Written Statement of

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before the
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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.

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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?