DJORGOVSKI: Let us, then, for a start talk about galaxy morphology. And in any science, empirical science, when you begin, you don't know what you're looking at. The natural approach is to first try to classify things in order and, in some way they're measured or observed properties. And so this happens with galaxies, as well.

But first, let me define galaxies are really the basic building blocks of the universe at large. And interesting thing is, they're not all the same. They have a very broad range of different physical properties, in terms of mass, and luminosity, and star formation rate, and what have you. And whatever we observe today is clearly a product of billions of years of galaxy evolution until the present day.

So a big goal of cosmology or extragallactic astronomy is to indeed understand how did galaxies form; how do they evolve; and got to be the way they are today. So in rough numbers, within our observable universe, which is how far we can see since the Big Bang started, there is of the order 100 billion galaxies, probably more if you count some dwarves. And on average, they each have like 100 billion stars. Their masses range from 200 million solar mass for things like dwarf galaxies to 10 to the 12, in 10 to the 13 solar masses for really big ones.

And as you can see, that there really is a very broad range of properties. So indeed, just like biology, really begun with Darwinian classification of living creatures, so did extra galactic astronomy. Hubble first proposed his eponymous classification in a popular book called, *The Realm of the Nebulae.* Because even then, they were still calling them nebulae because the concept of galaxy as island universe was still relatively recent, even though Hubble was the one who actually proved that that's the case. And then others have tried to improve on it, but there hasn't been any major change. And we still use Hubble's classification, even though it's not the perfect one. And I'll talk about that in a moment.

Now a better, more quantitative way, to do this is to actually measure stuff and look how different physical properties group together, or separate, or correlate. And objectively define sets of galaxies as belonging to same families of objects. But then we can also look at building blocks of galaxies, like those that we talked about last time in terms of stellar populations, bulge, disk, and so on.

So anyway, here is Hubble's famous classification, Tuning Fork Diagram, as they call it. And it begins with elliptical galaxies. And then goes to spirals, which he split into 2 different branches -- those with central bar and those without. He ordered ellipticals in their apparent elasticity in the sky, which clearly is subject to projection effects. And now we know, in fact, doesn't really matter very much or any other physical property of ellipticals. But that was the visible thing.

Spirals he sorted in sort of degree in which spiral arms are prominent. And that also corresponds into the relative importance of bulge and disk. You can think of bulge as a little elliptical in the middle of a spiral. And Hubble thought that this was an evolutionary sequence, that goes from left to right. And he called ellipticals early-type galaxies, and spirals as late-type galaxies. And now we know that this actually has nothing to do with reality and galaxies don't evolve this way. If anything, you can mirror flip this image, and merge two spirals to make an elliptical, but that's a different story.

So elliptical galaxies. Here is a nice prototype. Actually it's an unusually big one. It's M87, biggest galaxy in the Virgo cluster. And it exemplifies many of the properties of big ellipticals. You can note is that there isn't any structure to speak of, anything, so these things that you see on top of M87 are just foreground or background galaxies. So there are no spiral arms. There is no obvious star formation. And so, in fact, Hubble kind of defined them that ellipticals would not have any star formation, or spiral arms, and things like that. He was actually incorrect in terms of star formation. There can be some star formation in ellipticals, but that's a more recent development.

So they are very smooth, symmetric. As the name implies, they are elliptical. Here are two other big ellipticals in Virgo cluster. And they don't have much cool gas, unless they have just created some. However, they are not gas poor. There is plenty of gas in elliptical galaxies, except it's heated to millions of degrees of Kelvin. It's an extra gas and a hot gas like that cannot be converted easily into stars because stars require formation from cold interstellar medium.

Now ellipticals are largely made up of old, but metal-rich stars. You may remember that Baade's original idea was that Population I stars were those lacking disk, chemically-well, metal-rich. And Population II be the old stars. These are old, but they're not metal-poor. They actually underwent substantial amount of evolution. And another important thing is that the elliptical seem to like dense environments, clusters of galaxies, cores of clusters, and things like that.

Spiral galaxies, while we covered that at some level when we spoke about Milky Way and spiral structure, that is the defining characteristic. And there, there is actually an interesting correspondence between Hubble types and real properties of galaxies. And so there are two sequences that are parallel, one with bars, one without. As you go from the earliest type -- where the bulge is dominant, least developed spiral arms -- to the other end of the sequence, where bulges are essentially non-existent, there is, spiral arms are very prominent, a lot of star formation. There is clearly some sort of degradation in meaningful physical properties.

But of any given Hubble type, there is a huge range in masses and luminosities, and so on. So many of the very important physical properties of these objects are not correlated with Hubble types. This is a textbook example of a barred spiral. There is a bulge. There is an elliptical bar from the end of the bar begins spiral arms. And roughly about half of spiral galaxies have bars, including our own. And there can be very luminous parts, maybe up to a third of all starlight. As we already discussed, they're dynamically distinct systems. They rotate like a solid body rotation. And whether or not galaxy has a bar, depends on the exact balance between gravity of the dark halo, and the self gravity of the disk. So spirals are just like on the margin of that, and they're not density waves. They're a completely different dynamical thing.

There is the intermediate type, so-called lenticular, or S0, before SA galaxies. And those are these galaxies without spiral arms. Now this was going to be the most famous ones, called sombrero galaxy. And as you can see, it does have dust and actually has some star formation in there. But the gigantic bulge and no spiral arms. By and large, these galaxies -- former disk galaxies -- are all the galaxies that have lost their gas somehow. Maybe they just burnt through all of it, but more likely the gas is swept as they move through, say clusters of the galaxies. And then that extinguishes star formation.

The ultimate end of Hubble sequence are so-called irregulars. And much like clouds, are local, good examples. This is the Large Magellanic Cloud. It turns out actually it's not a great example of our galaxy. This is a small spiral that is being eaten up by Milky Way. And what's left here is for the remains of its own bar, a display of star formation. Not all dwarf galaxies make stars or gas. In fact, majority don't. And they've been called dwarf ellipticals or dwarf spheroidals, and they're neither elliptical nor spheroidal. The example of the dwarf elliptical is one of the Andromeda satellites, and you see 205. You can see there's a little tiny nucleus in the middle. Old stars mostly supported by random motions. And dwarf spheroidals are these collections of stars that seem to be actually, well they are, embedded in halos of dark matter. But there isn't much light left.

There are many of those. Milky Way has couple kinds of satellites like these that we have found so far. And so the outer galaxies, as well. We think that these are the original building blocks of galaxies, that when galaxy formation begins, it starts first in smaller pieces, like the dwarf galaxies today. And many of them then can merge, accumulate into bigger galaxies, in Hubble sequence. But these will be in some sense primordial building blocks, because if you do something to a dwarf galaxy, it's gone. So they can be gobbled up by bigger galaxies, and that happens all the time.

And they come in at least 2 flavors, gas-poor and gas-rich. We may be transitioning from one to the other, but they're by far, more most numerous galaxies in the universe. But they don't contribute the bulk of the stellar mass of star formation.