Unit 4: The Evolution of Universe

In Unit 3 we learned about the evidence for the big bang. In this unit we'll do a more detailed telling of the story of the evolution of the universe from the big bang until today. If we were to describe the history of the universe in as short a way as possible, we would probably say something like, "there was a bang about thirteen and a half billion years ago and the universe has been cooling ever since." However since the story is more interesting than that, we'll describe what happens at the various times. Temperature is a central part of the story we'll focus on since it tells us both about the energy of the particles and the atoms in the universe, as well as how big the universe is at any given time. Both things are important because the size of the universe tells us about how often we are likely to get two atoms near each other, and the energy tells us how they will interact.

In some sense, the history of the universe is the story of how the particles have been interacting over time and how they came to form the stars, galaxies and planets today. We'll describe the history of the universe in a number of stages which are:

- The early universe
- The first three minutes
- The next 300,000 years
- The next billion years
- The next ~13 billion years, until today.

Chapter 13 will cover the early universe and the first three minutes. Chapter 14 will cover the rest of the history, until the modern day. In Unit 5 we'll go back and talk about the formation and death of some of the biggest things in the universe: stars, galaxies and black holes. Since many people are interested in the ultimate fate of the universe, and what happened at times closer to the bang itself we'll describe how we think about those issues in Unit 6.

Chapter 13: The Early Universe

Ideally we would start telling the story of the history of the universe at the very beginning, the big bang itself, and then move forward from there. We would maybe even talk about what came before the big bang. Unfortunately, we don't really understand the bang part, what caused the bang, or what was before the big bang. Why not? Well, there are lots of reasons. General relativity can't tell us because it cannot make predictions at infinitely small sizes. Quantum mechanics cannot be the whole story because it does not work in curved space-time. Since the universe appears to have gone through a period when it was in thermal equilibrium it's not obvious how to determine how it all started. The bottom line is that we have a lot of ideas and data, but no conclusive evidence that tells us the whole story. The best we can do at the moment is start by describing the universe a short time after the big bang. The good news is that we have a lot of confidence this part of the story is correct. We can then work our way forward and backward in time from there.

A bang occurs…then what? After the bang, the universe expands and cools. Along the way different things happen as the universe evolves. As we will see, our understanding of how the universe turns into what we have today is dominated by the energy the particles, nuclei, and atoms have when they interact (have collisions). In the last chapter we spent a fair amount of time talking about what happened at early times and then a long time later. In this chapter we'll spend more time on the times in-between and give a short history of time. We start with a quick overview of the whole history, and then step through it in more detail by describing what happens in a number of different chunks of time. We begin with a description of the very early universe, well before the first second after the bang, and then proceed through the first three minutes. In the next chapter we'll talk about the next 300,000 years, the next billion years, and on to about the next thirteen and a half billion years later (now).

13.1 A brief history of time

If asked to describe the history of the universe in as short a way as possible, we would probably say something like, "there was a bang billions of years ago and the universe has been expanding ever since. The temperature has been dropping and eventually the stuff from the bang evolved into the universe we have today with lots of galaxies, stars and black holes." This is shown in Figure 1. Probably the easiest way to describe and remember what happened at any point in time is to remember that as time goes by the energy of the particles goes down, and what can happen in a collision is dictated by the energy of the particles involved. Thus, a description of what is happening in the universe at any given time is essentially what is happening in collisions. The history of our universe is a history of particles banging into each other.

In each collision a number of things can happen. If there is enough energy different types of particles can be created – like what we do in particle accelerators today. For example, two photons can collide and produce an electron and a positron (like in Figure 7 of Chapter 9). Another possibility is that colliding particles can combine to form a composite object such as a proton, neutron, or atom (like Figure 1 of Chapter 12). High energy collisions can also go the other way and break atoms and nuclei apart (like Figures 2 and 3 of Chapter 12). Thus, the energy of the particles and what particles can exist in nature has a huge impact on what happens at any point in time. To understand the history of the universe is to understand what happens as particles collide and interact. Since particles behave the way they do, the history of the universe can essentially be broken down into a couple of different stages. We can roughly categorize them as:

- The early universe
- The first three minutes
- The next 300,000 years
- The next billion years
- The ~13 billion years after that

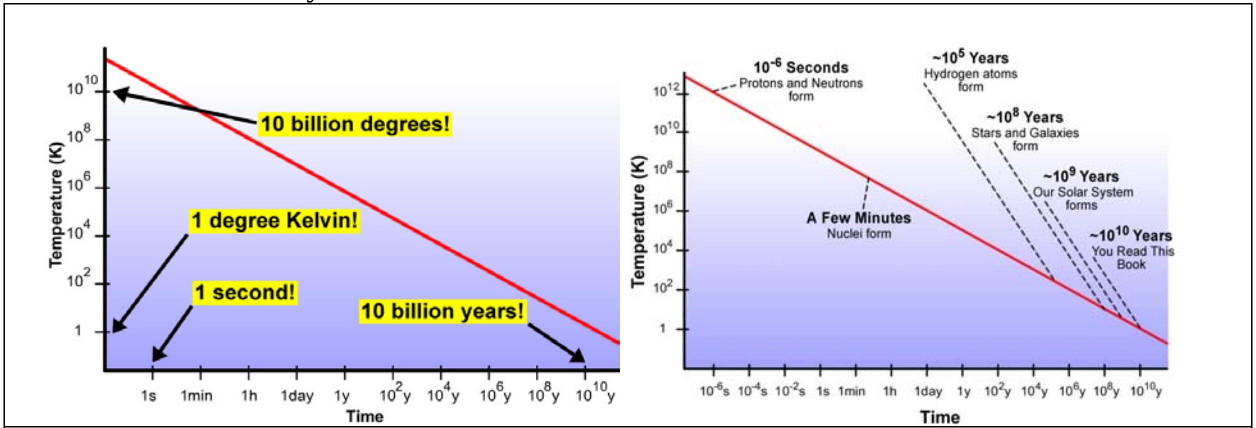


Figure 1: The history of the universe in two different timelines. As time goes by the temperature drops. As the temperature changes different types of particle reactions can occur and different things happen in the universe.

We next we present a brief history of time in a simple table. Next we will talk about the very early universe and what's happening during that time.

How long after the bang	What's happening
Zero	The big bang
One millionth of one second	Quarks combine to form protons and neutrons
A few minutes	Protons and neutrons combine to form deuterium and helium nuclei
A few hundred thousand years	Nuclei and electrons combine to form atoms
100 million to 1 billion years	Lots of atoms combine to form stars and galaxies
9 billion years	Our solar system forms around our star
~13.5 billion years	You read this book

13.2 The very early universe

While we'd like to start our history of the universe with the bang itself, we have to start at some time after the bang. We'll start by describing a time right after the bang, about a millionth of a second after the bang itself. While this may seem like a really short time after the bang, it might surprise you that the universe had already changed an enormous amount before this point in time, and is still changing very quickly.

At about a millionth of a second after the bang the universe was very, very hot (more than a trillion degrees!), and there were a lot of high energy particles moving around. While today most protons and electrons are part of atoms which are part of stars and planets, but back then there were no composite particles. Back then the quarks, photons, and electrons (and all the other fundamental particles) were all moving about by themselves as shown in Figure 2. It's not hard to understand why this is. At a millionth of a second after the bang the universe is really small and the particles are really energetic. Particles can combine, but as shown in the figure they quickly encounter another high energy particle, like a photon, and get broken apart. This is especially true in the very early universe because it was smaller than it is today so all the particles were much closer to each other and more likely to bang into each other.

There are also lots of different types of particles in the early universe that we don't see today in everyday life. Back then the particles were extremely energetic, like the ones produced in the world's highest energy accelerators; Fermilab (outside of Chicago) and the Large Hadron Collider or LHC for short (in Geneva, Switzerland). In these high energy collisions lots of different types of particles, like the ones listed in Table 1 of Chapter 3, are produced. We know from Chapter 9 that when an electron and positron collide they can produce two photons. Similarly, if the photons were energetic enough, they could interact and create an electron and a positron. Another possibility, if the energy is high enough, is that a collision between two high energy photons could create a muon and an anti-muon. We haven't talked much about these particles, but for now think of them as a heavier cousin of the electron, and we'll talk more about them in Chapter 20. Basically, if the energies are high enough we could create any and all the particles in Table 1 of Chapter 3.

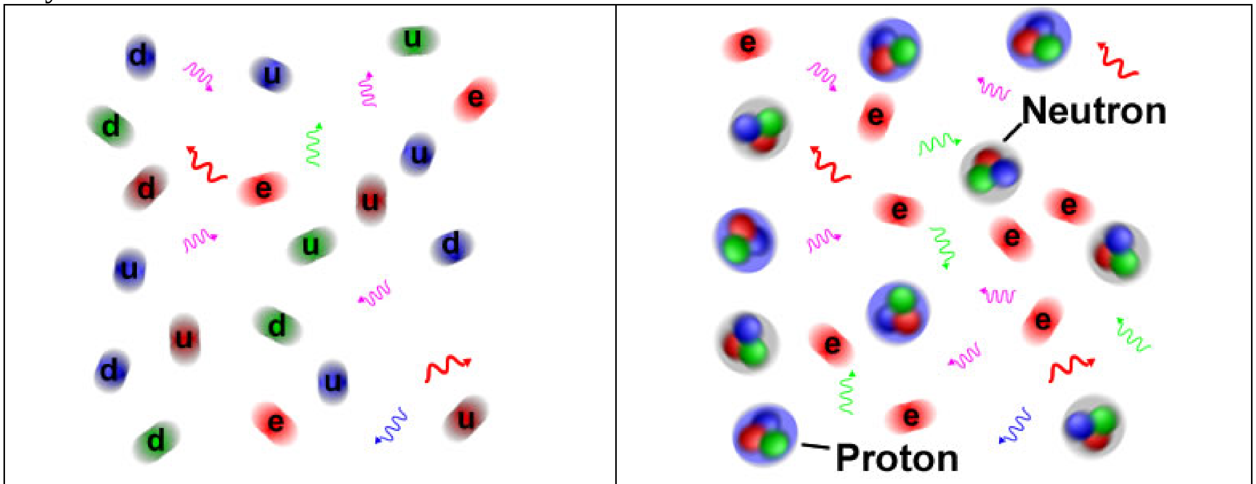
One of the most important ideas is that if these particles *can* exist then they can be produced in high energy collisions, which makes them an important part of the early universe. Figure 3 shows them in action as they join the other particles in thermal equilibrium. In the same way that electron pairs can produce photons, muon pairs can collide and produce photon pairs. In fact, electron and positrons can collide, annihilate and produce a muon and an anti-muon. There are lots of possibilities which are determined by a cosmic roll of the dice since this is quantum mechanics at work.

Because any particle which can exist will eventually be produced in a collision, this makes a full description of the very early universe complicated. A proper description of everything back then requires a full knowledge about what particles can exist in nature and how they interact with all the other particles. We already saw from the list of fundamental particles in Table 1 of Chapter 3 there are a large number of different types. At times earlier than a millionth of a second the energies are so high we can create lots of each type. Thus, what was happening in the very early universe depends critically on what particle can exist in nature. Unfortunately, while scientists have discovered lots of particles and have studied many of them in great detail, we don't know if we have discovered *all* of the fundamental particles. In fact, we have good reasons to believe that there are undiscovered particles out there. However, we need bigger particle accelerators and/or other tools to detect them. The bottom line is that in the very early universe there were lots of different types of particles in thermal equilibrium. For now, we'll concentrate on what happened to the particles we don't typically see any more.

Where did all of the particles, like the muons, go? Why aren't they around anymore? Since we can produce many of these types of particles in particle accelerator experiments we can study them. What we observe is that in a really short time, usually less than 10^{-10} sec, most of them decay into the particles we know like electrons, photons and protons[1]. So, we have two

[1] Neutrons are more complicated since they decay after awhile if they are by themselves, but they are "stable" and live forever if they are inside a nucleus.

types of particles: stable and unstable. The stable ones, like electrons and photons, are still around, and the unstable ones have decayed into the stable ones, which makes the stable ones the only ones left.



Above left: Before a millionth of a second after the bang, the quarks and other particles hang out by themselves in thermal equilibrium. Above right: After a millionth of a second after the bang the photons aren't energetic enough to break apart protons so we have a universe filled with protons and neutrons. Below: During early times quarks can combine to create protons, but because there are so many high energy photons in the universe, they are quickly broken apart.

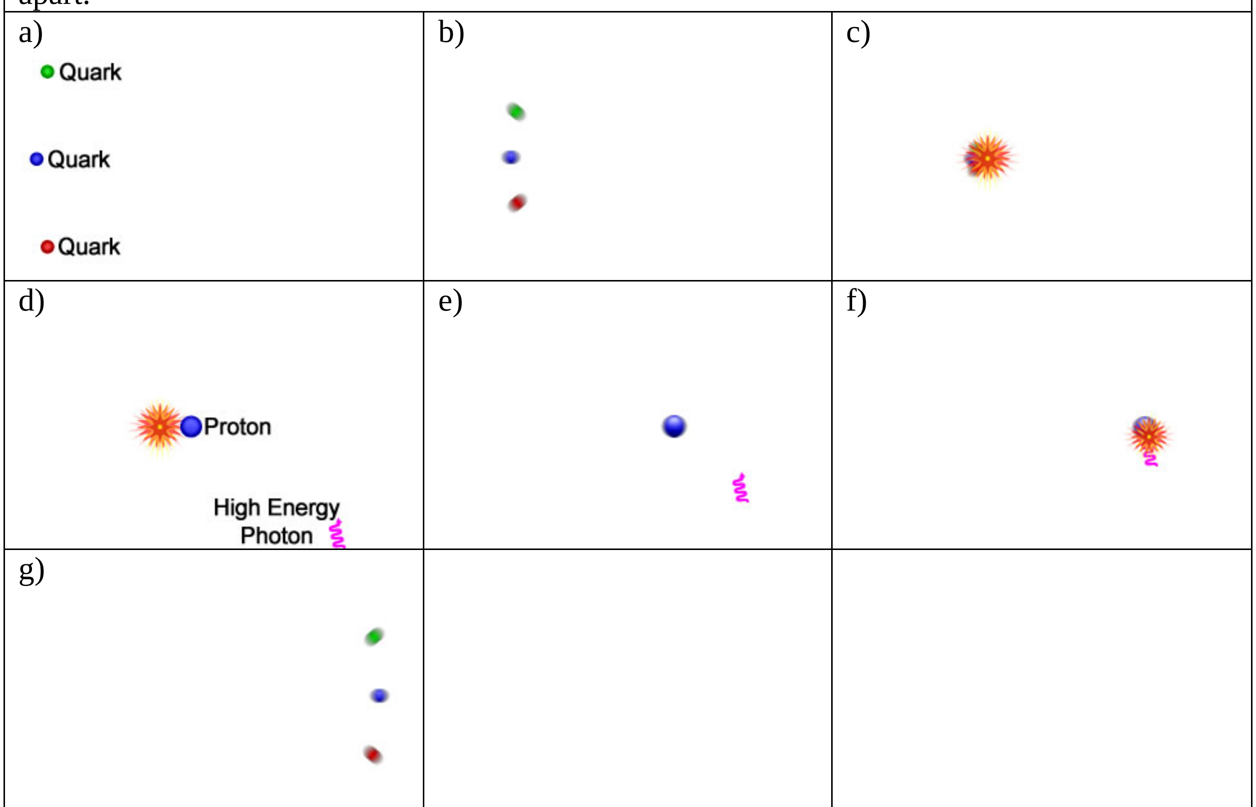


Figure 2: Particles in the very early universe.

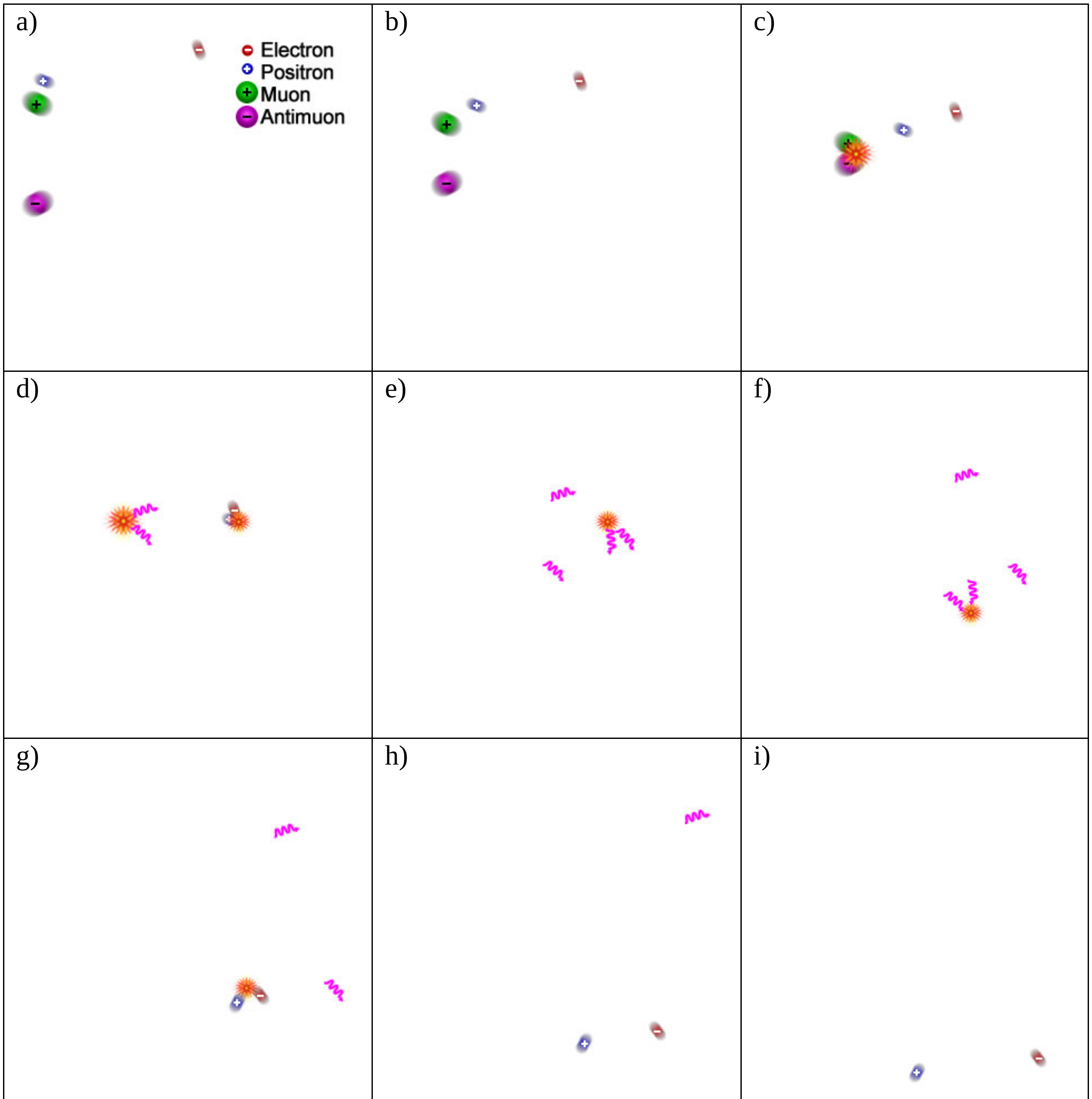


Figure 3: In the early universe the energy of the particles is high enough that there are lots of unstable particles, like muons, in thermal equilibrium. These can interact and produce photons which can, in turn, produce electrons and positrons.

Ultimately, the way we describe the universe at a millionth of a second after the bang is as a hot universe with a large number of different types of particles in thermal equilibrium. It's also changing rapidly. Figure 4 shows an example of our universe as if it were a bathtub with water in it. The amount of water in the tub represents the number of a type of particle in the universe, for example the number of protons. Every tub has a faucet that can put more water into the tub. In our analogy, high energy collisions producing particles would be like the faucet putting more water into the tub. Similarly, every tub has a drain which, by analogy, would be how particles decay or collide and turn into other particles[2]. Ultimately, what's happening with the faucet and drain for each bathtub will determine how much water there is in the tub for that type of particle. Said differently, the energies of the particles and how the particles interact at that energy determine how much of each type of particle there is in the universe at any given time in its history.

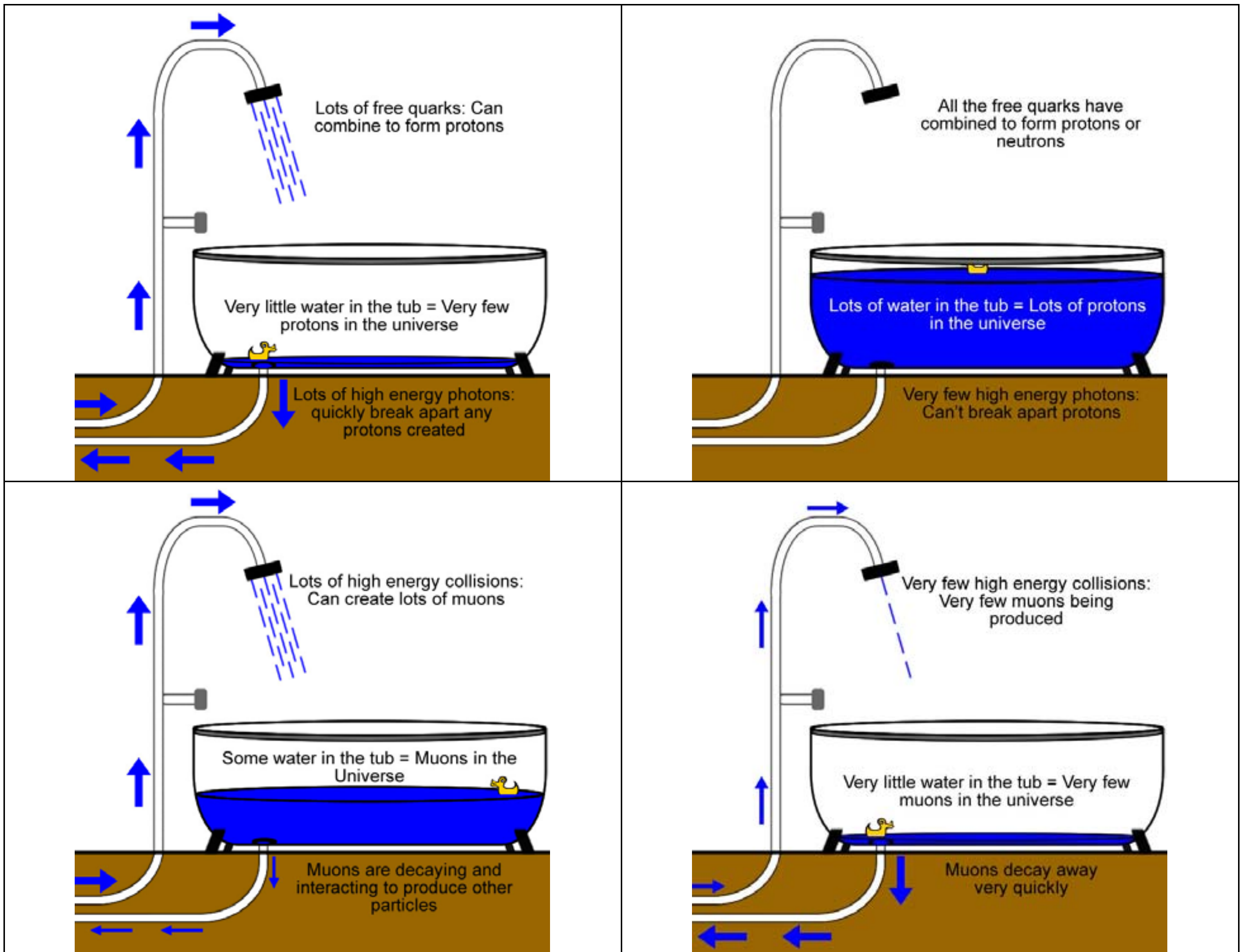


Figure 4: Some pictures of bathtubs that represent the number of particles in the universe. The faucet represents particles being created and the drain represents them decaying or changing into something else in a collision. The top left shows the number of protons before a millionth of a second after the bang; there are lots of quarks that combine to become protons, but they keep getting busted apart in the early universe. Thus, there aren't many in the universe and there isn't much water in the tub. The top right shows a later time, when the universe isn't so hot that the photons don't break up the protons any more. The bottom row shows the same thing but for muons at early and later times.

Let's look at our proton example. In the early universe quarks can collide and combine to form protons, raising the number of protons in the universe; this is the faucet in the figure. Before a millionth of a second there are lots of high energy photons that can break apart any

[2] In essence, this would provide a faucet for a different type of particle.

proton created, thus the drain is draining away protons faster than the faucet is filling the tub. As shown in the figure, for this case there will not be much water in the tub. However, as the universe gets older and colder the average energy of the photons get small enough that the protons don't get broken apart any more. Essentially, the drain in the tub gets closed so the water level rises. This can't keep happening forever. Eventually all the free quarks will be used up, no more are produced and the faucet gets turned off as well. At this point the tub will be as full as it will ever be.

The tub analogy holds for other particles as well. In the very early universe there were lots of different types of particles, stable and unstable, because the high energy collisions created them. An example for muons is also shown in Figure 4. Here there is some water in the tub as high energy collisions produce muons (the faucet), but it never gets too full because the muons are constantly decaying and/or colliding (the drain). As time goes by the temperature of the universe dropped and they stopped getting created, but they kept decaying. By around a millionth of a second after the big bang, the photons weren't energetic enough to make any more muons so it was just a few microseconds before there were almost no muons left in the universe.

We can now understand better why we started our discussion at about a millionth of a second after the big bang. At this time the universe had a temperature where the average energy of the particles was too small to create more unstable particles and too small to break apart protons and neutrons any more. In addition, all the unstable particles like muons already decayed away, and we're left with the lighter, stable particles that we know and love – protons, neutrons, electrons, photons, etc. It's not that this time is special or more important; we just started here since it is just easier to tell the story from here on out.

13.3 A hundredth of a second after the bang

We pick up the story about a hundredth of a second (0.01 seconds or 10^{-2} seconds) after the big bang. The universe expanded and cooled significantly; it's now only about 100 billion degrees. There are no unstable particles left and all the quarks are in protons and neutrons, so the story is simpler to tell. The universe basically only consists of matter (protons, neutrons, electrons, and neutrinos) and photons (also known as radiation).

With all these protons and neutrons in the universe it's natural to think that they might be starting to combine into nuclei. Similarly, with lots of protons and electrons one might expect them to start forming atoms. However, the universe is still very hot and the particles are very energetic. Every time protons and neutrons combine to form a deuterium nucleus, a high-energy photon or electron busts them apart as described in the previous chapters (see Figure 2 of Chapter 12). Similarly, a high-energy photon can break apart any protons and electrons that come together to form a hydrogen atom. It will be awhile before the universe is cool enough for atoms and heavy nuclei to stick around very long.

We make a couple of quick comments on other particles in the universe before we move on. The energy of the particles in the universe is still high enough for there to be lots of positrons produced, so there are still lots of them around. However, since neutrons aren't part of nuclei, they can decay as shown in Figure 5. This means that there will be more protons than neutrons in the universe. It will stay this way for awhile.

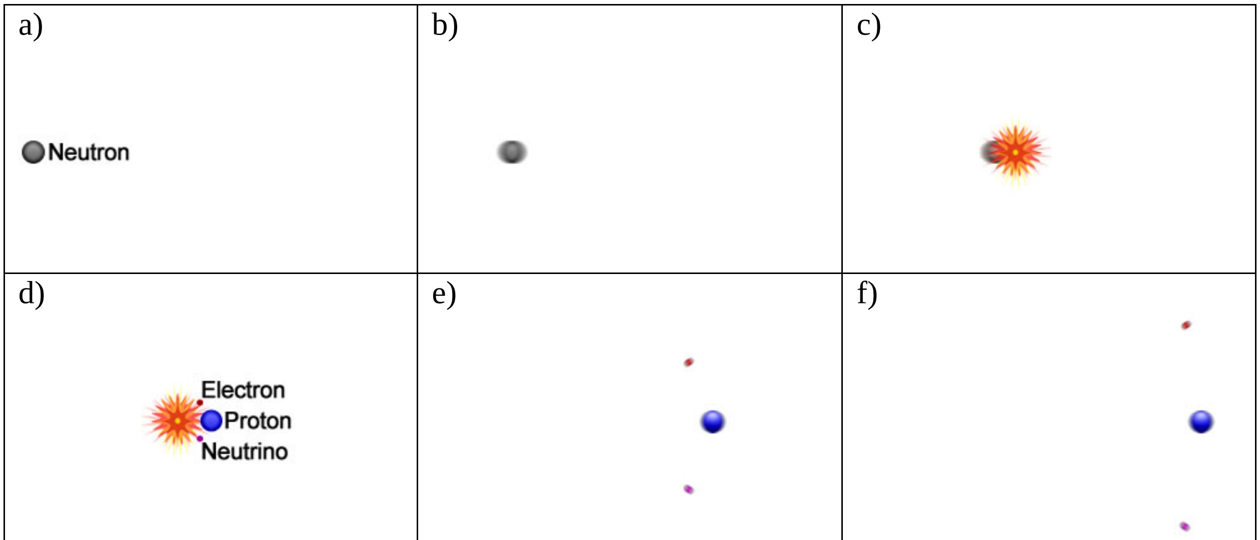
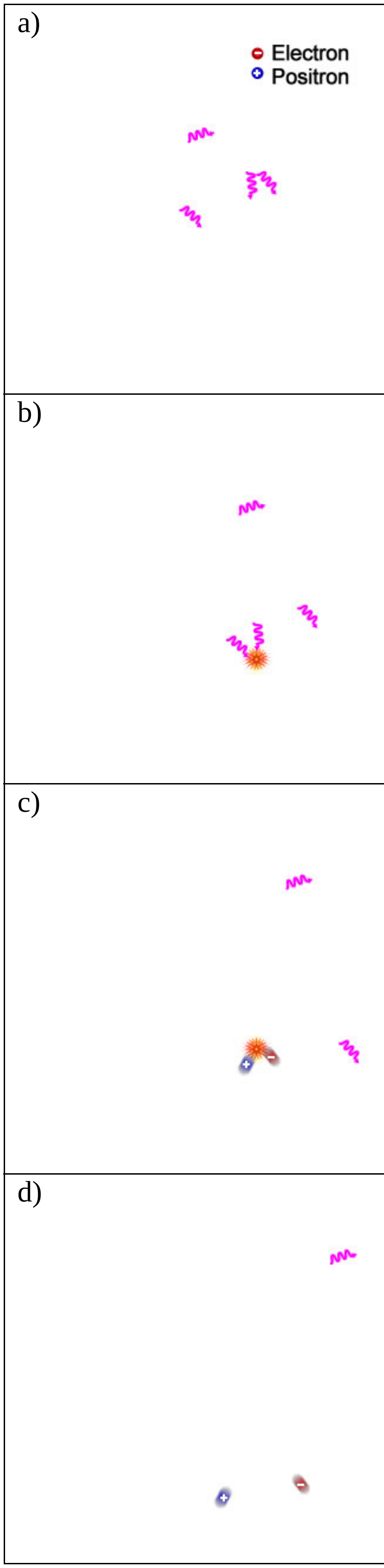


Figure 5: A neutron decaying into a proton, electron and a neutrino.

13.4 Fourteen seconds after the bang

Not much will change until about 14 seconds after the bang, but at that point the universe will start to change dramatically. At this time the universe is only about 3 billion degrees and the temperature is now low enough that photons at these lower energies cannot break apart nuclei. Thus, nuclei such as deuterium can be produced and but not broken up[3]. Another important thing is that photons are now no longer energetic enough to produce electron pairs. Electron pairs can interact and annihilate, but photon pairs no longer turn into particle pairs. This is shown in Figure 6. This causes the number of electrons and positrons to drop rapidly. We continue in the next chapter at the three minute mark.

[3] It is also now cool enough for Helium nuclei, like He_4, to form. However, this doesn't happen too often because it requires that there be enough He_3 in the universe for two of them encounter each other and combine. That takes awhile because it takes a long time for many He_3 to get produced and meanwhile the universe is getting bigger and bigger by the moment meaning the atoms are getting further and further apart as time goes by.



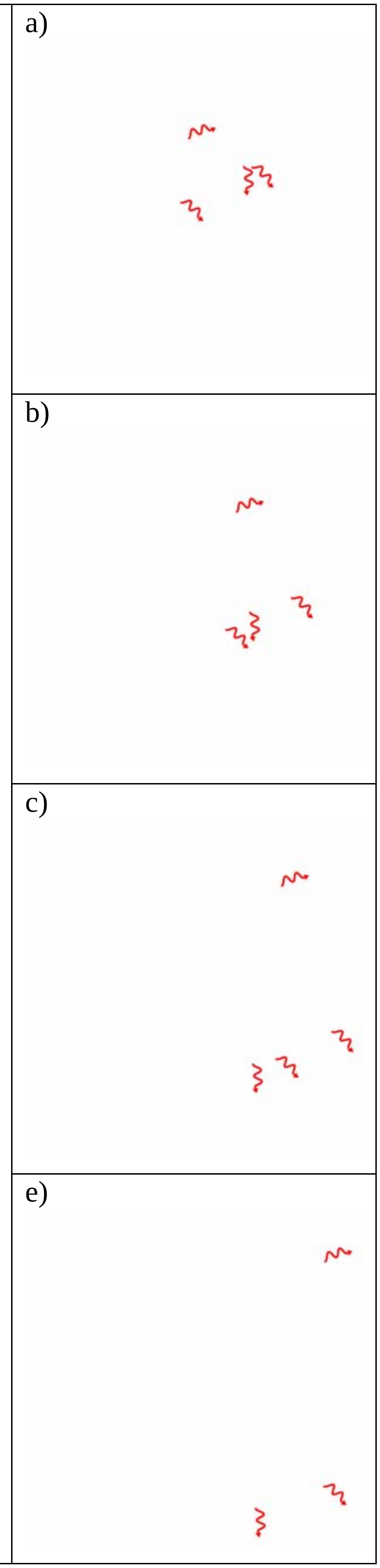


Figure 6: Photons at high and low energies. At very early times after the bang the average photon is energetic enough to produce pairs of particles and anti-particles, like on the left. At later times, like on the right, the photons still interact, but they aren’t energetic enough to produce any type of particles. When this happens the number of that type particle in the universe drops because they can annihilate away, but there is no way for new ones to be produced. At a millionth of a second after the bang, muon pairs are not produced very often any more. At 14 seconds after the bang the photons are no longer energetic enough, on average, to create electrons and positrons. After these times, the number of each of these types of particles in the universe will quickly drop.

Chapter 13: The Early Universe

Problem 13 Problems:

1) Which of the following are present in large amounts at times well before a millionth of a second after the bang? Select all correct answers

A) Free quarks
B) Muons
C) Protons
D) Electron
E) Photons
F) Heavy nuclei
G) Atoms

2) Which of the following are present in large amounts at about a thousandth of a second after the bang? Select all correct answers

A) Free quarks
B) Muons
C) Protons
D) Electron
E) Photons
F) Heavy nuclei
G) Atoms

3) One-hundredth of a second after the big bang what was present in the known universe?

A) Mostly the known elementary particles such as the photon, proton, and neutrino
B) It was at this time the early stars and supermassive black holes formed
C) In addition to wormholes, many posit that this is when the strings of string theory came into existence
D) There is no evidence that can help indicate what could have existed about a hundredth of a second after the big bang

4) At a nanosecond after the bang there were very few protons in the universe because

A) They were all used up in atoms
B) They couldn't be created
C) They were being destroyed as quickly as they were being produced
D) They had all decayed

5) When did there stop being a lot of free quarks in the universe?

A) A nanosecond after the bang
B) A microsecond after the bang
C) A millisecond after the bang
D) A second after the bang
E) Ten seconds after the bang
F) Three minutes after the bang
G) None of the above

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6) When did there start to be lots of atoms in the universe?

A) A nanosecond after the bang
B) A microsecond after the bang
C) A millisecond after the bang
D) A second after the bang
E) Ten seconds after the bang
F) Three minutes after the bang
G) None of the above

7) When did the amount of deuterium start rising quickly?

A) A nanosecond after the bang
B) A microsecond after the bang
C) A millisecond after the bang
D) A second after the bang
E) Ten seconds after the bang
F) Three minutes after the bang
G) None of the above