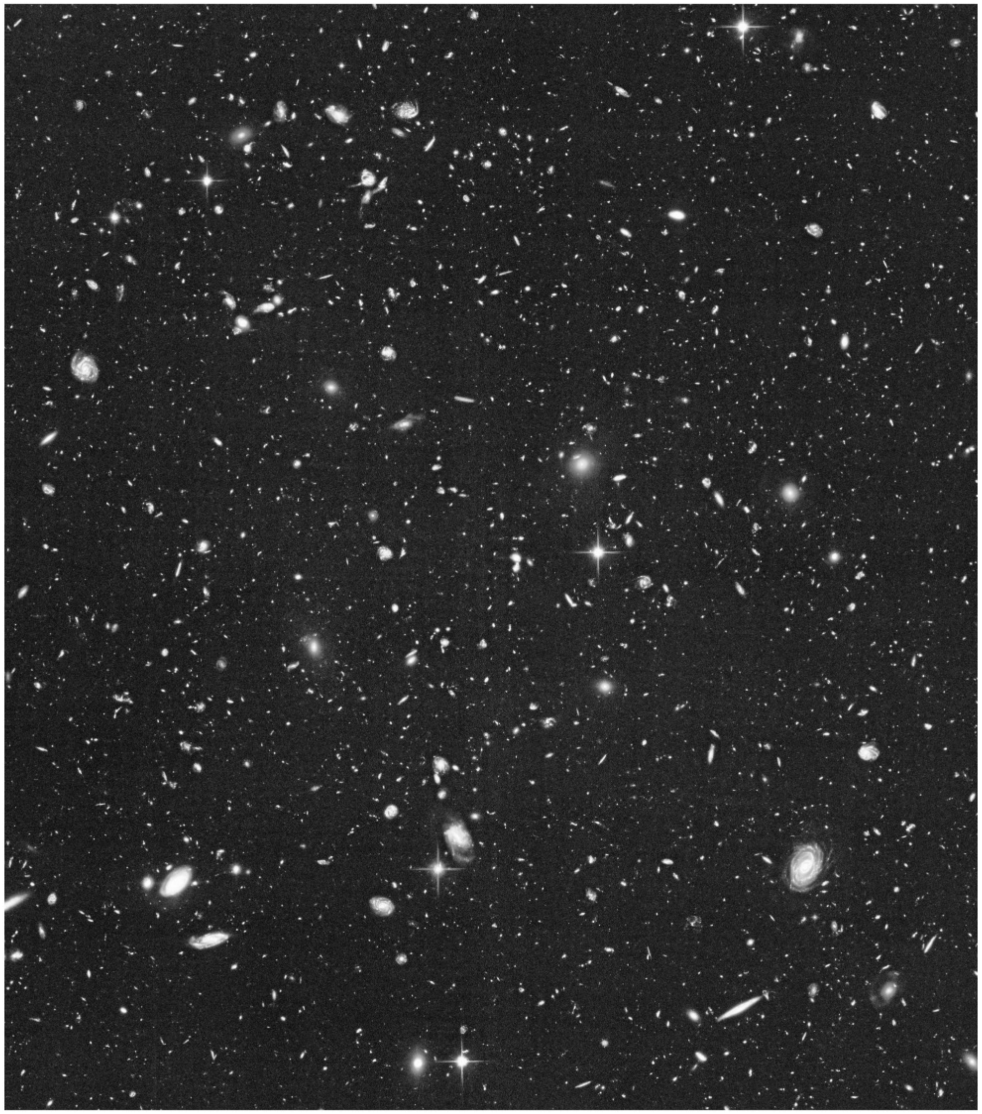
Chapter 17
Cosmology



Units of Chapter 17

The Universe on the Largest Scales

The Expanding Universe

Cosmic Dynamics and the Geometry of Space

The Fate of the Cosmos

The Early Universe

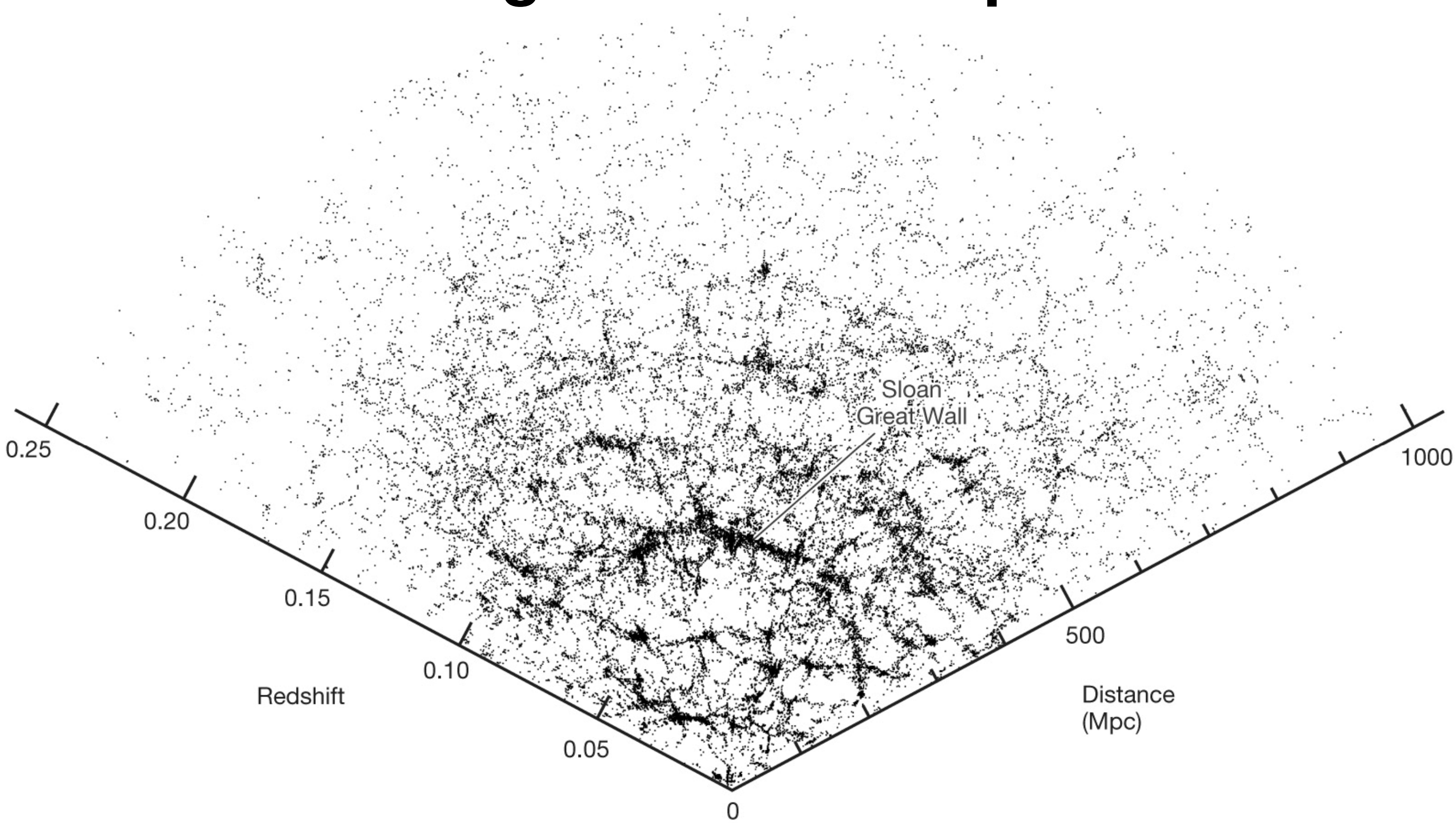
The Formation of Nuclei and Atoms

Cosmic Inflation

The Formation of Large-Scale Structure in the Universe

17.1 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.



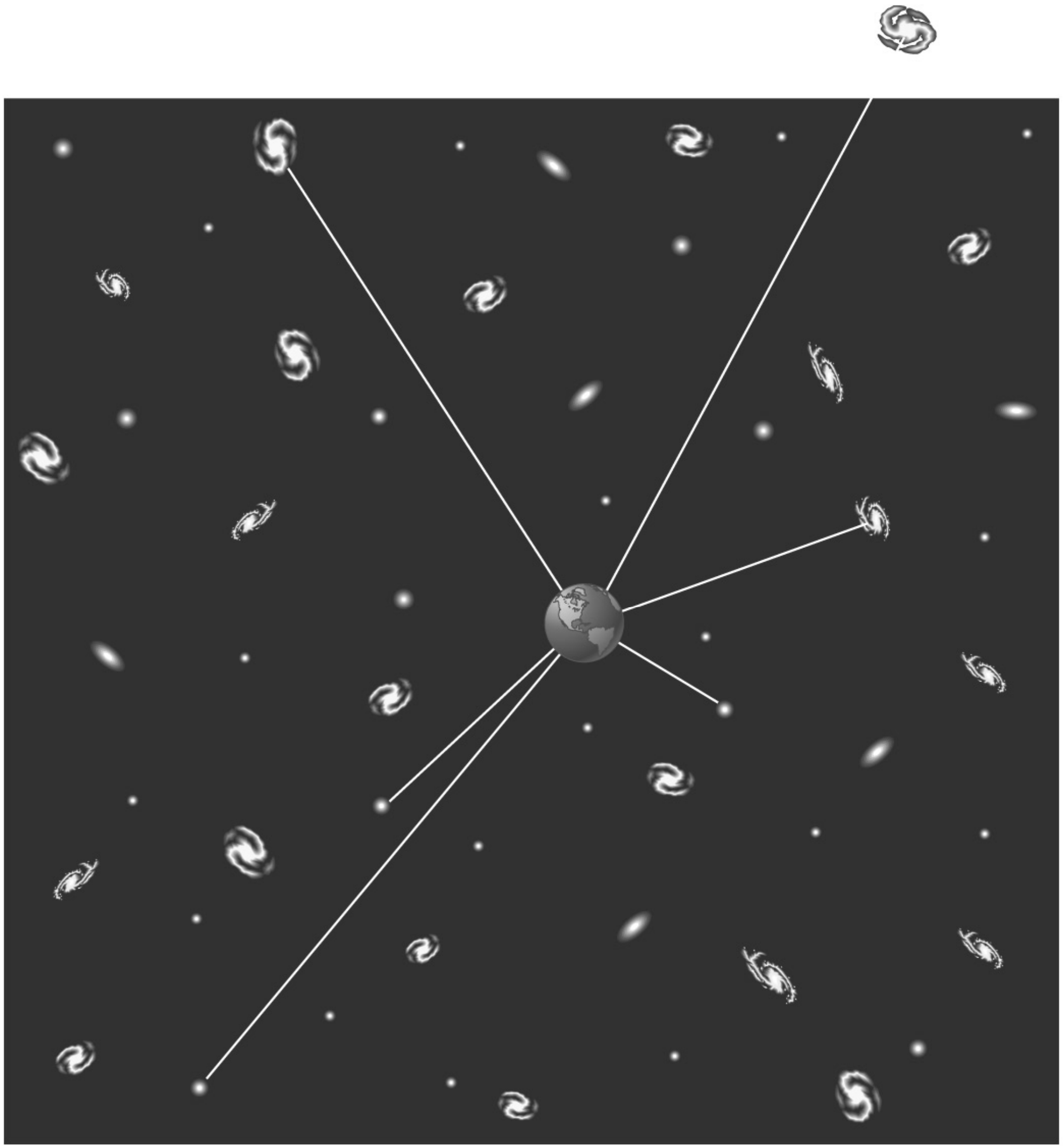
17.1 The Universe on the Largest Scales

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.

17.2 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.

17.2 The Expanding Universe

So, why is it dark at night?

The universe is homogeneous and isotropic –

It must not be infinite and/or unchanging.

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

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

17.2 The Expanding Universe

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

$$\text{time} = \frac{\text{distance}}{\text{velocity}} = \frac{\text{distance}}{H_0 \times \text{distance}} = \frac{1}{H_0}$$

17.2 The Expanding Universe

Using $H_0 = 70\ \text{km/s/Mpc}$

we find that time is about 14 billion years.

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

17.2 The Expanding Universe

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

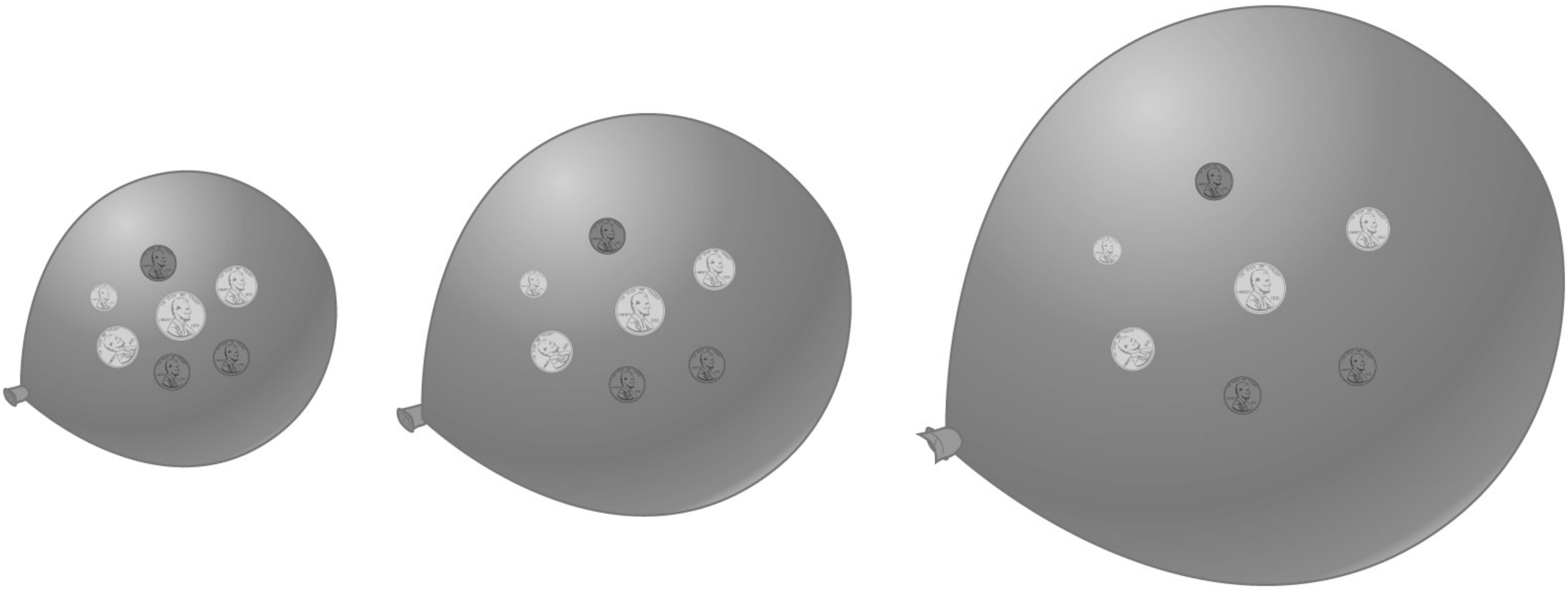
So, where was the Big Bang?

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.

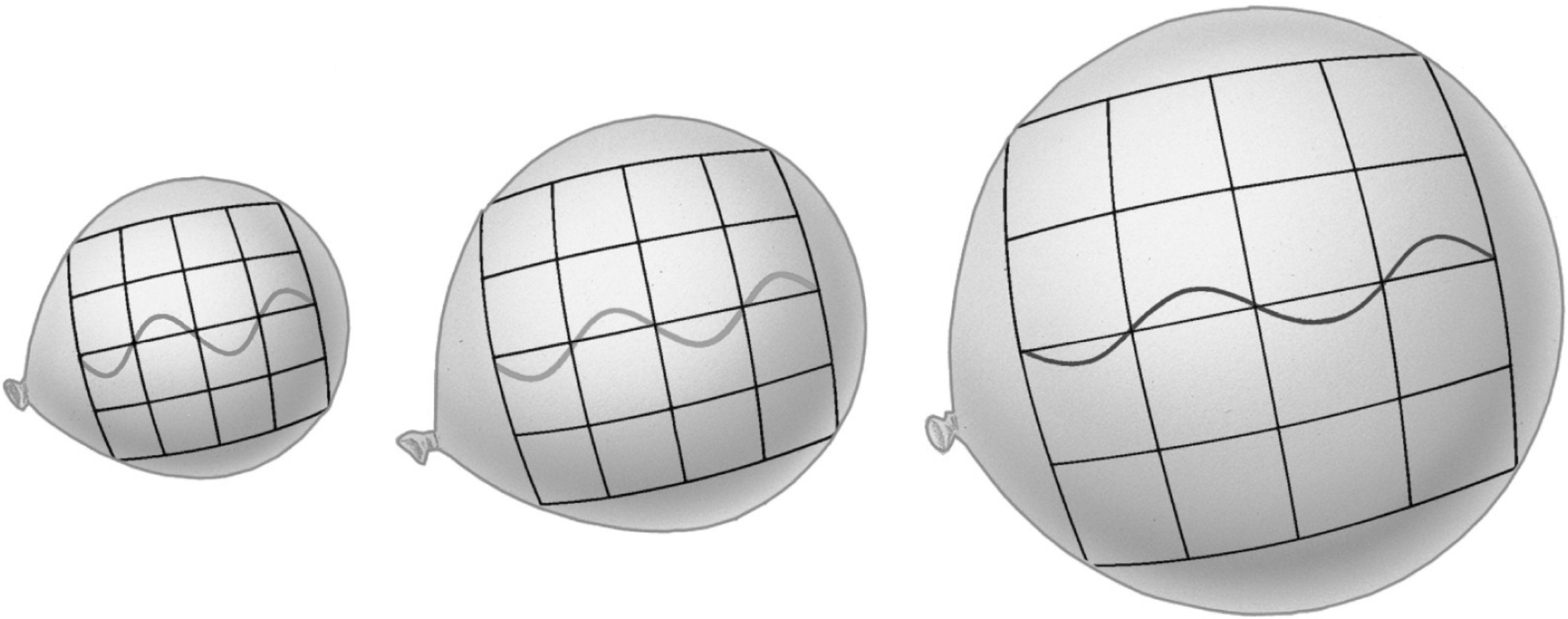
17.2 The Expanding Universe

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.



17.2 The Expanding Universe

The same analogy can be used to explain the cosmological redshift:



17.2 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!

17.4 Cosmic Dynamics and the Geometry of Space

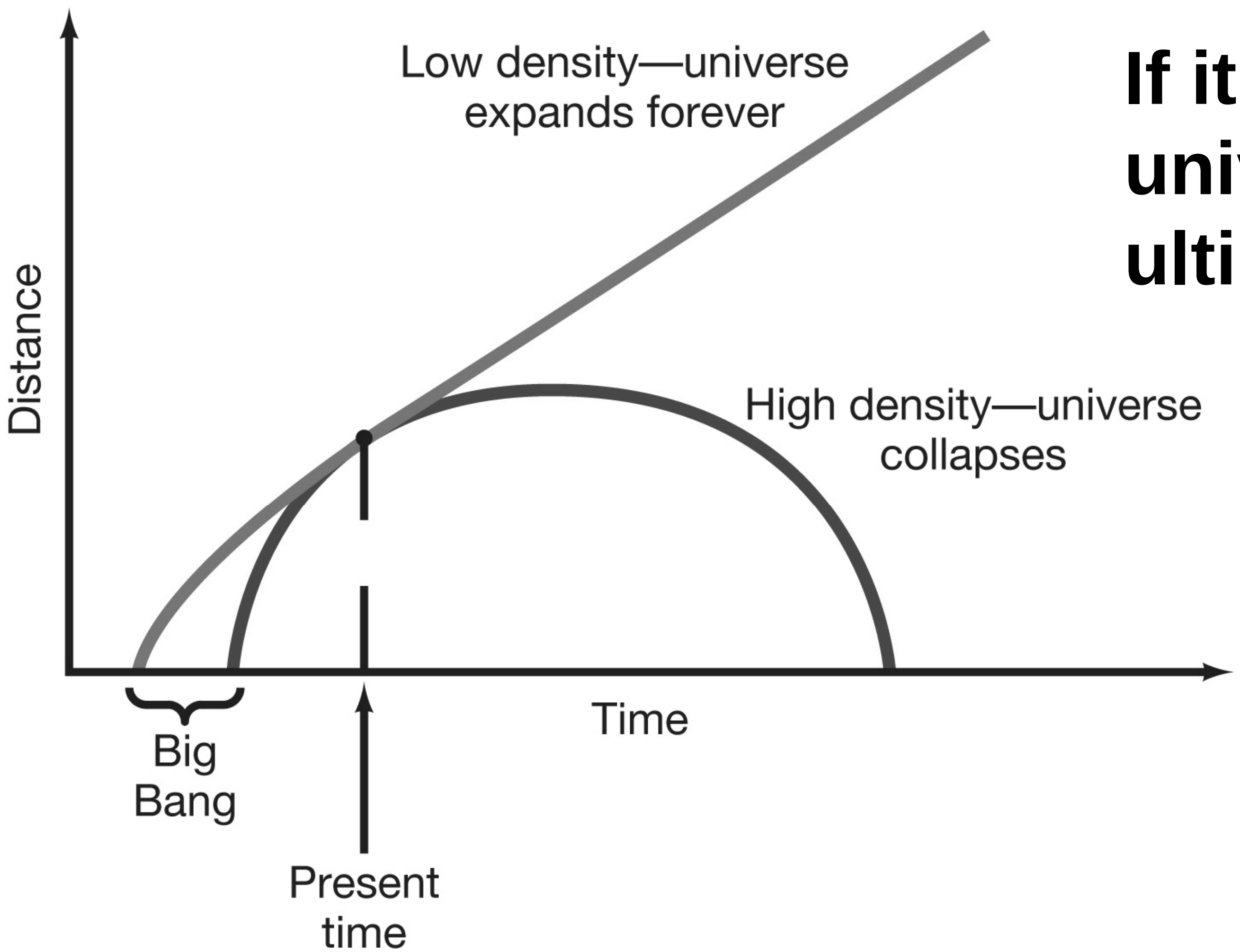
There are two possibilities for the Universe in the far future:

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.

17.4 Cosmic Dynamics and the Geometry of Space

If the density is low, the universe will expand forever.



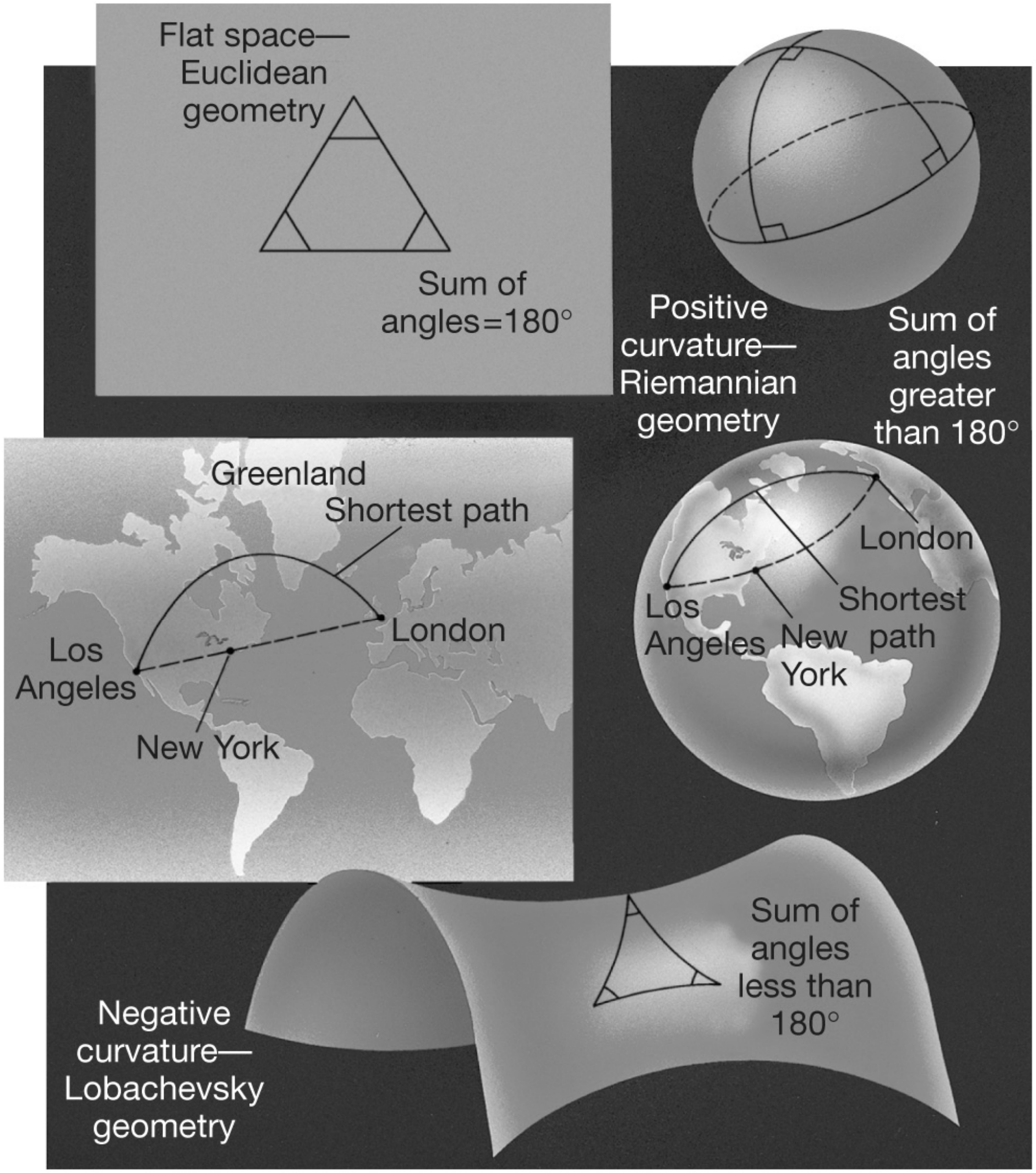
If it is high, the universe will ultimately collapse.

17.4 Cosmic Dynamics and the Geometry of Space

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

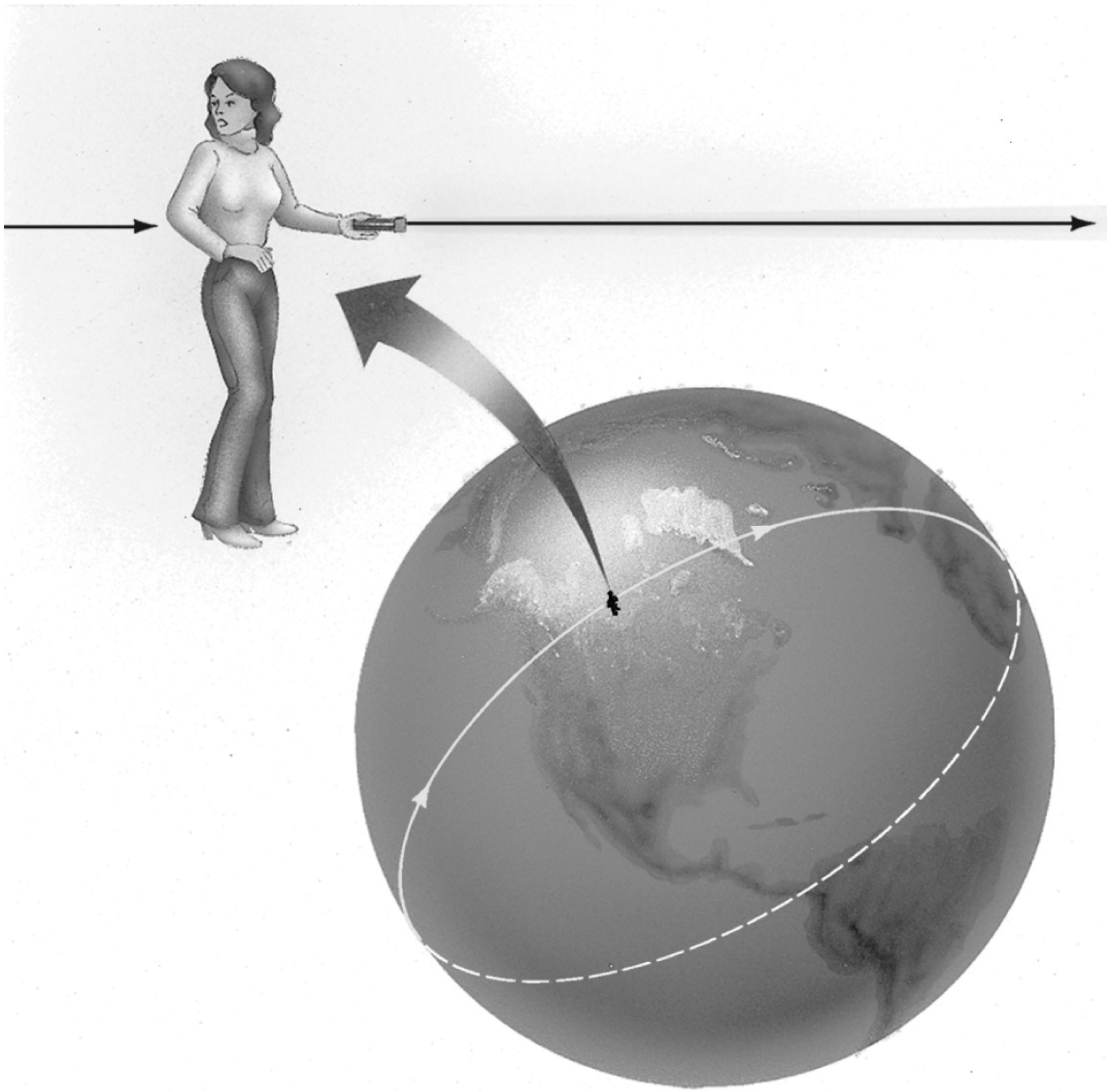
1. **Closed – this is the geometry that leads to ultimate collapse**
2. **Flat – this corresponds to the critical density**
3. **Open – expands forever**

17.4 Cosmic Dynamics and the Geometry of Space



These three possibilities 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.

17.4 Cosmic Dynamics and the Geometry of Space



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In a closed universe, you can travel in a straight line and end up back where you started.

17.4 The Fate of the Cosmos

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.

17.4 The Fate of the Cosmos

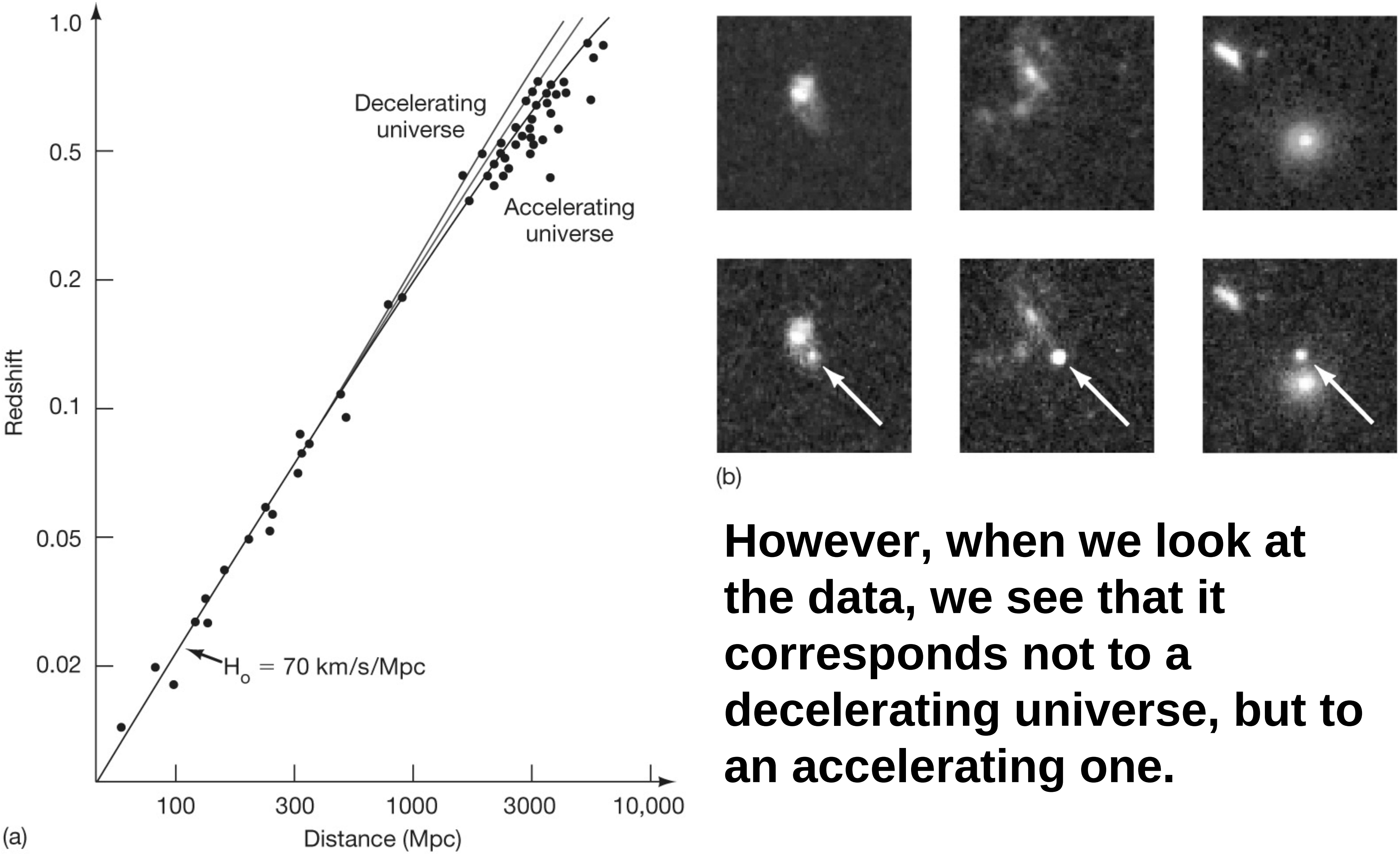
However, the best estimates for the amount of dark matter needed to bind galaxies in clusters, and to explain gravitational lensing, still only bring the observed density up to about 0.3 times the critical density, and it seems very unlikely that there could be enough dark matter to make the density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

17.4 The Fate of the Cosmos

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

If the expansion of the Universe is decelerating, as it would 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.

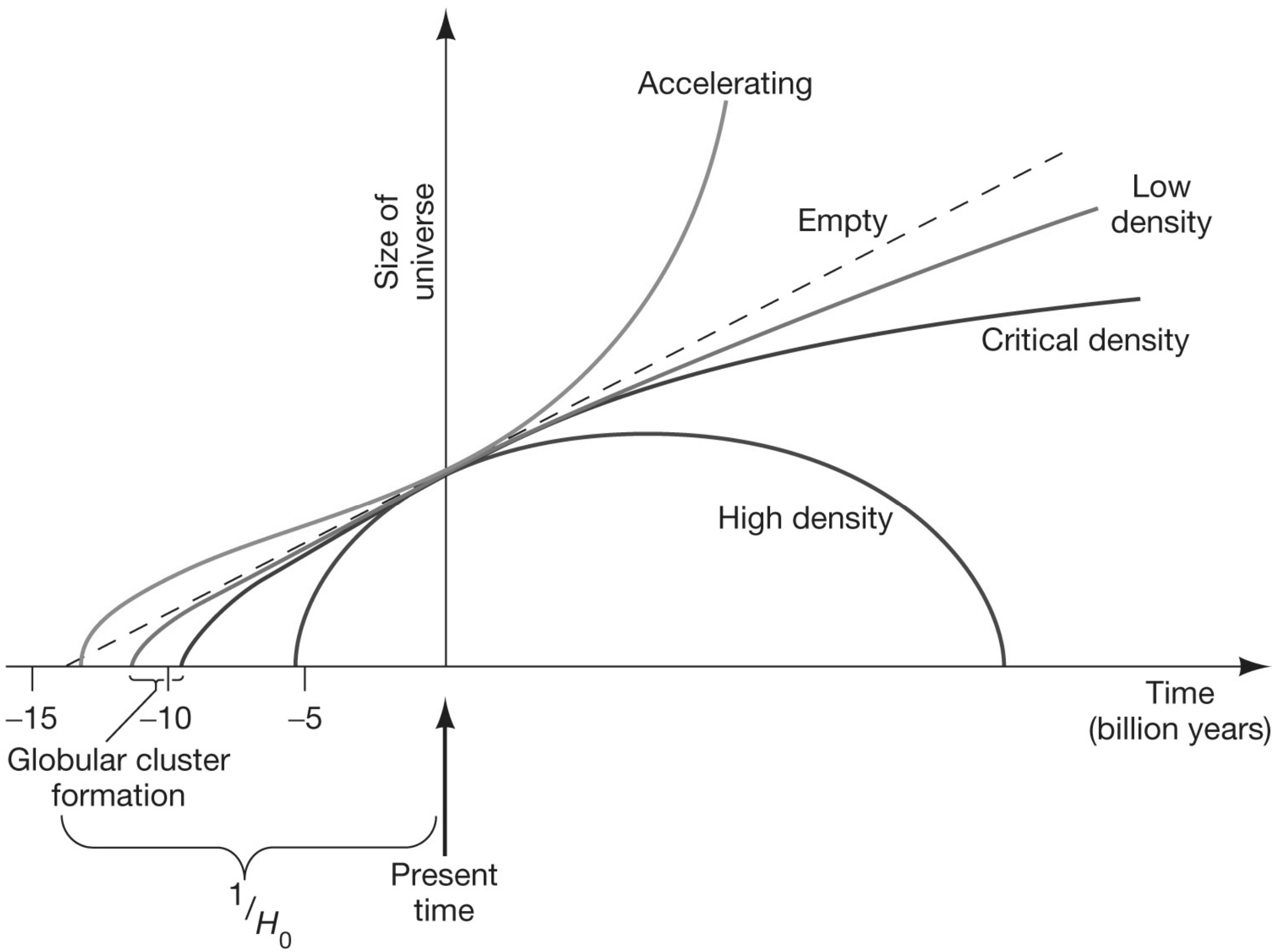
17.4 The Fate of the Cosmos



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

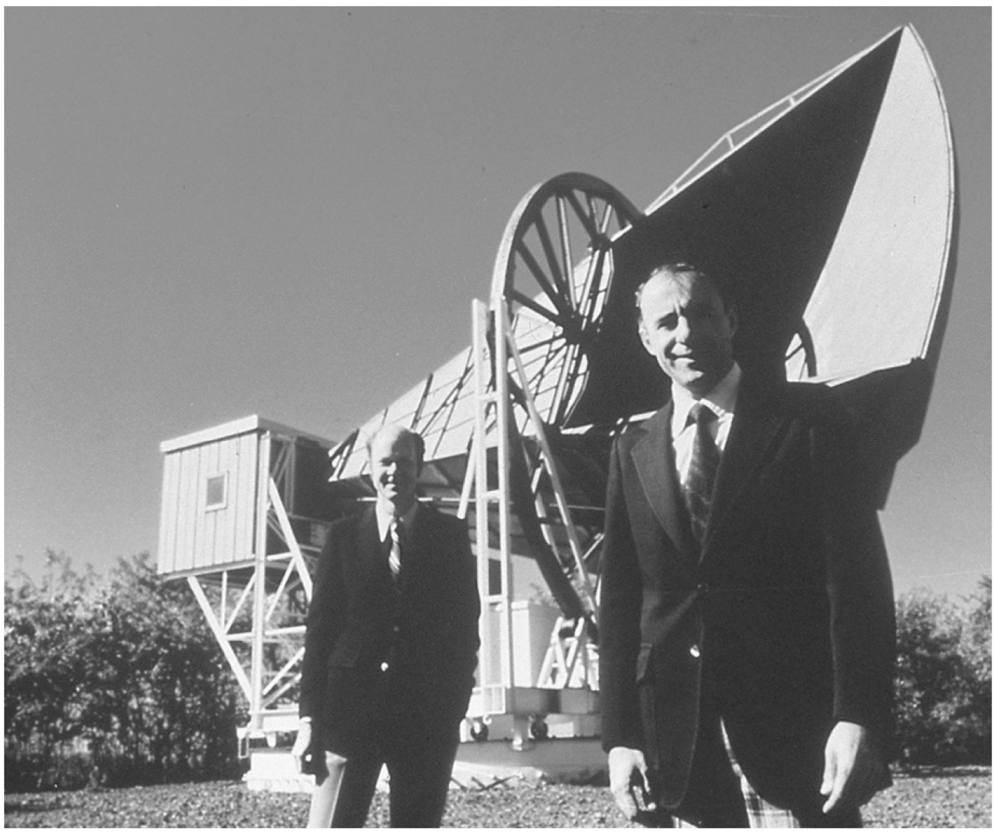
17.4 The Fate of the Cosmos

Possible explanation for the acceleration: vacuum pressure (cosmological constant), also called dark energy.



17.5 The Early Universe

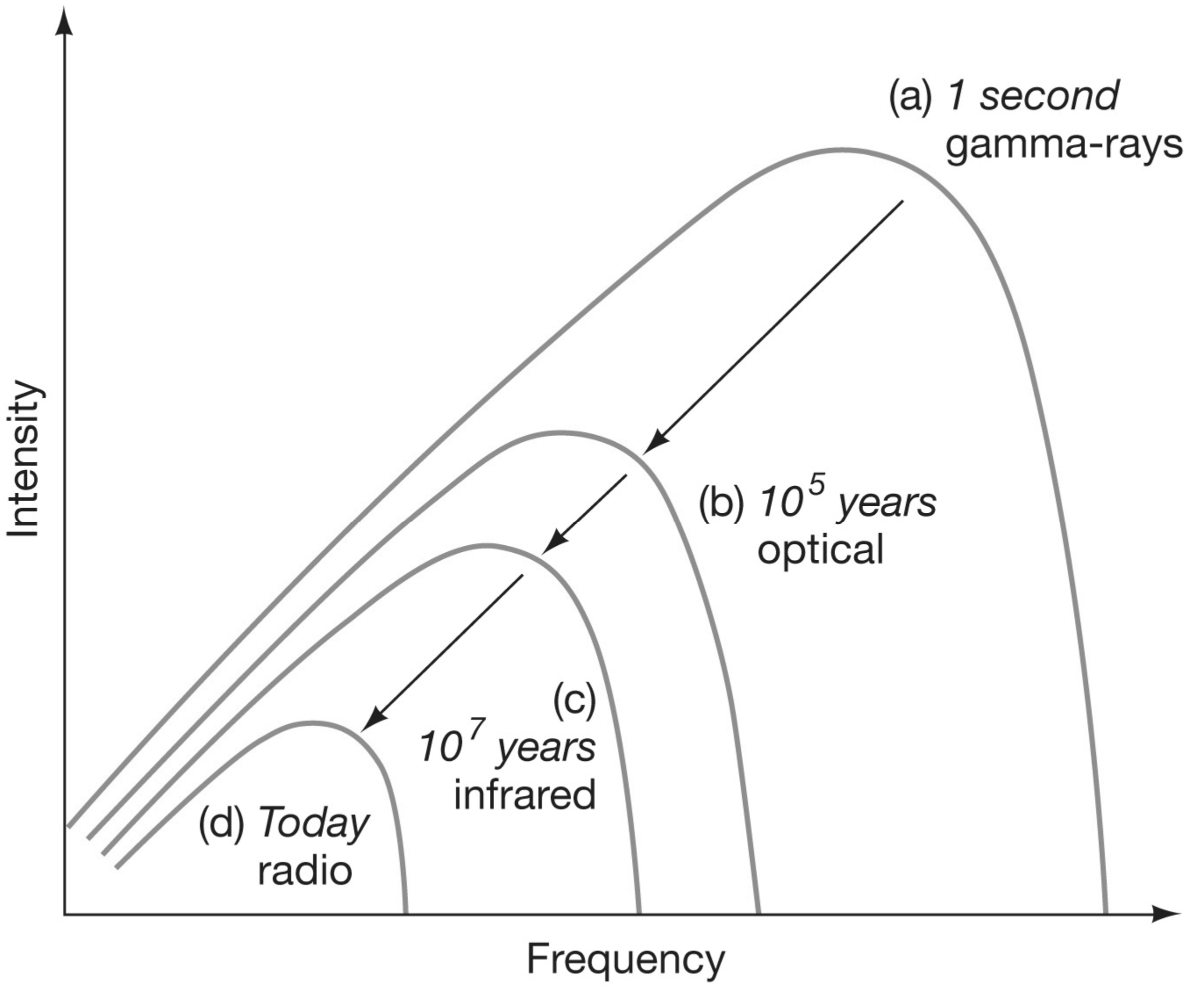
The cosmic microwave background was discovered fortuitously in 1964, as two researchers tried to get rid of the last bit of "noise" in their radio antenna.



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.

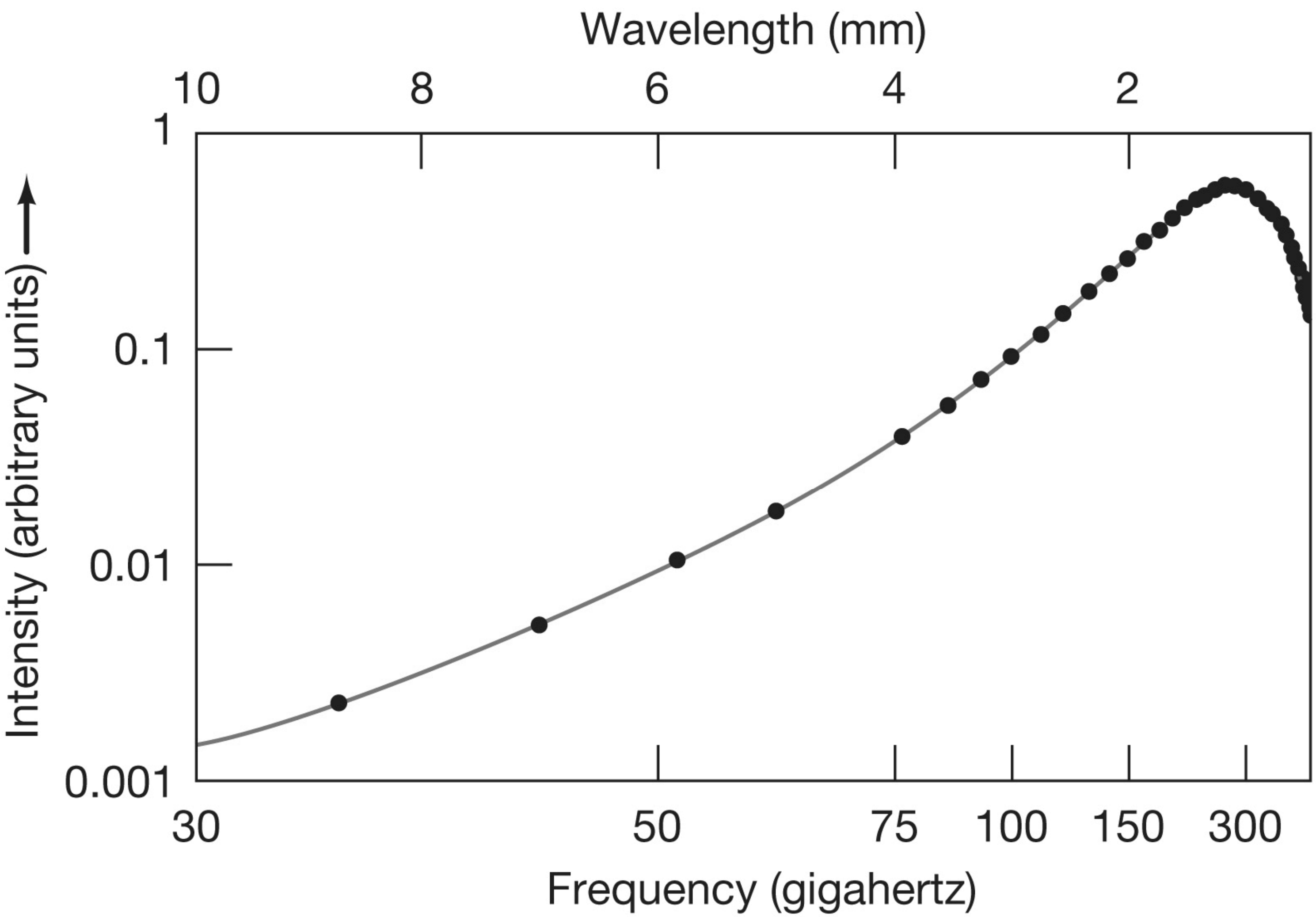
17.5 The Early Universe

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.



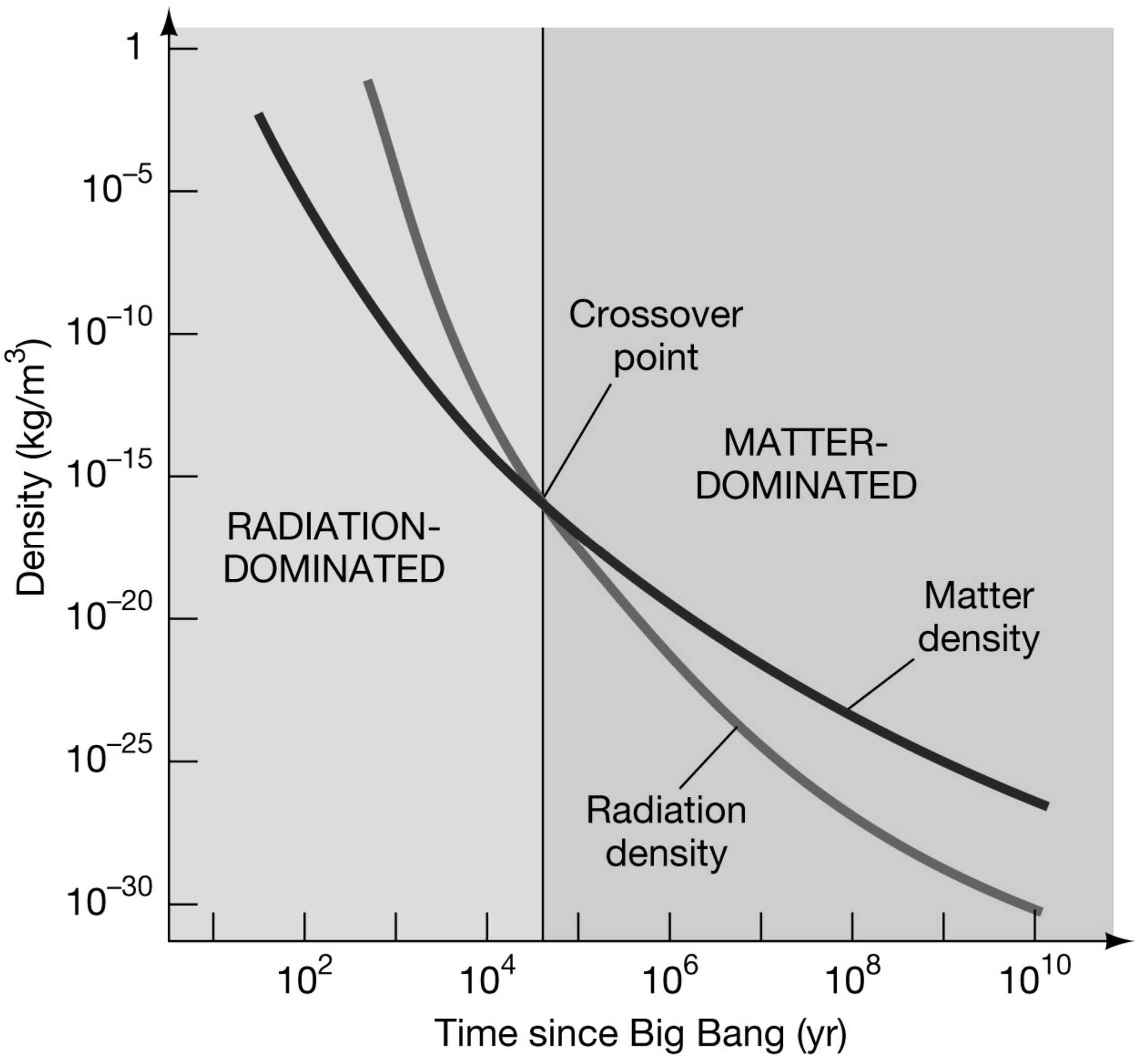
17.5 The Early Universe

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



17.5 The Early Universe

The total energy of the universe consists of both radiation and matter.



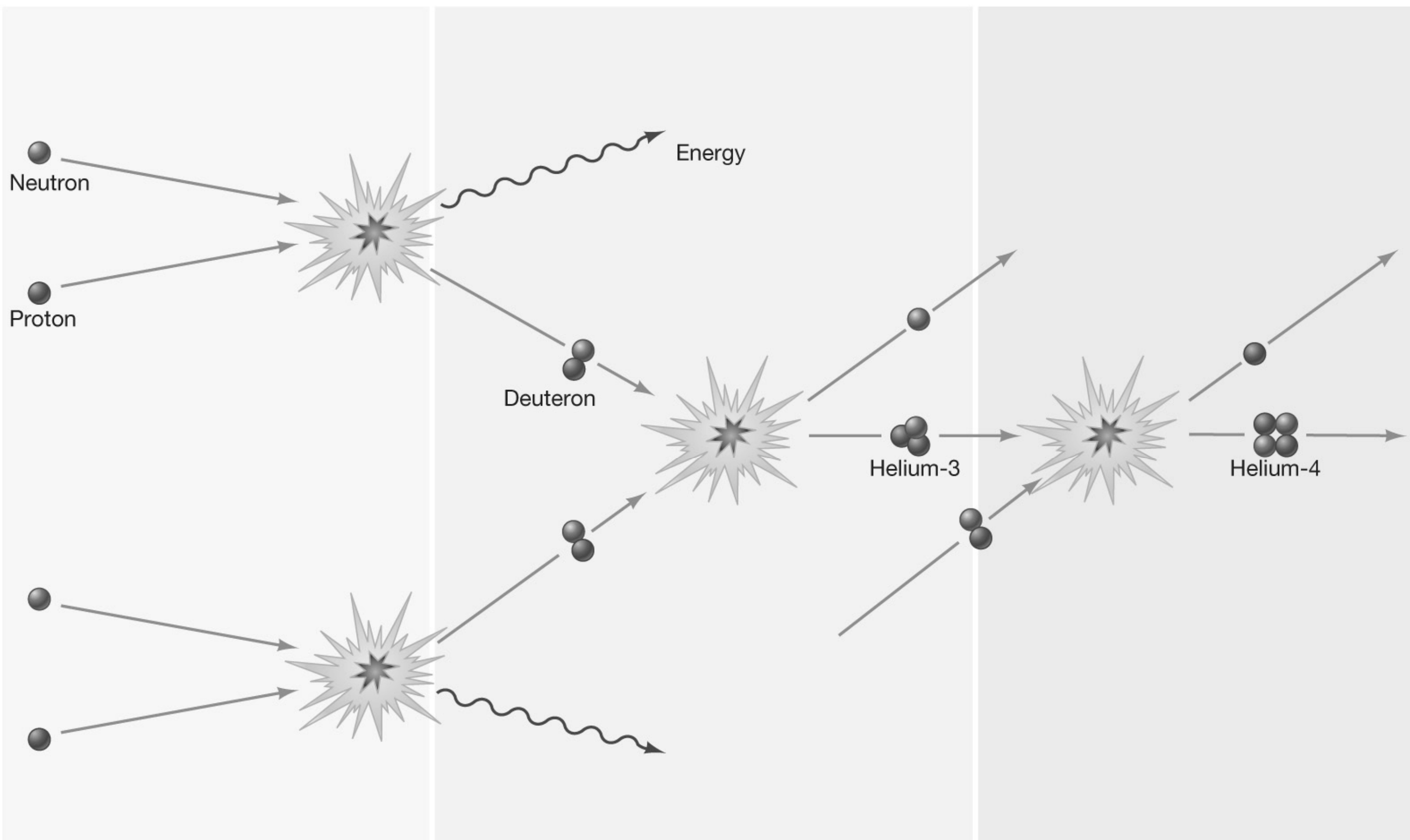
As the Universe cooled, it went from being radiation-dominated to being matter-dominated.

Dark energy becomes more important as the Universe expands.

17.6 The Formation of Nuclei and Atoms

Hydrogen will be the first atomic nucleus to be formed, as it is just a proton and an electron.

Beyond that, helium can form through fusion:

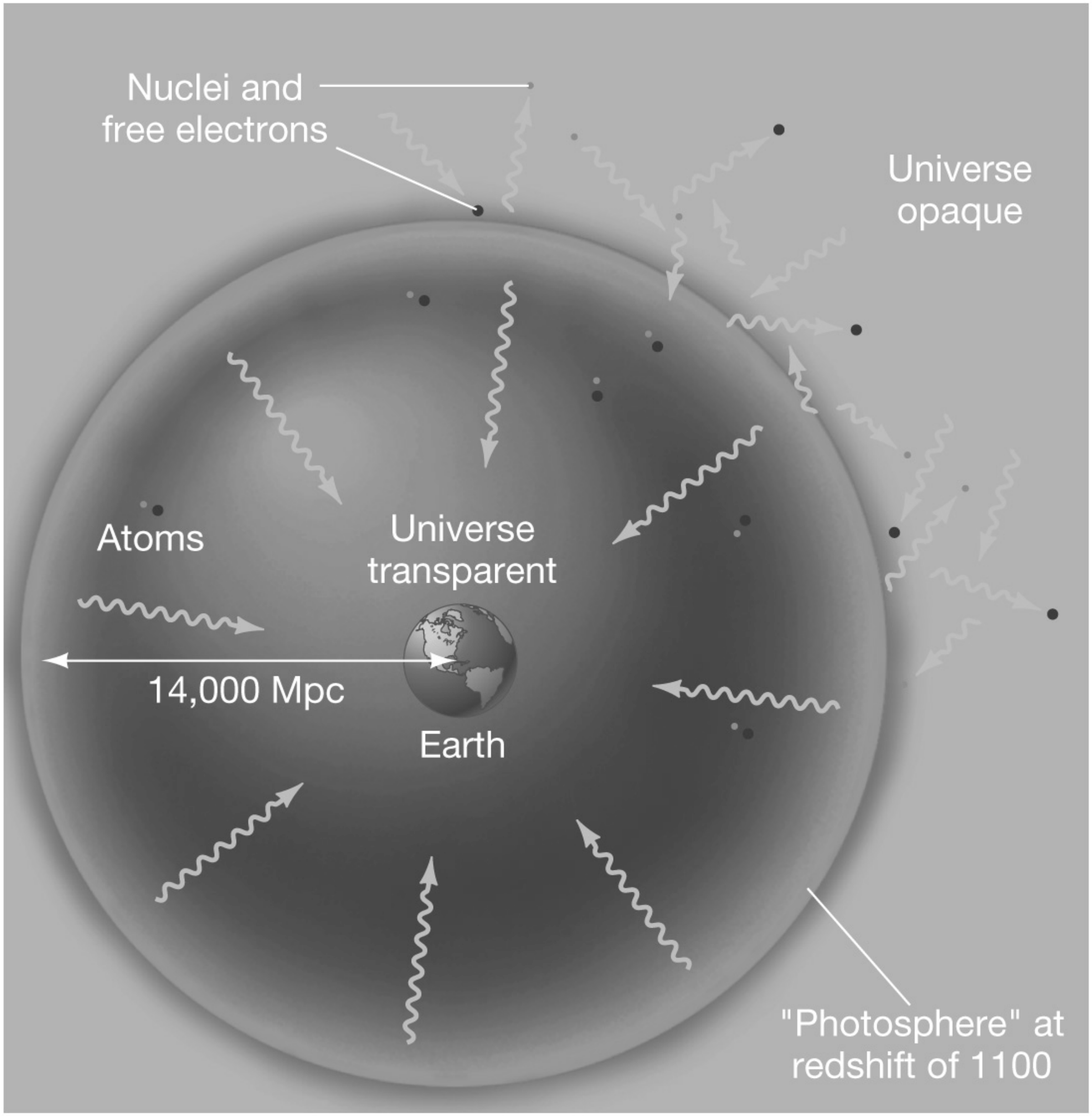


17.6 The Formation of Nuclei and Atoms

Most deuterium fused into helium as soon as it was formed, but some did not.

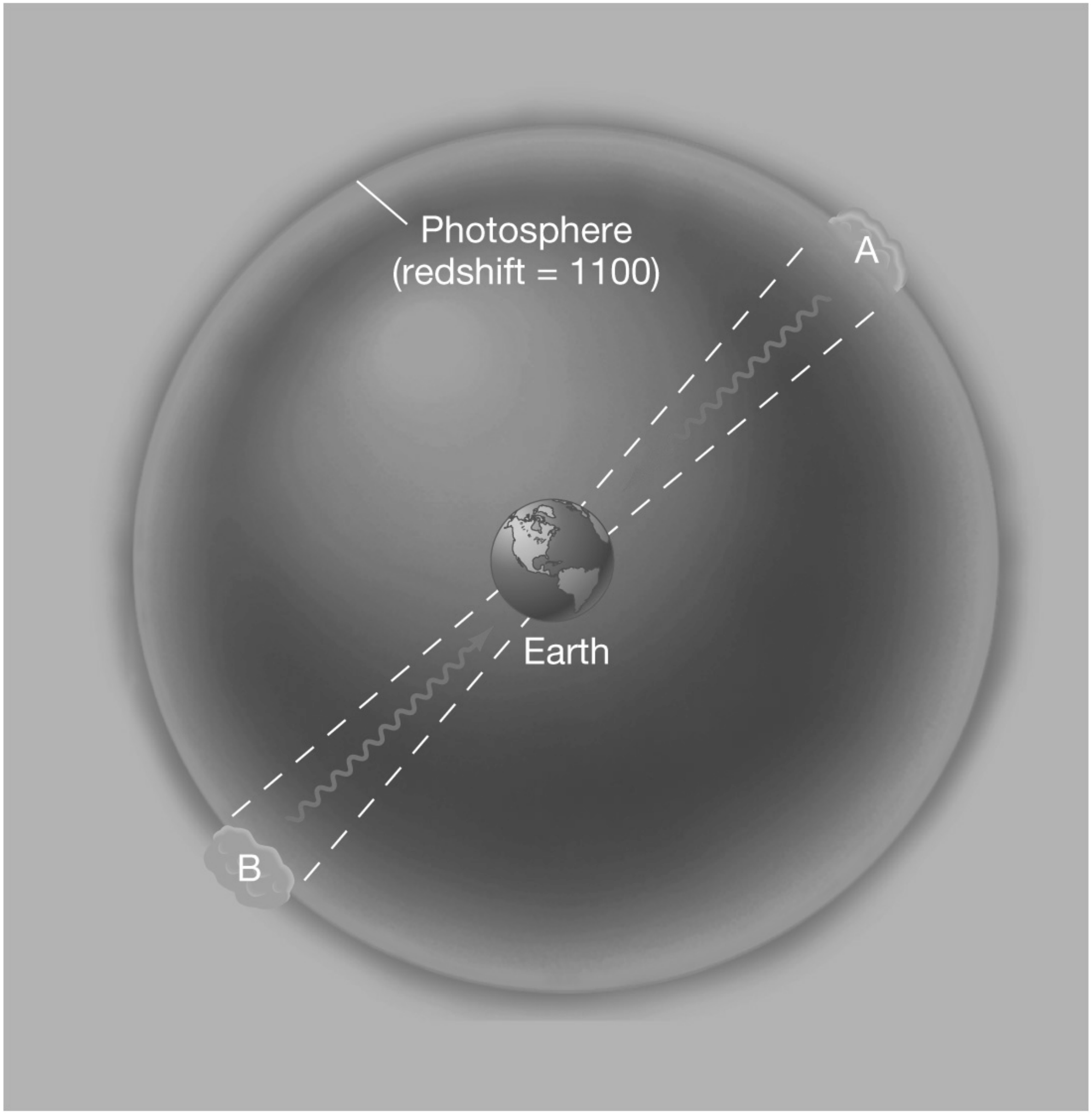
Deuterium is not formed in stars, so any deuterium we see today must be primordial.

17.6 The Formation of Nuclei and Atoms



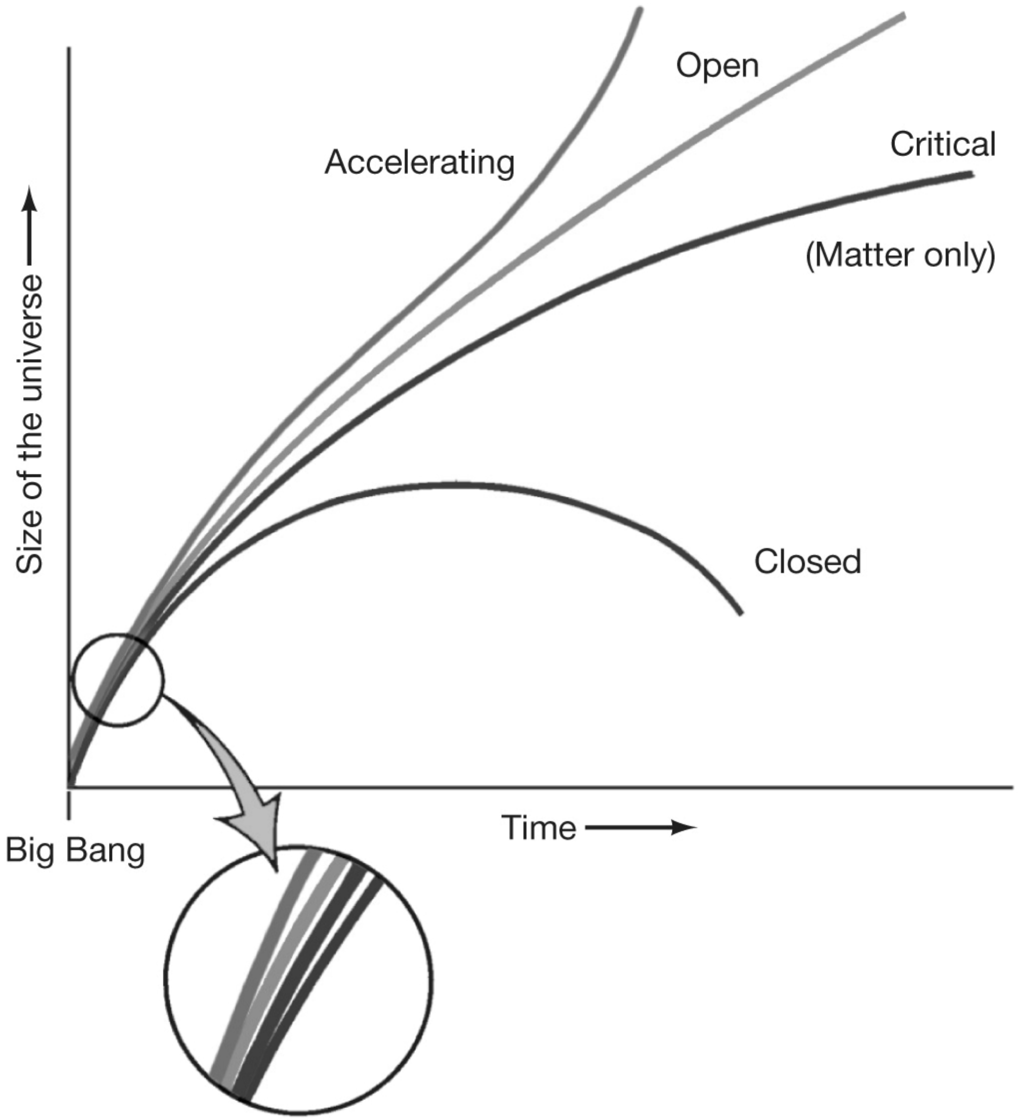
The time during which nuclei and electrons combined to form atoms is referred to as the decoupling epoch. This is when the cosmic background radiation originated.

17.7 Cosmic Inflation



The horizon problem: When observed in diametrically opposite directions from Earth, cosmic background radiation appears the same even though there hasn't been enough time since the Big Bang for them to be in thermal contact.

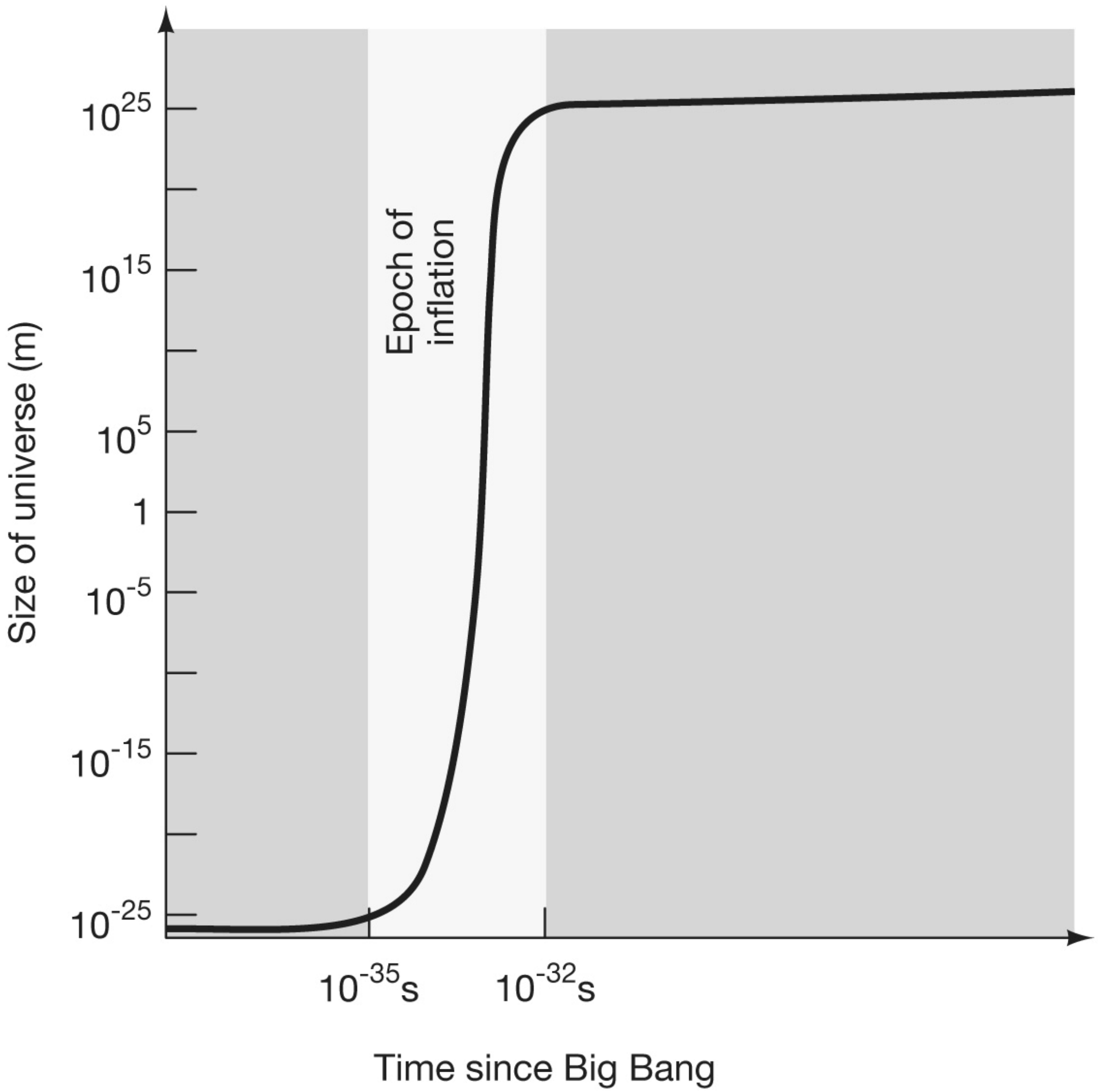
17.7 Cosmic Inflation



The flatness problem: In order for the Universe to have survived this long, its density in the early stages must have differed from the critical density by no more than 1 part in 10^{15}.

17.7 Cosmic Inflation

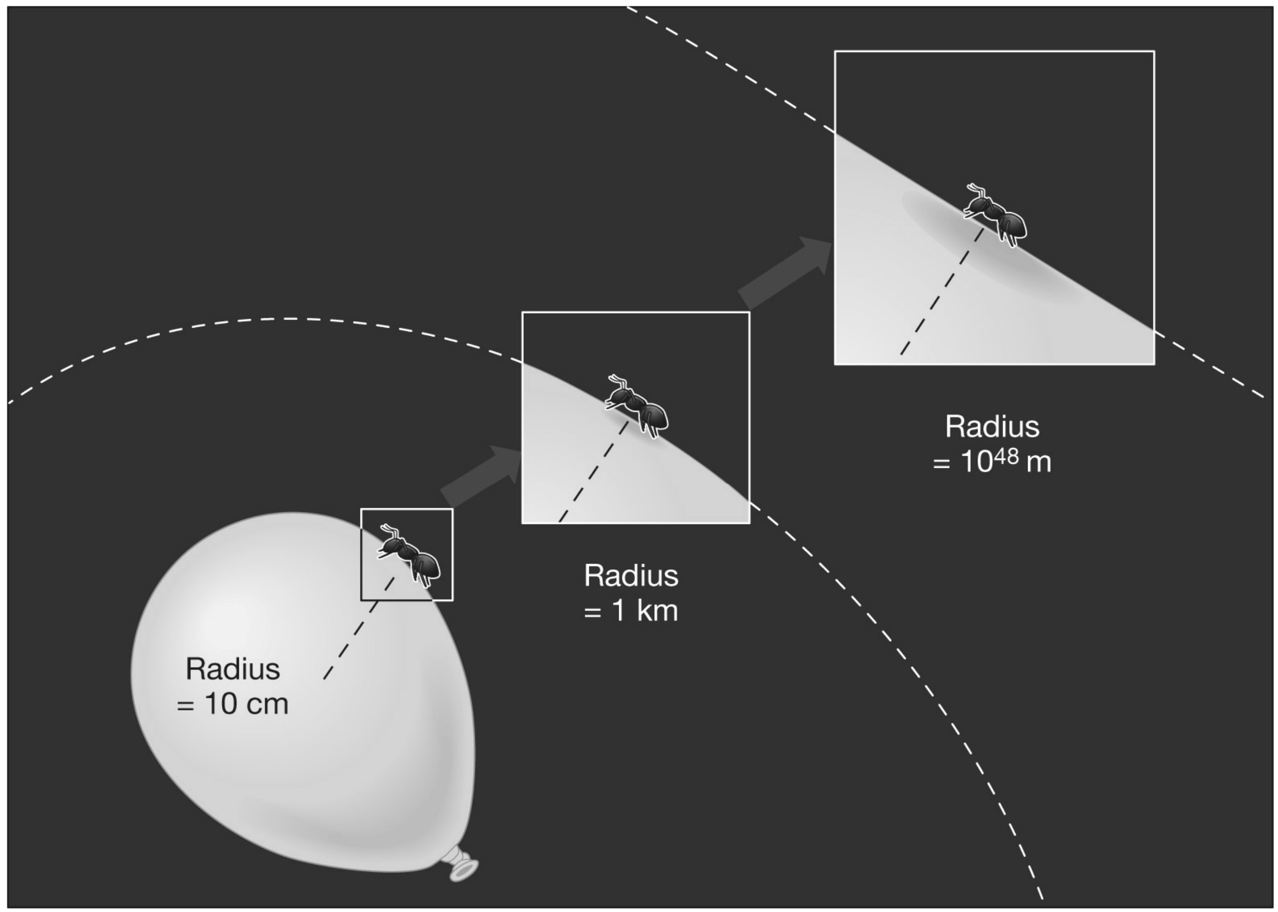
Between 10^{-35} s and 10^{-32} s after the Big Bang, some parts of the Universe may have found themselves in an extreme period of inflation, as shown on the graph.



Between 10^{-35} s and 10^{-32} s, the size of this part of the Universe expanded by a factor of 10^{50}!

17.7 Cosmic Inflation

Inflation would solve both the horizon and the flatness problems. This diagram shows how the flatness problem is solved – after the inflation the need to be very close to the critical density is much more easily met.



17.8 The Formation of Large-Scale Structure in the Universe

Cosmologists realized that galaxies could not have formed just from instabilities in normal matter:

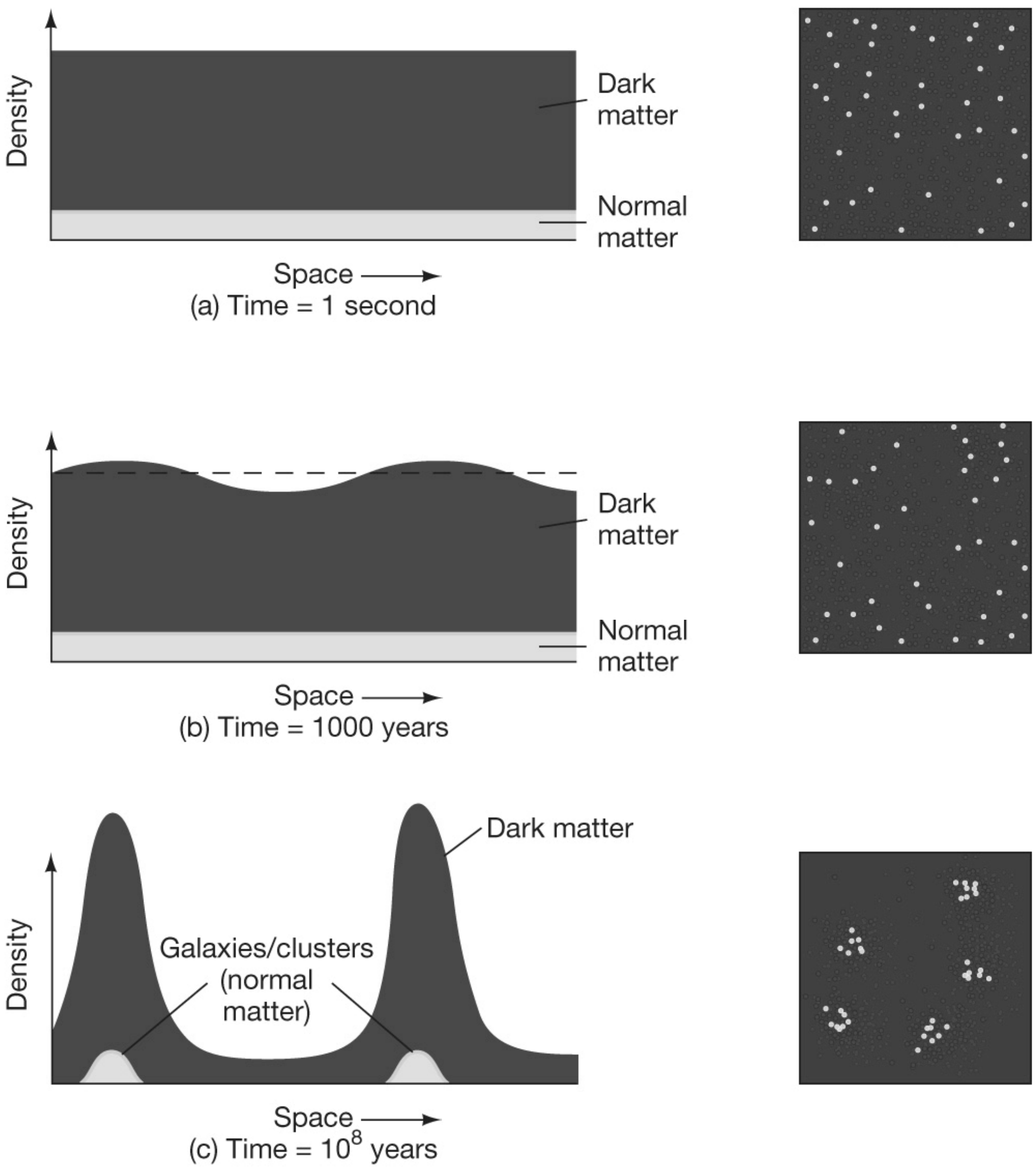
- Before decoupling, background radiation kept clumps from forming
- Variations in the density of matter before decoupling would have led to variations in the cosmic microwave background

17.8 The Formation of Large-Scale Structure in the Universe

- Because of the overall expansion of the universe, any clumps formed by normal matter could only have had 50-100 times the density of their surroundings.

Dark matter, being unaffected by radiation, would have started clumping long before decoupling.

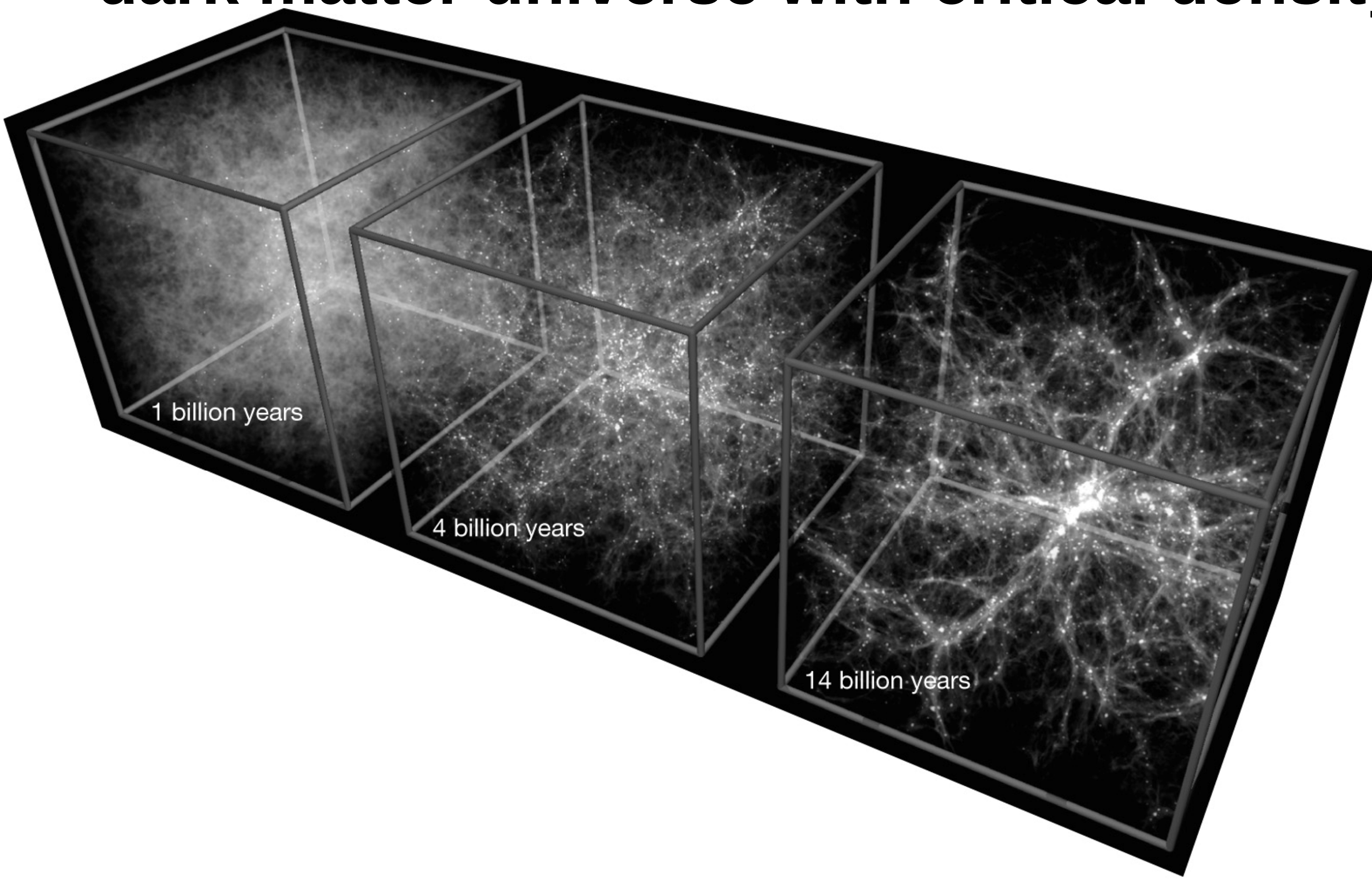
17.8 The Formation of Large-Scale Structure in the Universe



Galaxies could then form around the dark-matter clumps, resulting in the Universe we see.

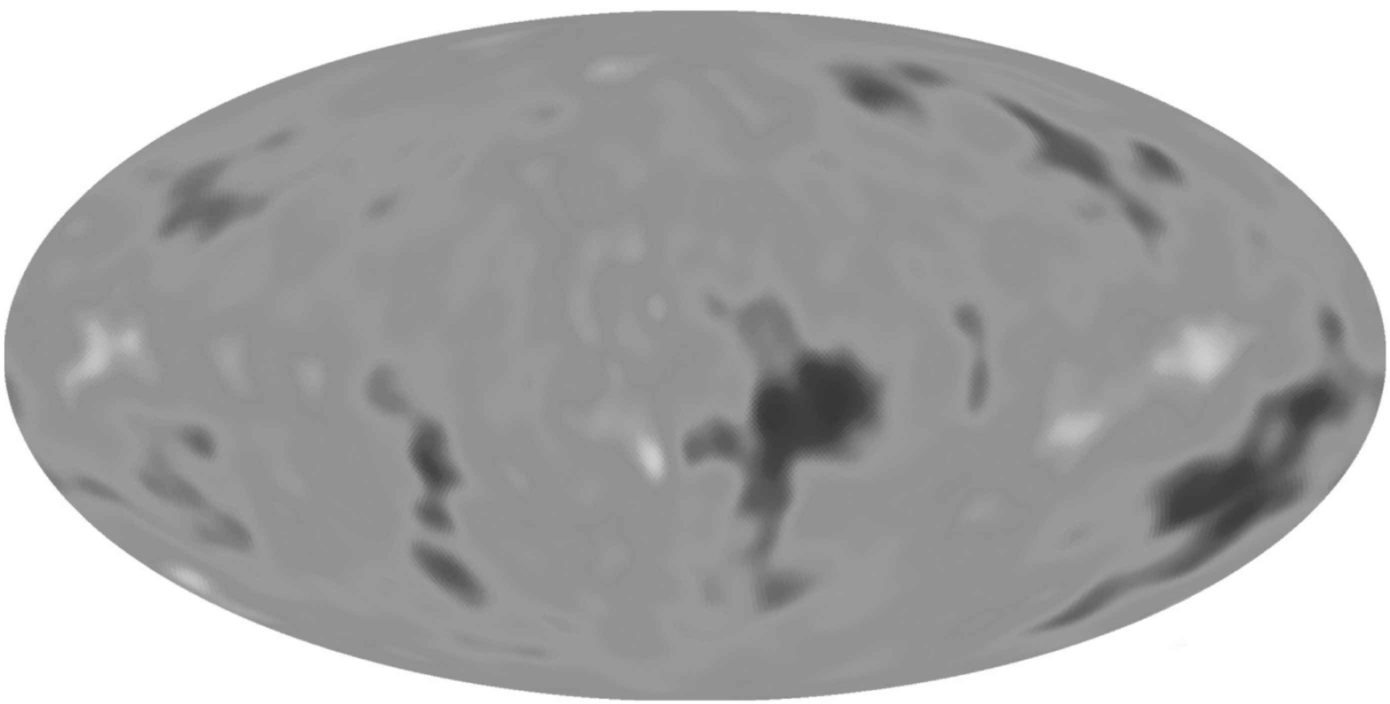
17.8 The Formation of Large-Scale Structure in the Universe

This figure is the result of simulations of a cold dark matter universe with critical density.

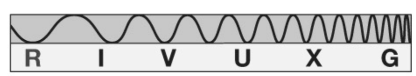


17.8 The Formation of Large-Scale Structure in the Universe

Although dark matter does not interact directly with radiation, it will interact through the gravitational force, leading to tiny “ripples” in the cosmic background radiation.

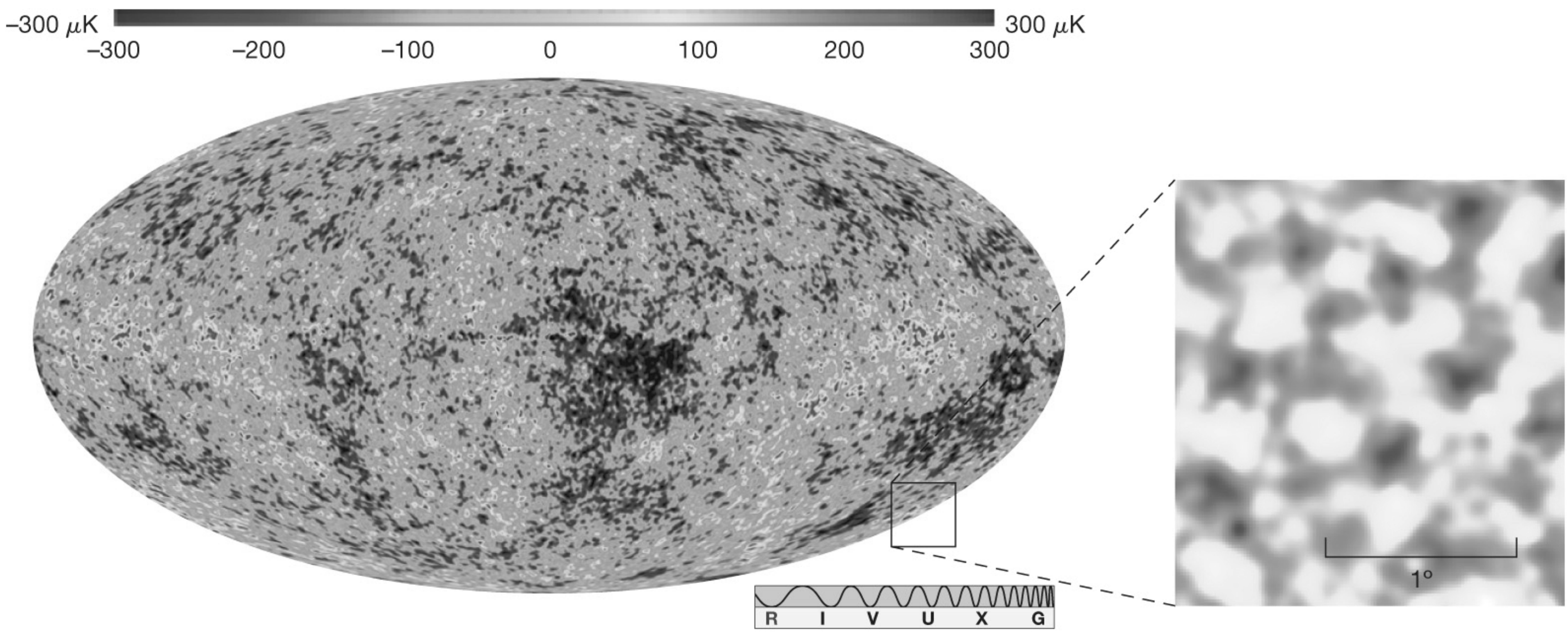


These ripples have now been observed.



17.8 The Formation of Large-Scale Structure in the Universe

This is a much higher-precision map of the cosmic background radiation.



Summary of Chapter 17

- 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 17

- **A high-density universe has a closed geometry; a critical universe is flat; and a low-density universe is open.**
- **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**

Summary of Chapter 17

- At present the Universe is matter-dominated; at its creation it was radiation-dominated
- When the temperature became low enough for atoms to form, radiation and matter decoupled
- The cosmic background radiation we see dates from that time
- Horizon and flatness problems cam be solved by inflation

Summary of Chapter 17

- **The density of the Universe appears to be the critical density; 2/3 of the density comes from dark energy, and dark matter makes up most of the rest**
- **Structure of Universe today could not have come from fluctuations in ordinary matter**
- **Fluctuations in dark matter can account for what we see now**