EVENT HORIZON TELESCOPE: THE BLACK HOLE SEEN ROUND THE WORLD

HEARING

BEFORE THE

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
HOUSE OF REPRESENTATIVES

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C O N T E N T S

May 16, 2019

EVENT HORIZON TELESCOPE: THE BLACK HOLE SEEN ROUND THE WORLD

THURSDAY, MAY 16, 2019

HOUSE OF REPRESENTATIVES,
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY,
Washington, D.C.

The Committee met, pursuant to notice, at 10:02 a.m., in room 2318 of the Rayburn House Office Building, Hon. Eddie Bernice Johnson [Chairwoman of the Committee] presiding.

U.S. HOUSE OF REPRESENTATIVES
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
HEARING CHARTER

Event Horizon Telescope: The Black Hole Seen Round the World

Thursday, May 16, 2019
10:00 am – 12:00 pm
2318 Rayburn House Office Building

PURPOSE

On Thursday, May 16, 2019 at 10:00 am, the Committee on Science, Space, and Technology will hold a hearing to review the scientific knowledge gained from the very first image of a black hole; how this new imaging capability may enable yet more scientific discovery; how the image was created, including the domestic and international partnerships that made this result possible; and future plans for the Event Horizon Telescope.

WITNESSES

- **Dr. France Córdova**, Director, National Science Foundation
- **Dr. Sheperd Doeleman**, Director, Event Horizon Telescope; Center for Astrophysics | Harvard and Smithsonian
- **Dr. Colin Lonsdale**, Director, MIT Haystack Observatory
- **Dr. Katherine (Katie) Bouman,** Postdoctoral Fellow, Harvard-Smithsonian Center for Astrophysics

BACKGROUND

In April 2017, a group of eight telescopes at different sites around the world were synchronized to observe radio waves emanating from the center of a galaxy called Messier 87 (M87). Together, these telescopes make up the Event Horizon Telescope (EHT), a global project with the goal of capturing the first-ever image of a black hole. Leaders of the EHT project, a collaboration of more than 200 scientists, revealed their first result on April 10, 2019.

Black Holes

Einstein's theory of general relativity postulates that gravity is not a force, as described by Newton, but a geometric bending, or distortion, of space-time.[1] Any massive object creates a distortion in the space-time around it. The higher the curvature of this distortion, the stronger the

[1] Space-time is a four-dimensional continuum composed of three-dimensional space and one-dimensional time.

"pull" of gravity. A black hole is an extreme case in which the curvature of space-time is infinite. At a sufficiently close distance to a black hole, the gravitational pull is so strong that nothing, not even light, can escape. This "point-of-no-return" is called the event horizon.

Black holes generally come in two varieties, stellar-mass and supermassive. Stellar-mass black holes are around 3-10 times the mass of the Sun and are scattered throughout the Milky Way and other galaxies. Supermassive black holes are millions to billions of times the mass of the Sun and lie at the centers of galaxies. Most galaxies are thought to host a supermassive black hole in their center, including our own Milky Way galaxy. Studying supermassive black holes can help us understand how galaxies form and evolve over time and to test Einstein's theory of general relativity in the most extreme conditions.

Black holes were once considered to be a mathematical artifact of Einstein's theory, not real objects. Even Einstein had doubts about the reality of black holes. Since black holes emit no light of their own, scientists examine the gravitational effects black holes have on nearby matter and light.

In recent years, evidence of the existence of black holes has been mounting. For instance, by tracking the orbital motion of stars in the innermost region of the Milky Way, scientists have determined that an object with a mass equal to 4 million Suns and a size smaller than twice that of Pluto's orbit lies at the center of our galaxy.[2] Most scientists now agree that this central object can only be a supermassive black hole.[3] In the M87 galaxy, NASA's Hubble Space Telescope observed gas clouds orbiting rapidly about the galaxy's center, indicating the presence of a black hole about 6 billion times the mass of the Sun.[4,5]

Despite the growing body of indirect evidence that black holes exist, a black hole had never been directly imaged until the EHT. By definition, black holes are invisible. If a black hole is surrounded by light-emitting material, however, general relativity predicts that this material should cast a "shadow," or an outline of the black hole and its event horizon. The goal for the EHT was to image this shadow.

Event Horizon Telescope

One of the targets for the 2017 EHT observing run was the supermassive black hole at the center of the M87 galaxy. While very massive, the black hole at the center of M87 is small in astronomical terms, about the size of our solar system. It's also far away, about 55 million light-years from Earth. To resolve something that small from such a large distance requires a telescope impossible to build, as it would have to be about the size of Earth.

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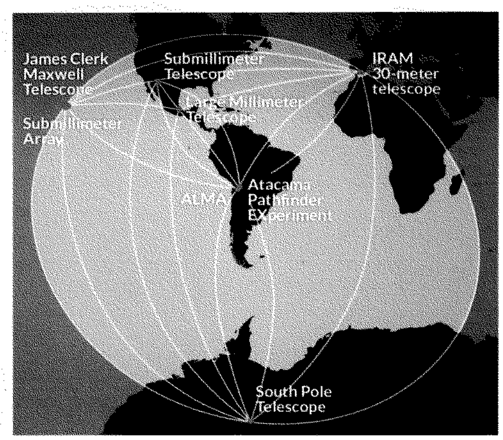
[2] Ghez, Andrea M. *et al.*, "High Proper-Motion Stars in the Vicinity of Sagittarius A*: Evidence for a Supermassive Black Hole at the Center of Our Galaxy," https://iopscience.iop.org/article/10.1086/306528
[3] The black hole at the center of the Milky Way galaxy is called Sagittarius A*.
[4] Walsh, Jonelle L. *et al.*, "The M87 Black Hole Mass from Gas-dynamical Models of Space Telescope Imaging Spectrograph Observations," https://iopscience.iop.org/article/10.1088/0004-637X/770/2/86
[5] The black hole at the center of the M87 galaxy is called M87*.

To get around this, the EHT team used a technique called very-long-baseline interferometry (VLBI). VLBI combines data collected simultaneously at multiple telescopes around the world to emulate a telescope the size of their separation (baseline). VLBI only works for radio waves, or a type of light with wavelengths longer than infrared light (1 millimeter to 100 kilometers). Fortunately, radio waves are also the only type of light that can travel unimpeded by dust and gas all the way to Earth from the center of M87.

Eight telescopes in six locations around the globe participated in the 2017 observations, their operations perfectly synchronized with the help of atomic clocks.

- SMT[6] in Arizona
- JCMT[7] and SMA[8] in Hawaii
- LMT[9] in Mexico
- ALMA[10] and APEX[11] in Chile
- IRAM[12] in Spain
- SPT[13] in Antarctica



Source: https://www.sciencenews.org/editors-picks/event-horizon-

By collecting data in unison and stitching it together, the EHT array acts like a single Earth-sized telescope with enough resolving power to read the date on a coin in Los Angeles from New York City. This is an unprecedented resolution for astronomy, more than 1,000 times better than that of the Hubble Space Telescope.[14]

Combining the Data

Each telescope of the EHT produced enormous amounts of data – about 350 terabytes per day – which was stored on high-performance hard drives. The team collected so much data (5 petabytes[15] in total) that the hard drives had to be shipped via FedEx from their respective

[6] http://aro.as.arizona.edu/
[7] https://www.eaobservatory.org/jcmt/
[8] https://www.cfa.harvard.edu/sma/
[9] http://www.lmtgtm.org/
[10] https://www.almaobservatory.org/en/home/
[11] http://www.apex-telescope.org/
[12] https://www.iram-institute.org/EN/30-meter-telescope.php?ContentID=2&rub=2&srub=0&ssrub=0&sssrub=0
[13] https://pole.uchicago.edu/
[14] NSF, "Planet-sized 'virtual telescope' expands to the South Pole to observe black holes in detail," https://www.nsf.gov/news/news_summ.jsp?cntn_id=134758
[15] One petabyte contains 1 million gigabytes (GB). An iPhone has 64 GB of data storage.

telescopes to two sites for processing – MIT Haystack in Massachusetts and Max Planck Institute for Radio Astronomy in Germany. It would have taken 10 years to transfer all of the data over the internet.

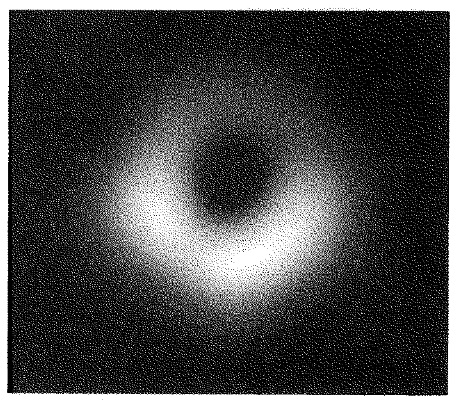
At both locations, a highly specialized supercomputer, called a correlator, combined the data. Since each telescope is at a different position on Earth, each had a slightly different view of the black hole. Using time-stamps created by the atomic clocks at each site, the correlator matched up and compared the data streams from every possible pairing of EHT's eight telescopes. From these comparisons, the correlator eliminated the noise and identified the black hole signal. This signal is called a "fringe."

The alignment of the black hole signals from each telescope was further refined by identifying and correcting for minute timing perturbations at each observing site and rerunning the correlation until the data could be thoroughly verified.

Constructing the Image

The correlated data was then released to four separate imaging teams charged with constructing an image. The teams worked in complete isolation from each other in order to not influence each other's results. Each team developed its own imaging algorithms to convert the radio signals into visual images.

One of the biggest challenges for the imaging teams was that the data had huge holes in it. The eight telescopes in the EHT array provided coverage for only a small portion of the entire virtual Earth-sized telescope. There are an enormous number of images that could match the data collected at the eight sites.



Source: https://eventhorizontelescope.org/

To solve this problem, the teams used machine learning with synthetic data and data from other astrophysical objects to train their algorithms. The algorithms were trained to generate images that satisfied the data in the simplest possible way, weeding out images that were physically impossible or contained overly complicated features.

Once the imaging teams were confident in the accuracy of their algorithms, they ran them on the M87* data. When the teams compared the four images they constructed, they found that they were remarkably similar. The images were then blurred and averaged together to create the final result.

NSF Support

To achieve the M87 result, the EHT collaboration relied on National Science Foundation (NSF) investments of three types: investigator grants directly for EHT research and instrumentation; existing multi-user observatories and facilities; and long-term investments in the foundational techniques and facilities for radio astronomy, particularly VLBI. NSF has awarded $28 million across 22 grants for instrumentation and facility upgrades, data analysis, and theoretical modeling directly related to the EHT. The multi-user facilities and infrastructure built and/or operated at least in part with NSF funds included three of the eight telescopes used for the M87 result (ALMA, SMT, and SPT) and high-performance computing infrastructure used as part of the image processing and theoretical modeling.

The foundational techniques of radio astronomy, including VLBI, were developed through several decades of NSF investments, including in facilities like the Green Bank Observatory in West Virginia, the Very Large Array (VLA) and Very Large Baseline Array (VLBA) in New Mexico, and the Combined Array for Millimeter-Wave Astronomy (CARMA), which was decommissioned in 2012.[16]

Future Plans

During the 2017 observing run, the EHT team also collected data from the black hole at the center of the Milky Way galaxy, called Sagittarius A*. The EHT imaging teams are currently working to construct images from that data. Since the Milky Way galaxy is less active, meaning less material is flowing into the black hole, light from the region immediately outside of the event horizon varies on shorter timescales than the region outside the black hole in M87. This makes it more challenging to construct an image. The upside is that there is a potential for the EHT imaging teams to construct a video of these variations.

The EHT array expanded to include a ninth telescope for its 2018 observing run, the Greenland Telescope.[17] Unfortunately, the observations made in 2018 were compromised due to bad weather. For its 2020 run, the EHT will include two more telescopes – the Kitt Peak 12-meter telescope[18] in Arizona and the NOEMA Observatory[19] in France – for a total of 11 telescopes. The additional telescopes will allow the team to construct sharper images.

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[16] NSF, "History of NSF'S Early Support for Very Long Baseline Interferometry (VLBAI) and Black Hole Observations, 1966-1985," https://www.nsf.gov/news/special_reports/blackholes/PDFs/EHT_VLBI_History_v1.pdf
[17] https://www.cfa.harvard.edu/greenland12m/
[18] https://www.noao.edu/kpno/
[19] https://www.iram-institute.org/EN/noema-project.php

Chairwoman JOHNSON. Good morning. This hearing will come to order. And without objection, the Chair is authorized to declare recess at any time.

We're delighted to see everyone this morning and welcome to our witnesses. I'm eager to hear more about this exciting breakthrough. Not long ago, scientists were not sure black holes were real. Even Einstein had his doubts. Scientists have since uncovered evidence of black holes, but they had no way to capture an image until the Event Horizon Telescope.

In science, most knowledge is gained incrementally. From efforts to peer into the far reaches of the universe, to experiments conducted at the smallest scale, our collective understanding of the world around us is built piece by piece. Each hard-earned discovery brings reality into better focus.

Every once in a while, a discovery will jolt us forward. Such breakthroughs generate entirely new avenues and tools for scientific study and a new appreciation for what we can achieve. The black hole image captured by the Event Horizon Telescope is both a jolt and the culmination of decades of incremental advances, most of which were made possible by the National Science Foundation (NSF).

The dark shadow bounded by a ring of light may look simple enough, but don't be fooled. The first-ever image of a black hole is a groundbreaking advancement in science, setting the stage for a new era of black hole astronomy. This new Earth-sized telescope also opens up a new window for observation of other astronomical objects and may further our understanding of gravity and the evolution of galaxies.

An enormous amount of effort went into clearing the necessary technological, logistical, political, and scientific hurdles. While there was never a guarantee that this project would succeed, the National Science Foundation invested in a good idea with potentially enormous payoff. This achievement demonstrates that when the Federal Government invests in our Nation's best and brightest and in the facilities necessary to do cutting-edge science, and, importantly, remains committed to those investments, we are limited only by our imaginations.

I congratulate each of our witnesses and the entire Event Horizon Telescope team on this astonishing achievement.

Another important part of this story is the international partnership. This discovery would not have been possible without contributions from partners around the world, including from Spain, Chile, Mexico, Europe, Taiwan, China, South Korea, and Japan. At a time of rising global tensions, let this be a reminder that the pursuit of science is still a unifying force.

Perhaps the most lasting impact of this discovery will be the inspiration for students to pursue STEM (science, technology, engineering, and mathematics) studies. The excitement of this discovery has no doubt instilled a hunger that will drive the next generation of scientists to make discoveries of their own. Today, we celebrate your success. I look forward to learning more about this incredible image, the global team that made it possible, and future plans for the Event Horizon Telescope.

[The prepared statement of Chairwoman Johnson follows:]

Good morning and welcome to today's hearing.

Welcome to our witnesses. I am eager to hear more about this exciting breakthrough. Not long ago, scientists were not sure black holes were real. Even Einstein had his doubts. Scientists have since uncovered evidence of black holes, but they had no way to capture an image until the Event Horizon Telescope.

In science, most knowledge is gained incrementally. From efforts to peer into the far reaches of the universe, to experiments conducted at the smallest scale, our collective understanding of the world around us is built piece by piece. Each hard-earned discovery brings reality into better focus. Every once in a while, a discovery will jolt us forward. Such breakthroughs generate entirely new avenues and tools for scientific study, and a new appreciation for what we can achieve. The black hole image captured by the Event Horizon Telescope is both a jolt and the culmination of decades of incremental advances, most of which were made possible by the National Science Foundation.

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Today we celebrate your success. I look forward to learning more about this incredible image, the global team that made it possible, and future plans for the Event Horizon Telescope.

Chairwoman JOHNSON. I now will recognize Mr. Lucas for his statement.

Mr. LUCAS. Thank you, Chairwoman Johnson, for holding this hearing, and thank you to all our witnesses for coming to discuss this incredible discovery.

Since Einstein predicted the existence of black holes, scientists have been able to observe their effects and refine theories on how they affect our universe, but this is the first time we've been able to see a black hole directly, and it marks a huge milestone in our understanding of the universe.

We have this first-ever image of a black hole thanks to a pioneering collaboration between observatories around the world. To detect an image of a black hole we needed a telescope as big as our entire planet. Not surprisingly, building that was out of the question. But every challenge presents an opportunity.

And science funded by the National Science Foundation joined forces with astronomers, data scientists around the world to coordinate their observations, in effect, creating a global telescope. This is a great example of NSF's approach to basic research and driving scientific progress.

And, as Dr. Córdova told this Committee just last week, NSF's 10 Big Ideas are about enabling research that crosses scientific disciplines to make big discoveries. NSF's coordinated and interdisciplinary approach has already produced two groundbreaking discoveries in its "Window on the Universe," first the detection of gravitational waves by LIGO (Laser Interferometer Gravitational-Wave Observatory) and now this image of a black hole.

I want to put these achievements in perspective. When Einstein predicted the existence of gravitational waves, he also questioned whether these ripples in space-time could ever, ever be observed on Earth. The signals are so small, traveling over such an enormous distance, that he doubted whether we would ever be able to create instruments sensitive enough to detect them. But now, 100 years later, technology funded by the NSF, developed over decades, makes it possible for us to confirm this fundamental prediction.

That matters not only because it helps us understand the universe in which we live, also because it contributed to the creation of other technologies that directly affect scientific progress, including semiconductors that our cellphones and computers use more powerful.

The NSF's investments in ground-based astronomy have also given birth to technologies used in everything from airport security to Lasik eye surgery.

But the scientists these projects have produced may be the greatest return on our investment. Hundreds of graduate students worked on this discovery, and their careers will be informed by this experience. And thousands of young students who watched this announcement may be inspired to pursue careers in STEM. These are whole generations of new discoverers that will contribute to scientific knowledge and American progress.

We don't yet know all the ways in which the Event Horizon Telescope will broaden our knowledge of the universe or our technological development here on Earth, but it's certain that this image is just the beginning of what's to come.

I'm looking forward to learning more about this from our witnesses, what their discoveries teach us about the universe, what lessons we can take away from how to coordinate basic research in the U.S., and what's next for this project.

Thank you for being here, and I yield back the balance of my time, Chair.

[The prepared statement of Mr. Lucas follows:]

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Thank you for being here, and I yield back the balance of my time.

Chairwoman JOHNSON. Thank you, Mr. Lucas.

If there are Members who wish to submit additional opening statements, your statements will be added to the record at this point.

And at this time, I'll introduce our witnesses. Our first witness will be Dr. France Córdova. Dr. Córdova was confirmed as the 14th Director of the National Science Foundation in 2014. She's President Emeritus of Purdue University. I think we might have some people here on this Committee who might be a little biased for Purdue—and Chancellor Emeritus of the University of California at Riverside.

Previously, she was Chief Scientist at the National Aeronautics and Space Administration. Dr. Córdova also headed the Department of Astronomy and Astrophysics at Pennsylvania State University and was Deputy Group Leader in Earth and Space Sciences at the Los Alamos National Laboratory.

She received her bachelor of arts from Stanford, her doctorate in physics from California Institute of Technology.

And our next witness is Dr. Sheperd Doeleman. Dr. Doeleman is Director of the Event Horizon Telescope and an astrophysicist at the Harvard & Smithsonian Center for Astrophysics. He's also a Harvard Senior Research Fellow and project co-leader of the Harvard Black Hole Initiative.

He received his bachelor's of arts degree from Reed College and his Ph.D. in astrophysics from MIT.

Our third witness is Dr. Colin Lonsdale. Dr. Lonsdale is the Director of the MIT Haystack Observatory, where he has worked as a radio astronomer for 32 years. He's been heavily involved in the development of new techniques and instruments in radio astronomy, including the VLBI (very-long-baseline interferometry). He's been involved in the EHT (Event Horizon Telescope) project from its early days. He also serves on the governing Board of the international EHT Collaboration, is Vice Chair and member of the Board Executive Group.

He received his bachelor of science from St. Andrews University in Scotland and his Ph.D. in radio astronomy from Nuffield Radio Astronomy Labs in England.

Our final witness is Dr. Katherine Bouman. Dr. Bouman is currently a postdoctoral fellow at the Harvard & Smithsonian Center for Astrophysics. In June 2019 she will be starting as an Assistant Professor in the Computing and Mathematical Sciences Department at the California Institute of Technology.

As a member of the EHT collaboration, she worked to develop innovative ways to combine techniques from astronomy and computer science to construct the first image of a black hole.

She received her BSE from the University of Michigan and her Ph.D. from MIT.

Our witnesses should know that we will allow each of you 5 minutes for the spoken testimony. Your written testimony will be included in the record for the hearing. When all of you have completed your spoken testimony, we will begin questions, and each Member will have 5 minutes to question the panel. We'll start with Dr. Córdova.

TESTIMONY OF DR. FRANCE CÓRDOVA, DIRECTOR, NATIONAL SCIENCE FOUNDATION

Dr. CÓRDOVA. Chairwoman Johnson, Ranking Member Lucas, and Members of the Committee, thank you for holding this hearing and for the opportunity to discuss the Event Horizon Telescope, or EHT, collaboration and the resulting first image of a supermassive black hole. And thank you for your commitment to science.

We're excited by this remarkable accomplishment, one that will transform and enhance our understanding of black holes, and I'd like to pause for a minute so that we can all in this room recognize the representatives of the EHT team.

[applause].

I want to focus my remarks today on EHT's history with the National Science Foundation, the vision and support of so many dedicated researchers, and what this discovery means for the future of scientific research. Black holes have captivated the imaginations of scientists and the public for decades. No single telescope on Earth has the sharpness to create an image of a black hole. This team did what all good researchers do; they innovated. The EHT observation synchronized telescope facilities around the world to form one huge Earth-sized telescope.

While this technique, called very long baseline interferometry, or VLBI, was initially supported by NSF in the late 1960s. The EHT team took it to a whole new level. They developed the extraordinary sharpness and sensitivity required to image a black hole.

Enabled by technology, observations have always advanced our understanding of the universe, and that is why, for more than 30 years, NSF has supported technology development for astronomy through the advanced technologies and instrumentation program. This program supported EHT with eight separate awards that got the project started and sustained its early development. Without this early seed funding, the EHT would not have succeeded. Thanks to its early support, the EHT project grew from a small exploratory group to a large international collaboration.

This discovery would not have been possible without cooperation and coordination. Such cooperation is exemplified in the telescope in Chile called ALMA (Atacama Large Millimeter/submillimeter Array), which was crucial to EHT's success. While ALMA is a major NSF-supported facility, it's also supported by international partners.

The success of the EHT also highlights the need for midscale research infrastructure, one of NSF's 10 Big Ideas. After more than a decade of development and piecemeal funding, the EHT was finally reviewed as a whole in our Division of Astronomical Sciences Mid-scale Innovations Program where EHT received the funding that enabled these observations. Increased NSF support of midscale research will enable more effective support of comparably sized projects in the future.

Supporting basic research has tremendous benefits. As an example, the methods developed by astronomers in the late 1960s for measuring positions of distant galaxies had surprising down-to-Earth benefits. These galaxies served as a reference for measuring imperceptible changes in the orientation and rotation of the Earth. Such measurements are now used routinely to aid modern satellite navigation and the global positioning system, GPS. Everyone who uses a smartphone to find directions or search for a nearby restaurant or reserve a rideshare benefits from astronomy and decades of Federal investment in such basic research.

In producing the first image of a black hole, the EHT has generated a global phenomenon. Astronomy is a point of entry for young people into STEM. This is incredibly important to our Nation's competitiveness and economic success, as science and technology are drivers of the economy. Our future prosperity depends on inspiring the next generation to be curious to learn and explore, and I'm happy to see lots of next-generation scientists and engineers in the audience today.

Astronomy is a source of such inspiration. It's just as important that we continue to support the students and postdocs as they enter their chosen fields. Their contributions were key to the success, and this experience will prepare them to reach even further in the future. This discovery is historic for astrophysics, it's incredibly meaningful for me personally as an astrophysicist.

NSF exists to enable scientists and engineers to illuminate the unknown, to reveal the subtle and complex majesty of our universe.

Thank you again for your continued support for NSF's mission and for holding this hearing today and the opportunity to testify.

[The prepared statement of Dr. Córdova follows:]

Dr. France Córdova
Director
National Science Foundation

Before the
Committee on Science, Space, and Technology
United States House of Representatives

on
"Event Horizon Telescope: The Black Hole Seen Round the World"

May 16, 2019

Chairwoman Johnson, Ranking Member Lucas, and Members of the Committee, thank you for holding this hearing, and for the opportunity to discuss the Event Horizon Telescope (EHT) collaboration and the resulting first direct visual evidence of a supermassive black hole, and its shadow. We are all very excited by this remarkable accomplishment, one that will transform and enhance our understanding of black holes. I want to focus my remarks today on EHT's history with the National Science Foundation (NSF), the vision and support of so many dedicated researchers, and what this discovery means for the future of science.

Black holes have captivated the imaginations of scientists and the public for decades. In fact, we have been studying black holes so long that sometimes it is easy to forget that none of us had actually seen one. We have simulations and illustrations, and thanks to instruments supported by NSF, we have detected binary black holes merging deep in space. We have observed the episodic transfer of matter from companion stars onto black holes. Some massive black holes are surrounded by particles and radiation we can observe. We have spotted subatomic materials flung across millions of light-years from near a black hole, but we had never actually directly seen the shadow of an event horizon, that point of no return after which nothing, not even light, can escape a black hole, until now. No single telescope on Earth has the sharpness to create an un-blurred definitive image of the black hole. This team did what all good researchers do, they innovated.

The Beginning...

More than six decades ago, NSF-funded researchers helped lead the development of radio astronomy. Beginning with the Green Bank Observatory in 1955 NSF has supported multiple radio astronomy facilities including: Arecibo Observatory in Puerto Rico (operations partly funded by NASA); the Very Large Array on the Plains of San Augustin in New Mexico; the

Very Long Baseline Array (operations partially funded by the U.S. Naval Observatory) with 10 field sites throughout the U.S. and the Virgin Islands; the Combined Array for Millimeter-wave Astronomy; and, most recently, the Atacama Large Millimeter/submillimeter Array (ALMA) in Chile.

The EHT observations were particularly dependent upon Very Long Baseline Interferometry (VLBI), which synchronizes telescope facilities around the world to form one huge, Earth-sized telescope. VLBI began in the late 1960s and this capability advanced as new radio telescopes were constructed. Research in this field was supported initially by NSF for astronomy and subsequently by NASA and other agencies for geodesy.

Observing at shorter wavelengths improves VLBI resolution, or "sharpness." Original VLBI observations operated at centimeter wavelengths. Building upon this early VLBI research, NSF supported the MIT Haystack Observatory in extending VLBI observations from centimeter wavelengths into the millimeter-wavelength regime. Currently, the EHT observes at 1.3 millimeters and achieves a resolution of 20 micro-arc seconds. This incredible resolution is equivalent to seeing a grain of sand on a beach in Los Angeles from a telescope in New York. It enabled the EHT to image a black hole.

Developments in computing and data storage technologies also helped make the EHT possible. One measure of progress is the data recording and processing rates, which determine the sensitivity of the observations, or the faintness at which celestial objects can be observed. Systems circa 1969 recorded data at 0.720 megabits per second (Mbit/s). Current EHT stations record at 64 gigabits per second (Gbit/s). This corresponds to a 90,000-fold increase in the data recording rates over the last fifty years! To put it another way, during its 2017 observing campaign, each element of the EHT downloaded data from the universe at more than one thousand times the speed of a broadband internet connection.

A natural consequence of using telescopes in different countries for VLBI was international collaboration. At the heart of VLBI lies the fact that no single telescope can accomplish alone what many telescopes can do together in unison. As it is for radio telescopes, so it is for the scientists who use them. Over the years, the EHT project grew from a small exploratory group to a large international collaboration. The current collaboration includes more than two hundred members from twenty different regions and countries. This team learned to take advantage of institutional, cultural, and individual diversity to unite around the common goal of imaging a black hole.

A key program in this international collaboration was NSF's Partnerships for International Research and Education program, which allows the agency to leverage U.S. dollars and improve scientific outcomes. A partnership project on black hole astrophysics led by the University of Arizona (with partners in Germany, Mexico, and Taiwan) contributed critical data on weather conditions at all EHT sites that enabled the 2017 EHT observations. The research team also developed the cloud computing infrastructure for the EHT's main post-processing system. Other funded activities involved detector development and fast data transfer.

Creating the EHT was a formidable challenge that required upgrading and connecting a worldwide network of eight pre-existing telescopes deployed at a variety of challenging, high-altitude sites. These locations included volcanoes in Hawai`i and Mexico, mountains in Arizona and the Spanish Sierra Nevada, the Chilean Atacama Desert, and Antarctica. The telescopes contributing to this result were ALMA, the Atacama Pathfinder EXperiment (APEX), the Institute for Radio Astronomy in the Millimeter Range (IRAM 30-meter telescope), the James Clerk Maxwell Telescope, the Large Millimeter Telescope Alfonso Serrano, the Submillimeter Array, the Submillimeter Telescope, and the South Pole Telescope. The ALMA telescope has the largest collecting area of any radio telescope and incorporating this telescope into the EHT array enabled its successful observations. Without federal funding of over $500 million to construct both the ALMA and South Pole Telescopes, EHT could not have imaged a black hole. Petabytes of raw data from the telescopes were processed by highly specialized supercomputers hosted by the Max Planck Institute for Radio Astronomy and MIT Haystack Observatory.

Throughout the history of astronomy, improved observations advanced our understanding of the universe. For example, precise naked-eye observations of the planets by Tycho Brahe and calculations by Johannes Kepler circa 1609 proved that Earth orbited the Sun, and that the planets orbited in ellipses. In modern times, the NSF Laser Interferometer Gravitational Wave Observatory functions by measuring the movement of test masses to extraordinary precision, less than an atomic diameter. This enabled detecting gravitational waves from distant colliding black holes and neutron stars. Improving observations requires new technologies. That is why, for more than thirty years, NSF has supported technology development for astronomy through the Advanced Technologies & Instrumentation (ATI) program. This program enables innovative ideas and transformative science such as the EHT. The ATI program supported EHT with eight separate awards that got the project started and sustained its early technical development. Without this early seed funding, the EHT could never have succeeded.

Supporting basic research has tremendous benefits for humankind. VLBI research had unanticipated, though obvious in hindsight, practical benefits. VLBI enabled exquisitely precise images of distant astronomical objects. These positions were used to anchor a celestial reference frame of coordinates against which the Earth itself could be compared. It measured the separations of its telescopes to millimeter accuracy. Since these telescopes were grounded on the Earth, the orientation and rotation of the Earth itself could now be measured with unprecedented accuracy. Nowadays VLBI observations of distant quasars are undertaken on a daily basis by the U.S. Naval Observatory. Their measurements are used to update the positions of satellites, in particular those of the Global Positioning System (GPS).

GPS has become ubiquitous for finding positions. Methods developed by VLBI researchers improved the accuracy and capability of GPS, and ushered in aircraft precision landing, vehicle positions and a host of other widely used applications. Everyone who uses a smartphone to find directions, search for a nearby restaurant or reserve a ride-share benefits from astronomy and decades of NSF and NASA-funded VLBI research.

NSF played a pivotal role in the EHT discovery by funding individual investigators, interdisciplinary scientific teams and radio astronomy research facilities since the inception of the EHT. It required expertise in areas ranging from detector development to high-performance computing and theoretical physics. Over the last two decades, NSF has directly funded twenty-two different awards totaling more than $28 million in EHT research, which is the largest commitment of resources for the project. Other supporters include international funding agencies, especially the European Research Council, as well as the Ministry of Science and Technology of Taiwan and others. Private foundations such as the Gordon and Betty Moore Foundation and the Templeton Foundation also supported the project.

It is important to note that the $28 million investment by NSF was complemented by billions of dollars of investments in infrastructure worldwide. As described above, this discovery would not have been possible without the construction of the South Pole and ALMA telescopes. The South Pole Telescope provided a key calibration capability and will be necessary for future observations. ALMA provided the necessary sensitivity to image the black hole. Because no other ground-based facilities have their unique capabilities, without each of them, the EHT could not have succeeded. Sustained support for the construction of new research infrastructure is critical to our ability to advance scientifically. Without this research infrastructure tens of thousands of scientists and students would not have the tools they need to make these great advancements.

The Present...

On April 10, 2019 NSF and EHT unveiled to the world the first image of a black hole, and the event horizon, outside of which matter and photons can escape and inside of which they are captured by the black hole This incredible moment caught the imagination of scientists and the public alike. The Washington D.C. press conference was viewed more than 1.2 million times, with at least 737,378 people watching the broadcast live. This resulted in 17,000 new subscribers to the NSF YouTube pages. The press conference was viewed live in universities and schools all over the world and more than over 400 broadcast news stories aired about the announcement. The NSF gained 25,000 new Facebook followers and 40,000 new Instagram followers in the days after the announcement. On April 11, one day after the public announcement, the image of a black hole appeared on the front pages of the New York Times, the Washington Post, the Wall Street Journal and many other newspapers around the world. These facts and statistics demonstrate the natural fascination and wonder that people everywhere have for astronomy.

How did we get here? Through the imagination and dedication of scientists around the world, willing to collaborate to achieve a daunting goal. Through world-wide investment in research infrastructure, technological development, and basic research. And finally, through long-term financial commitments from NSF and other funders, both here and abroad, willing to take risks in pursuit of an enormous potential payoff. Without international collaboration, the contributions of hundreds of scientists and engineers, and sustained, stable funding, the EHT would have been impossible.

The Future...

As we look to future discoveries, NSF has put forward bold questions – 10 Big Ideas - that will drive NSF's long-term research agenda -- questions that will ensure future generations continue to reap the benefits of fundamental science and engineering research. These 10 Big Ideas capitalize on what NSF does best: catalyze interest and investment in fundamental research, which is the basis for discovery, invention and innovation. They are meant to define a set of cutting-edge research agendas and processes that are uniquely suited for NSF's broad portfolio of investments, and will require collaborations with industry, private foundations, other agencies, science academies and societies, and universities.

Funding these ideas will push forward the frontiers of U.S. research and provide innovative approaches to solve some of the most pressing problems the world faces, as well as lead to discoveries not yet known. The EHT project aligns with three of NSF's 10 Big ideas. Future astrophysical discoveries will benefit from new hardware and software advances generated by *Harnessing the Data Revolution*, particularly development of a new data cyberinfrastructure for timely handling, processing, analysis and modeling of astrophysical data. By integrating new ways to probe the cosmos, *Windows on the Universe* is providing a more detailed view of the cosmos, and *Mid-Scale Research Infrastructure* offers a new funding mechanism that is responsive to ambitious projects like EHT requiring a dynamic, holistic, and flexible investment.

In particular, the large data generated by the EHT illustrated the need for basic research in math, statistics and computer science that will enable data-driven discovery through visualization, better data mining, machine learning and more. NSF's Big Idea: *Harnessing the Data Revolution*, will support an open cyberinfrastructure for researchers and develop innovative educational pathways to train the next generation of data scientists. The EHT observations generated 5 petabytes of raw data from telescopes. It is equivalent to 100 years of high-definition YouTube videos. Such large quantities of data are most efficiently transported on physical media rather than over the Internet. Therefore, these data were ultimately stored on approximately one thousand hard drives that collectively weighed more than one half ton, costing approximately $3 million, and needed to be shipped across the globe for processing. Recording, storing, transmitting and processing these data were some of the key technical challenges that were overcome to successfully image a black hole. Increasingly in the future, science in general and radio astronomy in particular will generate tremendous volumes of data. Transforming these data into useful scientific knowledge will demand innovation and investment in new hardware and software that this Big Idea fosters.

In successfully imaging a black hole, the EHT captured the imagination of the general public to these enigmatic objects. It is yet another example that NSF-funded research brought popular attention to black holes and Einstein's theory of relativity. It follows on the discovery of gravitational waves from colliding black holes, supported by NSF for four decades, as well as numerous observations of black hole phenomena with NSF telescopes. The gravitational wave discovery was recognized with the 2017 Nobel Prize in Physics and ushered in a new discipline of multi-messenger astronomy. This discipline combines data from traditional telescopes that receive electromagnetic radiation with data from gravitational wave charged particles and/or neutrinos in an integrative view of astrophysical events. The *Windows on the Universe* Big Idea supports this integrative approach. It is a natural extension of the multiwavelength approach that astronomers have increasingly adopted in recent decades, whereby data from X-ray, optical, infra-red, submillimeter and radio wavebands of the electromagnetic spectrum are used to form a more complete picture of astrophysical processes than either waveband could reveal in isolation.

The success of the EHT also highlights the need for *Mid-Scale Research Infrastructure*. From its inception, the EHT was awarded twenty-two separate awards from five different NSF programs. Each award was the result of a separate proposal submission and competition. This substantial churn of the proposal writing and review process over a 19-year period was clearly ultimately successful. After more than a decade of development and piecemeal funding, the project was reviewed as a whole in our Division of Astronomical Sciences mid-scale program and received the final $6.5 million in funding that resulted in the successful set of observations. NSF support of mid-scale research concepts will enable more effective support of comparably sized scientific projects in the future.

This discovery would never had been possible without the global cooperation and coordination of the EHT. The United States led this international collaboration, showing the pioneering, trail-blazing spirit upon which our country was founded. Continued close cooperation with our international partners is key to taking the science to the next level.

In producing the first image of a black hole, the EHT has inspired the general public and generated a global phenomenon. The majesty of discovering our universe motivates such ambitious experiments, but as with all fundamental science, EHT offers other important benefits. This science will advance education, inspiring students and developing the workforce our society requires. It has, and will continue, to lead to collaborations in astrophysics, engineering, computer science and other fields. Astronomy is a point of entry for students and young people into Science, Technology, Engineering, and Mathematics (STEM). STEM education is an increasingly important part of the educational system. It prepares students for satisfying, well-paying jobs in a competitive, global workforce. Most of these jobs will not be in scientific research; however, the technical and critical-thinking skills of a STEM education are invaluable. Science and technology are drivers of the national economy. As such, the future prosperity of the U.S. depends in part upon motivating the next generation to be curious, to explore, and to learn and grow in the context of STEM. Astronomy is a crucial source of inspiration for this process.

We often say that NSF is where discoveries begin. It is also where many discoverers receive the support they need to make the next leap in their research careers. The ATI program, out of which the EHT began, trains early career scientists and develops them into the next generation of leaders of large and complex scientific projects and facilities. Programs like the Graduate Research Fellowship Program and the CAREER program, which support the next generation of researchers are also critically important. They invest in individuals who are poised to push their fields of study further. Equally important are our efforts to broaden participation and diversity in STEM. NSF has taken many steps in recent years to on both these fronts – from instituting our INCLUDES program as one of the Big Ideas, to issuing new terms and conditions on harassment. There is no room for discrimination in science and our continued leadership in innovation depends on us recognizing and drawing upon the full potential of our population.

In Summary...

Madam Chairwoman, this discovery is historic for astrophysics, and incredibly meaningful for me personally as an astrophysicist. We have seen what was before unseeable. Black holes have sparked imaginations for decades. They have exotic properties and are mysterious to us. Yet with more observations like this one they are yielding their secrets. This is why NSF exists. We enable scientists and engineers to illuminate the unknown, to reveal the subtle and complex majesty of our universe.

Basic research can be risky in the short term, but in the long term it is a certain path to revolutionary progress. The Event Horizon Telescope shows the power of collaboration, convergence, shared resources, and commitment to developing the technologies that enable discovery. These allow us to tackle the universe's biggest mysteries. All the contributors to EHT: Scientists, NSF, and Members of Congress, should take enormous pride in our collective accomplishment. Were it not for the support of Congress and the investment of taxpayer funding, this would not have been possible. With this discovery we can move forward with the science of understanding our universe —pushing the boundaries of discovery and innovation still further.

Thank you again for your continued support for NSF's mission and for holding this hearing today and the opportunity to testify. I will be pleased to answer any questions you may have.

Dr. France A. Córdova
Director
National Science Foundation

France A. Córdova is an astrophysicist and the 14th director of the National Science Foundation (NSF), the only government agency charged with advancing all fields of scientific discovery, technological innovation, and science, technology, engineering and mathematics (STEM) education. NSF is a $8.1 billion independent federal agency; its programs and initiatives keep the United States at the forefront of science and engineering, empower future generations of scientists and engineers, and foster U.S. prosperity and global leadership.

Córdova is president emerita of Purdue University, and chancellor emerita of the University of California, Riverside, where she was a distinguished professor of physics and astronomy. Córdova was the vice chancellor for research and professor of physics at the University of California, Santa Barbara.

Previously, Córdova served as NASA's chief scientist. Prior to joining NASA, she was on the faculty of the Pennsylvania State University where she headed the department of astronomy and astrophysics. Córdova was also deputy group leader in the Earth and space sciences division at Los Alamos National Laboratory. She received her Bachelor of Arts degree from Stanford University and her doctorate in physics from the California Institute of Technology.

More recently, Córdova served as chair of the Board of Regents of the Smithsonian Institution and on the board of trustees of Mayo Clinic. She also served as a member of the National Science Board (NSB), where she chaired the Committee on Strategy and Budget. As NSF director, she is an ex officio member of the NSB.

Córdova's scientific contributions have been in the areas of observational and experimental astrophysics, multi-spectral research on x-ray and gamma ray sources and space-borne instrumentation. She has published more than 150 scientific papers. She has been awarded several honorary doctorates, including ones from Purdue and Duke Universities. She is a recipient of NASA's highest honor, the Distinguished Service Medal, and was recognized as a Kilby Laureate. The Kilby International Awards recognize extraordinary individuals who have made "significant contributions to society through science, technology, innovation, invention and education." Córdova was elected to the American Academy of Arts and Sciences and is a National Associate of the National Academies. She is also a fellow of the American Association for the Advancement of Science (AAAS) and the Association for Women in Science (AWIS).

Córdova is married to Christian J. Foster, a science educator, and they have two adult children.

Chairwoman JOHNSON. Thank you very much. Dr. Doeleman.

TESTIMONY OF DR. SHEPERD DOELEMAN, DIRECTOR, EVENT HORIZON TELESCOPE, CENTER FOR ASTROPHYSICS – HARVARD & SMITHSONIAN

Dr. DOELEMAN. Chairwoman Johnson, Ranking Member Lucas, Members of the Committee, thank you for the opportunity today to describe the recent EHT results and their impact.

On April 10, 2019, our collaboration held simultaneous international press conferences to announce the first image of a black hole. And as you see—if you did see this image, you were not alone. On the front page of almost every major newspaper in the world you could see the bright ring caused by light bending in the immense gravity of a supermassive black hole that is 6.5 billion times the mass of our sun. It's estimated that 4.5 billion people saw these results, all eyes focused on the same cosmic wonder at the same time.

Why did this result resonate with so many people, scientists, and the curious public alike? In part it was because, for over 100 years, black holes have remained one of the greatest mysteries of modern physics. They are gravity run amok, a complete collapse of matter into a volume so small that nothing, not even light, can escape their gravitational pull.

And based on growing evidence, we now believe that supermassive black holes, with masses of millions or billions of times our sun's, exist in the centers of all galaxies, where the hot gas that surrounds them can outshine the combined light of all the stars in their host galaxy.

This animation shows how light rays from this hot gas are bent by the black hole, shown here outlined in red. Some light paths make complete loops around the black hole forming a bright circular boundary around the event horizon, the point where gravity traps the light, preventing it from reaching us.

Einstein's equations tell us the precise size and shape of this ring, so by measuring this feature for the galaxy M87 that's 55 million light-years from Earth, the EHT team has put Einstein's theories to the most stringent test yet. And this image, the highest-resolution picture ever taken from the surface of the Earth, is what we saw. It is confirmation of Einstein's theory at the edge of a supermassive black hole. It allows mathematicians, physicists, astronomers the ability to refine their models of how black holes reprocess matter and energy on galactic scales.

In fact, the brightening you see at the bottom of this ring is perfectly consistent with near light speed motions of gas around the black hole. It also opens a new window on ever more precise tests of gravity. This is critical because our theory of gravity is incomplete. We have not yet been able to unify our understanding of gravity in the quantum world.

To make this image, we developed specialized instrumentation that link together existing radio facilities, enabling them to work together as an Earth science telescope. We reached across borders, included experts from around the globe, and leveraged billions of dollars of international resources to deliver extraordinary scientific return on investment.

Support from the NSF was crucial. Before success of this project was assured, NSF funding enabled the small U.S. EHT team to grow and carry out key proof-of-concept experiments. As confidence in the project grew, we attracted additional investment from the international science community, which is why U.S. groups are in leadership positions within the larger collaboration today.

The EHT collaboration now has over 200 members representing 60 institutes working in over 20 countries and regions. It truly takes a global team to build a global telescope. And because the EHT relies on so many technical and theoretical advances, there are myriad opportunities for early-career researchers to make fundamental and profound contributions. Undergraduates, graduate students, postdoctoral fellows, and junior staff have taken on leadership roles and responsibilities in areas of high-speed electronics design, innovative imaging algorithms, and modeling black holes using national supercomputer facilities. The EHT footprint across STEM fields is exceptionally broad with rich opportunities for mentorship.

Building on this success, we are working with our international partners to enhance the EHT. We aim to move beyond the still images to making real-time movies of black holes, enabling entirely new tests of gravity and extreme astrophysics. We will explore purposefully situating new dishes to fill out the global virtual telescope and even launch radio satellites into orbit to realize an EHT that is not bound by the dimensions of the Earth.

Having worked on the EHT from the earliest stages, I experienced a deep sense of fulfillment following the result. But in the end, I personally feel the greatest accomplishment was assembling an expert and committed team. The look on the faces of my colleagues when the first M87 images appeared on computer screens will never leave me. A mix of astonishment, wonder, pride, awe, and humility. Imaging a black hole for the first time has inspired our team, and we hope it has inspired you, too.

Thank you for the opportunity to testify today, and thank you for your commitment to keeping the U.S. a global science leader. I look forward to answering any questions you may have.

[The prepared statement of Dr. Doeleman follows:]

Written Statement of

Sheperd S. Doeleman, PhD
Director
Event Horizon Telescope Collaboration

before the
Committee on Science, Space, and Technology
United States House of Representatives

Chairwoman Johnson, Ranking Member Lucas, and Members of the Committee, thank you for the opportunity to describe the recent Event Horizon Telescope findings and their impact here today.

On April 10th, 2019, the Event Horizon Telescope Collaboration (EHTC) held simultaneous international press conferences to announce the first image of a black hole. On the front page of almost every major newspaper in world, you could see the bright ring caused by light bending in the immense gravity of a super massive black hole that is six and a half billion times the mass of our own Sun. And if you did see this image, you were not alone. It is estimated, based on distribution and readership, that 4.5 billion people on Earth saw these results on April 10th and during the days that followed.

Background

Why did this result resonate with so many people, scientists and the curious public alike? In part it was because for over 100 years black holes have remained one of the greatest mysteries of modern physics. In 1915, Albert Einstein published his General Relativity theory, which showed that gravity could be thought of as a distortion in the fabric of space-time. Less than a year later, Karl Schwarzschild, working at the front of World War I, solved Einstein's equations, with the startling result that if enough mass were concentrated in a small enough volume, nothing – not even light – could escape its gravitational pull. Schwarzschild sent his findings on a postcard to Einstein who presented the solution to the Prussian Academy of Sciences in 1916.

These objects, black holes, were just mathematical curiosities for many years, but in the 1970's a growing body of evidence from the best x-ray, radio and optical astronomical observatories made a case for the existence of black holes in the night sky. Dying stars give birth to modest black holes, with masses that range from a few to one hundred times that of our Sun. Supermassive black holes, millions or billions of times the mass of our sun, exist in the centers of most galaxies, where the hot gas that surrounds them can outshine the combined light of all the stars in their host galaxy.

Results: Seeing the Unseeable

These "one way doors out of our Universe" were becoming more real, but we had never seen one; and seeing is believing. The ring of light imaged by the EHT marks the point at which light is bent into circular orbits around the black hole, forming a bright boundary around the event horizon, within which light is trapped and cannot escape. Einstein's equations tell us the precise size and shape of this ring, so by measuring this feature for the galaxy M87, 55 million light years from Earth, the EHT team has put Einstein's theories to the most stringent test yet. The result: General Relativity appears to hold up in the most extreme laboratory in the Universe. The map made by the EHT also put on solid footing decades of theory and complex simulations of what a black hole 'might' look like. In doing so it has provided resounding confirmation of some of the most advanced computational models of extreme matter.

But more than this, it points to the emergence of a totally new field of science: using black holes as precision tests of our Universal theories. Acceptance of Einstein's theories after hundreds of years of Newtonian Gravity did not occur until the most advanced techniques uncovered the smallest of discrepancies. And now we use Einstein's theory every day: It is responsible for our GPS systems running properly. Over the coming years we will refine the EHT to allow next-generation tests of gravity and to understand how black holes liberate energy to affect the large-scale structure of our Universe.

Building an Earth-Sized Telescope

Despite its gargantuan mass, the black hole at the center of galaxy M87 presented us with a photon ring that was only one one-hundred millionth of a degree in size. Mapping this black hole is equivalent to being able to read the date on a coin in Los Angeles while you are standing in New York City. Over the past decade the EHT outfitted radio dishes and facilities around the world with high bandwidth recording systems that allowed the team to capture radio waves from the M87 black hole with the precision of atomic clocks. When the recordings were later played back at a central location (one in Bonn, Germany, and the other in Massachusetts, USA) the data could be combined to create a virtual telescope that was the size of the distance between the geographically separated radio dishes. In effect, the EHT team created a telescope the size of the Earth. The EHT has the highest angular resolution ever achieved from the surface of our planet.

The EHT has concentrated on deploying specialized instrumentation at existing radio facilities that allow them all to be combined into a virtual Earth-sized telescope. This strategy has leveraged billions of dollars of international infrastructure through modest investment, thus delivering an extraordinary scientific return on investment. The EHT team takes very seriously its responsibility to funding agencies, and ultimately the taxpayers, to carefully steward the support it receives.

Building a Global Team

This effort required a dedicated group of experts from around the world to unite under the banner of a common science vision, and it drew upon resources from many countries and international funding agencies. In the early stages, when the risks to the project were highest, the National Science Foundation and US-based private foundations supported US scientists in this endeavor. At that time, when success of the project was not at all assured, this early support enabled the small EHT team to grow and carry out key proof-of-concept experiments. As confidence in the project grew, we were able to leverage that early support and attract additional investment from the international science community. Indeed that early leap-of-faith is in part why US groups are in leadership positions within the larger collaboration. The EHT Collaboration now has over 200 members, representing 60 institutes, working in over 20 countries and regions. It takes a global team to build a global telescope.

Because the EHT relied on so many technical and theoretical advances, there were myriad opportunities for early career researchers to make profound contributions. From development of high-speed electrical design of data processors to cutting-edge simulations run on computer clusters, undergraduates, graduate students, postdoctoral fellows and junior staff were able to take on leadership roles and responsibilities within the collaboration. So for the EHT, the footprint across STEM fields is exceptionally broad. The philosophy of inclusion has allowed working groups in the project to address challenges by engaging scientists at many career stages, with rich opportunities for mentorship.

The Next Steps

Now that we have made the first black hole image and published the results in a series of six scientific papers, the EHT is looking to the next steps of analysis and to the next phases of the project. In the short term, efforts within the project will focus on existing data on our other main target, SgrA*, the 4 million solar mass black hole at the center of the Milky Way. For this source, tests of Einstein's gravity can be even more precise. We will also continue work on M87, extending the analysis to include mapping of magnetic fields near the black hole, which are responsible for launching near light-speed jets of material that are seen shooting from the center of the galaxy.

On longer time scales, we will be working to enhance the EHT in targeted ways that will sharpen our focus on these two supermassive black holes. Additionally, we plan to move beyond making still image of black holes to making real-time movies of these objects, enabling entirely new tests of gravity and the physical processes that launch the jets we see on large scales. Already, we are partnering with our global collaborators on next-generation instrumentation and algorithms, aimed at novel ways to more completely fill in the virtual Earth-sized telescope

In 2009, our team wrote a white paper as part of the US Astronomy Decadal Review process, in which we said "The capabilities of Very Long Baseline Interferometry (VLBI) have improved steadily at short wavelengths, making it almost certain that *direct imaging of black holes can be achieved within the next decade.*" Our team delivered on this promise. In a similar way, we now can say that it is almost certain that *making movies of black holes on event horizon scales can be achieved in the following decade.* Let us see what comes to pass; we are confident in the team we have assembled.

STEM Impact and Outreach

Returning to the question posed at beginning, what is it about this image that has captured the attention of so many? Yes, it is partly the deep science questions it addresses, but it is more than that.
As students, we are told early on that black holes are invisible, cloaked by nature with a gravity so strong it traps light. And we are taught that they are exceptionally small, nearly impossible to discern on the sky. Yet driven by the attraction of attacking the deepest mysteries in the Universe, an international band of colleagues found a way to turn the Earth itself into a telescope to let us see the unseeable. This is a story not simply of scientific results, but of people innovating, working together to achieve something that just a generation ago was thought beyond our reach. At an even deeper level, one marvels at the fact that radio waves emitted by the hot gas just outside the event horizon are of the right wavelength to stream freely through the infalling rush of gas towards the black hole. And that at this wavelength, the resolving power of an Earth-sized telescope is perfectly matched to imaging the photon ring of M87's supermassive black hole. Like a solar eclipse, where the disk of the moon perfectly occults the sun, nature has conspired to let us see an entirely new region of the Universe.

Having worked on the EHT from the earliest stages, I experienced a deep sense of fulfillment following the result. But in the end I personally feel the greatest accomplishment was assembling an expert and committed team. The look on the faces of my colleagues when the first M87 images appeared on computer screens will never leave me: a mix of astonishment, wonder, pride, awe, humility. Imaging a black hole for the first time has inspired our team, and we feel it has inspired people around the world, too.

Thank you for the opportunity to testify today, and thank you for your commitment to keeping the United States a global scientific leader. I look forward to answering any questions you may have.

CENTER FOR
ASTROPHYSICS
HARVARD & SMITHSONIAN

Dr. Sheperd S. Doeleman
Director
Event Horizon Telescope Collaboration

Sheperd S. Doeleman is an Astrophysicist at the Center for Astrophysics | Harvard & Smithsonian and the Director of the Event Horizon Telescope (EHT), a synchronized global array of radio observatories designed to examine the nature of black holes. He is also a Harvard Senior Research Fellow and a Project Co-Leader of Harvard's recently established Black Hole Initiative (BHI). The BHI is a first-of-its-kind interdisciplinary program at the University that brings together the disciplines of Astronomy, Physics, Mathematics, Philosophy, and History of Science to define and establish black hole science as a new field of study.

As one of the founding members of the BHI, Doeleman leads a team studying supermassive black holes with sufficient resolution to directly observe the event horizon itself. Using Very Long Baseline Interferometry (VLBI) methods, the EHT telescope networks observe astronomical radio sources at 1.3 millimeter (mm) wavelengths. These sources include the supermassive black holes at the centers of our own Milky Way, called Sagittarius A* (SgrA*), as well as in Messier 87 (M87), the supergiant elliptical galaxy in the constellation Virgo.

Doeleman is a Guggenheim Fellow (2012) and was the recipient of the DAAD German Academic Exchange grant for research at the Max Planck Institute für Radioastonomie. He serves as a peer reviewer for the *Astrophysical Journal*, *Science*, and *Nature*, among others. Doeleman leads and co-leads research programs supported by grants from the National Science Foundation, the National Radio Astronomy Observatory (NRAO) ALMA-NA Development Fund, the Smithsonian Astrophysical Observatory, the MIT International Science & Technology Initiatives (MISTI), the Gordon and Betty Moore Foundation, and the John Templeton Foundation. He has taught at MIT and mentors students and post-doctoral fellows at MIT and Harvard.

Doeleman received his B.A. from Reed College in 1986, and left soon after for a year in Antarctica where he conducted multiple space-science experiments at McMurdo Station on the Ross Ice Shelf. With an appreciation for the challenges and rewards of instrumental work in difficult circumstances, he returned to complete a Ph.D. in astrophysics at MIT. After visiting to work at the Max Planck Institute as a recipient of the DAAD, he came back to MIT in 1995 for a postdoctoral fellowship, eventually serving as assistant director of the MIT Haystack Observatory.

Doeleman's interests focus on problems in astrophysics that require ultra-high resolving power—the ability to observe fine details of cosmic objects. His research employs the technique of Very Long Baseline Interferometry (VLBI), in which widely separated radio dishes are combined to form an Earth-sized virtual telescope. He has used this technique to study the atmospheres of dying stars, as well as stars that are just being born. His group at MIT pioneered development of instrumentation that enables VLBI to achieve the greatest resolving power possible from the surface of the Earth. He carried out the first global experiments using these new systems that successfully measured the size of the supermassive black hole at the center of the Milky Way Galaxy and in the galaxy M87. He now directs the international Event Horizon Telescope project, which recently succeeded in making the first image of a black hole. This project addresses several fundamental questions about the Universe: Do event horizons exist? Does Einstein's theory of gravity hold near a black hole? How do black holes affect the evolution of galaxies?

Chairwoman JOHNSON. Thank you very much.
Dr. Lonsdale.

TESTIMONY OF DR. COLIN LONSDALE, DIRECTOR, MIT HAYSTACK OBSERVATORY

Dr. LONSDALE. Chairwoman Johnson, Ranking Member Lucas, and Members of the Committee, thank you for the opportunity to talk to you about how the Event Horizon Telescope works and how its truly extraordinary capabilities allowed our team to achieve the scientific milestone we're recognizing today.

A conventional telescope creates an image by focusing light from a distant object onto a sensor, much like a digital camera with a really long telephoto lens attached. Naturally, the bigger the lens, the more detail that you can see. In fact, if you can make optically perfect lenses, the magnification you can get depends only on how big they are.

As Dr. Doeleman has already mentioned, since it's so far away, the black hole in the galaxy M87 appears extremely tiny on the sky, so to see it, you need a really big lens with a lot of magnification. So let's take a more careful look at just how tiny this black hole is as it appears from the Earth 55 million light-years away.

And I have a short video here. This is what my observatory looks like from 25 miles away, and that dome there has a large radio telescope inside it and down at the bottom right there's a small figure. That figure is Jason SooHoo, who is one of our staff members who went to the South Pole actually twice to support the EHT. And as we continue zooming in and zooming in, we get down to the level of individual human hairs. And if you look at an individual human hair under an electron microscope, it looks like that, and on this, to scale, that is the size of the black hole image. And just to reiterate, if we zoom all the way back out, the Event Horizon Telescope can see things much smaller than a human hair from a distance of 25 miles. So that's a fairly remarkable amount of magnification.

A conventional optical telescope would need a lens several miles across to see such a small object, which is impractical, but the EHT is no conventional telescope. The Event Horizon Telescope operates with short radio waves, not light, and at radio wavelengths our lens must be several thousand miles across, in fact, the size of a planet to get such precision. The EHT simulates such a lens by combining signals from radio dishes thousands of miles apart using computational techniques.

Imagine that these radio dishes sit directly in front of an Earth-sized lens. Radio photons come toward us from the M87 galaxy. Instead of hitting the giant imaginary lens and being focused onto a sensor, some of them are intercepted by our dishes. At each dish we capture the photons and record them as digital data on ordinary computer disk drives. So far so good. But to make images with our simulated lens, we need a lot of photons, the more the better. Getting enough photons to image a black hole simply has not been technically possible until quite recently.

So how did we do it? Well, first, with strong NSF support, we have greatly increased the available dish area at key sites like the ALMA array Chile. And second, we, quote, "listen" for photons at many different radio frequencies simultaneously, generating more digital data. The more digital data, the more photons. So we record to 128 disk drives in parallel at each dish site. It's equivalent to simultaneously downloading 11,000 full H.D. movie streams from Netflix. This fills up thousands of high-capacity disks in one observing campaign, weighing several tons.

Each campaign involves extensive preparation and logistical complexity. Talented and dedicated staff from different institutions travel to some of the most remote and inhospitable places on Earth like the South Pole, driven by a common goal to create a unique window into the most extreme environments known to science.

The effort level and unity of purpose is something I personally find to be truly inspiring as a tangible reaffirmation of the spirit of human curiosity that fuels basic research and the quest for knowledge.

We ship the recorded disks to two locations, my observatory in Massachusetts and the Max Planck Institute for Radio Astronomy in Bonn, Germany, where the data streams are combined in a complex, precise, and computationally intensive process known as correlation. Now, correlators simulate what a physical lens does, bringing photons that follow different paths to a common focal point, synchronized with pinpoint accuracy by atomic clocks at each observing site. After rigorous quality checks that can take several months, the correlated data are released for further analysis.

Because our dishes are few and far between, we can recreate only small pieces of our imaginary planet-sized lens. Our next speaker, Dr. Bouman, will talk about how the team has used innovative new approaches to make a reliable image from incomplete data.

I want to express my gratitude to the Committee for the opportunity to speak to you here today, and I'd be pleased to answer any questions you may have.

[The prepared statement of Dr. Lonsdale follows:]

Written Statement of

Colin J. Lonsdale, PhD
Director, MIT Haystack Observatory
and
Vice-Chair of the Governing Board,
Event Horizon Telescope Collaboration

before the
Committee on Science, Space, and Technology
United States House of Representatives

Chairwoman Johnson, Ranking Member Lucas, and Members of the Committee, thank you for the opportunity to describe the Event Horizon Telescope (EHT) and its truly extraordinary capabilities that have enabled this milestone scientific result.

A different kind of telescope

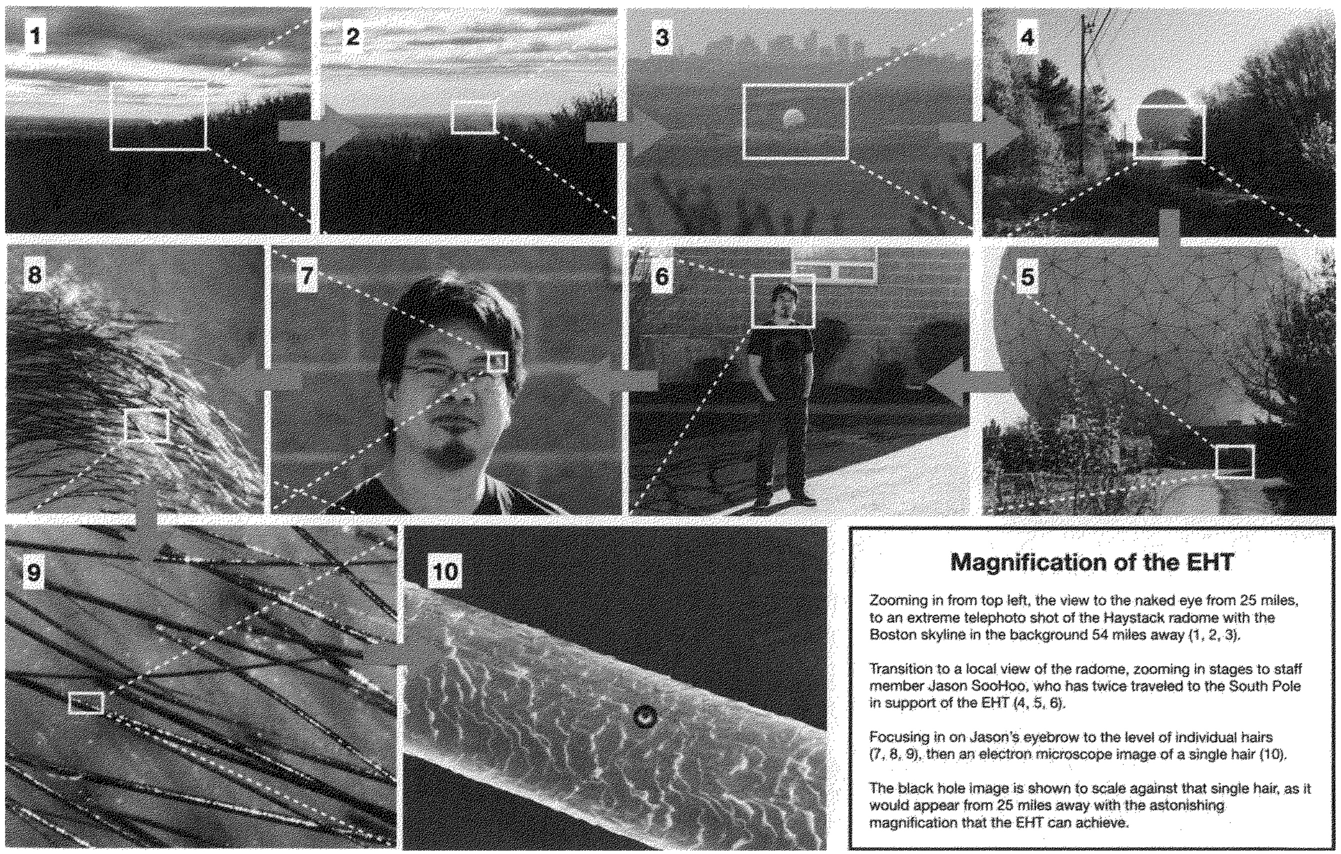
The EHT operates on the principle of interferometry. Rather than describe this in technical detail, it is useful instead to start with the mental image of a conventional telescope, creating an image by focusing light from a distant object onto a sensor array – like a digital camera with a really long telephoto lens attached.

Generally, the bigger the lens, the more light is gathered, the fainter the objects that can be seen, and the greater the magnification that can in principle be achieved. If the telescope optics are literally perfect, the amount of detail that can be seen, or equivalently the amount of magnification of an area of sky that can be applied, depends only on how big the lens is on the front of the telescope.

The black hole in the galaxy M87 is billions of times more massive than our Sun, which means that its event horizon is comparable in size to the extent of our entire solar system. This is a scale so huge that it defies human imagination to fully grasp. And yet, it lies so far away, 55 million light years, that it appears to us as something extremely tiny on the sky[1]. So tiny in fact that no optical telescope ever built, either on the ground or in space, has anything close to the magnification required to see what the EHT has seen. Such a telescope would need a lens, or a mirror, several miles across to achieve that level of detail, and the optics would have to be perfect.

We cannot physically build such a telescope, but by using a range of key, recently available technologies, we are now able to reproduce the capabilities of one. An optical telescope would need to be several miles across, but at the radio wavelengths used by the EHT we must synthesize a virtual telescope that is instead the size of the earth, many *thousands* of miles across. How is this done?

[1] A sense of the enormous level of magnification required for black hole imaging, and achieved by the EHT, is provided by the graphic on the next page.



Magnification of the EHT

Zooming in from top left, the view to the naked eye from 25 miles, to an extreme telephoto shot of the Haystack radome with the Boston skyline in the background 54 miles away (1, 2, 3).

Transition to a local view of the radome, zooming in stages to staff member Jason SooHoo, who has twice traveled to the South Pole in support of the EHT (4, 5, 6).

Focusing in on Jason's eyebrow to the level of individual hairs (7, 8, 9), then an electron microscope image of a single hair (10).

The black hole image is shown to scale against that single hair, as it would appear from 25 miles away with the astonishing magnification that the EHT can achieve.

Capturing and storing photons

The radio dishes of the EHT sit atop mountains around the world, and in one case on top of a massive ice sheet at the South Pole. Each of these dishes can be thought of as sitting directly in front of an imaginary earth-sized lens. If that lens were real, radio photon paths would be bent by it, and come to a focus point somewhere in space where we could place a sensor array to capture an image. Instead, we capture the photons that strike the radio dishes, and store them as digital data on ordinary computer hard disks – lots of them. A radio photon is a little bundle of energy, just like a photon of visible light, so more radio photons equates to more energy that can be measured. A key technical challenge of the EHT was to collect enough of these photons so that a faint object like a distant black hole could be detected.

One way to get more photons is to use bigger dishes, and to use dishes on mountaintops so that the earth's atmosphere does not bury those photon signals in unwanted noise. A major part of the recent success was an NSF-funded project, leading an extensive international effort to combine the signals from dozens of dishes of the Atacama Large Millimeter Array (ALMA) high in the Chilean Andes, allowing them act together as one much larger dish.

The other way to get more photons is simply to capture and record enormous amounts of digital data, by opening up the range of radio frequencies received by each telescope (like listening to many radio stations at once), and sending the resulting torrent of bits and bytes to a high-speed recording device. The more data that gets recorded, the more photons get captured, and the fainter the objects that can be seen.

Using modern disk drives with massive storage capacities, and specially designed electronics and systems to feed up to 128 spinning disks at once, the EHT systems are already capable of recording 64 gigabits per second at each radio dish. To put this in perspective, this is the equivalent of streaming more than 11,000 full HD movies at the same time. A full EHT observing campaign fills up thousands of high capacity disks, weighing several tons.

Capturing such data volumes at many sites takes extensive preparation, attention to detail, and extraordinary efforts by individuals, who travel to the far corners of the world and deploy their energies and talents to oversee the correct operation of the radio dishes and EHT equipment. The global nature of the telescope is mirrored by the international nature of the dedicated team of scientists, engineers and operational staff who make these remarkable observations possible from some of the most remote and inhospitable locations on the planet.

This work is difficult and demanding, but EHT staff engage in it with energy and enthusiasm for a truly inspiring research mission that exemplifies human curiosity and the quest for knowledge. It is a great privilege to be witness to, and in some measure to facilitate, the process of discovery pursued by a diverse team inspired by the prospect of opening a new window onto the most extreme environments known to science – the domain of warped spacetime, relativistic motions and prodigious energy release surrounding the event horizons of black holes.

Their efforts, and those of others with varied and essential responsibilities throughout the project, deserve our recognition and profound gratitude. It is my intent that today, with this testimony, we fully represent the contributions of the more than 200 members of the international EHT collaboration.

A computational lens

Photons that strike the dishes are detected, converted into digital data and stored, effectively capturing them. Those that miss the dishes are lost forever and never reach our imaginary planet-sized lens. But for those photons that were "captured", we can transport them to a central location using ordinary shipping methods, play them back from the disks, and manipulate them in such a way that they come to the same point at the same time, just as they would have done if the lens was real.

This is done by a process known as "correlation" which takes account both of ultraprecise synchronization of the recorded data as derived from atomic clocks at each dish, and of exquisitely detailed modeling of the imperfect rotation of the Earth which determines the precise positions and velocities of the dishes at any given instant, relative to the target on the sky. It then mathematically compares the properties of the signals coming from each of the dishes.

This is the essence of "radio interferometry", in which signals from widely separated dishes are combined and, provided they have been perfectly lined up with each other, compared in order to precisely measure how much they differ from each other from nanosecond to nanosecond. It is a complex and extremely computationally intensive phase of EHT operation, supported by teams of scientists, correlator operators and software engineers. And it has become technically and financially feasible for the massive quantities of data required by the EHT only in recent years due to relentless and dramatic advancements in the computing industry.

The EHT systems from the dishes all the way through to recorded data are complex, with behaviors that are not always wholly predictable. In addition, the data are affected by weather conditions at the various dish sites. Correlator operations at both the MIT Haystack Observatory in the USA and the Max Planck Institut für Radioastronomie in Germany are where such issues are diagnosed and corrected to the extent possible by experienced, expert staff. The data undergo a range of rigorous quality checks, sometimes taking many months, before being released to the broader EHT collaboration for further analysis.

Reproducing the function of a giant lens, at these short wavelengths and with such data volumes, represents a formidable achievement for our collaboration. It is testament to more than a decade of NSF-supported developments, on diverse and challenging technical fronts, and all of us here today are proud to have participated in this work. Without vision and risk-taking on the part of NSF, and the support and collaboration of our international partners, this result would not have been possible.

Nevertheless, because the dishes we use are few and far between, we can build only a miniscule portion of our ideal earth-sized computational lens. Given such sparsity of information, it has been necessary to develop advanced new techniques that take the correlated data and convert them into an image whose properties are well understood, and whose reliability can be objectively and quantitatively established. That is the topic of the testimony to follow, by Dr. Bouman.

The future

The results we are celebrating here today are just the beginning for our black hole imaging endeavor, and for this field of science. With data already in hand we will pursue Sagittarius A* at the center of our Milky Way galaxy, which is the only other black hole which appears big enough on the sky to be imaged with the current EHT.

But the technology will continue to advance on many fronts, and the path to additional rapid scientific progress is already clear. More dishes will be used to create increasingly precise images revealing subtle details and fainter features. Dishes will be sent into space to create a telescope even bigger than the Earth with even more magnifying power, putting other black holes with different environments, orientations and parameters within reach, and allowing us to explore the ones we are currently studying on ever finer scales. Movies of material spiraling into black holes will become possible, and some of the mysteries surrounding the generation of the remarkable jets of material emanating from these objects at close to light speed will start to be unraveled for the first time.

The black hole image, already iconic across the globe, will also surely fire the imaginations both of young scientists pursuing advanced degrees or starting their first postdoctoral appointments, and of high school students or undergraduates who may aspire one day to participate in groundbreaking discoveries. Such unique, high-profile and accessible scientific breakthroughs provide beacons with which to attract our brightest young minds from all backgrounds into science and technology, enriching and diversifying our national STEM workforce.

But we need not wait to see the impact of the EHT project, because even before the image was generated, the mere possibility of achieving such a result inspired a cadre of talented young researchers and students to join the project, in dozens of institutes all over the world. And this is epitomized by Dr. Bouman's story.

From a scientist's perspective, these are exciting times indeed!

Colin J. Lonsdale
MIT Haystack Observatory, Westford, MA 01886 USA
(617) 715-5575, cjl@haystack.mit.edu

Colin Lonsdale is a radio astronomer who has worked at the Haystack Observatory of the Massachusetts Institute of Technology for 32 years, and for the past decade has led the Observatory as Director.

He specializes in radio interferometric techniques using a variety of national and international facilities, and has published extensively on a wide variety of astronomy research topics. These include the jets and lobes of extragalactic radio sources, supernovae and hydroxyl masers in star forming galaxies, the relationship between star formation and active galactic nuclei, and masers in the extended atmospheres of young stars. More recently he has worked on solar and heliospheric studies at low radio frequencies.

He has also been heavily engaged in the development of new techniques and instruments in radio astronomy, including very long baseline interferometry (VLBI) and multiple, novel low frequency imaging arrays.

He has been involved in the Event Horizon Telescope project since its inception, and much of the technical development for the project was conducted at Haystack under NSF funding during his tenure as Observatory Director. He serves on the governing Board of the international EHT Collaboration as vice-Chair and member of the Board Executive Group.

Professional Preparation:

St. Andrews Univ., Scotland	Applied Mathematics & Astronomy	BSc. Hons., 1978
Nuffield Radio Astronomy Labs, England	Radio Astronomy	Ph.D., Fall 1981
Nuffield Radio Astronomy Lab, England	Radio Astronomy Postdoc Fellow	1981 - 1983

Appointments:

2008-present	Director, MIT Haystack Observatory
2006-2007	Assistant Director, MIT Haystack Observatory
2001-present	Principal Research Scientist, MIT Haystack Observatory
1986-2001	Research Scientist, MIT Haystack Observatory
1983-1986	Research Associate at the Pennsylvania State University
1981-1983	Postdoctoral Fellow at the Nuffield Radio Astronomy Laboratories

Chairwoman JOHNSON. Thank you very much.
Dr. Bouman.

TESTIMONY OF DR. KATHERINE BOUMAN, POSTDOCTORAL FELLOW, CENTER FOR ASTROPHYSICS – HARVARD & SMITHSONIAN

Dr. BOUMAN. Chairwoman Johnson, Ranking Member Lucas, and Members of the Committee, it's an honor to be here today. I thank you for your interest in studying black holes through imaging and your support of this incredible breakthrough enabled by the National Science Foundation.

My name is Katie Bouman. I'm currently a postdoctoral fellow at the Harvard & Smithsonian Center for Astrophysics and in a few weeks will be starting as an Assistant Professor at the California Institute of Technology. This morning, I want to tell you more about the diverse team and imaging methods that helped make the first picture of a black hole.

The Event Horizon Telescope is an Earth-sized computational telescope where instruments and algorithms work together to see something that would be invisible to even the most powerful conventional telescopes of the future. Unlike a backyard telescope you may have peered through to study the night sky, the EHT doesn't capture a picture directly. It collects light at only a few locations, resulting in gaps of missing information.

As an analogy, observing the black hole with the EHT a bit like listening to a song being played on a piano with many broken keys. Since the EHT only collects sparse measurements, there are an infinite number of possible images that are perfectly consistent with the data measured. But just as you may still be able to recognize a song being played on a broken piano if there are enough functioning keys, we can design methods to intelligently fill in the EHT's missing information to reveal the underlying black hole image.

To construct the image, we develop different imaging methods based on both established and newer techniques in radio astronomy. All of these methods require us to specify a preference toward certain images in order to choose among the infinite possibilities. And therefore, it was important that we carefully validate the results.

To assess the reliability of imaging results obtained from M87 data, we split roughly 40 scientists from around the world into four teams. Each team worked in isolation, blind to the others' work, while creating an image of M87. After 7 weeks, we held a workshop where members from around the globe gathered to reveal their images to one another. Here, we show the images that were revealed.

Seeing these images for the first time was truly amazing and one of my life's happiest memories. This test was hugely significant. Although each picture looks slightly different, we found the same asymmetric ring structure no matter what method or person reconstructed the data. After working for months to further validate this ring shape, we combined images produced by various methods to form the image that we showed to the world on April 10.

No one algorithm or person made this image. It required the talent of a global team of scientists and years of hard work to develop not only imaging techniques but also cutting-edge instrumentation, data processing, and theoretical simulations.

There is a particular group of members I wish to celebrate today, the early-career collaborators composed of graduate students, postdocs, and even undergraduates who have devoted years of work to this project. Early career scientists have been a driving force behind every aspect of the EHT. By providing opportunities for young scientists to take on leadership roles and direct significant work in the project, the EHT is training the next generation of scientists and engineers.

So I personally stumbled upon the EHT project as a graduate student studying at MIT's Computer Science and Artificial Intelligence Laboratory nearly 6 years ago and immediately fell in love. Like many big science projects, the EHT had a need for interdisciplinary expertise, and taking an image of a black hole shared striking similarities with problems I had encountered earlier in my studies such as capturing a picture of your brain from limited data using an MRI scanner.

Thus, although I had no background in astrophysics, I hoped that I could contribute from my area of expertise in advancing the EHT technology. If it wasn't for the help of the National Science Foundation Graduate Fellowship which gave me the freedom to work on risky projects, I may have never had the chance to be part of this incredible endeavor.

The EHT introduced me to an entirely new domain where emerging computational methods were essential to the success of scientific goals. Moving forward, the computational imaging tools that we developed to study black holes could help improve technologies of the future.

My story is just one of many. I'm one of the numerous early-career scientists who have devoted years of their lives to making this picture a reality. However, like black holes, many early-career scientists with significant contributions often go unseen. Although the EHT has been a remarkable success story, we must not forget the contributions of all these young scientists whose names might not make it into the newspapers, for only with them and the diverse group of astronomers, physicists, mathematicians, and engineers from all around the globe have we been able to achieve something once thought impossible, taking the first image of a black hole.

Thank you for the opportunity to testify and for your support of groundbreaking, collaborative, and interdisciplinary science.

[The prepared statement of Dr. Bouman follows:]

Written Testimony of

Katherine L. Bouman, PhD

before the
Committee on Science, Space, and Technology
United States House of Representatives

May 16, 2019

INTRODUCTION

Chairwoman Johnson, Ranking Member Lucas, and Members of the Committee, it is an honor to be here today. I thank you for your interest in studying black holes through imaging, and your support for this incredible breakthrough.

My name is Katherine (Katie) Bouman. I am currently a postdoctoral fellow at the Harvard-Smithsonian Center for Astrophysics, and in a few weeks will be starting as an Assistant Professor at the California Institute of Technology. However, like many Event Horizon Telescope (EHT) scientists, I began contributing to this project as a graduate student. My primary role in the project has been developing methods to reconstruct images from the EHT data, as well as designing procedures to validate these images. This morning I want to tell you about one piece of the full story that made this image possible: the diverse team and computational procedures used to make the first image of a black hole from data collected at seven telescopes around the globe.

THE EHT'S COMPUTATIONAL TELESCOPE

On April 10th we presented the first ever image of a black hole. This stunning image shows a ring of light surrounding the dark shadow of the supermassive black hole in the heart of the Messier 87 (M87) galaxy. Since M87 is 55 million light years away, this ring appears incredibly small on the sky: roughly 40 microarcseconds in size, comparable to the size of an orange on the surface of the Moon as viewed from our location on Earth. Physical diffraction limits, laws of nature that govern the behavior of light, require an Earth-sized telescope in order to resolve structure on these extraordinarily small scales. Since building a conventional single-dish telescope the size of the Earth is impossible, the Event Horizon Telescope Collaboration instead spent over a decade building an Earth-sized *computational* telescope in order to resolve structure on the scale of a black hole's event horizon. In this computational telescope the instrument and algorithms work together to see something that would be invisible to even the most powerful conventional telescopes of the future.

THE IMAGING PROBLEM

Unlike a backyard telescope you may have peered through to study the night sky, the Event Horizon Telescope doesn't capture a picture directly. Instead, by combining the signals received at pairs of telescopes, the EHT captures measurements related to spatial frequencies of the image; pairs of telescopes that are close together enable information to be collected about the image's large spatial structure, while pairs far apart provide information about small-scale structure. Though impractical, if we tiled the globe with telescopes we could collect the complete black hole image. However, since the EHT connects telescopes at only a few locations, we only capture some of these frequencies and are left with large gaps of missing information. As an analogy, you can think about the measurements the EHT makes a bit like notes in a song; each measurement corresponds to the tone of one note. Observing the black hole with the Event Horizon Telescope is a bit like listening to a song being played on a piano with over half of its keys broken. Additionally, the fact that there is a different, quickly changing atmosphere above each telescope causes our data to be very noisy, almost like each piano key has a different delay between the time it is struck and when you hear its sound.

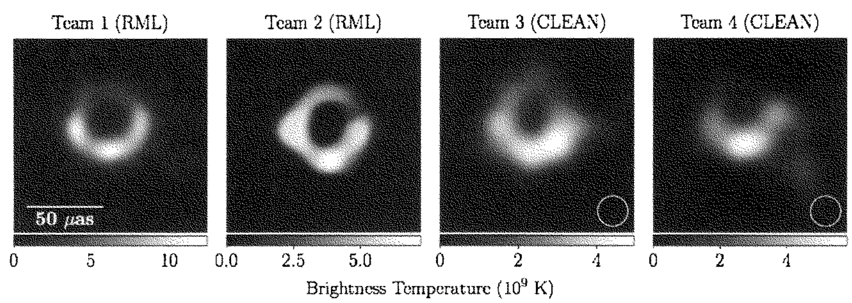
Once data has been collected, the challenge is to use these sparse measurements to form the image. Unfortunately, since we only obtain a few samples there are an *infinite* number of possible images that are perfectly consistent with the data we measure. But just as your brain may still be able to recognize a song being played on a broken piano if there are enough functioning keys, we can design algorithms to intelligently fill in the EHT's missing information to reveal the underlying black hole image.

To solve for the black hole image we developed two classes of imaging algorithms, based on both established (CLEAN) and newer techniques (regularized maximum likelihood) in radio astronomy. All of these algorithms require us to specify a preference towards certain images in order to choose among the infinite possibilities. However, since we have never directly seen a black hole before, how should we specify what images are preferred? And more importantly, how do we make sure our algorithms leave open the possibility of seeing an entirely unexpected structure?

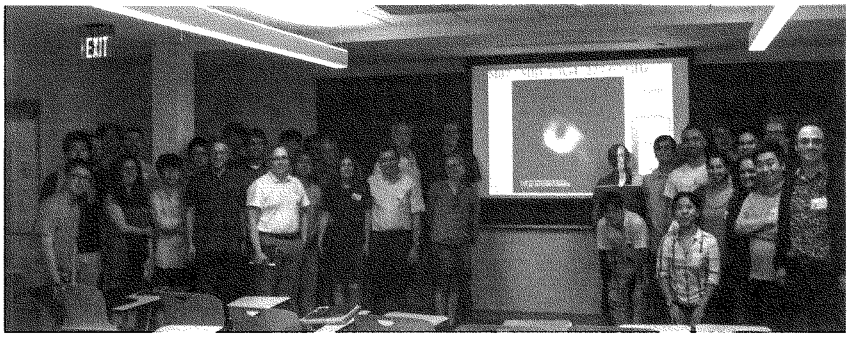
Consequently, a big question we faced when making a picture of M87 was not just how do we reconstruct an image, but also how do we validate the recovered image. Before collecting data with the EHT we tested our algorithms, making sure they could recover unexpected image structures. To do this, we drew inspiration from large-scale tests done in the computer science community that are used to validate new techniques. For instance, we generated synthetic data as if the black hole looked like Frosty the Snowman, and made sure all of our algorithms reliably reconstructed this unexpected structure. However, even though these tests built up confidence in our methods, when working with the M87 data we wanted to be especially cautious. Thus, to assess the reliability of imaging results obtained from M87 data, we implemented a two-stage imaging procedure.

THE M87 IMAGING PROCEDURE

In the first imaging stage, in order to avoid shared human bias and to assess common features among independent reconstructions, we split our group of roughly 40 scientists from around the world into four imaging teams. The goal of each team was to independently produce an image of M87. Each team worked in isolation, blind to the others' work, for seven weeks while trying to make their best image. After seven weeks we held a workshop in Cambridge, Massachusetts where members from around the globe gathered to reveal their images to one another. These pictures are shown below:



Seeing these images for the first time was truly amazing and one of my life's happiest memories. Each image had been recovered by a different group of people imposing a preference for a different looking image (e.g., smooth, compact, or sparse). Yet, although each picture looked different, they all contained the same basic structure: a ring of roughly 40 microarcseconds that is brighter on the bottom than the top. This test was hugely significant, as we found the same structure no matter what method or person reconstructed the data.



The image above shows the first picture of a black hole, made by averaging the images produced by the four teams at the historic workshop, and the imaging scientists that made it possible. Without having done this test, and having different people reconstruct with different methods, we never would have achieved the same level of confidence we have in our results. Nevertheless, we still wanted to make sure that we were not subconsciously imposing a preference for a ring structure in our images, so we spent the next couple months working to further validate this picture.

In the second imaging stage, our goal was to objectively choose algorithm settings and remove humans from the imaging procedure. To this end, we developed three different imaging pipelines, each developed by a different group of scientists and based on different methods. Each pipeline has its own knobs that are typically tuned by a human user. However, instead of having a human tune these knobs, we instead searched for the best settings to recover different types of image structure. For instance, we generated synthetic data as if the Event Horizon Telescope were actually seeing a disk on the sky, with no hole in the center, and found the best settings to recover this disk shape. Then, when we transferred these exact imaging settings onto M87 data we found that each imaging pipeline still produced a ring with a hole in the center. By doing this simple training-testing procedure on many different underlying sources structures, we found that all three imaging pipelines consistently produced a ring shape.

The images from the three different imaging pipelines were then combined together to form the image that we showed the world on April 10: a ring of light surrounding a black hole, roughly 40 microarcseconds in size, and brighter on the bottom than the top.

THE NEED FOR COLLABORATIVE AND INTERDISCIPLINARY WORK

As you can see, the first picture of a black hole is a combination of images produced by multiple methods. No one algorithm or person made this image; it required the talent of a global team of scientists and years of hard work. Even so, making an image was only one piece of the EHT puzzle that was necessary to pull off this seemingly impossible feat. In fact, just as we required a global telescope to make this image, we required a global team: a team composed of 207 members from 59 institutions around the world working on developing cutting-edge instrumentation, data processing, theoretical simulations, and analysis.

There is a particular group of members that I wish to celebrate today -- the early-career collaborators composed of graduate students, postdocs, and even undergraduates who have devoted years of work to this project. Early-career scientists have been essential to the EHT's success. They bring new ideas and have been a driving force behind every aspect of the EHT, ranging from developing high-speed electronics, to data processing infrastructure, to new imaging techniques, and even interpreting the results. By providing opportunities for young scientists to take on leadership roles and direct significant work in the project, the EHT is training the next generation of scientists and engineers.

Like many, I started working on the Event Horizon Telescope project as a graduate student. I stumbled upon the project as a student studying computer vision at MIT's Computer Science and Artificial Intelligence Laboratory (CSAIL) nearly six years ago and immediately fell in love. Like many big science projects, the EHT had a need for interdisciplinary expertise; taking an image of a black hole shared striking similarities with problems I had encountered earlier in my studies, such capturing a picture of your brain from limited data using an MRI scanner. Thus, although the project was well outside of my core area, and I had no background in astrophysics let alone black holes, I hoped that I might be able to make a difference. If it wasn't for the help of a National Science Foundation Graduate Fellowship, which gave me the freedom to work on risky projects, I may never have had the chance to be a part of this incredible project. By working on different aspects of the EHT over many years, even getting the chance to observe at telescopes over 15,000 ft above sea level, I was introduced to an entirely new domain where emerging computational methods were essential to the success of scientific goals. Moving forward, the computational imaging tools that we develop to study black holes could help improve technologies of the future, saving lives by improving the quality of medical images, seismic predictions, and even the performance of self-driving cars.

I have been incredibly fortunate to have found such a wonderful team that was supportive of my involvement in the project, and provided me with the tools I needed to make a difference. However, my story is just one of many; I am one of the numerous early-career scientists who have devoted years of their lives to making this picture a reality. However, like black holes, many early-career scientists with significant contributions often go unseen. Although the EHT has been a remarkable success story, we must not forget the contributions of all these young scientists whose names may not make it into the papers. For only with them, and the diverse group of astronomers, physicists, mathematicians, and engineers from all around the globe, have we been able to achieve something once thought impossible: taking the first image a black hole.

Thank you again for the opportunity to testify, and for your support of groundbreaking, collaborative, and interdisciplinary science.

Dr. Katherine L. Bouman

Katherine (Katie) L. Bouman is currently a postdoctoral fellow at the Center for Astrophysics | Harvard & Smithsonian. In June 2019 she will be starting as an assistant professor in the Computing and Mathematical Sciences Department at the California Institute of Technology. Her research focus is on using emerging computational methods to push the boundaries of interdisciplinary imaging.

Bouman's primary interests are in computational imaging, computer vision, and computational photography. By collaboratively designing systems that tightly integrate novel sensor and algorithm design, her goal is to develop a new generation of computational cameras that exceed limitations of traditional theory and allow us to observe things previously considered impossible to see and/or measure. As a member of the Event Horizon Telescope (EHT) Collaboration, she has worked on developing innovative ways to combine techniques from both astronomy and computer science to produce the first picture of a black hole using data from the EHT, as well as verify the recovered image structure. She has served as one of the leaders of the imaging team for the Event Horizon Telescope project. She is currently co-leading a study on the future of black hole science and expansions of the EHT project through the Keck Institute for Space Science (KISS). More generally, her work combines ideas from physics, signal processing, and machine learning to find and exploit hidden signals for both scientific discovery and technological innovation. In addition to astronomy, she has worked on computational imaging in a number of domains, including estimating material parameters from imperceptible motions in videos, improving medical imaging analysis, and seeing around corners. She also enjoys connecting her work to industry, having done internships previously at Qualcomm, Lincoln Laboratory, and Microsoft Research.

Bouman received her B.S.E. from The University of Michigan in Ann Arbor in 2011 in electrical engineering. During her time at the University of Michigan, she received the William Harvey Seeley Prize, presented to a student who stands first in the class of electrical engineering in their first year. She also received a Barry M. Goldwater Scholarship for research she had done in low-complexity image processing for sign identification on mobile platforms. Following her B.S.E, she attended graduate school at the Massachusetts Institute of Technology (MIT) in 2011 where she studied electrical engineering and computer science. In particular, she worked in a group that focused on computer vision research in the Computer Science and Artificial Intelligence Laboratory (CSAIL). She was awarded a NSF Graduate Fellowship and an Irwin and Joan Jacobs Presidential Fellowship during her graduate studies. She received her M.S. in 2013, and was awarded the Ernst A. Guillemin Thesis Prize for her master's thesis: "Estimating the Material Properties of Fabric Through the Observation of Motion." She received her Ph.D. in 2017 for her thesis: "Extreme Imaging via Physical Model Inversion: Seeing Around Corners and Imaging Black Holes."

Bouman serves on the IEEE Signal Processing Technical Committee on Computational Imaging, is a co-organizer for the Computational Cameras and Displays (CCD) workshop at CVPR, serves on the Center for Autonomous Systems and Technologies (CAST) advisory board at Caltech, is an area chair for the International Conference on Image Processing (ICIP), and has been awarded outstanding reviewer awards for peer reviews done in CVPR and ECCV. Bouman has participated in numerous outreach events to get youth interested in science and engineering. For example, she has spoken at local high schools and has given talks at local public events, such as TED and the Boston Museum of Science. Her a TED talk on "How to Take a Picture of a Black Hole" has received over 5.1 million views. Through these activities she has been able to share her own excitement in her work and excite a diverse body of students about careers in science, technology, and engineering.

Chairwoman JOHNSON. Thank you very much.

At this point we'll begin our first round of questions, and the Chair recognizes herself for 5 minutes.

And this question goes to all. NSF made a significant commitment to this project without any guarantee that it would succeed. In a time with many competing financial priorities, why is it important that the Federal science agencies take risks like this for basic research even if there's no foreseeable application?

Dr. CÓRDOVA. Sure, I'll start. Thank you very much for the question, Madam Chairwoman.

The definition of NSF is to take risks in science and engineering, risks that have potentially very high rewards. We saw an example of this with the first detection of gravitational waves on Earth a few years ago, and subsequently, a project that we invested in starting 40 years ago has just yielded tremendous results, most recently, many more detections of gravitational waves in the third run of LIGO.

And then just a short while ago we announced really a solution to the enduring mystery for over 100 years of the origin of cosmic rays, with the detection of neutrinos and high-energy gamma rays using our South Pole telescope and many other telescopes on Earth and in space.

Doing this kind of observation—and the discoveries—is really what NSF is about. We like to say that NSF is where discoveries and discoverers, as you heard from Dr. Bouman, begin.

In my testimony, I mentioned that GPS, and in previous testimonies MRI, companies like Google and Symantec, Qualcomm, all of these are benefits of investing in basic research. It just has—sometimes we can have benefits that happen immediately, and sometimes it takes a very long time to realize benefits. But the upside is that they are truly outstanding miracles that happen when we invest in basic research.

Dr. DOELEMAN. Could I add to that, Chairwoman Johnson? I'd also add that the risks taken by the National Science Foundation for basic science are really critical, that with basic science, you don't always know where you're going to go, where you're going to wind up, but by addressing the deepest mysteries in the universe, black holes, with the best technologies that we have, we have a chance to answer the deepest fundamental questions about our universe.

If you had asked Einstein, you know, what ramifications his theory of general relativity would have had when he came up with it, he would have had no answer, right? We would've said with our cell phones we can now locate ourselves to within pinpoint accuracy on the globe, and he would have looked at you and said what's a phone, right? He wouldn't have had any idea really to even understand the question. That's how long it takes sometimes for the fruits of basic research to be realized. But when you ask those basic questions, they almost always pay off.

Dr. LONSDALE. So I'd like to add something. I think that when the NSF invests in something speculative and high risk like this and it pays off, as it has in this case, it is a real attention-grabber not just for all the scientists who are interested in doing this but the whole world. We heard Dr. Doeleman say that 4.5 billion people around the planet saw this. And this is the way that young people can be inspired to think about, you know, emulating some of this work and getting involved in the STEM disciplines, so it is an important component of feeding the STEM pipeline.

Dr. BOUMAN. Yes, I agree with everything that has been said by my colleagues here. I think technology and basic science, you know, really drive each other. They feed off each other and they help each other grow. And so it's important that we continue to invest in basic science because we don't necessarily know the ramifications of how that will manifest in technology of the future. Lots of the techniques that we've developed for imaging black holes can be adopted potentially in the future for other applications that we might not have even thought of now.

And another thing is I do want to emphasize Dr. Lonsdale's point as well in that I think that this picture has really captured the imaginations of a generation of new young scientists, and I've even had, you know, 4-year-old girls come up to me and tell me about the black hole, and I think that getting that interest in science to young students at a young age, it will help them enter the STEM fields and make contributions to many different projects.

Chairwoman JOHNSON. Thank you very much. I'm not out of questions, but I'm out of time.

Mr. Baird?

Mr. BAIRD. Thank you, Madam Chair. And to all the witnesses, we really appreciate your testimony and the discoveries you're sharing with us today.

I would also like to congratulate all of you on receiving the Diamond Achievement Award this week at the National Science Foundation awards gala, so I commend you for that.

Dr. Bouman, I have a question that relates to the importance of the opportunity you had to do research at such a young age and a career as a scientist. I think you conducted some imaging research at Purdue University while you were still in high school. So would you care to elaborate on that?

Dr. BOUMAN. Sure. So I actually was—got a job at a lab in—at Purdue University when I was—in the summer after 11th grade partly because I had kind of stumbled upon a class taking a computer science class in high school, which I had never really thought about taking but I took on a whim and, because of that, I had an interest from—because I understood this new language of computing, a professor there, Professor Edward Delp, invited me to help his graduate students in the lab there that summer. And that was the first time I had exposure to real research, to imaging and the—kind of the exciting world of imaging.

And one thing that really grabbed me from that was being able to see the results. And I really loved being able to work on problems where you can visualize your results. And so from that I kind of gained a love of imaging and images, and that drove me in my future—my path toward studying electrical engineering and computer science, computer vision, and eventually being on the Event Horizon Telescope project. So I think that spark of passion at a young age really brought me to where I am now, so I'm eternally grateful to my opportunities at Purdue for that.

Mr. BAIRD. Thank you. My next question, maybe all of you might want to respond, but it's in keeping with the theme that you had for the National Science Foundation award. Do you have any recommendations on how we might ignite the spark that stimulated you to get into your profession so that we can keep these students encouraged and excited and fulfilling that pipeline to have more researchers in the future?

Dr. Córdova, do you want to start with that?

Dr. CÓRDOVA. Sure. Well, my own STEM spark was from watching a television show ages ago about neutron stars when they were first hypothesized as being responsible for certain phenomena that were being observed. And one of the MIT professors on the show talked about the energy that would be liberated if you dropped a marshmallow onto a neutron star. And I was so mesmerized by that concept.

The next day—I was actually doing an education project in Cambridge, Massachusetts—I took a bus and went right down to MIT to meet that professor, and I said this is what I want to do for the rest of my life. I want to work on this. And so for some reason they gave me a job for the summer, and it all worked out. So I really believe that you can have your inspiration from so many different places.

And what NSF is trying to do is find curriculum projects that happen in schools, like computer science in the classroom, and to help wonderful teachers get more skills. But we also spend part of our portfolio, as I think you know, on informal science education, such as money to museums and to television shows about science. There has to be a myriad of ways of reaching out and trying to inspire people to know more about science and be attracted to it.

Dr. DOELEMAN. It's a wonderful question, and it's one that we really focused on in the project. I think you've seen that this image and the pins you have in front of you are—really resonate with the public and scientists alike. It's a real opportunity to get people at a young age, which is really when you want to ignite that spark into science. Mine came about with a stint at a museum that I worked at actually looking over animals, so I got into this through biology if you can possibly believe that, so you never know where the spark is going to ignite.

But getting the outreach is really important for this. It's really important to get into museums, informal outreach, and also to invite the young people into labs in places where they can really do research.

Mr. BAIRD. I'm out of time, but the Chairwoman has allowed me to go ahead and let the other two finish.

Dr. LONSDALE. Thank you very much. Yes. Well, my own spark was at a very early age also, which seems to be a bit of a consistent theme. I was looking up at the night sky when I was 5 years old and had a hunger to read all about it, and my parents got me a telescope when I was 8. And also at the same time the U.S. space program was taking off quite literally, and that—all of this was completely mesmerizing to me, and it set me on a course for life to pursue this type of work.

And I see that in very tangible ways in what I'm doing now. My observatory, we have a fair amount of public outreach, and one form this takes, for example, is open houses. And just recently I held an open house where I was, for the first time, able to talk about the black hole result, and the children in the audience were by far—they were absolutely thrilled to pieces. And I got lots of questions afterwards. But the longest time and the most questions came from a 10-year-old.

And I think that connecting the scientists who have the enthusiasm for the work with the young people, you know, like 10-year-olds who are—who have minds that are sponges for information, that is incredibly potent. And that's been my experience throughout my work in public outreach.

Dr. BOUMAN. Yes, so I would say, you know, throughout my early years I had many different sparks, and I think having many opportunities to continue to grow that interest in science is so important, to have many different programs and opportunities.

However, I will—I want to highlight one that I had in sixth grade. My science teacher had us all enter the science fair, and I—this was the first time where I really did a science project that was outside of just your standard homework that you do, and I thought for ages about what I would work on. And I decided to work on how—what makes the best bread. So I actually baked probably hundreds of loaves of bread with different amounts of salt, different amounts of sugar, and different types of yeast, and I measured how big they rose and the taste. I even filled out IRB forms to have my friends taste the different bread. And that was a really fun experience, a wonderful experience. I entered it into the science fair in the area and won gold in my category. And that I think was my first true excitement where I knew research was a pathway for me.

Mr. BAIRD. Thank you, and I yield back.

Chairwoman JOHNSON. Thank you very much.

Ms. Bonamici?

Ms. BONAMICI. Thank you very much, Chair Johnson and Ranking Member Lucas. And thank you to all of our witnesses.

I also want to congratulate the National Science Foundation and the entire team around the world for this groundbreaking work on the Event Horizon Telescope project. Congratulations. Not only was this an incredible scientific achievement, the release of the first-ever image was of course—sort of shattered the glass ceiling for women in STEM, so it was a pretty significant day. I remember when the news hit, and it was an inspiring moment of course for young women who want to go work in what are still traditionally male-dominated fields in the sciences. This certainly demonstrates the value of teamwork and collaboration in scientific discoveries.

Dr. Bouman, I'm the Founder and Co-Chair of the STEAM caucus, where we advocate for integrating arts and design into STEM learning to spark creativity, to get more people involved, and to really have that well-rounded education that stimulates both halves of the brain. I appreciated the analogy in your testimony comparing the observations from the telescope to a song on a piano with broken keys. There is some research that shows the Nobel Laureates in the sciences are more inclined to be engaged in arts and crafts than other scientists, so it's just a little story there.

So why was it important to have an interdisciplinary team to develop the imaging algorithms, and what did you learn from the development of the algorithms that could benefit future unexpected observations going forward?

Dr. BOUMAN. Yes, so the EHT, like many big science projects, really draws on many different areas. So, you know, at its core it's a science project. We're trying to learn about black holes, and there, we need theorists to tell us, you know, what do we expect? But also it's an engineering project. You know, we spent over a decade building a telescope with new instrumentation that had to be put together, and because it is a computational telescope, we also had to develop algorithms and methods, and this requires us to understand computation and optimization and many different—kind of how do all these pieces play together and come together to give us this kind of amazing result, so we really had to have, you know, instrumentation, algorithms, theory. But it was really all—each part was essential.

And you also have to understand each part as a—you know, when I started this project actually, as I said, I came from a computer science kind of area, and I—you know, I met with Dr. Doeleman and I was like, oh, this is such an exciting project. And I kind of—I decided, oh, I really want to work on it, but I kind of went off on my own and started to try to read about the ideas of interferometry and how to make an image and, you know, coded up some little simple algorithm, but I really—you know, that doesn't get you anywhere just being by yourself. I didn't understand the intricacies of the data. What kind of challenges do we have with this data?

And so it was really essential when it really started—when we really started being able to push the algorithms is when we all kind of got together from different parts of the team, understood what kind of noise do we see in our data, what is really different about the data and challenging about the data. Even time that I spent at a telescope at over 15,000 feet above sea level I learned where does—where do things go wrong, and how do we account for this in our algorithms?

And so I think it was really essential even on just one—you know, making an imaging algorithm, which is just one part of this huge project, even combined information from across the project.

Ms. BONAMICI. Wonderful. Your enthusiasm is amazing. I hope it's contagious. I want to get a question into Dr. Doeleman, who I learned is an Oregonian.

And, Dr. Doeleman, you told me about some of your early days with all the hands-on learning at the Oregon Museum of Science and Industry, which is a gem in the Pacific Northwest, and I know gets a lot of children and adults engaged in science.

You noted that capturing an image of a black hole was presumed to be impossible just a generation ago but now can lead to the emergence of a totally new field of science. So how can black holes be used as tests of our universal theories and what further resources are needed to succeed in the EHT's next scientific feat?

Dr. DOELEMAN. Thank you for the question. There are a lot of different ways to proceed from here. This really is the tip of the iceberg. Imagine when Galileo was looking through the first telescope. It wasn't the end of astronomy, it was the beginning of astronomy. In the same way, this image you see here is creating the ability for us to use the most intense cosmic laboratory as a way to understand the universe. Normally, you would have to build a supercollider or something like that to attain the energies and the extreme physics to probe the unknown. Here, we're using the edge of a black hole that nature presents us as a natural laboratory.

So in the future, we want to make movies, not just still images, because what you're seeing here is light orbiting around the black hole. That's one test of Einstein. Now, we can move to matter orbiting around the black hole, make movies of this, a completely different test of Einstein, testing the period it takes for matter to orbit around. And more than that, we can see how these black holes are ferocious engines at the centers of galaxies launching these jets that can pierce an entire galaxy and disrupt star formation.

So black holes are at the heart of why the night sky looks the way it does. And, as we move forward, we'd like to fill in this virtual telescope with putting new telescopes tailor-made to fill out that virtual Earth-sized array, and that will sharpen our focus and let us make movies.

Ms. BONAMICI. Fascinating. My time is expired, but be assured we will be following the work. It's wonderful. Thank you. I yield back.

Chairwoman JOHNSON. Thank you. Mr. Biggs.

Mr. BIGGS. Thank you, Madam Chair, and thank you, Ranking Member Lucas. And thank you to each member of the panel for being here today. I appreciate you sharing your experience and sharing with us this important discovery and how you went about it. And I think many of us are very excited to see what the next step is going to be.

I would be remiss, however, if I didn't mention the contributions of the university in my home State, University of Arizona, where the submillimeter telescope on Mount Graham was used and coming up for the 2020 series will be the Kitt Peak Observatory will also be joining, and I'm excited about that.

So having made a commercial now for my own State University, I will now go to my questions. Dr. Doeleman and Dr. Lonsdale, when the news broke that the first image of a black hole was going to be released, many of us thought it might be Sagittarius A*, the supermassive black hole at the center of the Milky Way. What have been the challenges for imaging that black hole, and do you expect to be able to produce an image of that particular black hole?

Dr. DOELEMAN. It's a wonderful question. We have two primary targets in the Event Horizon Telescope project, both of which we—for both of which we can resolve that event horizon. We focused on M87 because the results started falling out very cleanly in a very pure way at the get-go, so we oriented all of the efforts of the collaboration toward that goal to get our first results out. But Sagittarius A* is next on our list.

It is a little bit more difficult because, during the course of one evening of observing where we fill out the virtual lens because the Earth rotates and changes our points of view of the object during the night of observing, the source itself is changing because it is 1,000 times smaller in mass and therefore it's 1,000 times faster in evolution than M87. During one night of observing, M87 stays static, but Sagittarius A* evolves in front of our eyes so to speak. So we're developing some new algorithms, courtesy of Katie and the other early-career scientists, to handle that.

Dr. LONSDALE. And I can speak a little bit to the ways that we might be able to enhance the Event Horizon Telescope. And, I'm sorry, thank you very much for the question. It is right on point for some of the things that we're thinking about for the future.

One of the things that Dr. Doeleman has already mentioned is adding additional telescopes to the array, and what this does is create more points in front of that giant imaginary lens to collect information. And, as it turns out, if you double the number of telescopes, you actually quadruple the amount of information that's available to reconstruct the images.

So because Sagittarius A* is changing quickly, we need to gather a lot of information in a shorter amount of time so that it doesn't change too much. There's a couple of ways to do that. One is to add telescopes. Another, which is perhaps a little further into the future, is to put dishes into low-Earth orbit because those move much more quickly than the Earth rotates and sample more data more quickly. So we've got a couple of ways to improve the potential for imaging and making movies of Sagittarius A*.

Mr. BIGGS. Yes. I'm looking forward to that. Dr. Bouman, what other applications can come from the computational, and you had kind of touched on this, but I want to know what other applications you think might develop from computational imaging tools that were developed to study black holes.

Dr. BOUMAN. Sure. If we're on the topic of Sagittarius A* and how it's evolving really quickly where you have this huge amount of evolution over the course of the night, this causes challenges from us from an imaging perspective because the measurements that we take are taken over the course of a night, so each measurement is basically from a different snapshot of the black hole. And so we're coming up with ways of tying this information together to make not just pictures of black holes but movies of it evolving over the course of a night.

And this kind of similar—this kind of approach could be applied to many different problems. So, for instance, one that has I think a very similar problem is an MRI. When you're studying, for instance, organs that are moving or even like a fetal MRI, taking images of a baby inside of a mother's womb—and because, as the MRI machine scans, the baby is moving, you actually also have to have kind of a model of motion and understand that the picture is also evolving. So techniques that we use for imaging a black hole, similar ones could be applied to this idea of how do we image a baby inside of a mother to get a better diagnosis of issues that might happen?

Mr. BIGGS. Great, thank you. I still have time. I'm going to zip through this question real quick. This project is a great example of international collaboration and science, and questions are these. What makes a successful S&T international cooperation agreement, and how do we ensure these agreements are two-way streets and not the U.S. feeding its knowledge and talents to other countries without reciprocation? So whoever wants to take those two questions.

Dr. CÓRDOVA. Yes, I'll start. We have a lot of international collaborations on our various facilities. A great example is the ALMA telescope that played such a big role in this observation. Also, we are contributors to the Large Hadron Collider at the CERN in Europe, and many, many of our biggest projects have international collaborators because the talent is worldwide, and also they help with the funding of course.

And so we have those principles for international collaboration, but it has to be a win-win situation, as you said, Congressman. Everybody has to gain from this, everybody has to contribute scientific talent and get something from it. And the collaborations have to do something really important that's going to move the discovery needle forward. Shep?

Dr. DOELEMAN. It's a great question. We wrestle with that, and we were successful because we adhered to some principles as we put together this collaboration. One was transparency. You have to make sure that you know what everybody is doing at all times. And we ensured that by making sure that all the working groups that we put together had members from all the different constituencies so everybody can see actively what's going on.

We didn't sequester one group here to work on one thing or one group here to work on something else. We really combined everything through the miracle or burden of videoconferencing. We tend to live our lives on video cons these days, but it's really true that you can publish with someone now that you've never met. And it's kind of an uplifting way to think about things, right? I mean, we can really broaden the team across borders and across cultures and across different practices in this way.

And we also had very strong policies on publication and how to proceed with allocation of resources and planning for the next arrays and how we're going to go to the next generation. So by being very inclusive, we got the best of everyone, and we also made sure that everyone saw what we were doing. And that is one of the principles that I think has made us successful.

Chairwoman JOHNSON. Thank you very much. Mr. Lamb.

Mr. LAMB. Thank you, Madam Chairwoman.

This is a question for anyone that's knowledgeable about it, but I was curious about the supply chain for the construction of the telescopes themselves, both the current ones that we have and the additional ones that may be coming. Are we relying on a lot of American businesses and American materials for these things? And I would ask the same thing about the software and computers that we're using for the imaging as well. So if anyone is able to address that, thank you.

Dr. CÓRDOVA. This particular project was completely reliant on telescopes that already existed all over the world, obviously on many continents. Their supply chains are all different. In the case of U.S. telescopes, of course, we try to do our best to use American-made products. We have a few telescopes that were used in Arizona and Hawaii, and we anticipate more of those. But this is really all about a global supply chain.

Dr. DOELEMAN. Yes, thank you for the question. I would add that while we all work together, all the constituencies within the project realize that they want to use local resources where possible, so we lever that. So Europe uses the best construction practices and companies in Europe, but we use the best construction practices and companies here in the United States. We define what the instrumentation has to do, and then we apportion who's going to do what based on the local resources. So we've been very careful to lever U.S. businesses when we can.

And I just want to give a shout-out to Arizona again that the submillimeter telescope on Mount Graham was involved in the very first observations that we ever made of Sagittarius A* that got this whole thing started, and it was the investment of the NSF in that U.S. site that really made that possible.

Mr. LAMB. Thank you. Is—are there particular companies in the American telescopes that have been leaders or been especially reliable for us in the construction of these things or that we might be looking to going forward?

Dr. DOELEMAN. Do you want——

Dr. CÓRDOVA. You may have particular examples, but we can certainly, Congressman, get together a list of that and give it to you. They are many and complex.

I do know that at our own universities, amazing work is going on by investigators that we fund to build a lot of telescope optics, so that's a great credit to the way the science engine works.

Dr. DOELEMAN. Actually, if I may, a very interesting tie-in here is that the size of the telescope you need depends on the bandwidth, as Dr. Lonsdale was describing. So by investing in high-speed electronics, for which we use, you know, like Xilinx, for example, which is a U.S. company to do the throughput on our field-programmable gate arrays get a little bit wonky, that decreases our reliance on steel necessarily, so we don't need to build huge telescopes. We can collect more data by recording bigger slices of the radio spectrum and make the dishes smaller. That changes the kind of company you go to or the kind of designs you do, so it's very interrelated. And it's a very interesting optimization problem, and that's what we're working on now.

Mr. LAMB. Thank you. Madam Chairwoman, I yield back.

Chairwoman JOHNSON. Thank you very much.

Miss González-Colón.

Miss GONZÁLEZ-COLÓN. Thank you, Madam Chair, for holding this hearing and for all of us that are here today, I think this is a remarkable event and achievement. I want to congratulate everybody involved in this.

Dr. Doeleman, from what I understand in reading your statement, the project is looking to expand by including three new additional telescopes. Do we identify where those telescopes are going to be included from, any country that you're working right now in that regard that you can share with us?

Dr. DOELEMAN. So we're looking broadly at how to fill in this Earth-sized virtual lens. So in the next year we'll be including a new telescope in France, NOEMA, which is an array in the French Alps, and that's already very—underway. The Kitt Peak Telescope that the Congressman mentioned will be lighting up on the Kitt Peak National Observatory. That's another one. And beyond that, we're looking primarily at potential new sites where we'd like to put new telescopes, and for that, we're doing some optimization studies now. In fact, we're putting a proposal in soon for that, which will lead to a global design for where we want to put the next site.

So it's very interesting, when you look at this image and you say, well, how can we make it better, there are metrics, right? You can say, well, it can be sharper, it can be more sensitive, and so where you put the telescopes affect those metrics. They affect how much better the image would look. And you can make what we call a heat map. You can look on the whole globe and find out where you need to put the next telescope to maximize the scientific return from this image. And so we're looking at that now trying to find out where we want to put them. And then we think we can put modest dishes, smaller dishes at these new locations to build out the full array.

Miss GONZÁLEZ-COLÓN. So that's the process to select the telescope and the places they're going to be installed?

Dr. DOELEMAN. That's what would like to do, yes.

Miss GONZÁLEZ-COLÓN. OK. And what are going to be the main challenges for you in that process of selecting which telescopes and where those telescopes are going to be installed?

Dr. DOELEMAN. Well—what's that?

Dr. CÓRDOVA. Getting funding.

Dr. DOELEMAN. Yes, getting funding. I'm told by Director Córdova that getting funding is very important.

Miss GONZÁLEZ-COLÓN. Very clever.

Dr. DOELEMAN. And it is. But the first part is design really. It's coming up with the new algorithms, the new metrics of the stuff that Dr. Bouman was talking about and the new electronics that Dr. Lonsdale was talking about. Folding that all into the equation and finding out where we can get the best value for the taxpayer's dollar, where can we target these—the locations of our next dishes to ensure that for the best return on investment that we can get that.

Miss GONZÁLEZ-COLÓN. The increase in cost, of course, by installing those new telescopes will mean that you need to plan ahead. Are we willing to look in the private sector investment to help out in this endeavor?

Dr. DOELEMAN. Well, that's a wonderful question. You know, it turns out that when you get a result like this, others want to invest in it, too, so we are currently—we currently have an NSF award for which Google is partnering with us to help us move some of the computation that we do because it is very computational-intensive, as Dr. Bouman said, to the cloud where we have virtually unlimited processing power, for example, the same thing with some of the high-speed digital electronics. So we're working in that—definitely in that direction.

Miss GONZÁLEZ-COLÓN. Dr. Bouman, I read in your statement as well that you mentioned that, given the limited number of telescopes and limited number of locations, there are information gaps. From what I understand, it's looking of course to increase the cooperation of those other countries. The Director just explained the process for the new challenges. Can you tell us about what we're expecting to see in using those new telescopes?

Dr. BOUMAN. So we aren't just observing M87 once. It's not like we observed it and then we go away and we look at other things. We're going to continue to every year go back, improve our instrument, and try to learn more and more. So—and look at other sources like Sagittarius A*.

So when—we are simultaneously improving the instrument and our algorithms to work together to answer these questions, and I think that now that we have a first image and see that it is possible to see this ring, then we can go back and say, OK, here—where is our missing information? Where—and we can target those areas through new instrumentation and algorithms and try to answer those questions and get a clearer picture of GR and light—general relativity and how it acts around a black hole. So I think that is something that we look forward in the future to seeing.

Miss GONZÁLEZ-COLÓN. Thank you, Doctor.

And thank you, Madam Chair. I know my time is expired, but I know that the broader implications of this discovery will help a lot of areas between physics and data science. I yield back.

Chairwoman JOHNSON. Thank you very much. Mr. Casten.

Mr. CASTEN. Thank you, Madam Chair. Thank you to all the panelists. I got to tell you, you guys should take this show on the road. Your enthusiasm is just so infectious and it's so cool.

The—so I learned a valuable lesson—I hope not to repeat last week, which is that if you miss an episode of Game of Thrones, you find out a couple days later that apparently it all ends with dragons. I don't want to do that again, so can you give us a little hint of what—you mentioned that we—you're going to be able to now tune this on the black hole at the center of the Milky Way. When should we be tuning in for that?

Dr. DOELEMAN. OK. Well, as they say, I would tell you, but—well, so, first of all, let me say that, bound by a common science vision, it really helps when you want to prevent a leak. So what really surprised people with this result is that people thought it was going to be on Sag A*, and we had 200 people from around the globe and nobody broke the code, right? Nobody broke the silence, and I think it's because we all understood the impact that it would have, and we wanted to be able to tell our story, the scientific story after peer-reviewed publication of our results, so that was a key part of it.

And as we go forward and look to Sag A*, of which we'll be using the algorithms and new computational platforms, we're going to be attacking that with the same rigor and the same crosschecking, the same purposeful tension within the collaboration that allowed us to produce this result. So we'll be splitting up into teams probably, as Dr. Bouman described, we'll be crosschecking, double-checking, making sure that one frequency gives us the same image as a different frequency, one polarization gives us the same image as the other polarization. We'll check everything, and only after that will we reveal in an episode of Game of Thrones——

Mr. CASTEN. I will take that as a constructive nonresponse, and I'll not pressure.

Dr. DOELEMAN. I would estimate within a year.

Mr. CASTEN. Well, part of why I'm intrigued is that, you know, you've talked about that you can—there are sort of tests of Einstein's relativity in this, that you'll have—be able to do other questions, and in this whole idea of like actually seeing a movie of this. And I guess I'd just love to hear your thoughts about what are the types of questions that we can answer once you tune it there both in terms of looking at the Milky Way and in terms of potentially getting some—you know, some movement? What types of questions are you going to be asking—be able to learn at that point that we don't know now?

Dr. LONSDALE. Well, the black hole at the center of our galaxy, Sagittarius A*, may look different from what you see on the screen there in a few different ways. The black hole at the center of the Milky Way is in a different environment. It's accreting material at a very low rate. It may be oriented on the sky in a different way. And so there's a lot to learn by looking at different black holes. We don't know what we'll find. It's one of those things where it's right at the frontier of what we're technically able to do, so it places a tremendous emphasis on checking and double-checking, as Dr. Doeleman said, to make absolutely sure that we know not only what the image is but what the uncertainties on the image are. So we're going to be working hard on that.

Mr. CASTEN. So if I understand, you've got a couple more telescopes that you're adding. You've got one that you added in 2018 and then two more in 2020 if I've got that right.

Dr. LONSDALE. Yes.

Dr. DOELEMAN. Well, we're adding two more next year for the observing campaign in 2020, and then we're looking to the future to add even more than that.

Mr. CASTEN. OK. So what sorts of things are you going to be able to see once you have those additional data inputs? And I'd love to know from Dr. Bouman, like as you think about sort of analytically, what holes in your data field if you will are going to be filled in with those additional—you know, what are you sort of salivating to see once you get those additional points?

Dr. BOUMAN. Yes, so I think, you know, one thing is we don't know what we're going to see, so that I think is part of the mystery and excitement of it all. But one thing is if we zoom in toward Sagittarius A*, all of this variability that hopefully, by adding new telescopes, we will get a better grasp of, we can better map out the space-time around a black hole.

So, right now, you know, we just have a static picture. But just like seeing a movie tells you so much about—more about your environment than just a single picture, getting that movie will allow us to learn so much more about the black hole. For instance, the black hole in M87, we get an estimate of its mass, the size it is, but by seeing this evolution around a black hole, maybe we can learn about not just its mass but its spin, and knowing both the mass and the spin tells us about how it should affect every—the space-time around it. And so I think that being able to have a grasp on that will teach us a lot.

Mr. CASTEN. Well, this is very cool. I yield back. Thank you.

Chairwoman JOHNSON. Thank you. Dr. Babin.

Mr. BABIN. Yes, ma'am, thank you, Madam Chair. And thank you all for being here.

Dr. Córdova, I enjoyed you accompanying our Committee. I guess it's been the year before last when we went to the Arctic and saw some neat things. Good to see you again.

I wanted to ask a question about return on investment, and I'd like to hear it from maybe all of you if you get a chance. We'll start with Dr. Córdova. Our constituents may ask why invest taxpayer funding in imaging a black hole? And that is what can you tell them or what can we tell them has been the return on their investment? And I liked what Dr.—is it Bouman or Bouman?

Dr. BOUMAN. I don't mind either, but Bouman is what I usually say.

Mr. BABIN. All right. Bouman. See, we don't know what we don't know, so that's kind of a mysterious thing to say, but you know, if we can ever get the James Webb Space Telescope up there, I assume that's going to open up some new windows and horizons for us as well.

But let's start with you, Dr. Córdova, on return on investment where somebody says, what are we getting for spending all this money on imaging a black hole?

Dr. CÓRDOVA. Well, there's three ways I like to answer that, but I want to give a lot of time to my colleagues here, so I'll just say the three words are inspiration——

Mr. BABIN. Right.

Dr. CÓRDOVA [continuing]. And that is—that's at the root of who we are as human beings, and that's what draws us in to our fields where our passion and our commitment is. And we all were sharing earlier our STEM spark, and so it's so important with young people to get them inspired, so we had great moments like landing on the moon and the discovery of the Higgs boson and this imaging of the black hole, and who knows how many people that will attract into science, all kinds of science and engineering.

Mr. BABIN. Right.

Dr. CÓRDOVA. The second one has to do with all the engineering and computational tools that go into a discovery like this, a challenge like this. It took them over a decade to do this, and, as you know, the LIGO gravitational wave experiment took 40 years.

And the amazing amount of engineering prowess and computational prowess that it takes in order to make those kinds of feats have many, many spinoffs. There are many things that are invented for the first time that then go into spinoffs.

And the third one is that when we invest in truly fundamental basic research, it can have enormous benefits, not just little incremental benefits. We talked earlier about GPS, about MRI technology, about new companies that are invented like Google itself. These start at the root with just a little piece of fundamental research.

Even the people who are discovering—we funded Charlie Townes, the Nobel Prize winner, we gave him 17 grants over his lifetime, and he never said I thought it would end up in the maser—and we use masers for the clocks in order to synchronize the telescopes—he never thought it would end up in the laser and doing eye surgery and all. But he did it because he was driven toward a fundamental discovery.

Mr. BABIN. Right.

Dr. CÓRDOVA. These have amazing benefits for the public but sometimes a little later on.

Mr. BABIN. The quest for knowledge and curiosity, that's quite——

Dr. CÓRDOVA. Yes.

Mr. BABIN. Dr.—is it Doeleman?

Dr. DOELEMAN. Doeleman.

Mr. BABIN. Doeleman.

Dr. DOELEMAN. I answer to many things. So when I talk to the team about what we're doing, I often use the analogy that we're jumping off cliffs and inventing parachutes on the way down, and that's really emblematic of this project. We're asking and hoping to answer the deepest questions. And you don't know where they're going to lead.

Mr. BABIN. Right.

Dr. DOELEMAN. If you limit yourself by attacking questions that you can see what the return might be, then you're really limiting where you're going intellectually and where we're going as a human—as humans is by asking these open-ended questions, that they inspire, as Dr. Córdova said, but also that you get these amazing discoveries and the ancillary benefits.

Mr. BABIN. Right.

Dr. DOELEMAN. Any normal portfolio advisor will tell you, you want some stocks, you want some bonds, but you also want some high-risk, high-return in there somewhere just on the off chance you're going to invest in Amazon or something like that. And sometimes it pays off, as it did here, and it really does inspire people. So if you want to make the discoveries and, you know, have the benefit, you've got to take some—a little bit of risk.

Mr. BABIN. Yes. Absolutely.

And, Dr. Lonsdale, we're running out of time.

Dr. LONSDALE. Yes, thank you. Yes. I'll try and be brief. So I—for me, I already mentioned the inspiration aspect for young people and getting people into STEM. I'd also like to very briefly mention that my observatory, we have an interdisciplinary research program. The techniques and technologies that went into EHT echo throughout all of the research that goes on at the observatory, and I think that that's true on a broader front as well. So, you know, we do geospace science, for example, and it's benefited from some of the work that's gone on at the EHT.

Mr. BABIN. Right. Thank you.

And can we indulge Dr. Bouman for just a second?

Dr. BOUMAN. Sure. So I think I want to just echo everything that my colleagues have said here. I think the technology and basic science really drive each other to be better. And things that we developed for imaging a black hole we don't necessarily know how the—what they'll manifest in technology of the future, but I think that they definitely will. I'm very confident of that. And I also think that just capturing the imagination of young students and turning them—getting them excited about science and STEM I think that in itself will lead to a lot of innovation in the future.

Mr. BABIN. All inspirational answers. Thank you very much, and I yield back.

Chairwoman JOHNSON. Thank you very much. Ms. Horn.

Ms. HORN. Thank you, Madam Chairwoman. And thank you to all four of you. What an exciting and important conversation and an inspiration this discovery is. I think, Dr. Córdova, the inspirational factor I think can't be undervalued and the discoveries that come after that.

And, Dr. Bouman, I want to turn to you first because we recently had a hearing on diversifying STEM fields with some really fantastic witnesses as well, and I think you are a prime example of what that looks like and how a diverse pool of scientists is important and can bring different things. So my first question really, as we work to inspire the future generation is what inspired you to pursue this field of study?

Dr. BOUMAN. Yes, so I think, you know, I didn't ever expect to come into this and work on this to be a figure of diversity. You know, I was just excited by the science, excited by, you know, the mystery of what we were working on and what we could achieve together as a team. And I think that highlighting just not my story but the stories of many different scientists in the collaboration who come from many different backgrounds who have many different experiences I think is wonderful, and I think that many—as we've been talking about, young students and getting them excited, it's important to show the diversity of people that was necessary to make it possible to get this picture because we required that we had many different people that kind of came to it with different ideas of what should we do and we kind of whittled it down to the best of the ideas, and I think that was really essential.

Ms. HORN. Thank you. I think that's an incredibly good point is it's not diversity just for the sake of diversity but creative new ideas and perspectives that people from different backgrounds, different experiences can bring to the table.

So following along those lines, I'd like to know a little bit more about your early research and the contributions and how you see that as helping to shape your next step as you move into becoming a professor, so——

Dr. BOUMAN. Yes, so I've learned a lot through the Event Horizon Telescope project. One thing that it provided—the Event Horizon Telescope project provided is many different opportunities for leadership, and there were many opportunities, and many different parts of the project were kind of guided by people such as myself, early-career scientists, and kind of we led the direction of different parts of the project and had to come up with creative solutions to problems that kept popping up everywhere.

And I think by doing this and having to lead teams of tens to hundreds of people in this and kind of converging on one story and one kind of result was really helpful for me in my next stages of my career where hopefully, I'll—you know, I'll be leading a group of students there, and I think that the skills that I learned as part of EHT will be invaluable for that and something that I think is rare to have at a young age, and so I'm really—I think that EHT is doing a wonderful job of providing that opportunity for young scientists.

Ms. HORN. Thank you very much, Dr. Bouman. I agree with you. It's easier to envision yourself as something that you can see, and I think there are a lot of ways that we can do that.

I want to turn to Dr. Doeleman for just a moment in the little over a minute we have remaining. And I want to ask, Dr. Doeleman, what can we—what should be done to help you in recruiting and maintaining postdocs and other students to help continue to grow the pipeline of scientists and researchers?

Dr. DOELEMAN. Thank you for the question. I just want to amplify something that Dr. Bouman said, that there is no EHT 101 course taught in astronomy curricula. Doing something new, so fundamentally fresh like this requires that we draw upon the best from many, many different fields. So I think the thing to do is to invest in some interdisciplinary positions, you know, perhaps postdocs and graduate student positions. At Harvard, for example, we started the Black Hole Initiative, which brings together mathematicians, physicists, astronomers, and also philosophers and historians of science, all of whom see the black hole as an anchor point in their respective fields. And in that crucible of interdisciplinary kind of mishmash of wonder, we've—we're now graduating our first students who have exposure to all of these different fields together. And that is really something that I think lifts up the EHT and it provides an example for the kinds of students and early-career people that we need.

Ms. HORN. Thank you very much. My time is expired. I just want to say thank you to all of you for the work you're doing, and it's really great to have you here. I yield back.

Chairwoman JOHNSON. Thank you very much. Mr. Posey.

Mr. POSEY. Thank you, Madam Chair, for holding this hearing, and thank all of the witnesses for appearing before what is clearly the most interesting and the most exciting Committee in Congress. I so enjoy it. And you just bring yet one more incredible dimension to the things that we get to explore with you.

You know, Dr. Córdova and Dr. Doeleman, given your statements that the capture of the first-ever image of a black hole by the EHT would not have been possible without American leadership, I just wondered if either one of you could elaborate just a little bit on some examples of what you mean by that.

Dr. CÓRDOVA. Well, in this case what I really mean is we were in it for the long haul—and that's true with most of the projects that we do of this nature—we've been funding this project for about 20 years or so. And we funded the LIGO gravitational wave project for 40 years. We consistently fund high-risk but potentially high-reward projects, so that was just essential in this case.

Mr. POSEY. OK. Dr. Doeleman?

Dr. DOELEMAN. Yes, if I could expand on that, and spring-boarding off of what Dr. Córdova said, this project started some time ago and was quite risky at the first stages. We really didn't know if there was even anything that small toward M87 or the galactic center Sag A* that Dr. Bouman talked about. And it was some early proof-of-concept experiments using cutting-edge instrumentation by primarily U.S. groups that set the stage for the eventual buildout of the EHT.

And so when we talk about leadership, it grew from a history of taking risks and being at the forefront at the very outset of the project. And then, as it became clear that the project could succeed, then we began to attract more international investments and investments even from within the U.S., so it grew but always with a nucleus of some U.S. expertise at its core.

Mr. POSEY. You know, if somebody had told me we're going to locate and coordinate these various telescopes around the globe and we're going to coordinate them so that you could read the data on a dime from New York with the dime being in Los Angeles, I'd think that's insane, so, you know, a lot for your courage and your faith in what could be accomplished.

Dr. Lonsdale, anything you'd like to comment?

Dr. LONSDALE. Well, certainly the accomplishment is something to be very proud of. The—I look at the scale that we were able to magnify this thing to, and it still blows my mind now even though I was deeply involved in it right from the beginning.

As Dr. Doeleman said, the National Science Foundation has been supporting this work—actually I think the foundations of this go even before 20 years ago when we started working on 3-millimeter VLBI in the mid-90s. So we've been—the foundations for this have been going on for a long time, and it was really quite visionary on the part of the National Science Foundation in my opinion to have sustained investment in this, and it became apparent, as Dr. Doeleman said, that the event horizon scale structure could be accessed. I have to admit I was skeptical initially. Dr. Doeleman convinced me after a bit of time, but it's been a wonderful experience and a wonderful ride.

Mr. POSEY. And, Dr. Bouman?

Dr. BOUMAN. Yes, I think it—one thing that has made this so strong is that we do have—you know, to make a global telescope, we have a global team, but it has been, you know, from many students—from students to, you know, senior scientists from the United States have really pushed this project forward from the beginning, and I—you know, as a younger person see this in my mentors, but I think that it's wonderful how they've kind of had the courage to stick with this for the last, you know, 20 years to achieve what we have today, so I think it's wonderful.

Mr. POSEY. You know, I don't think the accomplishment could be overstated, and I just hope the public learns more about it and would have to become excited about it and more about science and especially our young people.

Thank you, Madam Chair. I see my time is up. I yield back.

Dr. DOELEMAN. OK. I was—can I add one last thing? Would you mind? Yes. One thing that I think needs to be said is that the U.S. attracts the best and the brightest really. We have some of the best research universities in the world, and we get a result like this, we get a lot of interest from around the world from postdocs, from graduate students, from early-career researchers who want to come and join the team here in the U.S. So this is really a recruitment moment not just for early-career or early STEM people but it's a way for us to get the best people here. And some of them go back, some of them stay here, but they all infuse the project with their intellect.

Mr. POSEY. Thank you. Thank you for sharing. Thank you, Madam Chair.

Chairwoman JOHNSON. Thank you. Mr. Beyer?

Mr. BEYER. Thank you, Madam Chair, and thank you guys for coming back again. I've had a chance to be here on a fly out day when you presented a couple weeks ago, and it was very much fun to see it, but I was also incredibly impressed with the quality of the questions asked by our staff, and I was impressed to find out that we now have four astronomers and two physicists just on the Democratic side, and of those six, four of them are women, which is another thing to celebrate, so it's great to have you back.

Dr. Doeleman, you talked about how you might be able to make a movie of the black hole. How will that be different from Matthew McConaughey flying into the black hole in *Interstellar*? Is that what you're envisioning or——

Dr. DOELEMAN. Well, we're hoping to bring him onto our team.

Mr. BEYER. Put Ed Perlmutter on the team, too, please. You'd be glad to have him.

Dr. DOELEMAN. But it's a great question. The human intellectual palate gets sophisticated pretty quickly, so it wasn't 5 minutes after we released this image that people were saying, well, what's next? And we were, too, quite frankly. I think we were all asking what's next.

By making movies, we access a completely different realm, as Dr. Bouman was saying. We can add some new telescopes around the globe to sharpen and fill out the virtual lens, and by seeing the motions of matter orbiting around, which can't of course move at the speed of light, we test Einstein in a completely different way.

And for Sag A* it was very important. It's a completely different kind of object. Keep in mind that it's 1,000 times smaller in mass than M87 here, so it's a completely different kind of object from an astronomical point of view. It's much more similar to all the black holes in most of the galaxies in the universe, so by being able to study Sag A*, we can study most of the universe.

Mr. BEYER. You set up my next set of questions because I was very much intrigued that you guys hadn't been smart enough to come up with a theory of quantum gravity yet, so I've been asking a lot of people about it since and reading up on it, and I've long been a fan of string theory because the math works, right? But in string theory you have 26 dimensions, bosonic string theory; super string theory, 10 dimensions. How does this work on imaging a black hole help you think about quantum gravity?

Dr. DOELEMAN. Yes, so it's a really good question. So on the scale of the event horizon, we tend to think of black holes as classical objects. In other words, the quantum realm doesn't really take hold until you get to the singularity that's shrouded by the event horizon. When you get to that singularity, the density is so high and the force of gravity is so strong that finally gravity gets to play with the big forces like the strong force and the weak force that control things at the nucleon level. And only there does that happen. That's where we need to unify gravity and the quantum world.

At the event horizon, we don't think there's going to be much effect on quantum gravity there, but there could be. In other words, there are some theories where you get manifestations of the quantum world on horizon scales. And people have done some simulations now of what that might look like.

Mr. BEYER. When you get to the singularity, will you be able to think about things like quantum entanglement?

Dr. DOELEMAN. It's possible. I'm not sure—I'll be honest with you. I'm not sure how the Event Horizon Telescope is going to see through the event horizon. We haven't quite got there yet. But if the quantum fluctuations can be manifest outside the event horizon, then looking at the electromagnetic radiation from the black hole boundary, as the EHT does, could give us a window into that.

Mr. BEYER. So all of us here are big fans of James Webb, we're all big fans of WFIRST (Wide Field Infrared Survey Telescope). Will this work also give you insight into dark energy and dark matter? Or is it——

Dr. DOELEMAN. It is possible to think about dark matter and dark energy from this perspective, so, for example, there are theories that dark matter consists of, you know, black holes and things like that. And there are also some possibilities that axion particles, which could be the constituents of dark matter, dark energy, could be resolved or studied with the Event Horizon Telescope, but that kind of remains to be seen. That would have—be through a next-generation version of it.

Mr. BEYER. OK. Dr. Córdova.

Dr. CÓRDOVA. If I could just add that NSF has some other telescopes coming online like the large spectroscopic survey telescope, the LSST in Chile, that is going to really address dark matter and dark energy.

Mr. BEYER. Great, thank you. And, Dr. Bouman, it was fun to read in Dr. Córdova's statement about the 1,000 hard disks and too much data to go over the internet and three tons. So you're a computer scientist. What's coming in terms of data management to be able to deal with these huge amounts of data?

Dr. BOUMAN. Yes, well, luckily, from an imaging point of view, by the time we start making the images, this data has already been whittled down to a much smaller amount of data, and then our problem is we have too little data. But actually there are groups of people who take the five petabytes of data that we collected and get it down to megabytes. So basically they try to find this weak signal riding on a huge amount of noise and process it down and calibrate it so that we kind of can make these measurements that we then use to make images. But even then this has required, you know, huge amounts of computational power to whittle—to make these five petabytes down to the megabyte level. I'm going to—I think Dr. Lonsdale will have a lot to say along that line.

Dr. LONSDALE. Yes, well, just briefly, one of the biggest challenges that we face is actually taking the data from the telescopes where it's recorded and physically moving it to one place so we can combine it. And that's a particular problem for the observations taken at the South Pole. Of course, these observations happen in the northern spring, which is when winter is closing in in Antarctica, so we can't even get the data physically for months and months and months. And ways to ameliorate that problem are under study, including the possibility of laser-based communications via space relay, which has the potential for enormous data rates that would allow us to get the data much quicker and do the whole process more efficiently.

Mr. BEYER. Great. Thank you very much. Madam Chair, I yield back.

Chairwoman JOHNSON. Thank you very much. Mr. Perlmutter.

Mr. PERLMUTTER. This is an incredible panel. I just thank you. The enthusiasm, as Mr. Casten said, it really is infectious.

So many, many years ago I wrote my term paper in astronomy on black holes, OK? And I love volcanoes and I got to go to the Atacama Desert to the observatory there, which is surrounded by volcanoes and was focusing on the black hole. They didn't tell us the discovery, but they told us there was going to be big news coming. So you had a cone of silence, but they definitely gave us an indication what was coming.

And one of the things that I saw that was incredible was the teamwork among the scientists of all the different, you know, departments that you might be—in English, in Spanish, in Czechoslovakian, so we had young scientists down there with—you know, running the computers, and they were all working and each of them could speak the other's language.

So tell me a little bit about it, what it was like working with some of—and all of you, you know, some of your colleagues from other parts of the world because this was an incredible amount of teamwork. And then I want to talk about time travel after that.

Dr. DOELEMAN. Well, so, yes, maybe we could solve the time problem by first inventing time travel, and then we'll have more time to answer the question.

Well, I think that one of the points of pride in this project really is that our strength is in the diversity of the team, and the strength is in building bridges across borders at a time when I think, as the Chairwoman said, things can divide us. The technique that we use, very long baseline interferometry nimbly sidesteps all of that in a natural and organic way to work with the best experts around the world to build this global telescope with a global team.

And we ensured that, as I said before, by establishing working groups, the imaging working group that Dr. Bouman is in, technology working groups that Dr. Lonsdale participates in by making them interdisciplinary and by drawing on the different constituents around the globe as the fabric of it. And when you do that and when you bring everyone together, you find out quickly who can do the work regardless of where they are, and you crosscheck everyone.

And it set up, that environment that I called purposeful tension before. It really is a way to gain acceptance for your results when everybody's looking at it and everybody's asking questions regardless of language or culture or background.

Dr. LONSDALE. So I want to emphasize the VLBI technique. It's been around for a long time. And because it involves very long baselines, it automatically is international. It's been international for 50 years. And there is, you know, a real sense of community in the VLBI world and everybody's friends or nearly everybody is friends. But, no, I mean it's really a wonderful community, and it's been a delight to work in VLBI for the last several decades.

But in the EHT, there's also a key factor that ties everybody together. Everybody is totally driven by the mission. There is a tremendous drive on the part of everybody to get to results like this, and that crosses all barriers. And so when you combine those two things together, that I think is the spirit that you witnessed at the ALMA site in Chile, and it's across the project.

Mr. PERLMUTTER. All right. So let me just jump to time for a second. So does that picture tell you anything about time and what it is?

Dr. DOELEMAN. OK. I guess I'm going to be the sacrificial lamb here on this one. Well, I'll just say that there's no real indication that we can make inroads on time travel using these results. In one sense you're actually looking at a time machine because this black hole is 55 million light-years away. The images that you see is the way the black hole looked 55 million years ago. So in that sense we're seeing something that left the black hole when, you know, the dinosaurs had just been extinct here on the Earth.

Mr. PERLMUTTER. But going back to the question about Matthew McConaughey and *Interstellar*, does this, what you've done, help prove up some of Einstein's theory about time and space and something as dense and as massive as that?

Dr. DOELEMAN. Yes, absolutely it does. So what you're seeing here is the strongest proof we have to date for the existence of supermassive black holes, full stop. It really validates Einstein's theory as to the precision of our measurements around this black hole. For example, Matt McConaughey went to this fictitious black hole, and he went close to it and he came back and he had not aged as much as a companion astronaut in the mothership that was—had not gone down into that gravity well. That is a real phenomenon. You can go to a black hole, you can go close to it, your clocks will tick much more slowly than clocks farther away. And so in that sense we have validated Einstein at the black hole boundary and maybe put *Interstellar* on slightly better footing.

Mr. PERLMUTTER. Thank you, and thanks, Chair. I yield back.

Chairwoman JOHNSON. Thank you very much. Ms. Stevens.

Ms. STEVENS. Well, thank you to our incredible witnesses for today's hearing. There's a reason why we're doing this as a hearing today rather than a meeting, and that's because we are showcasing to the world from the halls of Congress your incredible achievement and accomplishments for humanity that really just put us at a tipping point frankly.

And the question I wanted to ask was around the technology and the data sets and the logarithms. And I was wondering, many of you have it in your testimony, but I wanted you to shed light on that technology and what that means for us in our everyday lives and what this means for us as, you know, a society and other applications that we maybe could use these data sets for. And, Dr. Bouman, if you would like to start, I'd love for you to take that question.

Dr. BOUMAN. Sure. So I've talked with—a little bit so far about how the methods that we've developed for imaging a black hole can be applied to many different applications. I've highlighted MRI taking better images of our brains and organs that are moving, and that can be—it's a very similar problem to imaging an evolving black hole overnight. I think there are, you know, a myriad of different applications, and so many of the applications today require that we take multi-modality information, sensor data, and merge it together with algorithms that kind of piece—that kind of fill in our gaps of information to come to some result. And I think that the merging of sensor data with algorithms, especially with—in machine learning where we're coming up with new computational techniques to push the boundaries of these methods.

I think the methods that we develop for the black hole imaging are similar in spirit as these other methods, and we have to come up with similar—there are similar problems with them as well like validating the information, making sure that these systems are robust under—in different situations, making sure that we don't impose too much prior information on our result, and then we can see something unexpected. I think that these are similar problems throughout a variety of applications.

Ms. STEVENS. How many people worked on the data set?

Dr. BOUMAN. So the imaging portion of it is only one small part of making an image of a black hole. There are many different steps from developing instrumentation, you know, installing these at the ends of the Earth in the South Pole even, you know, through data processing. Whole new data processing pipelines had to be developed with the challenges of the EHT in mind. Even though we were building on past VLBI technology, these kind of had to be modified for the challenges we faced. Imaging and then model fitting and theory, understanding the interpretation, all of these were essential parts in getting that picture.

And so we had over 200 collaborators on the EHT project——

Ms. STEVENS. Wow.

Dr. BOUMAN [continuing]. And there were additional collaborators who were not part of the collaboration who also were essential to making it possible.

Ms. STEVENS. So this was the international collaboration that we've been talking about that these large challenges, these big visions are really met by coming together, and that's something that we spend a lot of time on the Science Committee exploring and talking about, which is how to forge unlikely alliances, how to set the table. And frankly, that's something that the Federal Government does really well when it's working well is bringing folks together.

I have one last little question about the black hole. And Mr. Perlmutter got into some of the fun of this, but you sort of with your work have begun to normalize the black hole, which was sort of just this big vision and debated if it was true and what it is, and I was just wondering if you could shed light on how one cannot get lost in the black hole as it pertains to the work that you're doing? That's somewhat of a poetic question, but I ask it because your work has implications for what we are doing on the Science Committee and how we are inspiring research.

Dr. DOELEMAN. That's an interesting question. Let me try to answer it. Maybe you can course-correct me if I go astray here.

One way to look at this and not get lost in it is to put it in historical context. So think about in 1655 there was an image that startled people. It was the first drawing of a flea by Hooke. The microscopic world became real for us. All of a sudden something that was invisible to us became real, and it changed the way we thought about our lives and it changed medicine and disease and epidemiology just knowing that there was this microstructure.

And think also about the first x-ray made by Roentgen of his wife's hand. You could see the ring on the—with the bony structure underneath. It made something visible for the first time that was invisible prior to that.

And then think of the Earthrise over the moon, the first blue marble. It really put things in perspective for us. It made us feel connected in a way that we hadn't before. It made us feel vulnerable. These are iconic images. They're terrifying, but we can't look away.

And I think that if you wanted to get poetic, using your words, that this image may become an icon. It may be the first image we have of a one-way door out of our universe. It's something that we've been taught that is a real monster exists, that the visible has become visible. And then the maybe it's the beginning of something new, not just the end.

Ms. STEVENS. Thank you. That's exactly what I was looking for. And I yield back the remainder of my time.

Chairwoman JOHNSON. Thank you very much. Ms. Wexton?

Ms. WEXTON. Thank you, Madam Chair, and thank you to all the witnesses for being here today. I am really in awe of all of you and everything you've accomplished, and it's fantastic that you've inspired a new generation of Americans and beyond to pursue science and to look beyond our horizons.

One of the major—and this is something that the gentlelady from Michigan touched on a little bit. But one of the big challenges that you had to overcome was the huge volume of data and—that was generated and how it had to be transported because you couldn't use the internet to transport a lot of it and analyze. Dr. Córdova, can you talk a little bit about the need for new approaches to big data given the volume of data that we're seeing now and breakthroughs like these?

Dr. CÓRDOVA. Yes, this is a great example that put into the spotlight. One of our 10 Big Ideas for investment is called Harnessing the Data Revolution, and it's really a response to this enormous challenge that we have not just in this field but in all fields of scientific endeavor and other endeavors now. And we need to be continually stimulating the imaginations of would-be proposers and grantees to think about how we're going to effectively do data analytics and data science on this enormous scale of data that we have. We have a lot of grant opportunities to propose for new kinds of platforms and ways of thinking about this.

We're also working in collaboration with the private sector. We have, for one example, a collaboration with Amazon where they're putting in $10 million, we're putting in $10 million to work on artificial intelligence and see where that can take us in looking at how to do data science better.

And in our new convergence accelerator, we have a fast track to try to get a platform where people can access databases that may look completely different and actually kind of speak different languages. How do we interrogate them so that the average individual can go in there and say, I can understand how to use this database and this one and this one, and put them all together in order to synthesize a new knowledge from and extract the answer to new questions.

It's just an enormous challenge that our society, because it is technologically advanced, now has, and I think this illustration of the EHT project really puts that in focus. We're not just talking about 15 terabytes a night, which is what we expect on a telescope like the new one we're building in Chile, the LSST, but we're talking about much more.

Ms. WEXTON. And related to that I guess or as a part of that, I understand, Dr. Bouman, that the computer algorithms that were used to construct the image that was—that they leveraged open-source software, is that correct?

Dr. BOUMAN. Yes, that's correct.

Ms. WEXTON. So I would ask everyone on the panel, what in your view is the value of open-science practices such as making computer codes and raw data available to the public? How does that help spur innovation?

Dr. BOUMAN. Yes, so the algorithms, the code that we write to make images of black holes to model to extract the mass, many different aspects of the project we leveraged open-source software. And without this, you know, it would've taken us many more years to develop the tools necessary to do this. So we gained a lot. And if you look at the—basically the tree of contributors toward the project, it's not just the—tens of people, it's not hundreds of people in our collaboration but it's thousands of people that have really contributed to making this project through open-source software. And so I think it is really essential.

And in giving back to the community and also trying to expedite, you know, these results and acceptance of results, we've also made our code and algorithms available through open-source software online, along with the data that we used to make the picture so you can go off and develop your own methods to try to make a picture of a black hole as well. And so we are in big support of open-source software and pushing and continuing to do that.

Ms. WEXTON. Thank you. Dr. Lonsdale, do you concur with that?

Dr. LONSDALE. I fully concur with that, yes. I think it's been a tremendous accelerant for our work. It's made the work much more efficient, much more cost-effective to be sharing these kinds of codes and—through the open-source mechanism.

Ms. WEXTON. Dr. Doeleman?

Dr. DOELEMAN. Go ahead.

Ms. WEXTON. OK. Very good.

Dr. CÓRDOVA. I just would love to give you a recent example of where open data has really increased discovery. I recently visited Princeton University, and two young astrophysicists there took the entire database from the first two runs of the LIGO observatory that discovered gravitational waves, and with their own computer there and their own imagination and brains, they went through the entire data sets and discovered six more emerging black hole binary sources, which the original team had not found, but just because they had their own kinds of algorithms that they had developed to reduce the noise. The potential of releasing data and of course software is just enormous for discovery.

Ms. WEXTON. Thank you.

Dr. DOELEMAN. Would you mind if I said one more——

Ms. WEXTON. I will inquire, but Madam Chair says it's OK, so yes.

Dr. DOELEMAN. I would say often people say—like Newton, you know, said he stood on the shoulders of giants, a couple of giants. But with open-source software, many hands make light work, and so you can get thousands of people helping. And I would also add just very quickly that it's a way to get buy-in. It's a way to make people feel like they're part of something like this. So the people that wrote the libraries like, you know, Num Pi or Astro Pi that we use just to get a little wonky and some of the software that we use, they can look at this and feel a little sense of ownership, that they're part of it, right? So when you get such a result like this, and many people have contributed, everyone sees their self in this kind of project.

Ms. WEXTON. Thank you very much. Thank you, Madam Chair.

Chairwoman JOHNSON. Thank you very much. Mr. McNerney?

Mr. MCNERNEY. Well, I thank the Chairwoman for holding this fun hearing. I want to thank you, Dr. Córdova, for your leadership in science. I want to thank Dr. Doeleman, Dr. Lonsdale, and Dr. Bouman, for your dedication and hard work. I know how hard science is. You've got to spend a lot of hours alone in the lab and in front of your computer screen. When you're in college, your friends are out partying. After college, they're out making money. But they don't understand the kind of reward you get when you make these kind of discoveries, so thank you for your hard work.

I studied differential geometry and general relativity in grad school, so it was particularly rewarding to see these images.

Because of your hard work and the hard work of many dedicated scientists who are now, for the first time, able to create a definitive image of a black hole, well, we can't see black holes but we can see the effect of black holes, and we need to think of black holes as something bigger than ourselves. It's a punchline.

So this announcement was also a monumental moment for STEM education, which forms one of the cornerstones of the United States educational system. Dr. Córdova, exciting advances in science often inspire students to pursue STEM careers. However, not every scientific breakthrough gets this kind of attention. What steps is the NSF taking to engage young people when exciting discoveries are made in other fields?

Dr. CÓRDOVA. Thank you, Congressman, for that question, and thank you for always being a partner with NSF on its trips to both Poles and to the adventure of scientific discovery globally.

NSF has many, many programs to stimulate the imagination of young people. Some of the particular programs are Computer Science for All, or CSforALL it's called, which gets young people with the imagination of a Dr. Bouman at an early age involved in having the computer skills and literacies to go on and then go in any direction that they want, in science, engineering, finance, whatever.

We have a lot of programs to increase inclusiveness and diversity of the STEM workforce at all ages. We have programs to advance women and underrepresented minorities through the pipeline of academia and beyond. It's a major emphasis of ours.

In this particular discovery, I just have to credit the people that are in our Office of Public Affairs for seizing on what it would do to the imaginations of everybody, young people, older folks around the world, and realizing very early on, when you are submitting your first papers, that this was going to be the discovery which, when other people saw it, would just absolutely mesmerize. There would be a world pause to say, wow, you know, did that really happen?

And they just coordinated in a way to organize really the entire world. There were I think eight press conferences simultaneously around the world to announce this. It was just a major thing. Now, we can't do that every day. We don't have the workforce to be able to do that, but——

Mr. MCNERNEY. Well, I'd like to ask another question now——

Dr. CÓRDOVA. Yes.

Mr. MCNERNEY [continuing]. If you don't mind too much. Thank you.

Dr. Doeleman, did you use deep learning or other AI approaches in developing this image?

Dr. DOELEMAN. Well, I am—I'll give you a quick answer, and then I'd like to defer to Dr. Bouman on that. We didn't necessarily use artificial intelligence or deep learning as such. We did use very forward-looking new algorithms. So we created this tension in the program where we used traditional methods using radio astronomy, but also new methods invented purposefully for these data. And when we got corroboration between them, that was powerful evidence that we were on the right track. But we look forward to using these new kinds of techniques, deep learning, AI as we move forward in some of the videomaking that we plan on doing. But maybe Katie—or Dr. Bouman wants to——

Dr. BOUMAN. Yes. As Dr. Doeleman said, it was very important that—for these first results we were as confident as possible in them and so we had many different methods, both traditional and new methods that we had developed independently, and we actually imaged independently. And when we saw the same structure out of all—both of them, then we were very confident.

We have explored other machine-learning and deep-learning techniques for making images of black holes. However, we—this data was so amazingly beautiful that we didn't actually need these very complicated methods to get something robust out of it, so we actually decided to pare down and do basically the algorithms that we were most confident with in the community and had most acceptance within the community because they produced beautiful results themselves. And we actually liked it when we didn't have to impose as much assumptions into the problem.

And so I think moving forward, as we get harder and harder—data that is harder to work with, it will be essential that we merge in these new computational methods, deep-learning methods, other AI techniques with the data to get the best results. But for this result we found it wasn't necessary and so chose not to use them.

Mr. MCNERNEY. Well, thank you. I'm going to just ask one quick question. Could you possibly describe how you felt when you first saw that image on your screen?

Dr. BOUMAN. So I think we all have probably different stories for this, but I was personally in disbelief. You know, we had worked for years developing the methods, testing them, making—you know, but until you saw—we all kind of crammed into a little room, very hot, it was June, and we all pressed go on our computers at the same time. We all had an imaging script ready to go. And as the image—it just like started appearing, this ring shape, and I think none of us were really expecting that to happen. You know, we had for years been told, oh, you would—we would expect to get a ring, but you never know.

Everything—there's always something that goes wrong, right, so seeing something like that just appear on the screen, I kept going between excitement, awe, disbelief, and just hoping that it wasn't some cruel joke that was being played on us and it wasn't real data. So it took me a month before I was convinced it was real, but I was very excited. We were all very excited.

Mr. MCNERNEY. Yield back.

Chairwoman JOHNSON. Thank you very much. Dr. Foster?

Mr. FOSTER. Thank you, Madam Chairman, and thank you to our witnesses.

I have to say that, you know, this hearing has brought back a lot of memories to me. I was fortunate enough in my career in science maybe 2-1/2 times to have been at that screen seeing the results of your data analysis and learning something that previously was only known to, you know, your data and to God. And so it is an incredible feeling.

I remember the first time—my Ph.D. thesis was the search for proton decay, and for my thesis we built and designed and did the data analysis for a giant detector in a salt mine to look for proton decay, which was confidently predicted by the huge majority of theoretical physicists. And so we had multiple data analysis programs, and mine ran a lot faster than everyone else's, so I knew the answer first.

And so when we saw the first few days of data, realized that we were seeing neutrinos at the expected rate and not a sign of proton decay, you just sort of sit back in your chair and say, wow, all of these theorists were wrong.

About 160,000 years ago, a supernova blew off in the greater Magellanic cloud, and for 160,000 years the burst of light and the burst of neutrinos traveled toward the Earth and arrived in 1987. And where the signal was seen optically by the astronomers and at the same time in our underground detector what we saw neutrino burst. So at that time we were also limited by data transmission. And one of our collaborators drove down to the mine underneath Cleveland and then took the actual magnetic tape, which is how you move data, drove it to Ann Arbor where the analysis computers were, spun the tapes, did the analysis, and then realized that, yes, indeed, we had seen the neutrino signal and learned a lot about these incredible explosions.

I guess the third time was when I was working on the giant particle collider at Fermilab and I was looking for the discovery of the top quark into the decay mode of electron and muons. And so I had something that—looked every night, would spin through the interesting events on the last night's data and saw one morning when I was drinking my coffee that in the previous night we had seen an acollinear muon and electron event with enough energy that it pretty much had to be the decay of a top-antitop with a top mass of about 170 GEV. And so, you know, you see this thing and say, my gosh, that's it. And that's why you get into this business. I understand that smile that's on your face.

Before I forget, I would like to ask unanimous consent to enter into the record of this hearing the entire author list of your publication. You know, it is a tough thing to try to, you know, spread the glory for something like this appropriately because you have everything from the technicians that stay up all night and repair the circuit boards when they break in the middle of the night to the people that are really good at giving talks and so they always get sent to the big conferences, and then—it's a tough thing, and it's wonderful to have people with the entire range of skills on the author list. So I'd ask unanimous consent if it's——

Chairwoman JOHNSON. So ordered.

Mr. FOSTER. Thank you. And let's see. In my copious minute and a half I have left, I'd like to talk a little bit about, you know, the way forward on this, you know, what additional facilities, you know, if you could, you know, ask for, you know, a doubling or tripling of the effort in this area, you know, what would be the top of the list of ways to really expand your capabilities to do more of this kind of observation and analysis?

Dr. LONSDALE. So I think very near the top of the list is additional telescopes because they improve the fidelity of the data, will allow us to see fainter things in a picture like this. This particular object has a really spectacular jet of material coming out of it. The only reason you can't see it in this picture is because the dynamic range of the image, the brightest to the faintest isn't big enough, and one of the ways that you can improve that is by adding more telescopes.

And then, as Dr. Doeleman said, you know, increasing the amount of data that we can take increases the sensitivity and then going into space is the obvious next step because then you can get a telescope as big as you can space your spacecraft.

Mr. FOSTER. And what is the scaling of your resolution with the baseline——

Dr. LONSDALE. It's one-to-one. If you double the baseline, you double the resolution of your imaging.

Mr. FOSTER. All right. And so you're not statistically limited——

Dr. LONSDALE. You——

Mr. FOSTER [continuing]. For at least as long as you have a handful of satellites?

Dr. LONSDALE. Yes, it's actually——

Mr. FOSTER. Or additional telescopes.

Dr. LONSDALE. It's a fairly complicated tradeoff. If you have a low-Earth orbiting satellite, then it will get you a lot of information very quickly but not such high angular resolution. But if you have something further out, it gathers data more slowly but has higher resolution.

Mr. FOSTER. OK. And just one quick question. Did you publish the four pictures that got averaged to the final?

Dr. DOELEMAN. Yes. So——

Mr. FOSTER. You did. OK.

Dr. DOELEMAN. In the publication you see everything. Let me add one thing to what Dr. Lonsdale said. You can have telescopes, you can have satellites in orbit, you can do higher bandwidths and you can go higher in frequency and sharpen the image, but what I've learned in this project is it's all about the people. You know, you can have the fanciest equipment that you want, but if you don't have ingenious early-career scientists like Dr. Bouman and her colleagues, if you don't have people who are visionary in trying to see what they can do, if you don't push the data in new directions—and having the data is not always the final answer. So the other thing that I think we need is—I would say is an influx of positions that we can advertise to get the best and the brightest working on these new data sets.

Mr. FOSTER. Thank you much. Among other things, making me have a few tinges of regret at leaving science and getting into this crazy business. Thank you all. I yield back.

Chairwoman JOHNSON. Thank you very much. Some of us are glad you did.

I'm going to take the privilege of asking one final question before we end. You have mentioned the international collaboration, and we all know how important that is. But what are some of the key contributions made by the international partners involved in the project?

Dr. DOELEMAN. Thank you for that question, Chairwoman. So, as I said before, different telescopes are in different regions, so sometimes it naturally falls to the agencies or the institutes in that region to care for or outfit that particular telescope. So, for example, in Spain, one of our key telescopes that provides an outrigger that fills out this Earth-sized virtual lens was outfitted and maintained by the Europeans. And they're also establishing a new telescope in France, which will similarly round out the array. The Taiwanese are also working on the Greenland telescope, which is going in that area, and they're shouldering most of the burden there. And also we had buy-in from the European Research Council to build out some of the instrumentation that was deployed at all of the telescopes. So in very key ways we levered the international resources, not just the people but the resources, to build out the array.

Chairwoman JOHNSON. Yes, Doctor.

Dr. LONSDALE. I'd like to add to that the work that we do at my observatory in correlating the data, combining the data streams, that is done also at the Max Planck Institute for Radio Astronomy in Bonn, Germany. And we've been close collaborators with that group for decades in fact, and they're part of this VLBI community that I had mentioned and we—and the availability of a whole other team of people working on the correlation so we could do definitive cross-comparisons between what we were getting and what they were getting was an essential part of the data validation process that was carried through many different stages.

Dr. BOUMAN. Yes, just building on that, since we were building this new instrument that we had never used before, we needed to be very careful and test and make sure that every stage of the pipeline was getting a correct answer. So each stage from the correlation that Dr. Lonsdale just talked to, to data processing to imaging to model fitting and theory, each of these actually we developed different pipelines, different code bases, or different methods to check each other. And in all the cases that I can think of there was always an international method or group that kind of spearheaded one of those at least. And so I think it was really essential that we had these independent tests of each other, these crosschecks to make sure that our instrument was actually working as we expected. And that required the help of our international collaborators.

Dr. DOELEMAN. Madam Chairwoman, if I could add one thing, I'd be remiss, when you make lists like that, you always forget someone, right? I would also point out that the Japanese colleagues brought expertise in the area of imaging and also really helped phase up the ALMA array, the array that Dr. Córdova described. Our Chilean colleagues have worked very closely with us on ALMA and outfitting that telescope. In Mexico we had huge help from the institutes there with the Large Millimeter Telescope on top of Sierra Negra. And also in—from the Chinese, they also invested in the East Asian Observatory, which brought us the James Clerk Maxwell Telescope on Mauna Kea in Hawaii. So this really was a—truly a global effort.

Chairwoman JOHNSON. Thank you. Any other comments?

Dr. CÓRDOVA. Since we're coming to the end of this session, we want to mention about the Diamond Achievement Award that NSF gave the EHT team and Dr. Doeleman accepted on—a couple of evenings ago. So this is the highest award for really remarkable achievement that we can give. And of course diamonds spark all sorts of things in our imagination.

But I wanted to share with you something that I read in a book that's already been written and published about this project, a Scientific American writer named Seth Fletcher lived with this team for 6 years and he went all over the world with them, and he has a quote from Shep, who—they were at a very critical point in the observations, lots of things going on, and apparently Shep held his head and he said, "I'm under so much pressure I feel like I'm going to be squeezed into a diamond."

And that's when we decided we needed to call this award the Diamond Award because to reach out to all those people, all those scientists that—engineers that feel like they're under tremendous pressure and they may become diamonds, that sometimes they actually do become diamonds.

Chairwoman JOHNSON. Thank you very much.

Before we bring the hearing to a complete close, I really want to thank all of you for being here. It's been a tremendous hearing, and I think you got that indication with the participation and the enthusiasm. I think you've rubbed some of yours of onto us.

The record will remain open for 2 weeks for additional statements from Members or any additional questions you may have or for additional testimony.

The witnesses are now excused, and our hearing is adjourned.

[Whereupon, at 12:17 p.m., the Committee was adjourned.]

Appendix I

ADDITIONAL MATERIAL FOR THE RECORD

LIST OF AUTHORS SUBMITTED BY REPRESENTATIVE BILL FOSTER

Authors from the Six Event Horizon Telescope Publications

Names are from the following publications:

- The EHT Collaboration et al. 2019. "First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole." ApJL, 875, Pp.1.
- The EHT Collaboration et al. 2019. "First M87 Event Horizon Telescope Results. II. Array and Instrumentation." ApJL, 875, Pp.2.
- The EHT Collaboration et al. 2019. "First M87 Event Horizon Telescope Results. III. Data Processing and Calibration." ApJL, 875, Pp.3.
- The EHT Collaboration et al. 2019. "First M87 Event Horizon Telescope Results. IV. Imaging the Central Supermassive Black Hole." ApJL, 875, Pp.4.
- The EHT Collaboration et al. 2019. "First M87 Event Horizon Telescope Results. V. Physical Origin of the Asymmetric Ring." ApJL, 875, Pp.5.
- The EHT Collaboration et al. 2019. "First M87 Event Horizon Telescope Results. VI. The Shadow and Mass of the Central Black Hole." ApJL, 875, Pp.6.

Note: All names are listed in alphabetical order by last name.

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