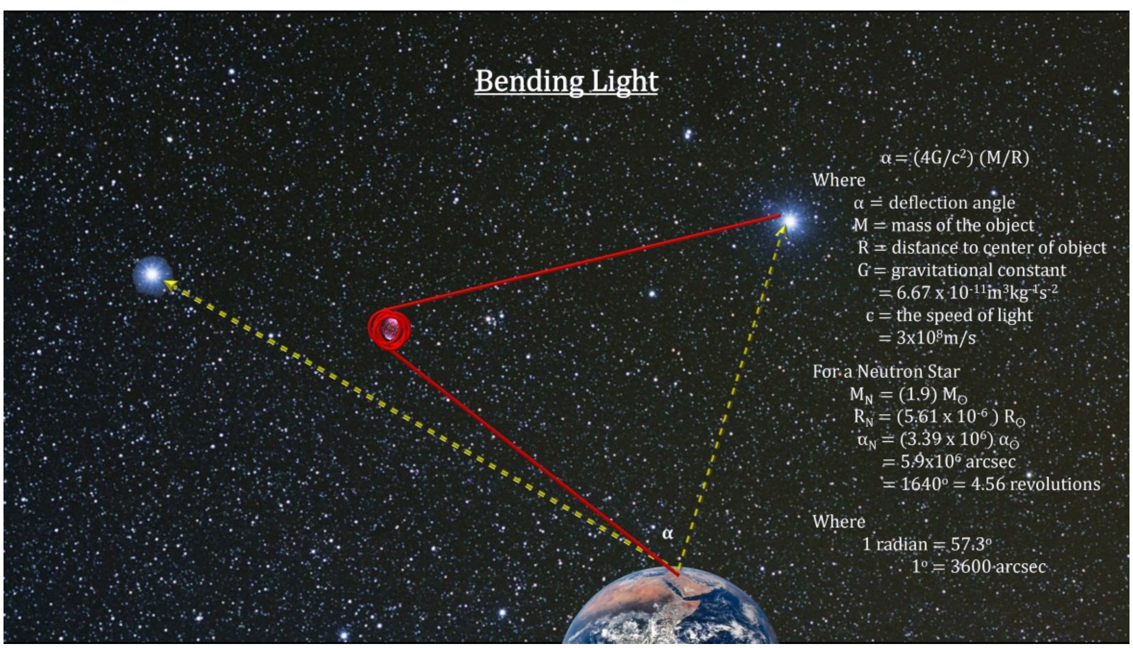
Black Holes

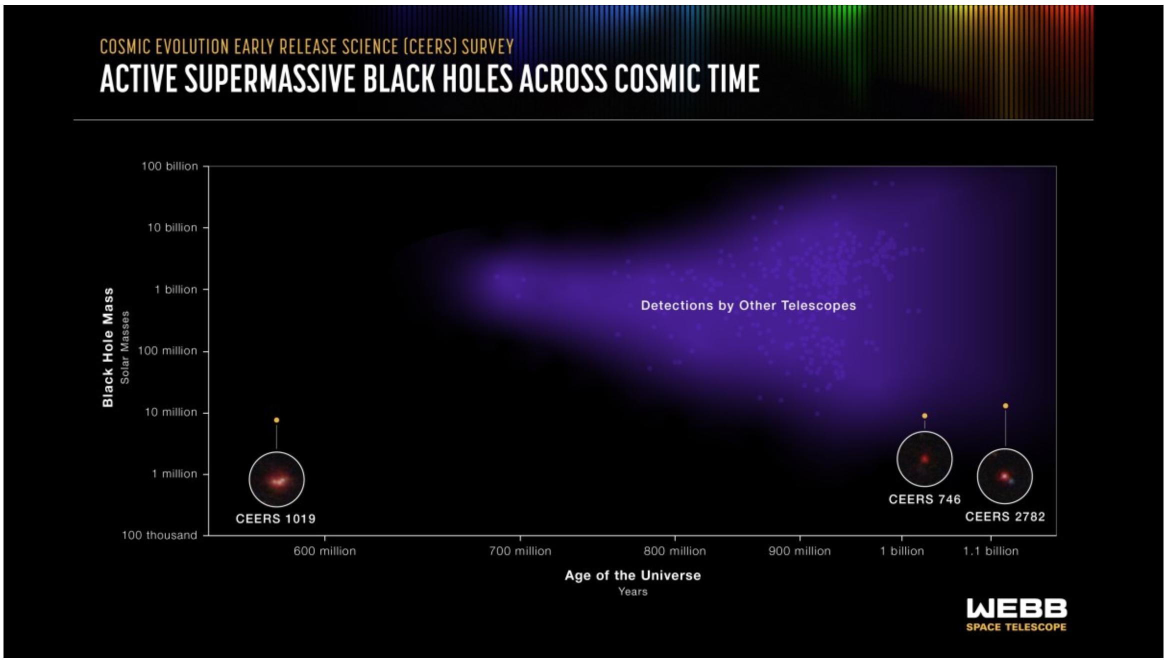
{**Abstract:** *In this segment of the "How Fast Is It" video book, we cover Black Holes: what they are; how they're categorized; how they form; and how they grow via accretion disks with jets that appear to accelerate matter to velocities faster than the speed of light. We cover the Kerr Metric for rotating energy densities that produce frame-dragging. We cover the anatomy of a black hole and the first image of a black hole ever taken. We cover how black holes are detected - including binary star system dynamics like Cygnus; galaxy center dynamics like our own Milky Way with Sagittarius a Star; by spotting disappearing stars; and with gravitational microlensing. We'll close with a look at the two oldest black holes discovered by the James Webb Space Telescope (CEERS 1019 and UHZ1) and their implications for the Big Bang timeline and two alternative black hole formation theories (Direct Collapse and Primordial).*}

01 - Introduction

We have seen how massive objects bend light. Einstein's general relativity theory shows that the more massive an object is and the smaller its radius, the greater the bending. If we were looking at light passing close to a white dwarf, we would see that the bending is 50 times greater that we get with our Sun. With a large enough mass and a small enough radius, like a Neutron Star, we actually get more than 360 degrees. In other words, the light will orbit the object several times before escaping and moving on to its final destination. So, it's not a stretch to see that if the mass is large enough and the radius is small enough, light passing by close enough could enter a long-lasting orbit or never get out. And with enough mass, light emitted by the object itself would also be stuck inside. Nothing including light itself can escape - hence the name Black Hole.



In this segment, we'll cover how Black Holes are categorized and how they form. We'll cover their structure and the various ways they grow. We'll cover examples from nearby black holes in our own galaxy to the most distant black hole ever discovered. . We'll cover the first image of a black hole ever recorded. And we'll end with coverage of a new theory for how the first black holes may have formed - a theory driven by the fact that the James Webb Space Telescope has found large galaxies that existed before current lambda cold dark matter cosmology predicted they would.

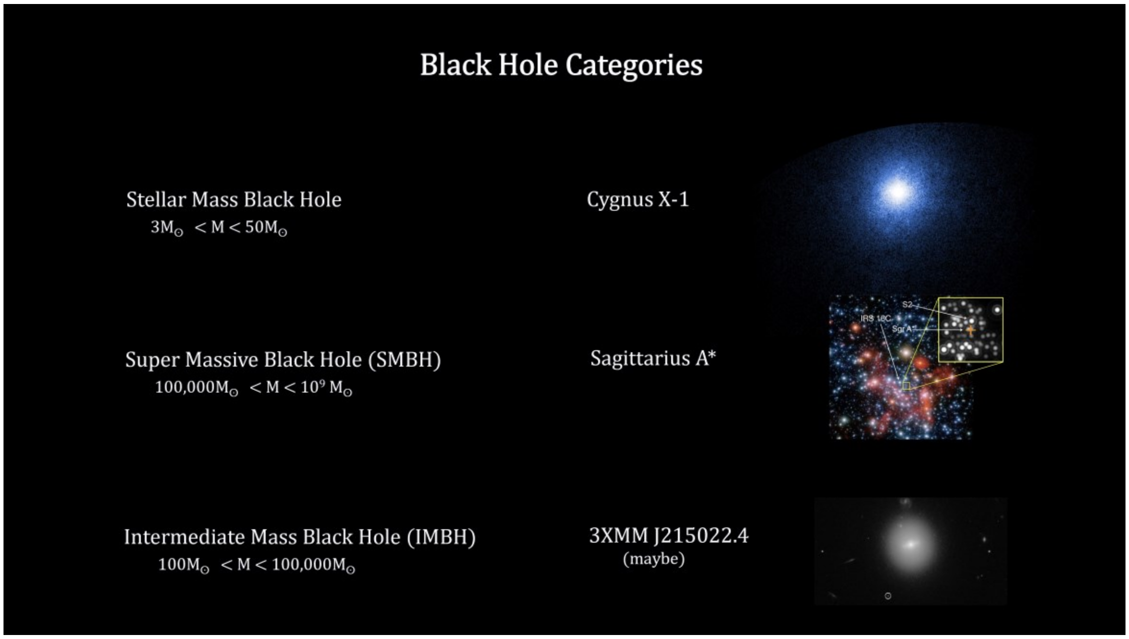


02 - Black Hole Categories

Black holes are categorized by their mass. There are currently three categories. The smallest are called 'stellar mass black holes.' They range from 3 to 50 times the mass of the Sun. They are formed by the explosion and collapse of a star. In 1971, the first black hole ever discovered was a stellar mass black hole (Cygnus X-1). It has 21 times the Sun's mass. We'll examine this system in detail later in the segment.

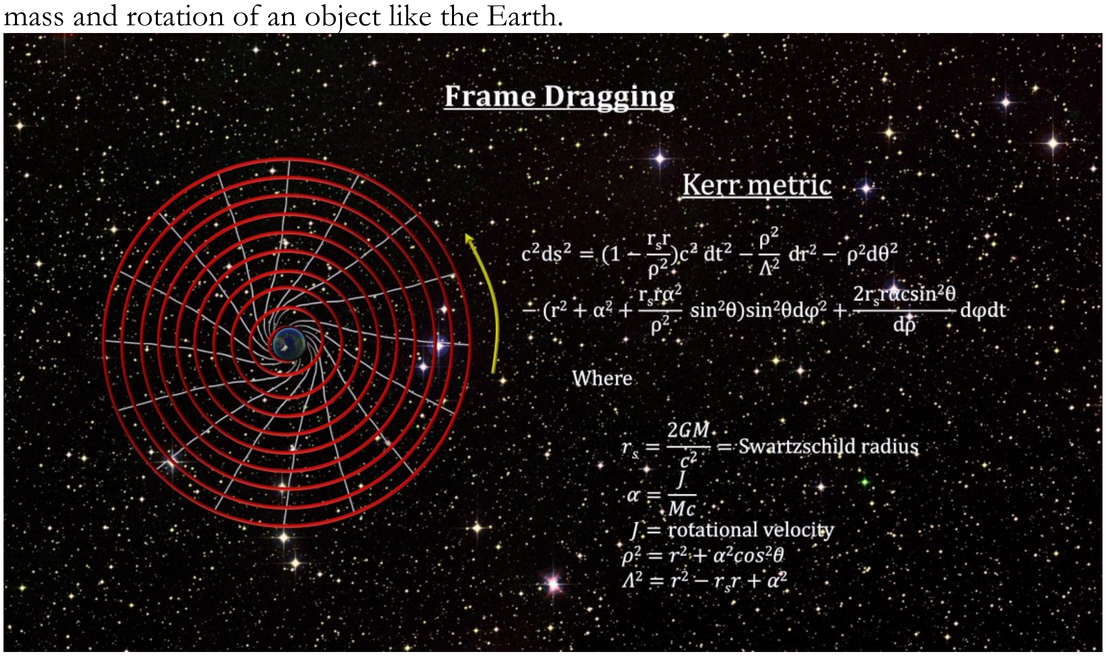
The largest are called 'super massive black holes' or SMBH for short. They have millions to billions of times the mass of the Sun. These are mostly found at the center of large galaxies. Sagittarius A* is the one at the center of our galaxy. It has 4.1 million times the mass of the Sun. Being the SMBH closest to us, it provides the most detailed information about these kinds of black holes. We'll be doing a deep dive into Sag A* later in the segment.

The third are called 'intermediate-mass black holes' or IMBH. They have from 100 to 100,000 times the mass of the Sun. They are thought to form by the merging of stellar mass black holes or the runaway collision of massive stars in dense stellar clusters that collapse into black holes. Several IMBH candidate objects have been discovered. But as of early 2024, none have been confirmed. The best candidate for one is named 3XMM J215022.4. It is indicated by the white circle.



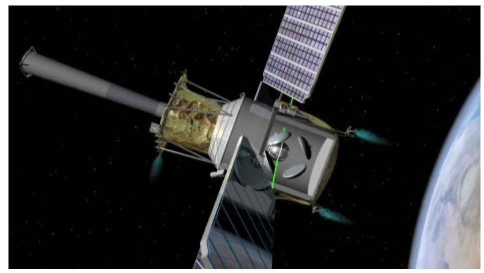
03 - Frame Dragging

In order to understand what is going on in and around a black hole, we need to cover the twisting effect of a rotating mass on the space surrounding them. The name given to the twisting is frame-dragging. The space is literally dragged along with the rotating mass. The effect was derived in 1918 by physicists Josef Lense and Hans Thirring, and is also known as the Lense–Thirring effect. They predicted that the rotation of a massive object would distort the space-time metric, making the orbit of a nearby test particle precises like a gyroscope. This does not happen with Newtonian gravity where the gravitational field of a body depends only on its mass, not on its rotation. It wasn't until 1963 that a mathematician named Roy Kerr discovered the significantly more complicated metric for rotating bodies that made it possible to calculate the precession one can expect from a given mass and rotation of an object like the Earth.

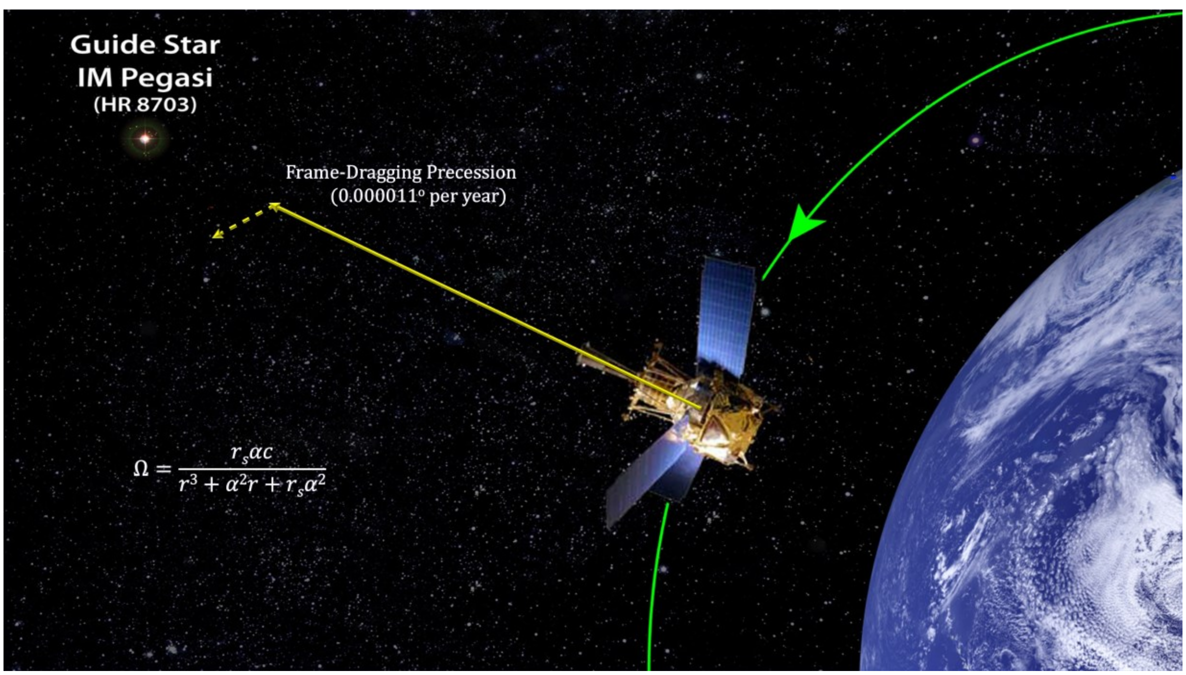


To test this effect, NASA developed a satellite called Gravity Probe B and put it into orbit 642 km above the Earth in 2004 where it operated for a year.

It used a set of super sensitive gyroscopes to measure precession due to frame-dragging. It also included a non-gravitational drag identification gyro and compensation micro thrusters to maintain a non-gravitational drag free environment. It compensated for solar radiation drag and atmospheric disturbances drag.

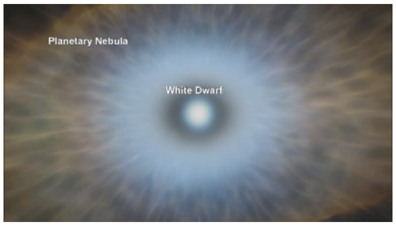


By 2011, data analysis had confirmed that frame-dragging did occur and measured it to within 15% of the amount predicted by the Kerr metric for Einstein's field equations.



04 - Black Hole Formation

With the Kerr metric in hand, we can take a closer look at the space-time around black holes. It helps to see how they can actually form, and it will provide information on how they might be detected.



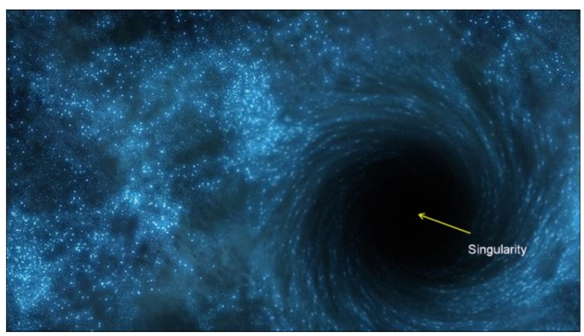
You'll recall that explosions at the end of life for stars less than 5 times the mass of the sun create planetary nebula and leave behind white dwarfs. In these stars, electron exclusion pressure is enough to counteract the inward force of gravity.

Supernova explosions at the end of life of stars more than 5 times the mass of the sun leave behind a neutron star. In these stars, electron pressure is insufficient to overcome the force of gravity, but neutron exclusion pressure is.

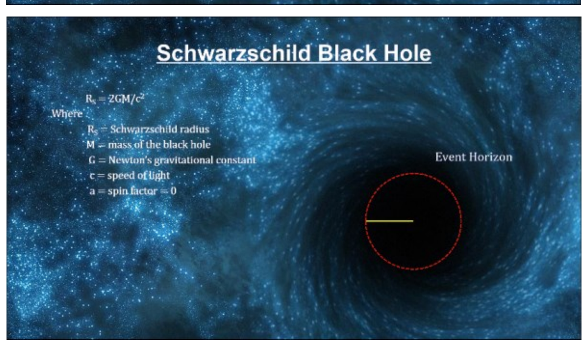
But if a star is greater than 30 times the mass of the sun, even neutron exclusion pressure won't do the trick. In fact, there is no known force that will counteract the inward force of gravity for such a supernova or hypernova exploding star.

[Note that it is also possible for stars to collapse into black holes without an explosion. We'll cover more on this later.]

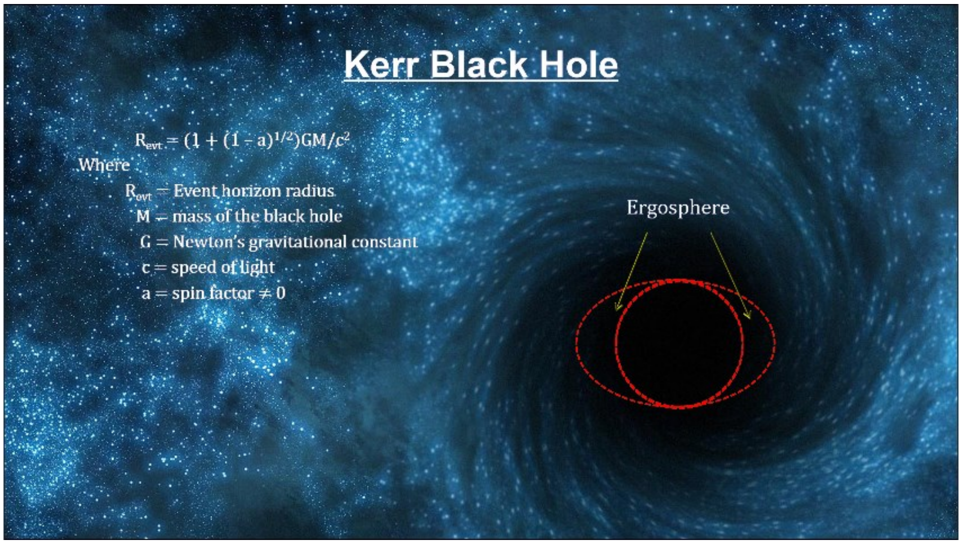
According to Albert Einstein's general theory of relativity, the star will collapse into zero volume and infinite density – called a singularity. This defines a black hole. It gets its name from the fact that such a singularity would create a gravitational pull that not even light could escape. The object literally becomes invisible.



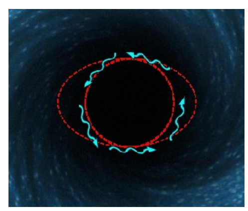
In 1916, Karl Schwarzschild, a contemporary of Einstein, solved his equation for the special case of a non-rotating sphere. He found that although the diameter of the singularity is zero, the radius at which light would be captured depends entirely on the mass of the black hole. This is called the Schwarzschild radius and it defines the Event Horizon.



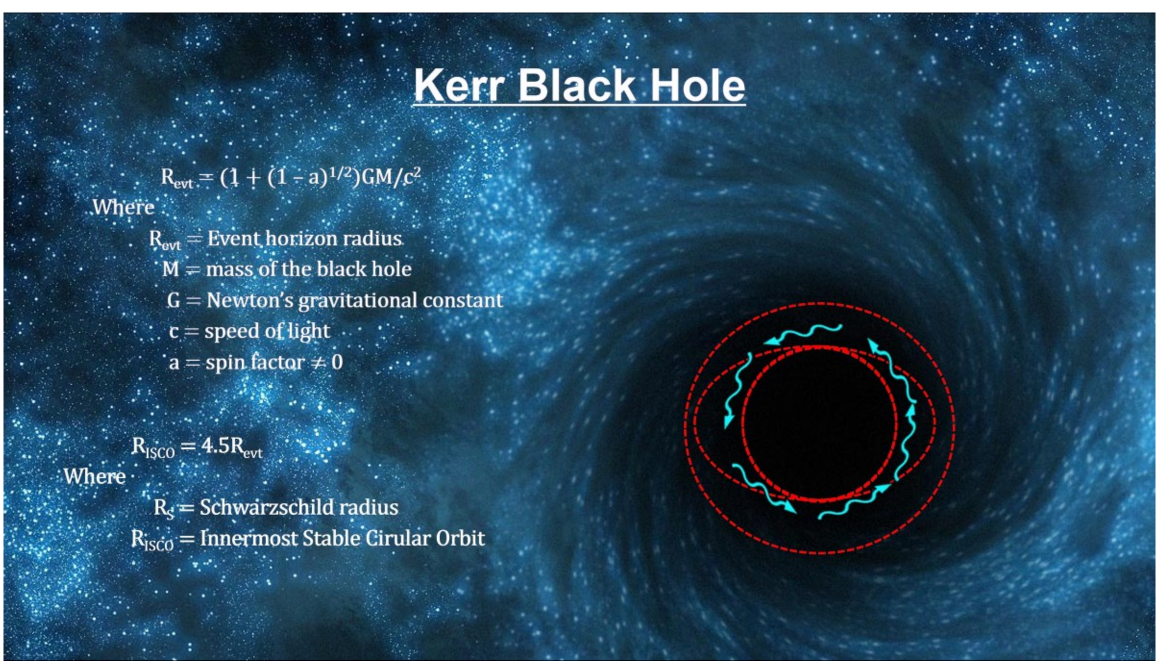
But it would be the rare black hole that doesn't spin. In 1963, Roy Kerr developed the general solution for spinning black holes. It showed that there is a second region beyond the event horizon that defines a volume around the black hole called the Ergosphere.



In this region, space itself is dragged around by a black hole's spin. Also, in this region, light can enter stable orbits around the black hole. This would produce a photon sphere shell incasing the black hole with light from all the stars in the universe accumulated over the entire age of the black hole. It would be a sight to see.



Another important boundary is the innermost stable circular orbit (ISCO for short). It's the smallest orbit where a particle can stably orbit the black hole. Its radius depends on the black hole's mass and spin.

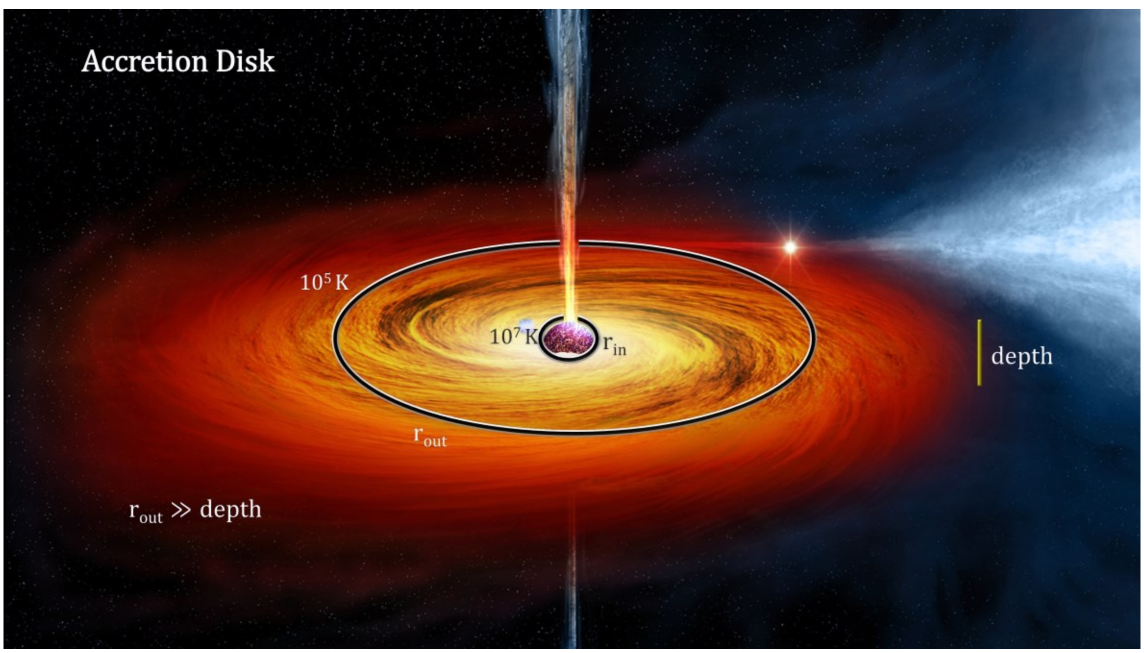


05 - Accretion Disk Dynamics

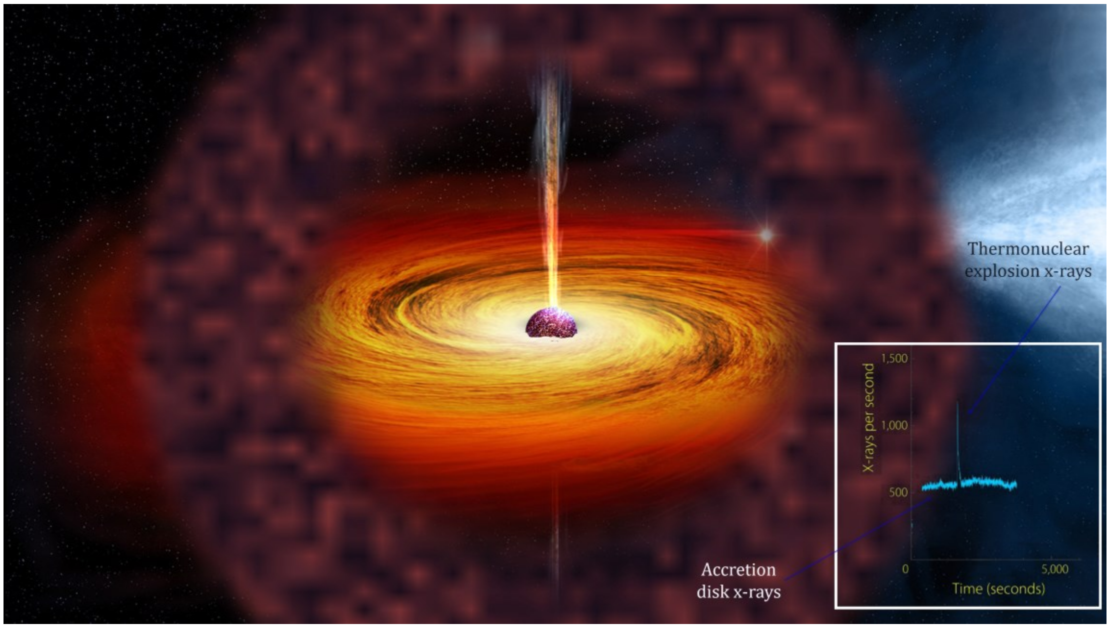
One of the ways for a black hole to form is to accumulate enough mass via an accretion disk to collapse. Here's an illustration with a neutron star surrounded by an accretion disk supplied by gas from the stellar winds of a nearby blue giant star. Driven by inward gravitational forces and outward centripetal forces, infalling matter into massive objects like stars, neutrons stars, and black holes always form accretion disks. There are a wide variety of these complex structures, but they all have two basic characteristics: They are thin in that the disk's radius is much much larger than its depth; and they are thick enough to ensure that photons created inside the disk will interact with matter inside the disk at least once before escaping.

The movement of the matter in the disk is controlled by the central object's gravity. It is said to be 'Keplerian' because it follows Kepler's laws. Here we have marked the outer most orbit and the inner most orbit. Gas in the outer ring has the velocity to remain in orbit. In order to spiral inward, something has to slow it down. In an accretion disk, that would be friction with adjacent matter. Note that a disk of 'dark matter' could never be a part of star or black hole formation, because it does not interact with anything, and therefore there is no friction to slow it down.

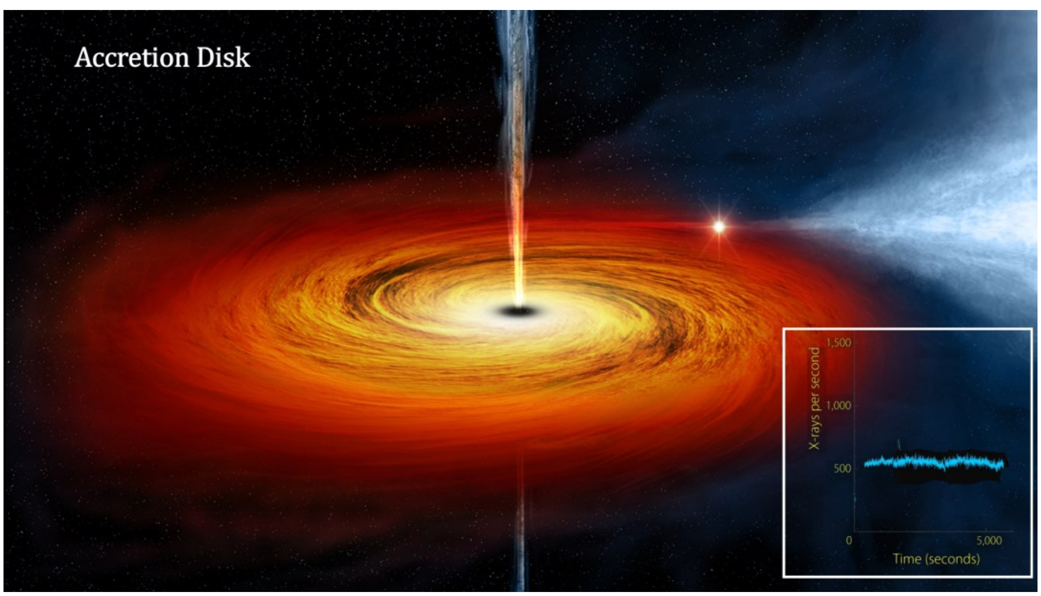
In addition to slowing the gas down, this friction causes the gas to heat up. The more massive the central object, the hotter the inflowing matter becomes. For neutron stars and black holes, the temperatures reach millions of degrees Kelvin. At these temperatures, the gas emits detectable amounts of x-rays in all directions.



When the gas reaches the innermost circular orbit, it crashes onto the surface of the neutron star. Over time, the material builds up on the surface and ignites in a thermonuclear explosion. Such an event produces a bright flash of x-ray emissions called a Type-I x-ray burst. Such bursts from low mass neutron binary star systems are very common. Thousands have been observed to date from over a hundred accreting neutron stars.



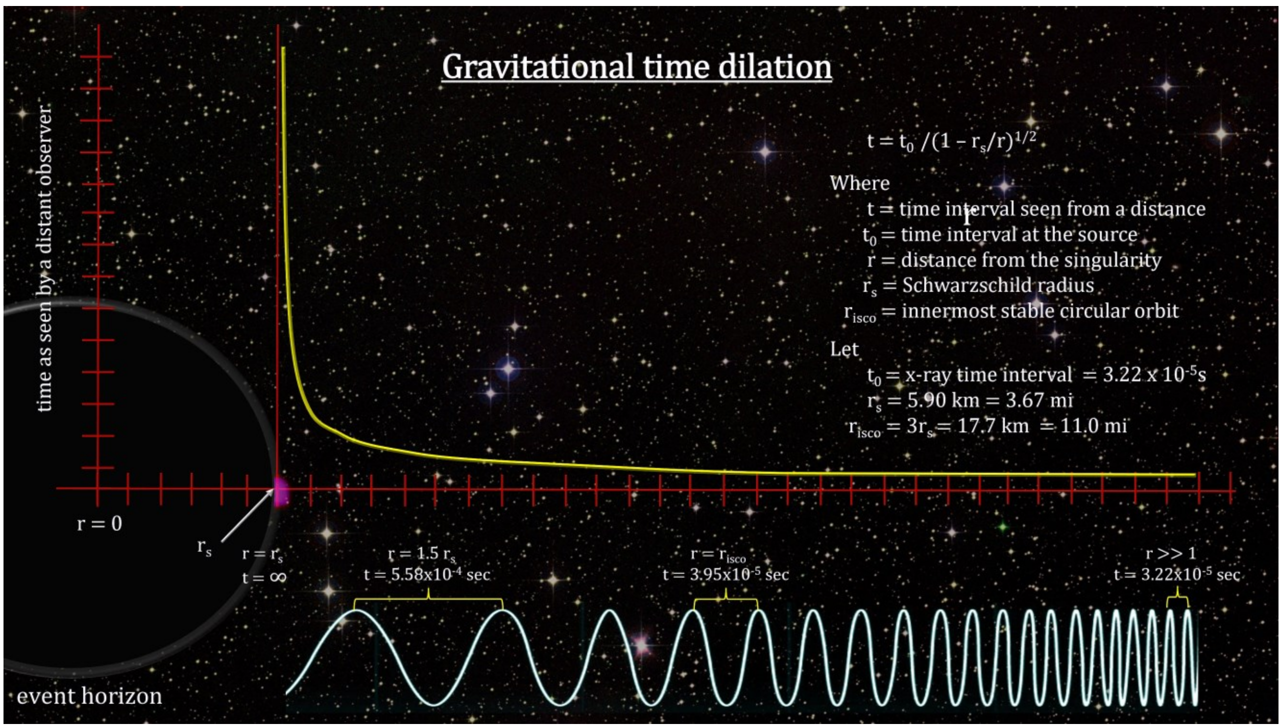
But, once the mass of the neutron star grows to the point that the gravitational inward pressure exceeds the neutron outward pressure, the star collapses. In a matter of seconds, all its mass recedes beyond the event horizon and it disappears.



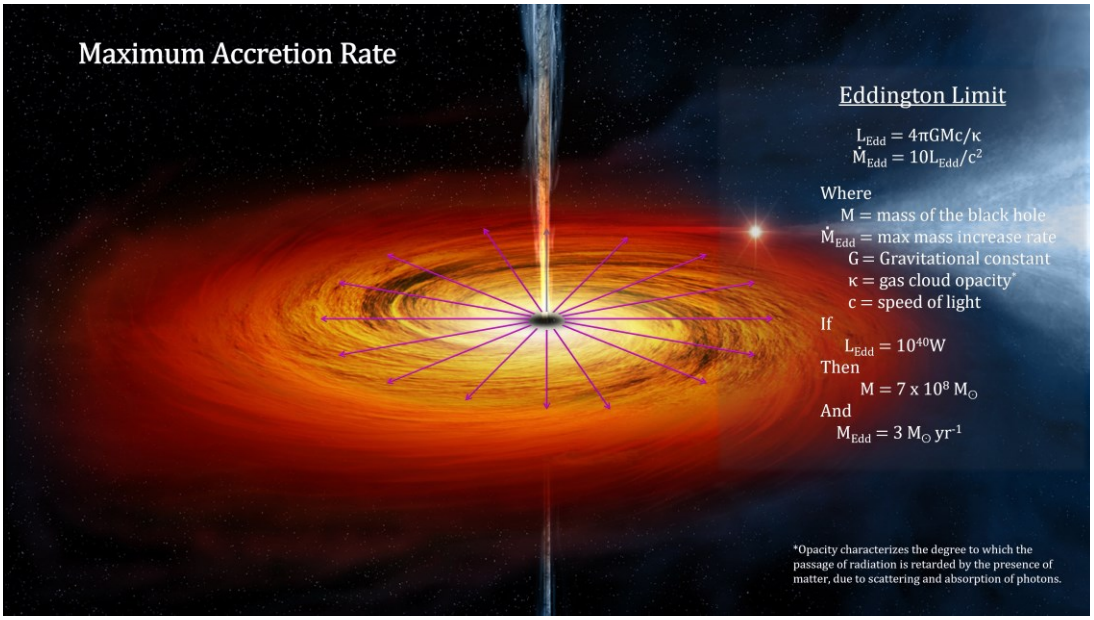
As a gas cloud moves from the innermost stable circular orbit to the event horizon, time dilation reduces the frequency of the x-rays emitted by the hot gas as viewed by a distant observer. In this example, the observer sees that the time between peaks at the start are exactly correct for x-rays. The closer the gas gets to the event horizon, the longer the peak-to-peak interval. But even at the innermost stable circular orbit, the increase is small.

But, as the gas approaches the event horizon, the interval quickly reaches hours, days, years. At the horizon itself, the time between an observed peak and the next one takes longer than the age of the universe. Any light emitted by the infalling matter becomes infinitely redshifted as the object passes over the horizon. The gas fades away, but you never see it enter the black hole.

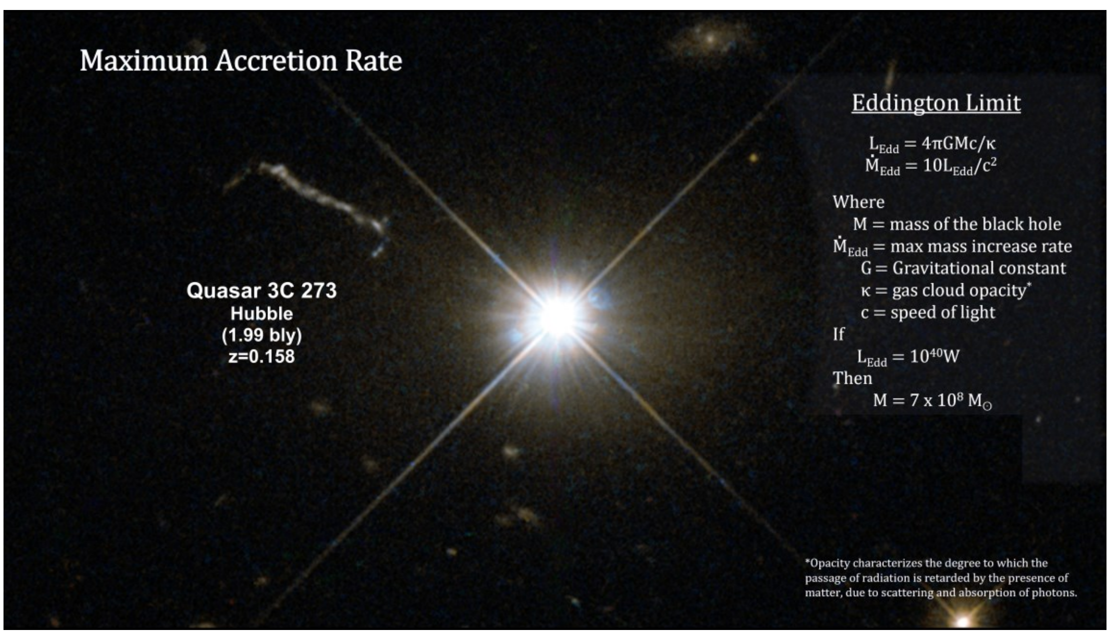
So, for a neutron star, there's a surface for the inflowing matter to crash into, accumulate and explode. But once it collapses into a black hole, the gas just disappears and the thermonuclear explosions cease. We can conclude that an x-ray binary system without thermonuclear x-ray bursts, contains a black hole.



Arthur Eddington, the astronomer who first captured the bending of light by the sun that supported Einstein's special relativity theory, proposed that: for any object in the depths of space, there is a maximum luminosity beyond which radiation pressure will overcome gravity, and material outside the object will be forced away from it rather than falling inwards. This maximum is now called the Eddington luminosity, and it puts a limit on how fast matter can flow into a black hole now called the Eddington Limit.

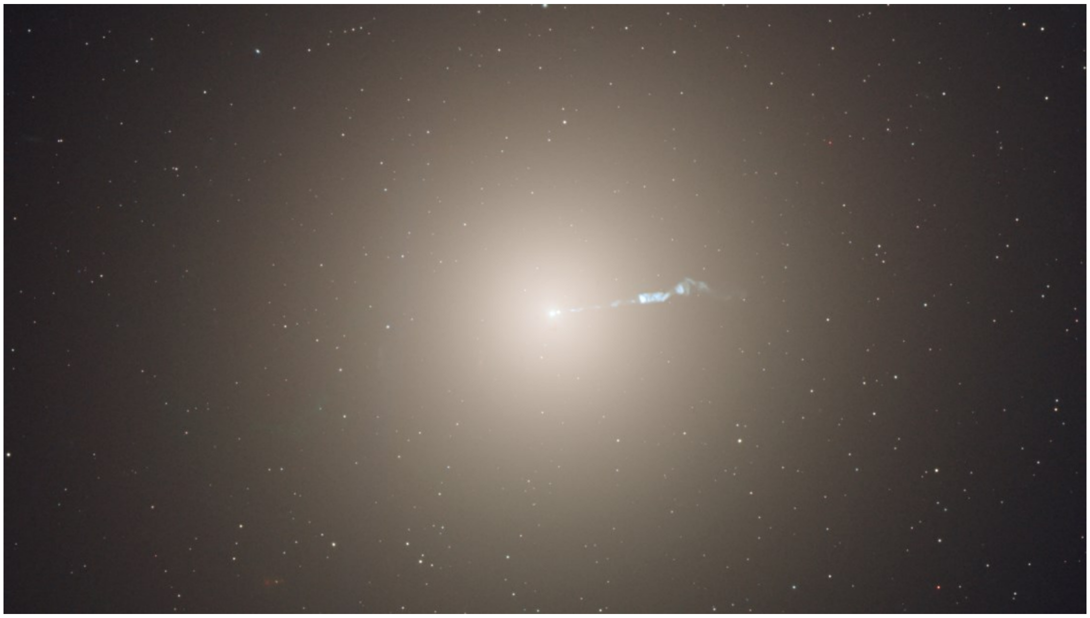


This is very useful for analyzing quasars. A quasar is an extremely active galactic nuclei thought to be created when vast amounts of matter are continually flowing into a supermassive black hole. With Eddington, a quasar's luminosity gives us the mass of the central black hole. And with the mass and luminosity, we can calculate the maximum rate for increasing the black hole's mass. For example, a black hole with a measured luminosity of 10 to the 40th watts has the mass of 7 hundred million suns. With this mass, its maximum rate of increase is approximately 3 solar masses per year. It will take 233 million years to double its mass.

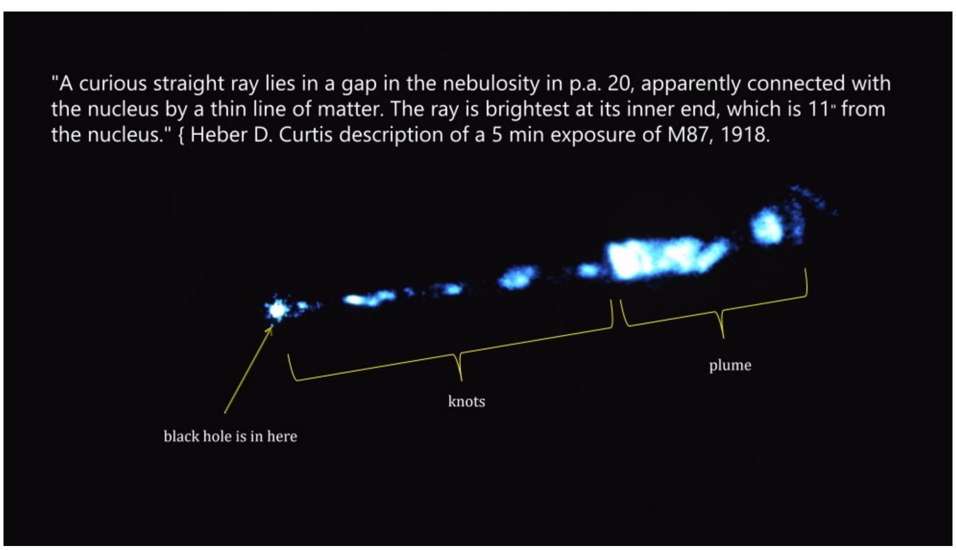


06 - Accretion Disk Jets

Accretion disks also create jets of material flowing out from the center to the disk in opposite directions perpendicular to the disk. This matter is orbiting a magnetic field that stretches out from the central mass to very great distances. We'll use M87's jet to illustrate how it works. The jet of material streaming out from the center indicates that the galaxy has an Active Galactic Nucleus (AGN for short). That is, it has a supermassive black hole at its center that is accumulating large amounts of matter from an accretion disk.

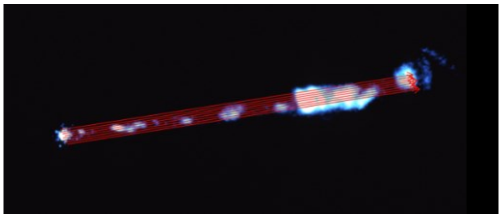


We've known about the jet of plasma shooting from the core of M87 since 1918, when astronomer Heber Curtis saw a ray of light connected to the galaxy center - five thousand light-years long and 2 light-years wide. Several things stand out about this jet: It's blue, it's very bright, it consists of chunks or knots, and it terminates in a plume. You may have also noted that there is no counter jet going out the other way.

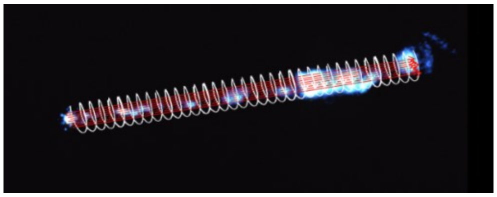


The jet is understood to have been formed in a strong magnetic field created by the interactions between the spinning black hole and the rotating accretion disk.

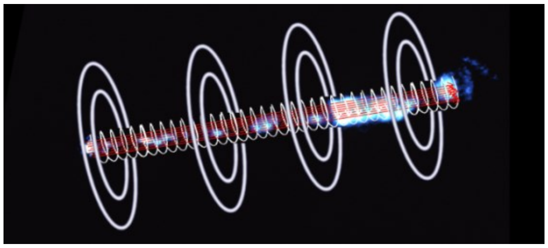
Then, at the point where matter from the accretion disk is crossing the event horizon into the black hole, a small percentage of the charged particles are swept into this magnetic field and ejected into the jet at the black hole's escape velocity, which is near the speed of light for objects as massive as a black hole.



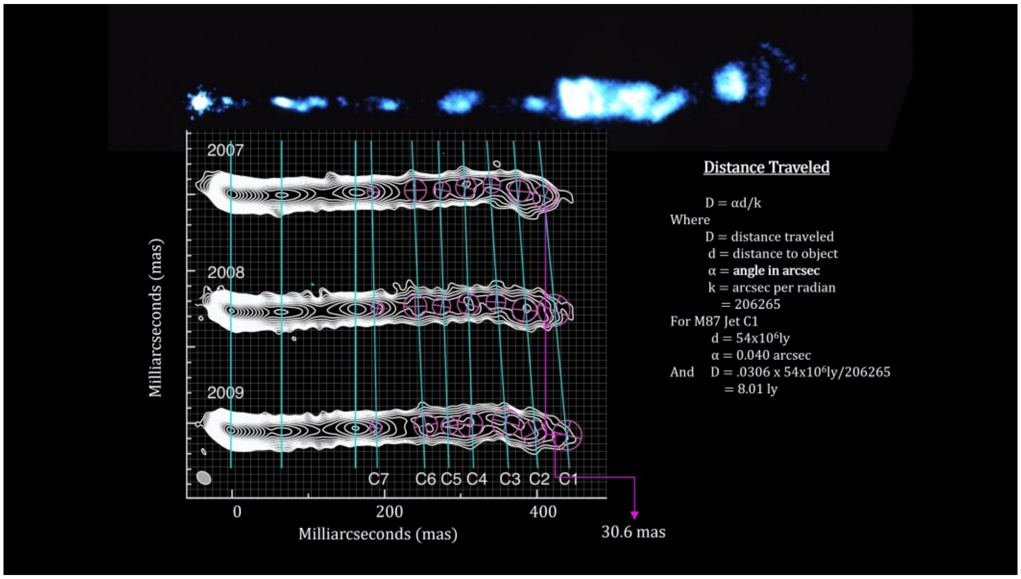
These escaping particles are forced into circular orbits around the strong magnetic field. The European Space Agency's Integral Gamma-ray Observatory has observed extremely hot matter just a few milliseconds before it would cross into a black hole. This study lends support for the theory. But just how this is accomplished is not yet understood.



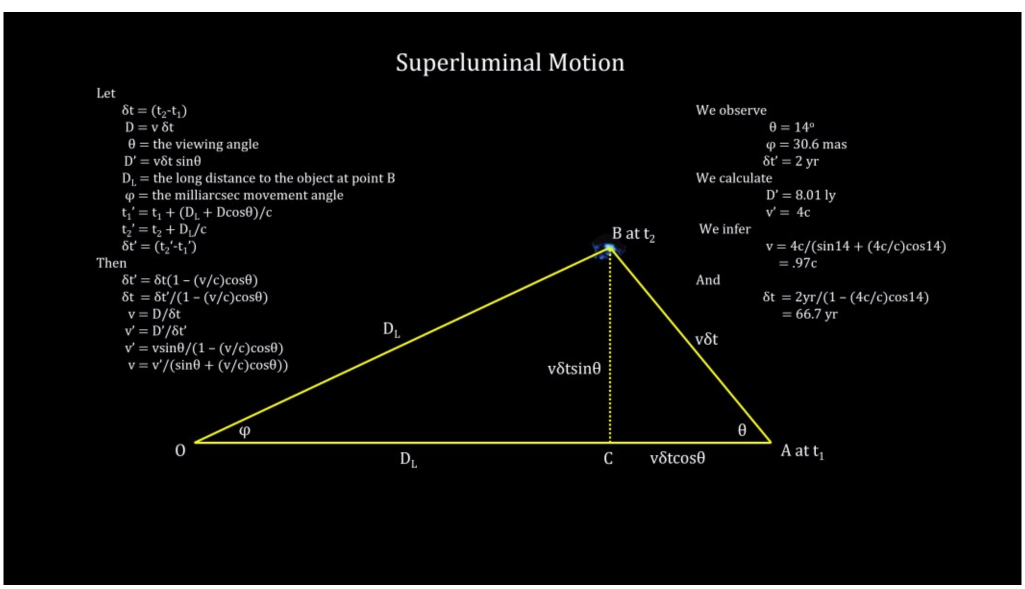
Thees circularly accelerating ions create electromagnetic radiation across a wide spectrum including radio, visible and x-ray light. This is what we are seeing with our radio, optical and x-ray telescopes. It's called synchrotron radiation and it's well understood because it's the same as the radiation from synchrotron particle accelerators we build here on Earth.



The two key jet features we observe directly are its apparent luminosity and its apparent motion across the sky. A study done by a team of astronomers using the European Very Long Baseline Interferometer Radio Telescope Network analyzed the motion of one of the knots near the jet's origin at the black hole. They found that one of the components moved 30 milliarcseconds over two years. That's a very tiny amount. But when we multiply it by the large distance to M87 we find that the distance traveled was 8 light years. To travel 8 light years in just 2 years means its velocity is 4 times the speed of light. We call apparent velocities greater than the speed of light 'Superluminal Motion.'

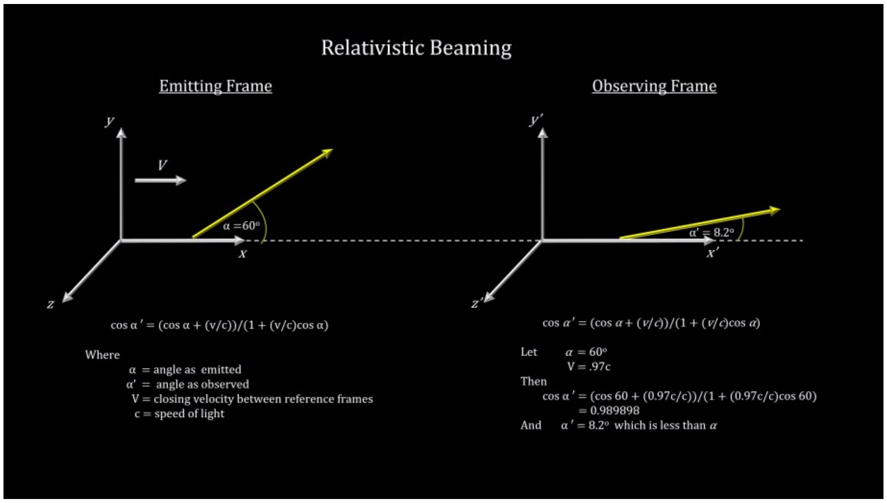


Here's how it works. Suppose we have an object at location A at time t_1 that moves to location B at time t_2 – the travel time being delta t. D is the distance traveled. It will equal the object's velocity times its travel time. We're observing this movement from a great distance at an angle θ from the object's line of motion. We see only the proper or transverse motion across the sky, designated here as D prime. Our start time is the object's start time plus the time it takes the light to get from points A to O. Our end time is the object's end time plus the time it takes the light to get from points B to O. With that, we can calculate the observers view of the object's velocity in terms of the object's view, and vis-versa. If we plug in the numbers, we found for knot C of the M87 Jet, we find that the apparent velocity of 4 times the speed of light turns out to be .97c in the object's frame of reference, and the apparent elapsed time of 2 years movement turns out to have taken the object almost 67 years. It was not traveling faster than the speed of light. (Note that this only happens when the velocity of the object is near the speed of light and in addition, the viewing angle is small.)

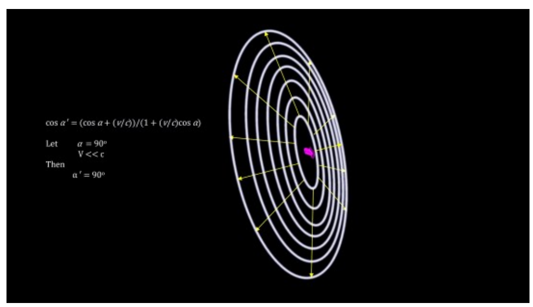


Relativistic Beaming

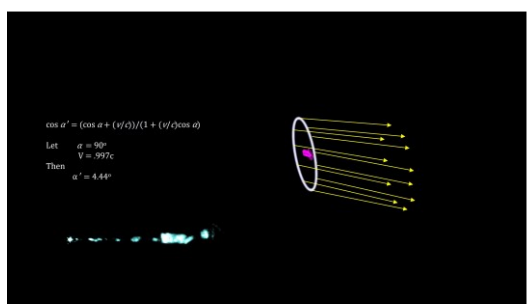
Another relativistic effect at play here is called Relativistic Beaming. To illustrate, consider an inertial reference frame moving to the right at relativistic speeds with respect to an aligned reference frame on the right. A particle emits a photon at an angle ∝ from the line of motion. The angle measured in the frame on the right can be computed using the Lorentz transformation. Using M87 C1's .97c as the velocity and 60 degrees as a sample angle, we see that the observed angle ∝' is considerably smaller at only 8.2 degrees.



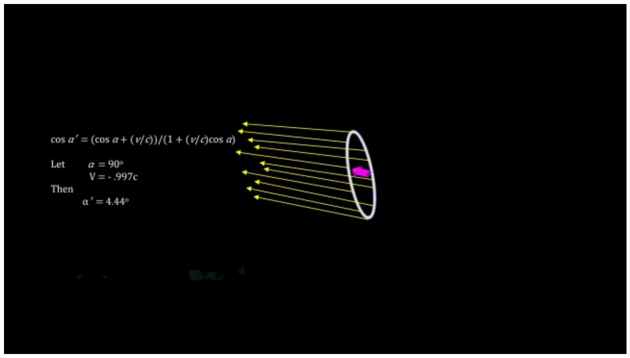
A synchrotron radiating electron moving at speeds far smaller than the speed of light will emit radiation in all directions. Distant observers would see just the portion of the light radiated in their direction. As the speed of the electron increases, these light rays shift in the direction the emitting object is moving.



As the velocity of the emitting particle approaches the speed of light, the observed angle approaches zero. The light is beamed ahead of the emitter in the direction of the emitter's movement. This is the case, no matter what the emitted angle is in its own frame of reference.

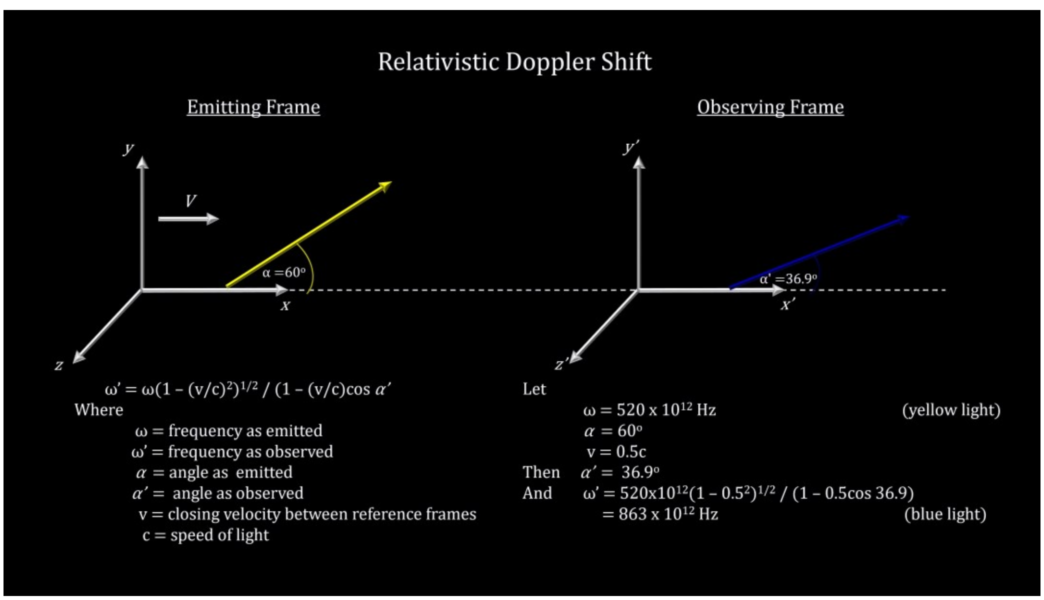


For trillions of continually emitting particles, like the electrons in the M87 Jet, this beaming effect increases the photon density in the direction of movement causing the jet's luminosity to increase. This explains why the jet looks so bright. And, because jets moving in the opposite direction will have their photons beamed away from the observer, the jet becomes invisible. This explains why we see only one jet in M87.



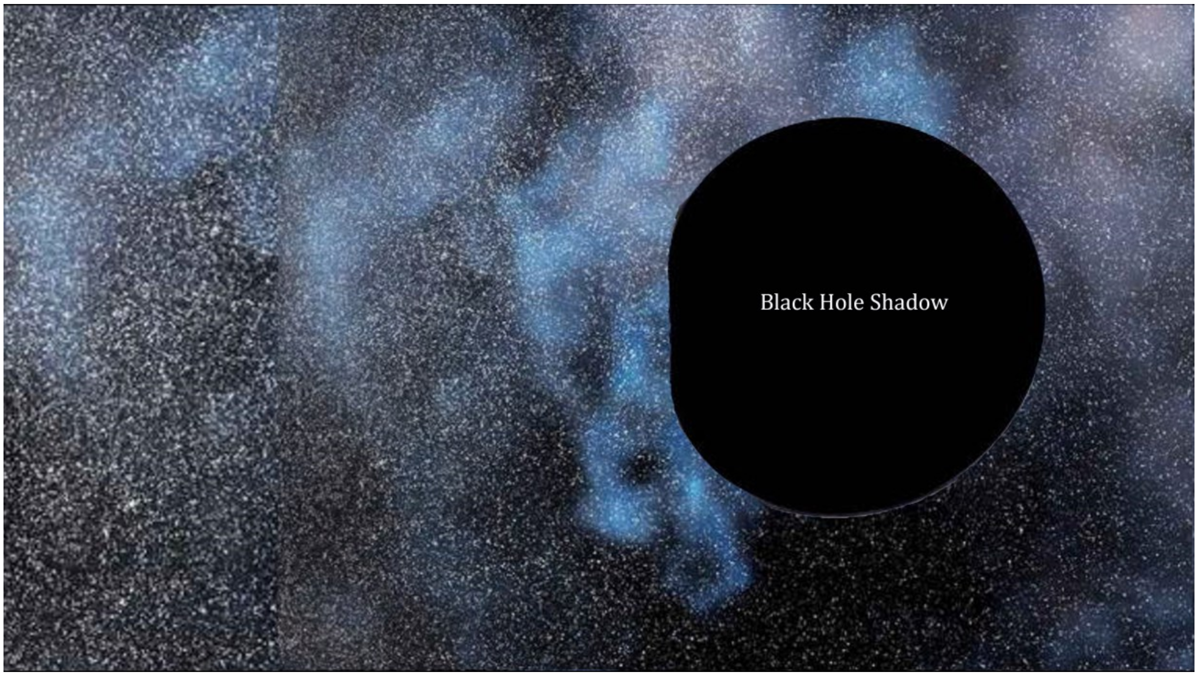
Relativistic Doppler Shift

Our last relevant effect is called relativistic doppler shift. Due to space contraction, when we apply the Lorentz transformation against the frequency of a photon emitted in the same fashion as we just covered, we find that the frequency observed is greater than the frequency transmitted. This explains why the M87 jet is so blue.



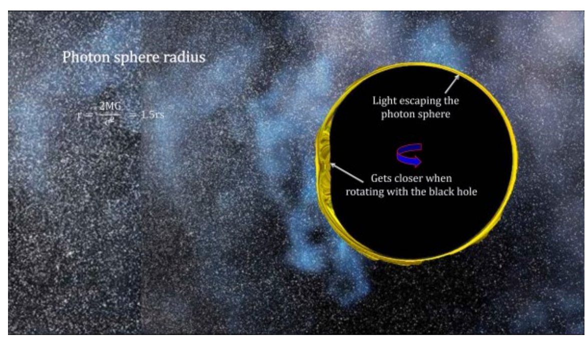
07 - Anatomy of a Black Hole

With what we've covered so far, we can build a back hole. This one is spinning rapidly with a minimally accruing accretion disk. That makes it a Kerr black hole without jets. It's modeled after the black hole 'Gargantua' in the movie "Interstellar." We start with the Black hole's shadow.

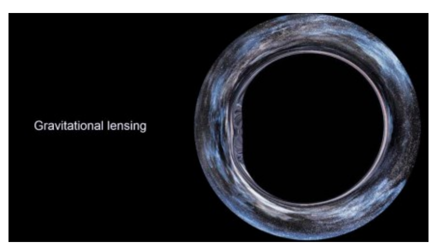


The Kerr metric shows that light can be captured in stable orbits outside the event horizon. For a rapidly rotating black hole, the orbital volume around the black hole would be significant. This would produce a photon sphere shell incasing the black hole.

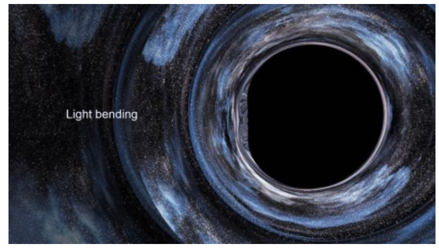
This thin ring represents the cross section of this shell we'd see because of light that leaks out in our direction. It is flattened on the left because light rotating with the Black Hole's rotation can get closer to the horizon than light rotating against the black holes' rotation.



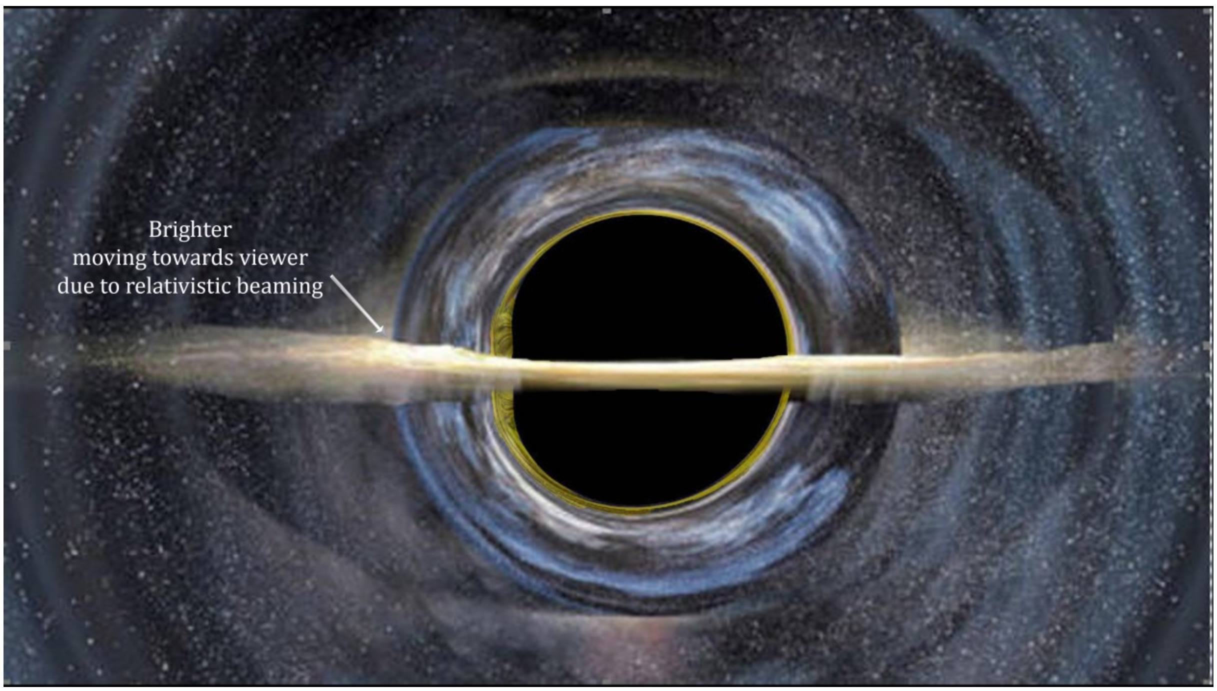
Next, we see a dense sprinkling of stars with a pattern of concentric shells. This is the pattern produced by the gravitational lensing.



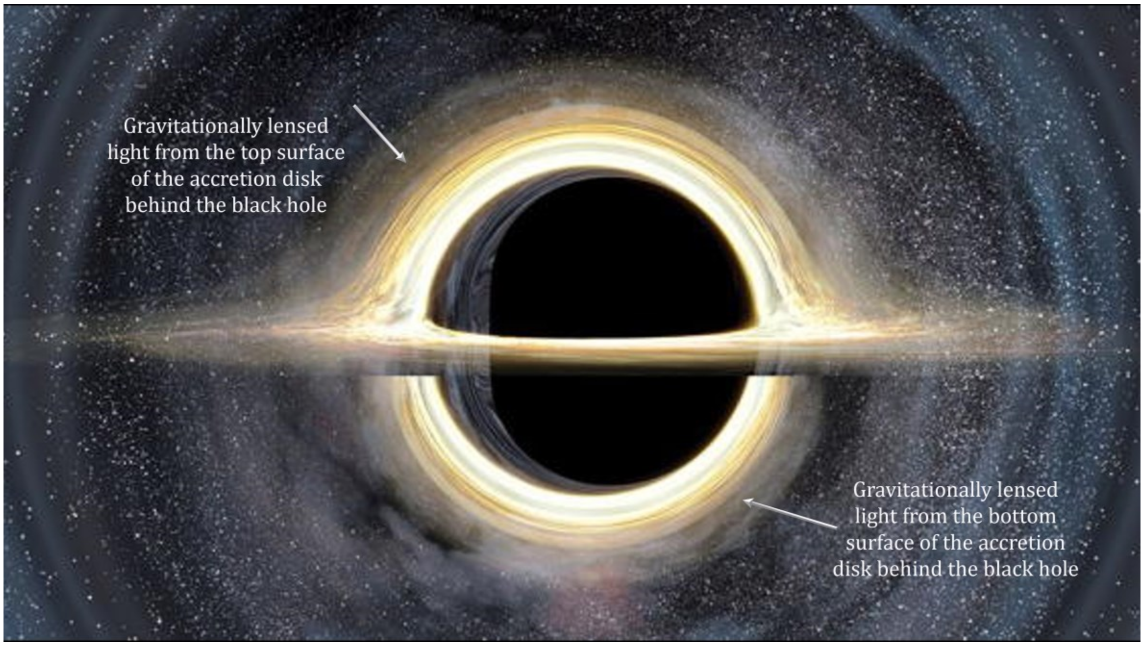
Further out we see the dislocation of star positions due to the bending of light by the gravity of the black hole.



This black hole has the remnants of an accretion disk that is no longer feeding the black hole. If the disk were not gravitational lensed, the black hole would have looked like this. (Note that it is brighter on the left where the matter is moving towards the viewer and dimmer on the right where the matter is moving away from the viewer. This is due to relativistic beaming.)



But, because of gravitational lensing, the massive amount of light rays emitted from the disk's top face travel up and over the black hole, and light rays emitted from the disk's bottom face travel down and under the black hole. This combination gives us the full image of how the black hole would actually look.

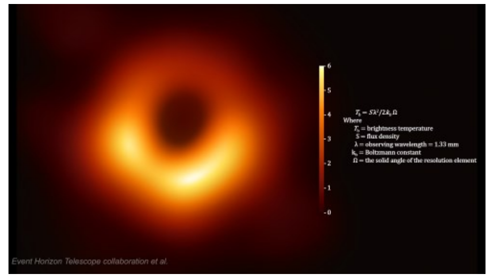


08 - First Ever Black Hole Image

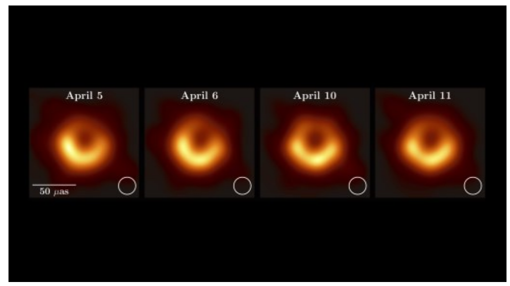
In 2019, the Event Horizon Telescope (EHT for short) team released an image of the supermassive black hole at the center of M87 that created and powers the M87 Jets. It illustrates many of the features of a black hole discussed in the previous segments.

This image represents the first direct visual evidence for a black hole. Basically, we're looking at an emission ring around a dark shadow. This is consistent with the idea that the ring is gravitationally lensed light produced by a hot, turbulent magnetized accretion disk orbiting close to the event horizon of a Kerr black hole and the darker center is the black hole's shadow.

The light recorded was radio light (1.33 mm) which we cannot see with optical telescopes. To create this image, the EHT team chose to display the measured radio light intensity in units of brightness temperature with orange signifying low intensity radio light, yellow signifying more intense radio light and black signifying very little or no radio light.

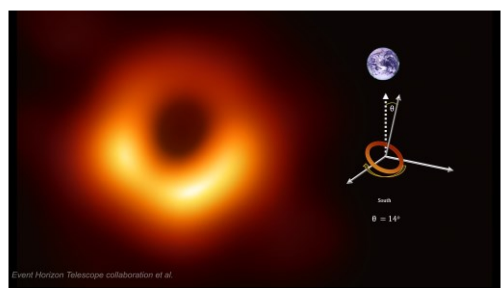


Four images were created from four different days in April 2017. They show movement with stability in the basic image structure. The movement indicates a clockwise rotation of the disk. But there is insufficient information to determine the disk's velocity.

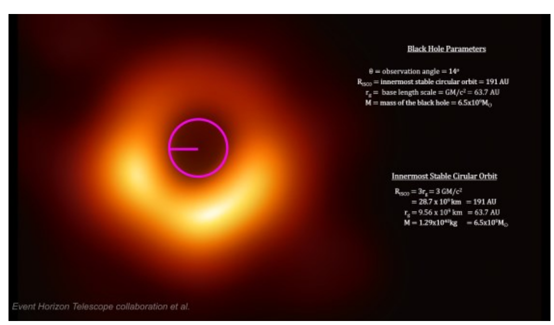


Note that the emission ring is brighter on the south side. From our M87 Jet analysis we found that we are viewing from around a 14o angle to the west.

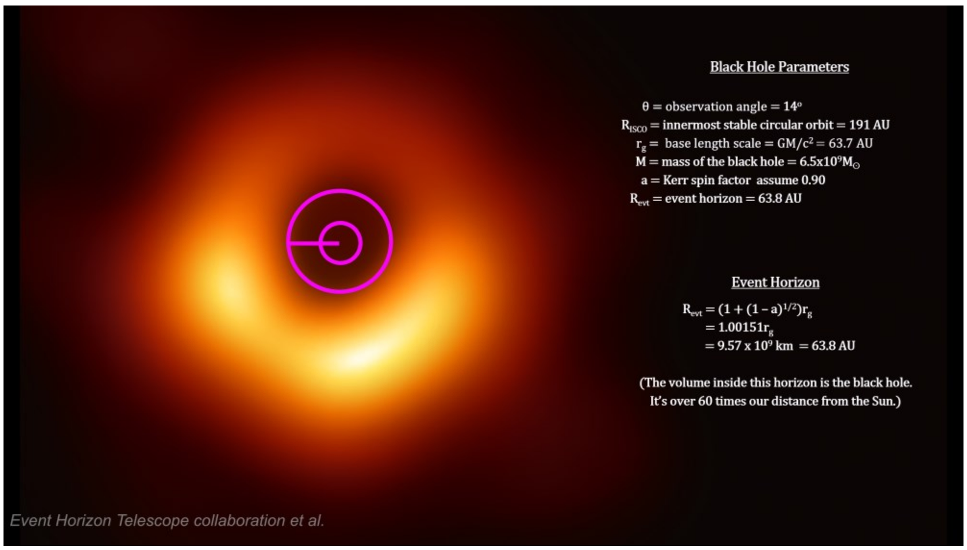
This orients the ring in such a way that matter rotating in the southern half of the ring is moving closer to us and matter rotating in the northern half of the ring is moving further away from us. It is thought that the southern portion is brighter due to the Relativistic Beaming effect we covered earlier. This would in turn imply that the disk's plasma is rotating at speeds that are a significant percentage of the speed of light.

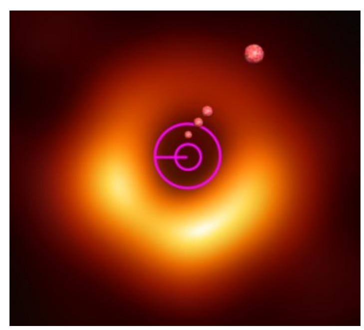


Here's the measured distance from the center of the black hole to the inner rim of the emission ring. This is the innermost stable circular orbit radius. It's also the photon sphere where photons can get trapped into an orbit around the black hole. With this radius, we can calculate the black hole's mass. Sag A* has the mass of 4 million suns. M87's black hole is 1600 time that mass with 6.5 billion suns. (This is in close agreement with star rotation studies that put the mass at 6.2 billion suns.)

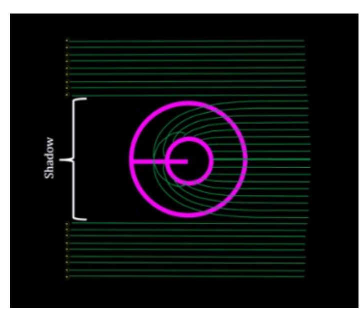


Modeling the disk as a rotating charged plasma in a strong and twisted magnetic field under general relativistic conditions, astrophysicists have determined that the spin of the black hole is aligned with this rotation. But again, there is not enough information to determine its spin. [I have seen estimates that range from 0.26 to .9 based on magnetic field twisting measurements, M87 Jet diameter shifts and on model-based behavior.] For our illustrative purposes we'll assume it's 0.9. With that we calculate the Event Horizon. It's over 63 times further away from its center than we are from the sun. The volume within this sphere is the black hole, and it is bigger than our entire solar system.



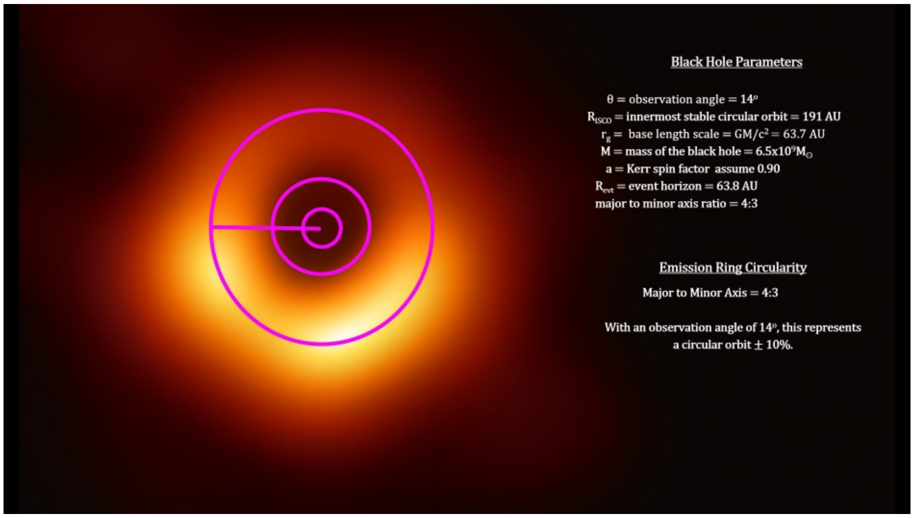


Unless it acquires additional energy, matter that crosses this innermost stable circular orbit threshold, will enter into a decaying orbit into the event horizon. But we know that the powerful magnetic field near the horizon is capable of accelerating charged particles to near the speed of light and ejecting them at escape velocity in jets perpendicular to the rotating accretion disk.

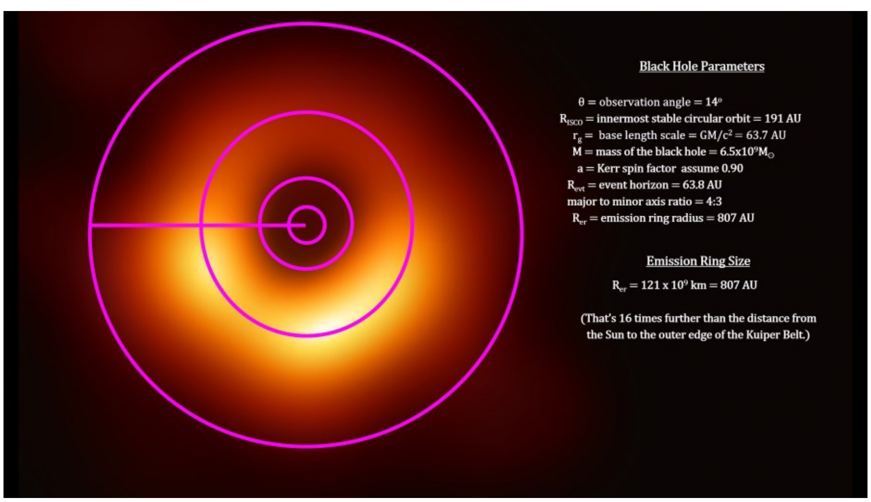


In addition, most photon trajectories into this region will also result in their eventually entering the black hole. This marks the extent of the black hole's shadow. Black hole shadows were expected to be significantly larger than the black hole itself. This one is triple the size of our entire solar system.

Here we have traced the peak of the emission in the ring in order to determine the shape of the image and obtain the ratio between major and minor axis of the ring. It's 4 to 3. With our 14^{o} tilt, this corresponds to a true circle give or take 10%. This is what the general relativity theory predicts for co-rotating black holes.

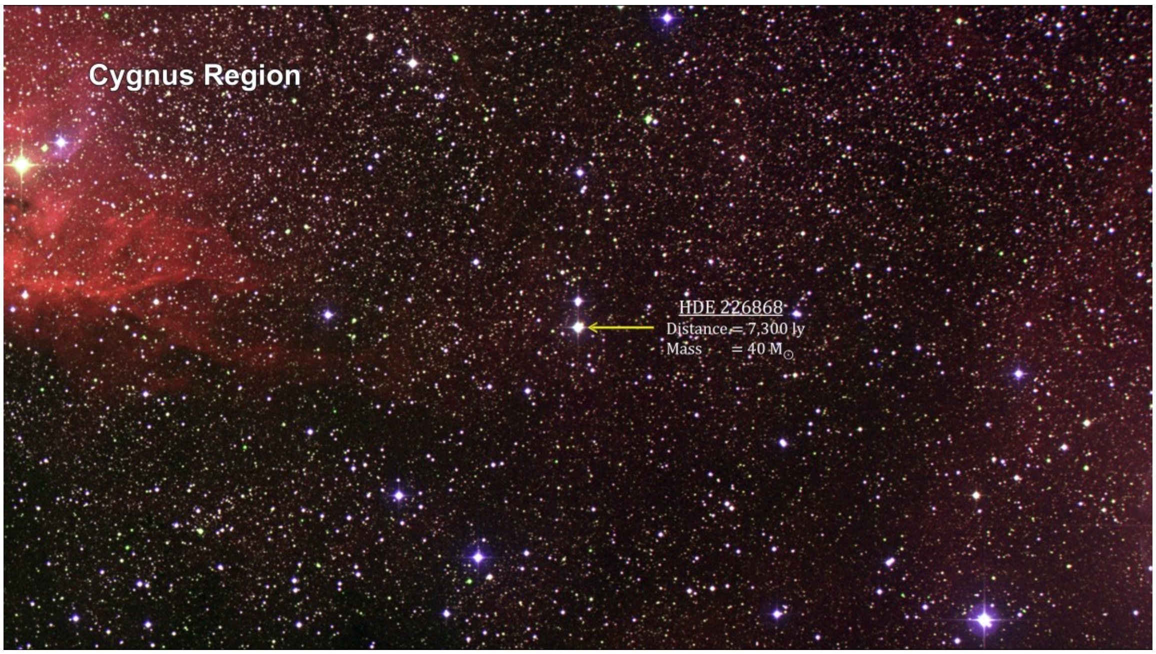


And here we have the full size of the black hole and its emission ring. It's ten times further out than Voyager 1 has travelled since its launch in 1977. This may seem like a very large object. But due to the fact that it is 54.8 million light years away, it only spans 43 micro arcseconds across the sky. The smallest that optical telescopes can resolve, including the interferometer telescope used to study Sag A* is on the order of hundreds of micro arcseconds. To detect this object, we needed a much larger telescope.

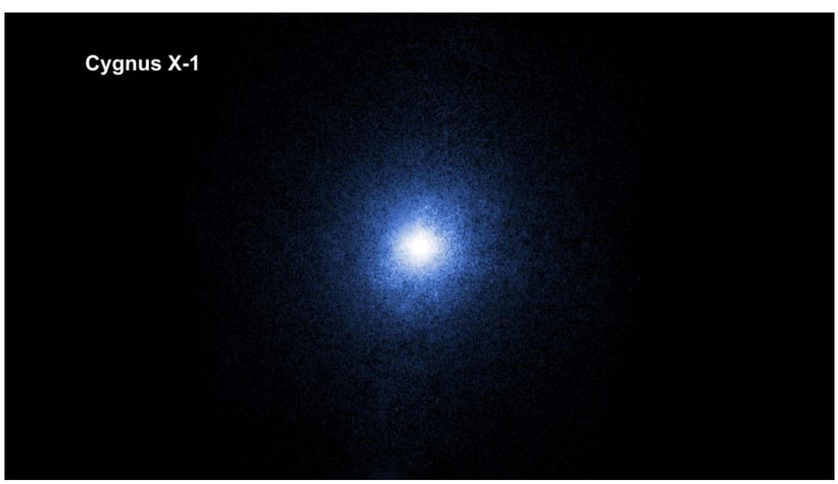


09 - Finding Black Hole Cygnus X-1 - 7,300 ly

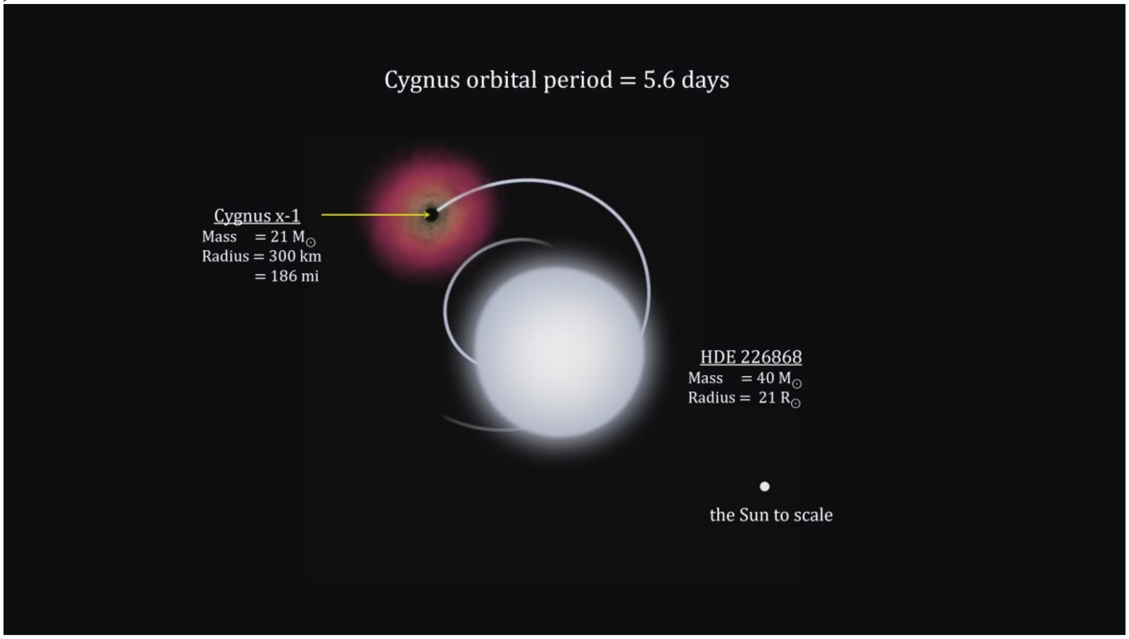
Given that nothing from inside a black hole can reach us, we need to look at the impact a black hole has on its surroundings to find one. We'll use real examples to illustrate how black holes are detected. A binary star system where one of the stars is not visible is a good place to look for black holes. The first one ever detected was found in the Cygnus region. Here's a Hubble image of the region. The star visible at the center is called HDE 226868. It's a blue supergiant star 7300 ly from Earth.



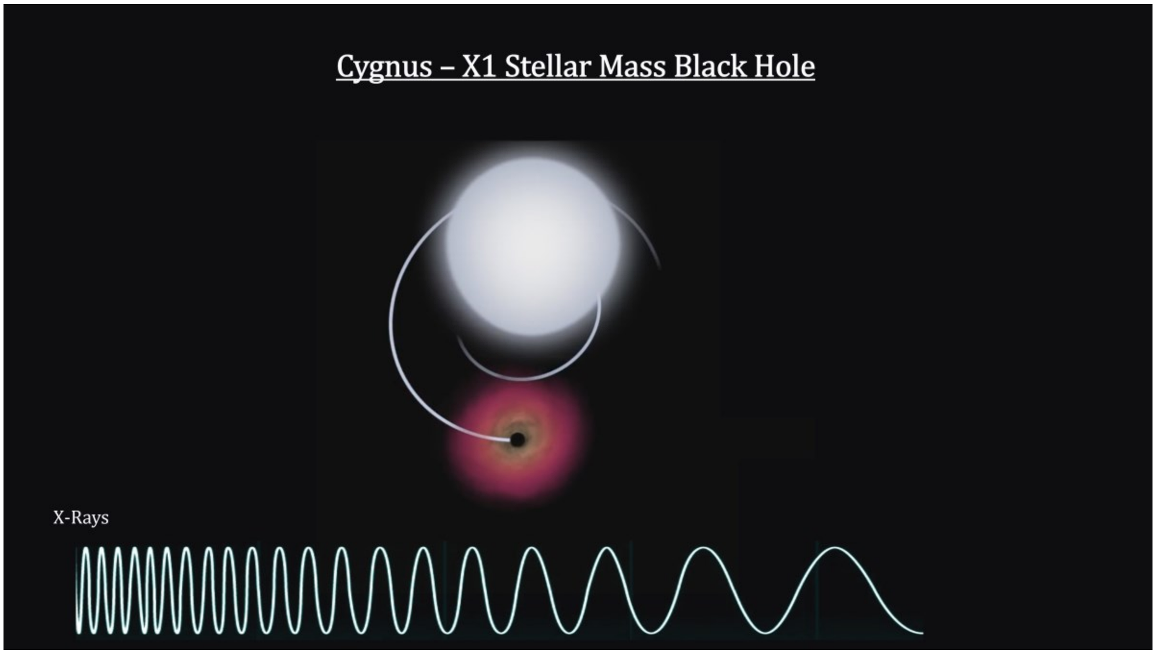
A very strong x-ray source called Cygnus X-1 was also found at this location. But blue supergiant stars cannot generate the volume of x-rays detected. This led astronomers to suspect that the source is a black hole orbiting close to the blue supergiant. We used this system earlier in our segment on accretion disks. [Cygnus X-1 was the subject of a friendly scientific wager between physicists Stephen Hawking and Kip Thorne in 1975, with Hawking, hoping to lose, betting that it was not a black hole. He conceded the bet in 1990 after observational data had strengthened the case that there was indeed a black hole in the system.]



Analysis of the system showed that the distance between the x-ray source and the star is just 1/5 of the distance between the Earth and the Sun. That's very close. These two objects are orbiting their center of gravity once every 5.6 days. This orbital motion gives us the mass of the two objects. The blue giant is 40 times the mass of the sun and Cygnus X-1 is 21 times the mass of the Sun. With that mass, it cannot be a neutron star because neutron stars cannot exceed three solar masses.

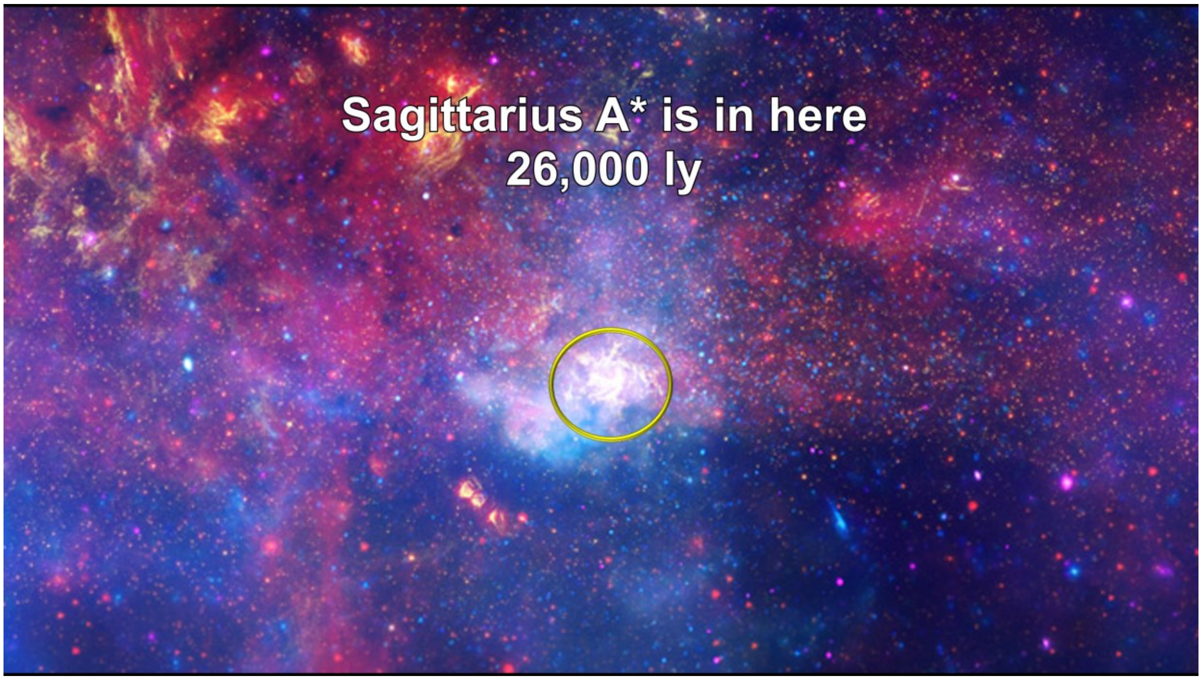


In addition, if the star that collapsed into a black hole had exploded as a supernova, the companion star would have been ejected from the system. That HDE 226868 remained in orbit, indicates that the progenitor may have collapsed directly into a black hole without exploding (or at most produced only a relatively modest explosion). Plus, additional evidence for a black hole comes from the x-ray fluctuations. Observations of Cygnus X-1 found a fading pulse. With all this, astronomers came to accept that Cygnus X-1 is indeed a stellar-mass black hole.

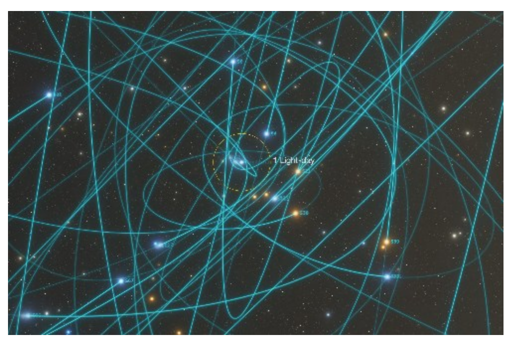


10 – Finding Black Hole Sagittarius A* - 26,000 ly

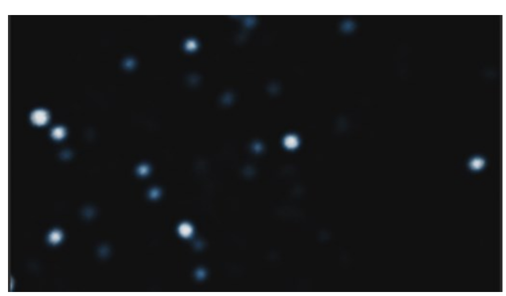
Another way to detect a black hole is to find stars orbiting an invisible point. The black hole at the center of our galaxy provides an excellent example. The central object in the Milky Way is known as Sagittarius A* or Sgr A* for short. (It lies approximately 26,000 light-years away). It is surrounded by so many stars and gas and dust that it is extremely difficult to see.



After decades of carful observations, the speeds, and orbits of around 45 stars around Sgr A* have been calculated. This enabled measuring the precise location of the point they are all orbiting around. The measured orbits also identified the gravitational pull from this point which in turn gave us its mass at 4 million times the mass of our Sun.

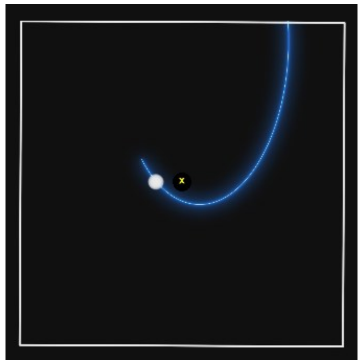


But, when we look at this point, we don’t see anything. This was strong evidence that Sgr A* was a black hole because stars are known to be unstable at much smaller masses.



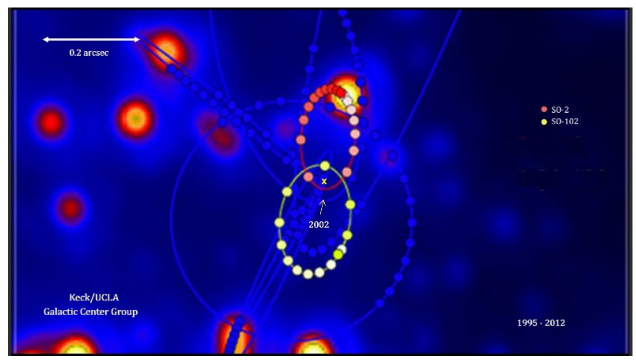
The star S2 is of particular interest because it passes closer to Sgr A* than any other. It's a single main sequence star with 10 to 15 times the mass of our Sun.

Observations of the star showed that its orbit took it to within 20 light hours of Sgr A* in 2002 without bumping into anything. That puts Sgr A*'s 4 million solar mass into a very small place.

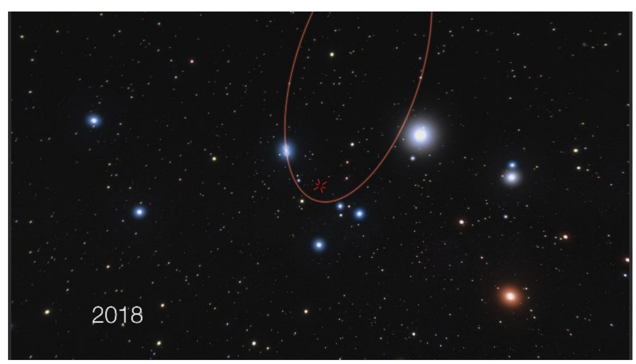


For many astrophysicists, this constituted proof that it was indeed a supermassive black hole. But others pointed out that an extremely dense dim star cluster could produce these results.

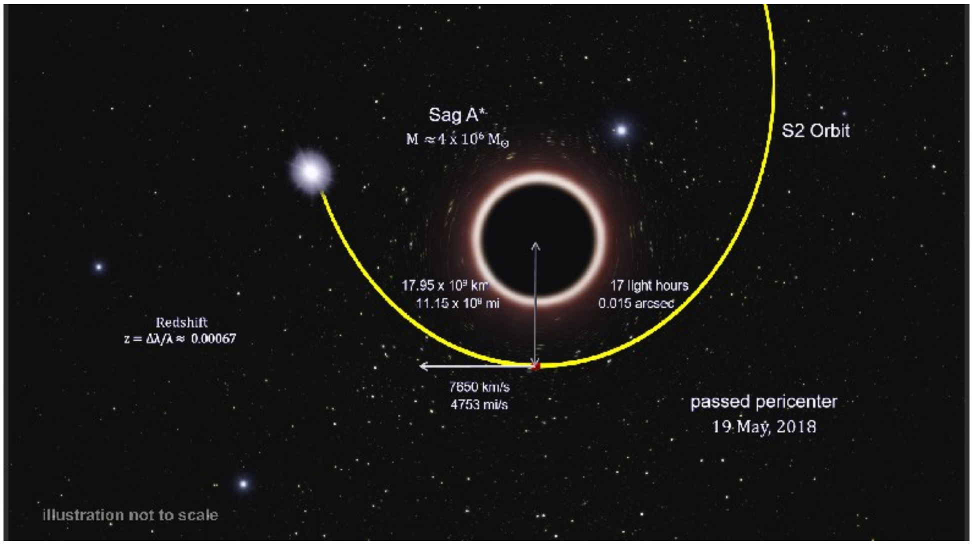
But if Sgr A* were a cluster, S2's orbit would have wobbled. It did not wobble. This was persuasive evidence that the object S2 is orbiting is a Super Massive Black Hole (or SMBH for short). 500 years after Copernicus put the sun at the center of our solar system, we have identified Sagittarius A* as a supermassive black hole at the center of our galaxy.



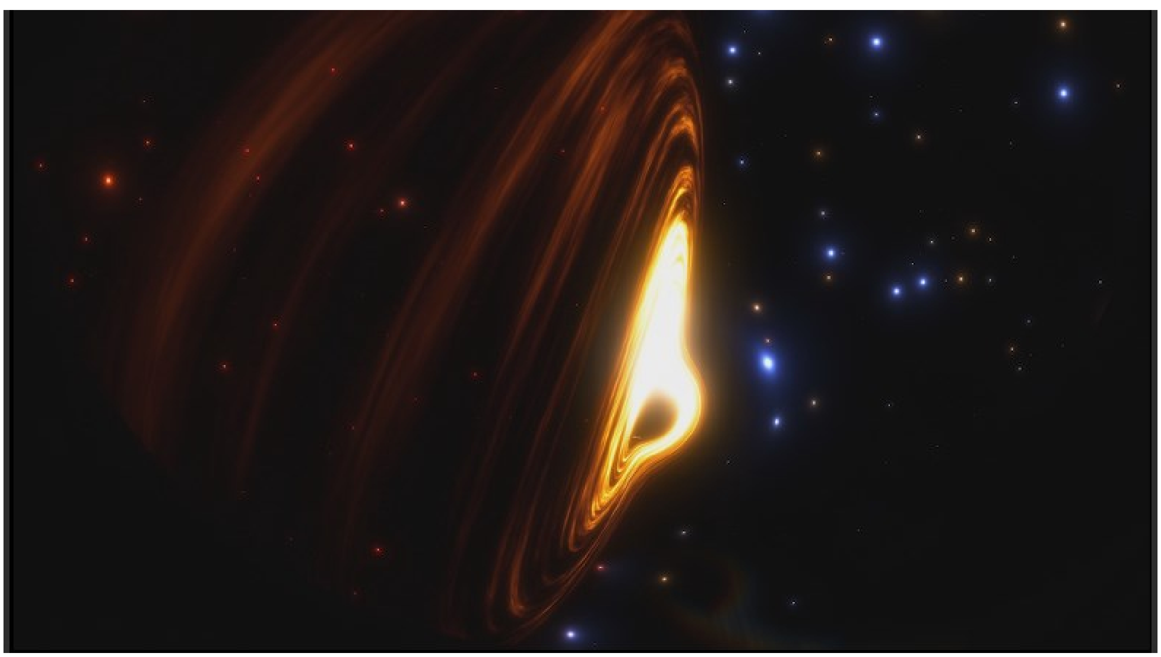
But we weren't done with S2. Its orbital period is 16 years. Following the 2002 passing, a major effort was mounted to upgrade ESO's VLT array of telescopes to enable the precision needed to reveal the true geometry of space and time near this object and test Einstein's theory of general relativity.



These new instruments followed S2 very closely. At the start of 2018 it was accelerating towards Sgr A* reaching relativistic speeds. On May 19th, it reached its closest approach. At that point, it was traveling at 7650 km/s (or 4753 mi/s). That's almost 3% of the speed of light. Its distance from the black hole was just 18 billion kilometers (or 11 billion miles). That's only 120 times our distance from the Sun. The separation on the sky between the two points was just 15 mas. It was also reddening in color as the black hole's gravitational field stretched its light to longer wavelengths. The color change in this illustration is exaggerated for effect. The reddening is quite small and would not be visible to the naked eye. S2's velocity changes close to the black hole were in excellent agreement with the predictions of general relativity. In addition, the change in the light wavelength agreed precisely with what Einstein's theory predicted.

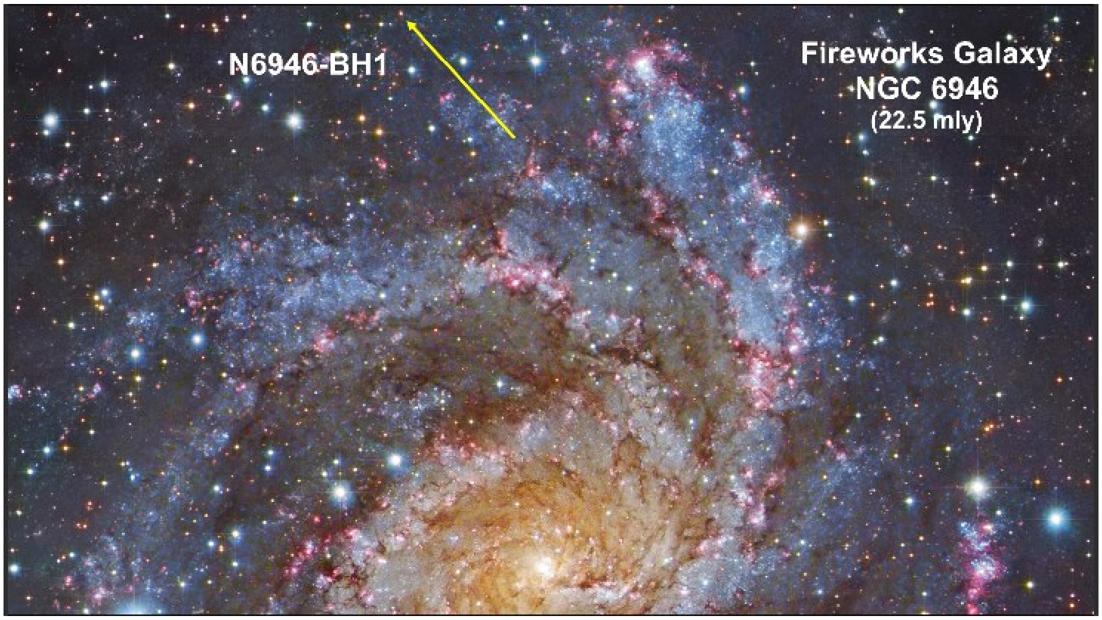


Here's a Fulldome illustration that shows how Sgr A* might look to viewers on a planet orbiting S2 as it orbits the black hole.

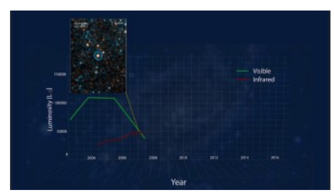


11 – Finding a Black Hole via a Disappearing Star – 22 mly

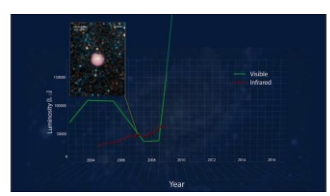
Another way to detect a black hole is to see a visible star disappear. The Large Binocular Telescope (LBT for short) in Arizona was scanning the Fireworks Galaxy 22 million light years away looking for supernova candidates. [The galaxy is known for having large numbers of supernova explosions.] They examined the star named N6946-BH1 – a star 25 times more massive than our Sun. Stars that size usually end in a supernova explosion – leaving behind a neutron star or a black hole.



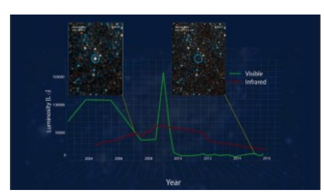
Here's a graph of the star's luminosity in visible and infrared light over time. In 2007, Hubble took this picture of the star.



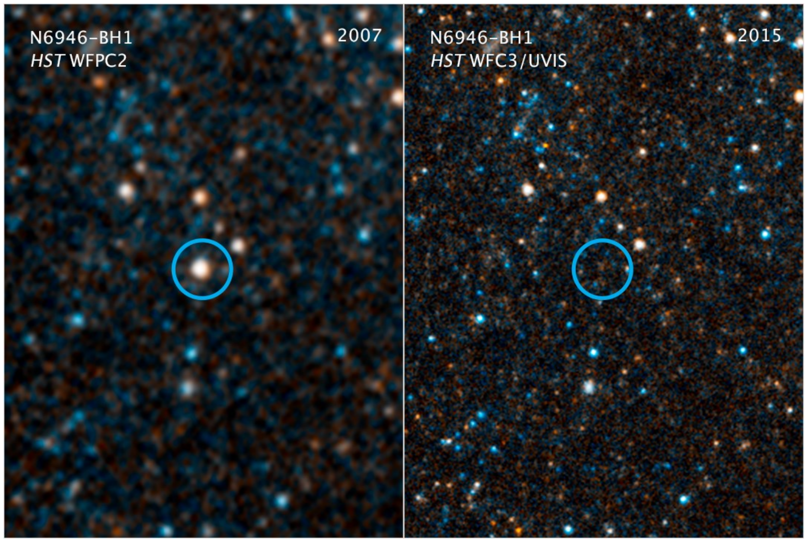
In 2009, the star shot up in brightness to become over 1 million times more luminous than our sun for several months. The expectation was that it was about to supernova.



But it didn't. It just seemed to vanish, as seen in this image from 2015. After the LBT turned up the star, astronomers aimed the Hubble (for visible light) and Spitzer (for infrared light) space telescopes to see if the star was still there. All the tests came up negative.

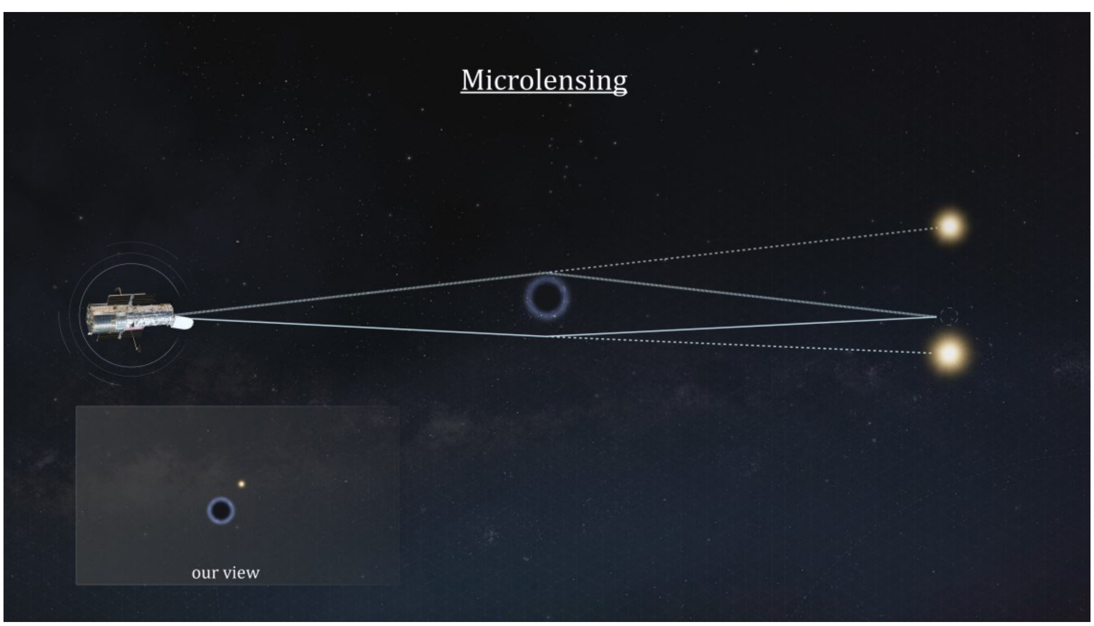


The star was no longer there. The researchers eventually concluded that the star must have become a black hole - without a supernova. It has been estimated that up to 30% of all massive stars that form black holes form them this way with the remaining 70% taking the supernova path.



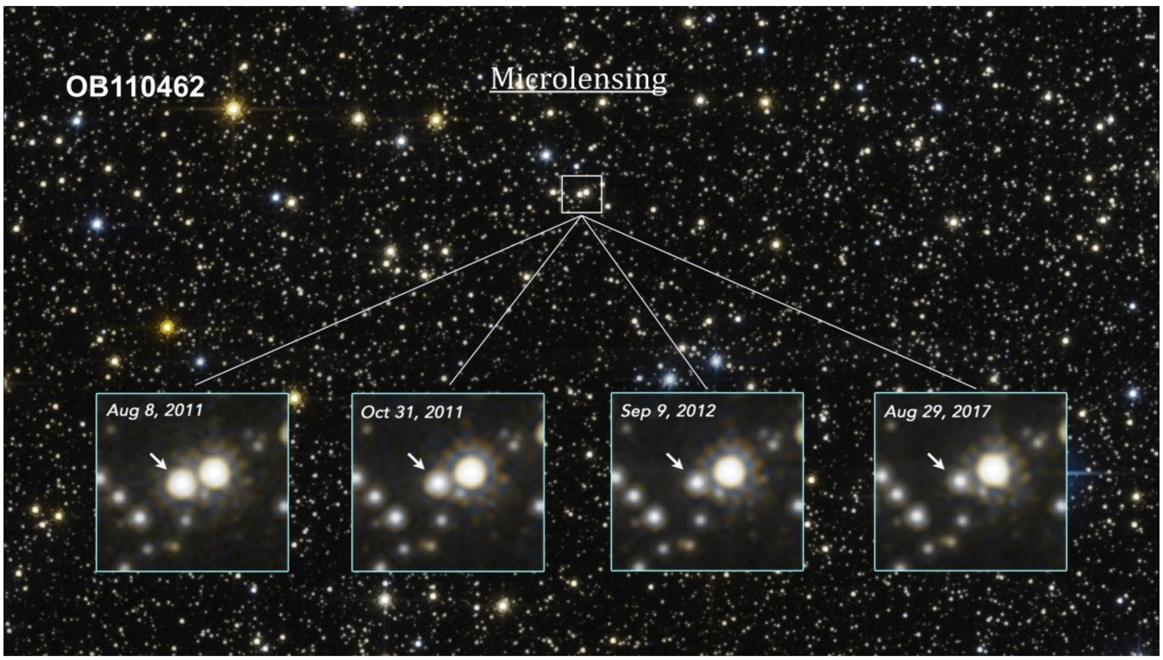
12 – Finding a Black Hole with Gravitational Microlensing - 5000 ly

Another way to detect a black hole is to find one distorting the image of a celestial object behind it. In our previous chapter on Gravitational Lensing, the lenses were mostly galaxy clusters and galaxy superclusters. But even a single planet can act as a lens – bending and magnifying light from objects behind it. These are micro-lenses and analyzing their lensing effects is referred to as microlensing. The greater the mass density of the micro-lens, the larger the lensing impact. This opens up the possibility of finding a free roaming black hole by detecting its microlensing effects.



It's estimated that there are over 100 million free roaming black holes in the Milky Way, representing almost 1% of the galaxy's total mass. The few dozen stellar mass black holes discovered so far have been found in x-ray binary systems. Astronomers had not identified an 'isolated black hole' until Hubble found one drifting through interstellar space in 2022.

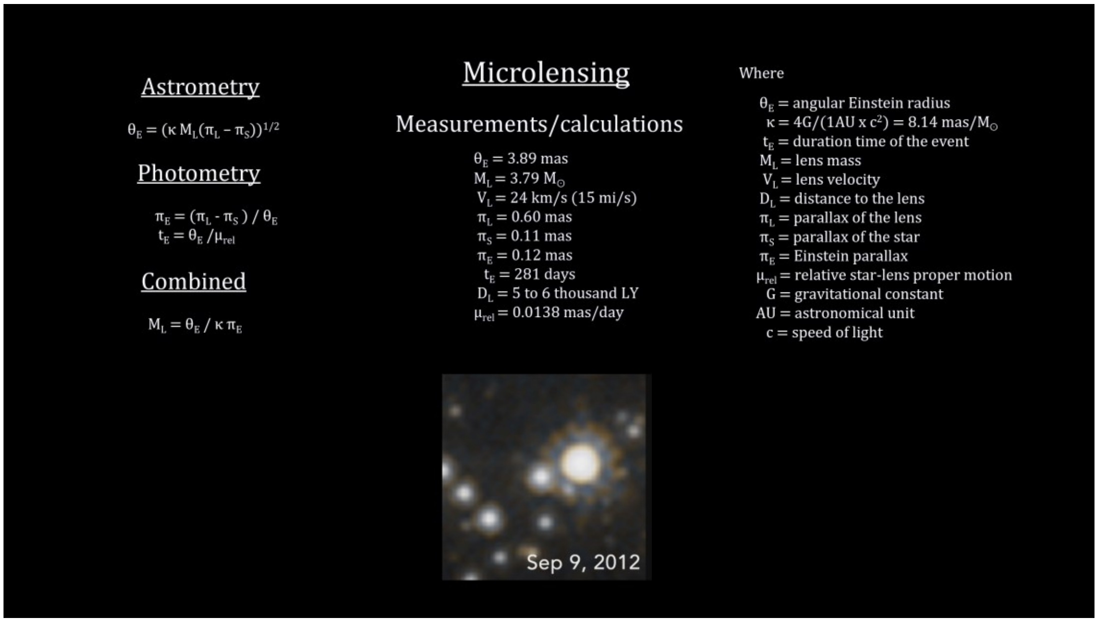
In this image, we see a star that measurably brightened, as first captured by Hubble beginning in August, 2011. This brightening was caused by a dark lens identified as OB110462 that drifted in front of the star. The background star both brightened and shifted in its apparent position. After over 200 days, it faded back to its normal brightness and position.



This long lensing event duration, combined with the lens dynamics associated with the amount of background star brightening, combined with the Hubble measurements on the amount of deflection of the background star's image provided the data to calculate the distance, velocity, and mass of the micro-lens.

The results showed that the star's image was offset from where it normally would be by just over a milliarcsecond. This amount of deflection indicated that the lens is 5 to 6 thousand light years away, is traveling at around 24 km/s (that's 15 mi/s), with a mass of 3.7 suns. This mass makes it a stellar mass black hole given that the mass separation between a neutron star and a black hole is around 3 solar masses.

It should be noted that there are other models of this event that indicate the there is a non-trivial chance that the lens is a neutron star. Further examinations should be able to confirm or refute this Black Hole claim.

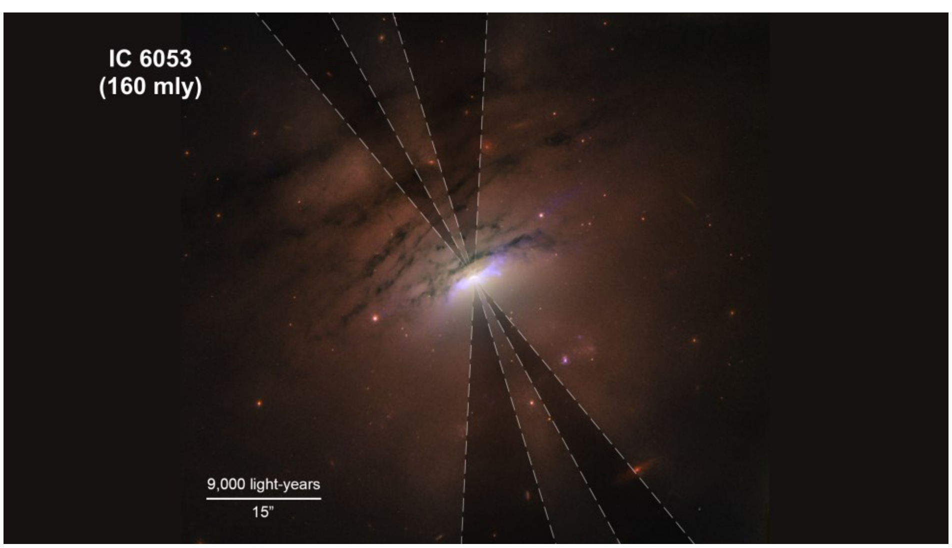


There is one additional way to detect a black hole. We'll cover it in the next chapter on gravitational waves.

[13 - A Few Interesting Super Massive Black Holes

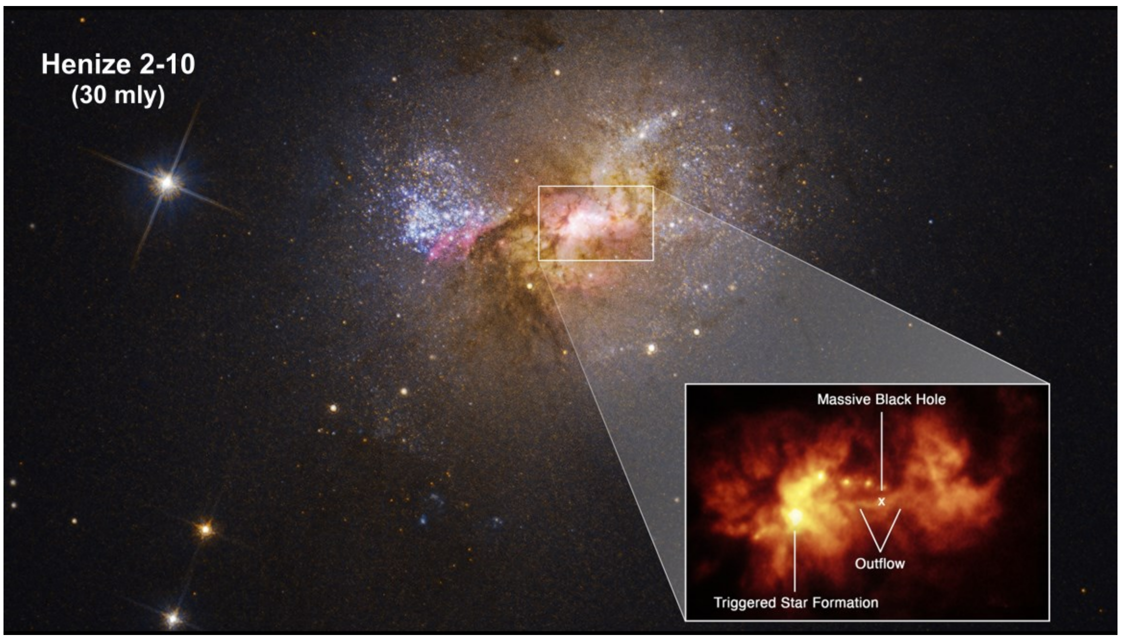
Here are a few interesting super massive black holes.

[IC 5063 – 156 mly] The center of nearby active galaxy IC 5063 contains a supermassive black hole. As material approaches the black hole's event horizon, massive amounts of radiation is released in all directions. But note the V shaped shadows emanating from the central core. Astronomers suggest that a ring of dusty material surrounds the black hole and may be casting its shadow into space by blocking some of this radiation. These dark shadows extend across at least 36,000 light-years.



Henize 2-10 Black Hole – 30 mly

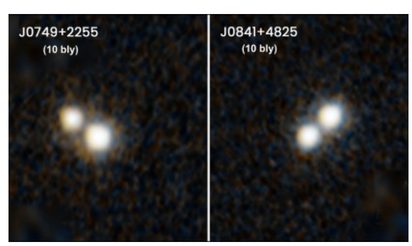
Here we have the black hole at the center of the dwarf galaxy Henize 2-10, 30 million light-years away. This galaxy contains only one-tenth the number of stars found in our Milky Way. What's unique here is that this black hole is located near a star-forming region with an outflow of gas moving at about 1.6 million km per hour (or 1 million miles per hour) towards the region. This flow is imbedded with a large number of new stars. This is the opposite effect of what's seen in larger galaxies, with larger black holes, where material flowing away and into surrounding gas, heats the gas to the point where new star formation is not possible.



Double Quasars - 10 bly

Quasars are brilliant beacons of intense light from the centers of distant galaxies. They are powered by supermassive black holes growing on infalling matter that unleashes massive amounts of radiation at the event horizon. They are scattered all across the sky and were most abundant 10 billion years ago. These Hubble images reveal two pairs of quasars that reside at the hearts of merging galaxies.

These galaxies, however, cannot be seen because they are too faint, even for Hubble. These quasars will tighten their orbits until they eventually spiral together and coalesce, resulting in an even more massive, but solitary black hole.

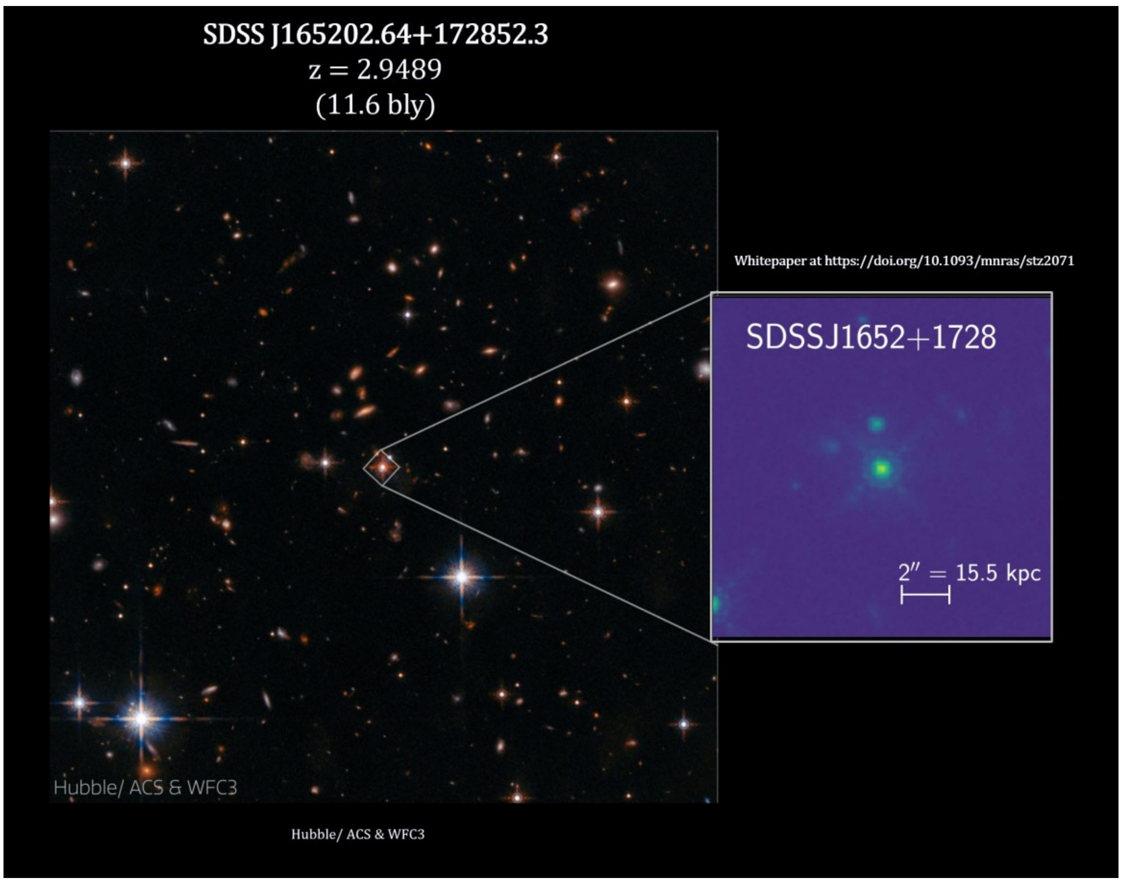


]

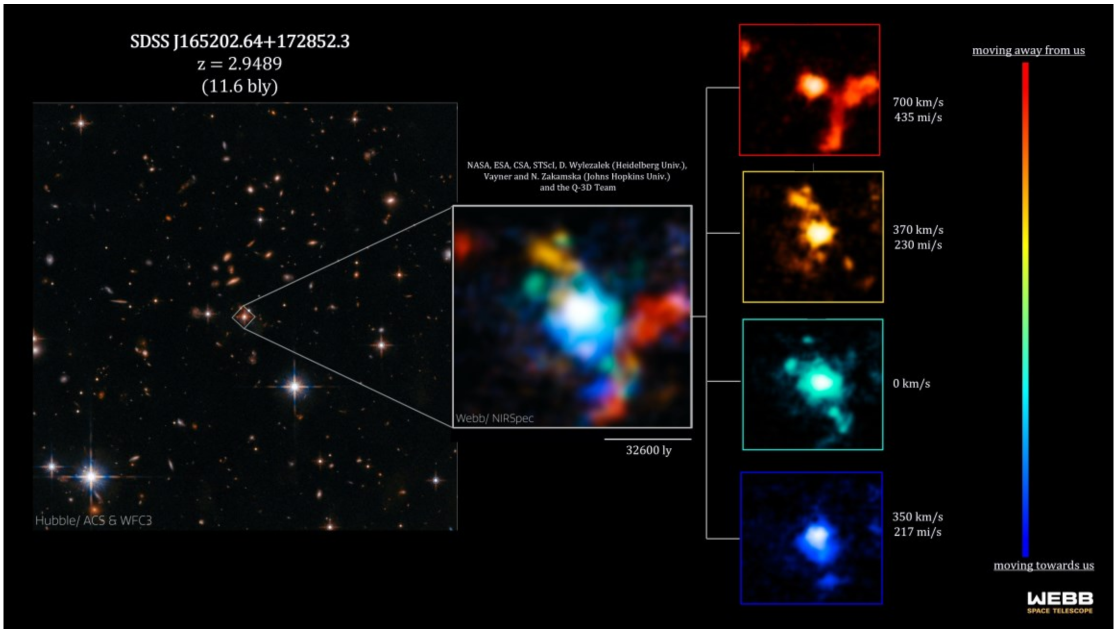
14 – Galaxies Orbiting a Distant Quasar

[J1652-1728   z=2.9489 - 11.6 bly]

As Hubble and James Webb probe deeper into the early universe, they are finding galaxies and even galaxy clusters orbiting quasars driven by their central super massive black holes much earlier than expected. Here's an example. At the center of this Hubble image, taken in visible and near-infrared light, is a distant quasar with a SMBH at its center. The light from this object took 11.6 billion years to get here. This quasar is one of the most powerful known galactic nuclei that's been seen at such an extreme distance. The Hubble team found that the quasar has a tidal tail indicating that interactions with other galaxies are involved.



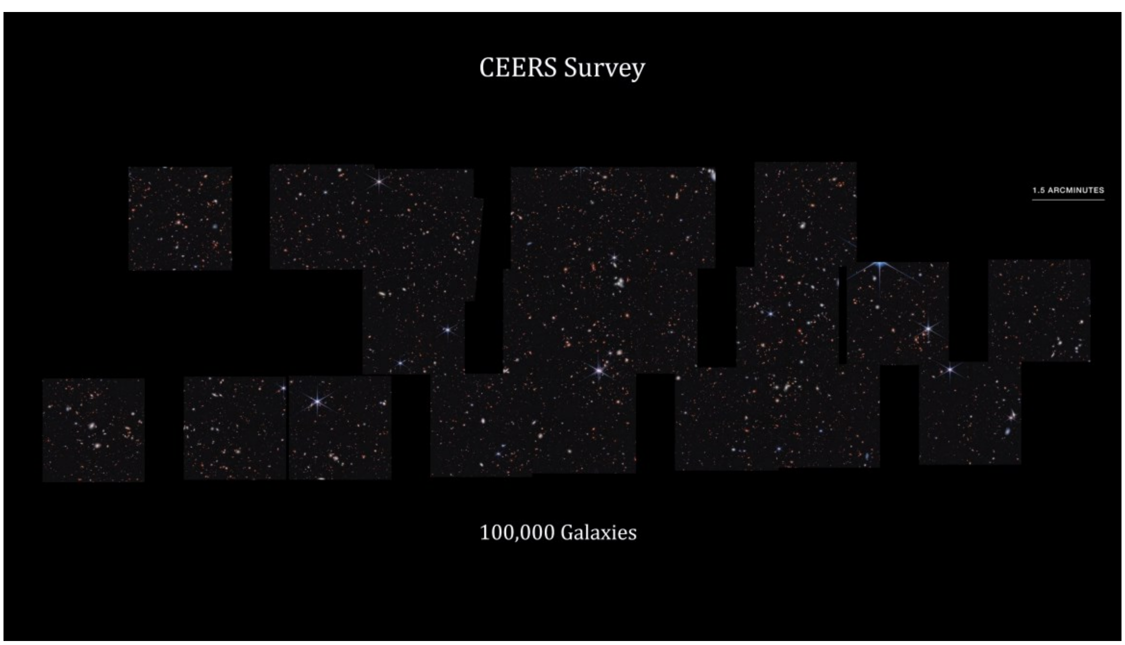
To investigate the movement of the gas, dust, and stellar material in the galaxy around the quasar, the research team used Webb's Near Infrared Spectrograph. Its data indicates that there are at least three massive galaxies orbiting the quasar. This makes the quasar a part of a dense grouping of galaxy formation. Webb, with its spectrograph, used light from doubly ionized oxygen atoms to measure the motions of all this surrounding material. Each color illustrates the relative speed of ionized oxygen gas across the galaxy cluster. The redder the color the faster the gas is moving away from our line of sight relative to the quasar, while the bluer the color the faster it's moving toward us relative to the quasar. The color green indicates that the gas is steady in our line of sight in comparison to the quasar.



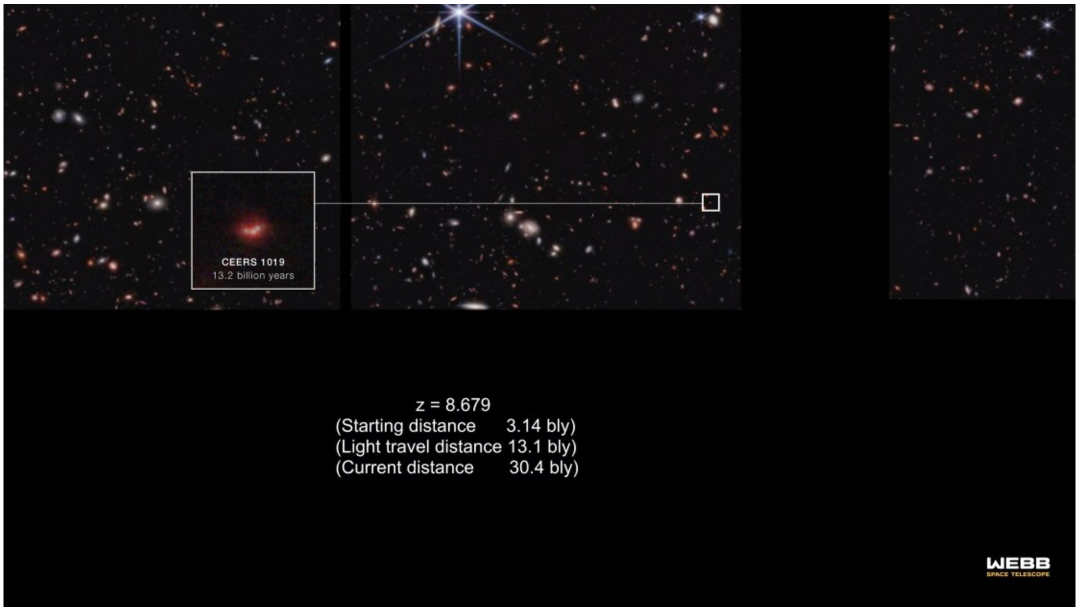
15 – Two Oldest Black Holes

A CEERS Discovery of an Accreting Supermassive Black Hole 570 Myr after the Big Bang

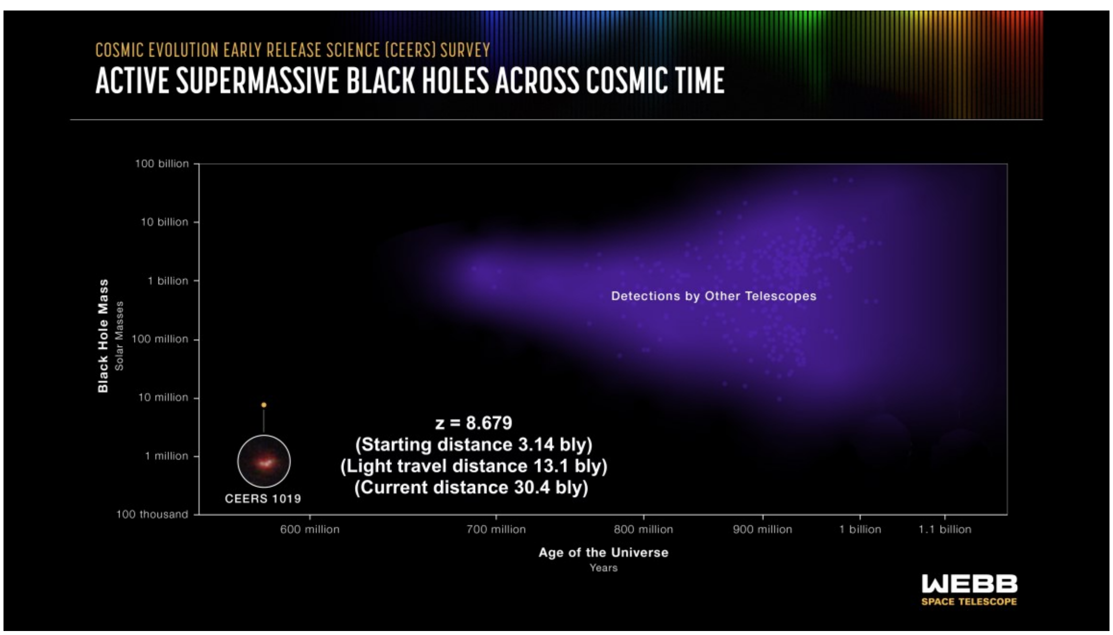
One of the key questions the James Webb Space Telescope was designed to answer was when and how the first black holes formed. Here are multiple images the telescope captured in near-infrared light. Combined, they show around 100,000 galaxies. It's known as the Cosmic Evolution Early Release Science Survey or CEERS for short.



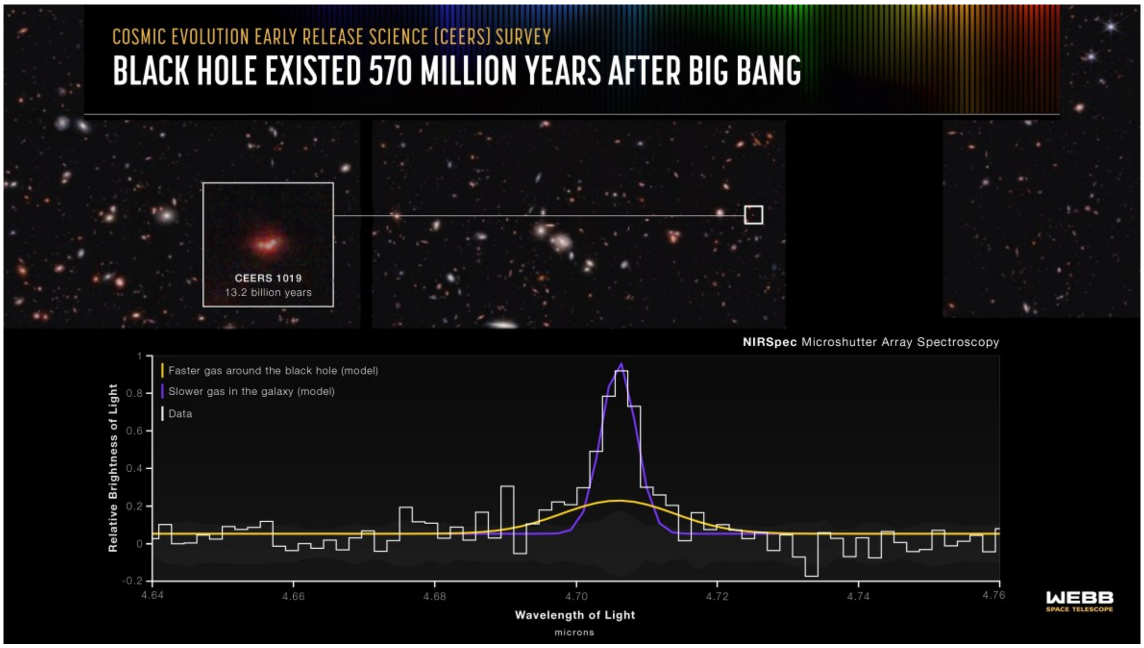
In 2023, the CEERS team, using Webb's spectral data, found that the redshift of the black hole named CEERS 1019 was 8.679. This puts its light travel distance at 13.1 bly.



This supermassive black hole existed around 545 to 570 million years after the big bang. That makes it by far one of the oldest black holes ever discovered. It is accreting at 1.2 times the Eddington Limit, and has 9 million solar masses. That's double the mass of Sag A*, the supermassive black hole at the center of our galaxy.



To distinguish between the black hole and the galaxy around it, Webb measured the brightness of the light it captures vs its wavelength. The peak just past 4.7 microns represents hydrogen. Webb's data clearly shows two models. The broad model, represented in yellow, fits faster gas swirling in the black hole's active accretion disk. The purple model, with a high peak, fits slower gas from new forming stars in the galaxy around the black hole.

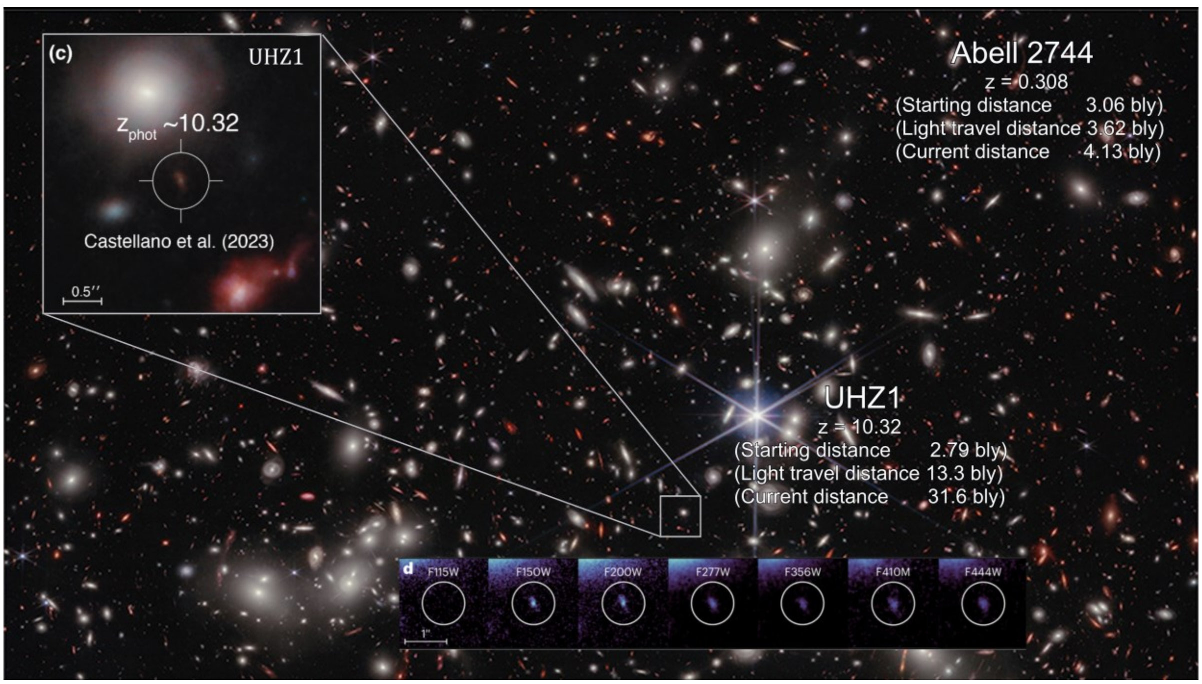


UHZ1 SMBH

Here's a Webb infrared image of the galaxy cluster Abell 2744. There are hundreds of galaxies in the cluster, along with a few foreground stars. It'd redshift is 0.308. Light from this cluster took 3.62 billion years to get here.

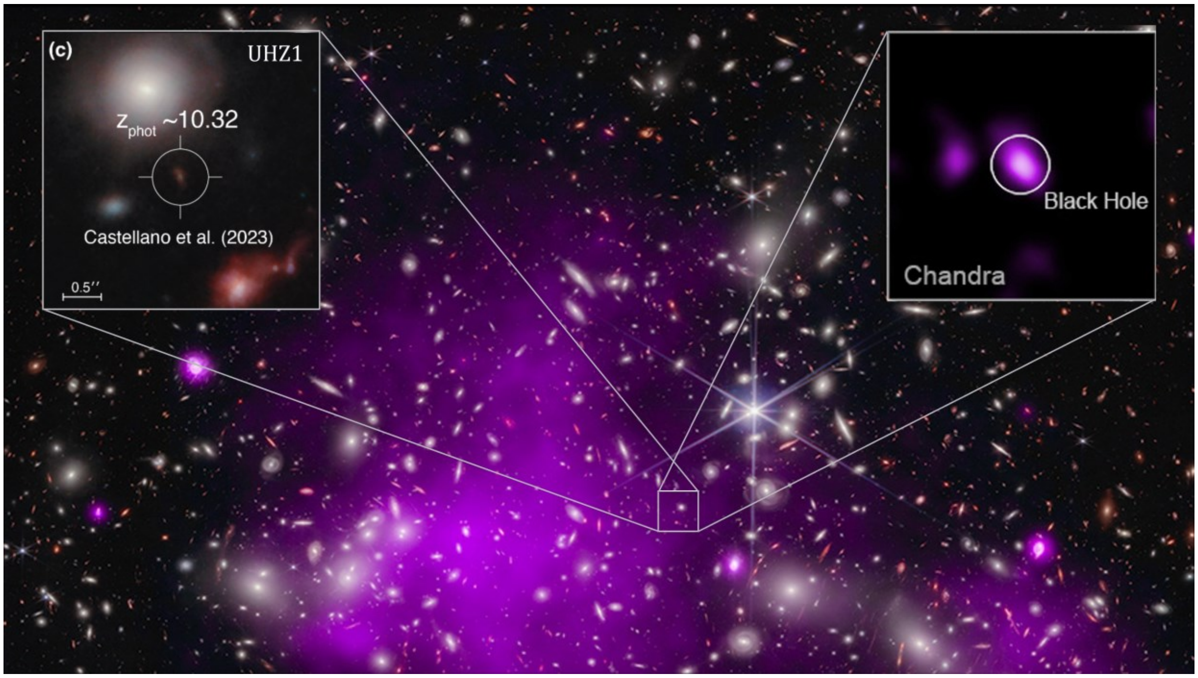
In this cluster, astronomers found a gravitationally lensed distant galaxy named UHZ1. To determine how far away this galaxy is, a technique called 'dropout' was used. Here's how it works. Hydrogen surrounding galaxies absorbs light with a wavelength around 100 nanometers. That's blue light. The source will be easily visible with filtered viewing wavelengths longer than blue, but "drop out" with blue light filters.

This is a standard photometric method for locating distant galaxies in deep field images. For UHZ1, Webb found the dropout with its F115W filter. The redshift needed to stretch blue light to this filter gives us the estimated distance. This galaxy's redshift is 10.32 making its light travel distance 13.3 bly – just a bit further than CEERS 1019.

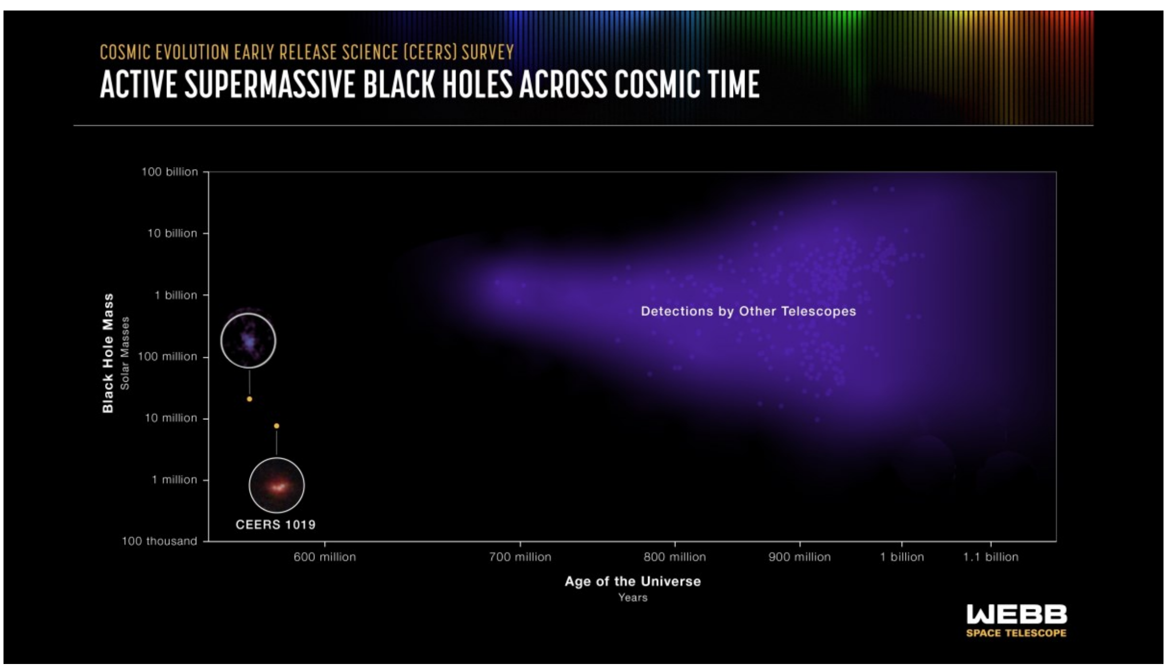


Here's the Chandra X-ray Observatory's overlay view of the area marked in purple. Using over two weeks of observations from Chandra, researchers were able to detect X-ray emission from the center of UHZ1. The X-rays come from a region that is much smaller than the galaxy. This is the signature of an accreting supermassive black hole at the center of the galaxy.

The X-ray signal is extremely faint, but Chandra was able to detect it because the Abell 2744 gravitational lensing enhanced the signal by a factor of four. Based on the brightness and energy of the X-rays, it's estimated mass falls well above 10 million suns. [That turns out to be 50 percent of the mass of its galaxy UHZ1. This is in stark contrast to black holes at the centers of galaxies in the nearby universe, that usually contain only about a tenth of a percent of the mass of their host galaxy's stars.]

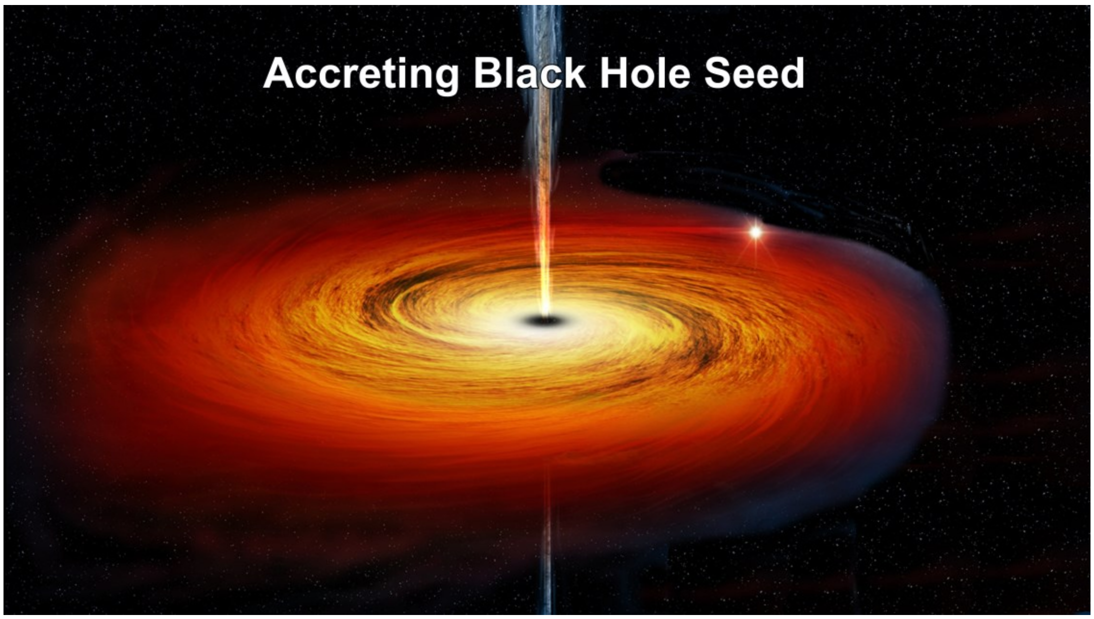


The extremely large masses of this SMBH and CEERS 1019, at such an early age of the Universe, has led to a conflict between the currently understood time it takes to form supermassive black holes, and the Lambda Cold Dark Matter Big Bang Cosmology time line. Astronomers call this 'tension' between the two theories, indicating that one or both will need to change. In our final segment of this video book on Black Holes, we'll cover a proposed change to how black holes can form that would relieve this tension.

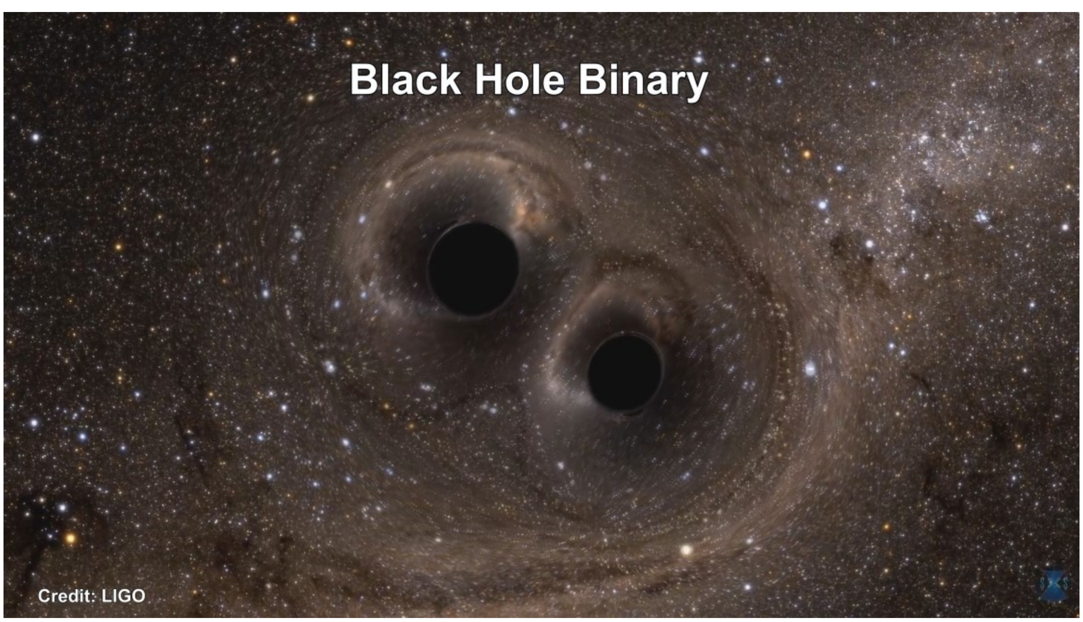


16 –Direct Collapse and Primordial Black Holes

In this chapter we covered how super massive black holes form in three phases: First, a gas cloud collapses into a super-giant star. This can take a few million years. Second, the star exhausts its supply of hydrogen and supernovas into a black hole or a neutron star that grows into a black hole. That also takes a few million years. At this point we have a new stellar mass black hole, referred to as a black hole seed. In the third phase, the seed grows by accretion to super massive sizes. This takes hundreds of millions of years due to the Eddington Limit on its growth that we covered earlier.



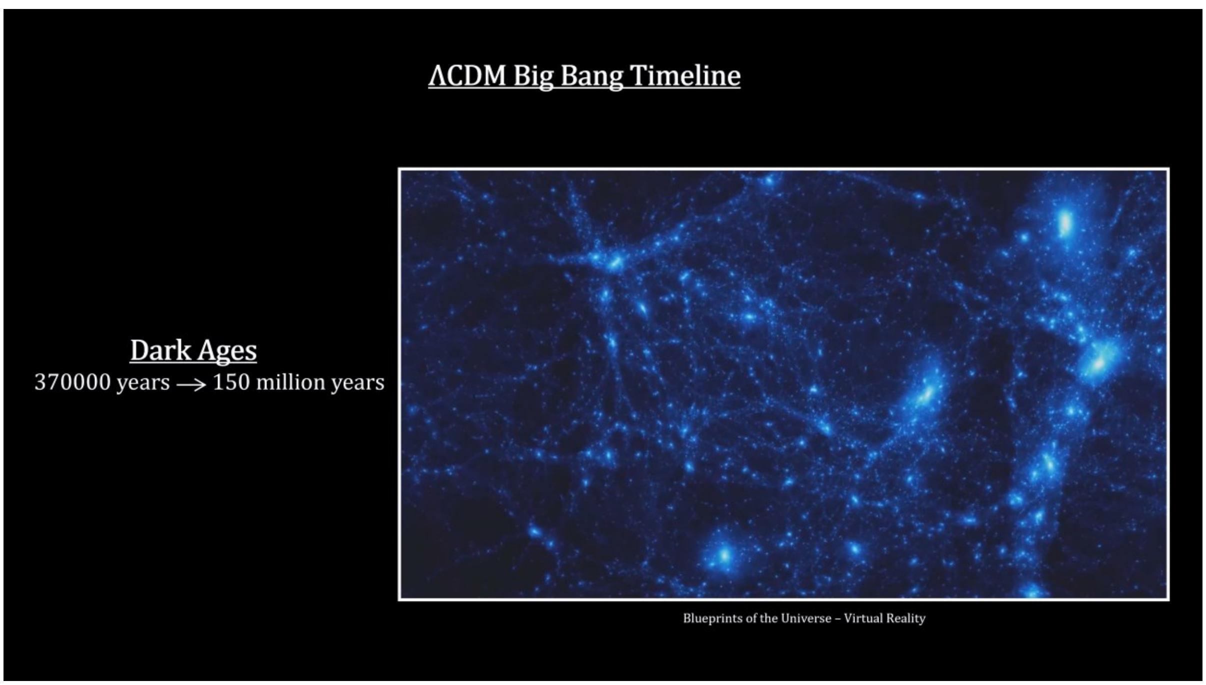
Black hole mergers might play a small role in black hole growth, but lots of black hole mergers would produce large numbers of intermediate black holes, and we can't seem to find any? Plus, the larger black holes get, the less likely they are to merge due to orbital energy and momentum considerations. They stabilize into a binary around 3 light years apart (that's 1 parsec).



Given that black holes form from stars, we can expect that the first black holes formed from the first stars called Population III stars. The Lambda Cold Dark Matter (ΛCDM) Big Bang timeline has the first supermassive stars forming around 150 million years after the big bang. This includes:

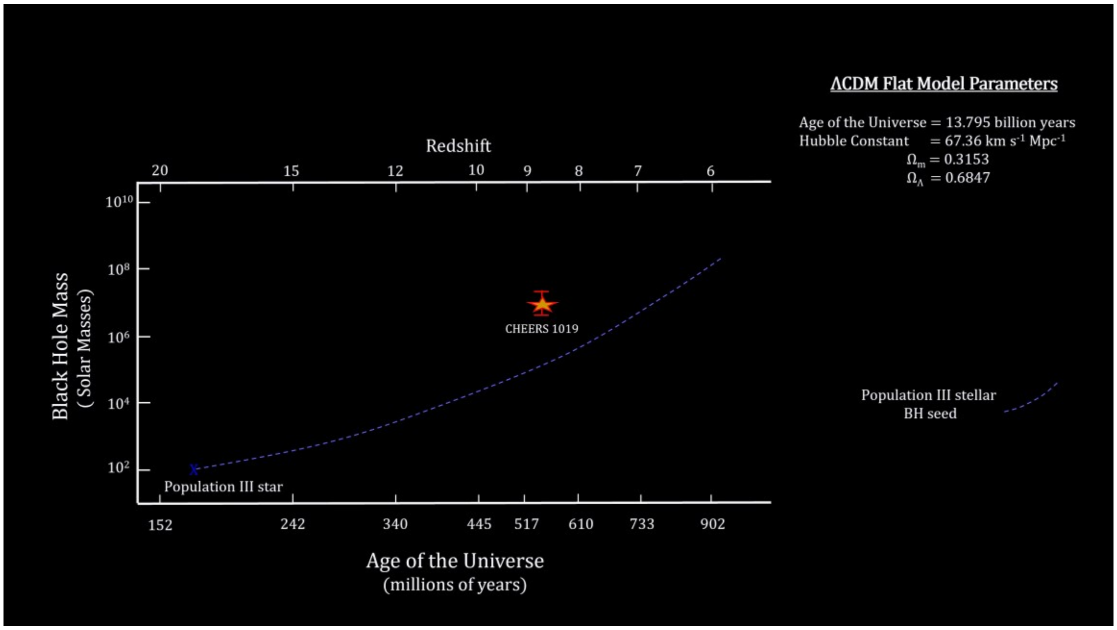
- 'Photon Epoch' [from 20 minutes to 240,000 years] - when the universe was filled with a hot, opaque plasma of photons, atomic nuclei, electrons, and dark matter.
- 'Recombination' [from 240,000 to 300,000 years] - when electrons reunited with protons creating a sea of Hydrogen and Helium atoms.
- 'Photon Decoupling' [from 300,000 to 370,000 years]- when photons were freed to travel across the universe. And the
- 'Dark Ages' [from 370,000 to 150 million years] – when the sky darkened as the expanding universe stretched the bright surface of last scattering radiation into the infrared range. During this time, the caustic process worked the dark matter into filaments with the baryonic matter (Hydrogen and Helium) tagging along.

At the 150-million-year mark, the dense clouds of cosmic gas in the filaments started to collapse under their own gravity, becoming hot enough to trigger nuclear fusion reactions between hydrogen atoms, creating the very first stars; some of which became the very first black holes.



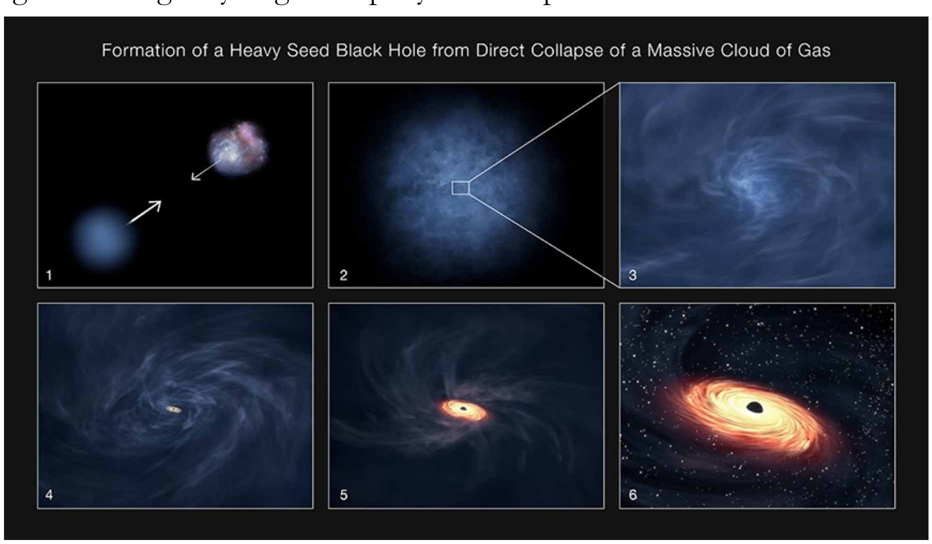
Here's a graph put together by the CEERS team that shows how, starting with the first Population III stars, a standard black hole seed would grow over time. Note that there wouldn't be any million solar mass black holes until around 625 million years after the big bang. But CEERS 1019 has 9 million solar masses and existed just 570 million years after the big bang.

Either the big bang timeline is wrong, or there is another way for supermassive black holes to form. Theories that stretch the Big Bang timeline abound, but none of them have gained much traction. But 2 new theories for early black hole creation are gaining support. One is called 'direct collapse black holes,' and the other is called 'primordial black holes.' We'll cover them both.

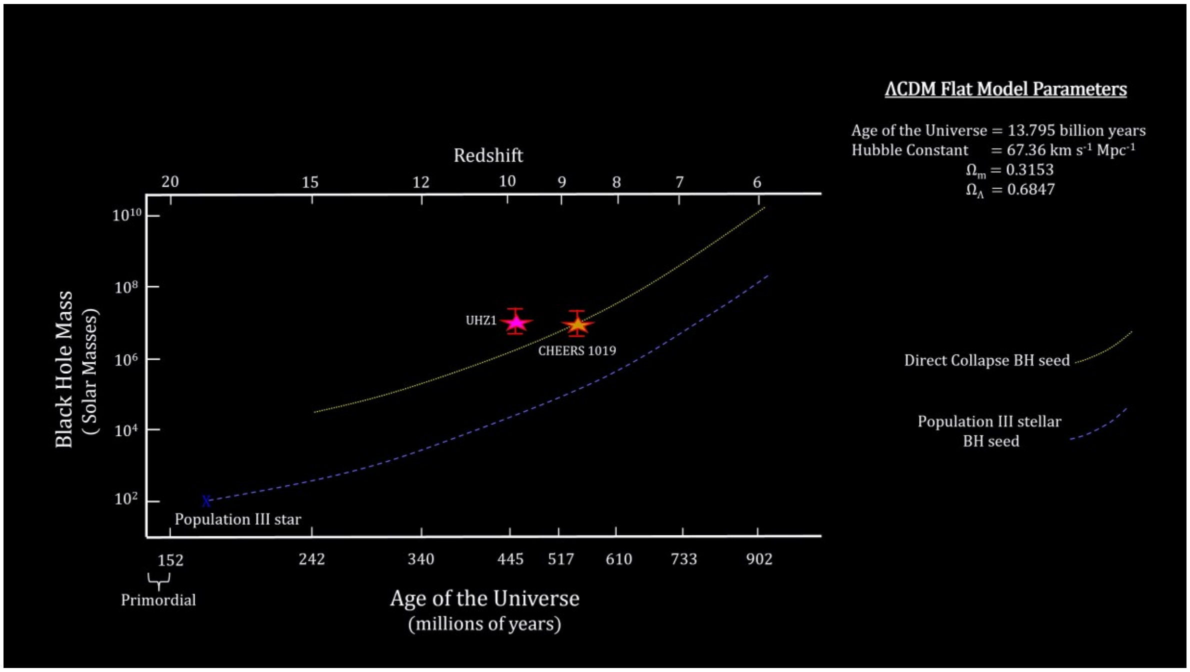


Direct Collapse Black Hole

As the name implies, direct collapse black holes are formed by the collapse of a massive cloud of gas just a few hundred million years after the big bang. But it doesn't go through a star formation phase. The key to the theory requires a mechanism to prevent the normal collapse of a cloud into stars. For example, you could have a massive gas cloud and a galaxy moving towards each other. If the formation of stars in the gas cloud is stalled by radiation from the incoming galaxy, the gas can instead be driven to collapse and form a disk and black hole. This massive black hole "seed" and its disk then merge with the galaxy to grow rapidly into a supermassive black hole.

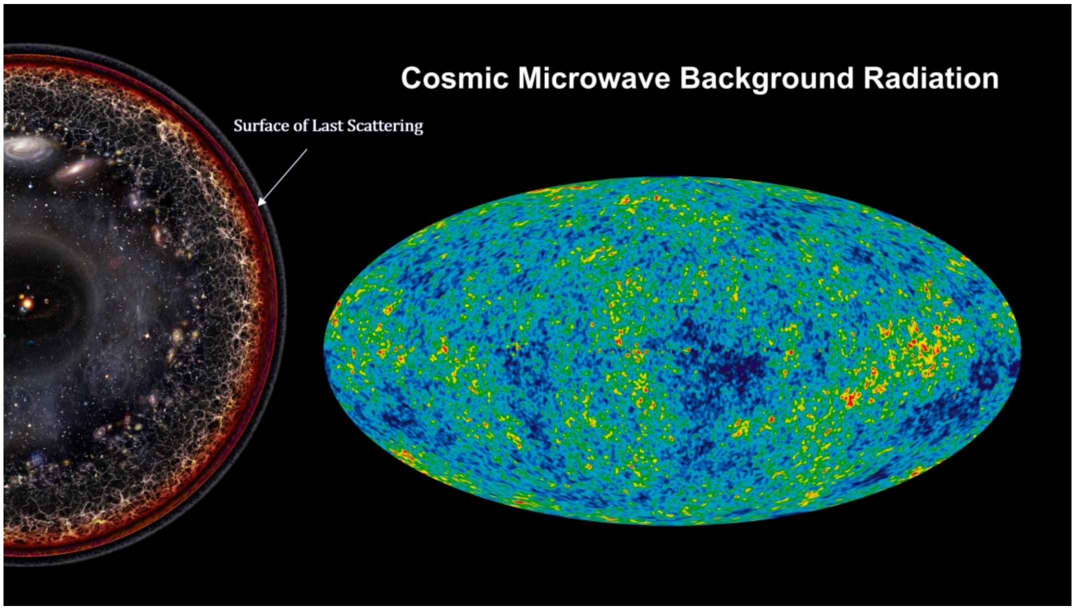


The CEERS team developed the timeline for the growth of direct collapse black hole seeds. But no sooner than they were done, the James Webb and Chandra teams determined that UHZ1's black hole had a mass of 10 million suns, and existed just 450 million years after the Big Bang. Clearly, this did not fit the direct collapse model timeline. This brings us to Primordial Black Holes.

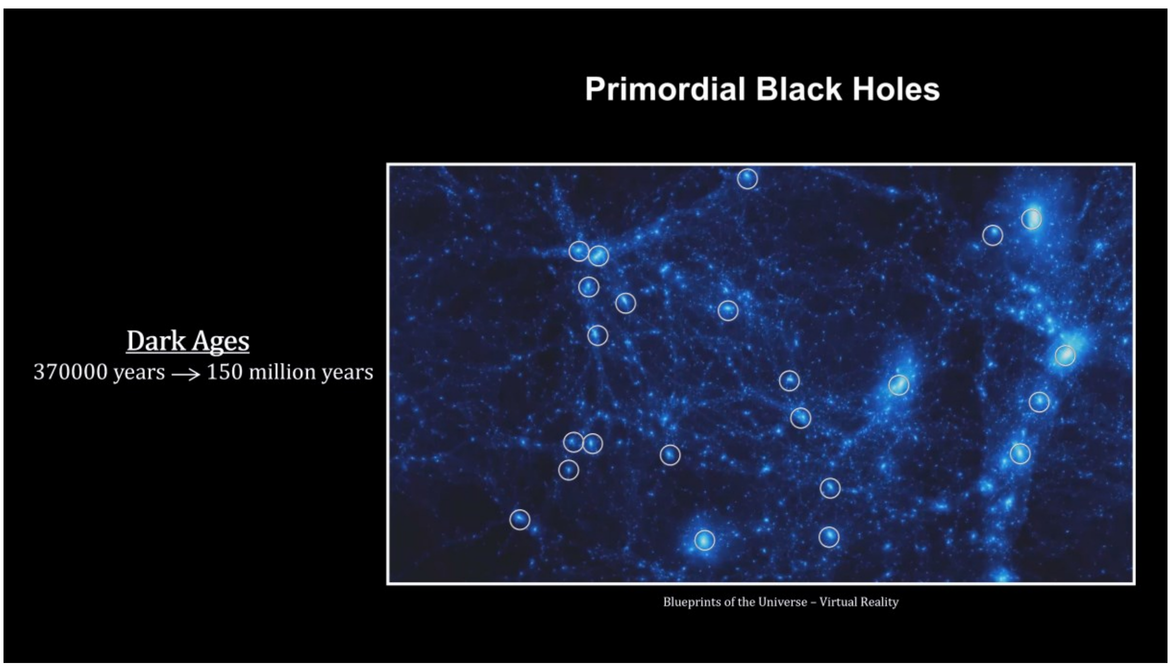


Primordial black holes are black holes that formed before the end of the Dark Ages, including all the way back to the original 'Inflation' period. Theories go from micro-black holes during Inflation that evaporated to massive black holes created via the caustic process on dark matter during the Dark Ages. For our purposes, it's the latter that explains supermassive black holes being found by the James Web Space Telescope just 450 million years after the big bang.

The key to any theory about what happened before stars started to shine begins with measurements of key quantities we can observe today, and extrapolating back to conditions that could reasonably have produced them. For Primordial supermassive black holes, the key quantities are the current distribution of baryons across the visible universe referred to as the Baryon Budget, and the quantum variations found in the Cosmic Background Radiation we see all around us. Extrapolating back into the Dark Ages involves a deep dive into Perturbation analysis on key energy and stress components of Einstein's field equations that are beyond the scope of this video book.



This Primordial Black Hole theory has it that, during the Dark Ages, gravitational attraction associated with super dense concentrations of dark matter would collapse into massive primordial black holes. No accretion disk is involved, so no interaction between dark matter particles beyond gravity would be required. These would be primarily dark matter black holes that then grow on baryonic matter via accretion disks over 150 million years earlier than normal black holes, giving them time to reach the UHZ1 and CEERS 1019 masses at their early date.



I personally like this idea because it is the simplest explanation for the early super massive black holes and the galaxies around them without any Big Bang timeline changes. But it will take a lot more data collection and analysis by Webb and other telescopes to determine just how this all came to be. Gravitational Waves, covered in our next chapter, are also playing a role in exploring how black holes formed in the early universe. So, stay tuned for that.

Music

@00:00 Suppe - Poet and Peasant Overture: Hungarian State Opera Orchestra; Janos Sandor; from the album "Franz von Suppé: Poet & Peasant" 2009

@06:04 Liszt - Les Préludes - Symphonic Poem No3: Vienna Symphony Orchestra; from the album "Franz Liszt: Piano Concerto No.1 in E-Flat Major; Piano Concerto No.2 in A Major; Les Préludes - Symphonic Poem No.3; Valse impromptu" 2010

@23:06 Dvorak - Cello Concerto, op 104: Nürnberg Symphony Orchestra and Othmar M.F. Mága and Jörg Metzger; from the album "Essential Adagio" 2009

@43:01 Mendelssohn - Symphony No 3 Scottish IV Adagio: Philharmonia Orchestra; from the album "50 Must-Have Adagio Masterpieces" 2013

Greek letters:
- α β γ δ ε ζ η θ ι κ λ μ ν ξ ο π ρ σ τ υ φ χ ψ ω
- Α Β Γ Δ Ε Ζ Η Θ Ι Κ Λ Μ Ν Ξ Ο Π Ρ Σ Τ Υ Φ Χ Ψ Ω

⇒ → ± ⊙ ∞ ↛ ∃ ∄ ∈ ∉ ∬ ∫ ≅ ≥ ≤ ≈ ≠ ≡ √ ∛ ~ ∝ ℏ ÷ ∂ ⊥