DJORGOVSKI: Now let's turn to cosmology with cosmic microwave background, which is what the real precision cosmology became. This is based on the angular diameter test. The apparent diameter will depend on the redshift according on which of these curves you sit.

And for many years people tried to do things with, for example, isophotal diameters of galaxies. Same problems as with Hubble diagram-- galaxies evolve, that doesn't work. They tried to use sizes of radio sources, but those blobs are expanding with almost the speed of light, so it's not a good idea of a standard ruler. They tried the mean separation of galaxies in clusters, and got clusters evolved. So nothing worked. Finally, micro background fluctuations provided the standard ruler that we can agree on.

As you may recall from the time we spoke about early universe, the fluctuations we see in micro background correspond to the size of the particle horizon at that time, how far an observer could have seen in the time that has elapsed since the inflation ended. And you can deduce sizes of those from reasonably well understood physics of plasma in expanding Friedmann models.

And so you have a standard ruler whose size you know, and it's put on a redshift that you know, which is the mean redshift of the micro background photosphere, 1,100. And so from that you can deduce what model fits. You only get one data point, and even that is done with such a precision that gives you good results.

So the theory predicts our spectrum. In spherical harmonics it looks like this, and these are the measurements of a seven year WMAP satellite. Now there are Planck measurements that are even better than this. And the data points have actual arrow bars on them-- you can barely see them-- and the curves are the spread of theoretical models.

The peak value is at harmonic 220. That corresponds roughly to angular size about 0.9 degrees in the sky. And translate that into the models, it tells you that Omega

Total is 1, within measurement errors. Nowadays this has shrunk even further, so it's even more precisely determined to be flat.

But you can also constrain all manner of other parameters, because it's not just curvature that matters. You can also look at the relative contributions of dark matter, and ordinary matter, and the dark energy, and the amplitude, since light shifts. And relative amplitude of different peaks are telling you something about those other parameters. So the way this is done, is you come up with a large number of cosmological models, Monte Carlo models, and they do Bayesian analysis-- which ones fit the data how well. And so that gives you possible combinations of parameters that describe the data very well. So usually you can't tell with great precision what any one of them is, but if you can have some products or something, that can be done.

Now this you do not have to read. Please don't. It's just a table of the results from the Planck satellite from last year. There is a slightly more modern version of this, and I'm just including it in your slide deck so you have one place you can go and look it up. But one thing that I want you to note as you're staring at this table without reading it, is how many significant digits there are. So roughly speaking, we now know a large number of different cosmological parameters with about 1% or 2% precision, which was completely unheard of in the past.

Now it would be nice if you could do the same angular diameter test somewhere else. And indeed the size of the horizon gives a preferred scale of clustering of galaxies-- 128, I think, parsecs. Something like that. And so if you can measure clustering of galaxies over a larger scale than that in different directions, you should see the signature. And sure enough. People see that there is a little excess of power that corresponds to the size of the horizon at the recombination.

And now you can see this with different redshifts. It was first done with only one redshift bin, 0.3 or so. And this gives you an additional point on your angular diameter test. So if you do very deep redshift survey, which is what people are trying to do now, they can do this in redshift bins. And you can see how the angle of size of the standard ruler changes in time, and that will provide even more precise measurements and constrain the evolution of dark energy.