Transcript (v2.0) of *Black Holes | The Edge of All We Know*

Stephen Hawking: A black hole is stranger than anything dreamed of by science fiction writers. A region of space where gravity is so strong that nothing can escape. Once you are over the edge, there's no way back.

Title Card:
Serdán, Mexico
January 2017

(natural sounds – birds, dogs, roosters, engines)

Shep Doeleman: Wow. It never ceases to get me, seeing these two mountains up here. It's a bit deceptive: it looks as though you can just hike up there in a couple of hours. But that is a big elevation shift from where we are now.

I was not a boy astronomer, I didn't have a telescope growing up, but I do remember seeing what a black hole was. I thought there are very interesting things in the universe to be explored.

The Event Horizon Telescope is a new instrument that a global team is assembling, that will have the magnifying power to resolve the region immediately around a black hole. That's never been done before. We are chasing down something that struggles with all of its might to be unseen. And we're saying "we're gonna catch you".

When you get to about 15,000 feet, you're above quite a bit of the atmosphere. You really need to be above the atmosphere to see through to the emptiness of space.

The goal of the Event Horizon Telescope is really easy to state: we're gonna take the first picture of a black hole.

Title Card:
LMT (Large Millimeter Telescope)
Altitude: 15,030 feet

Gopal Narayanan: What I had yesterday as of noon, was every part of the system of the front end working...

Shep: We've come to the LMT in January specifically to do what's called a dry run. And we're discovering problems.

Gopal: Then, we tried to replace the Gunn, now we've lost power, and that's what we're troubleshooting upstairs now. Today I'm going to try to get the Gunn working again, the old Gunn, Shep: But if we went back to this old Gunn,

Gopal: Yeah

Shep: then we're still compatible with the EHT

Gopal: By doing a double-down conversion

Shep: for January and April.

Gopal: Yes.

Shep: April is when we're going to have all the telescopes around the world, the full EHT working, and it's our best shot at imaging a black hole. But before we get there, we've got to make sure that everything is working.

Shep: ...So the first goal is to try to get the 232.1 gigahertz working again with the old Gunn

Gopal: right

Shep: If that doesn't work

Gopal: My plan B

Shep: Then what?

Gopal: My plan B is that ...

(beeping sound)

Gopal: The larger the telescope, the better it's able to see tiny objects. To resolve the black hole in the center of our galaxy or the bigger black hole in M87, we need a telescope nearly the size of the earth. Well, that's clearly impossible. So we do the next best thing. We take telescopes scattered around the world and make them all look simultaneously at the black hole.

Shep: Imagine taking a mirror and smashing it with a hammer and distributing these shards all over the world. And then recording what happens on each of those shards and then bringing them together and reconstructing that mirror in a supercomputer. That's what the Event Horizon Telescope is doing. So at every site, everything has to work perfectly.

Shep: ...I think this thing took quite a hit.

Lindy Blackburn: In shipping?

Shep: If it turns on and it smokes then we'll know there's something wrong.

Antonio Hernandez: Yeah.

Shep: We still have to make some tests. Tomorrow we are going to trigger a real observation. And that’s gonna involve the South Pole, Spain, Chile, and God willing, the LMT.

Off Camera Voice: You've got a clock ticking.

Shep: I know. Cue the Mission Impossible theme.

Title Card:
Test Observation Day
January 27, 2017

Gopal: Look at - that's the telescope, buried underneath that S-H-I-T, if I may say so.

Shep: Wait-wait what happened here? What happened?

Gopal: Weather happened to us.

Shep: Wait you’re shitting me. Last 16 hours it’s been beautiful and as soon as we come up like the gods hammer us? That’s crap.

Gopal: Well we can’t point and focus through this weather right now.

Shep: The schedule is supposed to start…

Gopal: In 40 minutes. In, uh. 35 now.

Shep: If we're still in the clouds and it gets really cold, it's going to be an ice situation.

David Sanchez: That's a possibility.

Gopal: That's what i’m worrying about -

David: Yeah, I'm really worrying about that.

Gopal: Everybody cross their fingers, use your favorite incantations, and we'll clear through this.

Shep: Okay, so we're gonna set levels in the other room and then we'll be ready to go.

Gopal: I need to adjust the power level of the upstairs a little bit.

Shep: You realize that we're firing this thing off in exactly 14 minutes and 15 seconds.

Gopal: Yeah, yeah, yeah, I know but...

Gopal: Aahh, Jeez.

Gopal: Did you say 6573?

Shep: So it's RCP and LCP high, right?

Lindy: We got one minute.

Gopal: Here we go people, hold onto your hats.

David: Okay, we're ready.

Gopal: Four, three, two, one, zero! Blast off.

(Intro music)

Title Sequence

Ramesh Narayan: Oh boy. What is a black hole? It is so deep, it's so hard to fully appreciate all of the physics that's going on. You can spend your life studying this.

Imagine an object where gravity has become so strong it has compressed all of the material with which it started down into a point. This object develops what's called an event horizon. And this event horizon has this amazing property that it's a one-way street. You can go from the outside to the inside, but nothing will ever get out.

Lydia Patton: The gravitational pull is so strong that anything that comes close enough to it will just vanish inside. If something disappears over the event horizon it's gone. And we no longer have any knowledge of it. It is no longer detectable, it’s no longer knowable. It might still exist, it might not still exist, we have no way of knowing. We have a contact with a kind of phenomenon that we don't fully understand.

Janna Levin: It's like a vortex in the universe in space and time. The darkest object we can imagine mathematically fundamentally emits no light, reflects no light. But it becomes the engine of the most powerful events we now observe in the universe. There's something about them that really pushes the mind.

Stephen Hawking: Can you hear me?

Audience: Yes.

Hawking: It is said that fact is sometimes stranger than fiction, but nowhere is that more true than in the case of black holes. Currently I'm working with my Cambridge colleague Malcolm Perry, and Andy Strominger from Harvard, on a new theory to explain the mechanism by which information is returned out of the black hole. Watch this space...

Andy Strominger: I met Stephen in 1982. Over the years we coincided on a number of topics, a surprising number, but the very kind of intense thing that's grown over the last, what is it now, three years?

Malcolm Perry: Three years.

Andy: Yeah, has been a whole new, wonderful level.

Malcolm: And quite different.

Andy: Quite different, yeah.

Malcolm: It was a fabulous warm day, kind of unusual in England for April, so we had a lecture outside. This was in a place called Great Brampton House.

Andy: For the last 10 years, Stephen and friends organized a small retreat. I had these ideas about the structure of the edges of infinity and how they could store information.

Malcolm: I was simply listening to this lecture and I felt that the phenomenon he was describing could be happening on the surface of the black hole.

Andy: Stephen picked up on that immediately. He said, this is it, this is the piece that we've been missing. He is very eager to unravel the paradox that he unleashed on the world in 1975.

Malcolm: Something called the information paradox, which basically says that black holes annihilate information, which should not be possible. That's the paradox. It implies that there's a breakdown of laws of physics in the presence of black holes.

Sasha Haco: This is why we're chasing this problem, because if information is lost, then that contradicts almost everything we know about physics. Something's gone wrong understanding how black holes work.

Hawking: From the outside you can't tell what is inside a black hole.

Sasha: When you look at a black hole, all you can tell about it are its mass, its charge and its state of rotation. And that's the same for any black hole no matter what it was made out of.

Hawking: This means that a black hole contains a lot of information that is hidden from the outside world.

Sasha: That was a very weird thing people to get to grips with and then Stephen Hawking made this amazing discovery of Hawking Radiation, that says actually stuff comes out of a black hole, and that's where the problem really started.

Laura Ruetsche: It turns out they're not black, they radiate. And as they radiate they lose mass and eventually disappear. An equivalent mass of elephants could form a black hole, an equivalent mass of Encyclopedia Britannica could form a black hole. The black hole evaporates and what's left behind is the same sea of Hawking Radiation.

Hawking: It appears that the information about what fell in is lost. The particles that come out of a black hole seem to be completely random and to bear no relation to what fell in.

Andy: If what Hawking said were correct, it can spit out anything. It can spit out a piano, it can spit out a trombone; anything can come out. That means that the basic nature of the universe is just random. There aren't really physical laws which govern the entire universe. This is every physicist's nightmare.

James Weatherall: Much of our knowledge of the universe is grounded on our belief that we can reliably predict using the laws of nature. We have a physical theory, we make predictions using that theory, we do experiments or observations to see if those predictions were realized. We understand the early universe by using the laws of physics to predict backwards and say what the world must have been like. If those laws break down, it's about the limits of knowledge. What sorts of things could we possibly know about the world?

Hawking: If the predictability of the universe breaks down with black holes, it could break down in other situations. Even worse, if information is lost, we can't be sure of our past history either. The history books and our memories could just be illusions.

It is the past that tells us who we are. Without it we lose our identity.

Andy: Since I was a graduate student, information paradox has been central in my thinking. It's a sort of 24/7 thing. I get up, I make myself a cup of coffee, I sit down with a pad of paper. I'm thinking about it when I brush my teeth, dream about it. It is the most interesting, well-posed question in modern physics. So interesting that I was ready to devote my life to trying to understand it.

Title Card: April 20, 2016

Andy: In the 40 years since Hawking's argument,

Andy: By the way, while Malcolm's erasing ....

Andy: There's certainly been thousands of papers about how the paradox might be avoided. None of them has gained universal acceptance and they all are problematic in one way or another.

Malcolm: So the magical formula I think I could write out in excruciating detail.

Andy: So while Malcolm's writing, what we've done is first of all worked out...

Andy: But now, Stephen, Malcolm and I have found a mechanism by which the information paradox *might* possibly be resolved.

Andy: Seems very exciting.

Malcolm: It's the beginning of something deep, we really quite don't know what...

Andy: Investigating this is vigorously underway now.

Malcolm: But central terms of what

Hawking: What is a super rotation?

Andy: So, the super rotations, so ordinary BMS group…

Andy: Physics is about finding the truth about the universe. We might not ever get all of it...

Andy: ...This then gives us a conservation law -

Andy: ...but I think there's a good shot that, in my lifetime, we'll nail this one.

Andy: *...And so that's conservation of super rotation charge. Now, let me erase here...*

Heino Falcke: Seeing is believing. That's the most credible and the most powerful sense that we have. We need to see things. We long to see things. In my mind, like for 10 years, there's no question there is a black hole and there's no question it's possible. I still want to see that stupid image. I want to see it.

Dimitrios Psaltis: We have never actually seen the telltale sign of the black hole which is that virtual region, the horizon, from which not even light can escape. With the Event Horizon Telescope we're going to zoom all the way to the size of the horizon and see if it will cast a silhouette, will cast a shadow.

Shep: The Event Horizon Telescope is the culmination of really decades of work. Once we began to realize that we could make an image, that became fascinating. So over the past years we've gone to new sites, and we've had to convince those new sites that the science is worthy, we've had to develop and install very specialized and expensive equipment at all of these sites in all of these extreme places. We are now at the moment when we'll be doing our first observing with the chance of making an image.

Title Card:
EHT Observation Window Begins
April 4, 2017

Feryal Ozel: That's still a question mark but local wisdom is a go.

Dimitrios: SPT weather good, no-go for pointing.

Feryal: Pointing issues.

Dimitrios: SMT technically ready, weather forecast possible of high wind but unlikely to cause anything.

Feryal: So night's outlook is good, right?

Dimitrios: Yes.

Feryal: We set up telescopes around the earth that can talk to each other, that can record data in tandem, so after the fact we can combine these data and make it act like they were actually one telescope. Right now, the Event Horizon Telescope is an array of eight dishes across the globe from the South Pole to the Arizona desert to Hawaii to Chile creating, effectively, an earth-sized telescope.

Dimitrios: Weather forecast is good for Pico.

Feryal: I mean, they say excellent, so...

Shep: Looks pretty good to me.

Feryal: I'm changing this to .2...

Shep: I'd like to see the LMT water vapor map.

Shep: When you have a single facility, it's the weather above that one telescope that has to be perfect for a night's observing. Now imagine you need perfect weather at every single site around the array.

Vincent Fish: By the time we start observing, it's going to have moved past but we don't know what else is going to move in. Seems to be accelerating.

Dimitrios: So SMT is getting worse.

Shep: So what are the pinch points here? It's really just LMT and SMT, and we're gonna have to make a decision at South Pole, just based on what we know now, which is they might have pointing issues.

Feryal: LMT, how worried are you about the maser?

Shep: I'm a little worried about the maser just because we haven't done some of the tests that would let us see how good it is.

Dimitrios: Shep, it's 3:30, we have half an hour, should we call it?

Shep: [Hesitant Noise] I basically think that we should trigger for tonight. I think it's probably the best weather we're gonna get, technical issues are breaking our way, I mean, of all the nights to have a question mark by South Pole this is the one to have it. We'll get some pretty good M87 scans, one hopes, right? [General agreement] So let it be written, so let it be done. I will… make the decision, I will broadcast it.

Feryal: Night five, track D is a go!

Dimitrios: May all future nights be as good as this one.

Shep: And then, all around the world, all the telescopes swivel at the same time and we will begin to record photons from the black hole.

Feryal: How big a black hole looks in the sky is a combination of its mass and how far away it is. The black hole at the center of our galaxy, Sagittarius A*, has the largest angular size in the sky followed by M87. M87's black hole is a thousand times bigger but roughly a thousand times farther away. They turn out to have pretty comparable sizes in the sky.

Title Card: Night 3 of Observation Window

Shep: This is central command, it's always manned 24/7, people write in and they say I'm having an emergency with one of my recorders, or my receiver, or something,

Lia Medeiros: We hope to be bored. We hope that there's nothing to do and that everything is going smoothly and that nothing goes wrong. But you know, we're here just in case.

Shep: We've just finished Day Three of the EHT observations. It's been unprecedented. We triggered three consecutive nights of observing and that's because the weather has been phenomenal. And the team is quite tired because we've been working round the clock for three days. They're at high altitude sites, they're paying a lot of attention to detail, they're under a lot of stress, they're trying to run down problems, and we're pushing people to the limit at this point.

Title Card: End of Night 5 of EHT Observations

Atish Kamble: Final scan of Sagittarius A* begins.

Shep: This is it, oh yeah, so this is it. The final scan of the 2017 observations on Sagittarius A*.

(Over the Rainbow by Israel Kamakawiwo’ole begins playing)

Shep: ♪ ...over the rainbow... ♪

Shep: Did you write that "woohoo"?

Atish: Yep.

Shep: ♪ Dreams that you dream of, dreams really do come true. ♪ ♪ Ooohh oooh ooh ♪ ♪ … upon a star ♪ ♪ Wake up where the clouds are far behind ♪ ♪ Meee, where … ♪

Shep: I think this song just really captures how good it is to realize something that you've been working on for ages.

(Off Camera): How long?

Shep: I've been working on this for, I dunno, 20 years.

Shep: Next at every EHT site, everybody will pack up the hard disk drives carefully, very carefully, ship them back to the central processing facility.

Shep: Wait. Guys, we're done! We've finished the whole thing? We're done, it's a wrap! We just finished the entire scan, and the entire schedule, and the entire campaign, and the entire Event Horizon Telescope observations for this year.

Shep: The great challenge for the Event Horizon Telescope is only when you get all the data back to the central correlation facility do you truly know that everything worked. And that will take over a month. Until then there's always this tension, there's always this slight uncertainty that something's been overlooked.

Shep: So May - springtime, rebirth, imaging black holes, it's gonna be quite a summer, I'll tell you that.

(cello music)

Lydia Patton: It's been a perennial question in the philosophy of science: if what we're primarily interested in are phenomena as they can be detected experimentally, how, in fact, do we come to have knowledge about unobservable entities?

Priyamvada Natarajan: I've always had a pull towards the invisible and the mysterious. I've sort of naturally gravitated to black holes. But a black hole is very, very hard to understand with just the equations.

Ramesh Narayan: If you really want to know anything at any level of detail, you're not going to do it with just pure mathematics, it's not going to happen. You need to simulate it on a computer. You have what's called an accretion disk that's orbiting the black hole. It's chaotic. It's ionized gas, it's got magnetic fields, the whole thing is churning. The gas gets hot and then it radiates. That gets a little too complicated for a theorist to calculate with pencil and paper.

Priyamvada: Simulations really help us make what is invisible, what is unseen, seen.

Title Card:
September 10, 2017
Brinsop Court
England

Malcolm Perry: It must be Andy.

Sasha: Hiya.

Malcolm: We have almost incredibly good news.

Andy: What?

Malcolm: But not quite. There's a missing link somewhere. If you don't worry about it you get the right answer.

Andy: Oh well, I never worry, so..

Malcolm: So once a year, Stephen Hawking and his friends take over some house somewhere, where we can exchange ideas, where we can have fun, where we can go off into the mountains and have a hike.

Malcolm: Stephen arrived.

Andy: Stephen's here, great.

Malcolm: So if you go all the way that way, you can say hello to him.

Andy: Stephen, Sasha, Malcolm and I found an chink in the armor of -- more than a chink, a huge gap in the armor -- of the information paradox.

Malcolm: Why don't we use the blackboard in there.

Andy: The old story was there just wasn't any way that a black hole could store information, it was just a hole in space.

Malcolm: What we've discovered is that the horizon does have some properties that encode information. Namely, the supertranslation and the superrotation degrees of freedom; what we now call the “soft hair”.

Malcolm: Uh oh, put it round.

Andy: The hair is spread around the horizon of the black hole. When you throw something into the black hole you change its hairdo. So you start like this, you throw something in, it goes like that. We discovered there's a record of what fell into the black hole. Some information is definitely transferred. We don't know yet if all of it is.

Malcolm: And that's really what we are currently trying hard to investigate.

Malcolm: It looks like this.

Sasha: Yeah, it only contains two derivatives in epsilon, so that'll vanish.

Sasha: We need to see if this soft hair and these soft particles can encode all the information in a black hole.

Andy: Okay, so we're not worried about that term.

Malcolm: No.

Andy: Did you look at that term too?

Andy: There's a formula, by Bekenstein and Hawking in the early '70s for exactly how many gigabytes of information can be stored in a black hole. So the very first test, which we have not yet passed, is counting the information using the soft hair and showing that it gives exactly the right answer.

Sasha: If we can get the central charge to be 12J, information is not lost. Information is conserved, and that we'll be able to trace this information by looking at the horizon. And we've spent about three months getting zero, then another three months getting infinity, and the last few weeks, Malcolm thought he got 12 and now we think that's actually wrong again. As of today, we have 12, but with a dubious step.

Andy: Are you saying that that integration by parts was done to get this last formula?

Sasha: I have a feeling.

Andy: Yeah, because there's no terms with two derivatives on zeta.

Malcolm: Well, the whole point was to get rid of two derivative terms on zeta.

Andy: But maybe they're really there. Let's see, okay, so I think we need to think a little more about this. Oh, Stephen's here. Saved! Hello Stephen!

Sasha: Hi Stephen.

Malcolm: Hello Stephen.

Andy: Why don't we give Stephen the executive summary.

Malcolm: Assuming everything is right.

Sasha: To be confirmed.

Andy: No, no, you never assume everything is right.

Sasha: To be checked, everything to be checked.

Malcolm: Everything to be checked.

Andy: It's the usual roller coaster, a few minutes ago we were very excited because the central term came out on the nose exactly what it needs to be to get the area law, then we realized we might have missed some terms. Something good seems to be happening. But we have our work cut out.

Malcolm: There's something else we might have forgotten.

Andy: What?

Malcolm: There was a question of an F plus minus term.

Andy: Yeah, I've been bothered by that.

Malcolm: So, it could be the F plus minus term takes this away.

Andy: Well, what are we doing about that, because...

Sasha: Well I thought I didn't produce anything with three derivatives of epsilon, but...

Malcolm: We better check that.

Andy: There's a number we're after. 12 times the angular momentum.

Sasha: So I think that is...

Andy: Or divergence of…

Andy: It's so hard to get the number, it's really hard to get the number. If you do get the number that will tell you that black holes have the capacity to store all the information that might have been lost...

Andy: I think there's a path in there somewhere.

Andy: ...A giant step towards solving the information paradox.

Sasha: And Malcolm got from that to this by integrating by parts. Illegally.

Andy: Yes.

Sasha: But, by using divergence of a three-form...

Andy: You can do the same thing.

Sasha: You can get to this exact equation and you always have room for...

Hawking: How many conformal killing vectors on the two sphere?

Malcolm: Three!

Hawking: An infinite number?

Andy: Six!

Sasha: Stephen's a very interesting person to work with because he's a man of few words, so everything he says is really important.

Malcolm: Globally well-defined strict killing vectors, there are three of them. Globally well-defined...

Sasha: He'll ask something which might at first sight seem to be he's just clarifying something, and actually it turns out to be he's got a slightly different idea or he just gives a bit of his insight or intuition. Which might then sort of confuse everybody and then we realize actually it's really important.

Andy: So we've been, we're religiously abiding by your instructions to forget about infinity.

Andy: I was laying some groundwork first, sort of circling the mountain, trying to figure out which was the best route to the top. And Stephen was like, okay, we're taking this one now. He's very daring. He doesn't want to spend a lot of time exploring all the subcases and different possibilities. He wants to go for the jugular.

Hawking: Would diffeomorphism give all the entropy?

Sasha: Which diffeomorphisms give you the entropy?

Malcolm: Ah, so the question is what are the diffeomorphisms...

Malcolm: This problem is probably too hard to do on your own, but different people think about things in different ways and, well, each brings their own little bit of it to the table.

Andy: It's basically E to the i-n-phi ($e^{in\varphi}$) around the... it's basically...

Malcolm: E to the i-n-phi ($e^{in\varphi}$) but somehow...

Andy: I tend to race to the end and then try to fill in the spaces, which is a methodology which is particularly prone to making errors because you've already decided what answer you want. Whereas Malcolm would be more likely to just start from the beginning and systematically work through it, which has the other problem that if you're not heading in the right direction, you'll never get there. So I think we compliment each other well. Sasha has been a fantastic addition. She started as Malcolm's graduate student, and she went from zero to sixty in a rather spectacular way.

Malcolm: We had it once and it went away, and we got it again about 10 days ago, but it's gone away again. We're on the right track, but it's turning out to be monstrously complicated.

Sasha: I think let's go this way.

Malcolm: I think go that way. We should've brought a helicopter. Well do you want to go down that way?

Andy: This one you mean?

Malcolm: No.

Title Card:
May 12, 2017
MIT Haystack Observatory
EHT Data Processing Center

Michael Titus (offscreen): This was a really convoluted international shipment because of what went on in Chile.

Shep: You know this is important data, right?

Michael Titus: Yes.

Shep: I don't like to hear the word convoluted in the same sentence as “your data.” The implement of destruction. This is freshly delivered data. All the way from Chile, recorder three, slot two, set two.

Vincent Fish: Nicely labeled.

Shep: Vincent? Photons from Chile. Frozen.

Feryal Ozel: When we get the data from these different telescopes, the amount of data is immense.

Dimitrios Psaltis: We really have to measure every single wave, every single trough and crest of the waves as they come to the telescope.

Feryal: We have to record this faithfully and then match up each wave front with the corresponding one from another telescope halfway across the earth.

Shep: Okay, the latest addition from ALMA. What else do we have here?

Dimitrios: We are generating about one and a half petabytes of data per night of observation.

Shep: Okay.

Vincent: Yeah, once we cleared...

Dimitrios: By far the largest amount of data per night of observing than any physics experiment in the history of science.

Shep: I want to see, okay, so here's a whole ALMA set…

Shep: We bring all the data back, all these disk drives to a super computer, one is at the MIT Haystack Observatory, and the other is at the Max Planck Institute for Radio Astronomy in

Bonn, Germany. Between these two sites, we process and handle all of the data. This is how you make an earth-size telescope. It's like a map of the entire globe. So up here we have modules that were recorded in Mexico, these are also from Mexico, this is from Arizona, this is from Spain over here, this is from Hawaii. We cannot do any of the processing from the South Pole. The South Pole station is closed now. Nothing can land or take off. All the data's in the deep freeze until October.
This is where all the data come together and we get the final data products. So, it's happening. It's hard to believe after so long, but it's happening.

Vincent: Drop it for now and let's try, let's just put the baseline in.

Shep: Once you correct the manual phase cals, then this will clean up and even the signal-to-noise ratio will go up and the amplitude will go up. That is really amazing.
lWe're getting the kind of sensitivities and the resolution that we have been after for about a decade. For me, personally, this is a moment of great anxiety. We've worked for a long time for this result. And we don't know even now what we have.

(music)

Title Card:
University of Nottingham
Nottingham, England

Silke Weinfurtner: Black holes are out of reach. We do not know if the equations we're using actually describes a black hole. That's what we cannot directly test, that's the dilemma we're in. In my laboratory I have a model that mimics certain features of black holes. Of course it is not a real black hole, it would be pretty dangerous. What we really have is a gigantic pool of water. You get this nice vortex forming right in the center. For small fluctuations on the surface it should look like a rotating black hole. There is physics associated to the horizon: light bending, Hawking radiation, superradiance. And these are the kinds of effects we can simulate. All the effects that happen outside the event horizon. And at the end you see an effect which has been predicted for many years without any experimental confirmation. That's real physics: it has been detected.
There is a limit to what we know about black hole now, but I'm a scientist, this is the best situation you can be in. We have this universe in a Petri dish. And it's holding fantastic new insights waiting to be discovered.

Title Card:
Four Months After Hawking Retreat
January 25, 2018

Malcolm: So zeta minus zeta-tilda-Y, and this contains an epsilon double prime, that contains an epsilon prime.

Andy: So that will go like one over W plus.

Malcolm: This goes one over W plus, which means you got to compute this thing to W plus, you're sure there's not something else?

Andy: No it doesn't. No, it doesn't, because it's only the one over W plus term that can contribute.

Malcolm: Right, so you--

Andy: We need that one over W plus

Malcolm: --have to compute, so you have to compute this to order W plus.

Andy: No.

Sasha: No, because you want one over W plus in the integrand.

Malcolm: Oh right.

Andy: Because the range of W plus is zero. So if we don't have one over W plus there, we get zero. We didn't understand this in Brinsop.

Malcolm: No, I guess we did not understand that. We thought at Brinsop that things were relatively simple, we didn't have to think about so much, but since then we've discovered all kinds of other things which do contribute and complicate matters.

Andy: In Brinsop we thought we could do it by hand. You know, 10 pages....(laughs) Turns out to be among the most long calculations that any of us has done.

Malcolm: That’s actually spot on.

Sasha: One thousand and fifty terms.

Andy: 1050 terms? You can't do, you cannot add 1050 terms without making a single mistake. Or I can't. I think that’s even beyond Malcolm.

Malcolm: I think I can do about half of that, but...

Andy: So a month ago, we realized we were going to have to use computers. Essentially adding up many thousands of terms; if they all add up to exactly 12J, it will mean the hair that's on the black hole is enough to completely reconstruct how it was made.

Malcolm: That's a long way towards solving the information paradox.

Andy: We haven't seen that happening so far. Which either means that there's a mistake in our computer program, a mistake in our input, or a mistake in our conceptual analysis of the problem. And we've been up and down in our level of optimism.

Malcolm: We must believe that actually it's going to work out properly for the very simple reason that we would not be putting this much effort into it if we didn't believe that. We are putting the effort in.

Andy: We are putting the effort in, yeah.

Malcolm: And the reason we're doing that is we believe it. If we didn't believe it we probably would have, ah--

Sasha: Given up months ago.

Malcolm: --been a bit more discouraged.

Sasha: I'm optimistic. But I think we're missing something quite-- we're missing a term or something.

Malcolm: Or an idea.

Sasha: Or an idea or something-- we haven't just not added things up correctly.

Andy: The information paradox says that because of black holes, the universe can't be described exactly by physical laws. I'm putting my money on an idea that there are physical laws and that we can figure out what they are. But it's not over yet.

Andrea Ghez: I think it is interesting when observations don't conform to our standard picture of how things behave. And that's when people start to look for more exotic explanations. And that's what happened with the black hole story. Black holes were initially very esoteric, mathematical, very hard to accept, and yet increasingly over time there were observations that didn't make sense. Black holes were the best explanation for what was observed.

What was still quite controversial were the supermassive black holes, the ones that were a million to a billion times the mass of the sun. Maybe all galaxies harbor supermassive black holes at their cores. Even our own galaxy. That was pretty controversial, and that is certainly the idea that I got very interested in.

I had this technique that I was working on, my group and then the group in Germany, that in principle could figure it out. And this was just as the Keck Observatory was opening up in Hawaii. It's kind of amazing that a very big telescope let us monkey around with the instrumentation at all. And yet it worked. All of a sudden you could see the stars at the center of the galaxy.

And if there's a black hole there that has a few million times the mass of sun, these things are gonna move really, really fast. '95 was our first measurement, '96, we saw a second picture, and oh my goodness: those things were absolutely not in the same place. These things were hauling! '98, '99, it was already clear that the ones that were really close, were starting to curve. The curvature gives you a direction to the black hole. And we had three stars that were curving so it was like three arrows and they all intersected at the same place. You need something very massive to drive that kind of short-period orbit. It's hard to conceive of anything else at its center other than a supermassive black hole. We're on our way in. You can just taste it.

Title Card:
EHT Image Hackathon
October 12, 2017

Title Card: EHT Imaging Team One (of Four)

Katie Bouman: No, I think, but Kazu told me to look at 120 yesterday and that's why that we were looking at that one.

Shep: Oh okay

Lia Medieros: So this is 3C345?

Katie: Yeah.

Michael Johnson: The fact that we're aiming so high with the EHT to see something that no one's ever seen before means we have to develop an entirely new set of tools.

Michael: It's a lot easier to start with a big field of view...

Michael: We have to reconstruct an image with sufficient fidelity that we can trust what we're seeing.

Katie: Anyway, I don't have it loaded on linear scale with them all in the same...

Katie: When we take a picture on our camera, right, you believe that picture is exactly reality, right? You actually saw that with your own eyes and you can see, oh, okay, that matches. When we take a picture of a black hole with the Event Horizon Telescope, we don't get to see that, we don't know if the picture we generate is actually what the black hole looks like. How do we evaluate what's the true image?

Shep: So which is right? What I'm saying is in general, which is right? People publish....

Katie: One way we approach the problem is by separating the teams into different groups that can't talk to each other. We generate data from lots of different kinds of images, realistic data like we would get from the Event Horizon Telescope, then release to the community but without the true image and we say, do your best job, get your best image from this data.

Shep: What happens in Team One room stays in Team One room, right?

Katie: If I see another team's image, I might start trying to push my imaging algorithms, even subconsciously, in a direction that would favor that kind of image.

Katie: Look at these amplitude error bars...

Katie: We want to have many rounds of imaging and refining that imaging process before we actually compare the images...

Shep: You look at all these different things with the same data, it's a cage match of love...

Shep: We should be able to cross-compare the different algorithms between the teams. And if we start getting convergence on those, then we'll know that we're in a good position to do the same for Sgr-A* and M87.

Mareki Honma: And here is low closure amplitude. There's a really big difference.

Sarah Issaoun: It is three days apart.

Scientist: Yeah, but the source has not changed that much, and you cannot change the speed of light.

Mareki: But you know, orange and blue, that's exactly same day, exactly same time...

Mareki: In Team Two, I would say we had a hard time. My feeling is that data are not yet ready, not yet well-calibrated for imaging. So there is still work to be done.

Malcolm: I just happened to be looking at the Guardian website at around midnight on the evening of the 13th, and they announced it. And that was it.

Andy: We had been talking about going to see him. Because we were worried, and because we knew that the work would lift his spirits.

Sasha: We kept saying as soon as we get somewhere, we're flying straight back to the UK to talk to him about it and discuss the next step with him. It would have made him so happy to realize that we'd got somewhere with this project. And unfortunately we just didn't get there in time.

Malcolm: We all think in different ways, and he has his own unique way of thinking about things and we're not going to be allowed to have access to his mind anymore. That's a huge loss.

Andy: There's a special kind of friendship that grows out of scientific collaboration and discovery that's in my experience like no other. And to have a, you know, scientific, a productive scientific interaction with somebody over many decades and then lose them, is very sad. It's sad in a different way than losing a relative or, but it's, it's a special thing and it's very sad to lose that.

Janna Levin: You can imagine if you were floating near two black holes that collided. As they orbit, space time begins to ring in response. They're like mallets on a drum. The drum is space time itself. It begins to ring. Gravitational waves, squeezing and stretching space. In principle, they would pluck your ear drum, you would hear them even though it's empty space. Gravitational waves are actually like a sound in the medium of space time.

And that was the greatest discovery of 2015. The experiment LIGO recorded the collision of two completely dark black holes. The final one-fifth of a second before the black holes merged and went quiet as a bigger black hole. And that's stunning. The only evidence we've had for black holes before then was what they do to their environment. This felt direct. The first completely direct evidence of not only the existence of black holes, but the existence of a pair of black holes. This signal comes after traveling over a billion years, and they record it. Just a spectacular, spectacular discovery.

My work very much was about theoretically how black holes collide, what it would sound like, simulating those sounds, and understanding the dynamics of black hole orbits. Gravitational waves are so quiet by the time that they reach the earth that the experiments only pick up the final few orbits. To dig deeper and hear the approach, my group has been doing approximations of the final several minutes. Listening to the longer run-up, we can tell if the black holes had a more interesting dynamic, if it was a more complicated motion. So in this case not only are the black holes different masses, not only are they on a more complicated orbit, but they're also spinning. The system begins to rotate in space and you can hear it get quieter as the gravitational waves are beamed away from you, and louder as they're beamed to you. And so these are all details we can extract from the gravitational waves sound just by listening. And then they get louder, faster, right before they merge. And then it goes quiet as one big black hole.

There is a human pleasure in being able to experience viscerally a recording like that. In some sense making black holes more real. What a remarkable time to be alive: to actually be on that cusp of not knowing, and then discovering.

Title Card:
M87 Black Hole Data Ready for Imaging
June 5, 2018

Shep: All right guys, we're gonna release the data.

Group: Whoo!

Shep: Big moment, let's do it then. Okay, I'm including everybody in the entire collaboration on this note.

Michael Johnson: The end goal is to have this snapshot of reality: how a black hole really looks. Black holes at the center of galaxies are bathed in this hot glowing plasma, and so there's light coming from behind the black hole and in front of it and every which way. They curve their spacetime so much that even light from behind the black hole can be bent around them to reach the observer.
You can imagine some of the photons would be far enough away they'd just come to you, some of them would be close to the horizon and they get bent inward, and some of them would be too close and they'd fall into the black hole. And so the shadow of the black hole is this circular area of diminished brightness with this bright ring around it. It's really a special thing that there's such a concrete prediction for something that no one's ever seen.

Katie Bouman: You know, if you're making an image, you have to come in the other room, so we all start at the same time.

Offscreen: Team One Imagers!

Title Card: EHT Imaging Team One

Katie: Okay, which day has the best coverage by the way? I'm doing 3601.

Andrew Chael: I was going to do 3601 for now.

Michael: Same.

Katie: Okay, are we ready?

Andrew: I'm giddy.

Katie: Oh my god, wait, should we close the door, are we ready?

Michael: Wait, what is happening?

Katie: We're trying to make an image right now!

Michael: Can we just pace things a little bit?

Daniel Palumbo: Well no, first of all.

Katie: Shep, close the door! Can we start Michael?! You don't have to start...

Andrew: Let's wait for Michael...

Michael: Can we just go on our little trajectories and you know meet up in 20 minutes?

Daniel: No.

Katie: I just think it's like a big moment, and I think for me, I'm just saying, like, I think it'd be fun for us all to do the first one together, see that shit, and then go off in our own little ways and fix it. I think it's just so exciting that you - do you want to do it alone?

Shep: I'd like to see it all together so we can kind of get some idea of the data.

Katie: Are we ready?

Group: Ready.

Katie: It's not gonna work at all!

Andrew: Enhance, enhance, enhance!

Katie: Ready?

Andrew: Set.

Group: Go!

Katie: Oh my god! Oh my god we pressed go!

Andrew: It's just a waffle.

Shep: Ah! That looks really, really interesting.

Katie: (Singing)

Shep: How's the waffling going?

Katie: Andrew's looks beautiful but there's no tweaking involved (laughs).

Andrew: ...I put compactness very high.

Michael: Daniel and I were both getting something like this, with - That's what I get when I use only closure.

Shep: Only closure?

Katie: Oh my god, look at the chi squareds!

Shep: That's pretty good!

Michael: And then this is, after a few more iterations, it smooths it out and gets rid of some of the extended junk.

(Offscreen): This is all on low-band?

Shep: Is this only one day?

Michael: This is only one day.

Shep: You know what –

Michael: That's pretty suggestive.

(Offscreen): Did you remove these outliers in the amplitude?

Michael: I didn't touch anything.

Shep: That is very cool guys. It's really, really cool. Which one is that?

Andrew: This is Katie's image.

Katie: See it looks different though, because you guys have a bright spot more on this side.

Michael: Okay, seriously?! Look, we're all getting kind of a crescent that's about the right size--

Shep: So what is the size on that, it's like -

Katie: This is about 40.

Shep: That's when you expect if M87 has six billion solar masses.

Michael: That's a high mass case.

Shep: You know what this is? This is a scale to weigh black holes.

Michael: Okay, seriously if we can get anything that looks remotely like that on all the days...

Shep: The only way anyone's leaving this room is if everybody gets over there so we take a picture. It could have been awful!

Lia Medeiros: Am I short enough that I can just stand here?

Shep: And you got to get the thing!

(Chatter)

Shep: We're at a point now where things could inadvertently go south. Okay, so I took a picture on my phone, of something on the screen.

Shep: See you guys tomorrow, we'll do some more imaging tomorrow.

Shep: All it’s gonna take is for one of these images to be texted to the wrong person, people will look at it, they will measure it off of a screen, they'll go write a paper. I guarantee you. There has to be an absolute, 100% embargo. No one outside the EHT collaboration can see anything, anything that happens here can never leave Team One.

This is pretty wild. It's all wrong, I'm sure it's all wrong, but if that works out, it's pretty amazing.

Malcolm: Things are going well. We think that we have managed to do this part of the project.

Title Card:
Brinsop Court, England
September 16, 2018

Malcolm: We've managed to get our target answer of 12J. There's a little bit left to do.

Andy: I think the only thing that matters is three point five.

Malcolm: Three point five?

Andy: Yeah.

Sasha: Good to see you.

Andy: Hey Sasha!

Sasha: Oh hey, you're here already!

Andy: Yeah, we've already done like five pages of calculations, you're late! (laughs)

Andy: You're allowed to put your stuff away and go to the bathroom.

Sasha: (laughs) That’s alright, I’m needed.

Malcolm: No time for that!

Sasha: Nope.

Andy: Okay, ah -

Sasha: So where are we at, what still needs to be done?

Andy: The only things I see now is understanding this G plus minus to the P.

Malcolm: Right. And the past horizon.

Andy: And the past horizon. Does anybody see anything else?

Malcolm: No, that’s it.

Sasha: Back at Brinsop, one year on. Last year we thought it'd be pretty plain sailing, we would spend a few more weeks then we'd just sum up all these terms and get the answer we wanted. And then over the course of last year we realized actually it's so much more complicated than that.

Sasha: T-left, over T-right plus T-left-

Sasha: We found there were millions of terms and it was never going be a two-week job, and we got out computers for the first time, and that didn't work.

Malcolm: One over Y.

Sasha: And then, what we realized is that you can actually break this equation we had, we could break it down into an integrable part, and a non-integrable part. I think that was the breakthrough. We had to realize that we had almost everything we needed, but there was somehow-- a few terms got lost I guess.

Sasha: N, D, here -

Sasha: What we’ve discovered is that the equation is the sum of the variation of the inertia charge and the variation of the angular velocity of the horizon. Which, when evaluated you get 12J. Before, we just had a few of the terms involved in the angular velocity of the horizon. And without the full thing it wasn't integrable. Now we've found a nice physical picture and a nice way of getting 12J and now's the final, you know, finishing touches, to make sure that we really believe in it. I'm just very sad that Stephen won't be able to see this through to the end. He would have been really, really excited.

Andy: It's weird how personal physics can become. One of the saddest things about Stephen's passing in the middle of this is that if it works we can't tell him.

Malcolm: One bottle in front of ...

Andy: To Stephen.

Group: To Stephen.

Andy: One of the impressive and wonderful things about Stephen, was how much he really cared about these questions. We know that it's somehow very different inside a black hole. And so the prize is a really big one if you figure it out. The nature of spacetime.

Malcolm: That's about right.

Andy: Hawking handed us the biggest clue that we have. If this project we're on now works, it will be like a giant sign post, there's gold in this direction. You look up in the night sky and of course you don't see them. But you know they're up there. Almost mocking us: “try and figure me out.”

Title Card:
EHT Imaging Team Two
Two weeks until teams compare images

Heino Falcke: I just want to check my audio

Kazu Okiyama: Can you hear me?

Heino: Yeah, I can hear you.

Kazu: Hi Monica, can you hear us?

Monica Moscibrodzka: I can hear you-- Hello!

Kazu: Okay, so I just want to start, the first telecon actually showing the first images of M87. All images are very consistent, there is a shadow-like feature. Really really encouraging results.

Heino: Wow, it worked. I mean, it definitely worked. We see the ring, and then you've got to be very skeptical, actually. I would love to see that thing and that's what makes me very suspicious about myself and what I see.

Heino: I think it's okay to call that a shadow feature, if you like, as you see in the middle, but we should be really careful of what we think we see.

Monika: Are we going to see other teams' images?

Kazu: No, no, no, no. When we meet at imaging workshop to inspect images from each team.

Kazu: I could not sleep last night because I was so excited. I mean, I've waited for this data set and this image for eight years.

Sarah Issaoun: I'm really happy that we're all getting pretty consistent results, and I'm excited to see what the other teams are doing. We all kept pretty good secrets!

Title Card:
EHT Imaging Team Three
One week before image comparison

Alan Marscher: Imaging Team Three has been doing mostly the standard technique where we use this algorithm called Clean. We have about half a dozen individuals on the team who are making the images. The central part of the image we're in general agreement on. I'll be interested to see what the other teams using "maximum entropy" and some of the other methods, what they got next week. We hope that they will be consistent. We're trying to be very, very careful about it. The worse thing would be to say that we've seen black hole shadow and then find out later it was an imaging artifact.

Title Card: EHT Imaging Team One

Katie Bouman: Right now within Team One, we feel pretty confident in the structures that we're getting.

Andrew Chael: We are feeling pretty good about our consistency in our images, but we haven't seen anything from the other teams, so, it's possible that everything will be a complete mess when comparing between the teams.

Katie: And I'm a little scared for: what is our plan moving forward, if we do get different images?

Andrew: Yeah.

Title Card:
EHT Image Comparison Workshop
July 23, 2018

Joseph Farah: Good morning!

Michel Johnson: How's it going.

Joseph: Pretty good.

(General chatter)

Katie: Hey, nice to meet you finally. I'm Katie, nice to meet you! Thanks for coming all this way!

Shep: This is an incredibly exciting moment. For the first time we're gonna see if all the teams are seeing the same basic structure. I have not seen any of the results from anywhere else. So this is really a Christmas, Hanukkah moment, right? This is when you unpack, this is when you open up the gifts: did you get a pony? I don't know.

Monika Moscibrodzka: And then I self-calibrated and then amplitude plus closure phase...

Monika: I had a little bit goosebumps. I've been waiting for this moment for like 10 years. I've been modeling black holes for 10 years, and finally it becomes real.

Lia Medieros: Let's see what we could do if we were to just use the exact same script without changing anything, without any fine tuning, to see what it will do.

Joseph: Okay, yeah that would be very interesting to see

Lia: Just out of curiosity. To see if we can come up with one script that could consistently...

Michael Johnson: …all on microarcsecond scale. So it does seem like kind of filling in the vacuum with more. So I guess we have two options for response to zero baseline. And in both it's producing more or less the same image, right?

Scientist: It doesn't make any sense to use it in that.

Michael: It does actually, they do bring extra information.

Scientist: But it could be completely extraneous information...

Katie: Michael, I still haven't received an image from Team Three, should I bug them? Okay.

Jose Gómez: ...Then it’s going to be much much worse...

Katie: Okay

Michael: Sorry, real quick - How much longer do you need before you're ready?

Katie: Um - I - I don't know...

Michael: Like 15 minutes?

Katie: Sure, if everything goes smoothly here, 15 minutes.

Michael: How long does Team Three need?

Jose Gómez: Couple of minutes if it is working?

Katie: Let's just do that, you can see the numbers, if they look fine to you...

Jose Gómez: Okay

(knock)

(offscreen): Hey, I -

Kazu: I'm ready. I'm ready, yeah.

Katie: All right, so first we did a normalized cross-correlation comparison between all of the images. A value of one is going to be a perfect consistency between two images, zero is pretty bad. So are we ready for the moment of truth?

[drumroll, laughter]

Katie: Okay, I will scroll down.

Group: Oh my God.

Group: Look at that.

Group: Wow! (Applause)

Katie: It's M87! (Laughter)

Katie: We compared, basically pixel by pixel, you know, how close the images were. We haven't talked at all among the teams, but these numbers tell us that despite that, we're all broadly seeing the exact same structure, so it's really promising.

Sera Markoff: It was surprisingly emotional. You know it from a mathematical point of view and we've been looking at pictures quite similar to that from our own models. But when you look at it and you have to tell yourself that it's actually data, that you're not seeing a simulation but

you're really looking at a black hole... I found myself just with my cell phone staring at it for hours.
Sera Markoff: What's going to have to happen now is, the whole collaboration has to come together and agree.

Title Card:
Nijmegen, Netherlands
Worldwide EHT Collaboration Meeting
November 8, 2018

Heino: It's the same latitude as ALMA…

Heino: This is a very, very critical phase of the project. We have to bring very different people with very different backgrounds together to agree on something that will be work representative of 200, 250 people.

Shep: That's a great question. I think that what would be best...

Shep: It's very easy to lose your credibility. And the Event Horizon Telescope has built up credibility over many years. We have to get it right.

Sera: How do you decide what's the key essence? What do we all agree on? This has been a discussion and it's been contentious. And it's probably not fully decided. (laughs)

Heino: Yes, we do want to have a single image, but we do want to show the variations as well.

Katie: Yes, t's a compromise we have to come up with.

Heino: Something that works. That thing that works.

Silke Britzen: I think it's not what we want to show, I think we should go for the best data set and the best image of this, easily reproducible for anybody who wants to do it again.

Rusen Lu: I kind of like the average image but since it's not consistent with any data, are we going to use this image to do for instance a parameter estimation?

Dimitrios Psaltis: Everybody came in with their own funding, their own expectations, so it is all about convincing each other and coercing each other to find one way forward.

Dimitrios: I mean, do you think there are unmodeled systematics in the synthetic data...

Dimitrios: That made it very democratic... but it's not easy, I will not lie.

Ramesh Narayan: I think the dream of any physicist who studies black holes is to be able to go through the horizon and to the other side. If I could take this trip, having decided that I've had enough of this world, what would I see?

Shep: Just as ancient explorers were drawn to the sea, we're drawn to the horizon. We're drawn always to the limits.

Andy: The horizon of a black hole is the edge of our knowledge, of our understanding of the universe. And the great exciting problem is to go beyond that edge.

Shep: That's the ultimate. That's the place where there's no “beyond”.

Heino: It’s something that doesn't exist as a physical, measurable part of the universe. But you personally could still go there and experience it. But you cannot tell anybody. And you don't exist anymore to the outside world. People always make the link intuitively to death.

Title Card: October 5, 2018

[Skype chime]

Andy: There they are. Smiling. It's nice to see you again. Miss you guys, miss you guys. So we're free. We've finished the paper. That's why everybody's smiling. I'm feeling pretty good.

Malcolm: I must say I’m feeling amazingly good. Simply because it has taken an amazingly long time to actually get done. (laughs)

Sasha: It's a great relief. It's nice to be able to think about the bigger picture a bit more, I feel like, I spent a lot of time getting really bogged down in --

Malcolm: You feel liberated.

Sasha: Yeah, I feel liberated, to be able to work out more what's going on, and I feel like the result we have is very compelling.

Andy: We've shown that the soft hair can account for all the information that's stored in a black hole.

Andy: But we have to be very smart about what to do next.

Malcolm: Yeah, absolutely right.

Andy: The big challenge is trying to show not only that this could happen, but that it does happen. And that there's a mechanism for the flow of information in and out of the black hole. That is a much more complicated problem.

Andy: That's what Stephen would want us to be doing.

Malcolm: Are you coming to this press release on the 15th?

Andy: I'm, I'm hesitating.

(Press release host): Well, good afternoon. Welcome to the press launch of the final book by Professor Stephen Hawking. Now, up until his death he continued to search for answers with his final paper, a work with his long-time collaborators, Professors Malcolm Perry and Andy Strominger, on one of the most puzzling problems facing the scientific community today: the information paradox. So Malcolm, Andy, give us a capsule summary of the paper.

Andy: Yeah, you know, it's a huge problem that Stephen gave to us. It took 50 years to understand what a black hole was before you started worrying about quantum...

Andy: It'll be a decade before we know whether this path is gonna get us where we want to go. We also don't know that it can't. And, I also have to confess, not very scientific of me, it has the right feel. I'm very excited to be part of this grand adventure.

Malcolm: To Stephen.

Group: To Stephen.

Andy: To soft hair.

Malcolm: To soft hair. And to the demise of the information paradox. (laughter)

Andy: And to the next paper.

Andy: It's a great life. It's what life is about.

Title Card: April 10, 2019

[General greetings chatter]

NSF Host: Okay. Welcome to today's press conference. Brought to you by the National Science Foundation and the Event Horizon Telescope project.

Brussels conference host: Good afternoon, we have very little time before the actual announcement goes live across the globe, in six simultaneous press conferences, so I will...

Santiago host: Buenos dias a todos, today is an extraordinary day for astronomy. We are...

Mareki Honma: (welcome in Japanese)

Taipei Host: (welcome)
[Crosstalk]

Shep: Thank you assembled guests, black hole enthusiasts. Black holes are the most mysterious objects in the universe. Now, we are members of a large collaboration: we are 200 members strong, we have 60 institutes, and we are working in over 20 countries and regions. We worked for over a decade to expose part of the universe that was invisible to us before.

And we are delighted to be able to report to you today that we have seen what we thought was unseeable. We have seen, and taken a picture, of a black hole. Here it is.

We now have visual evidence for the existence of a black hole. We now know that a black hole that weighs 6.5 billion times what our sun does, exists in the center of M87.

And this is just the beginning.