

# UNLOCKING THE SECRETS OF THE UNIVERSE: GRAVITATIONAL WAVES

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## HEARING BEFORE THE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY HOUSE OF REPRESENTATIVES ONE HUNDRED FOURTEENTH CONGRESS

FIRST SESSION

February 24, 2016

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**UNLOCKING THE SECRETS OF THE  
UNIVERSE:  
GRAVITATIONAL WAVES**

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**WEDNESDAY, FEBRUARY 24, 2016**

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

The Committee met, pursuant to call, at 10:07 a.m., in Room 2318 of the Rayburn House Office Building, Hon. Lamar Smith [Chairman of the Committee] presiding.

LAMAR S. SMITH, Texas  
CHAIRMAN

EDDIE BERNICE JOHNSON, Texas  
RANKING MEMBER

**Congress of the United States**  
**House of Representatives**

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

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***Unlocking the Secrets of the Universe: Gravitational Waves***

Wednesday, February 24, 2016  
10:00 a.m. – 12:00 a.m.  
2318 Rayburn House Office Building

**Witnesses**

**Dr. Fleming Crim**, Assistant Director, Directorate of Mathematical and Physical Sciences,  
National Science Foundation

**Dr. David Reitze**, Executive Director of LIGO, California Institute of Technology

**Dr. Gabriela González**, Professor of Physics and Astronomy, Louisiana State University

**Dr. David Shoemaker**, Director, LIGO Laboratory, Massachusetts Institute of  
Technology

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

*Unlocking the Secrets of the Universe: Gravitational Waves*

**Wednesday, February 24, 2016  
10:00 a.m. – 12:00 p.m.  
2318 Rayburn House Office Building**

**Purpose**

On Wednesday, February 24, 2016, the House Science, Space, and Technology Committee will hold a hearing to discuss the recent and groundbreaking detection of gravitational waves by the National Science Foundation (NSF)-funded Laser Interferometer Gravitational-wave Observatory (LIGO) detectors. It is the confirmation of the existence of gravitational waves, as first predicted by Albert Einstein a century ago. The purpose of the hearing will be to learn more about the discovery, its meaning for American science and innovation, the NSF's role in supporting LIGO, and what new research and applications may be generated by this breakthrough.

**Witnesses**

- **Dr. Fleming Crim**, Assistant Director, Directorate of Mathematical and Physical Sciences, National Science Foundation
- **Dr. David Reitze**, Executive Director of LIGO, California Institute of Technology
- **Dr. Gabriela González**, Professor of Physics and Astronomy, Louisiana State University
- **Dr. David Shoemaker**, Director, LIGO Laboratory, Massachusetts Institute of Technology

**Background**

On September 14, 2015, gravitational waves were detected by the twin Laser Interferometer Gravitational-wave Observatory (LIGO) detectors located in Livingston, Louisiana, and Hanford, Washington. On February 11, 2016, scientists published their findings and announced the discovery.<sup>1</sup> The LIGO detectors are funded by NSF, and were conceived, built, and operated by the California Institute of Technology (Caltech) and the Massachusetts Institute of Technology (MIT).<sup>2</sup> The operation was carried out by LIGO's team of scientists, engineers, and staff at Caltech and MIT, and the 1,000 scientists that make up the LIGO Scientific Collaboration, with members from over 80 scientific institutions world-wide.

<sup>1</sup> Abbott *et al*, "Observation of Gravitational Waves from a Binary Black Hole Merger," *Physics*, 12 February 2016.

<sup>2</sup> "Gravitational Waves Detected 100 years After Einstein's Prediction," National Science Foundation. Available at: [https://www.nsf.gov/news/news\\_summ.jsp?cntn\\_id=137628](https://www.nsf.gov/news/news_summ.jsp?cntn_id=137628)

*Gravitational Waves and the General Theory of Relativity*

Gravitational waves are the ripples in the fabric of space-time resulting from the most violent phenomena in our universe, such as black holes or supernovae explosions. The gravitational waves radiate outward like ripples or waves across a pond.

In 1916, Albert Einstein predicted gravitational waves as part of the Theory of General Relativity, which challenged the understanding of gravity that had prevailed for more than 200 years, since the time of Isaac Newton. Newton theorized that gravity affects everything in the universe, that the same force that pulls an apple down from a tree keeps the Earth in motion around the sun. Einstein's research led him to a new Theory of Relativity, the idea that there is no fixed frame of reference in the universe – everything is moving relative to everything else.

Einstein's theory was that what we perceive as the force of gravity is an effect of the curvature of space and time, interwoven into a single whole known as "space-time." In the presence of matter and energy, space-time can evolve, stretch, and warp. Einstein proposed that objects with mass--such as the sun and the Earth--curve the geometry of space-time like a marble placed on an outstretched sheet of fabric or a pebble that causes ripples in a pond. Einstein further postulated that if the gravity in an area of space-time was suddenly changed by intense energy events – such as around black holes or supernova—gravitational energy waves would be emitted to distort space-time like ripples we observe from a pebble in a pond. These waves would travel at light-speed like other forms of energy, and the distortion of space-time should be able to be observed.<sup>3</sup>

*Efforts to Detect Gravitational Waves: LIGO and NSF*

Scientists have sought experimental evidence of gravitational waves for more than 40 years. In 1979, NSF commissioned Caltech and MIT to design the Laser Interferometer Gravitational-Wave Observatory (LIGO). The National Science Board approved funding for initial construction in 1990. LIGO consists of two interferometers located in Livingston, Louisiana and Hanford, Washington that are operated in unison. The sites were chosen in 1992, and construction began after approval by Congress in 1994. NSF has invested approximately \$1.1 billion in construction and upgrades, operational costs, and research awards to scientists who study LIGO data.

The LIGO detectors are made of a laser interferometer (an instrument in which wave interference is employed to make precise measurements of length of displacement in terms of the wavelength) inside an L-shaped ultra-high vacuum tunnel. Inside the vertex of the L-shaped LIGO vacuum systems, a beam splitter divides a single laser beam into two beams, each travelling along a 2.5 mile-long tunnel. The beams reflect back and forth between precise mirrors that are suspended. A gravitational wave could be observed if both LIGO detectors sense the lengths of the paths that the divided laser beams take along each arm are slightly different. If the laser light took a longer time to reach both detectors this means there was a

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<sup>3</sup> "Instant Expert: General Relativity," *New Scientist*, Available at: <https://www.newscientist.com/round-up/instant-expert-general-relativity/>



disturbance or ripple in space-time caused by a gravity wave. From this small change, scientists are able to identify the wave's source and approximately where in the universe it originated.

Between 2002 and 2010, LIGO operated without detecting any waves. Scientists concluded that the initial design was not sensitive enough, and in 2010, NSF began funding over \$200 million in improvements to increase the sensitivity of LIGO (Advanced LIGO). In September 2015, Advanced LIGO began initial test detection runs. On September 14, 2015, during one of the first test runs, the LIGO location in Livingston, Louisiana picked up a gravitational-wave signal, and seven milliseconds later, the observatory in Hanford, Washington detected an identical signal. This signal exactly matched the calculated behavior of gravitational waves produced when two black holes collide. LIGO scientists estimate that the black holes that created the waves were about 29 and 36 times the mass of the sun, and that the collision took place 1.3 billion years ago—only reaching the Earth last September.<sup>4</sup>

#### *The Impact and Future of Gravitational Wave Research*

LIGO's scientific impact reaches beyond physics, astrophysics, and astronomy. The effort to design and build the LIGO detectors and to understand the characteristics of the expected gravitational wave signals have resulted in multiple scientific and technological applications and advancements in many fields including mathematics, computer science, and material science. According to LIGO scientists, innovations in areas as diverse as lasers, optics, metrology, vacuum technology, chemical bonding and software algorithm development have resulted directly from LIGO's work.<sup>5</sup>

The discovery by LIGO opens up a new field of gravitational astronomy. Scientists believe that astronomers will be able to locate where exactly each set of the ripples is coming from, and by pinpointing the sources of gravitational waves will allow astronomers to point other telescopes to that direction, boosting the chances of learning more about the phenomena causing such gravitational waves via other spectra such as x-rays, gamma-rays, radio waves, neutrinos and other tools.<sup>6</sup> Since gravitational waves do not interact with other matter, they travel through the universe unimpeded, unlike electromagnetic radiation, and give scientists a crystal clear view of the gravitational-wave universe. The waves could give scientists a new way to view "dark energy" and "dark matter"—the majority of the universe not visible with today's telescopes.<sup>7</sup>

One of the developers of LIGO, Dr. Kip Thorne, describes the future; "With this discovery, we humans are embarking on a marvelous new quest: the quest to explore the warped side of the universe – objects and phenomena that are made from warped space-time. Colliding black holes and gravitational waves are our first beautiful examples."<sup>8</sup>

<sup>4</sup> "LIGO Fact Sheet," National Science Foundation, Available at:

[https://www.nsf.gov/news/special\\_reports/ligoevent/pdfs/LIGO\\_factsheet\\_v01.pdf](https://www.nsf.gov/news/special_reports/ligoevent/pdfs/LIGO_factsheet_v01.pdf)

<sup>5</sup> "Science Impact," LIGO. Available at: <https://www.ligo.caltech.edu/page/science-impact>

<sup>6</sup> "The Future of Gravitational Wave Astronomy," *Scientific American*, Available at:

<http://www.scientificamerican.com/article/the-future-of-gravitational-wave-astronomy/>

<sup>7</sup> "Why Detect Them?" LIGO. Available at: <https://www.ligo.caltech.edu/page/why-detect-gw>

<sup>8</sup> "Gravitational Waves Detected 100 years After Einstein's Prediction," National Science Foundation. Available at: [https://www.nsf.gov/news/news\\_summ.jsp?cntn\\_id=137628](https://www.nsf.gov/news/news_summ.jsp?cntn_id=137628)

**For Further Reading:**

[http://www.nytimes.com/2016/02/12/science/ligo-gravitational-waves-black-holes-einstein.html?\\_r=0](http://www.nytimes.com/2016/02/12/science/ligo-gravitational-waves-black-holes-einstein.html?_r=0)

<http://www.nytimes.com/2016/02/14/opinion/sunday/finding-beauty-in-the-darkness.html>

<https://www.washingtonpost.com/news/speaking-of-science/wp/2016/02/11/cosmic-breakthrough-physicists-detect-gravitational-waves-from-violent-black-hole-merger/>

Chairman SMITH. The Committee on Science, Space, and Technology will come to order,

Without objection, the Chair is authorized to declare recesses of the Committee at any time.

Welcome to today's hearing titled "Unlocking the Secrets of the Universe: Gravitational Waves." I'll recognize myself for five minutes for an opening statement and then the Ranking Member.

Last September, American scientists in Louisiana and Washington State detected a signal from an event so powerful that it sent a detectable ripple 1.3 billion light years ago through time and space to Earth. Albert Einstein was right: gravitational waves do exist. A century ago, Einstein developed his theory of general relativity. He then predicted that intense energy events, like the collision of black holes, could cause such disruption to the universe that they would emit waves that distort time and space much like the ripples on a pond caused by a thrown rock.

After decades of effort, scientists have now observed Einstein's theory in practice. They witnessed the effect of two black holes colliding, which released 50 times the energy of all the stars in the universe put together that emitted a gravitational wave across the universe that was, for the first time, detected on Earth. The discovery was the work of hundreds of scientists, decades of ingenuity and innovation, and the commitment of the United States through the National Science Foundation.

Forty years ago, a group of scientists began to design an experimental system to detect gravitational waves on Earth. Then they submitted a proposal for funding to the National Science Foundation. In 1990, the National Science Board approved funding for the project. Since that time, NSF has supported development of the Laser Interferometer Gravitational-Wave Observatory, or LIGO. This included construction and upgrades, operations, and research awards to scientists who study LIGO data. Today we will learn more about the value to America of that investment. We will also hear about the monumental success that has resulted from advances in physics, astronomy, engineering, and computer science. The NSF's support for the LIGO project is a great example of what we can achieve when we pursue breakthrough science that is in the national interest.

We have the privilege today of hearing from a panel of witnesses who helped make the discovery. They are leaders of the 1,000 scientists and 80 scientific institutions that make up the global LIGO Scientific Collaboration. We look forward to hearing more about the discovery, what it means for American science and innovation, and what new research and applications may be generated by this breakthrough. With this discovery, we embark on a new and exciting time for American physics and astronomy, and we move closer to a better understanding of the universe.

This is a quote by Dr. Kip Thorne, a renowned American physicist and one of the founders of LIGO: "With this discovery, we humans are embarking on a marvelous new quest: the quest to explore the warped side of the universe, objects and phenomena that are made from warped space-time. Colliding black holes and gravitational waves are our first beautiful examples."

Congratulations to the scientists on their great discovery.

[The prepared statement of Chairman Smith follows:]



COMMITTEE ON  
**SCIENCE, SPACE, & TECHNOLOGY**  
Lamar Smith, Chairman

For Immediate Release  
February 24, 2016

Media Contact: Zachary Kurz  
(202) 225-6371

**Statement of Chairman Lamar Smith (R-Texas)**

*Unlocking the Secrets of the Universe: Gravitational Waves*

**Chairman Smith:** Last September, American scientists in Louisiana and Washington State detected a signal from an event so powerful that it sent a detectable ripple 1.3 billion light years ago through time and space to Earth. Albert Einstein was right – gravitational waves do exist.

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"With this discovery, we humans are embarking on a marvelous new quest: the quest to explore the warped side of the universe – objects and phenomena that are made from warped space-time. Colliding black holes and gravitational waves are our first beautiful examples."

Congratulations to the scientists on their great discovery.

###

Chairman SMITH. That concludes my opening statement, and the gentlewoman from Texas, Eddie Bernice Johnson, is recognized for hers.

Ms. JOHNSON. Thank you very much, Mr. Chairman. I'm delighted that you're having this hearing today. It is gratifying to be hearing about a very exciting scientific breakthrough.

I want to congratulate each of the panelists, and welcome you, for your role in anything that you participated when it comes to LIGO. Thank you for being here this morning to talk about what this achievement means for science, and for our Nation, and about the long-term commitment to high-risk, basic research that made it all possible.

The story of the Laser Interferometer Gravitational-Wave Observatory is a story about the talent, creativity, and perseverance of U.S. scientists and engineers. It is a story about the 65-year commitment of the National Science Foundation to high-risk, basic research. I truly believe that a Nobel Prize will be coming. And it is a story about what we stand to lose as a Nation if we fail to maintain faith in our scientists, and in the scientific process exemplified by the National Science Foundation that is the envy of nations around the world.

When LIGO was first proposed by a small group of physicists from MIT and Cal Tech, many scientists responded, "You're crazy. It is not possible to build a gravitational-wave detector." Many of the scientists at the National Science Foundation and the National Science Board also quietly wondered if it was possible. But the project leaders presented a compelling plan, and the Foundation, then under the Administration of George H.W. Bush, decided to take the gamble. Because that is what the National Science Foundation does. It supports high-risk, but potentially high-reward, basic science that nobody else will do.

Today, we celebrate the scientific and technological achievement that LIGO represents. However, the path to this point was not smooth. When the National Science Foundation first proposed to build LIGO, debates raged in the scientific community and in Congress. Many scientists were concerned about protecting funding for competing physics and astronomy projects that were also important. They were also concerned about squeezing resources for research grants. Those concerns were understandable, and eventually led to the creation of a separate facilities construction account at the Foundation.

Members of Congress, including Members of this Committee, were also skeptical. This was a very expensive project, and some scientists doubted that it was technologically feasible. Members also wondered, what exactly are gravitational waves and why should we care? Throughout these debates and despite the elimination of funding by Congress in the first year that LIGO was proposed and the attempt to do so again in the second year, the National Science Foundation kept faith in the scientists and in its own mission.

Notwithstanding some of the debates we have had here in recent weeks, the primary purpose of the National Science Foundation is not to strengthen national security, or improve public health, or even to grow our economy. To be sure, those are all critically im-

portant outcomes of National Science Foundation investments in basic research across all fields of science and engineering, and some NSF-funded research has intended applications even at the proposal stage. However, the essential, core purpose of the National Science Foundation is to promote the progress of science, whether or not there is a foreseeable or intended application, and to train the next generation of U.S. scientists and engineers. And it is clear that the Foundation's bold investments in LIGO, driven by that core purpose, have led to a major scientific breakthrough.

Today's hearing serves as a reminder not just of how talented U.S. scientists and engineers are, but of why we must work hard to maintain our status as the best country in the world to do science by continuing to fund NSF and encourage high-risk taking. This is a lesson that we should apply to the entire agency, and not just to certain fields of our choosing.

Twenty-five years ago, many Members of Congress did not want to fund the search for gravitational waves. After all, how was that in the national interest? But enough Members did dare to imagine, and here we are today.

Again, I want to thank you and congratulate the witnesses, and now I will yield the remainder of my time.

[The prepared statement of Ms. Johnson follows:]



**OPENING STATEMENT**

Ranking Member Eddie Bernice Johnson (D-TX)

House Committee on Science, Space, and Technology  
Full Committee

*“Unlocking the Secrets of the Universe: Gravitational Waves”*

February 24, 2016

Thank you, Mr. Chairman, for holding this hearing on this very exciting scientific breakthrough. I want to congratulate each of you on the witness panel for your role in LIGO’s success. Thank you for being here this morning to talk about what this achievement means for science, and for our nation, and about the long-term commitment to high-risk, basic research that made it all possible.

The story of the Laser Interferometer Gravitational-Wave Observatory – or LIGO – is a story about the talent, creativity, and perseverance of U.S. scientists and engineers. It is a story about the 65-year commitment of the National Science Foundation to high-risk, basic research. And it is a story about what we stand to lose as a nation if we fail to maintain faith in our scientists, and in the scientific process exemplified by the National Science Foundation that is the envy of nations around the world.

When LIGO was first proposed by a small group of physicists from MIT and CalTech, many scientists responded, “You are crazy. It is not possible to build a gravitational wave detector.” Many of the scientists at the National Science Foundation and the National Science Board also quietly wondered if it was possible. But the project leaders presented a compelling plan, and the Foundation, then under the George H.W. Bush Administration, decided to take the gamble. Because that is what the National Science Foundation does. It supports high-risk, but potentially high-reward, basic research that nobody else will.

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Members of Congress, including Members of this Committee, were also skeptical. This was a very expensive project, and some scientists doubted that it was technologically feasible. Members also wondered, what exactly are gravitational waves and why should we care? Throughout these debates and

despite the elimination of funding by Congress in the first year that LIGO was proposed and the attempt to do so again in the second year, the National Science Foundation kept faith in the scientists, and in its own mission.

Notwithstanding some of the debates we have had here in recent weeks, the primary purpose of the National Science Foundation is not to strengthen national security, or improve public health, or even to grow our economy. To be sure, those are all critically important outcomes of National Science Foundation investments in basic research across all fields of science and engineering, and some NSF funded research has intended applications even at the proposal stage. However, the essential, core purpose of the National Science Foundation is to promote the progress of science, whether or not there is a foreseeable or intended application, and to train the next generation of U.S. scientists and engineers. And it's clear that the Foundation's bold investments in LIGO, driven by that core purpose, have led to a major scientific breakthrough.

Today's hearing serves as a reminder not just of how talented U.S. scientists and engineers are, but of why we must work hard to maintain our status as the best country in the world to do science, by continuing to fund NSF and encourage its risk-taking. This is a lesson that we should apply to the entire agency, and not just to certain fields of our choosing. Twenty-five years ago, many Members of Congress did not want to fund the search for gravitational waves. After all, how was that in the national interest? But enough Members did dare to imagine, and here we are today.

Once again, I want to thank and congratulate the witnesses, and now I will yield the remainder of my time to my colleague from Illinois, Mr. Foster.

Chairman SMITH. Thank you, Mrs. Johnson. I might point out that 25 years ago in 1994, we had a Republican-controlled Congress who took the lead in funding LIGO, and I know it was a bipartisan effort, but it's nice to see that reach over the span of 25 years.

Ms. JOHNSON. Could I yield to Mr. Foster?

Chairman SMITH. Sure. We will recognize the gentleman from Illinois, Mr. Foster, for one minute.

Mr. FOSTER. Thank you, Mr. Chairman, and thank you to the witnesses for coming here today to talk about this very exciting discovery. As the only Ph.D. scientist in Congress, I'm probably more excited about this than most others who've come to hear this today.

A century after Einstein theorized the existence of gravitational waves, 50 years after Rai Weiss began thinking of an interferometric gravitational-wave detector as part of a class exercise at MIT, 40 years after the spin-down of orbiting neutron stars starting giving the first hints that gravitational waves were being emitted from astrophysical sources, and 25 years after the National Science Foundation began courageous and sustained funding for an international collaboration of hundreds of scientists to begin constructing this large and technically risky project, physicists have spectacularly confirmed Einstein's theory. This is a discovery that will live on in the science textbooks forever.

And with this discovery, we have opened a new window onto the universe and we have verified that our new telescope is working and now the fun begins.

Thank you, and I yield back.

[The prepared statement of Mr. Foster follows:]

**Congressman Bill Foster**  
***Unlocking the Secrets of the Universe: Gravitational Waves***  
February 24, 2016

Thank you Ranking Member Johnson and thank you to the witnesses for coming together to talk about this very exciting discovery. As the only Ph.D. scientist in Congress I am probably more excited than most to come talk about this today.

A century after Einstein theorized the existence of gravitational waves, physicists have finally confirmed his theory. With this discovery, we have opened a new window into the universe and now the fun begins.

Very much like the proton decay detector that was built for my Ph.D. thesis that ended up seeing the neutrino burst from a supernova, we expect LIGO to provide surprises for decades to come. This project is an important reminder that investing in scientific research not only supports economic development, but helps us unlock the secrets of the universe.

In Congress it can be easy to focus on the short-term, but here today we have the chance to think much, much bigger.

Thank you again and I yield back.

Chairman SMITH. Thank you, Mr. Foster.

I keep telling Dr. Foster that my going off to college thinking I was going to be a physics major counts almost as much as his Ph.D. but not quite.

Our first witness today is Dr. Fleming Crim, Assistant Director, Directorate of Mathematical and Physical Sciences at the National Science Foundation. Dr. Crim joined NSF in 2013. Prior to his time at NSF, he was the John E. Willard and Hildale Professor in the Department of Chemistry at the University of Wisconsin-Madison, where his research group used lasers to understand chemical reaction dynamics that occur in gases and liquids. Dr. Crim has lectured around the world and published more than 150 papers. He received his bachelor's degree from Southwestern University and his Ph.D. from Cornell University.

Our second witness today is Dr. David Reitze, Executive Director of the Laser Interferometer Gravitational-Wave Observatory at the California Institute of Technology. Dr. Reitze's extensive work in the area of experimental gravitation-wave detection dates back to the mid-1990s. He has authored or co-authored over 250 peer-reviewed publications. Dr. Reitze is currently a Fellow of the American Physical Society and the Optical Society, and has served on numerous scientific advisory and program committees within the physics and optics communities. Dr. Reitze received his Ph.D. in physics from the University of Texas at Austin.

Our third witness today is Dr. Gabriela Gonzalez, Professor of Physics and Astronomy at Louisiana State University, where her research involves the detection of gravitational waves with interferometric detectors. Dr. Gonzalez was a founding member of the LIGO scientific collaboration and has participated in the commissioning of the LIGO detector at the Livingston Observatory. Dr. Gonzalez received her master's degree from the University of Cordoba in Argentina and her Ph.D. from Syracuse University.

Our final witness is Dr. David Shoemaker, Director of the LIGO Laboratory at the Massachusetts Institute of Technology, where his research focuses on instrumentation to enable the observation of gravitational radiation by precision measurement techniques. Dr. Shoemaker's work in the field of gravitational-wave detection began in 1980. He spent several years at Max Planck in Garching, Germany, and the CNRS in Paris, France, where he helped to develop specific technologies for gravitational-wave detection. Dr. Shoemaker has served on numerous scientific advisory and program committees for the NSF, NASA, and for the European Gravitational Wave Observatory. He received his master's degree in physics from MIT and his Ph.D. in physics from the University of Paris.

We welcome you all. We really appreciate your efforts in being here. You all are the experts. You led the way in one of the greatest scientific discoveries that we will ever hear about. What really caught my attention was the energy release being far beyond the energy of all the stars of the universe. That tends to rivet one's not only attention but imagination, so we appreciate you all being here, appreciate your expert, and Dr. Crim, we'll begin with you.

**TESTIMONY OF DR. FLEMING CRIM,  
ASSISTANT DIRECTOR,  
DIRECTORATE OF MATHEMATICAL  
AND PHYSICAL SCIENCES,  
NATIONAL SCIENCE FOUNDATION**

Dr. CRIM. Thank you, Mr. Chairman.

Before I begin my remarks, I would like to show a short video clip, just over one minute, on LIGO and its detection of gravitational waves.

[Video shown]

Chairman SMITH. Thank you. We won't count that against your five minutes.

Dr. CRIM. Thank you very much. Mr. Chairman, Ranking Member Johnson and members of the Committee, I appreciate your interest in the historic observation of gravitational waves by the Interferometer Gravitational Wave Observatory.

My colleagues will describe the exciting science but I will spend a few minutes describing the role of the National Science Foundation and the rewards of fundamental research.

Although Albert Einstein predicted gravitational waves in 1916, their direct observation was a daunting, seemingly impossible task. Nonetheless, the possibility of opening a new window on the universe was so tantalizing that NSF began funding research on prototype laser interferometers in the 1970s.

In the 1980s, the NSF committed almost \$300 million to a group led by Kip Thorne and Ron Drever of Cal Tech and Rainer Weiss of MIT to transform these prototypes into a full-blown gravitational-wave observatory. This effort driven by brilliance, vision, enthusiasm, experimental prowess and deep theoretical insights persuaded the NSF, the National Science Board, and Congress to take a risk.

Even though NSF had never funded anything on such a scale, the potential for transformative science was worth it. LIGO was the first of our Major Research Equipment projects, now known as MREFC projects. It illustrated the importance of distinct funding for instruments of this scale and prompted fruitful discussions with Congress. NSF embraced a new role in funding large, high-risk, high-reward research platforms serving the Nation by betting boldly on the future.

The National Science Board approved construction of LIGO in 1990, and following Congressional approval, work began in 1994. LIGO started operations in 2002, allowing researchers to gather data and develop innovative technologies.

One of the primary motivators for this arduous research was the question of whether it was possible to build an instrument of the requisite sensitivity. Indeed, the answer turned out to be yes. Thus, in 2008, NSF and Congress understood the compelling case and approved the \$200 million of funding for constructing the next generation Advanced LIGO, the instrument that detected a gravitational wave last fall.

That gravitational wave arose in the collision and merger of two black holes approximately 1.3 billion years ago. The wave propagated to the detectors in Livingston, Louisiana, and Hanford,

Washington, and produced a chirp that opened a new window on the universe.

This discovery is a beginning, not an end. It marks the birth of gravitational-wave astronomy, a new tool for understanding the cosmos.

The really good news is that Advanced LIGO was designed to be three times still more sensitive and should begin observations with even greater reach this summer.

The United States has led this international collaboration. However, continued close cooperation with our international partners is key to taking the science to the next level. New observational capabilities that our partners in Europe, Japan and India are either building or planning promise an exciting future.

LIGO is a national and international collaboration in which cooperation drives the science and leverages precious resources. The LIGO scientific collaboration is a group of more than 1,000 scientists at universities around the United States and in 16 countries. I'm pleased to add, Mr. Chairman and Ranking Member Johnson, that 30 members of that collaboration come from Texas.

Mr. Chairman, this historic measurement illustrates the importance of NSF and exemplifies its role in advancing discovery. The majesty of exploring our universe motivates this ambitious experiment, but as with all fundamental science, LIGO offers other important benefits. The science will advance education, inspiring students in developing the workforce our society requires. It has and will continue to spawn collaborations in engineering, computer science, and other fields to make the Nation more competitive. The fruits of NSF-sponsored research drive our economy, enhance our security, and ensure our global leadership.

Basic research is uncertain and risky but it is also revolutionary. LIGO is a striking example but not the only one. Fundamental science has transformed our world and will continue to change it in ways we have not yet imagined. All the contributors to LIGO—scientists, the National Science Foundation, the National Science Board, and Members of Congress—deserve to take enormous pride in our collective accomplishments.

These comments conclude my testimony. I'll be pleased to answer questions.

[The prepared statement of Dr. Crim follows:]



Testimony of

**Dr. F. Fleming Crim**  
Assistant Director  
Math and Physical Sciences Directorate  
National Science Foundation

Before the

**U.S. House of Representatives**  
Committee on Science, Space, and Technology

On

**Unlocking the Secrets of the Universe: Gravitational Waves**

**February 24, 2016**

Mr. Chairman, Ranking Member Johnson, and Members of the Committee, I sincerely thank you for holding this hearing and for the opportunity to discuss the historic observation of gravitational waves by the National Science Foundation's (NSF) Laser Interferometer Gravitational-Wave Observatory (LIGO). We are all excited by the remarkable science, but I want to focus my remarks on LIGO's history with NSF, the vision and support of so many, including this Committee and Congress to see it through, and what this discovery means for the future of science. Before I begin, however, I note the quotes on the back of the Committee's hearing room wall. They could not be more appropriate for this celebration of science because it truly is about having vision.

**The Beginning....**

In 1916, Albert Einstein published a paper using general relativity to predict gravitational waves — ripples in the fabric of space-time resulting from the most violent phenomena in our distant universe. This prediction has stimulated scientists around the world, who have sought to detect gravitational waves directly and have relentlessly pushed the technology to do so. NSF's funding of laser interferometer research and construction of a prototype began in the 1970s. In the 1980s, NSF committed about \$300 million to a group led by Kip Thorne and Ron Dreyer of Caltech and Rainer Weiss of MIT to move these prototype studies into a full-blown gravitational wave observatory. My colleagues will tell you more about the early work that led to this point, but this effort — driven by brilliance, vision, enthusiasm, commitment, experimental prowess, and deep theoretical insights — persuaded NSF, its National Science Board, and Congress to take a risk. Even though NSF had never funded anything on such a scale before and the discovery of gravitational waves might not occur for decades, the potential for transformative science was worth the cost and the risk.



In the mid-1970s, Marcel Bardon, the NSF Director of the Physics Division, began the Gravitational Physics Program to support science that set the stage for LIGO. The Program funded the development of LIGO, and NSF Program Directors oversaw the construction projects that built Initial LIGO and ultimately Advanced LIGO. (I use these terms to distinguish the two separate projects that brought us to today's observatory.) The NSF Physics Division has supported the operation and maintenance of LIGO and made investments, determined through NSF's merit review process, which produced the remarkable technological advances at the heart of Advanced LIGO. The Foundation devoted almost \$480 million to constructing LIGO and a total of approximately \$1.1 billion to all aspects of the project (including research support for scientists and students) over the past 40 years.

LIGO was the first of our agency's Major Research Equipment projects (now known as Major Research Equipment and Facilities Construction (MREFC) projects). It illustrated the importance of a dedicated funding account, separate from the Research and Related Activities account, for constructing instruments of this scale and prompted fruitful discussions with Congress. In many ways, LIGO pushed our agency to realize its potential in the exceptional—and critical—role of funding the high-risk, high-reward fundamental research platforms that propel science forward and transforms our future. Few organizations can bet so boldly on that future, and NSF powerfully serves the Nation when it does so. As the government agency with the mission of supporting fundamental science broadly, we take bold steps to further the frontiers of science.

The National Science Board gave the go-ahead to fund initial construction of LIGO in 1990, and construction began in 1992, following Congressional approval and appropriations. NSF continues to provide approximately \$40 million/year to support these facilities, which includes Caltech, MIT and two interferometers located in Hanford, Washington, and Livingston, Louisiana.

LIGO began its first observations in 2000, searching the universe for the gravitational waves predicted by general relativity. For the next six years, researchers gathered data and developed capabilities that have already found applications well beyond LIGO. For example, the laser frequency stabilization technique used by LIGO, the Pound-Drever-Hall technique, is widely used to achieve narrow line-width lasers for a wide variety of applications. The primary goals of this arduous research was to prove that it was possible to create an instrument with the requisite detection sensitivity, and, indeed, the answer was yes.

Thus, in 2008, NSF and Congress understood the compelling case and approved \$200 million of funding for Advanced LIGO (AdvLIGO). Several of the key technologies that increased the sensitivity of LIGO came from the German-UK GEO collaboration. The AEI Hannover Atlas Cluster, the LIGO Laboratory, Syracuse University and the University of Wisconsin-Milwaukee contributed essential computer resources. In a model of efficient use of shared resources, several universities designed, built and tested key components for AdvLIGO: The Australian National University, the University of Adelaide, the University of Florida, Stanford University, Columbia University of the City of New York, and Louisiana State University. This national and international collaboration drove the science forward and leveraged precious resources.

I think all of us realized that detecting gravitational waves promised to open a singular new window on our universe, allowing us to see phenomena to which we were previously blind. Congress and the NSF saw that promise as worth the investment.

#### **The Present....**

At this point in our NSF story, I think most of us know what happened, and I do not want to dwell on the discovery here. I leave it to my colleagues to discuss the events of September 14, 2015, a mere four days after the start-up of AdvLIGO. That date marks the first direct detection of a gravitational wave, resulting, remarkably, from the collision and merger of two black holes approximately 1.3 billion years ago. It has taken that long for the signal to propagate to the detectors in Livingston, Louisiana and Hanford, Washington and produce the "chirp", a 100 millisecond transient signal that opened a new window on the universe.

The LIGO Scientific Collaboration (LSC), which carries out this work, is a group of more than 1,000 scientists at universities around the United States and in 14 countries. Post-doctoral researchers, graduate students, and undergraduates are all active participants in this work. The LSC network includes the LIGO interferometers and the GEO600 interferometer, a project located near Hannover, Germany, designed and operated by scientists from the Max Planck Institute for Gravitational Physics, along with partners in the United Kingdom funded by the Science and Technology Facilities Council (STFC). This is an open collaboration in which anyone can participate, provided they contribute substantively to the work of the group. Everyone is working toward the same goal, but in different ways.

The LSC works jointly with the Virgo Collaboration — which designed and constructed the Virgo interferometer, which has 3-km-long arms and is located in Cascina, Italy. The Collaboration is enhancing the original facility to create Advanced Virgo, which should begin operation later in 2016 in concert with the next LIGO science observations.

International partners have contributed equipment, labor, and expertise to LIGO, including the UK's STFC supplying the suspension assembly and mirror optics; the Max Planck Society of Germany providing the high-power, high-stability laser; and an Australian Consortium of universities supported by the Australian Research Council contributing systems for initially positioning and measuring in place the mirror curvatures to better than nanometer precision.

#### **The Future.....**

The discovery in September is a beginning, not an end. In much the same way as when Galileo first turned his telescope towards the night skies or when radio astronomy transformed our view of the universe, we now have a tool to probe the most violent phenomena in the furthest reaches of the cosmos.

And here's the really good news: AdvLIGO has reached only about one third of its design sensitivity. The observatory is in the midst of further optimization and improvements that will allow it to begin six months of observations with increased sensitivity later this summer or fall.

The United States has led this international collaboration, showing the pioneering, trail-blazing spirit upon which the country was founded. However, continued close cooperation with our international partners is key to taking the science to the next level. With two detectors, it is only possible to localize the source of the signal to a large portion of the sky. With the advent of Advanced Virgo later this year, it will be possible to "triangulate" the source of gravitational waves and make other, more detailed observations. We look forward to even greater capabilities when the new Japanese detector, KAGRA, begins operations in a few years, and we hope that additional international partners will join the effort.

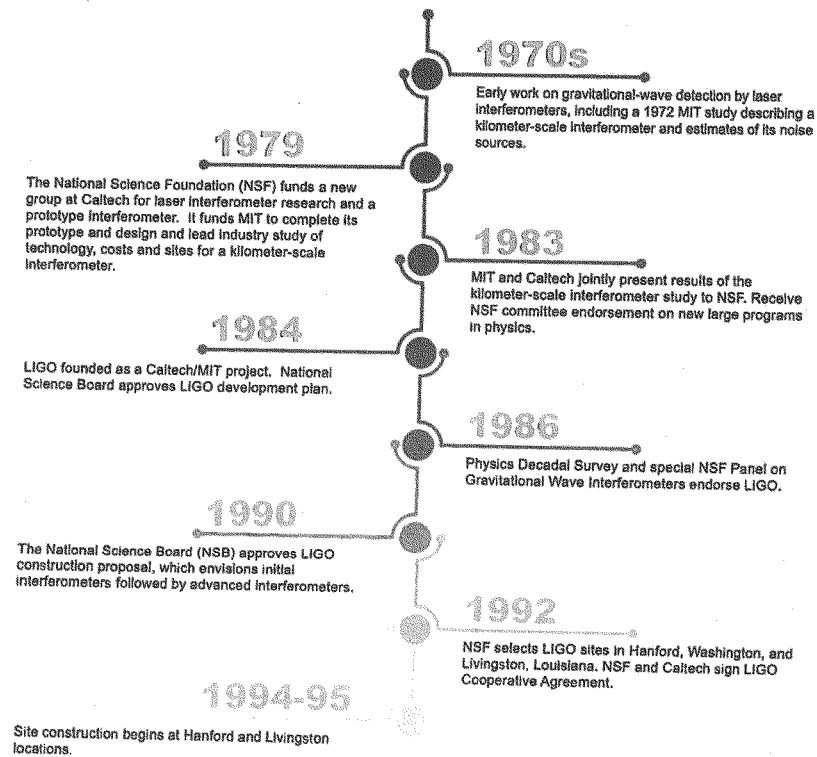
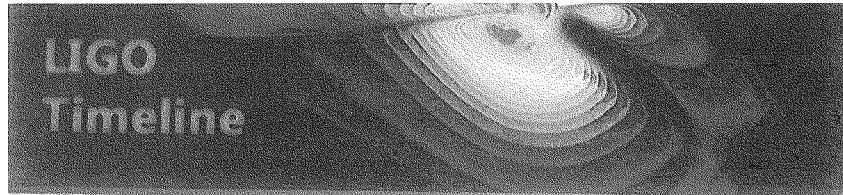
The majesty of discovering our universe motivates such ambitious experiments, but as with all fundamental science, LIGO offers other important benefits. This science will advance education, inspiring students and developing the workforce our society requires. It has, and will continue, to lead to collaborations in engineering, computer science and other fields. This project has already led to other unpredictable advances, enabling technology spin-offs ranging from vibration isolation to mirror coatings to vacuum technology, that make the Nation more competitive. Significantly, industrial manufacturers were crucial partners in an effort driven by the goal of making an unprecedented measurement.

#### **In Summary....**

Mr. Chairman, this historic detection of gravitational waves by LIGO illustrates the importance and singular role of NSF. This project exemplifies the vision of NSF: Advancing discovery, innovation, and education beyond the frontiers of current knowledge, and empowering future generations in science and engineering. NSF supports basic research that drives innovation and innovators that transform our future. The fruits of NSF-supported research drive our economy, enhance our security, and ensure our global competitiveness.

Basic research is uncertain and risky, but it is also revolutionary. LIGO is a perfect example but not the only one. Fundamental science has transformed our world and will continue to change it in ways we have not yet imagined. All the contributors to LIGO: scientists, NSF, the National Science Board, and Members of Congress, should take enormous pride in our collective accomplishment. With this discovery we can move forward with the science of understanding our universe —pushing the boundaries of discovery and innovation still further.

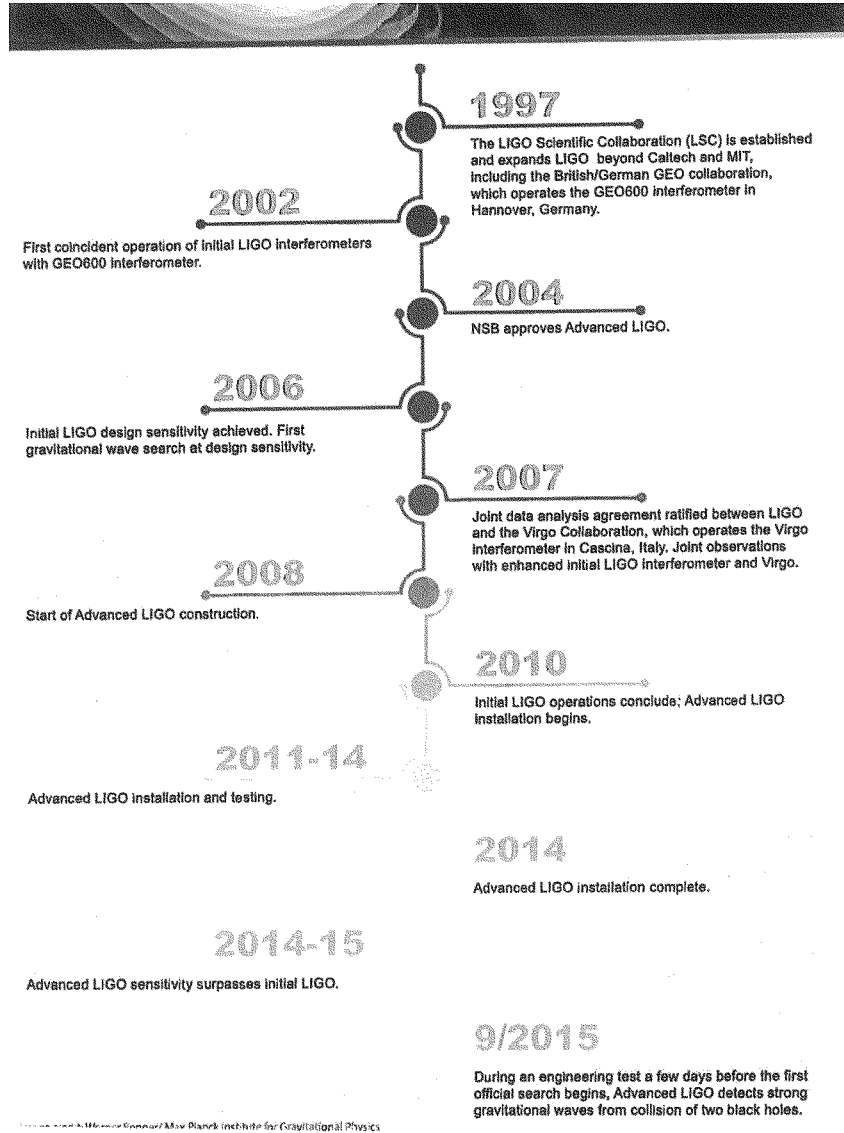
This concludes my testimony and I will be pleased to answer any questions.



Caltech



LIGO  
Scientific  
Collaboration



**Dr. Fleming Crim**  
**Assistant Director**  
**Mathematical and Physical Sciences (MPS)**  
**National Science Foundation**

As assistant director for the Directorate of Mathematical and Physical Sciences (MPS), Fleming Crim leads a staff of nearly 180 and oversees an annual budget of \$1.3 billion. MPS supports core research in astronomy, chemistry, physics, material science and mathematics.

Crim came to the National Science Foundation from the University of Wisconsin-Madison where he has been the John E. Willard and Hildale Professor in the Department of Chemistry and where his research group uses lasers to understand chemical reaction dynamics occurring in gases and in liquids.

He has lectured around the world and published more than 150 research articles. His research and teaching have earned many awards throughout his career, including the Plyler Prize of the American Physical Society, the Langmuir Award of the American Chemical Society, and the Centenary Medal of the Royal Society of Chemistry (London). He is an Honorary Fellow of the Chemical Research Society of India and an Honorary Professor of the Dalian Institute of Chemical Physics of the Chinese Academy of Sciences. He is a Fellow of the American Physical Society, American Chemical Society, and the American Association for the Advancement of Science. Crim is a member of both the National Academy of Sciences and the American Academy of Arts and Sciences. He received his doctorate from Cornell University and his bachelor's degree from Southwestern University.

Crim began his NSF appointment in January 2013. The scope of scientific and educational activity supported in MPS is enormous, ranging from phenomena at cosmological distances, to chemistry of life processes, through quantum mechanical processes in atomic and subatomic physics, to nanomaterials, to mathematics. MPS funds the operations and management of 14 major multi-user facilities, allowing thousands of scientists and students to press the bounds of scientific knowledge, and to invest in potential future projects needed to remain at the cutting-edge of research. MPS provides about 51 percent of the federal funding for basic research at academic institutions in the mathematical and physical sciences.

Chairman SMITH. Thank you, Dr. Crim.  
And Dr. Reitze.

**TESTIMONY OF DR. DAVID REITZE,  
EXECUTIVE DIRECTOR OF LIGO,  
CALIFORNIA INSTITUTE OF TECHNOLOGY**

Dr. REITZE. Chairman Smith, Ranking Member Johnson, Members of the Committee, thank you for holding this very important hearing. I'm delighted and honored to be testifying before you today. My name is Dr. David Reitze. I'm the Executive Director of LIGO. I'm based at the California Institute of Technology.

On February 11th, my colleagues and I announced to the world the first detection of gravitational waves from two colliding black holes. This is truly a stunning discovery. It comes 100 years after Einstein first published his general theory which predicted gravitational waves, and it was made possible only after a 40-year dedicated effort of experiment and theory funded by the National Science Foundation with your support, with Congressional support.

This discovery is in and of itself an incredible scientific and engineering feat and it proves that Einstein was right once again. However, the detection is really much, much more than that. Up until this point, humanity had never observed two colliding black holes merging to form one. This is a stunning discovery. It's what my colleague Kip Thorne calls "a storm in space-time." For the first time, we're probing the universe in a completely new way. Indeed, before this discovery, we hadn't even known that black holes existed in pairs.

LIGO is a new kind of astronomical receiver similar to a radio telescope and can directly hear vibrations in space-time. The gravitational window opened by LIGO dramatically differs from all other windows. LIGO should be able to detect things that no other type of astronomical telescope will detect.

Einstein tells us that space-time is warped, that gravity is geometric, and that black holes exist. It also predicts the existence of gravitational wave. As you pointed out, Chairman Smith, they are ripples in the fabric of space-time.

The effect of gravitational waves is mind-bogglingly tiny so it takes massive objects, 30 stellar-mass black holes colliding with each to produce detectable waves, and the changes that we measure to detect them are one one-billionth of one one-billionth of a meter, incredibly tiny. That's a tiny fraction of a proton's diameter.

First slide, please, Jose.

[Slide]

To detect gravitational waves, LIGO uses two interferometers. You see the one from Livingston, Louisiana, here, each having 4-kilometer arms, and the signal that we record is actually in the audio band. In other words, we can hear the signal when we play it through a speaker, and Jose, could you play the first? That is the sound of two black holes colliding. Play the next slide, please.

[Slide]

This makes it a little bit easier to hear. We just frequency-shifted it. Thank you.

Like many scientific discoveries, LIGO had very humble beginnings. Experiments were carried out in the 1960s and 1970s by

Rainer Weiss of MIT and groups at the University of Glasgow in Scotland and by Ron Drever in the Max Planck Institute in Germany along with theoretical efforts in gravitational-wave physics by Kip Thorne of Cal Tech as well as others.

When LIGO was first proposed as a large-scale project in the mid-1980s, some deemed the project too risky and too expensive. NSF, however, recognized both the huge scientific potential and the cutting-edge technology that could result from designing and building LIGO.

I believe this discovery is truly a scientific triumph but I want to set aside that for a moment and focus on some broader impacts.

LIGO in the United States leads the world in this new form of astronomy. Large-scale interferometers are currently under construction in Italy and Japan, and India just last week announced that it will partner with the LIGO Laboratory to construct a third identical LIGO interferometer in India. The world is following the United States into this new scientific frontier.

In addition, to make LIGO work, we had to develop the world's most stable lasers, the world's best mirrors and optics, some of the world's largest vacuum systems as well as push the frontiers of quantum-measurement science and high-performance computing. We use a lot of technology, and all the technology we use, we advance.

In addition, LIGO is a big data generator. We produce almost one petabyte—that's one million gigabytes—of data per year. LIGO scientists develop and employ sophisticated computer algorithms to sift through the data searching for these gravitational waves, and we use numerical modeling to model the signals that we expect to see, and that requires high-performance computers, supercomputers, supplied by NSF XSEDE and Blue Waters program.

All of this said, I believe that the largest impact from LIGO in the past and in the future will continue to be the scientific workforce, the education of scientists and engineers that we've done over the past 40 years and that we'll do going forward. Many scientists when they come to LIGO, they fall in love with it and they choose to stay. However, others go on to distinguished careers in both high-tech industry and international laboratories. And in addition, LIGO invites about 20,000 students every year to come and visit our observatory education and outreach program.

I'll close with the following statement. LIGO is a testament to the vision and tenacity of scientists like Rainer Weiss, Kip Thorne, Ron Drever, and others who began these research programs, but it's also a testament to the National Science Foundation, whose bold vision and steadfast support and stewardship enabled this discovery. It's with great appreciation that I also thank the U.S. Congress for recognizing the importance of this research and supporting it.

Thank you.

[The prepared statement of Dr. Reitze follows:]



**Testimony of**

**Dr. David Reitze  
Executive Director  
LIGO Laboratory**

**California Institute of Technology**

**Before the**

**U.S. House of Representatives  
Committee on Science, Space and Technology**

**on**

**Unlocking the Secrets of the Universe: Gravitational Waves**

**February 24, 2016**

Chairman Lamar Smith, Ranking Member Eddie Bernice Johnson, and Members of the Committee thank you for holding this very important hearing, and inviting me to participate today. I thank the Committee for its interest in Gravitational Waves and LIGO, and the amazing discovery we have made.

#### **INTRODUCTION**

My name is David Reitze and I am the Executive Director of the Laser Interferometer Gravitational-wave Observatory (LIGO) based at Caltech in Pasadena, CA. On February 11, 2016, my colleagues and I announced to the world the first direct detection of gravitational waves. These waves came from the collision of two black holes occurring 1.3 billion light years from earth. This is a stunning discovery, which occurred on September 14, 2015, and comes almost one hundred years after Einstein published his General Theory of Relativity that predicted gravitational waves. It was made possible after a dedicated forty-year scientific quest funded by the National Science Foundation (NSF) with Congressional support to design and build LIGO.

LIGO is the most precise scientific instrument ever developed. Using ultrastable laser interferometry (which I explain below), we are able to measure changes in distance to a tiny fraction of the width of a nucleus of an atom. This is a feat comparable to measuring the distance between our Sun and the nearest star to better than the width of human hair. And it has allowed us for the first time to detect, in the form of simple gravitational waves, a completely new astrophysical object from the ‘dark side’ of the universe.

## LIGO BACKGROUND

Like many great scientific discoveries, LIGO had humble beginnings. In the 1960s, Joseph Weber at the University of Maryland pioneered the effort to search for gravitational waves, using large cylinders of aluminum that vibrate in response to a passing wave. His experiments were ultimately unsuccessful, but led to efforts in the late 1960s and early 1970s by Rainer Weiss of MIT and Ron Drever and James Hough of the University of Glasgow to propose and investigate interferometry as a gravitational wave detector. Around the same time, Kip Thorne created a research group at Caltech working on the theory of gravitational waves and their astrophysical sources.

In 1980, the National Science Foundation funded the construction of a 40-meter long prototype interferometer at Caltech led by Ron Drever and Stan Whitcomb, and a smaller 1.5 meter long prototype at MIT directed by Rai Weiss. NSF also funded Weiss to design and lead a technical and cost study for a large scale, several-kilometer-long interferometer. In 1984 Caltech and MIT signed an agreement for the joint design and construction of LIGO, with administrative headquarters at Caltech, and with joint leadership by Drever, Weiss and Thorne.

When LIGO was first proposed as a large-scale project in the mid-1980s, it was met with great resistance and skepticism. Some in the astronomical community deemed the project too risky and too expensive, and felt that gravitational waves would never be detected. The chance of failure was perceived to be too high, and the scientific payoff too low relative to more established types of astronomy to justify the expenditure. Nonetheless, NSF and in particular Richard Isaacson and Marcel Bardon recognized both the huge scientific potential in gravitational wave physics and astronomy and the cutting edge technology that could result from designing and building a gravitational wave detector.

In 1990 the National Science Board approved LIGO construction, and in 1991 Congress appropriated LIGO's first year of funding. In 1992 Hanford, Washington and Livingston, Louisiana were chosen as the sites for LIGO's interferometers, and a cooperative agreement for the management of LIGO was signed between NSF and Caltech. In 1994 Caltech's Barry Barish was appointed LIGO Director and oversaw LIGO's construction phase as well as the installation and commissioning of LIGO's initial interferometers (1999-2002) and its first few gravitational wave searches (2002-2005). In 1997, the LIGO Scientific Collaboration was created to organize and coordinate LIGO's technical and scientific research and data analysis, and for expanding LIGO to include scientists elsewhere, beyond Caltech and MIT.

## THE SCIENCE BEHIND LIGO

Let me now turn to the science of LIGO. This is what excites us the most! General relativity tells us that space-time is warped, that gravity is geometric, and that black holes exist. These are complex concepts, deriving from a mathematically intricate but elegant theory. It also predicts the existence of gravitational waves. Gravitational waves are

ripples in space-time emitted by objects undergoing accelerations. A simple analogy to understand gravitational waves is this – drop a stone in a pond. Imagine the stone is the object and the surface of the pond is space (but in two, not three dimensions). When the stone hits the surface of the pond, it rapidly decelerates and slows down, losing energy as it produces outward ripples on the pond.

Gravitational waves are somewhat similar, although their effect on space is mind-bogglingly tiny. To make gravitational waves that can be detected by LIGO, it takes massive cosmic objects such as black holes or neutron stars colliding with one another or supernovae. Even then, the size of the emitted wave is incredibly tiny, requiring instruments that can accurately detect changes to better than *one one-billionth of one one-billionth* of a meter. The gravitational waves that LIGO detected on September 14 produce a change in distance in our detectors less than 5/1000 the diameter of a proton.

It is worth pointing out that even though Einstein derived the existence of gravitational waves as a natural consequence of general relativity in 1916, he himself doubted they would ever be detected because the waves are so incredibly small. It has taken new technologies and the ingenuity and dedication of over 1000 scientists and engineers to make this detection a reality.

To detect gravitational waves, LIGO uses two interferometers, each having 4 km long arms configured in an L-shape. In this simplified representation, an infrared laser beam from the world's most stable lasers is sent toward a partially reflecting mirror and split. When the gravitational wave passes, the space between the beamsplitter and the end mirrors stretches along one arm and compresses along the other arm, producing a signal.

The two beams are split equally and travel in a vacuum system over a 4 km distance to end mirrors and return to interfere again. When no gravitational waves are present, the light waves combine in such a way that no light is sent to the detector. When a gravitational wave passes, the light experiences constructive interference at the beamsplitter to produce a signal at the detector. The signal we measured is in the audio frequency range – humans can hear this signal!

Because LIGO's interferometers are so incredibly sensitive, they are susceptible to other forces and events that can produce signals that can mimic gravitational waves. This demands that we use two independent interferometers separated by almost 2000 miles to detect gravitational waves.

### THE SIGNIFICANCE OF THE DISCOVERY

The detection of gravitational waves by LIGO is in and of itself an incredible scientific and engineering accomplishment, proving that they can be directly measured and that general relativity has once again triumphed as *the* theory of gravity. However, this detection is much more than that. The signal that LIGO detected (we call it a chirp) captured the end stage of two stellar mass black holes locked in orbit and spiraling in toward each other until they collided and united to form a new larger black hole and

producing, as my colleague Kip Thorne calls, it ‘a storm in space time’. Up until this point, humanity has never observed this storm before. Indeed, until now we had not even confirmed that black holes could exist in pairs.

In essence, LIGO is a new kind of astronomical receiver, similar to a radio telescope, which can directly “hear” the vibrations in space-time produced by colliding black holes and other cosmic cataclysms. The gravitational-wave window opened by LIGO differs dramatically from all previous windows. The previous windows - optical, radio, and X-ray, all used radiation made from oscillating electric and magnetic fields. LIGO, by contrast, uses an entirely new kind of radiation: gravitational waves.

LIGO should be able to detect not only the two black holes of September 14, each tens of times more massive than our Sun, colliding with each other at nearly the speed of light, but also many other phenomena. We expect to discover black holes that rip apart neutron stars, and two neutron stars that spiral together, collide, merge, and then implode to form a black hole - and that generate short bursts of gamma rays. We are also searching for waves from massive stars exploding in our galaxies -- central engines of supernova explosions, as well as waves produced by cosmic strings that stretch across the universe - gigantic strings thought to have been created in the big bang by the inflation of fundamental strings, the building blocks of all matter.

#### **IMPACT ON U.S. SCIENTIFIC ENTERPRISE**

While the discovery of gravitational waves is a triumph of science and engineering, it is natural to ask ‘so what?’ or perhaps more specifically ‘what are the past returns for the \$1.1 billion United States investment in LIGO? What will we get going forward?’ Setting aside the excitement that comes from exploring our cosmos, the deep sense of satisfaction in learning how it works, and the awe it inspires, there are near term benefits, both tangible and intangible, that have come from these efforts.

First, LIGO leads the world in this new form of astronomy. In addition to the two LIGO detectors, large-scale interferometers are currently under construction in Italy and Japan, which will join in the search for gravitational waves in the coming years. India has just announced that it will partner with the LIGO Laboratory to construct a third LIGO Observatory in India, expected to be operational early in the next decade. The world is following the US into this new scientific frontier.

In addition, to make LIGO work, we had to develop the world’s most stable lasers, the world’s best mirrors, some of the world’s largest vacuum systems, as well as push the frontiers of quantum science and high performance computing. LIGO advances the state-of-the-art in every technology it uses, and it uses lots of technology. We have partnered with many commercial technology firms in the US and abroad to produce the incredible technology that LIGO uses.

In addition, the LIGO detectors produce almost 1 petabyte (one million gigabytes) of data per year – it is a Big Data generator. To search through that data, LIGO scientists develop

and employ sophisticated state of the art computer algorithms and high throughput computing to search through the data and reveal these miniscule signals. Numerical solutions of the equations of general relativity to model binary black hole mergers and supernovae require high performance supercomputers as provided by NSF's XSEDE and Blue Waters program.

However, I believe that the largest impact from LIGO has been in scientific workforce development --- the education of scientists and engineers over the past forty years. Funding from the NSF has produced over 100 Ph. D.s in Physics from Caltech and MIT alone, along with many more from leading US research universities in the LIGO Scientific Collaboration. Many scientists have chosen to stay with LIGO and pursued academic careers driven by their passion for fundamental research. Others have moved on to distinguished, productive careers at NASA and national laboratories such as Lawrence Livermore National Laboratory. Silicon Valley giants and start ups, defense and aerospace industries, biotechnology and telecommunications, and even investment banks all have employed Ph. D.s trained at LIGO. Still others have become K-12 educators. Nearly 500 undergraduate students have worked with LIGO scientists through summer research programs over the past 15 years, allowing them to explore careers in research.

And every year, LIGO's educational programs based at our Observatories host over 20,000 students, teachers, and members of the general public, inspiring them to become better teachers and learners. One teacher put it like this after completing a LIGO professional development program and applying what he learned in his elementary school classroom "My students frequently ask, "Are we going to do science today?" When they hear, "Yes" they cheer."

#### **CLOSING REMARKS**

LIGO is a testament to the vision and tenacity of scientists like Rainer Weiss, Kip Thorne, Ron Drever, and others who began research programs to develop interferometers for gravitational wave detection, and, equally, to the National Science Foundation, whose bold vision and steadfast stewardship has enabled this discovery. It is also with great appreciation that I thank the U.S. Congress for recognizing the importance of scientific discovery and funding the NSF so it can support groundbreaking research.

LIGO's first observation opens a completely new window onto the universe -- the window of gravitational-wave astronomy. 400 years ago, Galileo turned the first telescope to the sky and began the era of modern astronomy. Much of what we understand about the universe today comes from light -- electromagnetic waves spanning the electromagnetic spectrum ranging from gamma rays to radio waves. The gravitational wave universe is completely uncharted territory. With this detection, we've accomplished the gravitational wave equivalent of Galileo -- we've entered the era of GW astronomy and have just begun to explore the darker and more violent side of the universe.

This discovery is the first time we've been able to hear the cosmos communicating to us using gravitational waves. I am quite confident that that it won't be the last time. Even more exciting, we will see, or rather hear, something completely unexpected from the universe that will revolutionize our understanding of the universe. We cannot wait to get there.

Thank you.

**David Reitze**  
**Executive Director**  
**LIGO Laboratory**  
**California Institute of Technology**

**Biography** - David Reitze is the Executive Director of the LIGO (Laser Interferometer Gravitational-wave Observatory) Laboratory at the California Institute of Technology and a Professor of Physics at the University of Florida. He received a Ph. D. in Physics from the University of Texas at Austin in ultrafast laser spectroscopy in 1990 and has worked extensively in the area of experimental gravitation-wave detection since the mid-1990s. He has authored or co-authored over 250 peer-reviewed publications. He is a Fellow of the American Physical Society and the Optical Society. He has served on numerous scientific advisory and program committees and within the physics and optics communities, including the Science and Engineering Council of the Optical Society of America, the Division of Laser Science of the APS, the Gravitational-wave International Committee, and the National Research Council Committee on Atomic, Molecular, and Optical Physics. From 2007-2011, he served as the Spokesperson (leader) of the LIGO Scientific Collaboration, a group of almost 1000 scientists who conduct the science of LIGO.

Chairman SMITH. Thank you, Dr. Reitze.  
And Dr. González.

**TESTIMONY OF DR. GABRIELA GONZÁLEZ,  
PROFESSOR OF PHYSICS AND ASTRONOMY,  
LOUISIANA STATE UNIVERSITY**

Dr. GONZÁLEZ. Chairman Smith, Mr. Beyer and Members of this Committee—

Chairman SMITH. Is your mic totally on, or close enough? There we go. Thank you.

Dr. GONZÁLEZ. It is an honor to testify here on behalf of my collaborators. We thank you for your interest and support of gravitational-wave science.

I'm Dr. Gabriela Gonzalez, a Professor of Physics and Astronomy at Louisiana State University and the current elected Spokesperson of the LIGO Scientific Collaboration, or LSC.

Ours is an international collaboration that succeeded recently in detecting gravitational waves from black holes and will keep opening a new window to the universe. Can I have the first slide, please?

[Slide]

As shown in the slide, the LSC, which includes the LIGO Laboratory, has more than a thousand members in 15 countries with more than half of those in the United States. The collaboration was formed almost 20 years ago and is the entity that carries out the LIGO scientific research program. The LIGO Laboratory and the U.S. scientists have played a key, very important role in the LSC scientific and leadership activities. Also, LIGO has fostered the very effective relationship with other collaborations with the European Virgo Collaboration and with the Japanese KAGRA collaboration. The LIGO India project just approved by the Indian government is part of the LSC effort. We really lead the world.

[Slide]

As shown in the next slide—can I have the next slide, please—the LSC has a great diversity of colleges and universities in 22 different U.S. states. They are top-tiered private universities, large state universities, undergraduate and liberal art colleges, as well as institutions with many underrepresented groups in science. The collaboration effort is very broad, includes research in many different areas, and this investigation, all these activities, are geographically very distributed but the benefits of our research like the recent detection are common to all. That is one of the strengths of collaborative work.

We do not receive funding as a collaboration. Each LSC group seeks funding from agencies for their research based on their own individual merits. In the United States, the NSF funds the LIGO Laboratory with cooperative agreement but also funds the basic research in the many other U.S. groups through the very competitive research award system, and that guarantees the quality of the funded activities. Can I have the next slide, please?

[Slide]

In this chart, and in these pictures, you can see that more half the LSC members are graduate students, postdoctoral scholars or undergraduate students. These are young, busy and happy inves-



tigators in training in a very interdisciplinary and international scientific environment. Undergraduates contribute to the LSC research program not only in the LSC groups but also in research experience for undergraduate programs in the United States funded by the National Science Foundation.

The training in LIGO of all these young scientists is done at the forefront of science and technology. It's multidisciplinary. It involves precision measurement technology, Big Data analysis, a constant need for diagnosis and problem-solving, as well as basic physics and astrophysics.

There are many career options available to LSC trainees in academia, national laboratories, and high school science education as well as cutting-edge industry.

We compiled an incomplete list of companies employing LSC graduates and they are now working in the human genomics industry, the U.S. healthcare industry, biomedical information, oil industry, Microsoft, Google, Boeing, SpaceX, Northrop Grumman, Synaptics, Celestron, Luminit, Cytec Engineered Materials, GE Global Research, Geneva Trading, Seagate. We are training the workforce in the United States.

Many members of the collaboration dedicate a significant fraction of their time to K–12 education and outreach. The public's curiosity about our discovery has been intense. Only last Saturday, almost 1,300 people, some driving for hours to get there, visited the LIGO Science Education Center at the LIGO Livingston Observatory in Louisiana. The Science Education Center is also funded by NSF. And they went there to see where the science is done and meet some of the scientists who do it. The national as well as the local coverage of our detection showed the broad spectrum of scientists working on this field everywhere. There are many local heroes to celebrate.

In conclusion, the LSC will continue working hard on its mission to understand the universe better through the newly opened gravitational-wave window. We are very proud about the result of our work not just being amazing astrophysical results but also pushing the technology and contributing to the progress of society.

We thank NSF and the U.S. Congress for the support of our activities.

[The prepared statement of Dr. González follows:]

Gabriela González Written Testimony

*"Unlocking the Secrets of the Universe: Gravitational Waves"*

February 24, 2016

Mr. Chairman Smith, Ranking Member Johnson, and Members of the Committee: it is an honor to testify here on behalf of my collaborators. We thank you for your interest in gravitational wave science, and your support of the National Science Foundation funding our research in the US.

### **INTRODUCTION**

I am Gabriela González, a professor of Physics and Astronomy at Louisiana State University, and the current spokesperson of the LIGO Scientific Collaboration.

My colleague Dr. Reitze has described the exciting science of this discovery. I will describe the role of the international LIGO Scientific Collaboration in current and future research for LIGO, and the contributions of that research to the education and training of the future scientific workforce.

### **THE LIGO SCIENTIFIC COLLABORATION**

Our charter defines our mission: "The LIGO Scientific Collaboration (LSC) is a self-governing collaboration seeking to detect gravitational waves, use them to explore the fundamental physics of gravity, and develop gravitational wave observations as a tool of astronomical discovery. The LSC works toward this goal through research on, and development of techniques for, gravitational wave detection; and the development, commissioning and exploitation of gravitational wave detectors. No individual or group will be denied membership on any basis except scientific merit and the willingness to participate and contribute as described in this Charter."

The LSC was formed in 1997 to exploit fully the scientific potential of the LIGO instruments then under construction, and to engage in the research and development necessary to go significantly beyond the first generation of interferometers. LIGO is composed of the LSC and the LIGO Laboratory, with significant interweaving of membership and tasks. The LSC, including the LIGO Laboratory, is the entity within LIGO that carries out LIGO's scientific research program.

The detection of gravitational waves announced this month was the result of decades of our collaboration's effort on many different areas:

- Experimental research on low-loss optics, seismic isolation, multiple-suspension structures, high power stabilized lasers, and much more, was the basis for the technology used in the Advanced LIGO Detectors. The current

basic research by these groups guarantees even better technology for improved detectors.

- Working with instrument science researchers in the US and abroad, the LIGO Laboratory led the construction and installation of reliable LIGO gravitational wave detectors; the project depended on the expertise and help of the broader Collaboration, including the Laboratory.
- The data calibration and data quality diagnosis use novel and clever algorithms created by the LSC members, with a monitoring effort distributed around the world.
- The search for gravitational waves hiding in the detector noise is a Big-Data analysis effort, performed by many computer codes developed by the LSC and implemented in computing clusters in many different institutions.
- The LSC manages data flow and storage for the clusters in several different physical places, including making the appropriate data open to the public, as well as producing detection alerts for the scientific community.
- Scientists in the LSC carefully characterization and interpret the gravitational wave search results, including the conclusion that our first detection was produced by the coalescence of two black holes more than a billion light years away. This effort is justly receiving interest and attention from the entire scientific community. The number and diversity of the scientists involved is one of the key elements leading to robust results.

The LSC consists of more than 1,000 scientists from 15 countries (see Fig 1). More than half the LSC members work in the US, in 22 different states (including 12 states represented by members of this Committee) and 28 different congressional districts (See Fig 2). Groups are hosted in more than 90 different academic institutions around the world; in the US, the LSC has a great diversity of colleges and universities: there are top tier private universities, large state universities, graduate universities and undergraduate colleges, and several institutions with large student population of under-represented minorities in science. Although the LSC is an international collaboration, the LIGO Laboratory and the US scientists have played a clear leading role in the scientific and leadership activities.

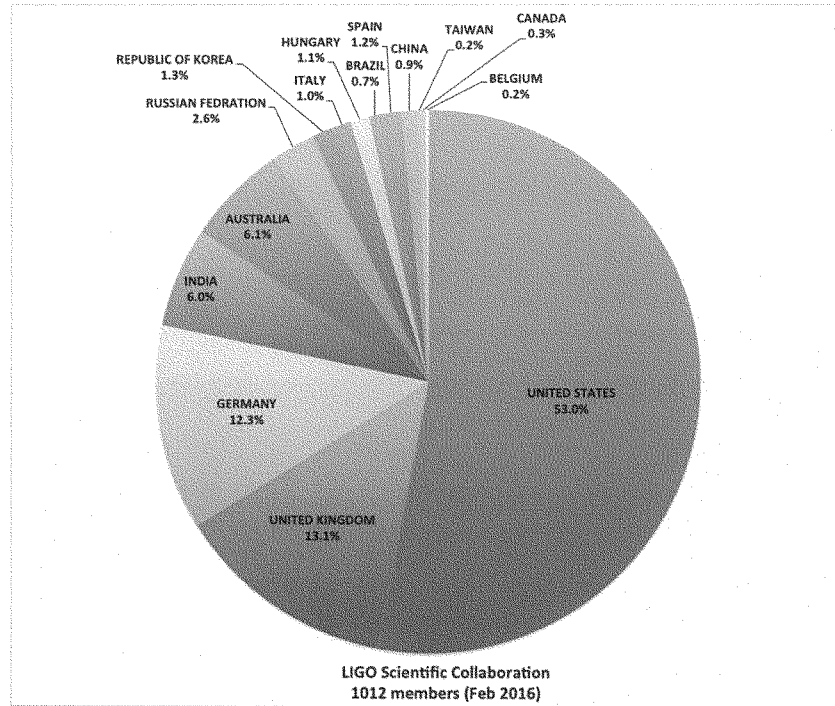


Figure 1: Membership distribution among countries in the LSC

Within the US, the very large majority of the financial support for research comes from the NSF. Groups outside of the US are supported by their national funding agencies. Our collaboration does not pool financial resources though – we agree to work together in scientific activities, sharing intellectual and human resources in “working groups” dedicated to different topics. Each group seeks funding for their research based on the merits of the research done in that group. The US funds the LIGO Laboratory with a Cooperative agreement, but also funds the basic research in the many other groups through the competitive NSF research grant system, guaranteeing the quality of the funded activities.

We are a democratic organization: we elect leaders of our working groups, and we elect the spokesperson, or leader, of the collaboration. I have the honor of occupying today this position – Prof Rainier Weiss from MIT, Prof Peter Saulson from Syracuse University and Prof David Reitze from University of Florida were my predecessors.

LIGO has fostered effective relationships to other gravitational-wave collaborations, like the European Virgo Collaboration, our closest partner. We share fully in the

science, data, computing, and technology with Virgo – we author papers together, including the recent paper describing the first observation of gravitational waves - this paper has more than 1,000 authors. The Japanese KAGRA collaboration is expected to form just as close a relationship once their instrument begins operating a few years from now. Just last week, the government of India approved a LIGO-India project to build an Observatory to house a third LIGO detector; the many LSC members in India and the LIGO Laboratory were critical to this development effort.

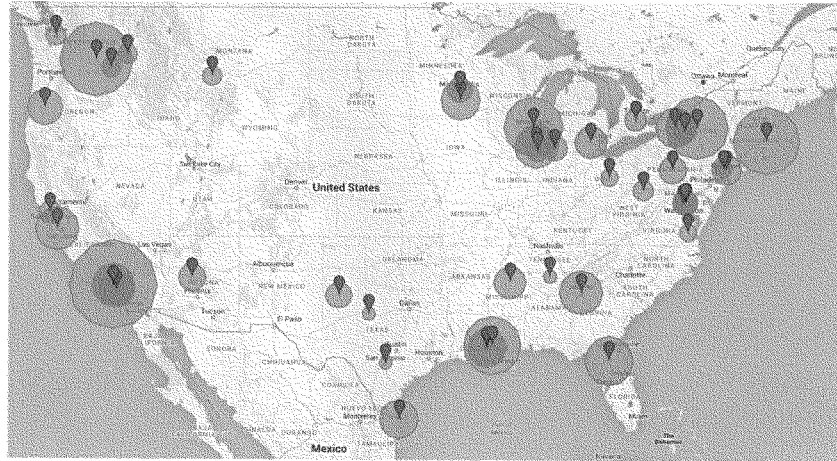


Figure 2: LIGO Scientific Collaboration groups in the US. [Created using Google maps].

### LIGO TRAINS THE SCIENTIFIC WORKFORCE

LIGO, with its scientific success now recognized worldwide, has grown the field of gravitational wave science through education and training of the next generation of researchers. The LSC, including university-based graduate students and postdocs, has fostered innovation in all aspects of the field, from experimental research for future detectors to the astrophysical interpretation of the results. The institutional diversity of the LSC means that in addition to students from the top-tier universities, LIGO is also involving first-generation college students from our nation's public regional universities, some with a large fraction of under-represented minorities in science.

The LSC and the LIGO Laboratory take very seriously their educational responsibilities, and work closely together on these issues. As displayed in Fig. 3, more than half of the LSC'S members are young investigators, either postdocs or students. Currently, there are 255 graduate students, 107 undergraduate students and 172 postdoctoral scholars in the LSC (see Figure 3). About half of the graduate students (119) and most of the undergraduate students (79) are in US institutions.

This strong contingent of postdocs and students receives training in forefront science and technology; many of them will take on leadership roles in the future of gravitational-wave and other science areas as well as in industry.

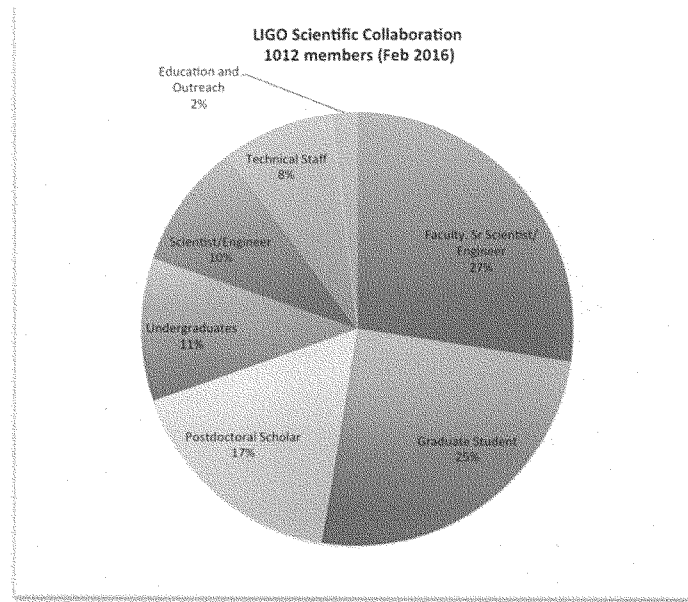


Figure 3: Positions of LSC members

The LSC is strongly committed to train a diverse workforce: We pledge to provide a welcoming, inclusive environment to talented individuals regardless of characteristics such as, but not limited to, physical ability, race, ethnicity, gender, sexual orientation, economic status, or personal religious practices, and to support the professional growth of all collaboration members. The LSC has a LIGO Academic Affairs Council (LAAC), responsible for overseeing and documenting the LSC's activities in representing and protecting the interests of students and postdocs. The LAAC is also responsible for providing education and training activities for new students and postdocs in the LSC.

Undergraduates contribute to the LSC's research program. Undergraduates conduct research with LIGO Laboratory and LSC groups in a number of different ways. Undergraduate researchers come from both primarily undergraduate institutions (for example, liberal arts colleges) as well as from large universities. Individual researchers at graduate institutions often supervise undergraduates throughout the academic year and the summer; much of this support (in the US) comes from NSF grants to individual researchers. Additional undergraduates not included in Fig. 3

are involved with LIGO through participation in summer Research Experience for Undergraduates (REU) programs at many LSC member institutions.

The small fraction shown in Figure 3 for K-12 Education and Outreach is the number of people solely dedicated to those activities. However, Education and Outreach constitute important parts of the LSC's activities, and many members of the collaboration dedicate a significant fraction of their time to this effort. LIGO has spent many years informing the general public about our science, and we have also prepared intensely in the last few months material, activities and talks to explain the significance of the first observation of gravitational waves. The public's reception to our discovery has been extremely positive and intense: last Saturday, almost 1,300 people visited the LIGO Science Education Center at the LIGO Livingston Observatory (also funded by NSF) to see where the science is done, and meet some of the scientists who do it. The local as well as the national coverage presented the broad spectrum of scientists working on this field – there are many local heroes to celebrate.

The broadness and openness of the collaboration research provides an important learning and education environment for all the young people. Thanks to this, the hundreds of people who received training in the LSC are now important contributors not just to higher education in academia, national laboratories and high school science education, but also to cutting-edge industry in the US. An incomplete list of companies employing LSC graduates are: the human genomics industry, US health care industry, bio-medical information, oil industry, Microsoft, Google, Boeing, Space-X, Northrop Grumman, Synaptics, Celestron, Luminit, Cytex Engineered Materials, GE Global Research, Geneva Trading, Seagate.

## CONCLUSION

The LSC will continue working hard on its mission to understand the Universe better through the newly opened gravitational wave window. We are very proud about the result of our work being not just amazing astrophysical results, but also pushing the technology frontiers and contributing to progress of society with a broadly educated and efficient workforce for academia and industry.

*"Unlocking the Secrets of the Universe: Gravitational Waves"*

Hearing of the House Committee on Science, Space and Technology

February 24, 2016

Gabriela González Biography

Gabriela González is the spokesperson for the LIGO Scientific Collaboration. She completed her PhD at Syracuse University in 1995, later worked as a staff scientist in the LIGO group at MIT until 1997, when she joined the faculty at Penn State. In 2001, she joined the faculty at Louisiana State University, where she is a professor of physics and astronomy. González group's current research focuses on characterization of the LIGO detector noise, detector calibration, and searching for gravitational waves in the data. She is a Fellow of the American Physical Society, and a Fellow of the International Society of General Relativity and Gravitation.



Chairman SMITH. Thank you, Dr. Gonzalez.  
Dr. Shoemaker.

**TESTIMONY OF DR. DAVID SHOEMAKER,  
DIRECTOR, LIGO LABORATORY,  
MASSACHUSETTS INSTITUTE OF TECHNOLOGY**

Dr. SHOEMAKER. Chairman Smith, Ranking Member Johnson, and Members of the Committee, thank you for holding this hearing and inviting me to participate today. I too would like to thank the Committee for its interest in gravitational waves and LIGO, and I hope our testimony helps the Committee in its work.

I'm Dr. David Shoemaker. I'm with MIT in Cambridge, Massachusetts. My role was to have the pleasure and honor to lead the Advanced LIGO Project. Let's take a look at the first slide, please.

[Slide]

This was a major project, MREFC, and it came in on time and on budget. Could we look at the next slide, please?

[Slide]

To round out our testimony, I want to paint a broad picture of our field and its future. Let's look at the next slide, please.

[Slide]

What you see here are various images of people at work in the process of putting Advanced LIGO together.

So our first goal is accomplished, as you heard. We made a detection, a remarkable thing, but it's just the start of the new astronomy.

There are more kinds of sources that LIGO can expect to see. Let's look at the next slide. That's great. Thank you.

[Slide]

One of the ones that I want to talk about are neutron stars. These are stars which have collapsed from their original size, not all the way back down to a black hole but to material so dense that a single teaspoon would weigh 10 million tons, if you imagine such a thing. They tend to be magnetized and spinning, and they've got some strange things going on in their interior that we don't understand. They also can form binaries like the black holes that we saw, and if we can observe them both with our gravitational-wave detector as well as with satellites in space that NASA puts up to look at X-rays and regular telescopes on the ground that the NSF supplies for our observatory, we can put together all this information into a complete package and know more than we could have ever known without gravitational waves or without this combination, this synergy of information. So it's a wonderful new way to reuse tools that have been used for astronomy in the past and also to learn new things about space and nature that we couldn't have learned otherwise.

We have other ideas of things we'll see. Supernovas are rare but they will be wonderful to see. The modelers still don't know how to make them explode, and we might be able to answer that question. There are collapsing stars. There are cosmic stringers. There are defects in space-time. There will certainly be surprises. There are a lot of things. Every time we open up a new window to the universe, we see new things and we're surprised every time. I think this is going to be another one of those surprises.

Just as we need radio telescopes and optical instruments in the electromagnetic spectrum to see the full range of possibilities, we'll also want different kinds of gravitational-wave detectors in the future. Already underway is using isolated neutron stars, these funny, magnetized, spinning stars, looking at their radio signals from neutron stars throughout the universe, bringing them back down to the Earth and forming a complete picture of what we see and resolving that there're ripples in space-time between the Earth and these neutron stars that may soon yield the result that gives us our first ideas of what it's like for universe galaxies to be spiraling together. But really, the ultimate way of doing that kind of thing sometime in the future would be to have a space-based antenna. Instead of having two-and-a-half-mile-long arms, in space you could make two-and-a-half-million-mile-long arms. Our sensitivity grows with the length of those arms. You could do phenomenal science that way, and at some point that will be something I think the scientific community will feel we must do.

Coming back to Earth, let me say a little bit about LIGO. Next slide, please.

[Slide]

The first events were only seen with one-third of the full sensitivity that we believe this instrument currently can do. Right now, we're tuning it. We're increasing its sensitivity, and we think that we'll be able to run again sometime in the fall, making more observations. We're hoping that when we next run we'll be running with the French-Italian detector, Virgo, which will be coming on just about that time, and with three detectors, you can do a great deal more science. You can see where the source is in the sky and you can get an idea of what the polarization nature is. It will really add to what we can learn, and it leverages our investigation to have, as people were saying, these other projects that are coming along behind us but will add to, supplement the science we can do and complement the science we get from our own detectors.

We are the leaders, but with these other observatories, we will have a worldwide global cooperation that will bring us all forward in science. Once tuned, Advanced LIGO can go even further with modest technology changes. We're learning how to squeeze light, how to get more uncertainty out of our measurement and improve our resolution by using squeeze states of light. We also are looking into making better optics, in particular, ones that have new and better coatings on them that can reduce noise in certain areas. And it could be at some point in the future if this field comes alive the way we think it will, that we'll need a new observatory. It's not there yet, but that'll happen.

So the window to this new world of gravitational waves has just been cracked open. As we open it wider, more people look out on the landscape, we'll be rewarded with discoveries that will time and time again give us all, scientists, students, leaders and laypersons, a thrill of understanding things much better than ourselves.

Thank you for your time. Thank you for your interest in our science and your continuing support for the spectrum of innovations in science and technology that we see in the United States.

We hope this glimpse of our field has allowed you to share in the sense of accomplishment you have enabled.  
[The prepared statement of Dr. Shoemaker follows:]

STATEMENT OF DR. DAVID SHOEMAKER, DIRECTOR, MIT LIGO  
LABORATORY AND DIRECTOR, ADVANCED LIGO PROJECT,  
ON "UNLOCKING THE SECRETS OF THE UNIVERSE:  
GRAVITATIONAL WAVES,"  
AT THE FEBRUARY 24, 2016 HEARING OF THE  
HOUSE COMMITTEE ON SCIENCE, SPACE AND TECHNOLOGY,

Chairman Smith, Ranking Member Johnson, and Members of the Committee:

Thank you for holding this hearing, and inviting me to participate today. I too would like to thank the Committee for its interest in Gravitational Waves and LIGO, and hope our testimony helps the work of the Committee.

My name is David Shoemaker, from the Massachusetts Institute of Technology in Cambridge Massachusetts. I had the honor and pleasure to lead the Advanced LIGO Project, the NSF-supported Major Research Equipment and Facilities endeavor to upgrade the detectors in the LIGO infrastructure. I note with pride that the LIGO Laboratory completed the upgrade on time and on budget. I would like to provide some broad sense of the importance of the discovery, and discuss the future of LIGO and the field.

As Dr. David Reitze stated, we succeeded in our first goal: The direct detection of gravitational waves. But it is just the beginning of the opportunity to use this new view on the universe to learn about otherwise inaccessible phenomena in the Universe. With gravitational waves, we can "see" events – like the inspiral and coalescence of two black holes – that produce signals that cannot be seen any other way. It also will allow us to work with other observatories using established technologies, such as radio, optical, and x-ray telescopes and satellites, to combine data from gravitational waves and traditional instruments. In this way we can test theories about fundamental components of the cosmos, such as neutron star matter and supernovae. We certainly also expect many surprises will be discovered and explained as we develop this new branch of astronomy.

One important consequence is that the value of the existing observatories on the ground and in space will be increased and leveraged by adding this new view on the universe. When a gravitational-wave trigger seen by LIGO indicates an astronomical event that is expected to have an optical signature, such as the coalescence of neutron stars, NASA x-ray satellites and NSF radio telescopes can now aim at the appropriate point in the sky earlier. They will obtain a more complete picture of the event, allowing us to understand much more about, for example, the neutron star composition and behavior, especially when combined with gravitational wave data.

I want to emphasize another point from Dr. Reitze's testimony: that LIGO's past, and future, development has many more earthly payoffs. Fundamental science at the cutting edge often requires significant technology advances at the cutting edge, and this is the case for LIGO. Our development in very powerful, stable lasers finds applications in high-end communications, time-keeping, and navigation; our seismic isolation systems

are being used for next-generation semiconductor fabrication and in seismometer design; low-loss optics have seen applications in NIST time-keeping references; and our work in signal identification in noise has found applications in defense related fields. Many of our precision measurement innovations are also used in other scientific research.

Echoing Dr. Gonzalez's testimony, we also note the large number of students who learn from working on LIGO then often follow careers in other academic or commercial fields, and in that way give back to society from this seemingly esoteric field. LIGO is training a new talent base on the leading edge of science and of technology. Some of them are continuing as gravitational wave researchers. Others are working for SpaceX, or Google, or for the defense industry at Lincoln Labs, bringing specific technical expertise with them but also an ability to develop innovative solutions to hard problems.

Gravitational wave science is just starting. In the very near term, the LIGO Laboratory and the LIGO Scientific Collaboration will complete its analysis of the first science observing run, which ended in mid-January 2016 – we can hope that we will find other events in those data. In Fall 2016, we will start another observing run, having made some improvements in the performance of the detector, which is already the best in the world by far but is only at about one-third of its design sensitivity. We hope to find that the French-Italian Virgo detector in Italy is ready to join us then. Combining their data with ours would give much better information on the position of gravitational-wave sources and allow us to read additional information from the combined 'signatures' of the sources.

Continued "commissioning" – the tuning of the detectors to reach the full sensitivity for which they were designed – will take place over the next few years, interleaved with more observations. Improvements in the optical alignment, in the systems which control the position of the optics, in baffling to control stray light, and in the sensors which convert the light to electrical signals, will all be pursued to bring the Advanced LIGO detectors to their full design sensitivity. Our data analysis teams will also be able to fine-tune their techniques as their understanding of gravitational wave sources and of our instrument deepens.

By 2019, we believe we will have a generous collection of observations of variety of sources of gravitational wave signals, such as:

*Black holes:* This is the system we have now see in our first detection: two black holes, orbiting around each other, losing energy through production of gravitational waves, and ultimately coalescing into a single black hole. Remember that black holes are called "black" because gravity is so strong that light can't get out. That includes everything from radio waves to gamma rays, so we've already seen something no traditional astronomical techniques could ever observe directly. Additional gravitational wave detections will tell us more about the very basic physics of black holes, for instance how their 'spin' (like a gyroscope) affects their behavior, and will allow us to look more closely at the final black hole as it wobbles right after the coalescence. This will allow

ever more stringent tests of general relativity and the models for the improbable nature of space when it is infinitely distorted.

*Neutron star binaries:* These are pairs of incredibly dense compact objects, where a teaspoon of neutron star matter would weigh 10 million tons on earth. By observing their coalescence, we can understand better this matter – how stiff it is, how the object wobbles when excited, and the transformation from two neutron stars into one black hole at the final coalescence. As they collapse, we believe they give off a very strong burst of energetic photons – gamma rays – which we can observe using satellites like the NASA Fermi satellite now in operation. Seeing both gravitational waves and gamma rays from the same object would be incredibly informative on the makeup of this strange matter.

*Spinning neutron stars:* Neutron stars are usually magnetized and when they spin they act like electric generators, sending off very strong radio signals, which can be observed with NSF's radio telescopes. If we can find the gravitational waves given off by these same objects, we can learn what sorts of mountains and other defects can exist on their surfaces, and how the magnetization and the material interact.

*Supernovae:* Supernovae close enough to the earth to be detected by LIGO are rare, roughly one per 100 years. There was one in 1987, but we did not yet have detectors of LIGO's exquisite sensitivity to observe it. We will continuously monitor for a supernova, as seeing it – with other observations in optical, radio, X-ray, and neutrino detectors (like NSF's IceCube detector) – may help us unravel the mechanism behind the explosion of a star. Remarkably, the very best models for stars do not yet predict how supernovae happen, and gravitational waves could well be the key to move beyond that challenge.

*Surprises:* As has always been seen with other new windows on the universe, we expect surprises, and those surprises may shed light on some of the profound mysteries of dark energy and dark matter. The first observations by Galileo with his telescope revealed things beyond the imagination of the time. Radio telescopes similarly showed that the universe is rich with sources, including the remaining heat from the Big Bang. We can't predict the surprises, but certainly we will look for them.

We can take the sensitivity of the Advanced LIGO detectors even further. Using our improved understanding of quantum effects of light, we can 'squeeze' some uncertainty out of our measurement of gravitational waves and improve the sensitivity by enough to double the rate of our signals by 2020 and with some additional refinement perhaps a factor of 10 by 2025 through the adoption of better optics and better mechanical systems closest to the most critical optics. By then we expect to be observing and fully sharing data with instruments in Japan and India. That should allow gravitational waves to really deliver on the promise of transforming our understanding of the most violent and inaccessible events in the cosmos.

I am proud to see that the United States is a leader in this field. At the same time, we will continue to work with researchers from other countries. International partners made significant contributions to Advanced LIGO, both in R&D and as in-kind contributions

(from Germany, Australia, and the UK), which helped in reaching our current sensitivity and will certainly help in the future as well. Because our detectors can give even more value when combined with other detectors, the LIGO Collaboration looks forward to aiding other countries as they bring their detectors on line. As the field matures, and as the community of scientists in the US and elsewhere grows, we will want to continue to lead in the development of better detectors through small-scale university R&D as well as in providing engineering and scientific management of the large-scale projects like LIGO that will be needed.

There are several longer-term visions that will help to complete our ability to ‘see’ or ‘hear’ all of the gravitational-wave sources in the Universe; here are two examples:

*Studies of the Cosmic Microwave Background:* There have already been efforts to find the traces of gravitational waves in the residual heat from the Big Bang, but the signals are (like LIGO’s) very small and elusive. With continued development of these instruments, though, these very first signals can be recovered, helping our story of the first moments in the Universe’s history.

*Pulsar timing:* The spinning neutron stars described above – also called ‘Pulsars’ – serve as wonderful clocks, spread throughout space. By comparing the signals from many such pulsars, small shifts in time earlier or later can be perceived, and can be interpreted as due to gravitational waves from galaxies with their central black holes coalescing over tens, hundreds, or thousands of years. Radio telescopes are used for this measurement, and may be sensitive enough quite soon to succeed in this approach.

I’ve also been asked to look at the really long-term horizon, and I thought I would leave you with a picture of where gravitational wave research might eventually go now that we have detectors that are starting to uncover fascinating data. There two “big ideas” I should note – “Ultimate LIGO” and “space-base detectors.” But let me emphasize that these projects are for discussion in future years, not now – we are racing at this time to understand the amazing developments that our just-proven tools can tell us about.

*Ultimate LIGO:* There are concepts even now for how to get the very most out of our terrestrial gravitational-wave detectors, ones which can reach back to the time of the Big Bang – the beginning of the Universe - and fill in missing parts of the story that lead to the Universe we now know. We can help explain the growth of large-scale structures like galaxies and their interactions, and detect *every* sun-sized black hole coalescence in the universe. This would require new observatories with arms tens of miles long, to enable additional discoveries after LIGO’s lifetime is completed and its mission fulfilled. These new instruments would require additional technology advances and would be championed by the greater astrophysics and astronomy community once gravitational waves are adopted as a universal tool for discovery in those fields.

*Space-based detectors:* The longer the arms of a gravitational-wave detector, the greater the sensitivity. Only in space is it possible to conceive of instruments with arms hundreds of thousands of miles in length, and only with these instruments can one make direct

time-trace measurements of the ripples in space-time from galaxies coalescing and search for deviations from general relativity with a precision of one part in a thousand. LISA – Laser Interferometer Space Antenna – is a project that has been studied by both NASA and by ESA in Europe, and we hope that the confirmation of gravitational waves by LIGO can help bring this transformational detector to realization, and speed its path to launch. It is, in addition to a unique tool for astrophysics, a fantastic opportunity to develop and test technology in space – lasers, formation flying of satellites, data transmission and control over great distances, and precision measurement in space.

In summary, I wish to repeat for the entire LIGO Team and the LIGO Scientific Collaboration our appreciation for the support from the NSF, from this committee, and from Congress. LIGO is a wonderful example of what can be accomplished by a science funding agency with vision and commitment, with consistent funding to allow the best use of taxpayer's money to be made, and with a dedicated science team working in collaboration and resonance with the overseeing agency.

The window to this new world of gravitational waves has just been cracked open. As we open it wider and more and more people look out on the landscape, we will be rewarded with discoveries that will, time and time again, give us all – scientists, leaders, and laypersons – a thrill of understanding of things much bigger than ourselves.

Thank you again for your time, your interest in our science, and your continuing support for a broad spectrum of innovations in science and technology in the United States. We hope this glimpse of our field has allowed you to share in the sense of accomplishment you have enabled.



David Shoemaker  
Director, MIT LIGO Laboratory  
Massachusetts Institute of Technology

**Biography** – David Shoemaker is the Director of the MIT LIGO (Laser Interferometer Gravitational-wave Observatory) Laboratory at the Massachusetts Institute of Technology, and Senior Research Scientist in the Kavli Institute at MIT, as well as a Visiting Associate at the California Institute of Technology. He received a Masters in Physics from MIT in 1980 and a Ph. D. in Physics from the Université de Paris in 1987. He has worked in the field of gravitational wave detection since 1980. He is a Fellow of the American Physical Society. He has served on numerous scientific advisory and program committees for the NSF, NASA, and for the European Gravitational Wave Observatory. He has served as the leader of the Advanced LIGO Project since 2006.

Chairman SMITH. Thank you, Dr. Shoemaker. Thank you all.

Let me recognize myself for questions, and I'd like to ask quick questions and ask you all to give brief responses if you could just to get through all these kinds of comments.

But first of all, what are the practical application of gravitational waves? Dr. Crim, any thoughts on that?

Dr. CRIM. Detecting gravitational waves is this fundamentally inspiring scientific problem, and the point that Dave was just making about a new window on the universe, instead of just looking in the electromagnetic region or just looking at parts from space, we can now look in a completely different way and see new things, but the practical consequences of doing this are really what Gabby was talking about. They have to do with workforce and they have to do with technology. There are miracles of vibration isolation, and none of us really believe they're miracles but they are remarkable efforts at vibration isolation, laser stabilization. All of those are spinning forward into technologies that are extremely important to the country.

In addition, the students—and I was very impressed with your list, Gabby—the students that come out of this are finding—are not just doing gravitational-wave physics, they are going on and transforming the semiconductor industry in SpaceX and many, many others.

Chairman SMITH. Thank you, Doctor. You gave several examples.

Any other examples that anyone wants to mention? Dr. Reitze?

Dr. REITZE. So I'll follow up a little bit. I actually believe what Dr. Crim said, that fundamentally, LIGO is about opening a new window on the universe. Just to give you an example, after we announced our discovery, the amount of reaction to it worldwide was awe-inspiring. I learned yesterday that—I'm not a social-media person but younger people are. There was 70 million tweets about this discovery which is, to me, mind-boggling.

I can focus a little bit on the technology to focus on some of the vibration isolation system. We can't talk about it, but we've been approached by companies that manufacture, you know, computer chips that do lithography, and the vibration isolation that we do, all right, because we have such good low-frequency vibration isolation, we keep things still for a long time. That's actually something that could be very, very beneficial for companies that make semiconductor chips. There are other examples too that I could talk about but maybe—

Chairman SMITH. Okay. Dr. Gonzalez, anything to add?

Dr. Shoemaker then?

Dr. SHOEMAKER. I have one thing I can add to that. Timekeeping is really important for a broad range of activities. I think GPS is one of the things that we most frequently use now and take for granted. It requires general relatively to work but it also requires very precise timekeeping, and some of the innovations that we've made both in laser stabilization as well as these mirror coatings that are low loss and low noise, they help us do a better job of timekeeping, and that really makes a lot of the economy turn, being able to get things to a place in time.

Chairman SMITH. Dr. Reitze, let me follow up real quickly, and it is this: What can we learn from the LIGO detector—you men-

tioned this briefly in your opening statement. What can we learn from the LIGO detector that we can't learn from traditional telescopes?

Dr. REITZE. Well, gravitational waves are dark. They're invisible to the electromagnetic spectrum. So everything we know about the universe comes from X-rays or gamma rays or light or an infrared radiation. This is a completely new sector, so in some sense it's the complete complement of astronomy, and the event we saw, black holes, we believe that you can't see them using conventional astronomy, so that's one example. As David mentioned, cosmic strings. There are a whole host of things that you cannot learn from any other type of astronomy that you can only learn from gravitational waves.

Chairman SMITH. I probably only have time for one more question, and let me address it to Dr. Shoemaker, Dr. Gonzalez, and Dr. Crim as well, and that is, for instance, Dr. Shoemaker, you mentioned coming surprises. Dr. Gonzalez and Dr. Crim both mentioned the future. So my two-word question is, what's next?

Dr. SHOEMAKER. I'll make a guess, and it's a bit of a hope as well, that it will be a pair of neutron stars spiraling into each other, which we may actually see also with our ground instruments. That would be very exciting.

Chairman SMITH. Great. Thank you.

Dr. Gonzalez?

Dr. GONZÁLEZ. Let me mention that this discovery of black holes was a surprise. We didn't know that these objects were in abundance, and we will now know a lot more about those. So this was the first surprise. We expect other surprises.

Chairman SMITH. You might discover something you're not even expecting.

Dr. GONZÁLEZ. That's right.

Chairman SMITH. Dr. Crim?

Dr. CRIM. Your last comment is exactly the point. At the budget presentation, the Director of the National Science Foundation, Dr. Cordova, said she wanted to tell us what the next discovery was but she didn't know because we had to discover it, and I think that is a very important point. Now we have a completely new way to look. I mean, to get out of the electromagnetic spectrum and have the complement of gravitational-wave astronomy is remarkable.

Chairman SMITH. Great. Thank you all for your responses. The NSF is well represented here today so I'm glad for them to hear your comments as well.

I'll now recognize the gentleman from Virginia, Mr. Beyer, for his comments.

Mr. BEYER. Thank you, Mr. Chair.

I'd like to begin by thanking the Chairman and the Ranking Member for having this hearing. This is great fun. I love this job just for what we get to learn, and I'd like to welcome the students from Oakton High School from northern Virginia. Welcome. It's great to have you guys here.

I feel like I'm in Bern, Switzerland, in 1905 or the United States in July 1969. This is just so exciting. And I have some—forgive me—nerd questions for you guys, and I'm not quite sure who to send them to.

So we have the strong nuclear force with the glue on and you have electromagnetic force with the photon and the gravitation force is supposed to have the graviton, gravitational waves and graviton wave particle, so tell us about the graviton.

Dr. GONZÁLEZ. The graviton is actually the particle nature of gravity. What we detect with our detectors is the wave nature of gravity. Those are the gravitational waves. So it's a classical version. Each of these gravitational waves we detected and the ones that—

Mr. BEYER. Will you be able to find something like the photoelectric effect with the gravitons?

Dr. GONZÁLEZ. Probably not with LIGO detectors, no.

Mr. BEYER. Okay.

Dr. GONZÁLEZ. We do not do quantum gravity. That is actually a very hot area of research but we do classical relatively, which is interesting enough.

Mr. BEYER. Okay.

Dr. REITZE. To follow up on that, so we actually calculated how many gravitons we saw or how many gravitons were released in this experiment or in this black-hole collision, numbers 10 with 80 zeros after it, so there's a huge number of gravitons here. We may discover something. I might—we may discover something interesting about quantum gravity that we didn't know before. That's one of the excitements of this business.

Mr. BEYER. Does the gravitational waves go at the speed of light?

Dr. REITZE. Yes. That's what we've learned in this experiment, that we've put a limit on it, that it can only—it can't go slower than .992 or 993, the speed of light. We believe it goes at the speed of light.

Mr. BEYER. So we didn't know that these black holes existed or were about to collide until we saw the gravitational waves from then, and imputed that backwards?

Dr. GONZÁLEZ. Yes.

Mr. BEYER. Very cool. So Einstein spent most of his life hating quantum mechanics and trying to reconcile quantum mechanics with general relativity, reconciling gravitation force with the electromagnetic and the strong force. Does this help?

Dr. REITZE. Actually it's interesting. Einstein, first of all, he goofed when he calculated the first gravitational-wave phenomenon. He actually got the term of the radiation wrong. He corrected that and fixed it, but later he actually believed that the—first of all, the effect was so tiny that it would never be discovered, so he never worried about it, and then later he actually believed that it didn't really exist and he had to be convinced by one of his postdoctoral associates that it exists. So Einstein himself doubted his own discovery.

Mr. BEYER. But will—Dr. Crim, will the reconciliation between quantum mechanics and general relativity come about?

Dr. CRIM. Well, we're certainly funding researchers who are working hard on pushing the theory and pushing that understanding. That's a great, outstanding question in physics and in science today. But it's interesting to think, if we think about—you mentioned the photoelectric effect. The things that gave us hints about quantum phenomena were people looking for often electro-

magnetic radiation to behave classically. So as we now have the ability to look at gravitational radiation, just as my colleague said, there may be a surprise lurking in there as we go and with this tool start to poke on that behavior.

Mr. BEYER. The cosmologists try to look as far in time in possible and, you know, we have that initial thousandths or millionths of a second that we can't see. Does gravitational waves help us to get back to there?

Dr. SHOEMAKER. We can say that it's unlikely that LIGO with a ground-based observatory will have a chance to see the primordial gravitational-wave background. At least our predictions right now insofar as we understand it would put them at a level which is too low to be seen, but it could be that either a space-based antenna could be seen—could see these sorts of effects or these ground-based antennas, which have been looking from Antarctica to try and understand the polarization of the Big Bang background, I think those experiments will also give a positive result shortly. I hope they will. That will be a very exciting result.

Dr. GONZÁLEZ. And let me say that one of the questions that people are drawing—one of the conclusions they're drawing from our observation is how early or how late the black holes formed. That is not well known at this point, and our observations are the ones giving clues about the origin of the small black holes.

Mr. BEYER. Dr. Reitze, one last question. String theory, yes or no?

Dr. REITZE. Maybe.

Chairman SMITH. Thank you, Mr. Beyer.

The gentleman from California, Mr. Rohrabacher, is recognized for his questions.

Mr. ROHRABACHER. Thank you very much, Mr. Chairman. I've got a wild question at the end to ask you, but in the meantime, let me do some business here.

We started off this program with a \$300 million grant in 1980. Is that correct? Okay.

Dr. CRIM. Ninety-four was actually when that was made.

Mr. ROHRABACHER. Okay. So—okay. I thought that you said it was 1980. In 1994, was the first major expenditure of \$300 million?

Dr. CRIM. That was when we went to the phase of actually constructing LIGO but these earlier dates where we're talking about funding research starting in 1979 had to do with a lot of demonstrations of both technology and science. For example, people built tabletop laser interferometers to start to show that they could reach the kinds of sensitivities—there was a chance to get there. My colleagues here can tell that story in some detail but this is a pattern that we often follow. We start out funding folks who lay the groundwork and then the community gets together, again as my colleagues said, and makes a compelling argument based on that early theory and experiment.

Mr. ROHRABACHER. Okay. So from those early experiments until now, how much are we talking about that's been spent on the project?

Dr. CRIM. We have spent a total of over a billion dollars, \$1.1 billion. About \$450 million of that went into actually constructing initial Advanced LIGO. The rest has supported operations and main-

tenance of the observatories as well as individual investigators that were doing that early kind of work and the laboratory work I'm talking about.

Mr. ROHRABACHER. We talked about everybody's working together and many different countries have contributed. How much have they contributed to this effort?

Dr. CRIM. David, why don't you comment?

Dr. REITZE. So Japan got started with a detector in the 1990s, and they're building a big one. I think their number, don't quote me on this, but I think it's on the order of 250 million, but they're well behind us.

Mr. ROHRABACHER. The Japanese, you say?

Dr. REITZE. That's the Japanese detector. The Italian Virgo detector, I think they're in—the way they do their accounting is a little bit different because they don't cost their people in it so it's not really an apples-to-apples comparison but probably they have spent about \$200 million not including the people that they've put into it.

Dr. CRIM. It's foreign countries—

Dr. REITZE. Oh, I'm sorry. Maybe I misunderstood the question. Foreign contributions to Advanced LIGO—David Shoemaker might be able to answer that question.

Dr. SHOEMAKER. Let me speak to that. NSF did fund us for a program to build Advanced LIGO detectors at \$205 million, but then of their own free will, the German Max Planck Society, the STFC in the U.K., and also ARC in Australia all made contributions with a total value of some \$17 million just because they wanted to be part of the experiment. They would've had access to the data. They would have enjoyed the profits of it. They wanted to be part of this activity.

Mr. ROHRABACHER. So would it be fair to say we've spent about half the money that was necessary for the project to be successful as you are today, and the rest of the world spent half of that, and—

Dr. SHOEMAKER. No, our fractional contribution is much larger than that, but as far as getting to the point of this observation, it is sort of 20 million versus 450 million of construction costs but Dr. Reitze was making an important point. Other nations are mounting large gravitational-wave detection elements and we are working in concert with those. So if you wanted to add up all of that, the money going into KAGRA, the money that's going into Virgo, that becomes a much bigger number, but as far as the U.S. investment in these instruments, it's about what I said.

Mr. ROHRABACHER. I've always supported basically research when we're looking out because I've been told that if we're looking out into outer space that we actually can determine what's going on in the molecular structures that can have impact, major impacts here, and sometimes it's easier to see it out there than it is to see it through your little microscopes. Telescopes and microscopes are very related from when I was first educated when I first came here, so I've tried to be supportive of both efforts.

Now let me ask a little—I know this—Mr. Chairman, just one—first of all, we're talking about waves, and I'm a surfer, of course, and I want to find out about riding waves, but will this discovery

that you are talking about today make time travel any more—I mean, this is one thing I’ve been hearing about. Will it make it any more likely?

Mr. LOUDERMILK. Beam him up, Scotty.

Dr. GONZÁLEZ. We wish. This actually does show distortions of space-time so we measure it as distortions of distance but it is distortion of time. We can see time traveling faster and slower but it cannot make us travel in time.

Mr. ROHRABACHER. Well, thank you very much.

Chairman SMITH. Thank you, Mr. Rohrabacher.

The gentlewoman from Connecticut, Ms. Esty, is recognized.

Ms. ESTY. Thank you, Mr. Chairman, and to the Ranking Member, and most of all, thank you to the four of you and these huge, exciting team of international researchers. So there are two topics I wanted to quickly touch on. First was the importance—and you’ve all mentioned it a little bit but the importance of robust, long-term funding for basic research. You know, if we’re going to break those boundaries, reach beyond what we know, it does take that kind of serious long-term committed investment, even in the face of if not failure, not the sort of data you would have wanted. So a couple of you can comment on that because we’re under constant budget strains, and it’s really easy for people to say, you know, I have bridges and roads and schools in my district that need fixing but I also believe that we will be better not just as a country but as a species if we continue the sort of cutting-edge research. So that’s one topic.

And the other was to talk a little bit—and Dr. Gonzalez, you particularly touched on this—about the diverse STEM workforce and the need to inspire a new generation, the collaboration that comes up, and what efforts are being taken in this project to make sure we’re seeing diversity because I know, you know, a suburban white boy may be thinking about using those STEM skills differently than a woman of color in the inner city, so hoping that we’re really making an effort as part of this collaborative endeavor. Thank you very much.

Dr. SHOEMAKER. Let me say one or two things about discussion of the sustained support for the research. I’m a professional scientist, I’m not a faculty member, and it’s been really invaluable for me and for other colleagues in the LIGO Laboratory supported by the National Science Foundation to be able to turn our careers to this and choose to, without striving every 6 months to look for another funding source, to be able to make plans, to be able to make small-scale experiments that take years to give results, to work with industries in a cooperative way through the manufacturing cycle. It’s that kind of continuity and intellectual input that allows something of this nature to take place. So that’s been a very, very important thing to us. Clearly, also, when students come to us and say they want to do a project with us, and we can tell them you’re going to be able to start and finish on this topic. It’s something that really gets people engaged, keeps their mind on the science and away from what’s happening next, so it’s been very valuable to us. Thank you.

Dr. GONZÁLEZ. I have to say that it’s not only us as members of this collaboration that are inspired to work on this because of black

holes and gravity and Einstein, we inspire people too, and we have made a very big effort, we have a big effort in outreach and diversity. We actually try very hard in the United States to increase diversity, not just of our collaboration but of the scientific workforce in general. We work with the National Hispanic Society of Physics, with National Black Society of Physics. We have fellowships that we work out with them. So we do have a very diverse effort.

But it's been rewarding with this discovery, especially to receive questions and visits, visits from schoolchildren, from parents wanting their children to learn about the science. We receive emails all the time—all day from many schoolchildren asking about gravity and Einstein and how do you do this and where is this done and how can I visit. It's inspiration that we provide that I think it is—it's going to help the diversity of our workforce.

Ms. ESTY. And to that point, if you have not already, I would hope that you are developing materials, links to websites that you can disseminate us to, we can to our districts and to our colleagues to allow that citizen exploration and inspiration because we find obviously the ability to use the internet really does bring this home, and I can tell you we had the astronauts here in a live link in this room, and I was able to have a live link with an astronaut from my district, and the inspiration for 3,000 school students who could watch a graduate from their high school speaking to them while he's spinning upside down was extraordinary, and I would hope—this has really captured the Nation's imagination so I urge you to develop good materials of a variety of ages and then we'd love to—I know I would, and I know all of us would love to be able to make that available to the students and—

Dr. GONZÁLEZ. We are working very hard on that. We already have a K–12 material about this discovery, and we also have translations on our website and our papers in different languages including Spanish.

Ms. ESTY. Terrific. Thank you very much. I really appreciate your hard work, and another 40 years for this project. Thank you.

Dr. CRIM. If I could—

Ms. ESTY. Dr. Crim, yes.

Dr. CRIM. —briefly comment to two of your points. Our Directorate for Education and Human Resources has been collaborating with us and generating the kinds of materials that you're talking about. We began thinking about that prior to the announcement and conversations with the leader of that directorate, Joan Ferrini-Mundy.

Your comment about long-term sustained funding and what David had to say about it is really important. We see ourselves trying to find ways to support these long-term risky bets to really get out on the edge and do something transformative, and I think we all recognize the challenges that—with the budgets the way they are but we see that as a constrained, a boundary condition within which we work, and we try what we can to accomplish what David was talking about to let these projects have the stability. It's not easy. It's a constant dynamic tension.

Ms. ESTY. Thank you all very much.

Chairman SMITH. Thank you, Ms. Esty.



The gentleman from Florida, Mr. Posey, is recognized for his questions.

Mr. POSEY. Thank you, Mr. Chairman. Thank you for holding this hearing, and I want to thank all the witnesses for their participation on this exciting subject.

For Dr. Reitze and Dr. Shoemaker, because the expansion of the universe is accelerating, I'm told that the science theorized a mysterious dark force is pulling us apart and that only five percent of the universe is visible to us. They say dark matter is 27 percent and dark energy is 68 percent of the universe. That's just what I read. Can the gravitational waves help us understand the missing dark matter and the dark energy better?

Dr. REITZE. So let me start, and David can comment. It may be possible—first of all, gravitational waves themselves exist. They're ubiquitous just like dark energy and dark matter but they're a very, very tiny fraction. I mean, you can sort of add up how much energy density is in from gravitational waves and it turns out to be very tiny. But it may be that gravitational waves interact with dark matter in a way that we haven't theorized yet or calculated so it may very well be that somebody will come up with an idea to use LIGO or maybe LISA, the space-based detector, to detect them. So it is—you know, it's one of those things where now that we've detected gravitational waves, people are going to start thinking about how can we use to understand other more fundamental things.

Dark energy is trickier. I once heard somebody say that dark energy overstates our knowledge of this phenomenon by two words: dark and energy. We really don't even know what—it's getting—there's getting better understanding of it but it's still—you can measure it but to understand it is kind of hard.

Dr. SHOEMAKER. Let me add that we're already one step along the way by having seen just how well our discovery, our first discovery, matches general relativity. It is astonishing how well Einstein's theory from 1916 matches what we saw, and that already excludes some possibilities for some things going haywire in our understanding of the universe. So that's already a set of constraints, and we think as we see each new source, we'll probably reach new limits. Maybe we'll discover something which is different than we expect, and that would really be a key, or maybe we'll find that our theories are better and better confirmed, but either way, this new window on the universe gives us a possibility to close some opportunities that would otherwise not be there to zero in on what the real answer is.

Mr. POSEY. You know, if it took 100 years to go from Einstein's equations to discovering they're actually correct, just wildly thinking, what do you foresee in the next 100 years? And all of you just comment on that if you don't mind.

Dr. REITZE. So my favorite philosopher is a gentleman named Yogi Berra, and he said predictions are difficult, especially about the future. You know, you can look back 100 years ago when general relativity was first postulated, when quantum mechanics were first postulated, and it was—at least it would have been impossible for me to project forward where we might be. That's the thing about science that's so great, that you never know where your big

breakthrough is going to come from. So for example, you know, everybody probably or some people have been through MRI, you know, getting diagnostic imaging from MRI. That comes from an obscure phenomena that was investigated in the 1940s and 1950s by nuclear physicists and condensed-matter scientists so I wish I could answer. If I could, I would probably make a lot of money in the stock market but I just don't know.

Mr. POSEY. We love wild speculation in this Committee, and that's just what Einstein was 100 years ago actually.

Dr. GONZÁLEZ. Let me say that I also don't have an imagination big enough to think what will happen in 50, 100 years from now, but I think there are surprises that are a lot closer. We are looking at the dark side of the universe. You talk about dark matter, dark energy. We are looking at the dark side, black holes of which we know very, very little. These surprises are just around the corner. That's what I imagine the best side of this story is.

Dr. CRIM. I want to emphasize how well chosen your time scale is in that it can take 20, 50 or 100 years for these discoveries to come out of ideas that start to emerge now and the consequences can play out over those time scales.

Dr. SHOEMAKER. I don't have too much to add. I'm an instrument builder. I love the technologies. I know we'll be doing wonderful things with the technologies that we're developing 5 or ten years from now. What will happen 100 years from now, I have absolutely no idea, but it will be neat.

Mr. POSEY. And finally, Dr. Crim, I was wondering as the field of gravitational-wave astronomy moves forward, how are the NSF and NASA corroborating on supporting the field?

Dr. CRIM. We have a very effective and close collaboration with NASA. The simple way to describe it is, we do ground-based astronomy; they do space-based astronomy. But that means that oftentimes experiments we fund are very complementary to ones they fund. For example, we have a collaboration on their exoplanet program making ground-based radial velocity measurements to understand the mass of planets around other stars. So we have joint committees where we talk constantly, and the physics and astronomy that unites this effort is common to us both, and we're in really good contact.

Mr. POSEY. Thank you.

Thank you, Mr. Chairman.

Chairman SMITH. Thank you, Mr. Posey.

The gentleman from Illinois, Mr. Foster, is recognized.

Mr. FOSTER. Thank you all again.

And just in terms of technology, I bet you have some fun facts about your mirror specifications and how that compares to the sort of mirror that you look at every day in the bathroom.

Dr. SHOEMAKER. Well, I've actually never done any metrology on my bathroom mirror and so I can't quote you the specifications for it. The optics which are hanging freely in space to respond to the passing gravitational waves are right circular cylinders. They're chunks of beautiful, clear fused silica, or glass. They're about 100 pounds each. They're about—they're 34 centimeters, about a third of a meter, about a foot and a half in diameter. Their surfaces are polished to the radius of curvature that matches our two-and-a-

half-mile-long arms so they're actually a very, very shallow curve and figured to within a ten to the minus 9 of a meter across or ten to the minus 10 of a meter across the full surface. This is work done by Zygo et al and they developed these techniques I think for some satellites that are looking down on us at the very moment. But they were able to figure these mirrors to an absolutely superb precision and then on that we put down layer after layer of alternating indices of refraction to get mirrors which reflect the light back extremely effectively with very little absorption but then also a curious additional requirement that the mechanical losses in the coating be low. This is part of the thermal noise. It's like the Brownian motion. Everything is jiggling around because it's at room temperature. Our coatings are the things that jiggle the most in our entire interferometer, and it's there where we have to put the most work in the near future in making our technology advances, and those are tough ones to do.

Dr. REITZE. And let me just follow up on that. This is where LIGO is so cool in so many ways for me. This is—the problem that David just alluded to is a material-science problem. You know, we have to solve fundamental material-science problems to be able to discover black holes so there's just a natural connection across lots of different disciplines.

Mr. FOSTER. Thank you. So cooling the mirror is not going to get around the coating problem?

Dr. SHOEMAKER. It would work. In fact, the Japanese detector, KAGRA, which is in the process of now going together, uses this technique of cooling mirrors. The noise goes down as the square root of the temperature and so it's a pretty hard row to hoe. You have to bring down the temperature of a lot of big equipment in the presence of a very intense laser beam, so it's a big challenge. It's going to be somewhere in our future but I think we can do a lot on the Earth with the LIGO infrastructure without getting into cooling, and I hope we can hold off on the cooling until we really know that it's the best path to take. It's complicated.

Dr. GONZÁLEZ. But let me say that like Dave said, this will take fundamental research in coating technology that it's not in hand yet. Advancing our detectors, improving—we can improve the detectors. We have technology already to improve the detectors a bit but to improve them ten times better, we have to make them 10 times longer or get technology for these coatings 10 times better.

Mr. FOSTER. And what do you think are the ultimate capabilities of ground-based versus space-based and what are the sort of sources that you can hope to see with each? And in particular, what would it take to get to the sensitivity where you could have seen SN1987A, the supernova that was detected in my—the detector built for my Ph.D. thesis?

Dr. SHOEMAKER. Let me say a little bit about the technical limits on the ground. What we'll probably find ourselves limited by is the lowest frequency we can observe which also corresponds to the biggest system of masses that we can measure, and it's finally the fact that the Earth is not just moving but also compressing and getting less dense as seismic waves pass that causes our mirrors to move because the amount of Newtonian attraction of the mirror is changing as a function of time, and that's a wall that's about one hertz

and that will limit us to, I don't know, something like a thousand solar masses as the biggest objects that we can really measure on the Earth, and at that point it will really be the time to go into space and see what's going on there. The others, if you want to respond to the other questions?

Dr. REITZE. Yes. If the supernova 1987A went off today and LIGO was on line, we'd have a good chance of actually seeing it. We would have actually seen it. Or if we didn't see it, it would've said something about the dynamics of the core collapse in that supernova process. So there's a star Beetlejuice that's a red giant and it's probably going to explode sometime in the next 10,000 years. We're hoping it explodes in the next—we're hoping it's already exploded and the signal's on its way——

Mr. FOSTER. Do you have any graduate students where that's going to be their Ph.D. thesis?

Dr. REITZE. They're lining up in 2028.

Dr. GONZÁLEZ. But let me say that the sensitivity to supernova is on the high-frequency end as opposed to the low-frequency end, and the coolest technologies that we will be applying is quantum manipulation of the light that will improve our sensitivity to supernova.

Mr. FOSTER. And so do you have an easy way to explain to this Committee what squeezed light is?

Dr. REITZE. Sure. So—I'm sorry. These are questions we love, okay, and shut me up if I'm getting—I'll be quick.

So electromagnetic waves are not very precisely defined. They have uncertainties in amplitude and in phase, all right, and that comes from the natural quantum nature of light, and the way that you distribute those uncertainties, somebody named Heisenberg told us that there was sort of a little fuzz ball. You can think about an electromagnetic wave as a vector with a fuzz ball at the end. You can actually squeeze the amplitude at the expense of phase or vice versa. So this is something that's existed since the 1980s and it's actually a technology that hasn't found much of an application until LIGO, and now we're using it, so——

Mr. FOSTER. Thank you. I yield back.

Chairman SMITH. Thank you, Mr. Foster.

The gentleman from Kentucky, Mr. Massie, is recognized.

Mr. MASSIE. Thank you, Mr. Chairman.

My first question is, how frequently do these observable events happen? You know, like when we talk about storms and floods, 50-year storm or a 50-year flood, 100-year-flood, this event that you observed from probability, how soon can we expect to see one of that magnitude or larger again?

Dr. GONZÁLEZ. Very soon. We——

Mr. MASSIE. Like five minutes or five decades or——

Dr. GONZÁLEZ. Well, let me tell you, the analysis that we presented was the analysis of one month of data taken with the two detectors that only had 16 days of effective time when the two detectors were working together and we need the two detectors to confirm the signal, and we saw one event in one month. Of course, you could say you can——

Mr. MASSIE. Well, that either means you got really lucky or your instruments aren't working, or it could mean a lot of things so——

Dr. GONZÁLEZ. That's right. That's right. So we can only predict from that one month of data. We can only say we saw one event in one month. But we have taken three months more of data that we are still analyzing, and everything we see is consistent with what we saw there, and we are going to take more data in the future, and from the theories that we derive even from this just one observation, we have a predicated rate that will mean at least a few a year.

Mr. MASSIE. Dr. Shoemaker, you're from the university I graduated from so—

Dr. SHOEMAKER. Oh.

Mr. MASSIE. —go ahead.

Dr. SHOEMAKER. So one other thing to point out, though, I mentioned that we're at one-third of the sensitivity we believe our instruments can achieve with just doing tuning. A really neat thing about gravitational waves, it's an amplitude phenomenon. It falls off as one over  $R$  and not over one over  $R$  squared, the distance from the source to us. If we can increase our sensitivity by a factor of two, the number of sources within reach goes up as two cubed.

Mr. MASSIE. So I was going to ask you about that. You said it's going to increase by a factor—or it's going to increase by three. Did you mention 3X or three orders of magnitude?

Dr. SHOEMAKER. I mean 3X.

Mr. MASSIE. Okay.

Dr. SHOEMAKER. That's to say we'll reach—

Mr. MASSIE. Darn.

Dr. SHOEMAKER. —three times further out, but that means that the effective—sorry. That means the effective rate will go up by 27 if you cube three, and if we saw one event in 30 days of observing, that says we might get to the point where we're seeing an event every day if this one event we saw is representative of the rate. So I think we can see that there's a lot of progress in the future—

Mr. MASSIE. Right.

Dr. SHOEMAKER. —that can go to increasing the rate.

Dr. REITZE. And that's just for binary black holes. We still haven't seen neutron stars, and we expect to see quite a few of them per year when we're at design sensitivity.

We talked about supernovas before. They are the ones that are going to be hard to see. We're going to have to get really lucky to see a supernova because they're just not that strong of an emitter.

Mr. MASSIE. One of the questions I did want to ask, and Dr. Gonzalez, you touched on it. Did you remember to leave it on when you came to the hearing? Like what is the duty cycle? How frequently is this collecting data, and maybe we've already observed things we don't even know yet and people just need to sort through that data. Maybe we've already observed simultaneously something that we saw in the electromagnetic spectrum but we just don't know it yet. Is this thing turned on now?

Dr. GONZÁLEZ. It is intermittently, but for diagnostic purposes, we have not taken data in coincidence but we have plans to take more, what we call engineering runs, opportunistic engineering runs. We have another run with the two LIGO detectors starting in this late summer, early fall, perhaps July, and that's how we

will know what the rate of these binary black holes and perhaps other events will be.

But let me say, you asked me if I remembered to leave it on. It's not me, and that's the strength of having a thousand people working on these. We have 200 people in the LIGO Laboratory and they are the ones who not only keep the detectors on but they improve them every day.

Mr. MASSIE. I have a question I want to make sure I get to ask. What are the sources of noise that you have to contend with? You know, like I imagine our sun is doing something. There may be nuclear tests where on Earth that are causing seismic. Maybe talk radio is interfering. It's a big source of noise. But what are some of the noises you'd have to filter out?

Dr. SHOEMAKER. Let me say what the basic noise sources are. One of them has to do with the sort of quantum effects that Dave Reitze was talking about. We use lasers, and the lasers emit photons in a statistical way so there's a fluctuation of the number of photons so there's a fluctuation in what we use as our measure of where the masses are.

Mr. MASSIE. Can you get smaller photons?

Dr. SHOEMAKER. The thing to do is get more photons, turn up the laser power. The next thing to do is address these questions of thermal noise that I mentioned earlier on, that everything is jiggling around due to Brownian motion, and the way we address that is to choose materials that have very, very low internal losses and squeeze all of that jiggling into a very narrow frequency band.

Lastly, you were talking about seismic motion. We built—and that's one of the really big improvements of Advanced LIGO over Initial LIGO, a system of seismic isolation which makes it so that we're effectively independent of the environment around us during normal weather conditions. We still can get knocked out of lock when there's a lot of wind. There was a tornado down in Louisiana just yesterday. So there's—

Mr. MASSIE. One last quick question before I yield back. When you get this third detector, does that just improve the reliability of your data or does having a third point on Earth give you an ability to triangulate? Dr. Crim, you were shaking your head. Maybe you could—

Dr. GONZÁLEZ. All of the above.

Dr. CRIM. All of us are shaking our head yes. That's—

Dr. GONZÁLEZ. To both.

Mr. MASSIE. But will it give you a bigger picture of what's going on? Can it do that?

Dr. GONZÁLEZ. It gives you better localization so you will better pinpoint what the source comes from, but also if you have three detectors, you need two to see a signal. If you have three, you can have one on and the other two and then you will still see the signal. With only two LIGO detectors, if one is down, we are in the dark.

Mr. MASSIE. Thank you, and I yield back. I could ask a hundred more questions. This is very fascinating. Thank you.

Chairman SMITH. Thank you, Mr. Massie.

The gentleman from New York, Mr. Tonko, is recognized.

Mr. TONKO. Thank you, Mr. Chair, and welcome to our panel. What a fascinating panel. Let me congratulate you and all the people and institutions who have inspired this tremendous moment. It's truly a phenomenal success, and certainly I'm grateful to the people who had the vision and pursued based upon the seed that they planted to be determined to come to the success that we've met. So I anxiously look forward to what else is out there, and you know, and can't wait to see what is yet to come. And if this doesn't serve, if this doesn't illustrate the value added of high-risk, high-reward basic research, I don't know what does. So hopefully we get the message, we invest deeply and soundly in research and move forward.

My question would be to all of you, any of you, what role did partners in industry play in the design and development of the—of this new technology? Certainly you've got infrastructure that we've seen in your slide presentations. There was a lot of talent you had to draw upon, so can you describe that, please?

Dr. REITZE. Just a couple of examples. I'll start actually with the first LIGO, Initial LIGO, which was built in the late 1990s and 2000s. We partnered closely with a firm called Chicago Bridge and Iron Works that developed our vacuum system, and this was a—this vacuum system at the time was the world's, I think, largest although maybe that's not true from a defense standpoint, highest vacuum system, and some of the work that they did for us went on to later inform what they did for the National Ignition Facility.

We worked closely with a company in Silicon Valley that developed layers, Light Wave Electronics. They developed the first laser for Initial LIGO that was actually used in some other applications such as newspaper printing.

As David mentioned, we worked closely with industry for developing optics and coatings so that's both in the United States and in with international partners. We worked a lot with companies in Colorado, in Boulder, Colorado, to develop some of the first LIGO mirrors and some of the first coatings, a company called Research Electro-optics, also advanced in films. We work a lot with companies like Nvidia, all right, because we use graphic—we use GPUs in some of our analyses. We're actually not using them right now but we will be using them so we'll working closely with them. So there're a number of touch points where we've actually worked—partnered closely with industry, and that's just a partial list.

Mr. TONKO. Right. Anyone else that—

Dr. SHOEMAKER. That covers a broad spectrum of the things that we used.

Mr. TONKO. Was there anything unique in the collaborations that you developed as a LIGO industry? Was there anything in particular that was a different approach?

Dr. REITZE. We developed—actually, this is one of the things that I worked on. We had to develop some novel electro-optic technologies for—it's sort of a technical thing about how we lock—how we keep our interferometer in an operational point. We had to develop something called electro-optic modulator that was actually new and it's patented. It hasn't been licensed—it hasn't been licensed yet. But there are things like that. Some of the work that

we did with the silica fibers, I think, with the Glasgow group has been spun off to some other applications.

Dr. SHOEMAKER. Then coming back to the mirrors once again, we knew what we needed for mirrors and so we found the very few bidders, one in Australia and one in France, by the way, who could deal with our basic requirements but they couldn't actually even measure what needed to be measured, and so we gave them instruction on how to proceed. We worked with them in a collaborative way to develop the technologies that were necessary and then we brought the optics back to Cal Tech where the very finest metrology in the world could be done and give them feedback about what they need—you know, what kinds of changes they needed to make in their technology. So in that way we were able to trade things back and forth between the academic side and the commercial sector and work in a collaborative way to get something to push the state-of-the-art forward.

Dr. GONZÁLEZ. I should mention also that information technology has been used. Many of the algorithms or some of the algorithms that we developed to search for gravitational waves in the data have been—have found applications in the genomics industry and in some other Big Data analysis, and that's why some of our graduates actually are sought by these industries.

Dr. SHOEMAKER. In particular, the kinds of challenges that we have of looking for small, intermittent signals against a complicated noise background are things that the defense industry finds interesting, so a number of people have gone off into that sector and discovered the skills that they developed with us were very useful. We don't hear much back from them, though.

Mr. TONKO. Well, it just shows the emphasis that we have on science and engineering, scientists and engineers to make it all happen.

And just quickly, Dr. Reitze, you made mention of the commitment of NSF to fund the development of LIGO as a scientific moon shot. Can you elaborate upon that?

Dr. REITZE. Yeah. Look, I think Chairman Smith said it, or somebody said it quite well, that the first time people, rational scientists hear about LIGO, they think it's crazy because they think how do you possibly make a device that can measure to the billionth of, one- one-billionth of a diameter of a proton, and you scratch your head, and then you start thinking about it and you realize that yes, it is possible. So in some sense, this was even bigger than the moon shot in the sense that I think most physicists—and it ran into resistance early on. Most physicists didn't believe it could be done. So I think it was due to a few key people including some key NSF Directors early on, Rich Isaacson and Marcel Berdon, that recognized that yeah, you could do this. It was just amazing.

Dr. CRIM. Just to briefly follow up on that, this is not a discontinuous process as people scratch their heads, they do calculations, they do experiments, and you persuade people. It's a very critical community competing for precious resources, and people have to make their case forcefully, persuasively, and part of what we try to do at NSF is to balance off all of those really good ideas, and it's a marketplace where people have to really meet a very high



standard, and this wasn't some longshot, it was a series of considered bets, and they were risky but it's paid off beautifully.

Mr. TONKO. Well, thank you, and again, congratulations, and with that, Mr. Chair, I yield back.

Chairman SMITH. Thank you, Mr. Tonko.

The gentleman from Georgia, Mr. Loudermilk, is recognized.

Mr. LOUDERMILK. Well, thank you, Mr. Chairman, and this is very exciting. It's a very exciting discovery, and I'm very proud that we discovered this here in America. This is the type of thing that we have been known for in the past, and I think it's large in part not just to investment but to the freedom that we have to investigate and explore.

And again, I see it much like the Apollo program that some of the spinoff technologies that we're going to have not just from the discovery itself but the tools and the technology that goes into the discovery I think is going to benefit future generations.

I've also been impressed with the large audience we've had here today, Mr. Chairman. I think this may be one of the largest audiences that we've had, and I really appreciate those students being here. This is the type of thing that I think we're setting the groundwork for future generations.

In Georgia we've had a little bit of a challenge of inspiring our young people to get into science and technology career fields. We have some of the world-class research institutes right there in Atlanta. We're leading the Nation in health IT and a lot of innovations and discoveries but yet our biggest challenge has been filling those jobs with innovators just seemed to be a lack of inspiration. But I'm becoming more encouraged by what I see here and something I did yesterday. On my way to the airport, I had the opportunity to stop by one of our high schools and notify two students, both high school sophomores, that they had won the app challenge that Congress had put on. Ryan Cabelli of Kennesaw Mountain High School and Alvin Potter of Wheeler High School took technology—they didn't develop the technology, the coding language, but they saw a need with other students and they took the technology someone else had discovered and they put it into a practical application called Grade Spar. As they informed me that GPA is everything to these students and one of the challenges students have is predicting what their GPA is going to be based off of their previous grades. So they have actually developed an app for your phone that students can put their grades in and they can estimate where their GPA is going to be and what they need to do, and so it's taking the research others have done and put it to a practical application, which I think this next generation will be able to do that same thing.

A couple of questions, though. I'm very interested in the technology you're using. I spent 30 years in the IT sector—but the technology that you use to actually do these discoveries. But first of all, from previous questions, I was very intrigued about what you've discovered about gravity, that from what I understand, it sounds like there's a lot of properties of gravity that's very similar to light, the speed, that there is actual waves, and particles. Are we seeing more and more relationship between the two the more you discover?

Dr. GONZÁLEZ. Well, yes, of course. There is a very strong relationship between the sky, what we learn about the sky from the electromagnetic and the gravitational spectrum. I think one of the biggest—I wouldn't say surprise because we are expecting it—one of the biggest events that we expect in the future is seeing a bright source both in the electromagnetic and the gravitational spectrum so that we can learn from the matter and the photons in there. That will be amazing. And it will happen. It will happen soon enough.

Dr. SHOEMAKER. But then on the more fundamental question of the similarity of the two different effects, it's true that in both cases it's information that travels at the speed of light or the speed of gravity as you prefer. In both cases, the effect is perpendicular to the direction of propagation of the effect. In both cases, as you make antennas longer under the conditions of long wave lengths of information, you get bigger and bigger signals.

A basic difference, though, is that a photon is a particle that travels in space time. And we looked at space time itself as it warped, and so it's a slightly different thing in that sense there.

Mr. LOUDERMILK. So as we get to the longer tubes, if I may ask—I know I'm running out of time—are you already seeing the—anticipate even at 4 kilometers you're seeing the gravitational pull on your lasers—a slight, somewhat bend of—

Dr. REITZE. Yes, we see actually—so we design our instruments so that the light itself—4 kilometers is not a lot of distance—

Mr. LOUDERMILK. Right.

Dr. REITZE. —distance for light, and we have to design our instruments so that we take into account the curvature of the Earth—

Mr. LOUDERMILK. Right.

Dr. REITZE. —so that we can go flat. But what we do see in our instruments are the tidal effect from, you know, the moon goes around the Earth, the Earth, you know—

Mr. LOUDERMILK. Right.

Dr. REITZE. —the Earth sort of breathes because of the tidal effects, and that actually shows up on our detectors. It changes the length of our detectors by about 100 microns a day. And we actually have to—

Mr. LOUDERMILK. Okay.

Dr. REITZE. We predict it. We can correct for it and we feed it back so that we don't have to—

Mr. LOUDERMILK. Well, that was kind of my other question as far as the calibration factor from seismic activity and having the thought about the effect of the gravitational pull on the moon. So there is a lot of technology, as you alluded to, just to go into the research itself, and I applaud you on these great discoveries. Thank you.

Chairman SMITH. Thank you, Mr. Loudermilk.

The gentleman from Colorado, Mr. Perlmutter, is recognized.

Mr. PERLMUTTER. Thanks, Mr. Chair. Just a couple questions. I find this so fascinating and so over my pay grade I don't know what to tell you. And you four really are inspiring to me. You talked about being inspiration to your students. You're inspiring to all of us. And thank you for your patience and, you know, looking

at this and talking about the space time continuum and warp speed and worm holes and I don't know what else. But just sort of just the basic human question for me is like can you describe the first few hours after the detection? Who found out about it? How quickly did, you know, word travel? Was it as fast as the speed of light? Is that how fast the sound was? And just generally how did the scientific community individually and as a whole feel about this discovery? And then I am just opening up and you can go one at a time.

Dr. GONZÁLEZ. Yes, let me tell the story. Actually, it's a very long story. We had been preparing for discovering gravitational waves for a long time, so we have computer programs that produce alerts, and we—and those alerts are alerts in the control rooms, but we didn't have those alerts quite ready yet when these came. So they were producing Web pages where codes—which had very smart codes produced by very smart people were producing Web pages. And because this event happened in the middle of the night in the United States, these Web pages were first seen by our collaborators in Europe because it was daytime for them. But that's again, the strength of having a distributed collaboration. So there was an email flurry saying what is this? Who is injecting this now? So it took us a while to find out that the detectors were all in fine state, this was not a test, this was not a dream, it was a real event.

But then we had a very hard work to vet the signal, to convince ourselves that this was a signal. And that took months to vet the signal to make sure that everything was okay, that all our hundreds of monitoring systems did not produce any earthquake, any lightening, anything strange that could have caused this, and then to also analyze this event to get all the physics and astrophysics out of it, that took months of work by many hundreds of people.

Dr. REITZE. Yes. We in California are usually the last to know about anything because we're on the farthest time zone. So I got to work—I took my daughter to school and I got to work at 7:30 this morning and I read my emails first. That's my routine. And I saw a number of emails saying you need to look at this. This is serious. And the more I looked at it, the more I went wow. This is actually unbelievable.

And this thing that Gabby pointed out about injections, one of the things that we do to test ourselves is we inject signals. We can actually wiggle the mirrors to produce the kind of signals that I showed you. And we do it sometimes secretly. So there was—after people saw this signal, they said to themselves, oh, this must be a blind injection. And there were only four people in the collaboration and I was one of them that knew that this was not a blind injection. So I got a lot of emails saying Dave, can you confirm whether this is an injection or not? And I would send back, no, this is not an injection. And at that point, interest ramped up very dramatically. By the end of that day, I think a number of—you know, probably the entire collaboration knew we had something really hot.

Dr. SHOEMAKER. I'd just add a little bit more. I talked a little bit about this dream of multi-messenger astronomy where you could see simultaneously on the ground with radio telescopes or the FERMI satellite and gravitational waves coming in all at once. An

important necessity for that to work is that we be able to identify the signal as soon as possible after it is detected. It was 3 minutes after the waves cross the Earth that we had a signal that was unambiguous and clear that said something has happened here that requires attention.

For me, it was, again, when I first woke up 3 hours before Dave did, I'd been actually working with a close European colleague in Germany on just this question of whether or not we could perform injections. And we've been pulling our hair out because we knew technically we had a problem that we needed to solve before we could properly do the injections. So he thought only four people knew, but I knew also. It couldn't be an injection. We didn't know how to do them at that moment.

It took only minutes to realize that something had changed, but it's taken months for me really to integrate it into my vision of things. You work on something for 40 years dreaming about the day when the detection will come. It takes months for it to finally sink in.

Dr. CRIM. So very quickly, first of all, this gave me an opportunity to walk into the Director's office and say I have good news for once. But I want to say something about the collaboration because, you know, we've watched as this information propagated through and our program officers learned about it and all. The way the collaboration handled this is a model of how you do modern big events in science. The rumors were circulating but they vetted the signal, they wrote the paper, they had it reviewed. They had it published in a premier journal before—they had reviewed in a premier journal before they had the press conference announcing the result. That's the classy way to do science.

Mr. PERLMUTTER. Well, thank you. And I yield back.

Chairman SMITH. Thank you, Mr. Perlmutter.

The gentleman from Alabama, Mr. Palmer, is recognized.

Mr. PALMER. Thank you, Mr. Chairman.

Dr. Reitze, in 2014 BICEP2 experiment team announced that they had found evidence of gravitational waves, but the observations were later shown to be the result of galactic dust and were discredited. How confident are you that this or some other type of error is not responsible for the detection of gravitational waves in this case?

Dr. REITZE. Yes, that's actually an excellent question and one that we worried very much about ourselves. I think the way—first of all, the thing you can say about it is that we actually had two different detectors. We had the one in Louisiana and the one in Hanford. They're independent. They're operated totally independently. They're uncorrelated. They both saw the same signal. It had the same characteristic in signal.

The data that we analyzed from that actually showed that the signal was completely consistent. It was found by many different methods. There were a lot of other checks that were done because, as was mentioned before, there are other things, noises that can creep in, so we looked at our detectors and convinced ourselves that there was nothing that was perturbing our detectors.

We also did a statistical analysis. Without going into much detail, we calculate what's the probability that this could actually be

false, and how many—if you had to run for how many years, would you see an event that looked real, was false? We couldn't actually put a bound on that number. It's more than 1 in 200,000 years.

That said, we also looked at other things. Could somebody have done an injection? We talked about injections. Could somebody have, you know, secretly hacked into our computers and done this? We checked every path that we could think of and even some that we couldn't think of after we thought about it a little bit more and convinced ourselves that, no, that was not possible either.

The answer to your question is I think we're very confident. I would say this, too. You know, we expect to see more of these signals, so we hope that in the next—you know, the data that we still have sitting—you know, we're analyzing right now that we'll see more of them. And having more of them gives you confidence.

Mr. PALMER. I want to give you somewhat of a follow-up on that, and any of you can answer this, and that's the practical application of this because, as my colleague Mr. Massie from Kentucky and I were discussing, GPS doesn't work without relativity. Do you see any practical application of this? And I'm not implying that this is not viable for the sake of science and science—what would any of you see as a practical application?

Dr. REITZE. Of—

Mr. PALMER. That doesn't mean my time's up.

Dr. REITZE. Yes. Of detecting gravitational waves? It's hard to see anything in the short-term. Some people, for example, thought about you might be able to use them for communication because they go through everything. I mean, your bodies are being—my body is being bathed by gravitational waves right now. But it turns out that to generate them you need big huge black holes, so it's hard to see that.

I think in the short term—and, you know, I feel more confident talking about the short term—the things that we'll see that will come out of this research are the technology, you know, transfers that come from the work that we do to build these detectors in computing and optics and lasers, servo controls, vacuum systems, things like that.

Fundamentally, it's hard to see. But again, you know, for me this is inspiration because it allows us to see the universe in a way we've never seen before. And for all of us, that's why we got into science. That's why we like to do it.

Dr. CRIM. I really love the GPS mention that you make because it's certainly the case that when Einstein did general relativity, he had no idea it was going to help me find a Starbucks. And there are remarkable things like that in the future. But as I said before, I wish I could tell you which one, I think we all do, but they're out there.

Mr. PALMER. I have to credit Mr. Massie with that question. It helps to sit by a physicist from MIT.

Mr. MASSIE. Engineer.

Mr. PALMER. Engineer, okay. Dr. Shoemaker, not long after the announcement on February 11, the Indian Cabinet granted approval for LIGO-India Project. Can you give us an idea of the impact of additional observatories coming online?

Dr. SHOEMAKER. Yes. The really wonderful thing about the India opportunity is that it's far to the south of all of the other existing detectors. We have the Hanford, Washington, and Livingston, Louisiana, detectors. There's the Virgo detector from Italy, which is in Pisa. There's KAGRA, which is a Japanese detector. But if you look from a big distance from the Earth, they're all pretty much in a line. And the wonderful thing about the India site is that it's to the south of that. And that gives us a bigger tripod that we can use to look in the sky and try to localize the source of a gravitational wave, and it will have a remarkable and unique effect on our ability to pinpoint in the sky.

Mr. PALMER. Thank you, Mr. Chairman. My time is expired.

Chairman SMITH. Thank you, Mr. Palmer.

And the gentlewoman from Massachusetts, Ms. Clark, is recognized.

Ms. CLARK. Thank you, Mr. Chairman and Ranking Member Beyer. This is truly just a great hearing and we are so excited about the results. And as you said, Doctor, it just really—this is inspirational science and sort of fulfills our cravings as human beings for exploration. But what I find really impressive is that—and this has been touched on by some of my colleagues—it's really a decade—decades of partnership and significant funding, I think 1.1 billion total over many, many years going from basic research to building LIGO.

And what I want to know because I feel this is such a success story for us to tell about what it means when you can talk to your students and say you can begin, you can end, and you can remain on this project, what that means. How do you put together a project of this size? How do you keep benchmarks with it? How do you manage something that goes on for many different people over such a long period of time and end with the success that you've had? And I certainly appreciate the classy rollout. But I think that, you know, I'm very interested in how you do that because I think some of the technology that you ended up using you couldn't foresee in the beginning, so if you could just speak to that.

Dr. REITZE. Let me try and start, and I know David Shoemaker will also have some, I think, good answers or good comments about that.

First of all, when you get the project—I mean the idea of interferometry, you know, goes back to actually the '70s, Rai Weiss and even some guys in Russia thought about it. And so the question is what you then have to do to make this work. And so you write down a list of things that you need to study and investigate. You start investigating them using, you know, money from the National Science Foundation, what I would call individual investigator grants, and then you get to a point where you realize that that it could work and that there's lots of work to be done but it's more of an engineering. You know, you take the ideas that you've tested—you've studied and you have to engineer them. And then you get into the project phase.

And I think one of the things that LIGO—well, first of all, LIGO got started—I think it was the first big major project that NSF had done, and it had a rocky start to it because, well, you know, it was so big. It was a factor of 100 bigger than anything else had ever

done. We'd done prototypes 40 meter that you—we didn't think of everything. And so there was some management changes that had to take place, but eventually, we got an organizational—a robust organizational structure in place that understands project management, the fact that you have budgets, accounts, and things like that. You have to track them. You have to make sure—you're given a finite amount of money. You have to make sure that you build everything you need to build with that finite amount of money. You have to understand how everything fits together, system engineering.

So there are a lot of things that we learned and then borrowed to make LIGO work. And I think both initial LIGO and in particular advanced LIGO was quite successful because we take these things that we learn from project management and we apply them, too. So it's actually a testament to not only the scientists but a lot of businesspeople. We had a lot of accountants and things like that working on doing this. So there's lots to be proud of here.

Ms. CLARK. And was that a different model, sort of having lots of accountants, or was that just continuation of work you'd done before—

Dr. REITZE. Well, no, no, no. It was—

Ms. CLARK. —being on a different scale?

Dr. REITZE. —a complete—to do big science, you need to have an infrastructure that not only includes the scientists and the engineers and the students—we had a lot of students involved—but you need to have, you know, people that know how to track projects. You need to have people that know how to, you know, track budgets and things like that. So that was something that we figured out once we had to go into the big science model of it, and we put together a structure that ended up being successful.

Ms. CLARK. Yes.

Dr. GONZÁLEZ. Let me say that the project model has been very successful in this case due to the very good management it had, but the human side of this is that, like you were saying, there are graduate students whose career in this is in research. It's 4 or five years, not 20.

Ms. CLARK. Right.

Dr. GONZÁLEZ. But they are still interested. They were then. I was one of those graduate students in the beginning that I knew I wasn't going to be discovering gravitational waves in my Ph.D. thesis. I did a thesis on something that was going to help the construction of these projects, the sensitivity of this detector, and that was exciting enough. It's inspiring people to be part of something bigger, and that is what inspires our undergraduate and graduate students to work for a few years even though some of them have been part of the detection now. But many are proud of having been part of this in the past, and we are attracting many more.

Ms. CLARK. Wonderful.

Dr. CRIM. May I briefly—

Chairman SMITH. Yes.

Dr. CRIM. —comment?

Chairman SMITH. We are—we do have a time factor involved here—

Dr. CRIM. Okay.

Chairman SMITH. —but please go on and—

Dr. CRIM. I—

Chairman SMITH. —respond.

Dr. CRIM. Let me just very briefly go from the inspiration to some of the practicalities of doing this. At the Foundation we have these remarkable program officers. The collaboration that we build is through what's called a cooperative agreement, and the—one of the striking things I've learned that I've been at the—been at the foundation is how complicated project management is. And the program officers, working with the people and the project, it's really a hand-in-glove relationship. And there's an enormous structure if you're going to spend \$400 million of the taxpayers' money. And we're careful about it, and it involves these close collaborations.

Chairman SMITH. Thank you, Ms. Clark.

Ms. CLARK. Thank you.

Chairman SMITH. The gentlewoman from Virginia, Mrs. Comstock.

Mrs. COMSTOCK. Thank you, Mr. Chairman. And I'd like to thank our witnesses so much. It's so exciting to see your enthusiasm. And I'm thrilled that we had one of our local high schools here. I think we still have some of the students here from Oakton High School in Fairfax, and we appreciate them being here. And I wanted to ask you, even though we don't have that time travel thing that we could do, if for each of you if you could go back to being in high school and you were looking at this field and you were looking at how someone might get engaged and involved in this exciting opportunity and career that you all have had an opportunity to do, what would you tell them to do today and going forward in their educational experiences, their volunteer experiences, you know, where they can get internship opportunities and any Web sites or other resources that you might provide for the Committee that we could share with them or that you might direct them to here today if you could speak to that.

Dr. SHOEMAKER. Let me just start by saying briefly, this field didn't exist when I was in high school, but I think what I found was really crucial was to find something I was passionate about and just throw myself into it. That was really the key for me in being able to focus enough on a topic—you know, I was a young and wild one at one point, and it took finding something and also finding someone. It wasn't actually when I was in high school but when I was in the university that I found Rai Weiss, who has remained my mentor for the—all of my career, someone who was inspiring to me, somebody who was a role model, who looked to me like they understood what was important in what we were trying to do and could—was also good with a soldering iron. And I think those kinds of things, you find somebody that really turns you on. It gives you the focus to actually follow through with things that look really tough when you start out. Thank you.

Dr. GONZÁLEZ. Let me say that when I was a high school student I began liking science and physics because I liked asking questions. So that's what you need to do the most, ask questions. Don't shy away from questions. There are no dumb questions.

About material, we do have in our Web site in LIGO.org a lot of material, and we also have people, emails of people who you can



contact to ask any questions, and we are receiving lots and lots of questions and we answer them all. And we also have some material for teachers to use in their science classes. There are also programs organized by the American Physical Society for high school like Adopt-a-Physicist so you can ask teachers to contact LIGO people, collaboration people to act as a consultant and answer questions.

Mrs. COMSTOCK. So is there like a package we can give to our high schools that you—

Dr. GONZÁLEZ. There's a K-12—

Mrs. COMSTOCK. —all have?

Dr. GONZÁLEZ. —packet—

Mrs. COMSTOCK. Great.

Dr. GONZÁLEZ. —for students that we have developed, yes. And there are a lot more material—

Mrs. COMSTOCK. Great.

Dr. GONZÁLEZ. —for teachers and students.

Mrs. COMSTOCK. Right. Thank you.

Dr. REITZE. Just to follow up a little bit, one of the things that I think is very important more when you get to the college level but it can happen at a high school level is to go up to a professor, all right, and ask them is there interesting research that you're doing that I can get involved with? So all of us got started actually doing research as college students. You know, we hadn't even decided what we wanted to do yet. And even in high school—so at Cal Tech, for example, we have in the—just in LIGO alone we take in three or four high school students every year, all right, and we give them, you know, a pretty well-defined project, and, you know, we mentor them to make sure that they get through it. They get exposed to, you know, seminars and things like that.

And I suspect that a lot of universities especially in the Washington, DC. area there are a huge number of universities. I would imagine that those kinds of things exist here, too. If they don't, they're not that hard to set up so—

Dr. CRIM. I want to associate myself with the comment about passion. I think being passionate about science is something that's driven us all.

As far as this research comment is an important comment, and the Foundation supports research experiences for undergraduates to just provide that kind of an opportunity. There are programs that reach down into the K-12.

I want to make one brief comment, though, about how your question relates to how we function as a nation. I am a child of Sputnik. That event and the focus on science directed many, many people for more than a generation into science. And the Nation made a huge commitment to our being the global leader in science. Those kind of moments are the things that will invite these folks to come in.

Mrs. COMSTOCK. Thank you. I appreciate that passion and for the students, these are your role models that you are looking for in the science field. If they look and sound like this, grab them. Thanks.

Chairman SMITH. Thank you, Mrs. Comstock.

The gentlewoman from Oregon, Ms. Bonamici, is recognized.

Ms. BONAMICI. Thank you very much, Mr. Chairman.

What an exciting topic and thank you so much for holding this hearing today so we can learn more about this very exciting research. And I wanted to align myself with the comments of Mr. Tonko and others about the value of taking risks and the value of this sort of persistence and perseverance over the years and sometimes decades.

I want to take just a moment to acknowledge my alma mater, the University of Oregon, for their efforts in this discovery. The university was one of the founding groups of the LIGO scientific collaboration. And I know that the university scientist Dr. Robert Scofield participated in testing the detectors at the site in Livingston, Louisiana, on the day that the gravitational wave was recorded.

And almost simultaneously, the LIGO's partner site in Hanford, Washington, where University of Oregon graduate students were stationed, registered the wave. University of Oregon is responsible in part for the environmental monitoring and really investigating that the wave was in fact a gravitational wave. When anything happens in the Northwest, we think it's an earthquake, right, so they in fact confirmed that this was a gravitational wave.

And I know Professor Frey as well, Raymond Frey, who leads the university's physics department and their team on the LIGO project—that includes five Ph.D. students, a post-doc, and three faculty members. So I'm proud of the University of Oregon. I know that their report really helped the scientists with their confirmation.

One of the problems with being one of the last Members to ask a question is that a lot of the topics have already been touched on. I was actually in an Education hearing with the acting Education Secretary, so I wanted to ask to—if you could follow up a little bit. I know the question was asked about how we could get materials to teachers in classrooms, but I also was wondering if a researcher who's unaffiliated with the LIGO collaboration has access to the data.

Dr. GONZÁLEZ. Yes. We have—we—in LIGO.org you can find the actual data, one hour of data before and after the detection. And people have already downloaded and——

Ms. BONAMICI. Terrific.

Dr. GONZÁLEZ. —are analyzing it. We are going to—we have made the data from initial LIGO runs. They are also available and people have been looking at that. And we will make the formats of data that we have taken available to the public in the future. So we are very committed to open access and the public access to the data.

Ms. BONAMICI. Terrific. And I really appreciate all the comments that I've heard all of you make about the importance of engaging especially students and the internship opportunities and how do we help students follow their passion? I know Mr. Loudermilk was talking about the App Challenge. My office did that as well. I had Adam Barton from Sunset High School win the App Challenge. He also happens to be a very talented pianist, which is confirming my theory that integrating the arts into STEM results in more creative, innovative people.

Do any of you have any sort of new approaches to bringing, you know, first generation students, for example, and students from underrepresented groups into the STEM fields?

Dr. GONZÁLEZ. Yes. We are very committed to increasing the diversity not just in our collaboration but in general in the scientific community. We have been working very closely with the National Society of Hispanic Physicists and Black Physicists for including—for affiliating students and teachers from colleges with large underrepresented—

Ms. BONAMICI. Excellent—

Dr. GONZÁLEZ. —minorities. We work with several of those universities like Southern University, University of Texas, Rio Grande Valley. Thank you for that work. It's important to get them interested and also to retain them by having positions and having good working environments.

And then finally, I know it's been touched on this morning, but could you expand a little bit on the importance of international collaboration? I know that there was a lot going into this, but we also talk about this when we talk about, you know, space research. You know, we have jurisdiction over NASA, for example. Can you talk about the importance of the international collaboration with LIGO and this discovery?

Dr. GONZÁLEZ. Yes. We are very proud of having had very international effort on this. It's been led by the United States. The United States has been a leader in this effort both within the scientific—the LIGO scientific collaboration, which is an international collaboration. We have been living this in the United States but also living—uniting all the other collaborations, getting agreements with all the other collaborations so that we don't compete with each other but we collaborate for better science. We collaborate in forming a network.

And that has been very important and very efficient, too, because we have recruited many students and scientists from other countries to help us here in the United States, for example.

Ms. BONAMICI. That's a great model for collaboration. And I see my time is expired. I yield back. Thank you again, Mr. Chairman.

Chairman SMITH. Thank you, Ms. Bonamici.

That was very deftly done to include the University of Oregon to the extent that you did.

Ms. BONAMICI. It is my alma mater.

Chairman SMITH. Totally understandable.

Thank you all for being here today. This was really a special and even unusual hearing just because there was so much to learn and so much excitement about a new discovery. It's also nice, I think, from our point of view just to see how much mutual support there is among you all, how much collaboration, even camaraderie perhaps. So I appreciate that. We had a full house when we began today. They've trickled out over time, but it was nice to start off with every seat in the room occupied and a tribute to what you all have done. So thank you all very much.

Dr. GONZÁLEZ. Thank you all for holding this hearing.

Dr. CRIM. Thank you, Mr. Chairman.

[Whereupon, at 12:05 p.m., the Committee was adjourned.]



## Appendix I

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### ANSWERS TO POST-HEARING QUESTIONS

## ANSWERS TO POST-HEARING QUESTIONS

*Responses by Dr. Fleming Crim*HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY  
SUBCOMMITTEE ON RESEARCH AND TECHNOLOGY  
SUBCOMMITTEE ON OVERSIGHT

“Unlocking the Secrets of the Universe: Gravitational Waves”

Dr. Fleming Crim, Assistant Director, Directorate of Mathematical and Physical Sciences, National Science Foundation

Response to Questions submitted by Rep. Randy Hultgren

1. How has NSF implemented the recommendations from the National Academy of Sciences report, *Challenges and Opportunities in Undergraduate Physics Education*, especially Recommendation D2 and D5?

**Recommendation D2** - Agencies should educate principal investigators in all areas of physics research about how physics education research (PER) methods and PER-based materials can help them build a relevant educational component for their research projects so that they have a broader impact on the formal or informal education of broad and diverse populations of learners.

**Recommendation D5** - Agencies should support research into the impact of instructional improvements on students from groups underrepresented in physics and the impact on capable students who choose not to pursue physics.

**NSF Response:** National Science Foundation staff are regular organizers of and presenters in workshops and panel sessions at major professional meetings such as the American Physical Society, the American Astronomical Society, and the American Association of Physics Teachers, with special attention paid to educating attendees (which include both current and prospective Principal Investigators) about Physics Education Research results and methods. For the past two decades the National Science Foundation has funded the “Physics and Astronomy New Faculty Workshops” which provides a forum for newly hired tenure track physics and astronomy faculty across a range of institutional types to learn about Physics Education Research from its leading researchers. Many National Science Foundation funded projects examine questions regarding the impact of Physics Education Research and other discipline-based education research efforts on improving student learning. An important emphasis in such projects is consideration of factors that affect physics learning, and learning in STEM disciplines more broadly, by students underrepresented in their participation in physics (or STEM more generally). National Science Foundation program officers look regularly for opportunities to co-fund such work.

*Responses by Dr. David Reitze*

**HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY  
SUBCOMMITTEE ON RESEARCH AND TECHNOLOGY  
SUBCOMMITTEE ON OVERSIGHT**

"Unlocking the Secrets of the Universe: Gravitational Waves"

Dr. David Reitze, Executive Director of LIGO, California Institute of Technology  
Professor of Physics, University of Florida

Questions submitted by Rep. Randy Hultgren

1. The National Academy of Science report, *Challenges and Opportunities in Undergraduate Physics Education*, noted some problems with some in the "physics community remain[ing] in a traditional mode in which the primary purpose of physics education is to create clones of the physics faculty." How have your institutions and programs utilized and engaged the undergraduate communities that may not go into academic careers in physics? Specifically, how have your programs implemented the detailed recommendation for physics department leadership in Recommendation B2 and B3?

**Recommendation B2 - Departmental leadership should discuss and consider how to implement physics-specific learning goals, recognizing the needs of varying student constituencies, the needs of future employers and teachers of these students, and the views of alumni.**

**Recommendation B3 - Departmental leadership should recognize in the overall program the role of activities outside the classroom.**

**Response:** I will answer specifically with respect to programs that the LIGO Laboratory have developed and instituted in cooperation with the California Institute of Technology (Caltech). While the LIGO Laboratory is not a degree-granting department, one of our primary missions is the training of scientists and engineers. LIGO Laboratory administers a number of formal and informal programs that support the recommendations above.

As noted in *Challenges and Opportunities in Undergraduate Physics Education* (p. 87) important goals for physics majors should include participation in undergraduate research programs. Through Caltech's Summer Undergraduate Research Fellowship (SURF) program, LIGO hosts 30-40 undergraduate physics majors each year at the Caltech campus and at the LIGO Hanford and Livingston Observatories. Each student is placed in a research environment where they work closely with senior scientists, junior scientists, postdoctoral fellows, and graduate students in physics to carry out meaningful and challenging research projects related to different aspects of gravitational-wave science involving theory, experiment, computation, and modeling.

As part of their program, all SURF students are required to write interim and final research reports and give oral presentations on the outcomes of their research (p. 88), and many are required to carry out statistical analyses to assign error bars or confidence levels to their results. In addition, students become familiar with current themes in numerical simulations using MatLab, Mathematica, or by writing their own algorithms in Python.

Caltech faculty and LIGO Lab senior research staff mentor undergraduate SURF students and provide advice on graduate programs, academic careers in physics, as well as on alternative career paths (p. 89). The students participate in an active social program developed by the SURF program designed to build camaraderie (p. 89), living in co-located housing, and taking part in social programs including visits to the Observatories and surrounding areas.



*Responses by Dr. Gabriela González*

**HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY  
SUBCOMMITTEE ON RESEARCH AND TECHNOLOGY  
SUBCOMMITTEE ON OVERSIGHT**

"Unlocking the Secrets of the Universe: Gravitational Waves"

Dr. Gabriela González  
Professor of Physics and Astronomy, Louisiana State University  
Spokesperson, LIGO Scientific Collaboration

Questions submitted by Rep. Randy Hultgren

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**Response:**

The LIGO Scientific Collaboration (LSC) takes pride in taking care of career development for all its younger members, including undergraduate students. Although most of the students involved in LSC projects are graduate students, several institutions have programs for summer undergraduate research, where younger students not from LSC institutions broaden their horizons learning about not only gravitational wave physics and astronomy, but also about working in a large project in national facilities and with large teams – these are essential skills especially for non-academic careers.

As mentioned at the hearing, the broadness and openness of the collaboration research provides an important learning and education environment for all the young people. Thanks to this, many people receiving training in the LSC are now important contributors not just to higher education in academia, national

laboratories and high school science education, but also to cutting-edge industry in the US.

An incomplete list of companies with LSC graduates as employees are the human genomics industry, US health care industry, bio-medical information, Microsoft, Google, Boeing, Space-X, Northrop Grumman, Synaptics, Celestron, Luminet, Cytec Engineered Materials, GE Global Research, Geneva Trading, Seagate. (A few other companies not mentioned at the hearing: IBM, Lincoln National Laboratories, Thermo Fisher Scientific, Two Sigma Investment management, Raytheon, Accuray medical equipment).

The physics and astronomy learning goals we have for contributors to our LSC science recognize the needs of future academic and non-academic employers, and we plan to get help from LSC graduates in tailoring the learning experiences, both for undergraduate and graduate students, to help them succeed in a broad range of careers.

We take advantage of the list of LSC alumni not in academia to overcome the perceived bias towards an academic career due to the daily and natural contact with academics for undergraduate and graduate education. Examples of activities “outside the classroom” we pursue are:

- Workshops at Collaboration meetings with LSC alumni sharing their experience, and differences in how to find and pursue a career in industry.
- Job advertisements sent to all LSC members highlighting opportunities in industry and national laboratories, as well as international opportunities.
- A LinkedIn group with LSC alumni and current LSC members. The group has currently 162 members, about a third LSC graduates not in academia.
- Site visits to companies and laboratories guided by LSC alumni. In the last Collaboration meeting in Pasadena, CA, interested attendees visited Space-X facilities.

*Responses by Dr. David Shoemaker*

**HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY  
SUBCOMMITTEE ON RESEARCH AND TECHNOLOGY  
SUBCOMMITTEE ON OVERSIGHT**

"Unlocking the Secrets of the Universe: Gravitational Waves"

Dr. David Shoemaker, Director of LIGO MIT, Massachusetts Institute of Technology

Questions submitted by Rep. Randy Hultgren

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**Response:** The LIGO Laboratory at MIT participates fully in the academic life at MIT, and MIT has four faculty members in our roughly 27-person group: two active teaching members, one emeritus, and a new position just created, to support our academic and teaching responsibilities to the MIT community.

As a research staff member rather than a professor, I work with many students outside the classroom but not generally inside; thus I am better qualified to respond to the second part of your question. But let me tell you a little bit about how undergraduate physics is taught in MIT classrooms, and then I'll talk about how undergraduates play a role in MIT's larger research groups like the MIT LIGO Lab.

All MIT undergraduates are required to take two semesters of physics as part of the General Institute Requirements (which also include courses in Biology, Chemistry, Math, Communications, and Humanities, Arts, and Social Sciences). Since only about 7% of them go on to get Physics degrees, we obviously have quite varied constituencies. And we do recognize that in our programs. There are multiple tracks for fulfilling the core Physics requirement—for example, there are three different introductory mechanics courses. One is taught at a mathematically advanced level for students who enter MIT with a strong background in physics and math. One is

an extended semester which slows down the pace a little for students with less than average preparation. But the one in the middle is the biggest. For about fifteen years now, it's been taught using what we call the TEAL format— Technology Enabled Active Learning—in which students and teachers can easily move back and forth between lecture mode, experimentation, demonstrations, and discussion, much of it done in teams. This learning format draws heavily on work in the Physics Education Research community over the last 25 or more years<sup>i</sup>, which is very relevant to

**Recommendation B2.** MIT continues to explore new teaching methods and learning environments, for physics as well as many other subjects.<sup>ii</sup>

As for **Recommendation B3**—MIT has always emphasized a mix of learning activities. Our motto is “Mens et manus”, or “Mind and hand.” There are many different programs and opportunities for undergraduate students to get their hands dirty (or very clean, if they are working on our optics) as they learn. Most – 88% – of our undergraduates participate in research (for pay or academic credit) through our Undergraduate Research Opportunities Program. The MIT LIGO Lab, as a microcosm of physics education at MIT, subscribes fully to this approach, with 5-10 undergraduates active each year and some 100 undergraduates over the lifetime of gravitational research at MIT. Projects involve interaction with faculty, post-docs, engineers, and professional scientists, as well as graduate students. An undergraduate thesis is required in physics at MIT, and this puts undergraduates in frequent close contact with researchers with extensive non-classroom experience. While working with the MIT LIGO group, undergraduates participate fully in the life of the LIGO Scientific Collaboration, and see the full range of activities undertaken there. Due to MIT’s long history in instrumentation for gravitational wave detection, many of the undergraduate projects are ‘hands on’ giving the undergraduates extensive experience for practical applications of their physics education.

While it is difficult to track undergraduates in the long term, a survey of recent graduate students from the MIT LIGO Laboratory show that 7 of 17 – 41% – have chosen non-academic careers. An informal survey of MIT undergraduates indicates that 20-30% go on to physics graduate school, and so a significant number choose other paths than a linear one to an academic path. Thus, we believe we are training scientists ready to attack a wide range of challenges in but also certainly outside of academia.

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<sup>i</sup> For recent reviews see Docktor, Jennifer L., and José P. Mestre. “Synthesis of discipline-based education research in physics.” *Physical Review Special Topics-Physics Education Research* 10.2 (2014): 020119 and Singer, Susan R., Natalie R. Nielsen, and Heidi A. Schweingruber. *Discipline based education research*. Washington, DC: National Academies Press (2012).

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<sup>ii</sup> The website [future.mit.edu](http://future.mit.edu) details the work of an Institute-wide *Task Force on the Future of Education at MIT* in 2013. A follow-on study, sponsored by the Carnegie Foundation, looks at how online tools can catalyze educational reforms based on research advances in multiple fields. It is available at [oei.mit.edu/final-report](http://oei.mit.edu/final-report).