Astronomy 1 – Fall 2019

←Not your typical nebula!

Sa (NGC 1357)

Figure 23-5a
Universe, Tenth Edition
Adam Block/Steve Mandel/Jim Rada and Students/NOAO/AURA/NSF

Lecture 15; December 2, 2019

Previously on Astro 1

- The Milky Way Galaxy
  - Contains ~$2x10^{11}$ stars
  - Sun is in a nearly circular orbit 8 kpc from the center
  - Stars (Pop I) in disk are young and metal rich
  - Stars in halo (Pop II) are older and metal poor
  - The central bulge has a radius of 1 kpc and a mass about 1000 times larger than the supermassive BH.
- The velocities of the stars in a galaxy determine its mass
  - This mass is much higher than the mass of the stars and gas
  - That the Universe as whole contains about 5 times more "dark matter" than normal matter.
- Galaxy formed from coalescence of smaller galaxies.
  - Tidal forces rip satellite galaxies apart now
  - Will collide with the Andromeda galaxy in about 4 Gyr.

Today on Astro 1

- **The Universe is full of billions of galaxies.**
  - Why this wasn't clear to Einstein.
  - Hubble's discovery of Cepheids in Andromeda
  - Distances to galaxies
- **Those galaxies are flying away from us!**
  - Hubble's remarkable observation
  - The expansion of the universe
- **Galaxies are found in bubble-like structures**
  - They live in groups, clusters, and superclusters
  - Absence of super-duper cl-usters underlies cosmology
- **The formation and growth of galaxies**
  - Small galaxies collided to form bigger galaxies
  - Tidal forces drive gas into the centers of galaxies where it forms molecular clouds, stars, and new solar systems.

(iClicker Question)
How did Edwin Hubble show that M31 in Andromeda is a distant galaxy and not part of the Milky Way?

A. By measuring the distance to M31 using Cepheid variables.
B. By measuring the distance to M31 using RR Lyrae variables.
C. By precisely measuring the parallax of M31.
D. By observing a nova in M31.
E. By observing a supernova in M31.

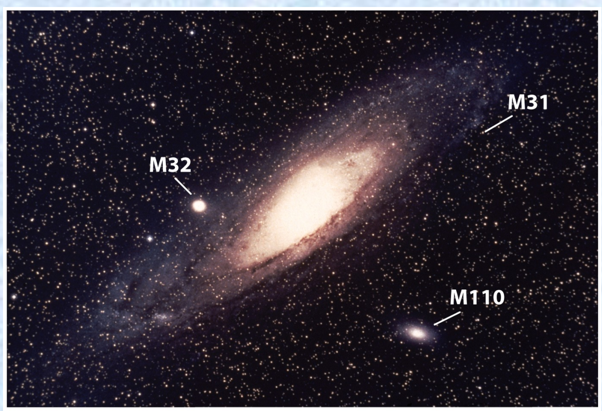

Figure 23-3
Universe, Tenth Edition
Science Source

Q23.7

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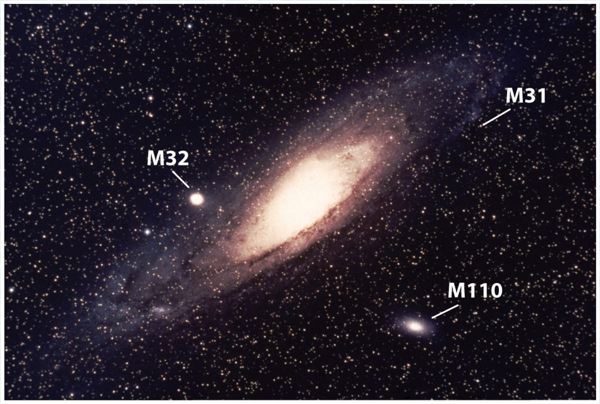
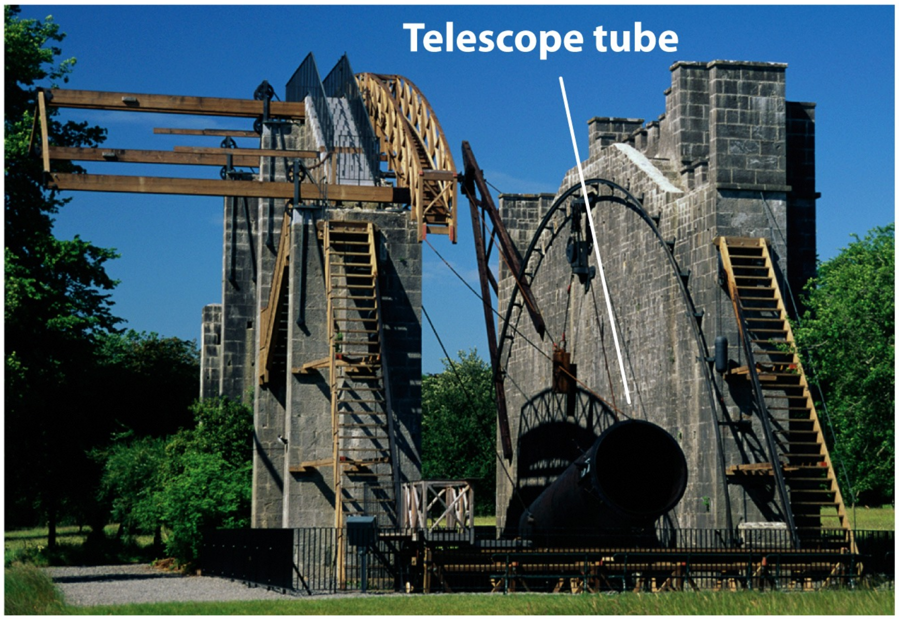


Figure 23-3
Universe, Tenth Edition
Science Source

The Distance Problem

1845 – Drawing of M51

Components of the Galaxy or Island Universes?



Rosse's "Leviathan of Parsonstown"

Figure 23-1a
Universe, Tenth Edition
CFHTRichard T. Nowitz/Corbis

M51 as viewed through the "Leviathan"

Figure 23-1b
Universe, Tenth Edition

1920 – Debate about the Distance to “Spiral Nebulae”

- Harlow Shapley
  - Thought spiral nebulae were relatively small, nearby objects scattered around the Galaxy like globular clusters
- Heber D. Curtis
  - Each spiral nebulae is a rotating system of stars much like our own Galaxy
- The debate resolved nothing.
- Needed a direct measurement of the distance to a spiral nebula. But how?

1924 – Hubble Proved that the Andromeda Galaxy (M31) was well beyond the Milky Way

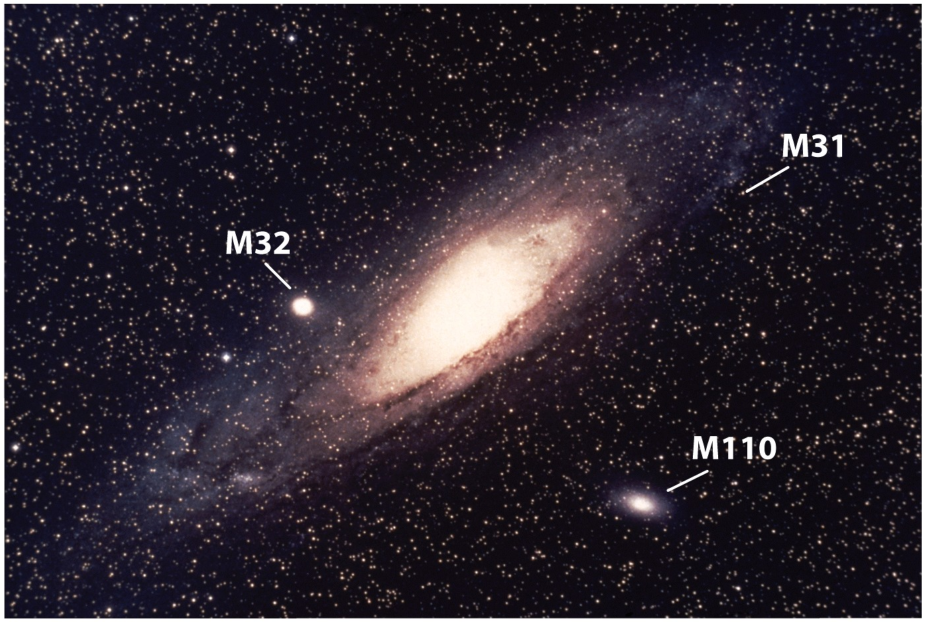


Figure 23-3
Universe, Tenth Edition
Science Source

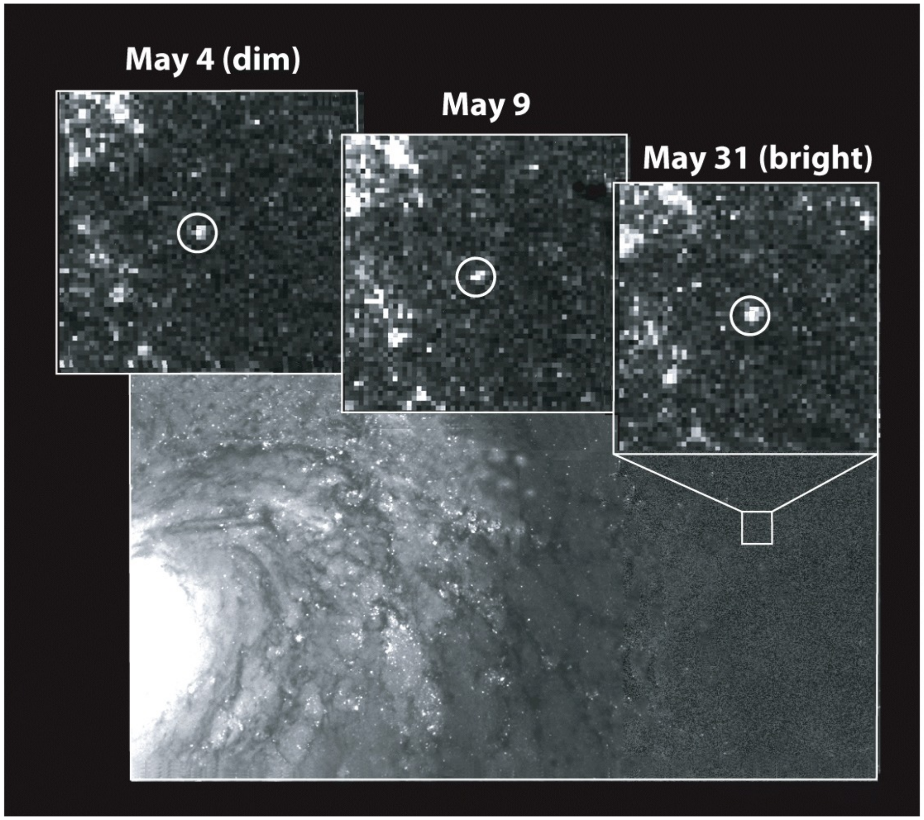
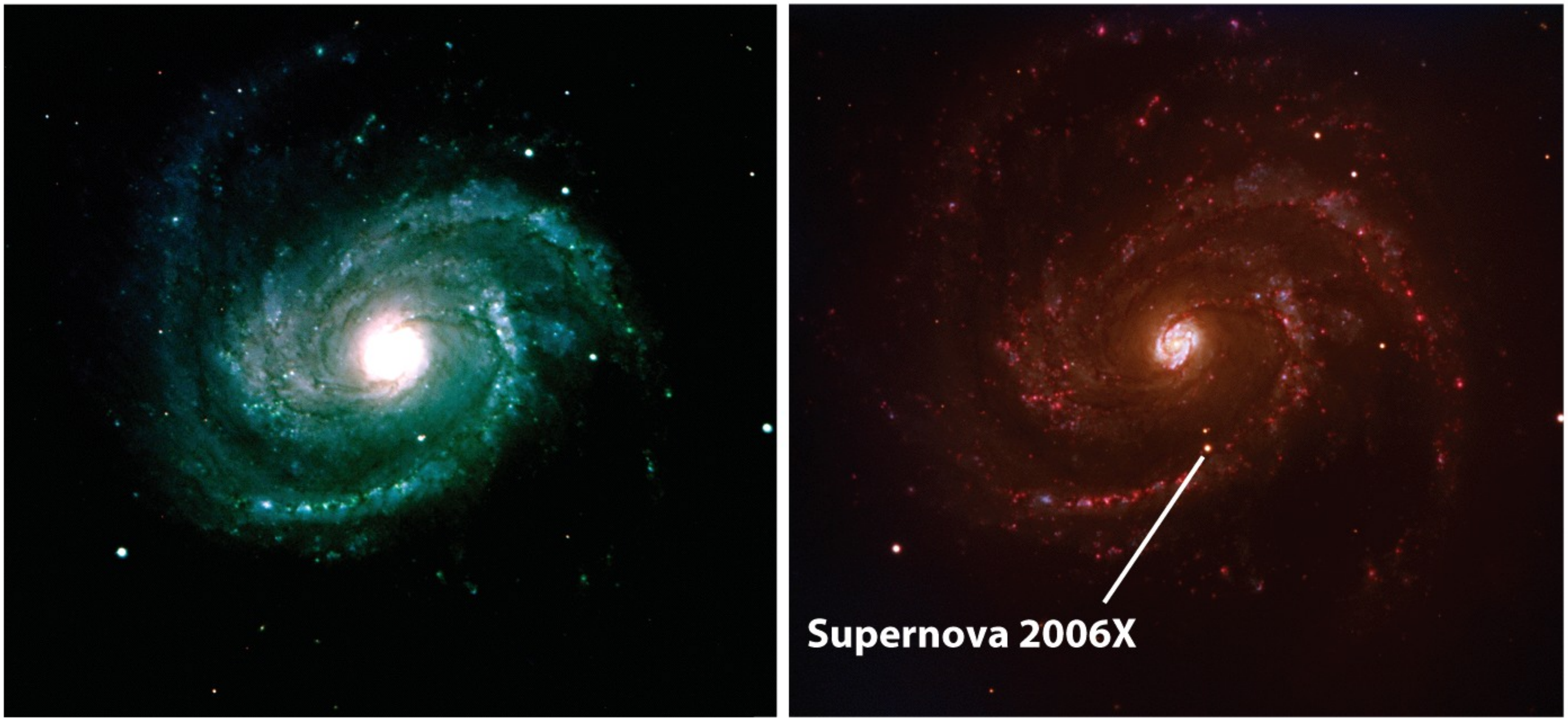


Figure 23-4
Universe, Tenth Edition
Wendy L. Freedman, Carnegie Institution of Washington, and NASA

Distances from Type Ia Supernovae



(a) M100 in March 2002

(b) M100 in February 2006, showing Supernova 2006X

Figure 23-13
Universe, Tenth Edition
European Southern Observatory

The Cosmic Distance Ladder:

We Can Measure Distances to Galaxies Now

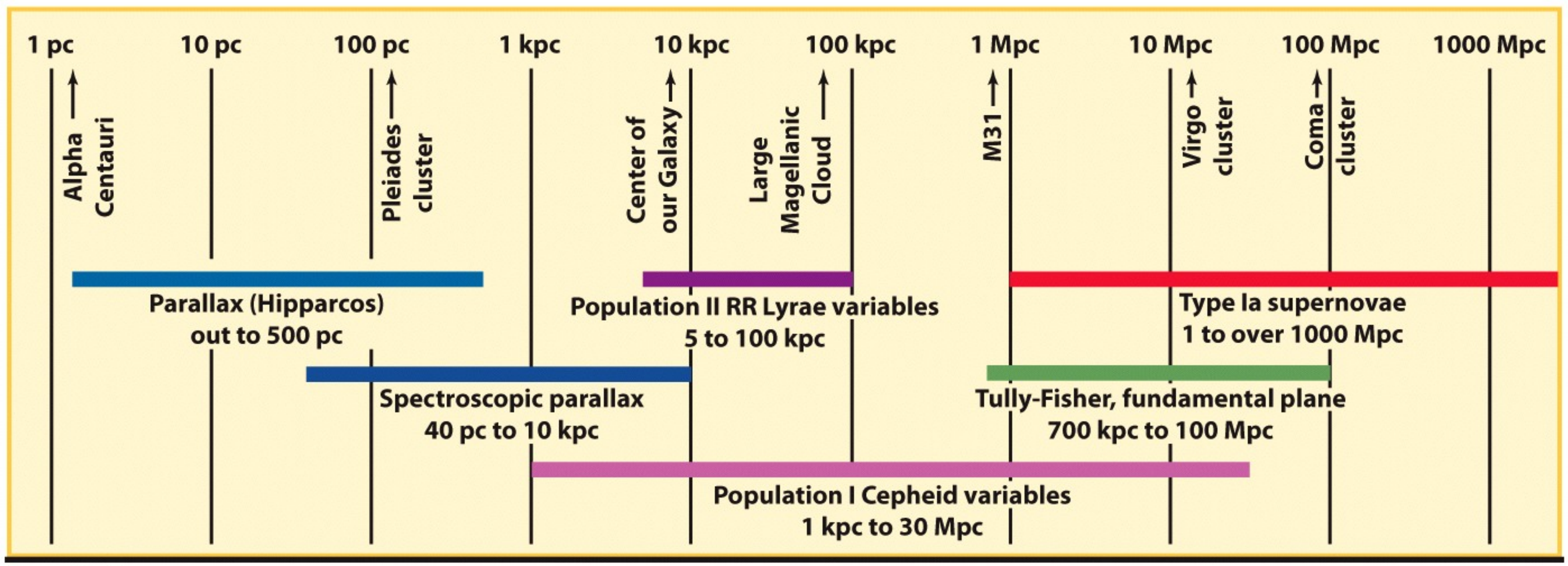
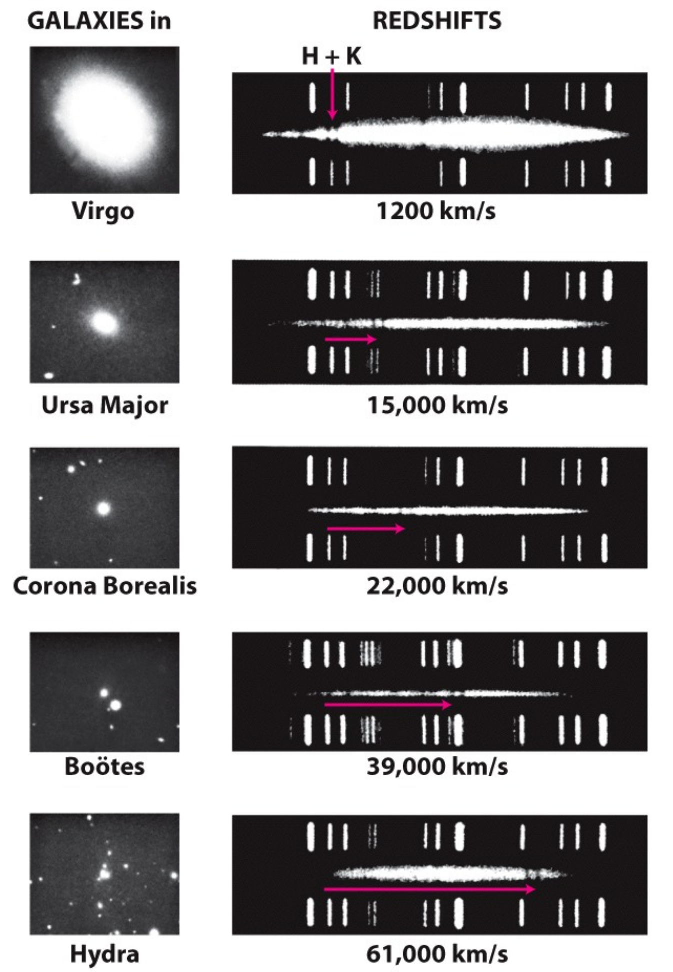


Figure 23-14
Universe, Tenth Edition

Galaxies Map Out the Structure of the Universe as a Whole

Hubble's Remarkable Discovery:



The more distant the galaxy… …the greater its redshift and the more rapidly it is receding from us.

Figure 23-16
Universe, Tenth Edition
Carnegie Observatories

Definition of Spectroscopic Redshift

λ = observed wavelength

λ_0 = laboratory wavelength

$\Delta\lambda = \lambda - \lambda_0$

$$z = \frac{\lambda - \lambda_0}{\lambda_0} = \frac{\Delta\lambda}{\lambda_0}$$

Looks like the Doppler Shift formula for v << c, so we talk about galaxies moving away from us. But be careful ….

$$z \approx \frac{v}{c}$$

Hubble's Remarkable Discovery: All the Galaxies are Flying Away from Us!

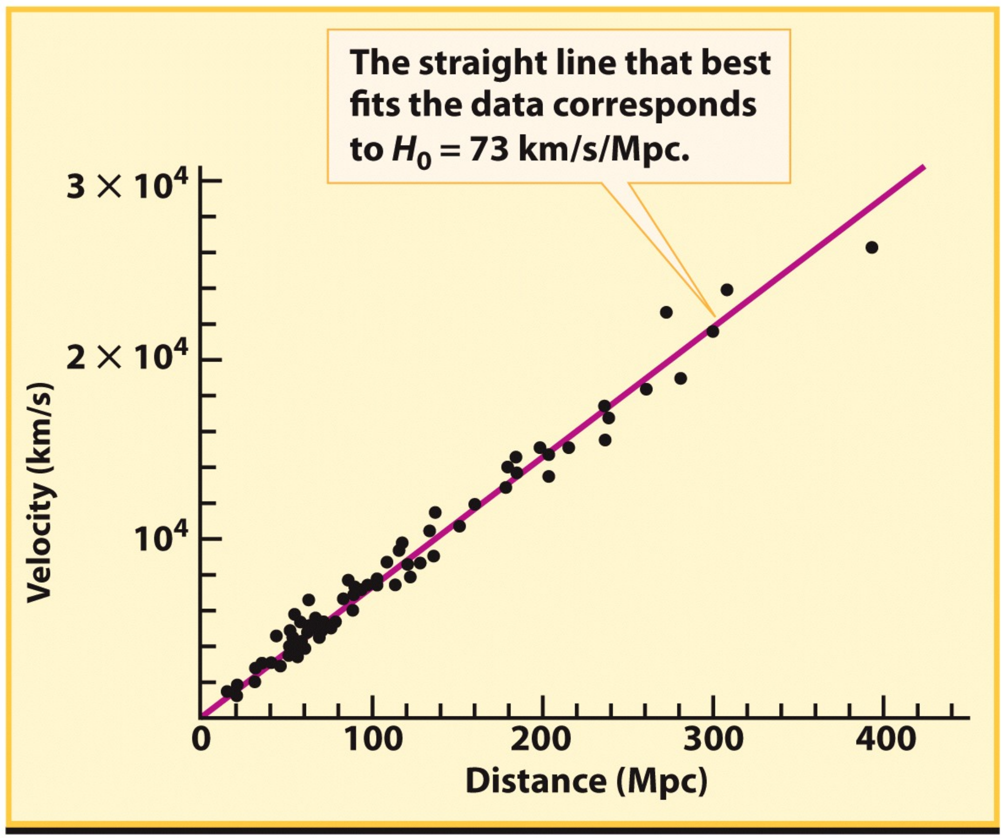


Figure 23-17
Universe, Tenth Edition

Hubble's Law

$$v = H_0 d$$

v = shift of spectral lines in km/s

d = distance to galaxy in Mpc

H_0 = fitted constant of roughly 73 km/s/Mpc

A galaxy is 2 × 10^8 parsecs from our Galaxy. According to Hubble's law, what would you expect the distant galaxy's velocity of recession to be? (Use H_0 = 73 km/s/Mpc.)

A. 2.74 km/s

B. 146 km/s

C. 200 km/s

D. 1.46 × 10^4 km/s

E. 3.65 × 10^5 km/s

Q23.11

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D. <u>1.46×10^4 km/s</u>

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What does Hubble's law tell us about how galaxies are moving?

A. All galaxies are moving away from us at the same velocity.
B. Galaxies close to us are receding from us slowly, and galaxies farther from us are receding more rapidly.
C. Galaxies close to us are receding from us rapidly, and galaxies farther from us are receding more slowly.
D. Galaxies have random distribution of velocities—there is no pattern.

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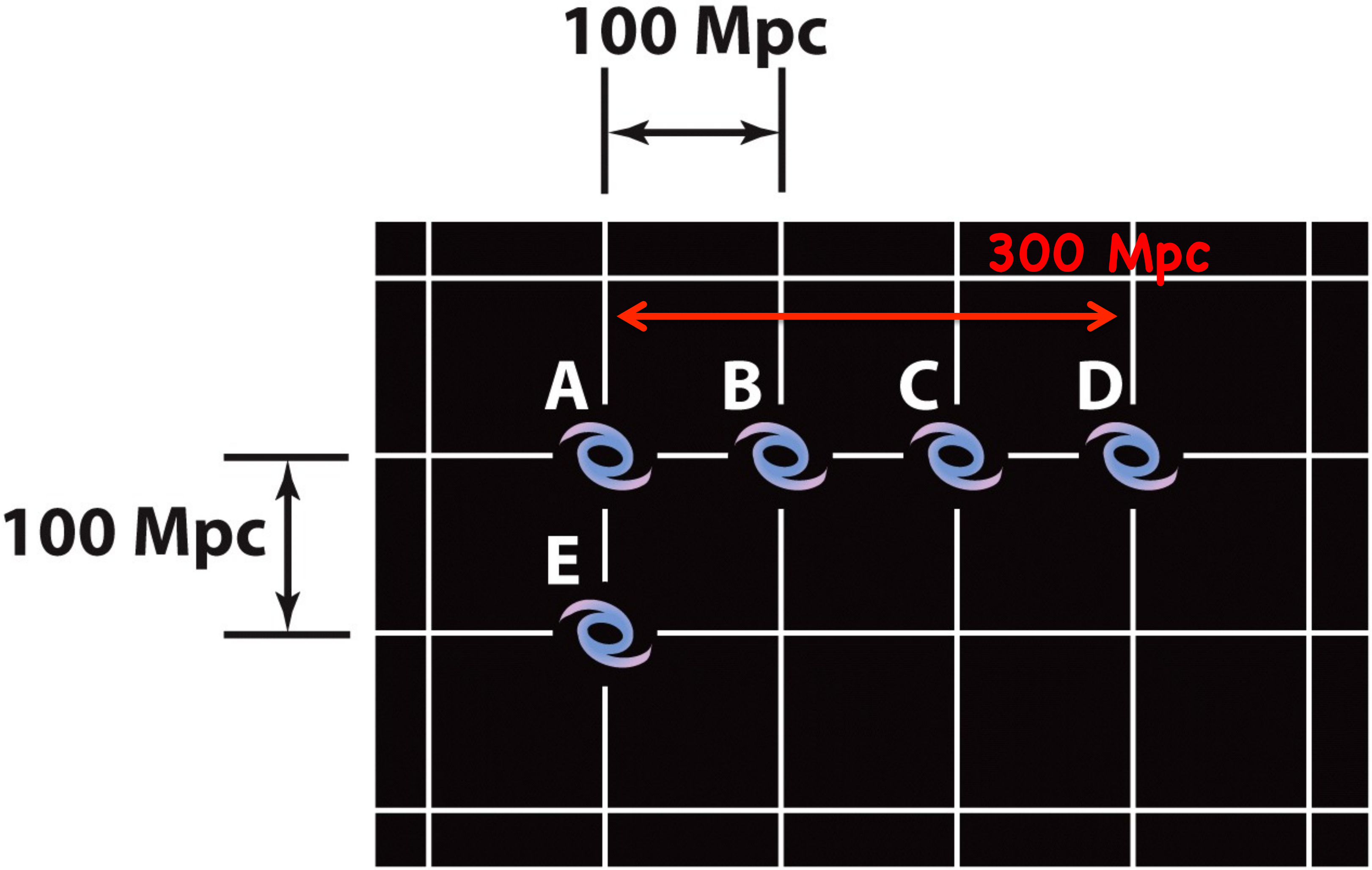
D. Galaxies have random distribution of velocities—there is no pattern.

Important Clarifications

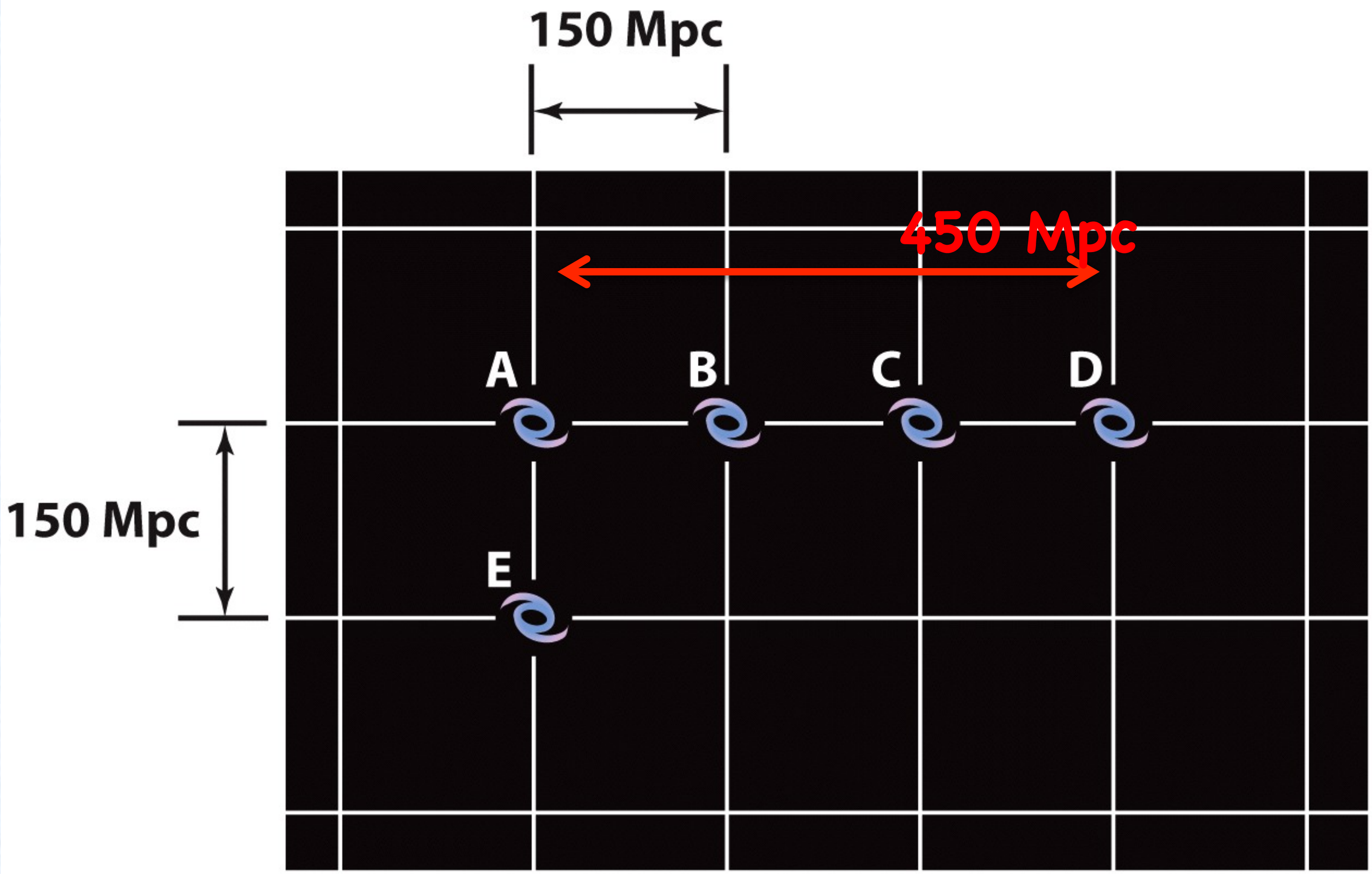
- We are NOT at a special place in the center of the universe.
- The redshifts that Hubble measured are not Doppler shifts.
- They reflect the expansion of the fabric of space-time.



Five galaxies spaced 100 Mpc apart

Figure 25-3a
Universe, Tenth Edition

The Expansion of Space Carries the Galaxies with It



The expansion of the universe spreads the galaxies apart

Figure 25-3b
Universe, Tenth Edition

Expansion of Space-Time Stretches Light Waves

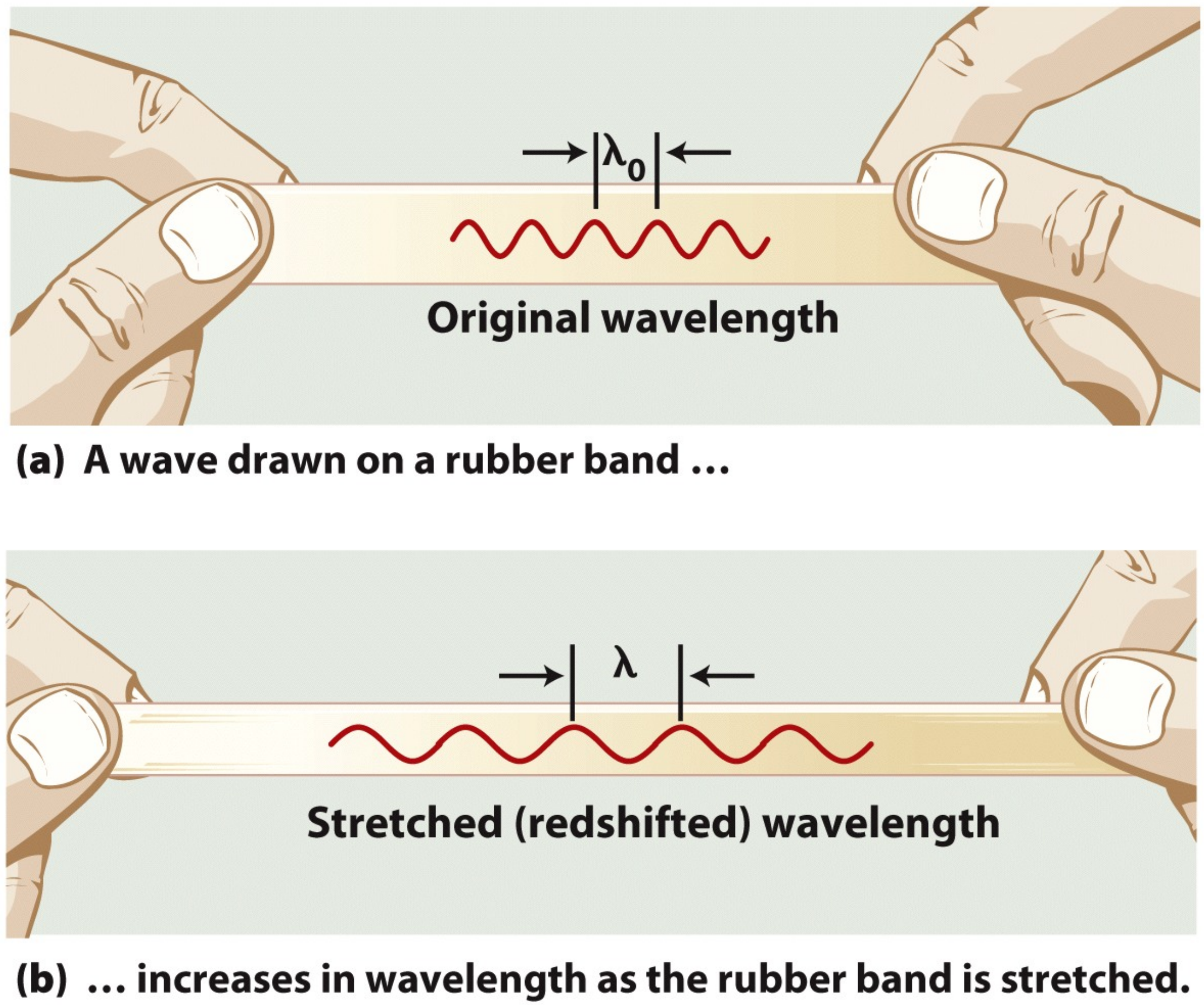
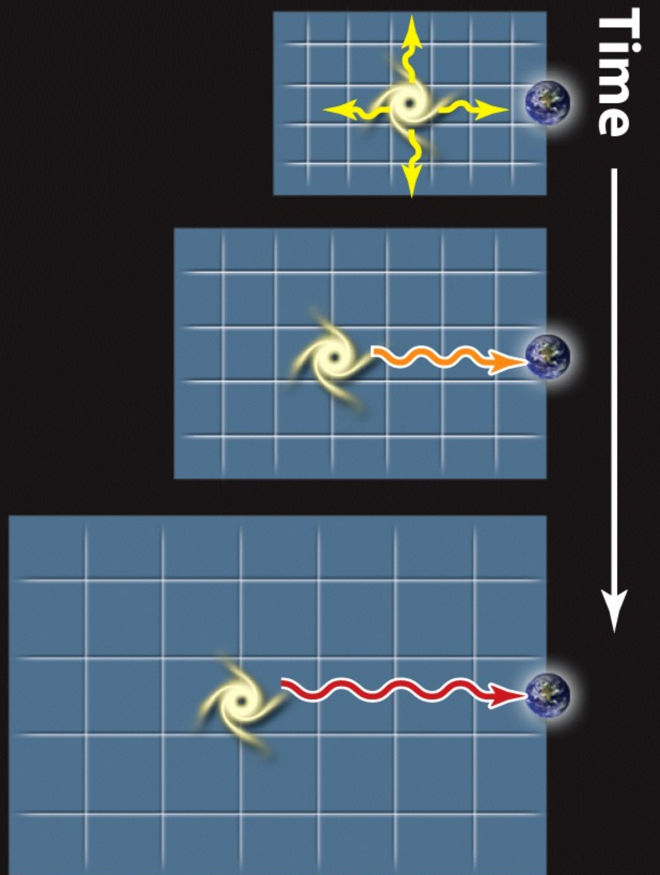


Figure 25-4
Universe, Tenth Edition



Reality:
As light travels through intergalactic space, its wavelength gradually expands as the space through which it is travelling expands. This is called a cosmological redshift.

Redshift Measures Distance

- Step 1: Measure the redshift from a spectrum. Exact.
  - Step 2: Small redshift (roughly z < 0.1), then the distance is

$$d \approx \frac{cz}{H_0}$$

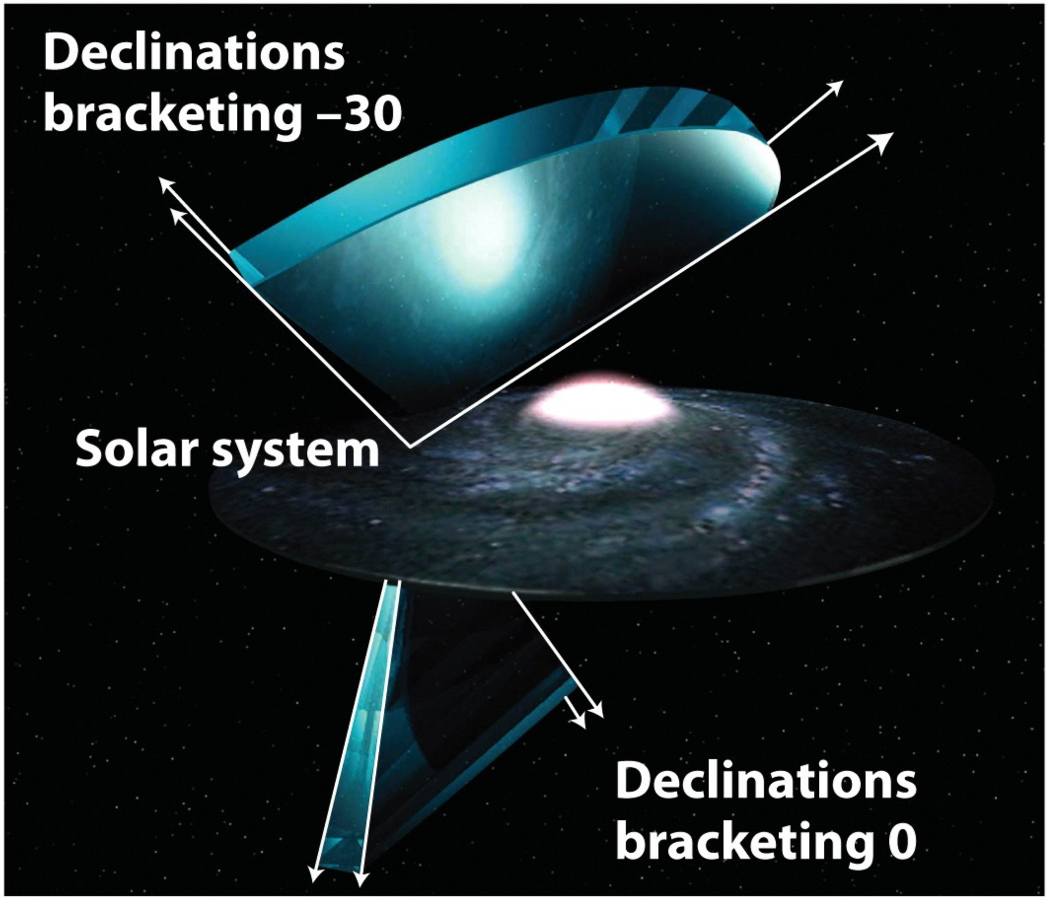
The Doppler shift equation looks like the definition of spectroscopic redshift when Δv << c. So we can write Hubble's Law in terms of either redshift or velocity.

$$\frac{\Delta v}{c} \approx \frac{\Delta \lambda}{\lambda_0} \text{ so } \qquad z \approx \frac{v}{c}$$

  - Step 2: Redshift z > 0.1, then the equation describing the distance in terms of redshift is more complicated.

29. Box 23-2 In the spectrum of the galaxy NGC 4839, the K line of singly ionized calcium has a wavelength 403.2 nm. (**a**) What is the redshift of this galaxy? (*Hint:* See Box 23-2.) (**b**) Determine the distance to this galaxy using the Hubble law with $H_0 = 73 \text{ km/s/Mpc}$.

Redshifts (Distances) Map Out the Distribution of Galaxies



Fields of view in the 2dF survey

Figure 23-24b
Universe, Tenth Edition
Courtesy of the 2dF Galaxy Redshift Survey Team/Australian Astronomical Observatory

Projection of the 1.6 Million Brightest Galaxies on the Sky

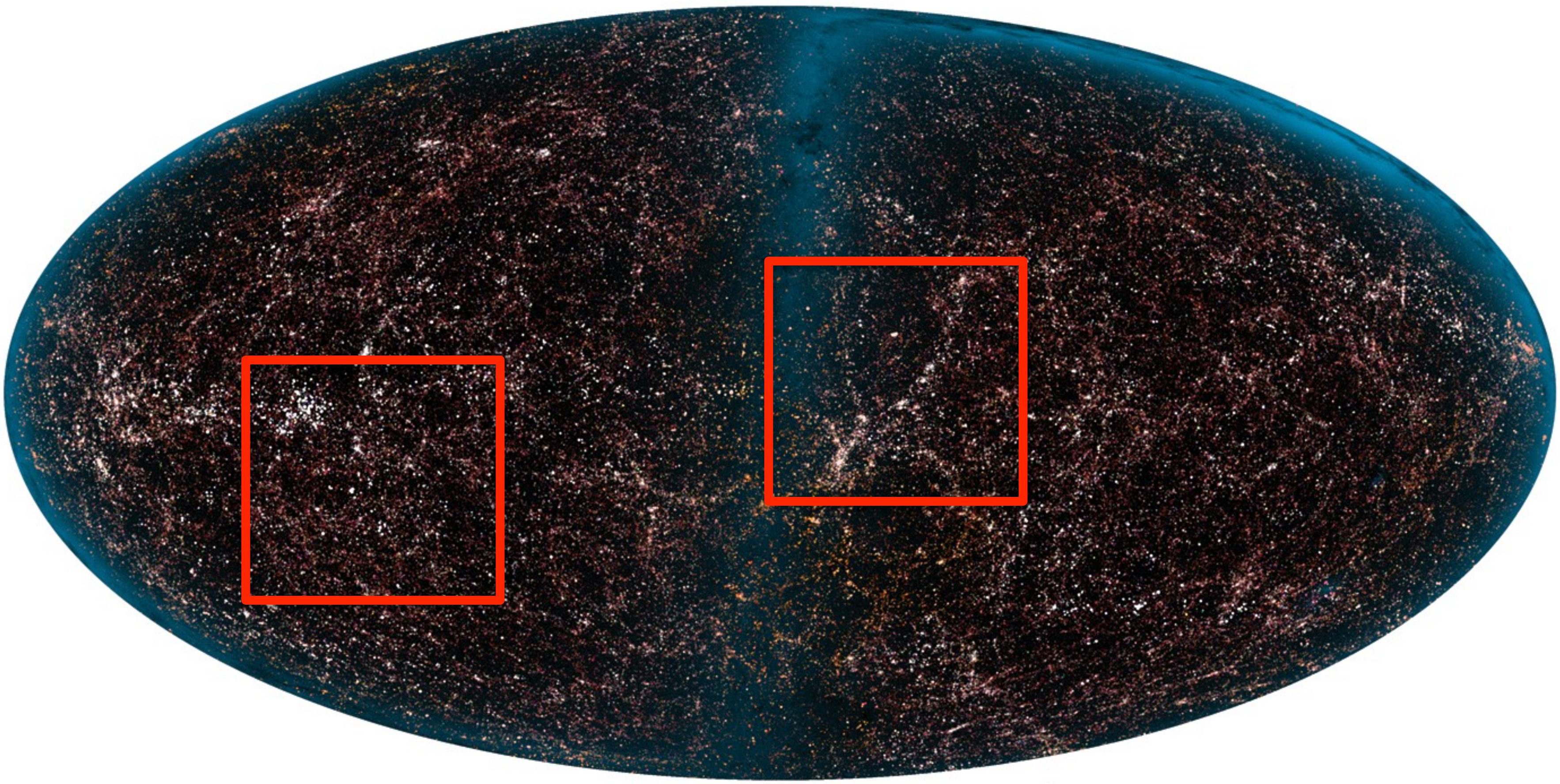
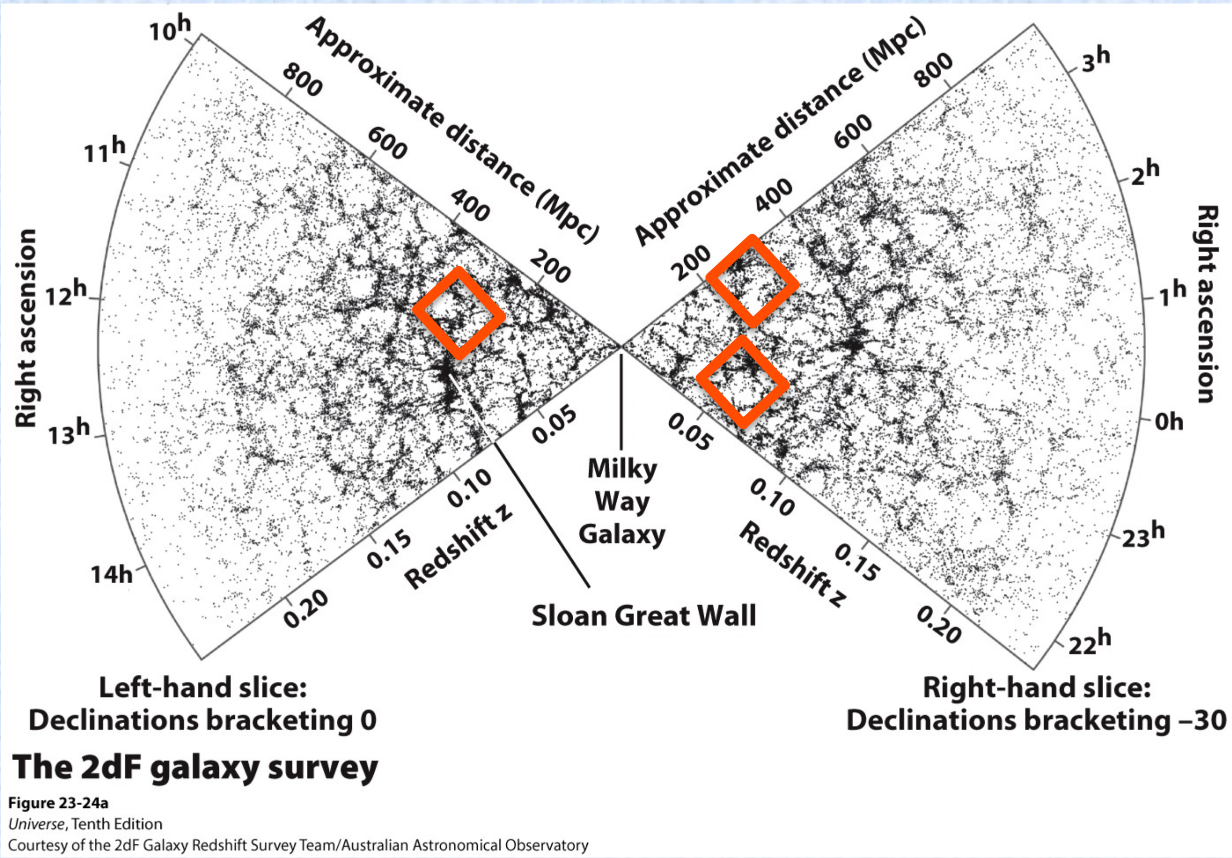


Figure 23-23
Universe, Tenth Edition
Two Micron All Sky Survey [2MASS]

The distribution of galaxies is the same in every direction, or isotropic.

Two Wedges of Sky Showing the Distances to 62,559 Galaxies



The distribution of galaxies is homogeneous on large scales.

How Did Galaxies Form?

Two approaches:

1. Near-field cosmology, or the archaeological record
   – "Old" RR Lyrae stars in halo globular clusters and the bulge
   – Star-forming regions (nebulae) in galactic disks
   – Supermassive black hole in the center of the bulge
- Observing very distant galaxies, which is equivalent to looking back into the past.
   – Use cosmological redshift to identify distant galaxies.
   – The light left them 13 billion years ago, so we see these galaxies when they when the universe was young.

Distant (Young) Galaxies are Small

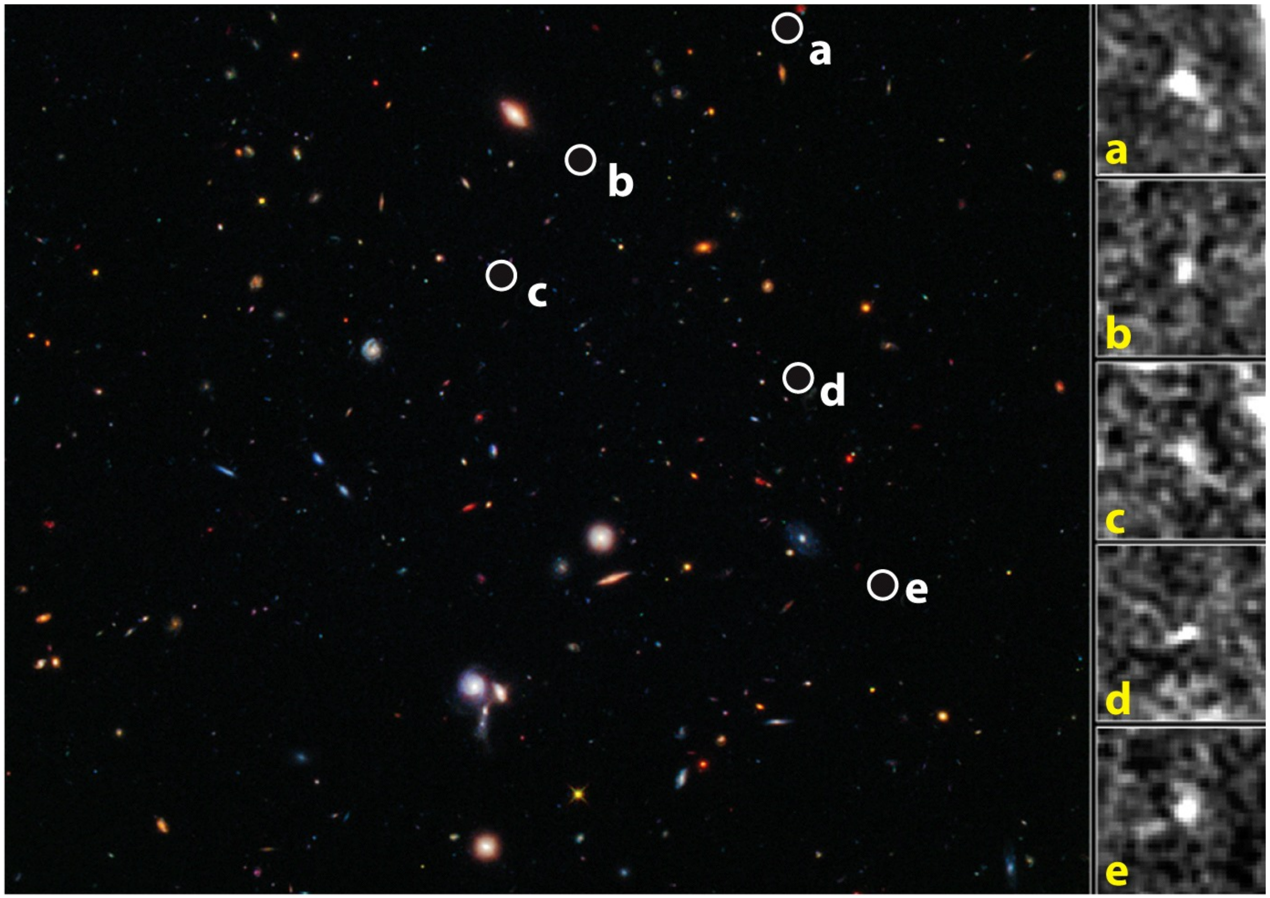


Figure 23-35
Universe, Tenth Edition
University of Colorado, Boulder, and Institute of Astronomy, University of Cambridge, UK), L. Bradley (STScI), and the BoRG team

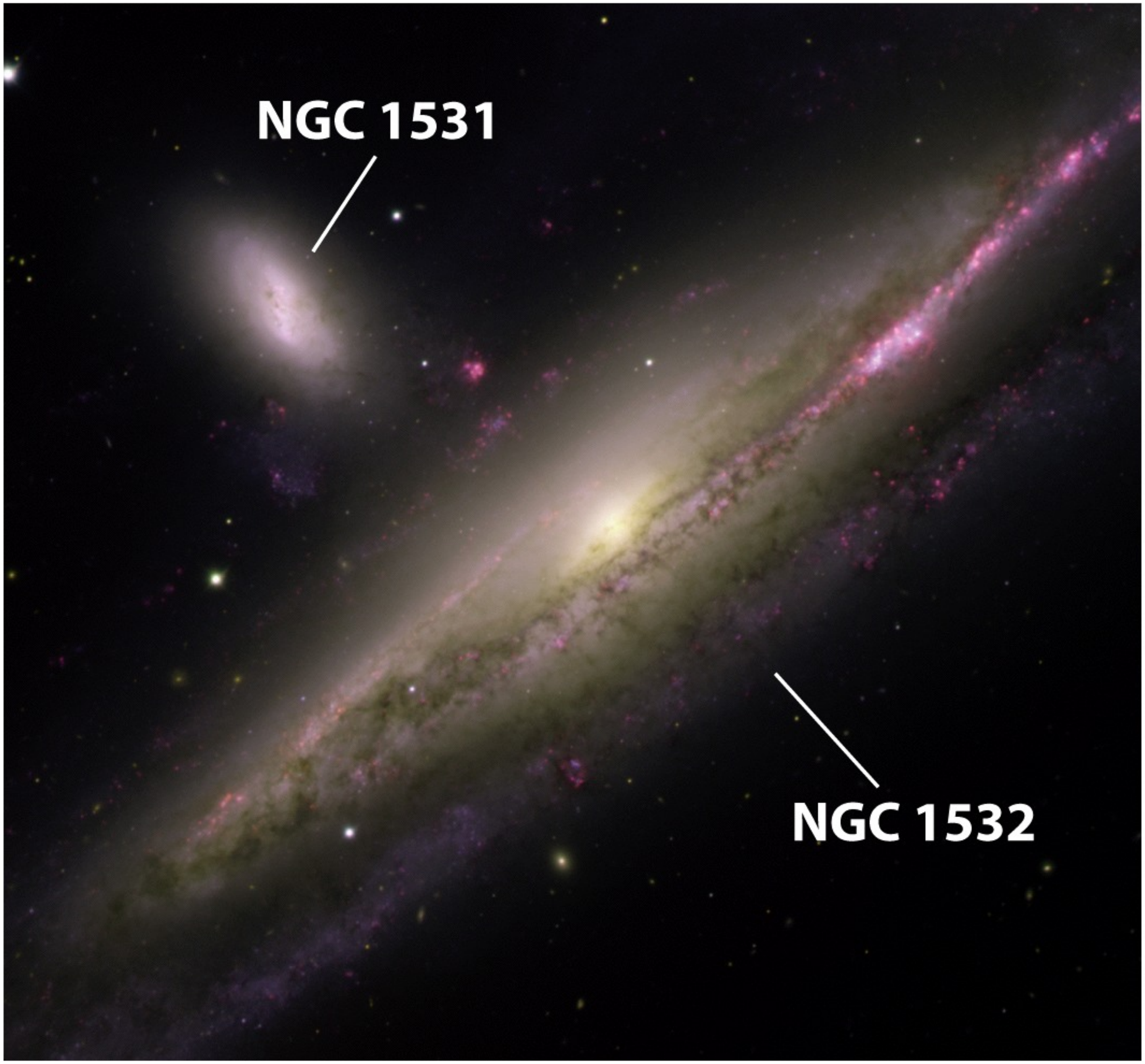
Objects in the circles are 13 billion light years from Earth (z ~ 7).

Galaxies Form Hierarchically

Galaxies formed from the coalescence of smaller galaxies.

The Milky Way Will Collide with Andromeda (M31) in about 4 Gyr

This illustration shows a stage in the predicted merger between our Milky Way galaxy and the neighboring Andromeda galaxy, as it will unfold over the next several billion years. In this image, representing Earth's night sky in



Chapter 23 Opener
Universe, Tenth Edition
Gemini Observatory/Travis Rector, University of Alaska, Anchorage

Galaxy Groups: Example M81 Group

Optical Image shows the starlight.

The Hydrogen Gas

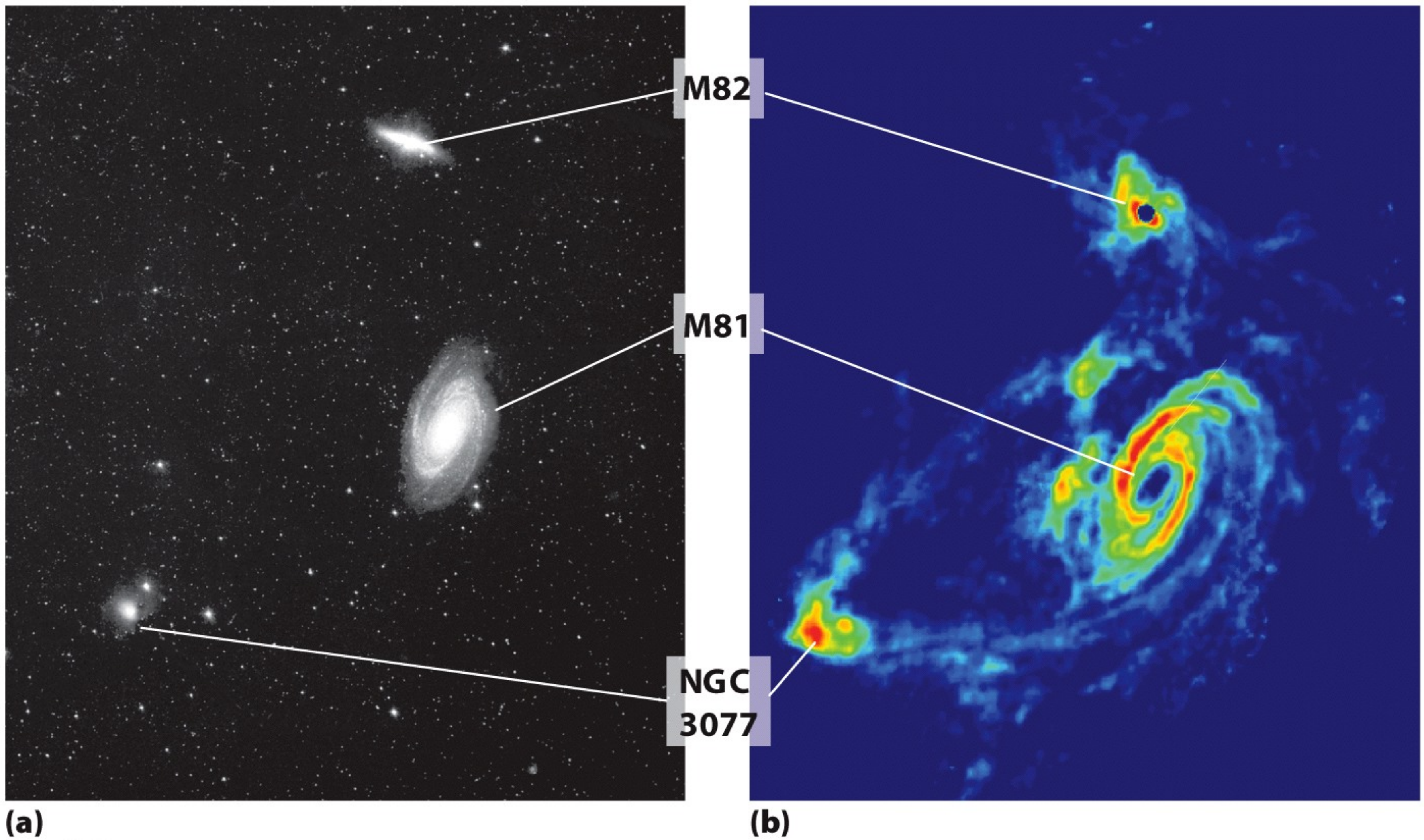


Figure 23-28
Universe, Tenth Edition
a: Palomar Sky Survey; b: Image courtesy of NRAO/AUI

M51

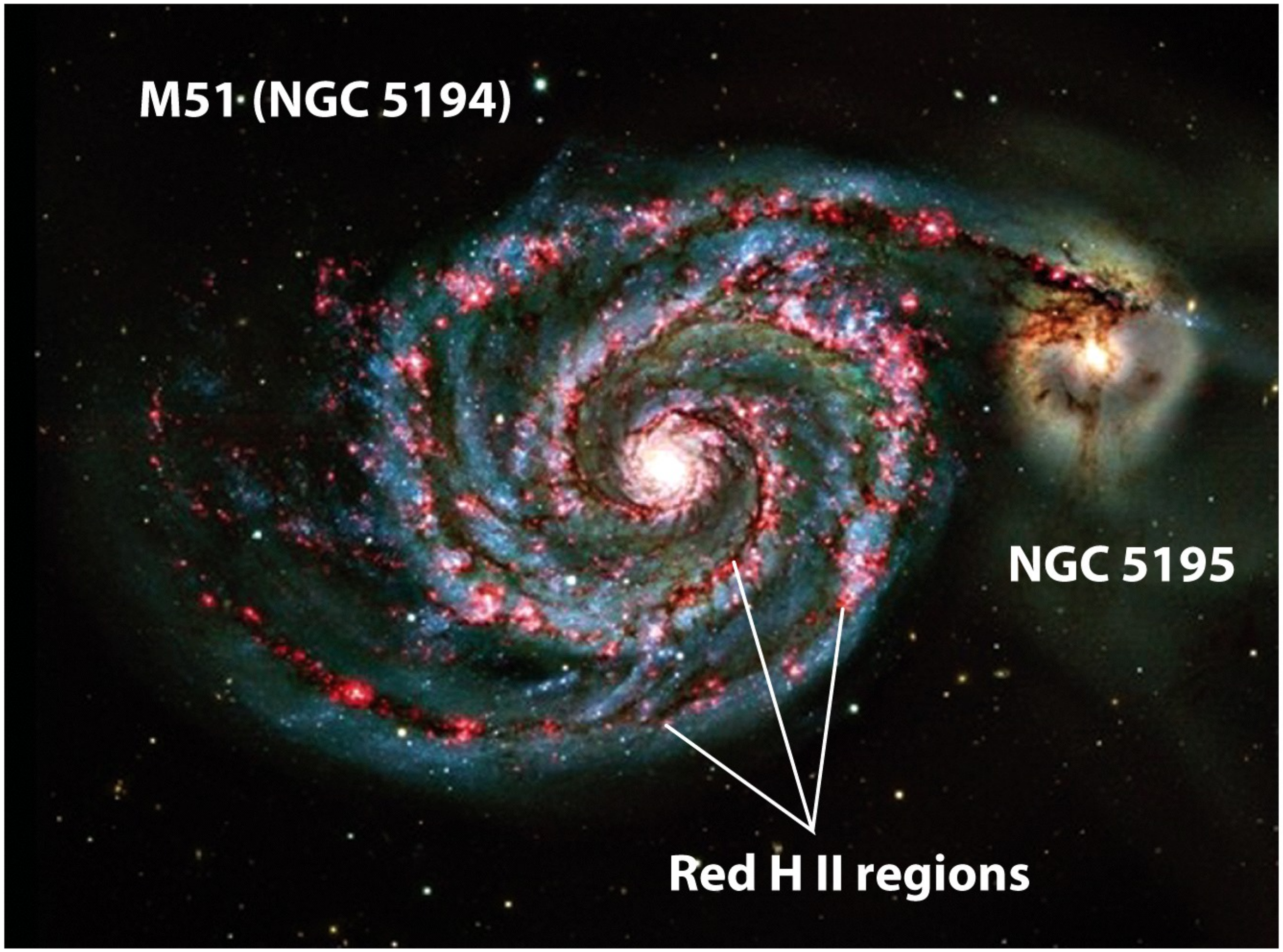


Figure 23-2
Universe, Tenth Edition
CFHT

Computer Simulation

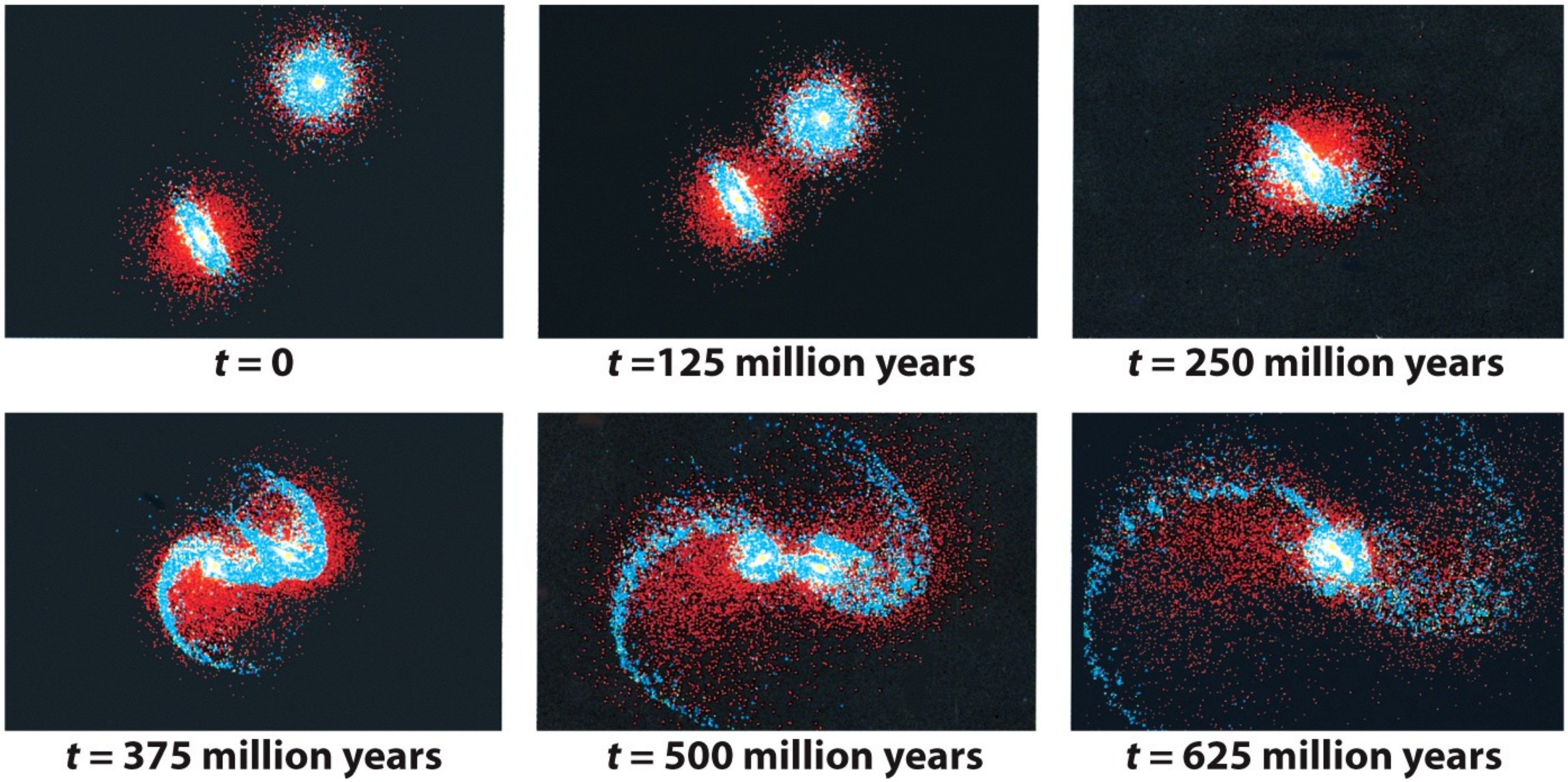
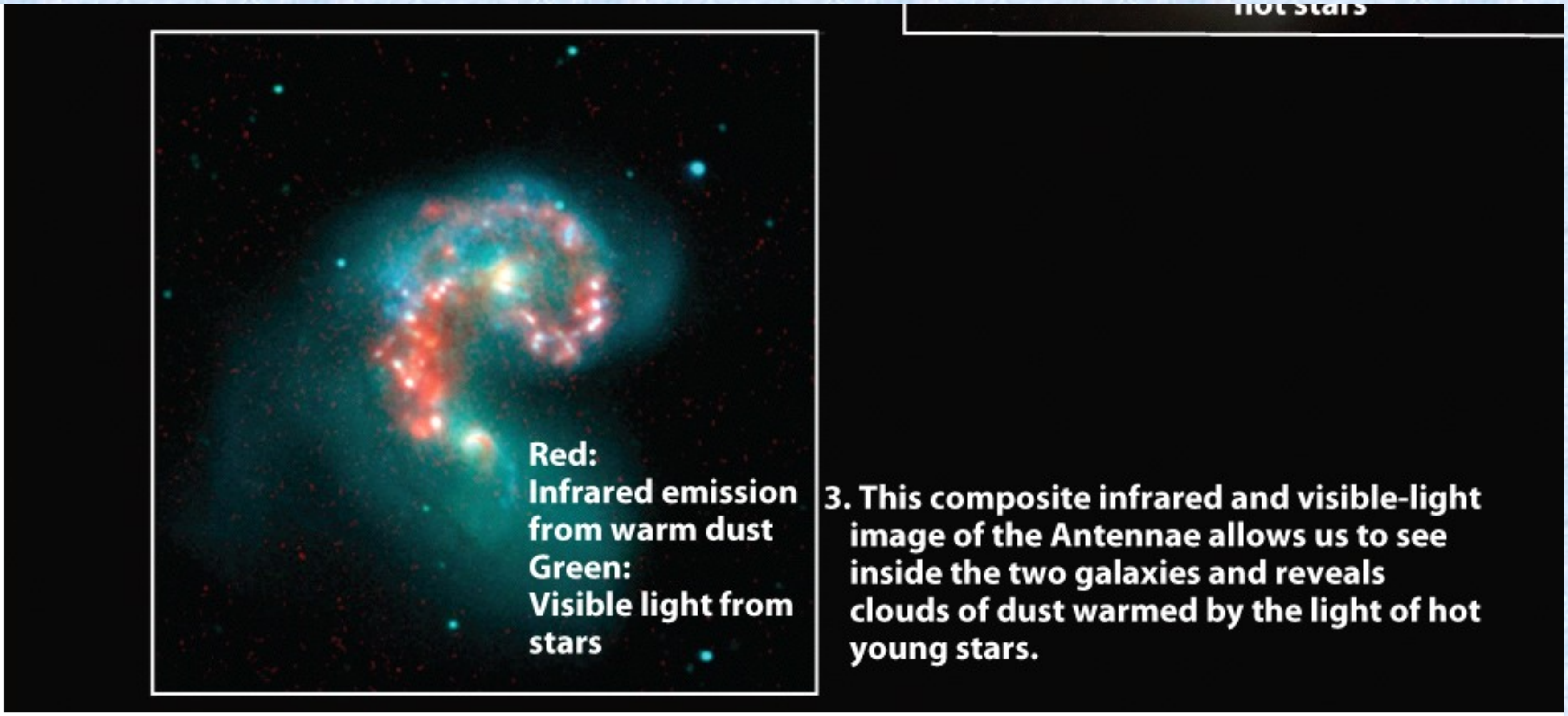


Figure 23-29
Universe, Tenth Edition
Joshua Edward Barnes, Institute for Astronomy, University of Hawaii

1. One example of a galactic collision is the pair of galaxies called the Antennae, which lie 19 Mpc (16 million ly) from Earth in the constellation Corvus (the Crow). They probably began to interact several hundred million years ago.

Tidal forces between the galaxies pulled out these long “tidal tails” 200 to 300 million years ago.

2. As the gas and dust clouds of the two galaxies collide with each other, they are greatly compressed. This compression causes stars to form in tremendous numbers.



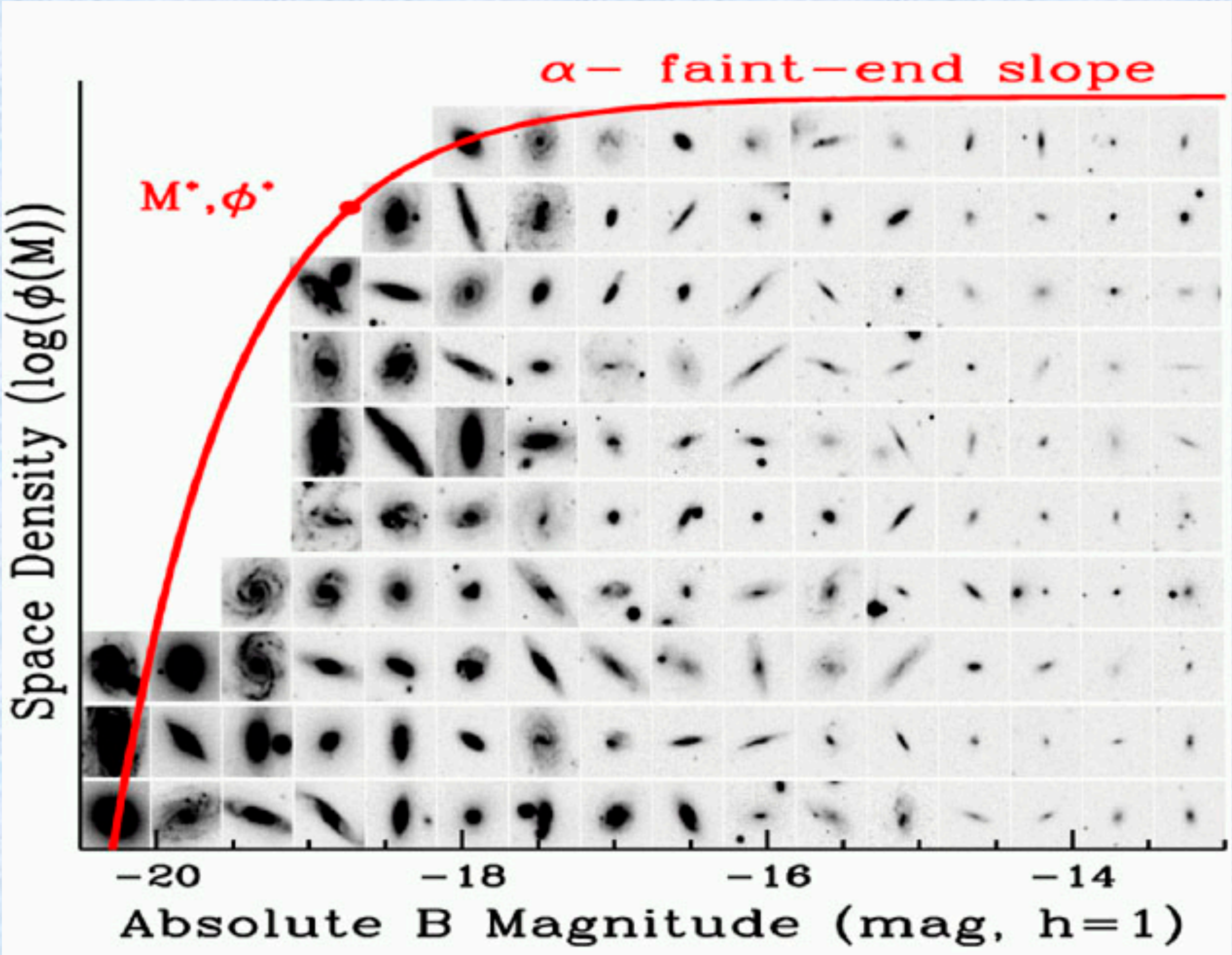
Cosmic Connections 23a

Universe, Tenth Edition

1. Bob and Bill Twardy/Adam Block/NOAO/AURA/NSF; 2. NASA, ESA, and the Hubble Heritage Team (STScI/AURA)-ESA/H Collaboration; 3. NASA/JPLCaltech/ . Wang (Harvard-Smithsonian CfA

Distribution of Galaxy Sizes

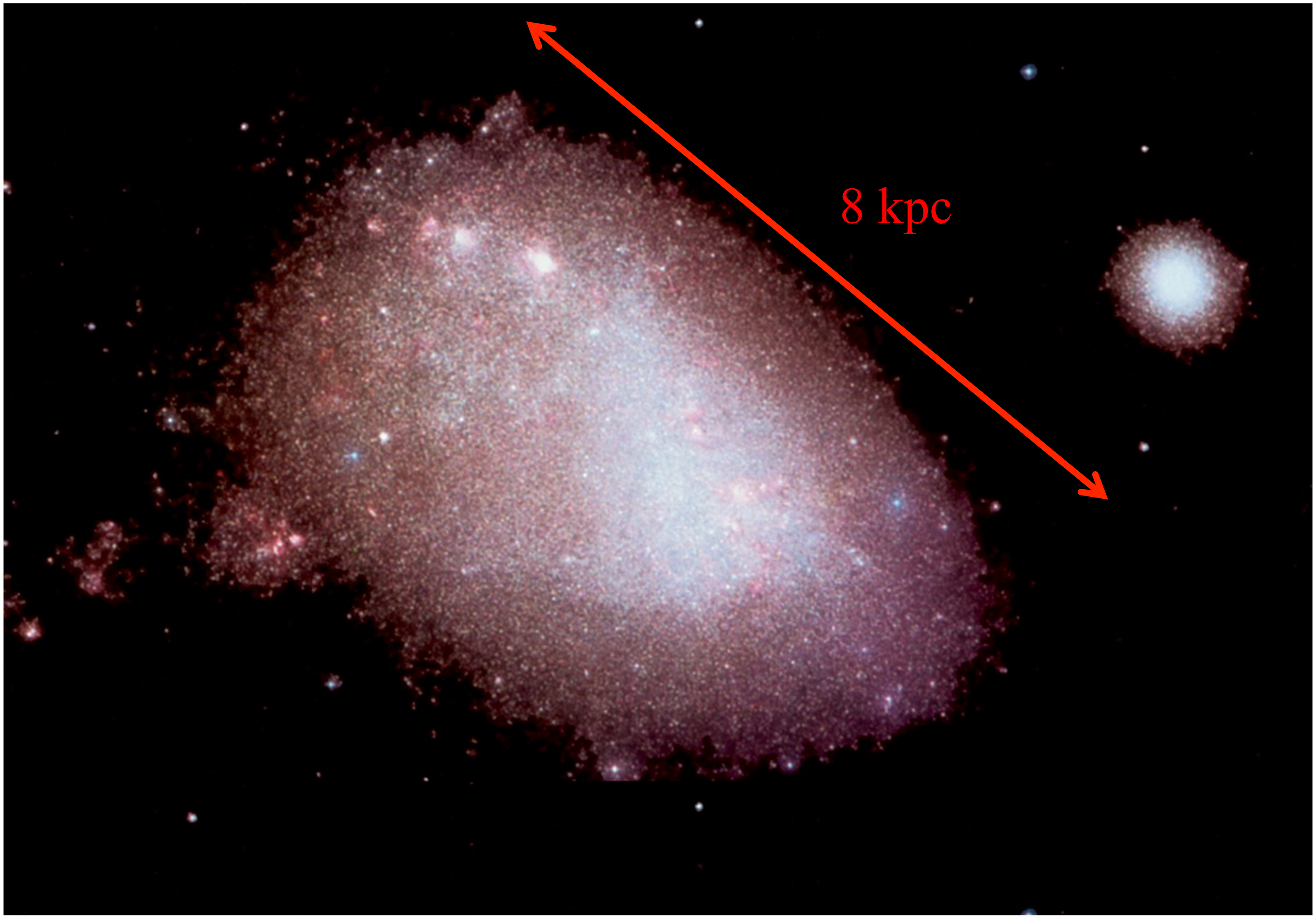
There are plenty of small galaxies for every big galaxy, so this merging process can continue for a long time.



Bright Faint

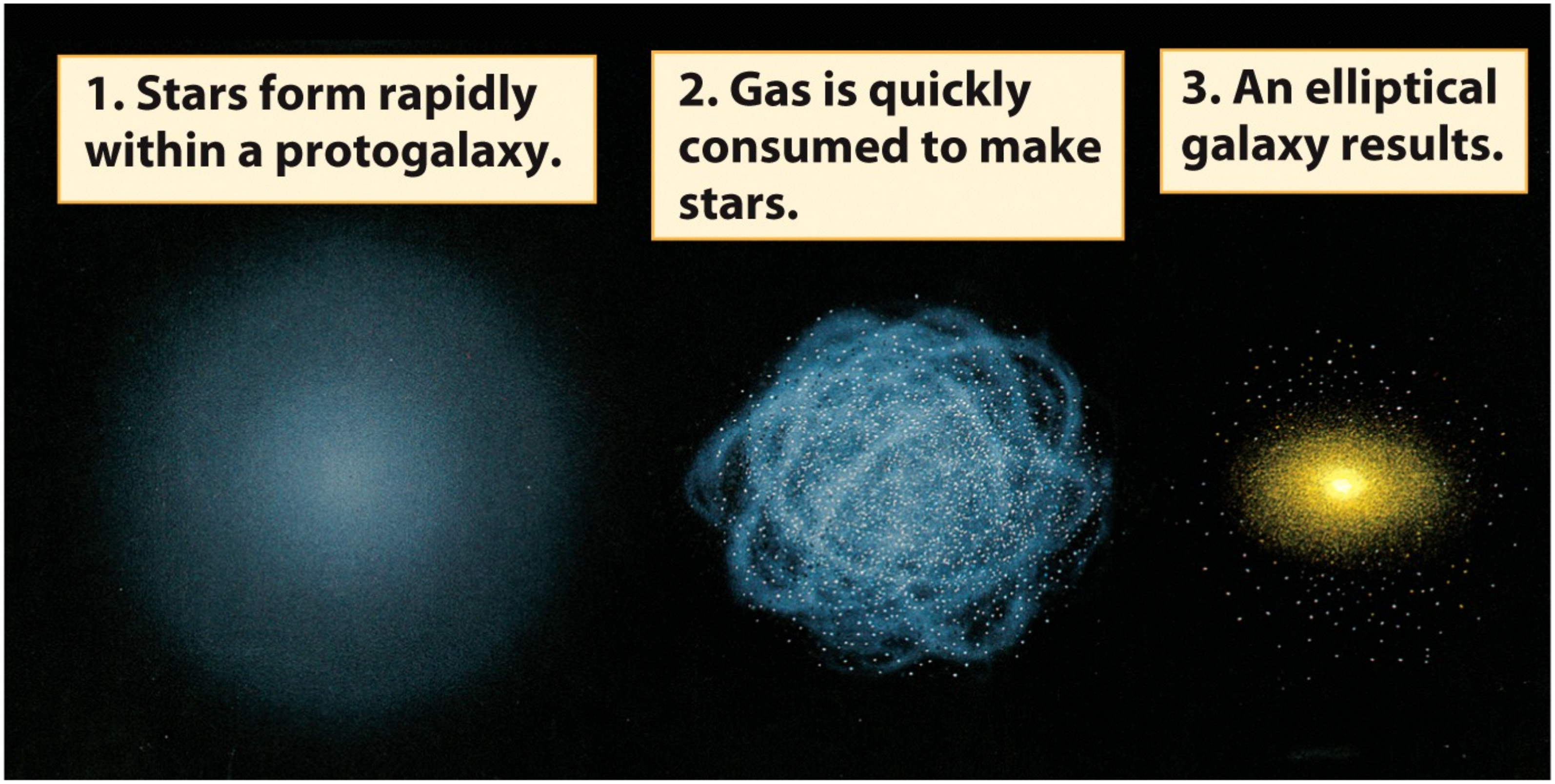
Figure 23-9
Universe, Tenth Edition
NASA and The Hubble Heritage Team [STScI/AURA]

Small Magellanic Cloud



Problem 23-35
Universe, Tenth Edition
Australian Astronomical Observatory/David Malin Images

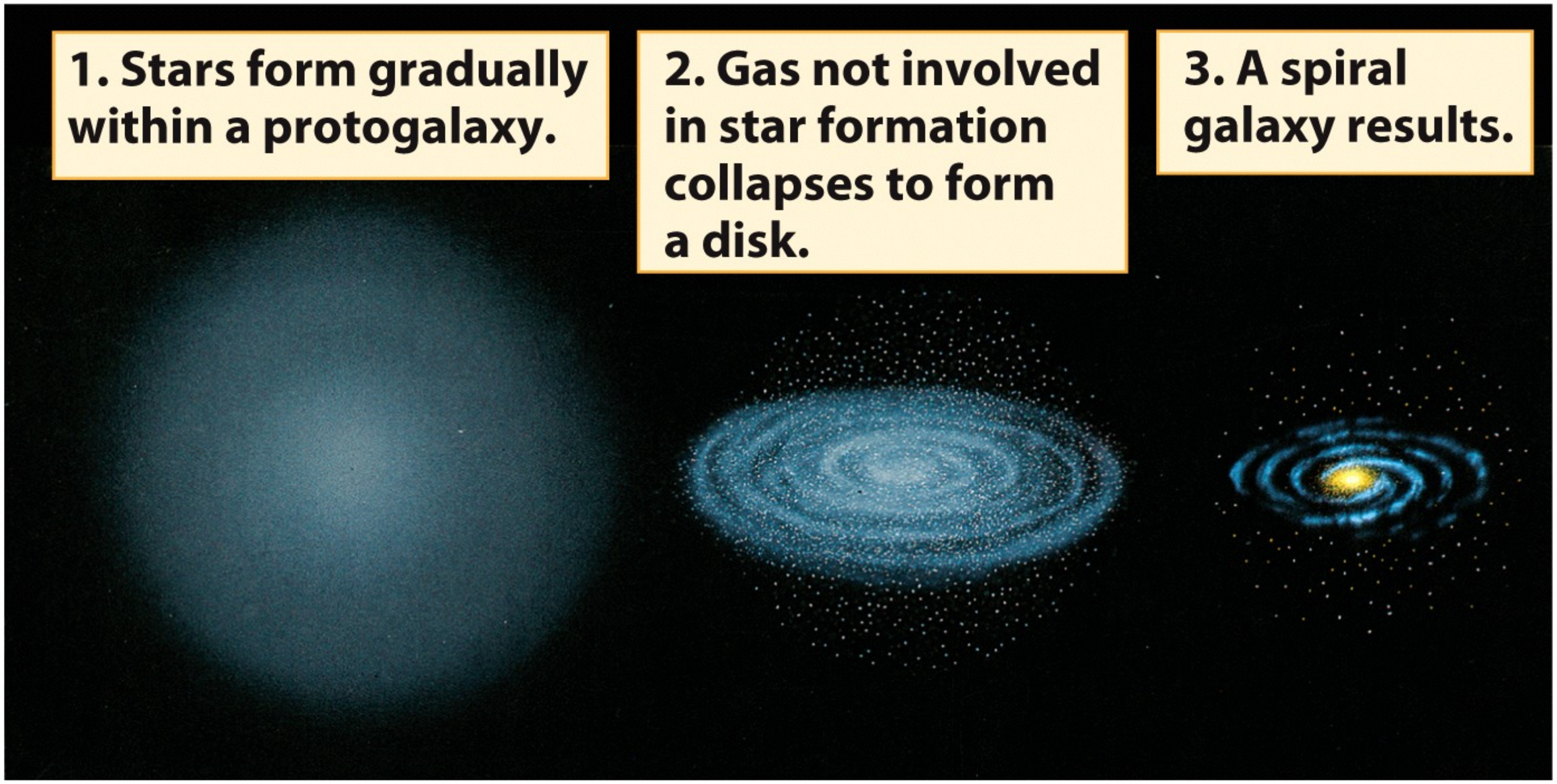
Two General Types of Large Galaxies.
I. Little Net Angular Momentum (Elliptical Galaxies)



Formation of an elliptical galaxy

Figure 23-36b
Universe, Tenth Edition

Second Type of Large Galaxy.
II. High Angular Momentum (Spiral Galaxies)



Formation of a spiral galaxy

Figure 23-36a
Universe, Tenth Edition

In which of the following types of galaxies would you be least likely to find a newly-formed star?

A. Elliptical

B. Spiral

C. Irregular

D. Misleading question — newly-formed stars can be found in ellipticals, spirals, and irregulars

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A. *Elliptical*

B. Spiral

C. Irregular

D. Misleading question — newly-formed stars can be found in ellipticals, spirals, and irregulars

The Properties of Large Galaxies Reflect How They Formed

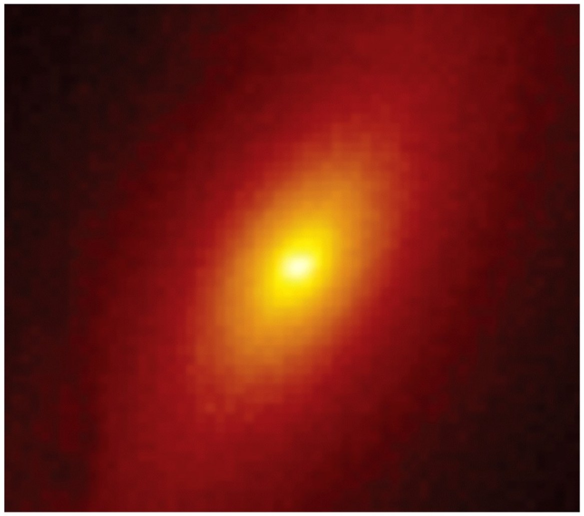
TABLE 23-1 **Some Properties of Galaxies**

	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 1
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.*

Table 23-1
Universe, Tenth Edition

Hubble Sequence. 1. Ellipticals

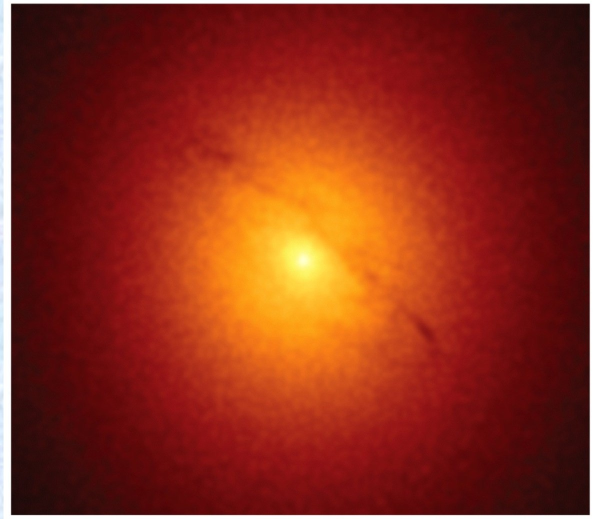


E6 (NGC 3377)

Figure 23-7c
Universe, Tenth Edition
Karl Gebhardt (University of Michigan), Tod Lauer (NOAO), and NASA

E3 (NGC 4406)

Figure 23-7b
Universe, Tenth Edition
Jean-Charles Cuillandre, Hawaiian Starlight, CFHT



E0 (M105)

Figure 23-7a
Universe, Tenth Edition
Karl Gebhardt (University of Michigan), Tod Lauer (NOAO), and NASA

More spherical, more random motion, & less rotation

Hubble Sequence. 2. Spiral Galaxies

Sc (NGC 4321)

Figure 23-5c
Universe, Tenth Edition
FORS Team, 8.2-meter VLT, ESO

Sb (M81)

Figure 23-5b
Universe, Tenth Edition
Robert Gendler/Science Source

(a) Sa (NGC 1357)

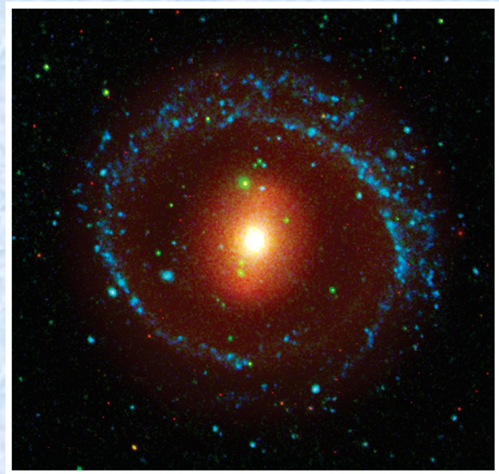
More tightly wound arms & large bulge-to-disk ratio

SBc (NGC 1365)

Figure 23-6c
Universe, Tenth Edition
FORS Team, 8.2-meter VLT, ESO

SBb (M83)

Figure 23-6b
Universe, Tenth Edition
FORS Team, 8.2-meter VLT, ESO

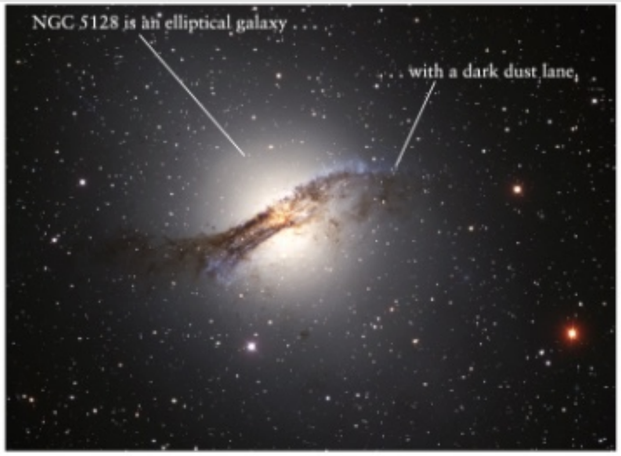


SBa (NGC 1291)

Figure 23-6a
Universe, Tenth Edition
NASA/JPL-Caltech/CTIO

Homework Problems

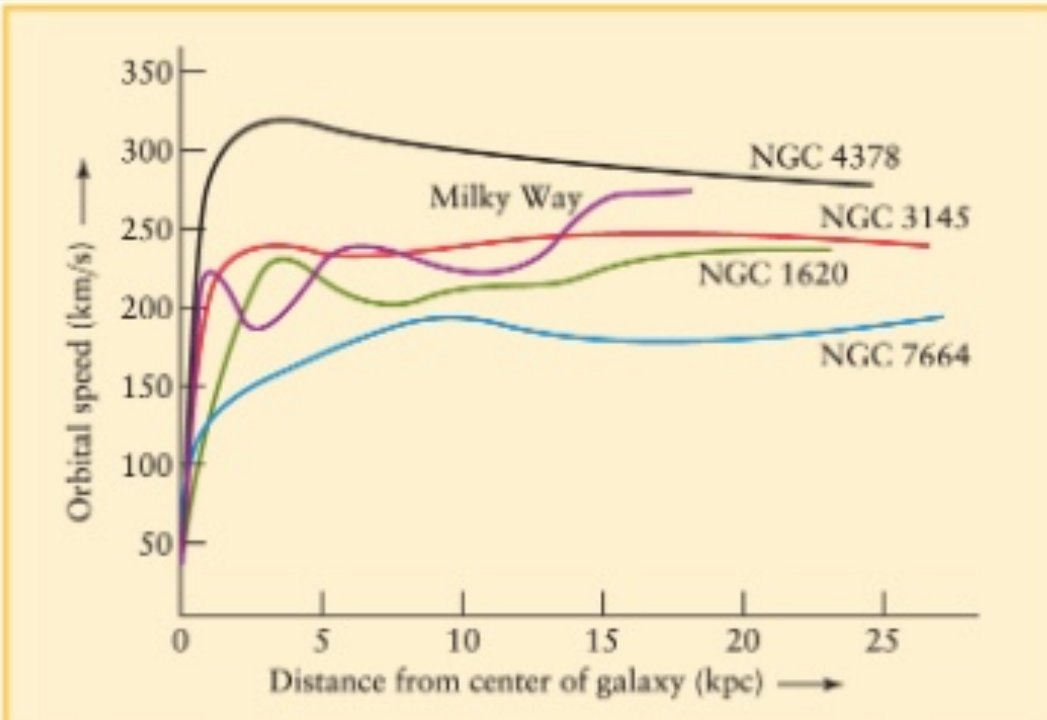
41. The accompanying images show the unusual elliptical galaxy NGC 5128 in visible and infrared wavelengths. Explain how the properties of this galaxy seen in the infrared image can be explained if NGC 5128 is the result of a merger of an elliptical galaxy and a spiral galaxy.



Eric Peng, Herzberg Institute of Astrophysics, and NOAO/AURA/NSF

Homework Problems

47. Figure 23-31 shows the rotation curve of the Sa galaxy NGC 4378. Using data from that graph, calculate the orbital period of stars 20 kpc from the galaxy's center. How much mass lies within 20 kpc of the center of NGC 4378?



Geller et al., *Universe*, 11e, © 2019 W. H. Freeman and Company

The Cosmological Principle

The Universe is homogeneous and isotropic.

In space, time, or both?

Galaxies Grow Over Cosmic Time

- Collisions between galaxies
  - Produce bigger galaxies
  - Provide fuel (new gas) for star formation
  - Transform spiral galaxies into elliptical galaxies.
- Star formation from interstellar gas
  - Still converting interstellar gas into new stars today.
  - Star formation rate was much higher in the past.
  - Supernovae regulate how fast galaxies turn their gas into stars.

Galactic Wind

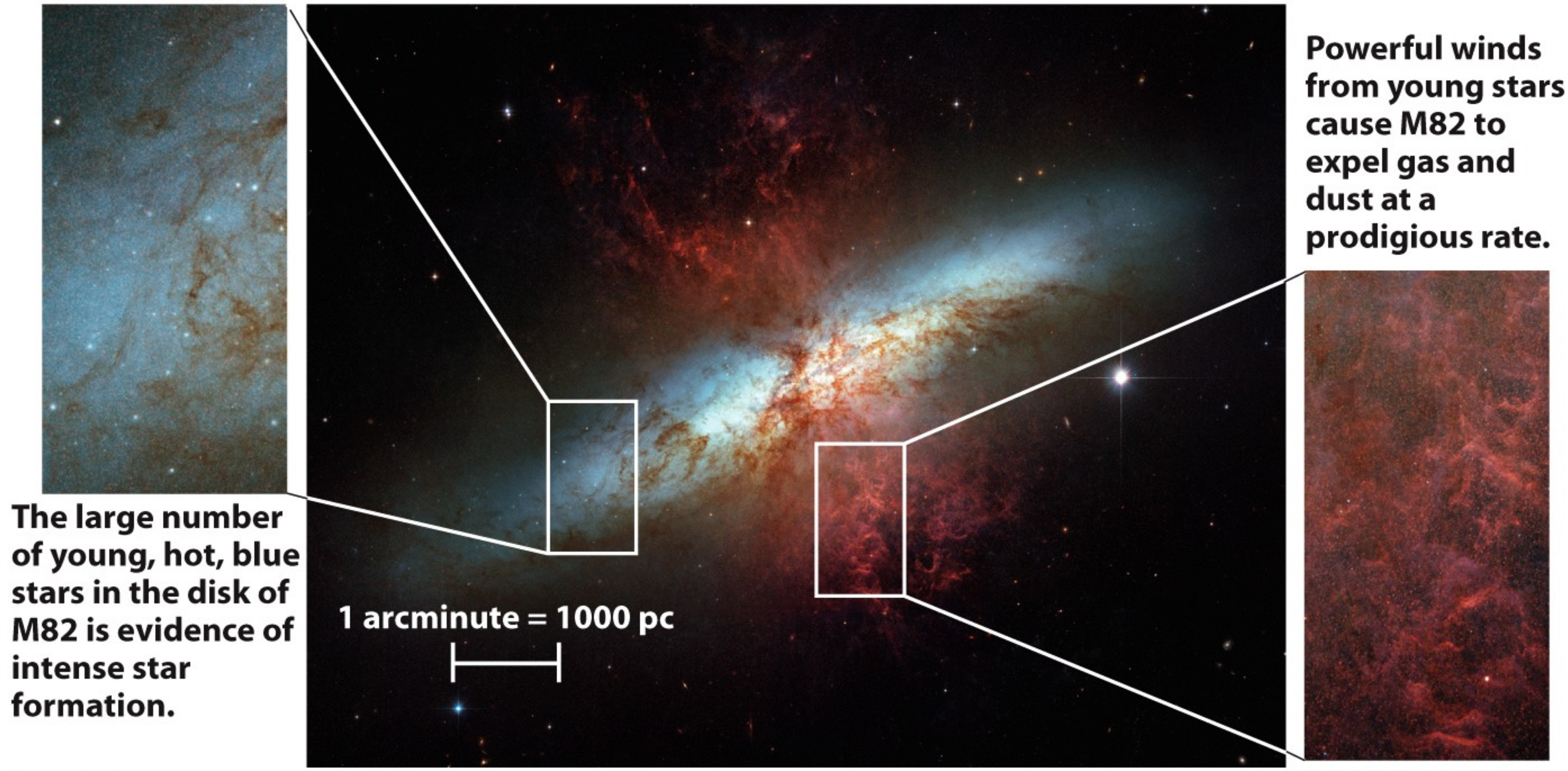


Figure 23-27
Universe, Tenth Edition
NASA; ESA; and the Hubble Heritage Team, STScI/AURA

Galaxy Formation and Cosmology

- The Universe contains the same amount of matter today as it did 13.8 billion years ago.
- The Universe was smaller in the past.
  - It is (1 + z) times larger today than at redshift z.
  - The Universe has expanded by a factor of 10 since redshift z = 9.
- Higher density of intergalactic gas in the past
- Gas clouds had less angular momentum
- Compact galaxies formed stars very rapidly

Summary

- **The Universe is full of billions of galaxies.**
  - Why this wasn't clear to Einstein.
  - Hubble's discovery of Cepheids in Andromeda
  - Distances to galaxies
- **Those galaxies are flying away from us!**
  - Hubble's law
  - The expansion of the universe
- **Galaxies are found in bubble-like structures**
  - They live in groups, clusters, and superclusters
  - Absence of super-duper clusters underlies cosmology
- **Properties of galaxies reflect how they formed**
  - The first galaxies were small and grew from merging
  - Collisions fuel new star formation
  - Winds remove gas and metals from galaxies