S. GEORGE DJORGOVSKI: So let's start first with some basic ideas of how we would go about studying galaxy evolution. And first of all, galaxies have to evolve for the simple reason that they're made up of stars and stars evolve. But, moreover, they're not in isolation, there are galaxies all around them, so emerging and encounters will happen no matter what.

And so you expect that these two generic processes of assembling the mass together, that's just Newtonian geography, and then converting gas into stars. And then stars making energy are two inevitable and probably somewhat related processes because merging can stimulate burst of star formation. And since most of the mass is dark matter, this is not something you can observe directly. And also it takes a billion years to digest the galaxy in a merger, but, on the other hand, we can model it real easily.

The opposite applies now for a star formation. We don't actually understand star formation all that well, so, therefore, we can not model it really well, but it's easy to observe. So first, it's interesting to us the time scales in which this can happen. All right? Galaxy free-fall time scale, rotational period if you will, it's in the order of a couple 100 million years. And massive stars, which do a lot of action, are tens to up to 200 million years lifetime, and we also think that Active Galactic Nuclei, like quasars, go in spurts, which are about same order of magnitude.

And about billion years is what it takes for proper merger to complete, and then we have about 12-13 billion years for galaxies to evolve. And so there are several different ways in which you can try to study this. You can begin with Milky Way with the fossil evidence in form of stellar population and dynamics and so on. You can look at nearby galaxies, other Milky Way, and look for systematics, like those correlations we were studying before. And the most direct thing, of course, is to look far away and see what galaxies were doing. This is the speed of light is finite.

The further away you look, the deeper in the past you look, so it's like a built-in time machine. Just by looking far away we can tell what was going on in the past and

Cosmological Principle, this generalization or Copernican Principle, that, you know, is the same everywhere so that's a fair sample.

So there are two parts to modeling of galaxy evolution information. First, assembling of the mass, and that is routinely done now with large computers. A lot of dark matter particles, maybe stars, just Newtonian gravity and expanding space. You let them go and produces structures just like those that we see. There is no mystery there.

And then, of course, there's evolution of stellar populations, and we understand stars fairly well. You may not really understand star formation all that well but, once you make stars, we know how they evolve. And there are all those isochromes that nature diagram and so on. So there are plenty of movies that you can find on the web. Some day I'll link some of them to the web page, and you can see bits and pieces flying together and merging, and creating ever bigger galaxies.

And, at any given time, it kind of looks the same but on different scales. So, early on, there's a lot of small pieces, with some volume, but then later on those have merged but, if you zoom out, look at the larger role, it's going to look exactly the same as the other ones. So it's very self-similar evolution, and people, now, do simulations with literally billions of particles.

This is one of the large ones, called the "Millennium" simulation. You see this interesting mass of filaments and knots. Turns out that, well, dark matter or any matter, when collapses in the gravity, will naturally make such structures. Talk a little more about this when we talk about formation of large scale structure. And then there will be dense spots and intersections of these filaments, and that's where galaxies will form.

So you can start from some large red shift, where things are fairly uniform. You'd have just slight non-uniformities which serve as seeds of galaxies which create more material. And, as time goes on, you get the density contrast increasing, and the scale is indeed spatial, the spatial scale. And then, as time goes on, these knots, which are really galaxy halos, keep growing and growing. And about zero red shift, you could match them to what's observed, at least in terms of dynamically inferred distribution of dark matter.

So this is now being done very extensively on all kinds of scale, like whole universe scale, just the Milky Way scale, and so on. And so this is-- if you had eyes that could see the dark matter, this is maybe how Milky Way would look like. It would be a whole lot of little tiny dark hills they didn't get absorbed yet, and those will be really small dwarf galaxies that are eventually going to be consumed through tidal friction.

And so the other aspect of this is stellar evolution, and, again, here is HR diagram, which we understand fairly well. So you can say convert bunch of massive gas into stars, according to some formula, and then just let it age, and we know which way stars will go. Now, interesting thing to remember is that, on the upper main sequence, luminosity scale is the fourth power of mass.

On the other hand, there are fewer massive stars then low mass stars, and the first approximation goes inverse second power of mass. So fourth power wins over inverse second power, and, therefore, the most massive stars will dominate the luminosity even though there are few in the number. And because those are the bluest stars, the young stellar populations also tend to be blue. And so those are genetic expectations, and they would also evolve very quickly and become redder as the main sequence peels off into very smaller masses.

So, we know how to make models of evolving stellar populations, and we expect generically that they'll be always dominated by the stars around the main sequence turn-off, because those are the most [? luminous ?] ones, and the most numerous ones available at any given time, and, because they're relatively small in number early on, they're will be big fluctuations of that.

The key assumption one has to make, and this was purely assumption so it's not something you can ferret easily from data, is what's the history of star formation. Do you do it all at once, like a delta function? Do you do it constant over time, or anything in between, and there is more or less everything in between. And we believe that ellipticals and bulges are our best fit, if you assume that most of the star formation happened very early on with the first billion years or there about, and then you just let them evolve past that.

Whereas, in this galaxies star formation, it keeps going on all the time, so you have a mixture of stars of all different ages, like a solar neighborhood. There's range from zero to maybe about 9 billion years and we're kind of in-between. So this is the type of model spectra added over all the stars, in some evolving galaxy are. And you can see the time steps are labeled, you can't see them very well, and the youngest ones are at the top. So yes, they're most luminous, but also you can see that they're bluest and ends up, as galaxy ages, you start losing these stars that dominate beauty. And red giants keep showing up, so the color changes to the red.

So generic expectation is that, as galaxies age, they get dimmer and they get redder. And, in fact, that is the case, so the simplest thing you can do is look at colors of galaxies, and color, as you may recall, is logarithmic ratio of the fluxes into filters. And here it's ultraviolet, the blue and blue to visual, and if you plot those distributions there by model, there is a kind of narrow spike of very red stuff, that's ellipticals and bulges. They have very small spread of colors because color doesn't change much, at large ages. And there is a very broad range of younger stuff that's bluer distribution. So that all seem to make reasonably good sense.