DJORGOVSKI: So now let's turn our attention to large scale structure in the universe. And first let's review some of the basic observations about large scale structures and how we get to measure it. This is of course a numerical simulation not the real universe. But it kind of shows what the universe might look like, visible galaxies embedded in this cosmic web of dark matter filaments.

So the densities in the early universe serve as seed for all of us. I will talk about how that happens. And so they fall upon themselves using their won gravity, and they create smaller pieces. And that's how galaxies and clusters and other things form. So on a scale larger than galaxies we talk about large-scale structure. And that could be just general field or groups and clusters and so on, but distinct from galaxies. And when you look at the sky you don't see just kind of uniform web of matter. You see galaxies as very distinctive little island universes. And the reason for that is important. They actually form with an additional process atop of what drives formation of large-scale structures, which is pure gravity.

So the way we map this out is we need to measure distances to galaxies that form large-scale structures. And we do this by measuring redshifts, the velocities of galaxies. You probably know that the universe is expanding and the recession velocity for galaxies are proportional to it's distance. We'll look through that in more detail later. But the point is that if you can measure the distance that can be translated into the radial distance to the galaxy. And with the two coordinates in the sky you kind of know where it is.

So in order to map three-dimensional structure in the universe you need to measure distances and large surveys that measure up to a couple million redshifts by now have been done. And we have a fairly good understanding of the morphology of large-scale structures.

Now cluster of galaxies is something that was very obvious and visible very early on. But amazingly it took a long time, until about the 1980's, to realize that's actually galaxies are not uniformly randomly peppered through the universe with an occasional blob like a cluster. But they actually form coherent structures of filaments, and sheaths, and whatnot.

So this is the 6,000 brightest galaxies in the sky. And the number was chosen because with the naked eye, on a good sight, with perfect vision, you can see 6,000 stars in the sky. Well, in two hemispheres. So this is plotted in the equatorial coordinates, which remember is just an outer projection of earth's equatorial coordinate system. And so there is a dark band in the sky. Any guesses what it could be? It's called the zone of avoidance. Yes?

STUDENT: [INAUDIBLE].

PROFESSOR: That's correct. It is the dust of the Milky Way, absorbing light from the galaxies outside. And as soon as people realize that there is such thing as interstellar absorption became obvious, this is the case. There are of course galaxies behind it just as well. You'll also notice that there are some interesting structures and features. And they're labeled here. Here are shown in more detail. Now this is in a different coordinate systems. This is in a coordinate system, a galactic coordinate. So the galaxy plane is at the equator. And this is galaxies from two mass, that's two micron all sky survey in near infrared. So it's easier to see through the dust. And some of the important structures are labeled. You can look at this later. But you can see that there is clearly non-uniform distribution.

Now starting from smaller scales there is the local group about which we spoke already. And it's our immediate neighborhood, about two megaparsecs in size. The Milky Way and Andromeda are the two big galaxies. And there is a whole lot of smaller stuff around them. And our local group is 1 of many, many other groups. In fact most galaxy's universes are in groups.

And we belong to what we call the local super cluster, which is a bigger structure, about 60 megaparsecs. And it's flat. About 6 to 1 flat ratio. And it's centered in the Virgo cluster of galaxies, about 15, 17 megaparsecs from us. And it includes some other poor clusters and a lot other groups which are labeled here. And kind of indicated in this quasi 3-D plot.

So super clusters are the biggest structure we know about. And so far a number of them have been mapped around us. But in some sense their boundaries are somewhat arbitrary. Once you get them to scale of hundreds of megaparsecs you're really talking about describing the overall density field of the large structure.

So one of the first large lecture series was done for a center for astrophysics at Harvard Smithsonian. And they did it again. And since they couldn't observe enough galaxies to cover the whole sky they used a new strategy. Instead of doing a full sphere they just did cuts. They would do thin slices in right ascension, in sky terms, but very narrow in declination. And that gives you a fair sample of what the universe might be. You're losing one dimension, but it can extrapolate it's all the same. And then artists immediately did all these interesting structures. They're centered on a rich cluster of coma. There is a feature pointing at us. And those have been called fingers of God pointing at you. We now understand where they come from. But you also see there are all these filaments and voids. And because those are essentially 2-D cut through a 3-D structure chances are what we're looking at really is more like a sponge like structure, if you do a think slice through a sponge it might look like this.

So what we're measuring really is not the distance, it's redshift. And that this a combination of the actual cosmological expansion velocity, which we could translate directly into distance. But also galaxies have their own velocities that have been caused by gravitational infall. And so in the real space they say if you have a dense cluster of galaxies, galaxies in it will have velocity dispersion, kinetic energy, and random motions, just to balance against the gravitational potential of this massive cluster. You're not observing sideways motion. That's much too slow to see. But you can see the radial component. So that radial component adds to the overall cosmological expansion velocity. And so instead of seeing a round blob in the redshift space you see it highly elongated, elongated by the dispersion of galaxies along the line of sight.

And in a thinner and less than structure what's happening is that galaxy is still falling in. So galaxies on the far side of it are coming towards you. Galaxies on your side going a little extra away from you, that kind of powers them up at the distance of this filament. And so the filaments look thinner than they really are. So both effects play some role and one can model it exactly.

So the field has been really transformed by very large redshift surveys. There were two of them. The first one is called a two degree field redshift survey. It's named after the instrument an Anglo-Australian telescope in Australia. And then measured a quarter million galaxies not over the entire sky plus quasars and whatnot. And that was surpassed by the mother of all surveys, the Sloan Digital Sky Survey, which surveyed about a third of the sky, and measured redshifts close to a million sources by now.

So this is what slice cut through 2dF survey looks like. Now this is going much deeper than the previous older CFA redshift survey, you can actually see labeled on the cone how far it goes both in terms of redshift and billions of light years. So this is obviously plot for public consumption because astronomers will never use light-years, they use megaparsecs. and again you see this same structure goes on, voids, and filaments, and dense concentrations, and so on. But you don't see structures that are bigger than about 100 megaparsecs. And that's about it. Beyond that it's pretty much a uniform universe.

The same kind of thing was observed by Sloan Digital Sky Survey going a little deeper. And again this is projecting their redshift volume onto two slices in the sky. So there is some smearing. You again see the same kind of pattern of voids that are typically in the order of 10's of megaparsecs in size and measure filaments connecting and ending in clusters of galaxies.

Now to go deeper there isn't enough telescope time in the world. So instead of that people do what say census studies do. You don't need to ask every American about something. You can only ask a representative sample, a few thousand, say. And so the equivalent of that is doing a deep, deep redshift survey in a narrow patch of the sky. Now those are called a Pencil Beam Survey, sort of drill a thin cone all the way out through the large redshifts. And the idea there was to probe the galaxy of evolution. But turns out also to be constraining structure of evolution. And now this is been done, again on an industrial scale, a couple of 100,000 thin galaxy redshifts have been seen. And lo and behold we see the same kind of structure all the way out.

So these are two little slices through one of those surveys, so seen in Keck telescope. And they're exaggerated in thickness. Because that's a narrow beam compared to the depth. But you can see that it's intersecting the same kind of structures, sheaths, filaments, voids, so on. And if you plot the density of redshift distribution, which is the distance distribution, you see the spikes. Every time you cross one of those filaments you see excess number of galaxies. So it's just like nearby. And this is interesting in of itself.