Phys 321: Lecture 9

Nature of Galaxies

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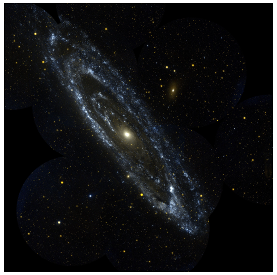
The Great Debate

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



M31 (Andromeda Galaxy)

M101 Pinwheel Galaxy

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

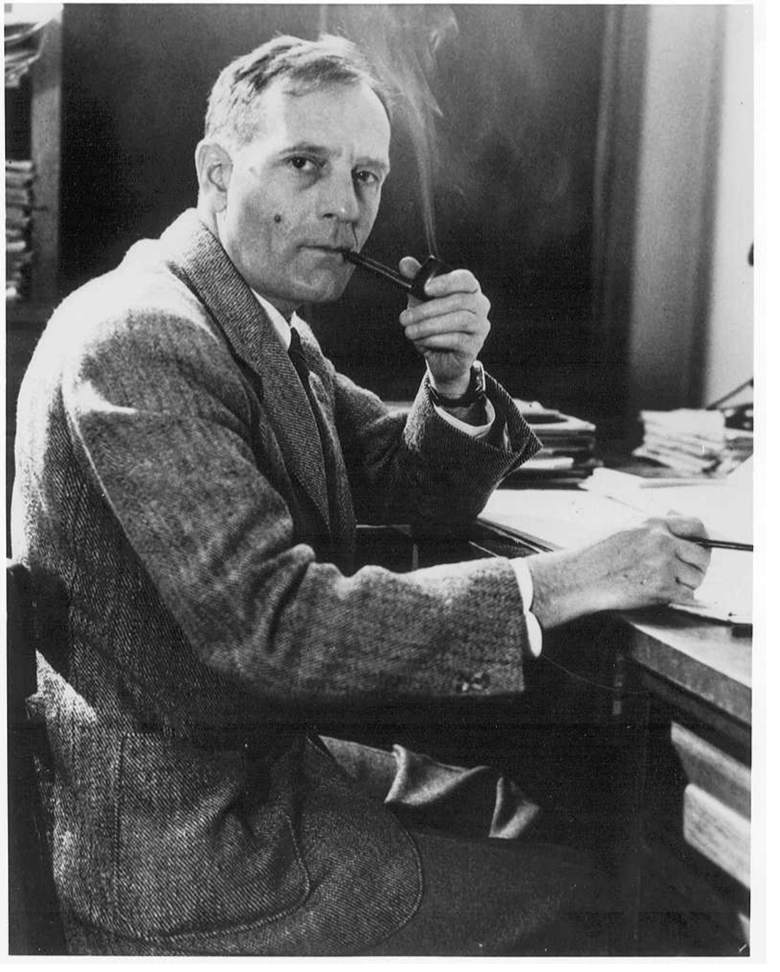
Harlow Shapley Heber Curtis

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 estimate 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

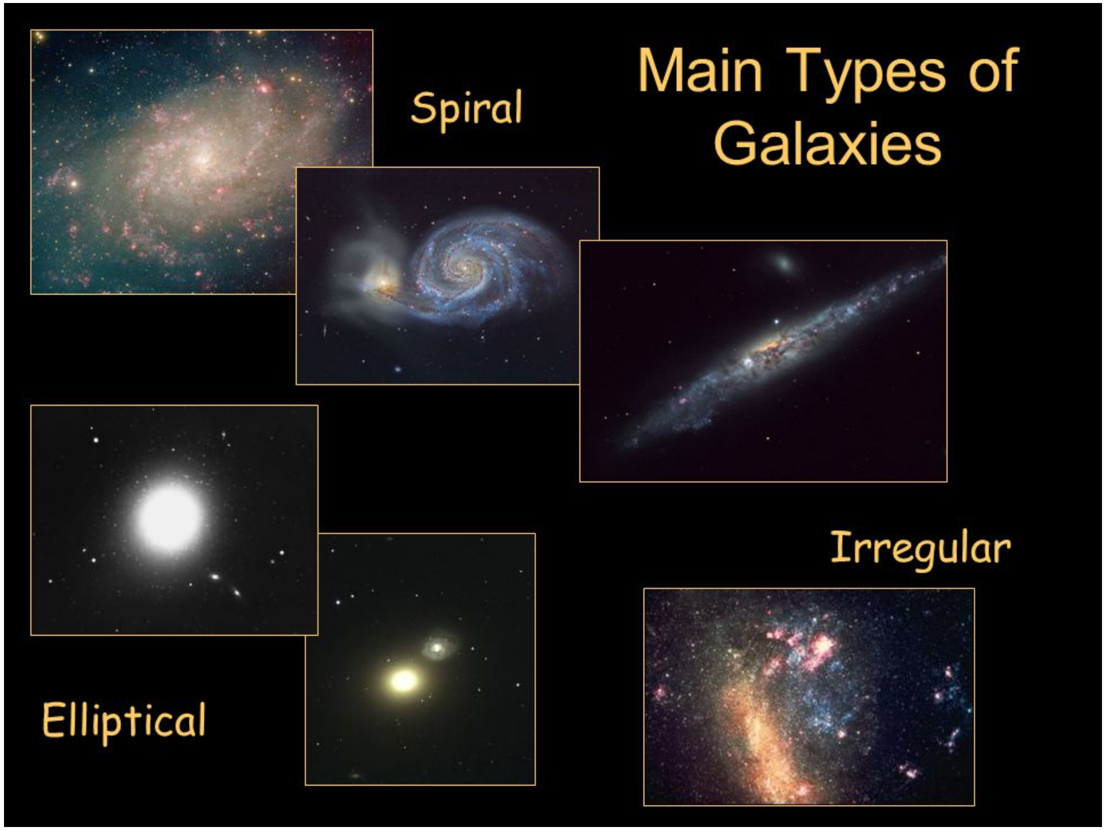
- Debate settled in 1923 when **Edwin Hubble** detected Cepheid variables stars (a "standard candle") in M31 and determined its distance to be several hundreds of kpc

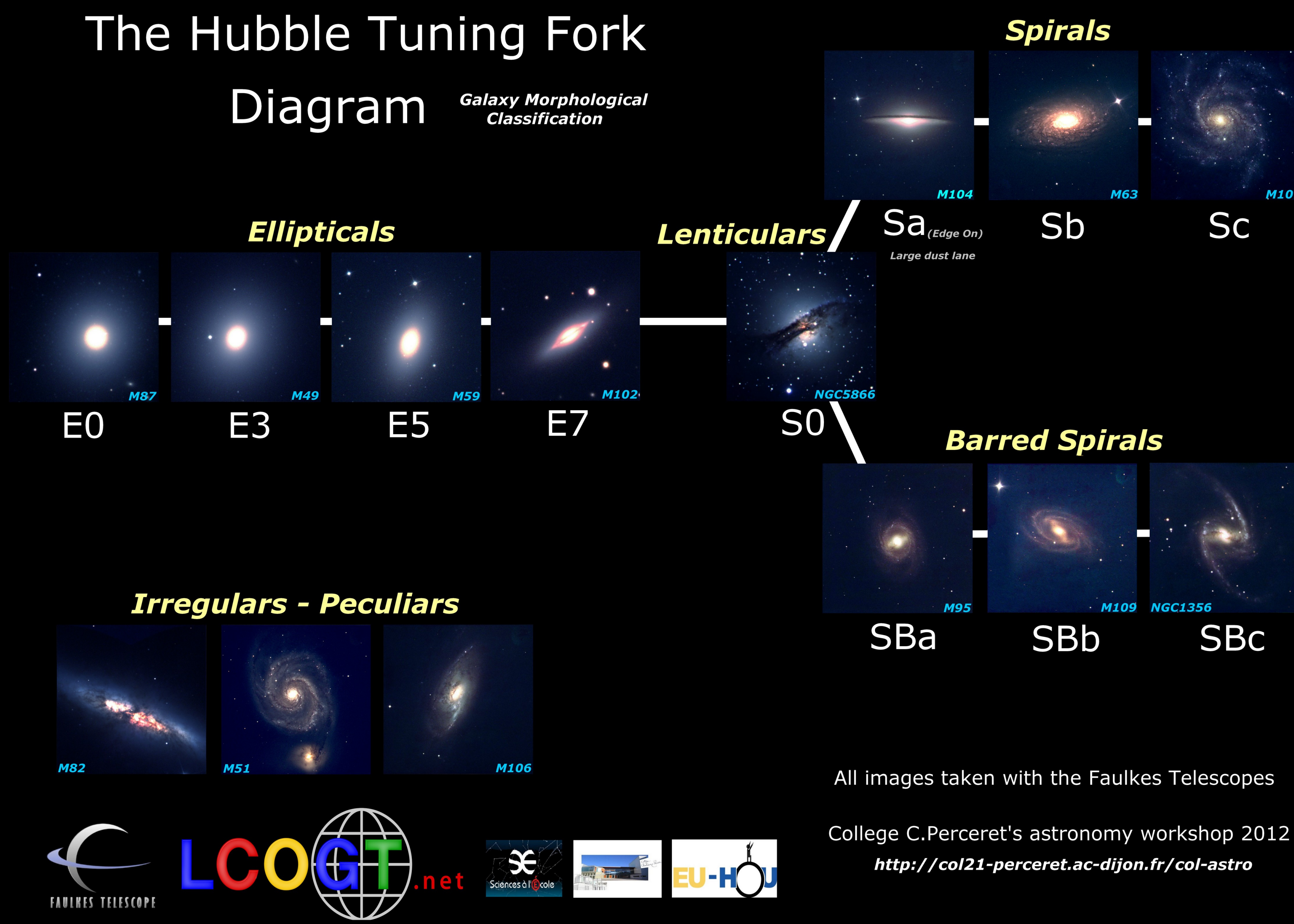


Edwin Hubble

A zoo of galaxies

- Ellipticals
- Spirals
- Lenticulars
- Irregulars
- Interacting/Merging galaxies
- Test yourself!




The Hubble Tuning Fork Diagram
Galaxy Morphological Classification
Spirals
M104
M63
M101
Sa (Edge On)
Large dust lane
Sb
Sc
Ellipticals
Lenticulars
M87
M49
M59
M102
NGC5866
E0
E3
E5
E7
S0
Barred Spirals
M95
M109
NGC1356
SBa
SBb
SBc
Irregulars - Peculiars
M82
M51
M106
All images taken with the Faulkes Telescopes
College C.Perceret's astronomy workshop 2012
http://col21-perceret.ac-dijon.fr/col-astro
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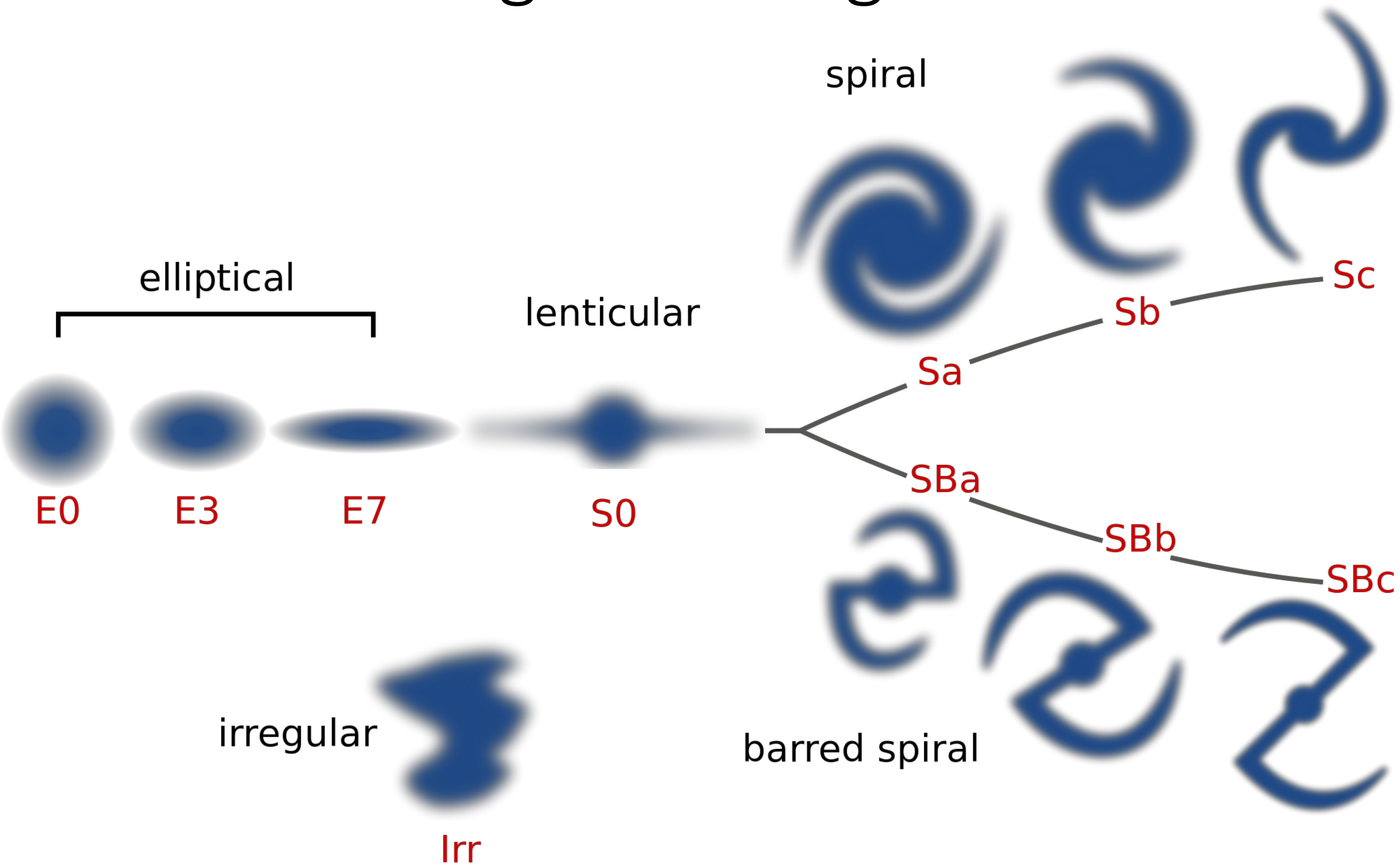
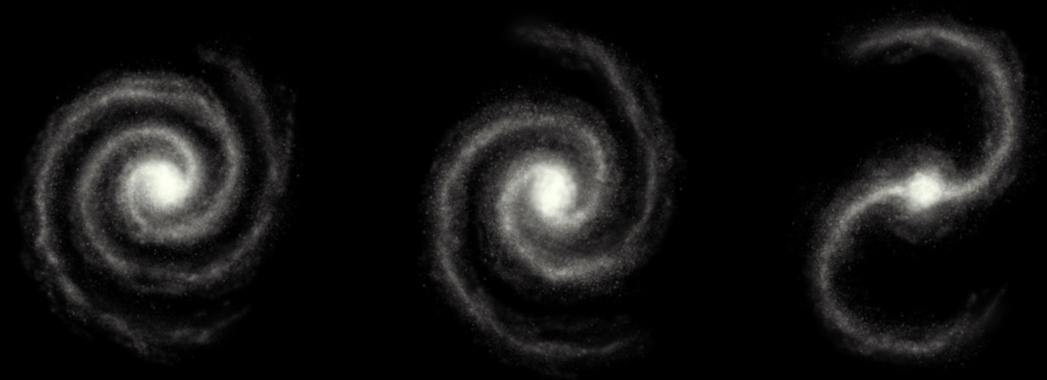
Hubble Tuning-Fork Diagram



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

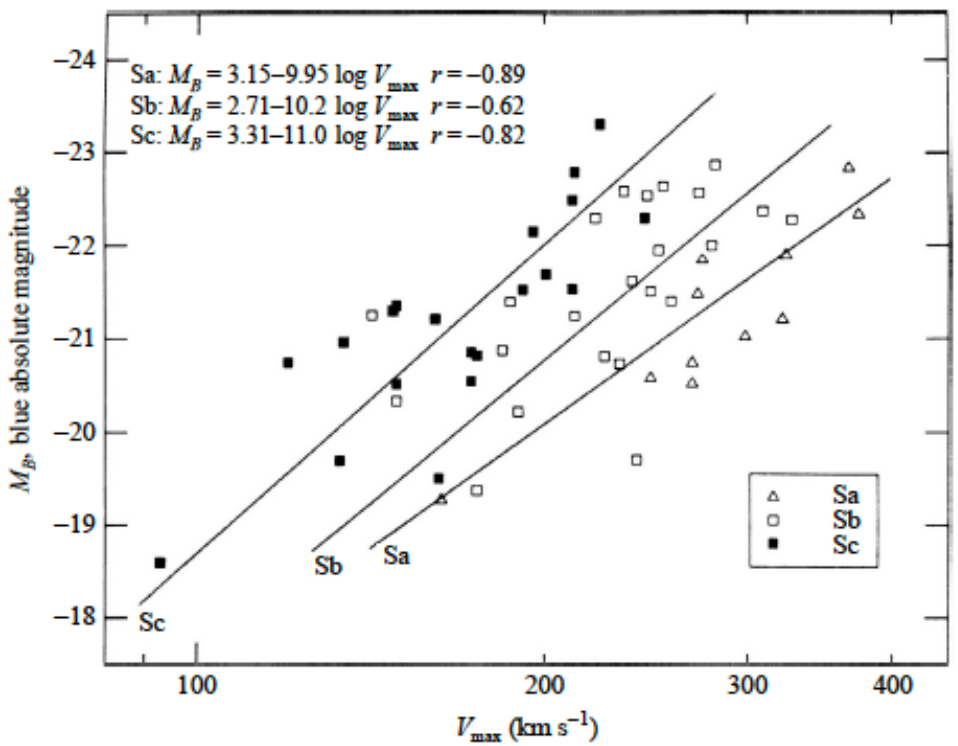
b M83: an SBb galaxy

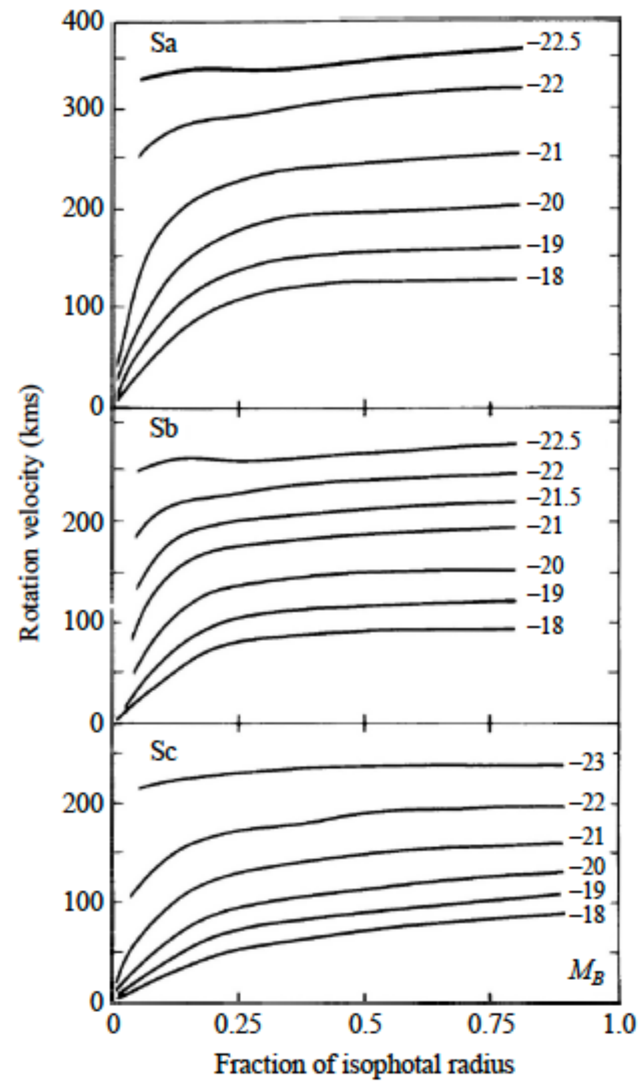
c NGC 1365: an SBc galaxy

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}
$\langle L_{\rm bulge}/L_{\rm total}\rangle_B$	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 ± 0.6	4.5 ± 0.4	2.6 ± 0.2
$\langle V_{\rm max}\rangle$ (km s^{-1})	299	222	175
$V_{\rm max}$ range (km s^{-1})	163–367	144–330	99–304
pitch angle	$\sim 6°$	$\sim 12°$	$\sim 18°$
$\langle B - V\rangle$	0.75	0.64	0.52
$\langle M_{\rm gas}/M_{\rm total}\rangle$	0.04	0.08	0.16
$\langle M_{H_2}/M_{\rm H\,I}\rangle$	2.2 ± 0.6 (Sab)	1.8 ± 0.3	0.73 ± 0.13
$\langle S_N\rangle$	1.2 ± 0.2	1.2 ± 0.2	0.5 ± 0.2

The Tully-Fisher Relation



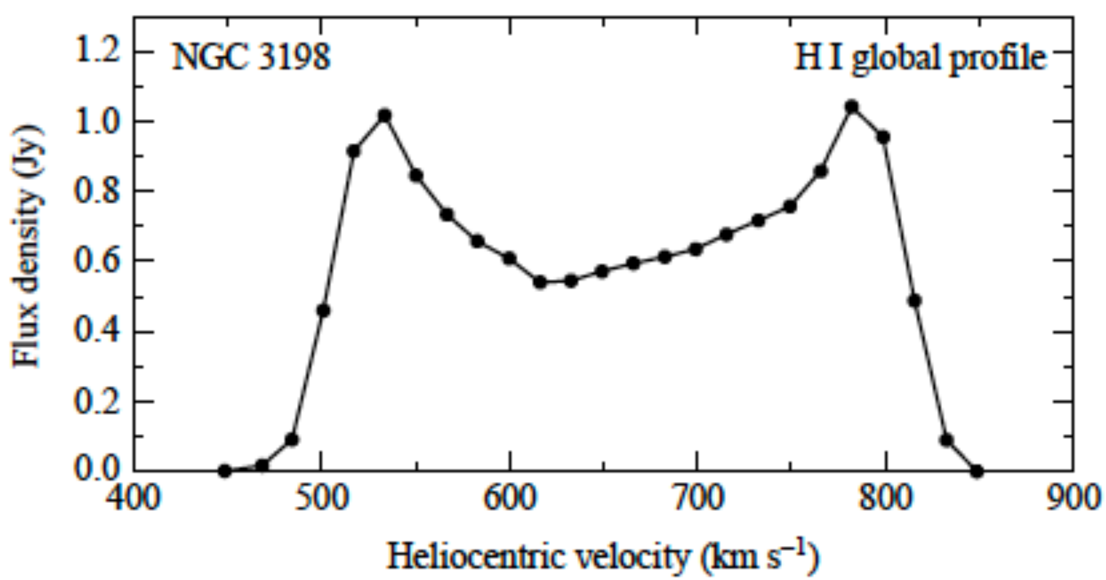


Brighter spiral galaxies tend to have a **larger maximum rotation velocity**

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

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: $M = \frac{V_{\rm max}^2 R}{G},$

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

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

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

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

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

Absolute magnitude is

$$= M_{\rm Sun} - 2.5 \log_{10} V_{\rm max}^4 - 2.5 \log_{10} C + 2.5 \log_{10} L_\odot$$

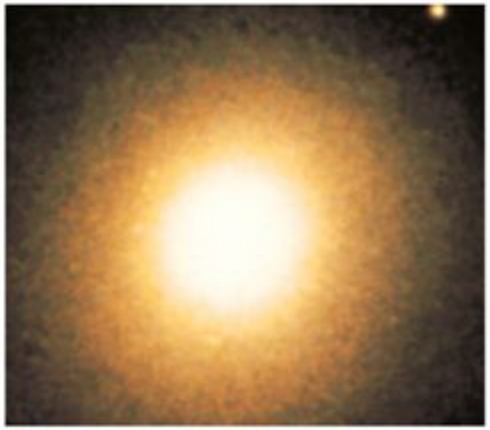
$$= -10 \log_{10} V_{\rm max} + \text{constant}.$$

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

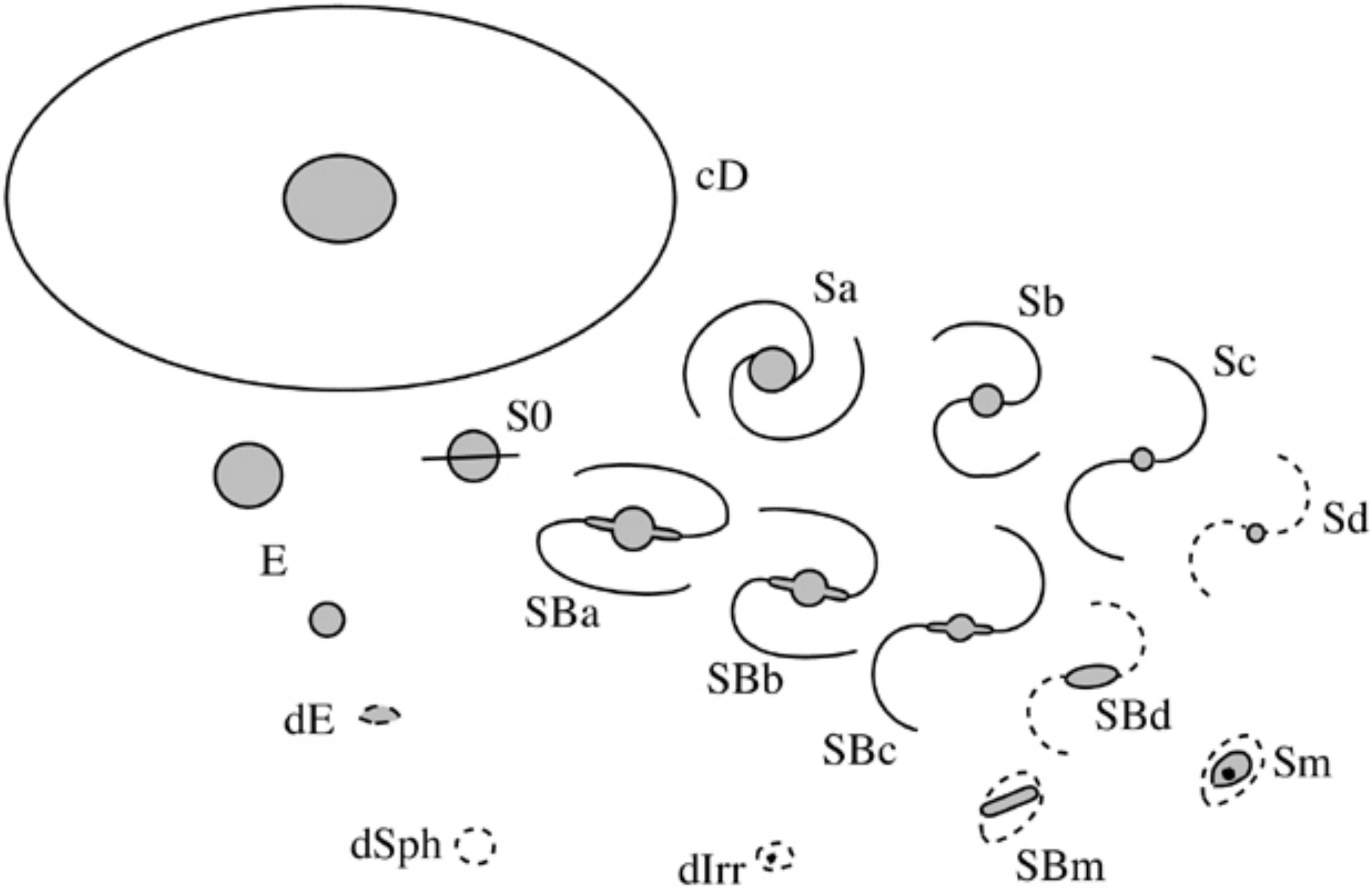


a M105: an E0 galaxy

b M49: an E4 galaxy

c NGC 4526: an E7 galaxy

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	~ 10
$\langle S_N \rangle$	~ 15	~ 5	~ 5

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

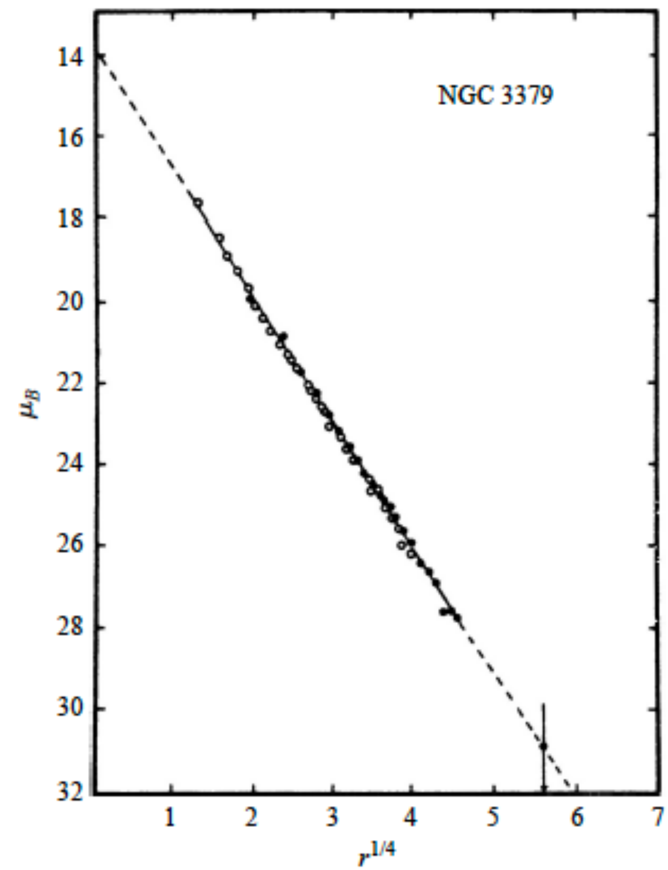
	dE	dSph	BCD
M_B	-13 to -19	-8 to -15	-14 to -17
M ($M_\odot$)	10^{7}–10^{9}	10^{7}–10^{8}	$\sim 10^{9}$
Diameter (D_{25}, kpc)	1–10	0.1–0.5	< 3
$\langle M/L_B \rangle$ ($M_\odot/L_\odot$)	~ 10	5–100	0.1–10
$\langle S_N \rangle$	4.8 ± 1.0	—	—

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 ½ of the light is emitted
- Interestingly, bulges of spiral galaxies also follow this law
- May arise from frequent random interactions of stars

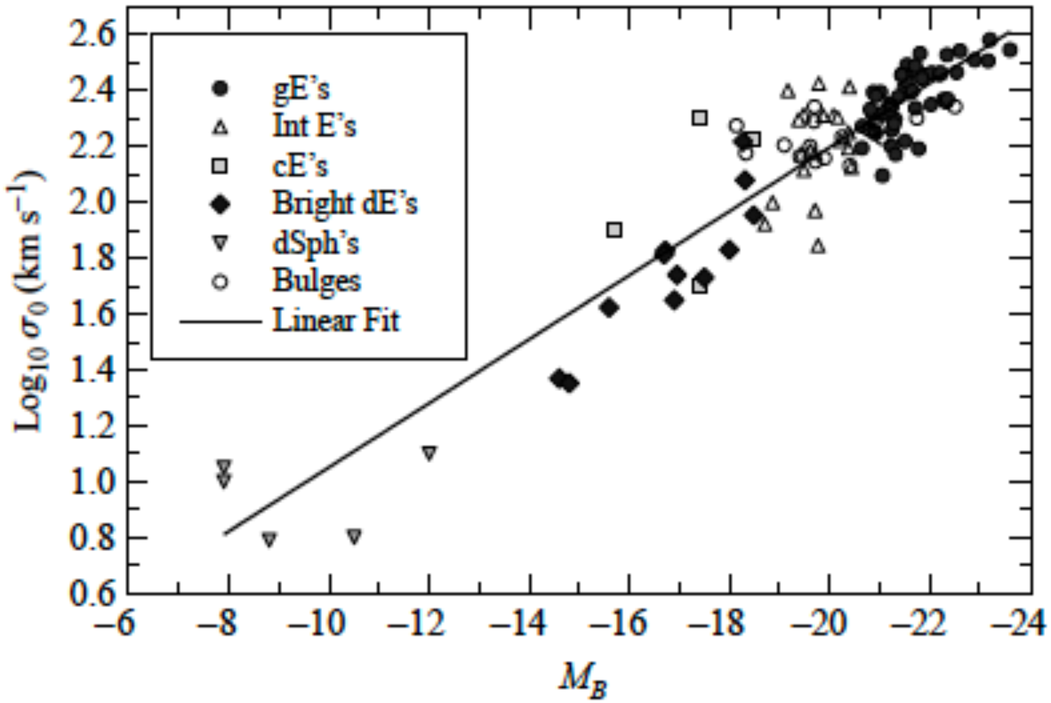


The Faber-Jackson Relation

- 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

$$\boxed{L \propto \sigma_0^4,}$$

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



The Faber-Jackson Relation

24.1 Hubble's Galaxy Classification

A summary of galaxy properties by type:

TABLE 24.1 Galaxy Properties by Type

	Spiral/Barred Spiral (S/SB)	**Elliptical[1] (E)**	**Irregular (Irr)**
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.

[1] *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.*

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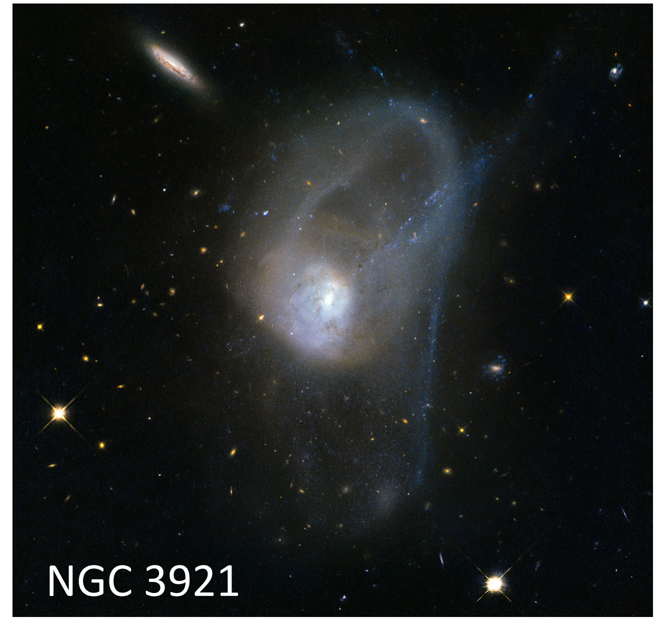
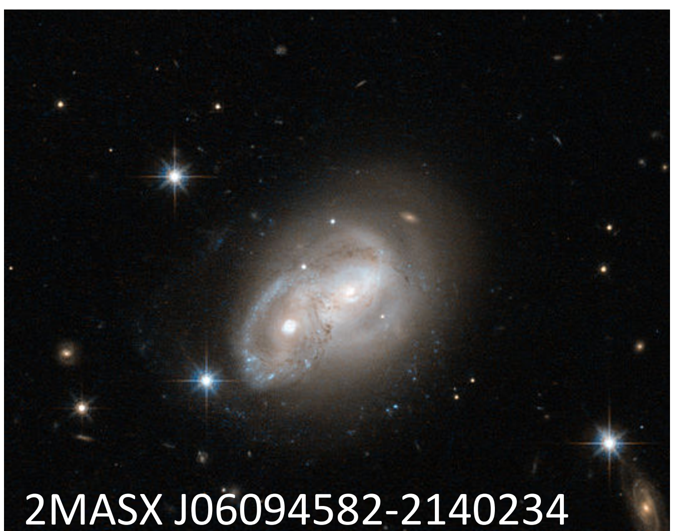
Interactions of Galaxies


The Antennae Galaxies


NGC 3921


2MASX J06094582-2140234


NGC 4676

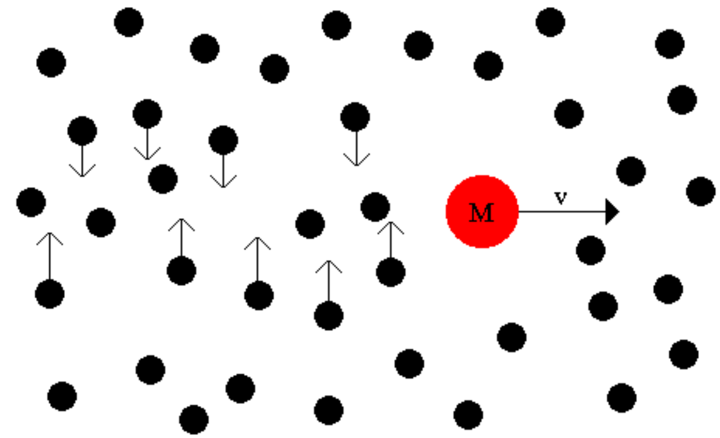
Interactions of Galaxies: How?

- (Gravitational) dynamic friction

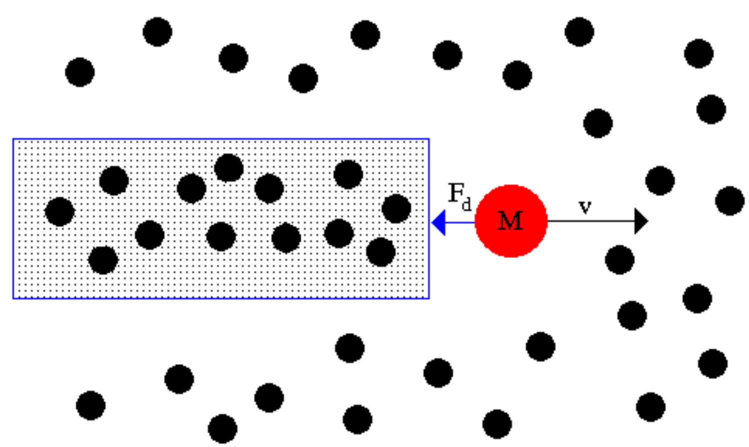
Also known as Chandrasekhar friction (first discussed by Subrahmanyan Chandrasekhar in 1943)

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

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

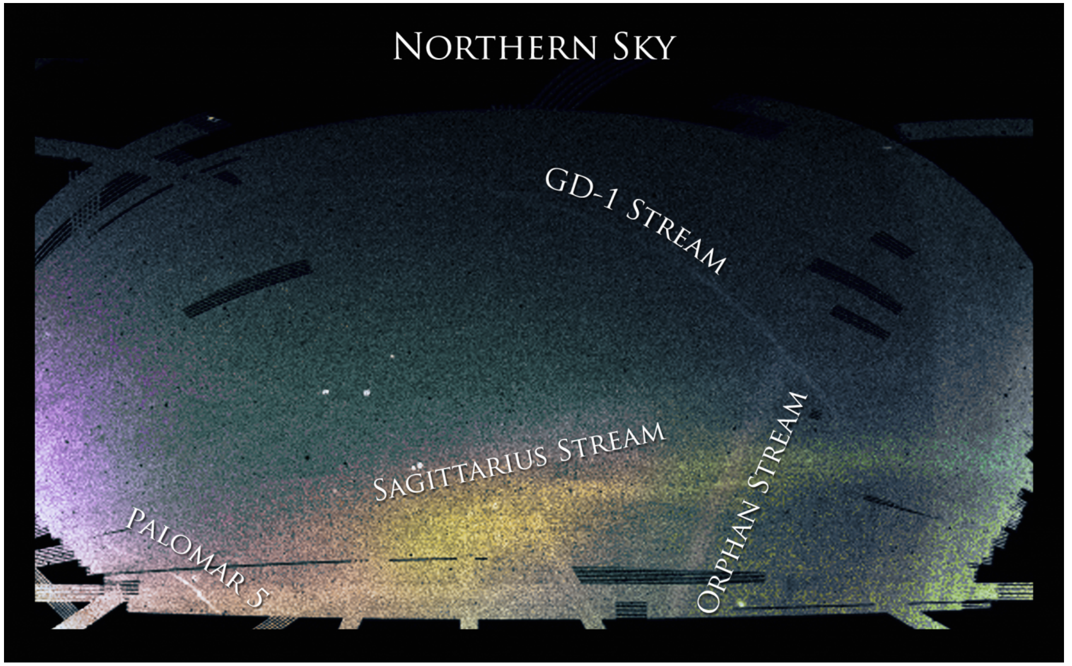


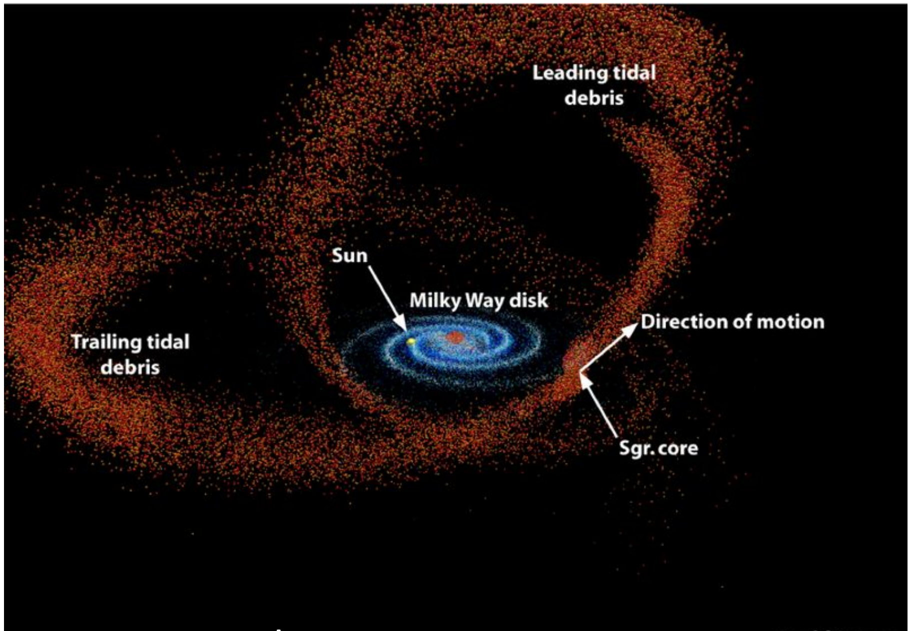
this results in an enhanced region of density behind the mass, with a drag force, F_d known as dynamical friction



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





The Sagittarius Stream

Merging Galaxies

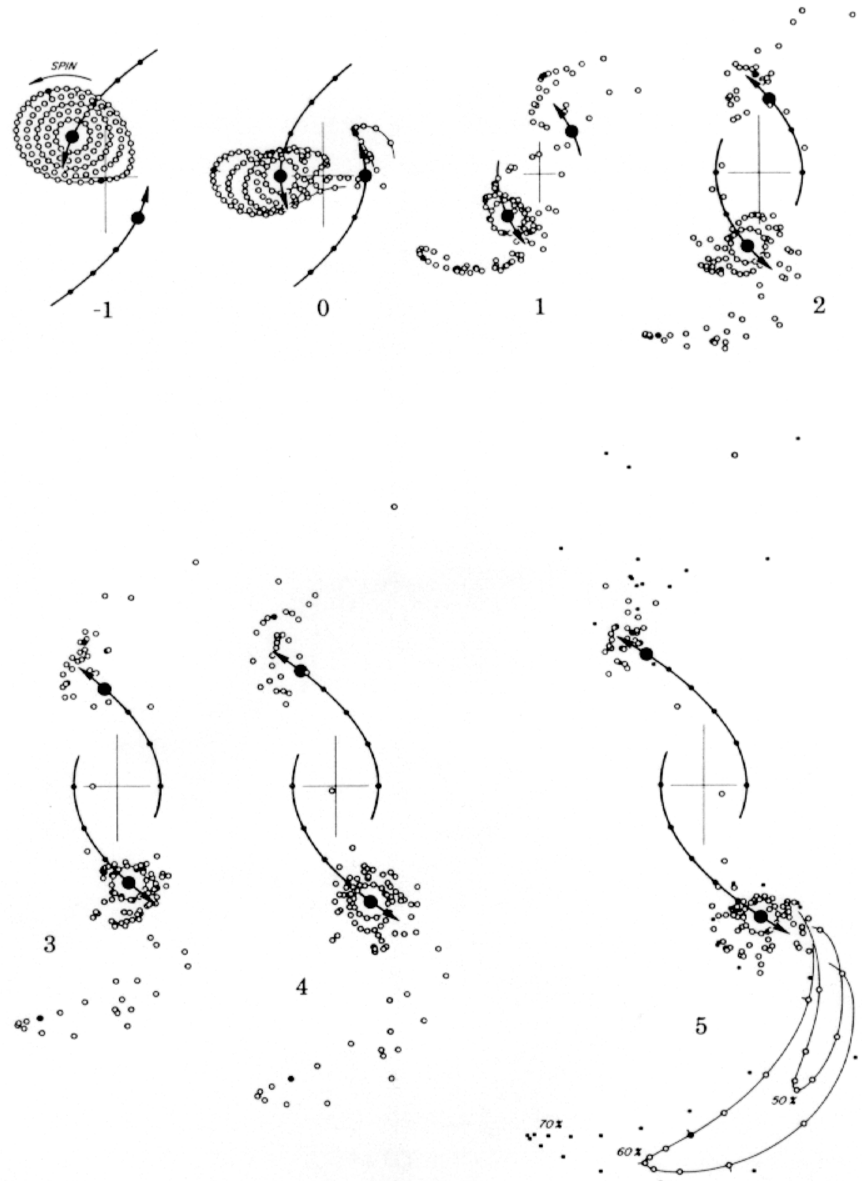


Figure 7-14. The same setup as that shown in Figure 7-13 except that the disk of test particles now corotates with the binary orbit. Reproduced from Toomre and Toomre (1972) by permission of *The Astrophysical Journal*.

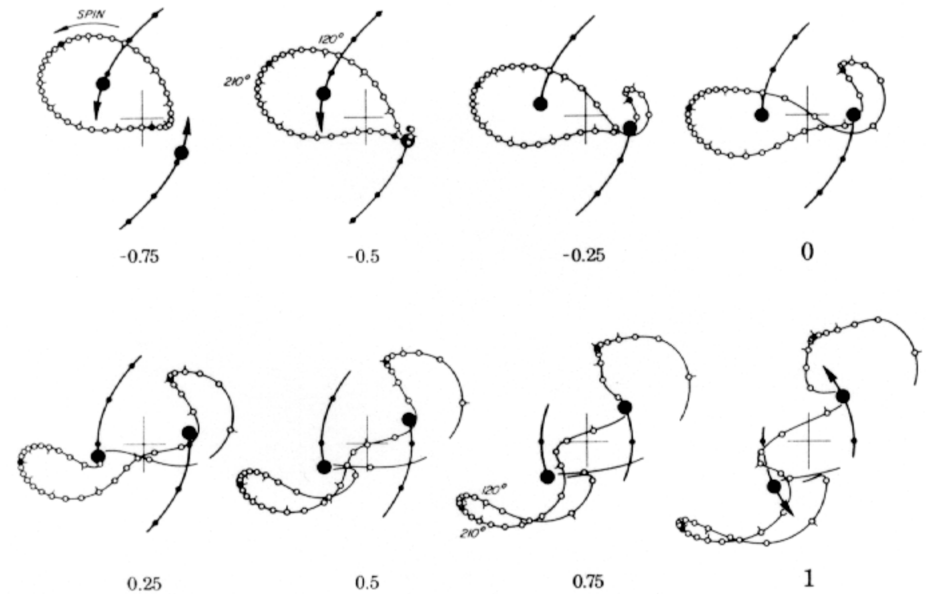


Figure 7-15. A slow-motion replay of the destruction of the outermost ring in Figure 7-14. Reproduced from Toomre and Toomre (1972) by permission of *The Astrophysical Journal*.

N-body simulation by Toomre brothers 1972

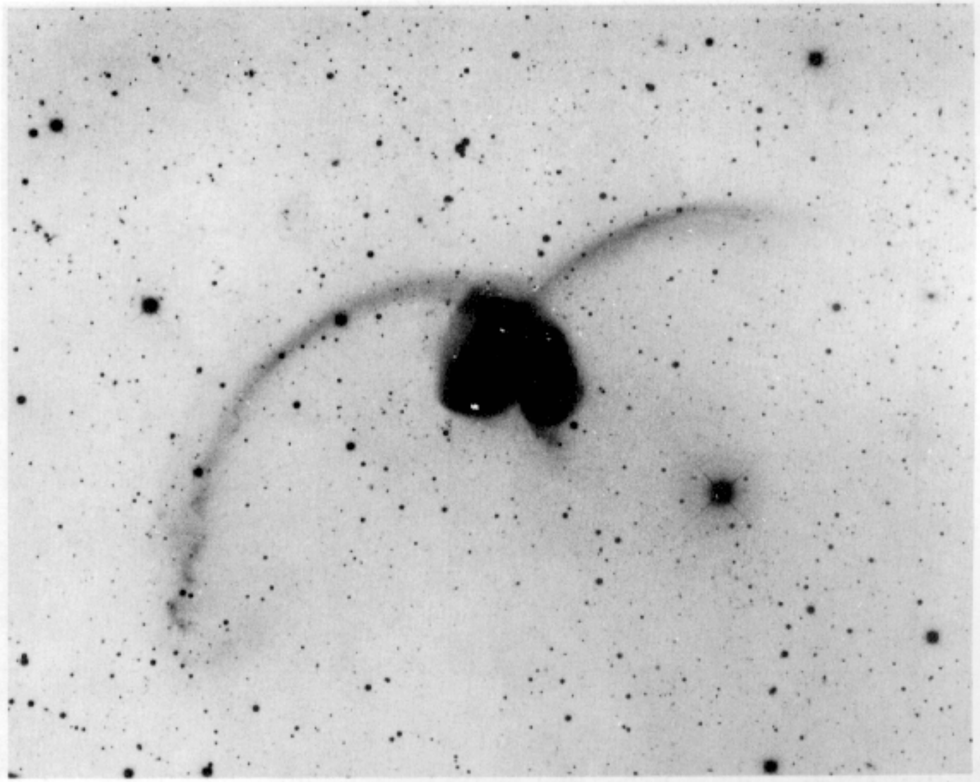


Figure 7-17. The interacting galaxies NGC 4038 and NGC 4039. Courtesy of D. F. Malin and Kitt Peak National Observatory.

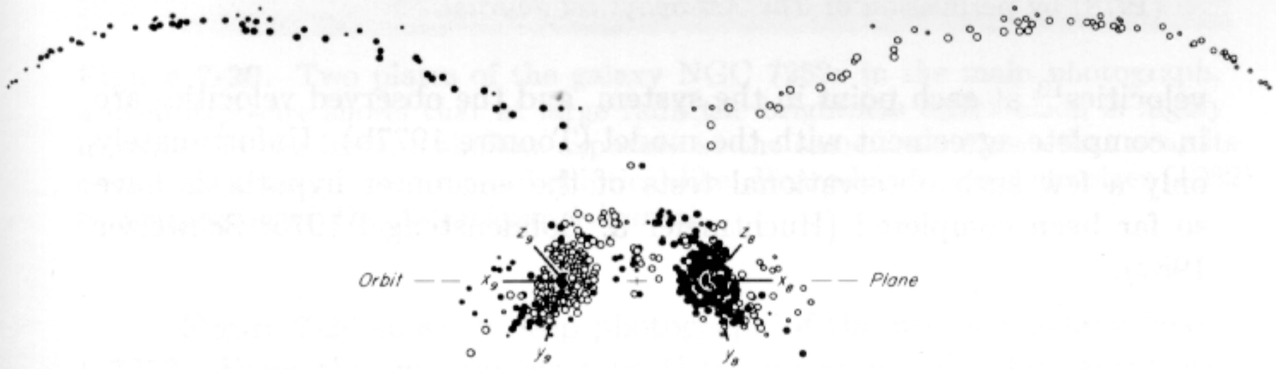


Figure 7-18. A model of the NGC 4038/4039 pair by Toomre and Toomre (1972). Reproduced by permission of *The Astrophysical Journal.*