Episode 80

Titanium Physicist
Episode 80: Picturing the Bach Hole
Physicists: Dr. Leo Stein, Dr. Katie Bouman
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Transcribed by Denny Henke

Never be afraid. There's nothing which is known which can't be understood. And there's nothing which is understood which can't be explained. For over fifty episodes now my team and I have brought you to the very frontier of knowledge in physics and astronomy. And still our mission goes on: to present you with your birthright, an understanding of the universe. I've traveled the world seeking out a certain type of genius, masters of not only their academic disciplines but also at explaining their research in understandable ways and I've bestowed upon these women and men the title of Titanium Physicist. You're listening to the Titanium Physicist Podcast and I'm Ben Tippett, and now allez physique!

Music

1:46

Ben: One of the joys I have in my new job as a physics and math instructor at the College of the Rockies is to teach a course called Introduction to Astronomy. Oh, it’s really neat, the class size is fairly small, the students are all first year. Most of them aren’t planning on being astronomers or physicists, they’re just, you know, interested in astronomy. And once a week there is a lab scheduled in the evening where you go up to the college rooftops with a bunch of telescopes and you learn to use them. Well, if it’s not cloudy or raining or snowing. And this year it was only not cloudy twice. But the stars in the Rocky Mountains are big and bright and you can see the Milky Way painted like a band of smoke from horizon to horizon. Anyway, in teaching the course I reflected a lot on how much has changed since I was in my students shoes. When I was 19 my astrophysics professor told us to get ready because the upcoming generation of telescopes were going to change everything. And he was right. Space-based x-ray and infrared telescopes and the refinement of huge, adaptive optics telescopes on Earth means that we can see space stuff with new and different and bigger eyes. And so, when I’m talking to my class of students, many ideas and explanations which I learned as conjecture or supposition have been confirmed and refined. It’s almost heartbreaking how far we’ve come in the last 20 years because honestly, seeing so much further, seeing so much deeper with so much more clarity, doesn’t just come from a momentary stroke of genius. It requires new instruments and strategy and technology and leadership and coordination of huge teams. You need to build the cameras yourself and you need to convince people to give you funding and you need to convince other people to help you and collaborate for decades. My heart swells to see the work that has gone into these projects. But among these victories there are a few which I never thought I would see. These are the really audacious projects, arrogant in their conceit and requiring technology which didn’t exist at the outset. To see things that no one was even sure exists. Requiring such precision and care and resources and coordination that I, a guy who can’t even get he car radio on the correct radio frequency without help, thought it would never be done. I’m talking about the Higgs Boson at CERN, I’m talking about the detection of black hole mergers a billion light years away with LIGO and I’m talking about the direct imaging of a black hole by the Event Horizon telescope. So many people needed to be right about so many things for these projects to work out that it really is a testament to their expertise but also their carefulness and their ingenuity and their faith in one another. And all I can do from my humble seat in a humble town in the Rocky Mountains is applaud them and appreciate their hard work. Today on the Titanium Physicists Podcast we’re talking about the Event Horizon Telescope and the first successful imaging of a black hole. Speaking of having to trust your collaborators, our guest today is in accomplished actor and improviser. Based out of Chicago and affiliated with the iO Theater he’s been performing and teaching improve since 2007. But if you don’t live in Chicago you’ve probably heard of him from the hit podcast “Hello From the Magic Tavern where he plays Chunt, the talking, shape-shifting king of the badgers. And he also has a new podcast called *Hey Riddle Riddle*. If you want to hear these podcasts, follow a link from our website. Welcome, today, to our show, Adal Rifai.

5:04

Adal: Thank you so much for having me.

Ben: Alright. So, Adal, understanding how a photo of a black hole was taken and understanding exactly what they were taking a photo of is a fairly ambitious task. Luckily for us, two amazing titanium physicists have decided to help us today. Arise Leo Stein.

Leo: Dodododoodoot.

Ben: Dr. Stein got his PhD from Massachusetts Institute of Technology and is currently an assistant professor at the University of Mississippi where he's an expert in testing and exploring beyond Einstein's theory of gravity. And arise Katie Bouman!

Katie: Ca caaaa.

Ben: Dr. Bouman is an expert on computational imaging. She got her PhD from the Massachusetts Institute of Technology where she worked on the Event Horizon Telescope. She's currently an assistant professor at CalTech in the department of computing and mathematical sciences. Alright everyone, let's start talking about black holes. Alright, Adal, did you hear the news, is this a familiar thing, when it came out?

Adal: I did. So, I saw the news appear on like, my twitter timeline and stuff like that. So, I, in passing, I flicked by it to see that there was some sort of blurry image taken. I did not read any of the articles about it. It did seem very exciting. But it seemed like, from what I could discern, it seemed like it was a fairly young woman working with the telescope, caught the image. Is that correct?

Ben: That's Dr. Katie Bouman. You're speaking to her.

Adal: Oh my gosh! You're the woman who got the photo?

Katie: Well, no, it was a big, big team. Many different people from around the world, actually, worked together to get it. It was just one little part of a big project.

Ben: So, today, the ambitious project is to explain, exactly, what you flicked past in those articles. Alright. So, we've got lots of time, we can do this. It will be fun. But we have to talk about what we were trying to look at, so, what a black hole is and the black hole, specifically, that we're looking at. We have to talk about, kind of, the basics of the instrument that they used and then we have to talk about, exactly how that instrument, the Event Horizon Telescope, put together all that data and it's a bonkers thing to talk about because it's a new aspect of astronomy that we've really gotten into in our modern age of super computers. It's fantastic. So, let's start by talking about black holes. Do you know anything about black holes Adal?

Adal: The extent of my knowledge of black holes is located entirely within the three and a half minutes of the song Blackhole Sun by Soundgarden.

Ben: Okay, right, so, they wash away the rain, primarily?

Adal: Exactly. Okay, here's my idiot take on it. Black hole, big thing in space, hole, stuff inside, suck inside, you go inside, you die.

Ben: Yeah, yeah, yeah.

Leo: You're pushing a lot of my buttons.

Ben: Oh, what, no, that's way better than Soundgarden explained it, honestly.

Katie: And also, I think we should change the Soundgarden lyrics to blackhole shadow instead of blackhole sun.

Ben: Oh, that's true, that's true. So, there's kinda one basic thing that you need to get to understand what a black hole is and it has to do with Einstein's theory of gravity. Ah, so, Einstein came around at the turn of the 1900s and wrote a bunch of papers and everybody thought he was super famous and great. But one of his greatest accomplishments as a scientist was that he came up with a new, extra explanation for how gravity works.

Adal: And this is the newest take since, like, Newton?

Ben: Yes, exactly. So, Isaac Newton imagined that there were, like, invisible strings between the moon and the earth or apples in your tree above your head. And these strings were pulling objects down towards the center of planets. So, depending on how much mass your moon or your apple had, the planet would pull harder or softer, alright. So, a big heavy thing is heavy because the planet is pulling it in harder, right?

Adal: Mmhmmm.

Ben: Einstein had a different take that was kind of bonkers and it's got a lot of attributes to it. You can spend years exploring all the ways it's different. But the basic idea here is that every object in the universe, and the universe itself, exists as something called spacetime. K. So, spacetime is, essentially, the big four dimensional sheet that everything lives on and in and over time you kind of move forward in spacetime like a little ant crawling around on a table. So Einstein's picture said that gravity wasn't caused by forces, it was caused by curvature in spacetime. So, the idea is the sun is sitting there right at the center of the solar system and it's causing spacetime to bend around it. It's kind of like, did you ever see, like, ah, a kid on a skateboard and they're just kind of riding a big curved skatepark, that the concrete in the skatepark will be bent and curved and the kid will be kinda going along a big, weird curved path?

Adal: Yes.

Ben: So, the trick to that is that they're not turning exactly. What they're doing is they are following the curvature. So, it's not like when you turn a car where you have to turn the steering wheel. Instead it's kind of like a NASCAR track where the curvature of the surface you are traveling over causes your path to bend.

10:02

So, the idea here is that it's not the sun pulling everything towards it, what it is, is, the sun causing spacetime to curve and then the pull that we think we feel toward the center of the objects is just us interacting with the curvature. The curvature of the spacetime is bending us towards things. Which is fine, you don't need to worry too much about that. But the big take away here is that, it's not that the object, the sun, is pulling us in. It's that the object is making curvature and then the curvature is what's causing us to move in towards it.

Katie: Sometimes, like, on the Discovery Channel, sometimes they show, they have planets on this grid and it kind of like, a rubber sheet kind of bending the space around it.

Ben: All we need to remember here is that it's not that the object is pulling us towards the middle, it's that the curvature is what's causing us to pull towards the middle. The object's causing the curvature and the curvature is what's causing you to go to the middle. Okay?

Adal: Gotchya.

Ben: So, what's a black hole? You know, earlier Katie Bouman said you shouldn't call it a black hole sun and said we should call it a black hole shadow.

Adal: Mmmhmmm.

Ben: A black hole forms when an object gets so heavy that its structure can't resist the gravitational crush of its own mass. So, the idea here is that if a star gets massive enough there aren't any forces that are strong enough to keep it from resisting its own collapse and it will collapse down to a point, okay? But the notable thing here is when it does so it leaves behind its gravitational curvature.

Adal: Okay.

Ben: So, a black hole isn't an object, it's just a gravitational footprint of a star that collapsed to a point.

Leo: Yeah, this is something that is really funny about general relativity. That in Newtonian gravity you need some stuff there, you need some, ah, you know, a table or a gas or some atoms or something to make a gravitational field. But in general relativity it has this weird property that a gravitational field can itself create a gravitational field. So, if you have a strong enough gravitational field it can just exist on its own and that's, essentially, what a black hole is. It's a gravitational field that's strong enough, like, you don't need any more matter there to create the gravitational field.

Adal: That's wild.

Ben: Yeah, nothing's there.

Adal: So, black holes always used to be stars, is that correct?

Leo: The ones that we know about that are about, say, 10x the mass of a typical star or 30 or 50x, those as far as we know, they used to be stars that then died. It's possible that some of those became black holes and some of them smashed into other black holes and so that's how they got to be 60 or a 100x the mass of of the sun. So, those kinds of black holes, they just used to be stars. But there are other types of black holes out there in the universe called super massive black holes that are like a million to a billion times the mass of the sun and those were not enormous stars that collapsed. Ah, we think that they kind of grew up in mass as the galaxy that they are in was also getting bigger and bigger. And it's not really totally understood whether it's the black hole that's driving how the galaxy grows or whether it's the galaxy that's controlling how the black hole grows. But we see these supermassive black holes in the centers of most galaxies.

Adal: So, if a star collides with another black hole you said it will become a black hole?

Leo: So, if two black holes collide then they'll just become a bigger black hole and if a star gets close enough to a black hole then that black hole is going to rip it apart and it might eat all of it but it might just eat part of it and fling the rest out into space and that can be seen. We call these things tidal disruption events.

Adal: Okay.

Leo: And so, there are optical and infrared and radio observations of, you know, just a spot in the sky that suddenly gets bright and then dim again and based upon the precise way in which the light gets bright and dark, people think that it's a star that's getting eaten by a black hole.

Adal: So, if a black hole is made by a star collapsing under its own weight, what causes a star to gain weight?

Ben: Yeah, it's kind of like, um, at the start of the day when you have lots of energy but by the end of the day when you can't hold your own weight up anymore because you're too tired.

Adal: (chuckles). So, like a 9 to 5...

Ben: Yeah, that's right.

Adal: Just kind of.

Ben: You just get worn down. Stars should collapse down to a point but they don't because they're hot. The inside of the star has something called nuclear fusion in it. It's a nuclear process that releases energy and so the insides of a star gets really, really, really hot and the heat of it plumps up the star and keeps it from collapsing. Um, but the deal with that is that it can run out of fuel. And so when a star gets really old, it burns through all of its fuel and it no longer has that heat to keep it puffed up and then it will start to collapse and might collapse down to a black hole.

15:06

Sometimes it collapses down into a solid object but if it's too heavy the solidity of that object is too weak to resist the gravitational contraction and it will keep collapsing down until it's a point. And then you just get a black hole because nothing's left.

Adal: Hmmmm.

Katie: But, you can also think in terms of physics in high school, you might have calculated the escape velocity you need to, given some mass of an object...

Adal: Not in my high school.

Katie: If you were on it. Well, you can calculate, basically, you know, how fast you have to shoot off of some massive object to escape it and go off to infinity. So, you could say, okay, the escape velocity is related to the mass of the object that you're trying to escape from and the radius of how far you are from it. So, you can also say, well, how big of an object does it have to be such that the escape velocity is faster than the speed of light. So, if the escape velocity is so fast I could never escape it. For instance, for your mass, you can calculate the radius you need to compress it all down so that you couldn't ever escape it's pull. So, for, basically, any sized object of some given mass, you can calculate the radius it needs to be that you need to smash it down to, to make it into a black hole. And so this can be done for any size object. So, you could have these stellar mass black holes, these black holes that Leo was talking about that are only 10s the size of the mass of our sun. But this can also happen for black holes that are a billion times the mass of our sun.

Ben: Alright, let's break down what Katie just said because this is a super important point to talking about the attributes of black holes. Because one attribute of a black hole called the event horizon is really crucial. Ah, the Event Horizon Telescope is named after it and it's the reason why this photograph that you saw is just so breathtaking. And the idea is the event horizon is very, very, very small.

Adal: And so this is, the event horizon is a physical descriptor of a black hole.

Ben: Yeah.

Adal: It's something you can visually see.

Leo: The event horizon is place in space time. So, instead of saying that a black hole is a point, I prefer to think of a black hole as having a size and that size comes from the event horizon. So, it's like the boundary of no return. So, if you cross the event horizon then you can't come back out. So, actually, if you were falling into a black hole and you had, like, a laser pointer with you, and you, right at the second that you're going through the event horizon, if you try to shoot the laser pointer back from where you are falling, and the light from the laser pointer, it's just going to live on the event horizon forever. So, it's the place in spacetime where photons that are going at the speed of light are moving out at the same speed that space itself falling into the black hole. So, they're kind of trying to go upstream just as fast as the stream is going down and they can't make any progress, that's what the event horizon is.

Adal: So, it's like, if you're at a party and you're having your fourth drink, it's that. It's the point of no return. Once I have this fourth drink I'm committing myself to a night of going until the morning and ah...

Ben: Yeah, yeah. Because once you're past there you just, you just keep drinking faster and faster and faster. Yeah, so, let's list together everything that we talked about because it's, it's understandable and it's important. So, Katie introduced the idea of an escape velocity. And the idea here is, let's say Superman was at your house, ah, what's the first thing you would ask Superman to do.

Adal: Wait outside while I clean-up.

Ben: No. you would say…

Adal: My house is a mess.

Ben: …take this object and throw it straight up and let's see how long it takes to fall, right? The same way you do if a major league pitcher showed up. You just like it when people go into your front yard and throw things straight up, right?

Adal: I mean, you and I have very different ideas of what we'd do with Superman but that's fine.

Ben: So, the idea here is, you've heard the old adage, what goes up must come down?

Adal: Mmmhmmmm.

Ben: Ah, that's not entirely true. If you throw something upwards fast enough it will have enough energy to escape the Earth's gravity, okay?

Adal: Okay.

Ben: So, the idea is that there's kind of a threshold between not quite moving fast enough and will eventually fall back down and moving so fast that it will never come back down. And that threshold is called the escape velocity. If you throw something upwards faster than the escape velocity it will escape. And if you throw it up slower than the escape velocity it will not escape and it will fall back down to earth. So, there's one big aspect to this which is that the escape velocity doesn't just depend on how massive the planet you're standing on is. It also depends on how small the planet is, how wide it is. If you go up to the moon's orbit, the idea is that the Earth's gravity is much weaker the farther out in orbit you get from the Earth, right, you know that?

Adal: Yeah.

Ben: Right. So, the idea here is that, out by the moon the Earth's escape velocity is lower than down here on Earth. Now, on Earth, that's as fast as the escape velocity goes for the Earth because you can't go into the Earth because the Earth is a solid object.

20:00

But, in these situations where you have like a black hole, the idea is that the surface of the star in this case can get as small as you need it to and so it's possible for there to be things that are so small but also heavy that the gravity at that point is so strong that objects that are traveling at the speed of light won't be able to make it out. They're stuck on the planet.

Adal: Okay.

Ben: That's the introduction to the concept of an event horizon. The idea is that when you have a black hole the object has collapsed to a point so all that's left is kind of its gravitational footprint and so, when we describe black holes we have to describe what they look like in terms of the gravity of the object instead of the characteristics. You know, if you have, like a planet, you could be like, it's a red planet or it's a green planet or it's a wide planet or it's a puffy planet. But when everything is collapsed down to a point, all that's left is the gravitational footprint, the spacetime geometry that's left behind. And so, when we talk about black holes, we're making reference specifically to the spacetime geometry. And there's going to be a distance away from the middle where the escape velocity is, essentially, faster than anything can move, the speed of light. And so, the idea here is, if you're outside the event horizon, you're far enough away, the escape velocity is small enough that things can make it up to infinity. But at the event horizon not even light can escape and if you're inside the event horizon, the pull towards the middle, the flow of spacetime is so fast that not even light can emerge out. So, the event horizon is kind of our descriptor of how big the black hole is. But it's also a descriptor of, if you're outside of it, you're fine, if you're inside of it you're going to get crushed to a point.

Katie: And that event horizon scales with how massive the black hole is. So, a more massive black hole has a larger radius, so that if you're within that radius, you know, you'll get crushed into the black hole. But a less massive, smaller black hole is going to have a smaller event horizon.

Adal: So, when you talk about being sucked into a black hole and you mentioned it should be called black hole shadow, is there an actual hole in terms of sucking something in, is that correct.

Ben: If you want to use the terminology of holes, the event horizon is like the lip of the hole where if you're inside it you're in the hole and if you're past the event horizon, if you're farther away from the middle then you are safe.

Adal: Just trying to wrap my brain around, like, what I've seen in movies. If you go into a black hole it's not that you end up somewhere else, right, it's not like a tear in the fabric of spacetime, right?

Ben: It's more like you're riding a river into a sinkhole. Actually, that's a pretty fun descriptor for it. It's like, imagine they we're in Antarctica and the glacier has melted and so we're in a lake, a fairly shallow lake.

Adal: Mmhmmm.

Ben: Maybe in our kayaks and that there's, somebody pulled the plug on the lake. So it's all draining into this hole in the middle, okay?

Adal: Mmmhmmm.

Ben: The idea here is that the closer you get to that hole the faster the water is rushing and the harder it will be to escape. And so the event horizon is like the point of no return threshold around that hole. If you get to close to this the water rushing into the hole is going too fast for you to kayak out.

Adal: Got it.

Katie: But you mention the shadow and that is because of stuff that is around the black hole, actually. So, black holes are cloaked by this event horizon where, you know, the extreme gravity is preventing even light from escaping them. But matter kind of, more falls into the black hole than being sucked in. And as gas is spinning around the black hole it's actually super heated to hundreds of billions of degrees, so that before it passes through this boundary and we can't see it anymore it actually shines very brightly. And so, what we expected to see for many years is that we would see the shadow, the dark shadow of a black hole on a backdrop of bright material. And so that is what we predicted we would see and we called this the black hole shadow.

Leo: Yeah, that's a very important point, that, you know, that if there wasn't any stuff around the black hole, if it was just a black hole sitting in space with nothing nearby it, then you wouldn't be able to see it. I mean, you might be able to see that something is there because of the way that it kind of lenses the stuff that is behind it. That's something that we could talk about how it deflects light but it doesn't emit any of its own light. It's not like a star so there's no light coming out of the black hole. So, otherwise it would just be black.

Adal: Earlier it was mentioned that you kind of have to describe a black hole by its footprint versus, you know, saying the color or anything like that. Besides the size of it, is there a uniformity to what black holes look like in terms of like, they look identical except for the size of the footprint?

Leo: Yeah, that's a really good question and, I mean, I think this is one of the beautiful things about general relativity. That all black holes in the universe, as far as we know, are just described by two numbers. Just how massive they are which is also how big they are and how fast they are spinning. So, just like planets and stars can spin, black holes can also spin. And so, just those two numbers are enough to describe every black hole in the universe.

Adal: I will say, at home, when I'm watching the Olympics, that's how I describe figure skaters is how big they are and how fast they are spinning. Those two numbers.

25:00

Katie: This is called the no hair theorem, actually. Where there's no additional hairs, no additional terms you have to consider when thinking about how a black hole affects the spacetime around it. Black holes are bald.

Leo: I really wish I knew the history of why it got called the no hair theorem. I think that there was probably somebody who was going bald who was working on black holes.

Ben: Oh no...

Adal: If I'm going through it so is space.

Ben: Yeah, that's right.

Adal: Just projecting, you know, projecting on to it. Katie, what are the two numbers of the black hole you discovered? Like, is it possible to say it on the podcast or are the numbers so fantastically long that it wouldn't make sense to.

Katie: Yeah, no, so that's a good question. So, as Leo said, astrophysical black holes, we believed would only be described by their mass and their spin if general relativity is correct. So, this completely describes the size and the shape of them. The mass is the one that has the largest imprint and so, we see the shadow, the circular shadow, a ring of light and the size of the ring scales with the mass of the black hole. And then the spin kind of changes the shape slightly. But it only changes it by about a 10% difference. So, it's a much smaller imprint, I guess, on the shadow that we see. And so the black hole that we took a picture of which is a black hole in the galaxy M87 which is about 55 million light years away from us, we think that the black hole has a mass of 6.5 billion solar masses which is very, very big. A very big black hole. But I, we, are unsure of the spin of the black hole although we believe it is spinning. But because the resolution of the telescope we use to get that picture, as you mentioned, we got a blurry picture, so we can't see that 10% difference with enough accuracy yet to say what the spin is. But hopefully in the future we can improve our instrument and take more measurements over time and learn more about it and try and nail that down too.

Adal: And just for clarification, this is the first picture, ever, of a black hole?

Katie: Yeah, so this is the first picture of what a black hole looks like on the scale of its event horizon. So, again, we're not seeing the black hole itself, we're seeing the shadow of the black hole. But we've never seen anything at that kind of scale, right up to the black hole's event horizon, before. And Leo had said, black holes are defined by the mass and spin, but this is under the assumption that Einstein's theory of general relativity is correct. So, one reason that we wanted to take a picture of a black hole, apart from it just being really neat to see the first picture of a black hole is to see, oh, does this theory hold at the extreme boundary where it is most likely to break down around a black hole where you have this super small thing with extreme gravity. And so, although we can't say that our picture proved that the theory of relativity is correct, it, at least, is consistent with the theory. So that was pretty exciting to see.

Adal: That's very exciting. I have to ask, do you have like a framed copy of this picture at home, like, on a desk, above a couch.

Katie: Not yet but maybe sometime soon.

Adal: A picture of you and a black hole on a roller coaster...

Laughter

Leo: You've got to make t-shirts.

Ben: Yeah!

Adal: Katie, if I was involved in the first picture of a black hole it would be a tattoo, probably a couple tattoos...

Laughter

Katie: I did get, for all our friends, removable tattoos that we put on the night of the announcement so it was fun. And maybe seven tattoos.

Adal: But it would be my Christmas card, it would be a tattoo, it would be in every room of my house. Instead of saying hello I'd be like, a black hole, that's not, just like a black hole, nobody would ever escape the fact that I took that picture.

Katie: Yeah, we were so excited to be able to finally tell everyone about it. Because I actually, we made this picture awhile ago and so, we haven't been able to print any pictures of it so far because we were trying to keep our mouths closed. We didn't want it to leak ahead of the announcement. So, soon, I'm sure we'll all get it printed up.

Adal: In the Milky Way, are there any black holes that we know of or is it just, like you said, if we can't see it or detect them we might stumble upon it one day? Are we certain that there are or not?

Ben: That's, okay, yeah, so that's a good question because it's got a couple answers. One of them is that there's different types of black holes. There's super massive black holes like the one the Event Horizon Telescope took a photo of. Ah, in the center of our galaxy, there is one. But, there are also, ones that are about the mass of the sun, floating around, in space, in orbit, in the galaxy, along with us.

Adal: Oh wait, they can, this is news to me. They can move around?

Ben: Ah, well yeah, well, I mean, stars move around the galaxy.

Adal: Yeah. I thought, for whatever reason, in my head, in my mind's eye, they were stationary and pulled things towards them.

Leo: Yeah, this is something that pushes my buttons, when people say that blackholes are like cosmic vacuum cleaners or that they suck. But really, when you're far away from a black hole they act really, really similar to just anything else of that same mass. So, you could have a black hole and an ordinary star just orbiting each other like, two stars orbit each other. And that was actually the first , like, concrete piece of evidence, back in 1963 or 1964...

Adal: Mmmhmmm.

30:01

Leo: We saw, I mean, we, none of us were born.

Adal: Yeah, you weren't alive then.

Laughter

Leo: But, astronomers saw x-rays coming from this object that is called Cygnus X-1 that's kind of an ordinary star that's in orbit with a black hole that is like 10 or 15 times the mass of the sun that's actually eating a bunch of the gas from the ordinary star and that's why we can see it. Because all that gas that's falling onto the black hole is getting really, really hot and emitting x-rays.

Adal: Wow.

Ben: So, to answer your question about whether or not we can see one coming, that answer has to do with whether or not there's any gas around it, in orbit around it, okay?

Adal: Gotchya.

Ben: So, if there was a black hole orbiting the Milky Way that decided to pass through our solar system, we could only see it coming if it passed between another star and us and we somehow caught that other starlight wobbling. That said, if the black hole coming towards us had gas around it, gas can orbit a black hole in the same way that gas can orbit a star. Like, the solar system has gas in orbit around the sun, it happens. But the gas orbiting a black hole can get a lot closer to the black hole than it can the sun. And so it will get really, really hot the closer it gets. And really, really hot gas emits radiation. Like, in the Cygnus X-1 case, it has gas in orbit really, really close to the black hole and that gas is really, really hot and we're using emissions from the gas to see where the black hole is. So, the deal here is, if there is gas around the black hole, you can tell where it is even though the black hole itself isn't emitting any light. So, when we talk about imaging a black hole, what we're looking at is the light that's emitted by the gas that is orbiting it and then a big black hole in the middle where no light is coming out of it.

Katie: But another aspect of it is that we need a very certain size black hole in order to see it because we don't have arbitrarily large telescope. So, actually, in order to see the black hole in this galaxy M87, which is 55 million light years away from us, we had to build a telescope, a virtual telescope that is the size of the entire Earth actually. Because, the bigger your telescope, the finer the detail you can see and so, it actually, for the wavelength that we needed to see that black hole at, we actually needed a telescope the size of the earth. So, this was a big part of the project where lots of people had to develop new instruments and new algorithms in order to make this virtual, Earth-sized telescope. And actually, within our own galaxy we know that there are lots of, as Ben said, lots of black holes of different masses. But there's actually a black hole at the center of the Milky Way galaxy called Sagittarius A star that is a super massive black hole. It's about 4 million times the mass of our sun and it shines very brightly and we do think that there is all this gas moving around it and that we'd be able to see it, also with the Event Horizon Telescope. Ah, because it is so big. So, actually, M87 is a much bigger black hole but it's much farther away and then the black hole in the center of our galaxy is relatively small, for a super massive black holes, but it's much closer to us. We think they appear about the same size and we'd be able to see them with this new instrument we've developed. But the hard part about Sagittarius A* which is in the center of the Milky Way is that because it's smaller, actually, gas orbits around it much more quickly than it does around the black hole in M87. And so that means it's evolving, it's breathing, over the course of just minutes. We need, actually, to collect data over a long period of time to make a picture. And so, over the course of a night the black hole has evolved and is moving and so we actually get a much, basically, we would get a blurry picture or we'd have to reconstruct some sort of video, actually, of the black hole moving. And so, taking a picture of our galaxy's black hole is much harder than taking a picture of the M87 black hole.

Adal: That's wild.

Katie: But the, in order to see smaller black holes we would have to build huge, enormous telescopes much bigger than the size of our Earth. And so we don't really have any hope of seeing any of those in the near future.

Adal: That's so insane to think about.

Leo: I just wanted to stress this point in case it wasn't obvious, black holes are literally the hardest thing, of their mass, to take a picture of in the universe. Because they are the smallest thing...

Adal: They're like bed bugs.

Leo: ... that, how are they like bed bugs?

Laughter

Adal: I don’t know, aren’t bed bugs famously hard to see? I’m, guys, I’m trying to relate. I don’t have a lot to add, every once in the while I’ll throw in a joke and hopefully it lands. It didn’t.

Katie: No, this is great.

Leo: Yeah, so, if you think of everything in the universe that has the same mass as the sun, you could have something that is the mass of the sun and a different size. So, a black hole that has the same mass as the sun, would be literally the smallest of any of those objects. So, it’s the hardest thing to take a picture of, of that mass.

Adal: That’s wild. And Katie, you said the one that’s in the center of the Milky Way is called Sagittarius A*.

Katie: Yes, that’s correct. Sometimes people call it Sag A star for short.

35:00

Adal: I mean, I would. Or SAS. Why the addition of A star?

Leo: Ah, I mean, I think that this is just the weird history of how people name things in astronomy. So, Sagittarius refers to the fact that it’s in the constellation Sagittarius.

Adal: Okay.

Leo: Which really has nothing to do with the fact that it’s in the middle of the Milky Way galaxy. That’s just like, where on the sky is it.

Adal: Gotchya.

Leo: And then, astronomers, being so creative, like to name things A, B, C, D starting with whichever thing they found first. So, the first thing is A and then the second thing is B.

Adal: Ohhhh. So, it’s like, okay, so it’s going in alphabetical order. It’s not A as in, a, like, you know, a dog.

Leo: Oh.

Adal: I see.

Leo: Yeah. And I think that the star is referring to the fact that it’s a radio observation. Cause people knew of all these ordinary stars in Sagittarius before they started doing radio observations in the 60s.

Ben: When we say Sagittarius A*, we don’t mean star. The phrase corresponds corresponds to an asterisk in the name. So, it’s Sagittarius A* and so we say star instead of asterisk.

Adal: Okay. Yeah, cause...

Katie: Yeah, it’s not like a star like our sun.

Adal: Gotchya, yeah, because my hang up was thinking like Chance the Rapper, where I was was like, oh, it’s the name and then what it does, what it is, right.

Katie: But I think the naming, still, it’s not completely well known why you’d choose certain things. So, for instance when we published the results of the black hole in M87 it was a big conversation if we’d add a star at the end. So, you know, so, I think it’s not well defined what the star means.

Adal: And did you?

Katie: We did add a star but you can either say the black hole in M87 or M87*.

Adal: Okay.

Katie: It’s more of what people pick up as the terminology with the rest of the community will use.

Ben: To add confusion to this, the reason it's called M87 is because there was an astronomer named Messier who took all the photos of the puffy things that didn't look like stars. So, these were galaxies I guess and so each of those is in a catalog called the Messier Catalog and has a number. And so there's an M1, an M2, an M3, all corresponding to different lines in the catalog. So, M87 corresponds to a galaxy. So, it's named M87 because it's line number 87 in the Messier catalog.

Adal: There's an electronic artist name M83 and now I'm suddenly realizing that that's probably what they named themselves after.

Ben: Oh, cool.

Adal: So, that's my biggest epiphany and take away from this podcast.

Ben: Okay, so, let's talk about the machine itself, ah, the Event Horizon Telescope because it's kind of bananas. The question is, how do you take a photo of something that is really, really tiny? Black holes are absolutely minuscule. Like, the sun is an enormous ball but if the sun turned into a black hole it would be smaller than a city. It would be like a couple miles across.

Leo: It would be three kilometers across.

Ben: Three kilometers across. That's like two miles. There's nothing to it. So, long story short, black holes are really, really tiny. And even if we talk about gas around them emitting light, the ring of gas around them that's emitting light is also very, very tiny.

Katie: Well, I agree with that completely although, because the black hole in M87 is so massive, 6.5 billion times the mass of our sun, actually, its event horizon is about the size of our solar system, or, past Pluto, the size of our solar system. So, it's, for how massive as it is, it's very small. But it's actually, I guess, big in the grand scheme of things.

Adal: Yeah.

Ben: So, long story short, what we do to take these photos. The first thing is you have to choose things that are big enough even though they are really far away. But there's another aspect to this that kind of comes into basic, basic astronomy. I've got a question Adal.

Adal: Yeah.

Ben: You know, like, good cameras, they have big lenses, right? Like, if you buy a really good SLR camera with, like, a telescope zoom, it has a huge lens on it.

Adal: Yeah, exactly. Anytime you see sporting events, all of the photographers, that are, yeah, the official, professional have those long telescopic lenses.

Ben: Why aren't these lenses getting smaller. You know how our iPhone cameras have teeny tiny lenses?

Adal: Mmmhmmm.

Ben: Why do we need huge lenses still?

Adal: To compensate...

Ben: To compensate, the answer is actually subtler than that because you can't get away from getting a big lens. And the reason has to do with kind of a limitation. It has a name called the Rayleigh criterion or the Rayleigh criterion, but don't worry about that, it's named after a person.

Adal: Sir Walter Rayleigh.

Leo: No, no, I think it's Lord Rayleigh.

Ben: It's a different Lord Rayleigh. But here's the basic idea. It has to do with, like, you know how there's lots of mega pixels on our cameras?

Adal: Mmhmm.

Ben: On our CCDs? The idea is the more megapixels you put in your camera the more refined a photograph you can take, right, the more detail.

40:00

Adal: Mmmhmm.

Ben: There's an upper limit to that. There's a limit past which putting more pixels on our film doesn't increase the resolution. And that limit has to do with the mathematical field of optics. Um, but the idea here is that the wider your telescope lens is, the finer resolution you can get, the more zoomed in you can get.

Adal: Okay.

Ben: The idea here is, if you used an iPhone camera to take the same zoomed in photograph for your sports thing that your professional photographer did, it might be that the object is so far away that even with all the megapixels in the world you're still going to get a blurry photograph because you need a wider lens to get that resolution into your film.

Adal: Gotchya. To take a picture of a black hole, flash, no flash?

Ben: No flash.

Leo: No, you need a backlight.

Ben: Yeah, it has to be backlit. So, the deal here is there are two limiting factors to the resolution that you could get in a photograph or in your instrument. One of them is how wide your lens is and the other is the wavelength of your light. Do you know anything about wavelengths at all?

Adal: Not really. No.

Ben: Okay, the idea is that light has different colors and every color can be described in terms of a wavelength. So, blues are short wavelength light and reds are long wavelength light. Does that ring any bells?

Adal: Yeah, I remember seeing a certain diagram in a book that's, ah, as I was reading it my eyes glossed over like a great white shark but, ah...

Ben: Essentially, that's what we're talking about. There is, there is a relation, a descriptor, a numerical descriptor for the kind of color, okay.

Adal: Okay.

Ben: And radio waves are also a type of a light and so we can describe them in terms of a wavelength. But the idea here is that the wavelength number for radio waves is really, really big. And what that means, in terms of your camera, is if you had a camera that could photograph radio waves it would need a really wide lens to be able to take high resolution photographs.

Adal: Okay.

Ben: This is actually one of the limiting factors because when we take a photo of these black holes we need to take it in these radio waves because that's the type of light that the gas around them is emitting. So, the deal is that they are tiny objects that are really, really far away and so you need a huge lens to even be able to see the detail.

Adal: Gotchya.

Ben: But, when you do the calculation for how big the lens needs to be it needs to be the size of the Earth.

Adal: Yeah, which Katie mentioned and said you accomplished.

Ben: Yeah, isn't that bananas!?

Adal: It's going to take me like a week to digest that because, yeah, my brain is still reeling from that concept.

Ben: Honestly, you would have heard of it if we built a telescope the size of the Earth. Right?

Adal: Or I'd see it when I looked out my window.

Ben: Exactly. It would be huge, it would be like, yeah, so, what did we do instead? There's a trick in astronomy called interferometry which means it's a measurement tool that uses interference.

Adal: Hmmmmm.

Ben: Have you ever seen, like, Contact, that movie where Jodie Foster sitting on a car

Adal: Yeah, with Jodie Foster...

Ben: Yeah and there's all those radio telescopes side by side, behind her? Right, so, the idea is that all those telescopes, side by side, they're putting their signals together in a way that makes it kind of like having a ten mile wide telescope.

Adal: Aw, they're like a family.

Ben: Yes.

Adal: They're helping each other out. That's like in improv, it's a team sport, it's a group effort.

Ben: Yeah.

Katie: Totally.

Ben: It is a group effort. You know, in improv, the different people have to yes/and each other?

Adal: I've heard of the concept. I don't practice it but I've heard of it.

Ben: Oh, I see, okay.

Adal: You've clearly never listened to...

Ben: The idea is that we can combine the signals from all these different stations, all these different smaller telescopes, you can combine them together to affectively make a really, really, really wide telescope but doing it is kind of tricky because you need all of the telescope signals to combine in a really specific way.

Katie: So, one analogy that my friend Michael Johnson who is also on the Event Horizon Telescope project, uses it a lot and, I think it might help to explain the idea of interferometry. Is, he says, okay, think about it, like, you are in a pond and there are a bunch of ducks in the center of the pond and they are kind of flapping around, moving their feet and causing ripples in the pond. And you don't know where the ducks are. So let's just say you see, there's this one duck flapping around and you sit on the shore and you see the waves as they come to you and you see they come up and down and up and down, you might not be able to, on your own, to figure out where the duck is but if you get a bunch of friends and you put them along the shore at different locations, then you can actually triangulate where the duck is coming from. And if you have multiple ducks kind of flopping around and you record the times that the waves are coming up and down and you compare them to the notes of your friends of when the waves are coming up and down, you can try to figure out where the ducks are in the middle of the pond.

45:00

And so, basically, we can't build a telescope the size of the Earth but by having different telescopes distributed across the globe and that they're all watching the waves of light coming from the black hole and recording it, we can bring them back to a common location, compare the wave forms at each point and figure out, oh, where is the light coming from. What is the structure of the light. Just like those ducks. So, that's kind of how it, I think, on a high level, it kind of works.

Adal: I love that analogy and also my brain is a terrible thing and immediately when you mentioned the analogy I started to think of quack-hole. It's not fun or enjoyable to say...

Ben: No, I enjoyed it!! That was great.

Adal: It's just what my brain did and I apologize for my brain in advance.

Laughter

Leo: So, Adal, so I have a question. What do you picture in your mind when you think of a radio telescope?

Adal: Oh boy. I don't even know, I mean, I don't know if I've seen one before.

Leo: Have you seen the giant bowl shaped dish in *Golden Eye*?

Adal: I've seen it in the N64 game I played it.

Leo: Yeah, so that's a giant radio telescope.

Adal: Oh, okay.

Leo: So, radio waves are coming down from space and hitting every little patch of that giant bowl and then bouncing back up to a receiver and that receiver can be in different places but the idea is that this dish is designed in such a way so that the radio waves bounce off of it and add together when they get to the receiver. And that's called constructive interference, where they add together in the right way. So, actually this giant dish would work if you just took big chunks out of it. You don't need the entire bowl there. You could actually get away with just, you know, little chunks of the dish and it would still, kind of act the same, you would just get a weaker signal. But what's important is just that time differences between the radio waves that are hitting different parts of it are the right time differences.

Ben: Yeah, the bowl is shaped in a really, really specific way so that, you know, let's say our telescope is focused at one specific point in the sky, it's made so that the light from that one point is going to bounce off the dish and then come together at a point in a way that amplifies the signal. But, if there's another point in the sky, like maybe a star right next to it that's just a little bit off center, light from that star, when it bounces off this very carefully shaped bowl, it won't get amplified. And so the bowl itself is constructed in such a really, really, really specific way so that only the little patch you're looking at will have its signal amplified. And everything else around it will be quieter.

Adal: Gotchya.

Ben: And so, you can use it to focus on one little patch of the sky instead of just getting noise.

Adal: Where is the Event Horizon Telescope located?

Katie: That is what is so cool, actually, it's not located anywhere in particular. It's all around the world. So, we have telescopes in Hawaii and in Spain and in Chile and Mexico, in Arizona and even at the South Pole. And so, in order for us to make a picture of a black hole, actually, all the telescopes kinda had to swivel and look at the black hole at the exact same time and what they do is that each telescope records the wave form so it essentially freezes the light that has seen on hard drives and these, this data is kind of time tagged. We have atomic clocks at each of the telescopes that says precisely what time that signal was recieved. And then later on, once they've all been recorded, we recorded petabytes of data, many, many, many hard drives are then, we shipped them together and process the data at a common location. So, just like if you had a big dish, right, where you're kind of just seeing pieces of the light and then later on we combine them, like the light of a single dish telescope, combines it physically, we combine it computationally. One thing that people sometimes get confused at is we don't actually take a picture at every telescope. We're only collecting the light. Like, a single stream of light. So, it's not like we take a picture at every telescope and then combine them together. We combine the light together to make the picture.

Adal: I don't think I'll ever fully understand this but the little I do is mind blowing.

Ben: Okay, you know how IKEA furniture works, right? Most furniture store have the dignity to get the parts and put it together and then you buy it complete. IKEA, they send it to you and then you have to put it together yourself.

Adal: Mmmhmm.

Ben: But you have the instructions to do so, so you know how each of them fits together. The idea here is that if we did have a telescope the size of the Earth then all that light would hit all of the different parts of the bowl and then bounce back to the center and amplify itself. But instead of building it, what we do is we take a bunch of little individual telescopes and we receive their signal and it's like the unpacked IKEA furniture, you see. If I was a huge bowl, the bowl would combine and collect all these different pieces of data together to give us this couch. So, what we're going to do is instead of building this giant bowl, we're just going to collect the information and say hey, if it was a bowl, this is how that bowl would combine all the information.

Adal: Okay.

Ben: But to do it, to build the IKEA furniture, you need to know exactly when each signal was captured by each telescope.

50:02

Adal: So, that's why you had the time stamp, yeah.

Ben: Yeah, so you time stamp each and every data collection point and what that tells you is if it were a bowl this is what each part of the bowl would be receiving and bouncing towards the middle. And then we artificially combine them together when we get that flack-pack billy bookshelf home.

Adal: Can you do another analogy but with ducks now?

Katie: In the case of the duck analogy, if you put a person, if we all put ourselves along the edge of the pond and we all stood shoulder to shoulder, that would be like a dish the size of the earth. But now we, I only have so many friends, I don't have many friends. So my few friends stand along the edges of the pond and we don't see the wave form at every location as it hits the shore...

Adal: But you still have enough eyes to try...

Katie: ... but at some locations and so we try to combine the information.

Adal: That's wonderful.

Katie: Yeah. And I also think we missed one thing that might help, although you probably get the idea that a black hole is really, really small, but just to explain how small it is. It's about the same size as if you held an atom at arm's length. So, that is, we’re trying to see something that’s that small, one atom, an arms length away from you.

Adal: That’s insane.

Katie: Or, an orange on the surface of the moon. Or, what’s another one they do, I’ve heard something about, like, reading a newspaper in LA from New York, it’s like, that, so, it’s very small.

Adal: Yeah, that’s, absolutely insane. So, I’m grasping the size, I’m grasping hopefully, a lot of it, it’s unbelievable that we have this picture now, what’s next in terms of, Katie, are you working to get a clearer picture, are you working to get pictures of other black holes, like, what’s the focus, if you can speak to it?

Katie: Yeah, we’re just, kind of at the beginning. Basically, we were working on building an instrument that we had, you know, never used before. Looking at something we had no idea what it was going to look like. I mean, we had some predictions but we didn’t know what was going to happen. And so, it’s kind of just amazing that we’ve been able to show that, oh, we got something that theorists had thought for years that, you know, that this might be what it looks like. And so I think that’s kind of amazing that we saw something that was so amazingly consistent with the predictions, and so, and from this image we can start studying, not just about general relativity but also about the immediate environment around a blackhole. You know, how black holes have matter accrete onto them, how they impact their host galaxy, but it’s really, I think, just the beginning. Now that we know that we have this extreme laboratory of gravity, we can continue to test these things and we can try to improve our instrument and our algorithms in order to, you know, learn more about the black holes that we think we can see from it. So, where, I think, this is really just the beginning. There’s a lot of stuff, even with the data that we made this image from, that we can do. So, this is a total intensity image, we’re just looking at the intensity of the light. But actually, light is a vector, it has a polarization and we collect the polarization of the light too. And if we can make an image of the polarization, the direction of the light, we can learn things about the magnetic fields around black holes. And also, I talked about the black hole in the center of our Milky Way galaxy, Sagittarius A*, and that one is evolving on the time scale of minutes. You would expect gas to rotate around it every 4 to 30 minutes, so over the course of a night when we observe the black hole we might see a lot of evolution and we can learn more about the spacetime around a black hole and how gas orbits it and the dynamics of it. And so these are things that we can now go back and study, now that we know it's possible. And we're definitely working on that in addition to thinking of how to improve our instrument in the future either by adding more dishes to the array. We only have a very small number of dishes that we used so far. It's like a sea...

Adal: Yeah.

Katie: Like, a very sparse array of dishes so if you add more we can get a clearer picture and even adding dishes to space, we're thinking, about. You know, having satellites orbiting the Earth that would give us a way to make movies of the black hole over time.

Adal: Wow. That's exciting.

Katie: So, these are things we are doing now. But actually, a big reason of how we are improving our instrument and a lot of people are working on, how can we improve it, is because of the fact that we work with such a small number of dishes and the, also, the data that we collect from every dish is really noisy for a number of reasons but partly because of the atmosphere above every dish kind of corrupts the signal that we get. And so we get this really sparse and noisy data and so actually making a picture from it is very difficult. And so, if we can try and improve it by adding more dishes to the array then hopefully we can get better pictures and learn even more.

Adal: Wow. That's very exciting.

Ben: I think we should speak to that particular detail a little bit more because it's honestly, kind of bonkers. Like, so, far our explanation of how we're artificially taking the signals that each of these telescopes and combining them in a computer to essentially, to make an artificial telescope the size of the Earth, I mean, that makes sense.

55:00

But, the devil is in the details when it comes to putting that information together. Have you ever woken up at, like, maybe 5am because you have to go catch a plane or something and the lights are all out in your house and you can just barely see anything because it's super, super dark.

Adal: Mmmhmmmm.

Ben: And you like see a shape and you're like, is that a lamp or is that my dog or you can't quite figure out what you're looking at because there's not enough light?

Adal: Mmmhhmmmm.

Ben: That's almost the threshold because having a dozen telescopes around the world, the width of the Earth, increases the resolution but it doesn't have the collecting power that a telescope that big, that a lens that big, would have. So, it's still pretty dim and also, like Katie said, the data comes in kinda crummy. The real tour de force here is in taking those petabytes, like, how big is a petabyte, what is it, like, a thousand terabytes. Ohhooa, so many zeros, right? That much data and like, collecting it and refining it and turning it into these images. That's bonkers, like, that's, I don't even know how to start. Like, whhhoaoahahahaha. Like, how... so, essentially, like, they took all these computers but it it's still very, very, very dim. How do you take your computers and this noisy, noisy information and refine this pretty great image, this high resolution image out of it. So, yeah, I think that's worth talking about.

Adal: Absolutely. That's wild.

Ben: It's wild.

Katie: So, actually, from the measurements that we get from the small number of telescopes, we get some information about the structure of the black hole. And so, it actually turns out that for every two telescopes we get, we get something about the spatial structure of the image. So, the closer two telescopes are together, we get information about broad structures. So, large scale structures and to get the high resolution information we need to see the ring, we have to put our telescopes really far apart. And so it’s very much like hearing notes in a song. Ah, so, for two telescopes that are together, we hear, like, low notes of the song and then telescopes that are very far apart, we hear high notes of the song.

Adal: Oh wow.

Katie: But, we only hear a few notes of the song. And so, because we only have a small number of notes trying to figure out what the song is that’s being played on a broken piano, basically. And so, if you have a broken piano there could be an infinite number of songs that are perfectly consistent with the notes that are being played, right. The other notes could just be banging on them randomly. But if you hear a song with only a few keys that are missing you can probably still figure out what the song is.

Adal: And it’s probably Chopsticks. Or Heart and Soul.

Katie: Yeah, right. (Laughter) Well, yeah, hopefully those keys are not broken, for chopsticks. Um, but if you have too many keys that are broken you might not be able to figure it out. So it’s this hard problem. So from the data that we collect from the telescopes, we get basically only a sparse number of notes that we're hearing. And those notes are even jumbled, like they might have been played at the wrong time even and the goal of the imaging process. So how we had to make an image is we had to find what image would be consistent with those notes. So find the song that is consistent with those notes. But to do that, we had to also think about, oh, what is a likely image? What is a reasonable image? Just like you wouldn't expect if someone is playing Beethoven, right? You have some idea of oh...

Adal: Can we use Bach, for example, instead of Beethoven? Just so it's a Bach hole?

Ben: Ooooohhhhhhhhhhh!

Katie: Sure. Oh, that's great. I love that. So yeah, we're playing Bach, right. Or maybe we don't know all the songs, but we know it should be, you know, pretty.

Leo: So you kind of know what Bach sounds like, right?

Adal: Yeah.

Katie: Yeah, you kind of know roughly what Bach sounds like and you wouldn't expect the other notes that they should just be you just banging on.

Leo: It's not going to be John Cage or Philip Glass or something because those sound different than Bach sounds.

Katie: So the idea is, then we have to find an image that is consistent with the sparse and noisy measurements we take but also is a reasonable. The hard part about that is that we have to define, what is a reasonable image? And and that is a hard problem. For instance, we don't want to tell our algorithms that a reasonable image is something that looks like a ring. And then, you know, we're happy that we recovered a ring back in the end, right? We don't want to, we don't want to tell it something about what we're testing. We want it to be as agnostic as possible. So a big question we faced in dealing with the data from the Event Horizon Telescope is not just how do we make an image, but how do we actually verify what we're reconstructing is real. We wanted to really make sure that we weren't telling it what it should look like. We wanted to give it a lot of space to explore all possible explanations of images, but we had to still remove ones that are completely outrageous.

Adal: Of course.

Katie: You know, for instance, like if you had unplugged the cable on your TV and just saw white noise, we wouldn't expect it to look like something like that. We'd expect the light to be positive and for it to be somewhat compact and, and things like this, but even then we wanted to spend a lot of time in verifying what we were reconstructing was real. And that was actually a huge part of the process in getting the image was just testing the image.

1:00:08

Leo: So Katie, I think I remember hearing once that you did like image reconstruction tests or like competitions with the different algorithms. The, what were the weird images that you guys fed into your pipelines to reconstruct.

Katie: Yeah, so even before we collected data, so we collected data, April of 2017, and for years before that, we were developing imaging methods. And we actually wanted to test ourselves before getting the real data. So we set up a bunch of challenges. We called them the Event Horizon Telescope Imaging Challenges. And there we made synthetic data that was if you knew what the true image was on the sky, what kind of measurements will we expect to see with all the different kinds of crazy noise that we expected from the telescope all the problems that we face and with the telescope. And the point of these challenges was that a group of people would generate synthetic data and then we would pass it off to people who would use their algorithms to, to try to reconstruct the image from it. And we tested ourselves on lots of different things, things that we thought black holes look like, but also crazy things. For instance, we used, at one point a snowman. And we didn't tell anybody what the pictures looked like. So a lot of people, for instance, some people thought it was like a binary black hole that we were, that we were getting back in the end, but it's actually just a snowman. And so we tested crazy images that we wouldn't expect and made sure that our algorithms were still able to recover the general structure of the true source image and not just trying to get back rings in the end.

Leo: Was everybody able to recover the snowman?

Katie: Yeah, I mean, it so because every algorithm, you have to inject some sort of information about what images look like, and also different humans, tune knobs on their algorithms differently. Every image looks different, but all of them actually recovered the general shape of the snowman. And so that's quite important that we do something like this because it gives us confidence that we would be able to recover an image that was surprising in the real data, we weren't just recovering rings. But one thing that was also really important is, as I said, every image looks different, right? Based upon its underlying assumptions of what you say is a likely image. And so by comparing across the methods of the images that were done by different people and different methods, we could build up confidence in certain features, and then say, oh, no, that feature that's only appearing in one of those images, probably just an artifact. So this kind of informed actually how we were going to approach the real data from the Event Horizon Telescope, when we got the data from the M87 black hole.

Ben: Does this crazy process kind of make sense to you the idea that like, okay, so you get this data and it's like, even after you do all of the fancy, cleaning up of the data, using fancy statistical methods and combining the different telescopes in different ways to make the data a lot cleaner, you still kind of don't have enough to quite make it out. And then so you have to, you have to kind of make your computer guess what it's looking at.

Adal: Mmmhmmm.

Ben: And then so what she did, you were supervising the teams weren't you, Katie?

Katie: Oh, there was a number of people who are really integral to making the images, there was different levels of of team structures, of different leaders of different parts of it.

Adal: Katie, as far as I'm concerned, you did this.

Katie: No, I didn't, I really didn't. This was a big, big team effort.

Ben: We split them up into a bunch of different groups where the groups weren't talking to each other. And each group had to come up with its own kind of computer intelligence that would take the raw data and guess what shape they were looking at. So to test this, for instance, they they'd make a bunch of fake data. They take a computer image of like a snowman, and then they'd say, okay, if the telescope was looking at the snowman, here's what the crummy data would look like. And then they made the computer software, of each different group interpret that, and each of them saw kind of a different shapes, snowmanish.

Katie: The same shaped snowman, but different. Each one looks different.

Adal: Gotchya.

Ben: So because each of these groups were using a different homemade algorithm, you could kind of compare and contrast the different groups to get more information of what they're looking at. So you'd say, well, you know, they didn't know that it was a snowman shape but all of these different groups are kind of getting the snowman shape. So the original image probably had the snowman shape.

Katie: But because we have such little amount of data, sometimes the algorithms make spurious features, you know, you'll get a little whisper of light at one point. But that might not appear in all the images, because that's very dependent on the exact algorithm that was used to make the picture. And so by comparing across the images, you can kind of see, oh, these are common features that are appearing, no matter what algorithm or person made the image.

Adal: Carrot nose, stovetop height, the pipe, yeah.

Kaite: Yeah, yeah. But some random features are around it. You might say, oh, well, that doesn't look like it's real, because it only appeared in one of the reconstructions. And so this gave us a way to look at and assess common features among independent reconstructions.

1:05:00

And so when we approached the M87 data, we thought that this was a really important and we wanted to avoid some sort of shared human bias like we had done in these challenges. So what I mean by that is because these algorithms are sensitive, and sometimes you have to tune your knobs to get them to work. If I saw my friend made a beautiful picture of the data from the M87 blackhole, and I say, oh, my gosh, that's a beautiful picture, I might subconsciously make my algorithm produce an image that...

Adal: Gotchya.

Katie: ...looks similar, because there's so many degrees of freedom. And so we wanted to prevent this from happening.

Adal: This sort of cross pollination, set of unintended influence.

Katie: Exactly. So what we did is we split up our big effort of about 40 different people who either developed imaging methods or they're knowledgeable users of imaging methods, they have a lot of experience in it, into four different groups actually. And two of these groups kind of worked on more recent methods that have been developed in the last couple years. And then two of them worked on more on traditional methods used in radio interferometry and radio astronomy. And basically we told the teams, okay, we released the data to them, and we said, okay, go off in your separate rooms, and don't talk to each other from the other teams for seven weeks. And we gave people seven weeks to come up with their best image. And within our team, it was quite amazing. You know, we made this image, but we were still you know, maybe we're, we're having this human bias, maybe, maybe we're pushing the image in one direction. So actually, what was the most amazing part of the process is that after seven weeks, we all got together, and we showed our best images from every team on the screen at the exact same time. And we saw that although every image looked different, just like in the snowman example, they all look different. They were all done by different methods with different underlying assumptions and different people ran them. They all contain the same ring like structure, about the same size of 40 micro-arc second ring that was brighter on the bottom than the top. And so that was kind of, for me, the happiest moment I've had in this collaboration. Because, you know, when I made an image I had no idea. Was I biasing it too much, was I pushing it too much in one direction. But when I saw no matter the person, no matter the algorithm who had taken this data, they got a same basic structure back in the end.

Adal: Yeah.

Katie: That brought a whole level, a different level of confidence to their results. So that was...

Adal: Yeah, to know to be more likely to be true. That's wonderful.

Katie: Yeah. So I think that was a really essential part of the process that we had so many people who developed many different algorithms and work together to build our confidence in this result.

Adal: Was there like, and I'm going off of like *Apollo 13*, or movies like that. Was there a moment where you took a stack of papers and threw it in the air to celebrate or like a fist bump?

Katie: Ah, we didn't have that. But we were I was so nervous. So we all gathered at the Black hole Initiative building in Cambridge, Massachusetts. And I remember, I was supposed to click the button to reveal all the images at the same time and I was just so nervous. I didn't want to do it because, I don't know, I, we could have gotten anything from the other teams and I and I wanted it to be so so real and, and, but seeing all those images come on the screen.

Adal: Yeah, what a cool moment.

Katie: We have a picture from it. We didn't have anybody film it because we were very sensitive about leaking data. But we have a picture and you can just see everyone is just so, I mean, it was an amazing time for us. We were so excited to see that pop up on the screen.

Adal: Yeah, that had to have been very emotional, overwhelming.

Leo: Did you have like some champagne or some cake to celebrate?

Katie: We did, actually. So we had champagne later that night, it was a fun time. And we all went out for beers and sang *Black hole Sun*, actually, in karaoke. But we changed it to Black hole shadow.

Adal: Honestly, every time you hear that song, now, I'm going to just wherever I'm at, I'm gonna be like, it should be shadow. And then I'm gonna and then I'm going to launch into why.

Katie: That's my ultimate goal. But even then, actually, even after we had gotten these four pictures from the four teams that looked very similar, we still were afraid that maybe this could still be some result of human bias. Remember, I said we all have those knobs, and we all kind of, you know, we thought that it could be a ring, right? So maybe we all are still pushing it in a certain direction, the algorithm in a certain direction.

Adal: Trying to manipulate it to make it produce that? Absolutely.

Katie: Yeah. So we, we really wanted to be very sure with these results. So actually, we took the next couple of months to basically try to break our methods to try to make sure that if we remove humans from the loop as much as possible that we still get that ring back in the end. So to do that, we tried to remove humans by instead of humans choosing those knobs, we had computers try to choose those knobs by training, how to tune the knobs to get other sources structures back. So for instance, we created synthetic data from something like a disc. A disc that has no hole in the center. And we created synthetic data as if the Event Horizon Telescope were actually seen on a disk on the sky. And then we said, okay, let's tune the parameters of our imaging method to try to recover that disc shaped back as well as possible.

Adal: Yeah.

Katie: To make it so it doesn't have a hole in the center. And then we would transfer those parameters onto the actual data from M87 black hole and we found that our algorithm still required us to put a hole in the center.

1:10:03

Adal: Wow.

Katie: And so we did this with lots of different kinds of training, testing procedures on many different kinds of underlying sources, and many different imaging code bases. And we found no matter what, we basically needed to make a ring shape.

Adal: Yeah.

Katie: And so that was, you know, the second level of confidence that we had basically in our images.

Adal: Cool. Were you able to tell family? Were you able to tell like, or did you sign like an NDA? Or what's the protocol?

Katie: So we actually made the first images in the summer and we had to keep our lips shut. I mean, I might have leaked it to my husband, but, but my family like my parents and my siblings, I didn't tell them. Like, we didn't tell anybody. So yeah, it was it was fun to finally be able to tell people what we've been working on.

Adal: Can I ask something?

Katie: Yeah.

Adal: So I'm so sorry. What was the name for the black hole?

Katie: M87 is the name of the galaxy. Yep.

Adal: Okay. Did you have while working on it? Was there any sort of like interoffice...

Leo: Codename...

Adal: Name for it, like was there like a code name or...

Katie: No, actually.

Adal: Little Holey or something.

Katie: No, I can’t...

Adal: Or Big Holey...

Katie: But we did you know, like if people accidentally saw it, which I don't think happened, at least with my friends, but we were always be like, oh, that's just a simulation. So actually, we were very surprised that people in our office, we thought everyone would know, you know, but everyone said they were very surprised, actually, they didn't know. So I was, I was surprised at that, that that we were so good about not leaking it.

Adal: That’s fantastic.

Katie: One thing I do want to mention about the data processing, actually, so I mentioned that we take these petabytes of data. But actually, when we start the imaging when we try to make the black hole image, we don't take in petabytes of data, and then make it an image pops out at the end. There's this whole other stage of data calibration, whose goal is to take those petabytes of data and reduce them down into basically the megabytes of data that we use for processing. And so basically, what happens is that you record hundreds of terabytes of data at each telescope. And then it's so much data, we can't even send it over the internet. And so it actually has to be flown, flown in, in airplanes to a common location. And then at that common location, we actually have a special purpose supercomputer called the correlator that combines that data, using that precise timing from the atomic clocks I talked about. And then from that, there's also the stage of calibration where reducing even further trying to beat down the noise and get that tiny little signal that's riding on a huge amount of noise out of the data. And so this was also a big part of the, what needed to be developed for the project as in terms of data processing, developing this calibration pipeline had, had to be developed in a very unique way for the Event Horizon Telescope data and it was a big endeavor in itself. People kind of forget about this data processing because it doesn't...

Leo: It's not glamorous.

Katie: ...produce an image at the end, but it was really, yeah, it’s not as glamorous, but it's just as important to getting that image.

Adal: It's so funny to think about something is so big as, that it can't be processed by the internet. So you have to fly it to a super computer. It’s so funny to me. It's like...

Katie: Yeah, actually the data, so I mentioned, we take data at the South Pole. Although that data isn't actually used for the M87 black hole, it's used for other sources we look at. And because actually we record the data at the South Pole during their winter time, and there is no airplanes that go out or in from the South Pole during the winter. So we actually have to wait for their winter to be over in order to get the data.

Adal: Wow.

Katie: So we got the data. Like, we took the data in April, and we got the data in December. And if you were trying to send it over the South Pole internet, be something like I think someone calculated 25 years to transfer that data. So yeah, it's better just to wait for the airplanes to fly.

Adal: Yeah, of course.

Ben: Well, that was fantastic. Thank you, Katie. Thank you, Leo. You've pleased me, your efforts have borne fruit and that fruit is very, very sweet. Here's some fruit. Dr. Katie Bowman you get a plum.

Katie: Oh, yay. Mmmmmm. Nom, nom.

Ben: And Dr. Leo Stein, you get a Japanese persimmon.

Leo: Ooh, yum yum yum yum yum yum.

Ben: I'd like to thank my guest Adal Rifai from *Hello From the Magic Tavern* and his new podcast *Hey, Riddle Riddle* for links to his podcast you can google it or visit our website in the show notes. Thank you very much.

Adal: All I got was this celery.

Ben: What? No, you got the fruit of knowledge, this whole time.

Adal: Celery. Oh, an apple.

Ben: Well, that was absolutely fantastic. Don't forget that you can listen on past the final music and hear some excerpts from our conversation, some stuff cut, I cut out because it was interrupting the flow. You know, most of our episodes have little snippets of conversation after the last bit, right? Anyway, it's time for the announcements. So there's some pretty fun ones. So please pay attention. Now, first, the hiatus is over. Congratulations. We're now in a phase of the show I call the March to 100.

1:15:00

I'm going to try to have monthly episodes from here on out, I mean, we'll see. But I've got a little bit of a buffer now. So here is hoping. Number two, we're going to have a live show this coming February at the AAAS 2020 General Meeting in Seattle. That's a conference of the AAAS. I guess they regularly have a day or two of live podcasts. So we're going to participate this coming year. So if you want to come to this conference, you can hear us do a live show. Third, we now live in the promised arrow where podcasts are finally going mainstream. There's so many great shows out there. Even Conan O'Brien has a podcast, it's fantastic. But it's important when your mom or brother-in-law starts listening to podcasts, that they know there's more out there than just shows about celebrities or shows about true crime. In fact, there's a show for every interest, even if your interest is in black holes and neutrinos, which means I'd like you to spread the word, you know about us. Hopefully review us on the iTunes or the iPhone podcasting app, or talk about us on social media. We've got a Twitter page and a Facebook page. In addition to that, we're on Stitcher, Google Play Music, Spotify, I think we're on Pandora and we're even on YouTube. Any way you want to listen to us, you can, so please, talk us up. Fourth announcement, I've decided to start doing a thing, where if I can't find a cool guest, or our planned guest cancels at the last minute, I'll choose a listener for the show to come and sit in the guest chair and chat with us about physics. The way I do it is I put the call out on Twitter or Facebook. So to be a guest, you need three things. The first is to follow us on Twitter or Facebook. Secondly, you'll have to have a fast internet connection and a quiet room in your home or workplace where you can use this internet connection. And the third is that you need to be available when we want to record that's it. So if you follow on social media, and you want to be on the show, you might get lucky. Finally, we're still humbly soliciting your donations. Your donations go for paying our server fees and our episode transcription project and buying our physicist microphones and paying our travel costs to that live show. So if you'd like to help support us, you can send one time donation through PayPal off of our website, or you can go to our sweet Patreon site and give a recurring $2 or $5 donation. If you give more than $2 and supply your address I'll send you a postcard with a bunny on it. This particular episode of the Titanium Physicists has been sponsored by a collection of generous people. Firstly, I'd like to thank the generosity of PK and Amere Ial. I'd also like to thank Erin Wheeler, Sandra Boros, A Badger, Acecpted Baltz Feign, and Luke Edwards. A Mr. Astro Yuki, Shebank Patel, Mr. Mike Mihoka, Henry Rabum, Peter Scott, Russ Mutzi, Iesh Sing and Mathew Sullivan, a Daniel Lason, Patrick Yong, Kevin Forsyth, Yer Panet, Hoynim Dwong, Stein Henrickson, Atiper Jones, Pascal, a man named Ryan R. and Michael Usher, Senor Canada, Adrian Shonig, Sarah Stradler, Louise

Pantanela, a guy named Ben, a Mr. Mathew Lambert, a fellow named Aioosh Singh, a David Murtle and Mr. Ryan Foster, Janetco Fifenberg, Steve Smetherst, Magnus Cristisen, Bart Gladys, and Mr. Stewart Pollack. Our emperor Courtney Brook Davis, Mr. David Lindells, Mr. Carl Lockhart, our eternal friend B.S. and Randy Dazel. A Miss Tina Roudio, the enigmatic Ryan, a gentleman named Crux, and Gabe and Evan Weans, David D and Dan Vale, a Mr. Alex, WTL, Mr. Per Proden, Andrew Wattington, Mr Jordan Young and John Bleasy. A Brittany Crooks, James Crawford, Mr. Simon Sing, Two Songs Gang of One, Mr. Lawrence Lee, Sixton Linason, Mr. Simon, Keegan Ead, Andreas from Knoxville, Cadby, Joe Campbell, Alexandra Zany is great, Weena Brett, Eric Duch, Atein Raymond, and a gentleman named Peter Fan, Gareth Easton, Joe Piston, David Johnson and Anthony Leon as well as Doug Bee, Julia, Nora Robertson, Ian and Stu. A Mr. Frank, Phillip from Austria and Noisy Mime. Mr. Shlowmo Delow, Melissa Burke, Yaseem Omarasazee, Spider Rogue, Insanity Orbitz, Robert Johnson, Madam Sandra Johnson, Mr. Jacob Wick, a Mr. Jon Keyes, a Mr. Victor C, Ryan Klaus, Peter Clipsham, Mr. Robert Haupen, Elizabeth Theresa, and Paul Carr. A Mr. Ryan Knewl, a Mr. Adam Kay, Thomas Shiray, a Mr. Jacob S, a gentleman named Brett Evans, a lady named Jill, a gentleman named Greg, thanks Steve, a Mr. James Clausen, a Mr. Devon North, a gentleman named Scott, Ed Lowington, Kelly Weinersmith, Jocelyn Read, a Mr. S. Hatcher, Mr. Rob Arizato, and a Mr. Robert Stietka

1:20:05

So that's it for TiPhy this time. Remember that if you like listening to scientists talk about science in their own word. They're all lots of lovely other shows on the Brachiolope Media Network. If you're wondering which show to listen to try *Science sort of*. It's our old favorite. The intro song to our show is *Tell Balgeary, Balguery is dead* by Ted Leo and the Pharmacists. And the end song is Russia by Ramona falls. Good day my friends and until next time, remember to keep science in your hearts.

Music

Adal: What is, in terms of like the power of its, to destroy? Is there ever a fear in our lifetime or in the near future, I guess relatively, of like a black hole able to suck in earth at all. Like is that ever a thing that could happen? Because I know it again and movies and sci-fi, there is, you know, the planets and spaceships being sucked in, you know, sucked into black holes. Is that a thing?

Ben: Not really.

Leo: Well, there's nothing. There's nothing that says that it couldn't happen. But you know, we would just have to get pretty unlucky. Black holes are you know, not every type of star makes a black hole. Only the really heavy stars make black holes. So most of the stars in the universe are just gonna, you know, stop burning and then make make little dim things but they're not going to turn into black holes.

Adal: Yeah, it’s like Tom Cruise versus Mickey Rourke. Mickey Rourke just kind of fades away.

Leo: Yeah, so how many Mickey Rourkes are there for every Tom Cruise, right?

Ben: Wait, no black holes are Tom Cruise in this explanation. And Mickey Rourkes are like the red dwarfs.

Leo: So Tom Cruise might come along and jump on your on your table, but it's much more likely that you'll run into Mickey Rourke or you know, one of the many thousands of Mickey Rourke like people out there instead of Tom Cruise.

Adal: Gotchya. Exactly. Like what, the last time I, and this is a true story, the last time I went to LA, I went to a restaurant hoping to run into Jon Hamm and I ran into Pauly Shore, so...

Ben: Wow, that's that's some special luck you got.

Adal: Yeah, I know. So, so, there's there's a lot of Pauly Shores around, it's very unlikely to meet Jon Hamm. I don't think we have any fear of being sucked into a black hole anytime, at least in our lifetimes.

Adal: That's the only reason I came on this podcast is for my own safety. To assuage the fears of my family and friends.

Ben: Yeah, there's lots and lots and lots and lots and lots and lots of space between every, like, star. Stars rarely hit each other, stars rarely past really close to each other unless they were born together. So the likelihood of the solar system getting disrupted by a black hole is very, very small. Don't worry about that.

Adal: Katie, do you become like when you're out in the world do you become massively frustrated with, because you're, you're so incredibly intelligent, you just become frustrated with everyone around you?

Laughter

Katie: No, of course not. No, I, but actually, so actually I’m not a physicist.

Adal: I feel like you’re a level of intelligent where it's just like at some point you must just get just very frustrated with, with everyone, just the, the mundane idiocies of everyone around you.

Katie: No absolutely not. I mean, I love, I love trying to explain concepts to, to people who are not physicists. I'm actually not a physicist myself. I come from, I studied computer vision and basically, computer, an area of computer science. And so I, when I started on the project, the Event Horizon Telescope project, I didn't know anything about black holes at all. And and so I learned a lot by talking, just talking to people and so I, I find it very helpful to try to, to come up with analogies and everything to explain the project. So I hope this is, this is fun for all of us. I think, this is great to try to explain it.

Adal: Yeah, I haven't. But I was just joking in terms of like, you're just, it's just very fun and interesting to be surrounded by very intelligent people right now.

Ben: Ha, you included me in that.

Adal: Well, so real quick, am I the only one who didn't go to MIT?

Ben: I didn't go to MIT.

Adal: I went to Phoenix online. So that's comparable.

Ben: That's pretty cool. That's a legendary bird. Legendary school.

Adal: Also, I feel a little ambushed. In terms of Ben, you said we would be discussing the movie *Event Horizon*. I feel a little taken aback but I'm willing to go along with this. We will refer to the movie as often as we can, just to keep you in the conversation Adal.

Adal: Thank you.

All right. So black holes. What are they?

1:25:47

END