GEORGE DJORGOVSKI: First, let's take a look at some of the basic ideas about early universe and how we get to study it and deduce what happened very early after the Big Bang, and in particular, the cosmic microwave background as an important signal of the early universe. So here are some of the key ideas. As you push back in time, the universe was smaller. So it had to be denser. And it had to be hotter.

And if you push this far enough in the past to smaller and smaller expansion factors, it can get really really hot. And it does. And in principle, the Big Bang happens at the red shift of infinity, which is the universe is condensed into a point, and so it can obviously reach very high temperatures.

Now, if you have plasma in a thermal equilibrium-- and it doesn't matter which particles they are-- photons can create particle and anti-particle pairs. And they do. And the characteristic energies of photons will be Boltzmann constant times the temperature. And so that will give be of the order of rest mass energy of the particles that are being created.

So as you go deeper in the past, you have higher energies of photons. And therefore, you will be able to generate ever more massive particles. And both of these processes happen. So then as universe evolves from really, really condensed state early on, onward to different kinds of particles and therefore, different kinds of interactions will start playing an important role.

Now, this is very interesting, because in principle, if we can infer something about those early moments, we have an experimental way of probing fundamental physics that's way beyond anything that you can accomplish in terrestrial accelerators, no matter how big you imagine they can be. And for example, we still don't know what dark matter particles are. They're entirely outside the standard model of particle physics. Maybe Large Hadron Collider will find them, and maybe not. But maybe we can infer something about them from the early universe.

And in any case, even though in classical cosmology, you can extrapolate to the Big

Bang, time equals 0, space has no size, and time doesn't exist, that's not likely to be the case. At some point, that classical theory has to break down. And we have no idea when or exactly how, because we do not have quantum theory of gravity.

But there is a characteristic scale, the so-called Planck scale, that we'll define later. But it's roughly 10 to the minus 43 seconds after the Big Bang. And we're pretty sure that by the time you had reached to that high density in short times, quantum gravity must be playing a significant role. But that's entirely outside the regime of the non-physics.

So here is a story line. So the universe begins, or maybe something happened before the Big Bang. People are actually seriously thinking about that. Because once you realize that you can't really extrapolate to infinite forces in a really small universe. Something happened before the really, really, dense state. And there are different ideas

Then just a little bit later, universe undergoes a phase transition, just like when you boil a liquid and it turns into the vapor. Same thing happened to the physical vacuum. And that caused a so-called inflation.

Suddenly, the universe inflates by many orders of magnitude. And we'll talk about it in a moment. By the time that ends, when universe is 10 times as old, say, this is where we think that the strong nuclear force parts the way with electroweak force. So this is what's predicted theoretically, but it's way beyond what we can test experimentally. Gravity presumably split off right around Planck time.

When universe is micro second old, this is where protons and neutrons really form. Quark soup turns into the well-known types of particles. And then from about 1 millisecond to about 3 minutes of age, universe does what stars do in their core.

So if you squeeze the universe so the density and the temperature match those that are seen in the cores of stars, the universe is going to do the same thing. It's going to start fusing protons like hydrogen into helium and maybe some other stuff. And so the whole universe is like a stellar interior and produces helium and other things.

So they call that the primordial nucleosynthesis. Turns out it really just makes helium and trace amounts of a couple other light elements, nothing else.

And it's still hot and incandescent in thermal equilibrium that it keeps expanding. And when it gets cool enough, so that gas can no longer stay ionized, the ions recombine. And we call it Recombination Era. And this is at that point that the universe becomes transparent to radio waves. And that's where cosmic microwave background originates.

And then sometime after that, a couple 100 million years after that, first stars begin to form. And their radiation re-ionizes this newly created neutral hydrogen into the intergalactic medium that we know so far. So you can look at the history of the universe as a thermal history, how the temperature changes as a function of time, and therefore, what physics happens at appropriate energies.

This is sort of artist impression of what this might look like. It's probably hard to read. But you all have slides, so you can take a look. And so at the bottom is Planck Era. It's maybe better to talk about Planck Era than Big Bang itself, because we don't know if we can extrapolate to 0.

Rapid amount of expansion, unification of the forces is happening there. Then as you move forward in time, universe cools. Different particles interact, form some light elements. Eventually, things calms down and the universe becomes the one that we can observe today with telescopes, looking at galaxies and what have you. So take a look at this slide at your leisure once you have a look at the PDF of the slides. And it kind of explains a little better what's going on.

Well, how do we know all this? Because this is pretty wild extrapolation too right? Well, we have several probes of the early universe. The first and the most significant is the cosmic microwave background, which is the afterglow of the Big Bang, the radiation that was released when universe became neutral 380,000 years after the Big Bang. That's roughly red shift of 1,100.

Then we can look at the abundances of light chemical elements and deduce, once you remove those that are made in stars, what happened so that you can make those observed abundances of, say, helium, isotopes, deuterium, lithium, and so on. And that way you can have some empirical probe of universe when it was between millisecond and a few minutes old. This is well established physics, nuclear physics that is no beyond doubt. And it's tested experimentally and so on.

Then as you start going deeper and deeper, things become more uncertain. Because we enter the realm of high energies where of which particle physics hasn't really probed yet. So we think that-- we have some ideas as to how baryons and leptons originate in anti-matter. But that's going to be very, very iffy.

And then suddenly, when you get to the really early ages, like 10 to the minus 33 seconds, this is the inflation era. And that turns out to produce a whole bunch of verifiable signatures. And so it's amazing that by observing the universe now, we can actually infer something about physics that happened 10 to the minus 30 seconds after the Big Bang, which is many, many orders of magnitude beyond the energies that we can probe with accelerators today.

So this is why cosmology is now connecting with particle physics. And the universe itself becomes one gigantic lab for fundamental physics. All right, let's rewind a little bit.

So the cosmic microwave background-- once you accept that universe has been expanding for a while. It's trivial to run the movie backwards. And that's what Lemaitre did when he came up with the idea of primitive atom. That was a fairly qualitative story back then.

But then in lat 1940's, at that point, nuclear physics was better understood, thanks to nuclear weapons. And George Gamow and his collaborators, Alpher and Herman came up with a very solid treatment of what happens if you start squeezing things down.

You reach the states of plasma where nucleosynthesis would happened. And as you expand, they'll be afterglow. You'll get shifted. And they actually predicted that the universe would be filled with radiation corresponding to roughly 5 degrees Kelvin.

That was a little beyond what they would test experimentally. Actually, it turns out that this signals was detected indirectly in 1940, '41, something like that. Because you can observe molecular transitions in interstellar medium. And some of them can tell you what the temperature of the radiation field is. And the coolest they found was something like 3 degrees Kelvin. But nobody understood back then that that was cosmological.

So the real discovery was done by Penzias and Wilson in 1965. They were developing radio technology for the satellite communications in Bell Labs. And they discovered there was this extra source of noise that they just could not get rid of. And it came isotropically from everywhere in the sky. And somehow that was recognize to be that long sought signal of the cosmic microwave background.

And Bob Wilson, by the way, the one who's on the left here, was a Caltech student. So he got the Nobel prizes, deservedly, for this. And yes, that's the right expectations for you guys.

What's shown here on the right is Planck curve, or black body spectrum. And this is not theoretical curve. This is the actual observations. So this was from a satellite, the COBE satellite. And we now know that cosmic microwave background is as perfect black body as we can make it. In fact, it may be better black body than any that we can do in the lab, with the temperature about 2.73 degrees.

When this happened, cosmologists were still debating whether or not the Big Bang cosmology was something to believe in, because it had this unpleasant idea of the specific moment of creation. And there was a competing model of steady state cosmology, in which the universe is always the same. Just new matter keeps forming up. Then that model does not make prediction of radiation field baking the whole universe. And so once this was found, it was pretty clear that the Big Bang theory was right.

So when you take pictures of the microwave background over the entire sky, it's pretty uniform. Now, if you turn the contrast nob by a factor of 1,000, you see that there is a dipole. We're moving in a particular direction. And that's our peculiar velocity that we discussed earlier.

You subtract the dipole, and you see that there is a lot of mass from galaxy, electrons from supernova remnants, and so on, thermal emission from dust. And if you model a galaxy very carefully, then subtract it out, turn the contrast nob another factor of 1,000, you will see that there is this motley signal, which is parts in a million of the original signal. And those are the primordial density fluctuations, those that later on grow to become large scale structure.

Well, what do they come from? They're actually music of the spheres. So in the early universe, there are going to be some non-uniformities which are inherited from quantum fluctuations earlier on. And so baryons and photons will be falling towards the potential wells. And the largest scale-- we can think of that as the waves that are spanning the entire causally connected universe at that time, which is how far signal could travel since the Big Bang. That turns out to be of the order of some 100 of millions of light-years. And the waves would exist in all different scales. But the biggest ones will be the most prominent.

So then what happens when you suddenly recombine? You removal restorative forces of the plasma. Whatever waves where there then in the electromagnetic field, the radiation field, stay frozen. And these are these bumps that we see in microwave background. These just temperature fluctuations that were due to these very large universe-scale waves right around the time microwave background was released. And by studying them, we can learn a lot about the universe when it was the 380,000 years old.

The way we quantify this is we use spherical equivalent to Fourier transform. Remember, we use power spectrum, Fourier power spectrum of the density field of study large-scale structure. Well, we can do the same thing on a surface. We can do the same thing on a spherical surface. That's called spherical harmonics as opposed to traditional flat Fourier space waves.

And intuitively, it works the same. If you have big waves, big blobs then there is going to be some power at low frequencies. And if you have a lot of small bumps and wiggles, it will be a lot of power at high frequency, and so on. And there is, of course, power on all different frequencies. It's not simple like this.

So when this was measured originally first with COBE satellite, but really then much better with some balloon experiments and ground-based experiments from the ground, and WMAP satellite, not Planck satellite, this is what it looks like. So angular size is shown on the bottom. That corresponds roughly speaking to the angular size of the bumps that are seen.

And the y-axis is the amplitude of these fluctuations-- the square rather of the amplitude, because it's a power spectrum. And you can see that there is actually nontrivial signals. And there are data points. And the line that goes through them is particular model.

So this was a spectacular confirmation of our ideas of how things happen in pre-recombination of the universe. But the interesting thing is that the position of these waves in this angular parameter space spectrum are a superb probe of cosmology. And this is what resulted with what we now call precision cosmology.

The position of the very first speak is telling you what is the curvature of the universe. It's an angular diameter test at single red shift 1,100. And then the relative amplitudes of these peaks and so on are telling you about the other things, dark matter and dark energy and the amount of baryon and so on. When we talk about cosmological tests, we'll come back to this again.

So the punchline is that the cosmic microwave background, its very existence, is telling us something about early universe, the Big Bang. The spectrum is telling us something. And the angular fluctuations are telling us about the formation of first structures. Then it turns out that it can be used the probe inflation ear as well, but more about that in a few minutes.