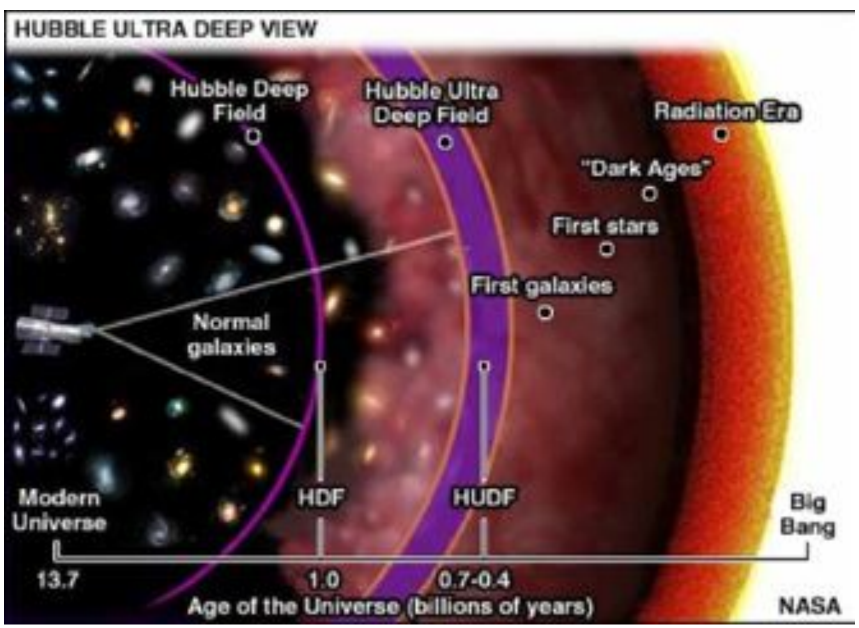
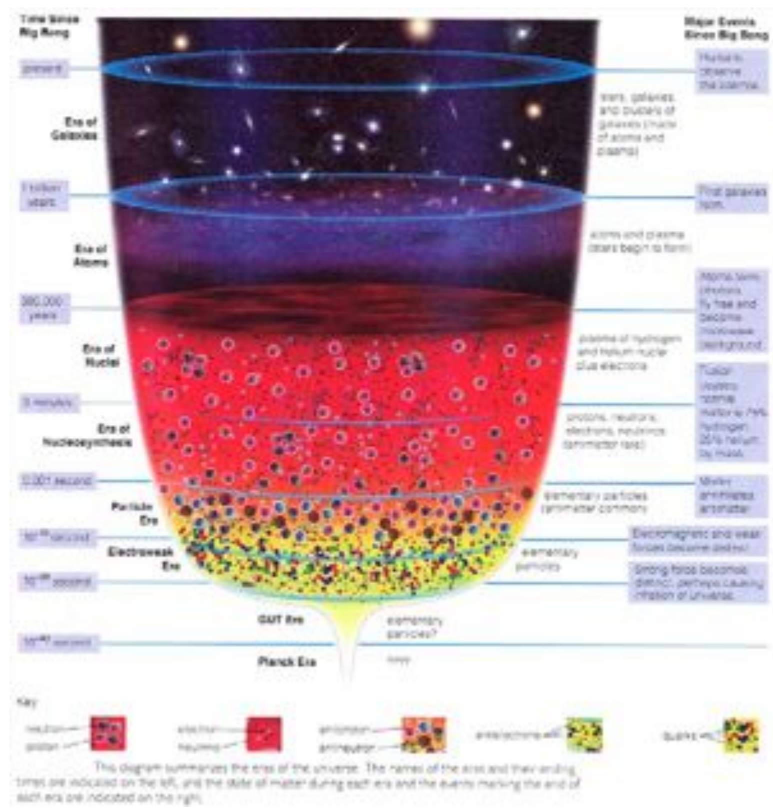
Chapter 26: Cosmology

"Cosmology" means **the study of the structure and evolution of the entire universe *as a whole***. First of all, we need to know whether the universe has changed with time, or if it has somehow always been similar to the way it is now, littered with stars, galaxies, and larger structures. We will see immediately that this is *not* the case: **The universe has most definitely evolved with time.** So our next task will be to understand what it was like in the distant past. By the end of chapters 26 and 27, you should be able to roughly understand the diagram on the left, and at least have an idea what the "evolution of the universe" diagram on the right is trying to illustrate.

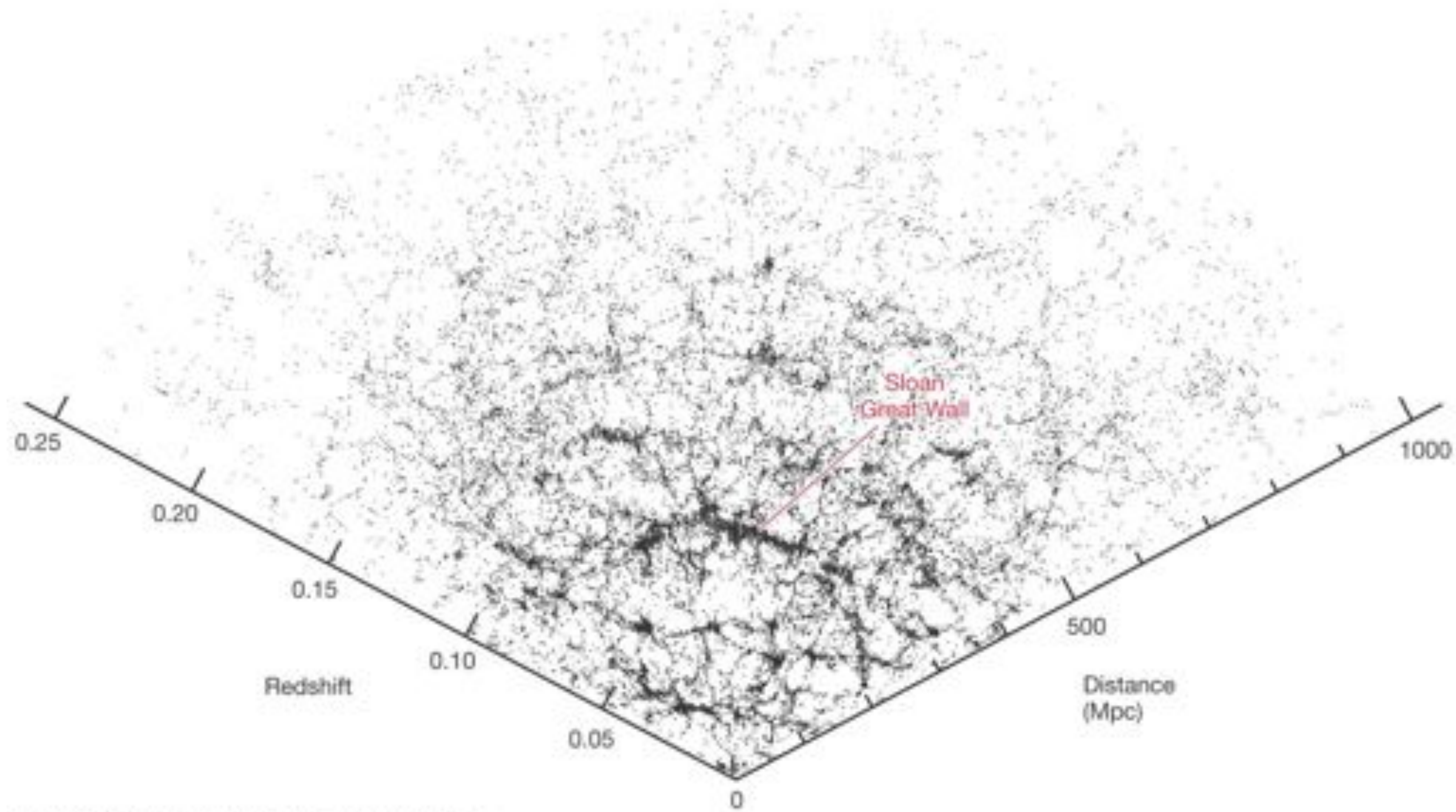




Units of Chapter 26

26.1 The Universe on the Largest Scales

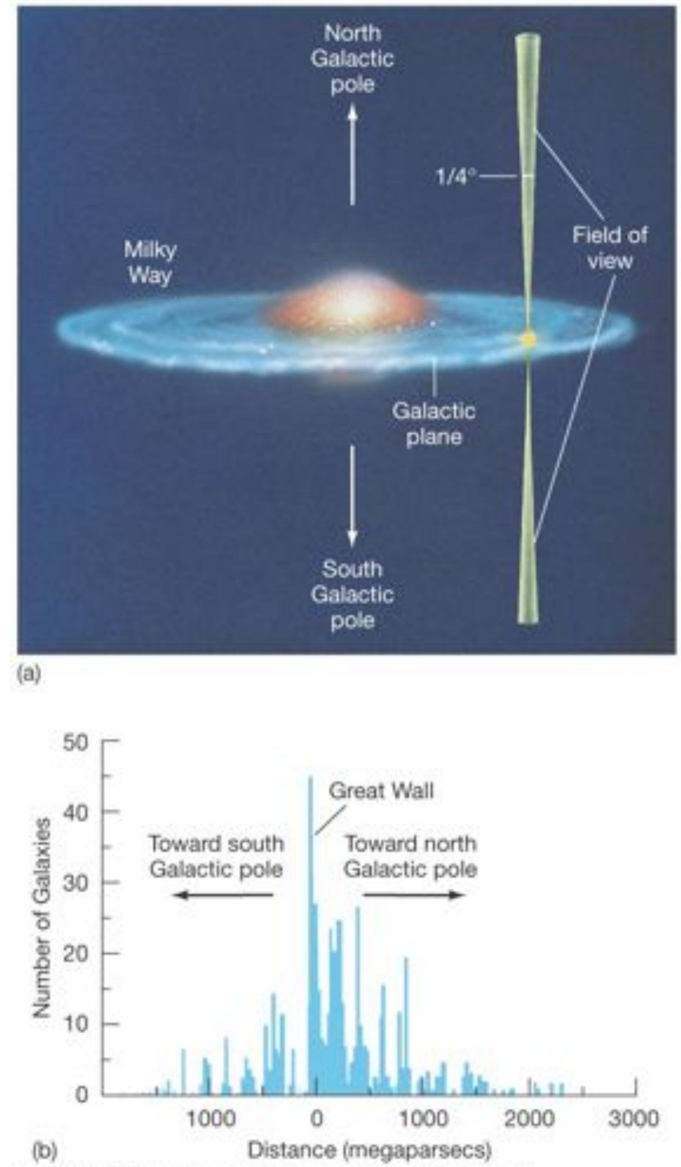
This galaxy map shows the largest structure known in the Universe, the Sloan Great Wall. No structure larger than 300 Mpc is seen. (We'll see why this is significant.)



26.1 The Universe on the Largest Scales

This **pencil-beam survey** is another way to measure **large-scale structure**. Restricting the observations to a narrow range of directions allows you to see fainter galaxies in that direction. Again, there is structure at about 200–300 Mpc, but nothing larger.

But we can observe the universe out to at least 5000 Mpc, so we conclude that there are no structures with sizes comparable to that of the observable universe. This is a basic assumption of all theories of cosmology, a simplification that is part of what is called the "cosmological principle."



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. “Homogeneous” doesn’t mean “smooth” or “featureless,” but that local regions look about the same anywhere in the universe.

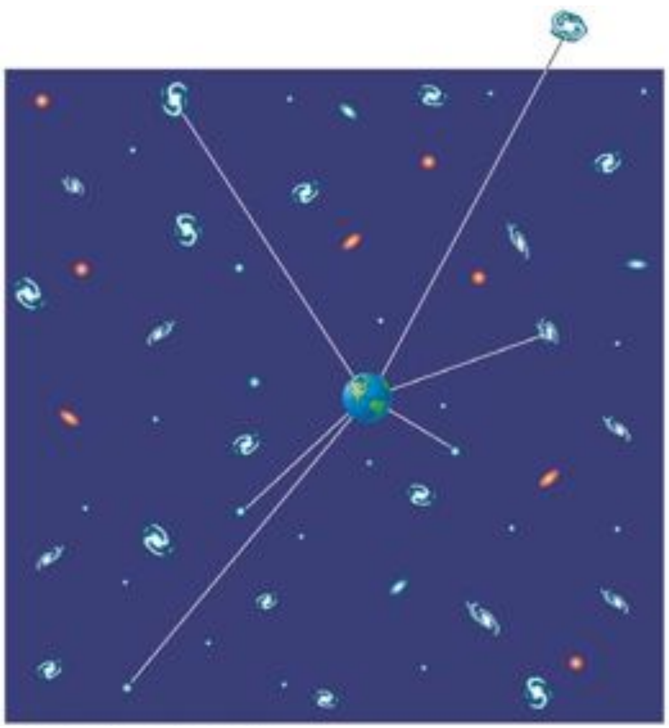
The Universe also appears to be **isotropic**—the same in all directions. If this weren’t true, and there was some preferred direction in the universe, we would need a much stranger model for how spacetime evolves!

The assumptions of **isotropy** and **homogeneity** together are called the **cosmological principle.** It is a simplifying assumption that allows theorists to neglect potential aspects of the universe that would introduce extreme uncertainty, for example, if the universe is different in different places, why and where? If different in different directions, what could be special about one direction over others? Instead, the cosmological principle allows us to treat the universe as one “object” that evolves as a whole. That “object” is actually “*spacetime*.”

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.

This is often worded: *Why is the night sky dark?* If infinite, we should see a stellar surface in any and every direction. We'll discuss a useful analogy concerning a forest in class; also see Fig. 26.3.



Since we see that the night sky *is* dark, and
We think we have evidence that the universe is homogeneous and isotropic, then either the universe is finite in extent,
or evolves with time, or both.

We'll discuss two lines of evidence: the appearance of very distant, and hence younger, galaxies, and the Hubble relation, which we have encountered before, but here will take us into the "big bang" model.

Discovery 26-1:
A Stunning View of Deep Space

This image, the Hubble Ultra Deep Field, is the result of a total exposure time of 1 million seconds, allowing very faint objects to be seen. It contains about 10,000 galaxies, and provided one of the "deepest" views of the universe ever obtained. This was the first time that we really were seeing "back in time" a significant fraction of the "age of the universe."

The galaxies that are the most distant in this image appear significantly different in Form from the types of galaxies in the nearby universe: Smaller, raggedy, bluer, … ***This shows that the universe has evolved with time*** --otherwise galaxies would look similar no matter how far back in time (I.e. how far away) you could see them.

But there is another, much more revealing observation showing that the universe has evolved, in a way that is more significant than just a change in time: The Hubble relation.

26.2 The Expanding Universe

Returning to the question: Why is it dark at night?

We think the universe is homogeneous and isotropic—it must *not* be infinite or *not* be unchanging, or both. We already saw from distant galaxies strong evidence for the latter. But long before we had telescopes large enough to perform observations of distant galaxies, the answer was at hand:

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

$$\textbf{recession velocity} = H_0 \textbf{ x distance}$$

Since it is difficult to interpret this Hubble relation as anything other than an expanding universe, it provides additional evidence that the universe is different today, compared to its state some time in the past.

26.2 The Expanding Universe

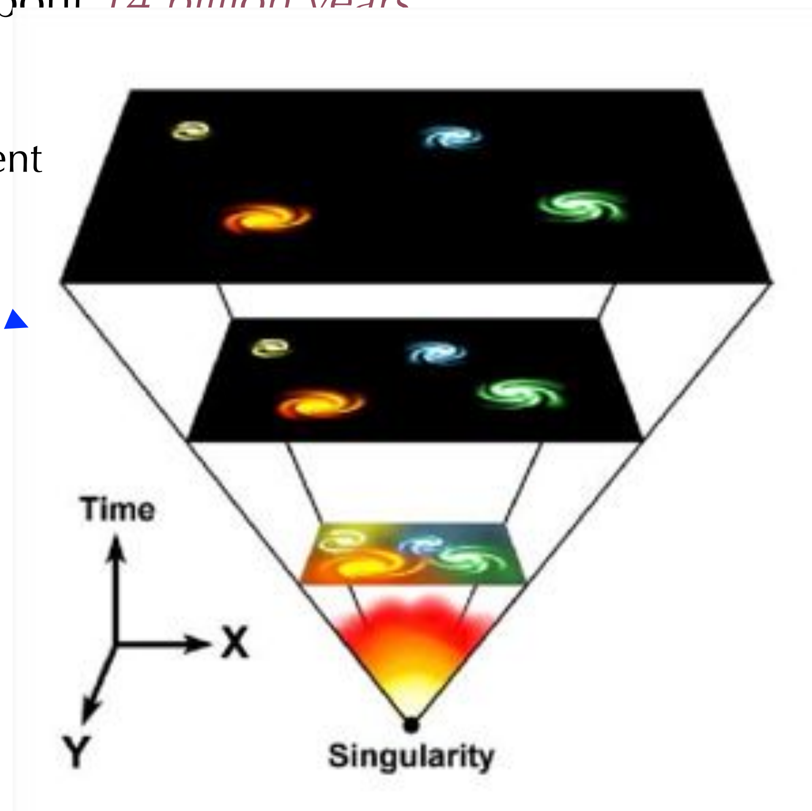
If galaxies are moving apart today, they must have been closer together in the past. So, how long ago were they all in the same place? (Infinite density, the "big bang")

$$\text{time} = \text{distance} / \text{velocity} = \text{distance} / (H_0 \text{ x distance}) = 1/H_0$$

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

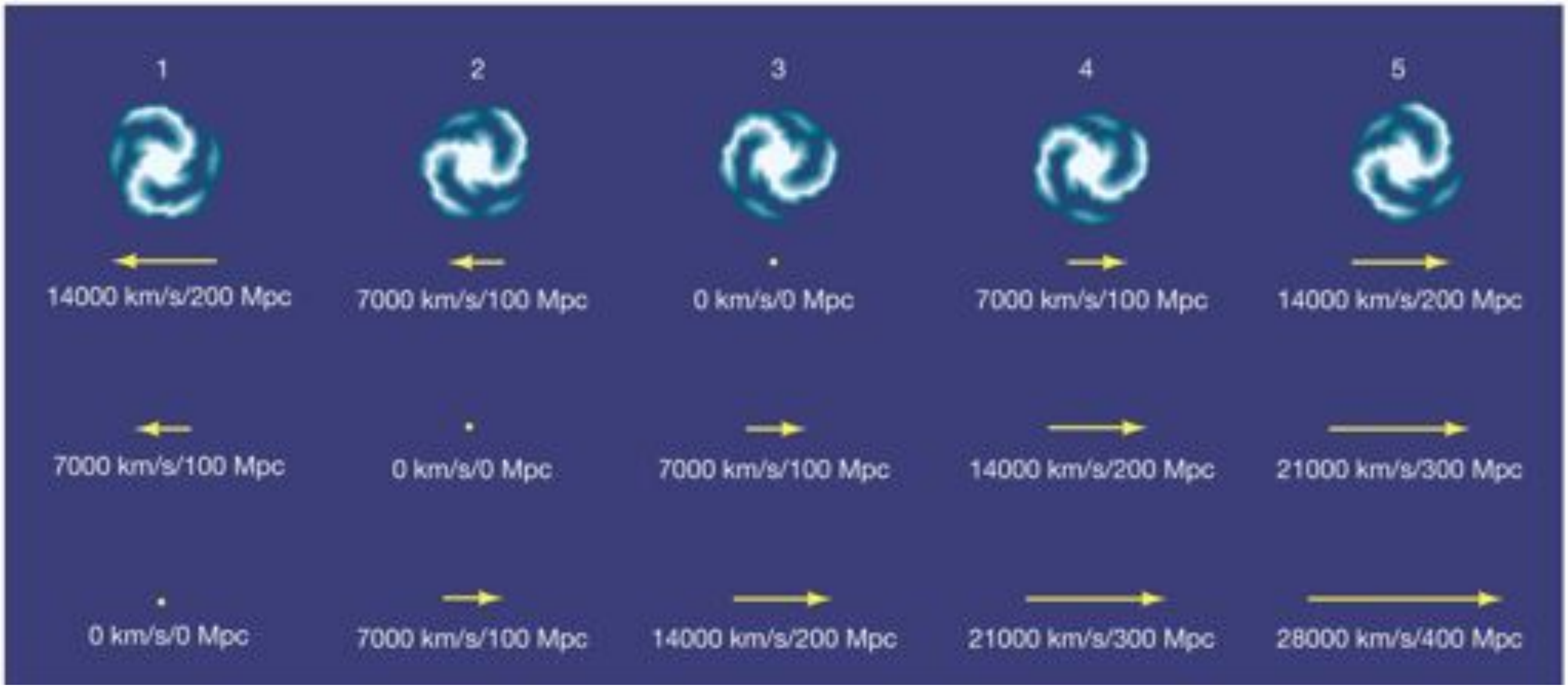
History of the universe in a space-time diagram. Present is at top, big bang ("singularity") is at bottom.

Correct interpretation of the galaxy redshifts: It's not that galaxies are moving away from each other, but that *space is expanding*. This "stretches" the wavelengths of all the light emitted. Light from distant objects was emitted long ago, and so has been stretched (redshifted) more. (See Fig. 26.6)



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 backwards in time, all galaxies are seen to originate from a single point in an event called the **Big Bang**.

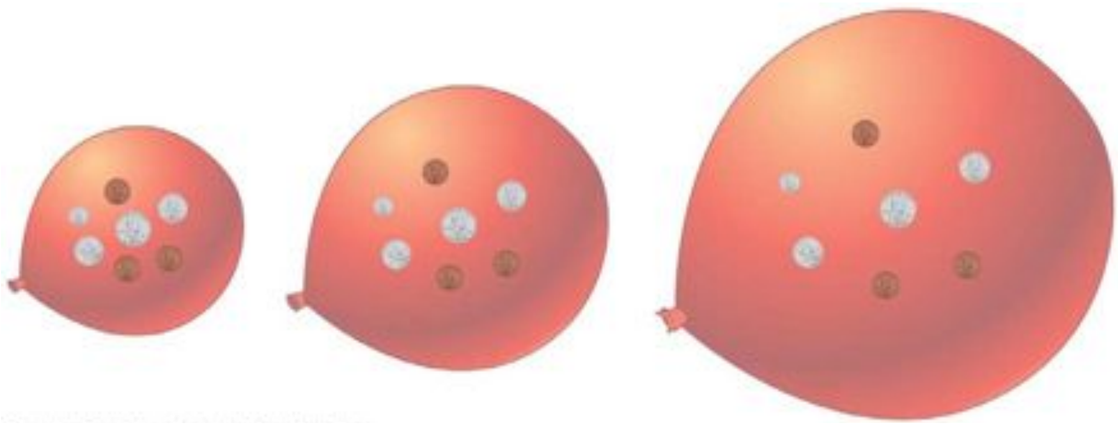
So, where was the **Big Bang**?

It was **everywhere**.

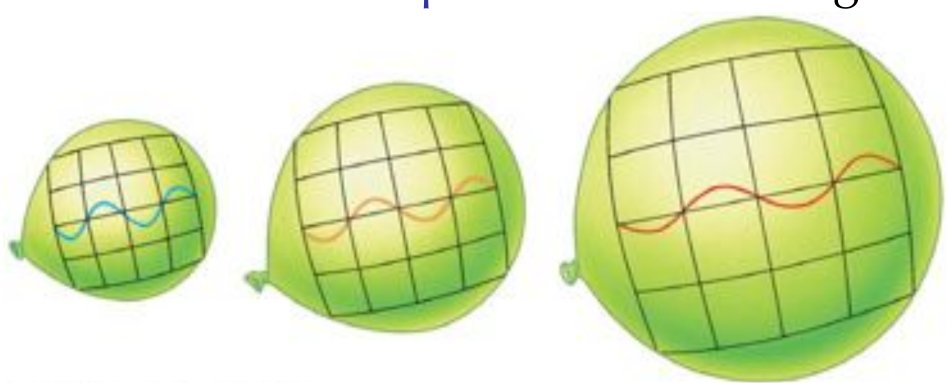
No matter where in the Universe we are, we will measure the same relation between recessional velocity and distance with the same Hubble constant.

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 (see explanation in textbook if you don't understand this).



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!

One question that can be discussed without using general relativity concerns the future of the universe:

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

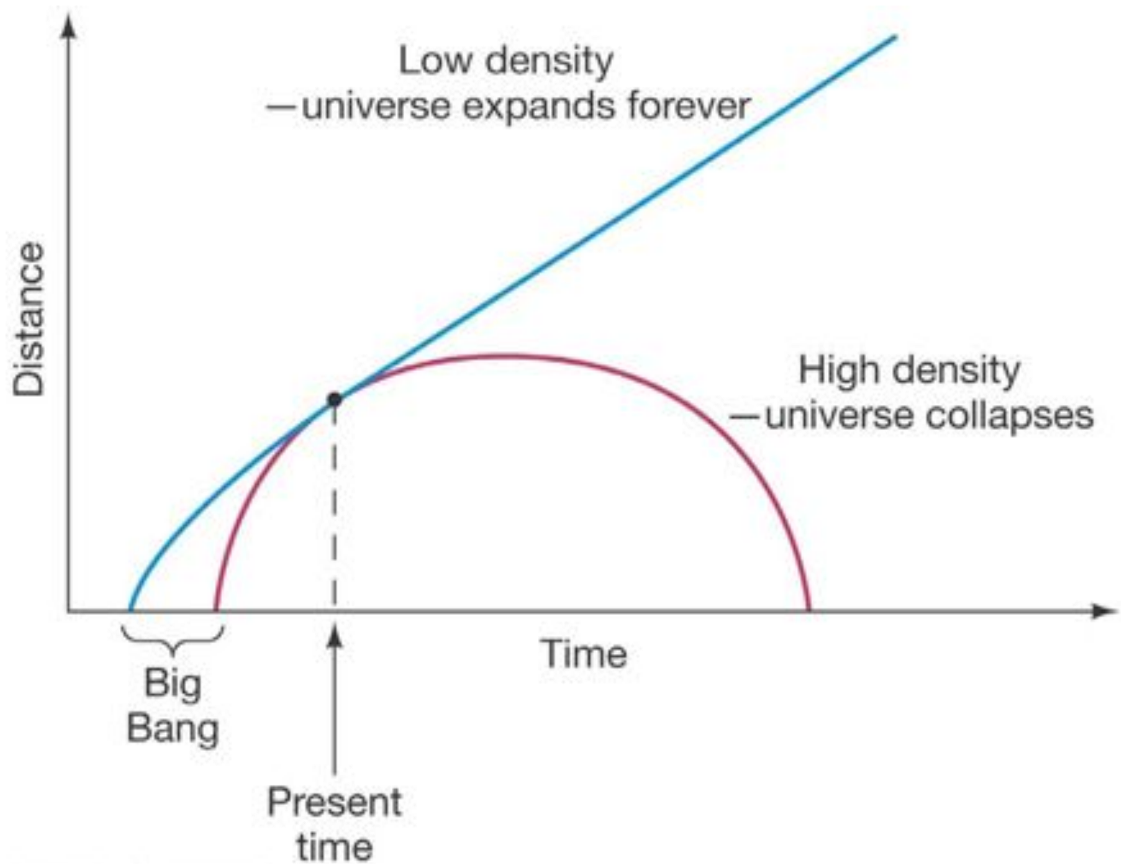
1. It could keep expanding forever.

2. It could collapse.

Assuming that the only relevant force is gravity, which way the Universe goes depends on its density, the average amount of mass per unit volume. Greater density, more gravity, expansion of universe becomes more difficult.

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:

$$9 \text{ x } 10^{27} \text{ kg/m}^3$$

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

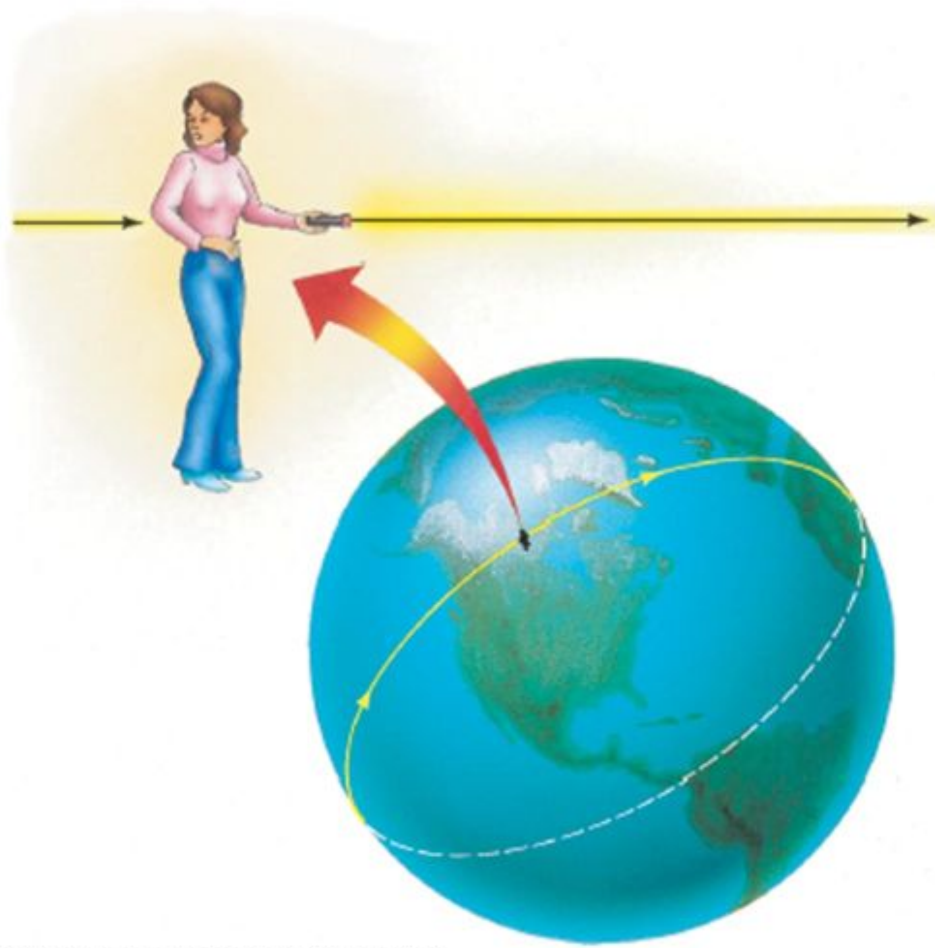
These three possibilities can be described by comparing the **actual density** of the Universe to the **critical density**.

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

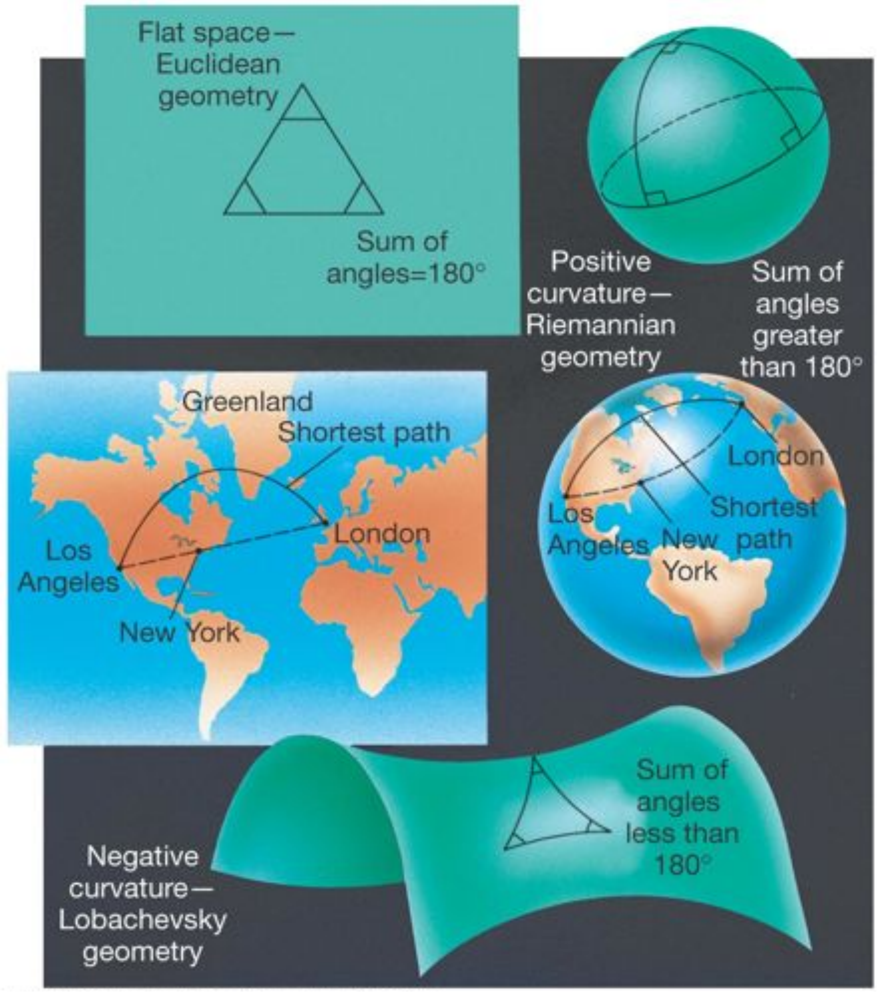
26.4 The Geometry of Space



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. How to estimate this crucial number?

Measurements of luminous matter suggest that the actual density is only a few percent of the critical density. The amount of *deuterium* produced early in the universe is another way to measure the average density, and it also gives a result that the "baryonic matter" (same as the kind of matter we can see) can only be a few percent of the critical density.

But, we know there must be large amounts of dark matter. Could ths change the result from an open to a closed (cyclical) universe?

26.5 Will the Universe Expand Forever?

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.

So, until recently, it was believed that the universe is “open” and will expand forever. Unfortunately, this was inconsistent with the theory of “inflation,” which solves many important problems, but requires that the density is *exactly* the critical density. One of the most exciting (to astronomers) results of the past decade was the evidence that there is still another kind of “something” in the universe, but it is not only dark, but it isn’t even matter. We don’t know what it is, except that it is an energy, so it is called “dark energy”.

26.5 Will the Universe Expand Forever?

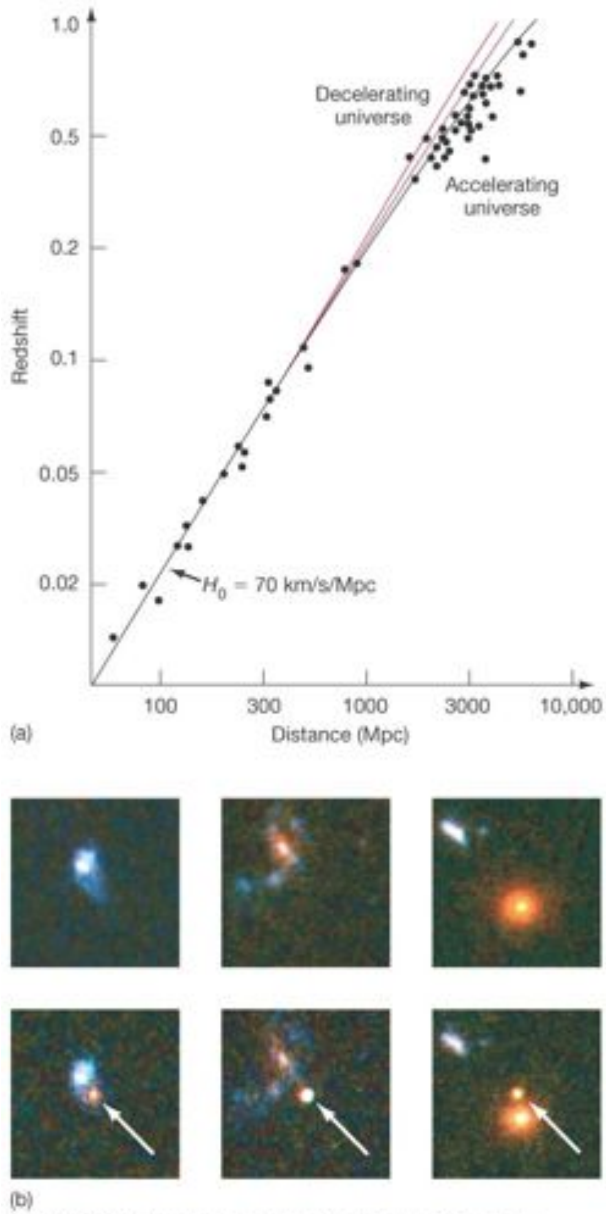
Now we turn to the evidence for this mysterious component of the universe, how it was discovered, and why it implies that the *actual* mass density of the universe is very close to the *critical* density. Yet the universe will probably expand forever, for reasons to be seen shortly. Not only that, it should expand faster and faster!

This is all due to "**DARK ENERGY**."

Type I supernovae can be used to measure the recession speeds 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.

26.5 Will the Universe Expand Forever?

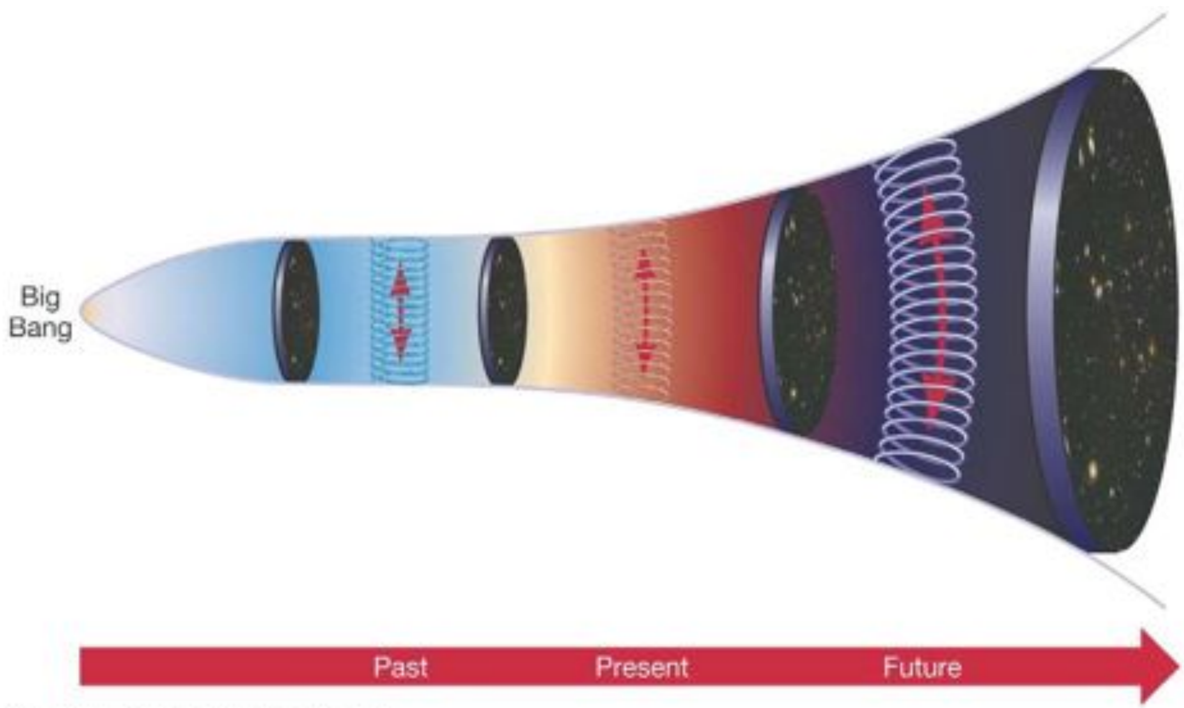


However, when we look at the data, we see that they correspond not to a **decelerating** universe, but to an accelerating one.

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. So even though space is *flat,* and the density is just about the value needed for gravity to balance the universal expansion, the expansion is still accelerating, a total surprise when it was first discovered several years ago.



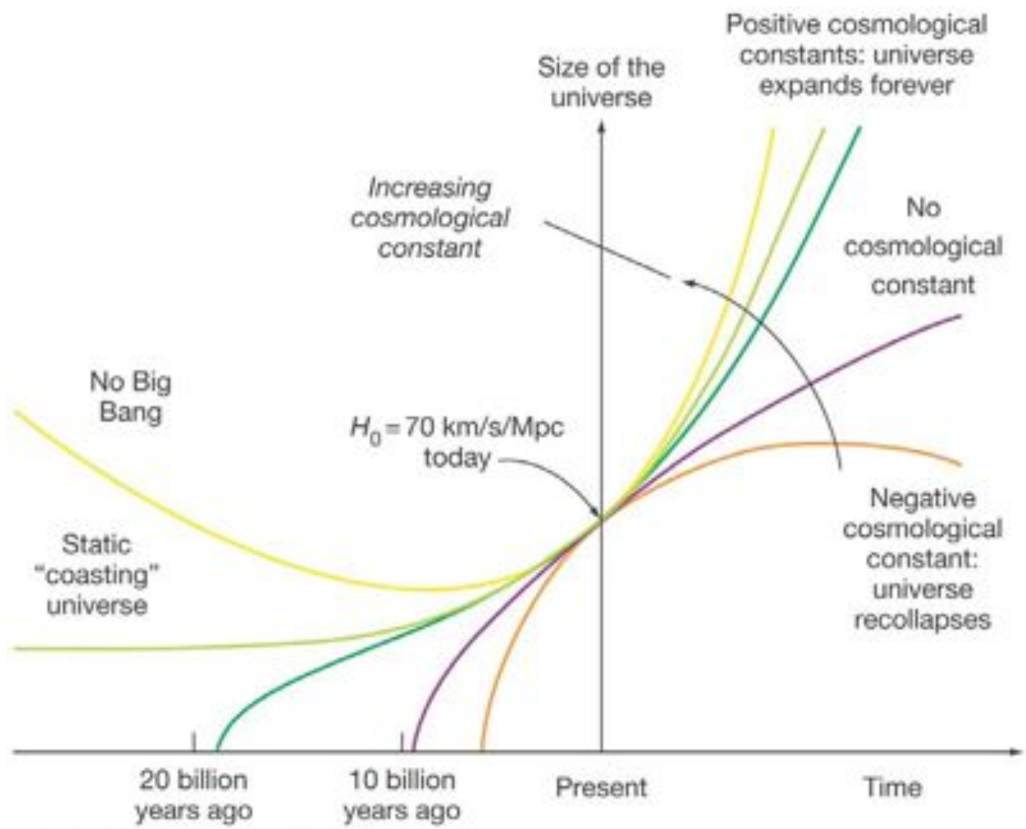
Discovery 26-2: Einstein and the Cosmological Constant

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

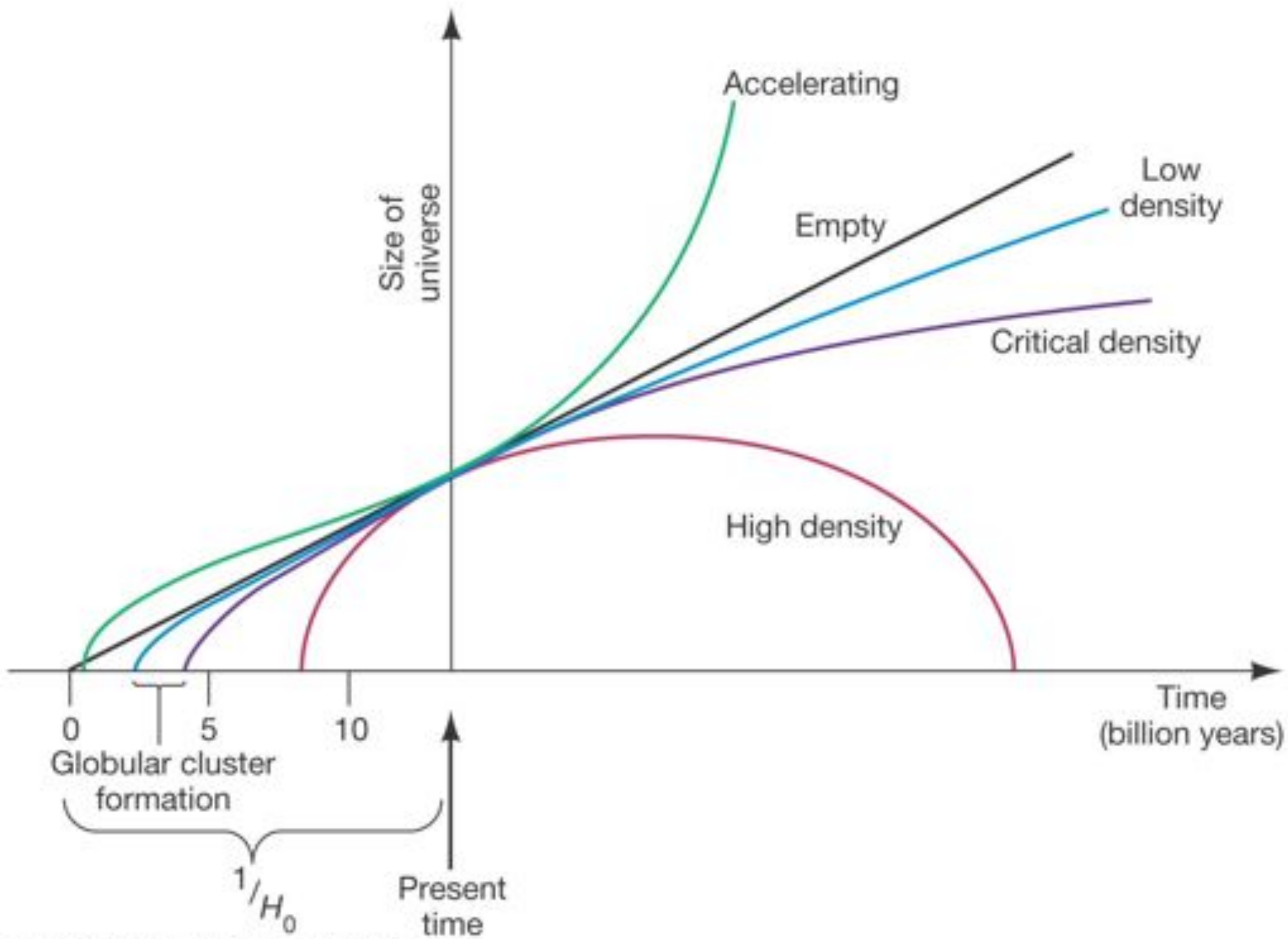
What else supports the "dark energy" theory?

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

- The assumption of a constant expansion rate is incorrect, so the acceleration due to dark energy means that the Universe is (a little) younger than we thought.

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: First galaxies form

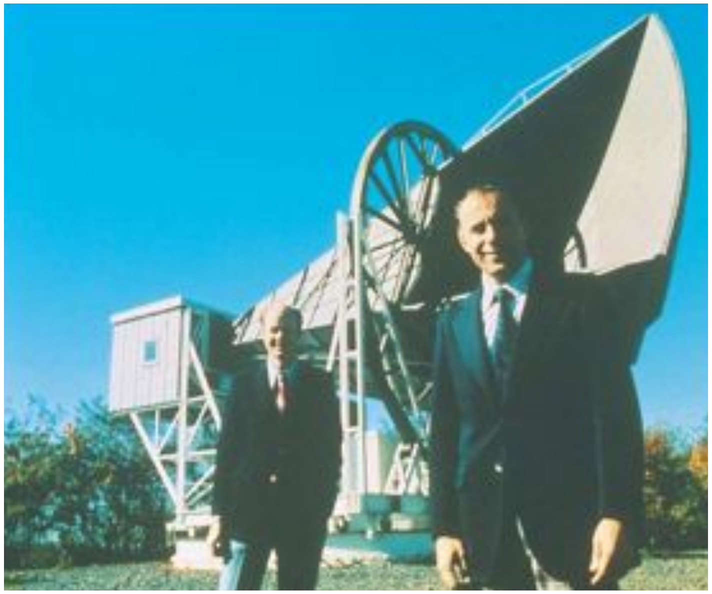
10 billion years ago: First stars in our galaxy form

Next, we discuss a relic from the big bang that will allow us to understand what happened before there were galaxies, filling in the so-far mysterious time just after the big bang, the red arrow above. Most of chapter 27 will be concerned with taking this back to the very earliest moments in the history of the universe.

26.7 Cosmic Microwave Background

The cosmic microwave background was *predicted* in the 1950s, when it was realized that at some critical time in the history of universe, ionized elements would "recombine" into atoms, removing electrons that had previous scattered the light that pervaded the universe.

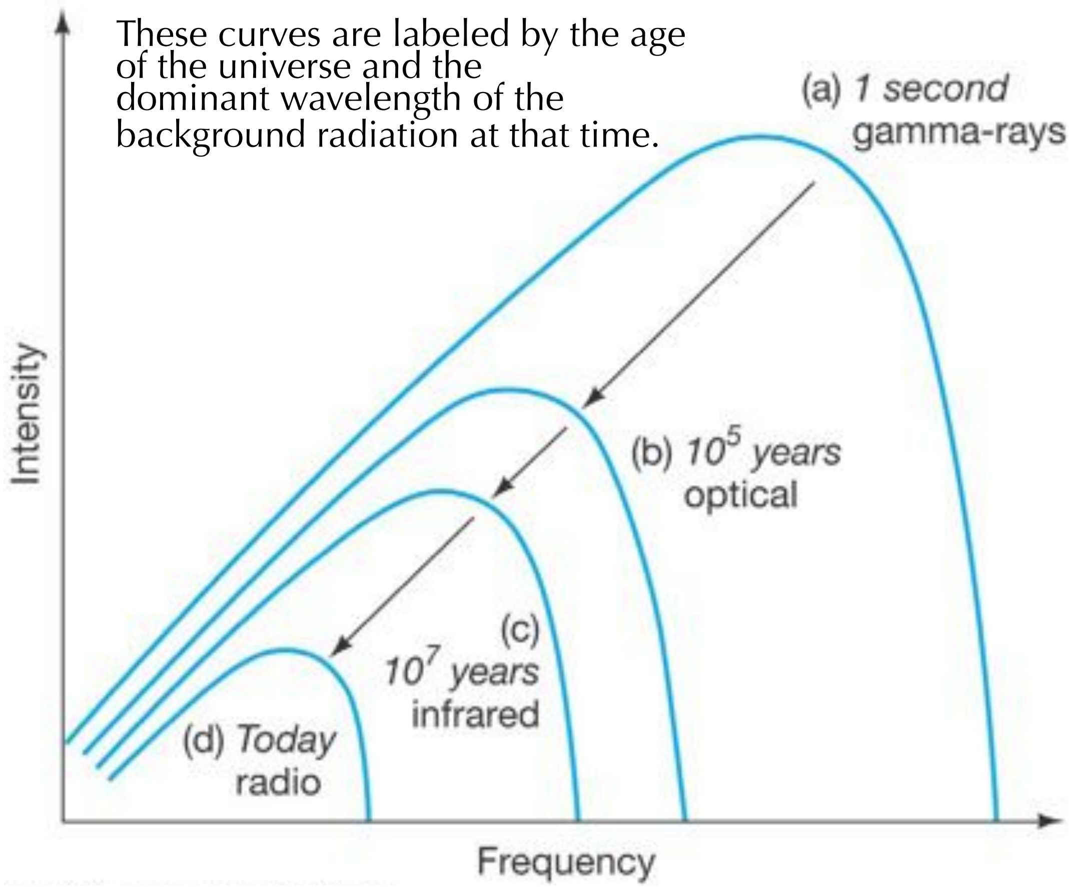
This radiation was "discovered" fortuitously in 1964, as two researchers from Bell Labs, Penzias and Wilson, tried to get rid of the last bit of "noise" in their radio antenna. They tried everything they could think of, until someone pointed out the magnitude of what they had found.



They had 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, but didn't know anything about astrophysics and had no idea such a thing had been predicted. Despite a complete ignorance of the significance of what they had found, they received the Nobel Prize for their "discovery," while those who predicted its existence, and others who were busily trying to build a radio telescope that could detect it, were left prizeless…

26.7 Cosmic Microwave Background

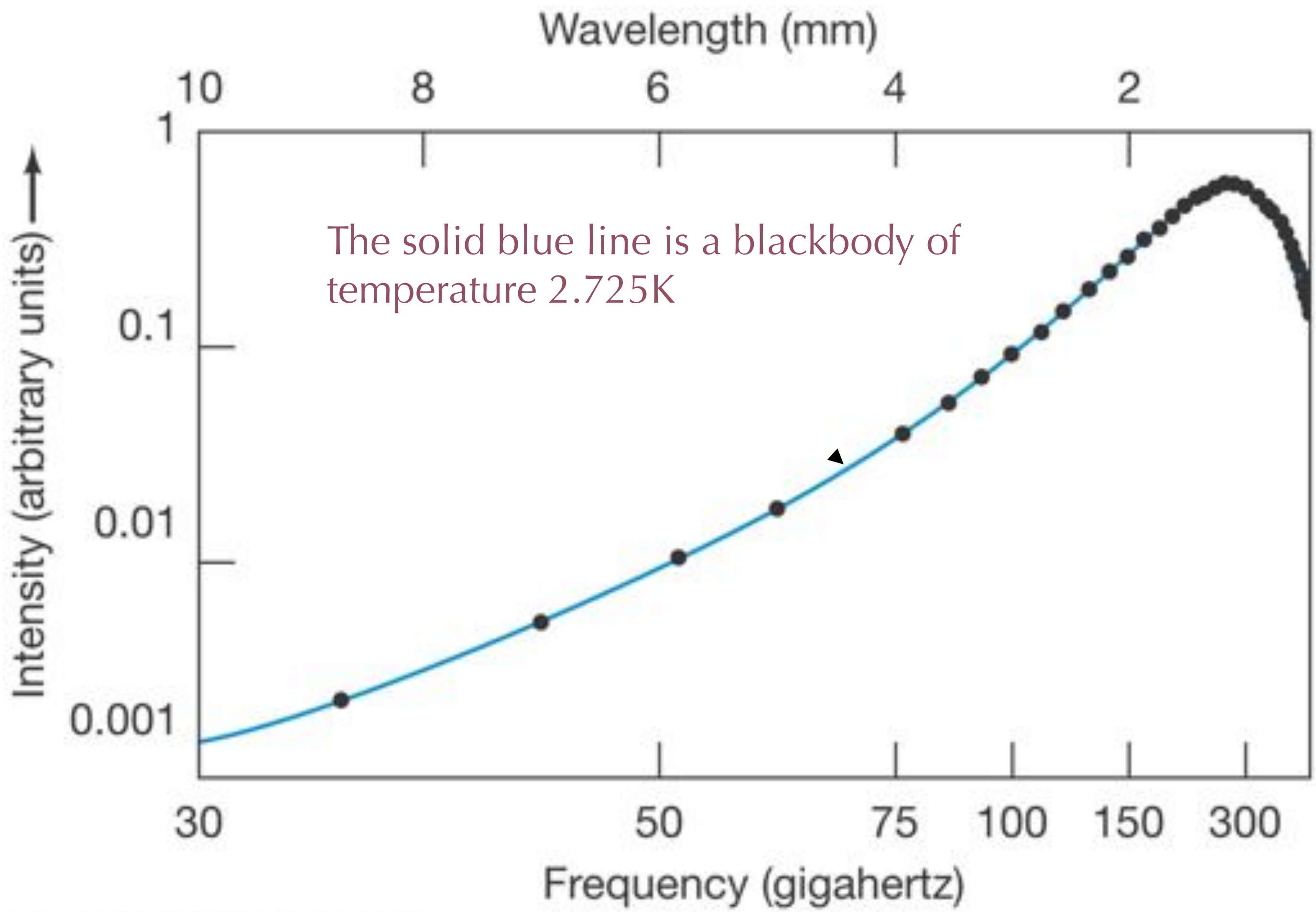
These photons were released from interacting with matter ever again when the universe was only about a million years old. Earlier, only one second after the Big Bang, they were very highly energetic gamma rays, as illustrated below



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 (three degrees Kelvin).

26.7 Cosmic Microwave Background

Since then, the cosmic background spectrum has been measured with great accuracy. The observations almost exactly fit a 3K blackbody, an important test of the bib bang model for the early universe.



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.