DJORGOVSKI: Let us now look in a little more detail what the properties, quantifiable physical properties of different galaxies are. And the first question is, what can we measure. And we can use photometry or imaging and quantify in some way how much light is there as, say, a functional radios in different filters, say.

We can also measure their metalicity or stellar populations as a function of spatial distribution. We can determine kinematics through Doppler shifts of rotational motions or just random motions that puff up the absorption lines. And those have to be put into some context.

It's impossible to invert these measurements and derive model directly from them. There's just not enough information. Instead of that, we make reasonably conceived models of galaxy evolution, both dynamical and stellar evolution. See what they would predict in terms of observable properties and then compare that with what's actually observed. That seems to work actually very well.

Now, the distribution of light is the simplest thing to answer. And since they're all centrally symmetric, it's the radial distribution of light. And for spiral galaxies, well, there are two components. There is a bulge in the middle. And then, there is a disk. The disks themselves are exponential, just like the Milky Way.

That's a semi-log plot. So straight line is the exponential. And you can see it in the outer parts. It's just that. And then, they have an extra component in the middle which bulge which we'll call elliptical.

Now, if you look in gas, you see some similarities and some differences. This is contours of the density of neutral hydrogen superposed on a invisible light picture of this galaxy. And you can see gas extends much further out than stars. And this is generally the case. So we think what happens is the galaxies get built up in terms of stars from the inside out.

The most early star formation happens for the bulge and then the disk. And the disk keeps growing. And there's still plenty of hydrogen left in the outer radii to provide for star formation.

On the other hand, if you look at dense gas, like molecular gas, you find out that it follows up spiral arms very nicely. And this is, again, not a great surprise because spiral arm by compressing gas is what stimulates a lot of star formation in the disks.

But these are just images taken in the lines of molecular hydrogen or carbon dioxide, carbon monoxide. Now, what about the elliptical galaxies and, by same token, bulges? Well, they're not exponential. They're fit with this funny formula which is exponential of radius to 1/4 power.

And that's due to astronomer named Gerard de Vaucouleurs. And I think he came up upon this purely by experimenting to see what will work. Now, there is a more general formula that reduces to this one. But this tends to be the one that fits a lot of elliptical galaxies fairly well.

The two plots, one is the log log diagram. So parallel will be a straight line. The one on the right is log brightness versus radius to the 1/4 power. And that gives you a straight line. This is where this came from.

Why this particular profile? Nobody knows. For that matter, we don't really know why these galaxies are exponential. Which they just are. These are a standard dynamical forms that galaxies assume. And they don't come in any other flavors. And understanding why this is the case is going to be one of very interesting things to figure out the future.

But what about their shapes? The shapes would clearly depend from what side you look at them. And so the observed distribution of elliptistic peaks around 0.2, 0.3, so it's just slightly flattened. But you don't know whether you're looking at the oblate ellipsoid that's tilted or prolate one that's elongated or something in between.

And turns out that actually elliptical galaxies triaxial. They have different flattening in the three orthogonal axes. Or it could be spherical. Now, the reason for this is interesting. It's not that they're flattened by rotation which is what naively assume.

Which is what people assumed early that the elliptical galaxies are just flattened by rotation, by centrifugal force.

Now, they're flattened or, rather, they're shapes are given by anisotropic velocity dispersion. This may look a little strange. Now, like pressure of gas in this room. You know, you don't feel it different when you look north versus west.

And yet, this is exactly what happens with gas of stars in elliptical galaxies. So there is nothing to prevent this from happening. You have independent dynamics, if you will, in each of the orthogonal directions. And so you could, and you do, get different amounts of random motion in the three orthogonal directions.

So in the direction we have the highest velocity dispersion of stars, they'll go further south. And those will be the longest axis. The one we have the least amount of motion will be the shortest axis. There will be one in between. And so they're not grossly triaxial. But they're just slightly triaxial. And dynamical measurements confirm this.

One interesting thing is that those that are bigger tend to be more anisotropic. And our understanding of this is that a lot of ellipticals form or grow by accreting outer galaxies. So if you, say, have to begin spherical, elliptical galaxies. And you drop another galaxy in from some direction. It gets eventually absorbed. But that has brought kinetic energy that kind of prefers that particular direction of the impact.

And so you'll end up with a stellar system that's a little elongated because we'll have a little extra random motion along that particular axis. All right? Do this million times. And so these incoming galaxies come from any odd direction. Depending from which direction you get more impacts, that's the one you're going to develop the largest velocity dispersion.

So it makes sense that the biggest ones that have eaten the most galaxies would have the largest anisotropies. And what about masses? We talked about massive spirals and flat rotation curves. For the ellipticals, we don't have rotation curves. That doesn't matter really.

But use random motions of stars or irritational lensing. And if you plot mass of stars, on y-axis versus total mass, dynamical mass inferred from measurement. So velocities they correlate all right, but in a tilted fashion. In a sense that more massive galaxies have larger fraction of the dark matter. And that means the smaller ones were more efficient in converting gas into stars while they could.

And finally, dwarf galaxies. I mentioned that they're really a very different kind of beast. And most notably, they are very different in their mean densities. So these two plots show three different families of what we call hot stellar systems, globular star clusters which are here really just for symmetry sake, regular ellipticals, and those dwarf royals.

You can see on these correlations of, say, radius versus projected density or projected density versus luminosity, they're sitting in a very different parts of the parameter space. And they have even correlations of some sort which are product of their physics.

So that tells us right away that these are really very different kinds of objects. Now, for a so-called dwarf elliptical galaxies, you can look at, say, some common luminosity and compared their mean densities. And it turns out the mean density between your typical dwarf elliptical and a regular elliptical is roughly like between air and uranium.

Something like four orders of magnitude. And so calling them dwarf ellipticals is like using cotton puffs and calling them dwarf cannonballs. And so they really are very different kind of objects.