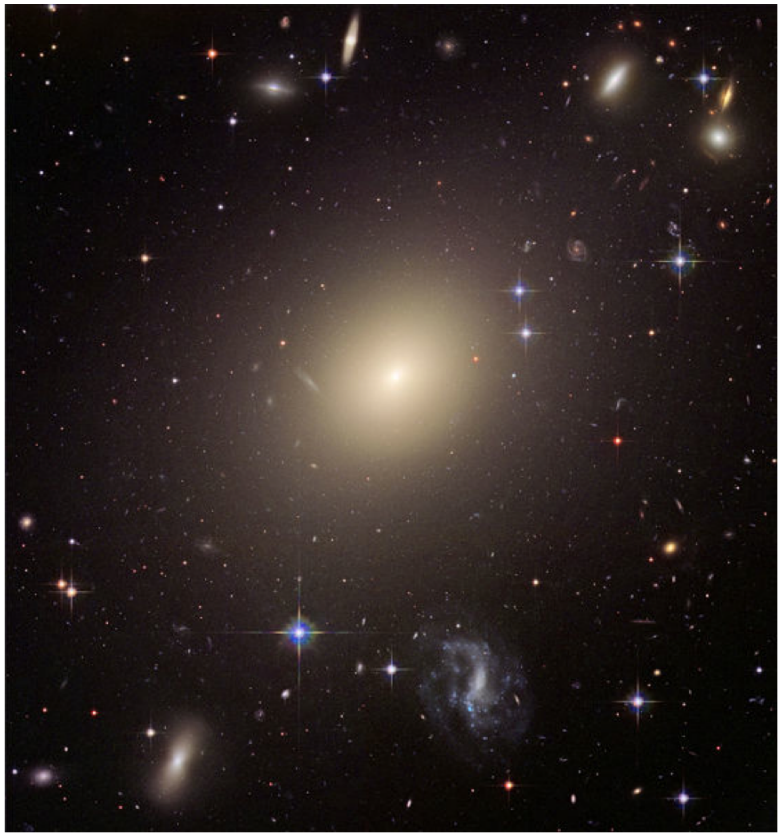
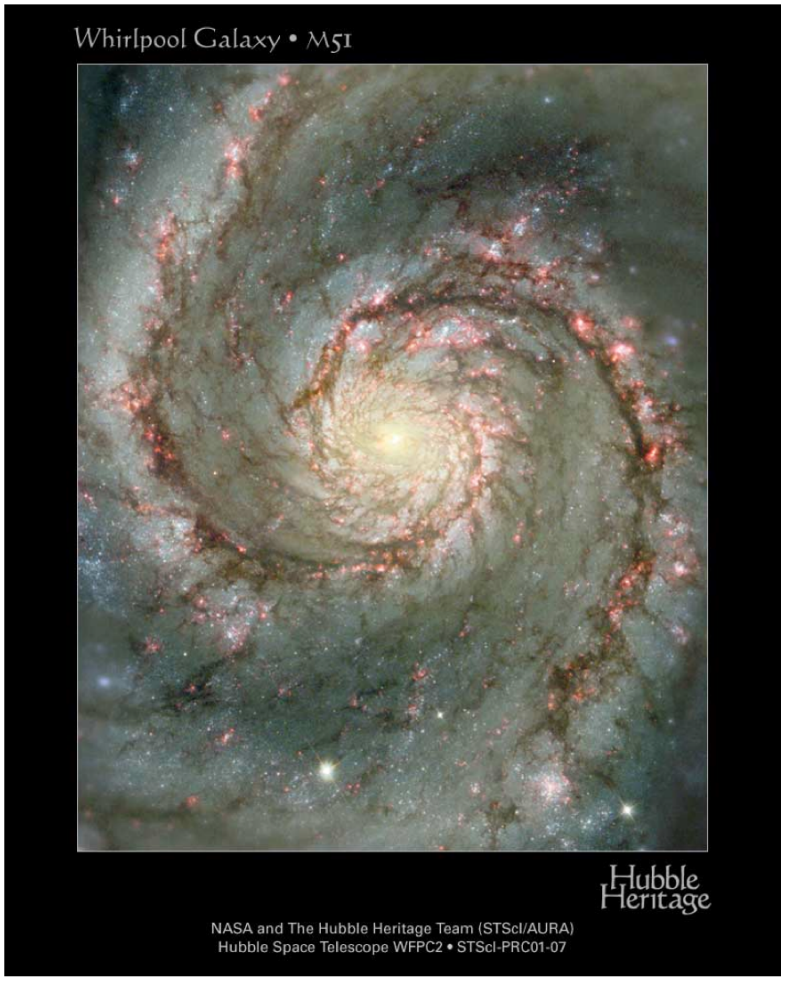
Galaxies



ESO 325-
G004



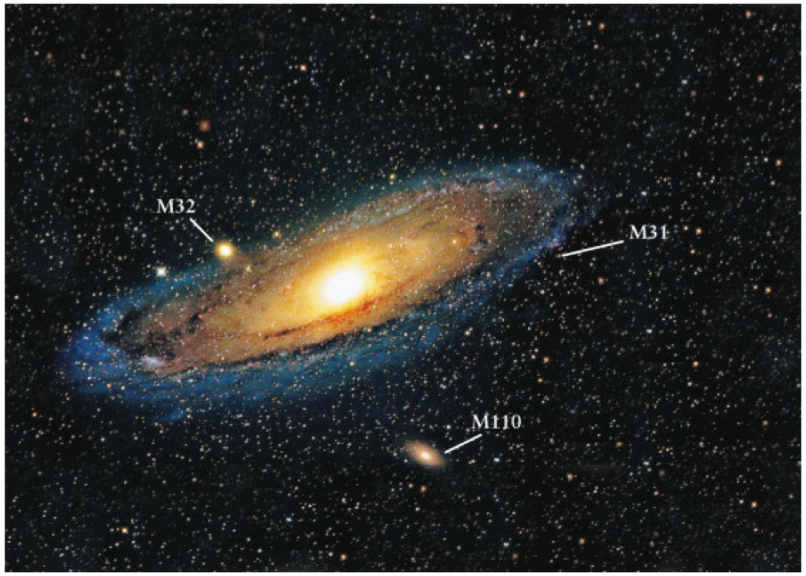
Galaxies

In the early 1900's astronomers were debating whether objects that appeared to be nebulae with spirals were:

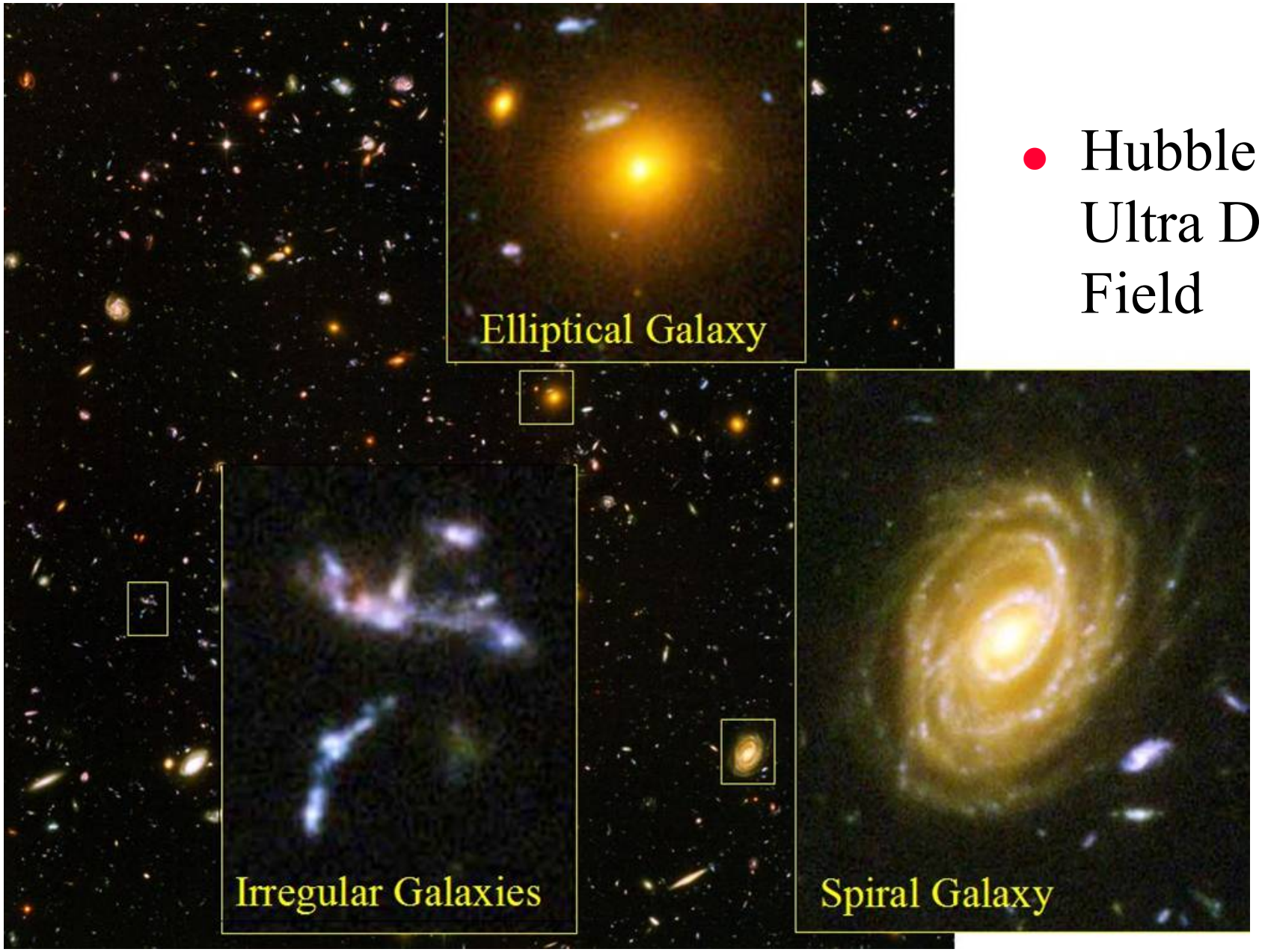
(a) objects located within our galaxy or,

(b) rotating systems of stars just like our Milky way but not a component of our galaxy.

Harlow Shapley and Heber Curtis debated this issue in DC in 1920. The issue was not resolved at the time.

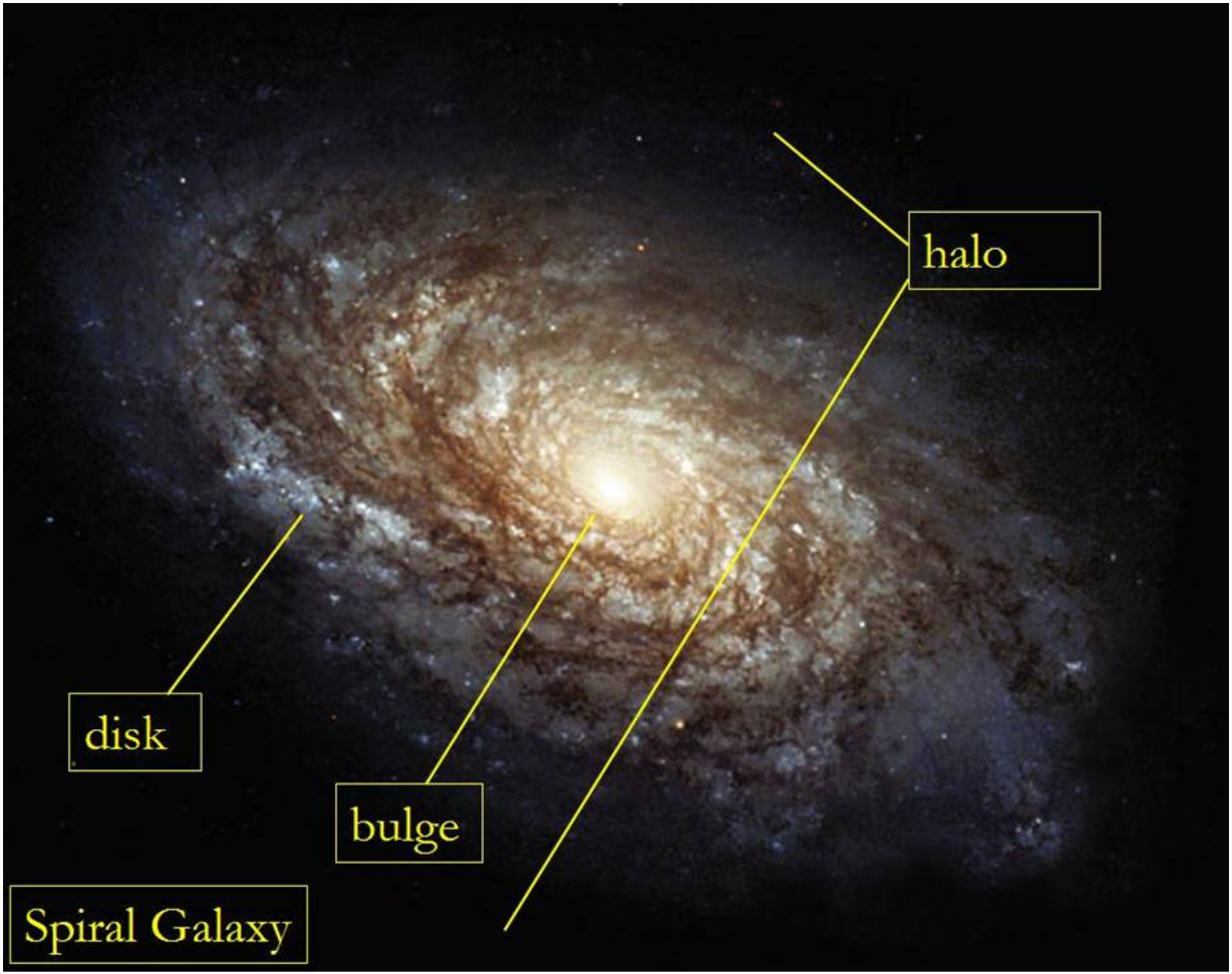


The nature of "spiral nebulae" was resolved with observations of Andromeda made by astronomer Edwin Hubble.



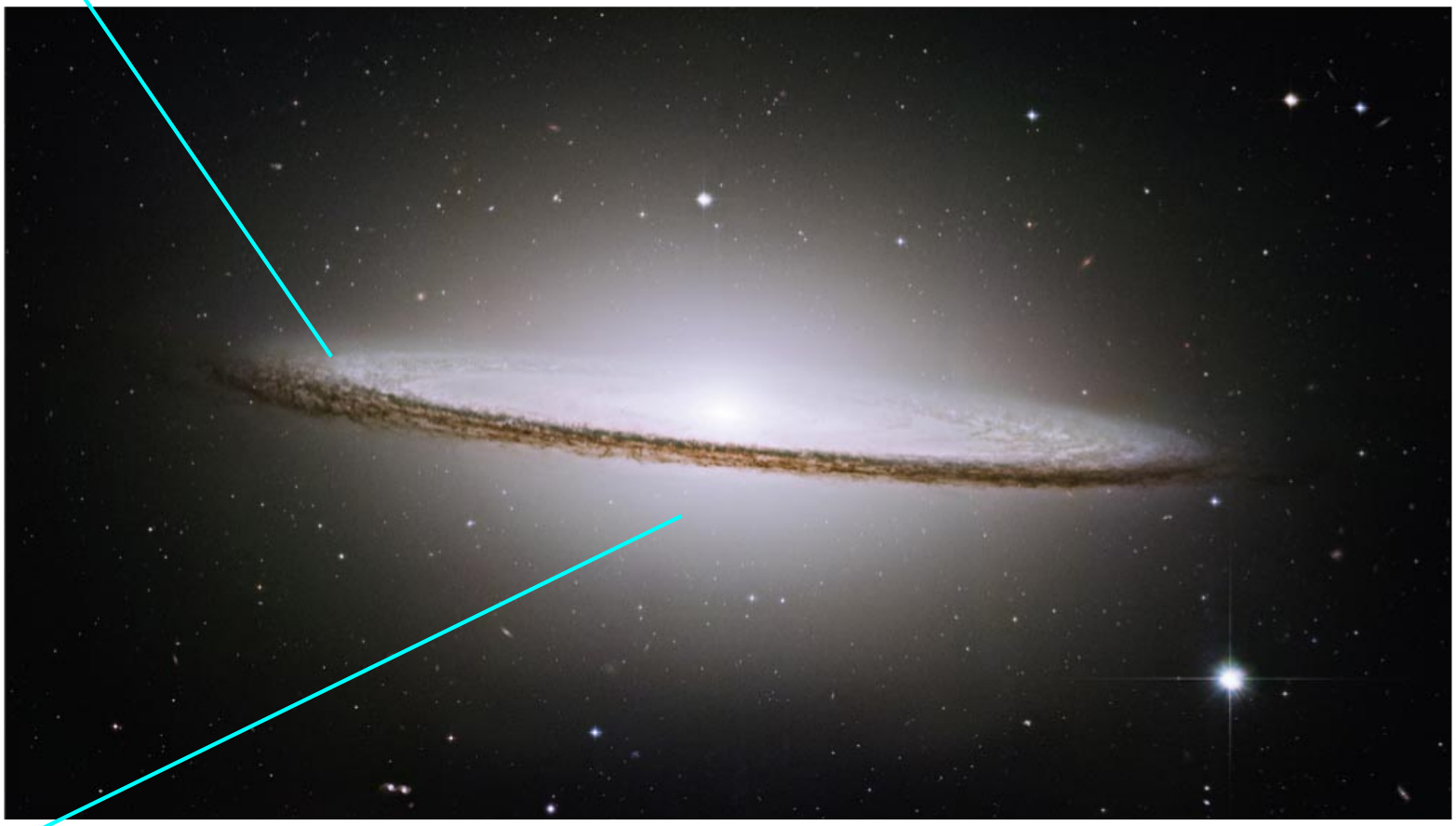
- Hubble Ultra Deep Field

Spiral Galaxies



Spiral Galaxies

Disk component:
stars of all ages, many gas clouds

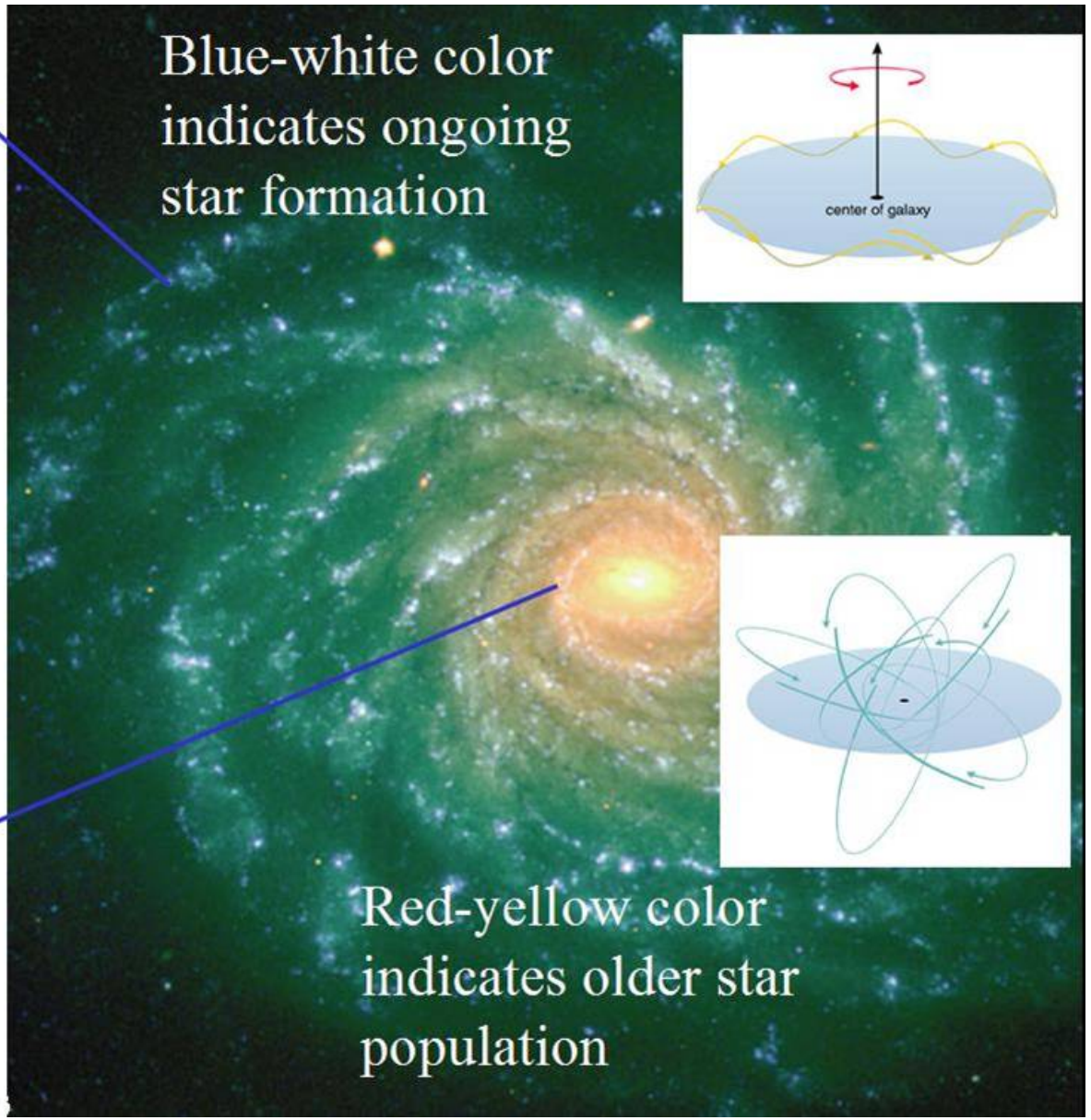


Spheroidal component:
bulge and halo, old stars, few gas clouds

Spiral Galaxies

Disk component: stars of all ages, many gas clouds

Spheroidal component: bulge and halo, old stars, few gas clouds



Spiral Galaxies



(a) Sa (NGC 1357)



(b) Sb (M81)



(c) Sc (NGC 4321)

Hubble further classified spirals into :

Sa galaxies: smooth broad and tightly wrapped spiral arms with a large bulge (~4% of baryonic mass in dust and gas)

Sb galaxies: moderate-sized spirals and bulge (~8% of mass in dust and gas)

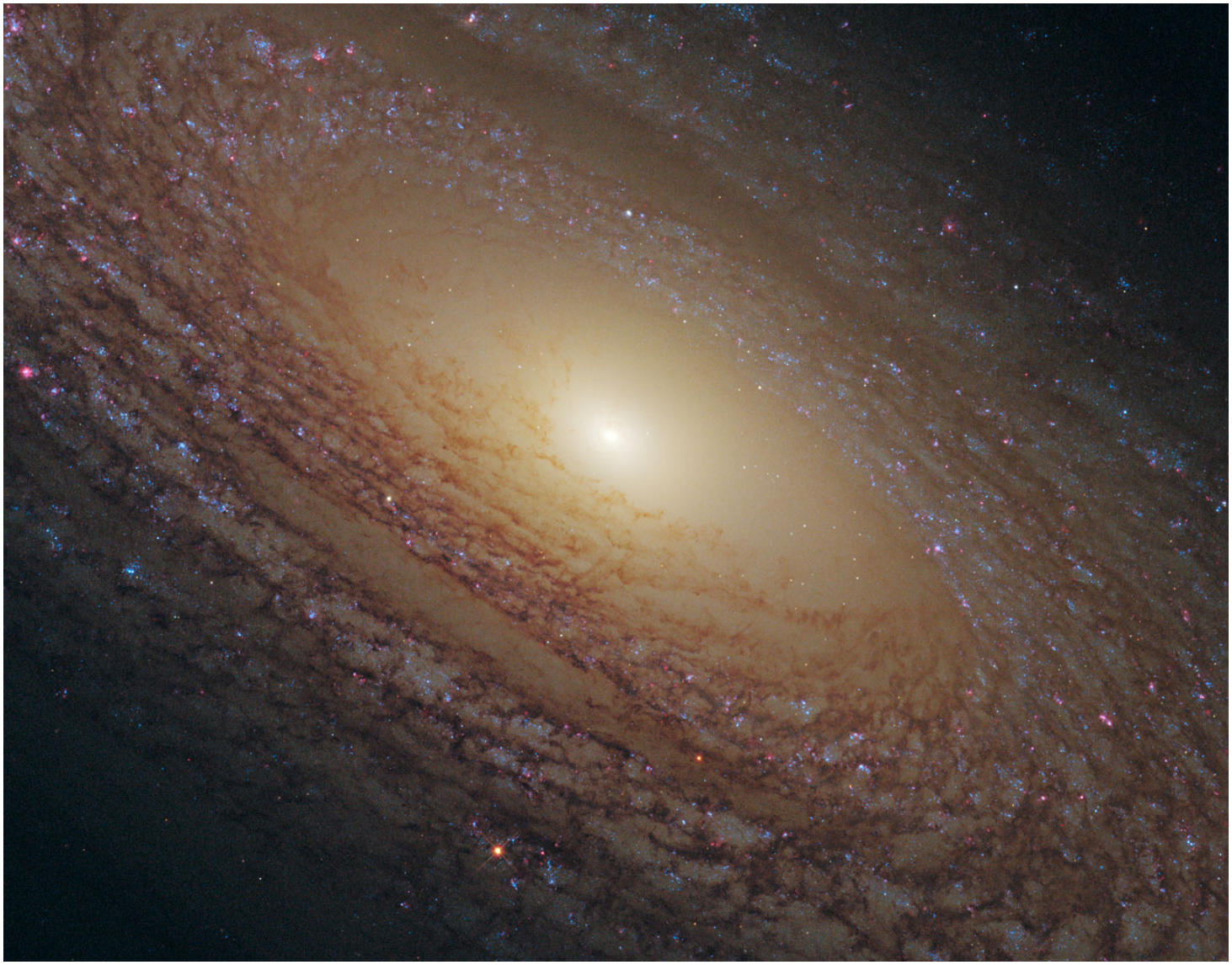
Sc galaxies: narrow loosely wrapped spirals and small bulge (~25% of mass in dust and gas)

Grand Design Spiral



The Whirlpool Galaxy M51
Grand Design Spiral

Flocculent Spiral



Flocculent Spiral NGC 2841

Spiral Galaxies

Spiral Galaxies

10% are Grand Design
60% have Multiple Arms
30% are flocculent

Elliptical Galaxies



a M87, a giant elliptical galaxy in the Virgo Cluster, is one of the most massive galaxies in the universe. The region shown is more than 300,000 light-years across.

- **Elliptical galaxy:** all spheroidal component, virtually no disk component
- Red-yellow color indicates older star population.

Elliptical Galaxies

Elliptical galaxies contain very little amounts of gas, dust and star formation. They are composed of mostly old red Population II stars.

Giant elliptical galaxies are about 20 times larger than typical elliptical galaxies and often found in clusters of galaxies.

Dwarf elliptical galaxies contain only about a few million stars compared to 100 billion in the Milky way.

The **spectrum of a galaxy** consists of the sum of the spectra of all its stars. Their absorption lines are broadened because of the Doppler effect produced by orbiting stars.



Blue-white color indicates ongoing star formation.

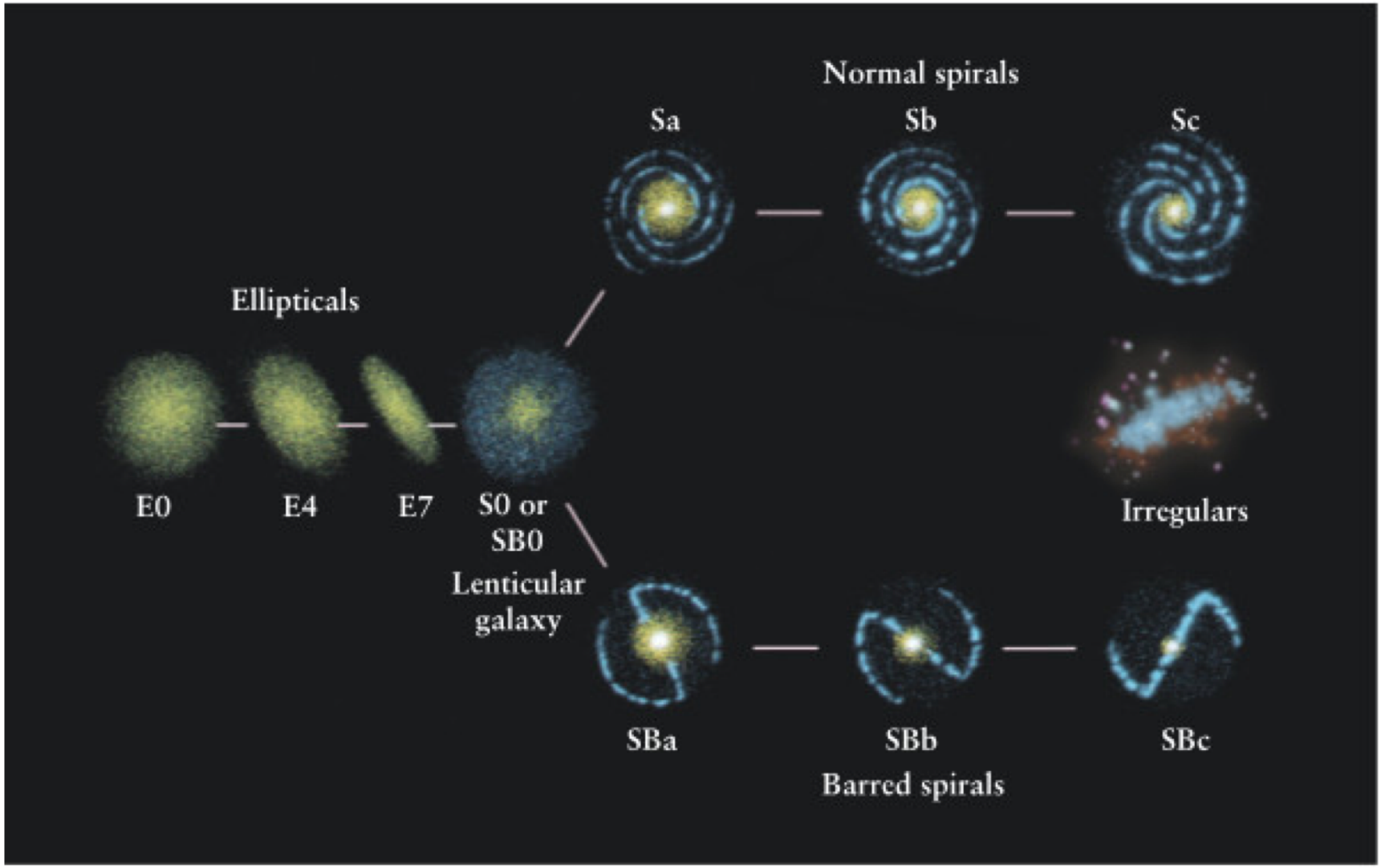
- Irregular galaxy(some have distorted shapes likely the result of collisions)

Lenticular Galaxies



- **Lenticular galaxy:** has a disk and bulge like a spiral galaxy bit no spiral arms and has much less dusty gas (intermediate between spiral and elliptical)

Hubble's Tuning Form Diagram

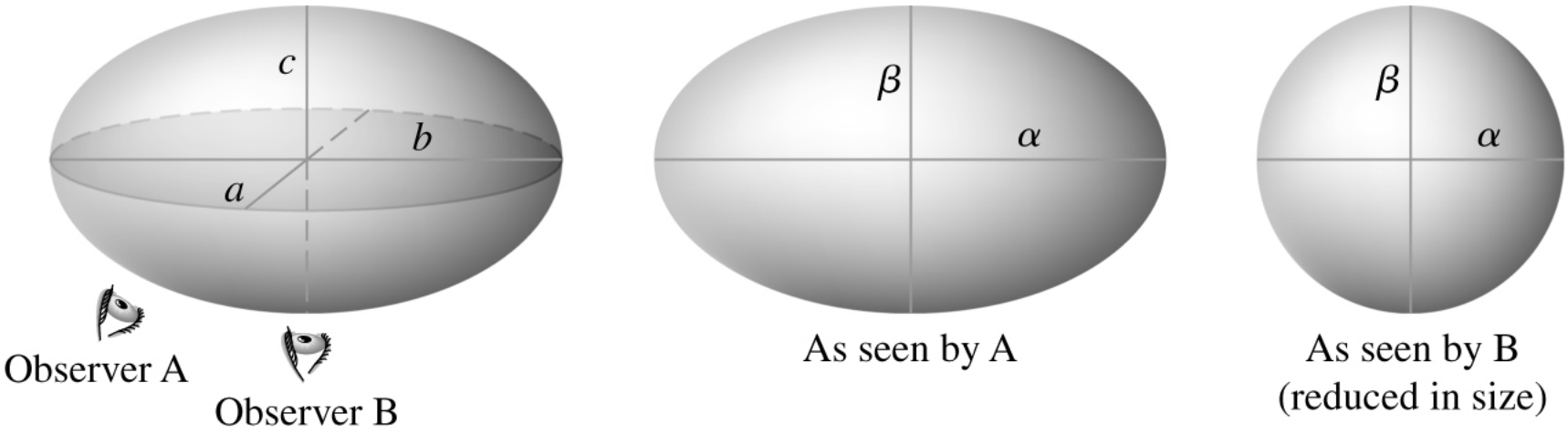


Spheroid dominates

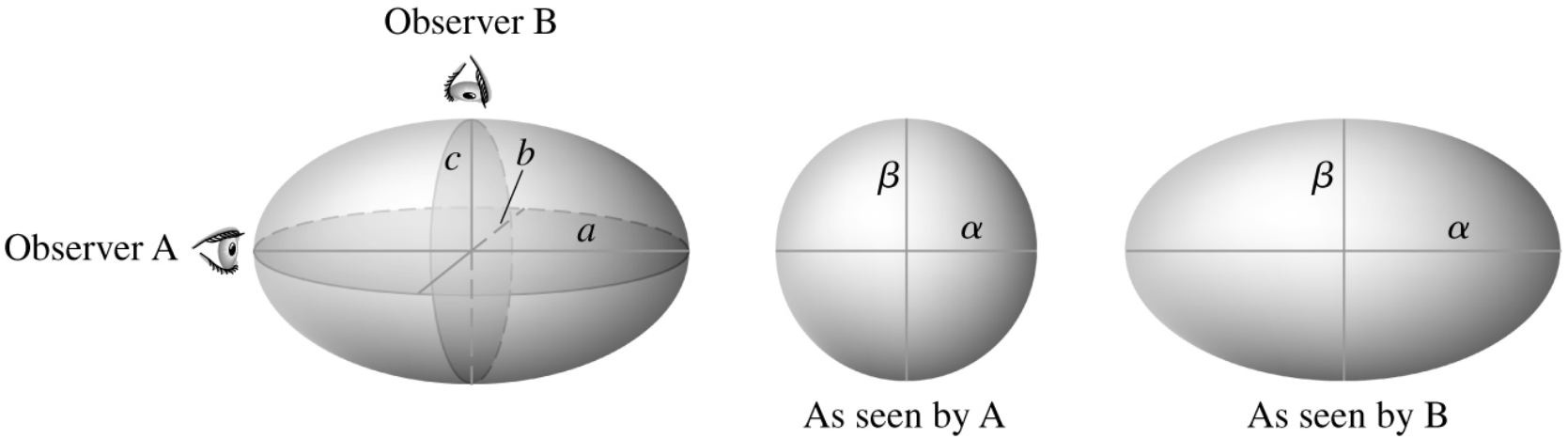
Disk dominates

Ellipticals: Morphological Classification: E0 – E7

E_x, with $x = 10(1-\beta/\alpha)$



oblate: flattened spheroid



Prolate: Football shaped

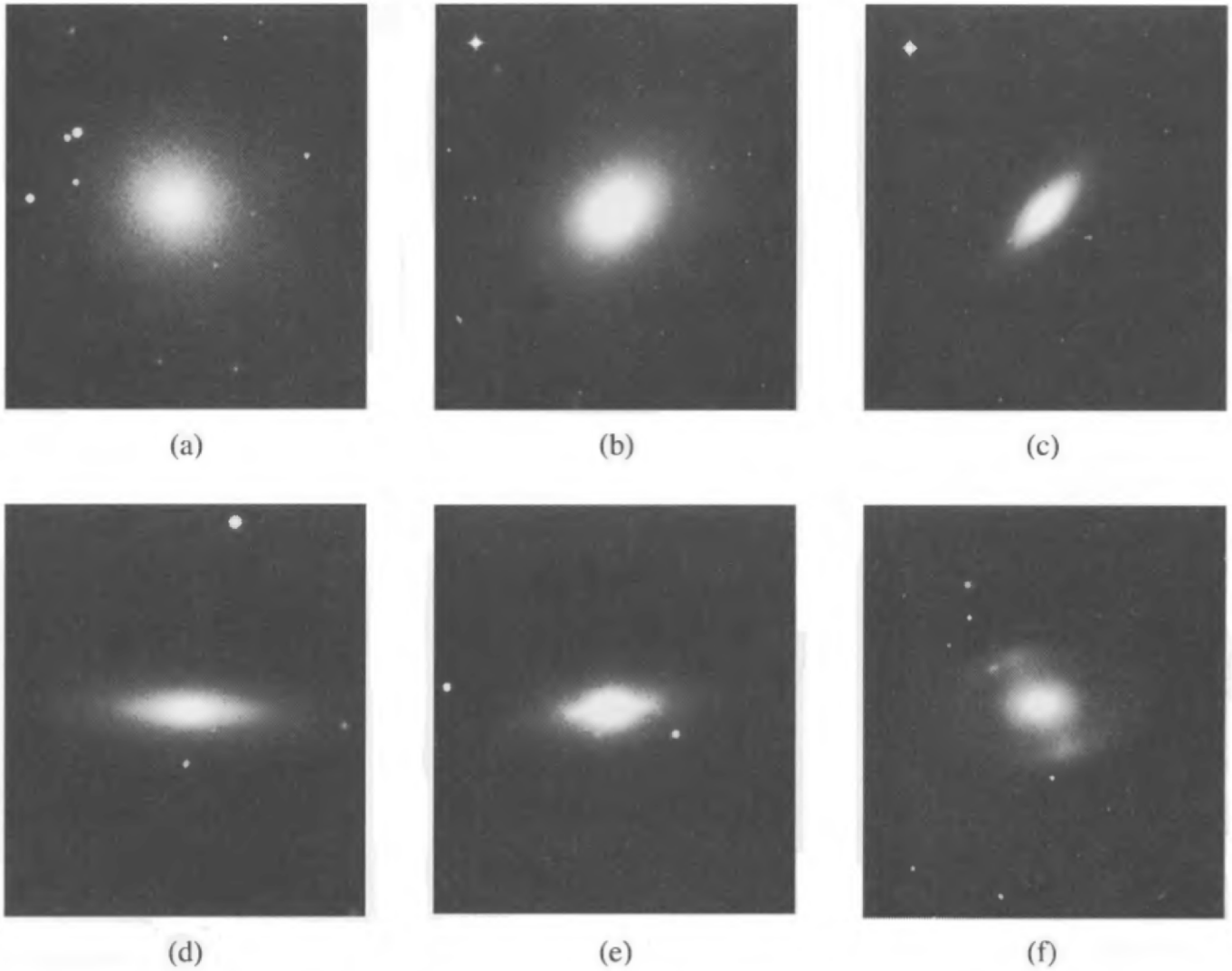


FIGURE 25.4 Typical early-type galaxies. (a) IC 4296 (E0), (b) NGC 4365 (E3), (c) NGC 4564 (E6), (d) NGC 4623 (E7), (e) NGC 4251 (S0), (f) NGC 4340 (RSB0). (Images from Sandage and Bedke, *The Carnegie Atlas of Galaxies*, Carnegie Institution of Washington, Washington, D.C., 1994.)

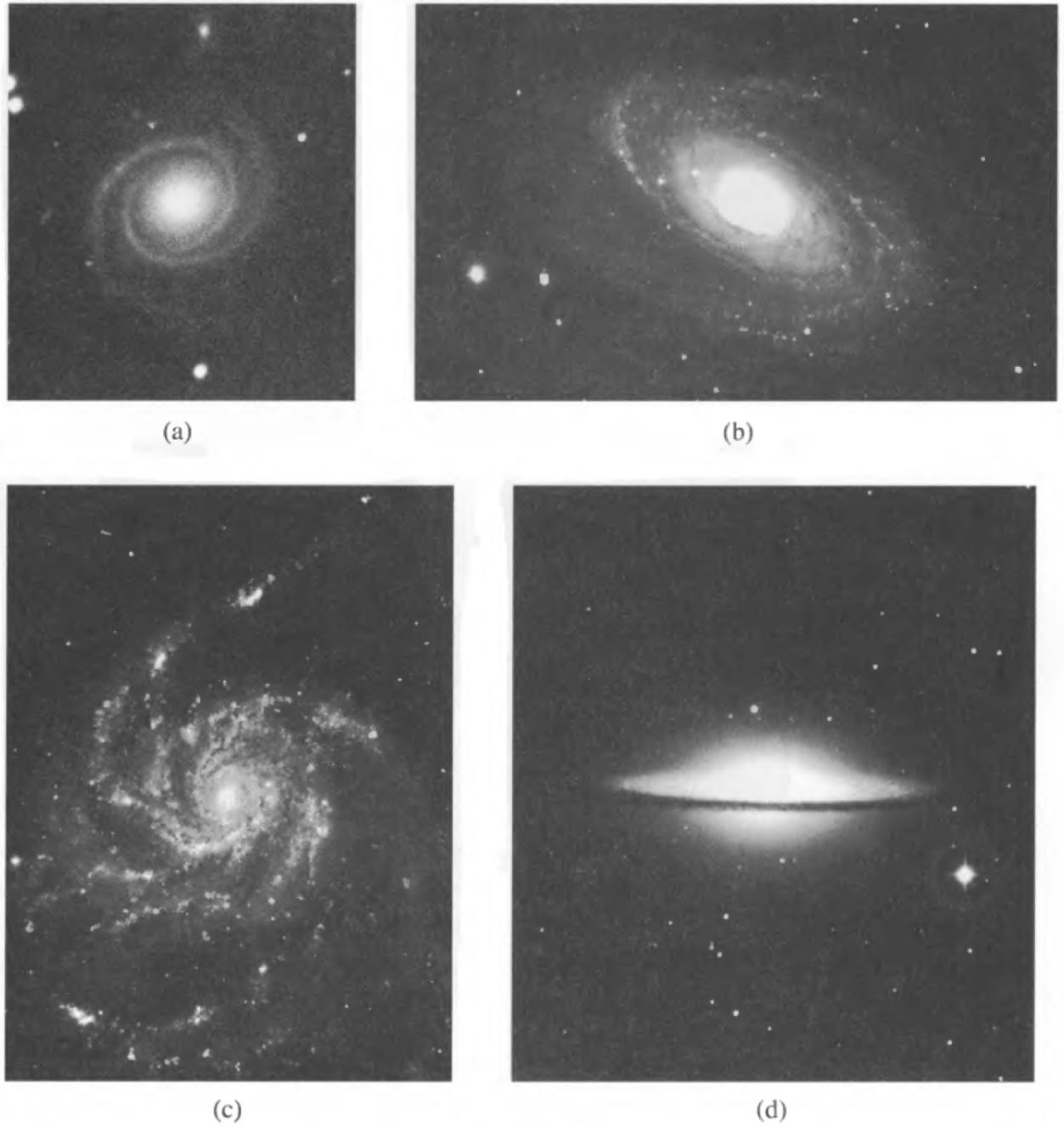


FIGURE 25.5 Typical normal spirals. (a) NGC 7096 (Sa(r)I), (b) M81/NGC 3031 (Sb(r)I–II), (c) M101/NGC 5457/Pinwheel (Sc(s)I), (d) M104/NGC 4594/Sombrero (Sa/Sb) seen nearly edge on. (Images from Sandage and Bedke, *The Carnegie Atlas of Galaxies*, Carnegie Institution of Washington, Washington, D.C., 1994.)

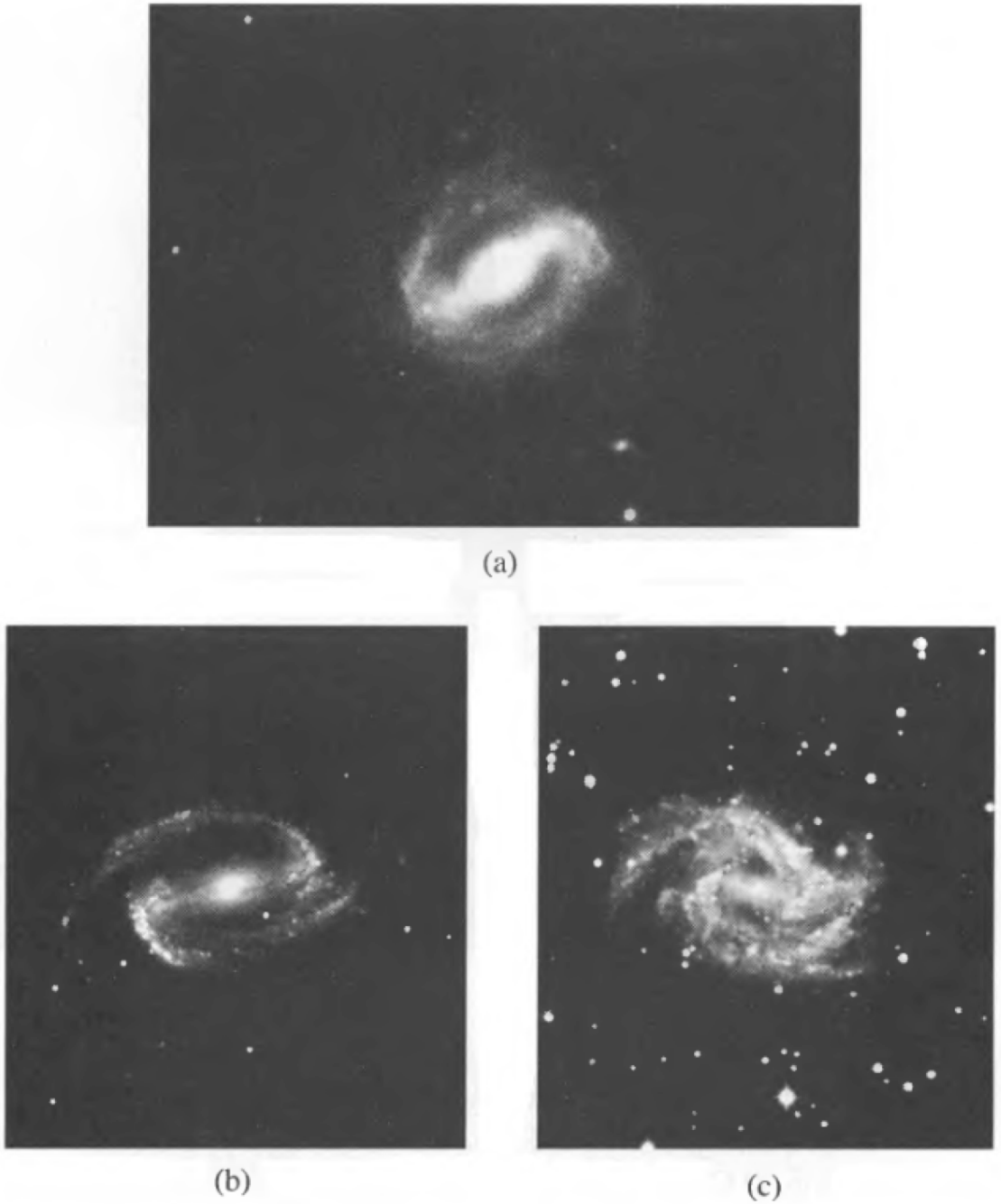
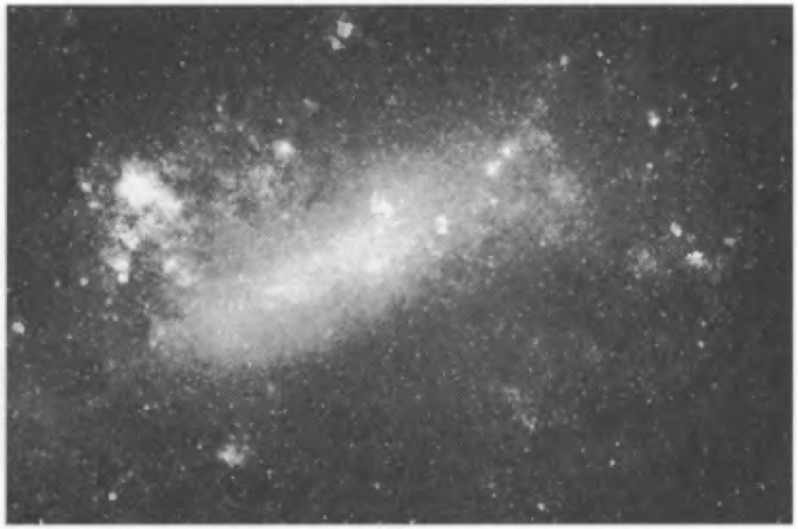


FIGURE 25.6 Typical barred spirals. (a) NGC 175 (SBab(s) I–II), (b) NGC 1300 (SBb(s) I), (c) NGC 2525 (SBc(s)II). (Images from Sandage and Bedke, *The Carnegie Atlas of Galaxies*, Carnegie Institution of Washington, Washington, D.C., 1994.)



(a)



(b)



(c)

FIGURE 25.7 Examples of irregular galaxies. (a) The Large Magellanic Cloud (Irr I/SBmIII), (b) the Small Magellanic Cloud (Irr I/ImIV–V), (c) M82/NGC 3034 (Irr II/Ir/Amorphous). (Images from Sandage and Bedke, *The Carnegie Atlas of Galaxies*, Carnegie Institution of Washington, Washington, D.C., 1994.)

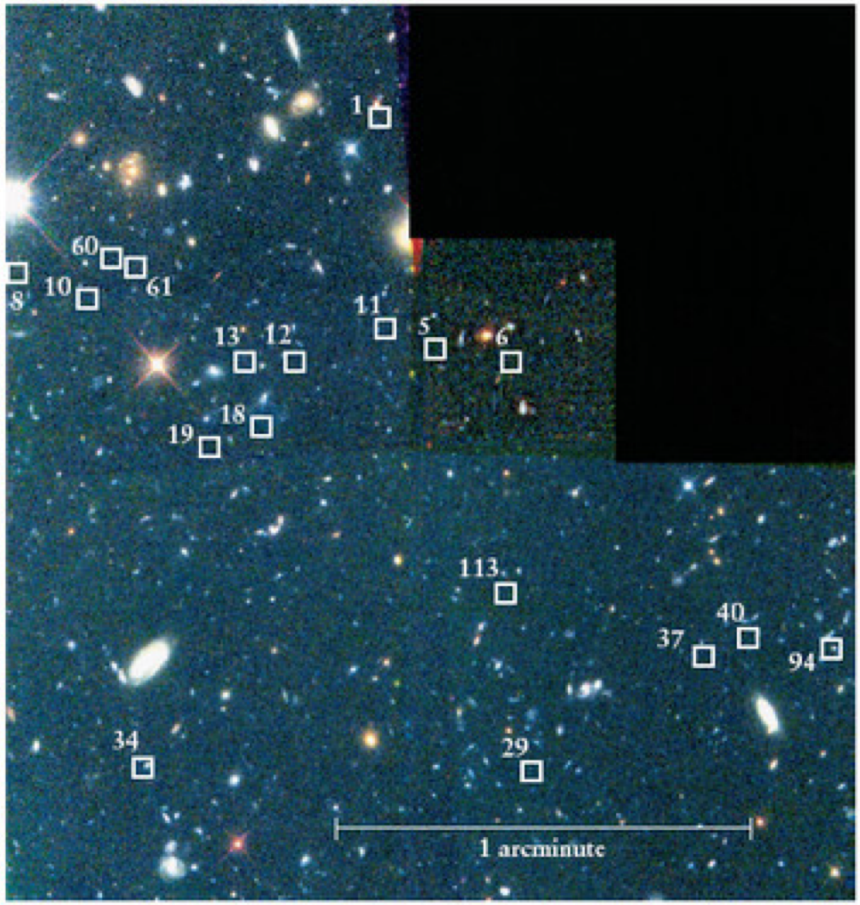
TABLE 25.1 Characteristics of Early Spiral Galaxies.

	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
$\langle M_{\rm H_2}/M_{\rm H\ I}\rangle$	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

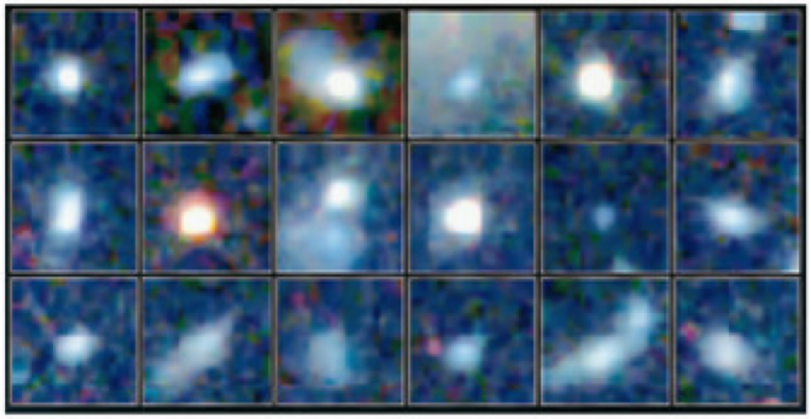
TABLE 25.2 Characteristics of Late Spiral and Irregular Galaxies.

	Sd/Sm	Im/Ir
M_B	-15 to -20	-13 to -18
M ($M_\odot$)	10^8–10^{10}	10^8–10^{10}
Diameter (D_{25}, kpc)	0.5–50	0.5–50
$\langle M/L_B\rangle$ ($M_\odot/L_\odot$)	~ 1	~ 1
$V_{\rm max}$ range (km s^{-1})	80–120	50–70
$\langle B-V\rangle$	0.47	0.37
$\langle M_{\rm gas}/M_{\rm total}\rangle$	0.25 (Scd)	0.5–0.9
$\langle M_{\rm H_2}/M_{\rm H\ I}\rangle$	0.03–0.3	~ 0
$\langle S_N\rangle$	0.5 ± 0.2	0.5 ± 0.2

Formation of the First Galaxies



(a) A portion of the constellation Hercules



(b) Closeup images of the numbered objects in (a)

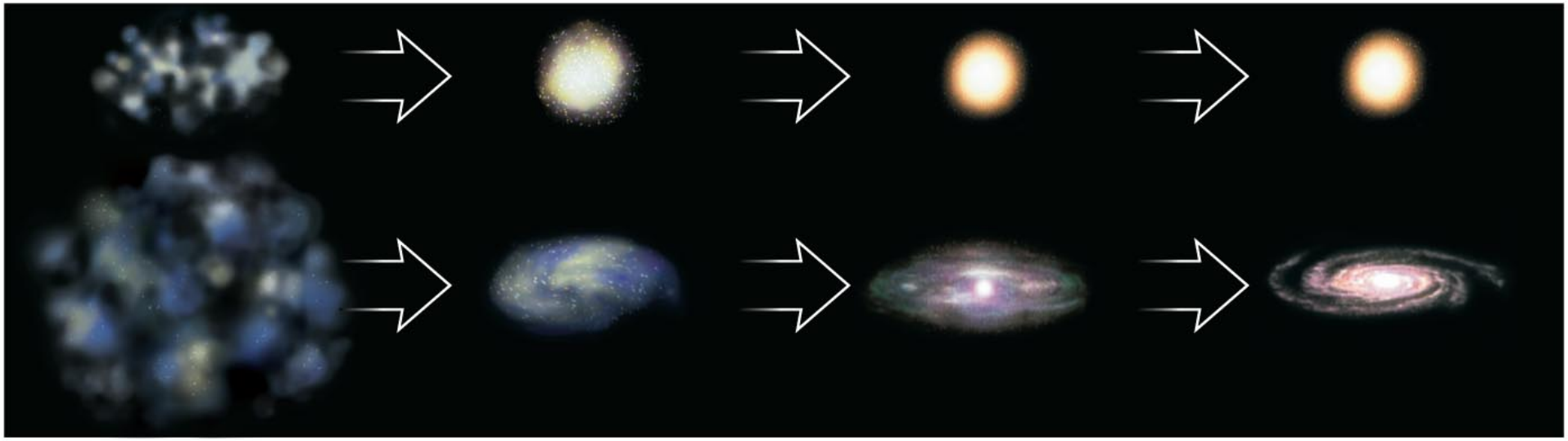
These very deep observations with HST show us how galaxies looked like in the distant past some ~11 billion years ago.

Recent observations of the very first galaxies in the Universe suggest that **galaxies formed from the merger of smaller objects**. This is often referred to as building galaxies from the "Bottom Up". The building blocks of galaxies are about a few 1000 ly across.

The **very first galaxies appear very blue** indicating significant star formation at this time.

Why do galaxies differ?
What are starbursts?

Why do galaxies differ?

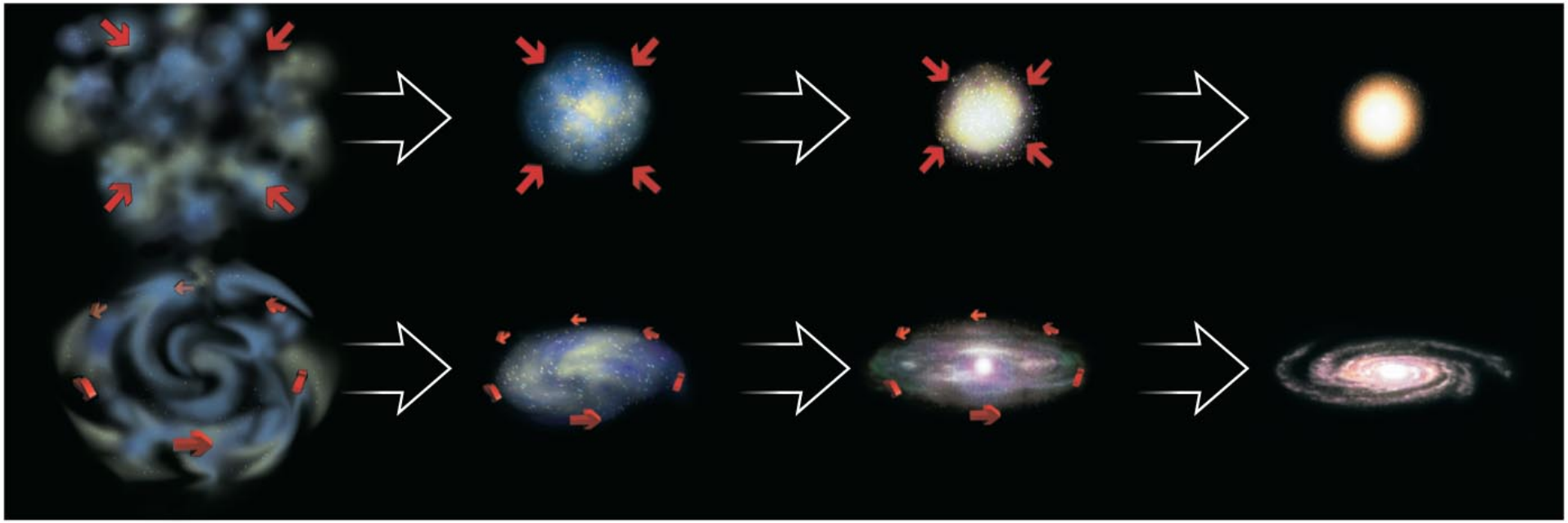


b The gas density of a galaxy's protogalactic clouds may determine whether it ends up spiral or elliptical.

1. Birth Conditions (rotation, density)

2. Mergers

Conditions in Protogalactic Cloud?

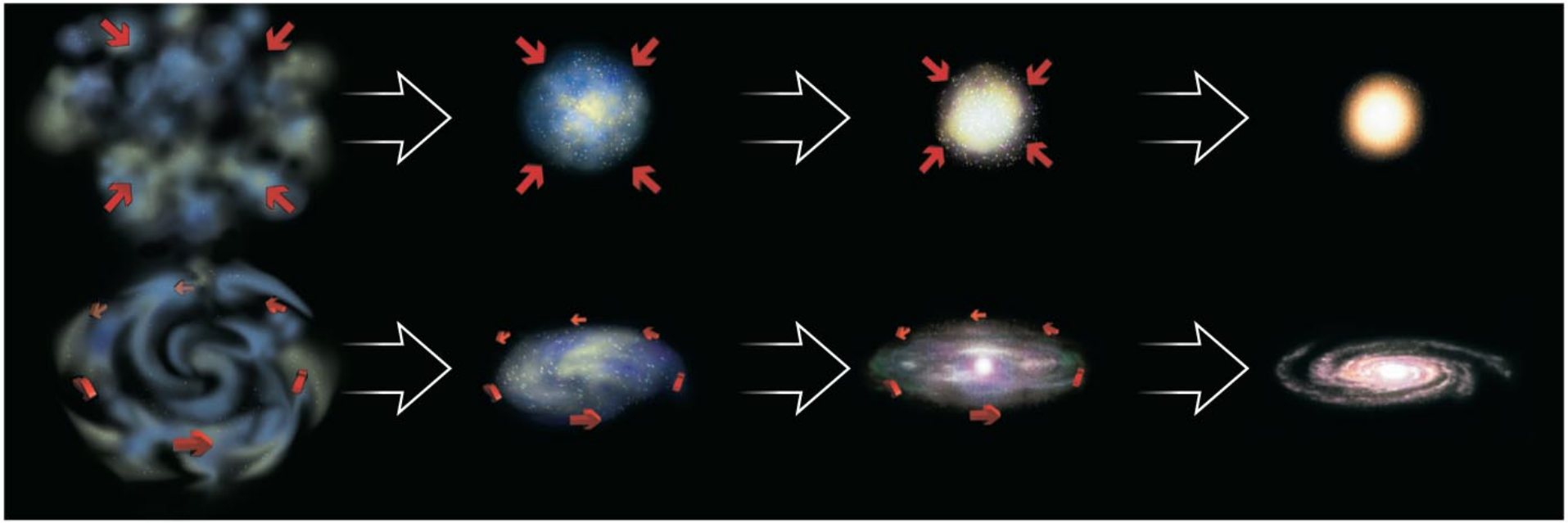


a The angular momentum of a galaxy's protogalactic-cloud system may determine whether it ends up spiral or elliptical.

Interactive Figure

- *Spin:* The initial angular momentum of the protogalactic cloud could determine the size of the resulting disk. Protogalactic clouds with large spin are likely to form a disk and the resulting galaxy will be spiral.

Conditions in Protogalactic Cloud?

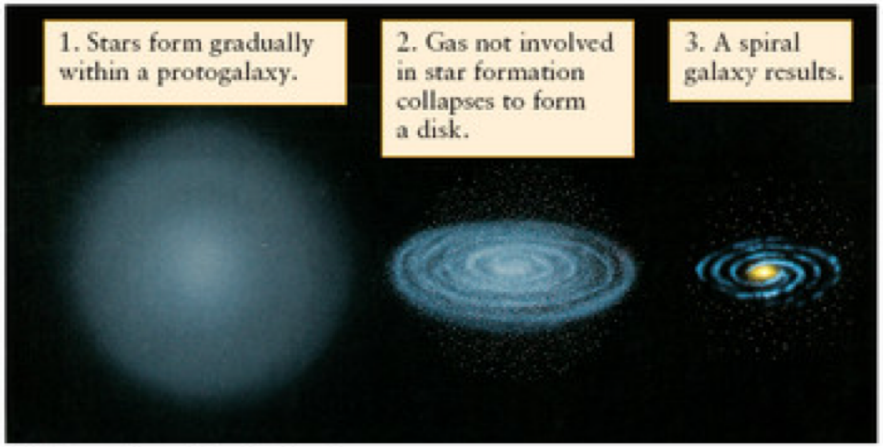


a The angular momentum of a galaxy's protogalactic-cloud system may determine whether it ends up spiral or elliptical.

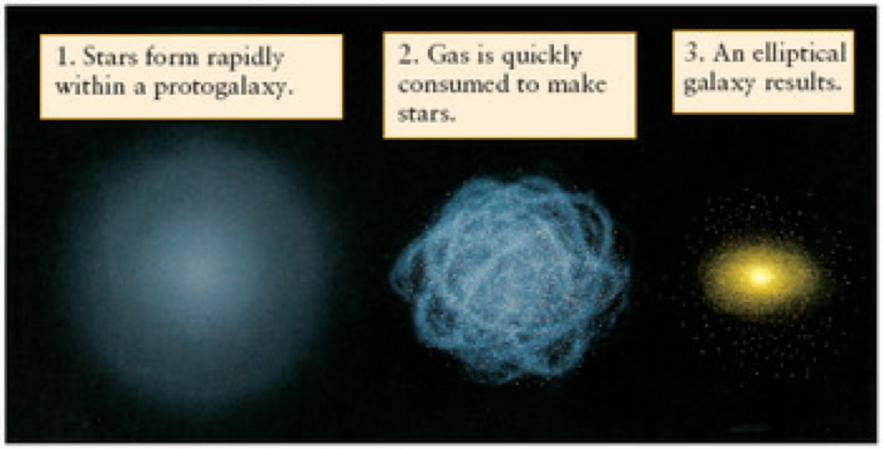
Interactive Figure

- ***Density:*** **Elliptical galaxies could come from dense protogalactic clouds** that were able to radiate energy and cool, forming stars before gas settled into a disk.

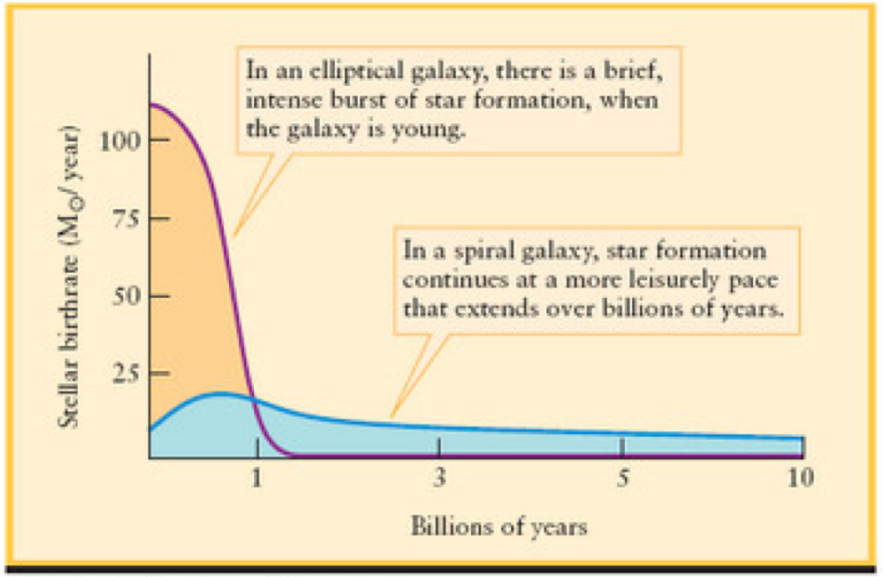
Spiral versus Elliptical Galaxies



(a) Formation of a spiral galaxy



(b) Formation of an elliptical galaxy

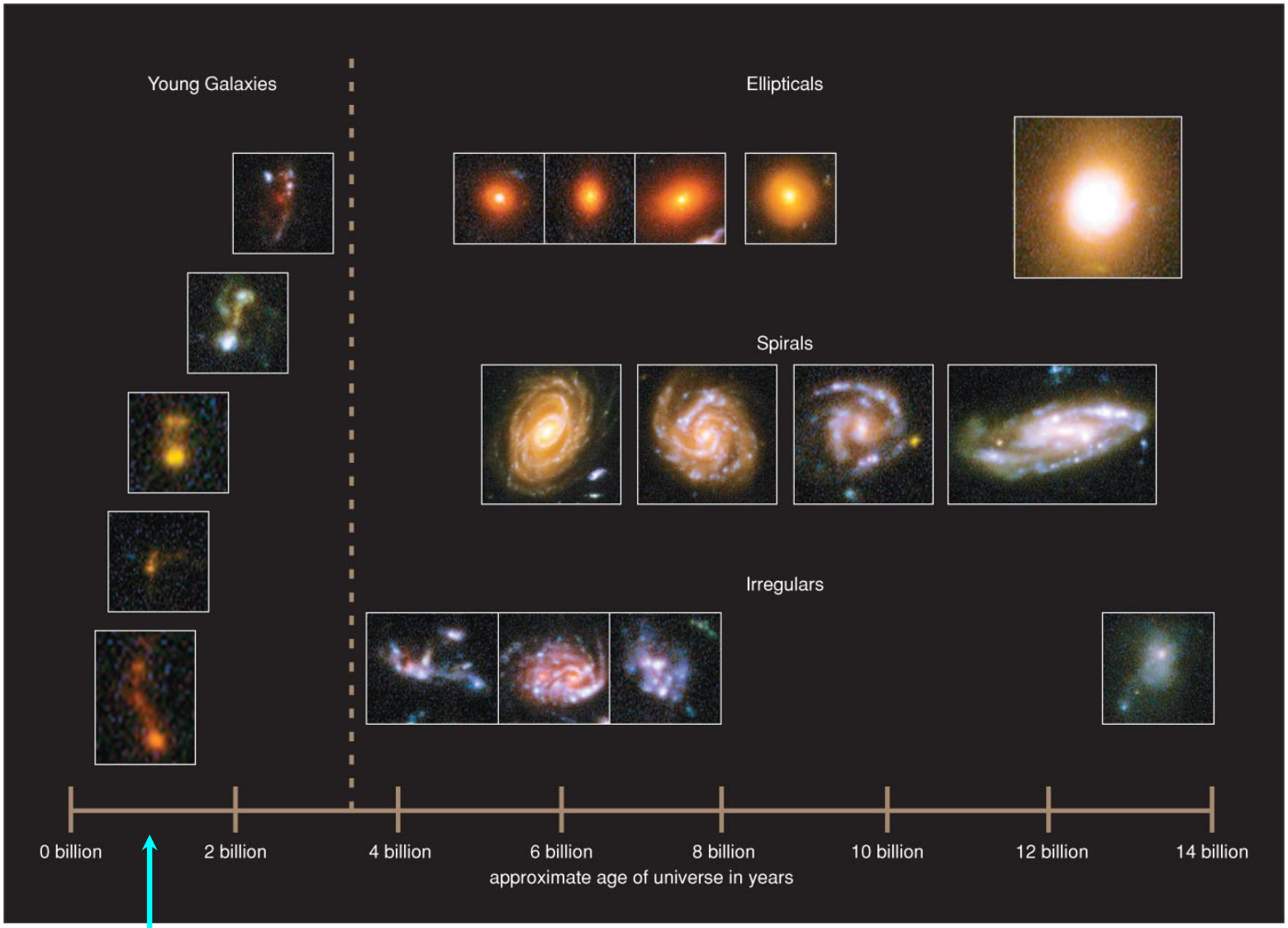


(c) The stellar birthrate in galaxies

One idea to explain why some galaxies become spirals and other ellipticals is that if star formation is large during the formation of the protogalaxy all the gas will be consumed quickly to form stars and no disk is formed resulting in an elliptical galaxy. Conversely, if star formation is weak within a protogalaxy the gas will have time to settle and form a disk resulting in a spiral galaxy.



- We must also consider the effects of collisions.



- Collisions were much more likely early in time because galaxies were closer together.

Table 24-1 Some Properties of Galaxies

	Spiral (S) and barred spiral (SB) galaxies	Elliptical galaxies (E)	Irregular galaxies (Irr)
Mass ($M_\odot$)	10^9 to 4×10^{11}	10^5 to 10^{13}	10^8 to 3×10^{10}
Luminosity ($L_\odot$)	10^8 to 2×10^{10}	3×10^5 to 10^{11}	10^7 to 10^9
Diameter (kpc)	5 to 250	1 to 200	1 to 10
Stellar populations	Spiral arms: young Population I Nucleus and throughout disk: Population II and old Population I	Population II and old Population I	mostly Population I
Percentage of observed galaxies	77%	20%*	3%

**This percentage does not include dwarf elliptical galaxies that are as yet too dim and distant to detect. Hence, the actual percentage of galaxies that are ellipticals may be higher than shown here.*

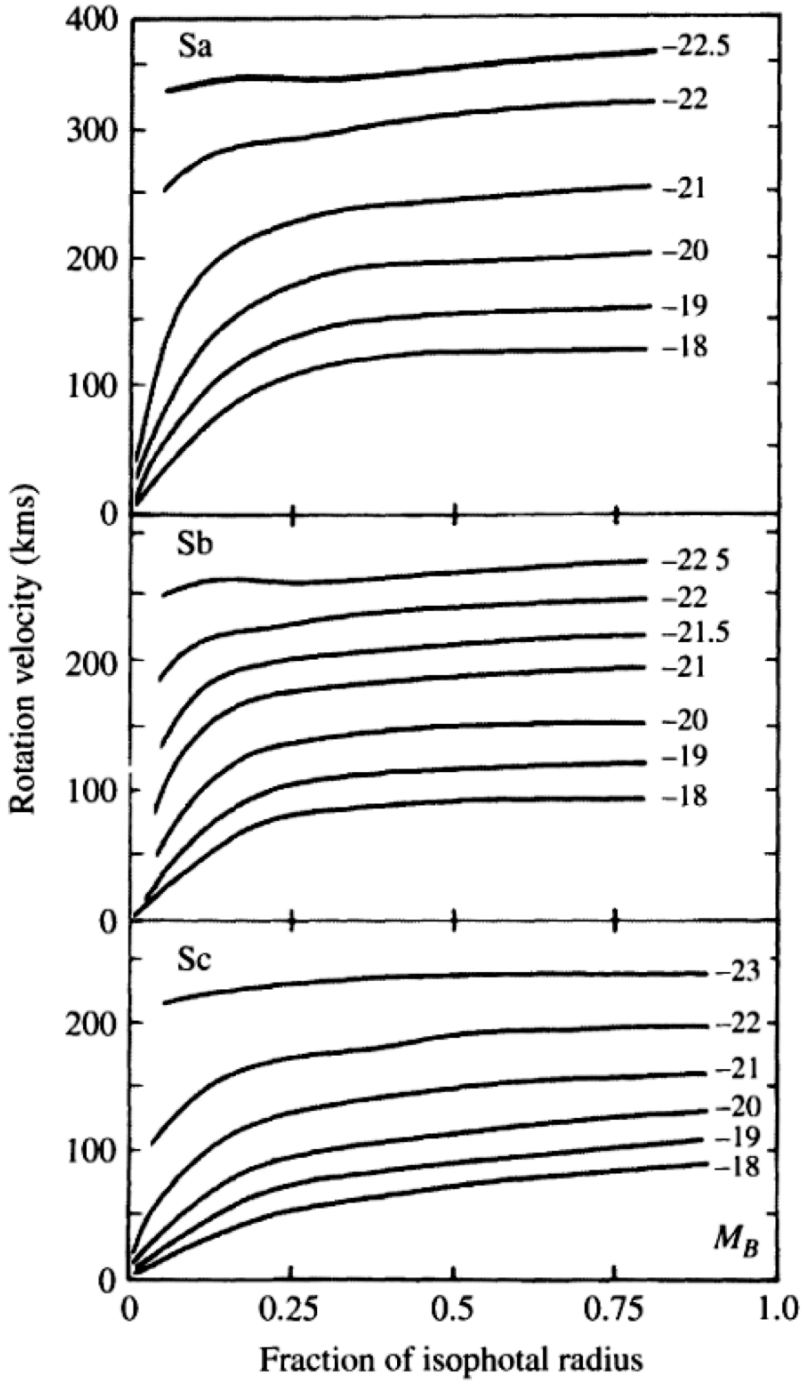


FIGURE 25.8 Variations in the average rotation curves of Sa, Sb, and Sc galaxies for various values of absolute magnitude in the *B* band. (Figure adapted from Rubin et al., *Ap. J.*, *289*, 81, 1985.)

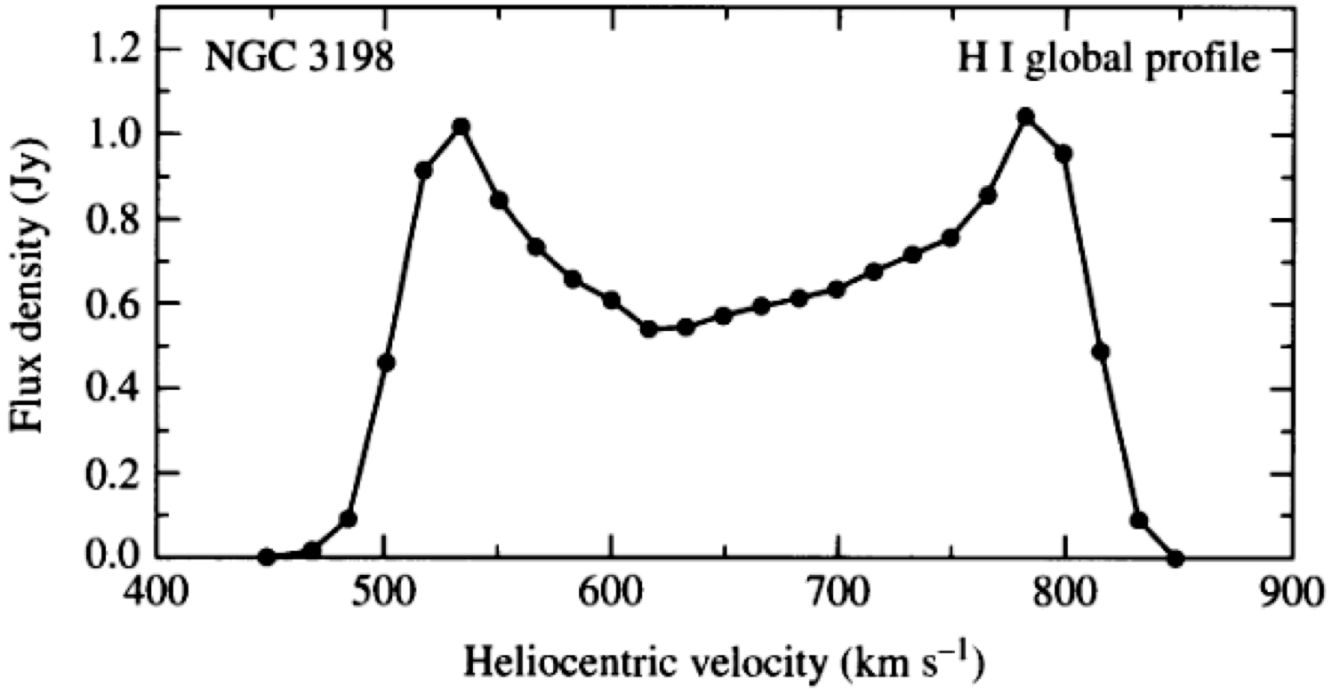


FIGURE 25.9 The global H I profile for NGC 3198. (Data from Begeman, *Astron. Astrophys.*, *223*, 81, 1991.)

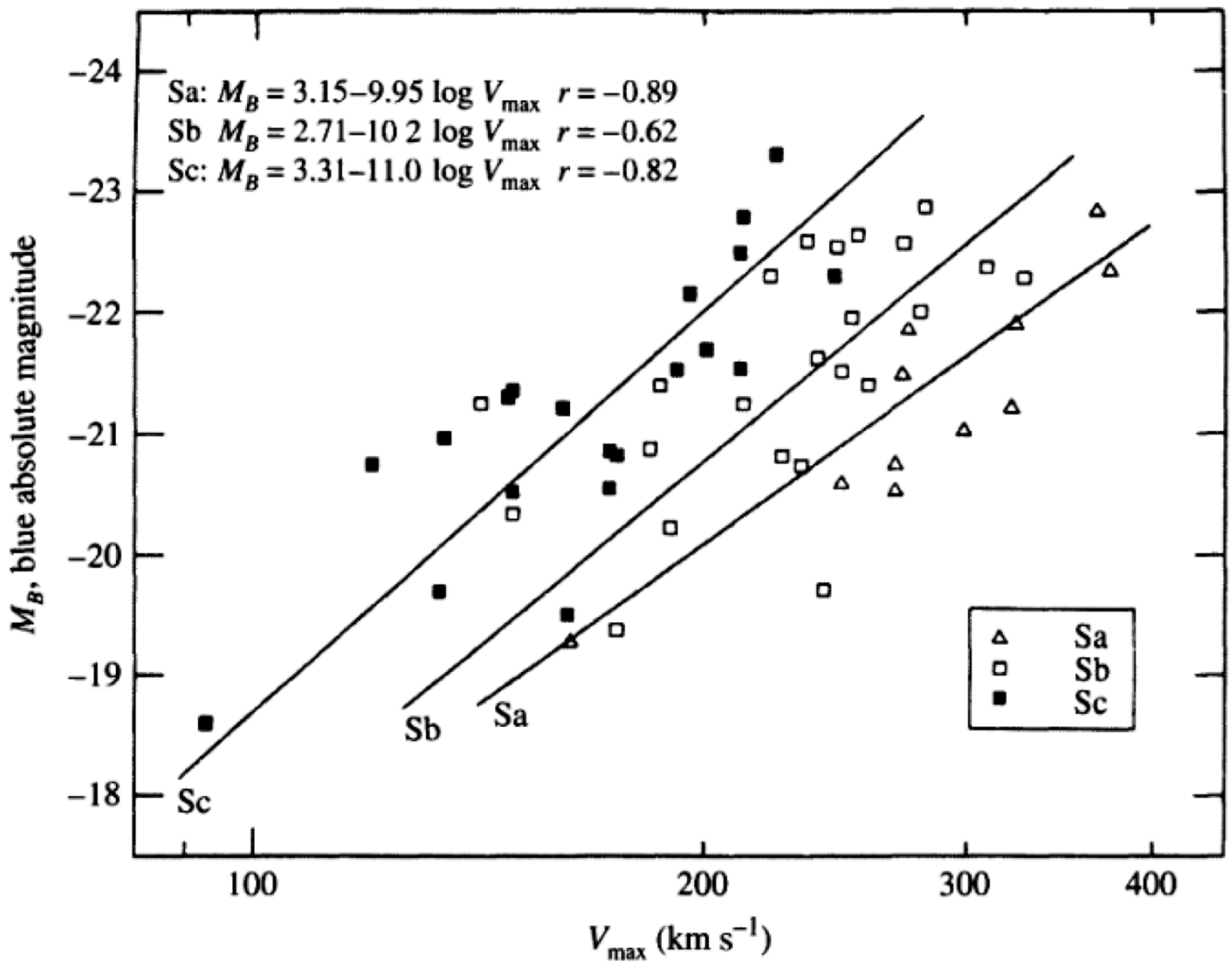


FIGURE 25.10 The Tully–Fisher relation for early spiral galaxies. (Figure adapted from Rubin et al., *Ap. J.*, *289*, 81, 1985.)

A composite image of **M51**, also known as the **Whirlpool Galaxy.**

X-ray data from the Chandra X-ray Observatory reveals point-like sources **(purple)** that are black holes and neutron binary systems. Chandra also detects a diffuse glow of hot gas that permeates the space between the stars.

Optical data from the Hubble Space Telescope **(green)** and **infrared emission** from the Spitzer Space Telescope **(red)** both highlight long lanes in the spiral arms that consist of stars and gas laced with dust.

A view of M51 with the GALEX telescope shows hot, young stars that produce lots of **ultraviolet** energy **(blue)**.



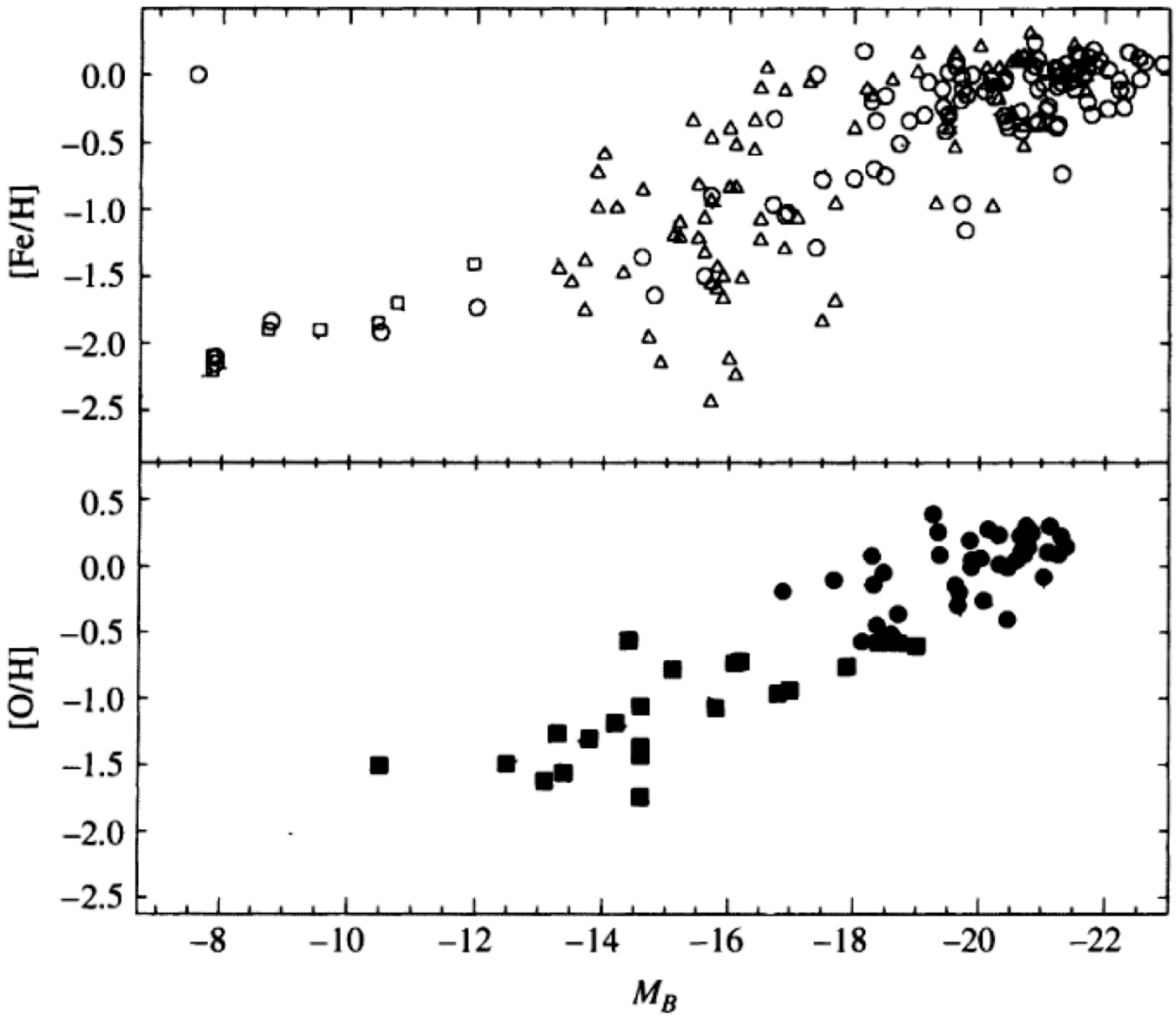
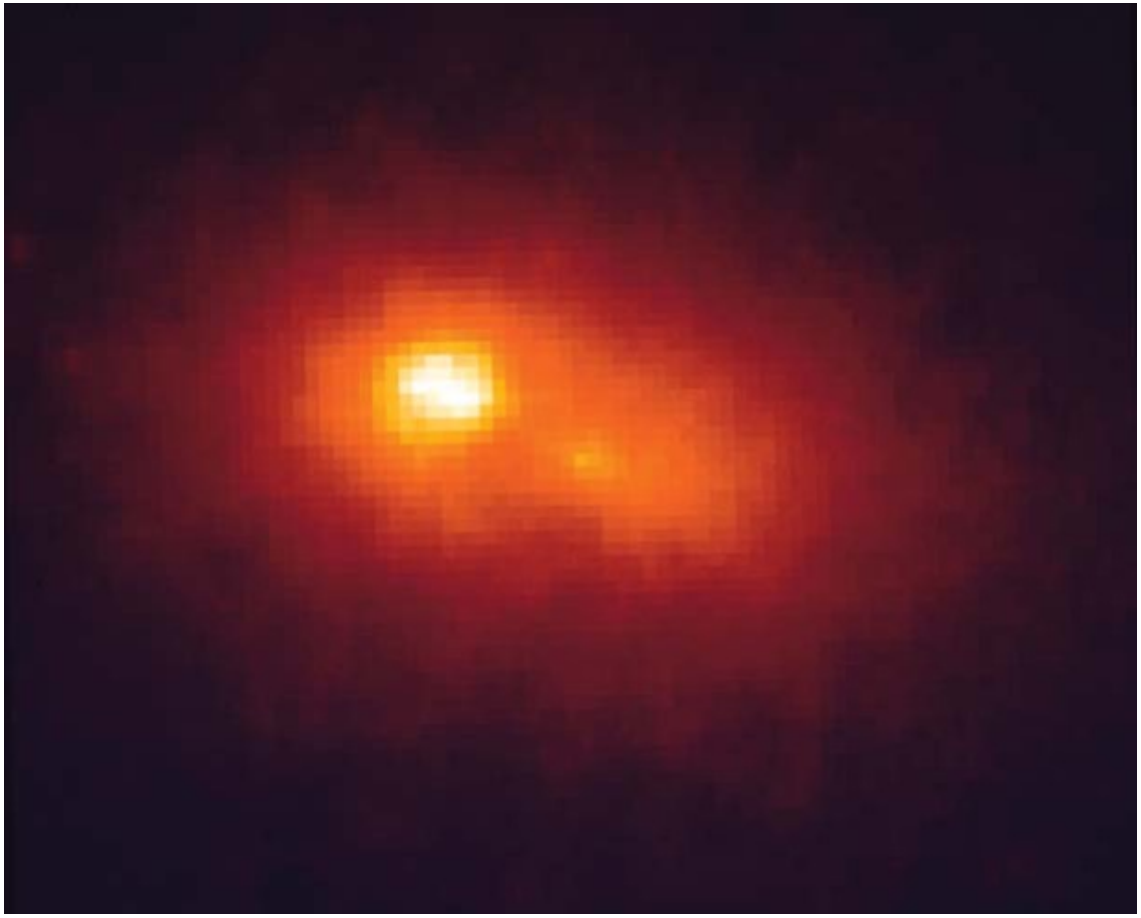
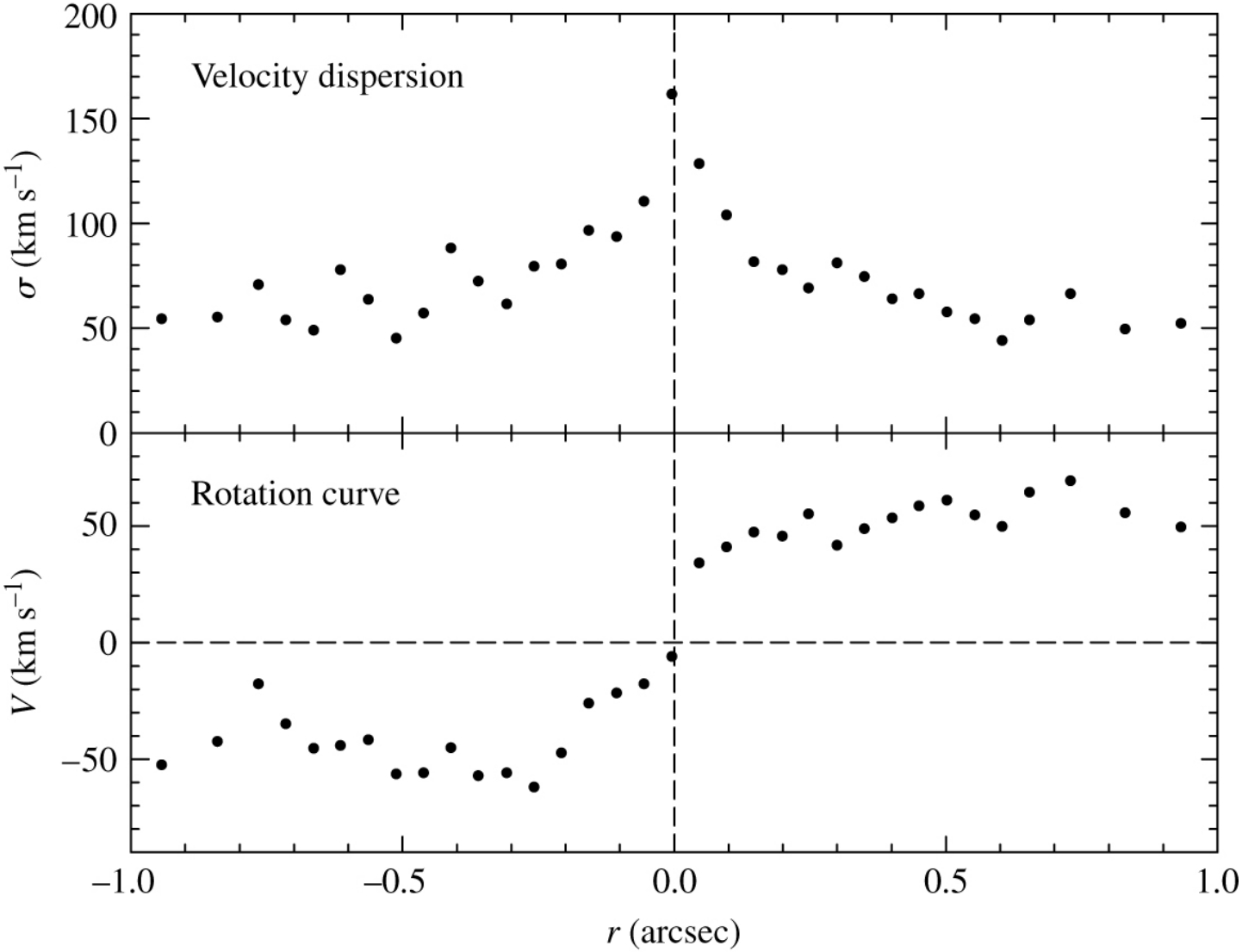


FIGURE 25.12 Metallicity is observed to increase linearly with absolute magnitude. The symbols in the upper panel correspond to dE's (dwarf ellipticals, open squares) and ellipticals (open circles and open triangles). In the lower panel, spirals are represented by filled circles and irregulars are indicated by filled squares. (Figure adapted from Zaritsky, Kennicutt, and Huchra, *Ap. J.*, *420*, 87, 1994.)

A Black Hole Census



Hubble image of the central region of the Andromeda galaxy (M31) in visible light. The stars form an eccentric disk around the SMBH ($M_{BH} \sim 140 \times 10^6 M_\odot$). The black hole is located closer to the fainter of the two peaks in the light distribution.


Velocity dispersion
Rotation curve
σ (km s−1)
V (km s−1)
r (arcsec)
200
150
100
50
0
50
0
−50
−1.0
−0.5
0.0
0.5
1.0

Black Hole Mass and Galaxy Bulge Mass

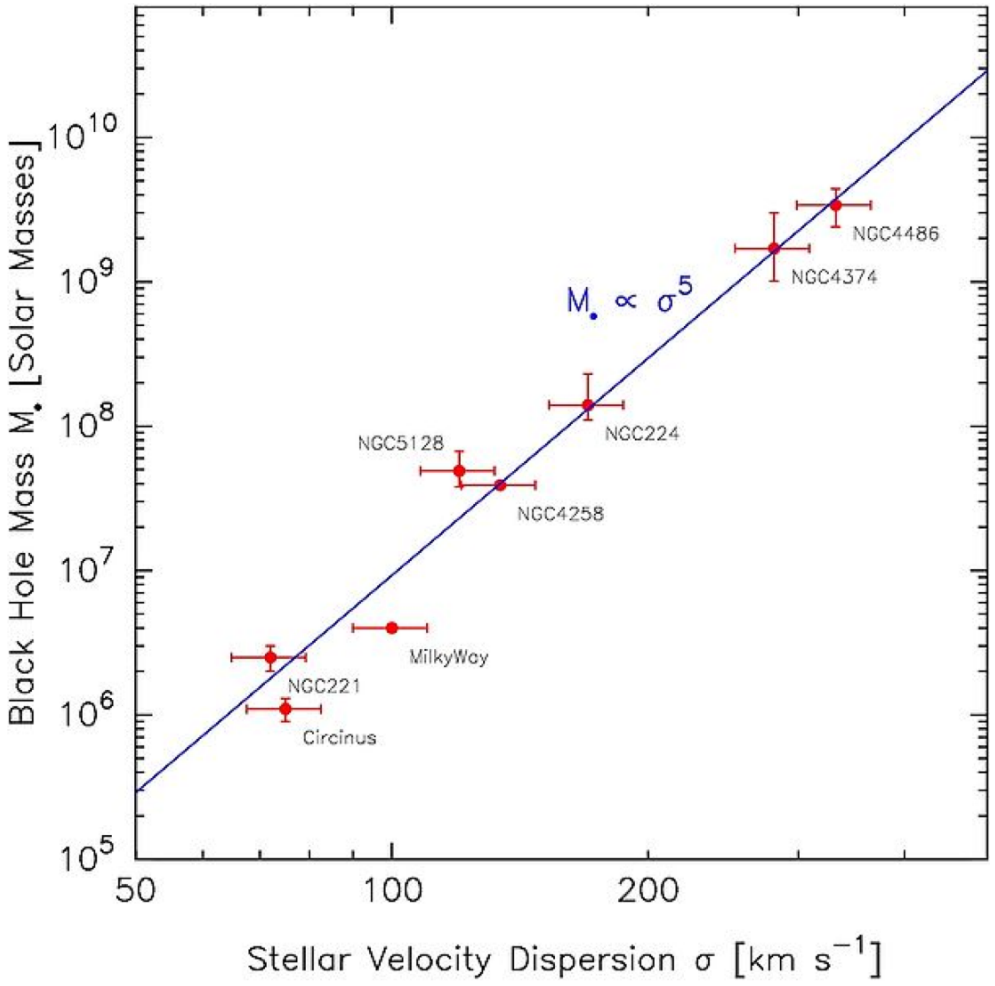
Observations in the 1990s had demonstrated a possible empirical relationship between galaxy luminosity and black hole mass but this relationship had larger scatter (*Magorrian Relation)*.

The mean ratio of black hole mass to bulge mass is believed to be approximately 0.1% , i.e., a bulge of one billion solar masses contains a black hole of approximately one million solar masses.

Black Hole Mass – Velocity Dispersion Relation

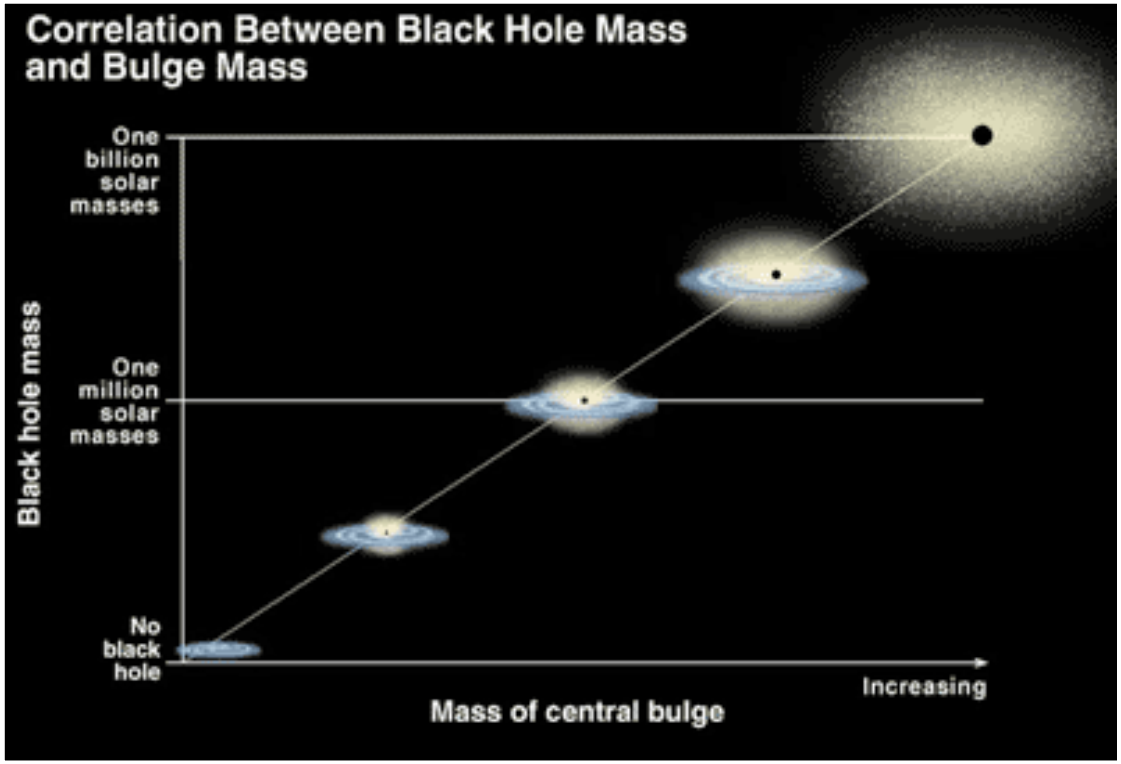
The M_{BH}-σ relation is an empirical correlation between the stellar velocity dispersion σ of a galaxy bulge and the mass M of the supermassive black hole at the galaxy's center.

$$\sigma = \frac{1}{\sqrt{N}}\left[\sum_{1}^{N}\left(u - \langle u \rangle\right)^2\right]^{1/2}$$



$$M_{BH} \propto \sigma^{\alpha},\ \alpha \approx 5$$

The influence of black hole winds on their environments



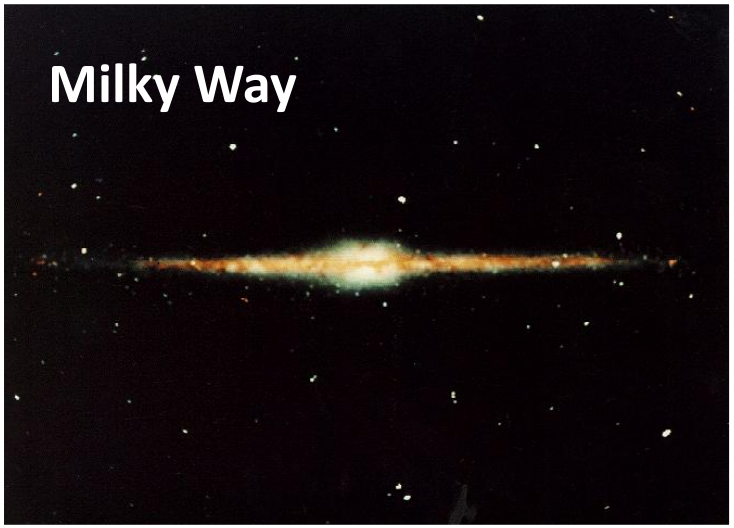


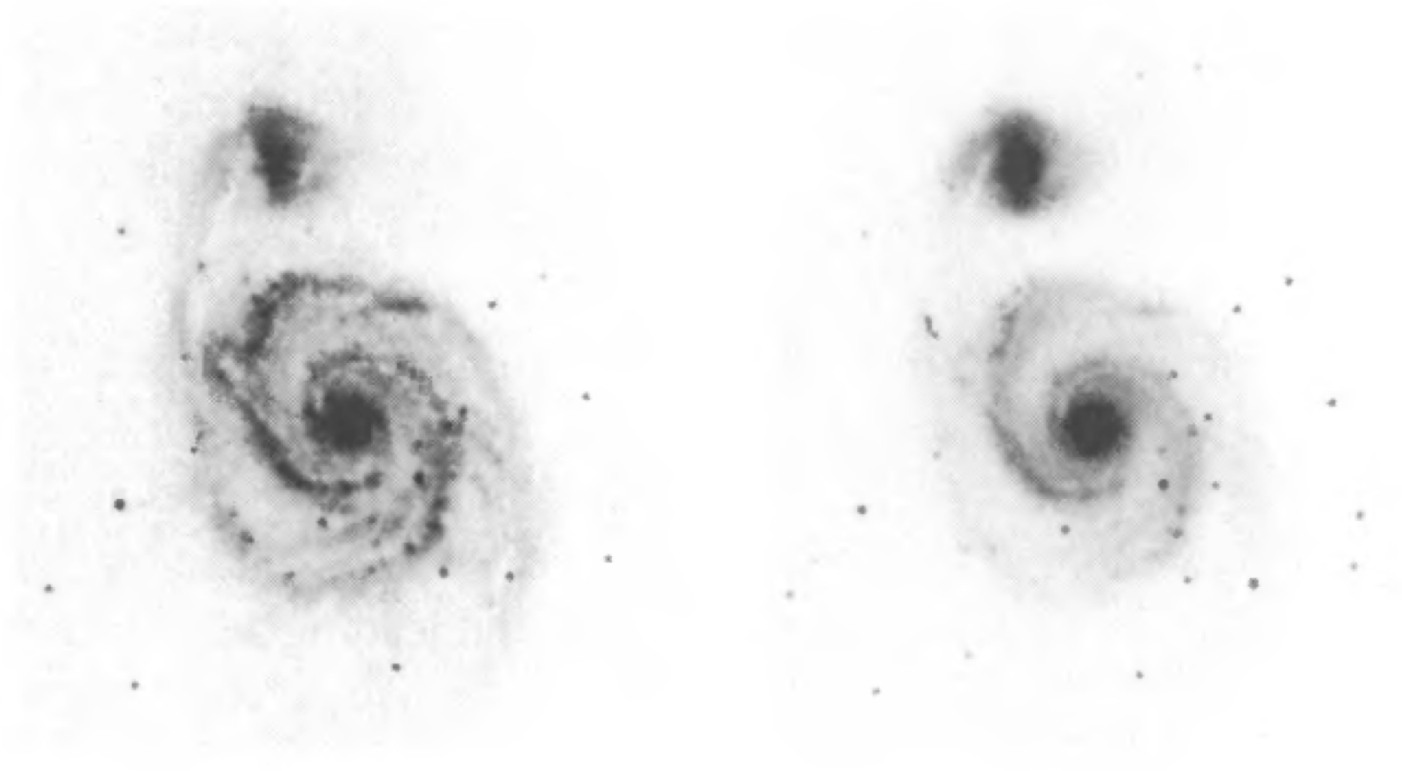




FIGURE 25.17 The Whirlpool galaxy, M51 (NGC 5194), is an Sbc(s)I–II grand-design spiral located in the constellation Canes Venatici (the Hunting Dogs of Boötes, just below Ursa Major). Also visible is its companion NGC 5195, situated near the end of one of the spiral arms. (Image from Sandage and Bedke, *The Carnegie Atlas of Galaxies*, Carnegie Institution of Washington, Washington, D.C., 1994.)

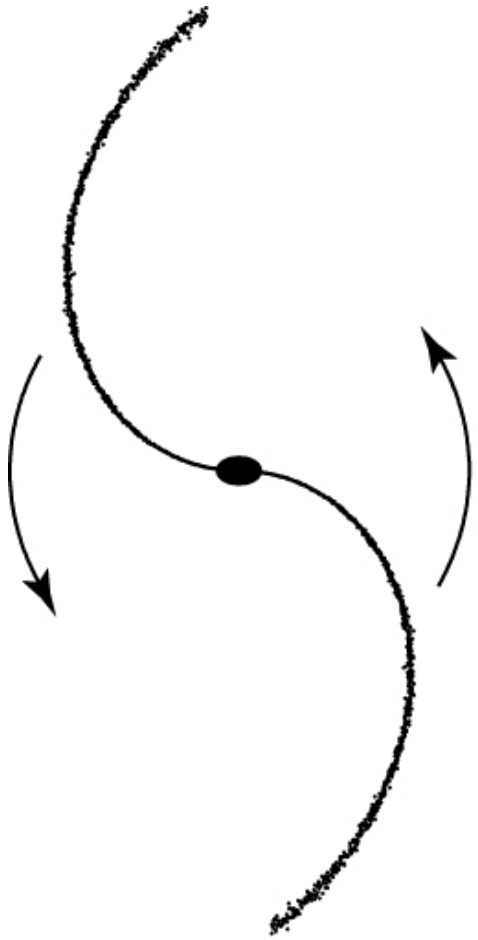


FIGURE 25.18 The Sb galaxy NGC 2841 is an example of a flocculent spiral. (Image from Sandage and Bedke, *The Carnegie Atlas of Galaxies*, Carnegie Institution of Washington, Washington, D.C., 1994.)

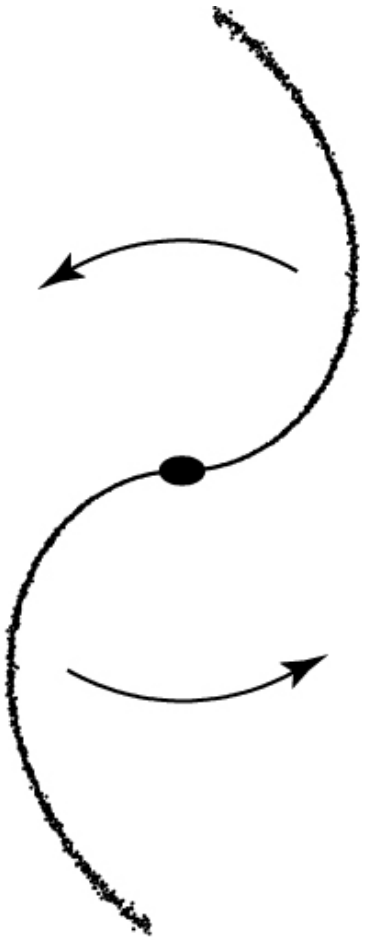


(a) (b)

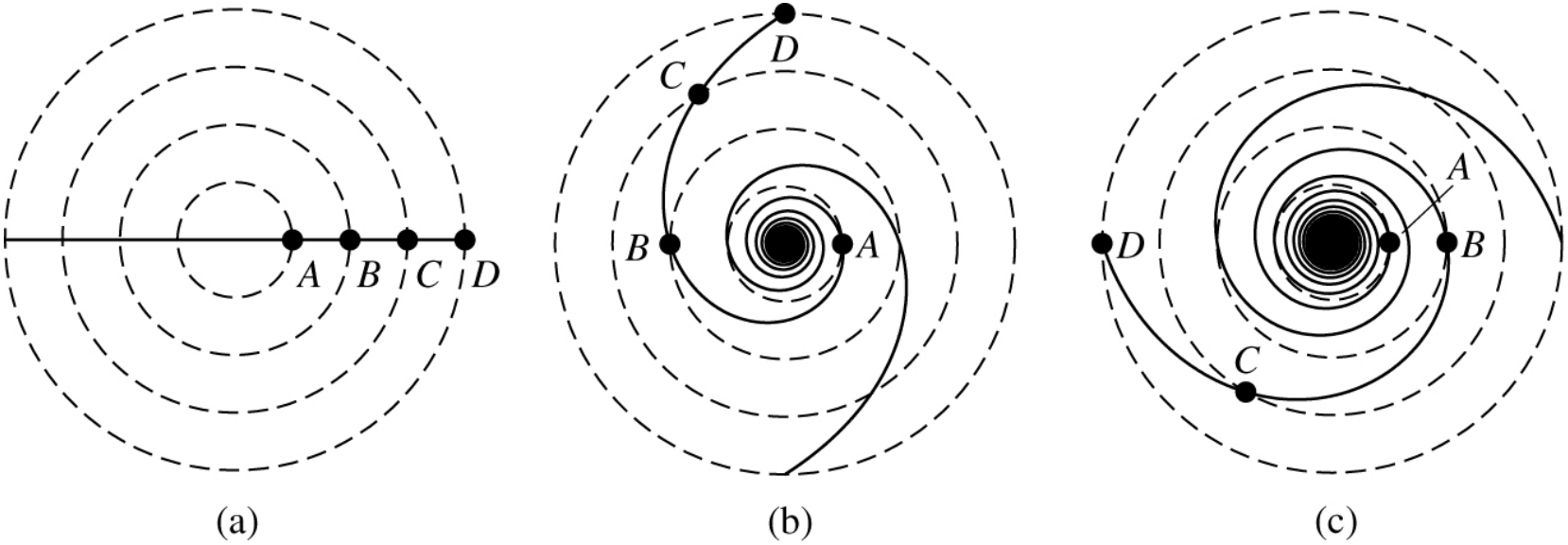
FIGURE 25.19 M51 as seen in (a) blue light and (b) red light. (Figures from Elmegreen, *Ap. J. Suppl.*, *47*, 229, 1981.)



Trailing structure



Leading structure


A
B
C
D
(a)
C
D
B
A
(b)
A
D
B
C
(c)

Density-Wave Model of Spiral Arms

Most of the stars, gas and dust in our Galaxy rotate around the center of the galaxy at almost the same speed. Any rigid pattern of stars could not persist after some time.

The **density-wave model** posits that the spirals are actually density-waves that travel around the disk just like ripples on water. These waves move around the galaxy more slowly than do stars, dust and gas near the center of the galaxy.

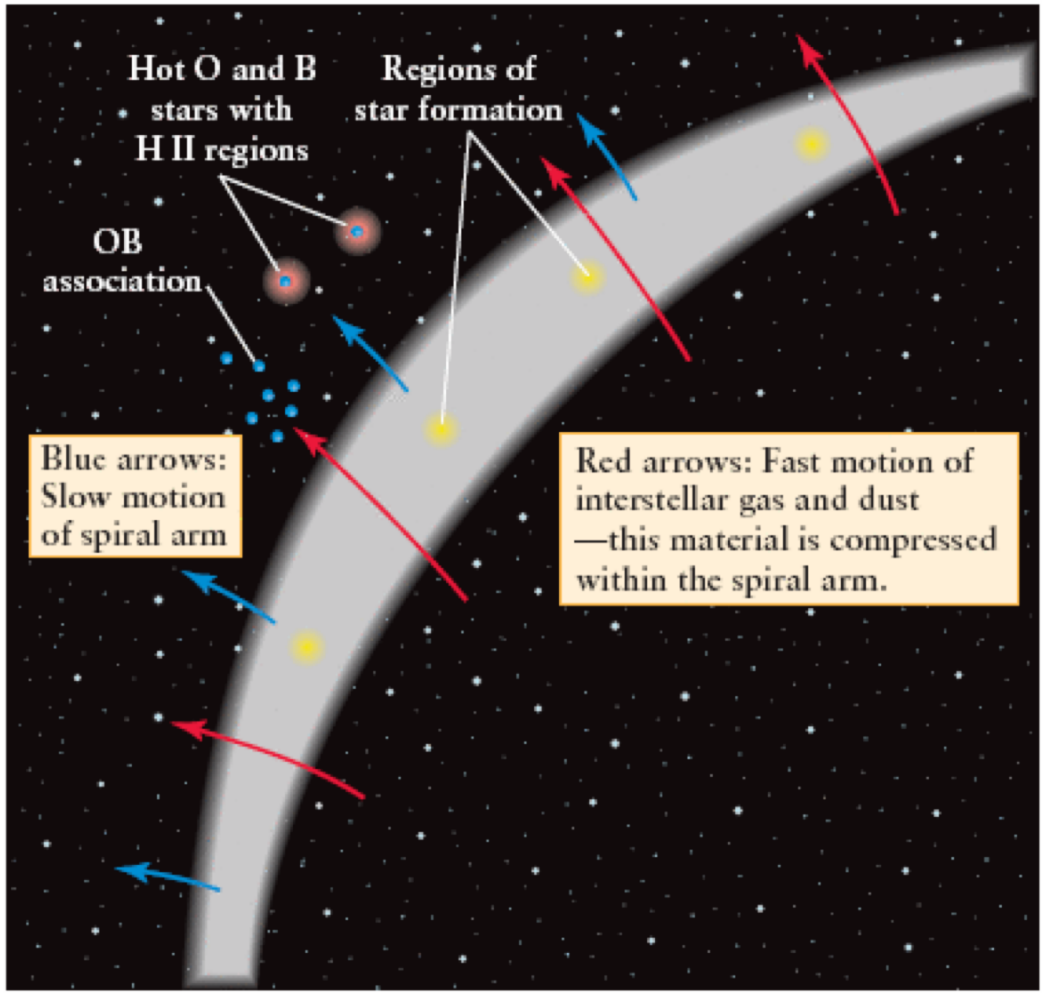
A density wave compresses the gases in the interstellar medium and this **leads eventually to star formation**.

Density-Wave Model of Spiral Arms

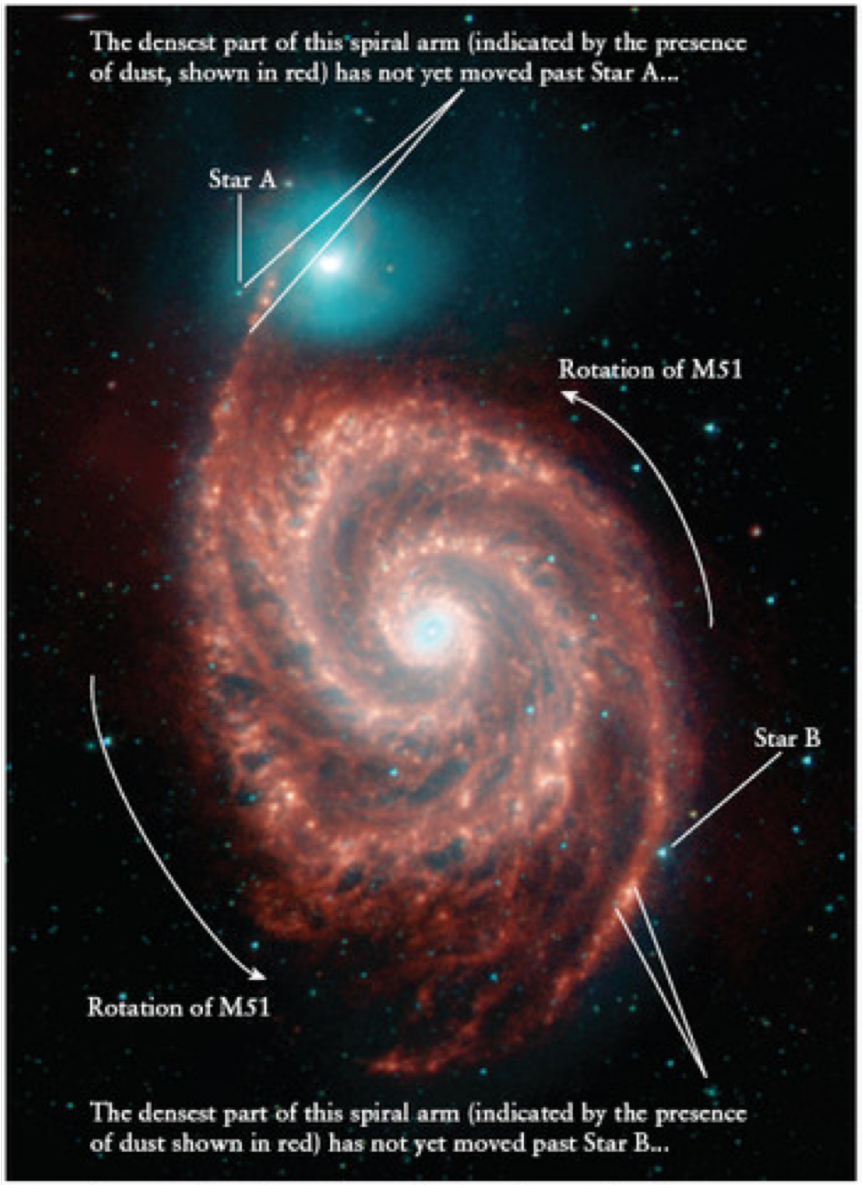
A spiral arm is a region where the density of material is higher than in the surrounding parts of a galaxy.

Interstellar matter moves around the galactic center rapidly (shown by the red arrows) and **is compressed as it passes through the slow-moving spiral arms** (whose motion is shown by the blue arrows).

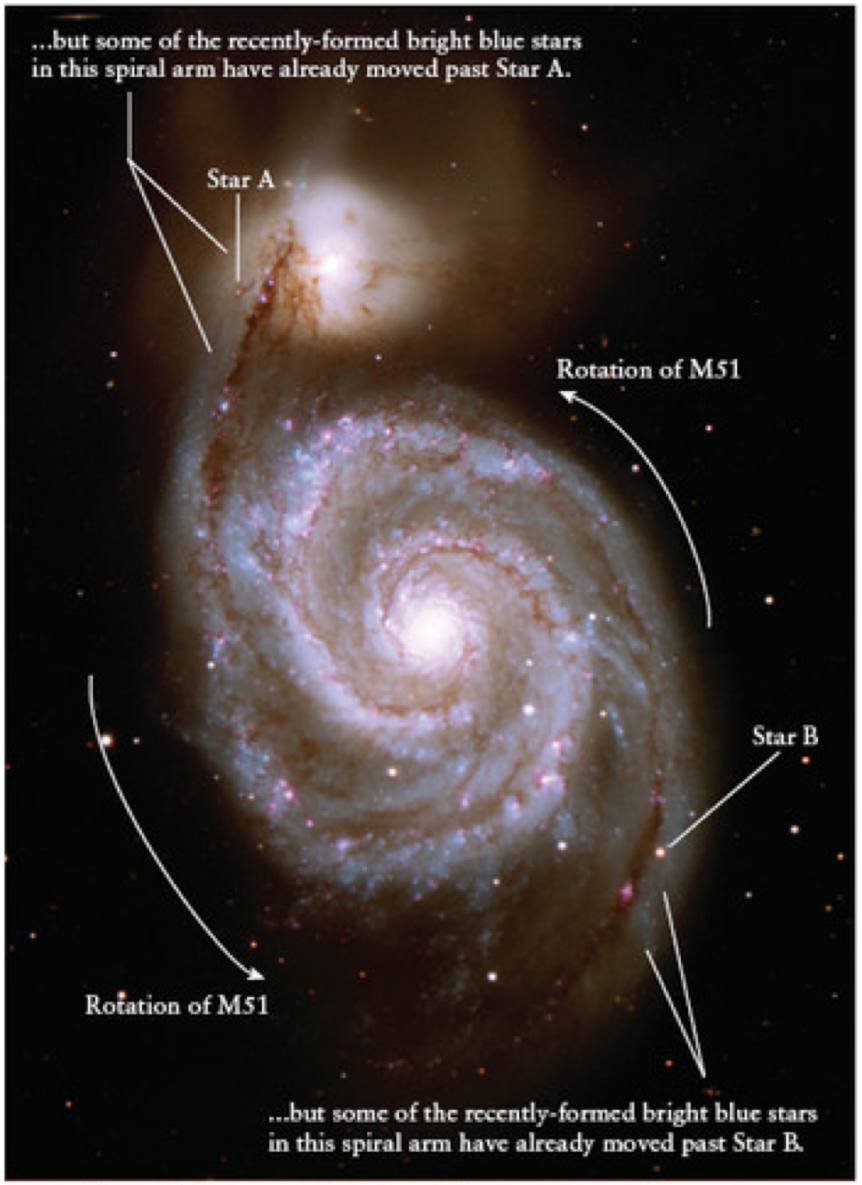
This **compression triggers star formation** in the interstellar matter, so that new stars appear on the "downstream" side of the densest part of the spiral arm.



Density-Wave Model of Spiral Arms



(a) An infrared view of M51 shows the locations of dust



(b) A visible-light view of M51 shows the locations of young stars

Self-Propagating Star-Formation Model of Spiral Arms



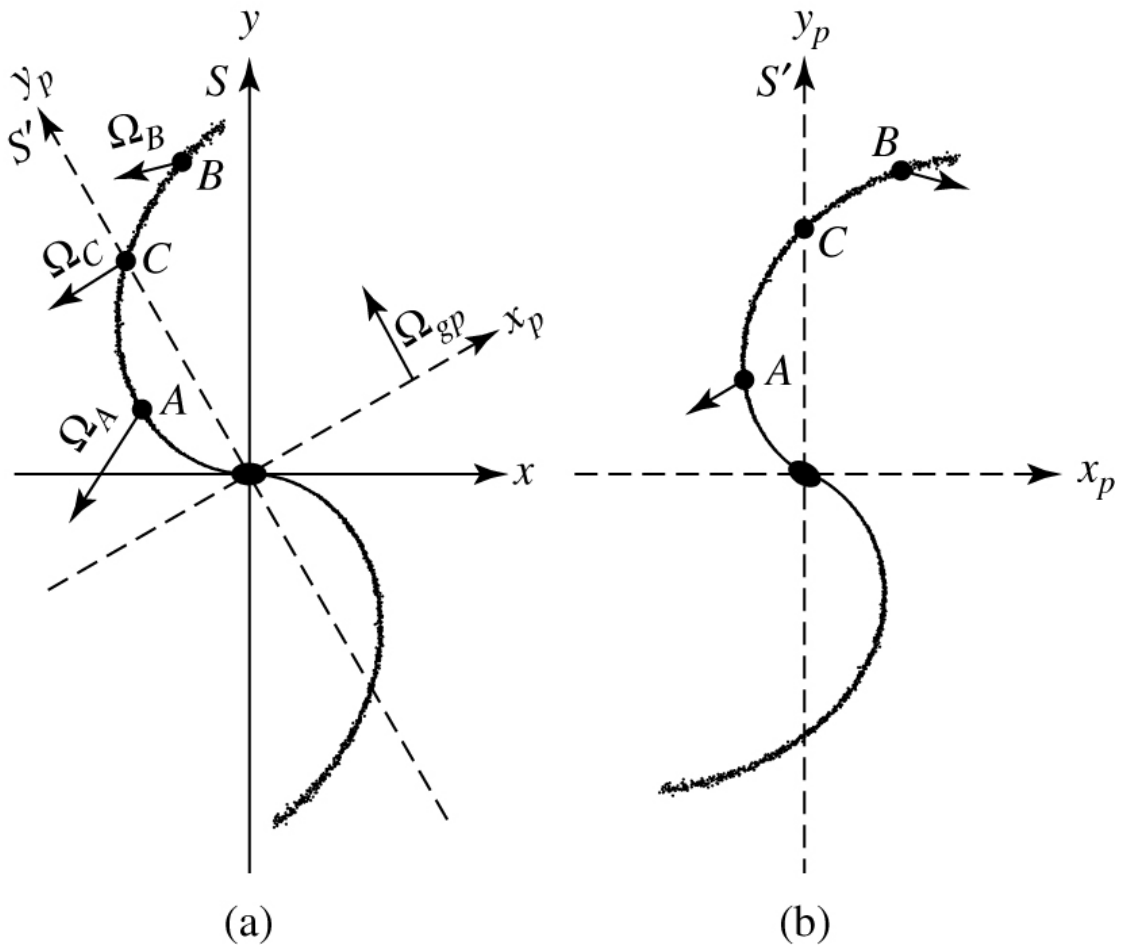
(a) Grand-design spiral galaxy

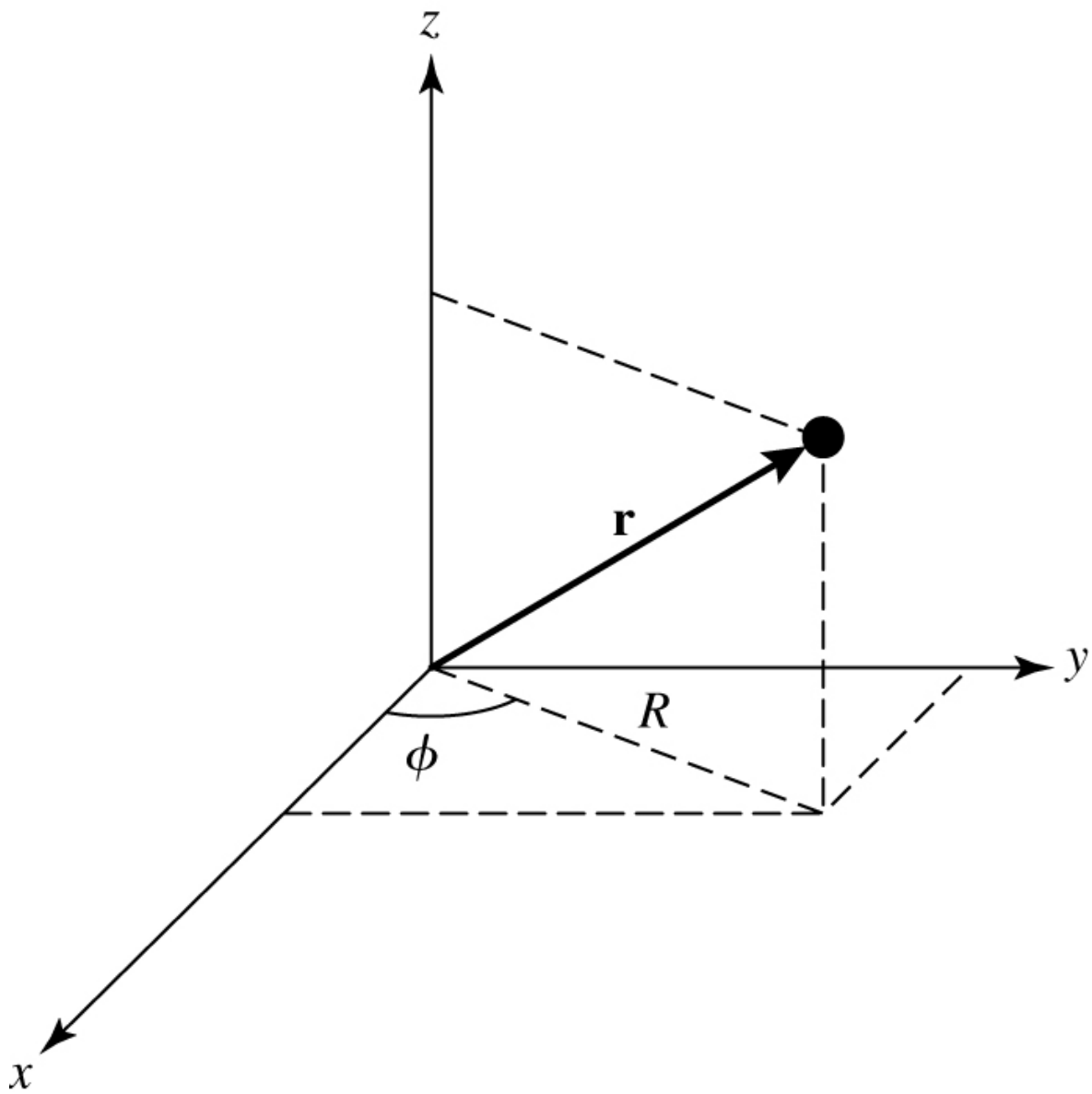


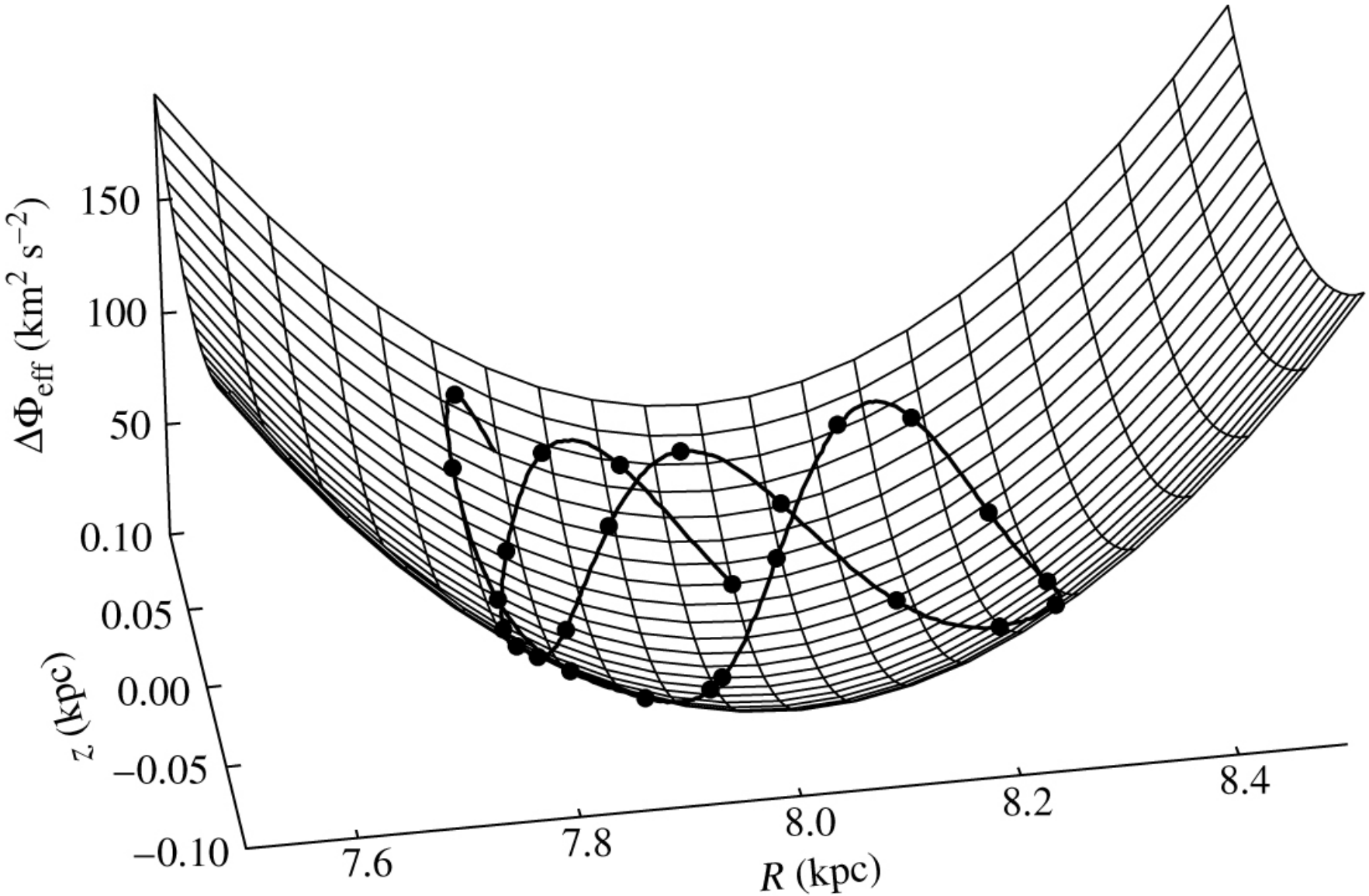
(b) Flocculent spiral galaxy

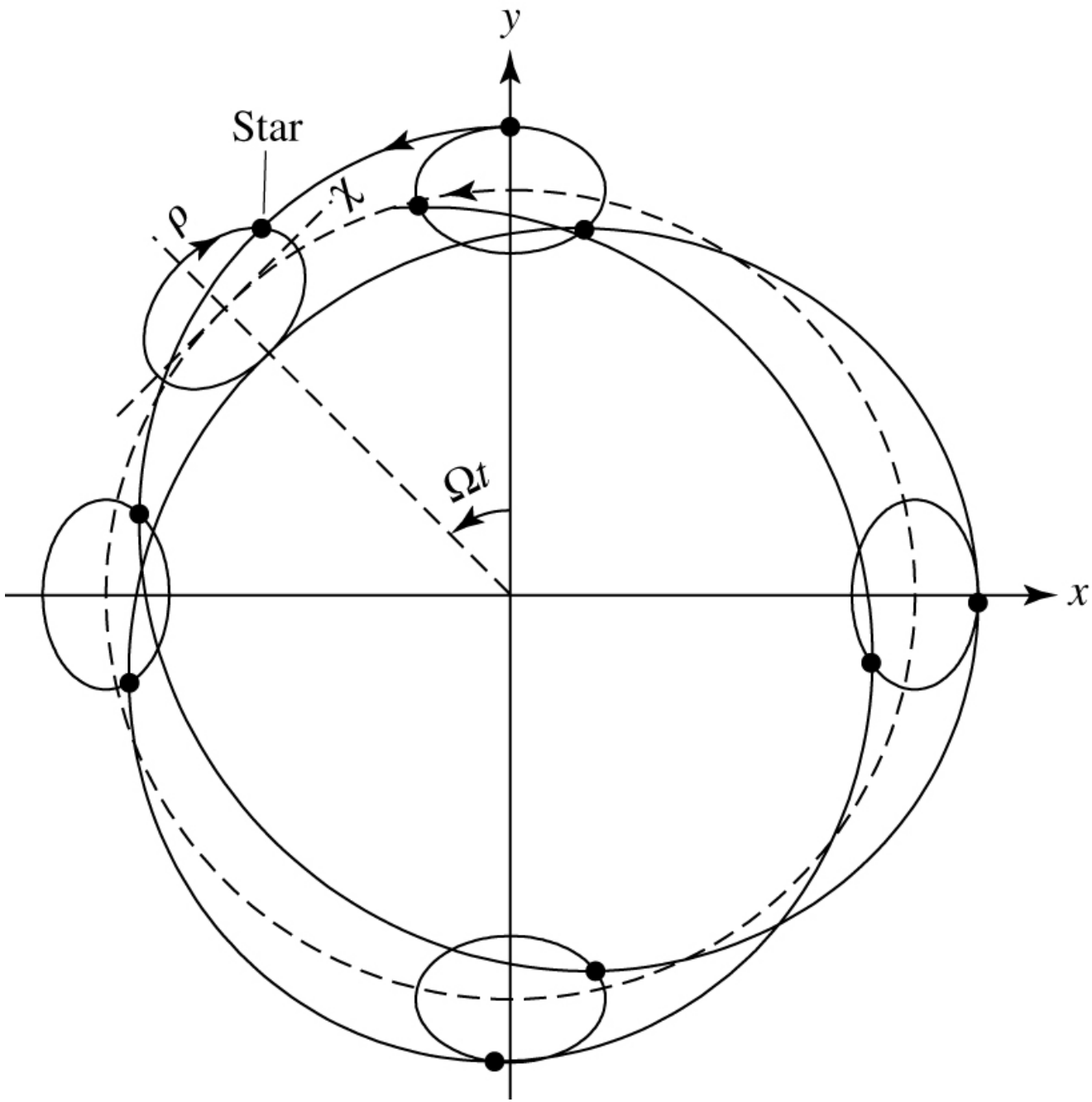
In the density wave model well defined spiral arms produce star formation.

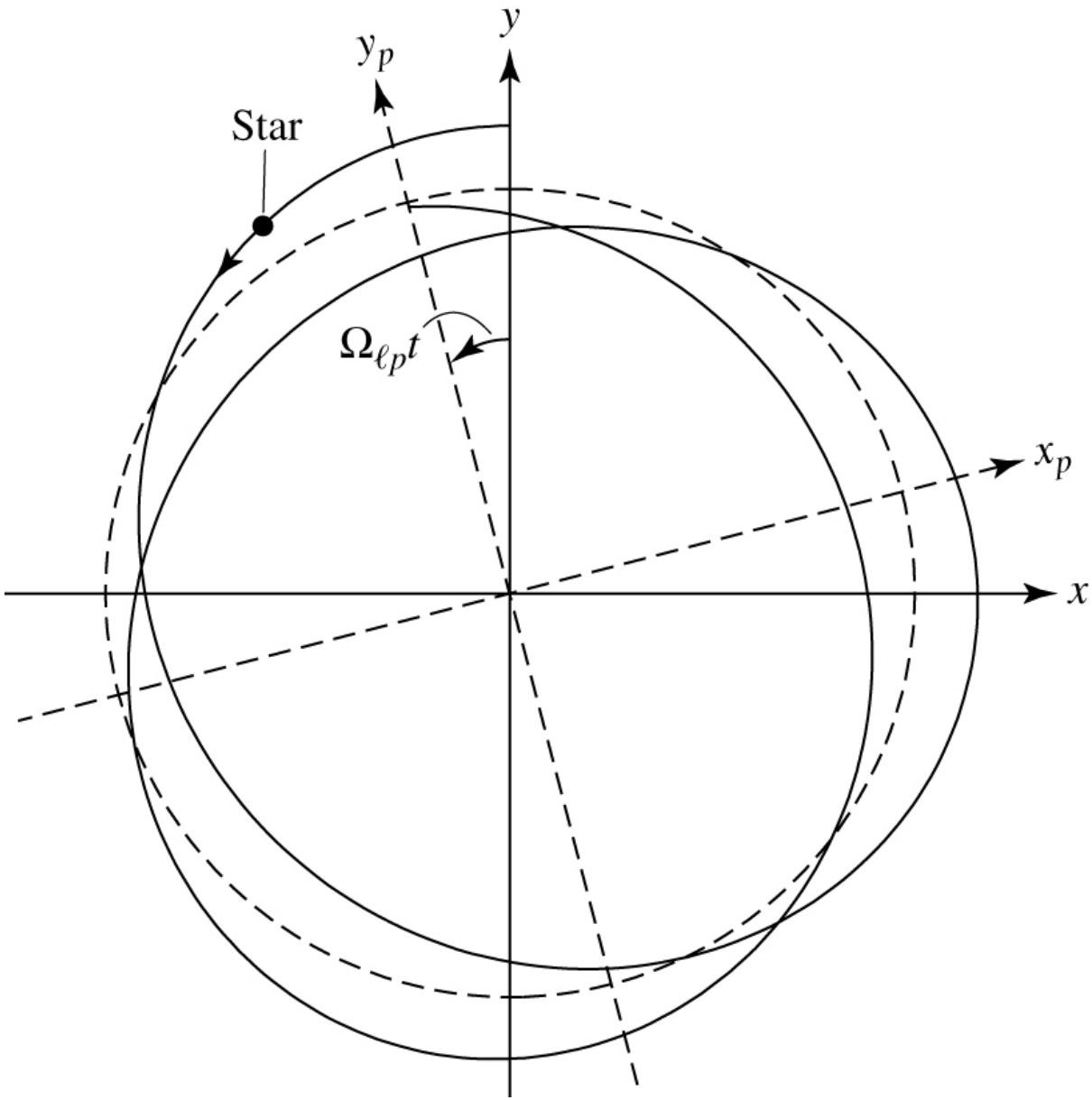
In the self–propagating model chaotic looking spiral arms are produced by star formation.

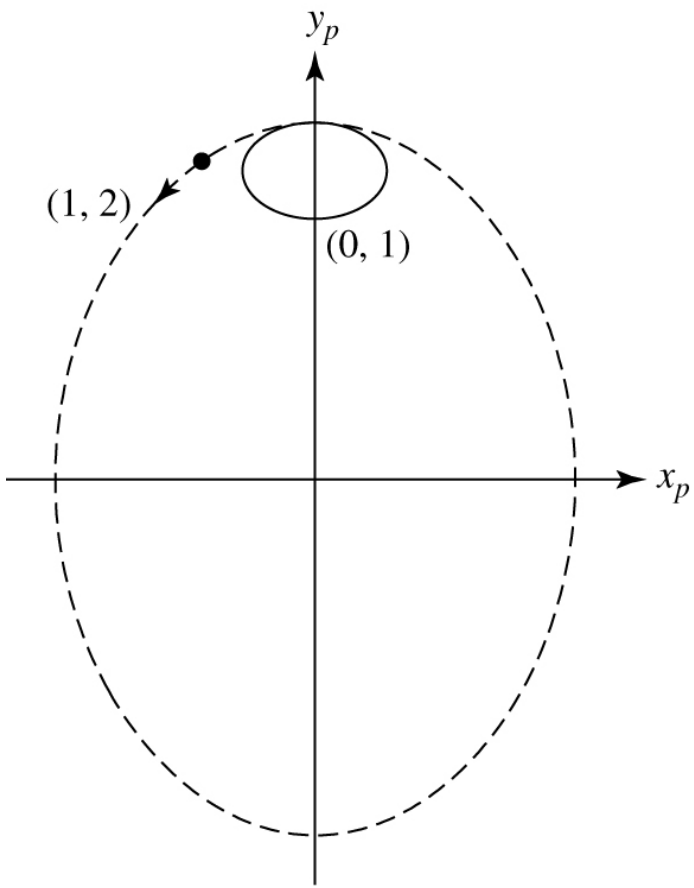

y
S
y_p
S'
Ω_B
B
Ω_C
C
Ω_gp
x_p
Ω_A
A
x
(a)
y_p
S'
B
C
A
x_p
(b)


z
r
y
R
ϕ
x

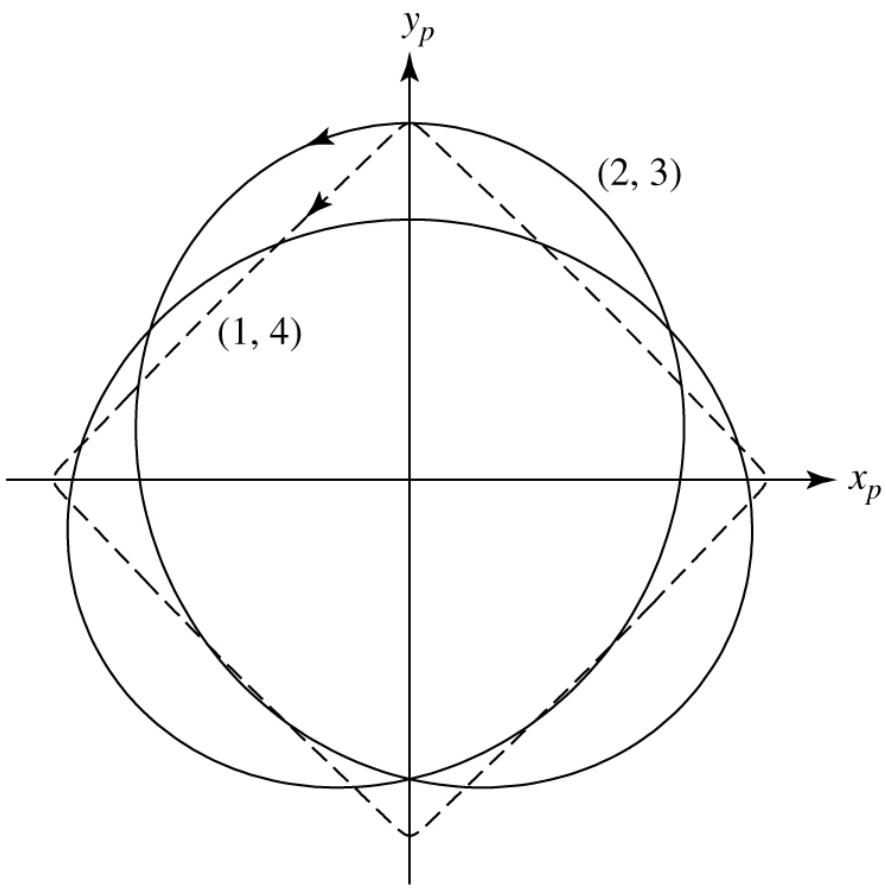

150
100
50
0.10
0.05
0.00
−0.05
−0.10
$\Delta\Phi_{\rm eff}$ (km^2 s^{-2})
z (kpc)
7.6
7.8
8.0
8.2
8.4
R (kpc)


y
Star
ρ
χ
Ωt
x

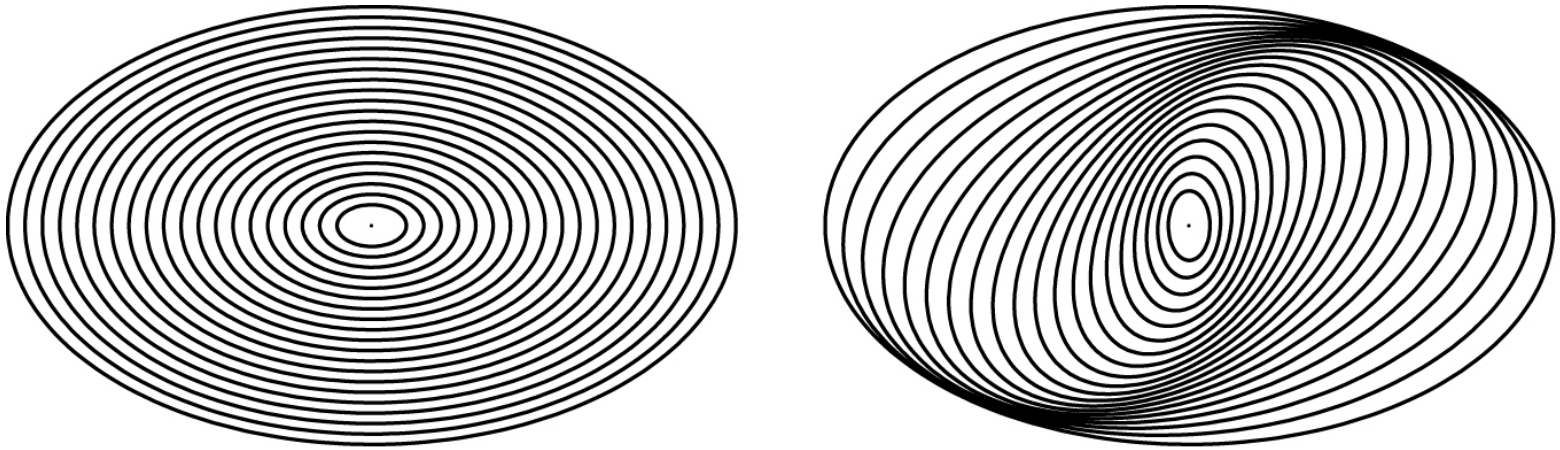

y
y_p
Star
$\Omega_{\ell p} t$
x_p
x



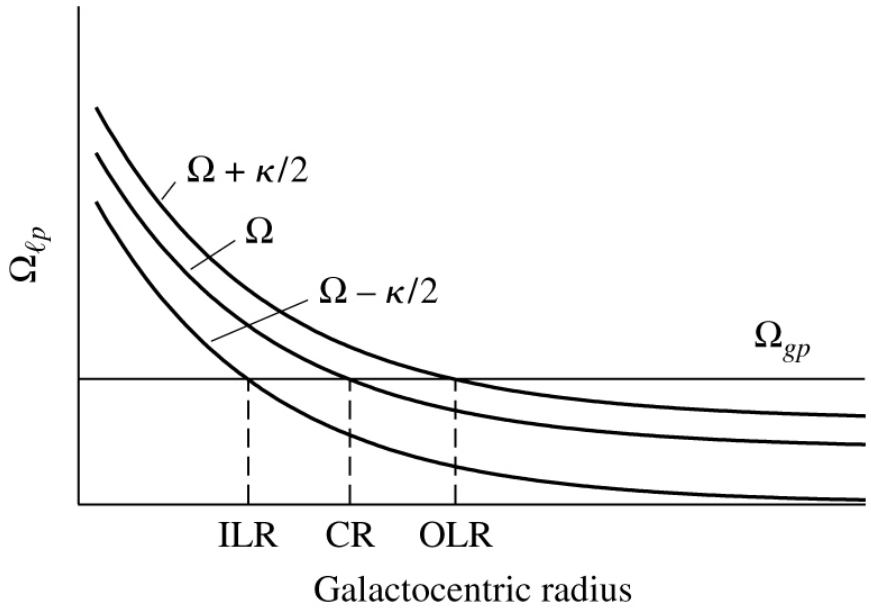
(a)



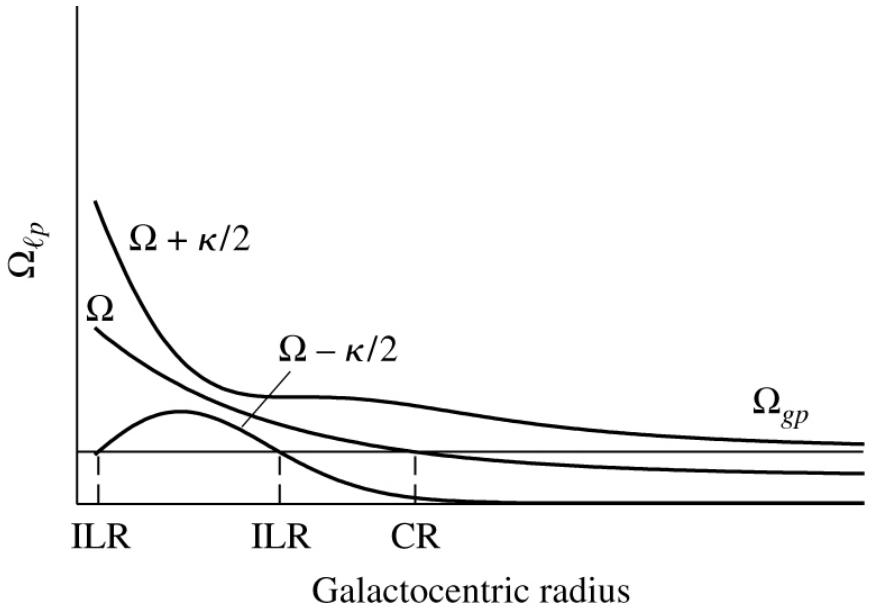
(b)



(a) (b)

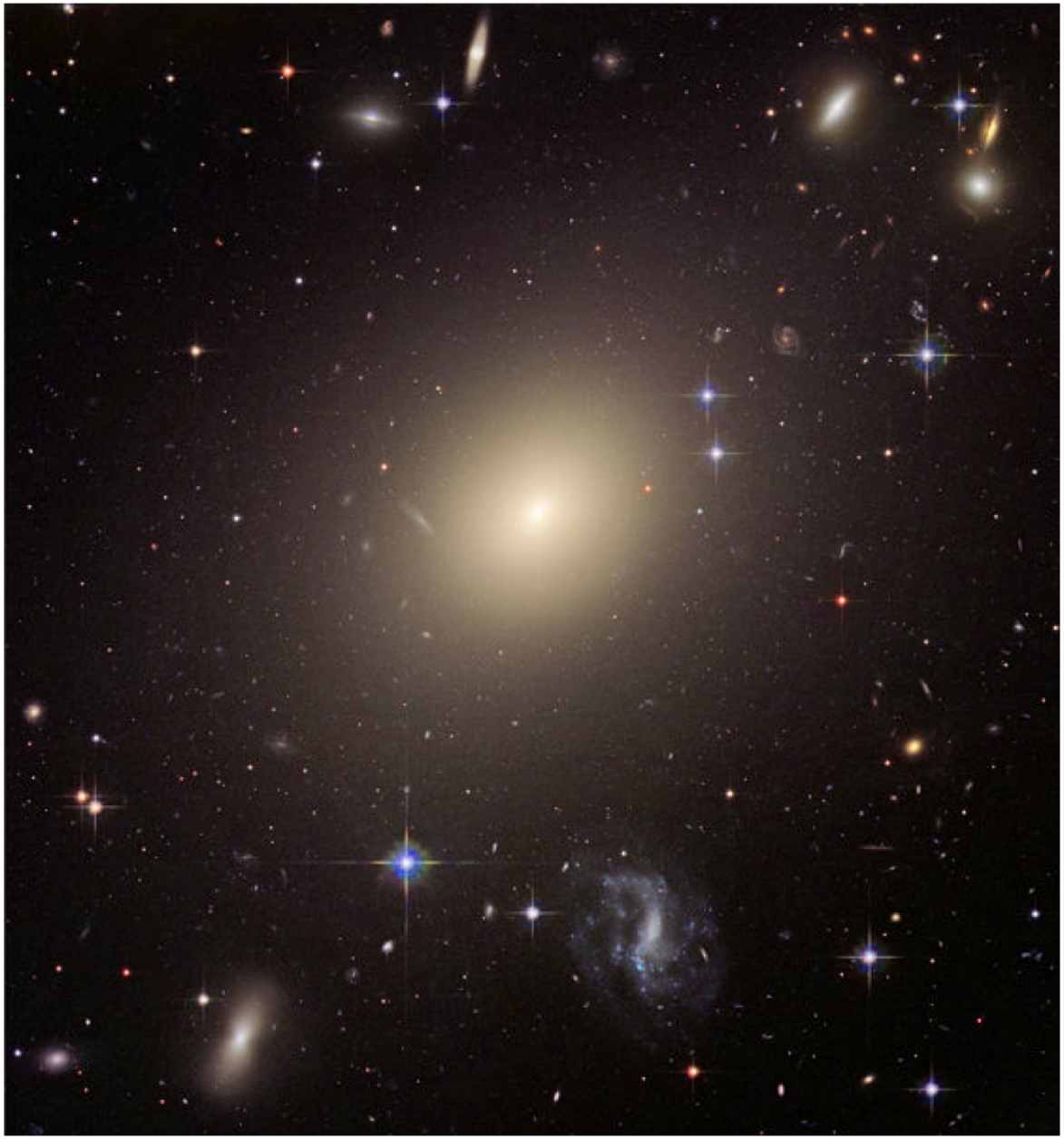

$\Omega_{\ell p}$
$\Omega + \kappa/2$
Ω
$\Omega - \kappa/2$
Ω_{gp}
ILR
CR
OLR
Galactocentric radius

(a)


$\Omega_{\ell p}$
$\Omega + \kappa/2$
Ω
$\Omega - \kappa/2$
Ω_{gp}
ILR
ILR
CR
Galactocentric radius

(b)

Elliptical Galaxies



The giant elliptical galaxy ESO 325-G004

TABLE 25.3 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 25.4 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	—	—

Tables 25.3 and 25.4 summarize some of the characteristics of early-type galaxies. Lenticular galaxies have also been included in the list, since they appear to have much in common with many ellipticals.

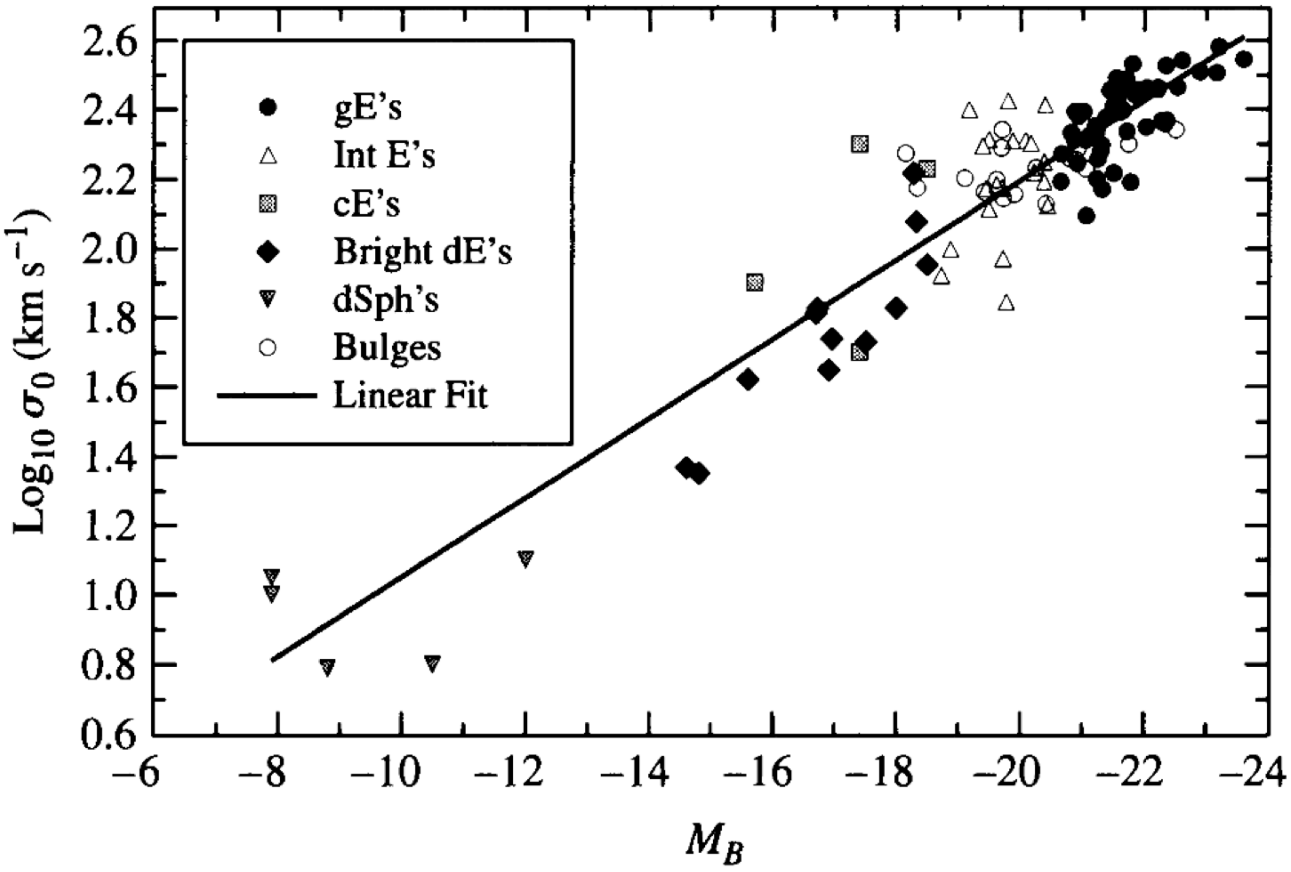


FIGURE 25.33 The Faber–Jackson relation represents a correlation between central velocity dispersion and luminosity. The relation is a consequence of the virial theorem. (Data from Bender et al., *Ap. J.*, *399*, 462, 1992.)

Estimating the distances to Elliptical Galaxies

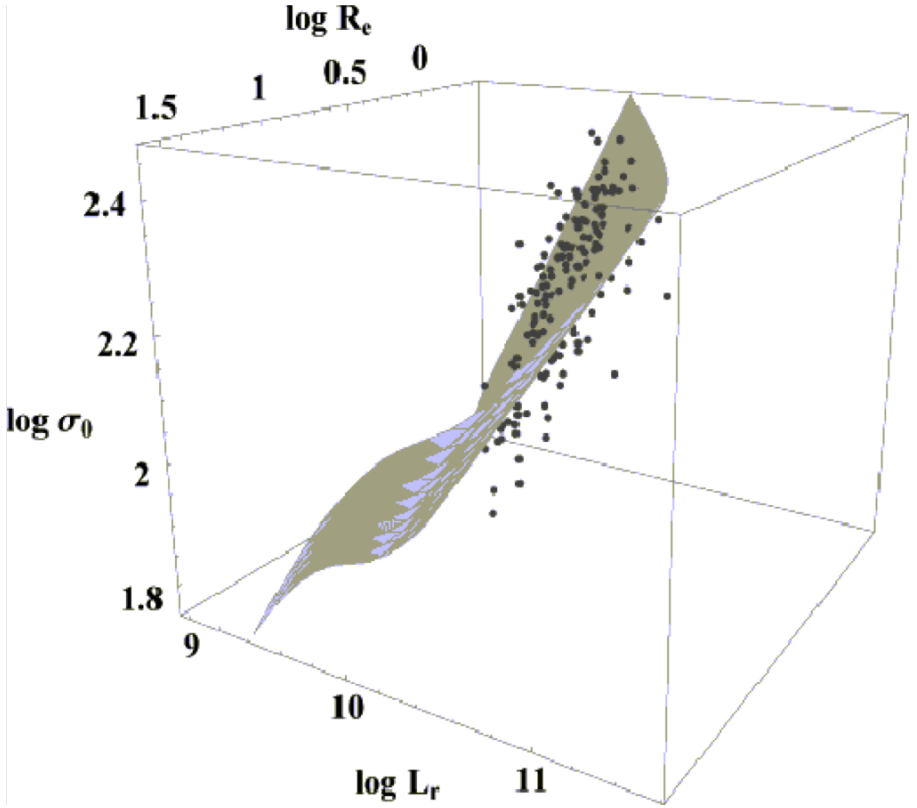
The fundamental plane is an empirical relation between the effective **size**, the average surface **brightness** and the central **velocity dispersion of the central stars** found in elliptical galaxies.

If one measures these three quantities for many elliptical galaxies and plots them they find that the points fall on a plane called the fundamental plane.

Estimating the distances to Elliptical Galaxies

Having found the fundamental plane for nearby galaxies one can estimate the distance to remote elliptical galaxies:

First one measures the central velocity dispersion of the stars and the average surface brightness. Then using the fundamental plane one can infer the effective radius of the galaxy and use the small angle formula to estimate the distance.



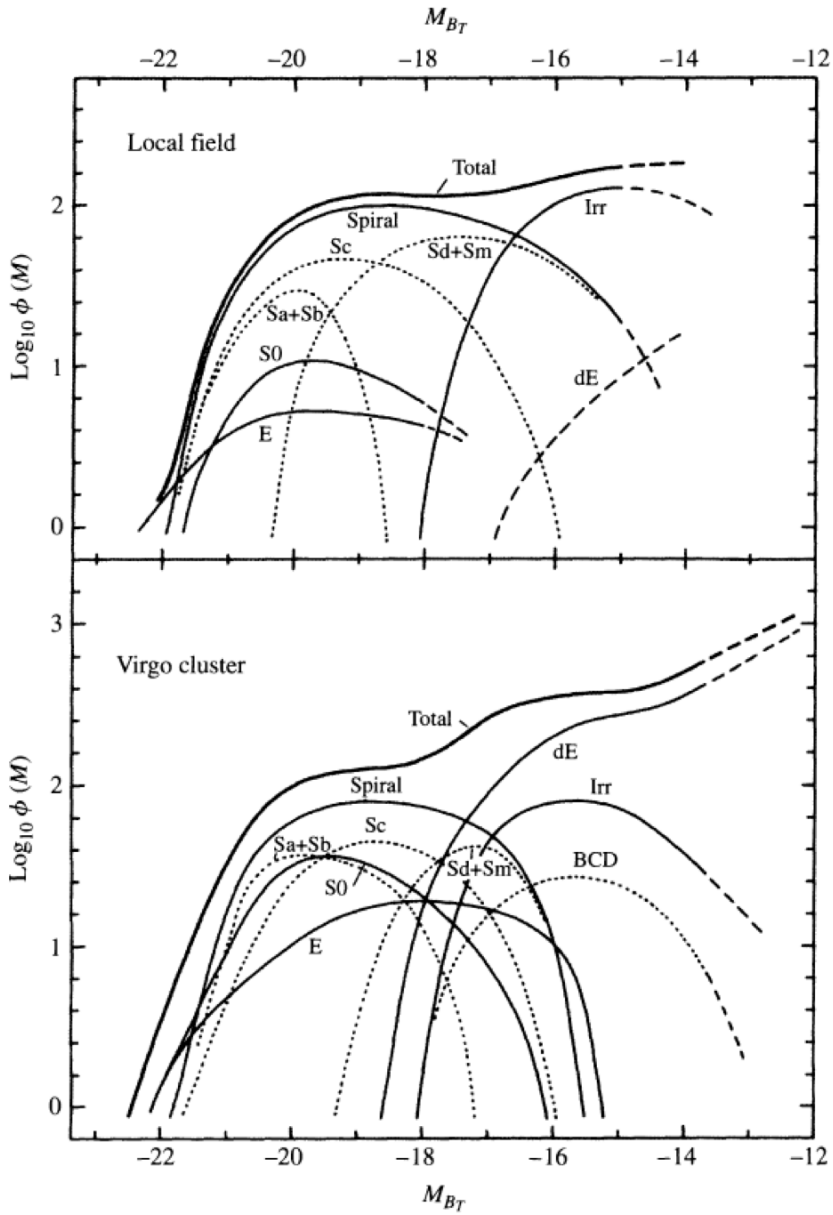


FIGURE 25.36 Luminosity functions for two samples of galaxies. The top panel is based on a sample of galaxies near the Milky Way Galaxy, and the bottom panel is for galaxies located in the Virgo cluster of galaxies. The zero point of the $\log_{10}\phi(M)$ axis is arbitrary. (Figure adapted from Binggeli, Sandage, and Tammann, *Annu. Rev. Astron. Astrophys.*, *26*, 509, 1988. Reproduced with permission from the *Annual Review of Astronomy and Astrophysics*, Volume 26, ©1988 by Annual