DJORGOVSKI: First, we need to ask the question of how big is the universe. And that pertains to both spatial and temporal scale. And it involves concept of focal distance ladder, about which in a moment.

And the basic unit of distance in universe is the Hubble length, which is either flight divided by the Hubble constant today. Which is why it's so important to measure Hubble constant today. And the inverse of that gives rough temporal scale of the universe, commensurate with the age of the universe.

Now, both of those are completely independent of the parameters to describe matter and energy density content of the universe-- to find the curvature and all that stuff. And so that's useful, because we can separate the measurements of the two.

All the distances-- in cosmology, two galaxies, quasars, everything else, scale with this H9, and that's why it was so important to find what it is. Now, we cannot measure directly distances to very distant objects. So instead of that, we deploy what we call distance ladder.

The only real distances that we measure, ever, are trigonometric parallaxes for stars. And as you may recall, that's within a kiloparsec or so. It's going to get better with Gaia.

But everything, then, is based on that. We use parallaxes to calibrate distances to stellar indicators. And then we use those to calibrate distances to nearby galaxies. And then we use those to calibrate some other relations for more galaxies. And of course, the errors will add up, but we have no choice.

And you want to push this until it can get through the regime and expand your velocities, the dominant velocity which we call the Hubble flaw.

It turns out that we can independently estimate the age of the universe-- at least, provide lower limit on it-- and that provides a kind of handle on what the Hubble constant might be. So this is what I mean by the distance ladder. If you look at logarithmic distance scale, we can measure parallaxes to nearest stars. And then use methods associated with clusters of stars, like main sequence fitting and things like that, to find distances to whole bunch of clusters within our galaxy. That's now kiloparsecs.

Then we can use those to calibrate distances to pulsating variable stars, which turn out to be very useful ways of measuring distances, both between galaxy and also nearby galaxies. Then we use those to calibrate distances to galaxies, now to megaparsecs out, to some tens of megaparsecs.

And we use those to calibrate distances for indicators like supernovi and whatnot that can be now for 100 of megaparsecs out. And there are some that can be used on a really large scale, but they're very model dependent.

So not any one of those spans the full range of distances that we need. They just don't exist. And so that's why we have to do this feedback or ladder of calibrating one after the other, after the other.

As you can tell, this is going to be very tricky business, because before you know it, your error bars will add up very fast. Amazingly enough, people who used to do this kind of thing never bothered adding up the errors properly.

And in astronomy work, I'm always joking how Hubble constant was always known to 10% or better. But its value changed by an order of magnitude since Hubble first measured it. And that's because a lot of systematics were not taken into account.

So parallaxes you know. And then the next basic step is, we need to have calibrated hr diagram, which is in itself a good example of what we call distance indicator relation. Because if the x-axis is temperature or spectral type which is independent of distance, on the y-axis is luminosity, which is very much dependent on distance.

And so, once you calibrate this, you can slide any stellar group until it matches. And then from absolute and apparent magnitudes, figure out how far it is. Most importantly, we do this to calibrate pulsating variable stars that we use.

And the 2 of them-- two kinds that are really very useful. In particular, cepheids, which are young, luminous giants that are instability strip part of the H-R diagram. And since they're so luminous-- absolute magnitude is minus 4 to minus 7-- we can see them far away. Some tens of megaparsecs out, with Hubble space telescope.

And so, this gives us the principal bridge between measuring distances in our galaxy and measuring distances to a whole bunch of other galaxies. And it turns out that these stars obey a very good relationship between period, which is distance independent, and luminosity, which is various.

This was first noted by Henrietta Leavitt, who found that Magellanic clouds, they are all the same distance, basically. And it does this became one of the basic tools for observational cosmology.

Now, RR Lyrae stars are population two stars. So they're found in halo and globular clusters. They operate in similar principle but there's horizontal branch equivalent of the regine branch cepheids. And so they're much dimmer. And don't depend very much on-- the pure doesn't scale very well with luminosity. But nevertheless, they can be used.

So this was the basic step that was used to finally achieve the modern value of Hubble constant, which up until the '90s, was very much in dispute by factors of 2, which is kind of embarrassing. And took a lot of observations with Hubble space telescope of nearby galaxies, 18 spirals.

They had to find cepheids by taking a lot of pictures and looking for stars that change in brightness, just like Hubble first noticed cepheids in m31. As you can tell, this is not going to be very easy, right? And moreover, these stars tend to be in regions of star formation, because they're luminous young stars. So you have to account for extinction, things like that.

So after many years of effort, they did do this. They calibrated different things, supernovi and whatnot. And here is the hubble diagram they got. And the slope of this is the Hubble constant, right? It's the velocity versus distance.

So their value-- and they did very careful error analysis-- was that Hubble constant is 72 kilometers per second per megaparsecs, with random errors about 5% and possible systematic errors about 10%.

This is scales very well to the present day. And there are minor, minor disagreements, if you will, with modern measurements from Planck satellite. But 70 is as good number to remember as any.