DJORGOVSKI: Let's move on then. What do we do to get a little deeper than the distances of some kinds of megaparsecs, which is what Cepheid can give you. Now, why do we want to do this?

Well, remember Hubble law is direct proportionality between expansion velocity due to expansion of universe and the distance. But what we measure is not just the Hubble velocity. We always measure the vector sum of galaxy's peculiar velocity due to whatever gravitational acceleration acting on it and the actual cosmological velocity.

And now we know that those peculiar velocities could be as high as several 100 kilometers per second. Our own is 600 kilometers per second relative to micro background. So if all galaxies do that kind of thing, then that means you really need to push much further out than 600 kilometers per second. It turns out actually 300 is typical RMS.

But let's say you want to go to 7,000 kilometers per second of Hubble velocity, just to minimize the effects. Well, that's 100 megaparsecs, according to our Hubble constants. 100 megaparsecs is pretty far. You can't see Cepheids that far away. So you have to do something else.

So you need to find some kind of objects that are really very bright that can be seen very far way and are very large for the same reason. And that's, in fact, how this was done. So general trick here, and this applies as well in galactic astronomy, is to find correlations between something that depends on distance, like luminosity, and something that does not depend on distance, like, in the case of the galaxy, it could be said velocity width.

And then you look at clusters of galaxies and plot those in apparent sense. Then the relative shift is telling you what's the relative distance of one to the other. And so if you can calibrate some of them, absolutely. Then from that, you can compute everything else. So that's the generic idea behind distance indicator relations.

There is one very clever approach to this, which was first invented by Ivan King, but nobody used it. And then John Tonry reinvented it. And it's like this.

You look at the galaxies and take their pictures. And so they're a bunch of stars, and they map onto your pixels. And the amount of flux in a given pixel is the number of stars times the luminosity per start.

Now, you push that galaxy twice as far away, say. Now there are four times as many stars. And Poissonian Variations always goes the square root of the number of stars. So the Poissonian fluctuations and the mean fluxes per pixel do not scale equally with distance. And because of their two different powers of distance, the ratio of the ends of the RMS to the mean flux per pixel is a direct function of the distance. The further away galaxy is, the smoother it looks because there are more stars within each pixel.

And so this works beautifully for elliptical galaxies and bulges because there are no Cepheids in ellipticals. Cepheids are young stars. They are long gone from ellipticals. And this was a very important approach to carry to deeper Hubble flow. So Cepheids work beautifully for spirals. Surface brightness fluctuations are used for ellipticals.

We already talked about galaxy scaling relations, like Tully-Fisher for spirals, absolute luminosity versus rotational speed, or fundamental plane if elliptical. It's also like radius versus a combination of surface brightness and velocity dispersion. In the case of spirals, the x-axis, the line is distance-independent. Y-axis in luminosity is distance-dependent.

For fundamental planes the other way, y-axis does not depend on distance. The x-axis is radius. It depends on distance. And so we can use these correlations for galaxies and clusters to find out how far they are. But we need to calibrate the 0 point somehow. And the way 0 point's calibrated for spirals is using Cepheids, and for ellipticals, it's using surface brightness fluctuations.

Now, we can bypass this whole distance later and push into really distance university using two different methods. One is using gravitational lensing, and the other one is Synyaev-Zeldovich Effect, about which we spoke when we talked about clusters of galaxies. And how does this work?

Well, gravitational lensing, you have some mass that splits image of some background source. And then, if the background source varies in time, equations stand to vary, you can monitor all images of it and see if a variation that you see in one then repeats in a different one sometime later. And the delay times the speed of light gives you the difference in the light path.

So typically, let's say, we have two lensed images, and the light path is slightly different in length between one and the other. So the geometry of this you can deduce from modeling the images on this guy, and without necessarily knowing what the absolute distance is, but just relative angles of things you can get from physical modeling. So the difference in the light path is proportionate to the light paths themselves. All right? The whole thing scales up or down depending on what your choice of Hubble constant is.

And so if you can measure absolutely just the difference in light path, that nails down everything else. So of course, the uncertainty is first the model. And the second, you have to make sure that the variations that you observe are really just delayed versions of each other. But if you can do this reliably, and it has been done with some kinds of gravitational lenses, then you have a completely independent path to Hubble constant depot in Hubble flow. Now at first, this was giving a little lower results than the nearby measurements. But now I think there is convergence.

And again, Synyaev-Zeldovich Effect, which you probably recall, is due to the fact that clusters of galaxies are filled with X-ray gas. So micro background photons get up scattered, scattering on those hot electrons, and that creates a bump in the temperature or micro background By measuring that, you can infer how deep was the cluster.

So from X-ray measurement, finding temperature. From micro background measurements, finding the magnitude of this. And that's directly proportional to the depth. So that gives you the depth in megaparsecs.

Then you measure angular extent or cluster in the sky. And different clusters will be different orientation shape, but on average the size on the sky should be the same as size along the line of sight. And so therefore, you can use angular diameter testing.