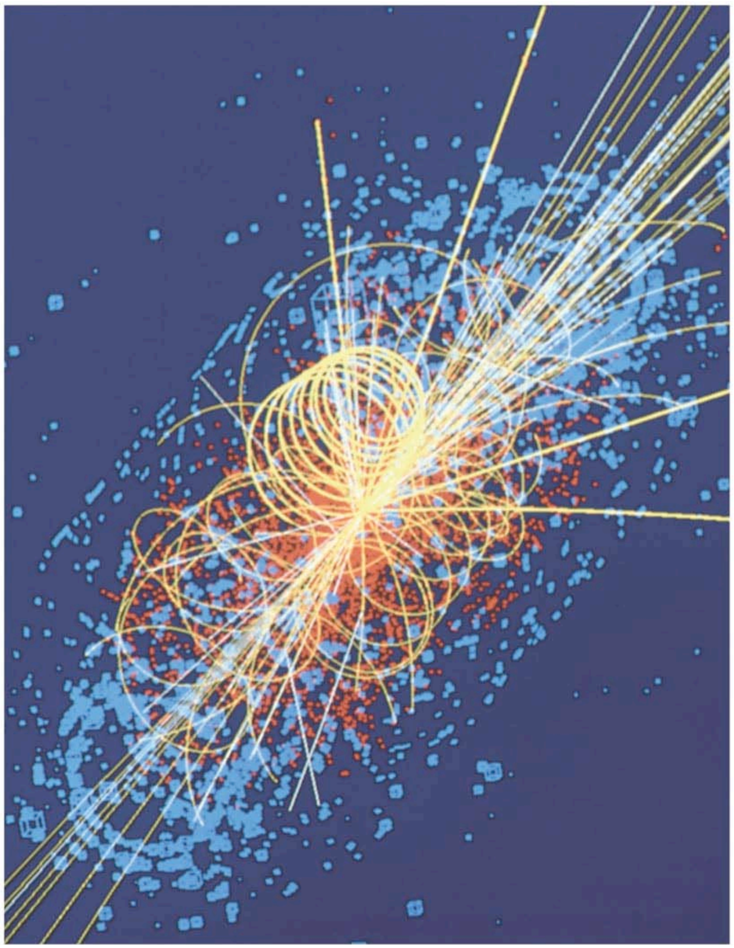
Chapter 27: The Early Universe



The plan:

1. A brief survey of the entire history of the big bang universe.

2. A more detailed discussion of each phase, or "epoch", from the Planck era through particle production, nucleosynthesis, recombination, and the growth of structure.

3. Then back to the (near) beginning, and "inflation."

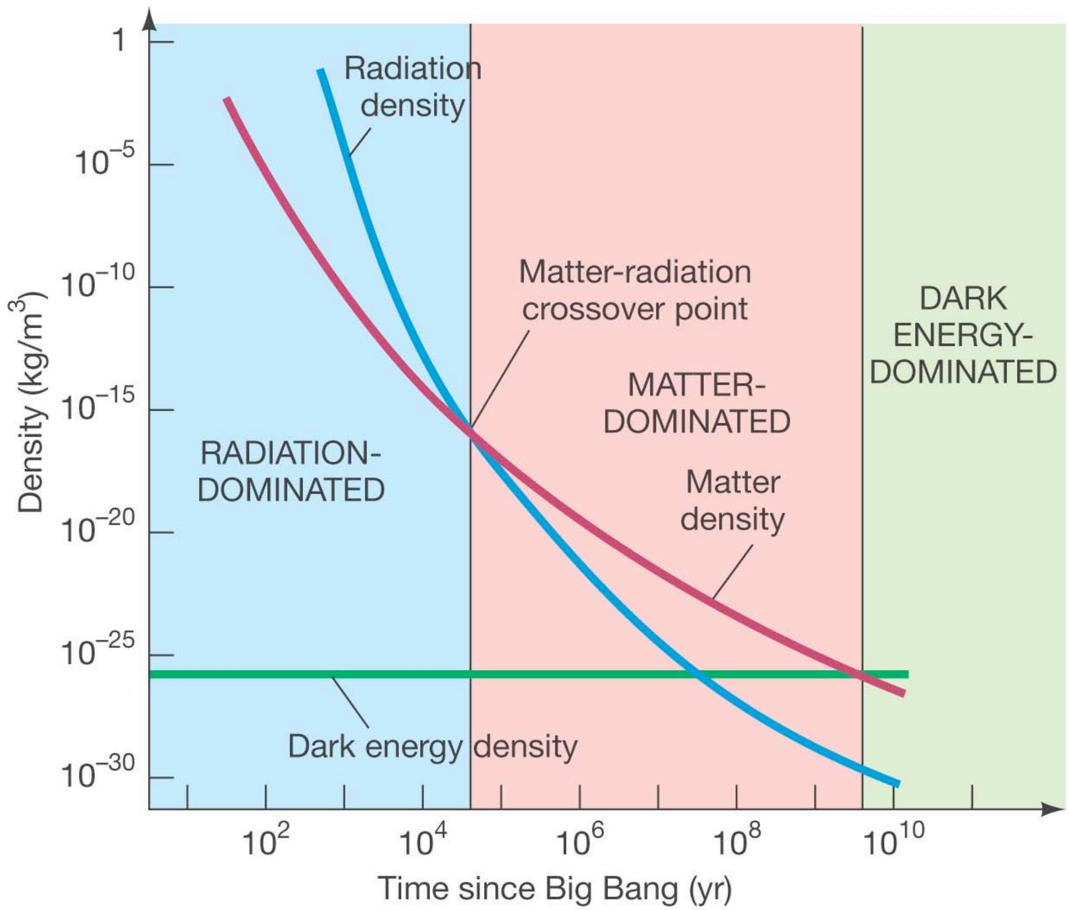
4. Finally the demonstration from the WMAP CBR map that the universe is almost perfectly flat. This ties together several separate strands of the big bang model for history of the universe.

It also shows that inflation probably did occur, and dark matter and dark energy exist, whether or not we know what they are made of.

Units of Chapter 27

27.1 Back to the Big Bang

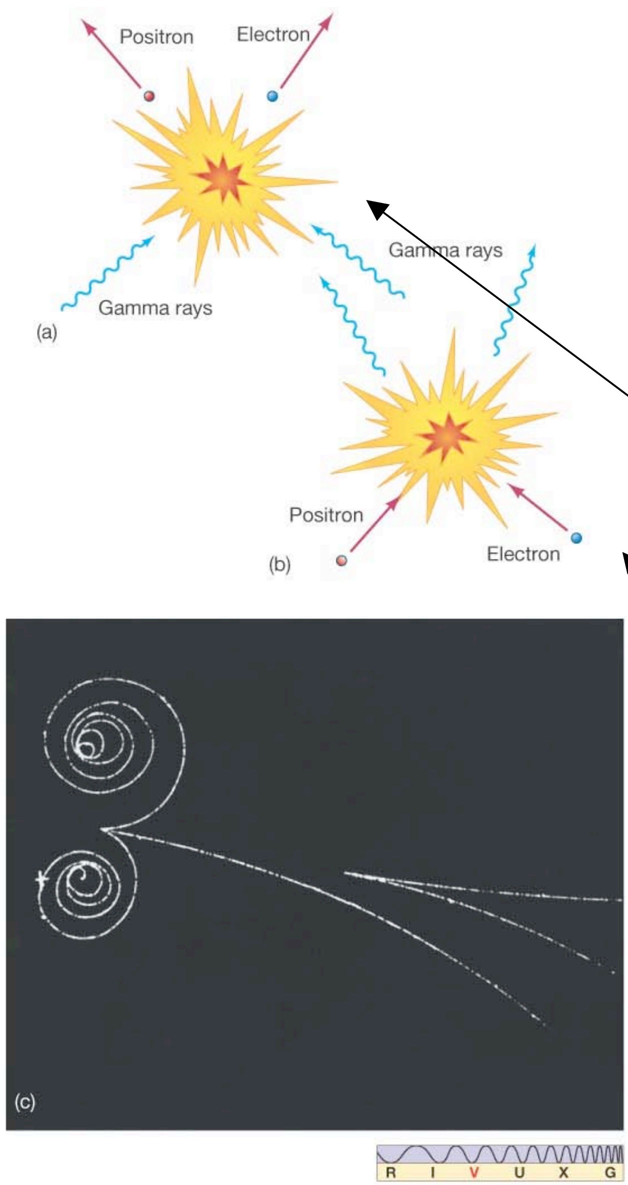
The total energy of the universe consists of both radiation and matter.



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

Dark energy becomes more important as the Universe expands.

27.1 Back to the Big Bang



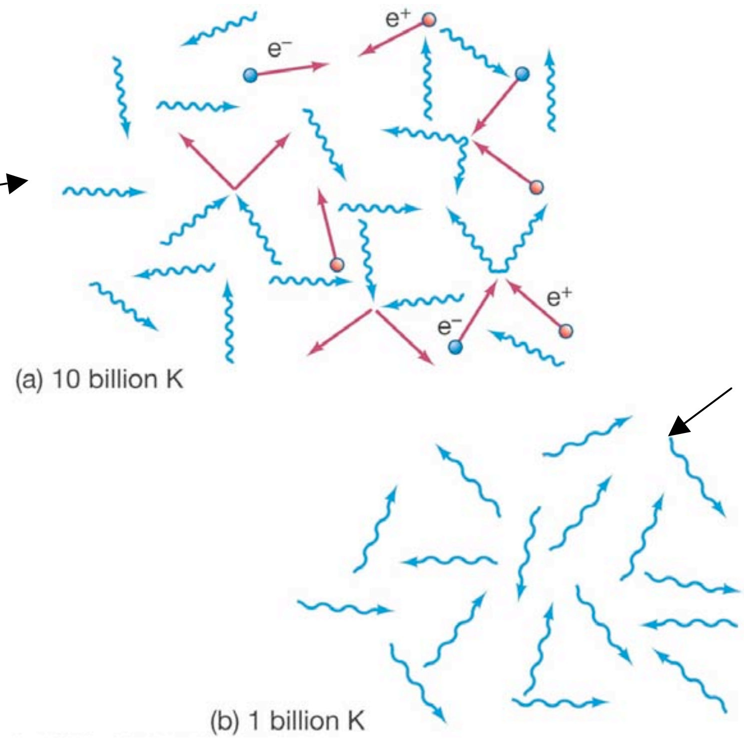
In the very early Universe, one of the most important processes was pair production: Virtual particles and photons were created from the high-energy vacuum state, from *nothing*. The temperature and density were trillions of times their current values.

The upper diagrams show how two gamma rays can unite to make an electron–positron pair, and vice versa. Electron-positron pairs are matter-antimatter pairs, and annihilate, producing gamma rays again. These two processes come into balance, or *equilibrium*.

The lower picture is of such an event occurring at a high-energy particle accelerator.

27.1 Back to the Big Bang

In the very early Universe, the pair production and recombination processes were in **equilibrium**: Equal rates of production and destruction, no particle or photon permanent.



When the temperature had decreased to about **1 billion K**, the photons no longer had enough energy for pair production, and were "frozen out." This means the remaining photons (still gamma rays) were now permanent, although still frequently scattered by the electrons in the surrounding gas.

We now see these photons, greatly redshifted, as the cosmic background radiation.

27.2 The Evolution of the Universe

This table lists the main events in the different epochs of the Universe. You don't have to memorize the numbers, or even all the epochs (I'll tell you which ones are important to remember), but you *should* be able to read from the top to the bottom and understand it is a summary of the primary components of the universe at each time.

TABLE 27.1 Major Epochs in the History of the Universe

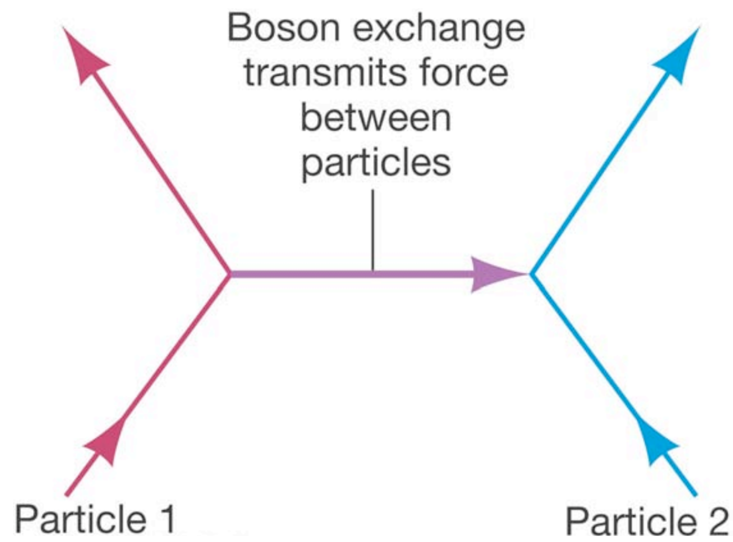
Era	Epoch	Time (after Big Bang)	Density (kg/m^3)	Temperature (K)	Main Events
Radiation Era					
		0 s	∞	∞	
	Planck				Unknown physics; quantum gravity.
		10^{-43} s	10^{95}	10^{32}	
	GUT*				Strong, weak, and electromagnetic forces unified.
		10^{-35} s	10^{75}	10^{27}	
	Quark				Strong force frozen out. Heavy and light particles all in thermal equilibrium. Electroweak force freezes out at 10^{15} K.
		10^{-4} s	10^{16}	10^{12}	
	Lepton				Only low-mass particles still in thermal equilibrium; neutrinos decouple at 10^{10} K.
		10^{2} s	10^{4}	10^{9}	
	Nuclear				Deuterium and helium formed by fusion of protons and neutrons during first 1000 s.
		5×10^{4} yr (2×10^{12} s)	6×10^{-16}	16,000	
Matter Era					
		5×10^{4} yr (2×10^{12} s)	6×10^{-16}	16,000	
	Atomic				Matter begins to dominate; atoms form; electromagnetic radiation decouples.
		2×10^{8} yr (6×10^{15} s)	10^{-22}	60	
	Galactic				Large-scale structure forms; first stars and quasars shine; galaxies form and grow.
		3×10^{9} yr (10^{17} s)	2×10^{-25}	10	
	Stellar				Galaxies merge and evolve; star formation peaks. Dark energy begins to dominate.
Dark Energy Era		$>10^{10}$ yr (3×10^{17} s)	3×10^{-27}	3	

**Grand Unified Theory; see* More Precisely 27-1.

27.2 The Evolution of the Universe

Current understanding of the forces between elementary particles is that they are accomplished by **exchange** of a third particle.

Different forces "**freeze out**" when the energy of the Universe becomes too low for the exchanged particle to be formed through pair production.



Time = 0 ? No singularity, just ignorance

If we extrapolate the Big Bang back to the beginning, it yields a singularity—infinite density and temperature.

This result is probably artificial, reflecting our lack of understanding concerning matter at temperatures and densities so large that gravity had not yet "frozen out" from the other forces. Any occurrence in physics or math of a "singularity," where physical quantities appear to become infinite, is a sign of missing physics (or a mistake).

This is called the era of "quantum gravity," when quantum effects and gravitational effects were important on the same size scales.

This is the same reason we can't say what happens when something falls into a black hole--another "singularity."

We can only (hope we) understand what happens back to 10^{-43} seconds after the Big Bang. Therefore, we cannot predict anything about what happened *before* the Big Bang; indeed, the question may be meaningless. We don't even understand whether "time" would have been relevant during these earliest of times, in which case talk of "before" and "after would not even make sense.

However a *lot* happens after that time, and theories of big bang cosmology predict certain crucial events that can be observationally tested.

Planck era, GUT era, …

This first 10^{-43} seconds after the Big Bang are called the **Planck** era.

This is called the era of "quantum gravity," when quantum effects and gravitational effects were important on the same size scale. There were no separate forces.

At the end of that era, the **gravitational force** "freezes out" from all the others, becomes separate. That is why today we can speak of "gravity" as if it acted independently from other forces.

The next era is the **GUT** (Grand Unified Theory) era. Here, the strong nuclear force, the weak nuclear force, and electromagnetism are all unified. At the end of it, there was not enough energy for the corresponding production of heavy particles, and the forces (which were just one unified force before this time) became separate forces.

…quark era, lepton era

The next era is called the quark era; during this era all the elementary particles were in equilibrium with radiation.

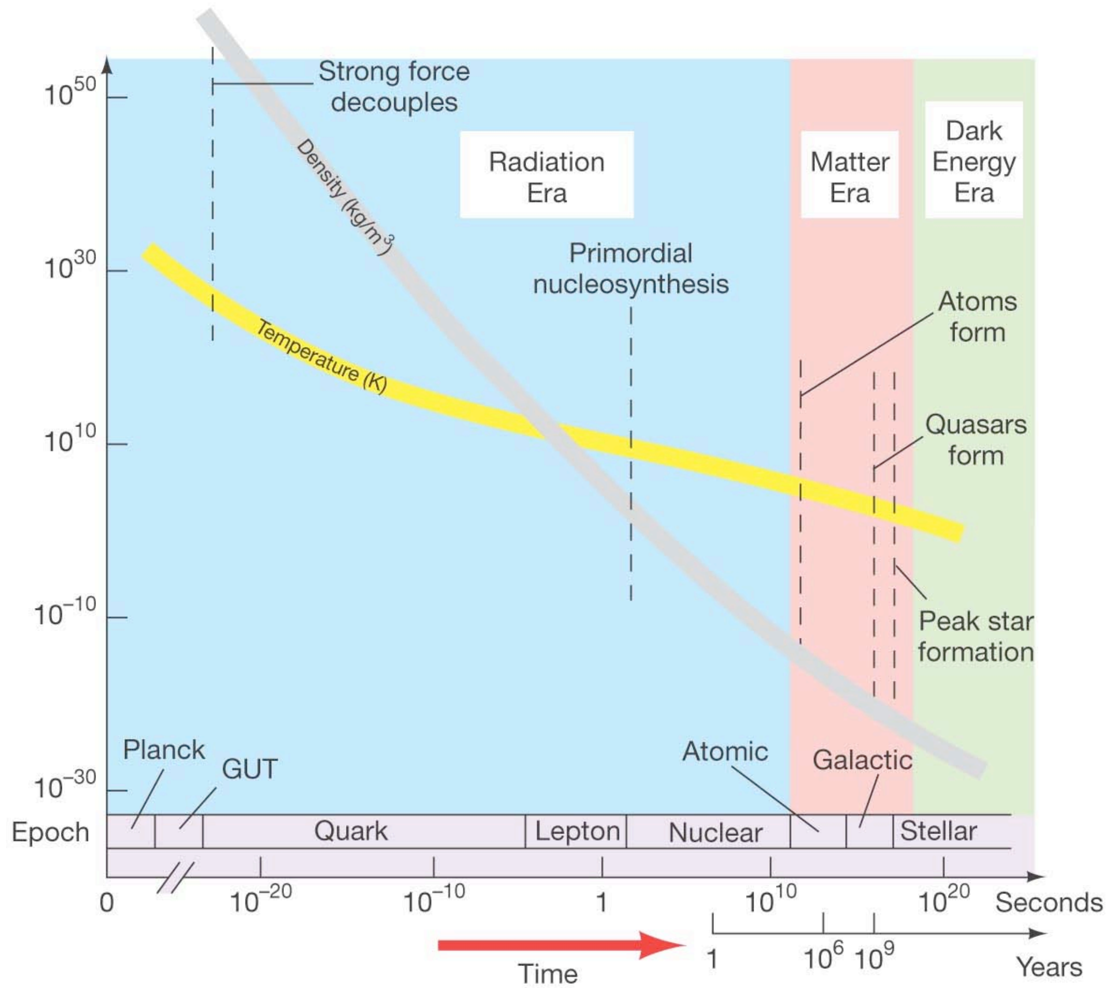
About 10^{-4} s after the Big Bang, the Universe had cooled enough that photons could no longer produce the heavier elementary particles; the only ones still in equilibrium were electrons, positrons, muons, and neutrinos. This is called the lepton era.

About 1 second after the Big Bang, the Universe became transparent to neutrinos. (Note: this is the equivalent of the era of recombination for photons, to come much later; so there should be a "cosmic neutrino background" all around us, those same neutrinos from when the universe was 1 second old; no one has proposed a way to detect them.)

After 100 seconds, photons became too low in energy for electron–positron pair creation—this marks the end of the radiation era, and the end of particle creation.

Epochs in cosmic history

The evolution of the universe in a single graph--look at it slowly, especially as a review tool. Yellow and grey bands show how the density and temperature decreased as a function of time (horizontal axis). Notice, on the bottom right, the transformation from fundamental particles, to atoms, and finally to galaxies and stars.
Meanwhile the mysterious "dark energy" has been increasing in importance.



The era of recombination releases the cosmic background radiation; formation of structure like galaxies follows

The next major era occurs when photons no longer are able to **ionize** atoms as soon as they form. This allows the formation of **hydrogen** and **helium** *atoms* to form, taking out the free electrons. This "era of recombination," about a million years after the big bang, frees the photons because their former interactions with electrons no longer occur (the electrons are "recombined" in atoms).

The cosmic background radiation is then "frozen," never to interact with matter again, and available for observation by us. It contains an imprint of the vibrations or waves of spacetime that were to become galaxies and larger structures.

This formation of cosmic structure from these waves probably took a tenth of a billion years or so. It had to wait until the temperatures in some regions had dropped low enough for gravity to dominate pressure.

For the next 3 billion years, **galaxies** begin to form. These correspond to the galaxies we see at the highest redshifts (distances).

After that, they merge; larger and larger structures arise, galaxies evolve into the ones we see now, and star formation goes through many generations.

More Precisely 27-1: More on Fundamental Forces

You do NOT have to know this terminology for the exam, except for the four kinds of forces.

Table 27-2 lists the four fundamental forces and the particles on which they act. There are six types of quarks (up, down, charm, strange, top, bottom) and six types of leptons (electron, muon, tau, and neutrinos associated with each). All matter is made of quarks and leptons.

Dark matter is believed to be made of particles created when the universe was very young, but it is still "matter," created by interactions of fundamental particles.

We don't know where dark energy fits in at all, only that it probably exists.

TABLE 27.2 Fundamental Forces and Particles

Force	Range (m)	Particles Affected	Unification (temperature)		
strong	10^{-15}	matter composed of quarks (protons, neutrons, etc.)		GUT/superforce (10^{28} K)	quantum gravity (10^{32} K)
electromagnetic	infinite	charged particles (protons, electrons, etc.)	electroweak (10^{15} K)		
weak	10^{-17}	leptons (electrons, muons, taus, neutrinos)			
gravity	infinite	everything			

More Precisely 27-1: More on Fundamental Forces

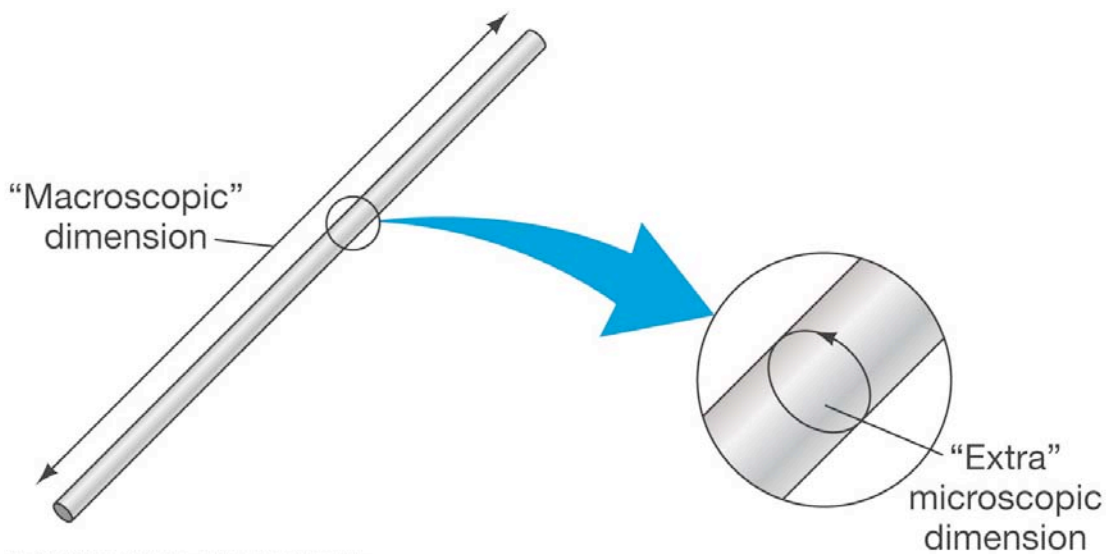
(Again, not on exam--read for your own interest)

The theories of the weak and electromagnetic forces have been successfully unified in what is called the electroweak theory. At a temperature of 10^{15} K, these forces should have equal strength.

Considerable work has been done on unifying the strong and electroweak theories; these forces should have equal strength at a temperature of 10^{28} K. One prediction of many such theories is supersymmetry—the idea that every known particle has a supersymmetric partner.

More Precisely 27-1: More on Fundamental Forces (cont'd)
(Again, not on exam--read for your own interest)

Unification of the other three forces with gravity has been problematic. One theory that showed early promise is string theory—the idea that elementary particles are oscillations of little loops of "string," rather than being point particles. This avoids the unphysical results that arise when point particles interact. It does, however, require that the strings exist in 11-dimensional space. The extra seven dimensions are assumed to be very small.



27.3 The Formation of Nuclei and Atoms

The era of nucleosynthesis

Hydrogen was the first atomic nucleus to be formed, as it is just a proton, so it was there from the very early time when particles as massive as protons were created.

Much later, a few minutes after the big bang, the average temperature of the universe fell to about a billion degrees, and for a short time temperatures were right for nuclear fusion. This is the *era of nucleosynthesis*. However only one element was produced in appreciable quantities, *helium*.

Helium can form through fusion reactions that are just the proton-proton cycle that occurs in stars:

$$^{2}H + {}^{1}H \rightarrow {}^{3}He + \text{energy}$$

$$^{2}H + {}^{2}H \rightarrow {}^{3}He + \text{neutron} + \text{energy}$$

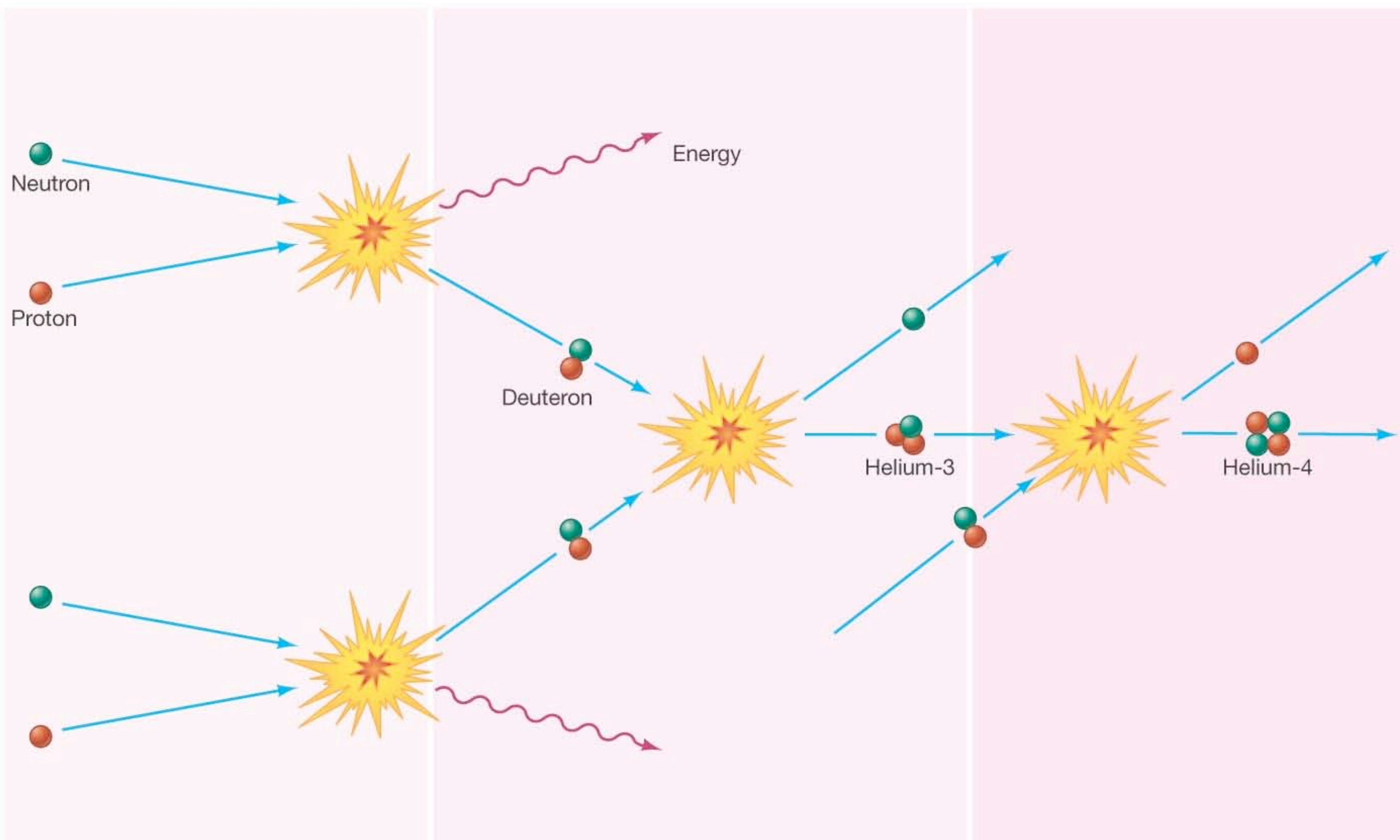
$$^{3}He + \text{neutron} \rightarrow {}^{4}He + \text{energy}$$

Your textbook has a great derivation of the fraction of He produced from protons during this era: 25 percent (by mass; 8 percent by number). It is difficult to get a much different answer! This is a *major* prediction of big bang model. Everything in the universe should have at least 25 percent helium. At the time it was made, no one was sure what the helium abundance was in, say, distant galaxies.

Note: Helium is the *only* major element that was *not* primarily produced by fusion inside of stars: stars produce only a few percent.

The Formation of Nuclei and Atoms

This diagram illustrates that fusion process: Note that it is not the same as the fusion process that now goes on in the Sun's core.



The Formation of Nuclei and Atoms

This would lead one to expect that ¼ of the mass of atoms in the universe would be helium, which is consistent with observation (remembering that nucleosynthesis is ongoing in stellar cores).

$$\frac{1 \text{ helium nucleus}}{12 \text{ protons} + 1 \text{ helium nucleus}} = \frac{4 \text{ mass units}}{12 \text{ mass units} + 4 \text{ mass units}}$$

$$= \frac{4}{16} = \frac{1}{4}.$$

Deuterium as a probe of "Omega"

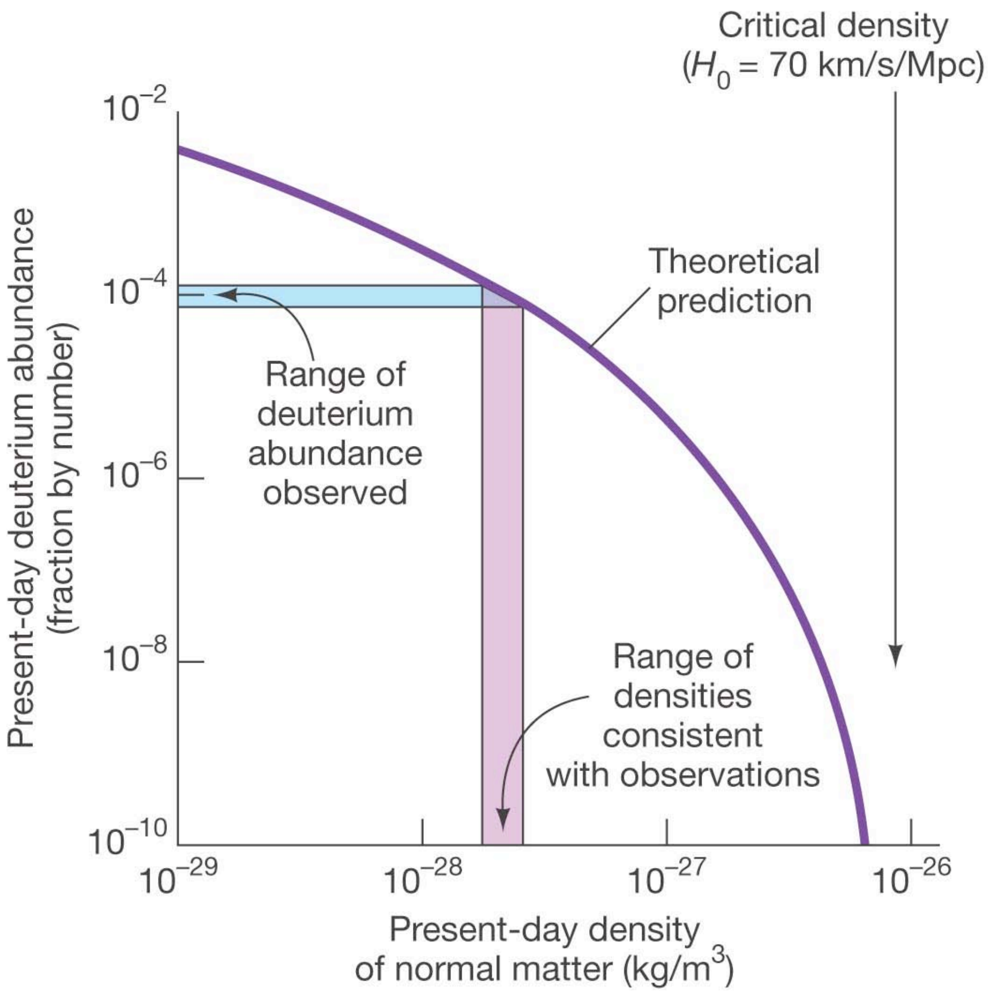
Most deuterium fused into helium as soon as it was formed, but some did not.

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

This gives us a very sensitive way to estimate the present-day matter density of the universe.

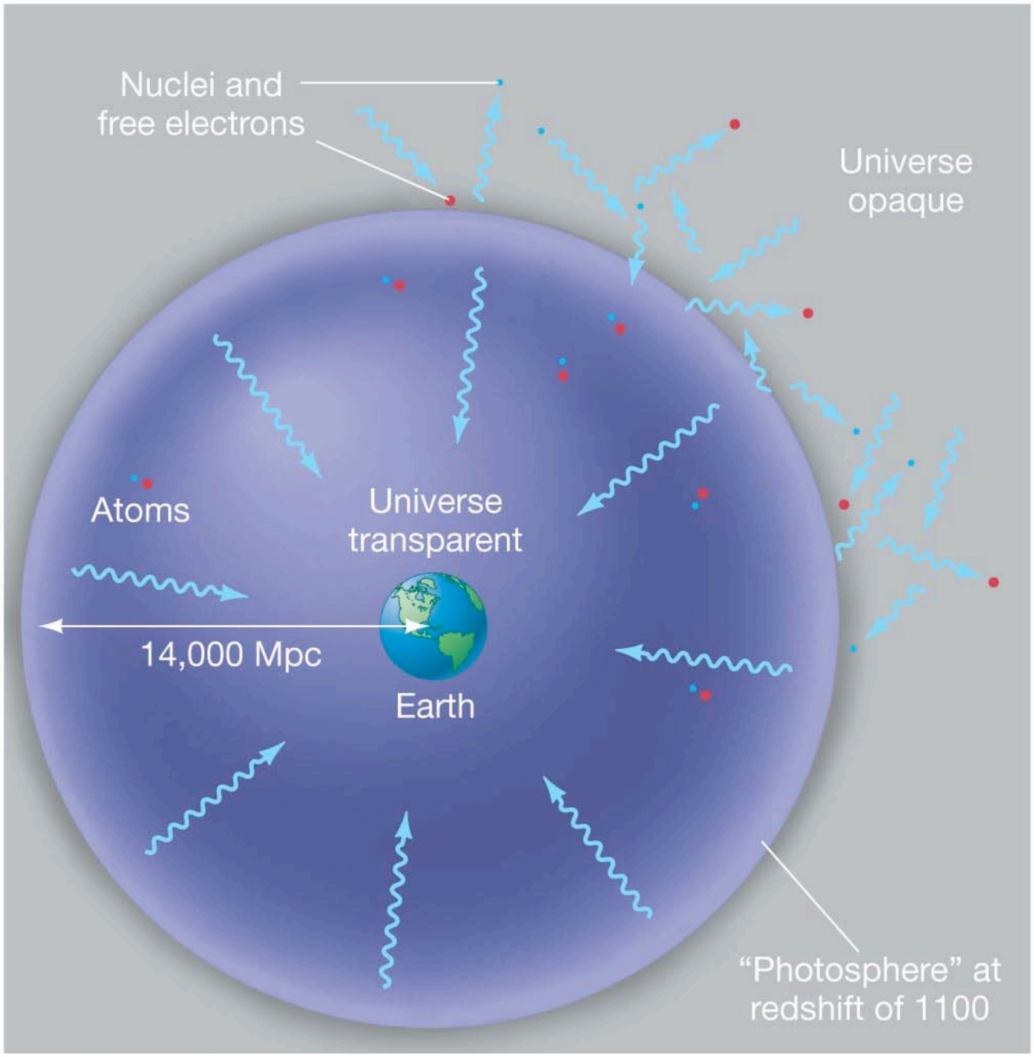
Today's deuterium abundance tells us the average density of baryonic matter in the universe.

Recall that we needed that in order to estimate "omega nought" in discussing the future of the universe and the shape of spacetime.



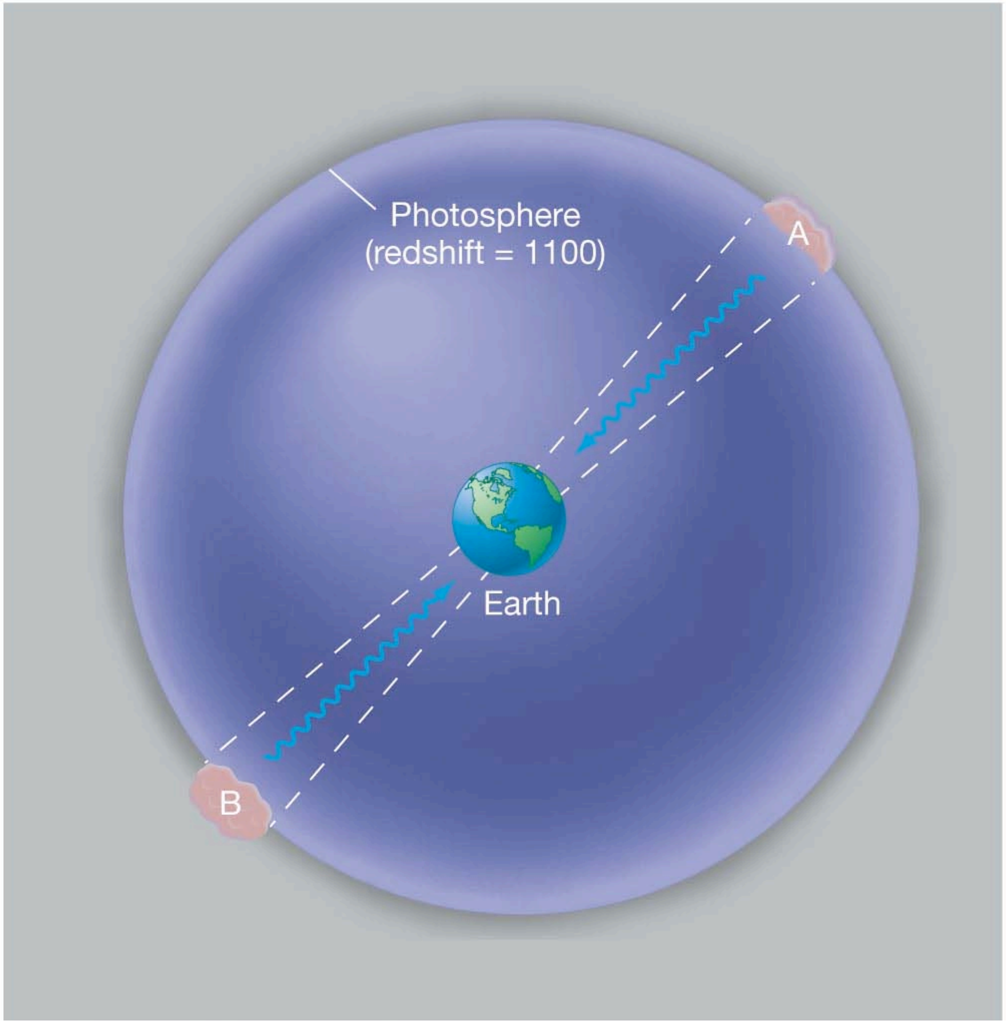
As with galaxy measurements, the total matter density determined by deuterium abundance shows that the matter density is only a few percent of the critical density.

The era of decoupling: nuclei become atoms, electrons are no longer free, CBR "released" for us to see today



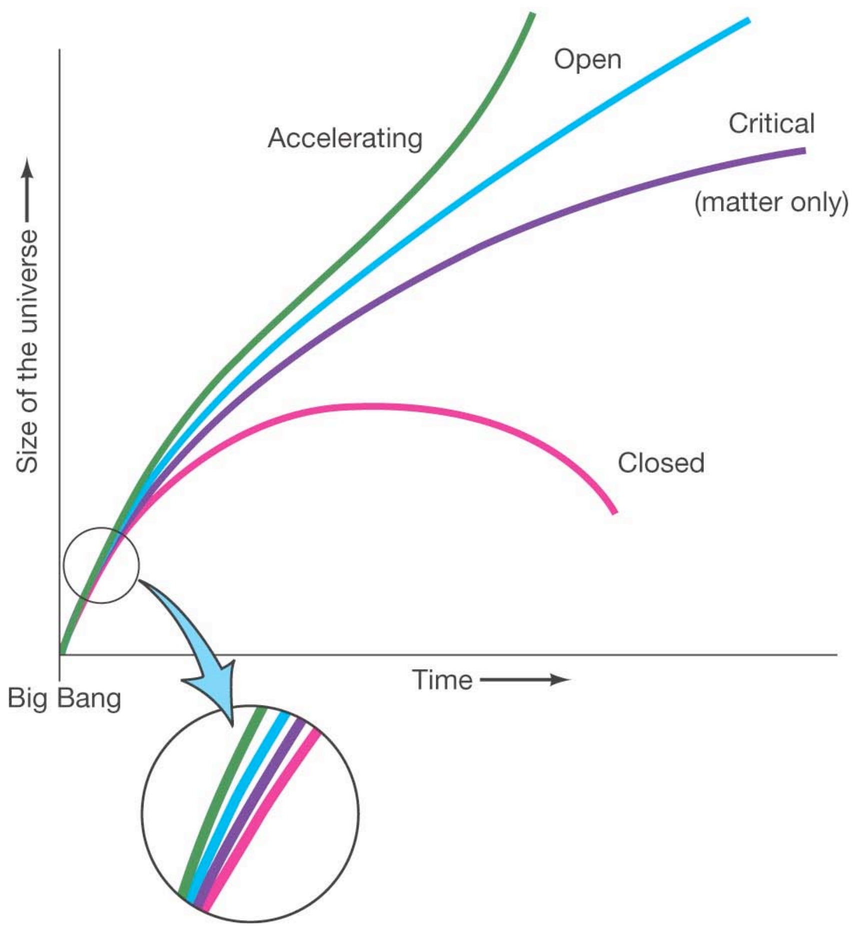
The time during which nuclei and electrons combined to form atoms is referred to as the **decoupling** epoch. This is when the cosmic background radiation originated.

27.4 The Inflationary Universe



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.

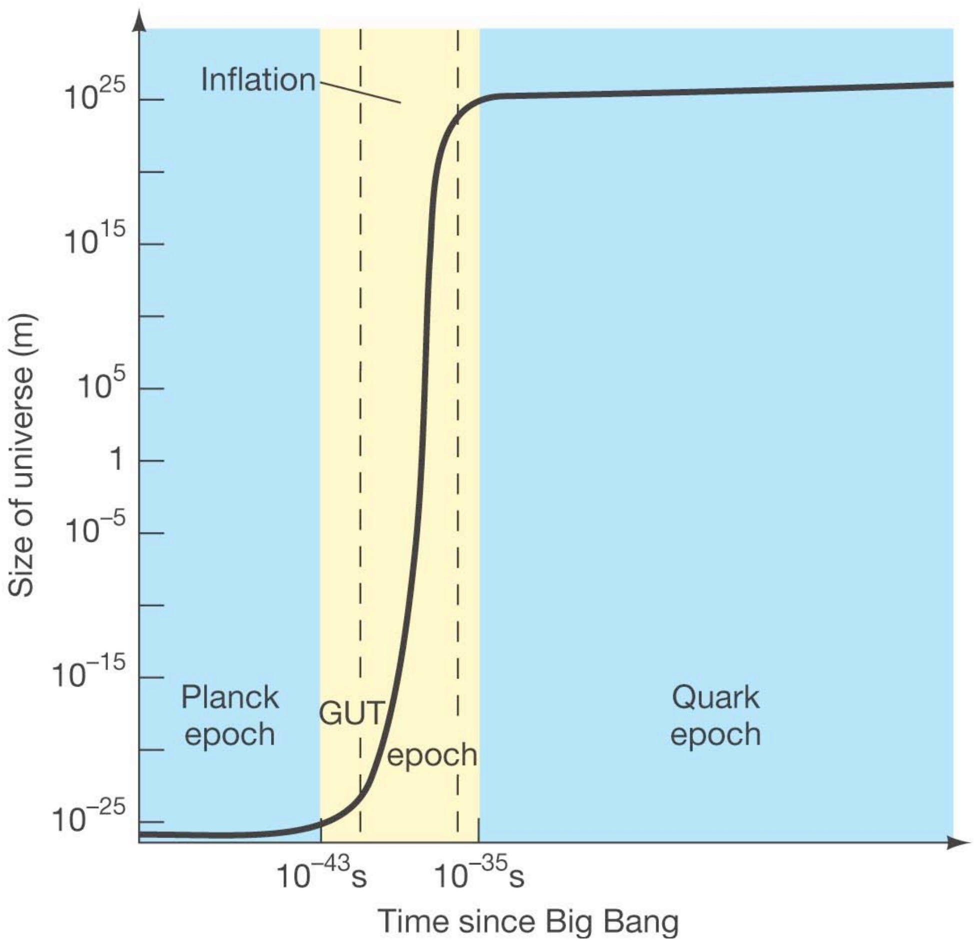
The Inflationary Universe



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}.

The Inflationary Universe

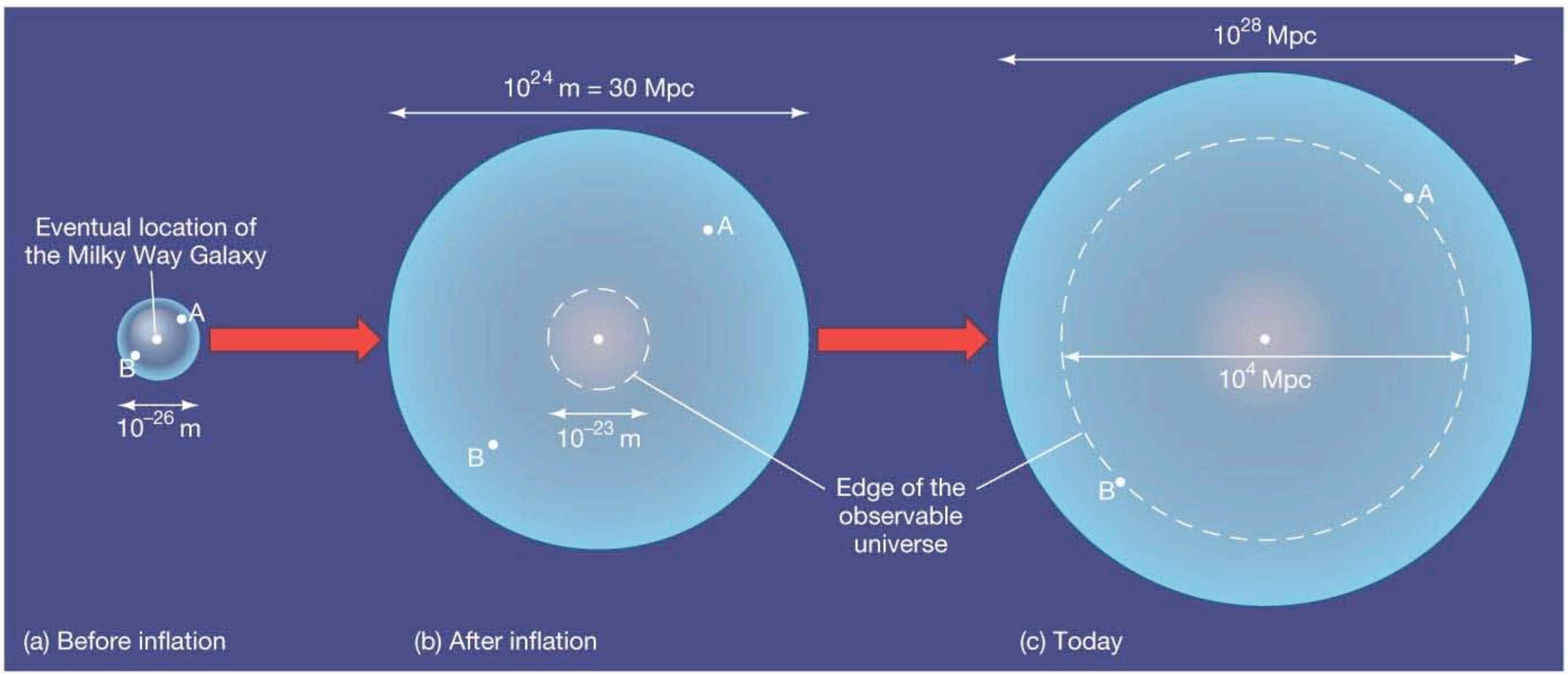
Between the **GUT** epoch and the **quark** epoch, some parts of the Universe may have found themselves stuck in the unified condition longer than they should have been. This resulted in an extreme period of **inflation**, as shown on the graph. Between 10^{-35} s and 10^{-32} s, this part of the Universe expanded by a factor of 10^{50}!



The Inflationary Universe

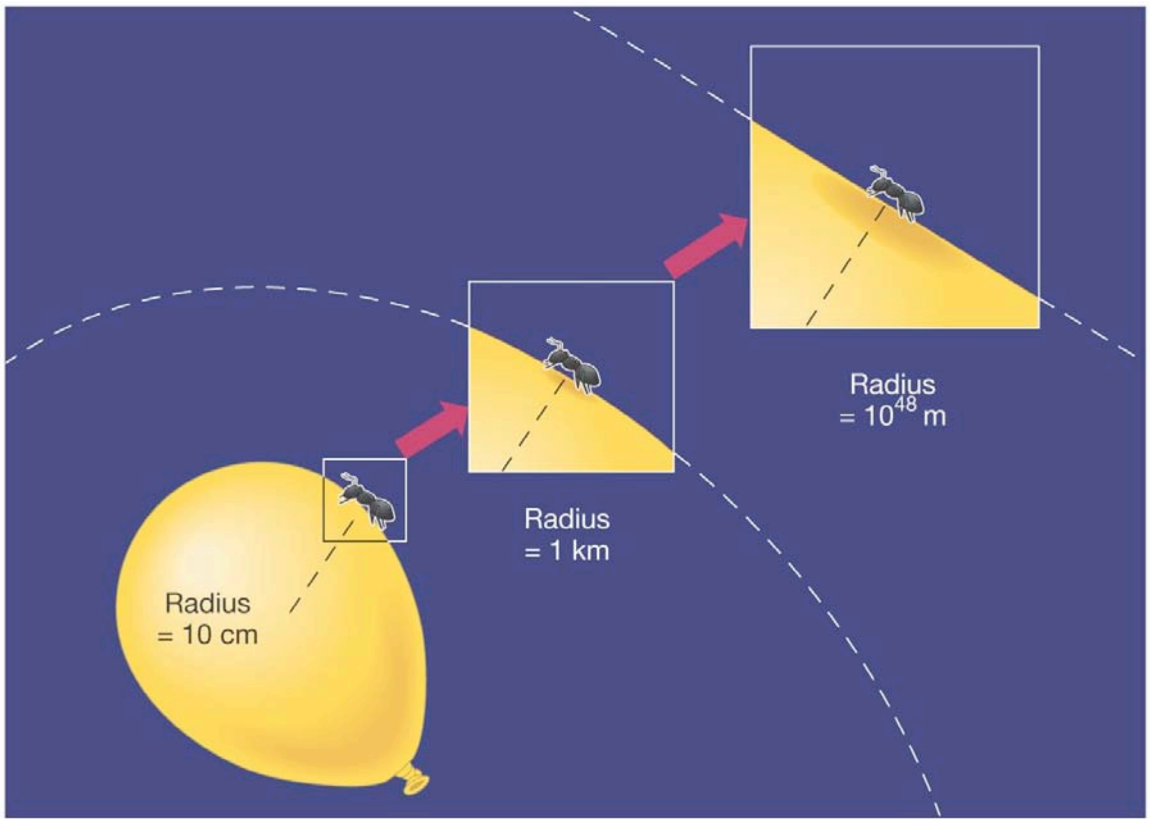
Inflation, if correct, would solve both the **horizon** and the **flatness** problems.

This diagram shows how the **horizon** problem is solved—the points diametrically opposite from Earth were, in fact, in contact at one time:



The Inflationary Universe

The **flatness** problem is solved as well—after the inflation, the need to be exceedingly close to the critical density is much more easily met:



27.5 The Formation of Structure in the Universe

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

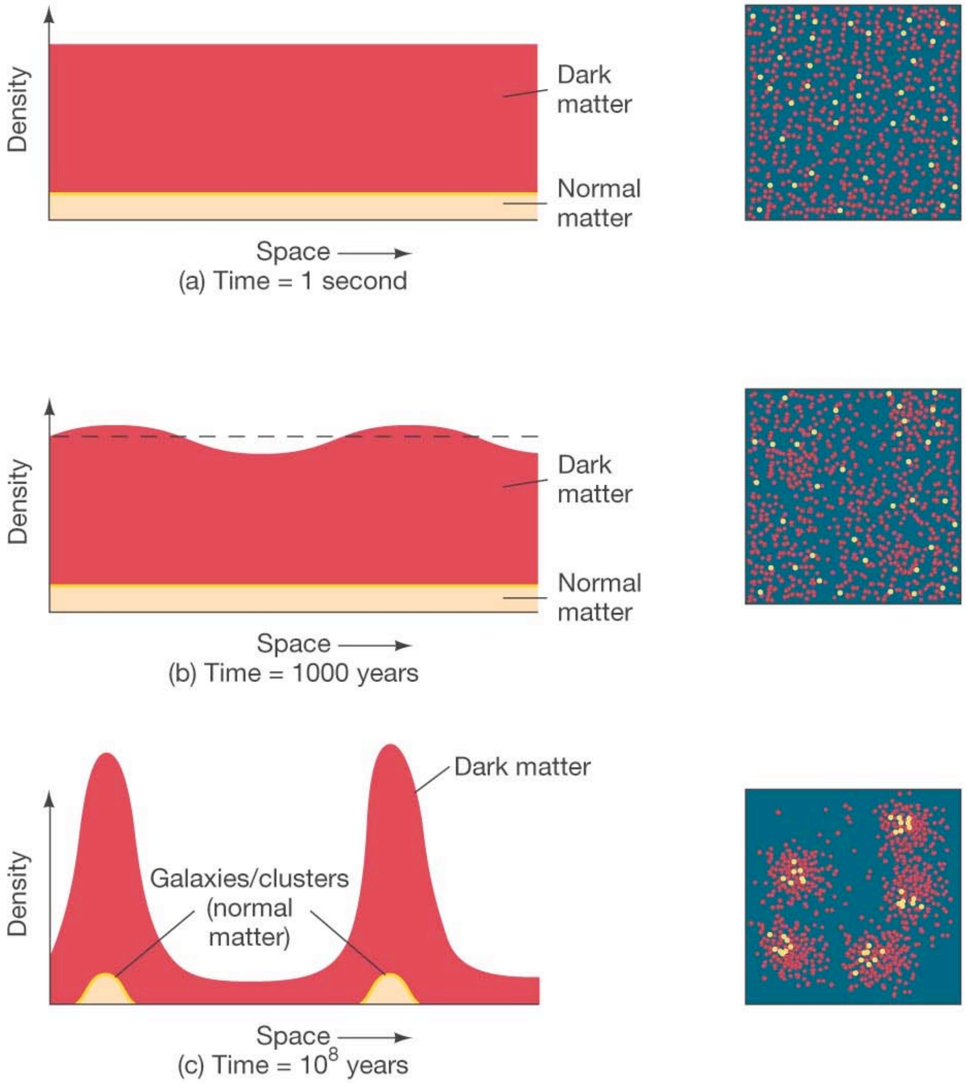
- Before **decoupling**, **background radiation** kept clumps from forming.
- Variations in the **density** of matter before decoupling would have led to variations in the **cosmic microwave background.**
- **Galaxies**, or **quasars**, must have begun forming by a redshift of **6**, and possibly as long ago as a redshift of **10** to **20**.

27.5 The Formation of Structure in the Universe (cont.)

- 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.

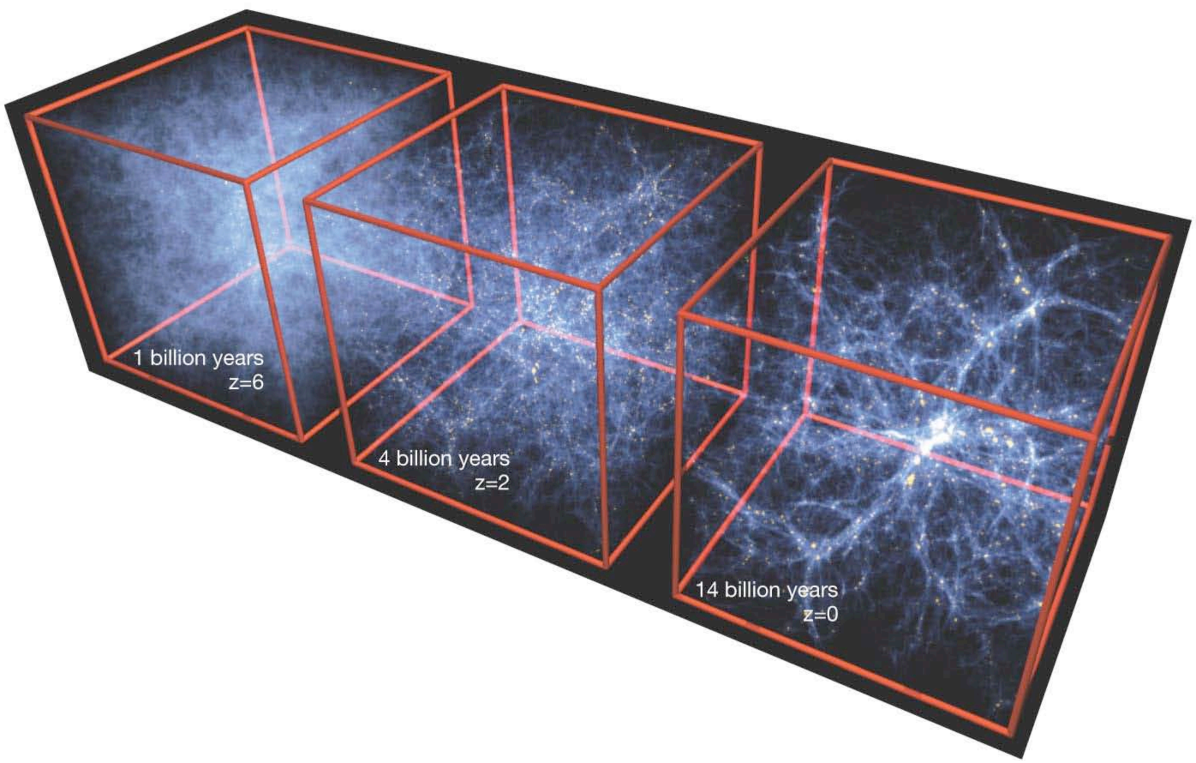
27.5 The Formation of Structure in the Universe



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

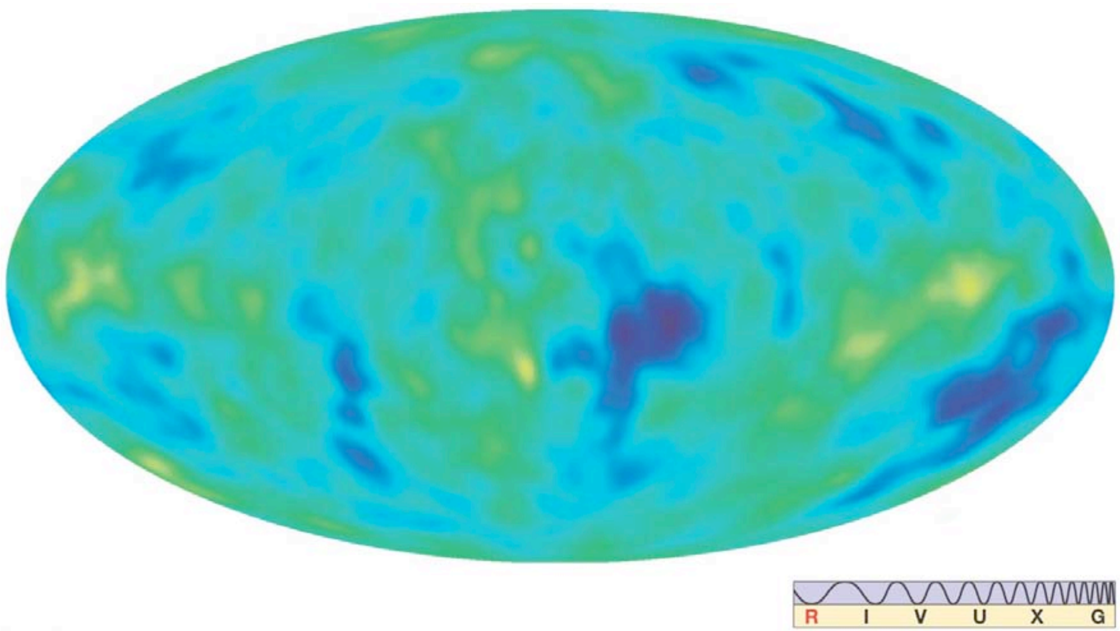
27.5 The Formation of Structure in the Universe

This figure is the result of simulations, beginning with a mixture of 4% normal matter, 23% cold dark matter, and 73% dark energy:



27.6 Cosmic Structure and the Microwave Background

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.

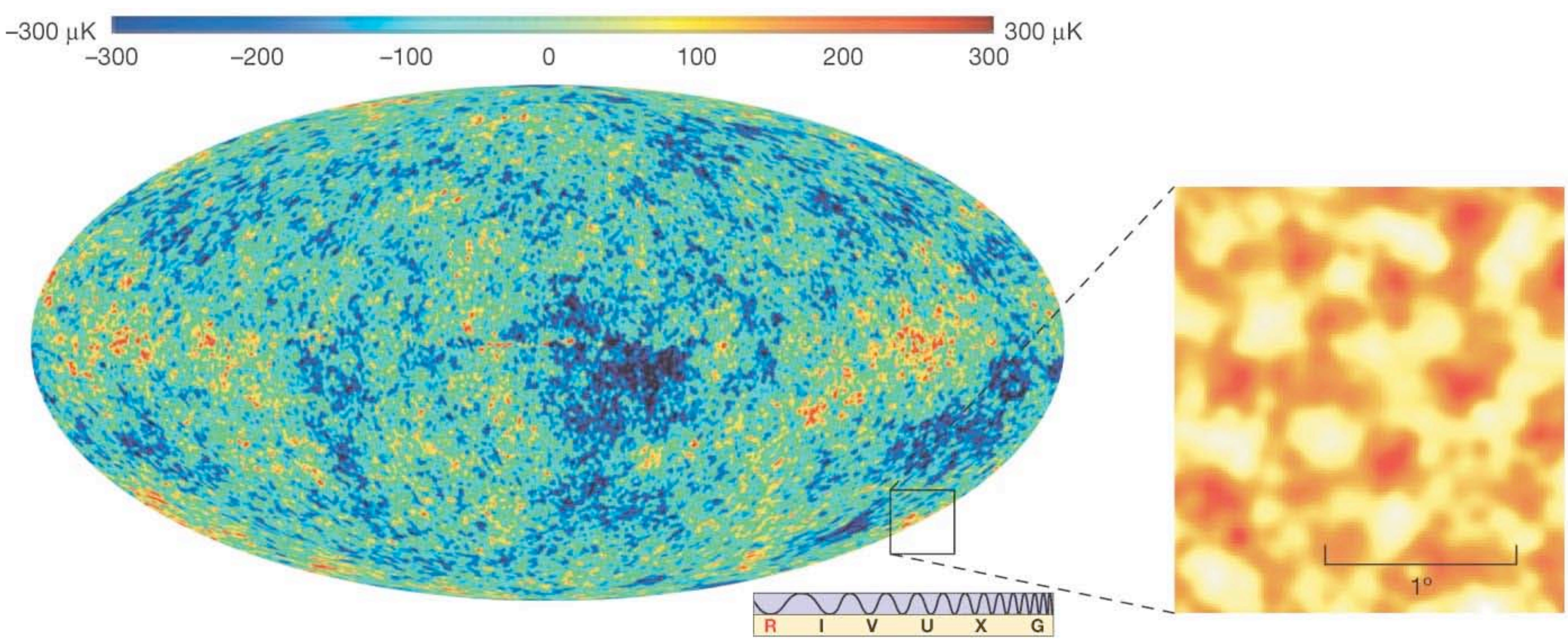


These ripples have now been observed.

27.6 Cosmic Structure and the Microwave Background

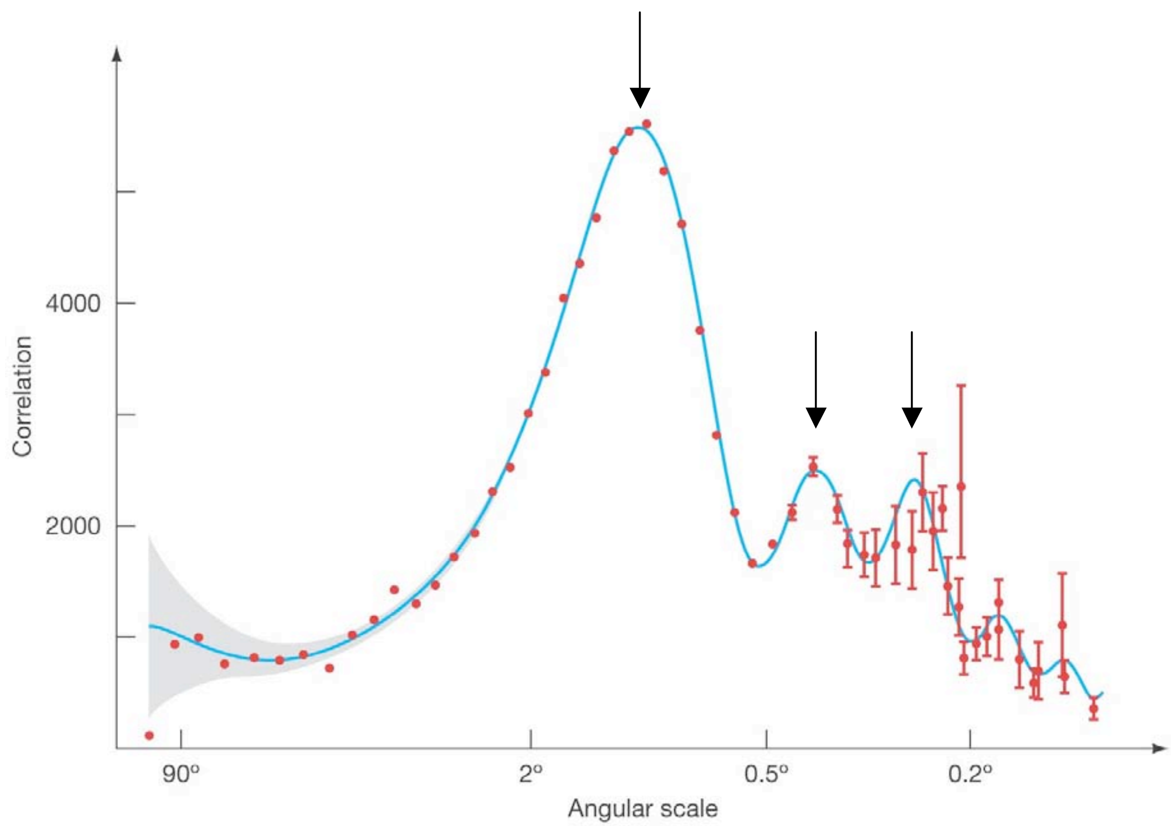
This is a much **higher-precision** map of the cosmic background radiation, and the crowning achievement of current-day observational cosmology.

(Until the Planck telescope, just launched, collects its data…)



The strongest (and strangest) evidence that we live in a *flat* universe, and that *inflation* remains a likely (if bizarre) event that is responsible for the existence of all structure in the universe

Here, the **red** dots are **measurements** derived from the data in the last image, and the **blue** curve is a **prediction** for a universe with $\Omega_0 = 1$, showing excellent agreement. The placement of the large peak is particularly sensitive to Ω_0. Notice the secondary peaks, which are sensitive to additional combinations of parameters (like the age of the universe, and the contributions of dark energy and dark matter.



Summary of Chapter 27

- At present the Universe is matter dominated; at its creation it was radiation dominated.
- Matter was created by pair production.
- We do not understand the physics of the universe before 10^{-43} seconds after it was created.
- Before that, we believe all four forces were unified.
- Gravity "froze out" first, then the strong force, then the weak and electromagnetic forces.

Summary of Chapter 27, (cont.)

- Most helium, and nearly all deuterium, in the Universe was created during primordial nucleosynthesis.
- 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 can be solved by inflation.

Summary of Chapter 27 (cont.)

- 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.