S. GEORGE DJORGOVSKI: Let's take a look now at the cosmic inflation, which is now the dominant theoretical paradigm of what happened in the very, very early universe. And the basic idea was mostly credited to Alan Guth. But a couple people before him, including Alexei Starobinsky in the Soviet Union, came up with the same idea, but did not really follow it or interpret it in the correct way. And then it was developed by many others, including Andrei Linde. And so the three of them, Guth, Starobinsky, and Linde, just shared the Kavli Fundamental Physics Prize for 2014, for their work on inflation. And they got the prize now because the Caltech experimental cosmologists found a pretty good signature confirming inflation was right.

This is a page from Guth's notebook, where he figure out what was going on and wrote a spectacular realization. And the theory was so compelling that almost instantly people started believing it, even though there was no clear experimental prediction or proof yet. People believed it because it explained some long-nagging problems. And two of them in particular are very striking.

The first one is the universe today is close to flat. Even back in 1980, it was so close to 1, but it was somewhere between 0.1 or 0.2, or something like that. Anyway, it's very close to unity.

The second problem was the so-called horizon problem. I'll deal with this in a moment.

The third one is the monopole problem. Early theories predicted there will be a large abundance of magnetic monopoles, which are so massive that they would completely dominate and close the universe. And yet, here we are. And there were no detections of monopoles. So somehow, they had to be diluted away.

It also explains the power spectrum of large-scale structure and it predicts the spectrum of primordial gravitational waves. So let me tell you a little bit more what these problems are.

The flatness problem is that if you look at the Friedmann-Lemaitre models, omega, the total, evolves in time. And it always evolves away from 1. If it's a little less than 1, it's going to be ever less so as time goes on. If it's a little more than 1, it's going to get hot, stronger and stronger.

And so in order for it to be so close to 1, and now, it had to start extremely close to 1. Now, this is a vivid illustration of it. And this was from Ned Wright.

If you look at the behavior of the scale factor of the universe, over, say, 12 billion years, and ask what was the density one nanosecond after the Big Bang-- and so you have this number of 400-odd septillion, or whatever, grams per cubic centimeter-- if you add 1 gram per cubic centimeter to this number, the result would have collapsed into a Big Crunch by now. And if you subtract 1, it would have been twice as big. It's that sensitive.

And so, obviously, it had to be just amazingly well-tuned not to blow itself apart exponentially or to collapse back into Big Crunch. I'll tell you quantitatively exactly how much.

The horizon problem is this. At any given time, you can see particles that are as far as it took time for the light to come to you. And so as longer time goes on, the deeper into the past you can see. And the question is, how far could you see at the time of the cosmic recombination, when the universe 380,000 years old?

It wasn't 380,000 light years, the expansion slope. But it was about a few 100 million light years, or 120 some megaparsecs.

So you ask the question then, what was the angular diameter of the observable universe at that time, projected in the sky now? And the answer is of the order of 1 or 2 degrees. So there are tens of thousands of patches on the sky today, each of which was not in a causal contact with any others at the time the microwave background was produced. And yet, they all have the same temperature, to a few parts in a million.

How did they know that regions that was causally disconnected from them had the exact same temperature? And the inflation explained why this happens. Essentially that they were in thermal contact earlier, and just got carried apart by the inflation.

So how does this work? The idea here is that the modern view of the physical vacuum is that it's not vacuum, like empty. But it's filled with virtual particle pairs that annihilate, and so on. And in any quantum mechanical system, there is uncertainty principle, which is if you know exactly what some energy level is, you don't know which one it is. Is it the lowest or not? So you cannot at the same time know that this is something truly ground level and measure it.

This can happen to physical vacuum too. And so supposedly, for whatever reason, the physical vacuum was one energy level up. It was just like exciting atom of hydrogen by one orbit level. And then for reasons that the theories worry about, at some point that field decays and the physical vacuum drops to a lower energy state, which means a great deal of energy has to be released, everywhere, at once.

And this turns out to be also cooled into a phase transition, like, say, boiling liquid into steam. At some point, things are not stable. In this case, it would be like freezing, going from liquid to frozen. It's a solid state. And it starts in different places, but very quickly spreads out. And just like there is latent heat for evaporation, latent heat for freezing or melting, the same thing happens here.

So this amount of energy then drives exponential expansion. And also, though some processes is responsible for all of the matter and energy density content of the universe since then. So these bubbles are through vacuum, then forming false vacuum. And there could be many of them. Those will be independent universes.

But this is where the idea of multiverse comes in. The problem is that they're not a priori, not testable. But it could have happened. We just don't know. So this is called chaotic inflation.

Well, let's look at this a little quantitatively. So remember, cosmological constant in the form of dark energy corresponds to the energy density of the physical vacuum. This is what we're talking about here. But we're talking now about something that's many, many orders of magnitude higher than the cosmological constant today. And that vastly dominates everything else. There could have been no other matter at all.

The Friedman equation for just the constant vacuum density eliminate all the terms to matter, radiation, and so on. It just has cosmological constant term, which is energy density of physical vacuum then. It

Is very simple differential equation. Take the square root. It's dx over x. The solution of that is an exponential. And that tells you that in the situation where there is a constant energy density, the universe is going to expand exponentially. And then, at some point, something else happens and stops that expansion.

But, according to the theoretical estimates, this happens over about 100 e-folding times. 100 e-folding times is 43 orders of magnitude, powers of 10. And this is how you can have the size of the universe, maybe the size of a subatomic particle, suddenly inflate, carried apart regions that were previously in causal contact. And now, they're distributed over a much larger volume. But they used to be in thermal contact at one point. And this is why they all have the same temperature.

Now in terms of what happens with density parameter, evolution of the density parameter, as it deviates from unity, it has this negative exponential, and exactly to the minus 200 power. And that tells you that if you want to have omega as observed today, you have to tune it to 87 orders of magnitude, roughly speaking, in order not to mess it up later. So the universe becomes asymptotically flat.

This is the expansion history, except this is flipped. Remember, 1 plus ratchet is inverse of the scale factor. So this should inflate vertically as a function of time on the logarithmic axis. And sometime around the Planck Era, the universe did something. Maybe it was expanding.

Then suddenly, this inflation period happens. It was a very rapid period of expansion. And inflation ends, and then resumes as normal Friedmann-Lemaitre model. And so this extra period of size inflation is what produces interesting things.

So how does this solve the flatness problem? Well, if you take the surface of sphere, some region on it, you can see there is a curvature. If you keep that region the same size, but make sphere much bigger, eventually it becomes hard to tell whether it's not flat. It's just like people used to think that the Earth is flat because it looks flat, right?

But when you look from space traffic, it can see it's a sphere. And it's the ratio of the region you can look at, to the curvature radius, that determines just how close locally it is to flatness. So this is exactly what happened. The universe got inflated by so much that the size of the observable universe is tiny in comparison. And therefore, it looks flat no matter how much curvature there was originally.

How about the horizon problem? What I told you already, you can have a region that's in a thermal equilibrium. And then different pieces always get carried apart faster than the speed of light because space can expand faster than the speed flight and become reconnected causally only later, like today. And yet, they start with there with the same temperature and follow the same physics. So therefore, they're going to look the same way in the epoch of recombination.

So this was such a beautiful explanation for these two very fundamental problems, which are otherwise completely mysterious, that people said this must right, somehow. Moreover, as a benefit, inflation said, well, in early universe there are quantum fluctuations as particles get annihilated and formed, and so on. And so there's going to be density and energy density fluctuations. And when you compute this correctly and expand them to large scales, you expect to see mass density spectrum, power spectrum, that is a power law. And that's exactly what's observed, as you may recall, so-called Harrison-Zeldovich spectrum.

So inflation explained several fundamental observations. It did not predict them because we already knew the answer. We just didn't know why. This is pretty good. But it's really nice if you can make a prediction.

And it did have one important prediction. And that is that the universe would be filled with primordial gravitational wave background, which is sort of like gravitational equivalent of the cosmic microwave background, but from the Planck Era, because that was sort of the equivalent of Recombination Epoch, but for gravity, with particular spectrum.

Now, the energy density of that background is so low that there's just no chance at all of observing it in any form or fashion here and now, with LIGO or whatever. However, back at the Recombination Era, it had very, very slight effect on the polarization of the electromagnetic radiation from the plasma at that time. And that effect is 1,400 million of the signal.

So the microwave background signal itself is 1,400 million of the thermal background in this room, or in Antarctica. And this is 100 millionth of that 100 millionth. This is really precise experimental physics.

And, in fact, they did that. And this is a plot of piece of sky. Blue and red are the density fluctuations they measured. And these little lines are indicating the polarization vectors. And it's exactly what inflation predicted.

And this is why there was this big hoopla about BICEP2 result. And now, people are scrutinizing it. Could it be polluted by something else? But if it holds, this will be a direct experimental verification of what was the sole prediction of inflation theory, something that we didn't know before.

Explain important stuff is already pretty good. But this was actually prediction. Theories have to live dangerous lives, stick their neck out. And this one did. And this is why Linde, Starobinsky, and Guth just won the Kalvi Prize.