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NICHOLAS Last week I talked about the basics of the Big Bang Theory, which essentially says that there was a beginning of time. We call it the Big Bang. And at this moment in time every piece of matter and energy in the whole universe was concentrated at a single point. So the density of the universe was extremely high, in fact, in principle, infinite. And the temperature of the universe was also much higher because, as we discussed last time, when you compress something it gets hotter. So if you rewind the history of the universe to the very beginning, the universe will be very, very hot and at the Big Bang should, in principle, be infinite. And then after the Big Bang the universe has-- universe started to expand, and expand, expand and here we find ourselves today. Does anyone have any questions about-- yes.

DIBELLA:

AUDIENCE: If it's at that high temperature and all that matter in the universe compressed into [? a neutron, ?] whatever-- wouldn't it create some sort of fusion or something [INAUDIBLE]?

NICHOLAS Oh, well, yeah, so very early in-- very early-- so the question is since the temperature is so high and the early universe, wouldn't all the atom-- all the nuclei fuse together and--

DIBELLA:

AUDIENCE: Yes, yes.

NICHOLAS Oh, yeah. That's exactly what happens. In the very early universe you start off bas-- you start off with protons and electrons and so forth. And these protons, when you go back far enough in time-- these protons-- yeah, because the temperature is so high they're going to be so energetic that they literally fuse with each other. And so you form-- you start to form the light elements. So a proton and proton will form a deuterium atom. So that's an isotope of-- well, they will form atoms yet. They'll form a deuterium nucleus. So that's a two-proton nucleus. And then a two-proton nucleus could collide with a very energetic proton, then form a three-proton nucleus and so forth and so forth. And this-- yeah, this happens in the very early universe. It's called the big bang nucleosynthesis era.

Because this is where nuclei were being created and you can actually-- you can actually calculate the abundances-- the proportions of elements-- of that light elements that were created in this era. And then you can compare it with the abundances that you actually observe it by looking at stars and stuff in the sky. And you actually find amazing agreement with the Big Bang-- the Big Bang model. And-- so that's also very good evidence for the Big

Bang. So last time I talked about the existence of-- yeah?

AUDIENCE: [INAUDIBLE] it's just weird [INAUDIBLE] fusion of all this matter into one area [INAUDIBLE] why would it explode?

NICHOLAS Why would it-- so why-- so why the bang? What banged? How did it bang?

DIBELLA:

AUDIENCE: [INAUDIBLE] explode if it's in the process of heating right [INAUDIBLE] in such a small area-- the temperature [INAUDIBLE]?

NICHOLAS Why would it explode?

DIBELLA:

AUDIENCE: Yeah, why would all of the matter shoot [INAUDIBLE].

NICHOLAS Yeah, so-- I like-- essentially your question is why the bang?

DIBELLA:

AUDIENCE: Yeah.

NICHOLAS Yeah, that's something I'll come to later. Yeah. Any other questions? Yes.

DIBELLA:

AUDIENCE: If the space between galaxies expanding-- is expanding why isn't the space inside the galaxies?

NICHOLAS Why isn't the space inside, yeah, so the-- I'm just repeating the questions because

DIBELLA: microphone's here, so the question is if the space between the galaxies is increasing, then why isn't the space between people increasing, for example. There's a funny quote from a Woody Allen why isn't-- I forget the exact quote-- but the gist of it is Brooklyn is expanding. Yes. So your question is why-- yeah, so your question is, why aren't objects that we see around us expanding?

And the answer is that-- so this expansion-- the physical theory that describes this expansion is general relativity. Which I'll describe in a little bit. And the expansion only applies over a large scales. When you actually work it out it only applies over large scales. The equation that you write down are only valid for large things like galaxies and the large structure of the universe. And to describe smaller things-- to describe stars or even a single galaxy, the

equation that you use in describing the whole universe are no longer valid. And so you have to use others-- other equations. And when you use those equations, you don't get that space is expanding. You have to-- yeah, so real-- so if you want to describe everything in the universe-- have to patch together these different solutions. And so that's why I'm not drifting away from you or something like that. Any the other questions?

So as I mentioned-- so the physical theory that you need to describe-- to really describe the Big Bang Theory and to really describe the expansion of space is called general relativity. And in general relativity was a theory that Einstein proposed in 1916 and it's basically a theory of space, time and gravity. In fact they're all related to each other. So general relativity.

Space, time, gravity. I'll have a lot more to say about general relativity in the next two lectures-- well, a lot more in-- when I talk about time travel, which will either be next week or the week after. I haven't decided. But for now it just-- just know that it's a theory that explains gravity and explains space and time-- they're all related to each other.

Now, general relativity is one of the two most successful theories that have ever been proposed-- two most successful physical theories that have ever been proposed. Every single-- oh, the other one is quantum theory, by the way, which I'll also talk about in the future, but not today. Every test that has been put forth to test general relativity, general relativity has passed. It can make predictions to the 10th decimal place, or even past the 10th decimal place, and it gets it. That that's how good general relativity is and so this theory is actually quite weird. You'll see when I talk about it. But it's enormously successful, and its success is the reason that we talk about it and that we even think about it.

So when general relativity was first proposed in 1916 people wanted to know what are some of the consequences of the theory and, in particular, what does general relativity have to say about the universe. And so in 1922, a mathematician by the name of-- a Russian mathematician by the name of Alexander Friedmann solved it-- solved the universe. So let's see-- Friedmann applied GR to the universe.

Now the universe is a pretty messy place. I mean, just look around. It's just messy. It just seems like it would be so hard to analyze and its-- the universe is also pretty big. So you have to be a pretty confident guy to say, hey, I've got a-- I'm going-- I've got a theorem, I'm going to explain the universe. It seems mind-boggling to me at first that it should even be possible. Because I'm having trouble coming up with a model for girls or something, and so to model the

universe that's just-- it's just mind-boggling. So it's a hard question, I mean, to actually describe the universe.

But, fortunately, physicists have a trick in tackling hard problems. They have a trick. And the trick is when you're faced with a hard problem, you just solve a simpler one. That's the trick. So what Friedmann did was he made a couple of assumptions about the universe-- a couple of assumptions.

The first assumption that he made is that the universe-- let's see-- so the first assumption he made is that the universe is homogeneous, which means that it's uniform. If you travel from one place to another, it doesn't change very much. The density of the universe is roughly constant, doesn't change very much. So two assumptions-- the first is homogeneous.

Now, in my remark about the messiness of the universe-- it certainly doesn't look like the universe is homogeneous. I mean, just look around you. Yeah, there are some people over there, there's some chairs over there, there's a chalkboard over here, I just heard a plane up there. The universe surely doesn't look homogeneous. And so you might think that this plan of Friedmann's to solve the universe would be doomed. It wouldn't work at all.

But this bias that we have in thinking that's the universe isn't uniform, it's not homogeneous-- it's really limited to the-- it's really due to our observations of the universe over small scales. I mean, we're pretty small things compared to the universe. I mean, this room is very small compared to the universe. But it turns out that when you look at the universe over large scales, when you look at the universe over large distances, this assumption of homogeneity is actually pretty good.

I mean, astronomers have looked around the universe and they've noticed that it's a pretty boring place in terms of large scale structure. I mean, you see a galaxy here, you see galaxy there, you see another galaxy there, it starts to get boring after a while. And the density doesn't really fluctuate a whole lot-- doesn't really vary a whole lot. So this homogeneity assumption is pretty good.

The second assumption he made is that the universe is isotropic. And isotropic just means that if I look in this direction, I look in this direction, I look in this direction-- every direction I look the universe looks the same. That's all that isotropic means. Of course, over small scales it doesn't look like that, because I see you over there, but I don't see him over there. I see somebody else. [INAUDIBLE] once again this isotropy assumption is actually a pretty good

assumption over the large scales.

And last week I talked about the cosmic microwave background radiation. It turns out that if you look at this radiation, regardless of where you look, it's-- the temperature of the radiation is pretty constant. It's pretty much the same. So this isotropy assumption is a pretty good assumption.

It's possible-- I mean, it's possible for there to be one of these [? mets, ?] but not the other. You can have an isotropic universe that's not uniform, for example, if you had something like-- so here's two and not one-- two and not one. You can have isotropic universe, for example, if you had, say, a series of shells where the first shell is more dense than the second shell, which is more dense than the-- this third shell and so once you go out the density goes down, but it looks the same regardless of where you look. So you can have isotropy without homogeneity.

You can also have homogeneity without isotropy. You can have something like-- the matter can be distributed in something like this. You can be sitting over here and you look up, you see some matter, you look in another direction, you don't see matter. So you can have-- so they're not equivalent to each other. Although, if the whole universe is isotropic, then it has to be homogeneous. But I-- we'll just make this assumption of-- about just one point in the universe when I made those assumptions. It's also possible, of course, that the universe is neither homogeneous nor isotropic, that's another possibility. But when you look at the universe it is roughly homogeneous, it is roughly isotropic. Oh, and by the way, this-- these two assumptions-- homogeneous plus-- homogen-- homogeneous plus isotropic form what's called the cosmological principle.

Cosmological principle. Last week I talked about one-- I talked very briefly about one alternative to the Big Bang model called the steady state theory where the universe actually exists. It didn't have a beginning, it's eternal. In the steady state theory the universe is both quite homogeneous, and isotropic and it's also the same in time. So it's also homogeneous in time in a sense. And so in the steady state model it actually-- the steady state model actually satisfies what's called the perfect cosmological principle, which is even more than that and which is even more elegant or more pleasing than this standard cosmological principle. But it doesn't look like the steady state theory's right because steady state theory doesn't imply the existence of the cosmic microwave background which we observe, which the Big Bang Theory predicts. So we throw the steady state theory out. But this perfect cosmological principle

actually-- it's found a new life in certain classes of extensions of the Big Bang model, which I'll talk about later-- so-called inflationary theories of the universe. Does anybody have any questions about these two assumptions that Friedmann made?

So Friedmann made these two assumptions. He said, hey, let's make the universe-- let's consider the simpler problem. The universe itself is pretty complicated, but let's consider this simpler problem. We make the universe homogeneous and isotropic, and let's solve this. So let's put this into the equations of general relativity, which, of course, I won't show you. Let's put this into the equations and see what we get. And so he did that. He that and he came up with three possible solutions for the universe. Three possible solutions as three possible universes.

Oh, it turns out that the type of universe that you have, that is, the type of history that the universe has, the type of shape it has, the type of size it has depends on the density of the universe. Well, it depends on the average density of the universe relative to a certain density called the critical density. So let me just write down this critical density before I talk about these universes. So the critical density is a density that's a very small, but it's very important. It's about one-- it's about 10^{-26} kilograms per cubic meter, which [? is ?] approximately-- does anybody have a feeling for how small that number is?

AUDIENCE: Really small.

NICHOLAS Really small. Yes.

DIBELLA:

AUDIENCE: [INAUDIBLE] 26 decimal places.

NICHOLAS Yeah. So the mass of a proton is about 1.67 times 10^{-27} kilograms. So this

DIBELLA: critical density is about 10 protons per cubic meter. So cubic meter-- meter-- [INAUDIBLE]. 10 protons in that amount of space, which is pretty small. It's-- per cubic meter. That's [? just ?] critical density.

So if the density of the universe is greater than this critical density, then you have this first type of universe that he discovered. So let's suppose-- let's say density is greater than critical density. I'm going to-- actually I'm going to give this critical density a symbol. I'm just going to write down a symbol just to make it easier to write it down. I'm just going to give it this symbol. This is the Greek letter rho that's c. I said I wouldn't do math. I'm not doing any math, I'm just

giving things different names. So I-- you can't accuse me of doing math, so I rho c.

So if the density of the universe, which I'll call rho-- if this-- if the density of the universe is greater than this critical density, then it turns out that-- well, first let me say something about all these three possible universes. In each one of them there's a beginning of time. Each one of them starts out with some kind of a big bang. But the future evolution, the future behavior of the universe depends on this density.

So if the density of the universe right now is greater than this critical density, then it turns out that the universe will eventually-- so it's expanding right now, but if the density is greater than the critical density, then it's going to eventually starts to contract because the gravity due to these-- due to the matter and the energy in the universe is going to be too great because it's greater than this critical density. It's can going to be to great that eventually it just starts making the universe-- collapsing onto itself. So if the critical density is smaller than the density of the universe, then the universe eventually re-contracts-- it contracts. The universe collapses-- collapses in some kind of a Big Crunch-- with the Big Bang as the beginning, Big Crunch being the end-- everything crunching together.

And this is also tru-- also this is true if the density is greater than the critical density, then general relativity implies that the universe is finite. So not only does the universe eventually collapse, but the universe is also finite. And the type of finite that I mean-- there are at least a couple of times-- types of finite that I can think of. The type of finite that I mean is a type of finite that the surface of the balloon is or that the surface of a bottle is. So if I'm sitting-- if I'm a two-dimensional creature-- if I'm like an inch worm from last time and I'm-- I hear voices.

AUDIENCE: Outside.

NICHOLAS Outside, on the second floor? There's a window there, oh, but it can be from the bottom and--
DIBELLA: if I'm sitting-- sorry, I have ADD. Sorry-- If I'm sitting on the surface of this bottle and I start walking in one direction, then I'm eventually going to reach my starting point where I started-- if I just keep walking in the same direction. I mean, you can just look at it, it's closed-- same thing with a balloon or some other kinds of surfaces. That's the kind of finite that I mean.

If I started walking in one direction for a very long time, or if I took a spaceship or whatever and just started traveling in the same direction for a very long time, then I would eventually get back to my starting point. It's hard to imagine how something like that would work in the real universe because this isn't the real universe. We could just see two dimensions living inside of

three dimensions. How does three dimensions close on itself? It's hard to imagine, but this is what general relativity implies. I mean, we might not be able to visualize it in our heads. We might not be able to see it, but we can still understand how it works. I keep walking in this direction, I eventually get back to my spot as if I was walking on the earth and eventually I returned to my spot.

There's not any kind of a boundary. There's no boundary in this kind of universe. There's not a sign-- if I were to keep walking in that direction, I wouldn't reach a boundary. I wouldn't reach a sign that says end of the universe, dead end. That's not what would happen. That's not the kind of finite that general relativity implies the universe might be. [INAUDIBLE] a question?

AUDIENCE: But if the universe were that kind of finite, what would the edge of the universe look like?

NICHOLAS If the universe were the kind of finite that it's not, you mean?

DIBELLA:

AUDIENCE: Yeah.

NICHOLAS What would the edge look like? I mean that's-- I mean, I'm not sure I-- like, what would it look

DIBELLA: like, I mean, you would-- if you were if you were standing in front of it and you just--

AUDIENCE: Yeah.

NICHOLAS Well, I mean-- so if that's the edge of the universe, then you obviously can't get outside of it

DIBELLA: because it's the universe. It might not look like anything. I mean, there might not be anything over there. There might just be empty space. So if you just walk there, you just might not be able to penetrate past it. But, I know, I know-- I mean the universe isn't that kind of a finite. So I'm not exactly sure if it's like really a sensible question, but it's an interesting thing to talk about, but I'm not really sure how you really answered because the assumptions are-- what's the word I'm looking for-- the assumptions are bad. Yeah. Did You have a question or are you just tired? Anymore question? Yes. You're also doing the fake question-- raise hand. No more questions?

This kind of a universe is called closed because it closes onto itself the same kind of way that a water bottle closes on the same kind of way that a balloon closes on. So this is called closed. Let's go to a new board. We can also consider the case when the density of the universe is less than the critical density.

So ρ , the density of the universe now, is less than the critical density now. And in this case the universe expands forever. It's always going to expand. And the universe is also infinite-- it's not finite, it's infinite. So if you kept walking in one direction you would not get back to where you started from-- bringing it back to that point.

I suppose if the universe is infinite-- I'll have whole lot more to say about this when I talk about parallel universes. But if the universe is infinite and kept walking in the same direction and then you might eventually get back to-- you might eventually get to some galaxy where there's a complete duplicate of yourself and you might think that you came back to your starting point. But you wouldn't really come back to your starting point. I mean-- and if I left here and I kept going, eventually I would reach a parallel universe where there's a complete duplicate of this, and there's this mark right here, and I would come to it and I would think I came back to my point. But if the universe is open, then it's not really the same point. That just something funny that I thought of. So the universe expands forever, the universe is infinite.

There is a final case. And that's if the universe is-- if the density of the universe is equal to this critical density. Oh, by the way, this is called an open universe, it doesn't close on itself. The final case ρ equals ρ_c . And in this case the universe also expands forever and the universe is also infinite, but there's a slight difference. So universe same as above, but we call it flat. We call it flat because-- so I haven't really talked about the geometry of the universe, but I've hinted at what that might be like.

So in the closed universe the geometry of the universe is like a sphere, although you have to use your imagination to-- you have to use your imagination to really visualize what it would be like. But it's like a sphere in the sense that if you drew a circle on it, for example-- if you-- or if you-- sorry-- if you drew a triangle on it and you-- if you added up the angles on the triangle, then the angles [? wouldn't ?] add up to 180 degrees. They would actually add up to-- is it more than 180 or less than 180? I think it's more than 180 degrees. I think it's-- yeah, so in a closed universe if you made a really big triangle-- if you just-- if you found that-- if you made a really big triangle and then added up the angles in the triangle, you wouldn't get 100 degrees. You'd actually get more than 180 degrees.

In an open universe and if you drew a very large triangle and you added up the angles in the triangle, you also wouldn't get 180 degrees. Now, you would get less than 180 degrees. I-- a picture might actually help. So let's say-- let's go back to the closed case. So if you have a sphere-- can you see this-- what I'm writing? So if he had the circle, let's pretend it's a sphere,

If he had a sphere and he drew a triangle on it, it would be curved.

It'd be curved [INAUDIBLE] something [INAUDIBLE]-- anyway like this. You can just-- you can go home and buy a balloon and then draw a triangle on it. And then look at the angle and see what it looks like and see if it looks like what I'm drawing over there. And then you can add up-- you can measure the angles on the triangle and add them all up, and you can see that they add up to greater than 180 degrees. I think that's right. I think that's right. It's one of the other.

Similarly, in this opening case, the geometry of the universe is, well, in some sense open. It's actually like-- it's like a saddle. I'm bad at drawing. It's like a saddle. It's some-- does anybody know-- can anybody draw a saddle? I'll send you a picture. I'll send you a picture of a saddle later, so you can get a better grip of this. Or, maybe next point-- next time I'll just bring my laptop. And if drew a triangle on a saddle--

AUDIENCE: [INAUDIBLE]?

NICHOLAS Sure.

DIBELLA:

AUDIENCE: Sweet.

AUDIENCE: [INAUDIBLE].

NICHOLAS [INAUDIBLE] draw a saddle.

DIBELLA:

AUDIENCE: Like the shape like--

NICHOLAS Just like the shape of a saddle.

DIBELLA:

AUDIENCE: No, [INAUDIBLE].

NICHOLAS OK. Yeah, I should have-- next time I'll bring my laptop. Yeah, so if it drew a triangle on a

DIBELLA: saddle then the triangle-- the angles wouldn't add up to 180 degrees. They would actually add up to less than 180 degrees. So you can buy a saddle for yourself at home and do this, and get a magic marker and just draw a triangle, and then add up the angles and you can see for yourself. And so I'll just try to draw it here. Add up the angles, see what you get.

In an open universe, this is what the geometry of the universe would be like. I mean, the kinds of saddles that we would buy or that we would get in some kind of way-- those would be two-dimensional surfaces and we have to use our imagination to imagine the three-dimensional saddle, but we could still talk about what we would observe. We might not be able to imagine the shape, but we could still talk about what we would observe. If we drew a triangle, add up the angles, you don't get 180 degrees. If you start walking in one direction, you're not going get back to your starting point.

So, now, on this last case, this third case, which I called flat-- it's similar to the opening case in that the universe expands forever and that the universe is infinite, but the kind of geometry is like a flat shape. It's like a plane. So in a flat universe-- I know how to draw a plane. I know how to draw a rectangle. In a flat universe, the universe has a, kind of, shape like this. And if you were to draw a big triangle in this universe-- if you were to find three points and draw a triangle, and then you added up the angles, you would get the happy 180 degrees.

So what Friedmann-- when Friedmann made these two assumptions of homogeneous universe and isotropic universe and then just put them into the equations of general relativity, he found out that there could be three possible universes-- the closed universe, the open universe, and the flat universe. So the important question becomes which universe is ours?

AUDIENCE: [INAUDIBLE].

NICHOLAS
DIBELLA: No problem. So an important question becomes which what universe is ours? General relativity, as I said, it's one of the two most successful physical theories ever, and so we believe it's true. And with this-- these two assumptions of homogeneity and isotropy, we also believe those are true. And so we probably believe that-- I mean, you should then believe that the universe would be one of these three types. Does anybody have a guess for which one best approximates our universe? Yes.

AUDIENCE: One.

NICHOLAS
DIBELLA: One, OK. So somebody guessed one. Do you have a guess?

AUDIENCE: Same one.

NICHOLAS
DIBELLA: You're also guessing one. Anybody else have a guess for which universe best describes ours?

DIBELLA: Yes.

AUDIENCE: Two.

NICHOLAS You say two. Anybody have a third guess? Yes.

DIBELLA:

AUDIENCE: In for two.

NICHOLAS You're also in for two. How about-- let's see a show of hands for one. See-- one, two, three.

DIBELLA: Let's see a show of hands for two. One, two, three, four, five, six, seven, eight, nine, plus or minus a couple. How about three? Who thinks three? One, two, three. Three for three. It turns out that the minority was right. This third one gives the best description of the universe.

So the question of which one best describes the universe was pretty much an open question until about 1998. Nobody really knew which one it was. We had set some limits for this density, but we didn't really know. Like, we knew-- we had some range of what the density could be, but we didn't actually know which one it was.

But, finally, in 1998, people discovered that the universe-- the expansion of the universe is actually accelerating and that immediately ruled out the first one. Because, in this case, the universe is expanding, but the rate of the expansion isn't increasing. The expansion isn't accelerating because-- it's acceler-- it's expanding now, but eventually it's going to stop expanding and then just collapse on itself in a big crunch.

But there was a discovery in 1998 that the universe is accelerating its expansion. And what people did was to look at these systems in the universe called Type 1a supernova, which are basically explosions of stars. And these explosions have a brightness. If you were to see how bright they are-- they always explode in the same way basically. They're always going to be the same brightness regardless of where it happens or what led up to it. And so for this reason we call these supernova-- these supernovas standard candles because it's-- you can just buy a candle and light it up wherever you want, it's always going to be the same.

And so what they did was they looked at these Type 1A supernovas, as they're called, and they measured the distance-- distances to a bunch of them. And they also measured how far away they're moving from us and from this they were actually able to calculate the expansion rates-- the expansion rate of the universe at two different times. And they found out that the expansion rate now is greater the expansion rate that was some previous time. And so that

implied that the universe is expanding and the expansion is accelerating. So we knew the expansion was accelerating by 1998.

But it was still controversial at that time. Some people didn't really think that the supernovas would be good standard candles and some people had criticisms with the way that they were interpreting the data. But, more recently, the 2000s, people had more precise ways of determining which one of these three cases was true. And-- so I said-- so I talked about this cosmic microwave background radiation and it turns out that regardless of where you look you see it.

And I also mentioned that it's approximately isotropic, meaning that the temperature is about the same regardless of where you look. So it's approximately isotropic, but it's slightly anisotropic. There's a slight deviation from isotropy, a slight fluctuation from isotropy. And from this slight fluctuation you can completely determine-- you can easily determine that this is the case-- it's a flat universe. Unfortunately, I can't really go into the details of how they did that. But you can feel free to ask me after class about it.

So here we are today, 2008. We know that there's-- we're pretty sure that there was a beginning of time-- big bang. Big Bang model says there's a beginning of time. And now we have a pretty good idea of where the universe is heading. We know about the fate of the universe. Because we're pretty sure now that the universe is flat. The universe is expanding, and accelerating and has this kind of geometry. So it will expand forever, and space will live forever, and time will live forever and the universe will have no end. And this is basically where we are today. And I'll take-- no-- we started at 1:30?

AUDIENCE: [INAUDIBLE].

NICHOLAS OK. Yeah, I take a break now. I take a five minute brake. I thought we might've started at 2:00.

DIBELLA: And I was looking at my clock-- 2:15?

AUDIENCE: [INAUDIBLE].

NICHOLAS Yeah, you feel free to ask me any questions during the break.

DIBELLA:

AUDIENCE: [INAUDIBLE] universe was like?

NICHOLAS So-- so we have these models-- all right. So-- I mean, I'm not describing any of the

DIBELLA: mathematical details of it. But we have-- I mean, there is, of course, math that goes along with this and so what people do is they look at this-- they look at this variation of temperature of this microwave radiation and, basically, what they do is a fit. They do a fit to the curvature of the universe. So this curvature-- this has no curvature. This has negative curvature. Open means it has negative curvature. And closed means it has positive curvature.

And there is a parameter that you have in your equations, and when you do a best fit it turns out that the universe is flat-- to within a really good range it's fits flats. I know that doesn't really tell you a whole lot more, but that's basically what they do-- is they do a best fits and it turns out the universe, from this best fit, is very likely flat.

AUDIENCE: So how fast is the universe expanding?

NICHOLAS
DIBELLA: How fast? So that question-- so maybe a better question is how fast are galaxies moving away from us? That might be a better question. Yeah, so there's-- so Hubble, I mentioned last time-- so Hubble discovered that most things are moving away from us, most of the galaxies are moving away from us. He actually discovered a law that's a little more precise than that.

He discovered that the speed-- so this-- I said I was going to write down a minimal of equations, but this isn't technically part of class. So Hubble discovered that the speed that galaxies move away from us, v , is equal to some constants times the distance that the galaxy is from us, so time is, say, d . And this constant, h -- this h -- it's called Hubble's constant. And it's approximately equal to-- I always forget the units-- well, I always have to think about units. It's some weird units-- something like 70 kiloparsecs per-- I'm going to forget about these units-- I'm-- these are the units it's usually given in, but you can always convert it into more familiar units.

And in familiar units it's equal to approximately 1 over 14 billion years. This con-- so this constant is related to the age of the universe. And so this is what that constant is, so it has units 1 over seconds. And then if I-- if you tell me how far away a galaxy is, then you can easily find out how fast it's moving away from you just based on this simple formula. And then you can--

AUDIENCE: [INAUDIBLE]?

NICHOLAS
DIBELLA: Yeah, yeah. So-- yeah, so it turns out that the speed that a galaxy is moving away from us is proportional to how far away it is and you-- that-- you can actually derive that from general

relativity, but I won't. So-- no, but it's easy to-- I think that's pretty easy to imagine though. I mean, you could take-- I mean, you can take a balloon, look at two points on it-- two points on the balloon and start to blow it up, and then you can-- then you can ask, well, how-- to tell you how something that's one inch away from a given point and something that's two inches away from a given point and then say, well, how fast does the first guy move compare with the second guy? And the second guy-- the guy that's farther away is going to move faster when you blow up the balloon.

And so it makes sense from that perspective. But, of course, the universe isn't-- I mean, the universe isn't closed, it's actually this geometry. And so it might be a little hard to see in this case. I mean, how do you blow up a sheet of paper? Maybe a little hard to imagine in that case. Ah, let's see.

AUDIENCE: [INAUDIBLE]?

NICHOLAS What's that?

DIBELLA:

AUDIENCE: If it's-- and if it's flat how come we can move around?

NICHOLAS How come we can move-- no, I mean, it's not really flat. I mean, that's just an analogy to understand. It's flat in the sense-- so it's like a three-dimensional kind of flat. I mean, it's easy to understand living on a circle-- I'm sorry-- living on sphere, living on a balloon-- walking around like that-- I mean, that's a closed shape, that's a spherical shape. And then you can imagine extending that to one more dimension. You might not be able to see it in your head, but you can imagine-- just keep walking and then eventually get back to where you started from.

And you can also imagine drawing a triangle, and then adding up the angles and then getting a number greater than-- did I say greater than 180-- one of those. In a flat universe-- in the flat universe the geometry is similar to the geometry on top of a-- similar to the geometry of a sheet of paper. But you have to add one more dimension, so if you kept walking in one direction, you would never get back to where you started from. And if you tried-- but if you tried drawing a triangle and adding up the angles, you would get 180 degrees.

Other than that it's-- I mean, other than that you might not be able to visualize, but you can certainly understand what happens in that kind of universe. And it's also infinite, so-- I mean,

this is just a finite sheet of paper. If the universe is flat, which looks like it is, then this is infinite, so it goes out at every-- it's pretty big-- infinity's pretty big. Question?

AUDIENCE: [INAUDIBLE] but you said the universe started and it's never going to end or [INAUDIBLE]?

NICHOLAS
DIBELLA: That's right. The universe had a beginning, but it won't have an end according to this Big Bang model, which is the conventional wisdom that we've gained within the past century.

AUDIENCE: [INAUDIBLE]?

NICHOLAS
DIBELLA: Well, I mean, my--

AUDIENCE: [INAUDIBLE] just seems like it's wrong because [INAUDIBLE] seems like cheating almost.

NICHOLAS
DIBELLA: Seems like cheating. I mean-- [? by ?] mean-- so this is an intuition that you personally have-- if it has a beginning doesn't have-- it has to have an end. Yeah, it's an intuitive lot of people have. But why should the universe care about our intuition?

AUDIENCE: [INAUDIBLE].

NICHOLAS
DIBELLA: What's that.

AUDIENCE: [INAUDIBLE].

NICHOLAS
DIBELLA: Yeah, there are a lot of people that before we had the experimental evidence to know which one's right, a lot of people were saying, well, this closed universe model, this model that you prefer-- it's too simple to be wrong. How could it be wrong? And then when we found it was flat they were upset, I guess.

AUDIENCE: [INAUDIBLE] I think that it's possible for it to have an end. It's-- I don't think it's [INAUDIBLE]. Everything can end.

NICHOLAS
DIBELLA: Well, I mean, yeah, general relativity-- I mean-- yeah, I mean, general relativity says that it can have an end. Friedmann derived that it might have an end depending on what the density is. But it doesn't have that density, so it doesn't have an end.

AUDIENCE: OK.

NICHOLAS I mean, it could have been-- it could have had an end, but [INAUDIBLE] were different it could
DIBELLA: of had an end, but it's too small. So it's not going to have an end. However, humanity might
have an end.

AUDIENCE: [INAUDIBLE].

NICHOLAS But humanity's different from the universe, I think, in any case.

DIBELLA:

AUDIENCE: [INAUDIBLE]?

NICHOLAS Sure.

DIBELLA:

AUDIENCE: You said that time doesn't end. And it doesn't end, why? [? Because the ?] universe
accelerates [INAUDIBLE]?

NICHOLAS Right, time--

DIBELLA:

AUDIENCE: But at a certain point, when it hits the speed of light [INAUDIBLE] eventually time end
[INAUDIBLE]?

NICHOLAS Oh. So-- I mean-- so general relativity definitely implies that some points in the universe. If you
DIBELLA: go far enough-- just-- I mean, the simple Hubble Law, that simple equation I wrote down,
implies that far enough away from us points of space will be moving away from us faster than
the speed of light. You actually reach the speed of light and then points will be moving away
from us faster than the speed of light. But that doesn't-- yeah, so that doesn't mean that time
stops.

So this statement that time stops, basically, for things moving at the speed of light, this is
something that's derived from special relativity. And it applies to objects that are in a fixed
space-time, a fixed space-time that's not expanding. And in an expanding universe-- I mean,
general relativity is a little more lax, I guess, in allowing faster than light travel. I mean no
signal is really traveling faster than the speed of light-- I mean, relative to the expansion of the
universe, nothing travels faster than the speed of light. But the universe itself, the space itself
can travel faster than light. There's no problem with that.

AUDIENCE: I have a question. I read somewhere, I can't remember, the-- some people thought that something travel faster than the speed of light, time goes backwards not forwards.

NICHOLAS
DIBELLA: Yeah, yeah. So-- well, first of all, yeah, so first of all, relativity says that if you start out at a speed lower than the speed of light, you can't get past the speed of light. You can't accelerate to get to the speed of light and then pass it, because that would be required an infinite amount of energy. But you might imagine, yeah-- maybe you were always faster than light for all your life or something something like that. And if that's the case, then, yeah, you can conceive of particles that have this property of traveling faster than the speed of light called tachyons, that's their name. If they do travel faster than light, then they could travel back in time. But we'll have a time travel lecture, it'll be either next week or the week after. So we'll talk about the questions like that.

AUDIENCE: I have another question. Since light is pure energy [INAUDIBLE], wouldn't you be stripped of energy?

NICHOLAS
DIBELLA: If you go faster than the speed of light would you be stripped of energy? Why would you be stripped of energy?

AUDIENCE: Well, because light is pure and [INAUDIBLE] energy [INAUDIBLE].

NICHOLAS
DIBELLA: Well, why can't things faster than light also have energy?

AUDIENCE: [INAUDIBLE] can't go beyond the speed of light--

NICHOLAS
DIBELLA: No. There's no reason for that. But I also like to think of energy more as a property than as a substance. I mean, things have energy. Light has energy. Light isn't energy, light has energy. It's-- the subtle distinction, but I thought about it a lot actually, yeah. And I think that the property. I think that the property is better. Did you have a question in the back? Yes.

AUDIENCE: Yeah, that's why Einstein said you can't go faster than the speed light [INAUDIBLE]?

NICHOLAS
DIBELLA: The universe is allowed to expand. Space is allowed to expand faster than light. There's no problem with that. But what is a problem is that is if you had a space that wasn't expanding, for example, and then something goes faster than light. That won't happen ever. But spa-- so here-- here's a statement that's always going to be true. If you come in-- if you go on a race with lights-- let's suppose there's a flashlight right over here, and you turn it on, and then I

were to go next to it, light would always beat me in a race. That's something that's going to be true.

But in an expanding universe you can think of it-- an expanding universe-- you can think of the galaxies and all the objects sitting in the universe as drifting away. And you can't you can't travel faster than light relative to this drift. So if there's already a drift like this-- if there's a drift like this-- suppose the universe is carrying me, then I can have a speed relative to this drift and that speed can't be faster than the speed of light. There's-- you can think of it like that, if that makes sense. Does that make sense a little bit? General relativity allows space to travel faster than the speed of light.

AUDIENCE: [INAUDIBLE]. Yeah.

NICHOLAS Yeah, question?

DIBELLA:

AUDIENCE: [INAUDIBLE]--

NICHOLAS Have you thought more about--

DIBELLA:

AUDIENCE: [INAUDIBLE]. The universe is infinite, correct?

NICHOLAS It looks like that. At least, it's definitely very big.

DIBELLA:

AUDIENCE: How can something infinite expand?

NICHOLAS How can something-- so this-- so the universe isn't expanding into anything. It's not expanding

DIBELLA: into anything. It universe just is. What is true-- when I say that the universe is expanding, what I mean is that points on the universe-- the distances between points on the universe is increasing. That's what I mean. The universe isn't expanding into anything, but the distances between points is increasing. That's what the expand means. That-- so then there's no problem. Yeah, it's confusing. Yeah, it's confusing. Let me get back.

AUDIENCE: Thank you [INAUDIBLE].

NICHOLAS What's that?

DIBELLA:

AUDIENCE: Thanks for being patient [INAUDIBLE].

NICHOLAS

DIBELLA:

Oh, no. No problem. So let's get back. Where was I? So it looks like the universe is flat and, therefore, looks like the universe will expand forever and there will be no time. Well, you might say, I guess, that's good for the universe. But what about me? Am I going to live forever? Or, are my ancestors going to live forever? Is Earth going to live forever? Is the sun going to live forever? What about all these other stars, are those going to live forever? Well, the situation looks better for the universe than it does-- than it looks for us. Because-- so the sun-- well, let's start with the sun.

So the sun shines because it has this core of nuclear fuel-- hydrogen burning into helium at a temperature of millions of degrees. But, eventually, this nuclear fuel is going to run out and the sun won't be able to provide for us the way it provides now. Actually, eventually, it'll engulf us all. And not tomorrow, not the next day, but in billions of years down the line when the star-- when the sun gets near the end of its life, it's going to engulf us all. And so the earth will be eaten up-- same thing is true for all the other stars. Eventually they will run out of nuclear fuel and they'll die out, they'll burn out and eventually turn into something like a white dwarf, which is a dead star basically, or a black hole, which is a region of space that sucks in everything and nothing can escape from it, not even light can escape from it.

And so the universe eventually is going to be pretty dead. The universe is still going to be alive, and it still going to exist, time will still persist, but everything in it will eventually-- pretty dead. Everything will burn out or-- actually, eventually, even the black holes are going to decay eventually, according to most theories. Eventually everything will decay eventually, even protons, according to some of our theories. And so this-- the prospect of an interesting universe for eternity seems rather bleak, even though the universe exists forever.

Now, you might counter to this ar-- you might counter to this by saying, well, your analysis of the universe-- it didn't take into account the existence of intelligence. I mean, we're intelligent beings maybe we can do something. Maybe we can fix the universe. We can fix the sun. If it runs out of nuclear fuel, let's just give it some more. Let's fix it. Let's fix these stars. Let's fix everything. I mean, we're smart. We were smart now, imagine us in 1,000 years or 10,000 years. I don't know. Maybe. But I do think it's an interesting question, though, of the role that intelligence plays in a changing universe.

AUDIENCE: [INAUDIBLE].

NICHOLAS What's that?

DIBELLA:

AUDIENCE: I don't think we'll even be humans anymore [INAUDIBLE].

NICHOLAS Yeah, we might be transhumans at that point or some kind of a higher consciousness.

DIBELLA:

AUDIENCE: [INAUDIBLE] thousands of years [INAUDIBLE].

NICHOLAS Or we'll--

DIBELLA:

AUDIENCE: Actually [INAUDIBLE]--

NICHOLAS Or we'll be ashes, which would be--

DIBELLA:

AUDIENCE: [INAUDIBLE].

NICHOLAS Yes.

DIBELLA:

AUDIENCE: I don't think we could evolve [INAUDIBLE]--

NICHOLAS Sorry, excuse me.

DIBELLA:

AUDIENCE: I don't think we can evolve at this point because-- I don't why [INAUDIBLE]. I mean, if you had a disability, you die [INAUDIBLE] technology can fix you, so--

NICHOLAS Yeah, so--

DIBELLA:

AUDIENCE: [INAUDIBLE] die [INAUDIBLE].

NICHOLAS So you don't think that we're evolving anymore because now we have technology?

DIBELLA:

AUDIENCE: Well--

NICHOLAS

Basically.

DIBELLA:

AUDIENCE:

[? Slower ?] [? than-- ?]

NICHOLAS

Well, we could say that technology-- I mean, if-- so here-- this is the universe all the stuff. This is all nature. And technology, in principle, is part of nature. And you can say technology, in principle, is part of evolution. And so you could say that if you want to. But I just thought it was interesting to mention that point. You might-- I personally-- I think it would be great if humanity can live for a long time or live forever. That there would be great. And, maybe, we can keep home, we can keep earth, as a reservation. It could be a historical landmark. Yes.

DIBELLA:

AUDIENCE:

Somebody told me that in the next 50 years [INAUDIBLE] something's going to happen to the sun-- [INAUDIBLE] start sending solar storms at us.

NICHOLAS

Maybe.

DIBELLA:

AUDIENCE:

Like wipe out all electricity.

NICHOLAS

I mean, there are a lot of bad things that could happen at any given moment in time.

DIBELLA:

AUDIENCE:

[INAUDIBLE].

NICHOLAS

Well, I mean, worse than normal. I don't know. I don't-- I don't think we have much-- I don't think-- just from what I've read and what I-- I don't think we have much to worry about the sun in the near future. I think we're able to sleep tonight, but tomorrow night we should worry. So this whole-- the past two weeks I've talked about the Big Bang and general relativity and this is the conventional wisdom in cosmology, the study of the universe as a whole. The conventional wisdom of cosmology that we've accumulated starting with Einstein-- but I've dodged a very important question that somebody raised earlier. I forgot who raised it. But-- so this big bang-- what exactly was it? What exactly was this big bang. I mean, general relativity says there was this thing that was the beginning of time. And we know from observation that the [? universe ?] was very hot very back in time, but what exactly was this thing, this bang? What was it exactly? Here's what we know.

DIBELLA:

We know-- we're very confident that we know what happened in the universe up till about three seconds after this moment in time that we call the Big Bang. At about three seconds after this moment that's presumed-- that was presumably the beginning of time-- after about three seconds or-- three seconds to three minutes or so, all the nuclei were being built. This-- the era of nucleosynthesis was happening and we understand that. But if you go further back in time, then you go to higher temperatures and higher temperatures means higher energy. And, eventually, if you go far back enough, then you're going to reach an energy that we just don't understand anymore. I mean, we have particle physics theories that describe the behavior of particles at high energies, but we don't know everything.

I mentioned last week-- we know a lot. We know a whole lot more than we knew 100 years ago, but we don't know everything. In particular, we don't know exactly what happens at very, very high energies. We know what happens at high energies, but we don't know what happens at very, very high energies. And in very early universe you have these very high energies. And-- so we have some theories to describe very high energies, but we don't know if they're right. We have these theories called grand unified theories that combine the electric-- the electromagnetic force, the nuclear forces-- but we don't know if they're right. And so really anything-- any talk about the universe before about a second or so is-- maybe a little earlier-- any talk of the universe before that time is really speculation. It's really speculation.

And if you go very far back in time these particles-- these high energy particle physics theories that we have-- they can't even describe what happens anymore because then eventually you get down to a scale-- you get down to an energy scale that-- well, you get-- you go back in time and then get up to an energy scale that's so high that you actually have to take into account quantum gravity, a scale where you have to take into account quantum effects as well as gravity effects. And, as of today, we don't have a theory of quantum gravity. I'll talk in a later lecture about some proposed candidates of a theory of quantum gravity like string theory, but nobody knows what the correct theory of quantum gravity is or if we can even find one. And so really what this Big Bang was, if there even was a Big Bang that was a beginning of time-- what it really was is really anybody's guess.

I mean, if you ask an honest physicist, I mean, what was the Big Bang-- explain it to me in rigorous detail, explain to me the particles, and the energies and everything-- an honest physicist would tell you that we don't really know. We don't really know what it was, and it's entirely possible that the Big Bang wasn't the beginning of time. It's entirely possible that there

was a preexisting time before the Big Bang. And as you can imagine people have theories, they have speculations about what happened before the Big Bang. I mean, they're just they're just ideas, but we can still think about it. They're ideas that are results of theories that we have that might be true, but we don't know if they're true.

For example, one type of theory, that's an extension to the Big Bang model, is called inflationary theory, which I'll talk about more in the future time. And so inflation was this period in the very early universe when the universe expanded very fast, exponentially fast. And there are a variety of types of inflationary theories and in one type called chaotic [? eternal ?] inflation, the Big Bang wasn't the beginning of time. There, in fact, existed time before the Big Bang, before what we observe as being the Big Bang. And our universe isn't the only universe, there's, in fact, a vast ensemble, a vast-- a multitude of universes that live inside of this vast multiverse, which is a cool word-- multiverse.

And in this multiverse, according to some versions of inflation, a number of big bangs have occurred in the universe's history. And our Big Bang was just one of them. So in some version of inflationary theory-- some versions of this theory the universe is very big, much bigger than we can possibly imagine, much bigger than we thought it was. And there are much more bangs. There-- this bang that we observe is not necessarily the beginning of time. And so mo-- so these-- so inflation implies that there probably won't be an end, that inflation will exist, inflation will happen at lots of places in this vast multiverse, and lots of big bangs will keep happening, and happening and happening-- you get a bubble and then inflation.

It's really a random process. You get-- you start off with one region of space and then, if it's lucky, you get a bang. In another region space-- if you look at another region of space, if it's lucky, you get a bang, you get a bang, you get a bang, and so forth, and so forth. And so in inflation-- in [? eternal ?] inflation the universe is infinite in the future-- I mean, has infinite future. It's not going to end. But it's still an open question though of whether there was a real beginning.

It doesn't look like the Big Bang that we observe was the beginning, but was there really a beginning before this Big Bang. I mean, there was more of time before the Big Bang in these theories, but this was there a beginning of time? And nobody knows. Some people speculate that there was, some people speculate that there wasn't. But, as of now, nobody really knows.

There's another interesting theory that's pretty recent, and it's actually a prediction of string

theory. And in this theory-- in this model the universe-- so string theory, as I mentioned, is this proposed theory of quantum gravity, and nobody knows if it's right. But a lot of people work on it. And there's a lot of controversy over whether it's actually physics or whether it's science or not. But, in any case, lots of people work on it and they try to discover its consequences.

And some people have wondered, well, what does string theory have to say about the early universe? And some people have found that-- so there exist in string theory-- there exist these objects called branes-- B-R-A-N-E-- short for membranes. There exist these things called branes. And these branes are three-dimensional objects or they-- well, you can have branes of various dimensions. But the type of branes that are important for this, I think-- I'm not an expert on this. The types of branes that you need in this model are three-dimensional branes. So just-- [INAUDIBLE] three-dimensional branes like our universe-- like our universe might be stuck on a brane. So a brane is an object that lives in higher dimensional space.

For example, you can look at this sheet of paper. It's a two dimensional object, but it lives inside of a three dimensional space. The brane would be something like a three-dimensional object that lives inside of a higher dimensional space. And string theory-- some versions of string theory space is actually 10 dimensional. You just need 10 dimensions for the theory to make any sense at all, for the theory to be consistent at all. It's very constraining, it's very restrictive.

So in this cyclic model of the universe you have the two branes. Well, we have many branes, but, in particular, you can consider two branes and they could collide with each other. And if they collide with each other, then the kinetic energy of these branes when they're colliding can be converted into energy that produces a variety of particles like quarks, and protons, and electrons and so forth.

And so if you collide them you can create a bang, which you can call the Big Bang if you want-- a big bang if you want. And you'll have a very high temperature state at this collision and you have this-- a very high temperature state and it can be-- it-- you can make it, so that it's completely indistinguishable from what we observe as being the Big Bang. And so-- until you have a whole series of these collisions and so universes undergo big bangs and then crunches, bangs and crunches, banging crunches and there-- vast variety of them. And so in this scenario there wasn't a beginning of time and there was-- and there won't be an end. But, of course, nobody knows that this is right. And nobody knows if inflation is right. These are speculations.

But they're none the less very interesting to think about and in the future they can-- they're testable. It's possible to test them and see which one would be right. And actually both of these two models can actually make a prediction for what we observe about the CMB, the cosmic microwave background. They can both make predictions about the fluctuations. And for a long time inflation was the only one that was able to predict the precise way that's-- it's anisotropic. For a long time inflation was only theory that was able to predict the precise fluctuations and the temperature that we observe in the microwaves.

But now this new theory-- this relatively new theory is also able to explain it. And so inflation looked like it was really the unique theory for a while, but now there's this new cyclic model that some people like. And who knows what's right? You had a question?

AUDIENCE: Oh, no.

**NICHOLAS
DIBELLA:** Oh, OK [INAUDIBLE] so right now so we-- so just to recap, we have conventional ideas about the way that the universe is and of the [? conventional ?] ideas about the past of the universe and its future-- its origin and its future. The conventional wisdom was that there was a beginning and there won't be an end. But if you think hard about it, if you think about what was the Big Bang really why-- what was the bang and what caused it to bang? What happened before the bang? Think harder about it then you realize that we're really still pretty confused. And so nobody really knows if there's a beginning of time or if there is going to be an end. But we're-- I think we're making progress. It sounds like we're making progress. Does anybody have any questions? All right.

I actually have a little extra time, so if-- let's see-- so I talked about-- I have a little extra time, so I'll talk li-- about some more stuff. So I talked about [? this ?] density of the universe. What kinds of stuff make up the universe? The kind of stuff that we're familiar with. The kind of stuff that we-- that make up what we see-- normal matter-- things like electrons, protons and neutrons. We can actually measure how much of this ordinary stuff there is in the universe, it's called baryonic matter. We can actually measure how much of this baryonic matter there is. And it turns out that the amount of baryonic matter in the universe, compared with all this stuff in the universe-- so I'll make a little-- so density of the universe-- so normal-- it's called baryonic. The kind of stuff that we're made out of only takes up about 4% of all of the stuff in the universe-- just 4%. The rest of the stuff in the US we have no idea what that stuff is.

There's two more kinds of stuff in the universe-- two more essential kinds of stuff in the

universe. There's just something called dark matter. So dark matter is matter that we've indirectly detected by looking at galaxies. What we notice that-- we noticed that galaxies spiral around at a rate that's-- is inconsistent with the amount of mass that we actually see in the galaxy. So through this observation we've inferred that there must be more mass somewhere, but we just can't see it. It doesn't interact with light, so we call it dark matter. And there's lots of other lines of evidence for the existence of dark matter.

But dark matter has properties-- a lot of properties different from ordinary matter. And you can-- [? you ?] actually measure the amount of dark matter in the universe, the fractional amounts, and it turns out that it's about 22%. We don't really know what dark matter is, we know it has mass. That's one thing we know. But besides that, we don't really know a whole lot.

Some particle physicists have ideas about what dark matter might be. Dark matter might be particles that have mass, but they also interact through what's called the weak nuclear force. The weak nuclear force is one of the fundamental forces of nature and it's responsible for decays of particles like beta decay and all for-- all the forms of radio-- a lot of forms of-- all forms of radioactivity is due to the weak nuclear force. So particle physicists have speculated that maybe the dark matter is particles-- they're-- dark matter is particles that have mass and interact with the weak force. So as an abbreviation call them weakly interacting massive particles, or wimps.

And there are a couple of other-- couple-- there are some other candidates that people have thought of, but nobody really knows. And some-- and people-- a lot of people here on earth-- I guess that's where most people are-- a lot of people here on Earth have tried to detect dark matter, and they're currently searching for it. No one's actually directly detected dark matter, so we don't really know what dark matter is.

So we have normal matter and dark matter, the rest of the stuff-- or actually a very small-- a very small percent is actually lights-- light and neutrinos, which is very, very light and very fast neutral particles. A very small proportion of all this stuff in the universe is radiation, is light. But I won't even bother to write it down because it's so negligible.

And so we have normal matter, dark matter, radiation and then the rest of the universe, the rest of the density-- we have no idea what this stuff is. We call it dark energy. And it takes up about [INAUDIBLE]-- 73 or so percent. So 73% of the stuff in the universe we just have no idea

what it is. We know some properties of it, we have some properties of it.

For example, as space expands, the dark matter-- the density of dark matter just-- it doesn't change. And with normal matter if you-- with normal matter if you have a certain amount of matter in a balloon, for example, and then you just blow up the balloon, then, obviously, the density of the matter decreases. It gets diluted. But this dark energy-- we call it dark energy-- dark energy doesn't get diluted. it's just always there. And we just have no idea what it is and makes up most of the universe.

But I think it's pretty amazing that we've been able to actually infer the composition of the universe. 4% is normal stuff. 22% is dark matter. And 73% is this dark energy. We only understand 4% of this stuff. And I just-- what do we know? I mean, we're just-- it just makes-- makes me feel futile or trivial or something. Yes, question?

AUDIENCE: [INAUDIBLE]?

**NICHOLAS
DIBELLA:** Oh, I guess that's a rounding error. I think this was like 4.4%, this might've been something else. A very small percent is radiation, but, yeah, I know that comes out to 99%. I think I just made a rounding error. But, I mean, obviously, yeah, should come out to 100%. I mean, the law of addition to 100% for probabilities still holds. And I think I'll end there.