S. GEORGE DJORGOVSKI: So those were the generic expectations. Now, let's look at what we actually observe. This is a picture of one of the deep fields observed at Hubble Space Telescope. I think this one the GOODS field, Great Observatories Deep, something, Survey. And there are a lot of galaxies out there. Every little dot you see there is a galaxy. So there are three things that we can do.

First, we can take pictures on all different wavelengths, and count how many sources are there given brightness, given color, or morphology, and things like that. But you don't know where they are. And to do that, you have to take their spectrum as your redshifts, Doppler shifts, because the universe expands. The further away something is, the more distant it is, right? So the faster it goes away. So you can use recession velocity as a proxy for distance. So when I say redshift, what I really mean is distance.

Or, by the token of looking back in time, deeper into the past. So you can measure spectra of galaxies, and find how far away they really are. But that's observationally much more expensive, because to get the spectrum you have to disperse the light over your detector. And so signal to noise goes down in every of the elements. So you need to integrate longer and in bigger telescopes, like Keck Telescope. Nevertheless, people do this, and I'll show you some results.

You also learn other stuff from spectrum. And then a completely different way to go about this is to say well, let's just integrate all the radiation we're getting from the universe in different wavelengths. And that's obviously the sum of all different sources, and those could be sources that are individually too faint to pick out using direct imaging. But together, they add up some energy. Now this is really hard to do, because you have to have absolute calibration. Has to be done usually from space, but nevertheless, that's been done on some level.

So the simplest thing you can do is count galaxies as a function of brightness. To first order, the fainter they are, the further out they are. And it just depends a little bit on cosmology, but the generic expectation is that they will be more smaller galaxies in the past, and they will be bluer. This is if you can see the star formation directly. If they're shrouded in dust, that energy is absorbed, and then re-radiated in far infrared. So there is two modes in which you can look, the obscured and unobscured.

And so the generic expectation is something like this. This is plotting log number of galaxies per unit, whatever, results essentially inverse log and flux, and near us, it's all Euclidean. It goes like geometry of inside sphere. And then as you go further out, relativistic effects start coming in, things bend over, but evolution would change the counts. Luminosity evolution would move things to the left. There were brighter than they should have been, so to speak. And density evolution would move things up, because there were more smaller pieces in the past.

And therefore, they produce the same observable effect, so you need redshifts to disentangle them. So what does this look like in practice? Well, these are the real faint galaxy counts from Hubble Space Telescope in three, four different filters. They're offset from each other for clarify. The one on the bottom is a new ultraviolet, the one on the top is new infrared, and two in between are visible light. And the curves show what you expect if there was no evolution, just geometry.

So you can see that points deviate in a sense that the deeper you go, the bigger the deviation. There is a larger excess of faint galaxies. And the excess is much more prominent in the lower filters. And that's exactly what you expected. There were more smaller pieces in the past, and they were bluer in color because of the younger stars.

So what's been done in this industrial basis over the last decade plus is a very good combination of deep imaging with Hubble Space Telescope, and then spectroscopy of faint objects using big telescopes on the ground. The 10-meter telescopes, Keck, 8-meter telescopes like VLT, and so on. And several deep fields have been selected which everybody observes so there is a maximum amount of information for anyone of them. And when you plot a redshift, which is really distance versus magnitude, kind of looks like this.

The larger magnitude is fainter, remember? Right? So you have many more faint galaxies than bright galaxies at any redshift. But as you go further out, you're just not seeing bright galaxies, they're too far, right? And you're always missing some faint stuff. But that's something you can model. So observations of galaxy counts-- so this is a bunch of magnitude and redshift in color-- all seem to obey exactly what we expected from these synthesis models. Another thing you can look at is then sizes of galaxies.

And that, again, was done with Hubble Space Telescope. And you can plot mean radius defining some objective fashion as a function of redshift. And you find out the galaxies were smaller in the past though, right? But there is a discrepancy. We're not changing. The curve would be more or less flat in these coordinates. But the fact is they're lower in the past, meaning they are physically smaller. So that too, is something that you expect. You start from smaller pieces, you build up larger galaxies.

And then you can take pictures and look at neighbor's galaxies near each other, and some fraction of them will be physically next to each other. Some will be purely optical but on average, there'll be some fraction always that merges. And if you count that as a function of redshift, you find out that there are many more close pairs further away. Which again, is what you expect. Because you start with a whole lot of little pieces, and you start eating them up. And there are fewer and fewer mergers as time goes on.

So that's all kind of confirms what we expected, and you can be actually used to distinguish between different versions of the models. And the correlations that we discussed earlier, Tully-Fisher and Fundamental Plane, can be also used to probe how galaxies evolve, because they're very sharp correlations. And this is a result that shows essentially how much brighter were stellar populations and elliptical galaxies in the past. And as you can see, it keeps going up.

So luminosity density, say projected within per square kiloparsec or something like that, was higher in the past. Which is what you expect if indeed stellar populations were intrinsically more luminous, regardless of the mass of the total galaxy. And so that again seems to follow with what we generally expect. So the take home thing is that galaxies in the past where bluer, because they're made of younger stars. That at the given mass, they were brighter because those stars were more luminous.

But on average, they were less massive, because the smaller pieces that later on merge. And also, they're smallest in size for the same reason. And they were more numerous because those pieces have merged since then. So all this makes really good intuitive sense, and it's exactly what observations are telling us.