

1. Appendices

1.1. Appendix A – Video Transcripts from Veritasium

1. How to Understand What Black Holes Look Like

- URL: <https://www.youtube.com/watch?v=zUyH3XhpLTo&t=263s>
- Publication Date: Apr 9, 2019
- Duration: 09:19
- Transcript: On Wednesday April 10th 2019 you will probably see the first-ever image of a black hole. That's when the Event Horizon Telescope will be releasing their results and I haven't seen them yet but I think they're going to look something like this and I can be relatively confident because well it's gonna look a bit like a fuzzy coffee mug stain. But if you are disappointed by this image I think that misses the gravity of the situation. From this image we should be able to tell whether the general theory of relativity accurately predicts what happens in the strong gravity regime that is what happens around a black hole what I want to do here is understand what exactly we are seeing in this image so here is my mock black hole of science and this sphere represents the event horizon. That is the location from which not even light fired radially away from the black hole could be detected by an outside observer. All of the world lines end up in the center of the black hole in the singularity once you're inside here there is no coming back not even for light. The radius of the event horizon is known as the Schwarzschild radius. Now if we were just to look at a black hole with nothing around it we would not be able to make an image like this because well it would just absorb all electromagnetic radiation that falls on it but the black hole that they're looking at specifically the one in the center of our Milky Way galaxy, Sagittarius A* has matter around it in an accretion disk. In this accretion disk there is dust and gas swirling around here very chaotically it's incredibly hot we're talking to millions of degrees and it's going really fast a significant fraction of the speed of light and it's this matter that the black hole feeds off and gets bigger and bigger over time but you'll notice that the accretion disk does not extend all the way in to the event horizon. Why is that? Well that's because there is an inner most stable circular orbit and for matter around a non-spinning black hole that orbit is at three Schwarzschild radii now in all likelihood the black hole

at the center of our galaxy will be spinning but for simplicity I'm just considering the non-spinning case. You can see my video on spinning black holes if you want to find out more about that. So this is the innermost orbit for matter going around the black hole if it goes inside this orbit it very quickly goes into the center of the black hole and we never hear from it again but there is something that can orbit closer to the black hole and that is light because light has no mass it can actually orbit at 1.5 Schwarzschild radii. Now here I'm representing it with a ring but really this could be in any orientation so it's a sphere of photon orbits and if you were standing there of course you could never go there but if you could you could look forward and actually see the back of your head because the photons could go around and complete that orbit. Now the photon sphere is an unstable orbit meaning eventually either the photons have to spiral into the singularity or spiral out and head off to infinity now the question I want to answer is what does this black quote-unquote shadow in the image correspond to in this picture of what's actually going on around the black hole. Is it the event horizon? Are we simply looking at this? or is it the photon sphere? or the inner most stable circular orbit? Well things are complicated and the reason is this black hole warps space-time around it which changes the path of light rays so they don't just go in straight lines like we normally imagine that they do I mean they are going in straight lines but space-time is curved so yeah they go in curves so the best way to think of this is maybe to imagine parallel light rays coming in from the observer and striking this geometry here. Of course if the parallel light rays cross the event horizon we'll never see them again so they're gone that will definitely be a dark region but if a light ray comes in just above the Event Horizon it too will get bent and end up crossing the event horizon it ends up in the black hole. Even a light ray coming in the same distance away as the photon sphere will end up getting warped into the black hole and curving across the event horizon so in order for you to get a parallel ray which does not end up in the black hole you actually have to go out 2.6 radii away if a light ray comes in 2.6 Schwarzschild radii away it will just graze the photon sphere at its closest approach and then it will go off to infinity and so the resulting shadow that we get looks like this it is 2.6 times bigger than the event horizon. You say what are we really looking at here? what is this shadow? well in the center of it is the event horizon. It maps pretty cleanly onto the center of this shadow but if you

think about it light rays going above or below also end up crossing the event horizon just on the backside. So in fact what we get is the whole back side of the event horizon mapped onto a ring on this shadow. So looking from our one point in space at the black hole we actually get to see the entirety of the black hole's event horizon. I mean maybe it's silly to talk about seeing it because it's completely black but that really is where the points would map to on this shadow. It gets weirder than that because the light can come in and go around the back and say get absorbed in the front you get another image of the entire horizon next to that and another annular ring and then another one after that and another one after that and you get basically infinite images of the event horizon as you approach the edge of this shadow. So what is the first light that we can see? It is those light rays that come in at just such an angle that they graze the photon sphere and then end up at our telescopes. And they produce a shadow which is 2.6 times the size of the event horizon. So this is roughly what we'd see if we happen to be looking perpendicular to the accretion disk but more likely we will be looking at some sort of random angle to the accretion disk. We may be even looking edge-on And in that case do we see this shadow of the black hole? you might think that we wouldn't but the truth is because of the way the black hole warps space-time and bends light rays, we actually see the back of the accretion disk the way it works is light rays coming off the accretion disk bend over the top and end up coming to our telescopes so what we end up seeing is something that looks like that. Similarly light from the bottom of the accretion disk comes underneath gets bent underneath the black hole and comes towards us like that and this is where we get an image that looks something like the interstellar black hole. it gets even crazier than this because light that comes off the top of the accretion disk here can go around the back of the black hole graze the photon sphere and come at the bottom right here producing a very thin ring underneath the shadow. Similarly light from underneath the accretion disk in the front can go underneath and around the back and come out over the top which is why we see this ring of light here. This is what we could see if we were very close to the black hole, something that looks truly spectacular. One other really important effect to consider is that the matter in this accretion disk is going very fast, close to the speed of light and so if it's coming towards us it's gonna look much brighter than if it's going away. That's called relativistic beaming or Doppler

beaming and so one side of this accretion disk is going to look much brighter than the other and that's why we're gonna see a bright spot in our image. So hopefully this gives you an idea of what we're really looking at when we look at an image of a black hole if you have any questions about any of this please leave them in the comments below and I will likely be making a video for the launch of the first ever image of a black hole so I'll try to answer them then. Until then I hope you get as much enjoyment out of this as I have because this has truly been my obsession for like the last week. I guess what would be exciting is to watch it over time how it changes, right? there's a lot of hope that there are blobs moving around and you know if you see a blob going round the front and then it goes around the back but you see it in the back image etc then that's gonna be kind of cool.

2. First Image of a Black Hole!

- URL: https://www.youtube.com/watch?v=S_GVbuddri8
- Publication Date: Apr 10, 2019
- Duration: 05:28
- Transcript: This is the first-ever image of a black hole released by the Event Horizon Telescope collaboration on April 10th 2019. It shows plasma orbiting the supermassive black hole at the center of the galaxy M87. The bright region shows where plasma is coming towards us and since it's traveling near the speed of light it appears brighter when coming towards us and dimmer when going away. This is called relativistic beaming. From the images scientists can tell that the plasma is orbiting clockwise. It takes around 2 days for the plasma to complete one orbit. Here we are looking at the black hole using electromagnetic waves with a wavelength of 1.3 millimeters - radio waves. This was the part of the spectrum used to make the image because it can show us the features close in to the event horizon and it can pass through the accretion disk and interstellar dust to reach our telescopes. The supermassive black hole in M87 is very active meaning it's constantly feeding on lots of matter from its glowing hot accretion disk, but it also has narrow collimated jets above and below it here shown in blue, thought to be created by incredibly strong magnetic fields. The jets extend out at least 5,000 lightyears and one of them appears to be pointing almost straight at us. Relativistic beaming is again the reason

we can see the jet coming towards us in this Hubble Space Telescope image but not the one going away. Since the jet is pointed almost straight at us I'm thinking our perspective is almost perpendicular to the accretion disk but let's have a look at what we would see if we were looking at different orientations. The warping of space-time around the black hole means we can see light even from parts of the accretion disk behind the black hole. They are lensed above and below the shadow region. Not gonna lie this is so trippy I could stare at it for a long time. So the big question most people are going to be asking is why is the image so fuzzy? The answer is because it's so tiny. Don't get me wrong the black hole itself is huge, supermassive in fact. As measured from this picture the black hole has a mass 6.5 billion times that of our Sun. The actual size of its shadow is nearly the size of our solar system, but located fifty three and a half million light years away its size from our perspective is only about 40 micro arcseconds - that's the angle it makes on the sky. To understand what that means take the whole sky and divide it into 180 degrees. Then divide a degree into 60 arcminutes and an arcminute into 60 arcseconds. Divide an arcsecond into a hundred and into a hundred again and into a hundred once more and that is the size of the black hole shadow only about 40 micro arcseconds. It puts us at the very limit of what we are technologically capable of seeing. In fact to get this sort of resolution due to the basic law of physics the diffraction limit we needed a telescope the size of the Earth. That being impractical the scientists used eight telescopes spread across the globe. They all simultaneously observed M87 and as the earth rotated that helped fill in the earth-sized telescope that they were trying to simulate. But M87 was not the only black hole they looked at. They also observed the supermassive black hole at the center of our Milky Way galaxy, Sagittarius A* - they haven't yet release an image of this black hole, but this simulation shows what it might look like. it's much closer at around 26,000 light years away but also much smaller with a mass only four million times that of our Sun. It's also less active, only periodically gobbling up matter, and it would have much more variation over time with matter orbiting every four to thirty minutes. That's probably why we'll have to wait a little longer to see the black hole at the center of our galaxy. For now, the striking image of the black hole in M87 confirms beyond a shadow of a doubt that black holes do exist. The general theory of relativity published over a hundred years ago is supported again in spectacular fashion in the strongest gravities and at the limits of our ability to test the theory. What I love about

moments like this is the ridiculous extreme things these scientists did these 200 scientists in pursuit of a goal that seemed impossible and yet they achieved it.

3. Spinning Black Holes

- URL: <https://www.youtube.com/watch?v=fu3645D4ZII&t=49s>
- Publication Date: Jan 11, 2019
- Duration: 10:13
- Transcript: On November 22, 2014 a burst of x-rays was detected by ASASSN that's the All Sky Automated Survey for Super Novae but this was no supernova the signal came from the center of a galaxy around 290 million light-years away and what we now believe happened was a star came too close to a supermassive black hole with a mass millions of times that of our Sun and it was eaten The black hole fed on the star and yes, this is the actual terminology astrophysicists use to describe it Events like these are thought to be rare occurring maybe once every 10,000 to 100,000 years in a galaxy they're called Tidal Disruption Events, or Tidal Disruption Flares as the star approached the side closest to the black hole experienced a much stronger gravitational pull than the other side, ripping the star to shreds matter spiraling into the black hole formed an accretion disk an annular ring of gas and dust that's accelerating and heating up emitting visible light UV and X-rays observable from Earth Now what's remarkable about this event is that it transformed a dormant or quiescent black hole one that wasn't really feeding into one that we can observe thanks to the matter falling in from that star and is what it looked like Okay if you're disappointed, check out these artists renditions of the same event but if you're cynical you might say "Well how do we know that's what really happened? what if the scientists are just making this up to get more grant funding or to inspire people to go into science" well I'll explain how we know this is actually what went down but first things got weirder scientists trained three X-ray telescopes to observe this part of the sky for years after the event and what they found was a strong and regular pulse of X-rays brightening and dimming every 131 seconds and it shows up in the data from all three telescopes they observed periodically over 450 days but the pulse maintained this rhythm and didn't get weaker in fact as time went on the relative strength of the pulse got stronger modulating the X-ray signal by around 40% and what was causing these periodic flashes of X-rays and what could it tell us about the

black hole well let's back up because black holes are some of the simplest objects in the Universe by that I just mean that they are characterized by only two attributes Mass and Spin Okay, there's also charge but since black holes should essentially be neutral mass and spin are the two that count mass is relatively easy to determine far away from a black hole, you can even use Newtonian physics. By measuring the gravitational effects of the black hole on other bodies you can estimate the mass of the black hole this has been done and black holes been found with masses ranging from just few times our Sun, stellar-mass black holes, up to billions of solar masses -- supermassive black holes it's generally accepted that there is a supermassive black hole at the centers of most galaxies, including our own. But what about spin? since black holes form from collapsing stars and all known stars rotate, all black holes should also be rotating I mean, what are the chances that a bunch of matter just collapses into a point perfectly with no rotation? It's just not going to happen. And then additional matter falling into the black hole contributes its angular momentum. So like a figure skater pulling their arms into a... point object, You can imagine black holes get spinning pretty fast. But spin is harder to measure because unlike mass, it only affects objects relatively close to the black hole. But there is a way to do it. Actually, 3 ways. To understand all of them, you have to understand isco. In Newtonian physics, around a compact mass, you can place an object in a circular orbit at any radius and it will be stable. It doesn't matter how close you get. This is not the case according to general relativity. Here, there is an innermost stable circular orbit, With a radius known as r_{isco} . Closer than this, and no orbits are stable: they all fall into the black hole. So when you're looking at a black hole that is feeding, the innermost edge of the accretion disk is at r_{isco} . What's useful for our purposes is that r_{isco} depends on the spin of the black hole. The faster it's spinning, the smaller r_{isco} becomes. Assuming it's spinning in the same direction as the matter in the accretion disk. The rotation enables particles to orbit closer to the black hole, than they'd be able to for a non-spinning black hole. So you can kind of think of it as though the spin is supporting the particles against the relentless pull of gravity. Now spin is normally discussed in terms of a dimensionless parameter that ranges from 0, no spin, to 1, maximum spin. Though I guess you could also have spins down to -1 if the black hole is spinning in the opposite direction from the accretion disk. Now, as spin increases, r_{isco} decreases. by a factor of 6, shrinking down to the size of the event horizon. And this sets what many scientists think is the

maximum spin a black hole can have. Because if the minimum stable orbit were the size of the event horizon, Then light could escape from the black hole, allowing us to see into the singularity. This is called a naked singularity, and it makes a lot of scientists uncomfortable. As yet, there isn't a strong theoretical reason why a black hole can't exceed this maximum spin, It's just that we haven't seen one, and the thought of an exposed singularity just kind of... feels wrong. Most suspect the maximum real-world spin parameter is around 0.998. So how can you use r_{isco} to measure the spin of a black hole? Well first, let's think of how we measure the size of anything far away from us in deep space, like the radius of a star. Most stars are so far away that they're simply point objects in our telescopes. So how can you figure out their radii? Well, first, look at the spectrum of their light. By seeing how red-shifted absorption lines are, you can determine how far away the star is. The spectrum also tells you the temperature of the star -- Because it should approximate a black-body curve. And now the power radiated per unit area is strongly dependent on its temperature. So if you know how bright the star appears from Earth, how far away it is, and how much power its radiating per unit area, Well, then you could work out its area and hence its radius. You can actually do something very similar for a black hole's accretion disk. Just instead of estimating the radius of a glowing sphere, you're estimating the radius of the dark circle, r_{isco} , in the middle of the glowing accretion disk. Then you can use r_{isco} to find the spin parameter. This has been done for a number of black holes, revealing spin parameters from around 0.1 up to close to the maximum. But this method only works if the radiation from the black hole is dominated by black-body radiation from the accretion disk. which, often, it's not. Another approach involves looking at x-rays emitted by iron around a black hole. Some black holes show a distinct iron emission line. But instead of the single frequency you'd expect, the line is broadened by factors like the Doppler shift due to the high velocity of the iron in the accretion disk. and gravitational redshift, due to the extreme gravitational fields close to the black hole. By looking at the low-energy limit of the iron emission line, you can determine how close the black hole it was emitted. And hence, r_{isco} . But what if there is no bright iron emission line? Well, luckily, there is a third way. And that, is to look for periodic oscillations in the data. Like the repeated x-rays observed every 131 seconds. The thinking is, these cycles must be caused by clumps of matter orbiting the black hole. And at frequencies that high, they must be orbiting very close in, probably near r_{isco} . Even

that close, they'd be going half the speed of light. But what kind of clumps or objects would these be? Well the study's authors argue that the best candidate involves an unlikely scenario: Years before the tidal disruption event, they propose that there was a white dwarf star in orbit around this black hole. Now, it might be stable, orbiting in this way, for perhaps one or two hundred years. By itself it wouldn't be visible from Earth. But then the other star wandered by, and was ripped apart in the tidal disruption event. Its mass fell in towards the black hole forming an accretion disk. With the addition of this stellar debris, the white dwarf was cloaked in glowing matter, creating an x-ray hotspot orbiting the black hole, and its period would directly relate to the spin of the black hole. In this case, the measured spin parameter turned out to be at least 0.7 and possibly as high as the theoretical maximum of 0.998, meaning objects in the accretion disk were going at least half the speed of light. This is the first measurement of spin made possible by a tidal disruption event. The implication is that this could provide a method for determining the spin of black holes. Particularly ones that have been dormant, which is about 95% of supermassive black holes. If they shred a star, we get insight into their spin. Now why is this important? Well, because it helps us understand the origins of black holes. If supermassive black holes grow in size mainly by feeding on a steady stream of matter from within their own galaxy, You'd expect their spins to be very large, because the angular momentum of that matter would be more or less aligned. so it would add up over time. But if instead, supermassive black holes grow predominantly by merging with other black holes, You might expect their spins to be lower, because the spins of two black holes are likely to be randomly oriented rather than aligned. As we are able to measure the spins of more black holes in different ways, farther out and therefore further back in time, We should be able to better understand their growth. And since supermassive black holes lie at the center of most galaxies, They also lie at the center of an understanding of how those galaxies have formed and evolved over billions of years.

1.2. Appendix B – Video Transcripts from Kurzgesagt – In a Nutshell

1. Black Holes Explained – From Birth to Death

- URL: <https://www.youtube.com/watch?v=e-P5IFTqB98&t=172s>

- Publication Date: Dec 15, 2015
- Duration: 05:55
- Transcript: Black holes are one of the strangest things in existence. They don't seem to make any sense at all. Where do they come from... ...and what happens if you fall into one? Stars are incredibly massive collections of mostly hydrogen atoms that collapsed from enormous gas cloud under their own gravity. In their core, nuclear fusion crushes hydrogen atoms into helium releasing a tremendous amount of energy. This energy, in the form of radiation, pushes against gravity, maintaining a delicate balance between the two forces. As long as there is fusion in the core, a star remains stable enough. But for stars with way more mass than our own sun the heat and pressure at the core allow them to fuse heavier elements until they reach iron. Unlike all the elements that went before, the fusion process that creates iron doesn't generate any energy. Iron builds up at the center of the star until it reaches a critical amount and the balance between radiation and gravity is suddenly broken. The core collapses. Within a fraction of a second, the star implodes. Moving at about the quarter of the speed of light, feeding even more mass into the core. It's at this very moment that all the heavier elements in the universe are created, as the star dies, in a super nova explosion. This produces either a neutron star, or if the star is massive enough, the entire mass of the core collapses into a black hole. If you looked at a black hole, what you'd really be seeing is the event horizon. Anything that crosses the event horizon needs to be travelling faster than the speed of light to escape. In other words, its impossible. So we just see a black sphere reflecting nothing. But if the event horizon is the black part, what is the "hole" part of the black hole? The singularity. We're not sure what it is exactly. A singularity may be indefinitely dense, meaning all its mass is concentrated into a single point in space with no surface or volume, or something completely different. Right now, we just don't know. its like a "dividing by zero" error. By the way, black holes do not suck things up like a vacuum cleaner, If we were to swap the sun for an equally massive black hole, nothing much would change for earth, except that we would freeze to death, of course. what would happen to you if you fell into a black hole? The experience of time is different around black holes, from the outside, you seem to slow down as you approach the event horizon, so time passes slower for you. at some point, you would appear to freeze in time, slowly turn red, and disappear. While from your perspective, you can watch the rest of the universe in fast forward, kind of like seeing into the future. Right now, we don't know what happens next, but we think it could be one of two things: One, you die a quick

death. A black hole curves space so much, that once you cross the event horizon, there is only one possible direction. you can take this - literally - inside the event horizon, you can only go in one direction. Its like being in a really tight alley that closes behind you after each step. The mass of a black hole is so concentrated, at some point even tiny distances of a few centimeters would means that gravity acts with millions of times more force on different parts of your body. Your cells get torn apart, as your body stretches more and more, until you are a hot stream of plasma, one atom wide. Two, you die a very quick death. Very soon after you cross the event horizon, you would hit a firewall and be terminated in an instant. Neither of these options are particularly pleasant. How soon you would die depends on the mass of the black hole. A smaller black hole would kill you before you even enter its event horizon, while you probably could travel inside a super size massive black hole for quite a while. As a rule of thumb, the further away from the singularity you are, the longer you live. Black holes come in different sizes. There are stellar mass black holes, with a few times the mass of sun, and the diameter of an asteroid. And then there are the super massive black holes, which are found at the heart of every galaxy, and have been feeding for billions of years. Currently, the largest super massive black hole known, is S5 0014+81. 40 billion times the mass of our sun. It is 236.7 billion kilometers in diameter, which is 47 times the distance from the sun to Pluto. As powerful as black holes are, they will eventually evaporate through a process called Hawking radiation. To understand how this works, we have to look at empty space. Empty space is not really empty, but filled with virtual particles popping into existence and annihilating each other again. When this happens right on the edge of a black hole, one of the virtual particles will be drawn into the black hole, and the other will escape and become a real particle. So the black hole is losing energy. This happens incredibly slowly at first, and gets faster as the black hole becomes smaller. When it arrives at the mass of a large asteroid, its radiating at room temperature. When it has the mass of a mountain, it radiates with about the heat of our sun. and in the last second of its life, the black hole radiates away with the energy of billions of nuclear bombs in a huge explosion. But this process is incredibly slow, The biggest black holes we know, might take up a googol year to evaporate. This is so long that when the last black hole radiates away, nobody will be around to witness it. The universe will have become uninhabitable, long before then. This is not the end of our story, there are loads more interesting ideas about black holes, we'll explore them in part 2.

2. What Happens If You Destroy A Black Hole?

- URL: <https://www.youtube.com/watch?v=cFslUSyfZPc>
- Publication Date: Aug 16, 2023
- Duration: 10:25
- Transcript: Black holes can destroy everything – but can they be destroyed? What happens if we push physics to the absolute limits, maybe even break it and the universe in the process? Let's create a tiny black hole, about the mass of our moon, in the Kurzgesagt Labs and try to rip it apart. Nuke It Big booms break things. So to set the mood, let's explode the world's entire nuclear arsenal around our black hole! Boom Black holes swallow whatever crosses their event horizon, matter and energy. And since $E = mc^2$, all the energy that enters a black hole increases its mass. The mass of a black hole is proportional to its size, so as we nuke our tiny black hole, it just gets bigger and more massive! Antimatter Matter and antimatter annihilate each other. What will happen if we throw a moon's mass of antimatter at it? Unfortunately, when an object enters a black hole, the black hole will completely delete its past identity – whether it's made of matter or of antimatter. Black holes only care about gravity, which only depends on the total mass-energy of an object. And the mass of a particle is the same as its corresponding antiparticle, so throwing an anti-moon has the same effect as throwing a moon. The black hole just gets more massive! This “deleting ability” of black holes is pretty interesting: It means that, despite their size and power, black holes are, in a way, similar to elementary particles. An elementary particle, like an electron, is an extremely simple object, fully specified by just three numbers: its mass, spin and charge. And amazingly, the same is true for black holes. They have a mass, they can rotate and carry an electric charge. Once a black hole forms, it doesn't matter if it came from a collapsed star, an anti-star or a banana: it will always be fully described by those three numbers, nothing else. But if a black hole is basically a weird particle – could we destroy it with an anti black hole? Anti Black Hole How exciting! A particle has the same mass as its corresponding antiparticle but opposite charge. Since a black hole has mass and electric charge, its corresponding anti black hole should have the same mass and opposite electric charge. What if we make them collide? Sadly, the charge will just add up and cancel out. So after the collision, we'll just get a new black hole twice as massive with no charge. OK. We need to think bigger and stretch physics harder. Destroy the Event Horizon It is true that a black hole can carry spin and charge. But even for these crazy

objects, there are limits. If the spin or the charge of a black hole becomes too large, something really weird will happen: the event horizon will dissolve. In a simplified way, we think of black holes as hiding a singularity inside – an infinitely compressed mass with such strong gravity that absolutely nothing can escape from its surroundings, not even light. This is why a black hole looks like a “black sphere of nothingness”. The event horizon is the outer edge of this ultimate prison. Cross it, and you’ll never be able to come back. But when a black hole rotates, it works a bit like a spinning washing machine. It is as if the rotation wants to repel nearby objects and push them out of the black hole – which doesn’t happen because its gravity is so strong. BUT – If the rotation gets too fast, this effect will win and the event horizon will disappear – nearby objects won’t be imprisoned forever anymore! The same thing happens with the electric charge. Make it too large, and our ironclad jail will break open. If we managed to destroy the event horizon, the singularity would still be there. And objects would still naturally fall towards it. If you hit it, you would still die horribly and quickly. But the vicinity of the singularity won’t be an inescapable prison anymore! You could get as close as you want and come back. This should count as destroying the black hole! Can we do it? Overfeeding. All we have to do is to overcharge or over-spin the black hole. We could do this by throwing objects with a small mass and a lot of charge or angular momentum, so that the charge or spin increases faster than the mass. We have to overfeed the black hole until it reaches the point where it breaks open. However, whether you can actually do this is the subject of passionate argument among physicists. Think of a charged black hole. Equal charges repel each other, and the more of the same charges you squish together, the more they push back. So let’s say that we have a negatively charged black hole and we want to overfeed it with electrons, for example, whose charge is far larger than its mass. The electrons will feel an electrostatic repulsion. And the more electrons we throw, the larger the negative charge of the black hole will be and the stronger the repulsion. But once we reach the upper limit, the electrostatic repulsion will be so strong that it won't allow any more electrons to come in. At this point, the black hole will refuse to be overfed. With the spin it works similarly. Once the black hole reaches its upper limit, it won’t gobble more spin. But some scientists have discovered what looks like a loophole. If an instant before the black hole reaches the limit, we throw the right amount matter in just the right way, it looks like we could actually overfeed it. Most scientists are skeptical, but let's give it a try anyway! Breaking Physics. There is a catch though. The event horizon of a black hole hides the singularity. So destroying the horizon would

leave us with a “naked singularity”, one that is not hidden by an event horizon. And this poses a problem: it could mean the end of physics as we know it. There is a big dirty secret about black holes. Contrary to widespread belief, the singularity of a black hole is not really “at its center”. No. It is in the future of whatever crosses the horizon. Black holes warp the universe so drastically that, at the event horizon, space and time switch their roles. Once you cross it, falling towards the center means going towards the future. That’s why you cannot escape: Stopping your fall and turning back would be just as impossible as stopping time and traveling to the past. So the singularity is actually in your future, not “in front of you”. And just like you can’t see your own future, you won’t see the singularity until you hit it. But you also can’t hit something that is in your future, only sort of... experience it, like you will experience your next birthday when it happens. So you will feel the singularity once it happens to you. Singularities that are in the future are not a problem because we can’t see them or interact with them. But a naked singularity would be in front of us, for all of us to see. What would we see? Well, the whole point is that it’s impossible to know. A singularity is a region of infinite gravity, and gravity is the bending of spacetime. At a singularity, the bending is so radical that the fabric of spacetime is literally broken. Space and time don’t exist anymore. This means that you cannot predict anything, since predicting means making a forecast about where and when something will happen. But “where” and “when” have lost their meaning! So we have an unpredictable thing with infinite gravity, and therefore infinite energy. This means that anything could come out of it for no reason – from a pile of bananas, to lost socks or a solar system. Predictability, causality and physics as we know it would break down. We think that singularities should exist in nature because we can prove that, under very general conditions, gravitational collapse leads to the formation of singularities. However, scientists think that nature forbids the formation of naked singularities. Something enforces the creation of an event horizon around them, to prevent their insanity from infecting the rest of the universe. Without event horizons, physics may not make sense at all. So although black holes have been portrayed as the ultimate monsters of the universe, they may actually be the heroes that keep us safe from the madness of singularities. So if we do destroy the horizon, we might destroy the fundamental rules of the universe. You know what? Let’s not do that. The Safe Option As far as we know, there’s just one safe method to destroy a black hole: Wait. All black holes emit tiny particles – a phenomenon called Hawking radiation. This process causes them to slowly lose mass until they eventually “evaporate”, leaving behind no horizon

and no naked singularity. The time it takes for a black hole to completely evaporate depends on its mass. For our mini black hole the size of a speck of dust, it will be about 10^{44} years: 10 billion trillion trillion times the present age of the universe. So, is it possible to destroy a black hole? Yes! We just have to wait. But you don't have to wait that long.

3. What If You Fall into a Black Hole?

- URL: <https://www.youtube.com/watch?v=QqsLTNkzvaY>
- Publication Date: Apr 27, 2021
- Duration: 12:17
- Transcript: Black holes are the most powerful and extreme things in the universe and they are wildly weird and complicated. What would happen if you fell inside one and what are they really? First we need to talk about space and time: Space and time are the grand stage where the play of the universe unfolds. But space isn't a fixed stage and time doesn't tick the same for everyone everywhere. In short, they are relative. Matter bends space and bent space tells matter how to move. Put some stars and planets on the stage, and it sags underneath them. That misshapen stage, with all its little warps and dips, gives us gravity. Black holes do not just bend the stage, they are like trap doors. Places with so much mass that the universe formed a 'no-go' zone where the rules change. Most black holes form when very massive stars die. We explained this process in detail in our neutron star video – all you need to know, that in the final moments of really massive stars, their insides implode, at nearly a quarter of the speed of light. This packs so much mass, so close together that it creates something so dense that it sort of breaks the stage of the universe. A black hole with ten times the mass of the sun would be barely 60 kilometers across. If you look directly at a black hole it looks like... nothing. The space under their control is blocked by an invisible, one-way border called the event horizon. The event horizon forms a shell around a region of space that, once entered, is shielded from the rest of the universe forever. Because the black hole trap door deforms space so much, not even light can escape it. And with nothing escaping to transfer information from the inside, it's impossible to tell what it really looks like. We still can observe black holes because of their effect on matter. Things can orbit black holes just as they can orbit the sun or a planet. Many black holes have discs of matter orbiting outside the event horizon. This matter can become incredibly hot as close orbits can

speed this matter up to half the speed of light, and tiny amounts of friction and collisions between particles heat them to a billion degrees, making the space around these black holes, ironically, incredibly bright. What would happen if you would try to get close, or even inside a black hole? First of all, you would see the strangest funhouse mirror in the universe. Matter isn't the only thing orbiting a black hole: gravity is so strong near them that light can orbit too. If you hovered just outside the event horizon, at the photon sphere, in any direction you'd just see... yourself! Straight ahead would be the back of your own head, as light from your back travels around the black hole to your eyes. Gravity also alters the passage of time itself. The stronger the gravity, the slower time passes. While you watch the universe above you speed up, those far away will watch you in slow motion. If you chose to fly away from the black hole, you might find that eons have passed for the rest of the universe, a freakish one-way time-travel trip to the future where your loved ones are long dead. But getting close to a black hole can be incredibly dangerous. A painful death by 'spaghettification' awaits you. Because your feet are closer to the black hole than your head they feel a stronger pull of gravity, enough to pull you apart. As you descend it gets worse, the pulling gets stronger, your body squeezed thinner and straighter until you've been reduced to a thin stream of hot plasma, gobbled up in one final slurp, never to be seen again. Spaghettification is only a risk with smaller black holes, since they have much smaller radii. If you go to the center of a galaxy and find a supermassive black hole, you might be able to experience crossing the event horizon. As you approach the event horizon, a distant observer would think they never saw you enter it, seeing you stop and fade. The last light you emit trickling up and out, away from the event horizon. Meanwhile, from your perspective the void of the black hole rises up to meet you, as light from fewer directions can reach you. The blackness envelopes you until your only view of the universe you left is a tiny spot of light. Here, inside the event horizon, space and time are so horribly broken that real time travel is possible, so it's probably a good thing that nothing gets out. If anything could escape it could create all sorts of time travel paradoxes and issues that break the universe. As scary as the event horizon is, it keeps us safe from that drama. Whether you have survived this long doesn't really matter, as now there is only the certainty of crushing death in your near future. Inside the event horizon space time itself is so bent and warped, that whatever direction you move here, every "forward" you go, leads only towards the center of the black hole. Trying to go any direction only brings you to the center faster. To survive the longest, you must do: nothing. In the center of the black

hole, we find the singularity. A single point with all the matter that has ever crossed the event horizon, all crushed to a point infinitely small. There is no memory of the things that made it as stuff disappears down the black hole trapdoor forever. The singularity makes all things equal. This actually breaks the universe in really cool ways. We made a whole video about this problem if you want to learn more. But in a nutshell, everything that comes too close becomes black hole matter, concentrated at the singularity. This lack of a memory of its past, means that a black hole has only three properties: their mass, spin, and electric charge. Everything else is lost. They're a lot like fundamental particles in that respect. This actually means that every single black hole in the universe is the same. Sure, their mass is different and some spin faster than others. But If we were to put all the singularities into a magical physics museum, they would be identical, like electrons. But just like fundamental particles, the properties of singularities are the best ways we can describe them on paper, rather than an accurate representation of reality. Our current theories about the Universe, namely general relativity, are just not able to describe or explain them. The curvature of space becomes infinite, density becomes infinite, and our rules just don't make sense. The singularity has no surface or size, something like a divide-by-zero error in the universe. So singularities might not even exist or be completely different things. But this is all we know right now, from the best prediction we have, from our best current theory of spacetime. Also, basically everything you've ever heard about black holes, even in this video, is about theoretical black holes that aren't spinning, because their math is so much easier. But since black holes were born from dying stars that were spinning extremely quickly in their last moments, as far as we know, all black holes in the universe should be spinning right now. At incredible speeds too, up to 90 % the speed of light. This means in reality, black holes are even more screwed up than they usually get credit for. The singularities of rotating black holes are even wilder. The rotation causes them to swell outwards into a sort of singularity. This rotation is so powerful, that space itself is dragged along. This creates another region around spinning black holes, called the Ergosphere where it's impossible to stay still, no matter how hard you try. Like a rushing whirlpool of spacetime, the tide is irresistible and black hole makes you orbit it whether you want to or not. Ok. So what will happen with black holes as the universe ages and dies around them? Again, we don't know but have some ideas based on our current understanding of physics: Hawking radiation. In quantum field theory the vacuum of space is boiling with quantum fluctuations. These fluctuations are creating matter and antimatter pairs

of particles from nothing which only exist for a very short time before annihilating. When this happens near the event horizon of a black hole, one of these particles can fall in, stopping them from annihilating. The escaping particle is Hawking radiation. Ultimately, the mass of this particle must come from the black hole, so over eons black holes will shrink and radiate away. Hawking radiation is not the stuff that fell into the black hole, it's new stuff, stealing mass from it. As the black hole shrinks the Hawking radiation gets stronger, faster and faster, until what's left eventually evaporates in a flash of high energy radiation like a nuclear bomb. And then, nothing. But that won't happen for a long long time. A black hole with the mass of our sun has a lifetime of 10^{67} years. Which means that it would take 10,000 billion, billion, billion, billion, billion, billion years, to lose 0.0000001% of its mass. But most black holes are way more massive than our sun. The most massive supermassive black holes in the centers of galaxies have lifetimes of 10^{100} years. How long is that? Imagine an hourglass, filled with one grain of sand for every single particle in the universe. Every ten billion years one single grain of sand falls to the bottom. If we waited for the entire sand to fall down, not even a percent of the lifetimes of these black holes would have passed. There is no good concept for our brains to grasp these time scales. Will we ever truly understand black holes? Really know what's going on inside them? No one knows. We can only see their outsides, and the theories we have probably get their insides wrong. But it's okay to not know everything. It just means there is still work to be done. It means there are still mysteries to solve and big ideas to think about, which is why humans do science.

1.3.Appendix C – Video Transcripts from TED-Ed

1. Could the Earth be swallowed by a black hole? - Fabio Pacucci

- URL: <https://www.youtube.com/watch?v=e9TLbZuvsko>
- Publication Date: Sep 20, 2018
- Duration: 05:10
- Transcript: From asteroids capable of destroying entire species, to gamma-ray bursts and supernovae that could exterminate life on Earth, outer space has no shortage of forces that could wreak havoc on our tiny planet. But there's something in space that seems more terrifying than any of these —something that wipes out everything it comes near. Could the Earth be swallowed by a black hole? A black hole is an object so dense that space and time around it are inescapably modified, warped into an

infinite sink. Nothing, not even light, can move fast enough to escape a black hole's gravitational pull once it passes a certain boundary, known as the event horizon. Thus, a black hole is like a cosmic vacuum cleaner with infinite capacity, gobbling up everything in its path, and letting nothing out. To determine whether a black hole could swallow the Earth, we first have to figure out where they are. But since they don't emit light, how's that possible? Fortunately, we're able to observe their effect on the space around them. When matter approaches a black hole, the immense gravitational field accelerates it to high speed. This emits an enormous amount of light. And for objects too far away to be sucked in, the massive gravitational force still affects their orbits. If we observe several stars orbiting around an apparently empty point, a black hole could be leading the dance. Similarly, light that passes close enough to an event horizon will be deflected in a phenomenon known as gravitational lensing. Most of the black holes that we've found can be thought of as two main types. The smaller ones, called stellar mass black holes, have a mass up to 100 times larger than that of our sun. They're formed when a massive star consumes all its nuclear fuel and its core collapses. We've observed several of these objects as close as 3000 light-years away, and there could be up to 100 million small black holes just in the Milky Way galaxy. So should we be worried? Probably not. Despite their large mass, stellar black holes only have a radius of around 300 kilometers or less, making the chances of a direct hit with us miniscule. Although because their gravitational fields can affect a planet from a large distance, they could be dangerous even without a direct collision. If a typical stellar-mass black hole were to pass in the region of Neptune, the orbit of the Earth would be considerably modified, with dire results. Still, the combination of how small they are and how vast the galaxy is means that stellar black holes don't give us much to worry about. But we still have to meet the second type: supermassive black holes. These have masses millions or billions times greater than that of our sun and have event horizons that could span billions of kilometers. These giants have grown to immense proportions by swallowing matter and merging with other black holes. Unlike their stellar cousins, supermassive black holes aren't wandering through space. Instead, they lie at the center of galaxies, including our own. Our solar system is in a stable orbit around a supermassive black hole that resides at the center of the Milky Way, at a safe distance of 25,000 light-years. But that could change. If our galaxy collides with another, the Earth could be thrown towards the galactic center, close enough to the supermassive

black hole to be eventually swallowed up. In fact, a collision with the Andromeda Galaxy is predicted to happen 4 billion years from now, which may not be great news for our home planet. But before we judge them too harshly, black holes aren't simply agents of destruction. They played a crucial role in the formation of galaxies, the building blocks of our universe. Far from being shadowy characters in the cosmic play, black holes have fundamentally contributed in making the universe a bright and astonishing place.

2. Hawking's black hole paradox explained - Fabio Pacucci

- URL: https://www.youtube.com/watch?v=r5Pcqkhmp_0
- Publication Date: Oct 22, 2019
- Duration: 05:37
- Transcript: Scientists work on the boundaries of the unknown, where every new piece of knowledge forms a path into a void of uncertainty. And nothing is more uncertain— or potentially enlightening— than a paradox. Throughout history, paradoxes have threatened to undermine everything we know, and just as often, they've reshaped our understanding of the world. Today, one of the biggest paradoxes in the universe threatens to unravel the fields of general relativity and quantum mechanics: the black hole information paradox. To understand this paradox, we first need to define what we mean by "information." Typically, the information we talk about is visible to the naked eye. For example, this kind of information tells us that an apple is red, round, and shiny. But physicists are more concerned with quantum information. This refers to the quantum properties of all the particles that make up that apple, such as their position, velocity and spin. Every object in the universe is composed of particles with unique quantum properties. This idea is evoked most significantly in a vital law of physics: the total amount of quantum information in the Universe must be conserved. Even if you destroy an object beyond recognition, its quantum information is never permanently deleted. And theoretically, knowledge of that information would allow us to recreate the object from its particle components. Conservation of information isn't just an arbitrary rule, but a mathematical necessity, upon which much of modern science is built. But around black holes, those foundations get shaken. When an apple enters a black hole, it seems as though it leaves the universe, and all its quantum information

becomes irretrievably lost. However, this doesn't immediately break the laws of physics. The information is out of sight, but it might still exist within the black hole's mysterious void. Alternatively, some theories suggest that information doesn't even make it inside the black hole at all. Seen from outside, it's as if the apple's quantum information is encoded on the surface layer of the black hole, called the event horizon. As the black hole's mass increases, the surface of the event horizon increases as well. So it's possible that as a black hole swallows an object, it also grows large enough to conserve the object's quantum information. But whether information is conserved inside the black hole or on its surface, the laws of physics remain intact—until you account for Hawking Radiation. Discovered by Stephen Hawking in 1974, this phenomenon shows that black holes are gradually evaporating. Over incredibly long periods of time black holes lose mass as they shed particles away from their event horizons. Critically, it seems as though the evaporating particles are unrelated to the information the black hole encodes—suggesting that a black hole and all the quantum information it contains could be completely erased. Does that quantum information truly disappear? If not, where does it go? While the evaporation process would take an incredibly long time, the questions it raises for physics are far more urgent. The destruction of information would force us to rewrite some of our most fundamental scientific paradigms. But fortunately, in science, every paradox is an opportunity for new discoveries. Researchers are investigating a broad range of possible solutions to the Information Paradox. Some have theorized that information actually is encoded in the escaping radiation, in some way we can't yet understand. Others have suggested the paradox is just a misunderstanding of how general relativity and quantum field theory interact. Respectively, these two theories describe the largest and smallest physical phenomena, and they're notoriously difficult to combine. Some researchers argue that a solution to this and many other paradoxes will come naturally with a “unified theory of everything.” But perhaps the most mind-bending theory to come from exploring this paradox is the holographic principle. Expanding on the idea that the 2D surface of an event horizon can store quantum information, this principle suggests that the very boundary of the observable universe is also a 2D surface encoded with information about real, 3D objects. If this is true, it's possible that reality as we know it is just a holographic projection of that information. If proven, any of these theories would open up new questions to explore, while still preserving

our current models of the universe. But it's also possible that those models are wrong! Either way, this paradox has already helped us take another step into the unknown.

1.4.Appendix D – Video Transcripts from SciShow Space

1. Black Holes: The Hungriest Things in the Universe | Compilation

- URL: https://www.youtube.com/watch?v=V_j1nJoLtv0
- Publication Date: Nov 26, 2021
- Duration: 32:23
- Transcript: You might think that when you sit down for a holiday dinner you are so hungry that you could eat everything in the universe but you cannot because you are not a black hole. black holes might be the hungriest things out there consuming everything that comes close enough to get sucked in but does that mean that we should be worried about them the short answer is no here's the long answer 26000 light years away a supermassive black hole is spinning at the center of our galaxy a black hole as wide as the orbit of mercury a black hole more than four million times as massive as the sun and everything in the galaxy is swirling around it so does that mean that the black hole is dragging everything into it until there's nothing left like a cosmic drain in the great space bathtub that we call the milky way in short no black holes have gotten a bad rap so let's set some things straight a black hole is just an object that is so dense that as you approach it the velocity you'd need to break free of its gravitation known as escape velocity exceeds the speed of light this means that within a certain distance from the center of the black hole not even light travels fast enough to escape and nothing can travel faster than light so nothing can escape and while that might sound a little bit terrifying to you the first thing you should know about our resident black hole which is named sagittarius a star is that it's not terribly big for its kind black holes are generally divided into two classes that are hugely different in size first there are stellar mass black holes which have the mass of several to maybe a few dozen suns these are formed from supernova explosions of giant stars at the end of their lifetimes then there are supermassive black holes which include the one at the center of our galaxy astronomers don't know for sure how supermassive black holes form but ours is actually pretty small with just 4 million times the mass of the sun compared to those at the centers of some other galaxies

which are more than 100 million times the mass of the sun so that makes our black hole sound nice and non-threatening right but the much more important fact is a black hole's gravity doesn't just suck things in like some sort of cosmic vacuum cleaner most things in our galaxy are so far away from it that they barely even feel the black hole's gravitation in fact here on earth the gravitational pull of a person standing 30 feet away from you is 10 000 times stronger than the gravitational pull of our galaxy's distant supermassive black hole and even objects that are a lot closer to it will most often just fall into an elliptical orbit around it the fact is our galaxy is orbiting sagittarius a star just like we're orbiting the sun but we're not getting drawn into it but i'm not saying that hanging out near a black hole is going to be pleasant or even comfortable in fact i don't recommend it at all this is partly because of the effect created by clouds of gas that form around black holes called accretion disks these disks of gas become superheated producing strong emissions at x-ray and radio wavelengths so in the immediate area of a typical supermassive black hole there is a lot of rather unfriendly high-energy radiation flying around and another concern if you happen to find yourself in the metro area of a black hole is tidal forces these forces are exerted because one side of a body like a planet or moon is closer to the massive object than the other side that closer side feels a stronger gravitational pull than the far one does and the closer that body gets to the massive object the bigger the difference becomes eventually this difference becomes so great that it causes the body to start stretching out now the boundary that stakes out the maximum danger zone around any black hole is its event horizon this is the distance from the center where the escape velocity equals the speed of light for our black hole the event horizon is about 30 percent the average distance between the earth and the sun so outside that range an object orbiting the black hole would be far enough away that the tidal forces wouldn't do too much harm but if the object manages to cross the event horizon then basically all bets are off the side that's closer to the black hole would begin to accelerate faster than the farther side creating an inescapable stretching force that physicists rather delightfully refer to as spaghettification so yes if you found yourself inside the event horizon your noodle would essentially be cooked nonetheless you don't have to worry your intelligent little head about any of that because our galaxy is orbiting sagittarius a star you can rest assured that the sun the earth and everything else is going to keep on turning blissfully unaware of the supermassive black hole at the heart of our galaxy I don't know about you but i

always feel better after watching that video there's a soothing feeling that comes from the knowledge that it is very unlikely that you will be sucked into a black hole tomorrow but just in case you can always arm yourself with some knowledge so here's some of the cool ways that those black holes could form do you think you can make a black hole out of light that might sound like a trick question or like something right out of the shower thought subreddit but physicists say that it should be possible to create a black hole out of nothing but light called a kugelblitz after the german word for ball lightning even though they have no idea what would actually happen if you tried to do it before we talk about that though let's talk about the more standard black holes usually a black hole forms when a lot of matter is packed into very little space which increases its density if the matter is dense enough the gravity at its surface becomes so strong that nothing not even light can escape its clutches so to make earth into a black hole you would have to compress its 6 trillion trillion kilograms of rock and water and metal down into a sphere with a diameter of just 16 millimeters that's how dense i'm talking about but we're just getting started here einstein taught us that $E = mc^2$ in other words that the energy stored in a bit of matter is equal to its mass times the speed of light squared this means that there are huge amounts of energy in tiny bits of matter like atoms which is the basic idea behind nuclear power and nuclear weapons it also means that energy can sometimes act like matter now light doesn't have any mass but it does have energy and thanks to $E = mc^2$ gravity can't tell the difference between energy and matter and pulls on them both and this raises an interesting possibility all it takes to make a black hole is to pack a bunch of matter into one place and gravity treats light just like it treats matter so you could theoretically make a black hole out of nothing but light a kugelblitz creating a kugelblitz would take a really really incredible amount of light though because now we're working with einstein's famous equation in the opposite direction before we had a tiny amount of matter producing a huge amount of energy now we have to supply a ton of energy in the form of light for it to act like tiny bits of matter so let's go back to that hypothetical black hole with the mass of earth if we wanted to make the same black hole out of light how much light would we need all of the lights on earth all of the sunlight that hits the earth in a day in a year what about all of the sunlight put out by the sun over the course of an entire year not even close to get an earth mass kugelblitz we would need all of the light put out over 10 years by all of the stars within 350 light years

of earth all squished into a bit of space the size of a mosquito okay that's a lot of light but what if we wanted to make a black hole that was way way smaller like at the mass of a big cruise ship like the titanic about 50 million kilograms to make a kugelblitz that small you would need to squeeze all of the sunlight that hit earth last year into a volume 8 000 times smaller than a proton it is hard to imagine how so much light could get shoved into one place or any sort of technology that could accomplish even a fraction of that in the foreseeable future but even if it could happen there is another problem making a kugel blitz means that you have to pump so much light energy into such a tiny region of space that it would get really hot since heat is just a form of energy we're talking hotter than the universe was a hundredth of a millionth of a trillionth of a trillionth of a second after the big bang and that extreme temperature physics as we know it sort of stops working space turns soupy gravity is nonsense and we have no idea how to describe anything so if space gets that hot gravity might go haywire and not be able to form black holes at all anymore or maybe gravity would get super strong and form a black hole with a million times less energy than we think it should take right now we just don't know we might never know for now it seems like kugelblitz's might be theoretically possible based on einstein's basic equations relating energy and mass it's a cool idea using lots of highly focused light to create a black hole something that even light can't escape from but we have no idea how we or the universe would make one or even if there's some undiscovered law of nature that forbids it from existing it's a little meta to think about a masochistic light that forms a black hole that other light can't escape from but hey black holes are intense and if you thought the kugelblitz is intense you will want to watch reed's video about some other maybe even more extreme black holes black holes are some of the most extreme astronomical objects out there they're dense enough to pack the mass of the earth into the size of a marble and at the heart of each one is a point of infinite density where space and time cease to exist but even among these extreme objects there are extraordinary ones we're talking black holes that grow larger consume more and spin faster than all the rest by finding and studying these outliers astronomers get a glimpse of physics at its limits here are three of the most intense black holes helping them do just that the most massive black hole astronomers have directly measured is located 825 million light years away in the galaxy home 15a it weighs in at around 40 billion solar masses but it didn't start out that big to reach its mass it had to

consume almost all the matter around it leaving basically a ghost town around its galaxy's center according to a study submitted to the astrophysical journal in July 2019 this likely happened when two black holes merged as they danced around each other whatever matter they didn't devour got ejected out of the region now while this whopper holds the current record pitting the blue ribbon on the most massive black hole isn't an easy job since black holes swallow up light we can't directly see them which means astronomers have to get creative about their measurements they got this one's mass by looking at how its gravity pulls on nearby stars but they can also use less direct methods to gauge the mass of a black hole like looking at the spectral lines or chemical fingerprints in the light surrounding it the shape of those lines can tell them how fast the source of that light is moving this method is less precise but scientists used it to measure one black hole that might be around 66 billion solar masses and another could be as much as 100 billion it's hard to say for sure how accurate these measurements are but regardless of whoever ends up with the crown all of these objects will help astronomers figure out if there's an ultimate mass black holes can achieve because we're not actually sure about that the next type of extreme black hole consumes an enormous amount of matter most supermassive black holes including the one at the center of our own galaxy are kind of lazy the occasional morsel might fall to its doom but for the most part stuff orbits far enough away that they barely eat anything there's a small group of them though literally the one percent that astronomers call active meaning they're constantly gobbling up matter around them we find this type of black hole in a region called an active galactic nucleus or agn the agn contains the black hole its accretion disk and the surrounding donut of dust and gas as these black holes devour matter the agn emits light in some cases outshining all the stars in the galaxy the hungriest black hole ever detected fuels an agn around 12 billion light years away in one of the oldest galaxies we can detect it devours a mass equivalent to our sun every two earth days and it shines as bright as 700 trillion suns for comparison if this thing were at the center of the milky way we could see it as a pin prick of light shining ten times brighter than a full moon and that's about twice as luminous as typical agm this discovery was so surprising that the team of astronomers that found it had to check that the brightness they detected wasn't exaggerated by any other phenomena for example many agns have bright jets of particles streaming out of either side but follow-up research suggested no jets and nothing else that could be boosting the

signal so it looks like this agn is just naturally brilliant the third extreme black hole is the fastest spinner that prize goes to the black hole known as well this and it's located in our very own milky way black holes spin because of a principle called conservation of angular momentum you've seen that principle in action if you've ever watched an ice skater spin faster as they pull their arms closer to their body a similar thing happens with black holes most black holes start out as the collapsed cores of massive stars those stars have some small amount of spin and as the center collapses into a black hole that spin gets faster except with black holes there's a little catch for a given mass there's a maximum speed if a black hole has too much spin it will actually release some of the energy in its system until it slows down to below that limit so rather than saying that a black hole rotates however many times a second astronomers assign it a so-called spin parameter that gives its speed as a percent of how fast it physically could spin the current prize holder as of january 2019 is rotating at between 92 and 95 of its speed limit so it might not be the fastest spinning black hole ever but so far it's the one spinning closest to its physical limit astronomers can't measure a spinning black hole itself of course so they rely on clues in the light around it but actually measuring a black hole spin is pretty complicated since there's a lot of light interfering with the signal as a result astronomers only have accurate measurements for half a dozen black holes with really high spin parameters meaning again this title could be up for grabs but as our technology improves and we find new record setters these extreme black holes will keep giving us ways to test our predictions about the limits of physics and reality as we know it so that's the birth and life of some awesome black holes but black holes aren't just our cool space neighbors as you might imagine from their name black holes have a dark side they have the power to consume everything around them so here is how black holes can overpower stars black holes are one of the most extremely dense objects in the known universe but even they can level up within the hearts of the largest galaxies you can find black holes with masses exceeding a billion times that of our sun and a fraction of these has superpowers all their own like driving a cosmic engine that outshines the rest of the galaxy and even serving as birth control for stars in the late 1950s astronomers began matching point-like radio signals in the night sky with optical signals coming from the same spot that visible light was also a point like all the stars we're used to seeing but when astronomers split up the light into its different colors they noticed that the combination of colors did not follow the pattern

for any known type of star so astronomers called them qsos quasi-stellar objects they're commonly known today as quasars short for quasi-stellar radio sources well it turned out the light looked different because the quasars were far away they were very far away far enough that the universe's expansion could noticeably stretch out the light waves on their way to us the amount of stretching could tell us these quasars were billions of light years away so in order to be visible to us a quasar would need to be super bright up to thousands of times brighter than all of the starlight in an entire galaxy an impressive feat considering that some of them are as small as a single solar system scientists did eventually learn how all of this is possible a quasar is a type of active galactic nucleus or agn to make one you need a supermassive black hole at the heart of the galaxy that is actively slurping up matter around it all that matter gets heated up through friction as it spirals down into the black hole becoming so hot it starts to visibly glow but because that black hole engine is so powerful the effect is a bit more intense than what you see happening in the coils of your space heater the brightest quasar we've found so far is as bright as 600 trillion suns but being bright isn't good enough for these guys between 20 and 50 of agns produce a kind of space wind astronomers call outflow where light and other particles are thrust out in all directions from the quasar at the center of the galaxy well the next question was how much of an influence this outflowing material could have on the rest of the galaxy like could it redistribute energy or matter so much it prevented a bunch of baby stars from forming or actually make a bunch of new baby stars astronomers have been looking for an answer for decades and just a few years ago the jury was still out a series of papers published in the astrophysical journal supplement series back in 2020 has thrown some additional data into the ring focusing on a narrow range of light we get from quasars high energy uv wavelengths these wavelengths are formed after the outflow smashes into the matter around the galaxy raising temperatures billions of degrees that means a lot of the light these outflows emit is in the ultraviolet and x-ray part of the electromagnetic spectrum the team behind these papers wanted to investigate both how fast these outflows were moving through the galaxy and how far they extended from the galactic center to determine if an agn had an effect on its galaxy to get those measurements they collected the spectra of 10 different quasars across several years using the hubble space telescope spectra are like chemical fingerprints dips in the signal at different wavelengths of light called troughs correspond to different elements flowing toward

us and away from the agn hubble provided clear signals from quasars up to 9.4 billion light years away and the super high energy uv part of the spectrum has way more troughs to analyze than longer uv wavelengths while also covering about 90 of the matter in the outflows across seven papers the team reported a number of results in one case studying 13 outflows from four quasar they found that nine of those outflows had extended anywhere from 326 to 6523 light years beyond their galactic centers although that outflow is smaller than what a galaxy measures across they are still bigger than what quasar models previously predicted in another paper they report on the same outflow but measured twice about three years apart they found that the outflow accelerated up to around 21 000 kilometers per second that's around 74 million kilometers per hour and they conclude that this new data suggests a quote-unquote large fraction of outflows produce aegean feedback which means that agm's influence how fast stars form in their galaxies in this case the gas that would have otherwise been cool enough to collapse down into baby stars suddenly gets too hot to handle and has to cool down all over again for them to form but the outflows can also push matter away one of the astronomers even said it's equivalent to hundreds of our suns in gas each year which could literally starve stellar nurseries of the material they need but the debate on outflows and feedback isn't settled completely 10 quasars is a tiny sample size especially compared to the millions we've catalogued new telescopes like the james webb space telescope will provide even better optics that will allow astronomers to view these distant beads of light in even better detail okay so black holes are the ultimate space eaters and space heaters they kind of win at space so when everything else in the universe dies they may be the last things left and the question is will we be there to see that day modern humans evolved a couple hundred thousand years ago and between ice ages volcanoes climate change earthquakes droughts floods and reddit being down sometimes we've seen some stuff but on cosmic time scales two or three hundred thousand years is just a drop in the bucket the longer we're around the more likely we are to witness something truly earth-shattering whether metaphorically or literally and someday if we're still here we'll have to face things like earth melting as it's engulfed by the sun or the sun going out or galaxies colliding one way or the other we're going to have to leave home if we want to survive and even if we had fancy starships how long could we actually outrun extinction before the universe became uninhabitable to us it's such a big question that we've made a special extra long episode about it because

the answer is a surprisingly long time now to be clear we probably won't have to leave home anytime soon so there's plenty of time to get our spaceships ready like we might hear a lot about climate change these days but no matter how destructive or disruptive it is researchers don't think that it will threaten our entire species there are plenty of variables to consider but overall the odds are pretty good that we'll get through it one way or another the same goes for one of the internet's favorite doomsday scenarios a super volcano even though that would be rough it probably couldn't take us all out there are just too many people spread throughout the world but we will have to leave earth someday because even if we dodge a huge asteroid impact or the takeover of artificial intelligence our planet will eventually stop being habitable thanks to the sun the sun brightens as it ages and generally that will make earth warmer over the next few hundred million years which will cause all kinds of problems for example rocks tend to erode more easily at higher temperatures so in the future more new rocky surfaces will be exposed to the atmosphere than today exposed rock can react with carbon dioxide so the more exposed rock there is the less CO_2 will be left in the atmosphere that might seem like a good thing given how worried are today about climate change but remember that plants need CO_2 like we need oxygen and according to some estimates in about 800 million years there actually won't be enough of the gas left in the atmosphere for photosynthesis if those estimates are right that would be the end of all life on earth bigger than a bacterium and they'd go extinct about a billion increasingly warm years later future people might prevent this by building something to block the extra sunlight or they could use repeated asteroid flybys to gravitationally inch earth's orbit away from the sun but they might also decide that earth just isn't worth it anymore and could leave the most obvious option would be to go to mars since its closest we'd still have to give the planet an atmosphere and a livable temperature but with a dash of terraforming we'd be fine although mars still won't be a permanent solution five or six billion years from now the sun will finally start running out of hydrogen fuel in its core after that it will fuse helium and it will start growing first it will engulf mercury and then venus and 7.6 billion years from now its outer layers will probably pass through earth's orbit too likely destroying almost everything we've ever built the people on mars wouldn't be much better off either mars will never fall into the sun but it will become too hot to be comfortable for life and with the sun so much closer solar radiation will rip apart any martian atmosphere our descendants tried to create but

we wouldn't be out of options yet because while the sun balloons the outer solar system may have it pretty good jupiter's moon europa and saturn's moon Enceladus are both ice covered today but they'll heat up as the sun expands and will eventually become water worlds and briefly we could live there but again that wouldn't last forever in fact we might be on the move after as little as a hundred thousand years once more because of the sun around that time the sun will have expanded so much that its outer layers will finally escape into space leaving behind a tiny white dwarf star surrounded by a big cloudy nebula comparatively speaking white dwarfs don't emanate much energy so the newly minted one at the center of the solar system will leave the remaining planets and moons as cold as interstellar space and without a good heat source there's no usable energy so any civilization that's still around we'll have to move on by this point though we'll probably just fold our dyson sphere into overhead compartments and head off to colonize some other planetary system because hey if we haven't figured out interstellar travel in seven billion years well we'll have a problem but let's assume we figure it out and don't spend the next forever binging netflix today the closest star is proxima centauri which is about four light years away it's a red dwarf star which means it will likely outlive the sun and it already has a potentially habitable planet but since red dwarfs also emit some seriously dangerous flares every now and then it might not be our best choice besides current estimates suggest that there are billions of planets out there that could support water so we have plenty of other options which is good because today there's really no way of knowing where proxima centauri will be that far in the future stellar orbits in the milky way naturally get rearranged over billions of years so proxima centauri might not be our closest neighbor anymore also and maybe more importantly the milky way won't exactly be a thing in seven billion years it will probably collide with the Andromeda galaxy even before the sun expands into the inner solar system or at the very least they'll pass close enough to each other to cause some chaos thankfully there's almost no chance of stars actually smashing into each other since stars are just too spread out but the collision will make long-term wayfinding tricky stars will be thrown all over the place while the new galaxy known as milkomeda takes shape over billions of years yes that is the real proposed nickname and no i don't support it so maybe the next star we'll go to hasn't been discovered yet or born and even if we do have the technology to leave the solar system we'll have to watch out for the dangers of interstellar space for example we'll

have to keep an eye out for supernovas since colliding gas clouds will produce lots of enormous short-lived stars that explode at the end of their lives and radiation from those explosions could easily wipe us out mid-journey but if we do learn to safely travel to new stars that would allow humans to keep thriving for a long time we're talking trillions of years because even when our new home star goes out we could hop over to another system as a bonus the formation of milkomeda will also make a good number of smaller longer-lived stars like our sun so we'll have a lot of options but even though trillions of years is an unimaginably long time it's not forever eventually all the sun-like stars in the universe will wink out one after another and there won't be enough big clouds of hydrogen-rich gas left to replace them but even then that won't be the end of humanity our corner of space will get darker and cooler since it will be lit mainly by tiny long-lasting red dwarfs but we could still survive around them like our ancestors hoveled around their flickering campfires we would have to find a way to live with the violent solar flares though or if nothing else we would have to find a way to harness the red dwarf's energy without being in the range of those flares but assuming we figure that out we'll be able to stay alive long into the future eventually though even those stars will die along with any remnants like white dwarfs and finally the universe will be black at this point our only decent source of energy will be black holes since there will still be plenty of those floating around with gas falling into them all the time if our descendants are surviving on homemade nuclear fusion power which seems likely considering all the stars will be gone they'll need that gas to keep making energy of course with black holes gobbling up that gas and the expansion of the universe spreading it out more and more diffusely it'll be hard for them to find enough fuel there will always be the odd proton or dead planet gliding through the vastness of empty space that we could somehow harness resources or energy from but just about everything else is eventually going into a black hole fortunately it will take a while for black holes to vacuum the universe and that's putting it lightly for you fans of metric prefixes astronomers estimate that it will be about a billion yatta years before there's pretty much nothing out there but black holes that's a billion trillion trillion years or a 1 with 33 zeros after it and i think we can agree that's a long time many physicists who are trying to combine everything we know about the universe into a single elegant idea think that coincidentally protons will decay after about this much time too and that would definitely be the end of all life but if they're wrong physicists and mathematicians

have found that even in that dark black hole-filled universe completely devoid of raw materials life could still persist they've discovered that if you dive close enough to a spinning black hole and drop something in it just the right way you can steal energy from the black hole itself the exact mechanism for how it works is pretty complicated and at the end of the day no one is totally sure if you could power civilization this way but for now we think it's still an option and we have time to figure out the details then again black holes aren't forever either in 1974 stephen hawking published his discovery that black holes very very slowly radiate energy in a process now known as hawking radiation hawking radiation is incredibly weak for any reasonably large black hole so it's not like we could use it to heat our space colonies but the important part is that it causes black holes to slowly shrink and after almost a google years that's a one with a hundred zeros after it even the biggest black holes in the universe will evaporate due to hawking radiation after that it's hard to imagine any kind of life flourishing there won't be many atoms left and any energy will be so uniform that we won't really be able to do anything with it this is known as the heat death of the universe and it's how today's best cosmological models predict the universe will finally end even here though there may be the tiniest glimmer of hope in 1979 the physicist freeman dyson the same guy who made dyson spheres famous imagined an organism that worked kind of like a computer when it's on it uses energy to think or do something and when it's sleeping it does essentially nothing dyson was able to show that by sleeping longer and longer between each pair of thoughts the organism could live an infinite amount of time but only ever use a tiny bit of energy so with a big enough battery this thing could last forever and that brings us to our final thought by this point in time humans might not technically be humans anymore thanks to evolution in fact we might have changed so much that nobody will remember that time when we had ten fingers and breakable bones and disease realistically that day could come much sooner than trillions of years from now so maybe we could become or even choose to become this weird species that waits a quadrillion years between thoughts maybe we'll decide that that's worth immortality or maybe we'll just decide we've lived long enough but hey we have a long time to sort out those decisions in the meantime the best thing we can do is keep taking care of the planet we have so we can make the most of the next 800 million years because ultimately scientists can tell us a lot about what the universe will be like in the far off future but as for what humans will do until then well that's

up to us the universe is born black holes eat everything and then the universe dies what an easygoing existence you'd have if you were just a black hole just exist and eat until the end of time.

1.5. Appendix E – Video Transcripts from Cool Worlds

1. Why Black Holes Break The Universe

- URL: <https://youtu.be/m1EZG6RZsyg?si=NyEJbj9xGBb38Txv>
- Publication Date: Apr 20, 2024
- Duration: 22:04
- Transcript: Tonight, my friends, we stand on the brink of a feat unparalleled in space exploration. I will travel where no man has dared to go. - Into the black hole? - Why, that's crazy! Black holes are the abysses of the universe. They're not really a thing, but rather a region of spacetime folded into an embrace so tight that even light is forever ensnared. And it's this nihilism that poses a major problem for theoretical physics, one which could unravel our very understanding of the universe itself. How does a black hole trap light? If I throw a ball into the air, it falls back down to Earth due to gravity following a curve, or at least to me it looks like a curve. But really the ball is following the shortest line, also called a geodesic, and it's spacetime that's truly curved. It's the mass of the Earth that curves spacetime, and if we made it heavier, then we'd increase that curvature and thus the ball would appear to follow a tighter curve back to the ground. Curiously then, although we often speak of gravity as a force, in this picture that Einstein painted for us, there is no force, just curved spacetime. Now, if I threw the ball hard enough, it would travel higher and thus take longer to come back down. And if I threw it really hard, I could give it enough speed that it totally escaped Earth's gravity and flew out into deep space. The minimum speed needed to achieve this is known as the escape velocity, and classically it can be solved by setting the kinetic energy of the ball equal to its gravitational potential energy. In 1783, John Mitchell did exactly that for a beam of light. He predicted that there should exist a certain mass, which is so great that the escape velocity equals the speed of light. Mitchell called these dark stars, but nobody really took them very seriously until GR came along. That's Einstein's theory of general relativity. While serving for Germany during the First World War, Karl Schwarzschild found a solution to GR, something that Einstein did not expect to be

achieved so easily, but his solution researched the possibility of these dark stars, something considered implausible by Einstein, and many others. By 1971, the astronomical discovery of Cygnus X-1 provided the first evidence that this wasn't a trick of the math, but a real phenomenon, a black hole as physicist John Wheeler later dubbed them. Of course, since then we've accumulated a wealth of observational support for their existence, from x-ray binaries to tidal disruption events, from gravitational wave astronomy to direct imaging. These enigmas that were so distasteful to Einstein are now understood to be a critical component to the universe, for example, with a super massive black hole appearing to be located in the center of every galaxy. Black holes are intoxicating because of their finality, an absolute end. Anything that falls in can never come out, but that also raises a problem. They seemingly destroy information for breakfast. In quantum theory, a basic precept is so-called unitarity, which essentially states that all processes are, in principle, reversible. For example, if I throw a book into a fire, it will quickly smolder, burn, and dissipate away, into fine particles of smoke and ash. In principle, unitarity dictates that we should be able to collect up all of those particles, piece them back together and reconstruct every word on every page. Of course, in practice you'd never be able to pull this off, but in theory, it is possible. This principle of unitarity is often cast as a conservation law for information akin to the conservation laws that we have for energy and momentum. But really, it's best to think of it as a statement of reversibility. Starting from some initial state, we should be able to calculate the final state and vice versa, from the final state, we can go back and calculate the initial state, hence reversible. The black holes are the cosmic wrecking ball to the principle of unitarity. If I throw a book into the black hole, then those words, that information becomes trapped within a region of spacetime from which nothing can escape. It's true that the book's mass will cause a slight ripple in spacetime as it falls in, like the black hole merge events observed by LIGO recently. But it turns out that those gravitational waves do not carry enough information away with them to reconstruct the words on the page. Now, as that book falls further into that dark abyss far beyond the event horizon, it will eventually reach the singularity. We usually think of the singularity as a location in space, the center of a black hole. But really, the warping of spacetime is so severe here that space and time swap roles. And really, the singularity is best described as a future moment in time, a point in our future from which we cannot avoid reaching anymore than we can avoid

tomorrow from happening. What happens when you reach the singularity is anyone's guess, general relativity explodes to infinities at this point. This uncertainty gave us this hope that the apparent destruction of information was not real. Maybe the information just gets trapped right down there near the singularity or something. At the end of the day, it didn't really matter because black holes seemed to live forever, and hence, we never actually have to deal with this information loss. This convenient excuse fell apart when Stephen Hawking came along and showed that black holes don't live forever as initially assumed. Quantum theory demands that they slowly evaporate. The event horizon is just a region of empty space, and like all empty space, Heisenberg's Uncertainty Principle allows for the spontaneous creation of particle pairs fizzling in and out of existence. Usually, these particles form and merge within the briefest of intervals popping in and out of existence, so fast that the universe doesn't have a chance to notice and complain. But if this particle pair pops up either side of the event horizon, one can fall in and the other can escape. From the outside, the black hole seems to radiate energy away, which means by $E = mc^2$, it is losing mass. This Hawking radiation means that black holes are gradually, very, very gradually, losing mass, and thus they will eventually die. It's an unsettling thought. Not only do stars eventually die, but even black holes one day perish. So the fact that black holes die means that we cannot ignore the information that they gobbled up. By the principle of unitarity, we expect reversibility, so I should be able to collect up all that Hawking radiation like the smoke and ash from the fire and reconstruct the book. But Hawking radiation doesn't comply, which can be understood in two ways. First, according to general relativity, a black hole can be completely described by just three numbers, its mass, its spin, and its charge. It has no surface features, no texture, and we call this the no-hair theorem. As a result, the Hawking radiation they emit can be thought of as purely thermal radiation, heat, and in fact, the temperature of that heat is completely governed by the mass of the black hole. So if we collected up all the Hawking radiation, we could reconstruct the mass of everything that fell into the black hole over time, but we wouldn't be able to reconstruct the arrangement of the particles that go into that mass. We couldn't reconstruct the book. The second way to understand this is through quantum entanglement. When a pair of particles pop up on the horizon, they are always entangled. This means that they are described by not two-way functions, but by just one joint way function, which describes the

superposition of their states. So for example, this wave function might say that the sum of the spins of these two particles is zero, but it doesn't tell us which one is up nor which one is down. When we measure one of these two particles, the entanglement breaks and this measured particle is forced to choose one of those two states, which instantaneously causes the other particle to choose the opposite state. In this way, the ledger remains a balance. We don't accidentally end up with two up spins by mistake. By the way, if you're wondering, no, you cannot use this for faster than light communication, see our earlier video as to why. Now for Hawking radiation, this entanglement poses a barrier to getting information out of the black hole. Let's say that I threw into a black hole the information XY. For this information to escape, we can imagine one Hawking radiation particle escaping at some later time and carrying away the X, and then at an even later time, one carrying away the information Y. But the problem is how does that second emitted particle know to carry Y and not X? That implies that it somehow knows that X has already been emitted. So to keep apprised of the full ledger of emitted information, we need these emitted particles to be entangled to one another. Fine, but there's the problem, because remember that those Hawking radiation particles are already entangled to their negative energy partner that fell into the black hole. And entanglement, like lobsters, are strictly monogamous. There's no mistresses or swinger parties here. They cannot be polygamously entangled. So this means that we have a paradox. Now, whenever we have a paradox, we can typically resolve them by removing one of the assumptions upon which the paradox sits. So for example, with the famous Fermi paradox, which is where are all the aliens, we can resolve that by trivially removing the assumption that aliens exist. Paradox resolved. - No! No! (glass breaking) - So what are the assumptions here? Well, there are three basic ingredients, the principle of unitarity, which we've already met, and then on top of that, we have the equivalence principle, and locality. The equivalence principle is Einstein's happiest thought that if someone fell from a roof, they would not feel their own weight as if there were no gravity. A consequence of this is that when someone passes the event horizon of a black hole, they wouldn't actually experience anything different. They wouldn't notice any demarcation. So that means that outside the black hole we have just empty space. And, similarly, on the horizon, we also just have empty space, hence why Hawking radiation can occur there. The third preset is locality, which is the trickiest to explain, but essentially says that if you drop a

stone in a pond, the sound, the splash, and the resulting ripple don't happen everywhere at once, they are localized to a specific point. It's pretty hard to imagine classical physics without locality. And so you can see that all three of these precepts are foundational to modern physics, and it would be painful to give up any of them. So which is it? Well, we don't know, but certainly many physicists have come up with many different ideas. For example, in a famous wager by Hawking and Kip Thorne against John Preskill, they hedged that the information that falls into the black hole was irretrievably lost to the universe, although it has to be said that Hawking later changed his mind on this and conceded the bet. Roger Penrose is in this camp too. And indeed, his conformal cyclic cosmology model, which is a kind of cyclic universe scenario, critically depends on the condition that information is in fact lost inside black holes. But today, most of the community believe that unitarity is preserved and somehow the information does get out of the black hole, which means we have to update our theories of how black holes work. There are many ideas out there. There are several variations of the information simply dumped somewhere else, and this could be a baby universe inside the black hole, episodes where the black hole reverses into a white hole that spits out information or that the black hole is in fact a wormhole to somewhere else. Recently, the idea of many micro wormholes existing has been suggested. Perhaps the particle that falls in enters a tiny wormhole inside the event horizon that carries it back out, and that's why we see Hawking radiation. Zooming out, it's also been suggested that information is indeed lost in our universe, but at the multiverse level, information is still conserved. Personally, anything involving multiverses feels like any media cop out, it's kinda like saying aliens did it. And anything involving wormholes risks violating causality, which Hawking argued was sacred, but Hawking did concede the bet, remember. So what persuaded him that unitarity could be preserved? As strange as it sounds, a path towards resolution might come from holograms. - What about the droid attack on the Wookiees? - In 1993, Leonard Susskind suggested the notion of black hole complementarity. Someone who falls into the black hole indeed seems to carry their information past the horizon and eventually reach the singularity itself. But someone watching from the outside of the black hole wouldn't see this because of the extreme time dilation down here, they would see the astronaut actually seem to slow down in time as they approach the horizon and eventually even seem to freeze there. They wouldn't actually cross the threshold. Yet more, their

light is redshifted and warped around the black hole. From the outside, the in falling person appears to be smeared across the horizon into a quantum thin layer. Eventually, their information reradiates from this thin layer back out into space as Hawking radiation, and thus information is conserved. But this picture seems to violate and contradict the astronaut's own experience. Susskind suggested that both perspectives are right, and although they contradict, they can never actually come together to note the discrepancy, and thus the universe is actually okay with us. This creates the strange idea that the information is stuck there, hovering in this incredibly thin layer just above the surface of the event horizon. But a surface is a 2D geometry, and we usually think of black holes as 3D phenomena. Surely, a 3D object contains far more information than the 2D surface. It turns out not. In fact, this has now been proven mathematically that the information content of a black hole can always be completely described by just its 2D surface. Indeed, this has now been generalized to basically everything. All 3D volumes must follow this rule. They can never hold more information than that which can be contained by their 2D surfaces. Yet more, if you try to, you'd end up making a black hole, which also of course adheres to this rule. This is a holographic principle that all 3D phenomena can in fact be reduced down to a 2D representation. We are all holograms, empty projections, just ghostly shells, nothing more. This equivalency, formally known as the anti-de Sitter/conformal field theory correspondence is a stunning result, but it doesn't actually prove that we are all truthfully holograms, merely that this is an explanation which is fully compatible with everything we know about the universe. Nevertheless, it was enough to persuade Hawking to concede the bet. The unitarity principle appears to survive. But in its place we sacrificed one of those other three key precepts, locality, because now what originally seemed to be distinct 3D events are all in fact collapsed onto a 2D surface. But perhaps Hawking was premature to concede the bet, as Kip Thorne thought, who refused to concede, because despite the progress made, questions remain here. Remember that Hawking radiation stems from the particle pairs produced in the vacuum near the horizon, and thus they are monogamously entangled. And also remember that information leakage requires the Hawking radiation particles to be entangled to each other at different times. So we still have an apparent contradiction that requires solving, and as always, the best way to solve any paradox is to let go of one of your assumptions. What if the Hawking radiation particles do not emerge from an empty vacuum, but instead from

a something? In that case, the sum of two entangled states need not be zero, like spin up, spin down. Instead, they could sum to something because they didn't come from nothing, they came from something. In this way, information can get out of the black hole whilst preserving the rules of entanglement. The implication is unsettling, though, at the event horizon, there must exist a fiery thin layer known as the firewall, which incinerates anything that tries to fall into the black hole. If this idea bothers you, it should. Many physicists don't like it. After all, this violates the equivalence principle, being incinerated at the event horizon is hardly Einstein's happiest thought, and so many physicists are still reaching for some other explanation. Those baby universes don't sound quite so unappealing now, do they? A deeper issue in all of this is that yes, we can come up with many possible explanations to resolve the information paradox, but how do we prove them? Obviously, flying into a black hole would help, but you'd discover the answer and never be able to share it. You know, it would be incredibly cruel if the universe insisted upon this as the only way which she would allow us to unlock her secrets. The ultimate deal with the devil. - The equation couldn't reconcile relativity with quantum mechanics, you need more, more. - More what? - More data, you need to see into a black hole. - In principle, studying Hawking radiation would help since we can measure its entropy, for example, but Hawking radiation is so pitiful that there's really no hope of observationally measuring it. We'd have to build a micro black hole in the laboratory for this, and such energy scales are still far beyond our abilities, and so it's quite possible that this puzzle will be with us for a very long time, a puzzle of which we can dream up many allowed mathematical solutions to, but frustratingly, we just can't prove any of them. But working on this is still valuable in size, like the holographic principle are changing the way we approach fundamental physics and providing new mathematical tools to make further progress. In truth, studying black holes may be our best hope for a unified theory of quantum gravity, the secret sauce to the ultimate theory of everything. Who knew that studying something so dark could reveal so much? So until next time, stay thoughtful and stay curious.