DJORGOVSKI: Let's move on there. So I've been referring to Gravitational Lensing as a tool, and I realize we need to talk a little more about this. This is a picture from Hubble Space Telescope of a cluster of galaxies. And you can see all these arcs and arc lights, and those are all gravitationally lensed images of background galaxies, way behind the cluster itself. And there geometry can be used to infer where the mass is.

So we recall that general relativity was proven to be right with Eddington's experiment of bending of light rays around the sun. It's just a couple of arcseconds. So that's a generic prediction. And so if you look at some source of light behind some mass distribution, it's going to bend light rays.

And just like a lens, it's also a chromatic lens because every photon gets the same change in the path. And this was predicted, even explicitly in terms of astronomical objects in 1920s, but it was not observable back then. So the first observation was in 1979 where image of a background quasar was split into two, and it was very quickly understood that that's what it was. And since then many hundreds of these have been found.

So the math behind this is simple. This is the basic formula for gravitational bending of the light. That if you've just assumed your Newtonian value, you would be off by a factor of two, and the actual value is this. So essentially it's proportional to the Schwarzschild radius and inversely proportional to impact parameter. So Schwarzschild radius is proportional to the mass. The more massive lens will bend light more, and input parameter means the further away you are from that line of sight, less bending you get.

And that's essentially the basic formula to use. Then you can make assumptions about mass distribution in the lens and see what happens. So if you had a perfectly aligned, perfectly symmetric mass, exactly in the line of sight in the source, then you have to split background image in the ring because of the symmetry of the situation. But, of course, that's never the case.

The mass distribution is never perfectly symmetric, and you're never exactly in the line of sight. It's a little off, and so this is why this ring then breaks up into bits and pieces. It could be two images, four, or any number of those, who are just pieces of arcs, and from that you can infer exactly where the mass is distributed.

So this is best seen in clusters of galaxies. This is another example of those. You can see that there are arcs and arch lights around this big elliptical on the left, but also the one up there on the upper right, and in cluster as a whole. So by measuring all this, inverting and distribution of observed distortions, you can learn how much mass is within given radius. And amazingly enough, that agrees perfectly well with what x-ray tells you.

More recently people have this, not just for clusters, but for galaxies themselves. They'll look for galaxies where there is a nice, long ring of a background galaxy seen through that galaxy. And this will happen very rarely, but if you have lots and lots of galaxies, then you can still find number of those, and a couple of hundred of these are probably known by now.

And so you can do exact same computation to figure out how's mass distributed inside galaxies. And again, amazingly enough, it gives the same result as rotation curves, that it's close to the Singular Isothermal Sphere and agrees also in quantitative sense.

This is important because this is a completely different physics and completely different observation from measurements like x-rays or rotation curves. So this is always a good thing. You want to measure the phenomena in multiple ways, and see if you can get the same result.

So now this is actually a real industry. People who do deep, deep surveys of galaxies, then they can invert the hole's deep panoramic scene, and there's big cervical cosmos that Nick Scoville here is leading. And so they've done that for this particular field of galaxies, and they found out where the dark matter is. And you can look at it and say, well, module different smoothings, it's distributed same way as the light.

Now because they can also estimate redshifts to these galaxies from their colors. They can get the 3-D picture. And so this is what the distribution of dark matter is in a volume that's projected on the sky for this field. So they're essentially doing tomography of the dark matter in the universe. And, in principle, if you do lots and lots of this, you can see exactly how the distribution of dark matter will be changing in time. And that's something that will be done in the future, I'm sure.

So by using irritational lensing, we can actually see where the mass is, whether or not we can see it, regardless of what is it made of.