Transcript from Epic of Evolution: Life, the Earth and the Cosmos (BEP 210A)
April 24, 2000 - Lecture by Claude Bernard

I'll start with the transparency I put up at the end of last time (transparency #11). This shows the three possible shapes for our universe: the so-called closed geometry (spherical shape), the open geometry (saddle shape), or the flat geometry.

Now it's important to keep in mind when you look at these pictures that they are two-dimensional analogues to the real situation. For example, if we say our universe is flat we don't mean that it's a flat two-dimensional sheet; we just mean that it's the three-dimensional analogue of a flat two-dimensional sheet. Obviously we're three-dimensions creatures --- we're not all lying here flat on the floor. To say our universe is flat means our three-dimensional space is flat in the sense of not being curved through higher dimensions.

When we try to draw pictures of curved spaces we need to use one dimension to show how the other two dimensions can curve. Therefore, since we are limited to drawing three-dimensional pictures, the most we can show is a two-dimensional space, possibly curved into the third dimension. The pictures in transparency #11 are of that type. But the real universe is a three-dimensional space, possibly curved.

So what do I mean when I say the observable universe is flat? I mean the space of our observable universe is not curved through higher dimensions. Since we can't observe our universe from outside, from out somewhere in the higher dimension, we have to determine if it's flat or curved by doing experiments within our space. In practice, that means measuring the angles in a very big triangle. If you find that the sum of the angles is 180 degrees that tells you your universe is flat and not curved in one of these other ways.

I described at the end of last lecture how we can measure the angles in a very big triangle. That is a complicated issue and certainly bears more discussion. In the write-up for the April 7th lecture I therefore put in the details very carefully and added a lot of other remarks that I hope will make it clearer to you. So although I won't go through the discussion again now, I urge you to read the transcript from that lecture.

One other thing I want to emphasize about these pictures (transparency #11) is that we're talking about the possible shapes of the entire universe. And by shape I mean the average shape on a very large scale. If you look in great detail --- imagine looking at one these pictures with a microscope --- then of course you would see all kinds of little bumps and wiggles caused by galaxies, clusters of galaxies, individual stars, planets, etc., all of which warp or curve the space around them. So on top of this general, average shape ---which is the average effect of all the matter in the universe ---- there's all kinds of local effects due to individual pieces of matter. We can make an analogy to the Earth represented on a globe, with mountains and valleys shown in relief. The overall shape of the globe is a sphere, but if you look close enough you can see all the bumps and wiggles of the mountains and valleys. Okay, any questions on that? Yes, sir?

[Student: Does this theory only allow for these three?]

That's right. What's involved here is General Relativity --- Einstein's theory of gravity --- plus the assumption that the universe is homogeneous (the same in every place). Assuming General Relativity and homogeneity,* these are the only three possibilities. I can't prove that to you --- it's a complicated mathematical consequence of Einstein's theory --- but that's the result.

[* Note added: Technically, the assumption that the universe is isotropic --- the same in every direction --- is also needed. I won't discuss isotropy because it is "almost" guaranteed once homogeneity is assumed. The logical distinction between isotropy and homogeneity is too subtle to get into here.]

From what I just said, you can understand immediately why the universe doesn't really look exactly like these pictures on small scales: the universe isn't really homogeneous. It's different near me than it is near you; it's different near the sun than it is near Pluto. There's more mass concentrated near the sun, less near Pluto. So there's a little indentation in the space-time near the sun that you don't see on these large-scale pictures. But, as I said last time, if you average over a big enough region, if you set out a big enough net (hundreds of millions of light-years on a side), then the universe is approximately homogeneous. So if you look over very big regions it would have a smooth shape. And these three are the only possible smooth shapes for the universe.

One other thing I said last time is that our patch (the observable universe) is very flat. It's believed by most physicists and cosmologists (but not by all) that this flatness is due to a period of extremely rapid expansion of the universe at early times. The rapid expansion is given the name "inflation," and would have occurred *before* the time (10^{-32} seconds) when I began my story. Remember that I chose 10^{-32} seconds as a time after which we have a pretty good idea of at least the basic features of what happened in the Big Bang.

Now inflation is something that may have happened before 10^{-32} seconds, and therefore it's less certain --- more speculative. There are of course some good reasons to think inflation actually happened, or I wouldn't be bothering you with the idea. We do know a little about the mechanism that *may* have caused inflation, but we know nothing about the details. In fact, from now on you should take everything I say with a grain of salt. These are speculative things, and as we get on in today's lecture it will become more and more speculative. So more and more salt will be needed, and you should be pretty thirsty by the end.

Anyway, it is believed that there was this period of very rapid expansion --- "exponential expansion" is the mathematical term. Before inflation our entire universe would have fit in a very small space (maybe 10^{-35} meters in radius, although estimates vary wildly). During inflation the universe would grow by an enormous factor, say 10^{50}. At the end of inflation (at 10^{-32} seconds) the entire universe might therefore be 10^{15} meters in radius. ($10^{15} = 10^{-35} \times 10^{50}$; 10^{15} meters is a tenth of a light-year.) Now remember that our little observable universe is supposed to be beach-ball sized at this time (at 10^{-32} seconds). A beach ball is less than a meter in radius, which should be compared to the 10^{15} meters size of the entire universe then.

So the inflation picture would indicate that our observable universe is only a tiny patch on a huge universe. Now a small patch on a big curved surface always looks pretty darn flat. For example, we live on a curved surface, the surface of the Earth, yet in a small region (out in the Quad or even in the whole state of Missouri) you don't notice very much that the Earth is curved. It's only when you look at very big distances that you start to observe the effects of curvature. So inflation would explain the flatness of our observable universe: it's flat because it's only a very tiny part of an enormous space.

And that's why I said last time that we don't know --- or are we likely to know anytime soon --- which of these three geometries describe the entire universe. Because our little patch is so small in comparison to the entire universe, our patch will be very flat no matter what shape the entire universe takes. Ursula?

[Ursula: Is inflation supposed to have occurred just at that time, 10^{-32} seconds?]

Inflation probably began at something like 10^{-34} or 10^{-35} seconds, and ended at 10^{-32} seconds. So it ended at the time I began our story before. But in that tiny fraction of a second, the universe may have undergone something like a 100 or 200 doublings. That's an enormous exponential growth.

[Ursula: When you say very rapid, are you talking about faster than the speed of light?]

Well, when you're talking about the whole space, that's not really a question that you get to ask because space can expand, and you can't measure the speed of space. Yes it is true, though, that this very rapid expansion means that the distance between two points that were close to each other could increase much faster than the speed of light. It doesn't violate Einstein's Relativity, however, but you have to work at it to understand why. Judy?

[Student: I'm just trying to get a visual picture for what this inflation would be like. Where did we did start when inflation began?]

Well, our observable universe is a beach-ball sized object at the end of inflation, 10^{-32} seconds. So at the beginning of inflation (10^{-34} or 10^{-35} seconds) our observable universe would have been an extremely tiny dot, maybe 10^{-50} meters in radius. That is much smaller than a nucleus of an atom. In fact that dot is to the nucleus of an atom as the nucleus of an atom is to the entire Milky Way galaxy! In the short period of inflation, that dot becomes a beach ball. And in the time since the end of inflation until now, that beach ball has become the current observable universe, about 40 billion light-years in radius.

Now the entire universe is much bigger than the observable universe, maybe 10^{15} (a thousand trillion) times bigger. At the beginning of inflation, the entire universe is also very small but still a thousand trillion times bigger than the dot we just talked about. At the end of inflation, when the current observable universe was a beach ball, the entire universe was maybe a tenth of a light year in radius, again a thousand trillion times bigger than the observable universe.

Let's go back to the analogy of the universe to a balloon being blown up. Then inflation would be a period where the balloon is very small but being blown up very rapidly. (I couldn't find my old blue universe so we have a yellow universe now.) Obviously I'm not going to be able to blow it up extremely fast, but let me blow it up as fast as I can to give you an idea. The red circle represents our observable universe, a small patch on the balloon. You can see that as the balloon gets bigger and bigger the small patch gets more and more flat.

Thus inflation gives some understanding of why our observable patch is so flat: Although the universe started extremely small, it inflated so rapidly at the beginning that it has become truly enormous. Our current observable patch, a mere 40 billion light years or so in radius, is thus just a tiny part of the whole thing, and is therefore very flat. Of course, if that were the only reason for believing in inflation, it wouldn't be very convincing. However there is a considerable amount of additional evidence for inflation, which I won't get into. But as I said it's still not proven by any means.

Another thing I said last time is that the shape of the entire universe is closely related to the average density of energy within the universe. Similarly, if we just focus on our observable universe, we can say that the shape of the observable universe is closely related to the average density of energy within the observable universe. Now there's a special density of energy called the "critical density," which we can calculate. [Note added: The critical density can be calculated only if we first know the Hubble constant, which relates the recessional speed of galaxies to their distance from us. So the Hubble constant needs to be measured, but that has been done.]

There are three possibilities. If the actual density of energy is greater than the critical density then we have the "closed geometry," a sphere-like shape. If the density of energy is less than the critical density we have the "open geometry," the saddle-like shape. And if the density is equal to the critical density, we have the flat situation. (The relation between the shape of space and the density of energy comes from Einstein's equations of General Relativity.)

Now all evidence says that our little patch is extremely flat. Therefore the experiments that tell us that our patch is flat also tell us that the density of energy in the observable universe is the critical density (or very, very close to the critical density). So we know (assuming the experiments are not in error and that there is nothing wrong with General Relativity) the average energy density in the observable universe. Since we also know the size of the observable universe, knowing the average energy density is equivalent to knowing the total amount of energy. Since mass and energy are basically the same thing, we can also say we know the total mass of our universe.

[Student: The critical density tells us how much energy there is?]

The fact that the observable universe is flat tells us that the actual energy density is equal to the critical density. The critical density is something that can be calculated (assuming we know the Hubble constant, which we do). So we know what the critical density is and we know that our universe has that critical amount of energy in it.

Well if all this makes sense, we should be able to measure the energy density directly and check that it is equal to the critical energy density. Measuring the energy density "directly" just means seeing how much there is of each possible various forms of energy or mass and adding up the total. In fact, there's been a big effort in the last few years to see where all this energy is.

Let's make a table of the various types of energy or mass and how much they contribute (expressed as a percentage) to the total energy of the observable universe.

Type of energy	**percent of the total**

And I reiterate that we know what the total energy density of our observable universe is (assuming there are no mistakes in the experiments, some of which are rather recent and therefore aren't checked very well yet.) Hopefully when you add up all the percentages it should add up to 100 percent.

Well, to start with, one expects that a lot of the mass of the universe is just ordinary matter. The technical term for ordinary matter is "baryonic matter." Remember that a baryon is a proton or a neutron. So when you say something is baryonic it means "made out of protons and neutrons." Since protons and neutrons make up the nucleus of an ordinary atom and since the nucleus is more than 99.9 percent of the mass of an atom, it makes sense to call ordinary matter "baryonic."

How much of the total energy density in the universe is made out of ordinary baryonic matter? Well, actually there are two categories of baryonic matter. One, which we see very directly, is what's called "luminous matter." Luminous matter is matter that shines --- namely stars. And if you look you can see there are maybe 100 billion galaxies out there and each galaxy has roughly 100 billion stars.

If you add up the mass of all those stars, what do you get? You get only 1 percent of the total that we're aiming for. So all the matter in all the stars is only approximately 1 percent of the total energy in the universe.

Well, maybe additional ordinary matter makes up objects that aren't shining --- non-luminous baryonic matter. What could that be? Well, actually most of it is probably just gas: hydrogen or helium gas left over from the Big Bang that hasn't condensed yet into stars or galaxies. So it could be intergalactic gas or interstellar gas (the second one is less important). There may also be a certain amount concentrated in planet-sized objects, which go by the weird name "MACHOs." You don't have to remember this, but MACHOs stands for MAssive Compact Halo Objects. (You'll see why they tried to name something MACHOs in a little while.) Ordinary matter concentrated into planet-sized objects (maybe the roughly the size of Jupiter) would not be that easy to observe. After all Jupiter isn't big enough to be a star so it's dark --- it doesn't make light, it just reflects a little of the sun's light.

But with various techniques we've actually been able to estimate how much non-luminous baryonic matter there is. You can observe intergalactic gas in some places because you can see the light from galaxies bouncing off it or being absorbed by it. You can observe MACHOs by looking at their gravitational lensing effects. When you add it all up, it comes to about 4 percent. That means that ordinary baryonic matter (the matter we know and love, which makes us up) is only about 5 percent (1 percent plus 4 percent) of the total energy of the universe.

There's actually a cross check on the total of 5% in baryonic matter. Recall that in the period of Big Bang nucleosynthesis, some protons combine with neutrons to make helium nuclei. At the end of this period, the neutrons are all gone (any of them that don't go into helium just decay), and we're left primarily with protons and helium nuclei, in a ratio of about 75% to 25%. Now the fractional amount of helium made depends on the density of protons and neutrons initially --- if the protons and neutrons were closer together more of them would hit and make helium. So the 25% fraction of helium made tells us something about the density of baryons in the early universe, which we can use to calculate the energy density in baryons now. The result is about 5% of the total (critical) density! This is very good evidence that we haven't left out any baryonic matter in our inventory.

Our table now looks like this:

Type of energy	**percent of the total**
Baryonic matter Luminous: 1% Non-luminous: 4%	5%

So there's a lot of stuff out there that we don't know much about, again assuming that all our logic and all our experiments are correct. Now if our patch weren't known to be flat, then one could suppose that there is *only* baryonic matter out there, making up 5% of the critical density. In that case we would deduce that our observable is curved like a saddle (open geometry, density less than critical density). And that was a logical possibility up until a few years ago. But as the experiments show more and more that our patch is flat, that becomes less and less of a logical possibility. The density therefore must be equal to the known critical density.

What else could be out there? Well, actually we have some direct evidence for other kinds of matter. The evidence comes looking at how fast stars revolve around the center of a galaxy. The observations have been made for various galaxies, including our own. Just as planets revolve around the sun, a galaxy is rotating and the stars revolve around the center of the galaxy. And you can measure how fast they're moving around the center and that actually tells you something important.

Let me just give you the general idea first: How fast the stars move around the center of the galaxies tells you how much mass there is in the galaxy. The result is that there's more mass in the galaxy than is just accounted for by stars or by the interstellar gas or by the MACHOs in the galaxy.

In more detail, this argument has to do with a fundamental property of gravity, which was proved first by Newton. Think about the sun: The sun of course has a gravitational effect on all the planets that revolve around it. Also, the sun is to very good approximation a spherical object --- like a ball.   What Newton proved is that whenever you have a spherical distribution of matter like the sun, its gravitational effect on objects revolving around it is the same as if the sun were entirely concentrated at its center.   In other words, it would make no difference in the orbits of the planets if the sun were removed and replaced by a highly compressed object of equal mass located at the old sun's center. Of course the sun it isn't concentrated at the center but as far as its gravitational effect goes the two are equivalent.

When Newton first developed his theory of gravity he needed to know how far away the planets were from the sun, in order to compute the orbital speed of the planets. And when you start asking that question you get confused immediately. What do you mean by how far is the planet from the sun? Do you mean how far is it from the nearest part of the sun? Do you mean how far is it from the furthest part of the sun? Do you mean how far is it from this part or that part?

Newton was able to prove that what matters is the planet's distance to the center of the sun, so the gravitational effects would be the same if the sun were concentrated at its center. It wasn't easy to prove; it took him 20 years. He held up publication of his book about forces and gravity (the Principia) for those 20 years until he completed his proof.   It took a while --- even though he was smart --- because he had to invent integral calculus in order to do it. (He didn't just have to take integral calculus; he had to invent it!)

The same techniques can be used to prove a related fact. It wasn't relevant to Newton's computations of the planets' orbits, but is it relevant to us now. Suppose you have a spherical shell of matter, like a rubber ball that is hollow inside. (See Figure 1.)   Instead of asking about

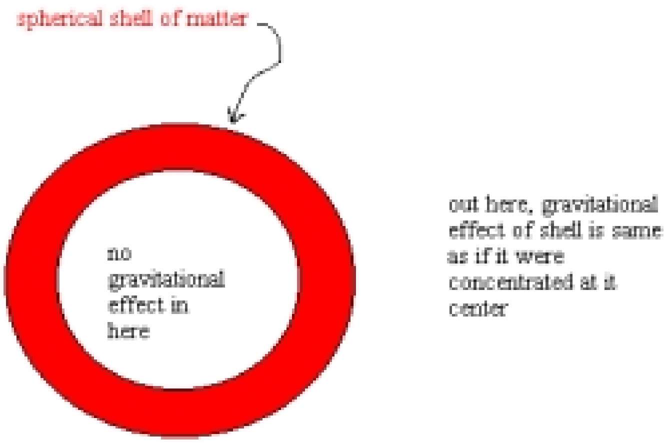

Figure 1: Gravitational effects of a spherical shell of matter.

the gravitational effect outside the shell (the effect on something orbiting around it), you can ask about the gravitational effect on something *inside* the shell. By Newton's techniques you can show that there's *no* gravitational effect inside the shell.

[Student: I'm sorry, what exactly does that inner circle represent?]

Instead of talking about a solid sphere of matter, I'm talking about a hollow shell with a certain thickness. The matter in the shell is colored red in the picture, and the inner and outer circles represent the inner and outer surfaces of the shell.

The fact that there's no gravitational effect inside has to do with a cancellation: If an object is inside the shell it will be attracted in different directions by different parts of the shell. The net result is that all the pulls in different directions cancel, and there's no gravity at all inside a spherical shell. That's not obvious, but it's another thing that you could prove with integral calculus. Of course, I've already said what would happen outside. Outside, there *will* be a gravitational effect, and the shell will act as if it's concentrated at its center.

[Student: What would be the effect inside the solid part of the shell itself?]

If you're inside the solid part of the shell, then it helps to think of the shell as being composed of two parts. (See Figure 2.) There's the part of the shell that's closer to the center than you are (blue in the figure) and the part of the shell that's further form the center than you are (green in the figure). Now, since you're outside the blue part, it acts as if it is concentrated at the center, and you feel its gravitational effect. On the other hand, since you're *inside* the green part it has no gravitational effect on you at all.

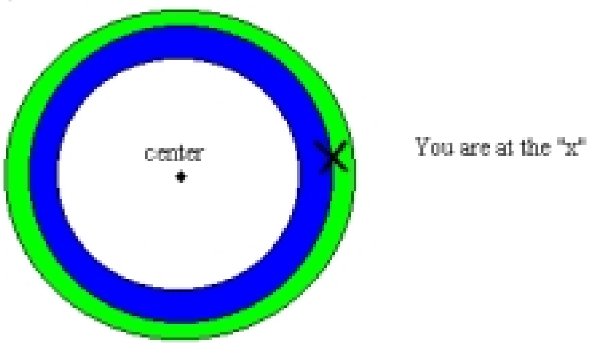

Figure 2: Effect of gravity inside the solid part of a shell.

Let me show you a graph of the revolution speeds of planets around the sun (transparency #12). This plots how fast various planets are moving versus their distance from the sun. The details are not important. What is important is that when a planet is further from the sun, its speed around the sun is less. That's just because the gravitational effect of the sun decreases the further you are from it. The exact amount can be computed and is shown by the curved line in the transparency. It goes right through all the points, representing each of the planets. To compute that line you have to use the fact that the sun acts as if it's concentrated at its center. So when they say the distance from the sun they really mean the distance from the center of the sun.

Now suppose that our solar system were different. Instead of just having the sun at the center, imagine that there was some additional matter that was attracting the planets. Picture this extra matter as being some kind of thin "dust" filling the space around the sun all the way out to Pluto. If that were the case, the planets would move differently because different planets would be affected by different amounts of dust. Look at Figure 3. Planet A is affected by the sun and by

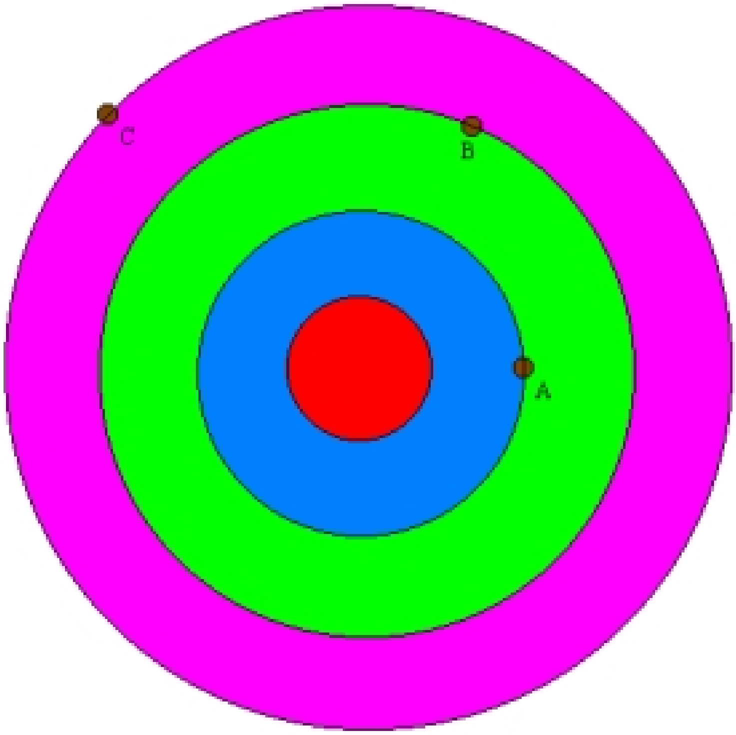

Figure 3: Planetary orbits in a solar system with a sun (red) plus dust (variously colored blue, green, or pink). The planets are the small brown circles and are labeled A, B, or C.

the "blue" part of the dust, but not the "green" part or the "pink" parts. Planet B is affected by the blue and green parts, but not the pink part. And planet C is affected by all three parts of the dust. A planet is only affected by that part of the dust that is inside its orbit; dust further from the center of the solar system than the planet is irrelevant to that planet.

Thus, the normal tendency of a planet that's further from the sun to orbit more slowly would be counteracted by the gravitational effect of the additional dust inside the planet's orbit. It would be as if a distant planet was orbiting a star with more mass than that orbited by a close-in planet. The dashed line in transparency #12 shows how orbital speed in a dust filled solar system would depend on distance from the center. The speeds would no longer fall with distance; they would instead be almost constant with distance, maybe even with some increase because each further planet would be affected by the mass of more and more dust.

Of course, the actual speeds of planets in our solar system fit perfectly with the assumption that just the sun is affecting their motion (the solid line in transparency #12). That is good evidence that there is no dust (or very little) in the solar system. We just have the sun, which acts as if it's concentrated at the center. Austen?

[Student: Does the speed of revolution about the sun affect any conditions on the surface?]

Conditions?

[Student: Maybe like weather conditions.]

Yes. I guess it could affect everything on the planet in some indirect way because the length of the year is different. Any seasons would be shorter or longer depending on how fast it took to go around, and that would affect climate. For example, if all seasons were shortened, the planet wouldn't have as much time to heat up (in summer) and cool off (in winter) so the weather would be more temperate, with fewer extremes. So everything would be different in that way.

Okay, now let's look at the same kind of plot for the Milky Way, instead of for the solar system (transparency #13). The plot starts with the sun, which revolves around the center of our galaxy, and then shows objects that are further out from the center of our galaxy than the sun. Now almost all of the stars in our galaxy are located near the galactic center (and there is also a black hole at the center, as we discussed previously). If the mass of our galaxy was just due those objects we can observe (stars + black hole) then the sun and any objects further from the center would all be orbiting approximately the same amount of mass at the galactic center. We would then get a curve of orbital speed versus distance that would look very much like what is actually observed in the solar system --- speed decreasing with distance from the center. That curve is shown as a solid line in transparency #13.

But if you look at the measured speeds of various objects, you see that the speed doesn't decrease with distance. The measured speeds are actually fairly constant with increasing distance, which means that as things are further and further from the center of our galaxy, they're actually affected by more and more mass. There must be a lot of mass in our galaxy that is not located near the galactic center. It's not the mass of the stars because the stars are primarily near the center. (We can see them!)

There's something else out there. It acts like "dust" spread throughout our galaxy, but it isn't dust made of ordinary baryonic matter. Such dust would be observable because it would absorb light. There's something else that has a gravitational attraction for ordinary matter, but isn't ordinary matter.

Okay, I did that relatively fast but I hope you get some of the flavor of it anyway. Any questions?

[Student: So you mean the objects further out in our galaxy have the same orbital velocity?]

Yes, they have pretty much the same velocity. In order for them to remain at the same velocity even though their distance from the galactic center is increasing, there must be more and more matter affecting them. As you go out further and further more of that matter is inside your orbit and therefore having an effect on your orbit.

Now, what is this extra stuff? As I said, it's not ordinary baryonic matter. We can eliminate that because we can observe at least fairly well how much ordinary matter there is. And this extra matter is also in other galaxies. If you make the same type of observations on other galaxies you find the same effect: orbital speed not decreasing with distance from the galactic center.

So we know there's a lot of extra matter. But beyond that, we know very little about it. It's sometimes called Cold Dark Matter. "Dark" is obvious: it's not making stars so it's not emitting any light. Why do we call it "cold?" Well, let's go back to something I talked about before. Remember that in the early universe the photons can't condense gravitationally because they move very fast. Photons are bouncing off things very rapidly, always pushing outward, so they do not condense into galaxies and in fact prevent the condensation of ordinary matter. It's only at the time of decoupling, when photons stop interacting with matter, that matter itself can condense.

The fact that this Dark Matter, whatever it is, has condensed around galaxies means that it's not moving fast like photons. It must be moving relatively slowly. Now things that are hot move rapidly; things that are cold move slowly. So this Dark Matter must be Cold. Let me add Cold Dark Matter to my table.

I'll give you some suggestions for what Cold Dark Matter is, but I won't explain these in detail. For one thing, although we have some ideas, there's really very little evidence for any one of these specific suggestions. It might be something called "WIMPs." A WIMP is a Weakly Interacting Massive Particle. (These guys have a lot of fun when they get to name stuff; the term MACHO, which I mentioned earlier, was chosen to contrast with WIMP.) These hypothetical particles would need to be massive so they would move slowly and therefore be "cold." They would have to be weakly interacting so they would have only a small chance of interacting with "anti-WIMPS" and getting annihilated in the Big Bang.

Other suggestions for Cold Dark Matter include "axions," "magnetic monopoles," "cosmic walls," and "primordial black holes." We really don't know. It has even been suggested --- I read this in a paper last week ---- that it might be "shadow matter." Shadow matter would be matter from some other "shadow universe" that is located off in a different dimension from ours. Matter in our universe supposedly only interacts gravitationally with matter in that universe --- the extra attraction we observe on objects in our galaxy would be the gravitational pull of stuff in the shadow universe!

There's not a shred of hard evidence for any of these suggestions at the moment. But you can look at these curves of the rotation of galaxies, and you can ask what the total amount of Cold Dark Matter is. For a while people were hoping it would be 95 percent. That would have been easier, but actually it's only about 35 percent. So 35 percent is Cold Dark Matter, 5 percent is ordinary baryonic matter:

Type of energy	**percent of the total**
Baryonic matter Luminous: 1% Non-luminous: 4%	5%
Cold Dark Matter (WIMPs, axions, magnetic monopoles, cosmic walls, shadow matter???)	35%

What's the rest? It gets even weirder. The additional energy cannot be clumped around galaxies because then it would have an additional affect on the orbital speeds, which is not observed. One possibility would be something called "vacuum energy." In ordinary life we think of the vacuum as a region where there's nothing. However, that's not the way physicists think of it. We describe the vacuum as just being the state that has the lowest possible energy. But just because it's the state of lowest energy doesn't mean that nothing is going on there. In fact, the vacuum contains what are known as "quantum fluctuations:" Particles can appear for a short periods of time and then disappear again. The vacuum is actually seething. The quantum fluctuations can have energy and they can affect things.

If vacuum energy were present it would cause the expansion of the universe to accelerate. I had prepared a vague explanation of the acceleration, but I don't have time to discuss it. It wouldn't have been very convincing anyway! You really have to know all about General Relativity to understand why vacuum energy would cause an acceleration of the expansion of the universe.

The amazing thing is that in the last 2 years astronomers have found pretty good evidence that the universe's expansion is actually accelerating. In other words, not only are things far away from us receding from us, but the speed of recession of a given galaxy is actually increasing with time. That sounds totally weird but it seems to be the case. They're actually speeding up, going faster away from us each year.

You can ask how much vacuum energy would be needed to explain the acceleration that's been observed. It is in fact about 60 percent of the critical density, roughly consistent with what we would need to explain the whole energy of the universe. So if you buy all this, you have a completed table:

Type of energy	**percent of the total**
Baryonic matter Luminous: 1% Non-luminous: 4%	5%
Cold Dark Matter (WIMPs, axions, magnetic monopoles, cosmic walls, shadow matter???)	35% (?)
Vacuum energy (or related things like quintessence.)	60% (??)

("Quintessence" is something like vacuum energy but can change with time.)

Another interesting feature of vacuum energy is that it could have caused the period of inflation in the very early universe. Unfortunately, what's needed in the early universe is a totally different amount of vacuum energy than seems to be present now --- so how that fits in with the current accelerated expansion is a mystery.

Now, as I said, this is all pretty speculative. The evidence that the universe is accelerating is pretty good but not ironclad. Another problem with vacuum energy is that we have not the slightest idea why it should have the "observed" amount of energy --- 60% of the total energy density. A computation using our current understanding of the laws of quantum mechanics says that the vacuum energy should be about 10^{120} times bigger than the 60% observed. Off by 120 orders of magnitude --- that has to be the biggest mistake in the history of humanity!

It may be that vacuum energy ideas will ultimately explain the origin of the universe. Perhaps in some previous universe, not ours, there was a little quantum fluctuation, a tiny variation like you can have in a vacuum. If that happened in just the right way it could have created a little bit of vacuum energy. Then that region with that little bit of vacuum energy would have undergone very rapid, accelerating expansion. And eventually that little region would have become our universe. So there's one vague idea of where our universe came from.

Transparency #14, which I don't have time to explain (and which you are therefore not responsible for), shows a possible formation of such a "child universe." If you want read more about it, look at the chapters 1 and 16 of the book by Alan Guth, <u>The Inflationary Universe</u> (on the library reserve list). Guth calls the process by which the universe might have formed "the ultimate free lunch" because everything would have come out of the vacuum, that is, out of "nothing."

Well, as you see it's all pretty weird. There is so much we really don't know. I wouldn't be very surprised if much of what I've said in today's lecture gets radically revised in the coming years. (I do want to contrast that with what I've described earlier in the course, which is considerably more solid.)

I also want to remind you that just because all this is weird doesn't mean that everything you hear that's weird is true. Truth may be stranger than fiction, but that doesn't mean that everything strange is true. Don't go investing your money in "vitamin O" or psychics or perpetual motion machines or devices that extract unlimited amounts of energy from seawater!

As you're leave take a look at this little video put together from Hubble Space Telescope pictures. This is a "deep field view," which means a view as far out as the telescope can see in a tiny region of the sky. This region of the sky could be covered by a grain of sand held it at arms length. All these little points of light are galaxies. This is what the universe is like.

After a couple of minutes the video zooms through the region. In other words, they can compute how far away each of these galaxies is (by its red shift) and then, by special effects, make it look like you're zooming along, going by the various galaxies.

[Student: Like they do on Star Trek?]

Right, but this is cooler because this is real.

[Student: What about the colors?]

The colors are enhanced. The Hubble can take pictures not only with visible light but also with infrared, ultraviolet, and other wavelengths. They take those different pictures and they show them here as different colors. So one that's red is actually shining brightly with infrared light. And one that's blue gives off a lot of ultraviolet light. So if you could just look at it with your naked eye it wouldn't look like that. You would see these objects but you wouldn't see the colors.

[end of lecture]