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IS THERE MORE TO THE UNIVERSE THAN WE OBSERVE?

Andrei Linde and Joel Primack compared notes at a Wonderfest panel at Stanford University, Palo Alto, 16, August, 1998

Joel Primack

I'm glad to be here. What we're going to do in this first portion of the presentation is Andrei and I will each give a talk of about forty minutes. I'm going to aim to end most of the talking part in about thirty minutes and then I'm going to show you some videos. So I want to start by talking about what the universe is like on the big scale, where we fit in and explain, essentially, why all professional cosmologists are pretty sure that the Big Bang really happened. Why are we so sure? What's the evidence? These three things and then a great deal of additional data that's coming in all the time and constantly reinforces this basic picture. Now, there's 2 aspects that we want to explore on this question as there are more to the universe than we observe. The vast majority of the matter in the universe is invisible. So one of the main things that's in the universe that we can't observe through light, or any other kind of electromagnetic radiation is the stuff we call dark matter. And I want you to understand why we're pretty sure that it's there and where we think it is, and what some of the ideas are concerning what it might be. And then, at the end, especially with the help of these videos, I thought I'd try to show you something of what difference it makes, that so much of the matter in the universe is invisible. But there's a lot more to this question of the material in the universe that's there that we can't observe. There's probably a great deal, maybe much more than everything that we can see in our own universe, that is hidden from us perpetually by, what we call, horizons. And I think that that's what Andrei Linde is going to talk about. So let me start with the geography part. Our place in the universe; well, of course we live on the third rock from the sun. There are these inter-rocky planets and then the outer gas giants that continue on for some distance. The amount of time it takes light to go to from the sun to the earth is about 500 seconds; eight minutes. But the amount of time it takes light to get to the nearest star is over four years. So, the whole solar system is a tiny little piece of a region near one of the many spiral arms of our galaxy, the Milky Way. The Milky Way itself is 100 thousand light years across. That's the visible part of the Milky Way; the invisible part is at least 10 times bigger than that. But the Milky Way itself is just a pin prick on the scale of the local super cluster of galaxies. There are two big galaxies in the local group, separated by about 2 million years - our galaxy and the great galaxy in Andromida, which is the only galaxy that you can see with the naked eye, aside from our own. If you can never see the Milky Way from the northern hemisphere, you can generally see the Andromida Galaxy, if the Andromida Constellation is up; you just have to know where to look. It's exactly as bright as the Milky Way. Smaller, but quite large enough to see, if you know where to look. Now, a little local group of about 30 galaxies, those two giants and lots of small ones, is just one of many groups of galaxies that together, make up this thing we call the local super cluster or sometimes the Virgo super cluster, because it seems to be centered on the Virgo cluster of galaxies. A cluster of galaxies is a remarkable thing. In the distance not much bigger than the size of the local group with its two giant galaxies and about 30 little galaxies, you can have 100 giant galaxies and 1000s of little galaxies. So, this is a galactic metropolis compared to the backwoods of our local group. And, these clusters are very interesting. They're the largest bound structures in the universe. The local super clusters fly apart; it's not bound or at least it hasn't fallen together yet. But the Virgo cluster and 1000s of other clusters that have been studied are the largest things that are actually held together by gravity and are not expanding with the universe. Now, all that, the local super cluster, is itself hardly a pinprick on the scale of everything we can observe, all the way out to, what we call, the huddleregis. We can't see beyond that, and the reason is that it's expanding away from us at the speed of light. So that's this other kind of invisibility; there's dark matter and there's horizons. Now, this is a picture that tries to illustrate the idea of the Big Bang and the expansion of the universe, in one dimension. One of the things that people are often confused about when they're told about the Big Bang or the expansion of the universe is, where's the center? If it's expanding, what's it expanding away from? Here's an illustration from Steve Weinberg's great popular book, one of the best earlier popularizations of modern cosmology called "The First Three Minutes", and he asks you to contemplate living on Galaxy A, so this is just a string of galaxies in one dimension. Of course, we imagine that there are galaxies in all three dimensions, but let's just focus on one direction. So, on one side is Galaxy Z, which is moving away at a certain speed, represented by the length of the arrow, on the other side is Galaxy B, moving in the opposite direction at the same speed. Twice as far as B is Galaxy C, and its speed is twice as great. Galaxy D is three times are far as Galaxy B from A, and its speed is three times as great. That's the Hubble Law, that the speed is proportional to the distance. So, from the point of view of Galaxy A, it's the center of the universe, with everything moving away from Galaxy A in a completely symmetric way. So Galaxy A says, "I'm the center of the universe." Galaxy B says, "Well actually, I'm the center of the universe", because from Galaxy B's point of view, it's exactly the same. Galaxy A is now moving away at exactly the same speed, but in the opposite direction, than A thought that B was moving. Z is moving twice as fast because it's twice as far away and you can see that the pattern is the same on the other side. So, B is also the center of the universe with everything moving symmetrically away from it. And the same for C; in fact, the same for all of them. So every point is the center of a uniformly expanding universe. There's no center or, they're all equally the center. Now actually, galaxies have random motions, not exactly random caused by the attraction of other galaxies, but if you average, over several galaxies, then you see that there is this uniform expansion pattern. How do you picture the expanding universe? There's two aspects that I want to discuss briefly. One is the expansion of the wavelength of light. When light is emitted, it always has a characteristic wavelength, if it's emitted by certain standard transitions and elements. For example, there's a kind of red light that's emitted by hydrogen. It's called H-alpha; it's the Balmer Transition from N=3 to N=2. Whenever you see that red light, you know that you're looking at hydrogen. Incidentally, hydrogen has a lot of other wavelengths; there's an ultraviolet one, with the N=2, N=1, the so-called myven alpha transition. But all of them have a characteristic wavelength, which tells you that you're looking at hydrogen or oxygen, or whatever the element is. Now, as the galaxies emit that light when they're far away from us, and the light travels toward us, the wavelength increases, just because of the expansion of the universe. When we observe the light, what we find is that this extra wavelength, this increase in the wavelength, is directly related to how long the light has been traveling and, for that matter, how far away, because the time times the speed of light gives the distance. So we can directly measure how long ago the light was emitted and actually more precisely we can measure how much the universe has expanded, that's what we can directly measure just by measuring the wavelength as we receive it, and recognizing from the pattern of the lines which element it was that was emitting the light. So, we directly measure this thing that we call the red shift, the amount of shift toward the red end of the spectrum, red being the longer waves, blue being the shorter wavelengths of light. So that's one important thing to appreciate, that's how we can directly tell how long ago and how far away objects were that emitted light towards us. Distant galaxies; this doesn't work within our own galaxy, there the motions are due to, the motions of stars around the center of the galaxy and things like that. But when we're talking about very distant galaxies, this red shift is an indication of how far away the object was when it emitted its light. Now the problem with that is that two things are going on simultaneously - the universe is expanding and the light is traveling toward us. How do we picture the whole pattern? The best way, when you're dealing with a four dimensional situation, the universe is evolving in time and it's also got 3 dimensions of states, the best way to picture it is to cut away a couple of dimensions and focus on some truly important dimensions. One dimension of space, which I'm representing just as circular lines that are in green, and one dimension of time, which is the blue lines heading outward from the center - that is the Big Bang, right there. So, all of the observers, all the galaxies can set their clocks to zero, at that point. Then, this is the material that will become, say, our galaxy, and there we are, receiving some light, and this is the path of light coming from that direction toward us. When the universe was younger, it was smaller. That's represented by the fact that the distance between these two lines, representing the path of the material of some other galaxy and our galaxy, the distance is getting greater as time goes on. Let's suppose that some light was emitted by this galaxy, at this moment, the galaxy was this far away, and the light travels toward us, we receive it now, the galaxy is much farther away. When we talk about how far away the galaxy is, we normally mean how far away it is today. Of course, we don't observe it today, we observe it as it was way back then. In fact, we can see galaxies farther and farther back, to about here, and then we can't see them anymore. We could have seen them if they were there, but they're not there. How do we know? I'll show you at the end. I'm going to show you a wonderful way of visualizing the data taken from the deepest exposure with the Hubble Space telescope, it's called the Hubble Lead Field, and this particular video allows you to zoom into the Hubble Lead field and go back in time and follow the path of this backward light cone in an expanding universe, back as far as you can, back when there aren't any galaxies anymore. Why do we take this so seriously? I summarized the three pieces of evidence - the Hubble Expansion, the cosmic background radiation, the abundance of light elements. The fact that the red shift increases with distance, in a nice linear way; the cosmic background radiation is truly heat radiation; and the abundance is the light elements. Now, if this were an astronomy course, I would go into some detail on these things, but I just want to show you some data so that you know that this is based on careful observation and not just speculation. So this is a modern Hubble diagram and this is real data, and this shows that the speed is directly proportional to the distance. This is what we call the spectrum of the cosmic background radiation. The curve is the prediction for heat radiation. This shows the intensity as a function of the frequency - higher frequency, lower frequency - the biggest intensity is right at this frequency of about 5 cycles per centimeter of finite unit that corresponds to about a centimeter wavelength. You'll see that there are some points, some observational data that's put on top of this curve. Usually we show the error bars, that's an indication of how uncertain the measurement is. In this case the error bars have been multiplied by a factor of about 100. If we actually put the data on the curve, the error bars are actually much finer than the curve. The agreement is better than one part in 10,000; it's actually a couple of parts in 100,000. That's simply an indication of how good the instrument is. No one has seen anything closer to heat radiation than this radiation that we receive from space. We can't make heat radiation in the laboratory as accurate as this. There's no question that this is heat radiation. What's the cause of the heat radiation? There doesn't seem to be any other alternative except to say that it's the heat left over from the Big Bang itself. It's coming at us uniformly from all directions. It's not exactly uniform, it's slightly hotter in a direction toward the constellation hydra and a slightly cooler in the opposite direction but we're pretty sure that that's because our galaxy is moving in that direction. If we compare the motion of our galaxy to a large number of galaxies some distance away from us, our galaxy is, in fact, moving with respect to those distant galaxies in that same direction. It's pretty clear that that's the reason for this, it's called the dypoanisoprothy in the cosmic background radiation. This is what happens when you run a standard computer program that calculates fusion. You start out with some neutrons and protons and you just let them interact with each other, according to the strong interactions. At one minute, the amount of diterium starts to shoot upward and most of this detetrium is then locked up in helium, and the deterium starts to decline; there's also some lithium produced and what's interesting is that these predictions for the amounts of helium, deterium, helium 3, and lithium 7, agree beautifully with the latest observations. The amounts differ tremendously; it's a few times 10 to the minus 5 in deterium atoms for every hydrogen atom, but that's in fact what's observed. An excellent agreement with the standard computer programs which are based on the kind of data that was used to design the hydrogen bombs. Incidentally, you may wonder when does most of the fusion in the universe occur? We all know that the sun is fusing hydrogen to make helium, and that's what keeps us warm. Well, it turns out that all the stars that have ever shown and that ever will only make a few percent of the helium. Almost all of the helium was made in the first three minutes. How do we know? Because the predictions are here with the observations. Now, I told you that the temperature of the cosmic background radiation is the same in all directions; that's only in approximation. It's actually slightly different in different directions by a couple of parts in 10 to the fifth, couple of parts in 100,000. The differences were just as were predicted by the cold dark matter theory which I developed back in the early eighties with other collegues from Santa Cruz and which other groups developed more or less at the same time, and we calculated what the expected fluctuations in the cosmic background radiation should be, and we actually got it right. Now, of course we could have just been lucky, and the actual explanation could be something completely different. But a lot of other things are also working out more or less as predicted by at least one of the variants on that cold dark matter theory. So, that gives us some confidence that, not only is the Big Bang right, but also this cold dark matter idea is right. We find that when we look at a kind of supernova which, when we look at the nearby ones, they all look pretty much the same. When we look at them at high red shift, they also look very much like the nearby ones except they go very slowly.

They're slowed down by as much as a factor of 2. It takes longer for the light to reach maximum brightness and then to fall off. Why is that? It's because these things are flying away from us so fast that it takes a little longer for the protons to reach us as the supernova is declining, and that spreads out the evolution of the supernova. That shows that this red shift effect is not due to anything like tired light, that the light is somehow losing energy. It really is because of the expansion of the universe. Alos the Big Ban theory predicts that the temperature should be higher at higher red shift. Red shift is this Z, and the 1+Z factor is the amount by which the wavelenght expands. Well, it turns out that it's actually possible to measure the temperature in galaxies at high red shift. And sure enough, just as predicted. Also, we can look at galaxies being lensed, having their light bent, by these great clusters of galaxies that I wax telling you about. We always find that the lensed galaxy has a higher red shift than the lensing cluster. Now, of course that's perfectly sensible, if what's causing the red shift is the expanding of the universe. But if we ever found even one example where that wasn't the case, the whole theory would collapse. No one has ever found even one example; when we find new instances of this constantly. Here's a classic picture of this lensing. So this is a cluster of galaxies, all of these galaxies are members of the cluster. But you see these faint arcs? This phenomena of the faint arcs was discovered by Vy Petrosium of Stanford and a collegue of his, about 15 years ago. It actually had been seen by many astronomers, who dismissed it. They thought it was some flaw in their plates or something like that, and it was Petrosium who first had the courage to say, "Hey, I think this is a gravitational lens!" And of course the proof was that they were able to get the spectrum of these things and to show that they're actually at much higher red shift than the lensing cluster. I brought a color version of this, I'm not sure how well it came out. This is actually a different cluster. It didn't come out well well but what you can see is that there are these arcs, and you can also see this big mess of light from the center of the cluster and you can see that the arcs are more or less around the center. In fact, there's three on this side and a counter arc on the other side. By reconstructing the galaxy from which the arc came, you learn a kot about the cluster and salso about the galaxy, and I'll show you an example of that a little bit later. There's dark matter in clusters of galaxies. We know this because those arcs are caused by gravity bending the light. We can measure several other ways, so here's an example of a cluster, the Virgo cluster, what I was telling you about earlier. The first indication of dark matter was a measurement by Fritz Wikee, who claimed the term "dark matter" in 1933. What he showed was that galaxies in the nearest really big cluster, not Virgo but another one called Coma, the nearest really big cluster has galaxies that are moving at 1000 kilometers a second or more, and the only way that those galaxies could be held together to make this very dense cluster of galaxies would be to have a great deal more mass than we can see in the galaxies themselves, at least 10 times more than the visible mass. You can also measure this by measuring the temperature of the X-rays, that's something that's been done for 20 years now, and by measruing the arcs, and also little arcs, arcs throughout the cluster. All of these essentially give the same answer fir every cluster for which we've done the measurement. The amount of dark matter is at least 10 times divisible. It's now about 20. And the number keeps going up and of course what people do is they look to see if there's any exception. Back in 990 I wrote an article about dark matter for the World Book "Science Year" and I incited my piece with a quotation from "The Sign of the Four" by Arthur Comondoro, that's one of the Sherlock Holmes mysteries. "When you have eliminated the impossible, whatever remains, however improbable, must be the truth", said Sherlock Holmes. When we exclude other possibilities, what we're left with is this realization that there must be some invisible stuff wich surrounds clusters of galaxies and individual galaxies, this dark stuff, for which there's a reward. Actually, I happen to own an inverness cape and a deerstalker cap. I've been a fan of Sherlock Holmes for years. So what we discovered is that in the solar system, the planets are moving more slowly as you move away from the sun. Our planet, the earth, is going around at 30 kilometers per second, but Jupiter, five times farther away, is going around at about 10 kilometers per second. And Saturn even slower. That's because almost all of the mass in the solar system is is in the center, the sun. Now if you look at a spiral galaxy, almost all of the stars are in the center, and we're out in the periphery. And so you might think that it would be pretty much the same story. But it's not. In our galaxy, and essentially all other spiral galaxies that have been studies, what we find is that it's as if all the stars are set on cruise control with the same speed. They're all going around at the same speed, regardless of the distance from the center. The only explanation that fits the fact is that the amount of mass keeps growing, the amount of mass interior to the stars keeps growing with the distance of the stars from the center of the galaxy. There's the data on the solar system. Speed of Mercury , Venus, earth at about 30, Jupitar about 10. Falling off is one over the square root of the distance, but in our galaxy and 100s, actually 1000s of other galaxies that have been studied, the speed is practically constant independent of distance. Now, the amount of mass must therefore grow, because the velocity is constant, the distance is increasing, so the must is growing linearly with the distance. The visible mass, however, is constant, once you get a certain distance away from the center of the galaxy. So what's that telling us is that the farther out this constant velocity continues, the more invisible mass there must be. How far out does it go for our galaxy? Well, the large mesolatic cloud has had its sideways velocity measured and also 2 other satellites of the Milky Way, the large mesolantic cloud is 150,000 light years away and the velocity is still constant, 220 kilometer per second. We don't know how far it goes, but the basic picture for our galaxy and essentially all other galaxies seems to be that the visible galaxy is the center of an enormous halo of dark matter that goes out very far, we're not quite sure how far, but gets less and less dense the farther away we go. So the density peaks in the center and falls off, roughly it's 1 over r squared, so that the total mass grows linearly with ours, since the volume is growing as r cubed. How much total mass is there? We don't know. If there's not enough matter then to reverse the expansion of the universe, it will just keep expanding forever. If there's a lot of matter, then eventually the expansion will reverse and turn into a contraction. The measurements are getting better and better and now it looks almost certain that we have a big chill rather than a big crunch in our future. Finally, what is this invisible matter? Well, it's basically two kinds of particles that were suggested from theoretical reasons before dark matter was even taken very seriously, observationally. The axion is needed to solve what we call the strong CP problem, I don't have time to explain what that is but we we have a theory of the strong interactions and according to that theory of the strong interactionsthere's a fundamental problem called the strong CP problem that predicts properties of the elementary particles that they don't have. To solve that problem, the neatest solution is to have ab extra particle called the axion, which incidentally was partly invented by the speaker this morning, one of the two speakers this morning, Helen

Quinn. She didn't realize it was a particle but she started the ball rolling that led to the prediction of the axion. The other idea is that neutrolino, or light of super partner, or WIMP (Winfey interacting massive particle), is based on the idea of super symmetry. Super symmetry says that for every thermeon, there's a corresponding bozon in the universe and this leads to a cancellation of infinities. Thermeons are the matter particles, the spin a half proton, neutron, electron, the particles we're very familiar with that make up the matter. The bozons that we're familiar with are the force particles - the foton, the gluons, the graviton, also. The weak bozons are all bozons. The claim is that for every thermeon that we know and love, like the electron, there's a partner, in this case it's called the selectron, and for every bozon, like the foton, there's a partner, in this case it would be called the fotino. We haven't observed any of these partners but they're supposed to exist, and if theydo exist, just more massive, then that leads to a cancellation of infinities and it makes the theory much better behaved. It may allow a unificational gravity, that's called supergravity, it will allow grand unification of all the forces, so that they all come together at a point of a sufficiently high mass, it can solve problems that otherwise, we don't seem to be able to solve. So it's a very popular idea, super strains, all of this super stuff in modern physics is based on this idea of super symmetry. It also turns out to predict that the lightest of these super particles should be stable, in most versions of the theory. And that means that that's a natural particle to be the dark matter particle, as was first pointed out by the late Heinz Bagles and me, back in 1982. So there are certainly some good candidates for the dark matter, and another candidate, let me just mention very briefly, is neutranos. Now we know that neutranos have mass because of experiments, especially at Super Comio Canom, but there's also two other experiments that have data that's not as impressive as Super Comio Cani, but corroborating. So this tells us that the fraction of critical density in the trinos is at least a tenth of a percent and then some other data suggest that maybe it's bigger than that. Well, that's at least a little bit on this aspect of the invisible universe but I wanted to, in the last part of this talk, is show these videos that I mentioned, so let's start the first video. What this first video illustrates is the formation of the center of a cluster of galaxies. I mentioned to you that a cluster is a remarkable thing. Now what this is is a blow-up of a tiny little region of a huge simulation. Just the part that's going to turn into a cluster. And what you see is that the dark matter is actually, these are little halos of dark matter, they're going right through each other. You see, dark matter is not like ordinary matter. There's nothing that prevents it from going through other bits of dark matter. Now I know that went very fast, here it is again, slightly different view.

Which is the matter you're referencing?

It's all dark matter. In this video, it's all dark matter. So look how these things just go right through each other but of course they get torn apart by the gravity. You're seeing gravity at work here. Incidentally, if this theory is right, these dark matter particles are probably going right through us, right now. This is about 10 mega parti-secs, so about 30 million light years across. And this little region is the center of a cluster and actually there's two clusters that are coming together, merging. And we actually see many, many clusters that look just like this, except of course we don't see the dark matter at all, we see the visible galaxy.

So is the cluster entirely theromatic?

I'm only showing you the dark matter.

Now what this next video does is that it shows you essentially the same thing, the formation of a center of a cluster of galaxies, but this time, only the stars are shown. No dark matter at all. But to make this work, the same kind of dark matter was assumed. So now you'll see what happens as the dark matter goes, those dark matter halos we call them, goes through each other. This is work by John Dubinsky. So these are galaxies, and in case you wonder how that sort of massive light at the center of a cluster gets formed, this is our best bet. Both of these two simulation videos I'm showing you are brand new. They were just made in the last few months. So this is state-of-the-art work. Real fireworks. All that you just saw was about the last 6 billion years. So less than half the age of the universe. Now, what you're going to see next is that same final state, but rotated around, so that you can get a better view. So it gives you a sense of what this looks like from different perspectives. It's what's called a CD galaxy, you see these irregular misshapen things at the center of essentially every clustered galaxy, sometimes we see two of them right near each other, which are probably in the process of merging, and these things always have a lot of hot X-ray emitting material, this is the same thing again. What's going to happen is that this is going to rotate around for a couple of minutes, for about a minute, so it's the same thing except it's a slightly different view.

You use dark matter there, but what are we seeing?

What you're seeing is the stars. The galaxies were started off with the usual distribution of material that makes up a spiral galaxy, so there's a center and there's a disk. And what's going to happen next, after this part is finished, is just the collision between two of those spiral galaxies. The computer can keep track of millions of particles, each spiral galaxy has about 30,000 particles, and so what you'll see next is the very beautiful interaction of two spiral galaxies. What's rather neat is that this process that you're about to see is something that we actually see happening in the universe. Astronomers have caught lots of examples of spiral galaxies interacting with each other and looking much like this. So this is one of those galaxies, that's the disk, seen face-on, and this tells you how many particles, so that's one million, 24 thousand Ks, 1000 particles. And there's another spiral galaxy. And they're color coded so you can see the different material. So this is this beautiful gravitational dance that two spiral galaxies do when they interact with each other. Now, this is just a tiny little excerpt from that formation of the cluster core that you saw in the previous video. There were fifty of these galaxies put into the cluster, many of which got torn apart at the center. The net result is that you form something called an eliptical galaxy to these collisions. Keep in mind that there's a great deal of dark matter surrounding each of these. The computer knows about it but we're only showing the stars. If you don't put the dark matter in, you don't get patterns that look like the way galaxies really look.

So if you just went out into space and took some sand, with no dark matter, and grains like that, it wouldn't do…

The galaxies would just fall apart, they wouldn't even be bound together. It's the dark matter that's making all of this happen.

If you don't know what dark matter is, how do you know what it would do?

That's a very good question. What we did about 20 years ago was to realize that there are certain basic properties that dark matter might have. It might have very high velocity in the early universe and we call it hot dark matter, or it might be moving very slowly, even in the early universe, and we call it cold dark matter, and that's all that we really need to know, certain basic things about the dark matter to be able to do these kinds of predictions. So what works very well is essentially all cold dark matter with maybe a little hot dark matter, and probably also some cosmological constant. That seems to be the recipe that works. But it doesn't tell us what the dark matter is, and one of the truly big questions of modern science is, what is the universe mostly made of? Because it is the dark matter that it's mostly made of. The visible stuff, all the stars, all the planets, make up about a half of one percent of critical density.

Earlier you said, in the simulation, that the dark matter passed through us. What do you mean "passed through us"?

Exactly that, that the dark matter clumps together gravitationally but these clumps can pass right through each other, they're interacting gravitationally, but nothing prevents the particles from going right through each other, even though the whole clumps. The only interaction seems to be gravity and maybe some weak interaction. Okay, time for the last video. This is not a simulation, this last video. This is the real thing. So, many of you heard of the Hubble B Field. What happened was the Hubble space telescope was pointed at the same patch of sky, a tiny little patch of sky. How big? Take two needles, hold them perpendicular to each other at arm's length, the intersection of those two needles is the size of the region that you're looking at, that we're panning around. It has about 10,000 galaxies in it. Every dot that you see is a galaxy. That's not a galaxy, that's a star. But that's a galaxy. A particular place was chosen that has very few stars nearby and no nearby galaxies. This is the deepest exposure ever taken. It beats what we can do with any ground based telescope because we don't have to worry about the atmosphere smearing out these images. The colors are more or less realistic. This was taken in three different colors and they're combined to give the colors that you see. It's a total of 40 orbits of Hubble space telescopes. Each orbit takes 90 minutes and about half of each orbit is spent on this picture. Again, that's a star, you've seen that before. That's a spiral galaxy sort of tilted, another spiral galaxy, a spiral galaxy more or less faced on an irregular thing. Looks like an eliptical galaxy - a star, a spiral galaxy, a spiral. Well, you're looking straight out. To get a better sense of what galaxies are like, the best way is to go straight into the picture. The red shifts of many of these galaxies have been measured, so we can space them out along the red shift access, and then go straight into the picture. So that's what we're doing now. So these are relatively nearby galaxies, we're now back about a billion light years. A couple of billion light years out now. The galaxies are all names, but they have names like G23, or something like that. None of these are galaxies that have been catalogued before. We're now back about halfway to the Big Bang. The images are all real. We're now back to the first 3 billion years. Two billion years after the beginning. One billion years after the beginning. We could see more galaxies if there were any to be found. They're not there. A Hubble space telescope could easily have seen much farther.

The resolution would go how much further?

Oh, we could easily see out to red shift 6 or 7. But the highest red shift is about 5 in that image. This is a picture of the center of one of those clusters of galaxies. And this little thing here is a very unusual arc. That's a normal arc, a bluish arc. But this thing here, there it is again, blown up, was for, a few months, the most distant galaxy ever seen. It was discovered by my collegue at Santa Cruz, Garth Ellingworth, and Myon Franks, from Holland. And this is what that galaxy actually looked like before it's light was so distorted, and turned into this arc by the cluster of galaxies. This is 10 times more magnified than any object we can see with the Hubble space telescope. The reason is that this cluster is acting as the largest lens in the universe. Clusters are the biggest telescopes in the universe. This thing is a red shift of 4.92. Subsequently, one was discovered at red shift 5.3 and then 5.6; that's the current record holder. But this is the only one that we have such a detailed image of. And that little bright patch of light is putting out, all by itself, that little patch right there, 10 times more light than the entire Milky Way. So the process of the formation of galaxies is a very dramatic and exciting one. And thanks to Hubble space telescope and these great clusters of galaxies and our big ground based telescopes like Keck, which let us determine the red shift, we're really trying to uncover how galaxies form. And it looks like we need dark matter to understand how all of this fits together. Well, this is a good place to stop and turn the thing over to Andrei.

Andrei Linde

Joel gave a wonderful talk and he told you what is good about the Big Bang theory and I will start telling you what is bad about it. In fact, the Big Bang theory was first introduced in the beginning of this century by a Russian mathematician, Alexander Friedman, who solved Einstein equations, for comidinus substance, feeling the whole universe, and he obtained three different solutions, and Einstein didn't like them and he said, "No, no, this is wrong." It took some time before he agreed because the solutions looked so strange. Einstein wanted to introduce something different from what Friedman did. He wanted the universe to be studied. What Friedman found and what Joel demonstrated, is that the universe is expanding. Here is something which is called radius of the universe, or scale factor, because either the universe is infinite, then it doesn't have radius but it may measure how this distance between galaxies grow. So, according to these Friedman models, in all cases of which we know, if the universe is homogeneous, and that's exactly what we hear around. Well, of course, you see around, you see many inhomogeneous, like our solar system, etc. but on a very, very large scale, the largest which our telescope can cover, our universe is extremely homogeneous with accuracy about 1 in 10,000, better than that. So if you think that the universe is homogeneous and expanding, all at the same time, and then if it was very dense, then it started expanding and then it collapsed on itself. So it is a closed universe. If it has just a little bit of density of matter, then I think it would be expanding forever. In the intermediate case, it continues expanding forever, it's just marginal cases called flat universe. The reason why you have such strange names for it can be explained if you study geometry of these objects because Einstein's theory is not just gravity, it's more complicated things. Einstein's theory says that our universe is curved. So the best idea of how one can visualize these three different models is to say, "Let's look at the universe at a given moment of time. Just slice the universe at the sections of a given moment of time." What will we see? If we have a closed universe, then at any given moment of time, you'll look at these two parallel curves, two parallel lengths, and these lines, you may start them at one point and then they meet at another. Parallel lines intersect in a closed universe. Just like if you have a surface of a globe, and you start moving from the south pole and you meet at the north pole, and these lines are parallel near the equator, this is the best analogy for the parallel line, but these lines intersect. So it's a closed universe. You go and then you return to the same point. Well, it's actually not true because the universe is expanding and collapsing and then before you return, the universe dies, so this is a closed universe with no return. Okay, with light years, at any given moment of time, it looks like a surface of a table, so two parallel lines are real parallel, except when expanding universe is distanced between these two lines growing. An open universe has a geometry which is a little bit more difficult to imagine, it's geometry of a hyberolide, the surface in which two parallel lines diverge at infinity. So these are three models and all of them start with singularity with the first Big Bang, etc., and then it was anti-intuitive. European culture was based on the assumption that the universe is static. And not only static, it should be finite. Why finite, because only God can be infinite and the universe is smaller than God so, the universe must be finite. Newton told that it is not so necessary because what has so many activities of infinity, he can give just one of them to the universe, the universe is infinite. But it still must be studied because it's just a sequence, a set of coordinates and matter in it and the coordinates, what can happen with them. So that's why it was like helk that maybe the universe expands and then maybe collapses, maybe disappears. So people didn’t want to accept this idea, but eventually, because of this experimental evidence accumulated, people accepted this idea, and this idea became the best tested theory of the universe, so everybody believed into the theory of the Big Bang, and if you go to any bookstore, you find out that it doesn't have books describing the theory of the Big Bang. Now in '78, something happened. People started unifying theory of elementary particles and cosmology. And they found that if they make this unification, something strange occurs in the universe. First of all, according to the modern theories of elementary particles, there are some strange objects in the theory of elementary particles, which were forbidden before, they are called primordial monotols. What is monotol? Well suppose you have a magnet and you cut the magnet into halves, so we have south pole and north pole. And then you cut it into half and you have two small magnets, each of them has south pole and north pole. You cannot cut off south pole, okay? You always have them in a pair. Well, it's not so simple. In this new theory of elementary particles, there may exist south pole and north pole, flying in the universe light that, not built into a metallic brick, but just like elementary particles. And people estimated how many of these strange objects which should be in the universe. They have found the number of such objects, according to simplest models of Big Bang, would be approximately as large as the number of protons. Each of these objects should be a million, billion times heavier than the proton. And this case, according to the standard Big Bang theory, married with the best theories of elementary particles, our universe must be a million, billion times heavier than what we see right now. And such a universe would be definitely closed - it would start expanding and more entirely collapse. And the fact that we're sitting right now here proves that there is something wrong with the Big Bang theory married with a normal particle physics. So this was the first sign of worry, we should worry about that. Then people thought that maybe this primordial monotols, maybe we can do something better, choosing a different theory of elementary particles. So the started speculating about super gravity and they have found that in super gravity predicts some other strange particles, gravitinos, which are super partners of gravitons, that's what Joel told you about, each particle has its super partner. So these gravitinos, the total density of matter in them should be about 15 oldest of magnitudes, greater than observed matter of the universe, so it is too much dark matter, we do not want it. People decided to switch to other, more advanced particles, N=8 super gravity, and then the one dimensional universe, and then some dimensions, six dimensional, are compactified into a small nut; you cannot hear and you cannot move there. That's why you see the universe as four dimensional. That's still the best idea of elementary particles. However, this predicted that the energy density of empty space should be about 122 odols of magnitude greater than what we see right now and has a negative sign. Starting from this point, people started taking cosmology seriously and cosmology started paying attention to particle physics. So they decided to invent something which would really work. So this was a good idea; this was the end of the seventies and this was kind of a crazy crisis. Simultaneously they started looking away from the theory of the Big Bang being as good as it seemed and they remembered that there are many questions which some people asked all the time but because everybody knew about these particular people that they are simply crazy, that nobody paid any attention. But now that they understood that there are some problems with the Big Bang, they start listening. And one of these questions was, what was before the singularity? Where did our universe come from? If you open a textbook on any Big Bang theory, you find out that there is no sense in which you can continue Einstein's solution of the equations to this negative time, and therefore, it does not make sense to ask this question. Well, it does not make sense but it's very hard not to ask it. Now another question: why the geometry of our space is almost flat? If I say that the universe may be closed, it may be open, why? What we see right now, nobody has ever seen parallel lines intersect. So why is our universe so flat? Except for, the best model for these parallel lines is beams of light, so that was this graviational lensing that Joe had showed you. This is the place where these parallel lines bend a little near the galaxies, but that's a tiny effect under the very specific conditions. Otherwise, parallel lines remain parallel, so the idea was that maybe, there was some natural parameter of dimensional flanks, which is so huge, that parallel lines will meet if they intersect but having this huge parameter, it is natural to expect that the radius of carriage, it would be very large. In gravity theory, together with quantum field theory, there is only one parameter of dimensional flanks and that's so-called flank length, and this plank length is a size 10 to the degree minus 33 centimeters. So if you try to draw a straight line, and your hand is shaking, you may just say, "Well, the universe, it was wiggly. Every 10 to the minus 33 centimeters, my pen goes a different direction, because the universe must be curved." But nobody has seen it. We see that the universe, at this scale, which is the size of the observable part of the universe, than to the plus 98 centimeters. Parallel lines remain parallel, with the exception of this small gravitational lensing. So there's an error of 60 orders of magnitude between what we expected and what we get. So things change. Now this sounds a little bit metaphysical, and that's why nobody has paid attention to this crazy questions. Another thing, why different regions of the universe started the expansion simultaneously? If the universe is infinite, the guy sitting here and the guy sitting here, they started the universe and this place started expanding simultaneously.

But who gave the comet, because they didn't have any time to communicate, to say, "Okay, let's start expanding. I start and you start with me." Because there is infinite distance between them, they were unable to talk. It took this distance divided by the speed of light before they start talking, so the universe simply could not start expanding simultaneous, so why it did? When I was a young student and I was reading popular journals about Big Bang theory, I thought that when I would grow older, I would open textbooks written by professors and they will find out the answer to these questions. So when I grew older and I opened these books, I have seen that the professors did not know that the depression exists. Why is the universe so homogenous? This is this great mystery. At large scales, the universe is practically homogeneous. Why is it so? Well, people did not know why it is so but they came with the answer in the form of principle, which is called cosmological principle, and cosmological principle says that the universe is homogeneous because it must be homogeneous. And I used to make a joke some time ago that those who do not have good ideas, they sometimes have principles. But I stopped making this joke after I have found that this principle was invented by Albert Einstein. What happened? In the beginning of the 80's, we were able to suggest a scenario, which was called inflationary scenario, which explains why the universe is so homogeneous and solved many of these problems; maybe not all of them, but many of these problems, and this was a very simple solution. The fame moment when we introduced this theory, we also predicted that in most versions of this inflationary cosmology, the universe is extremely inhomogeneous at the very large scale, and that's what I'm going to tell you about it. And this is something which did not find its way to the bookshelves of the nearby bookstores, and in those few cases where you can find something about this theory, 99 percent of this is wrong. Let me just tell you, that's how things penetrate to the public, so we have now Wonderfest here, so we can tell the truth. So let me tell you now about the secret model of inflationary cosmology, which may make things understandable. Don't be horrified by this equation; it is necessary for me to show them to you so that you understand it. I'm not "just" talking. Let's consider a theory of so-called scale field. What is this scale field about? You have 110 worlds in a circuit, okay? Suppose that you have 110, but now 0. So just 1 circuit. There would be no current then. You have 110 circuits all over this auditorium; you will not feel it, it will be just another vacuum state for you. You need this other 0 for current flow. Birds sit on the wire, which has 10,000 volts, and they just fly away, nothing special. Now if you touch by one hand United States and another hand Europe, you will fried, because they have 220. If you have a constant, then it's like a vacuum state. So scale field is very much similar to this electric study potential. If you have constant scale field in the universe, you say, "It's just another vacuum state." Trust me, according to the theory for which several different people already got their Noble prizes, you are, right now, surrounded by scale field with very large intensity and if this scale field would be turned off, every particle in your body would become massless, and you would fly. So the fact that you are sitting here is related to the fact that there is this scale field surrounding us, so this is an important part. I forgot to tell you one of the problems of cosmology, which I like so much, because we start talking about why you're sitting here.Why are there so many people in this auditorium? Well, it's Wonderfest and many people decided to come. Why did many people come? Well, this is Palo Alto, and the Bay Area is so large. Why is the Bay Area so large? Well actually, it's a very small part of the United States and there are so many people in the

United States, some of them live in the Bay Area, some of them decided to come. Why are there so many people in the United States? Well, there are so many people on the Earth and some of them live in the United States and the earth is so big. Why is the earth so big? Actually the earth is not so big. It's a small part of our solar system and in our solar system, you know, one sun in a galaxy, you have 10 to the 11 suns. So our solar system is actually very small. But why is our galaxy so large? Well actually our galaxy is not so large because there are 10 to the 11 galaxies in the observable part of the universe. Now the question is, why is our universe so large? And then the father told to his kids, "Just shut up. Our universe is just big. Because the universe is created in one copy, and you should not ask questions like that." Now when you study, for example, closed universe, with the smallest natural size, which is planken size, and push the matter to the limiting density, you cannot have matter greater than density with so-called planken density, otherwise all your rulers would start breaking and clocks would start stopping and rotating in opposite direction because quantum fluctations of space time is severe. So you take the smallest part and you put as much density as you can and let it expand and you ask, "If this typical universe was the largest possible amount of matter that you can put there, how many elementary particles you will find?" And the answer is: one elementary particle or maybe 10. But in order to build one normal person, you need something like 10 to the 26 or 27, I don't remember exactly, elementary particles. In the observable part of the universe, we see about 10 to the degree 88 elementary particles. Huge number. So the question of why there are so many people in the auditorium is a physical question. Normal universe would not have you. So we must explain why we're here, and that is one of the things which inflationary theory does, and when we learn the answer, you know, we cannot then forget it. This is a metaphysical question, so let's learn the answer, or at least the possible answer. So we are iterating that we have a scale field which is, if it is constant, if it doesn't move, it's just another vacuum state. But the scale field for it must have its potential energy, so that if it is too large, it tends to be smaller, if it is too large and negative, it tends to be smaller. It is not the case for this electrostudy potential. Energy associated with electrostudy potential is just 0, but for the scale field 5, this is a slight difference. For a scale field 5, it may have potential energy, it may want to be in a state, for example, 5= to zero to be absent. Just imagine that the universe just opened its eyes, it is just created, and the scale field 5 did not know yet, "Where is my minimum? To which place should I go down? What should be my behavior?" So what was the initial value of this scale field 5? It may occasionally be just directly in the place which is most energetically favorable for it. But what if it was out of this place? Then of course it would revolve to this place, to the place where it should. But it takes some time for this scale field 5 to roll down. So let us then study what happens with the universe during this small time when the scale of field 5 was rolling down. And the rolling down equation for the scale field 5 and a little bit simplified Einstein equation, so I will just explain to you what are equations and I will tell you how people solve them. It will not be very painful. This equation, if you wrote this 5 dots means acceleration. If you have something and it starts changing faster, then 5 dots measures how fast is the change of the speed of this something. Accelerating car - you know you must have powerful car to have fast acceleration, so here, instead of the coordinate of the car is the value of the field. Here is the mass of the field and here is the value of the field and here is the alien wife. This CH5 dot, this is something unusual. H is a Hubble constant and 5 dot is the speed at which field 5 is changing. So if you look at this equation, if you forget about this stuff, if you ever studied mechanics at the level of high school and you know what is a harmonic oscillator, you will see that you are looking at the equation for harmonic oscillator. The acceleration of a body connected to the spring, or acceleration of a pendulum; this is a distance of equilibrium for the pendulum. It is proportional to the deviation of the pendulum from its equilibrium point, just equation of motion for the pendulum. This thing is a friction term, which tells you that this pendulum moves in this coslickit. So if this term is large, then this pendulum does not swing like that; it just moves down very slowly. So that's what I have just shown you. You have this ball moving in this potential oscillating, but if this term is large, then it oscillates like in a minuscule sleepit; it does not oscillate, it slowly moves down. This shows you how you calculate, according to Einstein's equations, this friction coefficient here, this viscositi. It is Hubble constant, it is proportional to the energy density in the universe. And energy density in this case is given by the scale field. So what happens? If energy density is large, then Hubble constant is large and our universe expands fast. If Hubble constant is large, then the friction is large. If friction is large, then pendulum does not oscillate; it just moves down very slowly. If for a long time, pendulum does not move or this ball does not roll down, then for a long time it remains at the same height. If, for a long time, it remains at the same height, then this quantity, its energy, it does not change. If it is almost constant, then we solve the simplest differential equation. Speed divided by the quantity is equal to the constant. And it is well known that the solution of these differential equations is exponential growth. What means exponential? This means that you have radius of the universe and each unit of time, it starts doubling. This is a normally fast expansion, exponentially fast expansion. What is the difference? How is this theory different from a normal Big Bang theory. In a normal Big Bang theory, in this place, in density of normal matter. Normal matter, so you have many particles in the universe, universe expandede two times, distance between particles have grown two times, and therefore, density of particles decreased 2 by 2 by 2, 8 times. So density became very small, this speed of expansion became very small. So that is why normal Big Bang theory, it actually slows down its expansion very fast. That's why, if you start with a small universe, it never is able to incorporate all of us. This new theory makes the universe expanding very fast for very long time, and that's why the universe becomes very large. Now, how large and what is the role of this? First of all, eventually the scale field 5 still goes down; it goes down slowly but it goes down. When it goes down slowly here, it stops oscillating like pendulum because this thing, Hubble constant, broke down, friction terms broke down, so you have no more oscillation. At this stage of oscillation, this oscillating field produces, quantum mechanically produces, elementary particles. This elementary particles become interacting with each other, and this interaction heats the universe. The universe becomes hot, and after this moment, you have your lovely Big Bang hot universe theory then. So everything that Joel said is completely right. We have our Big Bang theory, after this stage of very rapid exponential expansion. So why do we need this rapid exponential expansion? Because during this small time of rolling of the scale field 5, in realistic theories, we can estimate how large is this expansion rate. And you will find out that during this time in typical models, universe expands by 10 to the degree 1000 million times. So it is 1 with a thousand million zeros times. That is interesting because if you take the smallest possible scale, 10 minus 33 centimeter, and multiply by this rate of expansion, you will get 10 to 10 to 12^{th}, which is a simplest way of showing that 10 to minus 33 is equal to 1. Now, and this is certainly incomparably greater than the total size of the universe which we observe. So the idea can be demonstrated like that. You have our universe originally like a small ball, and then the ball starts expanding, expanding, and expanding, and then the surface, we're living on the surface of this expanding cosmic balloon, and this cosmic balloon becomes absolutely flat. So that's why parallel lines do not intersect because the south and the north pole are far away, we are looking at the miniscule part of this surface. So that's why we do not see it, that's why Ocleal was right. You know, it's so pleasant that several 1000 years after the man make his hypothesis that parallel lines do not intersect, we finally know the answer why he was right. Of course, he probably died without any doubts that he is right, but now we understand why he was right. And now, if somebody tells, "Well no, we do not have experimental proof that inflation is working", we all have this experimental proof - parallel lines do not intersect. And you are here because the universe was expanding, and if you would not be here, then nobody would be interested in proving that inflation of the universe works, so your presence here is a proof. However, this is not quite satisfactory because, if universe expanded like a bomb, then it made everything so homogeneous, so straight, etc. that there were no inhomogeneates in the universe. We have terrific cosmological principle there, our universe is polished like a billiard ball, better than that, so then where do we get galaxies? Well fortunately, simultaneously was this invention of this scenario was also understood the mechanism, which also produced inhomogeneates, and that's a failing. Chea in this room would have quantum fluctuations all the time. If we have a microscope and we zoom it, very small distance, and make a sethoscopic device so what you look at what's going on there, we'll find out particles appearing, disappearing, appearing, disappearing, but just like in a movie, you do not see every second of this; you make an average of what you see. In average, you see a solid here and there are some appearing, disappearing stuff, just ignore it. Now, what happened in the early universe? In the early universe you also had quantum fluctuations, but the universe was stretching them. That is, this red shift which Joel had described to you before, you have quantum fluctuations like waves along this bedrock of expanding universe, fluctuating very fast, but universe stretched them. When it stretched them, this fluctuations became very homogeneous, they start seeing these friction terms here which I've showed you. These fluctuations, when they short wave, they do not care about expansion of the universe; they oscillate all the time. But when they become one wave, is that they see that the universe is expanding with a very large speed and they feel this friction term and they freeze. So what happens is fluctuation, and when its wavelengths become sufficiently large, it freezes. Then you wait a little bit more. And the next fluctuation, which previously was a very short wave, it becomes long wave and also freezes on top of the previously frozen fluctuation. And after awhile, if many fluctuations frozen on the top of each other, you do not have vacuum. You look at this part and you see that ZI have very large scale field 5 and here I have very small scale field 5 and the size, the distance from here to here is exponentially large, so it is not vacuum fluctuations which is disappearing and appearing in a very small scale. You produced something very large scale and something which does not disappear. So you produced something classical out of something quantum. Our universe worked like a laser, which produced beam of light. It produced it from viewed quantum effects. So the universe produced this strange beams of this scale particles, but you know, when you produce these pink beam, it always remains pink. But when the universe expands, it red shifts this pink beam, it makes its radiowave, etc. So what happens is during this process the universe produces wavelengths of all possible kinds, they interfere with each other, they produce inhomogenerities and then few billion years ago, a team of Kobi comes and measured and says, "Yeah, you know, we see these ripples on the ground of the universe". So these ripples are that what happened. You have this quantum fluctuations and they are responsible for the inhomogenities in the universe and these inhomogenities adding to each other, they build later. They are responsible for creation of galaxies. You know, you need some seeds of inhomogenity for the process, which Joe has shown to you, to start. Otherwise matter doesn't know where to fall, if everything is inhomogeneous. But this inhomogeneous, they produce seeds necessary for the galaxy production. So this is only part of the story. How do you interpret this? You know, this scale field 5, it freezes, then another wave freezes, and the freezing on these waves is independent. You know, the first one who has frozen has amplitude up here, the second one may come and freeze with amplitude up or amplitude down - it's unpredictable. It's quantum fluctuations. The best model for this quantum fluctuations is browneian motion. You have jump up, jump down, and this theory describing brownian motion is, of course the theory of the dankian solar. Because as you know, dankian solar made astep for one direction, another direction, then go back, when he goes away from pop, because he does not know the direction. So eventually, the distance from the pop is proportional not to the number of his steps, but to the square root to the number of his steps. And that's exactly what we have found when we have studied deviation from scale field 5 from its medium; we did not understand first what we are getting. We get some strange results of scale field 5 fluctuations that are proportional to the square root of time. If scale field 5 has potential energy, then he can fling dankian solar in the gutters. You know, he made start in one direction and another direction, and then one direction and the same direction, and it falls. So then, until the morning, he is all the time at some average distance form the minimum and that's where they also get for the scale field 5. So it was amazing how knowledge of facts of life help us in building quantum cosmology. It also helps us to understand some features of the theory which we did not anticipate. And that is, I start with this scle field 5 falling down, etc., everything is simple, but we may have more than one scale field in the theory. And the scale fields, they are interesting entities. People got Noble prizes for their discovery, not for their reasons; by the way, experimentally, they are not found yet. But the theory is built in such a way that we absolutely need these animals to be there because the scale field, they changes laws of physics. They make some particles massive and that's why you do not fly. But we make some parts of this particle massive and some not, and depending what kind of scale field you have, you change laws of physics in one way or another. You make one particles heavy or other particles heavier, it absolutely change the road. So in particular, there are some, just realistic theories of elementary particles containing some other fields and this theory, your energy of a scale field has a dozen of different minima. And if we leave from one of this minima, then we have weak-strong electromagnetic interactions; that's exactly what we see in our road. But this same theory, if scale field is slightly different, it produces new universe with completely different laws of physics from us. If there is no scale field, and there is also an option, then there is no difference between leftons, and quarks, and neutrinos, and electrons, so it is a very weird road, and the question is, why do we live here? Well, now we have an answer. Because even if we started here, and the universe expanded, then there's drankien solar forever. Scale field would start drifting from one gutter to another and back. And in some parts of the universe, when he opened his eyes in the morning when inflation stopped, he found himself here, and in exponentially large region of the universe around him, he see that universe was weak-strong electromagnetic interactions. And then some other solar found himself here, and in an exponentially large part of the universe he sees universe has different laws of physics around him. So maybe we live in our part of the universe, not for the reason, and we see laws of physics of all types, not for the reason that our universe is built like that, but for the reason that there was inflation that made all the tick. In fact, there's some inertia theories, it's called calutsa quan theory, according to each of our universe at the fundamental level has many dimensions and only some of them are compactified, some of them small. If many directions are compactified, then we cannot move in these directions, we can only move in our part of the universe. We started with one particular model, which was 6 dimension fundamental level, but it was compactified to 4 dimensions, which is 3 space one time. After that, unit inflation, this radius of internal dimension, may start wiggling and de-compactifying, and then the universe may locally become 6 dimensional here, and exponentially large. And then it is 4 dimensional here and also exponentially large. We say, okay, we see 4 dimensional universe , 3 spaces one time, and that's just a given. Our universe is is necessarily 4 dimensional. Now, the person who who would live here would be probably much more smarter because he had this 6 dimensional brain, there's many interconnections, but he would see only 6 dimensional space time, and he would try to construct a theory which would try to explain why our universe must be 6 dimensional, right? So we have a better perspective, we have, what I call, a cosmopolitan perspective. We made computer simulation of this; for example, we studied theory like that with 2 minima, and painted parts of the universe with a left minima of black, parts of the universe with a right minima of white. But in some parts of it, you jumped from black minimum to white minimum. So the next picture looks like that. So you see, structure becomes more complicated. You continue simulations and you get picture like that, picture becomes in more involved. And then you get something like that, which I call Coninski Universe, in the name of famous Russian actor-painter. And you see, it is a fractal. It is not an expanding ball. If you zoom on this part, and continue simulations, then you are taking, repeating, and seeing the same and the same pattern over and over again. And why it was called the Condinski Universe then , it becomes obvious when I show you you want happens in the theory of siminima, where I paint one of this minima with that and another green and another blue. So that's the picture which we are painting. And when we obtain this picture I even, in the beginning thought that I should patant it for the wallpaper. This universe is just as hard to do after painting, and if we just change a little bit of parameters of the universe, we obtain total universe. So the main result of this can be summarized in this way. This dankian solar, he can go to the direction where SUC is not broken, and he will die there, because life of all type is impossible there. There was some German person with a family named Draubon, who have found some specific minimum in exceptive potential of supersometic SU5, called Draubon Minimum, so we know who will eat this cellular if you go in this direction. But fortunately, they exist in oazia, where the wide of appetite is possible, so who cares about the drankian solar, who does not know where to go. One conference, somebody told me that I am a sixis peak, and after that, I introduced the real reason why people laugh this oazis, because he is genius live there, which makes it especially attractive. In the final picture is the other simplified picture illustrating the structure of the universe right now. After this, I'm going to show you a few slides and two very short computer generated movies, but I should first explain what is this here. So, standard sediation, Big Bang theory, you start with this expanding ball, and then if the universe is closed, this ball contracts, and then expands, and then contracts. If the universe is open, it continues contracting as Joel said, you're not choosing, it was already chosen for you what kind of death. Jokes aside, what happens here, , this universe, in some parts, it produces new babies, new places. Where in new expanding universes appear, the reason why it happens, you know, the scale field 5 tends to roll down classically. But quantum mechanically it may produce fluctuations, which jumps higher. This is an extremely improbable process exponentially suppressed probability. But if you jump high, you're rewarded by by exponentially fast expansion. So you jump high, you produce a lot of space, and in this space the scale field 5 is greater than before then, you have a possibility to jump higher. This is extremely improbable but if you jump higher you are rewarded by the exponential like space. Universe, as hope, is immortal. And it produces new and new babies. And I'm using here different colors to show that laws in different parts of the universe may be different. And we live in one of these balloons. And we see at this place, and we say, "Oh, this is the Big Bang." But this is not the Big Bang. This is a pretty big bang, but not the Big Bang. So in this case, we're on these three3 relief. This is infinite 3. Thus, the process is never going to stop. Then we leave somewhere here, probably infinitely far away from the Big Bang, if this thing had happened. So our place in the universe should now be recognized as something different, absolutely different form what we learned in our textbooks 20 years ago and what we are still continuing learning because in all textbooks in astrophysics, there is nothing about this and there's some 20 years outdated description of inflation and cosmology, so each time when I am giving lectures on astronomy to my students, I ask them, "Please do not read what is in the textbook, because it is wrong" and then I explain to them this story. So this is interesting because it gives you a different perspective on you're place in the world. First of all, makes it makes us a little more modest, we are not looking at the whole universe right now. Then it gives us some hope that even if our part will collapse, there will be some other parts where a life of all possible types will flourish even if our civilization will die. I don't know if it is any good news for us, but at least this is something which I myself consider very interesting. Now what I am going to show you right now first some results of computer simulations, some series of slides. Let me explain what you see. On the axis x and y, you have x and y 2 dimensional universe. I cannot show 3 dimensional universe because otherwise they don't have any axis to show you density. So that axis is the density of matter in the universe. So, I start with a homogeneous with large scale field 5, and then I allow the scale field 5 to fluctuate. So after awhile, these fluctuations of the scale first produce these mountains because scale field 5 in general, it tends to go down. But there are some quantum fluctuations. And then these quantum fluctuations overrupt with each other. Universe expands, computer cancels, you shrink every new image is exponentially greater size of the universe, and all the time with this quantum fluctuations overlap and they produce universe which looks like that. There are some parts of this universe, in the valleys, where everything looks smooth. Here we are and you look around and you see these small ripples, but somewhere here, there are still new and new pretty Big Bang occurring and the new parts of the universe continues inflating and come to life all the time. So this is what I call self-reproducing; eternally inflating universe. So this is an interesting concept which is different from what you would see if you would just believe in the Big Bang, then you would describe only part of the universe like that. But, for all practical purposes, Big Bang theory gives you perfectly good description of this part. Here is another set of calculations: I paint blue, green and red different parts of the universe, where you have physics of different types. And we start, say, from red, and then the scale field 5 jumps in different parts to different places. And you have the universe, in some of them, you have blue laws of physics, which correspond to our type of physics, green which is different from red. And then we continue these calculations and we obtain these Calidinski universe pictures. And then the last set of simulations, we have here 2 dimensional universe, x and y, and on this axis, you will see again density of the universe, so I am combining two previous sets. So by tradition, because I came from Russia, we start with red color, and then colors start changing and changing, and you see mountains start growing, and you obtain the picture which has a lot of change of color here, and here have red, and here have blue, and in the end you have pictures which loook like that. Now here, each of these peaks is actually much wider than this area, it's non-Euclidean in geometry, I cannot show it to you. Here, universe expands much faster, so we have a huge balloo, and here next is a huge baloon, and properties of laws of physics, absolutely different, gigantic all the time. Here you are already frozen. You are either here or here, in each size of this region is exponentially large. We live in this blue balloon, some live in this red balloon, and when they want to come from red to blue, they experience a lot of difficulties. Now, because here at boundary, You have a huge domain row. This is the region with large energy density. And it's very hard for you to go through the domain row, and when you cross the boundary, you disappear, because your particles do not leave in this vacuum state. So it's not reccomended. So this is the general structure of the universe and I showed you the last results of computer simulations which we liked especially because it does not have any particular meaning. This was one of the results of computer simulations which were obtained here at Stanford when we just came and we started doing all of this, and I must confess that all the computer part of the work was done by my son, which was at that time at school, he is a computer expert and you know, we did not have any computers available so we start begging at all companies, "Please, give us a computer, we want to make this simulation." I start calling companies, saying that we are going to show the screen of our computer universe at the scale which you will never see at any telescope, and they say, "Yeah, it's very interesting" and they never called us back. Then BBC called me and asked that they are going to interview me, so I told them, "Okay, when you come to interview me, maybe I will show you something." Start calling the same companies and explaining them that if they want to show on the screen of British T.V. their computers, they said, "Well, that's very interesting" and they never called me back. The last company which still called me was Silicon Graphics. They called me and they told me, "Yeah, unfortunately, it became finally clear to us, that unfortunately, we cannot give you a computer which you wanted." And at that time I was already mad and so I told him, "Well, you know, I don't care, you lost your game, because even if you gave me the best computer which you can possibly have, I will be unable to finish my calculation within the next week before these people come." And they say, "Well, wait a minute. We will call you tomorrow." They called me the next day and said, "Well, unfortunately it became clear for us that we cannot give you the computer for which you asked, but would you consider working at a computer which is three times faster?" And I said, "Yeah, I will consider it." So eventually they gave us a computer and we worked exactly seven days, because this was our week with this computer, and on the same day and evening we produced all this magnificent images and they were much better on the screen of the computer because you see these mountains. You can fly among them. You can feel it, you see the shining universe, and you see that the universe is good. At the eighth day, these BBC people come and they start filming me near Stanford University and I told them, "Would you like to see the results of my computer simulation?" And they say, "Well, not really. We are very interested in dark matter." And I tell them, "Okay, but would you like, in the end, to tear some cheek?" So they came to my house and they turned on the computer and when they seen what is produced they start shooting the screen until they were late to the airport. So this picture has kind of like a memory of our first calculations. And after they left, it was necessary for us to give this computer back to Silicon Graphics. So at the eighth day, I gave this computer back to the Silicon Graphics, and hard disk crashed, taking the universe away with it. I'm going to finish with showing you three very short computer generated movies. So what you are going to see right now, the first series, is just a movie which shows you the same images which you have seen right now, of the golden universe. Right now you will see how it all happens. So we have homogeneous universe and then these fluctuations start overlapping aiding and you see these golden mountains growing. So when you see the process, you may imagine what we have really seen on the screen of the computer with the colors are even better than what you see right now. So this is movie of the universe creation. As I said, on the y axis, you see density pertubations, and the logist peaks correspond to the next Big Bang. Now I would like to show you something else, which is this Kaninski universe, which this 2 dimensional space and this red and blue, etc. colrs showing you physics in different parts of the universe. I do not know what are these horizontal lines; maybe it is some defect of the video. So you see, I started with the red and then you have this colors changing and changing all the time in regions, and you may notice that, for example, the left upper corner, it was already green and blue, it is not going to change. So there, laws of physics are already fixed and not going to change, but nevertheless, in some regions, still this process is going on. And now the final thing, which I am going to show you is a combination of these two movies. You will see both the laws of physics changing and the density of the universe changing. This is the place where expansion of the universe is much higher and you see how the colors are changing. So that's essentially the main thing which I wanted to show you today, and then you may ask me questions about these, and I am thankful for your attention.

I did not put my movies in the highest resolution but I think that I will hopefully do it in the next few days.

Did you put it in storage code there?

No, service code, you must ask my family. He was, at that time, in the school and we were writing papers, we had written about eight papers together. But he decided to be a computer scientist. Unfortunately for me but fortunately for him.

Joe, if I could interrupt. Joe, I wonder if you could just, in some way, summarize the places where you agree and disagree for us?

Joe: I wasn't exactly sure what Andrei was going to talk about so I brought a variety of transparencies. I just want to show you a couple of different things. This is a summary of some key ideas in relativity. General relativity is the principle of equivalence, together with the global effects. The principle of equivalence says that the effects of gravity in some small region are the same as no gravity; just a enertial reference frame, this ball just keeps moving in a straight line, plus the effects of acceleration, just exactly as if a rocket were accelerating up, and that's what causes things to fall. Well that's gravity on the small scale. That was one of Einstein's great insights. But on the large scale, space time is actually a participant in the dynamics. Space itself is live. Here are two ways of illustrating it that also help to connect with some of the things that Andrei was talking about because what they do is they show you how horizons can exist. Horizons are the things that allow us to have multiple universes and allow the universe to be hidden from us, maybe almost all of the universe. Now there are two kinds of horizons that you may have heard about. This is supposed to be a black hole and this is the event horizon around the black hole, sometimes called the shwartshield radius, which is proportional to the mass of the hole. Now suppose that we have a bunch of points that don't move and at each point a light flash goes off and you look a little bit later, where the light sphere, but we're just going to show it as a circle, is. Far away from the black hole, the light circle surrounds the point where the light was emitted. But as we move closer and closer to the Black Hole, this curious thing happens that the light, after it is emitted, is dragged toward the Black Hole. Why is that? It's because space, this inertial kind of space which things behave simply, is dragged toward Black Holes. In fact, at the celestial radius, it's falling in at the speed of light. And light goes at the speed of light with respect to the inertial reference frame, but the reference frame itself is falling in at the speed of light, and so no light can ever get out of this region inside the celestial radius. In fact, inside the roles of space and time interchange. That means that an event horizon around every Black Hole is forever hiding from us whatever is going on inside. We can only calculate it using Einstein's theory but we can never observe it. Well, that's the fairly familiar story about a Black Hole, and you have heard about that. Now, try to imagine taking this picture and turning it completely inside out, so that the singularity now moves out to infinity and infinity is now at the center. That's basically the picture of an expanding universe. Consider a bunch of points, as before, fixed in space, and imagine that a light flash goes off and then somewhat later we look and see where the light is. Near us, you understand that the Hubble sphere surrounds every observer, so near us, the light still encloses the point at which it was emitted. But as we move closer and closer to the Hubble radius, the light sphere is dragged away by the expansion of the universe, and at the Hubble radius, its expanding at the speed of light. That's why we can never see anything outside of here. It turns out that if the expansion is slowing down, then our distant descendents can see a little bit more. But, the curious situation that the latest data is suggesting is that the expansion is actually not slowing down but speeding up. Maybe it's best to just focus on this top picture. Andrei showed you three pictures which corresponded to a contracting universe and one that's expanding but always flowing down and one that's basically going flat, going straight. I'm not bothering to show the contracting ones since it doesn't look like we live in that kind of universe. This is a universe with only matter corresponding to critical density and no cosmological constant. This is less than critical density, about a third of critical density, with the cosmological constant, and this shows the effect of the cosmological constant. The universe is actually accelerating its expansion. This measures the relative size of the universe, this is the present moment, this is before the present, the zero would be the beginning of the Big Bang; the conventional Big Bang, not the inflationary part. So this seems to be the situation that corresponds to the universe we actually live in. This is the set that seems to correspond to the data that we're getting from supernovi and satellites and other ways of trying to measure this. Well, getting back to this picture, the Hubble radius and all of that, what can we say about that? This is a picture of all the sizes in the universe, up to the universe itself; actually, more precisely the Hubble radius. What I'm plotting here is the mass versus the size and for the Hubble radius, as Andrei said, we have 10 to the 28th centimeters and the universe has a little bit less than critical density; critical density would be right on the screen line and it's a little bit less, with some uncertainty. Now, what this diagram is showing you is all of the different kinds of things we're familiar with. People, whales, microbes, all plants and animals actually lie right on this line because that's the water density line. Actually planets and stars also lie right on that line, because it turns out that they were all pretty close to water density. Except for white dwarfs and neutron stars, which are much denser, almost as dense as Black Holes. This green region is forbidden. If anything has that small a size for its mass, it collapses away to nothing at all, according to general relativity. Now quantum mechanics composes a different constraint. Quantum mechanics excludes this region of the diagram; basically it's the uncertainty principle that excludes this region. This region is excluded by gravity, this region's excluded by quantum uncertainty. You'll notice that the allowed region has a boundary on the left hand side. There's a size below which you can't go because of this combination of gravity plus quantum mechanics and that's called the plaunk length. That's the 10 to the minus 33 centimeters that Andrei mentioned. Notice that there's a smallest size and also a biggest size that we can see, the Hubble radius, and the difference is about 60 orders of magnitude, as Andrei mentioned. And I'd like to put all of those on one picture, so we can start at 10 to the minus 30th centimeters and go around to 1 centimeter and then up to 10 to the 28th centimeters, the horizon. So, this encompasses all the scales from the smallest scale, the plaunk scale, 10 to the minus 33 centimeters, around to the largest scale, 10 to the plus 28 centimeters; the larger scale we can see. An interesting fact is that we, people-size things or, more precisely, insects, are more or less in the middle of the diagram. And that's not an accident. Creatures like us depend on electricity and magnetism which is what is important at the bottom part of the diagram, between the size of mountains and atoms, and we have to be much closer to a mountain than an atom to have enough complexity to be able to discuss the sorts of questions that we're discussing today. So creatures like us have to be about the size that we actually are. I wanted to comment on a couple of the things that Andrei said and just give you a little bit different perspective on them. We don't actually disagree; I've learned this stuff from Andrei. I've checked it and I've written papers that are connected to inflation. But this is basically Andrei's picture, where ordinary inflation corresponds to an inflation rate. It turns out that the vertical axis is also the inflation rate; that's his Hubble perimeter. So this is ordinary inflation which is doomed to end quickly. But if the inflation rate gets high enough, then the quantum fluctuations are the most important aspect, and then you can have fluctuations up as well as rolling down, as fluctuations down, but the fluctuations up win, as Andrei explained. So the pattern basically is that the rolling down produces these doubles of ordinary expanding universe and in one such bubble, there's our whole horizon, everything that we can see, out to 10 to the 28^{th} centimeters, surrounded by a much larger region; we're not sure how much larger, maybe exponentially larger, but that would then be surrounded by an even larger region in which these amazing mountains in which Andrei described are causing still new inflationary regions to exist. Far away, there'll be another bubble and maybe even an infinite number of other bubbles. So that's another way of picturing the same ideas that Andrei is describing. Here is yet another way of picturing these ideas; I call it eternal inflation as cosmic Las Vegas. You understand, this is an analogy, but it's supposed to correspond to what Andrei told you. So the quantum fluctuations and the eternal inflation are supposed to be coin flips. If a coin comes up tails, it becomes suddenly half the size. But if it comes up heads, there are two coins, each twice the size. If a coin becomes small enough, the rate of inflation sewn off, it falls through the mesh floor and enters ordinary inflation and becomes a Big Bang and evolves into a universe, where structure forms. Small fluctuation as inflation ends becomes galaxies and cosmic voids and so on. So this is the picture. Out come the coins, they flip at random, if they come up heads, then there are two of them, and they're twice as big. If they come up tails, then suddenly they're half the size. Eventually, any coin will come up tails often enough that it's small enough to fall through and time begins, and it turns into a universe. Well, how does this affect our view of the universe and what it might mean. Let me end at this transparencie. First of all, let me go back to dark matter. Sigmund Freud, in his new introductory "Doctors and Psychoanalysis" modestly said that he was the third of the great revolutionaries after Copernicus and Darwin. Copernicus displaced us from the center of the universe; Darwin showed that we're just another animal, we people, not the crown of creation; and Freud showed that most of the mind is unconscious, not the rational reason. Well, it now turns out that we're not even made of the majority of the stuff of the universe. There might be more mass in neutranos, let alone in cold dark matter particles, than there are in all the ordinary matter that we can see, all the stars and all the planets. So dark matter is yet another displacement of man from the center of the universe, but perhaps inflation puts us back into the center of the universe, or at least the center of our own level. Ordinary expansion causes a dilution of the material in the universe. But the amazing thing about inflation is that while inflation is going on, it's practically a steady state. Alan Goobes, who coined the term inflation called it "the ultimate free lunch". Creating actually scaler field, but then the scaler field, this implicon field, at the end of inflation, turns into the energy density that includes the ordinary matter. So yeah, creating it out of nothing as it were. Actually, you might think that the books don't balance but they do. All of this is according to our very well tested theory of gravity, Einstein's theory. So, it may not be true but it's consistent with everything that we know. With eternal inflation, this idea that Andrei calls the self-reproducing universe, the steady state in Big Bang pictures becomes complementary; the steady state picture is what we would say is really true on the really big scale. These bubbles are forming and going through their evolutionary process, new bubbles forming all the time. The basic picture doesn't change yet, from a perspective of any observer who has to live in what Andrei called the "blue region", one of these horizons that has the laws of physics that we're familiar with, from that perspective, it's definitely a Big Bang picture. Whose [perspective is right? On a question of perspectives, there is no right, they're just different perspectives. So that's what I mean when I say the pictures are complementary. Do all the bubbles have the same physics, the same space-time, etc., are there many possibilities with intellignet life arising only in especially favorable ones? That's the kind of picture which also goes under the name of anthropic cosmology, that Andrei's eternal inflation seems to be leaning toward. Incidentally, quantum mechanics doesn't require any cause. These fluctuations are purely random, they're not caused by anything. So the first cause argument for the existence of God has gone out the window. But something that we haven't had time to talk about today, but which is quite interesting is that it seems that the universe is very fine tuned; the laws of physics are exactly just so, so that complemenic carbon chemistry can exist and creatures like us can eventually evolve. We don't know whether this is purely a matter of chance and zillions of other bubbles exist where intellignet life couldn't have arisen or where there is maybe a small finite number of possibilites and one of them, or maybe several of them, were just so, that creatures like us could ask these questions. One of the things that's going to be very interesting over the next decade or so is that it looks like we're in the final stages of putting together a picture of the Big Bang that really makes sense, that holds together, including this inflationary explanation for how the Big Bang got started so that galaxies form, and so on. But, inflation itself can be tested, any given version of inflation can be tested, and the test are coming out okay. The cosmic background radiation, for example, let's us make very precise tests. Let me leave you with this very interesting question that Andrei and I wanted to comment on. What we do not know how to do right now, but what's an interesting question is, suppose it turns out that inflation is right, that some version of inflation is right. How can we tell whether this internal inflation idea, the idea that there are many, possibly an infinite number of these bubbles like the one that we live in, that sort of perfolate up into this sort of eternal inflation process that Andrei described with the quantum fluctuations, how can we tell whether that's correct? I've been trying but so far not succeeding in finding a way to test that, even in principle.

Question: Assuming steady-state inflation, where does the matter go when it collapses?

Joel: Well, as I tried to explain, it doesn't look like a collapse is in our future. The universe appears to have much less mass than would be needed to turn the Big Bang around, to turn the expansion around. So the universe is not going to collapse, at least our part of it; it's going to expand forever, accelerating as far as we can tell.

Question: But you still have to answer both sides of the question.

Joel: If it doesn't collapse…actually, the matter is just locked up in a black hole. A black hole mass is the mass of everything that collapsed into it, so it doesn't disappear.

Andrei: Maybe I should add a little bit to this question, because it also related to some of the questions which appeared before. Where at all this matter appeared, first of all, because, in order to create this infinite universe, we do not need to have much. We just need to have this 10 minus 33 centimeters of plank size, and then all of a sudden, we have all of these people appearing from whatever. This does not have any mass in it, so it just looks like cheating, and we don't want you to leave this place with a feeling that we have cheated you, so we will explain to you the trick. And the trick is a failing, it does not sound like a good explanation, but nevertheless, it is. The total energy of all matter in the universe, in whole universe, is exactly equal to zero. What I said means fully. Suppose if you have two planets; one has a mass of just two stones, one mass has one kilogram, another mass one kilogram. So two stones would mass two kilograms, right? Wrong. They have massed less than two kilograms because they attract each other gravitationally and this gravitational attraction decreases their energy because the total mass is equal to the total energy and gravitational energy is negative. It takes you some force to exert, to put two gravitating bodies apart. So gravitational energy is negative. So we have energy which is equal to mass, according to Einstein, of one body, energy of mass of another body, minus gravitational energy. Well, if you make the total sum of the total amount of bodies in the whole universe, you will find out that the mass is exactly compensated by gravitational energy over these bodies interacting. Therefore, the total energy of the whole thing is zero. Now the trick is how you get mass out of nothing, out of the total zero, because we have these zero, and now you're sitting here, well because you do not care about gravitational energy of the whole universe. What is necessary is to make a trick to divide this zero into growing energy of matter, and growing but negative energy of gravitational field. So what inflation does, it is a channel of instability where you have this possibility of zero being divided into positive and negative, and this process goes exponentially fast, just like when you're on the hill and it can roll down and you're in an unstable state. So when you have a possibility to divide energy into positive and negative, and this possibility is exponential inflation, that's what happens. You have creation of energy of matter, but the total energy remain zero. So the balance of energy is not violated, it's just extremely anti-intuitive, it's not what you thought it is, but yes indeed, that's creation of the universe from nothing. When everything collapses, then everything reduces to nothing, if everything collapses. Goes that way, just gravitational energy becomes zero and energy of matter becomes zero. So, zero remains zero, no violation.

Question: Do black holes go from one universe to another universe?

Andrei: Well, there are some science fiction stories that you can just jump into the black hole and emerge in another universe. Well, it's not so much science fiction, it is really kind of fact. If there are several different types of black holes, one of them a normal black hole, see if you just jump then, well, farewell. But there are some black holes which are charged, which contain electric charge inside of them. Now if you jump into these black holes, you fall down and you see the singularity, but you have a possibility to avoid seeing the singularity and wind up in a different universe in an infinite future from you.

Well, at the classical level this picture is possible and some people may speculate about it. At quantum mechanical level, it looks like at the moment that you will try to go outside, you will meet some quantum mechanical singularity anyway. So I would not recommend this cosmic travel unless you insured your house for whatever.

Joel: Just on that, most of you have probably seen or heard of the Carl Sagan movie "Contact". I know that Wonderfest is dedicated to Carl Sagan. It was Carl who raised this question so that gravity experts paid attention to it and Kid Firm calls this sort of thing a Sagan question. And he is one of the ones, Kit Firm is one of the greatest living experts on general relativity, and he is one of the ones who though that it might be possible to actually travel across the galaxy through worm holes; going in one black hole and coming out a white hole. In his recent popular book, which I think is now out on paperback, Kid Farren tells the story of the scientific research he and others did to try and answer this question, and how Steven Hawkings showed that in fact, this process seems not to be possible, this is something that Andrei was alluding to. The book is quite readable; just look at the chapter on "Sagan Questions". There's also a nice book on inflation by Alan Goobe on a very popular discussion. Andrei doesn't like it. But it discusses his ideas. There's a nice popular book by Timothy Ferris called "The Whole Shebbang" and that's got a very nice chapter on this stuff. It's also very readable.

Question: How can gravity and charge be felt outside the black hole?

Andrei: Gravity does not disappear away from the black hole. Black hole is created by gravity. Gravity, in fact, is a carriage of space, so near the black hole the carriage is maximum. These two things, black hole and gravity, they do not contradict each other. You may ask a different question, for example, somebody tries to throw something away from the black hole and it falls down, but how about gravitons? Here is a widely spread misconception. People think that electromagnetic interactions are transferred by protons, and gravitational interactions are transferred by gravitons. This is wrong. They come entirely without any speed of light, if you have a charge, then at a distance infinitely far away from it, you still know that if you surround the charge with a huge sphere, an amount of