S. GEORGE DJORGOVSKI: So let's take a look how do these giant black holes interacting as they form and how does that relate to galaxy formation itself? So the first thing that people started studying when quasars were recognized as an interesting phenomenon in their own right-- and you probably know that this was done here at Caltech by Maarten Schmidt in 1963. They recognized what quasars were. They found out that there were many more quasars at higher redshifts than there are here now. In fact, there's like an exponential growth.

And you can't just look at any individual object. So there's a whole distribution. The easiest thing to describe is this luminosity function, the distribution of luminosities of objects. That turns out to be power law. And so at lower redshifts, you have power law distribution of luminosities. At higher redshifts, you also have power law distribution of luminosities, and it's shifted.

Now, you don't know is it shifted up and down, meaning same number of objects-- I'm sorry, the same luminosities, but more objects. Or at left and right, the same number of objects, but they used to be more luminous. And so those two are called density evolution or luminosity evolution. And insofar as the luminosity functions are power laws, there is no way of telling.

Fortunately, it's not pure power law. If you look at low enough luminosities, you see there is a bend. So there is a knee to this luminosity function of quasars. And when you then look how that behaves as a function of cosmic time, you find out that there is both luminosity and density evolution, or rather there is luminosity-dependent density devolution.

But thanks to the Deep Surveys, now we have a pretty good understanding of how that goes throughout the history of the universe. And the numbers evolve in time, interestingly enough. As you look from here back into the past, you see more and more quasars. And the numbers peak around redshifts of 2 or so, plus or minus 1. And then they decline again, at higher redshifts.

And this is just like history, cosmic history of star formation, and for the same reasons. The same processes that build up galaxies, which is dissipate emerging, that then causes star formation, are the processes that feed black holes and therefore increase their mass. And so at first, you have nothing. And you start building them up.

You add more and more. Galaxies keep merging. The process culminates, a couple of gigayears, a few gigayears after the Big Bang, and then slows down and declines, just like star formation in the history of galaxies.

So star formation, and history of galaxies, and history of supermassive black holes, or active nuclei, can attract each other. And, moreover, there is some real energy exchange too.

Now not only do the galaxy mergers affect what's going to happen with an active nucleus, but also the other way around. Because these things put a lot of energy out. Both through electromagnetic radiation, so they could drive like stellar wind equivalent from an active nucleus, and also mechanically, with these relativistic jets.

So that's now called feedback. And this is again picture of Centaurus A galaxy, with a radio map superposed. And the amount of mechanical energy that's pushed out through radio jets in the radio lobes is of the order of 10 to the 6 ergs. And a similar things is total amount of radiation that emits over a period of some tens of millions of years. And that is comparable to or even larger than the binding energy of this entire galaxy.

So if you could couple 100% of energy output of an active nucleus, it would just blow the host galaxy apart. It doesn't do that because it doesn't couple perfectly. But even if a small fraction of it gets coupled to the, say, interstellar medium, that can clearly affect the accretion rate because it will start pushing out the gas that normally would acrete in a black hole. So that would kind of go at a feedback cycle like that. And that may be why we see correlations between black hole mass and all the stellar mass in galaxies today.

So there is this whole co-evolution of galaxies and their supermassive black holes. They all assemble through mergers. The mergers stimulate star formation and feed the AGN, the AGN stop the process, and more merging happens, and so on. And people like Phil Hopkins here are studying this kind of stuff and explaining how the joint evolution of quasars and their supermassive black hole goes.

But then the question remains how did it all start? So you have hundreds of millions or maybe a billion solar mass black holes-- already at redshifts 5 or 6 million versus billion years old. And where do they come from? And there are several different possibilities.

First, you can say, well, there are some small black holes came out of the Big Bang for God knows what reason. That's pretty ad hoc, but it's not impossible. And then they can serve as seeds into which you grow more and more stuff. So there are good reasons why this can't be right.

The natural thing is that you have supermassive stars, Population III stars exploding, leaving black hole remnants of a few solar masses. Then those keep gobbling up stuff and growing and growing and growing. Remember, mass accretion starts and goes at an internal rate that grows exponentially.

Another possibility is you make a really dense star cluster, that there will seed star clusters forming in star-forming regions. Well, a star cluster can undergo gravitational collapse and make a black hole. Or maybe you don't need to make stars at all. All you need is sufficiently dense core, which could be a combination of dark matter and invisible stuff that goes over a critical limit and makes a black hole.

So whichever way it works, it has to work very efficiently to build up the quasars that we see. And so there are now simulations of how that could be happening, making stellar black holes, and ever bigger ones and bigger and bigger. And someday, we'll probably see gravitational wave signals of that original build up. There are also simulations that say, well, just start with a mixture of gas and dark matter and under certain conditions, you can dissipate enough energy that you can just collapse the thing directly. And that also works.

So in terms of how do you grow black holes, just like galaxies merge from smaller pieces into ever bigger ones, black holes would be assembled in the same fashion. There would be black holes and individual galaxies merged together, and so on. So you build ever bigger ones. So there is a merger tree like this.

And we actually see this happening in closed, binary, active nuclei. Here are pictures of them. The one on the left is a radio map. And you can kind of see there are two radio sources of the jets and they're spiraling in together. The one on the right is X-ray from Chandra to quasar-like nuclei in an elliptical galaxy nearby.

And we've seen lots and lots of binary galactic nuclei. But because of the limitations of resolution, we see them usually at kiloparsecs or a hundred kiloparsec separations. These will take many millions of years to merge.

And the cool thing will be to find those that are so close, they are going to merge in out lifetime. Well, that's one of the targets that is anticipated for gravitational observatories like LIGO or someday LISA. And people like our theoretical relativistic group here are doing simulations of merging black holes and all the signatures that can lead for observatories like LIGO to see.

The interesting question then is, is it just gravitational waves or is there also some electromagnetic signal that accompanies this merger, that we can detect with optical telescopes? And right now, this is somewhat unclear.