Written Testimony of

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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.

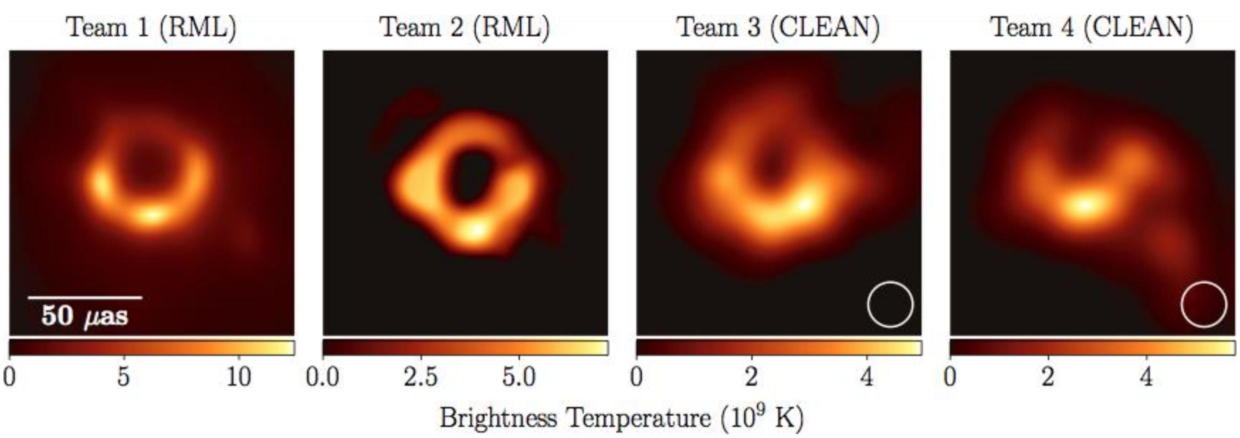
Once data has been collected, the challenge is to use these sparse measurements to form the image. Unfortunately, since we only obtain a few samples there are an *infinite* number of possible images that are perfectly consistent with the data we measure. But just as your brain may still be able to recognize 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?

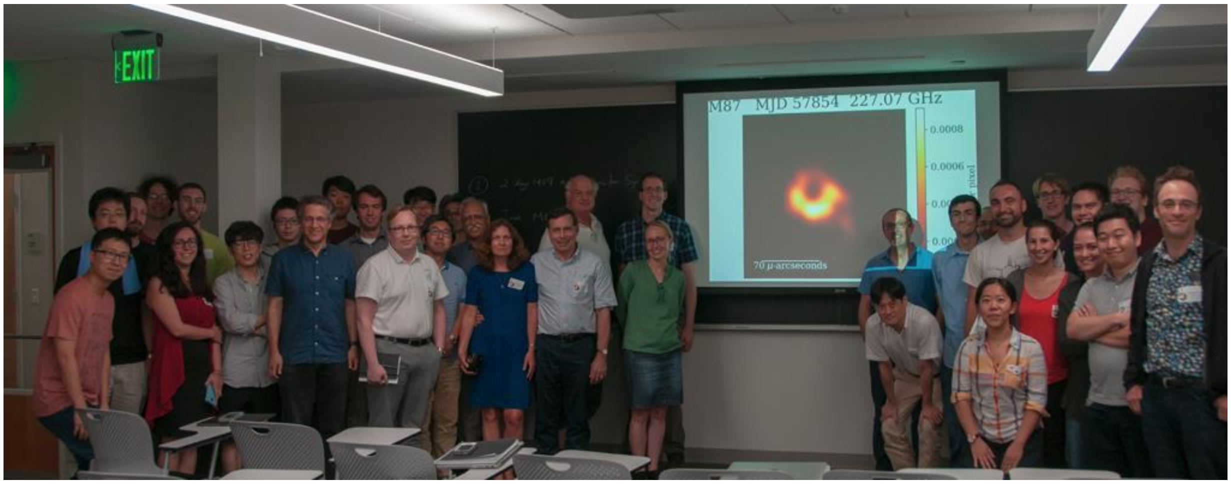
Consequently, a big question we faced when making a picture of M87 was not just how do we reconstruct an image, but also how do we validate the recovered image. Before collecting data with the EHT we tested our algorithms, making sure they could recover unexpected image structures. To do this, we drew 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.