DJORGOVSKI: So we now turn to the velocity field in large scales. We talked about the density field of the universe at large scales. What about velocities?

And this is characterized as so-called peculiar velocities. Because galaxies are too far away, we can't measure the proper motion of the sky. It takes long, long time to see the movement. But we can measure the radial component of the velocity. And so if it's all randomly distributed, that's still fair. So when you measure sum total velocity of some galaxy, you get cosmological expansion, and on top of that, you have projection on the radial axis of whatever its peculiar motion is.

Since you don't know *a priori* what that amount is, you just interpret velocity that is proportional to the distance. That leads to the errors in the Hubble diagram, and that can affect measurements of universal expansion rate, as well as other things.

Now why this happens is not terribly mysterious. If there is a large scale density field, there is going to be a large scale velocity field. Think of a galaxy as a test particle. It's got the Hubble time, 13 odd billion years, it's going to be falling towards the nearest, densest structures, clusters, superclusters, whatever.

So galaxies may start with a 0 velocity relative to the overall cosmic background, but in time, they're accelerated towards nearby mass concentrations, and they acquire these peculiar velocities. And that's not violating any cosmological principles, just like the air in this room is moving together with the planet earth, but inside the room, molecules have their own velocities. The same thing will happen with galaxies, and gravity is the cause.

Now if you can somehow de-project that velocity field, you can infer what's the underlying mass density field that's caused these velocities, and that, as pointed out earlier, need not be the same thing as light. Turns out actually it is but didn't have to be.

Now there is one peculiar velocity that we know with a great deal of precision, and that's our own. If we measure cosmic micro background, which is perfect black body uniform around, well, our galaxy just has some velocity relative to the photon gas of micro background, and it's moving in a particular direction with the speed of about 600 kilometers per second. So you can measure a slight Doppler shift effect. The sky looks a little hotter on one side and a little cooler on the other side. And this has been measured long, long time ago, late '70s.

Now if this is typical, that tells you you really have to go and map out stuff very far away because Virgo cluster, center of local supercluster, is a velocity that's only by factor of 2 of this. So if you don't know what these velocities are, you can make factor of 2 errors in distance nearby. And you want to measure things further out, then relative error shrinks.

Well, how do we go about measuring? There are two ways to do this. One way is if you can somehow measure distances to galaxies without referring to the red shifts. And there are ways to do this through so-called distance indicator relations, with supernovae, with pulsating stars, and we'll go over those. In that case, you know what Hubble velocity ought to be. The velocities do adjust to expansion of the universe. You subtract that from what's observed, and you get peculiar velocity, at least the radial component.

And in principle, this works fine. Problem is that these distance indicator relations have error bars, and they may even have systematic errors, which will really mess things up. And so you have to average over a lot of that.

A different way to do this is without measuring distances, using just the red shift measurements themselves and little bit of theory. And the way this works is we observe some density field in red shift space, and so we know that that's not really where galaxies are because they have some peculiar motions. But as a first approximation, you can say, well, that's where they are. And that tells you the first approximation of what the density field is.

Then you compute, saying, what will be the gravitational acceleration due to any given galaxy from this density field? And for each galaxy, you get the number. Then you can adjust their measured velocities by your estimated peculiar velocity component, compute new density field that's now a little better, and iterate this several times. And in the end, if your model is correct, then you will have both the density distribution and the distribution of peculiar velocities, which is by construction physically consistent with it.

So people have done that. And amazingly enough, at least in this neck of the universe, mass seemed to be distributed same as light on large scales. Not with small scales. Inside galaxies, there is obviously gradient. There is more light in the middle, more dark matter on the outskirts. But over large scales, locally galaxies are fair tracers over the actual dark masses.

So this is sort of our local kinematics. We're going around the sun at 30 kilometers per second, and sun is going around center of Milky Way at 220 kilometers per second. And Milky Way is falling into Virgo cluster at something like 300 odd kilometers per second, and a whole local supercluster is moving towards another supercluster nearby, the Hydra-Centaurus Supercluster. And that all together adds up to our observed cosmic micro background velocity of 600 odd kilometers per second.

Now Hydra-Centaurus is about 100 megaparsecs away. And now that's getting to be pretty large scale. But then there is a hint that, in fact, our whole local volume is still sliding towards an lot even more distant concentration of mass. It's called the Shapley Concentration, and it's a whole bunch of clusters of galaxies somewhere behind Hydra-Centaurus. And so they too exert some acceleration on the material that's around us.

So this is pretty much the state of the art that people who are measuring velocities, even larger scales. Not everybody agrees, but by and large, we think that we understand basics of what local velocity field is like.

So these are the key points to remember about peculiar velocities. There are two ways to go about it. Neither one is perfect. The first one, using distances, relies on the accuracy of distance indicator relations, which is somewhat iffy. The second one relies on assumed model. How will large scale structure evolve?

And we are falling into a local supercluster with about half the speed of a micro background, and we think that all of the rest of micro background origin is within about 50 megaparsecs or so. And our local supercluster is sliding towards bigger supercluster in Hydra-Centaurus constellations. Other clusters are falling in as well. But I think one final important point is that light, locally, seems to be good tracer of mass. This is not necessarily the case at high red shifts, but locally is.