PROFESSOR GEORGE DJORGOVSKI: Today we'll talk about exotic areas of cosmology. Dark matter, dark energy, and what we now call the concordance cosmology-- the picture that has emerged over the past decade plus.

First, let us take an overall look at the census of the matter and energy in the universe. This picture is a picture of a cluster of galaxies, and you see the optical images of galaxies. Let's superpose. The pink is X-ray gas, and the two blue blobs correspond to dark matter as sensed by gravitational lensing.

And the idea here is that there was a collision of two clusters. Dark matter passes through each other, but gas remains, and so eventually they'll settle in. But this is-- this kind of cluster is seen as one of the good pieces of evidence for the existence of dark matter.

Well, there are several components. First, there is stuff that you can see-- what we call luminous baryons, by which we mean stars as well as gas, like interstellar medium and whatnot. And then there are other baryons that we don't see directly, but we know they're there because of the cosmic nucleosynthesis and microwave background. And we call those the dark baryons, even though they're not really dark, they're just shining in a way that we can't detect. Together that's called the baryonic matter, because baryons protons and neutrons contribute most of the mass-- then electrons of course, right?

Then there is the non-baryonic dark matter. We know that there is mass out there which is not accounted for by the baryons alone. And so that together all is called the matter.

And then there is dark energy, which is a different kind of beast altogether, but because relativity mass and energy are connected-- speed of light squared-- you can express the density of energy just like density of matter, a modulated factor.

And then there is also radiation, which is completely unimportant today. The energy and density that corresponds to all the photons ever in the universe today is like 1 part in 10,000, roughly speaking. That was much more important in the early universe, like, before the recombination, when energy density of photons was comparable to that one of the matter. But now we can pretty much ignore it.

And so you may recall that for each of those we divide it by critical density, which is of the order of 10 to the minus 29 grams per cubic centimeter. And together they add up to the total density parameter of the universe, which determines whether the universe is open, flat, or closed.

The luminous mass is probably the most straightforward one. We can add up all the light in galaxies doing a red-shift survey, and then just adding up all of the galaxies in a fixed volume, interpolating to the very faint end. And that turns out to be, if you were to smear all the galaxies locally to uniform mush, it will be about a couple of hundred million solar luminosities per cubic megaparsec.

So that's light. To convert that into the mass of the stars, we need to make some assumptions about stellar population. Because you remember that more luminous stars, I'm sorry-- more massive stars are much more luminous per unit mass than low-mass counterparts. You have to do average over the entire stellar mass function. When you do this for the mixture of ages that we see now in galaxies, roughly speaking you get five solar masses for each solar luminosity worth of light. And then, adding the gas is maybe like 10% of the mass in stars.

So you add up all this, and you find out that luminous density, as shown here, divided by the critical density tells you that only half the percent of the matter and energy content of the universe is the stuff that we actually see. Everything an astronomer studies is like half percent of the universe. Which could be a bit embarrassing, but we have some idea of what the rest of it is.

Now how do we know the baryon density? From two sources, as you may recall. First one is the cosmic nucleosynthesis-- nuclear physics in the early universe. Well understood. It makes predictions of what would be the abundances of very light nuclei. And then we can compare it with observations of quasars and star-forming galaxies. And that gives the answer. It's somewhere between 2% and 2 and 1/2% for [INAUDIBLE]

In a completely different way, is from the acoustic peaks in microwave background, where the more baryons you have, the higher amplitude of those waves you're going to see. And so by measuring the amplitude itself for everything else being fixed, you can get a very precise measurement of how much of baryonic matter there was in the early universe.

And those two agree within the error bars beautifully. And so when you apply proper Hubble constant of the order of 70 kilometers per second per megaparsec, it's something like 4 and 1/2% to 5% of all of the universe is in baryons. And so we only see 1/9 of that. So there is actually many more baryons that we don't see than those that we actually do see.

And what are they? This has been subject to a lot of discussion in the past, and now people have pretty much converged to the idea that these are in the form of somewhat hot gas that's gravitationally bound to groups of galaxies, remnants of the cosmic web that we studied earlier, and that gas is heated to the virial temperatures of some hundreds of thousands, or maybe million degrees Kelvin, that corresponds to the right velocity dispersion. And its peak emission is in soft-X-rays, not hard UV. And those are exactly the photons that don't make it through the interstellar medium of the Milky Way. So Milky Way's atmosphere of neutral hydrogen is opaque to the photons that come from the bulk of the baryons in the universe.

But we know that they're there, because they also absorb light. When you shine quasar light through them, they absorb at particular wavelengths that correspond to highly ionized oxygen and things like that. And so from modeling of those transitions, we can figure out how much gas there is, and what temperature it is, and it all fits very well. So this is almost certainly where all of the hidden baryons are.

Now total matter density is measured in two completely different ways. One is dynamical, the other one is gravitational lensing. In dynamical sense, you can use some kind of test particles to tell you what gravitational potential is there. If they're in virial equilibrium, then their kinetic energy ought to balance potential energy.

And we can use stars. We can use gas, globular clusters, what have you. But the basic idea is the same-- that kinetic energies of particles tell you how much mass there is within a given radius, and rotation curves of spirals, velocity dispersions of ellipticals, temperature of X-ray gas in clusters, are all telling us the same thing.

A completely different approach to this is through gravitational lensing, which is sensitive to mass of any kind-- regardless whether you can see it or not. And, amazingly enough, those agree very well.

And also, there is a third way, which is micro background fluctuations, where the relative amplitudes of those peaks, acoustic peaks and their little shifts, depends on how much matter is there in the universe-- not just how many baryons.

Plus, this is all consistent with our picture of the large-scale structure, how it forms and evolves compared to those numerical simulations. And, in fact, if there was no dark matter, if there was only just the baryons, the large-scale structure we see today wouldn't have had time to form. So it's an indirect argument, but nevertheless. Also peculiar-- velocities are consistent with the amount of dark matter as implied by these other observations.

And so, if you look at it today this is what universe contains. The world is flat after all. Omega total is 1 within maybe a percent. And that's largely for microwave background, but also supported with other tests. And the latest numbers is that total matter density is maybe 31% of that. And of those 31%, 4 and 1/2 are the baryons. And those 4 and 1/2% are invisible stuff.

And so you have the set of inequalities, because omega total is greater than omega of matter, there has to be dark energy. And because omega matter is greater than omega baryons, there has to be non-baryonic dark matter. And because omega baryons is bigger than omega luminous baryons, there has to be invisible baryons.

And so-- so it all works fine.