DJORGOVSKI: Deeper in the past, closer to the big bang, the primordial nucleosynthesis. So you keep pushing to earlier times, higher temperatures, and higher densities. And what's going to happen there, you are going to start having some annihilation and pair creation equilibrium that involves protons, electrons, neutrons, and neutrinos. And these are the possible nuclear reactions that can happen.

As the universe expands it gets cooler. By the time it gets to the 10 billion degrees Kelvin, roughly 1 second, the whole thing pretty much freezes. Now, there is a difference in the number of protons and neutrons, because they are slightly different mass. And because they have slightly different mass there is going to be slight difference in their distribution, thermodynamic distribution. And so, when time-- when this is over, you're going to have certain ratio of the number of protons and neutrons. And that ratio is telling you how much helium you are going to make.

So neutrons decay, with a lifetime of the order of 15 minutes. And that destroys them before they can interact with the rest of the hydrogen. And so when you go down to about 1 billion degrees, and there is really no more possibility of forming helium. So like nuclea form before them are photodissociated by the gamma rays, which is progenitors of the cosmic microwave background.

And so that's how the nucleosynthesis ends. It begins when the universe is at the right temperature so the protons and neutrons are the dominant particles. Temperatures corresponding to gigaelectronvolts. It ends when it's too dense and too cold to fuse hydrogen into helium. So you can do this in a very detailed fashion. And theories produce curves like these.

On the x-axis is a temperature, you can think of the temperature as a proxy for time, right? And on the y-axis is relative mass fraction of different things. So, time is shown on the top axis. And so, as time goes on, first you have protons and neutrons, and the ratio is given by the mass difference. And then a lot of things happen. You start associating nucleon and so on. And product is on the right when everything is frozen and clear. And you have still mostly hydrogen, and then helium, and then deuterium, and mass 3 isotope of helium. And just a little bit of heavier stuff.

So this was actually seen as a failure of the big bang model early on, because it can explain the origin of chemical elements all the way up to helium, but not much beyond. But then people understood everything else is cooked up in stars and super nova, and so on. So, big bang nuclear synthesis, which is based on the nuclear physics that we know, makes predictions.

Predictions are the relative abundances of the light chemical elements. Mostly hydrogen and deuterium, and two isotopes of helium. A little bit of lithium, beryllium, and maybe even traces of boron, but those are actually not very sensitive. So if you can measure abundances of deuterium, helium 3, helium 4, relative to hydrogen, you can learn something about density at the time of the recombination. Density of variance, mind you.

And the result is shown here. So, for value of Hubble constant of about 70, which is 0.7 here. It'll be about 4.5%. Amazingly enough, that's exactly the same value that's obtained from a completely different way of measuring it from microwave background fluctuations, which is atomic physics at a much later time. And the fact that two different measurements from 2 different kinds of physics agree so well convinced everybody that this is really the case.

But this is essentially how this is done. What's shown here, on the x-axis is density of the variance at the time of nucleosynthesis. Sorry, today, extrapolate the system. And on the y-axis is relative abundance, relative to hydrogen. So different bands show predictions of the theory, they are not lines, they are bands because there's some uncertainty of the modeling and so on. And the boxes are showing you what's the actually observed value.

And you can see that they agree pretty well. And the smallest box, meaning the most precise measurement, comes from deuterium. Deutherium is really easy to burn into helium. And so it does, it's going to be very sensitive to the density of variance. If you have more variance, you're going to get rid of the deutherium. It has no chance of surviving. If you have fewer variance you can still keep some.

And so, this is it's the steepest line and the sharpest measurement. Now, the way this is done, stars also make helium, so what do you do about that? So you look at star forming galaxies, and measure abundance of helium in their spectra. We also measure abundance of something else like oxygen. Now, oxygen or nitrogen, doesn't matter, it's made in stars in the same proportion as helium.

So that the line that you see out there is slightly tilted. Its slope corresponds to the ratio of how much helium make for how much oxygen. And its intercept tells you how much helium is started with before there was any nucleosynthesis. So the intercept of this line is telling you what primordial abundance of helium was. Kind of getting rid of all the nucleosynthesis in stars. And it's about 0.24 by mass. And that agrees beautifully with predictions.

The way we measure deuterium is actually done in the spectra of intergalactic medium, as illuminated by background quasars. There is of the order of you know, a few parts into the 5, deuterium relative to hydrogen. And so what you want is a cloud of hydrogen sufficiently dense that you have a big signal so you can detect deuterium. Because of the isotope shift, heavier nucleus, with your constant is a little off. The deuterium equivalent of line and alpha line is shifted relative to the 1 of regular hydrogen by 80 some kilometers per second. And by measuring the relative strength of those two, you can figure out what's the fraction of the deuterium. From spectrum and modeling of spectrum you go back to this diagram, and read off what is the baryonic density that corresponds to that ratio, of deuterium to hydrogen.

This is actually a pretty safe way of doing it. It's not easy, but it's safe. And this is because deuterium is not produced by anything. Maybe occasionally by chance, by spallation, by cosmic rays. But deuterium can only be destroyed through a stellar evolution. It's hard to make it. And so in that way, by measuring the abundances of light chemical elements now, or for past x billion years, we can actually learn something about the universe when it was milliseconds to a few minutes old.