A vast field of galaxies, including spiral, elliptical, and irregular shapes, scattered across a dark cosmic background. The galaxies exhibit a variety of colors, from bright yellow and orange to blue and red, indicating different stages of star formation or chemical composition. The density of galaxies is higher in some areas, creating a rich, multi-colored galaxy field.

# Phys 321: Lecture 11

## Nature of Galaxies

# Outline

- Nature of galaxies (Ch. 25)
  - 25.1 The Hubble Sequence
  - 25.2 Spiral and Irregular Galaxies
  - 25.3 Spiral Structure (partial)
  - 25.4 Elliptical Galaxies
- Galactic evolution (Ch. 26)
  - 26.1 Interactions of Galaxies
  - 26.2 The Formation of Galaxies

# The Great Debate

- Are spiral nebulae within our own Galaxy or independent extragalactic sources, or “island universes”?

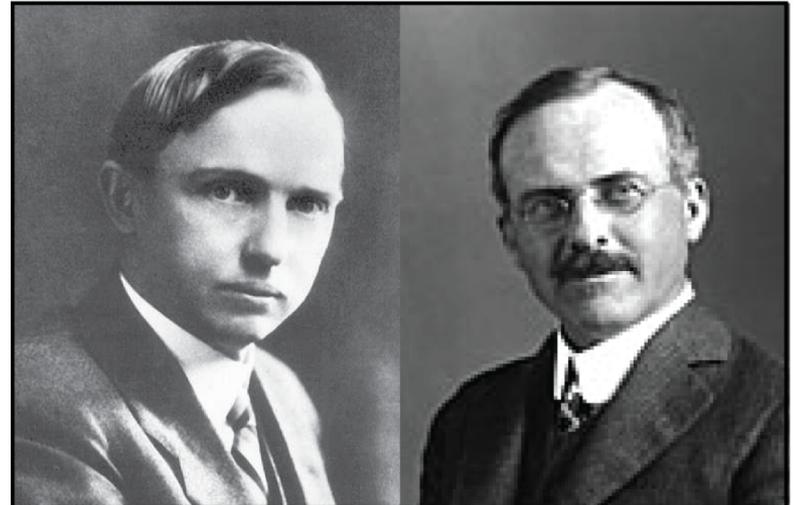
Held on April 26, 1920 at the Smithsonian Museum of Natural History, Between Harlow Shapley and Heber Curtis



M31 (Andromeda Galaxy)



M101 Pinwheel Galaxy



Harlow Shapley

Heber Curtis

# The Great Debate

- **Shapley** argued in favor of the Milky Way as the entirety of the known universe. His arguments:
  - Novae found in M31 would be too bright, if M31 has the same size as the Milky Way (his recent estimation gave 100 kpc)
  - Angular rotation of M101 based on observations from Adrian van Maanen (later confirmed wrong)
- **Curtis** argued in defense of the extragalactic hypothesis. His arguments:
  - Novae in M31 is not too bright, if the size of the galaxy is much smaller
  - More novae in M31 than in the entire Milky Way itself
  - Large Doppler velocities for many spiral nebulae
  - Dark absorption lanes can be seen in edge-on spiral nebulae

# The Great Debate

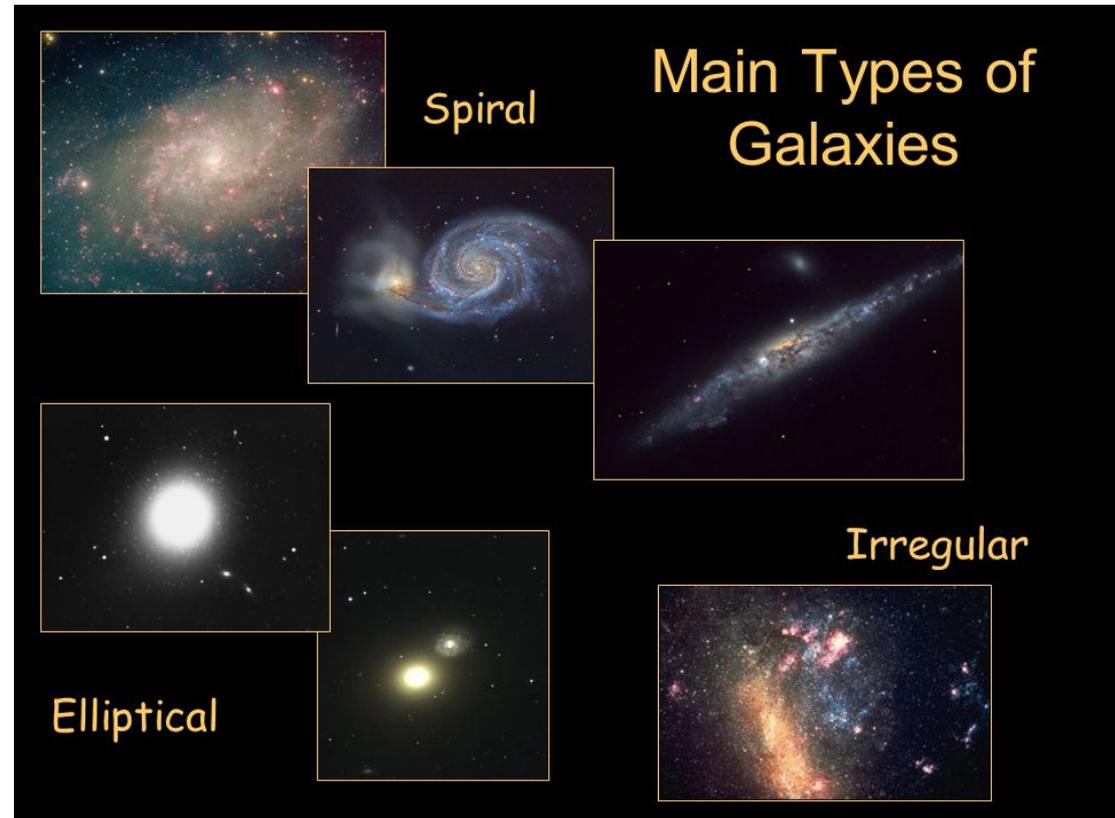
- Debate settled in 1923 when **Edwin Hubble** detected Cepheid variable stars (a “standard candle”) in M31 and determined its distance to be several hundreds of kpc



Edwin Hubble

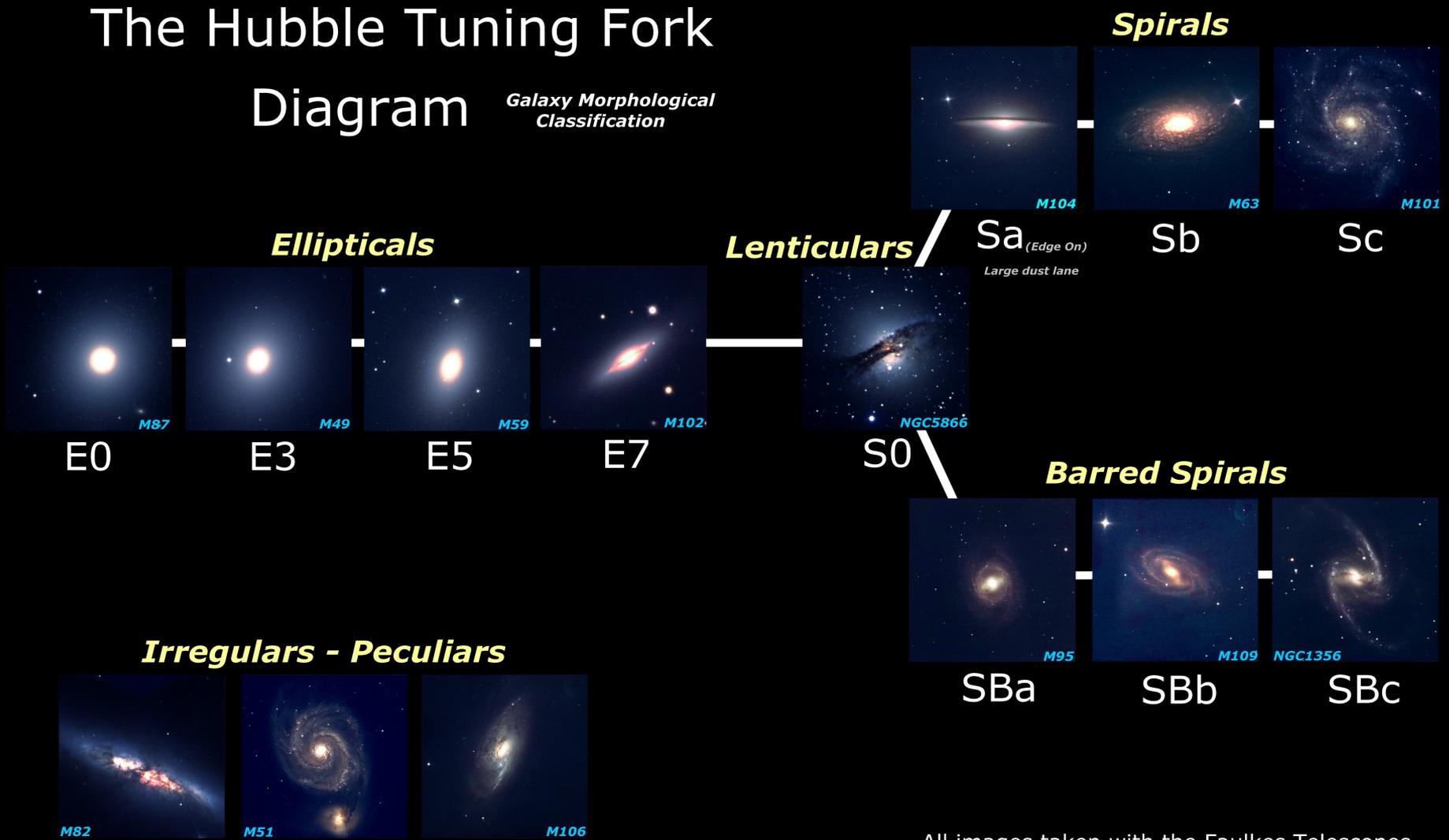
# A zoo of galaxies

- Ellipticals
- Spirals
- Lenticulars
- Irregulars
- Interacting/Merging galaxies
- [Test yourself!](#)



# The Hubble Tuning Fork

## Diagram *Galaxy Morphological Classification*

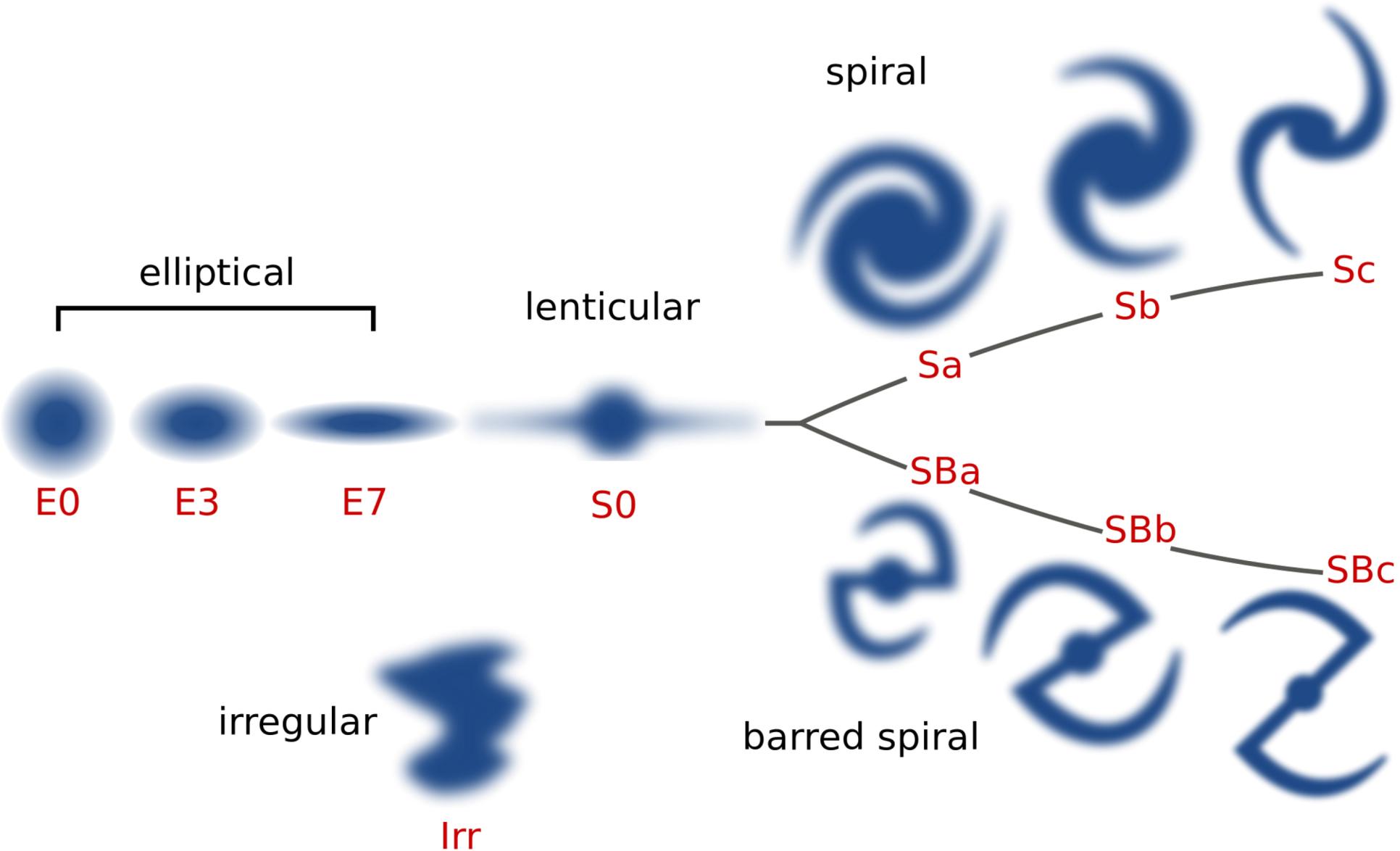


All images taken with the Faulkes Telescopes

College C.Perceret's astronomy workshop 2012

<http://col21-perceret.ac-dijon.fr/col-astro>

# Hubble Tuning-Fork Diagram



# Spiral Galaxies



Sa



Sb



Sc



Smaller bulge-to-disk ratio, less tight spiral arms

# Barred spiral galaxies

- SB galaxies are divided into SBa, SBb, SBc, with similar characteristics to regular spirals, except for a centrally-oriented bar



a M58: an SBa galaxy



b M83: an SBb galaxy

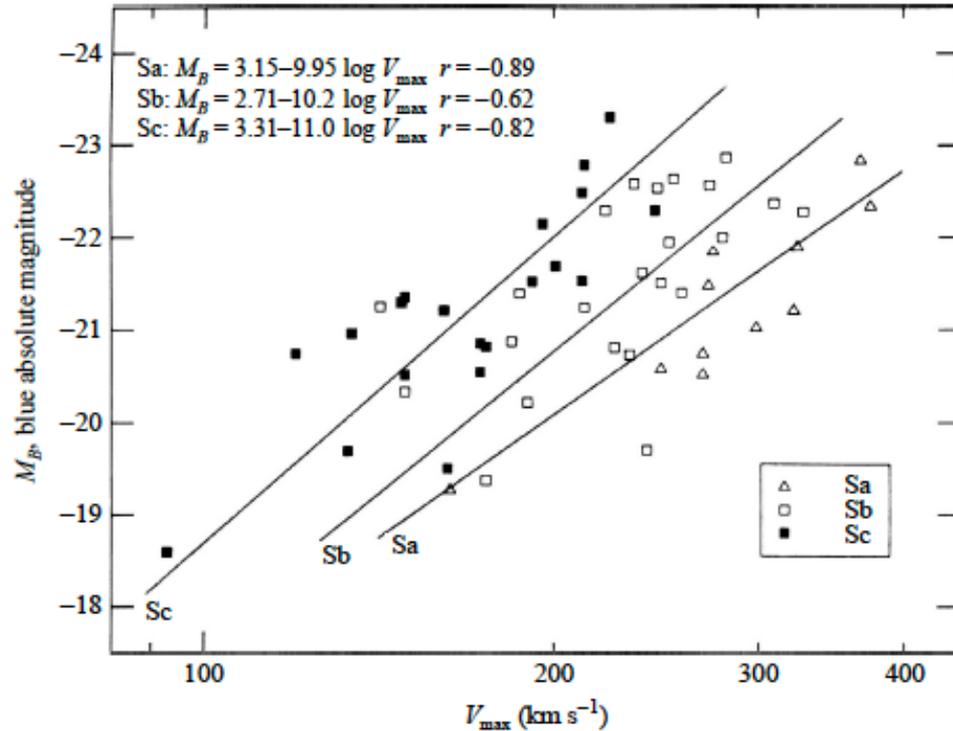


c NGC 1365: an SBc galaxy

# Characteristics of Early-Type Spiral Galaxies

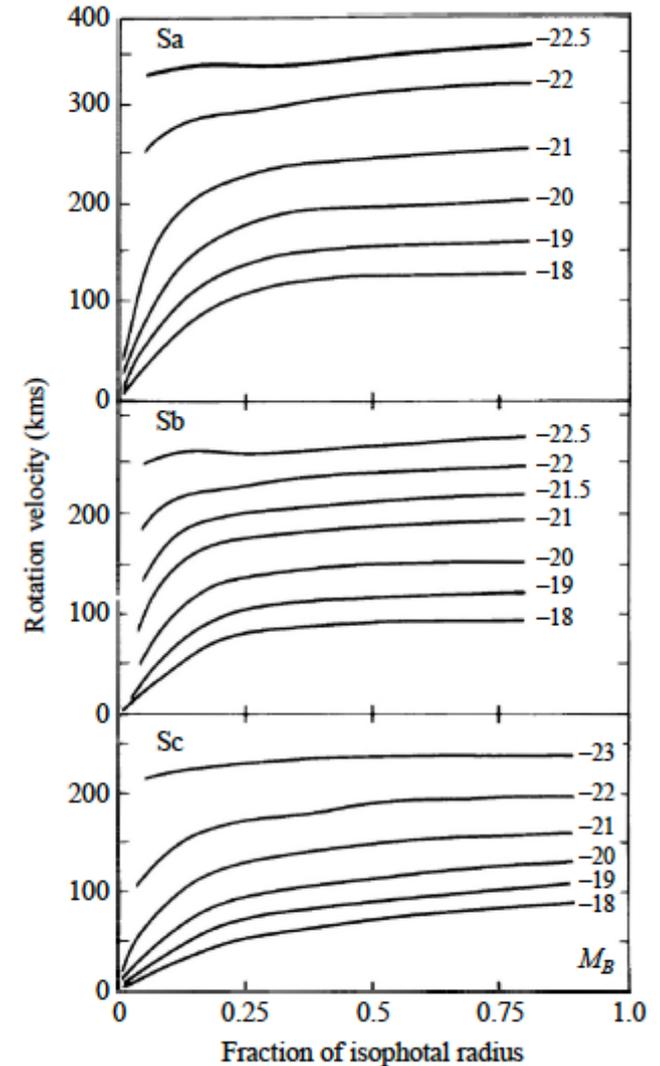
	Sa	Sb	Sc
$M_B$	-17 to -23	-17 to -23	-16 to -22
$M$ ( $M_\odot$ )	$10^9$ - $10^{12}$	$10^9$ - $10^{12}$	$10^9$ - $10^{12}$
$\langle L_{\text{bulge}}/L_{\text{total}} \rangle_B$	0.3	0.13	0.05
Diameter ( $D_{25}$ , kpc)	5-100	5-100	5-100
$\langle M/L_B \rangle$ ( $M_\odot/L_\odot$ )	$6.2 \pm 0.6$	$4.5 \pm 0.4$	$2.6 \pm 0.2$
$\langle V_{\text{max}} \rangle$ ( $\text{km s}^{-1}$ )	299	222	175
$V_{\text{max}}$ range ( $\text{km s}^{-1}$ )	163-367	144-330	99-304
pitch angle	$\sim 6^\circ$	$\sim 12^\circ$	$\sim 18^\circ$
$\langle B - V \rangle$	0.75	0.64	0.52
$\langle M_{\text{gas}}/M_{\text{total}} \rangle$	0.04	0.08	0.16
$\langle M_{\text{H}_2}/M_{\text{H I}} \rangle$	$2.2 \pm 0.6$ (Sab)	$1.8 \pm 0.3$	$0.73 \pm 0.13$
$\langle S_N \rangle$	$1.2 \pm 0.2$	$1.2 \pm 0.2$	$0.5 \pm 0.2$

# The Tully-Fisher Relation



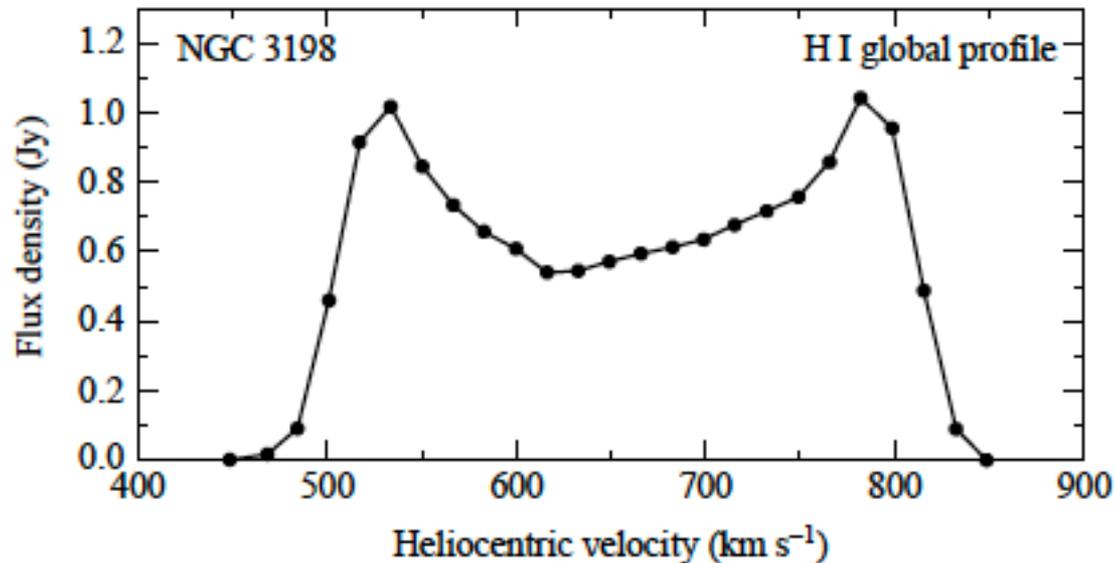
**Brighter spiral galaxies tend to have a larger maximum rotation velocity**

$$M \approx -10 \log_{10} V_{\max} + \text{constant}$$



# The Tully-Fisher Relation

- Can be used to estimate the distance to spiral galaxies by allowing the **luminosity** to be derived from its **directly measured line-width**
- Constitutes a rung of the **cosmic distance ladder**



# The Tully-Fisher Relation

Mass within radius R:  $M = \frac{V_{\max}^2 R}{G},$

Assuming the same mass-to-light ratio within a given galaxy type  $M/L \equiv 1/C_{\text{ML}}$

Then  $L = C_{\text{ML}} \frac{V_{\max}^2 R}{G}$

Further let's assume all spirals of a given galaxy type has the same surface brightness

$L/R^2 \equiv C_{\text{SB}}$       We have  $L = \frac{C_{\text{ML}}^2}{C_{\text{SB}}} \frac{V_{\max}^4}{G^2} = C V_{\max}^4$

$$M = M_{\text{Sun}} - 2.5 \log_{10} \left( \frac{L}{L_{\odot}} \right)$$

Absolute magnitude is  $= M_{\text{Sun}} - 2.5 \log_{10} V_{\max}^4 - 2.5 \log_{10} C + 2.5 \log_{10} L_{\odot}$   
 $= -10 \log_{10} V_{\max} + \text{constant}.$

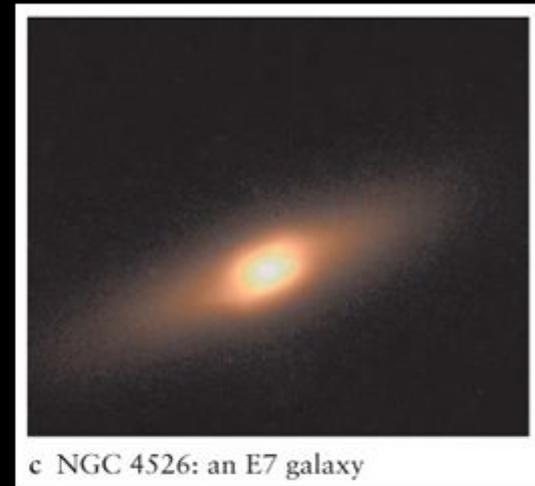
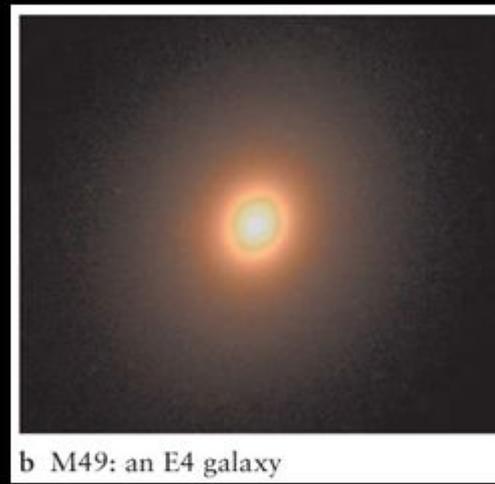
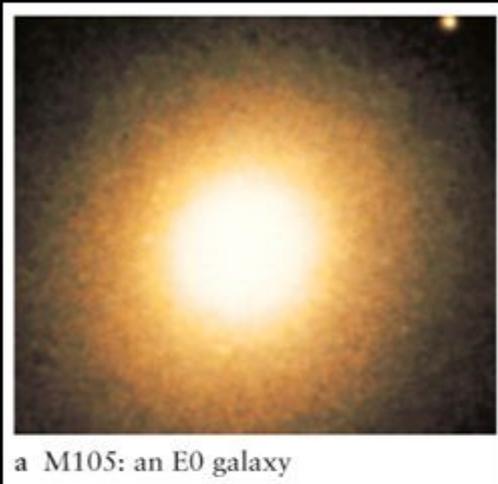
# Ellipticals

- Elliptical in shape
- Smooth light distribution – most of them are almost structureless
- Mostly old stars
- No or little gas – not much active star formation
- Red in color

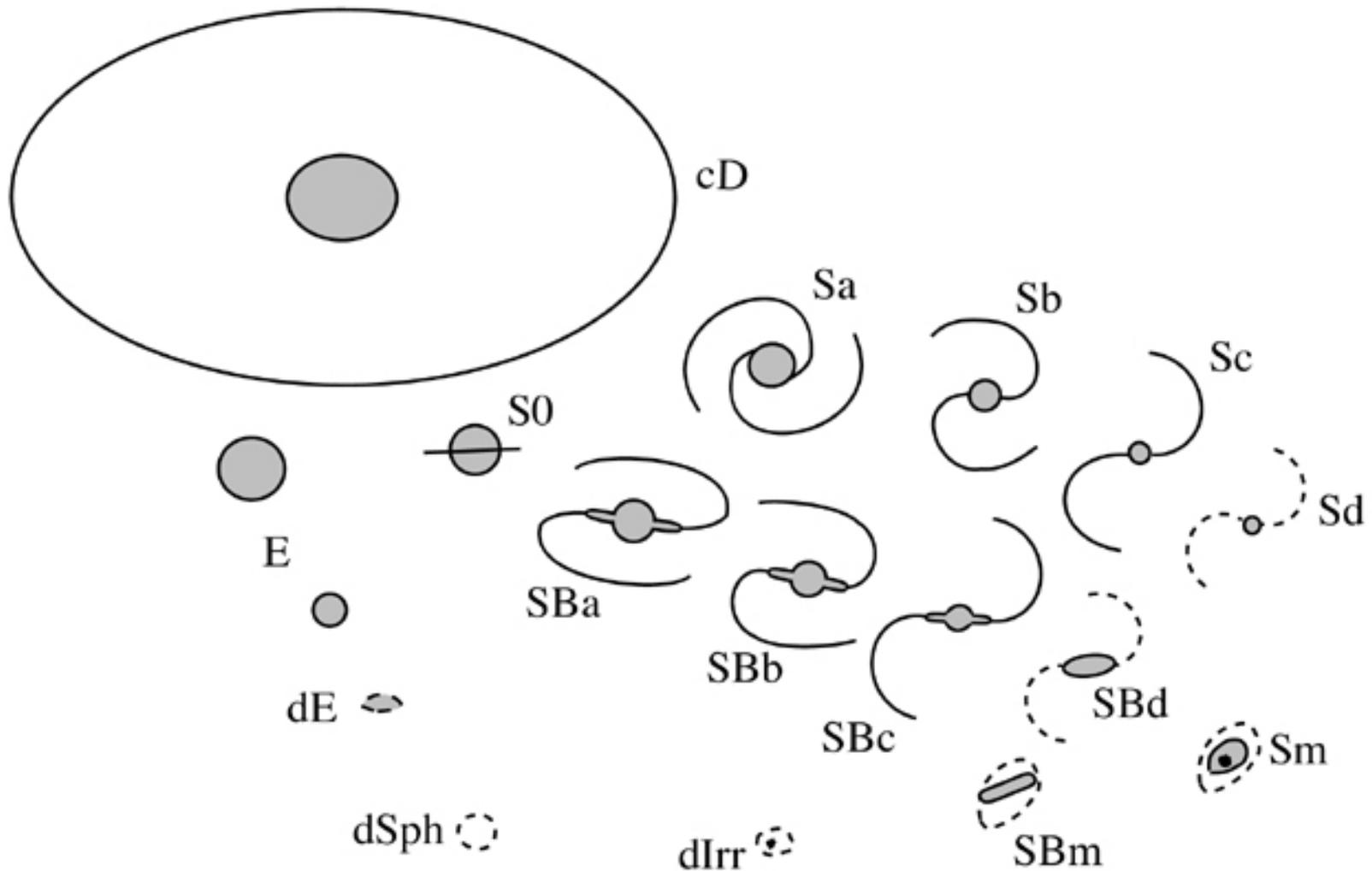


# Ellipticals: Hubble Classification

- Hubble type is largely based on **their apparent ellipticity** – later types are more elongated
- However, not very relevant in their intrinsic properties



# Ellipticals: Modified morphological classes



# Elliptical Galaxies: Properties

**TABLE 3** Characteristic Data for cD, Elliptical, and Lenticular Galaxies.

	cD	E	S0/SB0
$M_B$	-22 to -25	-15 to -23	-17 to -22
$M$ ( $M_\odot$ )	$10^{13}$ - $10^{14}$	$10^8$ - $10^{13}$	$10^{10}$ - $10^{12}$
Diameter ( $D_{25}$ , kpc)	300-1000	1-200	10-100
$\langle M/L_B \rangle$ ( $M_\odot/L_\odot$ )	> 100	10-100	$\sim 10$
$\langle S_N \rangle$	$\sim 15$	$\sim 5$	$\sim 5$

**TABLE 4** Characteristic Data for Dwarf Elliptical, Dwarf Spheroidal, and Blue Compact Dwarf Galaxies.

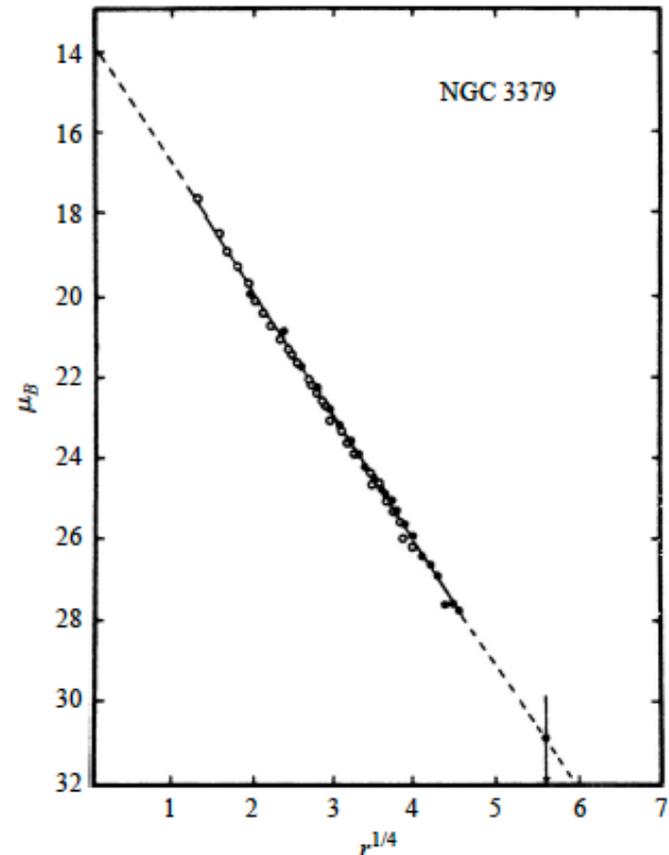
	dE	dSph	BCD
$M_B$	-13 to -19	-8 to -15	-14 to -17
$M$ ( $M_\odot$ )	$10^7$ - $10^9$	$10^7$ - $10^8$	$\sim 10^9$
Diameter ( $D_{25}$ , kpc)	1-10	0.1-0.5	< 3
$\langle M/L_B \rangle$ ( $M_\odot/L_\odot$ )	$\sim 10$	5-100	0.1-10
$\langle S_N \rangle$	$4.8 \pm 1.0$	—	—

# Surface Brightness Profile

- cD's and normal ellipticals have surface brightness profiles that follow the  $r^{1/4}$  law, also referred to as the de Vaucouleurs profile:

$$\mu(r) = \mu_e + 8.3268 \left[ \left( \frac{r}{r_e} \right)^{1/4} - 1 \right].$$

- $r_e$  is the radius within which  $\frac{1}{2}$  of the light is emitted
- Interestingly, bulges of spiral galaxies also follow this law
- May arise from frequent random interactions of stars

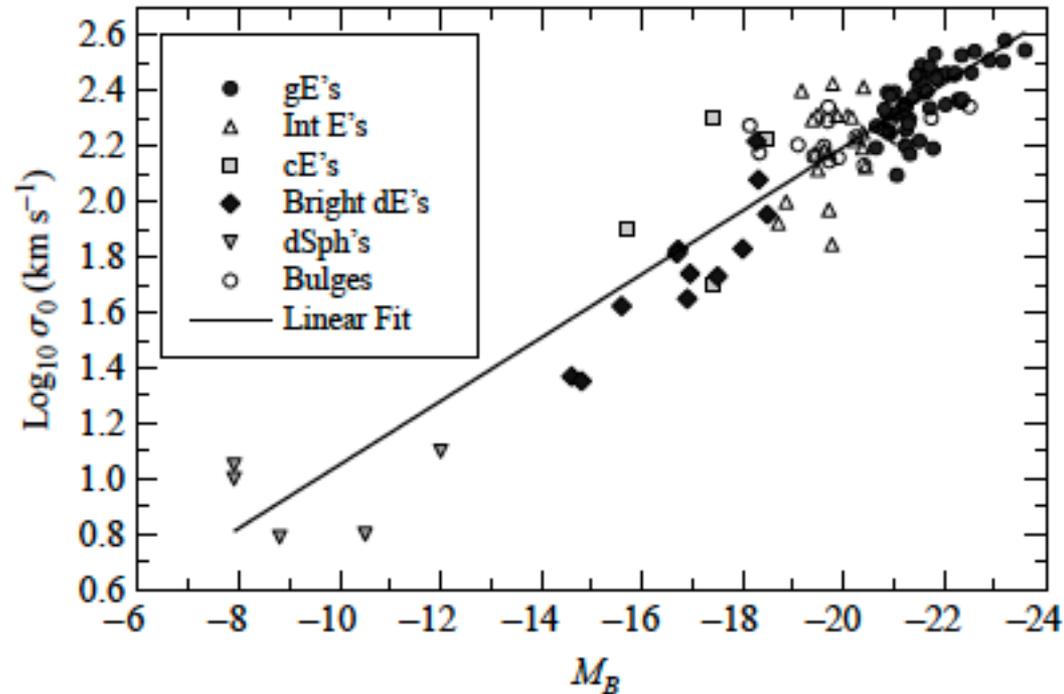


# The Faber-Jackson Relation

- Motion of the stars is rather random in all directions
- Similar to Tully-Fisher for spirals, but the velocity is now the **velocity dispersion** of stars

$$L \propto \sigma_0^4,$$

$$\log_{10} \sigma_0 = -0.1M_B + \text{constant}.$$



The Faber-Jackson Relation

# 24.1 Hubble's Galaxy Classification

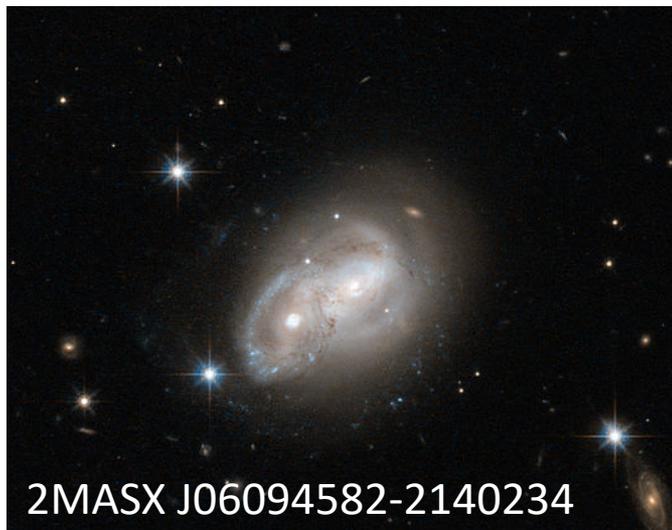
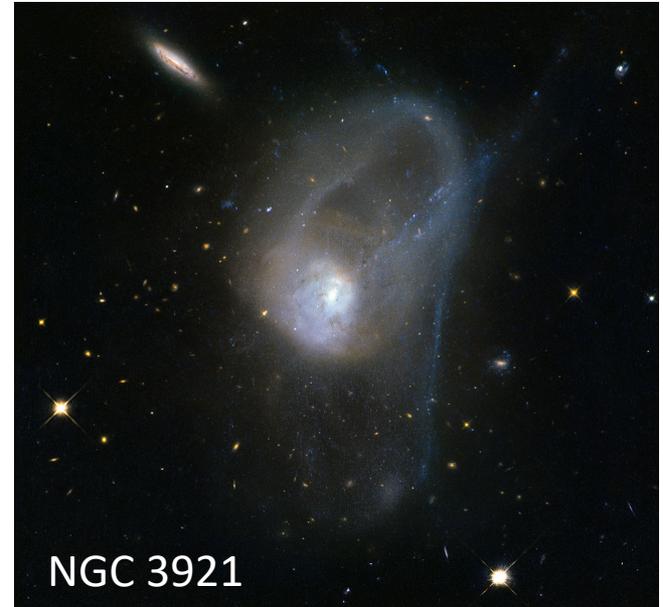
## A summary of galaxy properties by type:

**TABLE 24.1 Galaxy Properties by Type**

	<b>Spiral/Barred Spiral (S/SB)</b>	<b>Elliptical<sup>1</sup> (E)</b>	<b>Irregular (Irr)</b>
Shape and structural properties	Highly flattened disk of stars and gas, containing spiral arms and thickening central bulge. Sa and SBa galaxies have the largest bulges, the least obvious spiral structure, and roughly spherical stellar halos. SB galaxies have an elongated central “bar” of stars and gas.	No disk. Stars smoothly distributed through an ellipsoidal volume ranging from nearly spherical (E0) to very flattened (E7) in shape. No obvious substructure other than a dense central nucleus.	No obvious structure. Irr II galaxies often have “explosive” appearances.
Stellar content	Disks contain both young and old stars; halos consist of old stars only.	Contain old stars only.	Contain both young and old stars.
Gas and dust	Disks contain substantial amounts of gas and dust; halos contain little of either.	Contain hot X-ray emitting gas, little or no cool gas and dust.	Very abundant in gas and dust.
Star formation	Ongoing star formation in spiral arms.	No significant star formation during the last 10 billion years.	Vigorous ongoing star formation.
Stellar motion	Gas and stars in disk move in circular orbits around the galactic center; halo stars have random orbits in three dimensions.	Stars have random orbits in three dimensions.	Stars and gas have highly irregular orbits.

<sup>1</sup>As noted in the text, some giant ellipticals appear to be the result of collisions between gas-rich galaxies and are exceptions to many of the statements listed here.

# Interactions of Galaxies



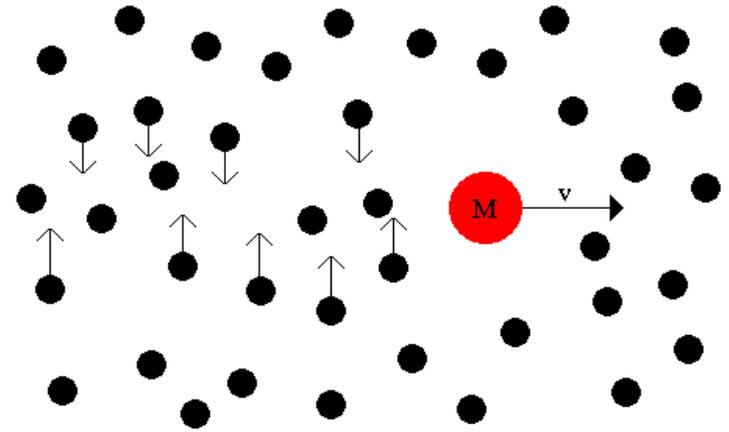
# Interactions of Galaxies: How?

- (Gravitational) dynamic friction

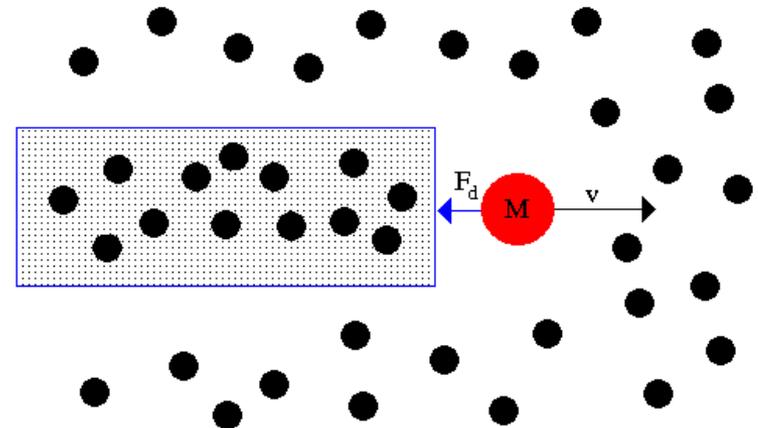
Also known as Chandrasekhar friction (first discussed by Subrahmanyan Chandrasekhar in 1943)

$$f_d \simeq C \frac{G^2 M^2 \rho}{v_M^2},$$

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

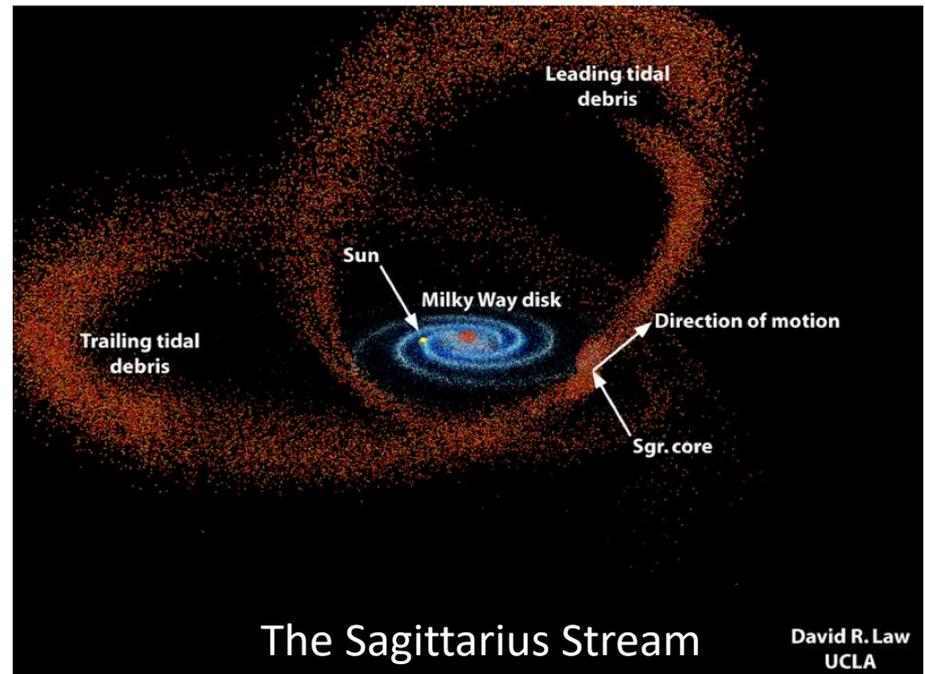
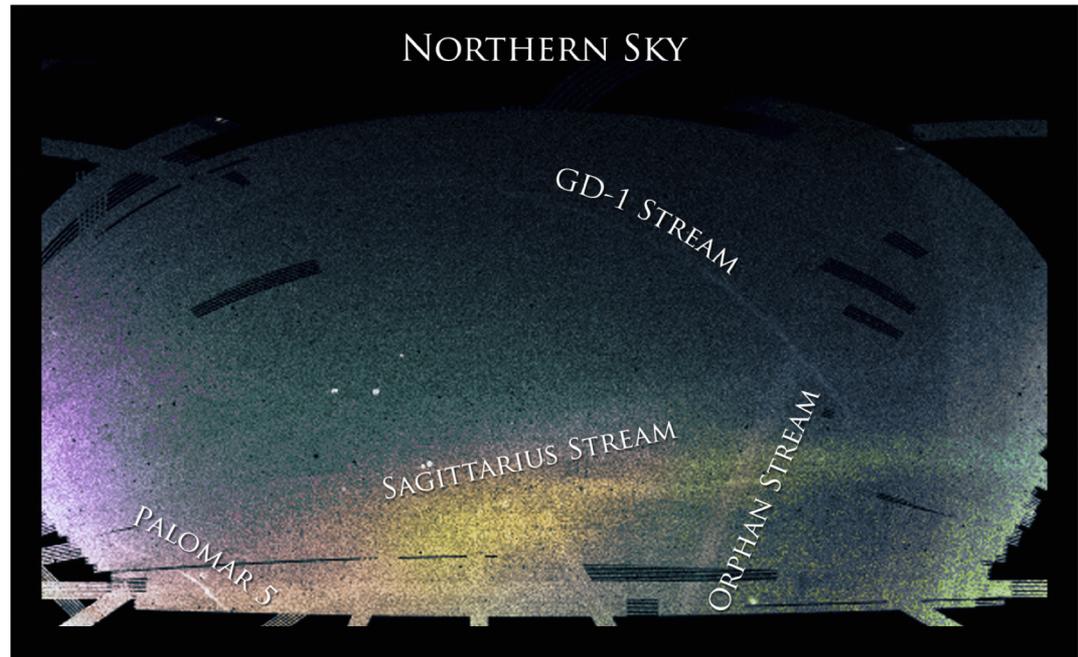


this results in an enhanced region of density behind the mass, with a drag force,  $F_d$  known as dynamical friction

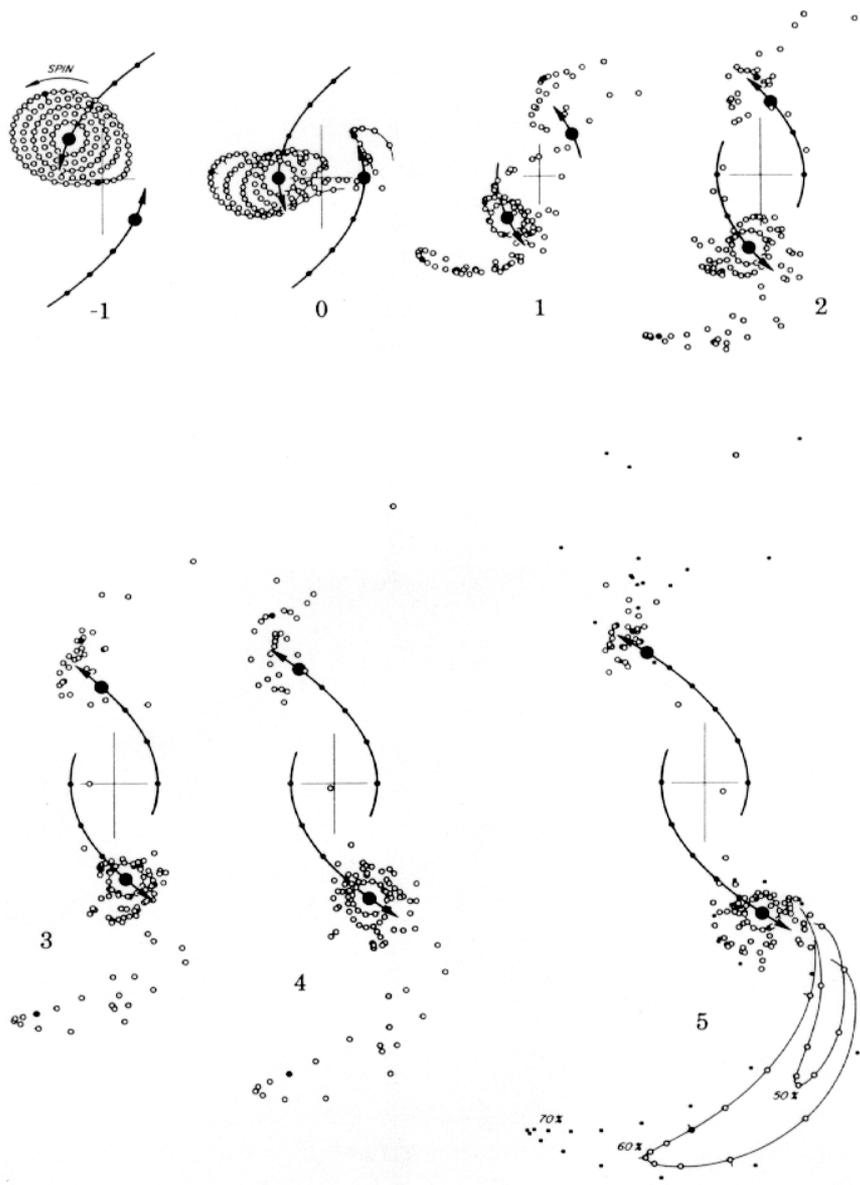


# Interactions of Galaxies: Dynamic Friction

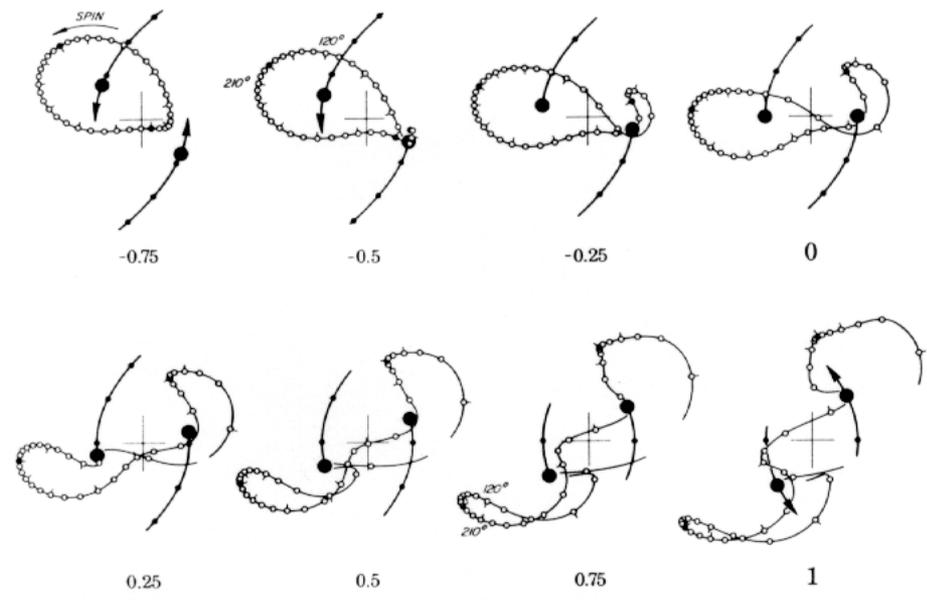
- A small galaxy that passes through the envelope of a larger galaxy will experience this friction force
- The small galaxy loses energy and spiral inward and gets “cannibalized”
- Our Milky Way Galaxy may have consumed numerous galaxies during its lifetime
- Some remnants are still observed today



# Merging Galaxies

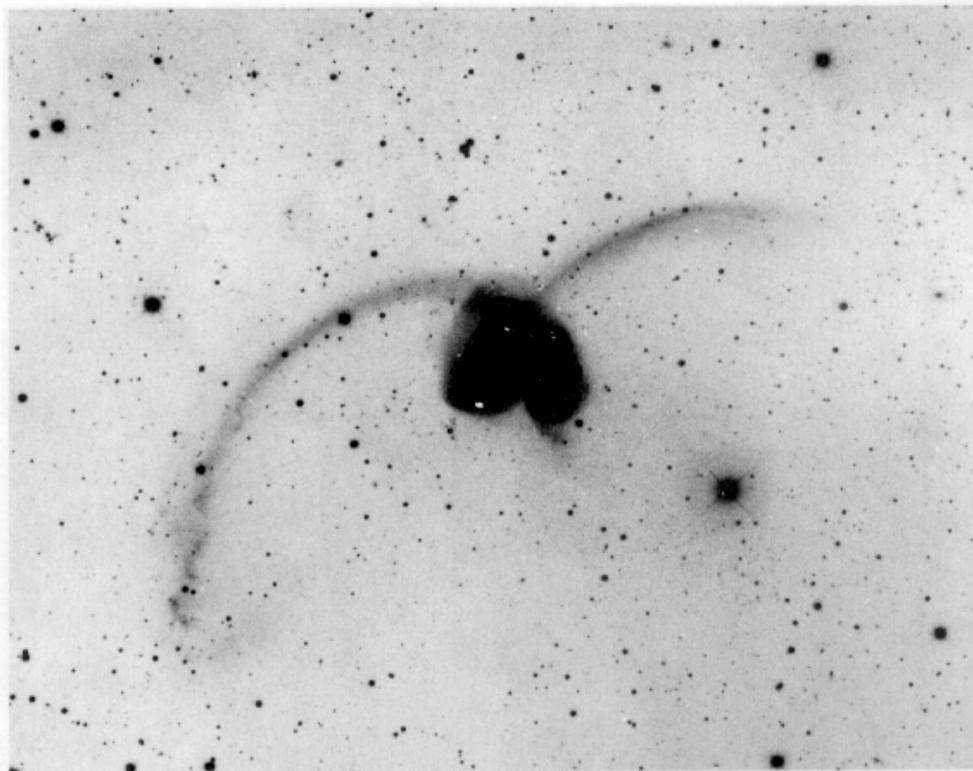


**Figure 7-14.** The same setup as that shown in Figure 7-13 except that the disk of test particles now corotates with the binary orbit. Reproduced from Toomre and Toomre (1972) by permission of *The Astrophysical Journal*.

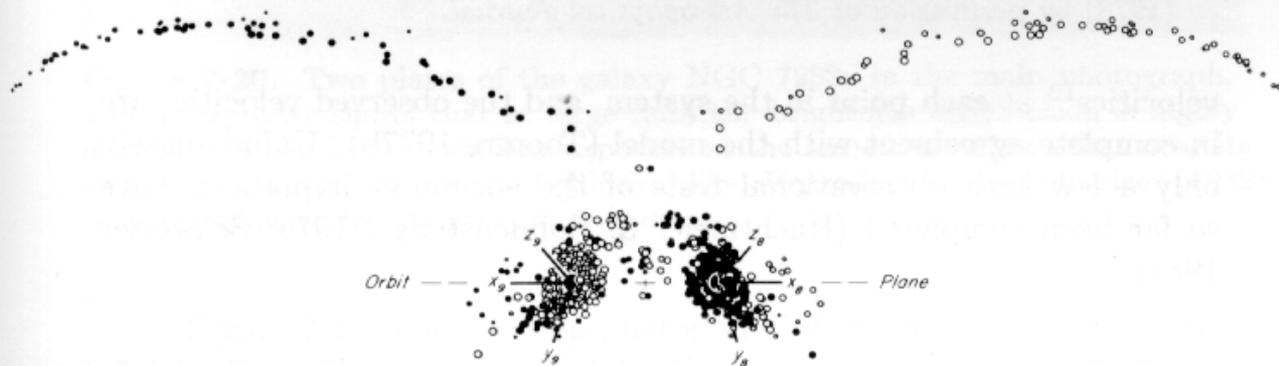


**Figure 7-15.** A slow-motion replay of the destruction of the outermost ring in Figure 7-14. Reproduced from Toomre and Toomre (1972) by permission of *The Astrophysical Journal*.

N-body simulation by Toomre brothers 1972



**Figure 7-17.** The interacting galaxies NGC 4038 and NGC 4039. Courtesy of D. F. Malin and Kitt Peak National Observatory.

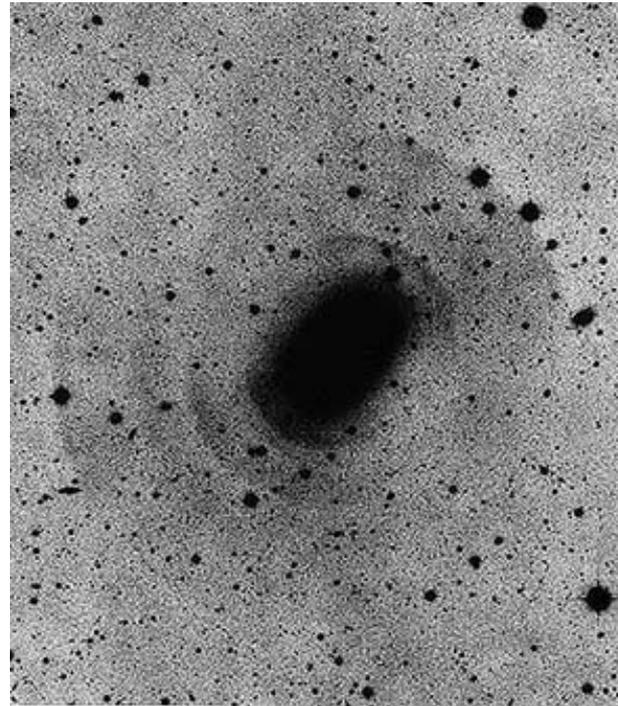


**Figure 7-18.** A model of the NGC 4038/4039 pair by Toomre and Toomre (1972). Reproduced by permission of *The Astrophysical Journal*.



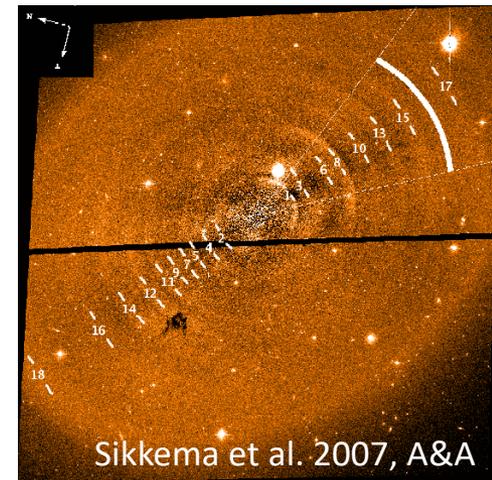
# Mergers in Ellipticals and cD Galaxies

- Mergers in disk spiral galaxies are usually more clear because they are the most susceptible to long tidal features
- Ellipticals, featured by rather random velocity distributions, is difficult to develop thin interaction features
- However, enhanced imaging in 1980s showed very faint, sharp-edged shells around some ellipticals



NGC 3923

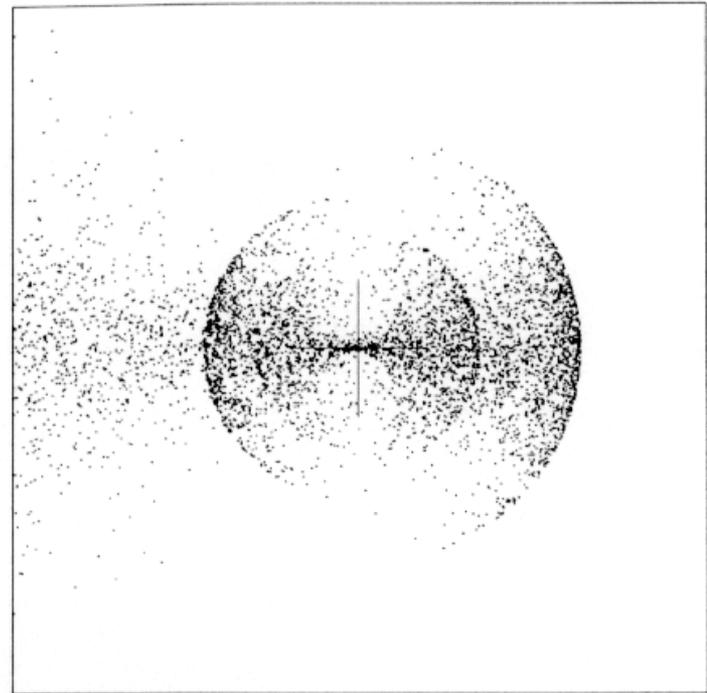
NGC 3923: Residual Image



Sikkema et al. 2007, A&A

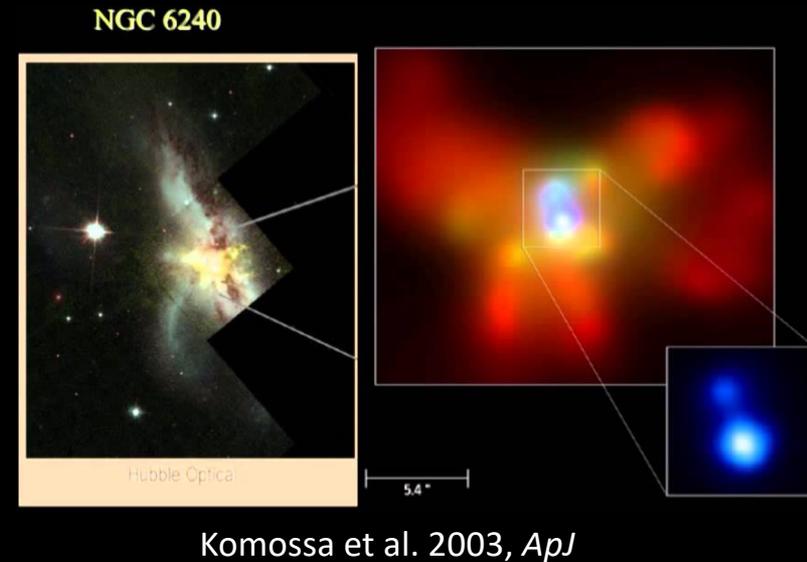
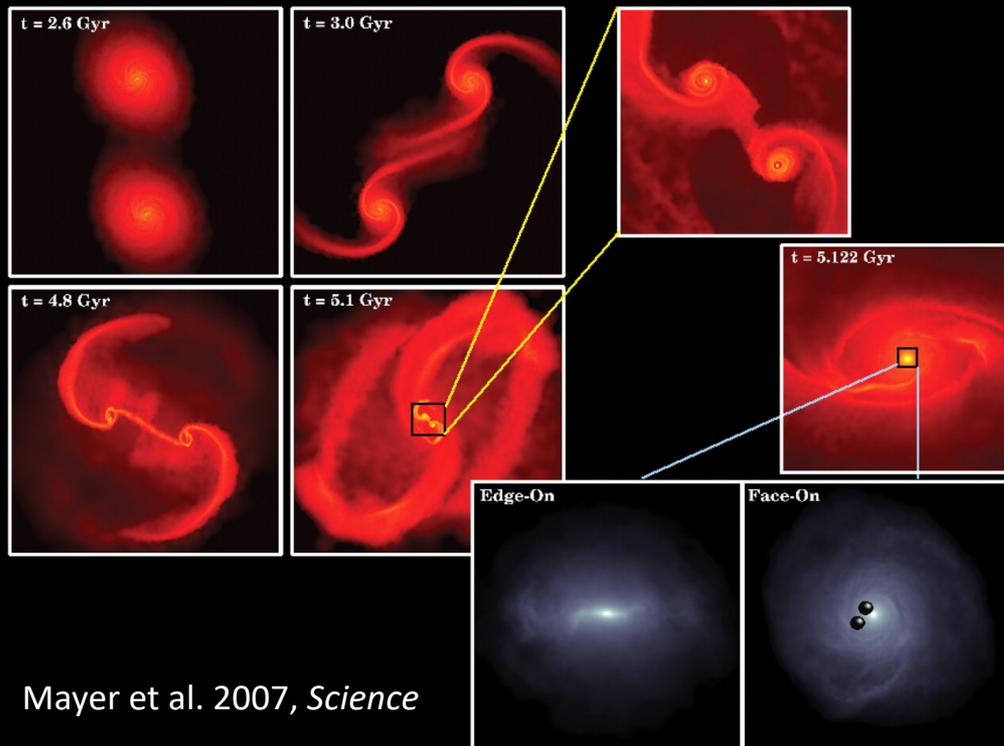
# Mergers in Ellipticals and cD Galaxies

The N-body theorists went cheerfully back to their machines to show that shells in “hot” galaxies (ellipticals with high internal velocity dispersions) where due to the infall of “cold” disks (spirals with coherent, rotational phase space shapes).



**Figure 7-23.** Ripples like those shown in Figure 7-22 are formed when a numerical disk galaxy is tidally disrupted by a fixed galaxy-like potential. (See Hernquist & Quinn 1987.)

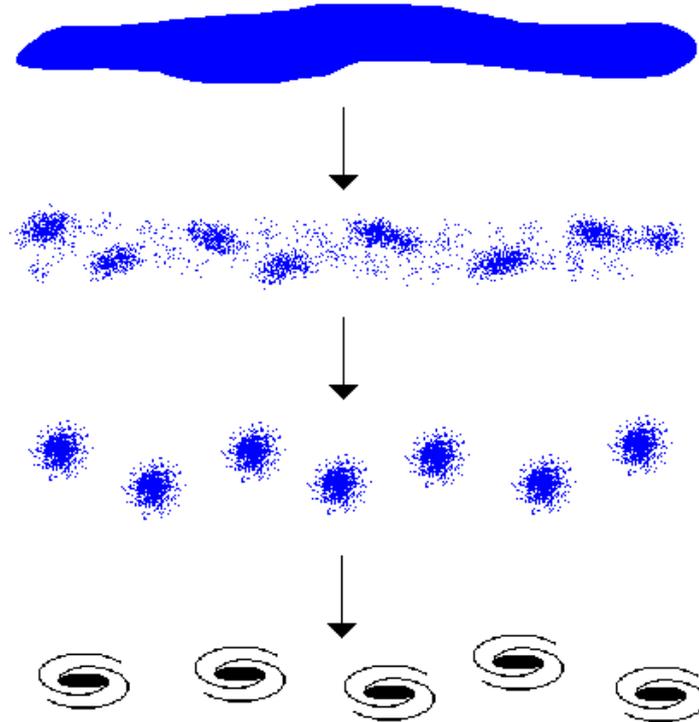
# Binary Supermassive Blackholes



# Galaxy Formation: Top-Down Scenario

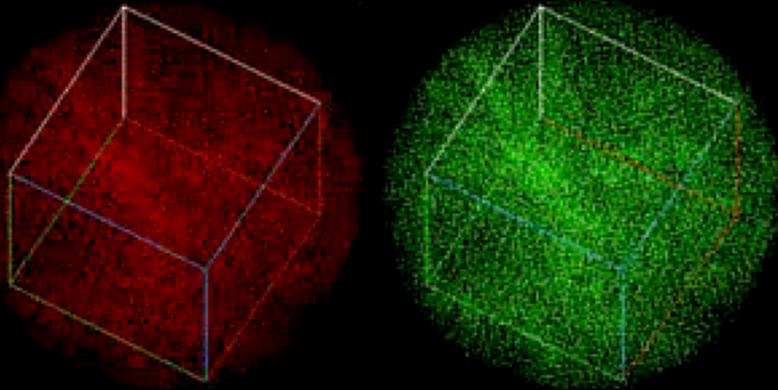
## Top-Down Structure Formation

in a top-down scenario, large pancakes of matter form first, then fragment into galaxy-sized lumps



From [Prof. Rafael Guzman's website](#)

$z: 20.7$



Gas

Dark Matter

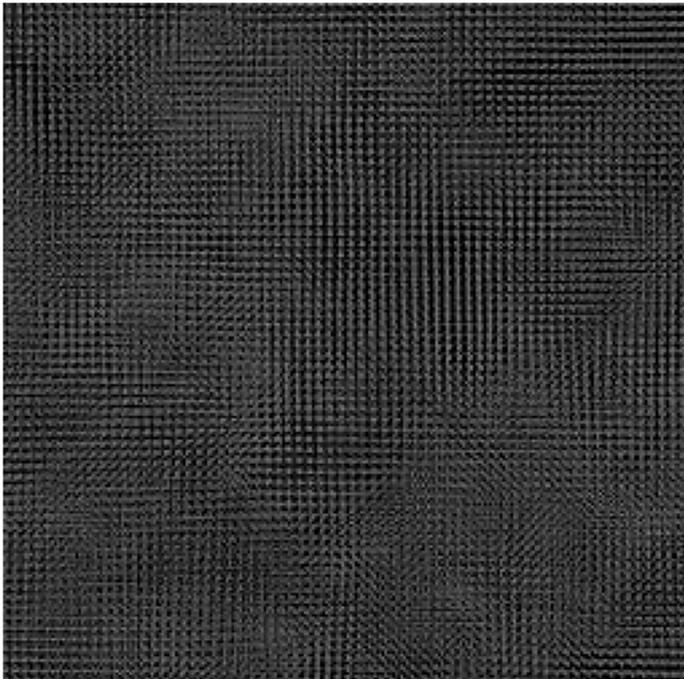
The Eggen, Lynden-Bell, Sandage Collapse Model

- Old halo stars form early during the collapse
- Disk stars form later as the collapse gas settled into the disk

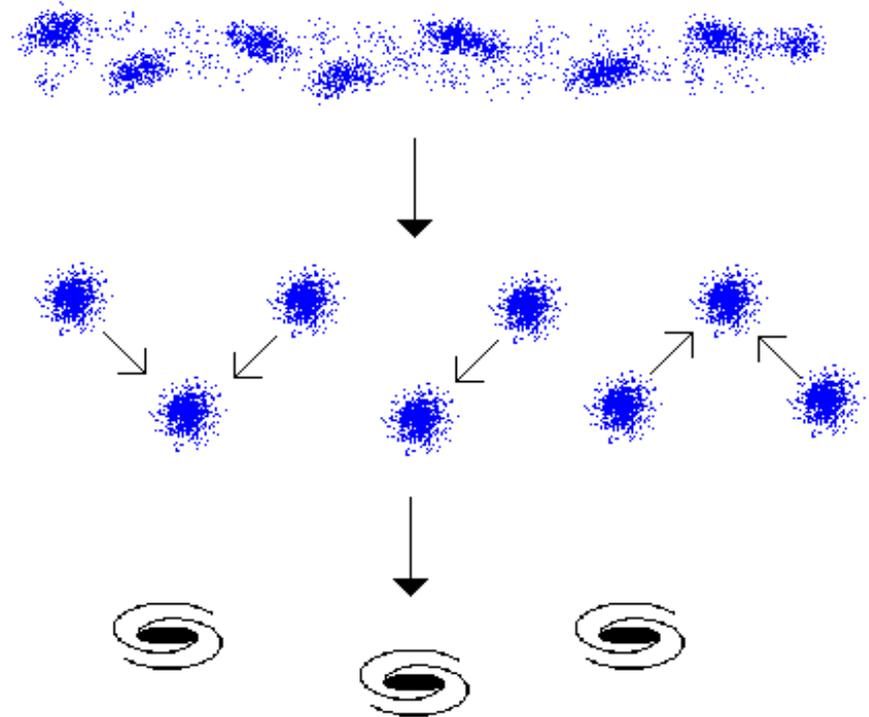
# Galaxy Formation: Bottom-Up Scenario

## Bottom-Up Structure Formation

in a bottom-up scenario, small, dwarf galaxy-sized lumps form first, then merger to make galaxies and clusters of galaxies

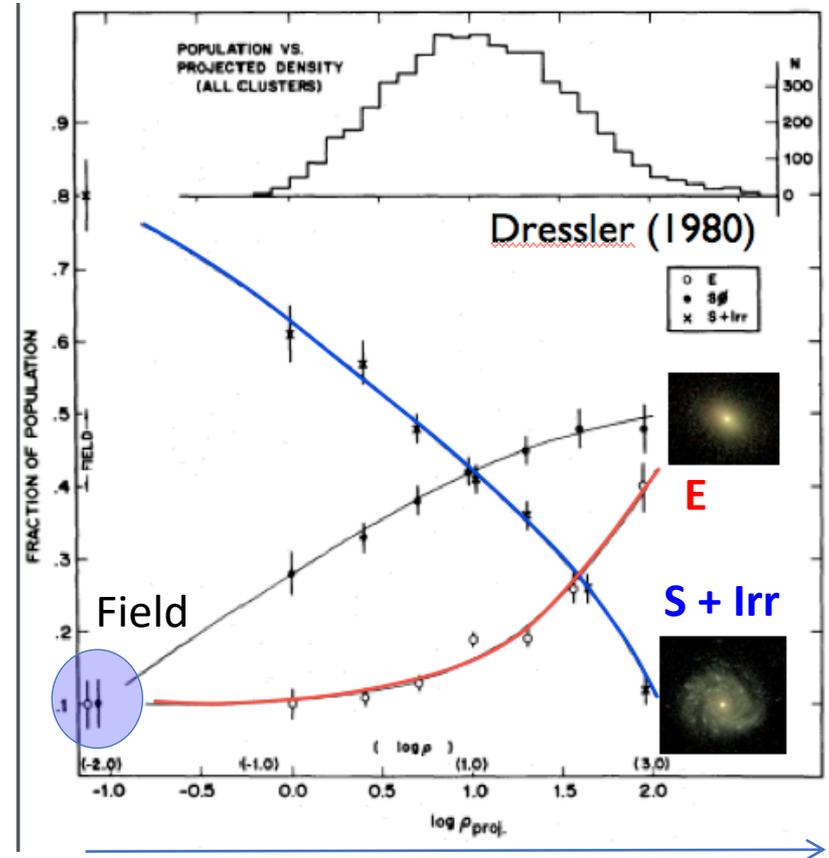
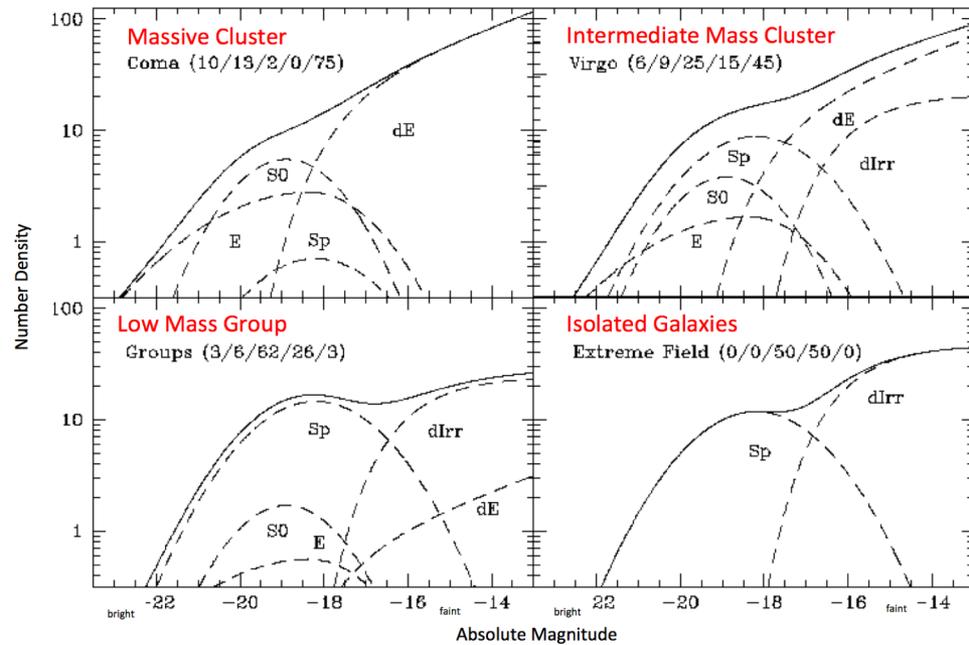


The Hierarchical Merger Model



From [Prof. Rafael Guzman's website](#)

# Morphology-Density Relation



Denser clusters

# Formation of Elliptical Galaxies

Two Spirals



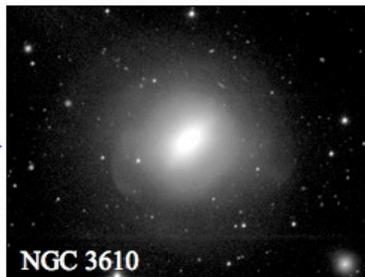
~1 Gyr

Chaotic



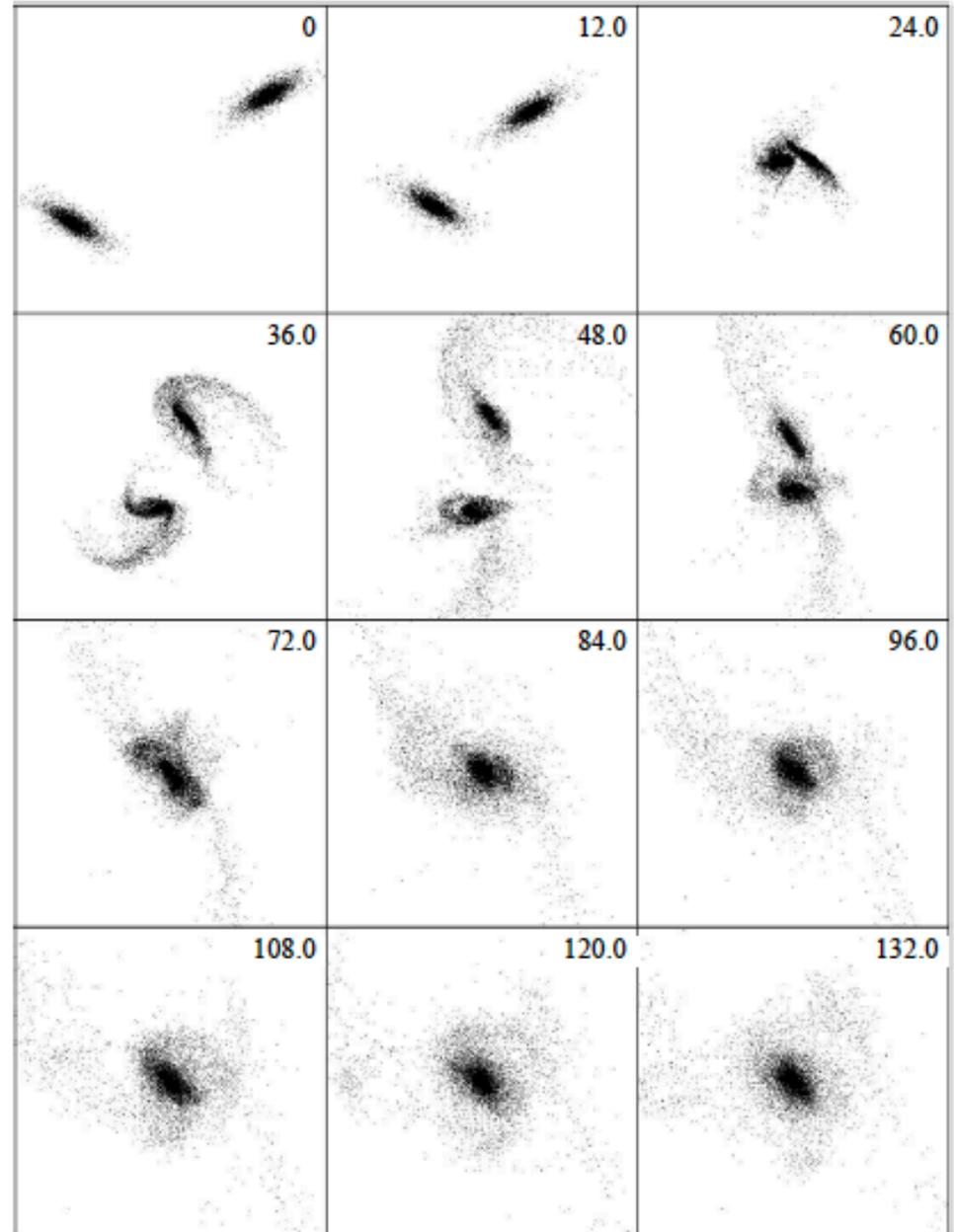
~1 Gyr

Faint Shells



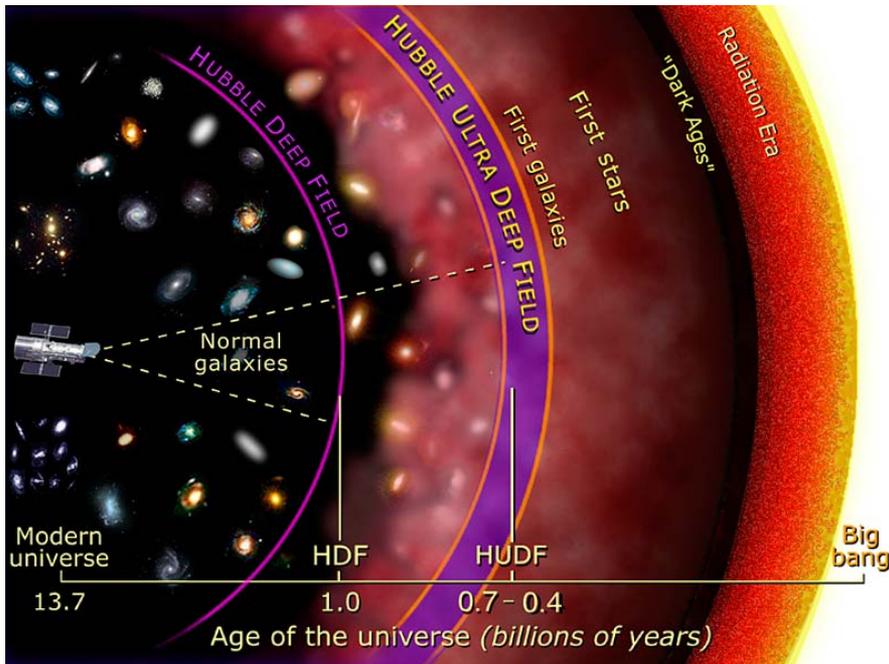
~1 Gyr

Normal Elliptical

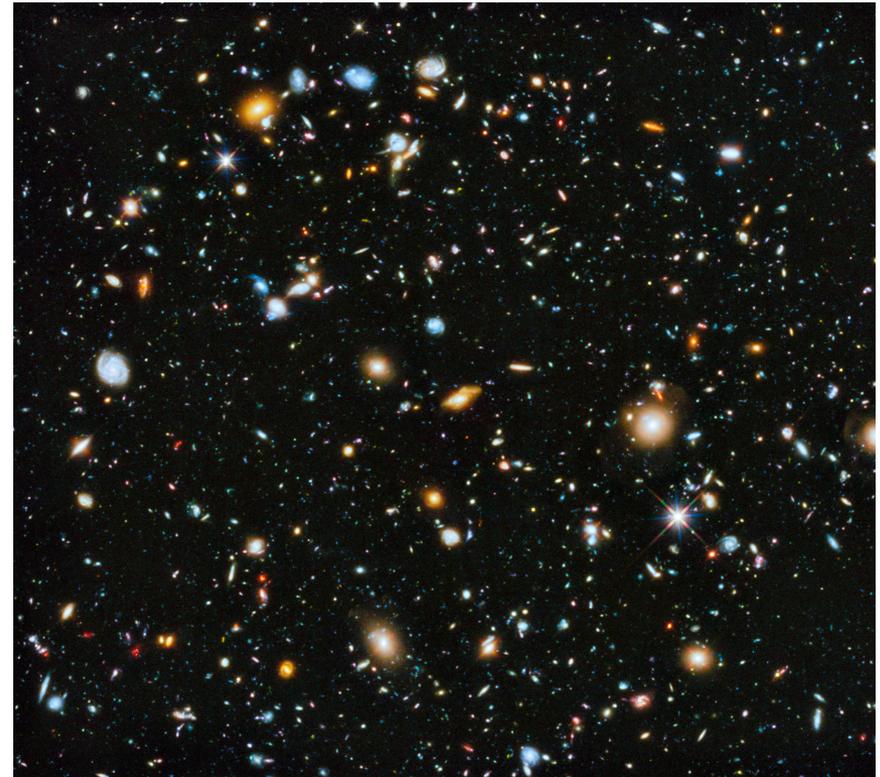


# Galaxy Formation in the Early Universe

Hubble Ultra Deep Field



Looking back in time..



2.4 arcminute x 2.4 arcminute area (1/10 size of Moon); 11.3-day exposure for ACS and 4.5 days for NICMOS

# Development of Massive Elliptical Galaxies

