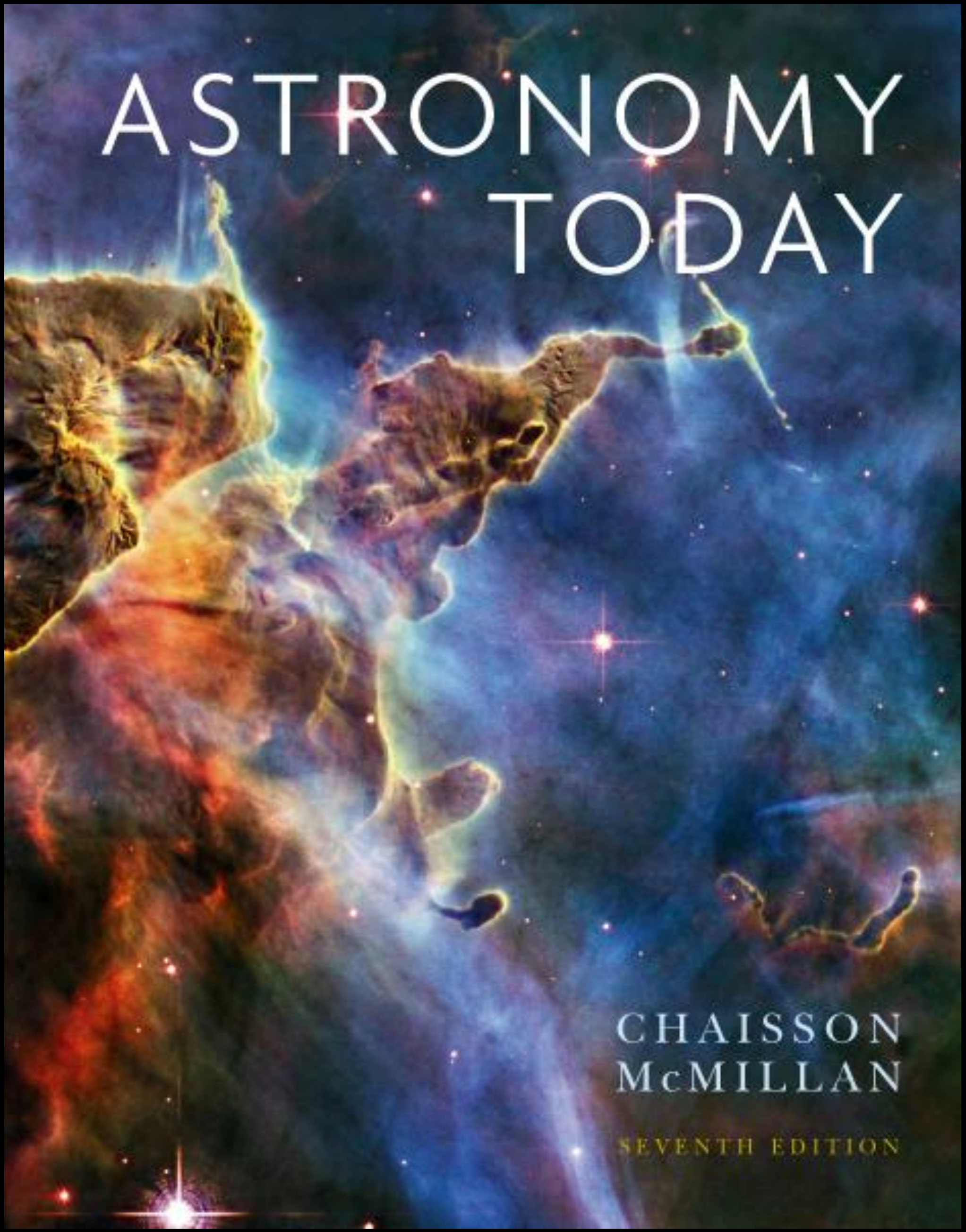


Lecture Outlines

Chapter 26

Astronomy Today

7th Edition

Chaisson/McMillan

Chapter 26
Cosmology

© 2011 Pearson Education, Inc.

Units of Chapter 26

26.1 The Universe on the Largest Scales

26.2 The Expanding Universe

26.3 The Fate of the Cosmos

26.4 The Geometry of Space

Curved Space

26.5 Will the Universe Expand Forever?

Einstein and the Cosmological Constant

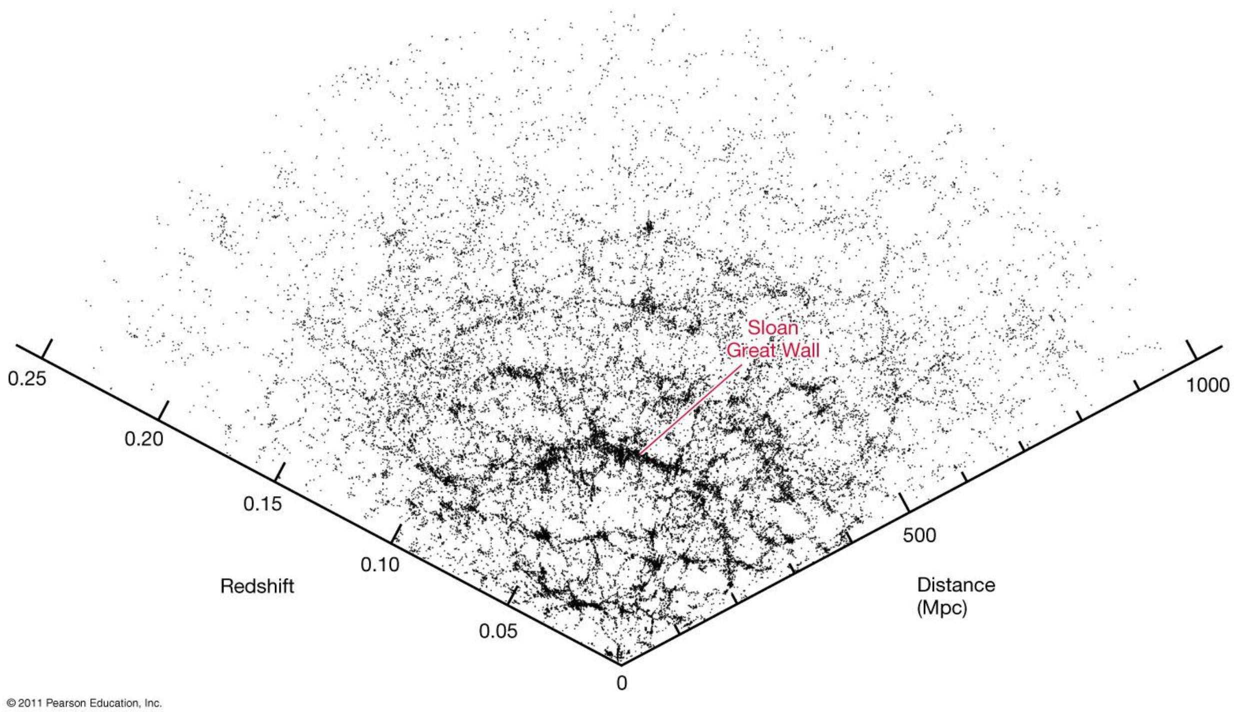
Units of Chapter 26 (cont.)

26.6 Dark Energy and Cosmology

26.7 Cosmic Microwave Background

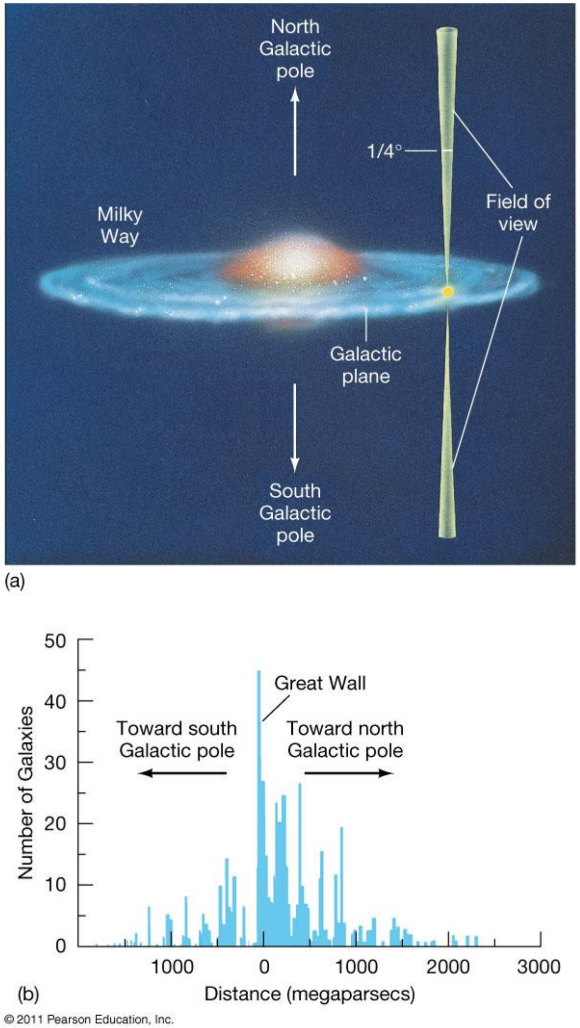
26.1 The Universe on the Largest Scales

This galaxy map shows the largest structure known in the Universe, the Sloan Great Wall. No structure larger than 300 Mpc is seen.



26.1 The Universe on the Largest Scales

This pencil-beam survey is another measure of large-scale structure. Again, there is structure at about 200–300 Mpc, but nothing larger.



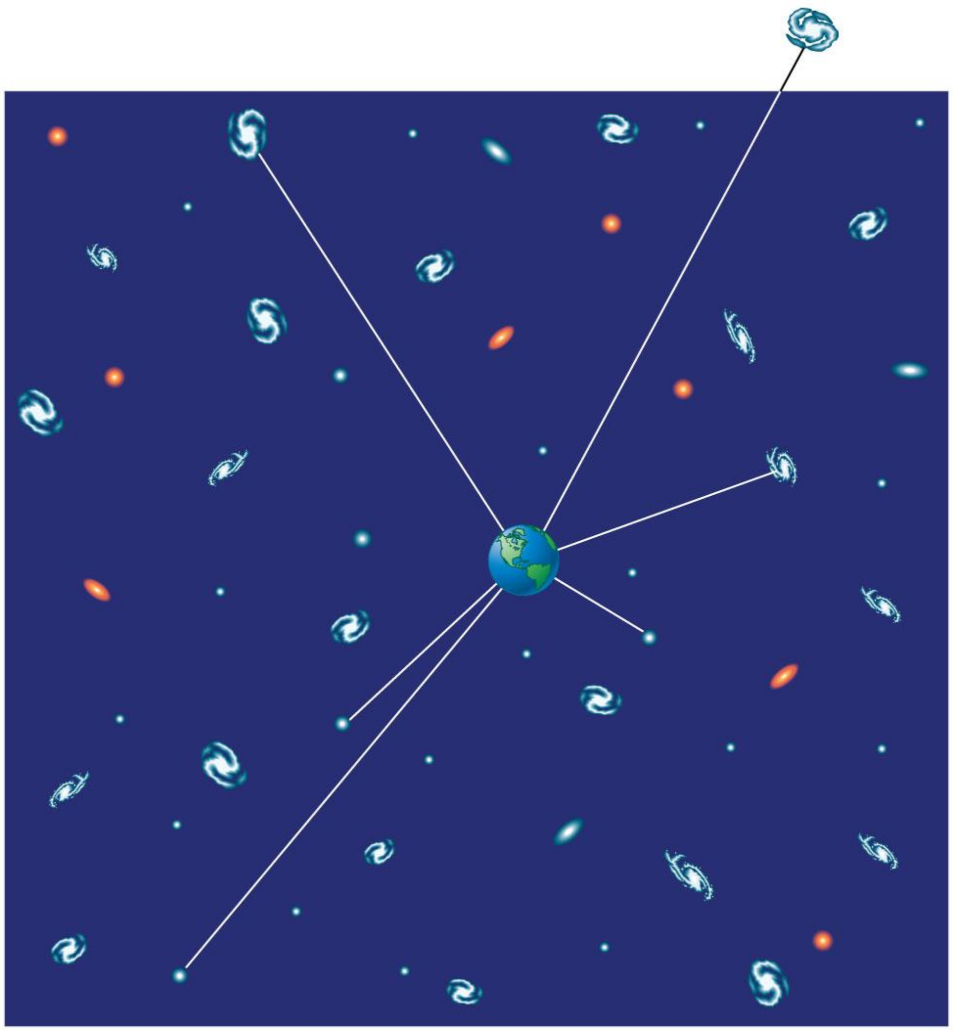
26.1 The Universe on the Largest Scales

Therefore, the Universe is homogenous (any 300-Mpc-square block appears much like any other) on scales greater than about 300 Mpc.

The Universe also appears to be isotropic—the same in all directions.

The cosmological principle includes the assumptions of isotropy and homogeneity.

26.2 The Expanding Universe



Olbers's Paradox:

If the universe is homogeneous, isotropic, infinite, and unchanging, the entire sky should be as bright as the surface of the Sun.

26.2 The Expanding Universe

So, why is it dark at night?

The universe is homogeneous and isotropic—it must not be infinite or unchanging.

We have already found that galaxies are moving faster away from us the farther away they are:

$$\text{recession velocity} = H_0 \times \text{distance}$$

26.2 The Expanding Universe

So, how long did it take the galaxies to get there?

$$\text{time} = \text{distance} / \text{velocity}$$

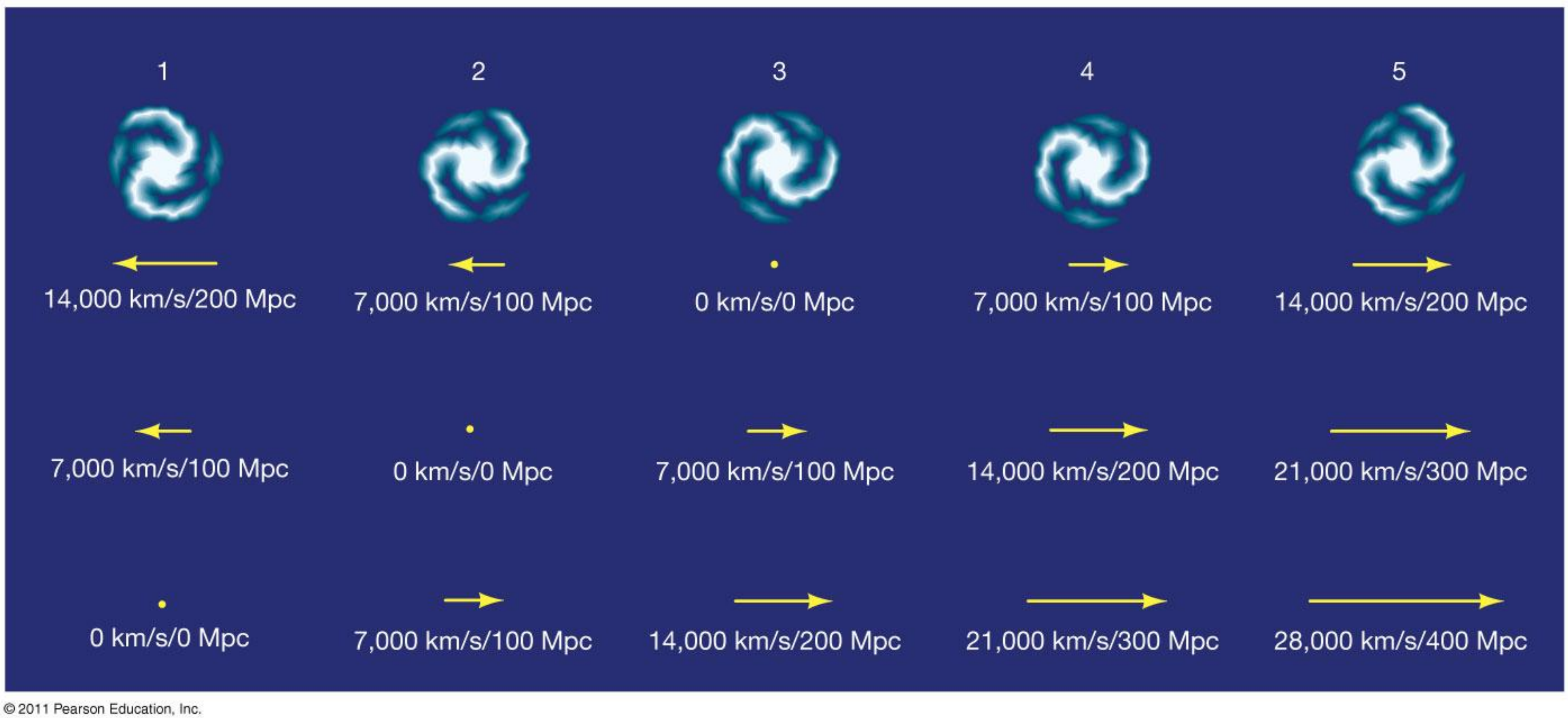
$$= \text{distance} / (H_0 \text{ x distance})$$

$$= 1/H_0$$

Using H_0 = 70 km/s/Mpc, we find that time is about 14 billion years.

26.2 The Expanding Universe

Note that Hubble's law is the same no matter who is making the measurements.



26.2 The Expanding Universe

If this expansion is extrapolated backward in time, all galaxies are seen to originate from a single point in an event called the Big Bang.

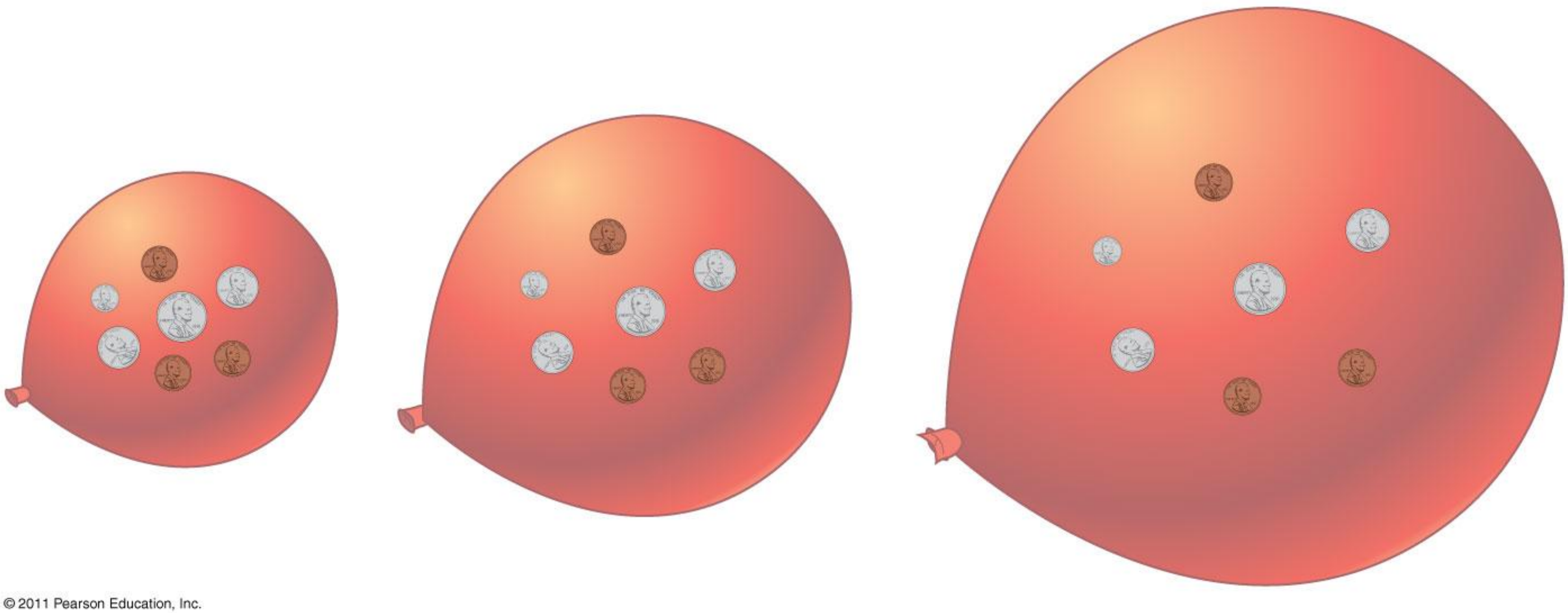
So, where was the Big Bang?

It was everywhere!

No matter where in the Universe we are, we will measure the same relation between recessional velocity and distance with the same Hubble constant.

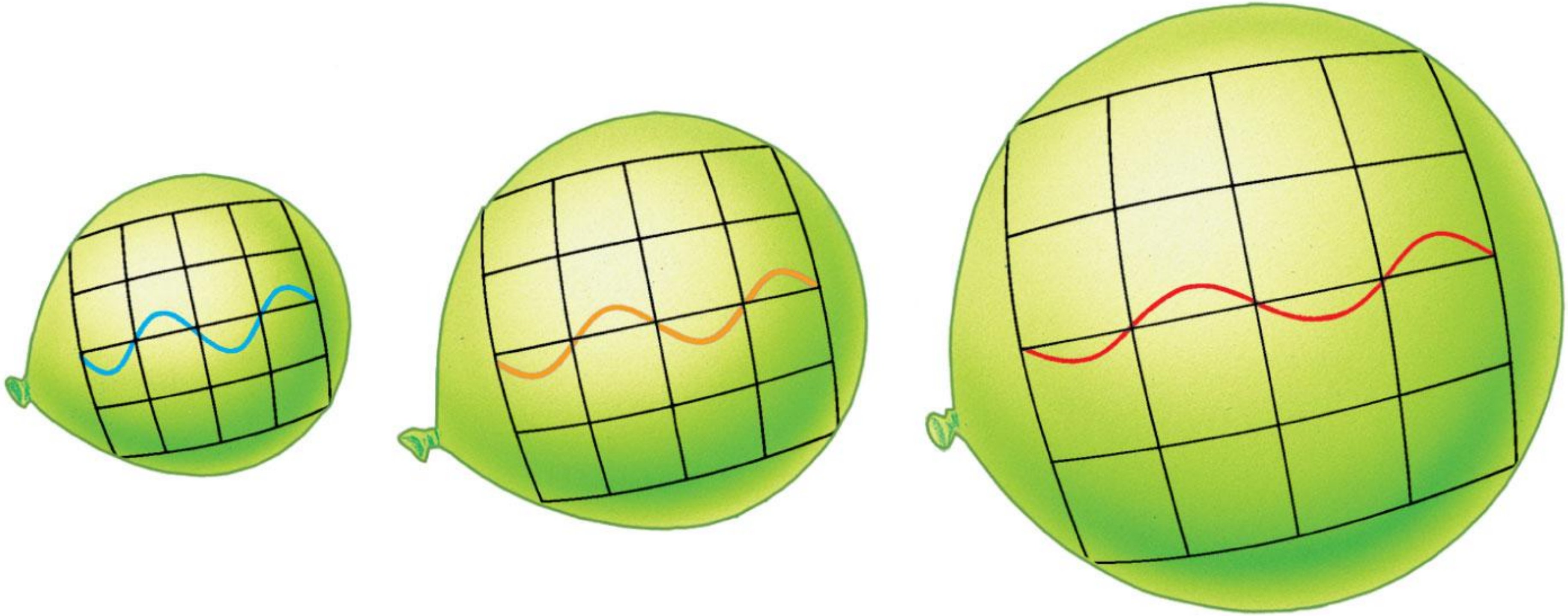
26.2 The Expanding Universe

This can be demonstrated in two dimensions. Imagine a balloon with coins stuck to it. As we blow up the balloon, the coins all move farther and farther apart. There is, on the surface of the balloon, no “center” of expansion.



26.2 The Expanding Universe

The same analogy can be used to explain the cosmological redshift



26.2 The Expanding Universe

These concepts are hard to comprehend, and not at all intuitive. A full description requires the very high-level mathematics of general relativity.

However, there are aspects that can be understood using relatively simple Newtonian physics—we just need the full theory to tell us which ones!

26.3 The Fate of the Cosmos

There are two possibilities for the Universe in the far future:

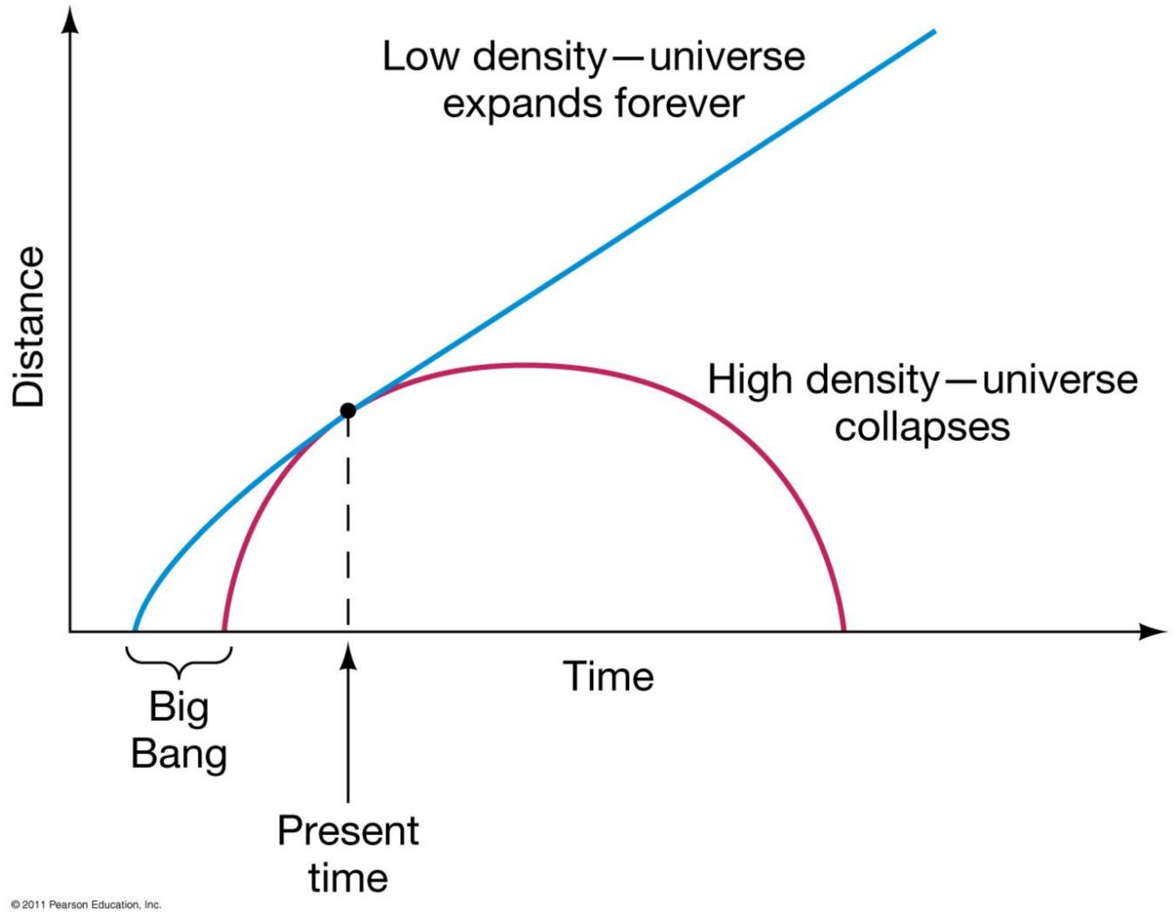
1. It could keep expanding forever.

2. It could collapse.

Assuming that the only relevant force is gravity, which way the Universe goes depends on its density.

26.3 The Fate of the Cosmos

If the density is low, the universe will expand forever. If it is high, the universe will ultimately collapse.



26.3 The Fate of the Cosmos

There is a critical density between collapse and expansion. At this density the universe still expands forever, but the expansion speed goes asymptotically to zero as time goes on.

Given the present value of the Hubble constant, that critical density is approximately

$$9 \times 10^{-27}\ \mathrm{kg/m^3}$$

This is about five hydrogen atoms per cubic meter.

26.3 The Fate of the Cosmos

If space is homogenous, there are three possibilities for its overall structure:

1. Closed—this is the geometry that leads to ultimate collapse
2. Flat—this corresponds to the critical density
3. Open—expands forever

26.4 The Geometry of Space

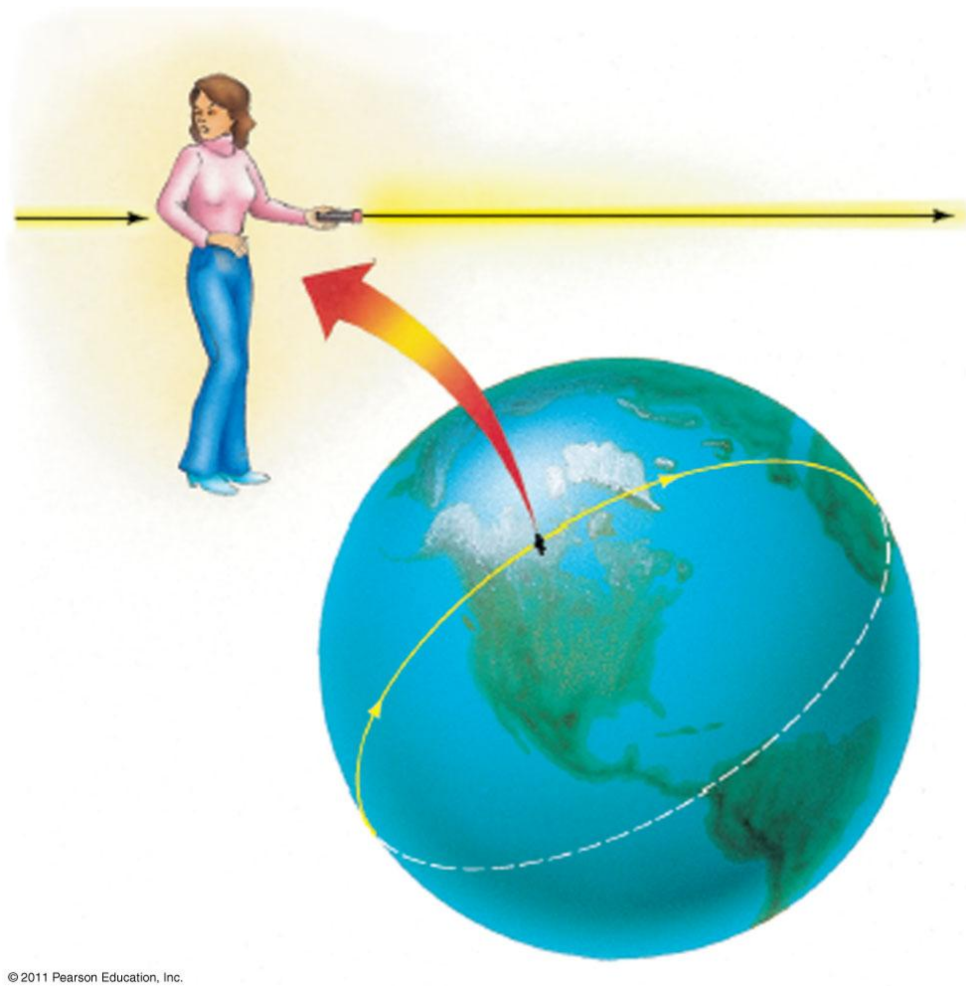
These three possibilities can be described by comparing the actual density of the Universe to the critical density.

Astronomers refer to the actual density of the Universe as Ω, and to the critical density as Ω_0.

Then we can describe the three possibilities as

$\Omega < \Omega_0$	Open geometry
$\Omega = \Omega_0$	Flat geometry
$\Omega > \Omega_0$	Closed geometry

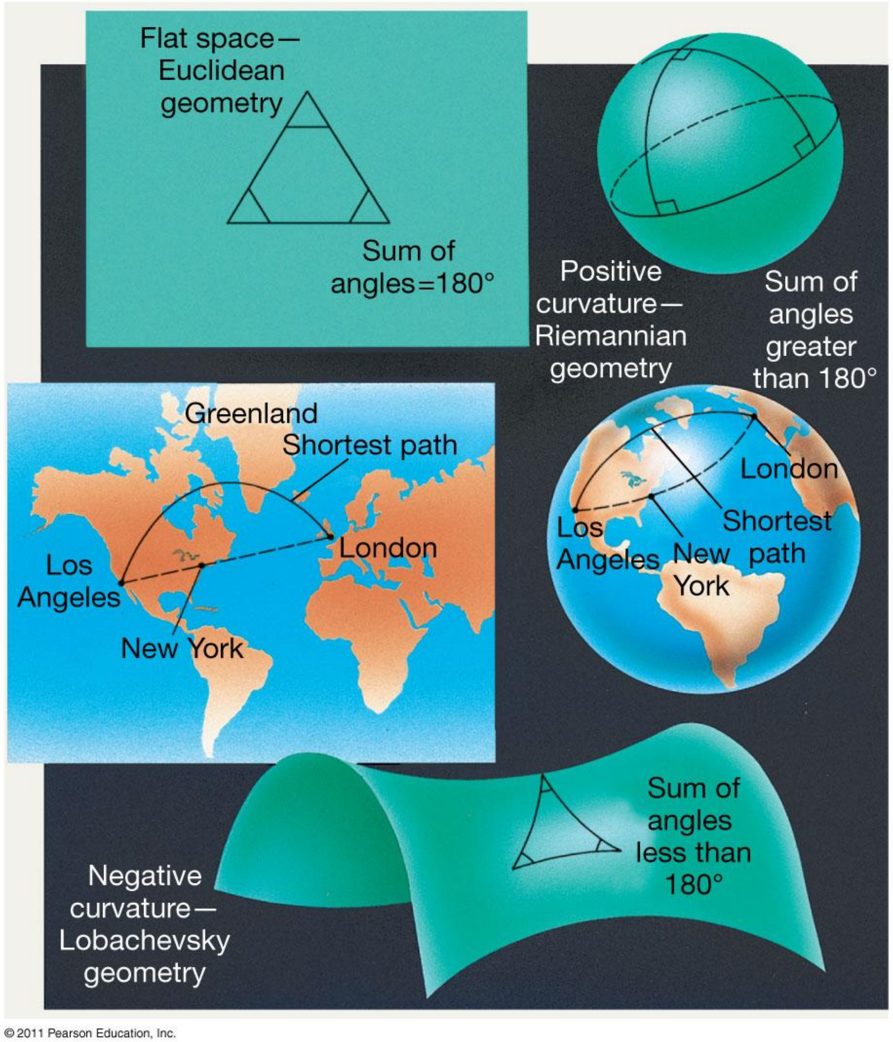
26.4 The Geometry of Space



In a closed universe, you can travel in a straight line and end up back where you started (in the absence of time and budget constraints, of course!)

More Precisely 26-1: Curved Space

The three possibilities for the overall geometry of space are illustrated here: The closed geometry is like the surface of a sphere; the flat one is flat; and the open geometry is like a saddle.



26.5 Will the Universe Expand Forever?

The answer to this question lies in the actual density of the Universe.

Measurements of luminous matter suggest that the actual density is only a few percent of the critical density.

But, we know there must be large amounts of dark matter.

26.5 Will the Universe Expand Forever?

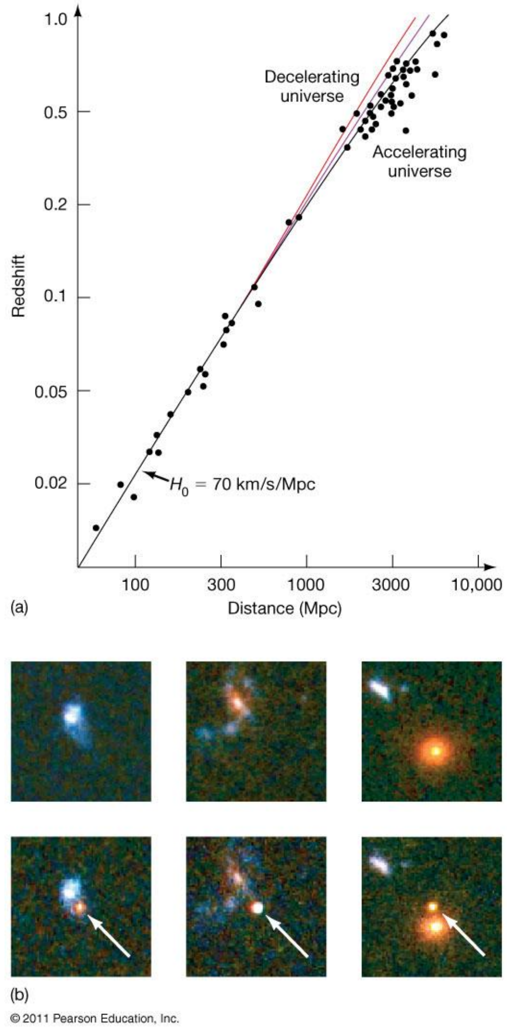
However, the best estimates for the amount of dark matter needed to bind galaxies in clusters, and to explain gravitational lensing, still only bring the observed density up to about 0.3 times the critical density, and it seems very unlikely that there could be enough dark matter to make the density critical.

26.5 Will the Universe Expand Forever?

Type I supernovae can be used to measure the behavior of distant galaxies.

If the expansion of the Universe is decelerating, as it would be if gravity were the only force acting, the farthest galaxies had a more rapid recessional speed in the past, and will appear as though they were receding faster than Hubble's law would predict.

26.5 Will the Universe Expand Forever?

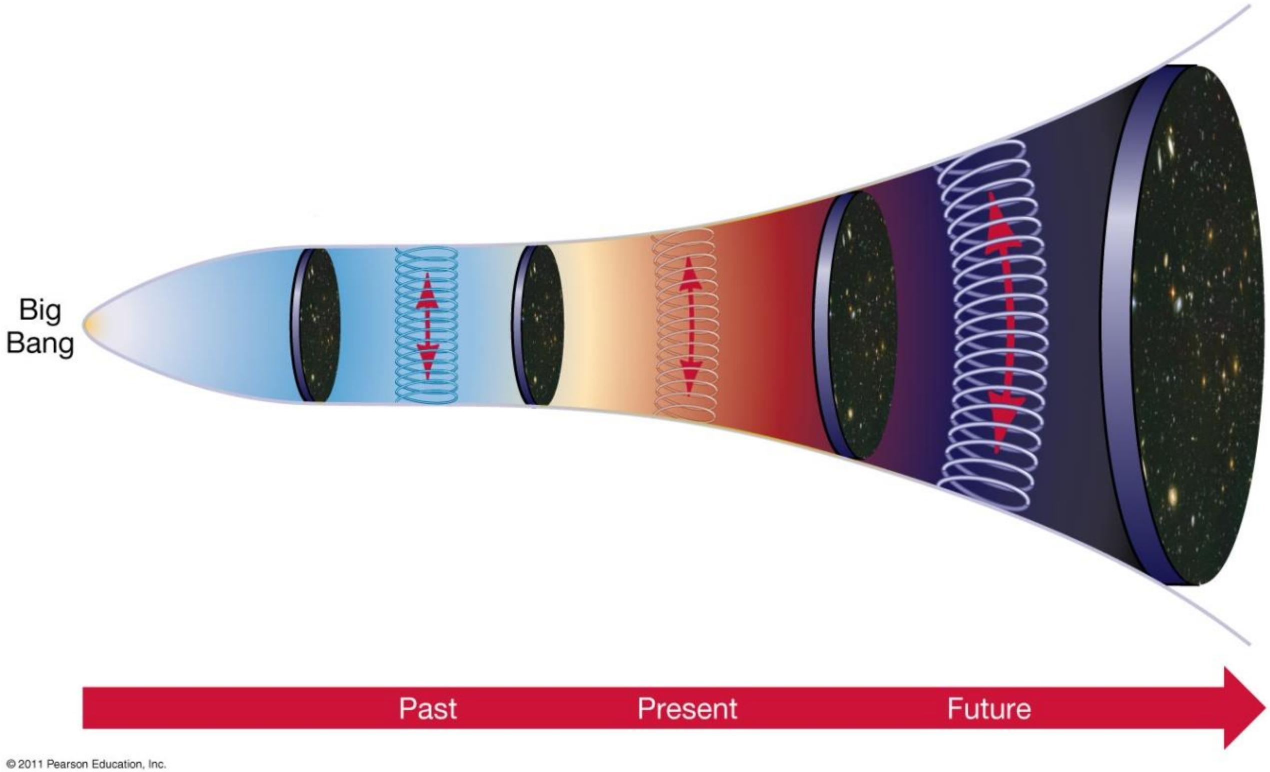


However, when we look at the data, we see that they correspond not to a decelerating universe, but to an accelerating one.

This acceleration cannot be explained by current theories of the Universe, although we do know it is not caused by either matter or radiation.

26.5 Will the Universe Expand Forever?

The repulsive effect of the dark energy increases as the Universe expands.



Discovery 26-2: Einstein and the Cosmological Constant

The cosmological constant (vacuum energy) was originally introduced by Einstein to prevent general relativity from predicting that a static universe (then thought to be the case) would collapse. When the universe turned out to be expanding, Einstein removed the constant from his theory, calling it the biggest blunder of his career.

Discovery 26-2: Einstein and the Cosmological Constant

Now, it seems as though something like a cosmological constant may be necessary to explain the accelerating universe—theoretical work is still at a very early stage, though!

26.6 Dark Energy and Cosmology

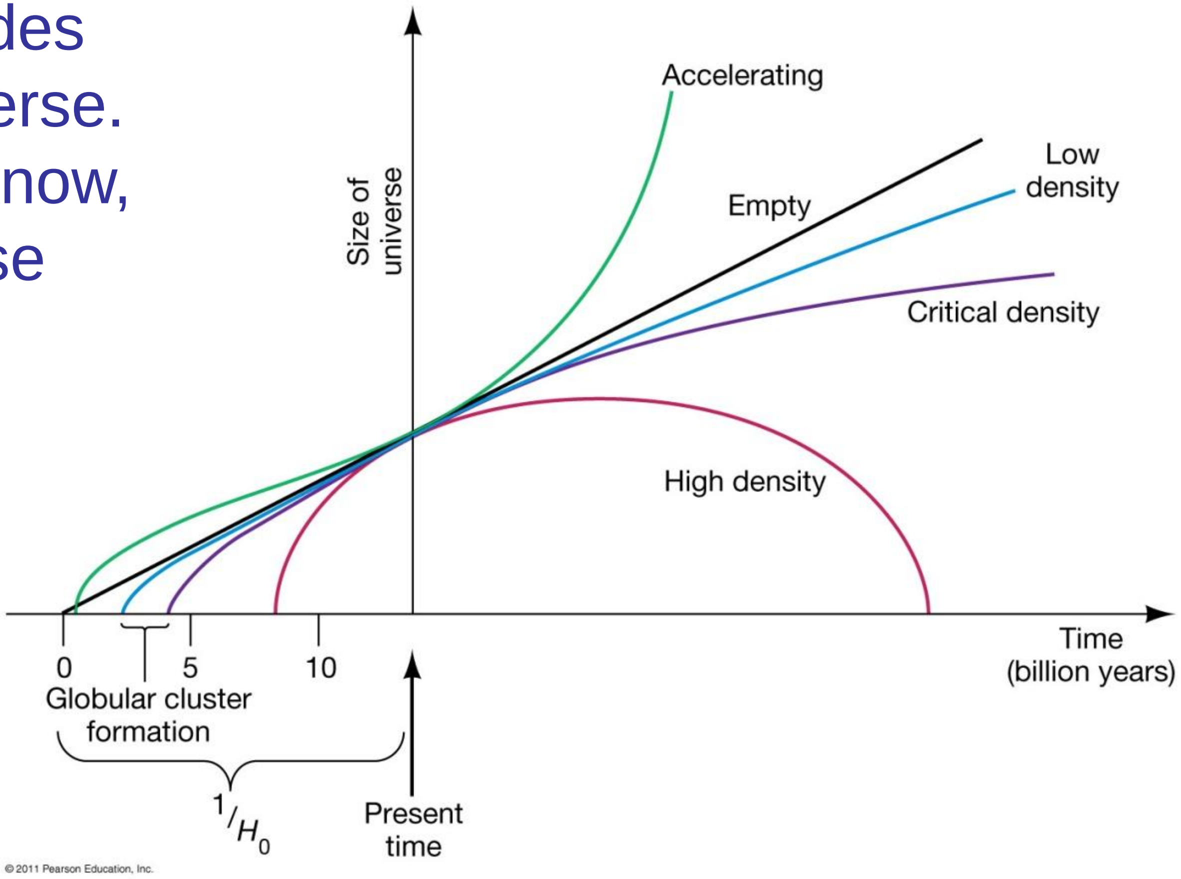
What else supports the "dark energy" theory?

• In the very early life of the Universe, the geometry must be flat.

• The assumption of a constant expansion rate predicts the Universe to be younger than we observe.

26.6 Dark Energy and Cosmology

This graph now includes the accelerating universe. Given what we now know, the age of the universe works out to be 13.7 billion years.



26.6 Dark Energy and Cosmology

This is consistent with other observations, particularly of the age of globular clusters, and yields the following timeline:

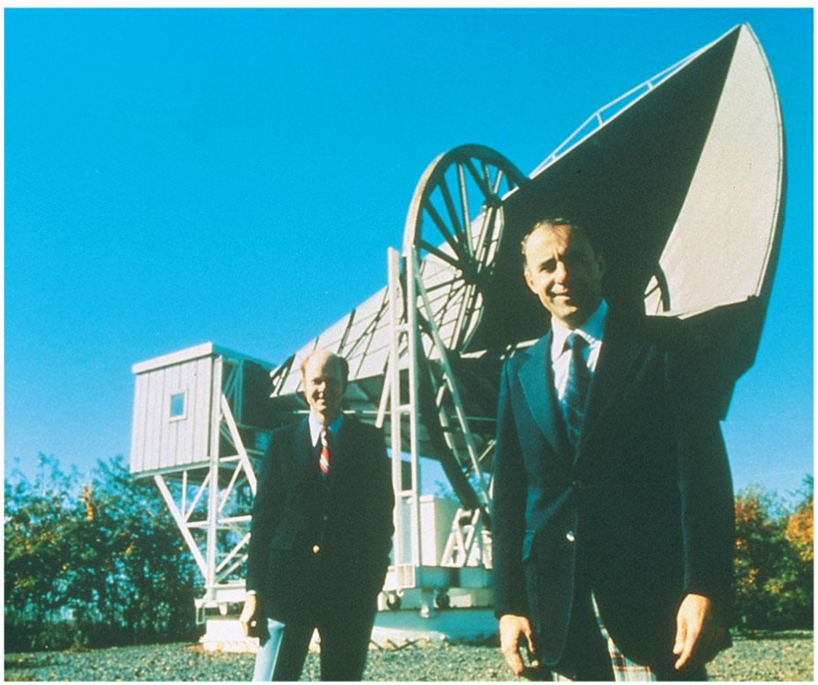
14 billion years ago: Big Bang

13 billion years ago: Quasars form

10 billion years ago: First stars in our galaxy form

26.7 Cosmic Microwave Background

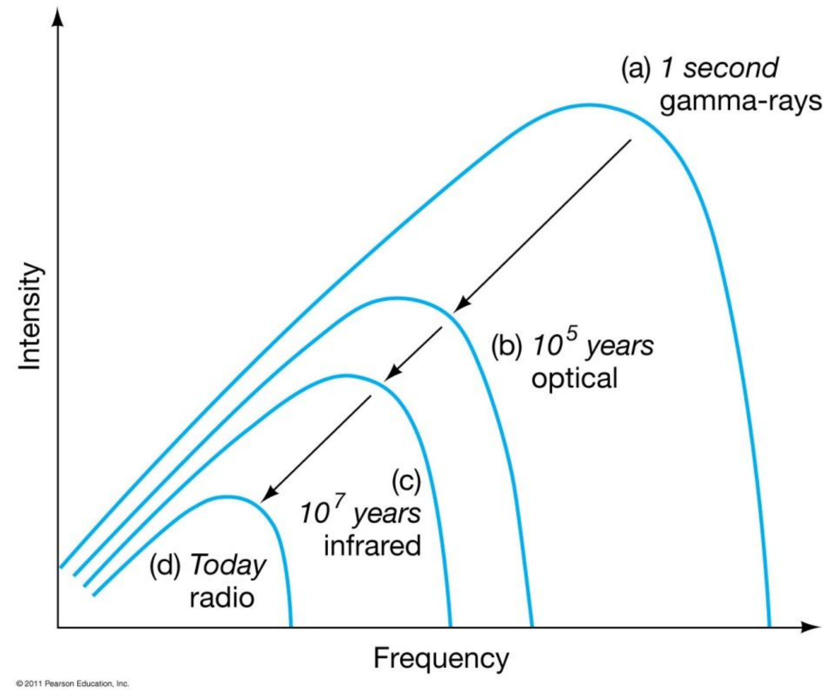
The cosmic microwave background was discovered fortuitously in 1964, as two researchers tried to get rid of the last bit of “noise” in their radio antenna.



Instead, they found that the “noise” came from all directions and at all times, and was always the same. They were detecting photons left over from the Big Bang.

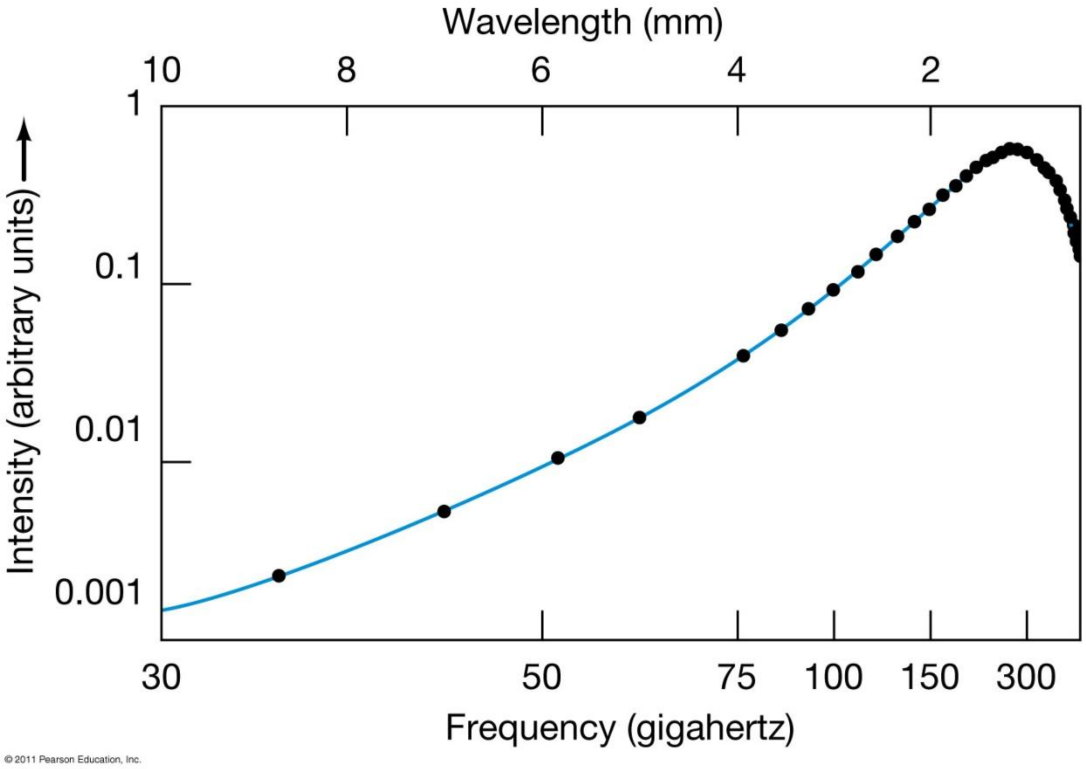
26.7 Cosmic Microwave Background

When these photons were created, it was only one second after the Big Bang, and they were very highly energetic. The expansion of the universe has redshifted their wavelengths so that now they are in the radio spectrum, with a blackbody curve corresponding to about 3 K.



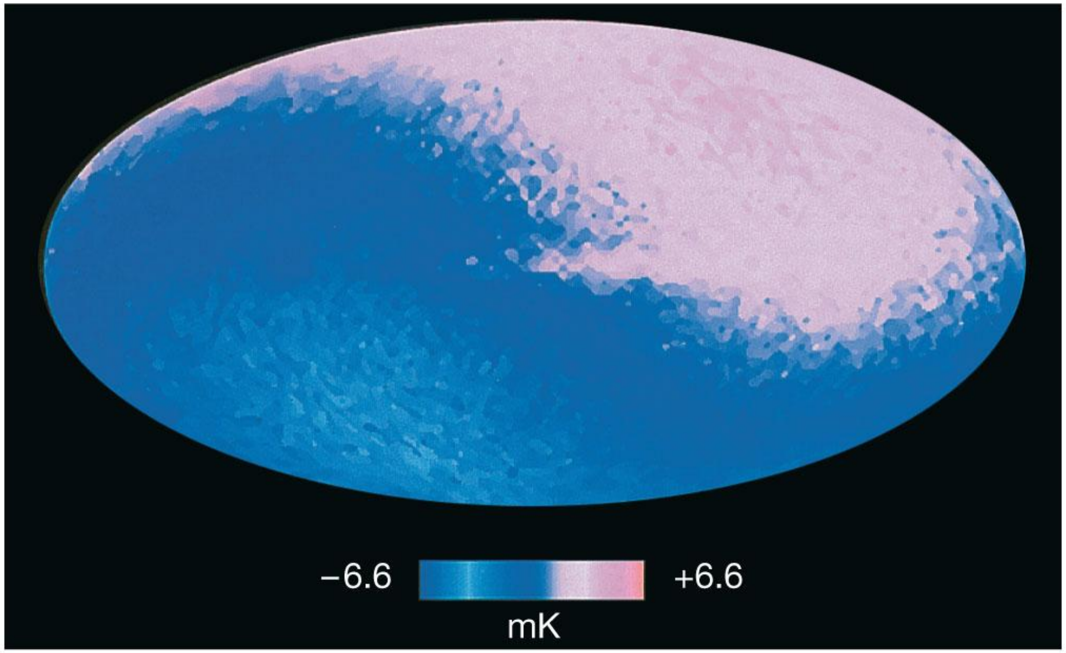
26.7 Cosmic Microwave Background

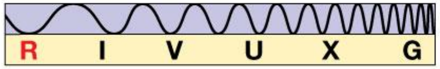
Since then, the cosmic background spectrum has been measured with great accuracy.



26.7 Cosmic Microwave Background

A map of the microwave sky shows a distinct pattern, due not to any property of the radiation itself, but to the Earth's motion





Summary of Chapter 26

- On scales larger than a few hundred megaparsecs, the Universe is homogeneous and isotropic.
- The Universe began about 14 million years ago, in a Big Bang.
- Future of the Universe: either expand forever, or collapse
- Density between expansion and collapse is critical density.

Summary of Chapter 26 (cont.)

- A high-density universe has a closed geometry; a critical universe is flat; and a low-density universe is open.
- Luminous mass and dark matter make up at most 30% of the critical density.
- Acceleration of the universe appears to be speeding up, due to some form of dark energy.
- The Universe is about 14 billion years old.
- Cosmic microwave background is photons left over from Big Bang.