S. GEORGE DJORGOVSKI: So now let's talk a little bit about their big cousins, supermassive black holes in galactic nuclei. We'll continue talking about them when we talk about quasars. But just to give you some flavor, this is obviously an artist's conception. There's a black hole colored correctly, with an accretion disk and twisted magnetic fields forming a jet.

And how do we know that they exist? We now know they actually are very common. Essentially every galaxy, aside from dwarf galaxies, seems to have one of these. And you cannot see them. But we can sense their mass if there are some test particles.

So if you can measure velocities of stars or gas really close to the galactic center, you can measure the gravitational potential in which those particles move. And it looks like this-- this is in Andromeda-- our nearby spiral galaxy. The top graph is random motions of stars. You can see there's a sudden spike in the middle. And the bottom is the rotation-- positive on one side, negative on the other side. And then there is a sudden jump in rotation as you approach the middle. And of course, it has to cross through zero.

So that increase in kinetic energy requires gravitational potential to be compensating for it. And so when you do the math, it turns out that you can make this with a combination of galaxy potentially itself-- galaxy has a mass-- plus a point mass in the middle. Because for all practical purposes, these are point masses.

Well the best studied one is actually in our own Milky Way. And this was done largely with Keck telescope by Andrea Ghez and collaborators UCLA, but also Reinhard Genzel of Max Planck institute.

The picture is the real picture. It's adaptive optics near an infrared image of the region, smack right middle of our galaxy. And the circles indicate the positions of stars-- you can see each of those ends on a star-- that they measured over a period of time.

And so then you have Keplerian motions. Because as far as these stars are concerned, they are like in two body systems. The only other mass that matters is the big mass in the middle. So if you have a whole lot of Keplerian test particles, you can infer how much mass you've got.

And you can plot that as a function of radius, and it looks like this. This is now enclosed mass-- log of the mass versus log of the radius-- and a large radius. As you get closer there is less enclosed mass. That's reasonable, you're leaving some mass outside.

But then as you start approaching the center, it flattens out. That means no matter how many stars are you not counting anymore because you're too close in, there is still some fixed amount of mass left, all the way to the middle. And the amount of it is now on the order of 3 million solar masses, give or take. And we cannot resolve this with any technology that we have. But we can probe it dynamically.

So this is very convincing evidence that there is indeed a very massive object in the middle of the Milky Way. Occasionally it gobbles up something, and then you see a little flair of converting binding energy into luminosity. There was a hope that there was a big molecular cloud passing by. And that can create a nice little flash. But so far it didn't happen.

Similar things have been done now using other techniques. And there is one that is particularly interesting. And that's using so-called water masers. Some of those young stars, or stars with big envelopes, actually can emit maser emission. Very sharp emission line of particular molecules like water. And so you can measure their velocities with a fantastic precision, because the line is really sharp.

If you use very long baseline interferometry, you can actually measure their motions on the sky, over a period of some years. And so that enables you to solve Kepler problem again. So again you have test particles moving in a point of point mass. And sure enough you infer the masses of the mass of these particular black holes are some kinds of millions of solar masses. But now this has been done for many other cases.

There are other reasons to believe that there are really massive black holes in galactic centers. And we'll talk more about those when we talk about quasars, or active galactic nuclei. Because that's where things really get to be spectacular. That accretion of material on black holes, with their 10s or 100s of millions of solar masses, or maybe billions of solar masses in some cases can produce fantastic luminosities. A thousand times more than total galaxy, which has 100 billion stars.

And there is absolutely no way in which we can produce such luminosities through thermonuclear fusion or a Kelvin-Helmholtz mechanism. The only way that we know how to generate such luminosity is through accretion. And this is again the extension of the same argument.

Something falls to the bottom of the potential while converts binding energy into kinetic and then radiation. So in case of galaxies, stuff falls in from kiloparsecs away. It comes down to near Schwarzschild radius, not exactly. And that is of the order of 10 microparsecs.

So you have on the order of 8, 9 orders of magnitude increase in radius. So it means it essentially doesn't matter where they started from. And if you compute binding energy of material at Schwarzschild radius, it turns out to be like the rest mass-- energy of the other stuff.

Now not all of that gets converted. It really depends on where does it land on the accretion disk. But typically of the order of 10% of the rest mass of the stuff that falls in, gets converted into luminosity. And 10% is a lot more than 0.1%, which is the maximum efficiency for thermonuclear reactions.

So there are essentially two sources of energy in the universe now. Thermonuclear burning in stars and accretion onto dense objects. And accretion onto dense objects-- black holes in particular-- is by far more powerful. 100 times more powerful. But it's rare.

And so overall, most energy actually is being generated through thermonuclear burning in stars. But when this happens, it gets to be very spectacular.