

An aerial photograph of a vast, flat, icy landscape, likely a frozen sea or a large ice field. A long, narrow, straight channel of open water or thin ice stretches from the foreground towards the horizon. The channel is flanked by thick, textured ice. In the distance, a low, hazy horizon line separates the ice from a pale, overcast sky. The overall color palette is dominated by blues, greys, and whites, with a slight brownish tint in the upper portion of the image.

# Gravitational Waves:





The 2015 detection of gravitational waves, ripples in space-time analogous to the electromagnetic waves that carry sunlight to the Earth, shook the international physics community. The feat not only validated Einstein's theory of general relativity but also opened a new field of astronomy that will essentially allow us to listen to the most energetic and exciting processes in the universe. [physics@mit](mailto:physics@mit) asked Professor of Physics Scott Hughes to describe the discovery and why it is so important.

by Scott Hughes  
with Elizabeth Thomson

# Opening Einstein's Ears



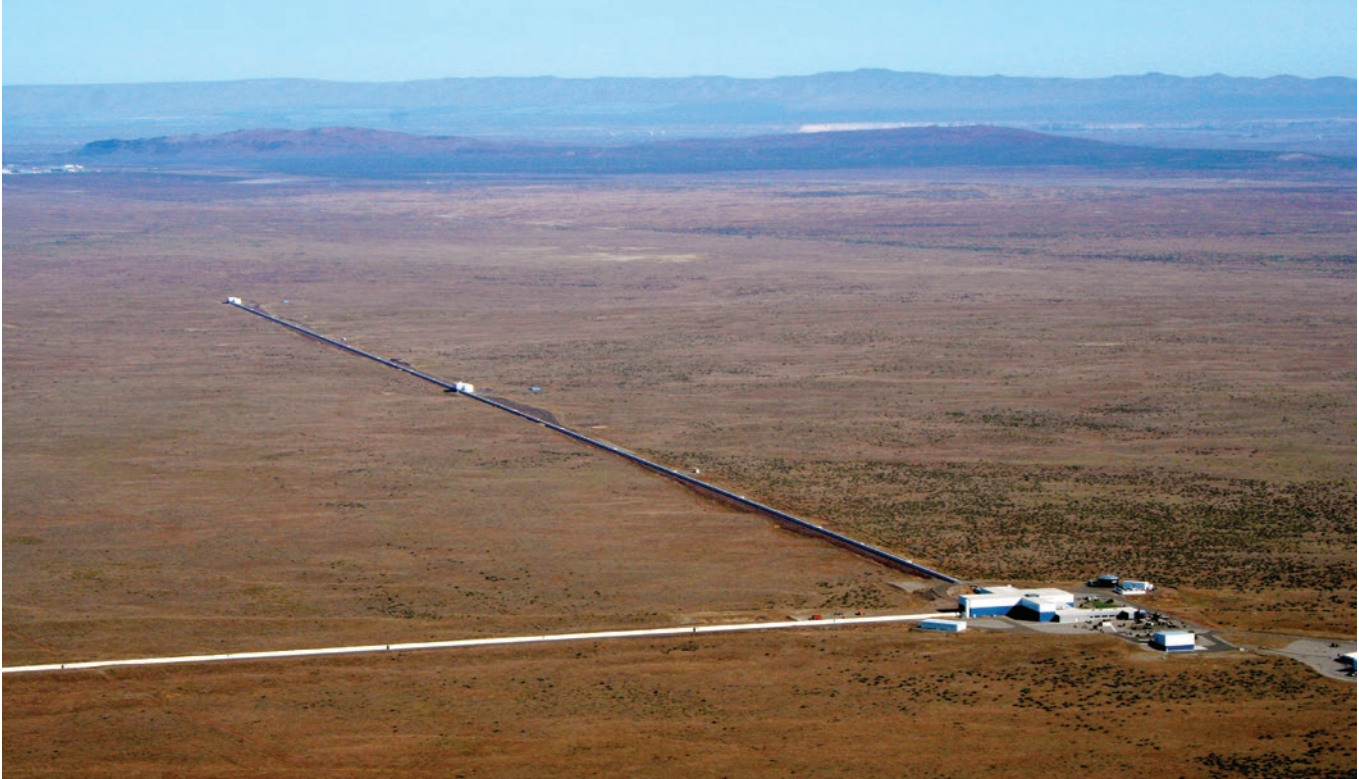


FIGURE 1

**Aerial view of the Hanford, WA, LIGO site.** This is one of the two large-scale laser interferometers in the U.S. that are used to detect and measure gravitational waves, and is part of a global network of such detectors. [Caltech/MIT/LIGO Lab]

## What are gravitational waves, and why have they been so difficult to detect?

Gravity is a field, or force, that acts across space. The Sun's gravity keeps the Earth in orbit around the Sun; the Earth's gravity keeps the moon in orbit around the Earth and us on the surface here. All fields have a form of radiation associated with them. If you accelerate the source of an electromagnetic field, you get electromagnetic waves of radiation, or light. If you accelerate a source of gravity—for instance, by having two stars orbit about one another—you get gravitational waves. But gravity is a very weak force. It's the weakest of the four fundamental forces that govern the interactions between matter and objects in our universe.

It's actually not hard to demonstrate that gravity is such a weak force—we do so every time we use a refrigerator magnet to lift paperclips off a table. That may seem kind of trivial, but there's actually something quite profound going on. Pulling the paperclips up is the electromagnetic force arising from a few grams of metal. Pulling the paperclips down is the gravitational force arising from six million quadrillion tons of the Earth. You can overcome the gravity of the entire Earth using electromagnetic effects arising from a tiny piece of metal.

Gravity may seem important to us on Earth, but in truth we only notice it because we live our lives right next to a very large body of mass. Changes to gravity due to distant objects will be really, really weak and very hard to measure.

## Why is the study of gravitational waves important?

For one, we physicists like solving hard problems. Can we tease out the weak signals associated with this weak form of radiation and see their imprint on a detector? Second, the study of gravitational waves gives us a new way of doing astronomy with some of the most fascinating objects in our universe. Like I said, gravity is weak. If you want its signal to have any chance of being measurable, it should

be as strong as it's possibly going to be. And if it's going to be strong, it's going to involve objects that generate really strong gravity like black holes and neutron stars, which compress the mass of the star into a ball that is just a few or a few tens of kilometers across. This gives us a new mechanism by which we can probe these fundamental constituents of our universe. Finally, because gravity is so weak, it's *really hard* to test it. So this also gives us a new way to do that.

### Can you give a history of the field?

In 1915, Einstein completed the theory of general relativity, which provided a description of gravity consistent with his earlier theory of special relativity. Right away people began examining the consequences. And what came out was the prediction of gravitational waves. However, their effects would be so weak that no one thought they could ever be measured. The theory sat for years.

Then in the 1960s astronomers began discovering objects like black holes that were so massive and compact that suddenly general relativity stopped being just of academic interest. People thought, "We need to understand general relativity to explain these objects." And they began to realize that gravitational waves could be important.

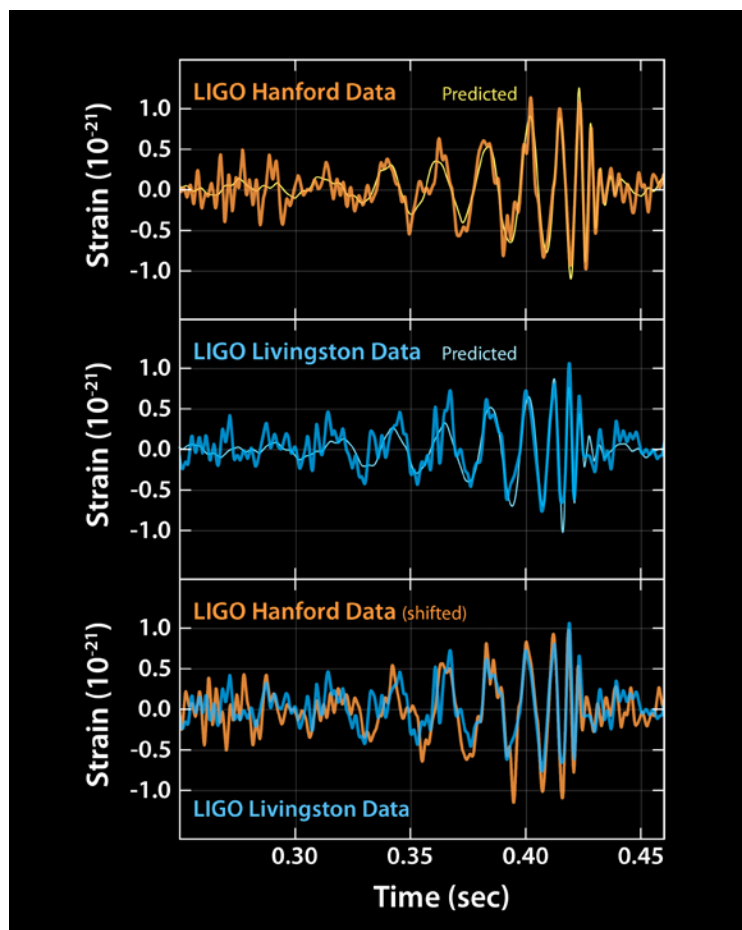
Joseph Weber was one of the first to say, "If these gravitational waves are out there, we should try to measure them," and he built a detector. It didn't work, but Joe was the first to realize that this could be done and took a stab at it. Others began to develop gravitational antennas. The idea is that these incredibly weak signals will cause masses which make up the antennas to wiggle a tiny, tiny bit. We read out the gravitational wave by monitoring the masses' positions. It's such a small effect, though, that a gnat sneezing could overcome that signal. So the experimental challenge was, "How can we get rid of all sources of noise so that the only signal that stands out is due to the gravity of some distant astronomical object?"

The person who is universally regarded as having thought this through from beginning to end and getting all the details right is Rainer Weiss, here at MIT. In 1972 he published the first detailed explication of how to build a detector like the Laser Interferometer Gravitational-Wave Observatory (LIGO) that captured the first signals.

In the meantime, Kip Thorne, who was later my PhD advisor at Caltech, was thinking about the sources of these gravitational waves. He was connecting the signal that a LIGO would measure to the astronomy of the event that generated it.

FIGURE 2

**The gravitational-wave discovery data.** Top panel shows data taken at the Hanford, WA, LIGO site on September 14, 2015, at 09:50:45 Universal time; middle panel shows the data taken at the Livingston, LA, LIGO site at the same time. In both plots, the lighter trace shows as a comparison the best fit model computed using a supercomputer simulation of binary black hole coalescence. Bottom panel: the data from the two sites are superimposed on one another. The Hanford data are shifted by 6.9 milliseconds to account for the time offset between the two sites associated with the speed of light propagation from one site to the other. [LIGO]



## Tell us about the discovery itself.

LIGO completed construction in 1999. A scheduled overhaul to improve its sensitivity became operative in September 2015. We didn't expect any immediate results. But soon rumor had it that something had been detected.

Not too long after this, some of the people in LIGO here at MIT realized that I needed to be briefed on what was happening. (I'm not part of the experiment, but I'm involved closely enough that they realized I had to be informed.) A friend who briefed me said, "Our analyses are suggesting that we picked up a gravitational wave signal from the merger of two black holes." He held out his smartphone and showed me the data.

I began my PhD in 1993. As it happens, the first chapter of my thesis is a study of the gravitational waves that we would expect from the merger of two black holes. So I had seen that shape, that particular pattern of wiggles, in my mind for over twenty years, and here it was in the output of the experiment, displayed on a smartphone.

## You've described the field of gravitational-wave astronomy as "opening Einstein's ears." Could you explain?

Most of astronomy to date has been based on gathering light in some form or another. You can think of every advance in astronomical technology since Galileo first pointed a telescope at Jupiter as essentially augmenting our eyes.

Now we have this new tool that allows us to learn about the cosmos in a completely new way: through the detection and analysis of gravitational waves. I describe gravitational-wave astronomy as being ear-like in part because it turns out that the typical signals we expect from events large enough to create measurable signals in LIGO happen to lie in the frequency range that our ears are sensitive to. So we can take this waveform, turn it into a sound, and listen to it. And there's science in that.

If I played for you the sound of the gravitational waves that theory predicts when two black holes merge with one another, you would hear a single tone, but the tone is slowly increasing in frequency and volume as it moves forward.

What's happening is that two black holes are orbiting one another. The frequency of their orbit is the tone that you are hearing. But gravitational waves take energy away from the orbit and they cause the two black holes to fall towards each other. And when that happens, the orbit gets faster, and the tone moves to a higher frequency. Also, because they're moving faster, the waves get stronger which is why the volume goes up.

So by analyzing the sounds created by gravitational waves, you're using general relativity to help you understand the characteristics of the sources that made those waves.

## How many MIT scientists are working on gravitational waves?

There are some 40 to 45 people involved, including faculty, research scientists, postdocs, and both graduate and undergraduate students.

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# Timeline of interesting events

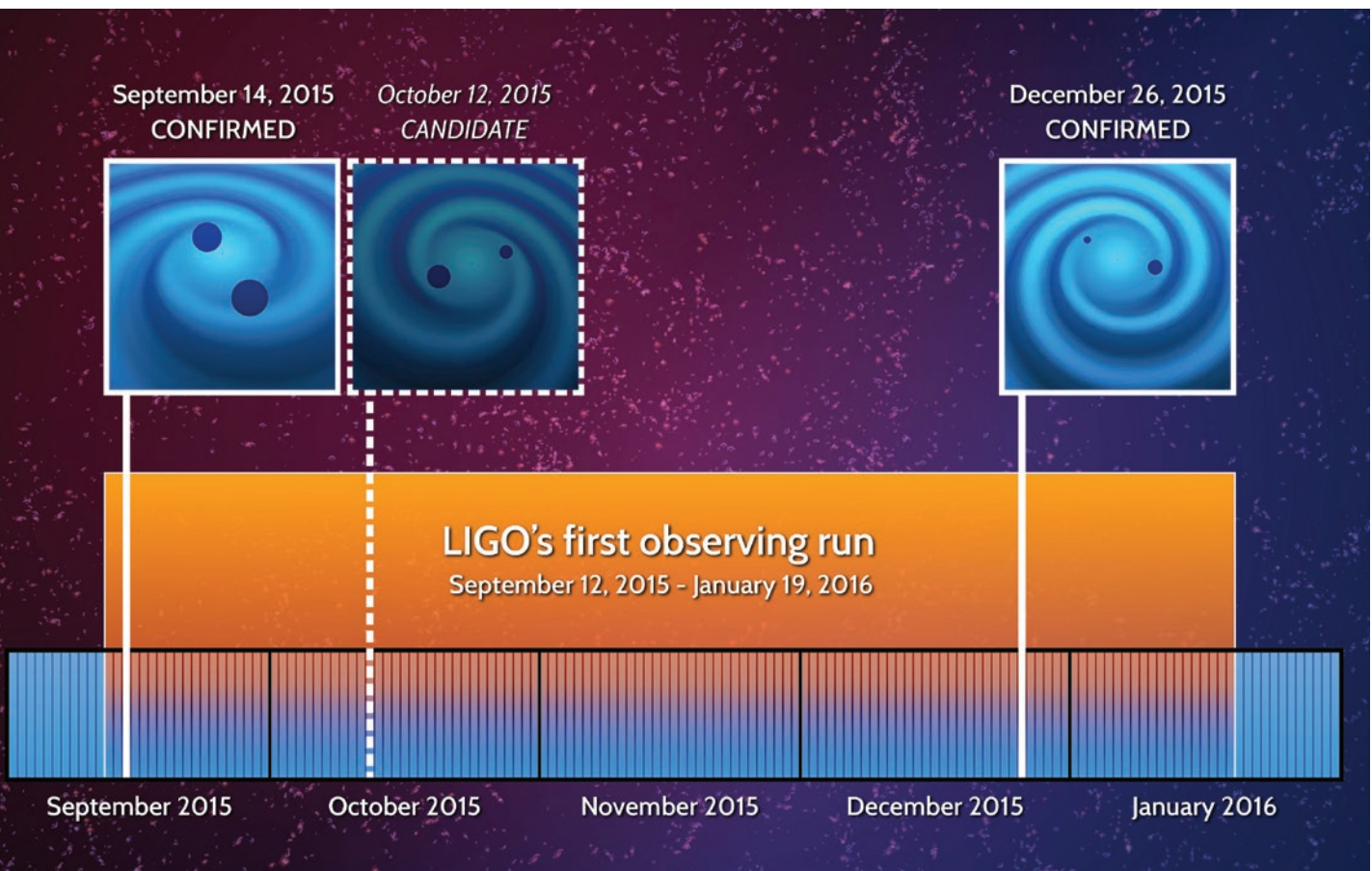
## registered in LIGO's first observing run in late 2015/early 2016

**In the first observing run**, two events [1] were statistically significant enough to merit confirmation as gravitational wave detections. The first event, GW150914, was measured on September 14, 2015, shortly after LIGO began its first observing run. This event was consistent with a 29 solar mass black hole merging with a 36 solar mass black hole, about 1.2 billion light years away.

On December 26, 2015, a second confirmed event was recorded, consistent with a 7.5 solar mass black hole

merging with a 14 solar mass black hole at a distance of about 1.3 billion light years.

Another possible candidate event, LVT151012, was detected on October 12, 2015. It appears to have come from a 13 solar mass black hole merging with a 23 solar mass black hole, at a distance of about 3.3 billion light years, but because of this great distance the signal is weaker and the statistical significance is too small to make it a confirmed event. *[Image Credit: LIGO]*



(continued from page 68)

The four current faculty at MIT are Nergis Mavalvala and Matt Evans, who work on the LIGO instrument itself; Salvatore Vitale, who works on data analysis; and myself. I work on theoretical modeling and understanding the astronomy of the sources. Rai Weiss is an emeritus faculty member but still very involved. Key among the MIT research scientists are David Shoemaker and Peter Fritschel, who respectively led the construction and commissioning of Advanced LIGO, and Erik Katsavounidis, who has long led MIT's activities in data analysis.

The MIT team is part of a collaboration of more than 1,000 scientists from over 80 institutions around the world.

### What's next?

Some of the big questions we're looking at right now include: How common are binary black holes? What kinds of properties are they going to have? Will there be other binaries? Will we get signals that involve neutron stars? Is there something going on in the universe that we haven't thought of that will produce a signal that we can unambiguously see and detangle in our detectors?

### What books could you recommend to people interested in this field?

One of the best is *Einstein's Unfinished Symphony: Listening to the Sounds of Space-Time* by Marcia Bartusiak (The Berkeley Publishing Group/Penguin Putnam Inc.; 2000). Marcia has written an update over the last year because the symphony is no longer quite so unfinished.

#### ENDNOTE

- [1] On June 1, 2017, the LIGO-Virgo Collaboration announced that they made their third confirmed gravitational wave detection on January 4, 2017, during their second observing run. The waves measured in this event came from the coalescence of a 31 solar mass black hole with a 19 solar mass black hole at a distance of 2.9 billion light years. This discovery was made public as this article was being finalized for publication.

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SCOTT HUGHES' research is in astrophysical general relativity, focusing on black holes and gravitational-wave sources. For the last few years he has been modeling the sources that a space-based version of a detector like LIGO could detect. The Laser Interferometer Space Antenna (LISA), which is currently under development, will be sensitive to signals involving much more massive black holes than those detected by LIGO. Hughes received his BA degree in physics from Cornell University in 1993. He received his PhD in physics from the California Institute of Technology. After spending one year working in computational relativity at the University of Illinois, he returned to Caltech as a postdoc and instructor in the Physics Department. Hughes then spent two and a half years as a postdoc at the University of California, Santa Barbara, before moving to MIT in January 2003.