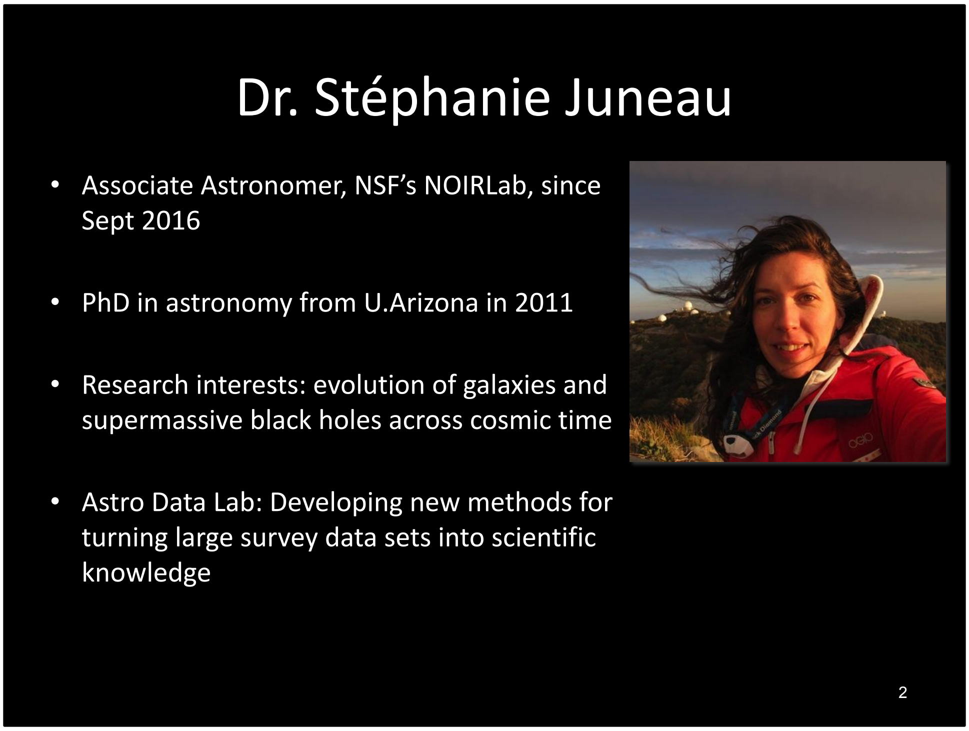

Welcome to the
Teen Astronomy Café



This activity was designed by Dr. Stephanie Juneau.


Black Holes
Dr. Stéphanie Juneau

Big Ideas

- What black holes are
- How astronomers find black holes
- How black holes can affect the fate of galaxies

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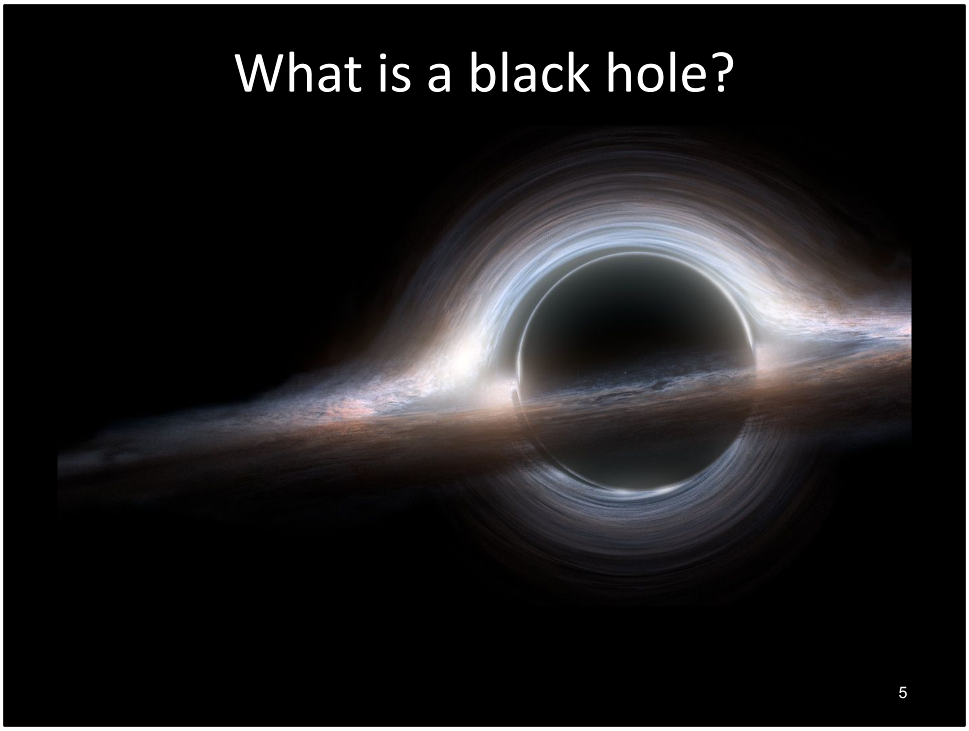
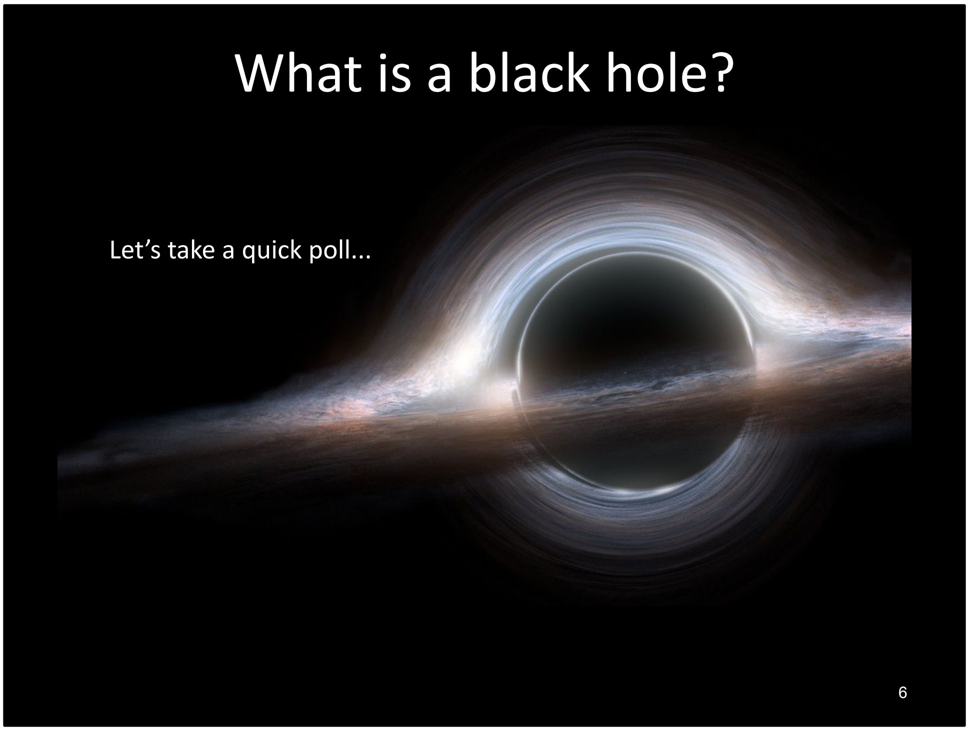
Today, we will cover 3 big ideas about Black Holes. First, we will talk about what black holes are. Then, we will see how astronomers find them, which is not always obvious since we cannot see them directly. Lastly, we will discover how black holes may influence the fate of galaxies. This is what the computer activity will be about.



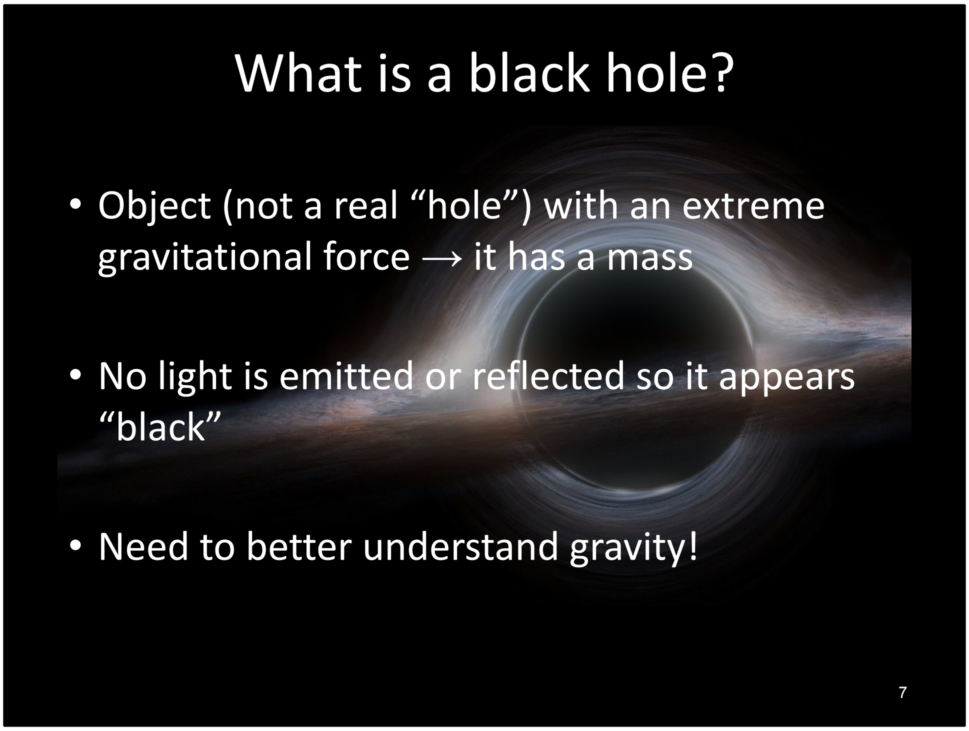
What is a black hole? Before telling you more, let’s take a quick poll to see what you all think (next slide prompts for taking a poll).



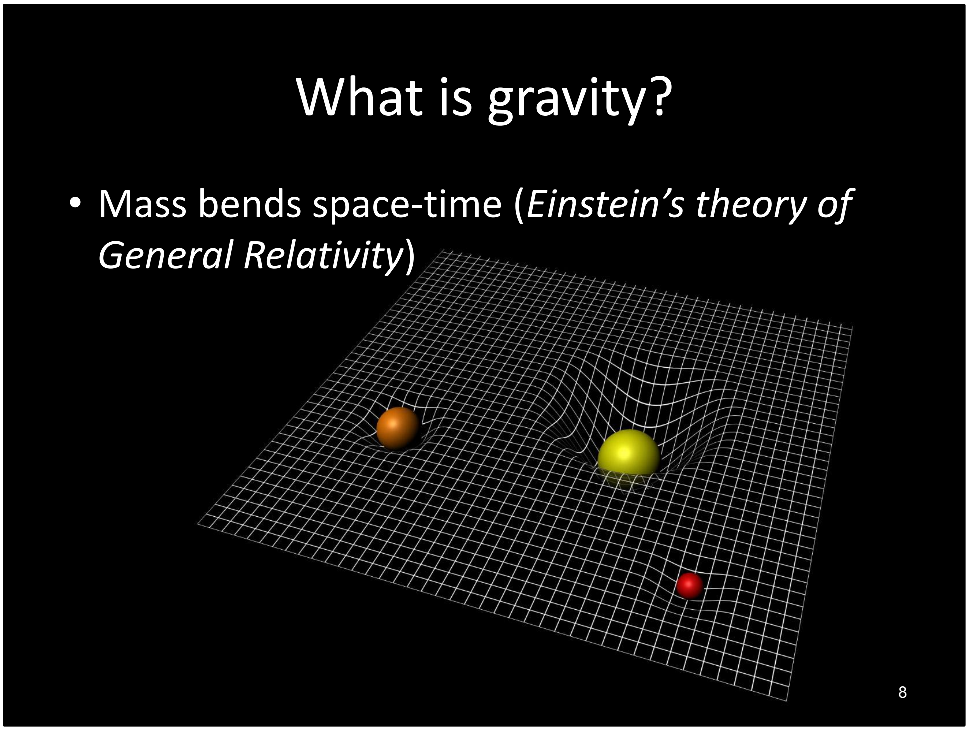
Poll question and answers below (we used Zoom to conduct the poll with "Multiple choices"):

What is a black hole? (You can choose multiple answers.)

1. A portal to another universe
2. A hole that sucks everything that comes near
3. A massive and dense object
4. Something that has extreme gravity
5. A void in the universe



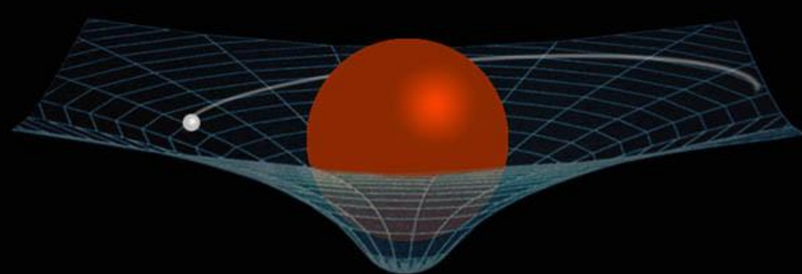
Here are some things that we know about black holes. A black hole is in fact an object with a mass. The most distinguishing feature of black holes with respect to any other object is their intense gravitational pull. It is not a hole. It is also not a vacuum cleaner and doesn't suck anything. It only acts through gravity. Also, because there is no light emitted and no light reflected by a black hole, it appears black. In other words, there is nothing to "see" with our eyes UNLESS there is something luminous around or behind it and then the black hole can make a shadow or silhouette. Since we cannot see black holes, we mostly find them through their gravity, so let's spend some time to better understand gravity.



Some of you might have heard of Newton's law of gravity, and a story about an apple falling from a tree. But the best current understanding of gravity is explained by Einstein's theory of General Relativity. According to this description of gravity, gravity is understood as the bending of space-time by any and all objects with a mass. SPACE-TIME refers to the description of the universe, it is everywhere around us, and you can think of it as the "fabric" of the universe. I might sometimes only say "Space" but what is coming always refers to "space-time". So according to Einstein's theory of general relativity, everything with a mass will bend space-time. The more massive the object, the more space-time will be bent (or curved).

What is gravity?

- The curvature of space-time explains the movement of objects & their orbits (Moon around the Earth, planets around the Sun, etc.)



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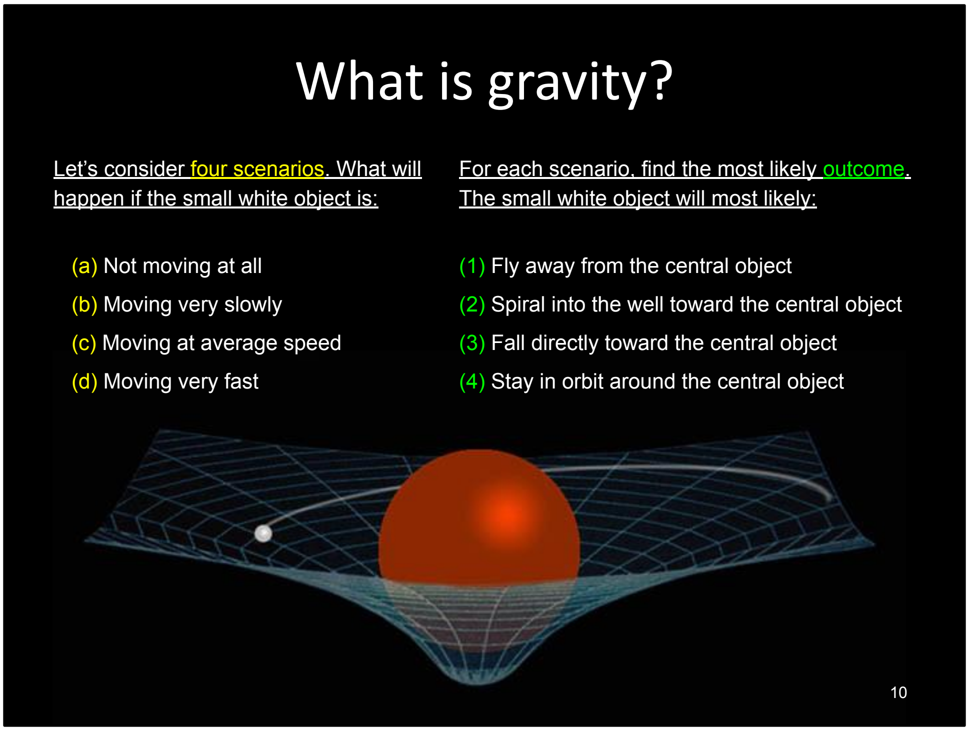
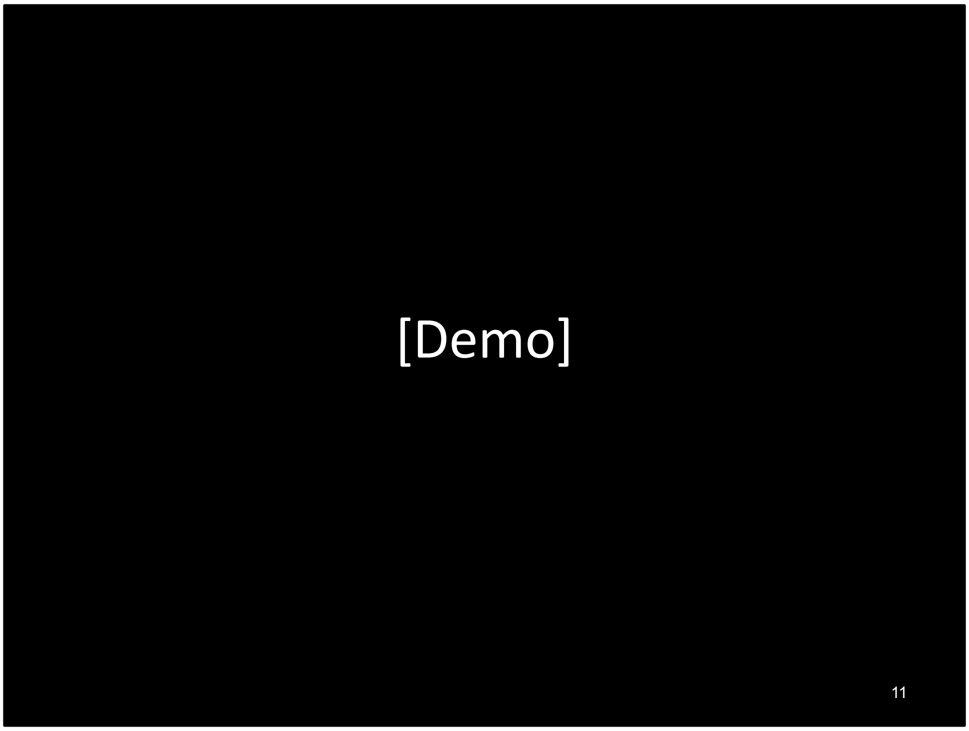
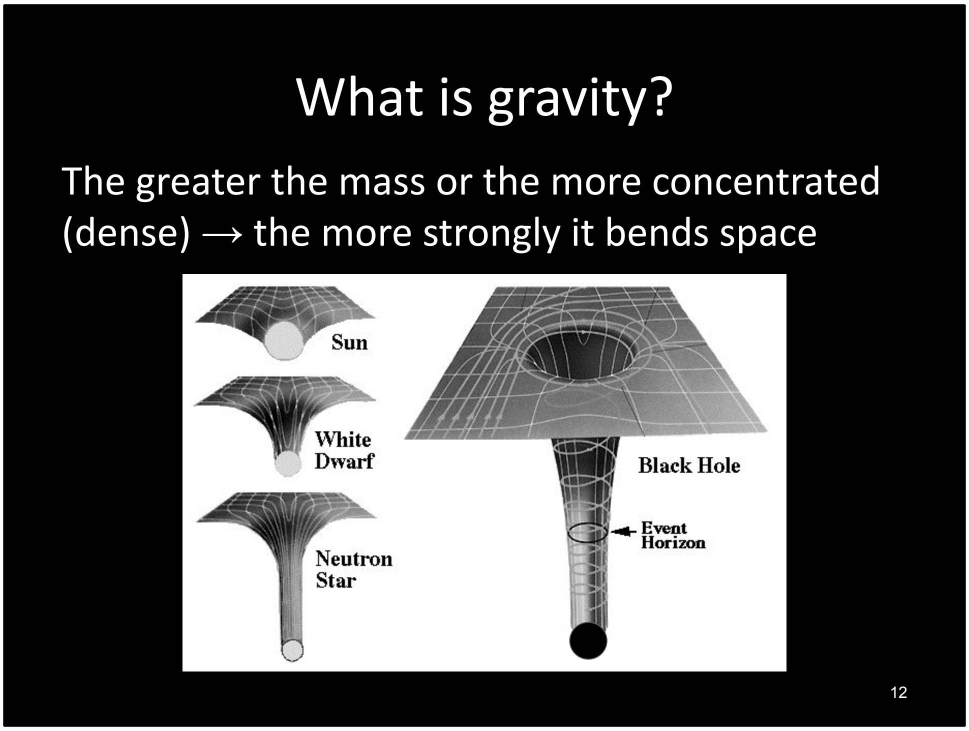


To better understand the concept, let's consider 4 scenarios (on the left-hand side), and for each one, we will find the most likely outcome (on the right-hand side). Let's read all 4 scenarios and all 4 outcomes then we will match them up. [When using Zoom, the presenter can Annotate the slide and draw lines to link each scenario to one outcome. The presenter can ask students to enter their answers in the chat, and go with the consensus] [Answers: a-3; b-2; c-4, d-1]



Gravity Well demo with a stretch fabric over a large bucket or circular shape. A mass is placed at the center and "bends" the fabric of space-time. Then a smaller object (marble) is used to demonstrate the 4 scenarios listed in the previous slide (e.g., letting it go without giving it any sort of push, giving only a slow speed, trying to let the marble make some orbits, giving too much speed so it flies off the surface -- this is where the demo can end and return to the slides.



Add a few explanations about the different objects shown here.

The Sun is about 333,000 times the **mass** of the **Earth (109 times larger in diameter)**

A typical **white dwarf** is about as massive as the Sun (maximum 1.4 times), yet only slightly bigger than the Earth. This makes **white dwarfs** one of the densest forms of matter, surpassed only by neutron stars and black holes.

A neutron star is about 20 km in diameter (12 miles) and has a mass between 1.4 - 2 times the mass of the Sun.

A black hole is even denser than a neutron star, and it can also reach much higher mass!!! “Small” black holes are a few to about a hundred times more massive than the Sun. **But** black holes can reach millions to billions times the mass of the Sun.

[technical detail: the largest “supermassive” black holes are more massive but actually less dense; I avoid getting into this unless the students ask a question]

Black Holes: Big & Small

- Stellar black holes
- Supermassive (giant) black holes

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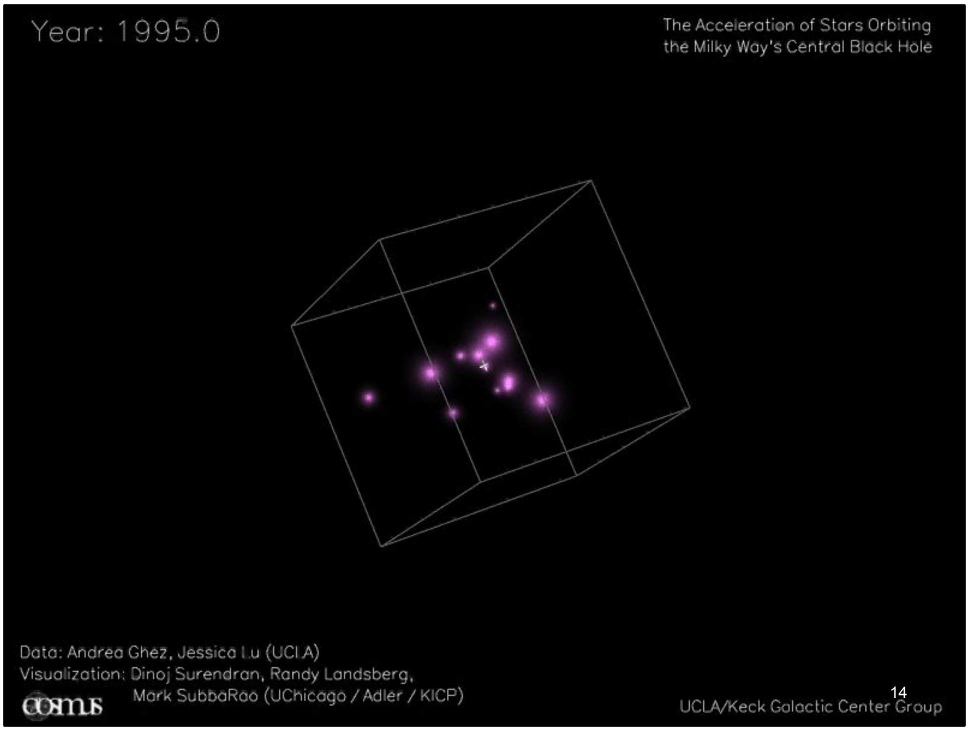
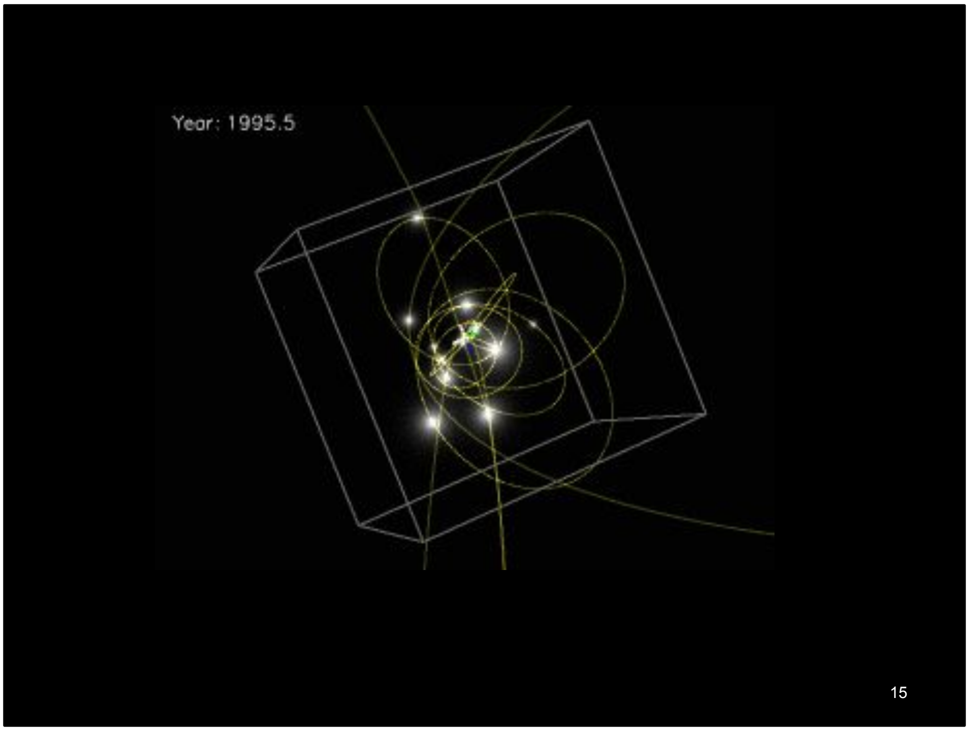
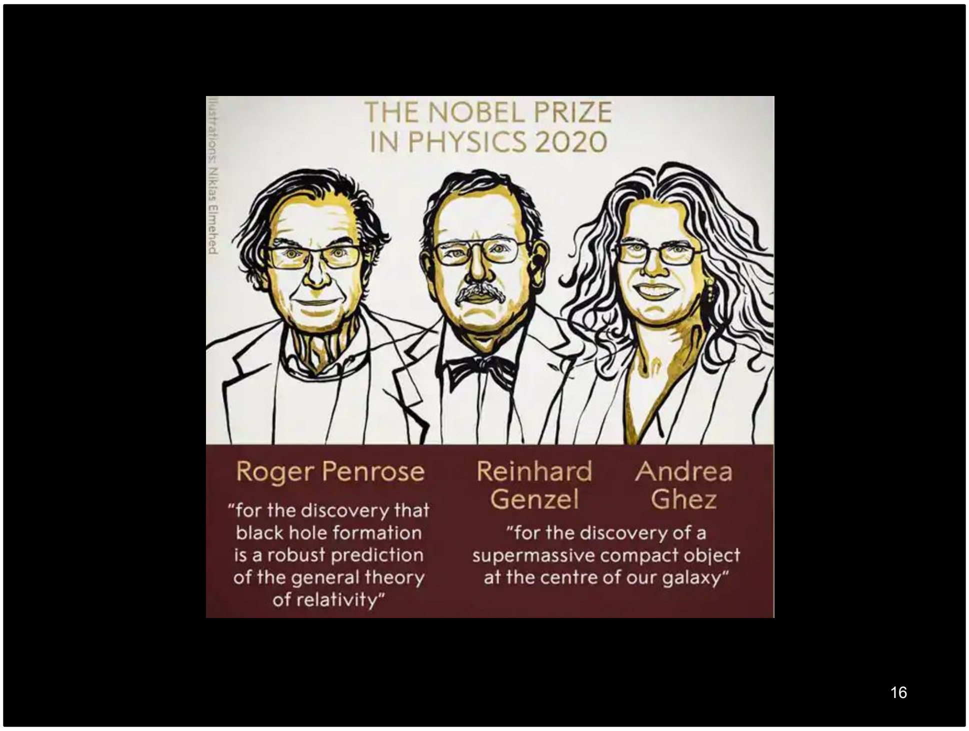
Not all black holes are the same! There are smaller and much larger black holes. The smallest black holes come from the end of a single star's life. This only happens to massive stars, from tens to hundred times the mass of the Sun. At the end of their lives, the outer layers explode as a supernova, whereas the inside portion collapses unto itself (or "implodes") creating a very dense object which is a black hole. At the other extremes, supermassive black holes can reach millions to billions of times the mass of the Sun. Those reside at the center of galaxies, and can grow in time as more mass can get added. Between the two, there are "medium-sized" black holes that are called intermediate-mass black holes but those have been very hard to find, so there's still a "treasure hunt" in astronomy to find them!



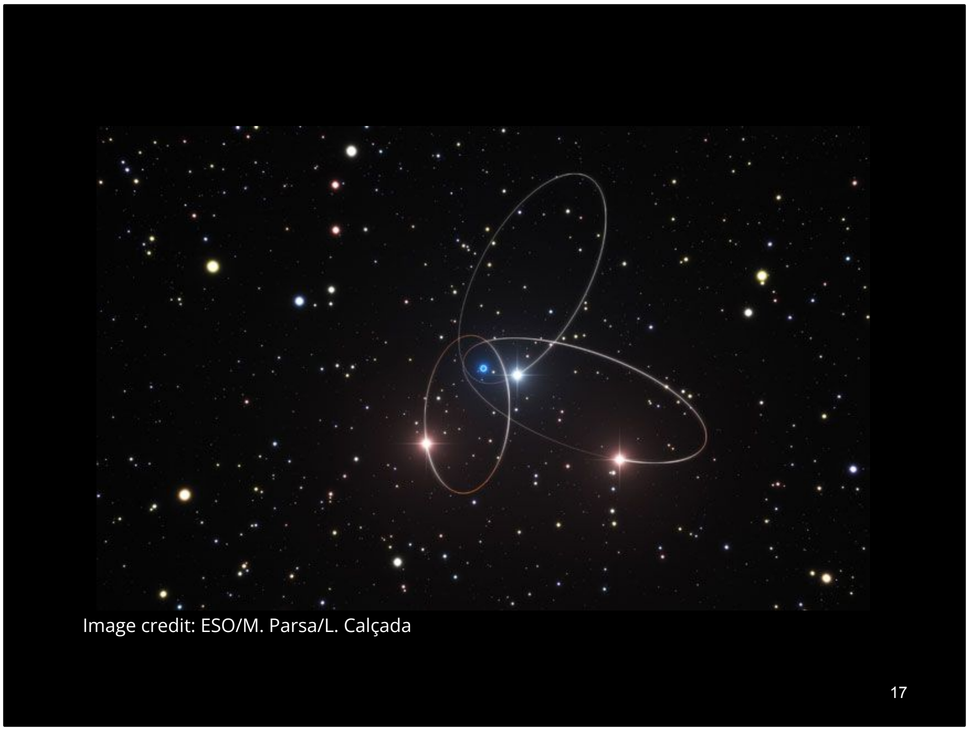
How do we find black holes since we cannot see them? One way it to study the movement and orbits of other objects such as stars that go around the black holes. In this case, you will see a study that tracked stars near the center of our own Milky Way galaxy over the course of over 20 years to measure their orbits, and then use those measurements to calculate the mass of the central object (which we cannot see so it looks like the stars are going around a common point of space but we don't see whether there's anything there.) The next slide will show the animation.



This animation starts with the positions of real stars in 1995 and shows their positions moving along their orbits. The orbits are drawn to help us see them. In details, the orbits are in 3-D so the calculations take that into account, and the result was that there is a mass between 3 and 4 million times the mass of the Sun, around which the stars are orbiting! It's such a large mass, in such a small region that the only possible object is a supermassive black hole. So this is how the presence and the mass of the black hole at the center of the Milky Way was found.
[Note: the animation extends into the future and shows how the stars will keep moving… may not need to go over this unless students ask]



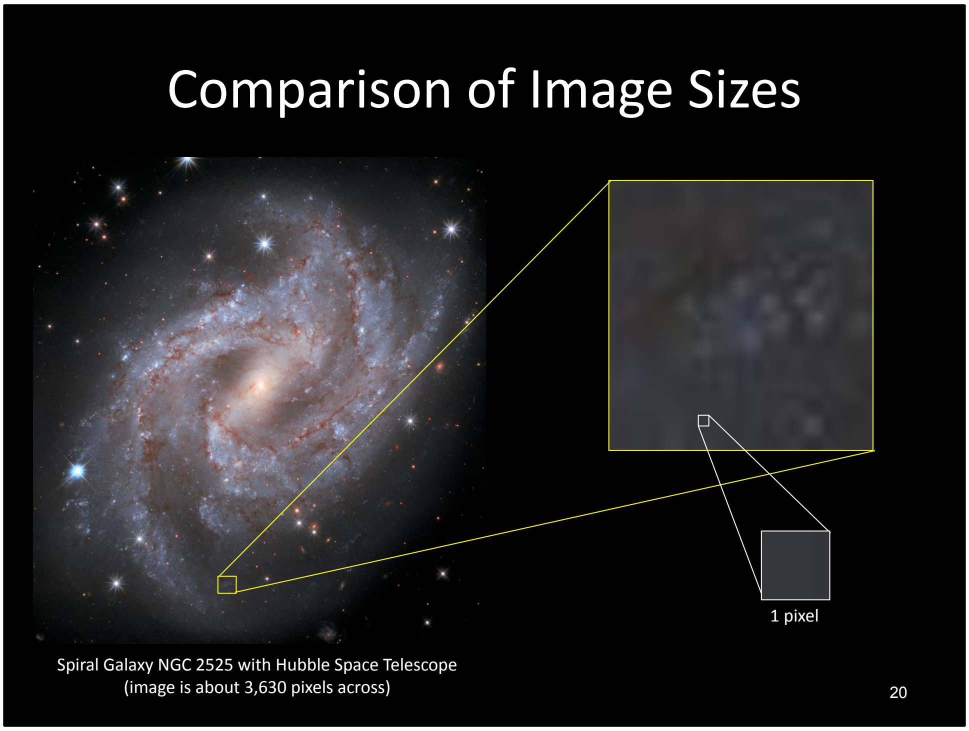
This discovery of the supermassive black hole at the center of the Milky Way was recognized with a Nobel prize in physics in 2020 to the two teams that made similar work. One team lead by Andrea Ghez, and the other led by Reinhard Genzel. (They shared the prize with Roger Penrose who did theoretical work on the topic of black holes.)



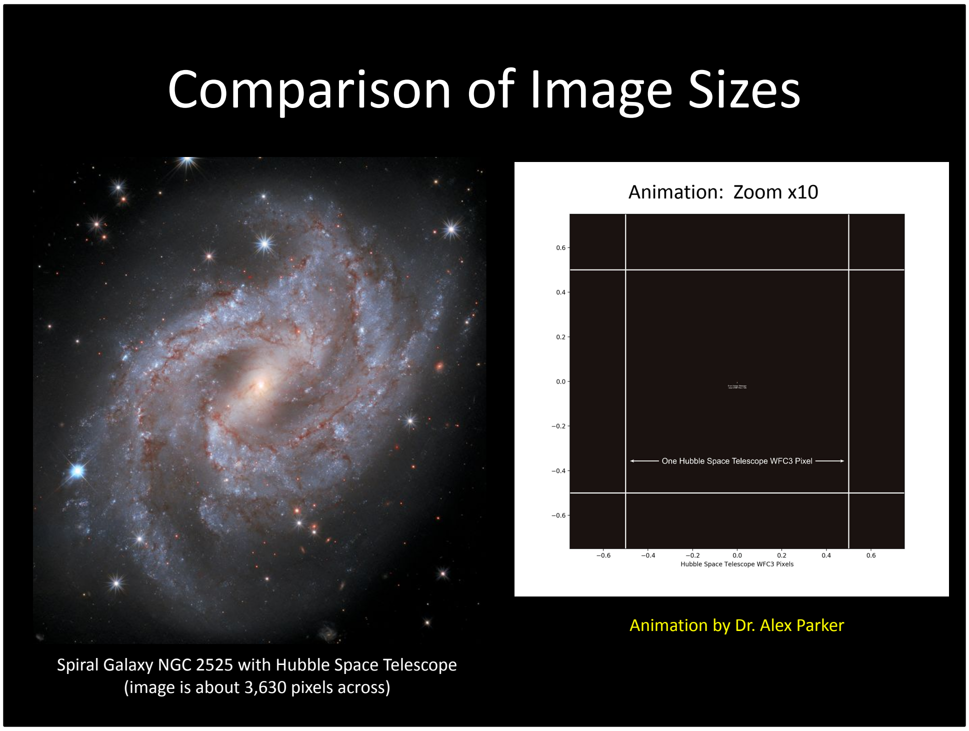
The ellipses are added in this artist rendition to help visualize the orbits of the stars around the central black hole (Again, a reminder that we cannot see the black hole, only bright luminous material around it if there is any; we will talk more about this later).

There was a very important new result in 2019 when astronomers managed for the first time to take an image of a black hole shadow. To do this, they had to build a network of telescopes covering the planet to use together, and point them precisely at the same place and observe at the same time, to then combine the data from all the telescopes as though it was only one giant telescope the size of the Earth. Before even looking at the observations, researchers from the University of Arizona created a computer model of what a black hole shadow could look like if we can see all the finest details (with infinite resolution). However, it's important to note that even with a telescope the size of the Earth, we still cannot see perfectly the finest details so we end up looking near the limit of resolution (like zooming at the maximum possible level), and as a result the image will look more blurry. So knowing that, the next slide will show the actual first picture of a black hole shadow.

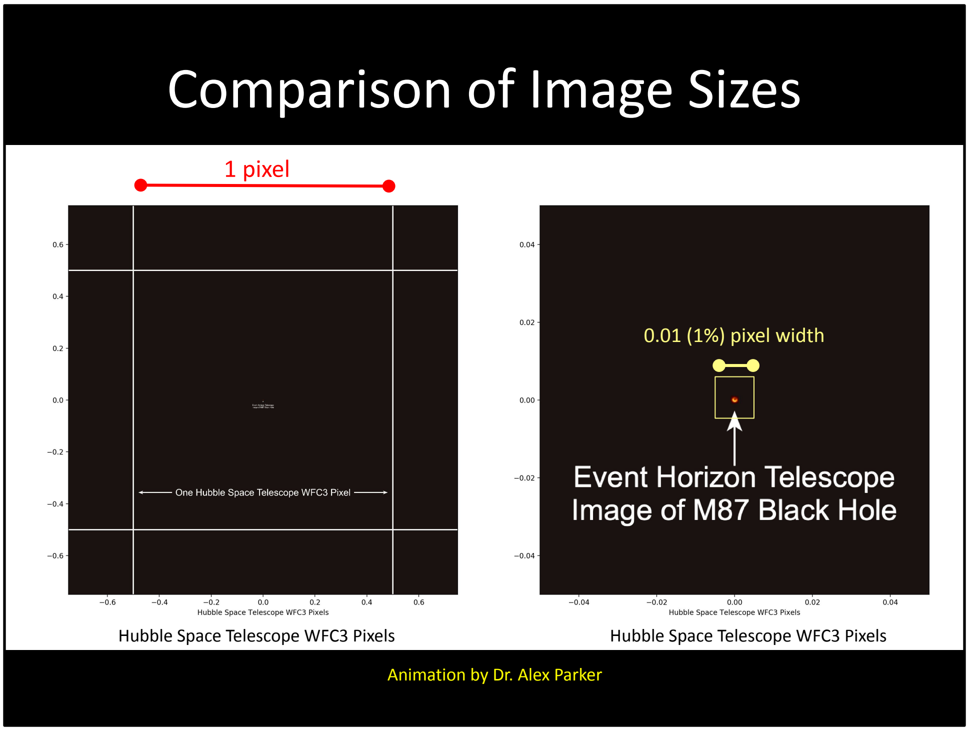
When one knows and realizes how much we had to zoom to see such a fine detail, this is a very impressive picture! A possible analogy is to consider that "Taking a picture of the shadow cast by a supermassive black hole is like taking a photo of a quarter in Los Angeles all the way from Washington, DC." A lot of people thought that this image was blurry and wondering why it couldn't be sharper. Let's compare it to other astronomical images to better understand.



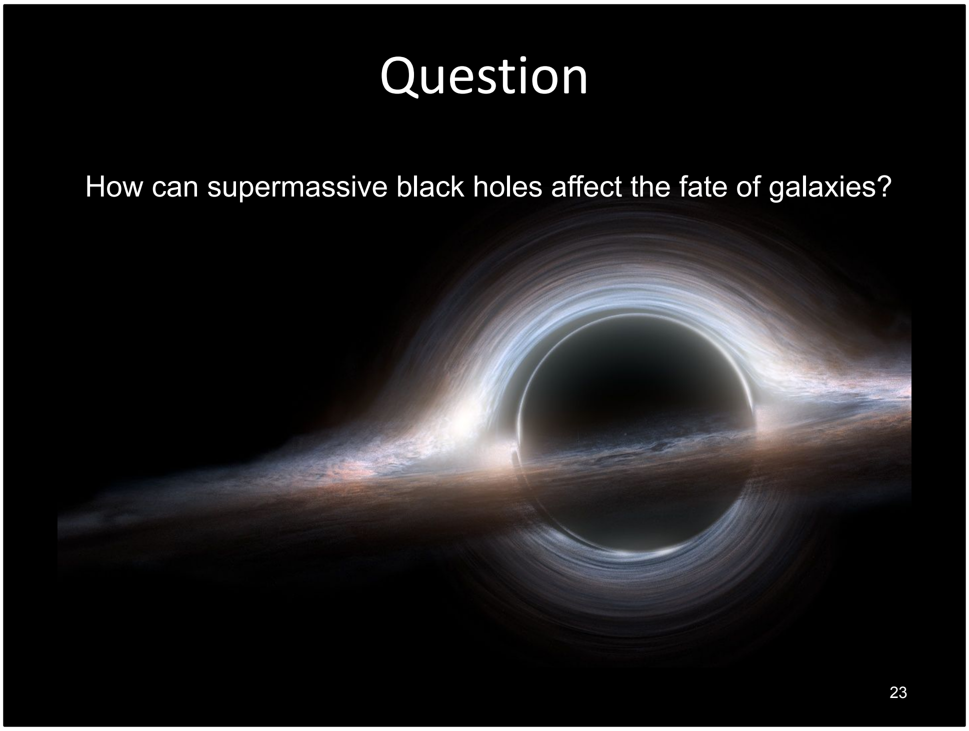
OK, so we'll compare with this beautiful image shown here on the left from the Hubble Space Telescope. This is an image of a galaxy, containing billions of stars. When we look at the full image, which is more than 3000 pixels across, we see all these nice details along the spiral arms and so on. [Can use the example of cell phone cameras to mention what pixels are]. Now if we start zooming in a small region, closer to the resolution limit, it starts to look more blurry. We can sort of see a group of brighter spots. If we were to look at a single pixel, it wouldn't be so interesting, right? It's only one flat color in this one tiny pixel. Well, the image of the black hole shadow is still MUCH smaller than a single pixel of the Hubble Space Telescope!



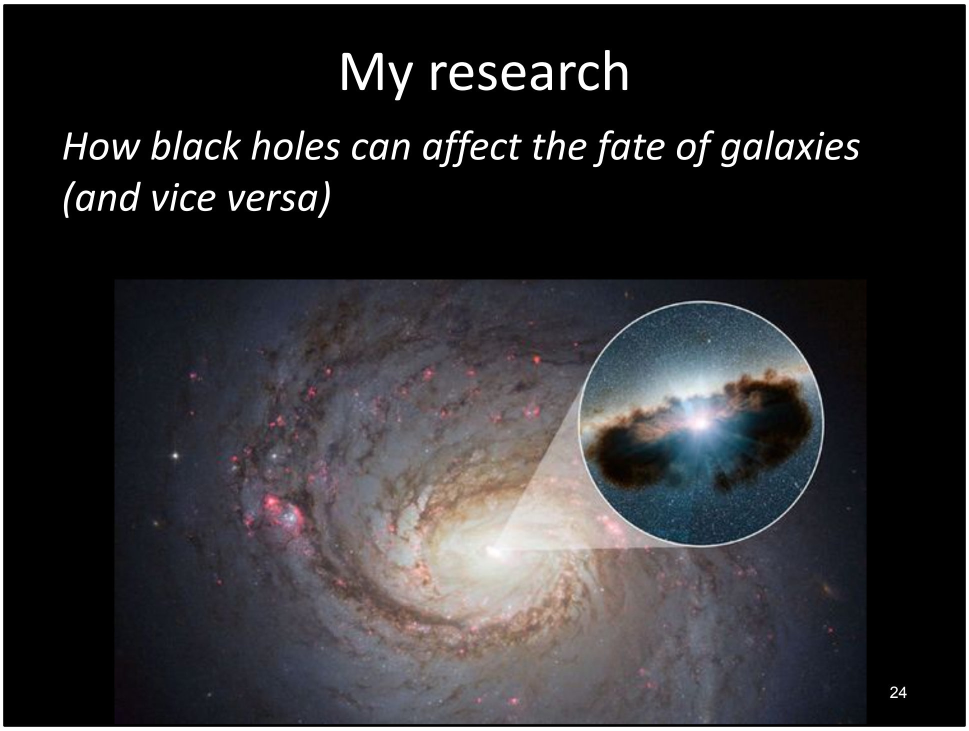
The animation on the right-hand side shows how, starting from the size of a single Hubble Space Telescope pixel, we have to zoom in by a factor 10 to even start to see the M87 black hole image. The next slide will show the first and last step of the animation so we can take a better look.



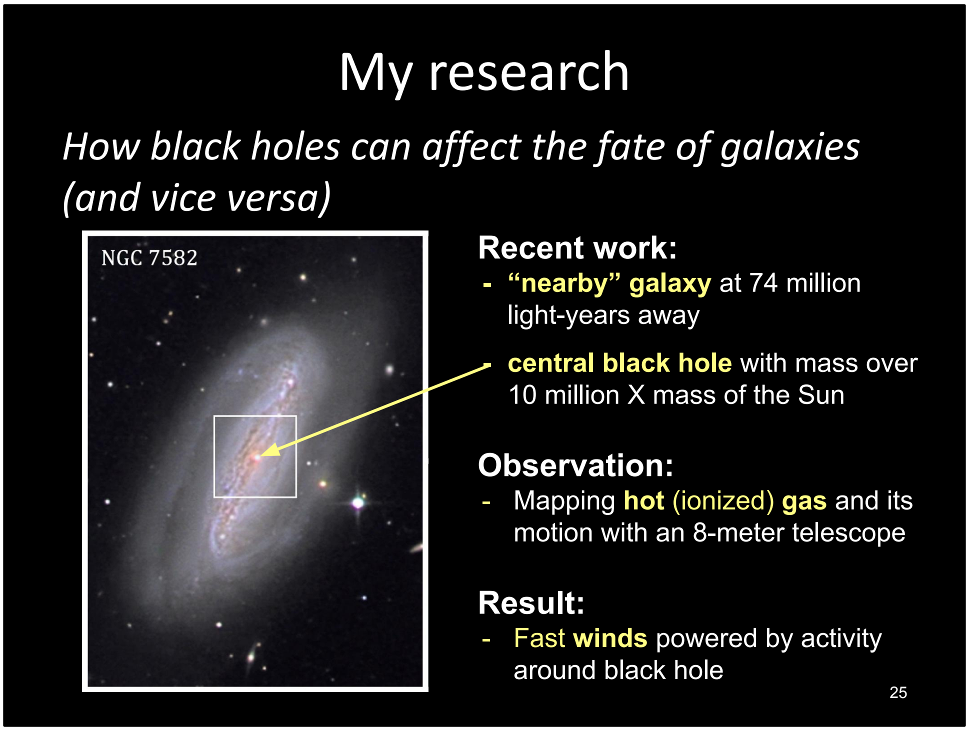
The animation started on the left, where the square shows the size of a single Hubble Space Telescope pixel. Then on the right, the yellow square shows a square that is 100 times smaller on a side compared to a single pixel. And as you can see, the actual image is still about 10 times smaller on a side. So this means that the image is about 1/1000 (one one thousandth) of a single Hubble pixel. I hope this helps to show just how tiny the image is, and why it still looks blurry because we had to “zoom in” so much. In fact, Hubble wouldn’t see this image at all as it’s only 1/1000 of one pixel. We really needed to build a telescope network the size of the Earth to see these details. Anything smaller doesn’t work.



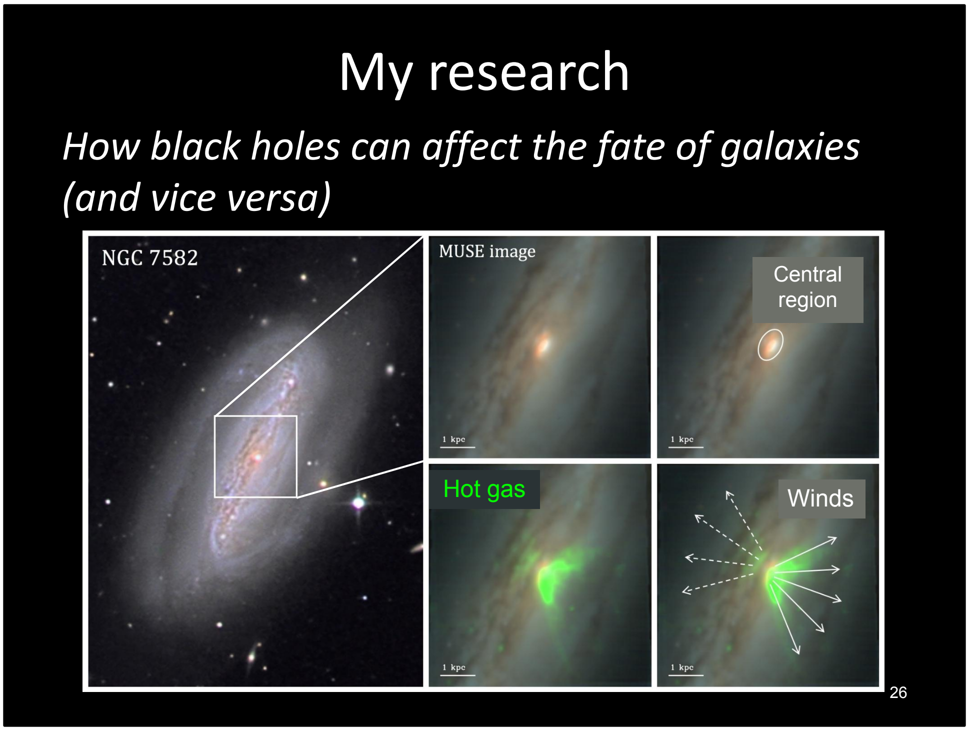
So now that we know more about what black holes are, and one way to find them, we can ask ourselves if these supermassive black holes can do anything the galaxies in which they reside. On the one hand, there is a very strong gravitational pull near the black holes, but on the other hand, the galaxies are still much larger and much more massive than their central black holes. So what can possibly happen?



It turns out that even though supermassive black holes are still like a tiny speck compared to an entire galaxy, there is a lot of energy that can be released just outside the black hole and that can be distributed and sent into the galaxy at large. We'll learn more about how that works in the last couple of slides here and in the computer activity that we will do next.

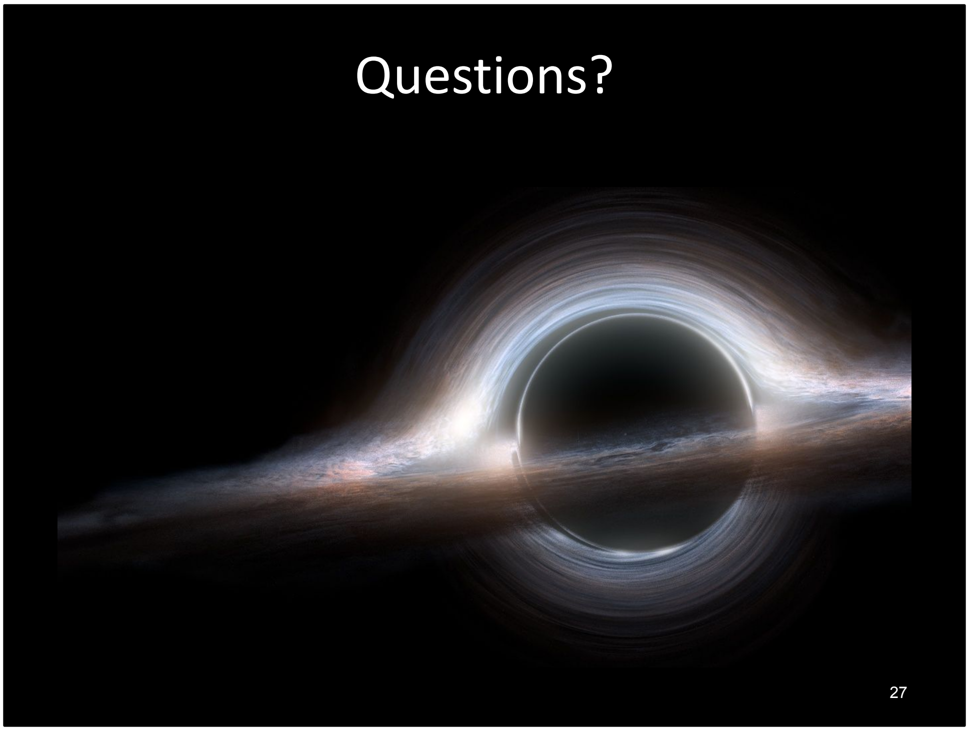


In my research, I have been very interested in this question and more generally how black holes and galaxies relate to each other. I’m showing one example galaxy here, You can see on its image that’s it a nice spiral galaxy. Relatively speaking, it is fairly “nearby” at 74 MILLION light-years away. OK, this is a very large distance compared to what we’re used to here on Earth, and compared to our Solar System or our entire Milky Way galaxy, but relative to the entire universe, it’s relatively close by. It has a central black hole over 10 million times the mass of the Sun, so that’s between 2 and 3 times the mass of the Milky Way black hole.



Around the central region of the galaxy there is a white square. We used an 8-meter telescope to map this region. In particular we were looking for hot gas that would be heated by what is just around the black hole. Stars can orbit the black holes or even loose gas will travel around a black hole very fast and get very hot. What we discovered from our observations are really fast winds coming from this hot gas just outside the black hole. The black hole does not create any light itself, but it has such a strong gravity that it can heat the gas that is spinning around it.

We measured the motion of the gas that is creating fast hot wind. This hot wind can push the gas, remove it form the galaxy, and heat it up. Galaxies need gas to make new stars. If we remove the gas, or make the gas too hot, this gas is not going to be able to make new stars.



Q&A