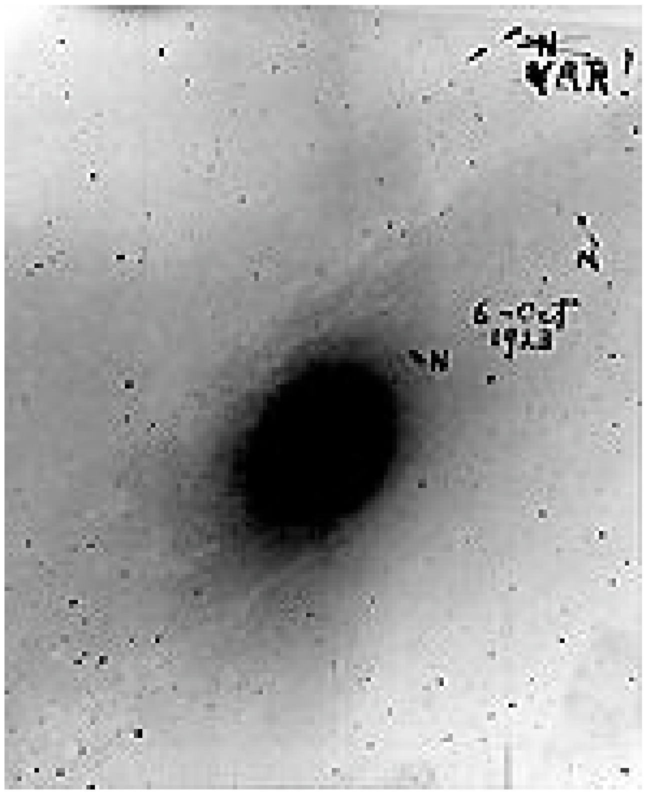
Nature of Spiral “Nebulae”

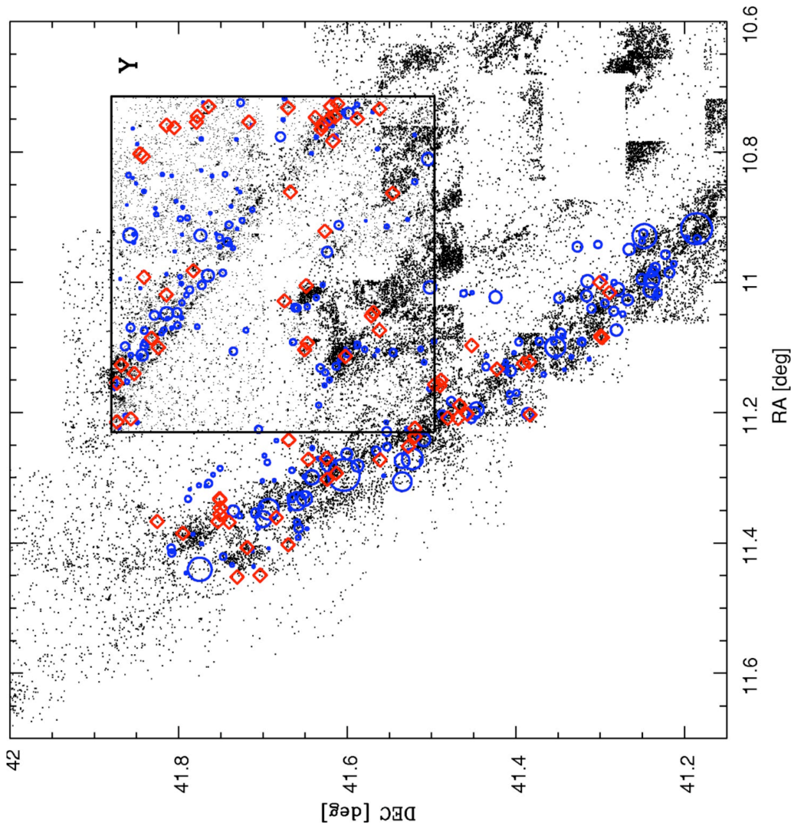
- Heber D. Curtis (1872-1942): novae in M31 much fainter than in Milky Way
- Adrian van Maanen (1884-1946): rotation of M81 & M101
- Harlow Shapley (1885-1972): great size of Milky Way Galaxy
- The Shapley-Curtis Debate (1920)
  – Shapley: Rotation of M81: if real and M81 were comparable in size to Milky Way, then rotation velocity > *c*. Must be much smaller and closer.
  – Both: Brightness of novae (white dwarfs which have new supply of H fuel added to them from companion star): confusion with supernovae.
  – Shapley: Recession of spiral “nebulae” as measured by Vesto Slipher (1875-1969): repulsion by Milky Way?
  – Avoidance of Galactic plane: further evidence of repulsion (Shapley) or obscuration of *external galaxies* by interstellar dust (Curtis)?



Erroneous measurement of proper motion of rotation in M81.

M31, the Closest Large Spiral Galaxy, Lies at a Distance of 2.6 Mly



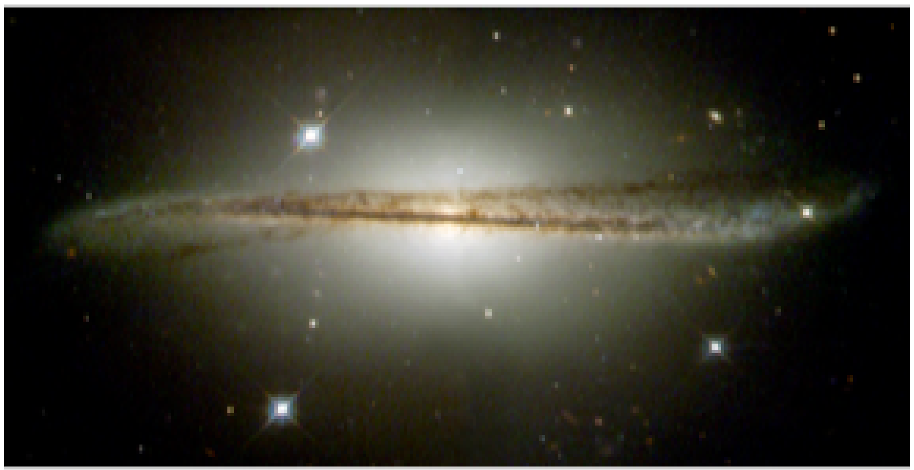


Bonanos et al. (2003, *AJ*, 126, 175).

- In 1923 Edwin Hubble (1889-1953) thought he found 3 novae in M31, whose positions he marked with “N” in the original photographic negative (left panel). Later he crossed out the “N” at the top, and substituted “VAR!” He had found a Cepheid variable in M31!
- Modern techniques (right panel) can find both eclipsing binaries (red diamonds) and Cepheid variables (blue circles). Cepheids indicate a distance ~ 2.6 million lt-yr (Mly), well outside the Milky Way. M31 is an independent galaxy somewhat larger than the Milky Way.

Two Edge-On Spirals

ESO 510 G13 with a large flattened bulge and a warped disk is perhaps a product of a recent collision of two spiral galaxies.



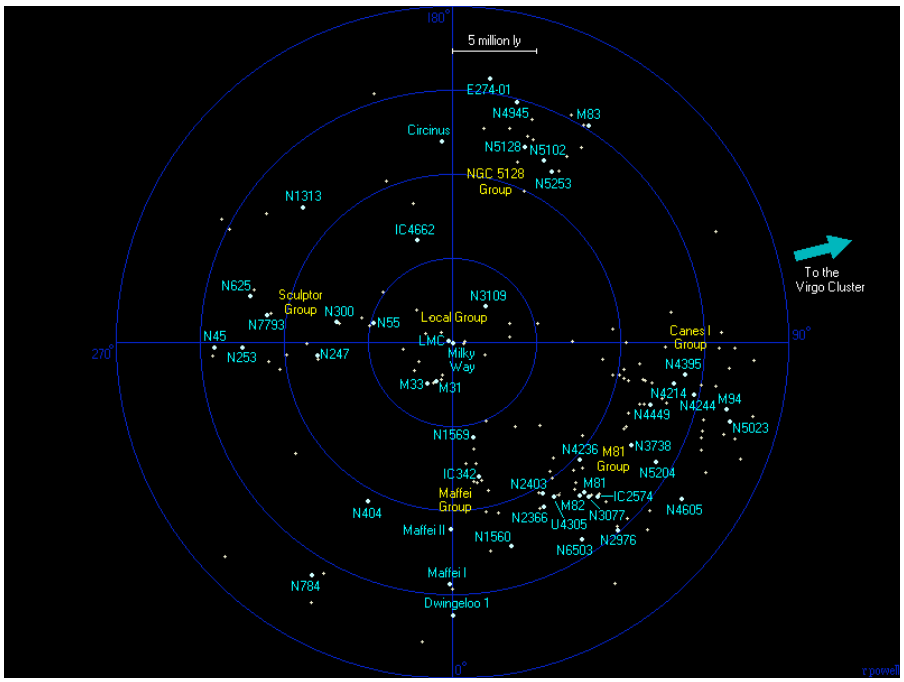
NASA/HST

More normal edge-on spiral, NGC 891

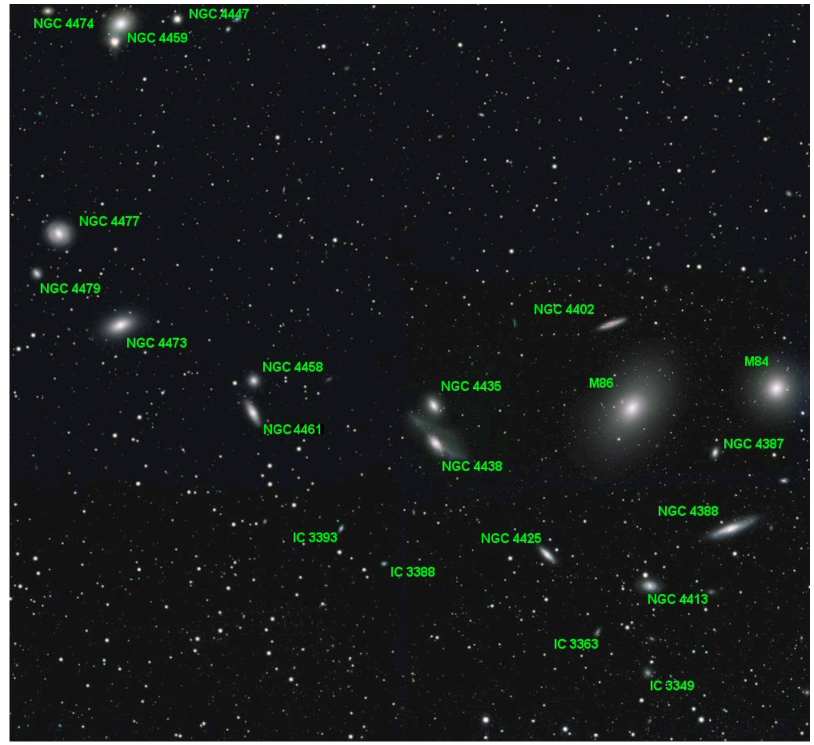
Two Ordinary Spirals

Two Barred Spirals

Spirals Dominate Small Groups While Galaxy Clusters Have Both Ellipticals and Spirals

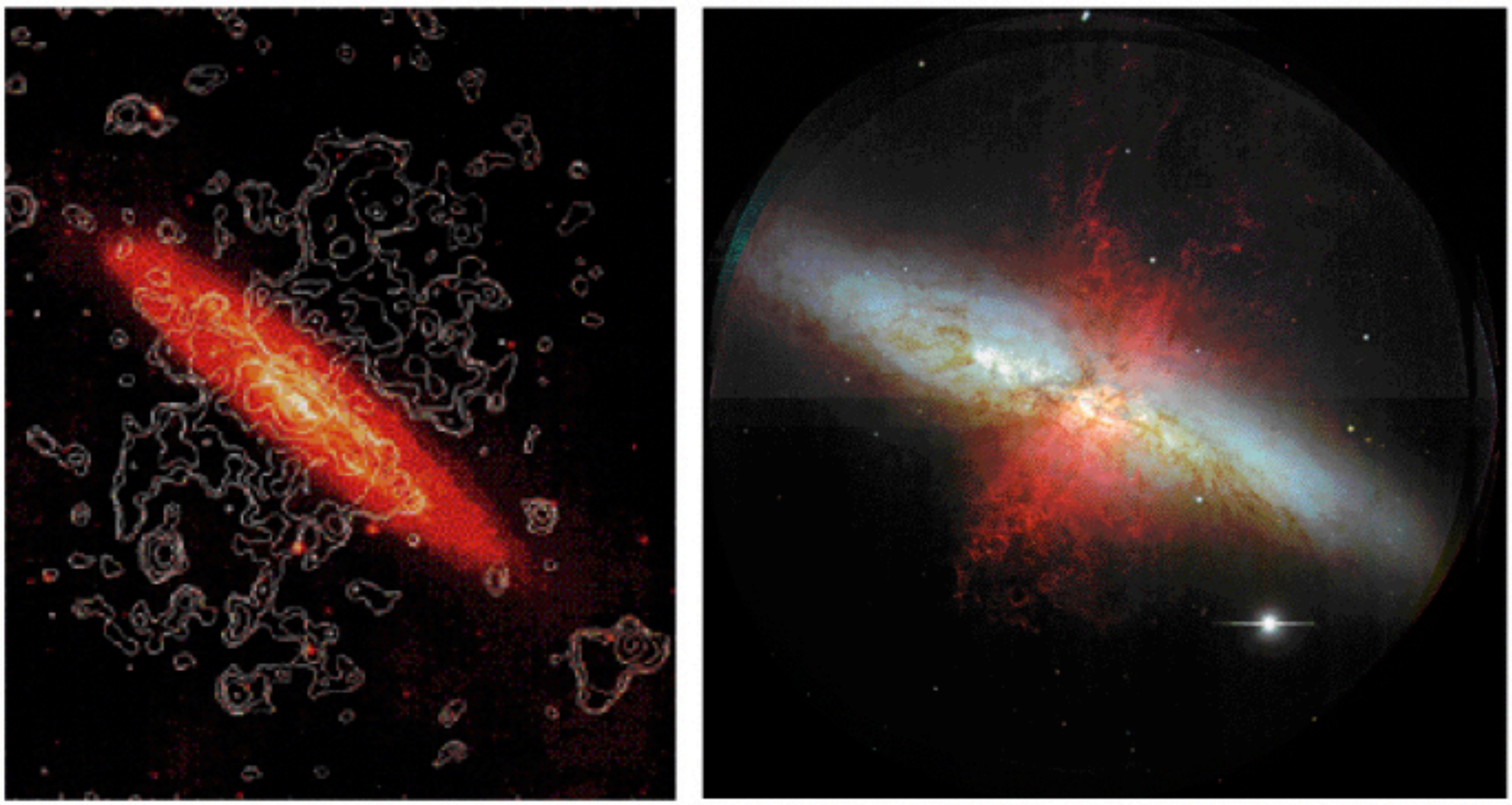


M31 and our Galaxy are the two largest members of the Local Group, which is similar to many other small groups found within 20 Mly of the Milky Way System. www.atlasoftheuniverse.com



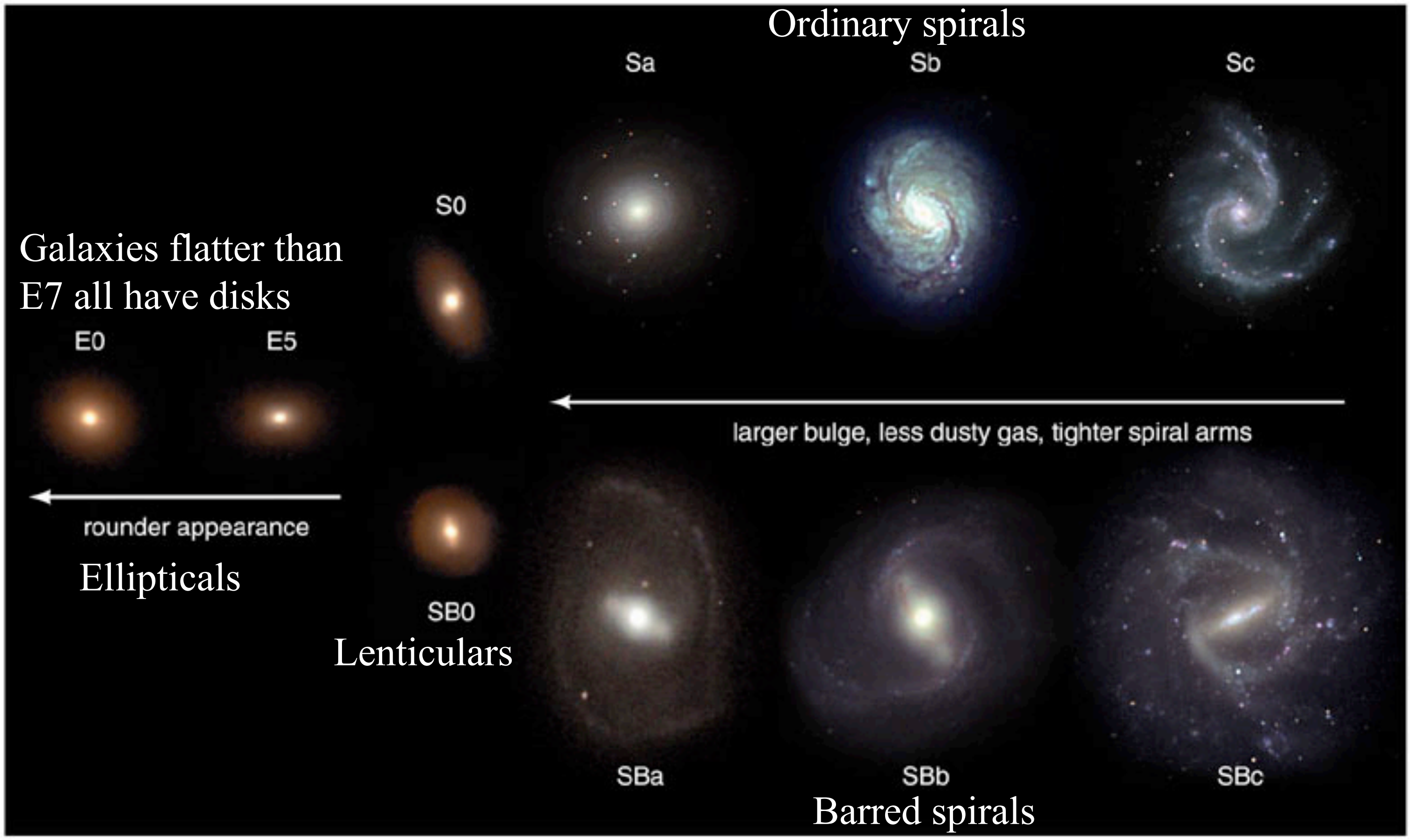
Virgo cluster at a distance of ~ 60 Mly is the nearest large collection of some 1000 spirals and ellipticals. Since our Galaxy is moving toward Virgo at ~ 300 km/s (see Lecture 21), it will probably become a member of this cluster in the distant future.

Irregular Galaxy M82
(Starburst in Central Regions)



(a) (b)

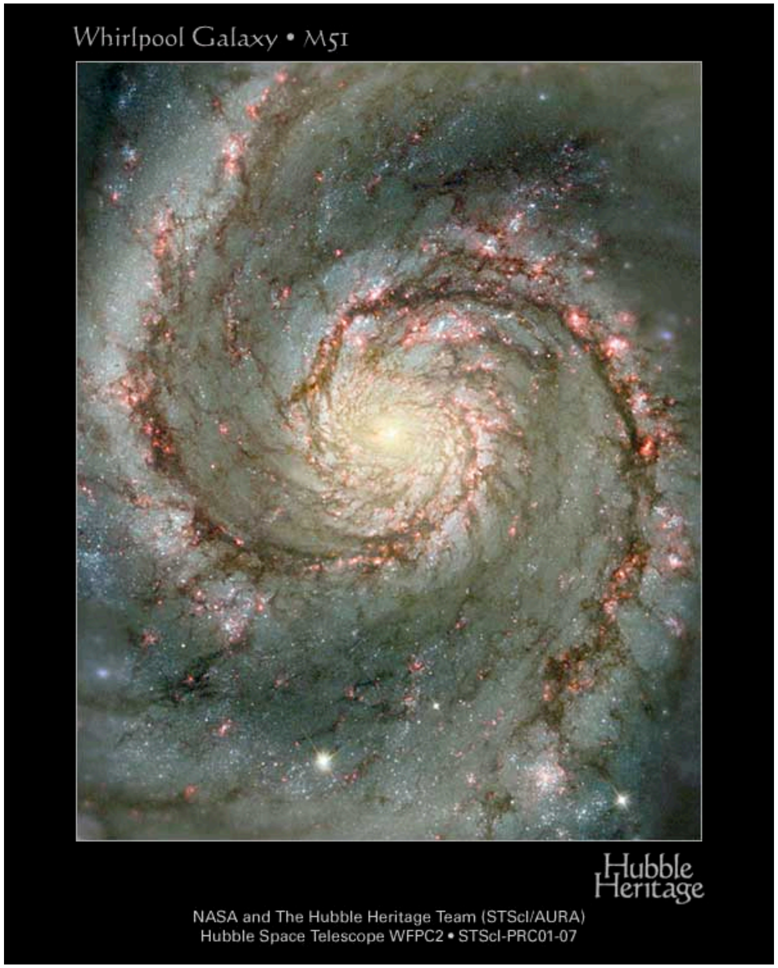
Hubble Tuning Fork Diagram: Classification of Regular Galaxies



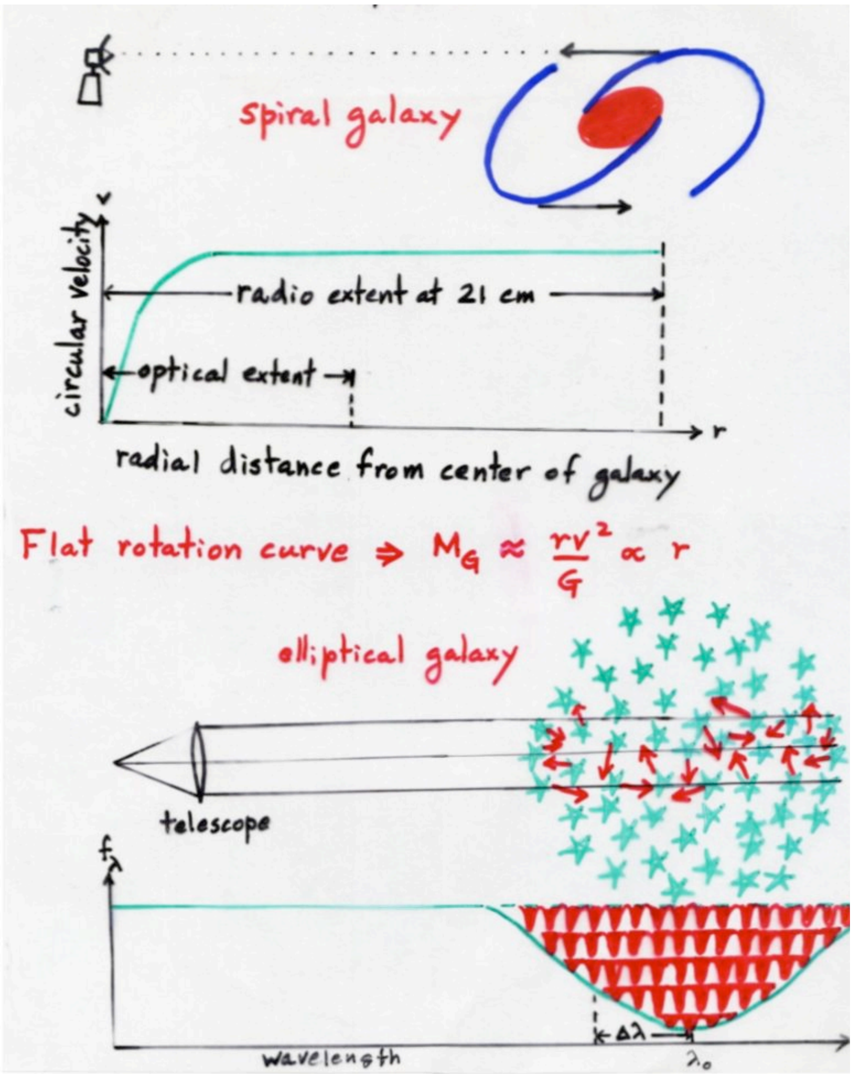
Van den Bergh Luminosity Classification of Spiral Galaxies

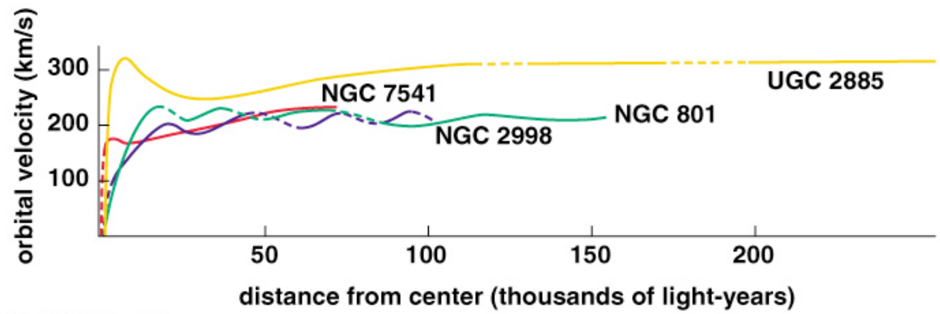
- Luminosity class I → IV
  - Most luminous → least luminous
  - Most pretty → least pretty
- Example: Sc I galaxy:
  - Ordinary spiral
  - Small central bulge
  - Loosely wound spiral
  - Very pretty galaxy, with well-defined spiral arms and large (reddish) H II regions

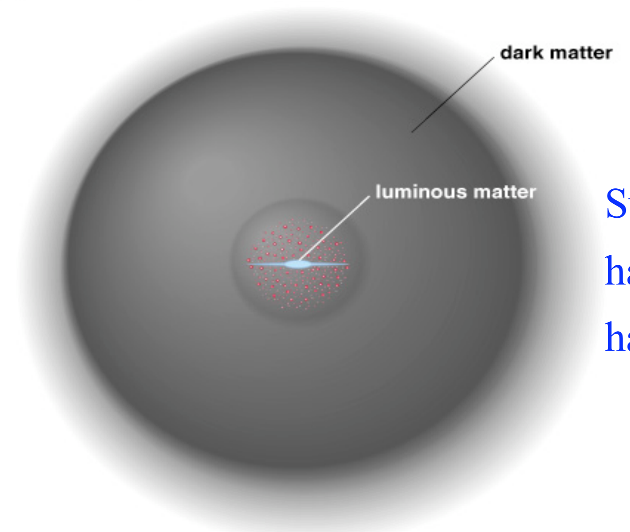
M51, one of the most beautiful spiral galaxies



Measuring Masses of Galaxies



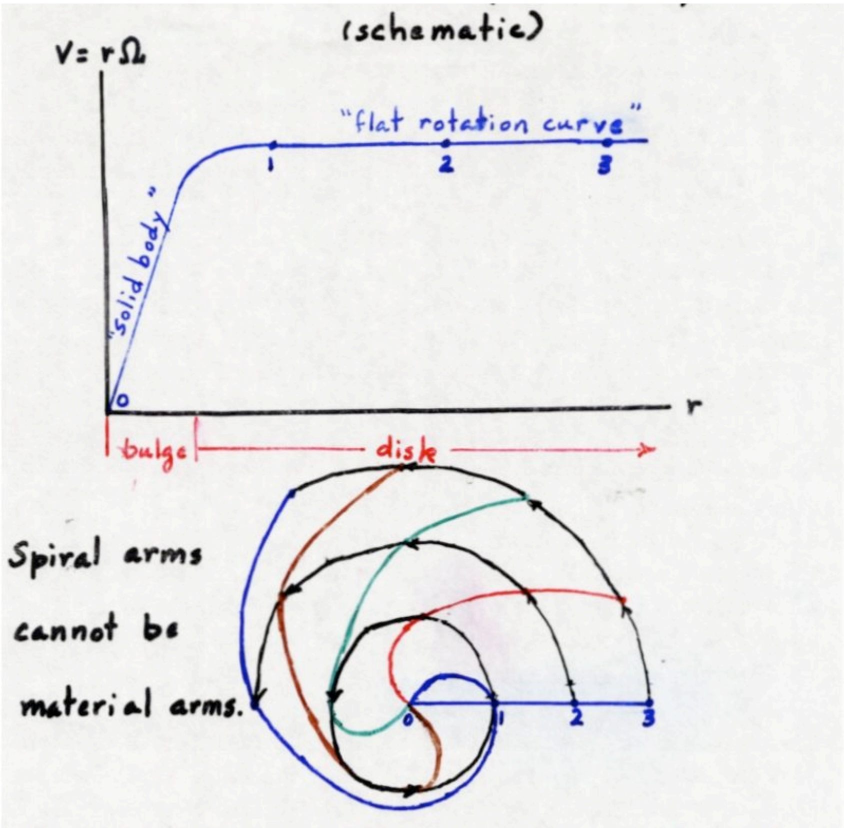




Surmise galaxies have dark-matter halos.

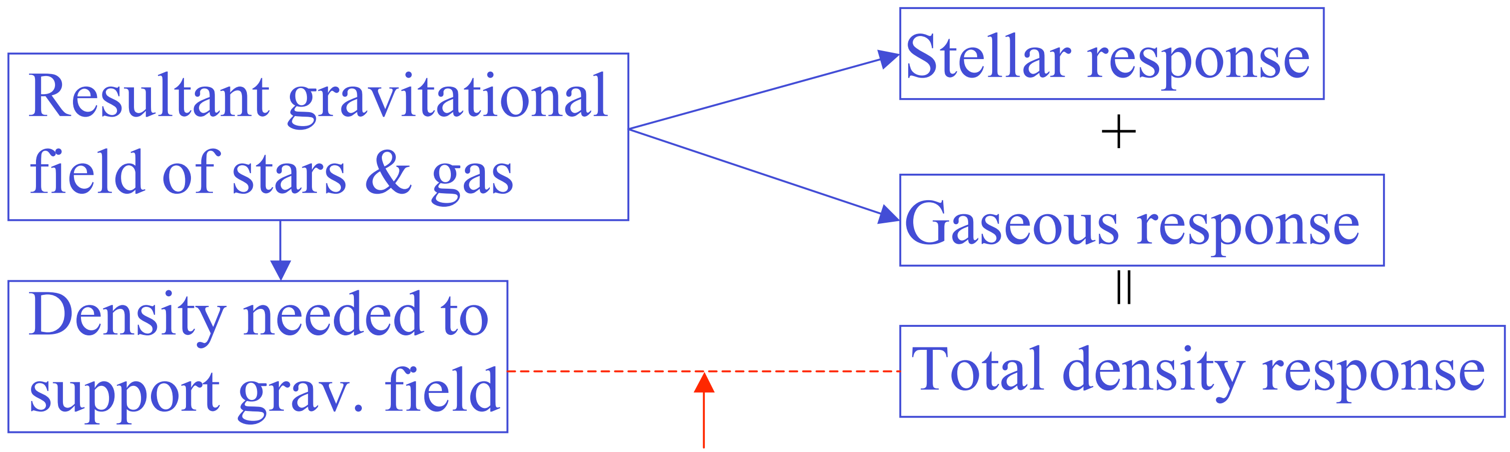
There is 5 to 6 times as much dark matter associated with galaxies as ordinary matter.

The Winding Dilemma of Galactic Spirals



After about 10^8 yr, material arms would add about 1 turn, but spiral galaxies are about 10^{10} yr old, yet don't have 100 turns.

Outline of Density Wave Theory (C. C. Lin & F. H. Shu 1964)

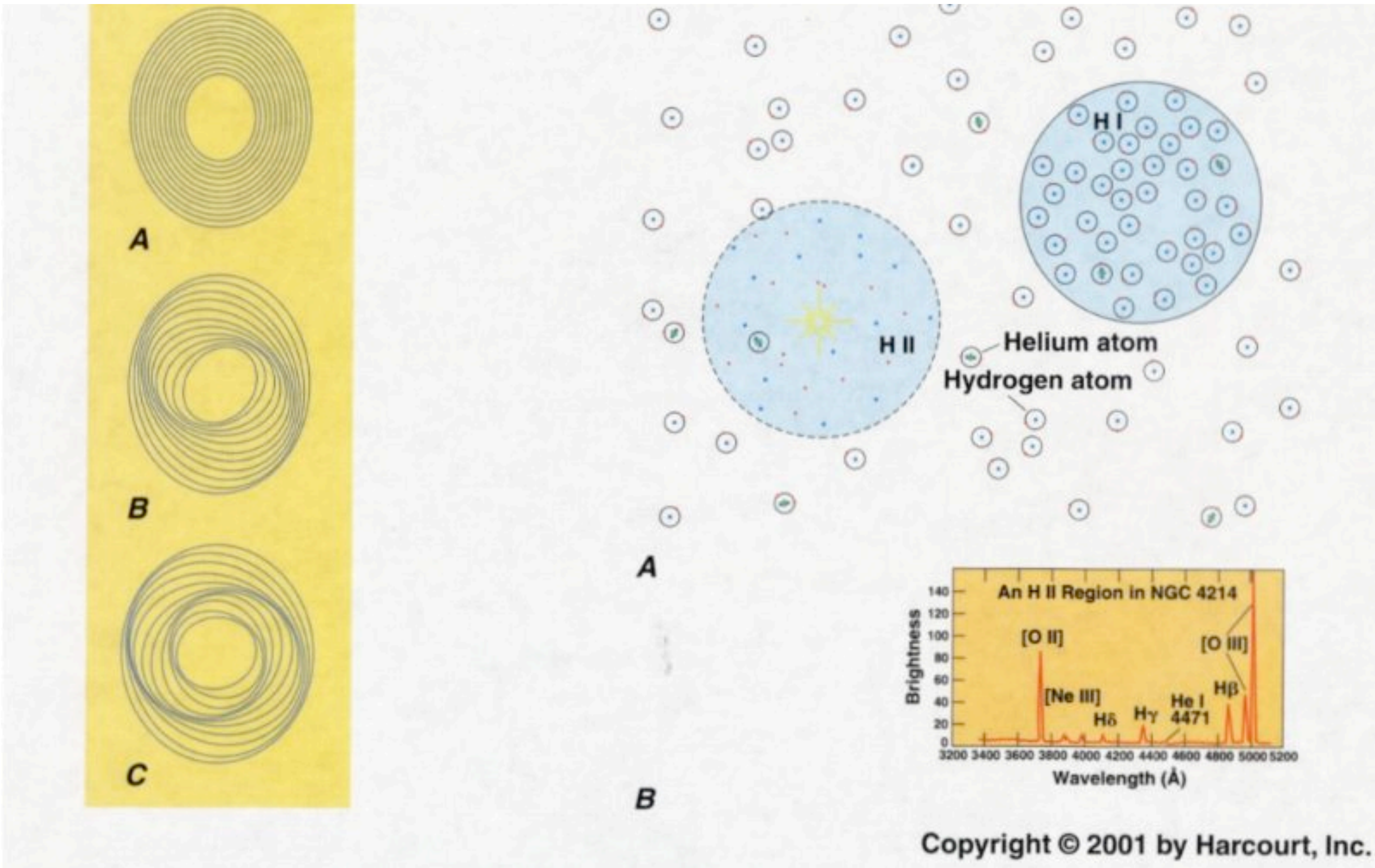


This equation determines properties of spiral density waves.

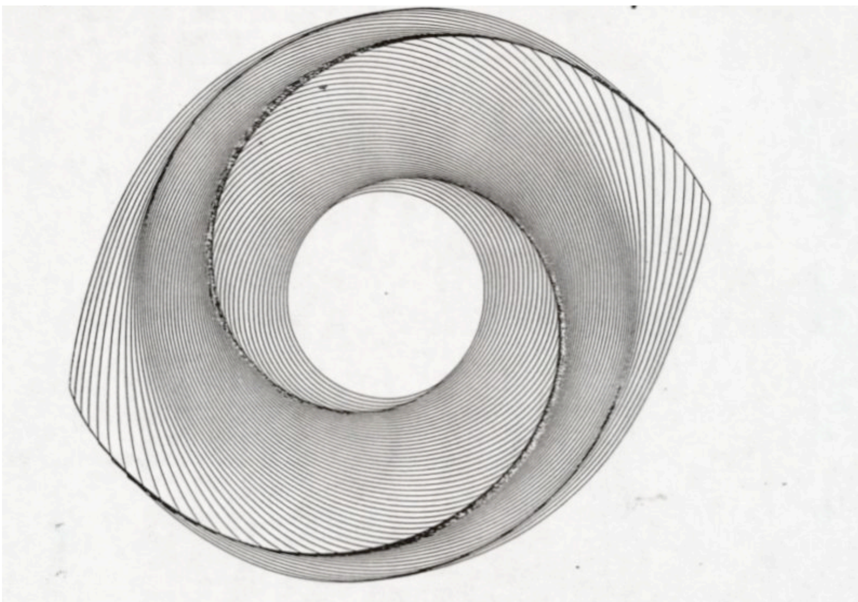
(Mathematics similar to that which determines discrete "normal modes" from wave mechanics for atoms.)

- Depending on the galaxy model, we find that disturbances of a spiral or barred form can grow spontaneously in the disk (a self-excited normal mode).
- This basic tendency arises because a transfer of angular momentum outwards (by gravitational torques) is energetically favorable for the system, allowing spinning inner parts of galaxy to contract gravitationally toward the center.

Compression by Orbit Crowding

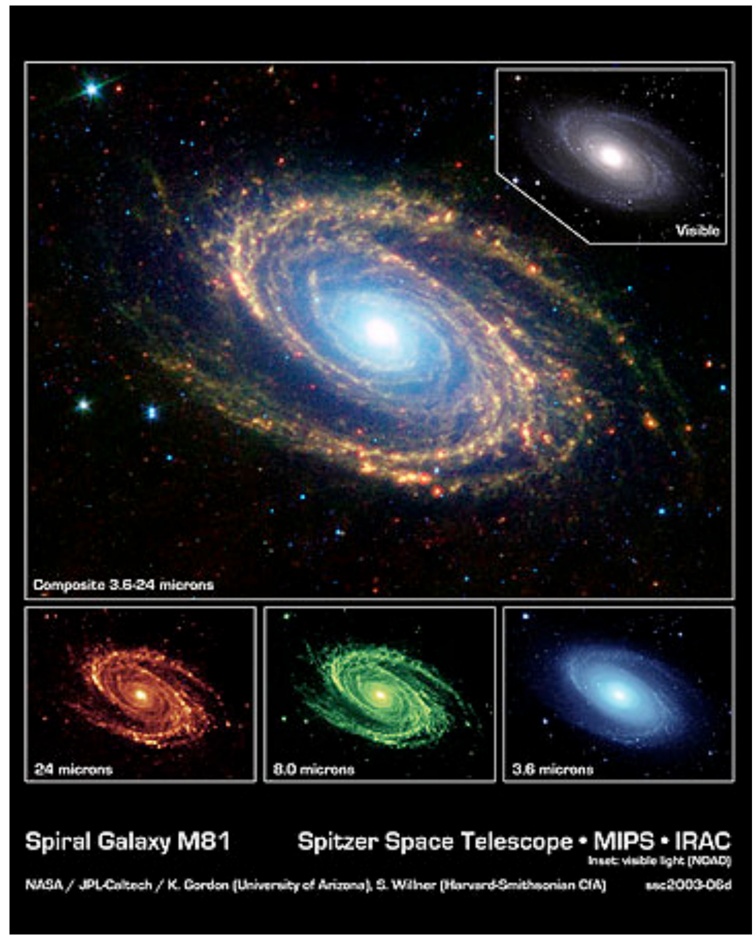


Spiral Structure as a Nonlinear Density Wave

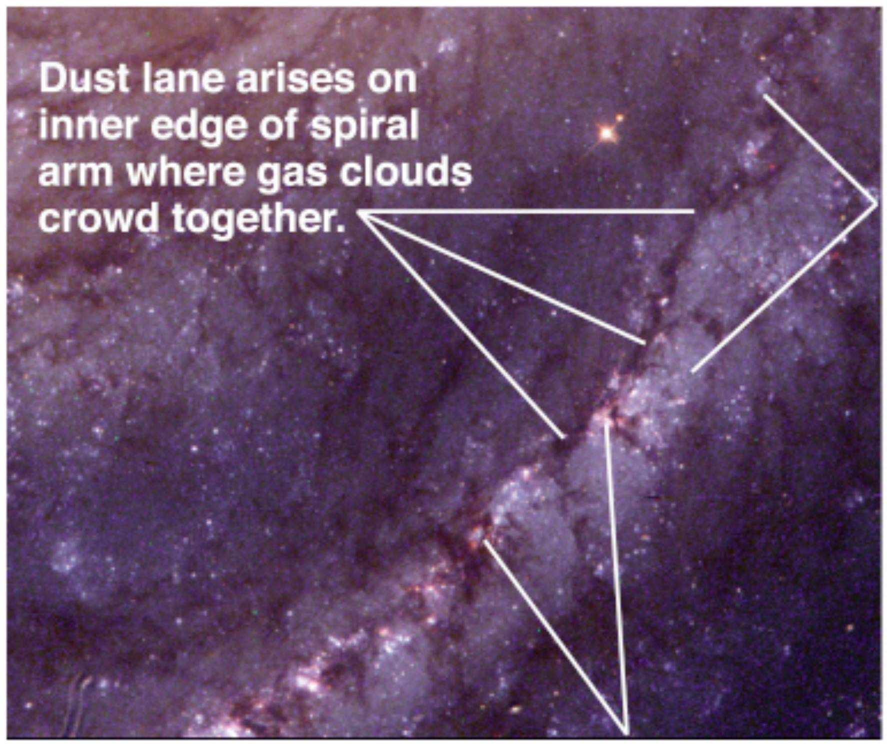


Model of gas streamlines in M81 with branching of 2-arm spiral galactic shockwaves: Visser (1980)

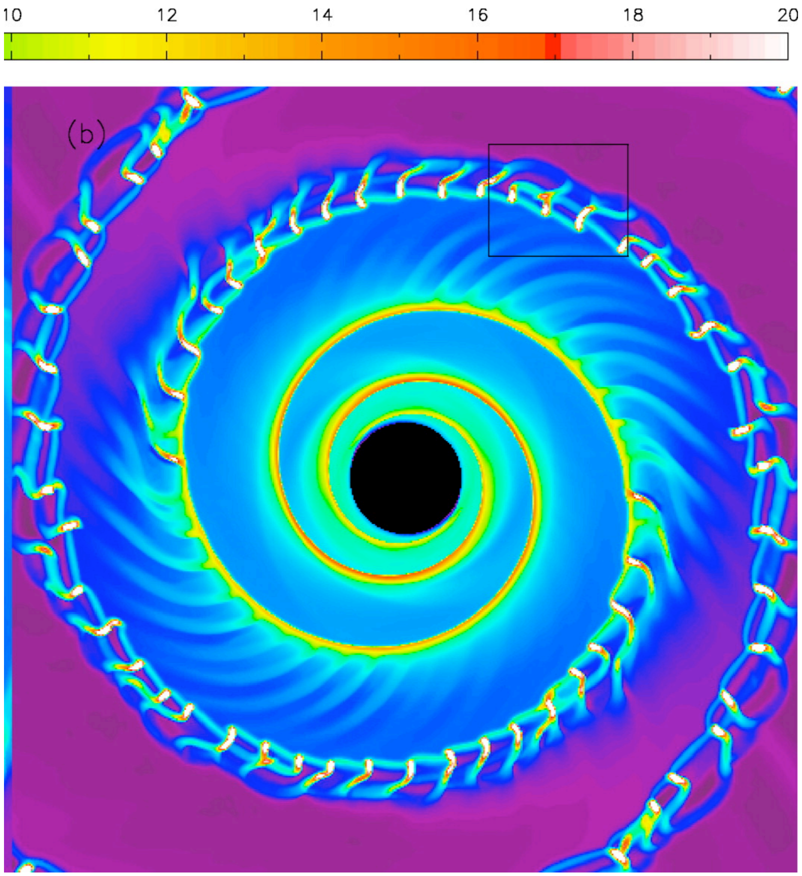
Analogy with a traffic jam.



Relationship Between Star Formation & Spiral Structure



Gravitational Instabilities Behind Galactic Shock Yields Feathering of Spiral Arms and Giant Cloud Complexes that Form OB Stars



Shetty & Ostriker (2006)

M100, a Sc I galaxy in the Virgo Cluster

Simulation of M51 as Interaction of Large and Small Spirals

Inner spiral structure is density wave.

What is nature of “bridge” to companion?

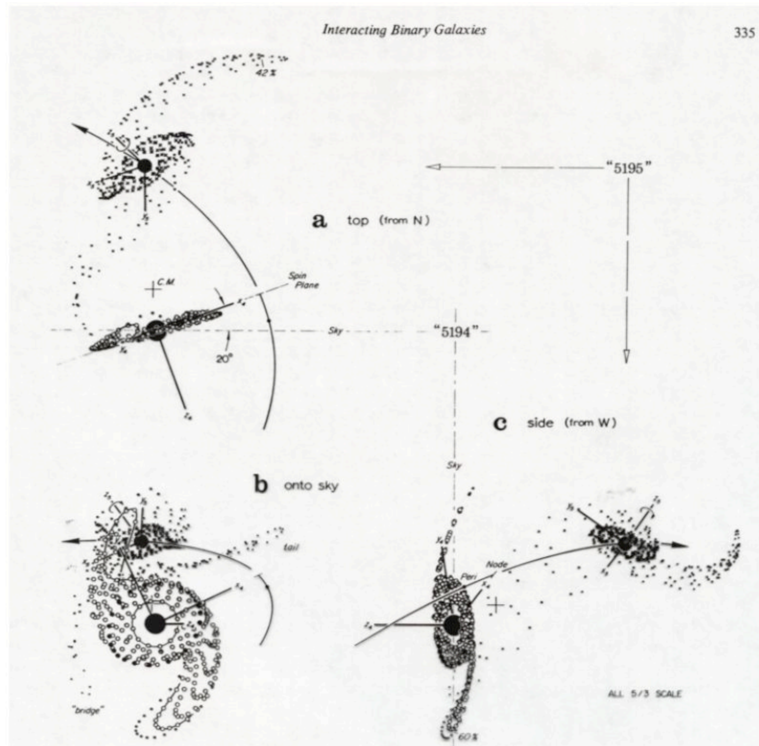


Figure 14.2. A numerical simulation of a bridge-producing encounter. A direct close flyby of a small galaxy past a big disk galaxy draws out a bridge of material which temporarily spans the gulf between the two bodies. Compare b with Figure 14.1a. (After A. Toomre and J. Toomre, *Ap. J.*, **178**, 1972, 623.)

Toomre & Toomre (1972)

Interacting Galaxies:
“Mice” and “Cartwheel”

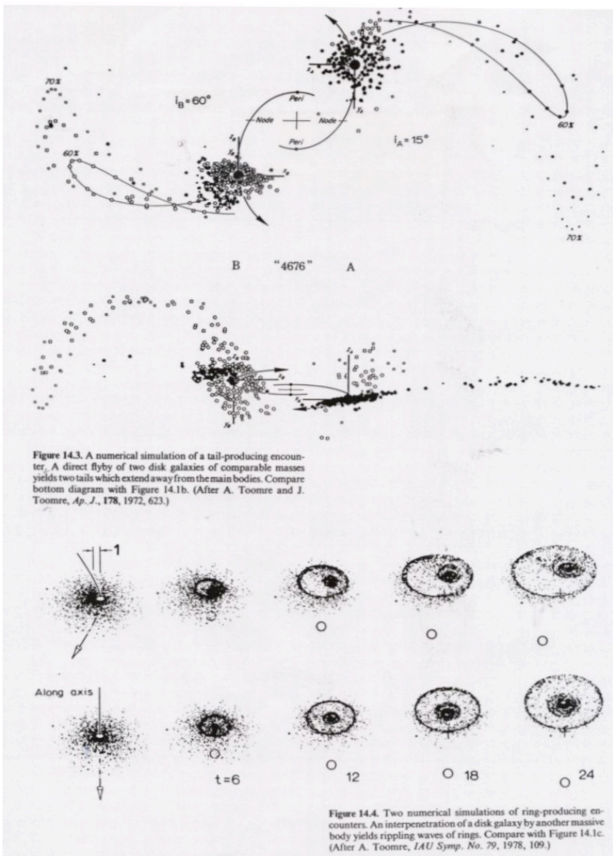
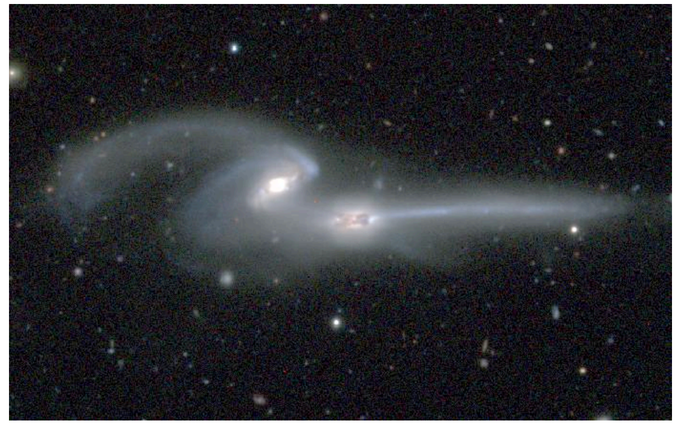


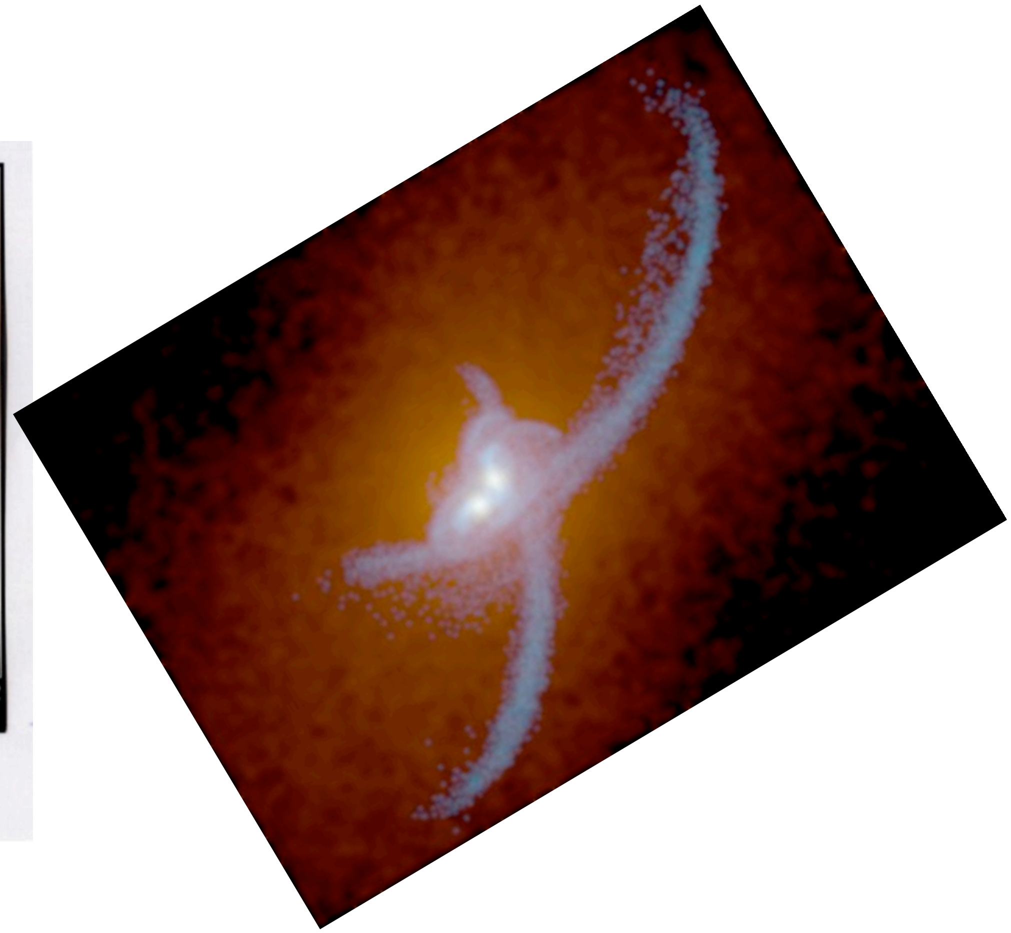
Figure 14.3. A numerical simulation of a tail-producing encounter. A direct flyby of two disk galaxies of comparable masses yields two tails which extend away from the main bodies. Compare bottom diagram with Figure 14.1b. (After A. Toomre and J. Toomre, *Ap. J.*, **178**, 1972, 623.)

Figure 14.4. Two numerical simulations of ring-producing encounters. An interpenetration of a disk galaxy by another massive body yields rippling waves of rings. Compare with Figure 14.1c. (After A. Toomre, *IAU Symp. No. 79*, 1978, 109.)

NOAO/Hibbard

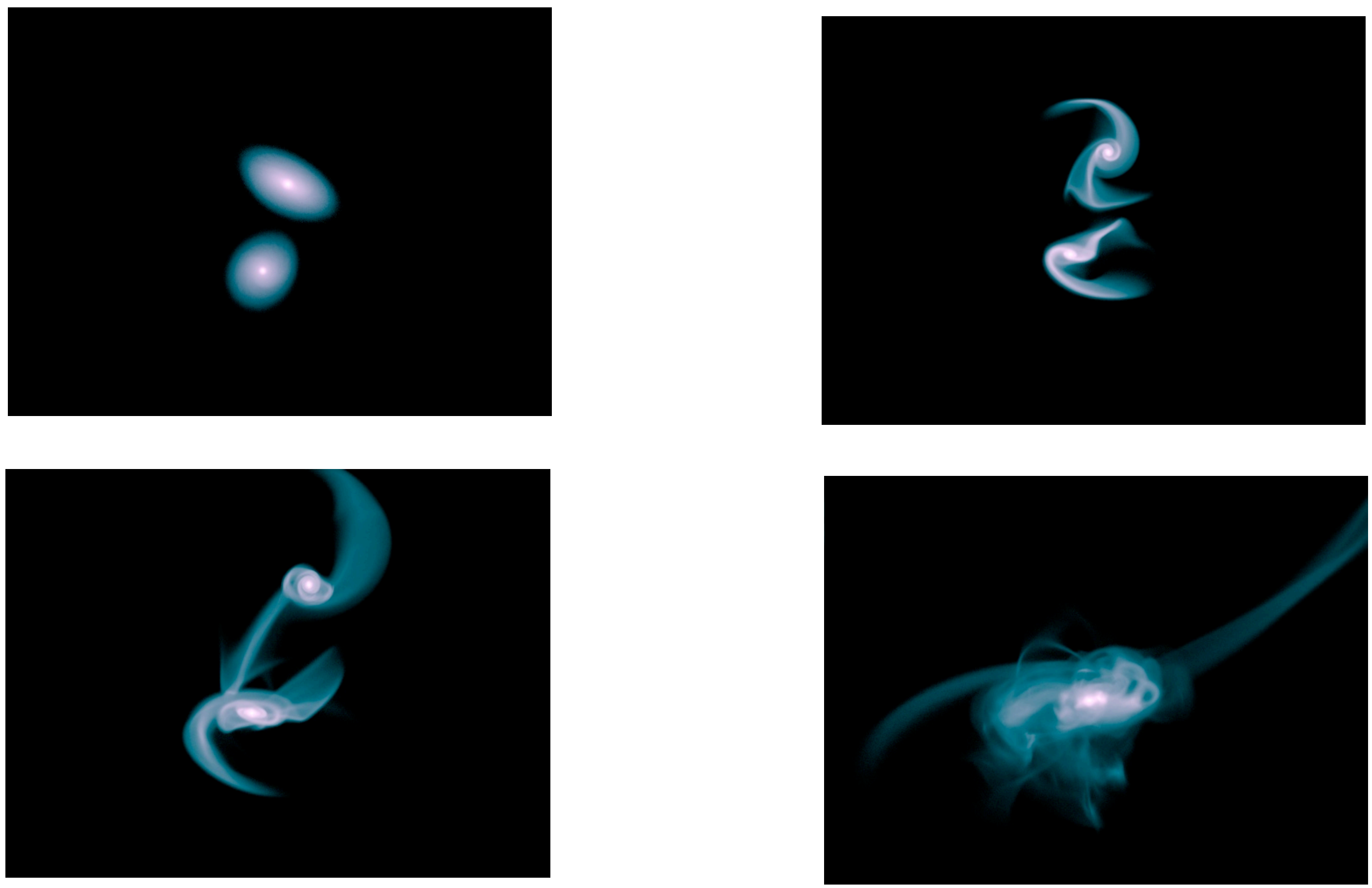


Antennae Galaxies Are in Process of Merging and Undergoing Starburst



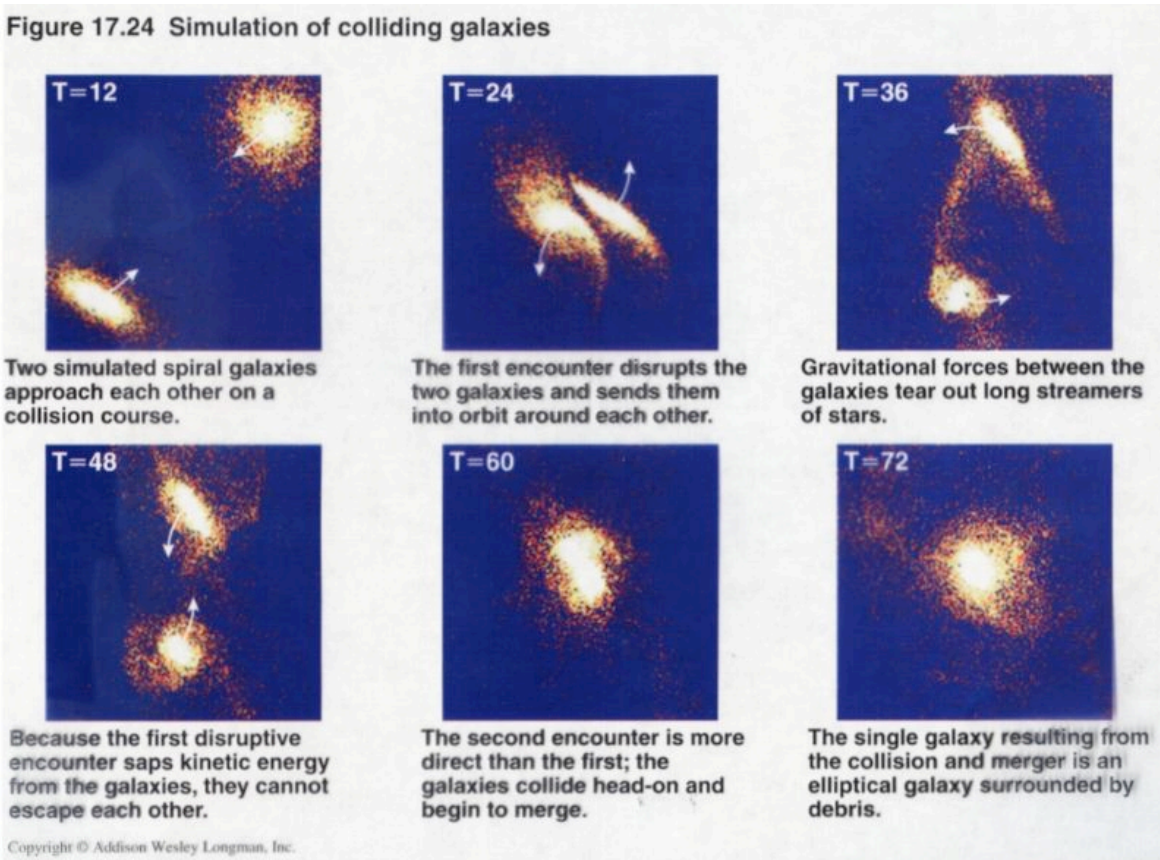
IfA/J. Barnes

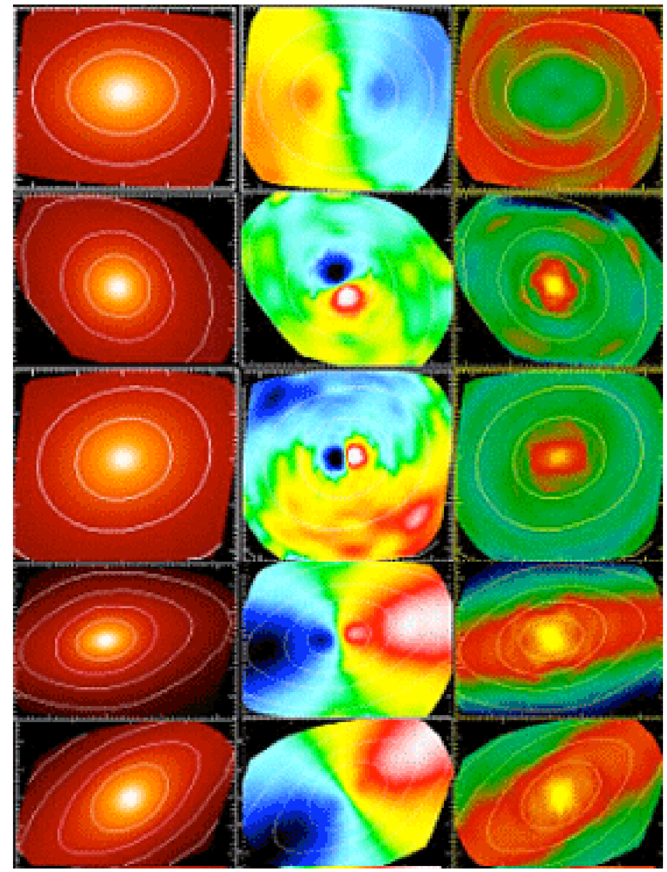
Merger of Milky Way and M31 Will Occur 3 Billion Years Hence



CITA/Dubinski

Mergers of Spirals Produce Ellipticals





Visible Light Image	Line-of-sight Velocity Field	Stellar Population Types

muse.univ-lyon1.fr

Galactic Cannibalism of Small Satellite Galaxies by Host Galaxy

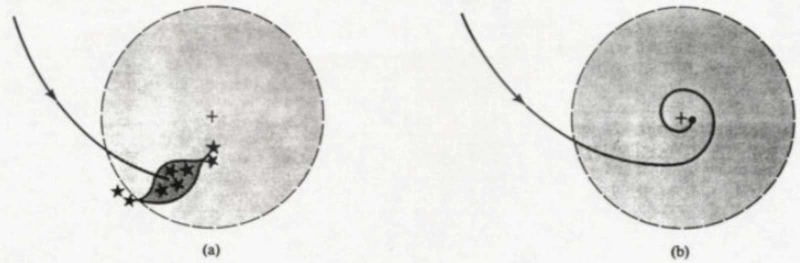


Figure 14.12. Galactic cannibalism. A supergiant cD galaxy devours a small neighbor in two stages. (a) Tidal stripping occurs when the stars at the periphery of the small galaxy are torn loose from the parent body. (b) Dynamical friction causes the dense core of the small galaxy to spiral gradually into the central regions of the cD galaxy.

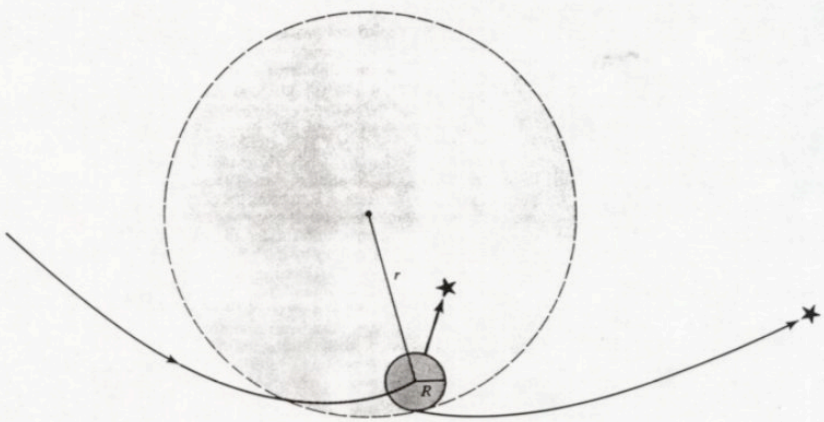


Figure 14.13. Tidal stripping can cause stars to be flung far from the cD galaxy as well as captured by it. The ratio of stars captured versus stars lost would depend on a variety of conditions, including the spin of the devoured small galaxy. Stars which are lost to the cD galaxy may not be lost from the cluster as a whole. Such stars may form a loosely dispersed sea which permeates the entire cluster.

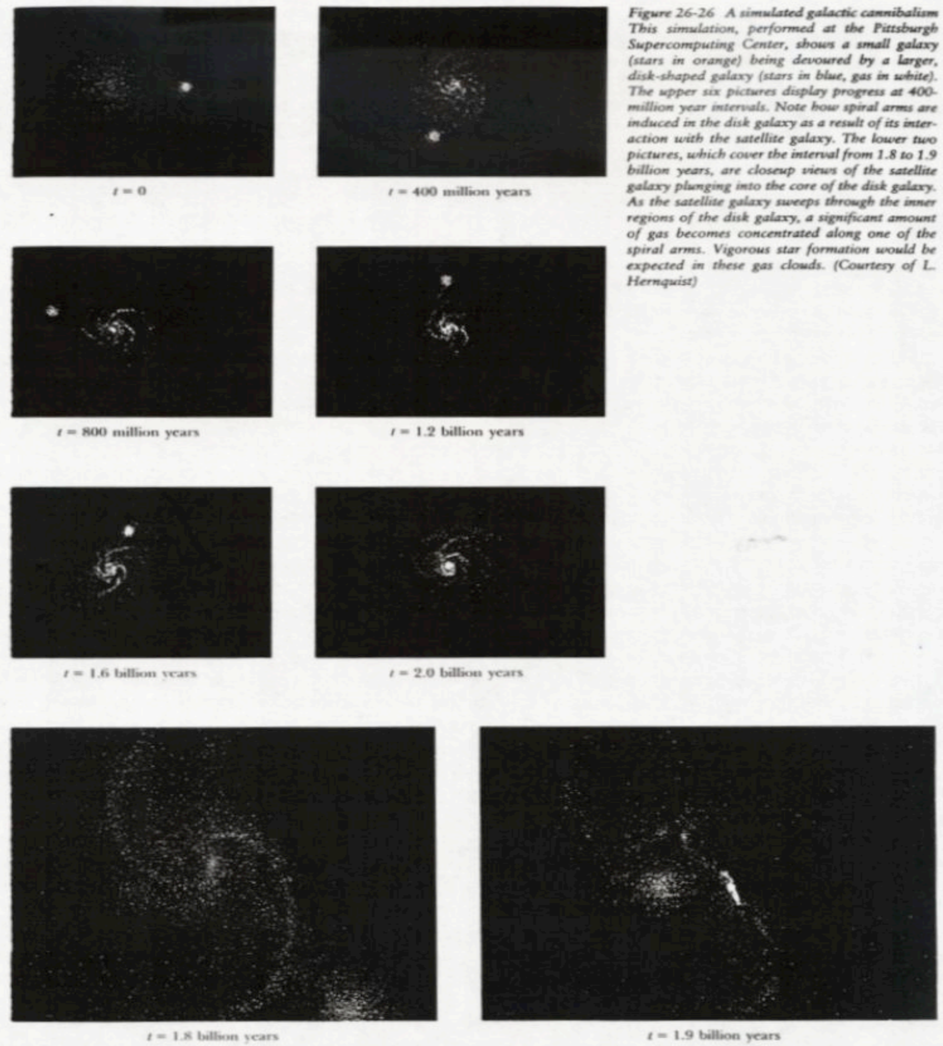


Figure 26-26 *A simulated galactic cannibalism This simulation, performed at the Pittsburgh Supercomputing Center, shows a small galaxy (stars in orange) being devoured by a larger, disk-shaped galaxy (stars in blue, gas in white). The upper six pictures display progress at 400-million year intervals. Note how spiral arms are induced in the disk galaxy as a result of its interaction with the satellite galaxy. The lower two pictures, which cover the interval from 1.8 to 1.9 billion years, are closeup views of the satellite galaxy plunging into the core of the disk galaxy. As the satellite galaxy sweeps through the inner regions of the disk galaxy, a significant amount of gas becomes concentrated along one of the spiral arms. Vigorous star formation would be expected in these gas clouds. (Courtesy of L. Hernquist)*

Giant Elliptical Galaxies that Have Cannibalized their Neighbors Dominate the Centers of Rich Clusters

Massive cluster acts as gravitational lens for background galaxies