Journey to a Black Hole
(How the Universe Works. S9E1)

We are on a journey to the heart of the super massive black hole, Our mission, to investigate one of the most mysterious places in the universe. M87 is a great target for us to visit because one, it's close, and two, it's active, it's feeding. Supermassive black holes are the engines that power the universe. Supermassive black holes are a key factor in the birth, life, and eventual death of galaxies. And the more we study them the more puzzling they become. They're the master key to most of the unsolved mysteries of Physics. The Physics inside a supermassive black hole are beyond weird. They are the final frontier of our understanding. Your imagination can run wild. Maybe it's even the source of other universes. There's only one way to find out, to go where no one has gone before and journey to the heart of M87 star. <**break**> 1:16

We speed across M87, a gigantic Galaxy 55 million light-years from Earth. At its heart lies a supermassive black hole, M87 star. It is the first and only black hole ever photographed. We want to find out how M87 star grew so large, what lies inside, and how it controls the Galaxy. 5,000 light-years out from the supermassive black hole, we get our first sign of the danger ahead. We see giant holes carved out of the Galaxy, starless voids thousands of light-years wide. As we approach, we can see that wreckage littered around the vicinity. It's like entering the lair of the Dragon in seeing the bones of all the explorers came before you. What cataclysmic Force tore these giant cavities and the galactic gas clouds? As we fly next to a brilliant shaft of energy thousands of light-years from M87 star, we get a clue. It's a deadly stream of radiation shooting out across the Galaxy, a jet. This jet looks like a Searchlight or a beam from a lighthouse. You're seeing this Monumental thing. It's screaming out of the black hole blasting out radiation. When I first saw a photo of a jet, I was like, "Whoa!" Am I like misreading the scale of this image? Because there was this crazy Star Trek like beam just coming out. In 1918 American astronomer Heber Curtis described the Jets as a curious straight ray. A century later, observatory images reveal they pulsate with energy. The images show knots and clumps in these jets. They show that it's just not smooth and nice, that there's been a history of violence inside this jet. This violent energy pushes the knots along the beams. The knots reveal the speed of the jets. It's like looking at a fast-moving train. Rail cars of the same color blur into one continuous image. But different-colored cars stand out against the others. It's the same with the knots moving along the jets. So we can figure out how fast the jets are really moving by looking at knots of material coming out from near the black hole. When astronomers measured the speed of 2 knots, they got a big surprise. One is moving at 2.4 times the speed of light, and the other is moving over 6 times faster than light. How could this possibly be? As weird as the Physics around a black hole is, that's not actually happening, nor is it allowed to happen. Nothing can actually go faster than the speed of light, so obviously, we're missing something here. The knots may seem to break the speed of light, but the universe is just playing with us. It's really just a consequence of the fact that a lot of this jet is pointed toward us, pointed partially toward the observer on Earth. That, in a sense, is a sort of optical illusion that tricks you into thinking it's moving faster. It's a simple trick of the light, a bit like the way a spoon in a glass of water looks bent and distorted. The impossibly fast speed of the jet is just an illusion of perspective. From our perspective, it looks like the whole thing is moving towards us faster than light. But really, it's just cruising along very, very fast. The jets aren't actually breaking the laws of physics. They're pushing up against it. They're going at 99.9999 5% the speed of light. Imagine the energies necessary to accelerate this entire jet to that speed. So what could produce enough energy to blast Jets across the Galaxy at close to the speed of light? There is a clue far ahead. the Jets shoot out from a tiny, brightly glowing object. This is where things go nuts. This is the center of the action. This is where the real stuff happens. A ring of super hot gas and dust swirls around the supermassive black hole. It's called the accretion disk, and it shines a billion times brighter than the sun. If you had a ringside seat next to M87 star, you would probably be fried very, very fast. But if you were some magical being and could survive anything, and if you had, million SPF sunscreen and really, really great sunglasses, what you would see is this enormously bright vortex of gas swirling this dark void. This bright Vortex spins around the supermassive black hole, at over 2 million miles an hour. So there's a tremendous amount of friction as material moving slower and faster rubs against each other. That's what's heating the diskup, and that's what's causing it to glow. Scientists think that the intense energy of the accretion disk is the source of the Jets. The hot, swirling gas and dust produces powerful magnetic fields. As the disc spins, it twists up the magnetic field at the poles of the black hole. Energy builds. Finally, the magnetic fields can't contain the energy any longer. They snap and blast the jets out into the Galaxy. Even many light-years away on the ship, we can see this violent release of energy. It's like the universe's biggest fireworks display. 2 Jets streaking out of M87 star's poles, one shooting away into the distance, the other racing past our ship. We are at a safe distance. Other things are not. So when these jets shoot outward from the supermassive black hole, they don't shoot outward into nothing. If a jet hits a glass cloud, it annihilates it. It just punches a hole right through it. It's like a train going down a snowy track, right? The gas is like the snow and the jets are like this freight train plowing across it. But here, a freight train traveling at close to the speed of light, smashing into clouds of gas, lighting our way to M87 star as we follow the trail of destruction. There is evidence of similar destruction across the Universe. In the Cygnus A Galaxy, supermassive black hole Jets have caused damage on a colossal scale. In many ways signature is like a cosmic shooting gallery. You see this crime scene, this beautiful mess. So when this jet comes out of the nuclei of Cygnus A, it's gonna encounter gas clouds. At that point, shockwaves set up, and this jet just rips right through this material, sending shock waves in every direction, creating absolute chaos. It's hard to believe how much devastation these jets can cause - they're punching a hole in the ga 100,000 light-year wide. I mean, that's - that's the scale of an entire galaxy. As we head towards the center of the M87 Galaxy, we enter hostile territory. The closer to the supermassive black hole we travel, the more dangerous it gets. As we approach the central core of M87, we start to feel it. But all this energy, all this ferociousness, is powered by that black hole. Intense winds will start to buffet the ship. They push away vital gas, quenching star birth. Could these winds end up killing the Galaxy and M87 star itself? <**break**>

We're on a mission to explore the supermassive black hole M87 star. First we have to cross the M87 Galaxy. It's 120,000 light-years across, and it looks like a giant puffball. M87 is an absolute monster. It's a giant elliptical galaxy, and that means that, as you go from the edges to the interior, you see a higher and higher density of stars. This vast Galaxy contains several trillion Stars. What's strange is that almost all of them are the same color. So as you see, you are -

your sky is covered with countless red points of light everywhere you look. Most of these points of light are small long-living stars called red Dwarfs. So what happened to the different colored stars that we see in other galaxies? When you create lots of stars, you make lots of blue and red stars. But the blue don't last very long. They explode and are gone. The red ones, the ones that are lower mass, those are the ones that live for many, many billions of years. M87 has not made stars in so long that its stars are mostly red. We call galaxies with mainly red stars, red and dead. So the only stars that are left in these red and dead galaxies are billions of year-old populations. And since it's not making new stars, the clock is ticking on M87. Essentially, it's a dead Galaxy walking. The M87 Galaxy hasn't made any new stars for billions of years. Something had to make that happen. Something had to deplete or heat up or push away the gas in those galaxies that would otherwise go into forming stars. We think that black holes in the centers of galaxies are the ultimate answer to this. So how did M87 star kill off star formation billions of years ago? As we cruise towards the supermassive black hole, we get a clue from the strong winds buffeting the ship. So these winds can be incredibly powerful and really, really fast, right? You think a hurricane on Earth is bad? You should see some of these winds. In space, winds are made up of gas and superheated plasma. The power that generates the winds lies ahead, the bright accretion disk surrounding M87 star. Because it's so incredibly hot, it liberates an enormous amount of light, and that light can drive a wind, and so black holes can power winds. They power winds with light itself. And the more material that's falling into that accretion disk, the bigger and hotter it gets and the more powerful the wind is that the black hole blows. We understand that light from the accretion disk creates the winds, but that is about all we know. We don't know that much about the wind. Is it expanding in all directions like a sphere? Or is it aimed in jets, very narrow and only moving in two different directions? Now, measuring the effect of the winds isn't as easy as you might think. It's not like going outside on a windy day, licking your finger and holding it up. You have to infer what's going on with the wind by studying the light emanating from this object. We wanted to find out if black hole winds expand like a bubble or travel in narrow streams. So we studied how iron dust from the accretion disk blocks the light driving the wind. Astronomers found the answer when they looked in the X-ray light spectrum. And what they detected was iron absorbing those x-rays in every direction they looked around the black hole. That's only possible if a black hole is blowing out a wind in every direction, which means that it is definitely blowing out a spherical wind, which is expanding into that Galaxy. And so these black holes can almost literally inflate this growing sphere bubble of gas that's outward flowing from the heart of the galaxy. These winds push out through the entire galaxy of M87, transporting heat and energy throughout the entire volume of the Galaxy. What we found is that it's expanding away from the black hole at a quarter of the speed of light, 40,000 miles per second. And for the M87 galaxy, that is bad news, because hot, powerful winds kill off star birth. The winds can push away the gas that would have normally formed stars so they can effectively quench star formation in a galaxy, causing it to gradually die. And it gets worse. In order for a galaxy to produce stars, it needs lots of gas and dust, and that gas and dust needs to be incredibly cold. Hot winds from the black hole heat up gas clouds so they can't collapse into stars. As M87 star has grown, it has slowly shut down star formation. As the black hole in the center of the Galaxy grows, it has stronger and stronger winds, and this means it's gonna drive out more and more matter. And that's what makes it a galaxy that can no longer support star formation. So a supermassive black hole can determine the star formation happening in the Galaxy. It can help to regulate the amount of gas in the galaxy and therefore the number of stars that are formed in the galaxy. Although M87 star is tiny compared to the vast Galaxy around it, it still controls its host. When you compare it to the size of the Galaxy it's sitting in, it's like comparing a grape to the size of the Earth. So to think that something so relatively small compared to the Galaxy could have such a profound effect over effectively all of Cosmic history is just this remarkable illustration of how energetic a black hole can be. In the relationship between a supermassive black hole and the material surrounding it, the black hole is in charge. Although M87 star calls the shots, it's past, present, and future are inextricably linked to its host Galaxy. The view from our ship is endless space, calm and unchanging. But the M87 galaxy has a violent past, a history of cannibalism, death and destruction. <**break**>

We travelled thousands of light-years across the M87 Galaxy, but it's supermassive black hole is still far in the distance. From our current position, M87 star may look small, but it is 6.5 billion times the mass of the Sun. So how did it get so big? One of the big mysteries that we're still trying to understand is what controls how big the giant black holes at the centers of galaxies become. And we know that it's tightly correlated with things like how big the Galaxy is. Bigger Galaxies have bigger black holes. To understand how M87 star became so big, we have to investigate the history of its Galaxy. We need to discover how M87 star's galaxy grew so large. M87 is huge. It's a big galaxy with a big black hole. It's really, really big. It's what we call the brightest cluster galaxy, and these so-called brightest cluster galaxies are among the most massive galaxies in the known universe. Usually, a galaxy with the mass of M87 is much smaller, but M87 is puffed up. Why? One lead comes from the layout of M87 stars. As we travel through the Galaxy, we see that the Stars spread out over an area 100 times larger than expected. So what scattered the Stars? Galaxie aren't static, every Galaxy is moving, and sometimes galaxies get very very close and interact with each other. Interact is a polite way of describing something extremely brutal. Galaxies are colliding with other galaxies, they're cannibalizing smaller galaxies are tearing each other apart. Sometimes they're like drive-bys and they'll warp each other's structures. Sometimes the Galaxies have head-on collisions and merge. Merging pulls in new gas and stars, so galaxies grow larger. Galactic cannibalism is common. Maybe the M87 Galaxy ate its neighbors. But how can we find out? We could try to identify stars that came from the consumed galaxies, but that's not straightforward. When you're trying to map out a distant Galaxy, it turns out using their stars is a really hard thing to do. They smear in with the foreground of the background. It's actually very difficult to see any evidence that the Galaxy merger ever happened. It's all smoothed out. It's kind of like throwing a bucket of water into a pond. And then asking after the waves go away to separate which molecules of water came from the pail of water versus which were in the pond. All you see is just a mixed pile of water, and it's similar to that with the stars of the galaxy. So how can you spot water from the bucket in the pond water? We need to detect signs of disruption, like ripples or distinct streaks of sand and mud thrown up by the disturbance. When galaxies merge, they may also leave a leftover that stands out, like a planetary nebula. Planetary nebulae are these bright beacons that you can pick out and map out the Galaxy with great precision. A planetary nebula forms when a dying, mid-sized star blows off its outer layers after running out of fuel - these outer layers of gas expand, forming a nebula, often in the shape of a ringor bubble. And you see this beautiful, glowing blue-green blob coming away from the star - these are so much bigger than stars. You can pick them out very easily. One team went planetary nebula hunting in the M87 galaxy. As they mapped the galaxy, they picked out 300 glowing points. The points for blue-green confirming they're planetary nebulas. Planetary nebulae are great. They really stand out like needles in a planetary haystack. The nebula's movements are distinct from the stars in M87. This shows they formed in a smaller, younger Galaxy, not M87. Because we see these planetary nebulae, something must have happened in this old, dead Galaxy. What was it? A galaxy collision.The discovery of the planetary nebulas shows that at some point in the last billion years M87 ate a smaller Galaxy. This galaxy strayed too close to the much larger M87. M87's powerful gravity snared the smaller Galaxy and dragged it closer and closer. You could actually see this galaxy getting bigger and bigger and bigger than the sky and it wouldn't stay the same shape - as the galaxy got closer, it would begin to distort, and your galaxy would distort, as well, until the sky was filled with rivers of stars. M87 pulled in the small Galaxy and swallowed it whole. Can you think of anything more dramatic than the Collision of two galaxies? A violent history of mergers explains how the M87 Galaxy grew so large. Each event brought in many millions of stars. The collisions also unleashed enormous gravitational forces, scattering the Stars like confetti. After a collision like this, the stars are probably ten to a hundred times more spread out than they were before. Some collisions threw Stars around. Others changed the shape of the entire galaxy. If that galaxy merger is violent enough, it injects so much energy into the galaxy that the stars basically all move away from the center, and it makes the Galaxy much more puffy. Gradually transforming it into the smooth, featureless, elliptical shape. Most Galaxies have a supermassive black hole at their center, including those galaxies eaten by M87. So what happened to those black holes? Did they merge with M87 star, increasing its size? M87, the fact that it's an elliptical galaxy also supports the fact that it has had multiple supermassive black hole mergers, which is howM87 star could have gained its sizable mass. Compared to its violent history, the M87 galaxy is now relatively calm. We think that in the past, M87 star grew by gobbling up other supermassive black holes brought in by collisions with other galaxies. But we don't really know, because physics suggests that supermassive black holes can never merge. Instead, they lock together in a cosmic dance for eternity. <**break**>

As we travel closer to the supermassive black hole, we pass the remnants of smaller galaxies eaten over the last 10 billion years. They reveal how the M87 Galaxy got so vast. Most of these consumed galaxies probably had a supermassive black hole of their own. If M87 got so large by eating galaxies, did M87 star get supermassive by consuming other supermassive black holes? So when galaxies merge, all their stars and nebulae mix together, and then also their supermassive black holes eventually find each other and find their way down to the center of the newly merged Galaxy. Just like dropping two stones into a pond, they'll both reach the bottom. They'll both move toward the center, and they will start to move ever closer together. But do the supermassive black holes actually collide? We've witnessed the merging of smaller, stellar-mass black holes, and we've seen supermassive black holes get close together, but we've never observed them merge. When galaxies merge, their central, supermassive black hole should merge. The first step in the merger process, they're sinking toward the center of this newly formed galaxy. As they plunge towards the galactic center, the supermassive black holes plow through fields of stars and clouds of gas. They don't just run into each other, they spiral toward each other, so they're gonna scatter stars everywhere, and the closer they get, the

more rapidly they will orbit each other. So things get even more and more chaotic and crazy. In all the chaos, something strange happens. The supermassive black holes stop moving closer to each other. This is a problem, and we will call this the final parsec problem. So what's going on? Why do they stall? The final parsec problem happens when two supermassive black holes run out of material to help them to merge if there's not enough stars or gas that the black holes can interact with it takes longer than the age of the universe for them to lose enough energy to merge. And so the black holes effectively stall at this final parsec of separation. The two supermassive black holes lock together in an eternal Cosmic dance, close but forever apart. But some supermassive black holes must have merged. It's highly likely that many of the galaxies M87 swallowed had supermassive black holes. And yet, on our trip, we haven't seen lots of supermassive black holes, just one - M87 star. So mergers take place, but how? In 2019 we got a clue from a Galaxy called NGC 6240. This particular Galaxy looks like the aftermath of a massive Galactic collision. There are lumps and clumps of stars, random groups at random directions and random velocities. It's all mixed up, which is what we think Galaxies look like after a massive merger. The merger aftermath reveals a more complex series of events than a two-galaxy collision. What we find the center of this galaxy isn't two, but three giant black holes, which suggests that there have been three galaxies colliding in recent history. So when this new Galaxy starts to merge with the galaxy that hosts the stalled pair, now it brings in its own supermassive black hole. Now this supermassive blackhole perturbs the system, and it makes what's at the center highly unstable. The gravity of this third supermassive black hole steals orbital energy from the stalled pair, pushing them closer together.It's almost a thief that comes in and takes away some of that rotational energy from this binary black hole system. As the two supermassive black holes lose orbital energy, they finally come together. The likeliest thing to happen is that the least massive supermassive black hole is ejected. And the remaining two merge very quickly. The high-speed merger will last just milliseconds, but it will trigger a gigantic explosion. When these giant black holes merge, more energy is released in this process than our entire galaxy will emit over the course of billions of years. Perhaps M87 star merged with other supermassive black holes in the same way - a third black hole, helping it to overcome the final parsec problem. It's possible that mergers with other supermassive black holes allowed supermassive black holes allowed M87 to reach its sizable mass of 6.5 billion solar masses. Supermassive black hole meet their match when they square off against each other, the fallout this cataclysmic, and as we get closer to M87 star, our mission becomes more dangerous. We enter the gravitational killzone surrounding the supermassive black hole. We know the dangers. Any unwitting stars that get too close are stretched, shredded, and torn apart, creating one of the biggest and brightest light shows in the universe.
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As we get closer to M87's supermassive black hole, we enter dangerous territory, not just for us, but also for wandering stars. If the black hole snares them, they are toast. But their death may solve one of the mysteries of supermassive black holes, how fast they spin. It's difficult to calculate just how fast a featureless black object hidden by a bright disk rotates. You need a lot of patience and a little bit of luck. Astronomy is sometimes a pretty opportunistic science. You have to be looking in the right place at the right time to figure out something new that we've never seen before. Recently, astronomers caught a break when they spotted an extremely bright flare in Galaxy PGC 043234. It was hard to miss. The flare was 100 billion times brighter than the sun. And the energy output was absolutely ridiculous. If this happened in the center of our galaxy, it would have been so bright, we could see it during the daytime. A routine search for supernovas, violent deaths of giant Stars, detected the intense flash. ASAS-SN is this network of telescopes designed to look for brief, high-energy events all around the sky, and primarily supernovas. They saw a bright flash, and they thought, “Oh, yay, another supernova.” If you see a bright flash of light coming from a Galaxy, that’s kind of like your first thought. But it didn’t look like a supernova at all. It didn't act like a supernova flash would. It didn’t have the right characteristics. It wasn’t behaving like a typical supernova. It had to be something else. So they send out an alert to the astronomical community saying, “Hey, there’s something cool happening in this region of space.” Once an event is flagged as real, then what happens is other telescopes turn their attention to that event. The data revealed something strange. After the initial flash, there are still smaller flashes that repeat, and if you’re gonna kill a star in a supernova, there’s nothing left to repeat like that. Intriguingly, it flashed on and off about once every 130 seconds. The flashe continued for 450 days. When astronomers looked at this galaxy in detail, they saw that this event happened right at the center, and there's a black hole there with about one million times the Sun's mass, and that was - that’s it, man. That’s the Smoking Gun. What they observed was an extremely rare phenomenon, a tidal disruption event. Catching one live as it happens is an astronomer's dream. In galaxy PGC 043234, a star wandered too close to a supermassive black hole. As this unfortunate star got close to the black hole, the black hole is spinning, and the gravity around this monster black hole is so strong that it could pull the star apart. The side of the star closer to the black hole is feeling a much, much stronger gravitational pull toward the black hole than the far side of the star because it’s farther away. And what this does is stretches the star. So it got ripped to shreds, it got shredded. It got pulled out and stretched and whipped around the black hole. And it stretches the star into some giant long arm, and that swirls around and is trapped as it orbits the black hole. The accretion disk snares the shredded star. And what this means is that that accretion disk is gonna increase its output of radiation, in particular, High-energy radiation. As the star embeds in the accretion disk, a massive flare of radiation erupts, lighting up the universe. After this initial burst, the spinning star debris sends out a continuous stream of light. Our telescopes only pick up his radiation on each rotation of the disk. It's like seeing the beam from a lighthouse every 130 seconds. The flashes are the final pulses of a dying star, and those flashes reveal both the width and the rotation speed of the supermassive black hole. We learned that the central massive black hole is about 300 times wider than the Earth, but it’s rotating every two minutes. It’s rotating at half the speed of light. That's over 300 million miles an hour. We don't yet know how fast M87 star is spinning, but we do know the accretion disk rotates at over 2 million miles an hour. This glowing ring, hundreds of light-years wide, now lies directly ahead of our ship. It is one of the most awe-inspiring and deadly places in the universe, and we are heading straight for it. <**break**> 50:45

After our long trek across the Galaxy, we finally face the mighty supermassive black hole at its center - M87 star. A dazzling glare confronts us. This is the accretion disk, a ring of hot gas and dust spinning at over 2 million miles an hour. M87 star’s accretion disk is so bright, the Event Horizon telescope photographed it from Earth 55 million light-years away. So I remember exactly where I was when that image was released - I was sitting with a bunch of my colleagues at the Center for Astrophysics, and we were all watching the press conference live and absolutely slack-jawed when that image hit the screen. I was sitting in the airport when I saw this black hole image, about to take a flight to New York. I got so excited that I actually walked away from my backpack sitting there. Seeing that picture, it really doesn't leave room for doubt. Black holes are real. The Event Horizon telescope photo is the first picture ever taken of a black hole. The image revealed M87 star spins in a clockwise direction and it's 23.6 billion miles wide. That's around 3 million Earths lined up in a row. The photo also confirmed M87 star's membership in a very exclusive club - the 1% of supermassive black holes that actively feed. The image from the Event Horizon telescope tells us that the M87 is indeed actively growing and accreting and eating materia around it - it shows gas swirling around that black hole on its way to being swallowed. But do all supermassive black holes consume material in the same way that M87 star does? <**break**>

Is it possible that different black holes have different table manners? Well, it turns out that's really true. Some are more delicate eaters. In 2018 we discovered a supermassive black hole 250 million light-years from Earth that eats on a schedule. Now we have this case of a black hole that looks like it's feeding three times a day. It's having three square meals a day. Intense bursts of energy pulse out from Galaxy GSN 069. We see X-ray flares and bursts coming from the center of this galaxy, repeating every 9 hours, and each burst is associated with a new feeding event. This supermassive black hole not only eats on a schedule, it has a very healthy appetite. Each one of these meals that this black hole is consuming is equivalent of 4 of our Moon's in a single bite. So what exactly is this supermassive black hole consuming? The most likely contender is a star. We think this star has been ripped apart and spread throughout an accretion disk, and then slowly over the course of hours, an instability builds up and some material falls in. When the infalling material from the Star hit the supermassive black hole, it triggered a burst of X-rays. Then, the system stabilized... until it sparked up again, creating a 9-hour cycle of bursts of energy. Then, in 2020 new observations spawned a different theory. The star wasn't caught on the accretion disk. The supermassive black hole had instead pulled it into orbit. Its orbit takes it near that black hole every nine hours, and every time it encounters the black hole, some of its material gets sipped off. Eventually, the GSN 069 supermassive black hole will lose its meal ticket. But it's luckier than many other supermassive black holes. Sometimes black holes just take a little nibble on the surrounding material and just give a little burp of radiation in response. A black hole burp generates strong shockwaves that radiate out across the universe. We detected two of these energy outburst in Galaxy J1354 + 1327, located 800 million light-years away. The huge burps suggested that the supermassive black hole at the core of this galaxy was snacking. It ate a bunch of material one time that caused a burst of energy flowing outward. Then it feasted again, and that caused another burp. What caused these separate outbursts? The belching black hole galaxy has a smaller companion Galaxy. A gas stream links the two galaxies, supplying an intermittent, on-off food supply. There's actually a smaller satellite going around the bigger galaxy. The black hole in the middle is pulling streams of material off this little Galaxy. Clumps of material from the companion Galaxy move toward the center of J1354. Once there, the supermassive black hole grabs them. Some gas streaming from the neighboring galaxy reaches the center of the bigger galaxy when the black feeds and then ejects a jet. When supermassive black holes like the one in J1354 receive an irregular supply of food, a cycle is established, a routine that scientists call feast… burp… nap. The supermassive black hole we're headed towards, M87 star, doesn't do burp and nap. It feasts all the time. Stars come in and get ripped apart, maybe once every ten thousand or one hundred thousand years. Whereas M87 has been shining brightly for millions of years. It clearly has a supply of gas other than ripped apart stars that's feeding the accretion disk. This helps explain how a M87 star grew to 6.5 billion solar masses. But what about the future? Will this supermassive black hole continue to feast, or will it starve? To find out, we have to move even closer, across the accretion disk, to discover just how M87 star satisfies its insatiable appetite. <**break**> 58:32

Our ship passes over the accretion disk of M87 star, a blazing ring of gas and dust hundreds of light-years across. This is the supermassive black hole's grocery store. Black holes are known for sucking in everything. But is that really true? Black holes don't really suck. It's a popular misconception. They don't just pull anything in. In fact, if the sun just instantly turned into a black hole today, the Earth would happily continue on in its orbit, because all that gravity cares about is how massive and how far away something is. Supermassive black holes like M87 star are a lot more massive than a regular sun-sized black hole. This means their gravity is greater and extends much farther into the Galaxy, allowing supermassive black holes to attract dust, gas clouds, and stars billions of miles away. But they don't gulp down everything they pull in. The way black holes eat matter isn't as straightforward as you might imagine. Earth gains mass every day from objects falling to it from space. So you might imagine that matter falling onto a black holes is like meteorites falling onto Earth. They can come in from any direction and land anywhere. That's not the case around a supermassive black hole. The most efficient way for a black hole to consume matter is for it to grow an accretion disk. Accretion disks grow when gas and dust dragged in by the supermassive black hole's gravity spiral inward and piles up in a ring. The ring starts to spin from the combination of gravity, and the momentum of the gas and dust. The spinning material flattens into a disc. The material doesn't fall straight in. It orbits its way in, and so it gets accelerated to incredibly fast speeds. Sometimes, the matter ends up inside the black hole. Sometimes, the matter ends up getting kicked away from the black hole. As we travel through M87, we witnessed jets and winds from the supermassive black hole blast this material out into the galaxy. But there may be other things that stop food from entering a black hole. The black hole at the center of our Milky Way galaxy, what we call Sagittarius A star, appears to be swallowing material or eating an incredibly low rate. To discover what's stopping Sagittarius A star, or Sag A for short, from feeding scientists studied infrared light moving out from the supermassive black hole. To do that, they needed to fly high in Earth's atmosphere. The problem is, water vapor in our atmosphere prevents the infrared light from space from getting down to the ground. Sofia is an infrared telescope built into the side of an airplane. As bizarre as that is, it's a very stable platform. Sofia can look at these objects emitting infrared in space and get really good observations of them. SOFIA focuses on the structure of the gas in the strong magnetic fields at the center of the Milky Way. The high-resolution telescope can track the finest grains of dust. When all the dust grains in a cloud are aligned by a magnetic field, they scatter the light coming at them in a certain way, we call this polarized light. The dust

grains can actually map out the magnetic field embedded in that dust cloud. The telescope picked out the grains arranged in a spiral pattern and revealed the direction the grains were moving. This movement reveals why Sag A star is starving. The magnetic field is channeling them into orbit around the black hole instead of allowing them to fall in. So it's literally keeping those dust grains away from the black hole. The magnetic fields also pushed clouds of gas, Sag A's food source away from the supermassive black hole. This is the situation now, but that's not necessarily the way things are always going to be. Because magnetic fields can switch directions. There's a lot of other junk out there, dust, gas and other stars, that as they get close, they can change the magnetic field, and that might allow that dust to fall into the black hole. Magnetic fields changing direction offers hope for Sag A star. And magnetic fields could help M87 star feed. Our mission continues, following this material plunging down into the supermassive black hole. We set a course towards the Event Horizon, the boundary between the known and the unknown universe where the laws of physics no longer apply.
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Our ship crosses the accretion disk. Ahead, the absolute darkness of the supermassive black hole, M87 star. According to black hole legend, this is where we meet our end, torn to shreds by gravity. We have so much wonderful imagery of what would happen if you were to fall into a black hole from science fiction. One idea that has caught popular attention is that you get spaghettified when you fall into a black hole. This is me. This is a black hole, which is pulling stronger on my feet than on my head. And if this black hole is a little bit heavier than our sun this difference in pull is so strong that I would actually get spaghettified, torn apart. So will M87 star spaghettify us? The answer depends on the black hole's mass and volume ratio. A stellar mass black hole with the mass of 14 suns is just 26 miles across. That's about the size of Oklahoma City. Such an enormous mass in a small volume creates a very sharp increase in gravitational tidal forces as you approach the black hole. With a small black hole the strength of gravity changes so rapidly with distance that your feet could be pulled a million times harder than your head. But with supermassive black holes, that doesn't happen. The mass of a stellar mass black hole is concentrated in a small area. A supermassive black holes mass spreads much wider over an area a billion times larger, so its gravity increases gently as you get closer. This means approaching a supermassive black hole feels more like walking down a slope rather than jumping off a cliff, so it won't rip you to shreds. Supermassive black holes have a bad reputation. The bad reputation belongs to stellar mass black holes that rips things to shreds. The nice thing about supermassive black holes is the so-called tidal forces are much weaker, so I would actually be just fine and able to take in this really bizarre scenery around the black hole, with light from distant objects being bent out of shape. So we can approach M87 star safely. Once there, we are faced with an awe-inspiring sight. The supermassive black hole distorts the light around it. Far away from the black hole, that warping isn't very strong, but the closer the light gets to the black hole, the more severely its path is distorted, and the starlight around the black hole becomes really bizarre. They get stretched into - rings and arcs. We can even see things hidden behind the supermassive black hole. I would see, for example, the galaxy behind here looking completely warped and out of shape, because light is bent around the black hole. Black holes can even bend light so it comes from my face, goes around and comes back on the other side. So I could, in principle, use a black hole, you know, as a mirror when shaving. To really understand what's happening around a black hole we need to understand gravity and the language of gravity is the language of spacetime. SpaceTime binds the whole universe together if we could put on special spacetime glasses we'd see stars, planets and galaxies floating on a grid of space-time. These objects have mass and mass distorts and curves spacetime. Imagine a trapeze artist with a flat net underneath them. When they fall from the trapeze onto that net, the net distorts. It forms a dimple right where that trapeze artist is. That trapeze artist is like a black hole. The net is like the fabric of spacetime and time distorting because of the mass in it. This distortion of the space-time net by objects with mass is called gravity. The more massive you are the more gravity you have, because the more you bend and stretch spacetime. So one trapeze artist may bend the net a little bit, but a hundred trapeze artists will bend that net a lot, and good luck trying to walk across it. M87 star's immense gravity bends space, forcing light to travel along the curves. But what does it do to the other half of the equation, time? Einstein realized that time actually runs slower near a black hole than back on Earth. It's a process called gravitational time dilation. Viewed from a distance, our ship appears to move in slow motion. But what do we see on board the craft as we approach M87 star? You would perceive time to proceed on normally. You'd look at your watch, and that second hand would be going around the dial just like normal but to an outside observer that apparent one minute on your watch could take millions to even billions of years. If I'm having a Zoom conversation with mommy back home, even though I'm feeling Im speaking normally, she would hear me go, "H-h-h-i-i-i M-m-m-o-o-m-m-m-m-y-y-y" And this is not some sort of illusion. My time really is going slower. So when I come home, she'd be like, "Hey, Max, you look so good, you look so youthful," and I would actually have aged less, because time ran slower over there. On our final approach into M87 star, we reach a crucial milestone. We are now at the innermost stable orbit. We go any further, we're not getting out ever. You have just two choices. You either escape to safety or you fall into the black hole. Well that's easy. We detach the probe to approach the black hole alone. You can think of the event horizon as being the surface of a black hole, but that a little bit of a misconception. There's not actually anything there. That's just the distance from the center, where the escape velocity is the speed of light. Because nothing can travel faster than light nothing can escape a black hole. Think of the event horizon as a waterfall. If you can imagine the flow of water over a waterfall, if you're a fish you could swim right up close that edge and still escape. But if you go too far, you hit the point of no return, and you're going over. At the event horizon the water moves faster than the fish can swim or our probe can orbit, so the waterfall or gravity carries them over and into the black hole. But what about the light around them? Imagine that fish that's going over the waterfall is carrying a flashlight. Say it's an alien fish. At a black hole, if that fish goes over that event horizon, not only does the fish and the flashlight get sucked in, but the light of the flashlight get sucked in. There's nothing that can turn around. Light, matter, cows, elephants that pass through the event horizon can never come back out. It is a one-way ticket. A one-way ticket through the event horizon. Back on the ship, though, we don't see the probe enter the supermassive black hole. Instead, from our perspective, the probe just gets slower and slower and slower. Until it appears that time simply stops for the probe frozen by the enormous gravity of M87 star. The probe appears stuck, glued to the surface. But that's just our perspective. In reality, the probe has already crossed the event horizon and is inside the black hole. If only it was that simple. The two major theories that explain how the universe works don't work at the Event Horizon. General Relativity

says the probe enters the black hole, but Quantum Mechanics throws up some major hurdles. According to some ideas rooted in Quantum Mechanics, there may be something called a firewall, a wall of quantum energies that prevents material from actually reaching through the Event Horizon. The question of what happens to anything attempting to cross the Event Horizon has challenged some of the greatest minds in physics. Will our probe enter the supermassive black hole or will it be burnt to a crisp in a wall of fire?
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Our probe is approaching the Event Horizon of M87 star, but there's a problem. The two major theories that explain how the universe works don't agree about what happens next. One says the probe passes through unscathed. The other theory says that's impossible. It suggests the probe hits an impenetrable barrier called the firewall. How can the same event have two different outcomes? There's a really interesting puzzle right now which is where General Relativity and quantum mechanics meet, and it's called the Black Hole Information Paradox. What we have is a very schizophrenic situation in physics where we java two theories that don't get along. Einstein's theory of gravity explains all the big stuff. Quantum field theory explains all the small stuff. So which one is right and which one is wrong? This is the mystery. General relativity says in theory crossing the Event Horizon is no big deal Verizon. If you're passing through the event horizon you wouldn't notice anything different. You can, in fact, cross the event horizon of a black hole like M87 star in your spaceship, without even knowing that you have, nothing would change you just peacefully drift inside. According to general relativity, our probe crosses the Event Horizon and enters the black hole. Quantum mechanics sees it differently. When it looks at the probe it doesn't see a robotic spacecraft. It sees information. Everything at a quantum mechanical level has information. You can think of things like a particle having a charge. Particles have spin, angular momentum, and that information and that information as far as we understand, can't be destroyed. What do we mean by destroyed? Well think of burning a book. The words are information. As each page burns, the words disappear. The information is gone, but not really. Because if you could track every single thing that was happening, track each smoke particle, put everything back together again, in principle, that information is still there. Because information can't be destroyed, the probes information even if mangled should be inside the supermassive black hole. If the information that fell into a black hole just stayed locked inside of a black hole, that would be fine. That doesn't violate any Physics. But Stephen Hawking threw a wrench in the works when he theorized that over time black holes evaporate, slowly shrinking particle by particle, emitting heat known as Hawking radiation. Hawking radiation itself doesn't carry any information out, and Hawking radiation eventually destroys a black hole. Eventually the black hole evaporates and disappears. As the black hole vanishes, so too, does information about the probe. This is a big problem for quantum mechanics. Can black holes really destroy information even though quantum physics suggests you cannot. So is the foundation of Quantum Mechanics wrong? This is the Quantum Information Paradox. To try to prevent this impossible situation, scientists came up with a workaround, Something that prevents the probe's information from ever entering the black hole, the firewall. Quantum Mechanics say that there is this quantum fuzz causing there to be ridiculously high temperatures literally burning you up as soon as you enter. If the firewall incinerates the probe, then its information will stay in the actions of the ship, just like the words

from the burning book. So which theory is right? Does the probe safely enter the black hole? Or would the probe burn up? I actually spent an afternoon at CalTech arguing with people about whether anything falls into a black hole or not, and the answer is we don't really know. To find an answer, scientists have come up with some crazy ideas. One, called Quantum Entanglement, suggests that the probe is both inside and outside the black hole, its information carried by particles constantly popping up on either side of the Event Horizon. Stephen Hawking, whose original idea that black holes lose information through heat, also came up with a solution. He suggested that black holes have soft hair. Traditional black hole science says they're bald. By which we mean they have no features at all except their mass, and their charge and their spin that you can measure from outside. Hawking's updated theory says that black hole hair is made from ghostly Quantum particles which store information. Thermal radiation from the evaporating black hole carries this information away from the Event Horizon. If Hawking is right, the probe's information will eventually escape into the universe. The concept of Black Hole hair would solve the Black Hole Information Paradox if it exists, but we don't know if black holes have hair, or if they're, you know, bald. Until we can unite quantum mechanics and general relativity at the Event Horizon the information Paradox will remain a problem for physicists. It's one of the most embarrassing problems in physics, which is still unsolved. I hope one of you who watches this will become a physicist and solve it for us, because physics is far from done. The failure to solve the Black Hole Information Paradox throws up a major obstacle to our understanding of how our universe works. This is the point where physics hits a wall. While a search for a solution continues, let's assume our probe dodges its way past the information paradox. It sails across the Event Horizon towards one of the most violent places in the universe, the core of M87 star. It's called The Singularity and there are no rules. Nothing makes sense, and nothing escapes.
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Our probe has crossed the Event Horizon. It's on a one-way trip to the heart of the supermassive black hole and M87 star. Anything that crosses the Event Horizon is not coming out - it's like Vegas. What goes in a black hole stays in a black hole. The probe leaves the physics we understand and enters the world of physics we do not. This probe is now moving faster than light or it is being carried by space itself faster than light. Once you cross the event horizon of a black hole, your future lies on the singularity in the center of the black hole there's no escaping the fact that you will eventually join space inside of a black hole - there's no escaping the fact that you will eventually join the singularity. The space inside of a black hole is like a 3D spinning vortex. The space in there is always moving. This is the nightmare version of the carousel ride. The whirling probe hurdles downwards, until it hits an even more bizarre region of black hole, the inner event horizon. Theoretical physicist Andrew Hamilton believes that all light and matter that's fallen into a black hole piles up in a tremendous collision at this location. The inner event horizon would be infinitely violent, because it's like the meeting point between two universes. This meeting point is like water falling and smashing into spray shooting back up from the rocks at the base of the falls. Inside the supermassive black hole, space races in and crashes into rebounding space at the inner Event Horizon. This will be a place of infinite energy. It's a place where infalling material, into the black hole, meets outflowing material. Everything falling into M87 star smashes together in a monumental release of energy. This energy has got to go somewhere. It's possible that this inner event horizon is so energetic that brand-new universes could be born in this space. But the question is, how do you actually sort of birth a new baby universe? The energy created at the inner Event Horizon could compress down into one tiny speck, which suddenly ignites, sparking baby universes into life in their very Big Bangs. We know that, a long time ago, our own universe was very small, very hot and very dense. It's possible that it could have been born in the inner event horizon of a spinning black hole. This is such a tantalizing, and very hypothetical idea, but if it's correct, it gives us insights into the origins of our universe itself. Do we have strong evidence that black holes create baby universes? No. Do we have strong evidence that they don't? No. If the probe survives the inner event horizon, it then heads towards the strangest place in the universe, the core of a supermassive black hole. The Singularity. As the probe gets closer and closer to the singularity, the probe gets further and further away from known Physics. We don't know what the probe will encounter when it reaches the singularity. We don't know what it will find. We don't know what it will experience. We don't know. In other words, there's a lot we don't know. Like what exactly is the singularity? It's a hard question to answer. Traditional science says it's an infinitely tiny point, but that's not the case with M87 star. What's interesting is that if your back hole is spinning, the singularity is not a point, but it's, in fact, a ring. Physics says the singularity is infinitely dense. A point of space and time collapses as far as it can go, it basically has infinite density in zero size. For many scientists, that's a big problem. I do not like singularities. I feel that they sound really un-physical. The word Singularity sounds so intimidating and scientific, but it's honestly just our physicists' code word for, "Uhh, we have no clue what we're talking about." Where else in nature do we find infinities? We're talking about a region that would have infinite density and infinitely small volume, basically zero volume. How could that exist? and I just don't see it. And frankly, we will never know for sure. Perhaps the probe breaks up and joins material consumed by M87 star over billions of years. Compressed down, not just to atoms, but to a sea of energy, absorbed into a ring of zero volume and infinite density. Or there could be another possibility. Maybe the singularity doesn't destroy the probe at all. Maybe the probe travels straight on through and passes into another universe. <**break**>

Our Voyage to the heart of M87 star has been a wild ride. We crossed the Event Horizon and fell towards the singularity, the core of the supermassive black hole. Is this the end of our journey or just the beginning? It could be that the singularity isn't the endpoint of the probe's journey. It could be that the probe passes through the singularity and enters into a new universe. Our probe has another option, an escape route out of M87 star. In our universe, we have black holes, objects where if you enter, you can't escape. It's also theoretically possible for there to be white holes,objects that you can't enter, you can only escape from. A white hole is basically a black hole running backwards. Some physicists have theorized that white holes may link to the singularities of black holes, connected by something called a wormhole. There have been interesting papers written suggesting that you could have a wormhole where something that falls into a black hole here comes out of a white hole somewhere else. It sounds like a great way for the probe to escape certain death, theoretically. A wormhole is the bridge in spacetime between those two things. It's easy to create in mathematics. It very well might not exist in real life and will almost certainly live out on our entire civilization and never know about it. That's because constructing a bridge between a black hole and a white hole creates a few issues. A) we don't know how to build them for sure. B) they might be unstable and collapse on themselves immediately, unless you invent - have some new, weird sort of matter that can support them. The problem is that it's hard to maintain this bridge open. It is not likely they would ever have any practical use because they're just not stable. But if M87 star does have a stable wormhole linked to its singularity, where might our probe end up? It could be that this probe's journey doesn't end at the singularity and all the information that it carries with it could be deposited in some distant corner of our own universe. Or perhaps in a different universe. One idea that sounded like science-fiction decades ago is actually now considered potential reality and that's the idea of parallel universes. If parallel universes exist, then some surmise that a black hole could be a gateway to a parallel universe. If there are parallel universes, who knows which one our probe may end up in. This universe may be just like our own, or it might be something completely different. We'll never get to find out unless we follow in after it. It could all work out just fine, and that probe just sails on through and gets to explore new adventures. We don't know. Only the probe knows. Supermassive black holes are some of the strangest and most fascinating objects in the universe. Ever since Einstein's Theory of Relativity predicted black holes a century ago we've been trying to understand how they work. The photograph of M87 star confirmed many theories, but there's still much to learn about the birth, life, and death of these remarkable objects, and even more to leave us fascinated. This is the ultimate unknown. This is the real Wild West. This is the frontier of human knowledge. I care about supermassive black holes first and foremost because they are awesome. They stimulate my childhood imagination and fascination. Supermassive black holes offer us a truly unique window into how the laws of physics work, especially the laws of gravity in extreme regimes far beyond anything that we can possibly imagine here on Earth. Supermassive black holes lurk at the heart of almost every large galaxy that we know of. So, in some way, we're just along for the ride with the super massive black holes. If I could make a request for a special favor before I die, what I would like to do is spend a few hours orbiting the monster black hole in the middle of the Galaxy. What a way to go