DJORGOVSKI: Finally, let's talk a little bit about circle scaling relations, and this turns out to be a very interesting subject. What's shown here are two different projections in a parameter space of radius, density, and kinetic temperature of elliptical galaxies, [INAUDIBLE], and globular clusters. Sort of like two pictures I've shown you before, but here's it's in 3D space. And in some cases, they're excellent correlations. And that's an interesting thing to understand.

Now, scaling laws are called that way because they're mostly within their power laws. You take the log of two quantities, they scale in a linear fashion. And they're built there by galaxy physics and galaxy formation. So trying to understand where they come from is teaching us something important. They're also different for ellipticals and spirals and dwarfs and so on. So that tells us that there really are kind of different families of galaxies. There isn't really continuum.

And interestingly enough, if you can correlate something that depends on distance, like luminosity or absolute radius, with something that does not correlate with distance, say rotational speed, then you can measure the distance in dependant quantities and figure out how far something is. This is just like using HR diagram to measure distances to clusters where luminosity is distance-dependant, but color or temperature is not. And so by measuring color of a star, you know from the calibrated diagram what its true luminosity is. You compare it with the apparent luminosity. You know the distance. So this is how we can do that for galaxies.

Well, there are two important correlations-- one is for spirals, one for ellipticals. For spirals, there is a correlation between the luminosity and maximum circular speed. That's called the "Tully-Fisher Relation." And those with luminosities, there roughly is a fourth power of circular velocity because it's mostly flat rotation curve. It gets a little better as you get from bluer filters into the near infrared, and that's probably because you just don't get fluctuations from young stars or dust. And it's an amazing correlation. It's good to about 10% of intrinsic scatter and maybe even 0.

Now, why is this interesting? Well, because the circular speed is a property of the dark halo, and luminosity is a product of the stellar evolution of the disk. And the fact that they're essentially perfectly correlated tells you that somehow history of star formation in the disk is governed in some way by the dark halo, even though dark matter, by itself, does not interact with regular stuff in any other way than gravity. And understanding this is going to be a very interesting thing. So we don't know why it's so good, but it is because anything we can think of will just foil that correlation.

For elliptical galaxies, there's something similar called "Faber-Jackson relation." But the really interesting one is bivariate correlation, which means there's a bunch of properties-- like the radii, luminosity, densities, velocities, inversions, what have you-- and any two of them can be expressed, can predict the third one. So just like Tully-Fisher relation is like a correlation on x, y plane of luminosity and velocity, this one is a plane embedded in 3-dimensional space of, say, measure of size-- like radius or mass-- measure of temperature-- like velocity or dispersion-- and measure of density. And that's why it's called "fundamental plane." And it's usually expressed in this form-- scaling of radius with velocity dispersion and surface brightness.

The two pictures here show what happens when you rotate this parameter space. The one on the left is you're looking at it nearly face-on. There is no correlation whatsoever. And then, you tilt your point of view and look at it edge-on. You see there is a beautiful correlation. And so this is actually pretty amazing that any number of important properties of ellipticals are united into just two numbers. And why just that? We don't know. Again, why is it so good?

Now, there is no mystery why there are these correlations. And you can go from just a very old theorem-- great potential in the kinetic energy, say, what you observe is not the same thing as mean mass radius and so on. Lock all this together and you say that, for a galaxy bound by Newtonian gravity, radius through scales, velocity is squared, surface brightness of minus 1, and mass-to-light ratio to minus 1. And luminosity shows scales of velocity to the fourth power, probably that we recovered from Tully-Fisher. Surface brightness of minus 1 power and mass-to-weight ratio minus 2 power.

Now, if any of those deviate from perfection, then it's going to create some scatter. Now, we know that, in reality, mass-to-weight ratios, surface brightness, and so on, they all differ systematically or randomly. And yet, somehow things composite to make perfect relations.

So for Tully-Fischer, we've got the right slope-- fourth power of velocity. For fundamental plane, we did not. And that's due to the systematic deviations of structure of ellipticals from being perfectly homologous-- meaning, ellipticals are not just scaled versions of each other, bigger and smaller but same structure. No. There is a systematic change in the way they're arranged internally as a function of, let's take, their mass. And that tilts the plane from very old theorem into what's observed.

So if you have galaxies bind by gravity, that means Virial Theorem applies. And they're almost, but not quite, homologous version of each other, then you expect to recover something like this. But any process that we can think of just spoils up these correlations or would puff them up into pure randomness. And somehow, that doesn't happen.

So instead of that, the opposite happens. And just like HR diagram was this 2-dimensional space of luminosity and temperature in which stars were on 1-dimensional sequences-- the Main Sequence, the Red Giant branch, and what have you, for galaxies, there is one extra dimension. The three dimensions-- one of which measures size, radius, mass, another one that measures density, and a third one that measures the kinetic energy, rotational speed, or velocity of dispersion. And in that space, they're not on lines. They're on sheets in different galaxies in different position.

And so no matter where they start from, they end on one of these correlations and no where else. So there's preferred dynamical states. And so the hope is that we can use this in the same way that HR diagram was used to develop theories of stellar structure in evolution and test the models. Our numerical simulations of the galaxy formation can reproduce these correlations, but again, nobody knows why that and not something else.