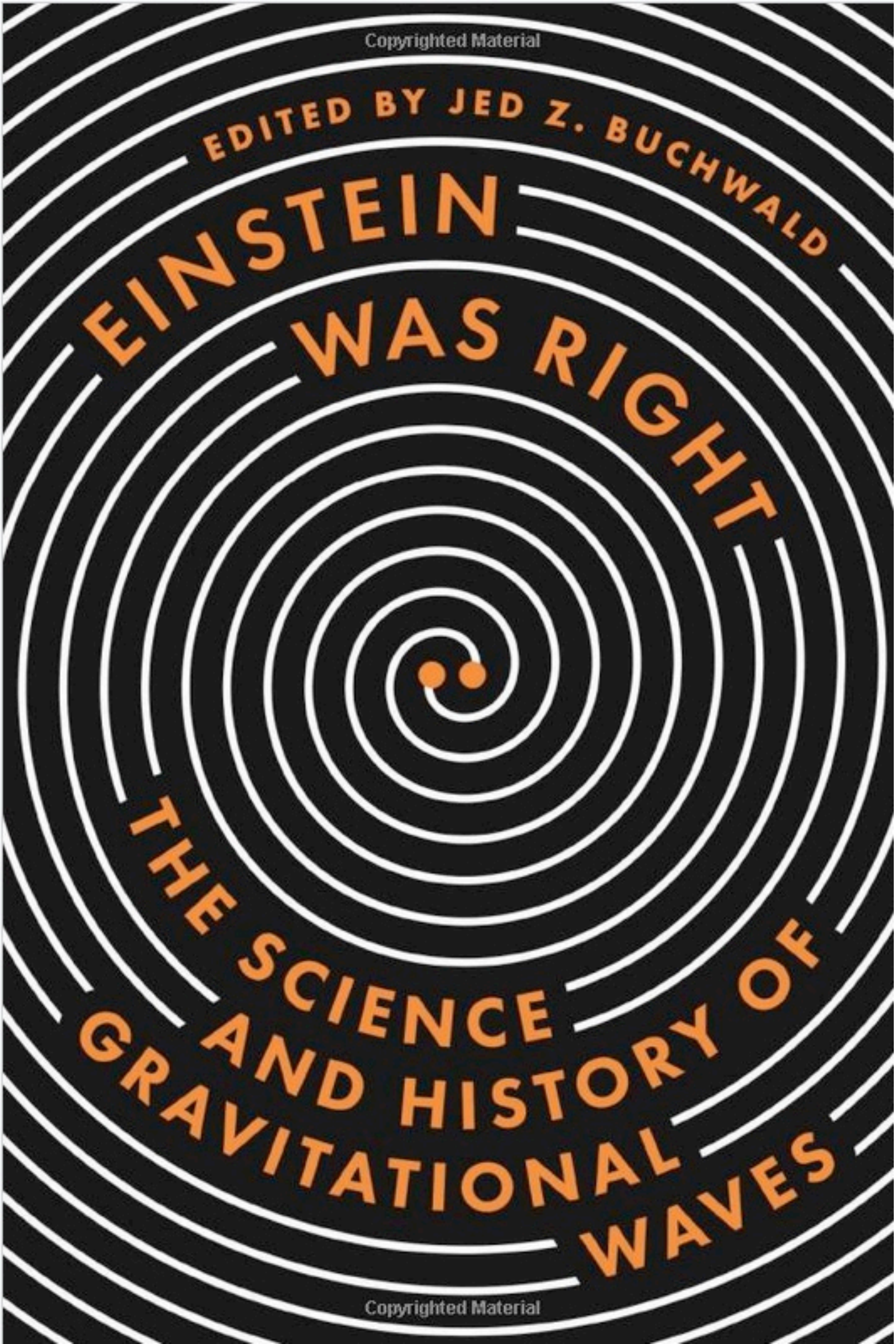

EDITED BY JED Z. BUCHWALD

EINSTEIN WAS RIGHT

THE SCIENCE AND HISTORY OF GRAVITATIONAL WAVES

GENERAL RELATIVITY AT ONE HUNDRED:

THE 6TH BIENNIAL BACON CONFERENCE

Thursday, March 10, 2016, to Saturday, March 12, 2016

THURSDAY, MARCH 10

Baxter Lecture Hall, Caltech

Bacon Award Public Lecture
4:00 p.m.

"The Genesis and Transformations of General Relativity"
Jürgen Renn, Director, Max Planck Institute for the History of Science

FRIDAY, MARCH 11

Rothenberg Hall, The Huntington Library, Art Collections, and Botanical Gardens

Morning Session
9:30 a.m. – 12:00 p.m.

Welcome: Steven Hindle, W.M. Keck Foundation Director of Research, The Huntington
Chair: Hirosi Ooguri, Fred Kavli Professor of Theoretical Physics and Mathematics; Director of the Walter Burke Institute for Theoretical Physics, Caltech

"The Quest for Gravitational Waves"
Barry Barish, Ronald and Maxine Linde Professor of Physics, Emeritus, Caltech

"The Search for Gravitational Waves: Sociological and Philosophical Investigations"
Harry Collins, Professor, School of Social Sciences, Cardiff University

Afternoon Session
2:00 p.m. – 5:30 p.m.

Chair: Jürgen Renn, Director, Max Planck Institute for the History of Science

"Was Einstein Right? A Centennial Assessment"
Clifford Will, Distinguished Professor of Physics, University of Florida

"Einstein & Caltech"
Diana Kormos-Buchwald, Professor of History, Caltech

"Unifying GR with Quantum Theory"
John H. Schwarz, Harold Brown Professor of Theoretical Physics, Emeritus, Caltech

GR 100 Public Lecture
7:30 p.m.

"100 Years of Relativity: From the Big Bang to Black Holes and Gravitational Waves"
Kip Thorne, Richard P. Feynman Professor of Theoretical Physics, Emeritus, Caltech

SATURDAY, MARCH 12

Hameetman Auditorium, Cahill Center for Astronomy and Astrophysics, Caltech

Morning Session
9:00 a.m. – 12:30 p.m.

Welcome: Hirosi Ooguri, Fred Kavli Professor of Theoretical Physics and Mathematics; Director of the Walter Burke Institute for Theoretical Physics, Caltech
Chair: Harry Collins, Professor, School of Social Sciences, Cardiff University

"Searching for a Cosmological Background of Gravitational Waves"
Jamie Bock, Professor of Physics, Caltech; Jet Propulsion Laboratory Senior Research Scientist

"History of Gravitational Wave Emission"
Daniel J. Kennefick, Assistant Professor of Physics, University of Arkansas

"Gravitational Waves: A New Tool for Observing the Cosmos"
Alessandra Buonanno, Director, Max Planck Institute for Gravitational Physics

Afternoon Session
1:30 p.m. – 4:00 p.m.

Chair: Barry Barish, Ronald and Maxine Linde Professor of Physics, Emeritus, Caltech

"How General Relativity Shaped Twentieth-Century Philosophy of Science"
Don Howard, Director, Reilly Center for Science, Technology, and Values, University of Notre Dame

"Quantum Information and Spacetime"
John Preskill, Richard P. Feynman Professor of Theoretical Physics, Caltech

Organized by Caltech's Division of the Humanities and Social Sciences and Division of Physics, Mathematics & Astronomy with the Research Division of The Huntington Library, Art Collections, and Botanical Gardens, this conference is made possible by the generous financial support of the Francis Bacon Foundation, Caltech's Walter Burke Institute for Theoretical Physics, and The Huntington. Additional information is available at gr100.caltech.edu.

FIGURE 0.1. Poster for the GR100 Conference, March 10–12, 2016.

3

One Hundred Years of Relativity From the Big Bang to Black Holes and Gravitational Waves

KIP S. THORNE

Newton, Einstein, and Their Frameworks for the Laws of Physics

In 1687, Isaac Newton gave us a framework for all the laws of physics that govern the universe, a framework that lasted for 218 years. It was based on the concepts of absolute space and absolute time, and on forces, accelerations, and other things of everyday experience.

In 1905, Albert Einstein gave us a *new* framework for the laws of physics, one that's now been in place for 111 years. Einstein called his framework the *Principle of Relativity*. It says that all the laws of physics must be the same in every freely moving laboratory everywhere in the universe. So his framework is actually a law that governs the laws of physics. That was audacious!

Einstein's framework has some amazing, counter-intuitive consequences. For example, if I measure the speed of light and get 300,000 kilometers per second, and you move past me at a speed of 200,000 kilometers a second, and you measure the speed of light, do you get the difference, 300,000 minus 200,000, that is, 100,000 kilometers per second? Our ordinary intuition about how speeds operate would say yes, you should measure 100,000. But Einstein's framework says NO, you must get the same as I got: 300,000.

How can that be? Something weird must be going on in space and time. And indeed it is. By exploring his framework deeply, Einstein concluded that you and I, moving at different speeds, must disagree about lengths, about times, and even about the concept of what events are simultaneous. So Einstein shook up the whole foundation of things that we thought we understood.

And then he looked at Newton's law of gravity, which says that the gravitational force by which the Sun pulls on the Earth varies inversely as the square of the distance between them. Einstein asked, the distance as measured by whom?

The Sun and the Earth disagree on their separation, because they're moving relative to each other. Hence, we have a quandary. Which distance should appear in Newton's law? That measured by the Sun, or the one measured by the Earth? This muddle shows, Einstein reasoned, that Newton's law of gravity violates my principle of relativity. Therefore, Newton must be wrong.

That was also audacious, since Newton then was universally recognized as the greatest scientific mind of all time. Here is Einstein, a very young man, not yet widely recognized as a genius, coming out and saying to the world that Newton was just plain wrong. Gravity has to behave differently.

Einstein's Search for a Relativistic Description of Gravity: The Warping of Time and Space; General Relativity

Einstein's next challenge was to find a whole new way to describe gravity, a way compatible with his principle of relativity. Jürgen Renn, in his beautiful Bacon lecture (which is included in this book), describes in careful detail how Einstein struggled to find his new laws of gravity, and the path that he followed. I'm going to give you an extremely simple version of this, one that I have chosen for fairly quick pedagogical clarity rather than faithfulness to Einstein's actual path.

Let me begin with what I like to call *Einstein's Law of Time Warps* (though that is not what Einstein called it): "Things like to live where they age the most slowly, and gravity pulls them there." (Isn't that where you would like to live?)

Einstein gave a beautiful mathematical formulation of this law, but I'll forego his math here. From his mathematical formulation, one can conclude that the Earth's mass warps time and this time warp produces the Earth's gravity. That's how Earth's gravity comes about. More specifically, time must slow by one second in 100 years on the Earth's surface compared to far from Earth, as that is the amount of slowing required to produce the gravity that we measure.

Now, that's not very much slowing. We don't gain an awful lot of extra life by living on the surface of the Earth. But that is the right amount of time slowing to produce the gravitational pull that we experience. In 1976, this quantitative prediction was verified to a precision of one part in 10,000, that is, 0.01%, when Robert Vessot of the Harvard-Smithsonian Center for Astrophysics flew an atomic clock in a rocket up to high altitude and compared its ticking rate to that of clocks back down on Earth.

Near a black hole, such as Gargantua in the movie *Interstellar* (I'll use *Interstellar* to illustrate several of Einstein's relativity predictions), gravity is enormously stronger than near Earth, so the slowing of time is enormously greater. In *Interstellar*, there's a planet (called "Miller's planet") that orbits near the surface (the "horizon") of Gargantua. One hour on that planet is the same as seven years on Earth. This enormous slowing of time produces gravity near Gargantua that is enormously larger than on Earth. This is illustrated compellingly in the movie. Cooper, speaking with his daughter, tells her that in his quest to save the human race, he may travel near a black hole and while there may age far more slowly than she does on Earth—so much more slowly that when he returns, she might be the same age as he, her father.

And that is what happens. When he emerges from the planet near Gargantua, she has grown up and become a brilliant theoretical physicist, while he has aged hardly at all. And then he goes down near the black hole Gargantua again, and returns to Earth and meets her. She is now a very old woman, and he still has hardly aged at all.

In this film, which was viewed by a worldwide audience of roughly a hundred million people, Einstein's Law of Time Warps truly came to life. That's one of the things that Christopher Nolan (the movie's director) and I wanted to achieve: to convey vividly some of the beautiful ideas, real science ideas, that are in general relativity.

In 1912, Einstein realized that, if time is warped, then space must also be warped. This warping of space was verified with high precision, again in 1976, by Robert Reasenberg and Irwin Shapiro, also of the Harvard-Smithsonian Center for Astrophysics. They led an experiment to measure the round-trip travel time of radio signals that go from the Earth to the *Viking* spacecraft (which was then in orbit around Mars) and back to Earth. Mars carried the spacecraft near the Sun as seen from Earth and then away, so the rays along which successive radio signals traveled on their journey from Earth to spacecraft and back were as shown in the bottom left of figure 3.1. Early in the experiment the rays traveled far from the Sun; later, quite near; and still later, far again. Reasenberg and Shapiro discovered that the round-trip travel times along these rays were not what you would expect if the space between the Earth and the spacecraft had been flat. There was an extra time delay in the waves' return (upper left

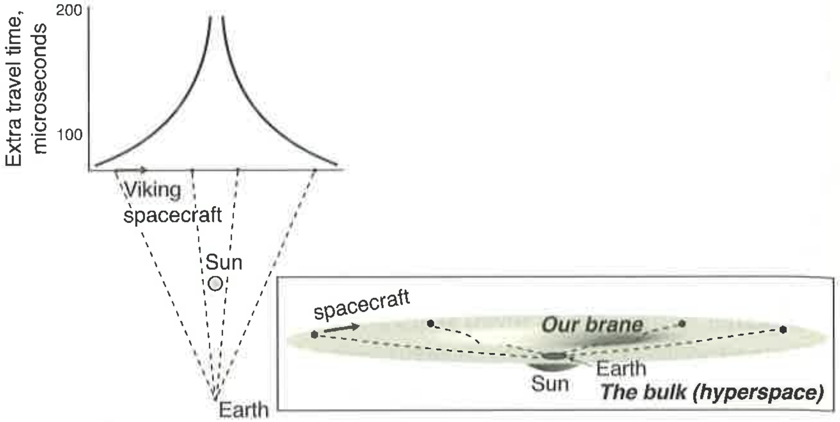

FIGURE 3.1. Reasenberg-Shapiro Experiment that measured the warping of space around the Sun using round-trip radio signals between Earth and the *Viking* spacecraft. Adapted from *The Science of Interstellar* by Kip Thorne.

of figure 3.1), which was small along rays that are far from the Sun, but grew as large as 200 microseconds when the waves passed near the Sun. From this and the fact that the speed of light (and radio signals) is always constant (according to Einstein's principle of relativity), they concluded that the *distances* that the signals traveled were longer than if space were flat. So space had to be warped. And they could infer the precise shape of the warped space from how the delay changed as the rays changed.

We can visualize this space warp by taking the plane formed by all the rays and embedding it in a three-dimensional flat space. Looking in from that flat space, we can see the warpage (lower right of figure 3.1). The warpage of space, inferred in this way, agreed beautifully with the predictions of Einstein's general relativity theory.

(As a side remark, in the movie *Interstellar*, our universe with its three space dimensions and one time dimension lives inside a "hyperspace" or "bulk" that has one more space dimension—the "fifth dimension" of the movie. If we ignore time, and focus on the surface formed by the radio rays of the Reasenberg-Shapiro experiment, then we get precisely the picture in the lower right of figure 3.1. *Thus, we can think of that picture as showing the warped space around the Sun as seen from the bulk.*)

Between 1912 and November 1915, Einstein struggled to discover the law that controls the warping of space and of time. On November 25, 1915, he finally figured it out. Today we call that law *Einstein's Field Equation*, and it has the deceptively simple form

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}.$$

Amazingly, once you know the meanings of this law's mathematical symbols and the physics that they embody, you discover that it contains almost everything there is to know about Classical Physics (non-Quantum Physics).

Consequences of Einstein's General Relativity Theory

In the remainder of this chapter, I will describe a few of the many things Einstein's equation has taught us in the past century.

If I had all day, I would talk about a huge number of fascinating consequences, among them:

- high-precision experimental tests of general relativity, in the solar system and in binary pulsars
- cosmology: the big bang, inflation, the cosmic microwave background radiation, the origin of galaxies and clusters of galaxies, dark matter, dark energy
- geometrodynamics: the nonlinear dynamics of warped spacetime
- gravitational waves: the opening of a wonderful new window onto our universe
- the incompatibility of general relativity and quantum theory: the quest for new laws of quantum gravity—string theory, M theory, loop quantum gravity
- speculations: cosmic strings, wormholes, backward time travel, macroscopic higher dimensions as in *Interstellar*

But as most of these are beyond the limitations of this chapter, I have chosen out of all of these topics just a few things that I find especially wonderful. My idiosyncratic choices are all topics that involve spacetime warps that occur without the aid of any matter whatsoever.

Black Holes

A black hole is the quintessential example of this: It is an object made entirely from warped spacetime. Figure 3.2 is a picture of what a non-spinning black hole would look like as seen from the bulk. In other words, it is an equatorial slice through the black hole, as seen embedded in a flat three-dimensional space, the bulk. The horizon of the black hole (its surface, out of which nothing can ever escape) is the black circle at the bottom. When we switch from visualizing an equatorial slice to the full three-dimensional black hole, that circle becomes a sphere (as the physicist Romilly explains in *Interstellar*); the horizon is actually a sphere.

As seen from the bulk, the black hole's space looks like a trumpet horn, and like the surface of a whirlpool. Far from the horizon (far off the printed page), the space asymptotes to a flat sheet, the distant universe. In figure 3.2 (see color plate 5), the space is color coded to depict the slowing of time that controls the black hole's gravity. In the yellow region, time flows at 10% of the rate far away (on Earth); at the horizon, time slows to a halt, and that infinite slowing makes gravity at the horizon be infinitely strong, preventing anything from getting out of the hole.

What produces this warping of space and time? It's not matter. There's no matter in the black hole at all. No material stuff of any sort. It's true the black hole was created by the implosion of a star long ago. But the star's matter is long since gone, destroyed at the center of the black hole; it no longer exists. With the matter gone, the only thing that can produce warping is the energy of the warping itself! The black hole is a *gravitational soliton*: an object held together by the "nonlinear influence" of the energy of its own warpage.

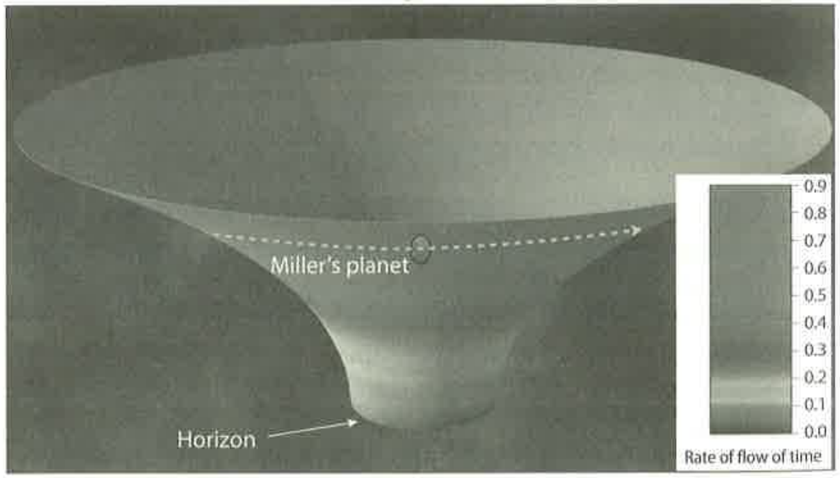

FIGURE 3.2. Equatorial slice through a non-spinning black hole, as viewed from the bulk, together with the smallest orbit that Miller's planet can have and not plunge into the hole. Adapted from a drawing by Don Davis, based on a sketch by Kip Thorne. Courtesy of NASA/JPL.

The water planet in *Interstellar*, "Miller's Planet," cannot be any closer to the black hole than the orbit shown in figure 3.2, because if it were closer, the orbit would be unstable and the planet would spiral into the black hole and be gone. That orbit is so far away from the horizon, that the slowing of time is quite small—by contrast with the huge slowing depicted in the movie. Consequently, it is impossible for the slowing depicted in *Interstellar* to be scientifically accurate if the black hole is nonspinning, as in figure 3.2.

But if the black hole spins very fast, then its spin drags space into a whirling motion around itself like the air in a tornado (figure 3.3, see color plate 6), and that whirl of space stabilizes the orbit of Miller's planet, so the planet can be down very close to the horizon and survive, as shown in figure 3.3. For one hour on the planet to be seven years on Earth, as in *Interstellar*, the spin must be far higher than seems reasonable astrophysically. But it is possible; it is not ruled out by the laws of physics, and Christopher Nolan wanted one Miller hour to be seven Earth years. So we gave the black hole Gargantua that very high spin.

In *Interstellar*, two gigantic water waves wash over Cooper's *Ranger* spacecraft on Miller's planet. Each wave is solitonic: It holds itself together by a nonlinear self-interaction, just like the black hole holds itself together by the nonlinear effects of its own energy of warping. The second wave arrives about an hour after the first.

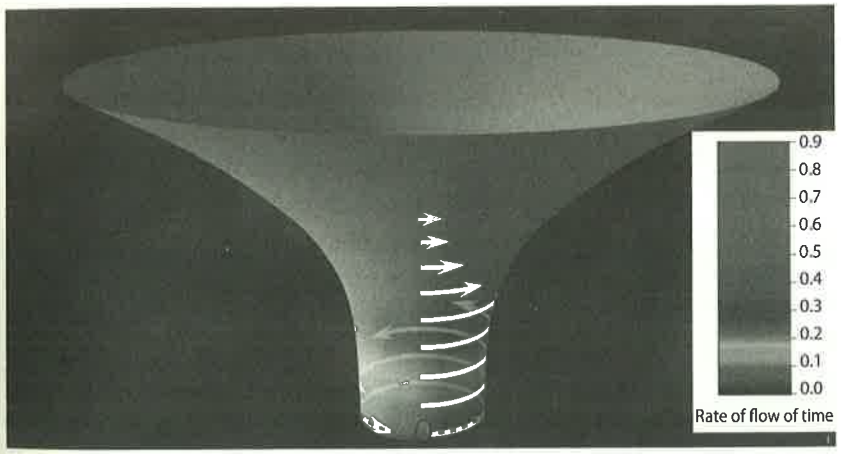

FIGURE 3.3. The warped space of the black hole Gargantua, which spins very rapidly. The white arrows depict the hole's dragging of space into a whirling motion, which stabilizes the orbit of Miller's planet, permitting it to be very close to the hole's horizon. Adapted from a drawing by Don Davis, based on a sketch by Kip Thorne. Courtesy of NASA/JPL.

What could possibly generate such water waves? The answer is the *tidal gravity* of the black hole Gargantua. This is the same type of gravity by which the Earth's moon creates the tides on Earth's oceans. In the left side of figure 3.4, the bottom of Miller's planet is closer to Gargantua's horizon than the top, so Gargantua pulls more strongly on the bottom than on the top, and as a result the planet gets stretched. And similarly, it turns out, the planet gets squeezed from the sides, and so deformed as shown. This same stretch and squeeze of the Earth's oceans (produced by the Moon's and Sun's gravity) results in the Earth's ocean tides. But for Miller's planet the stretch and squeeze are enormously stronger than for the Earth, since they are produced by a very nearby black hole.

In *Interstellar*, the planet has somehow been deposited into its near-horizon orbit quite recently, as seen by the planet, though long ago as seen from Earth, where time flows far, far faster. The planet is rocking back and forth, as shown in the right side of figure 3.4, gradually settling down toward an equilibrium state with the same face always pointed toward Gargantua. As the planet rocks, its oceans slosh, producing the giant waves seen in the movie.

Einstein's general relativity field equation governs the deformation of Miller's planet and also governs its rocking. The deformation and rocking are strongly influenced by Gargantua's mass. If Gargantua is much lighter than 100 million suns, the tidal forces will tear Miller's planet apart. In *Interstellar*, Christopher Nolan and I wanted the planet to be strongly deformed but not torn apart, so we chose the mass of Gargantua to be that of 100 million suns. From that mass, I compute that the time required for one rock, back and forth, of Miller's planet is about an hour, so this is the time between the giant water waves.

It's really quite wonderful, I think, that Chris was able to get all this relativity physics embedded into his movie in such a graphically compelling way: the slowing of time, the sloshing of water due to extreme tidal gravity, and more, much more.

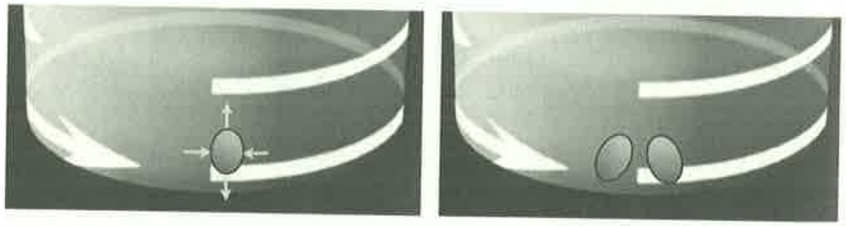

FIGURE 3.4. *Left.* Miller's planet is deformed by Gargantua's tidal gravity. *Right.* The deformed planet rocks back and forth, producing a sloshing of the planet's oceans that results in giant water waves. Adapted from a drawing by Don Davis, based on a sketch by Kip Thorne. Courtesy of NASA/JPL. See color plate 7.

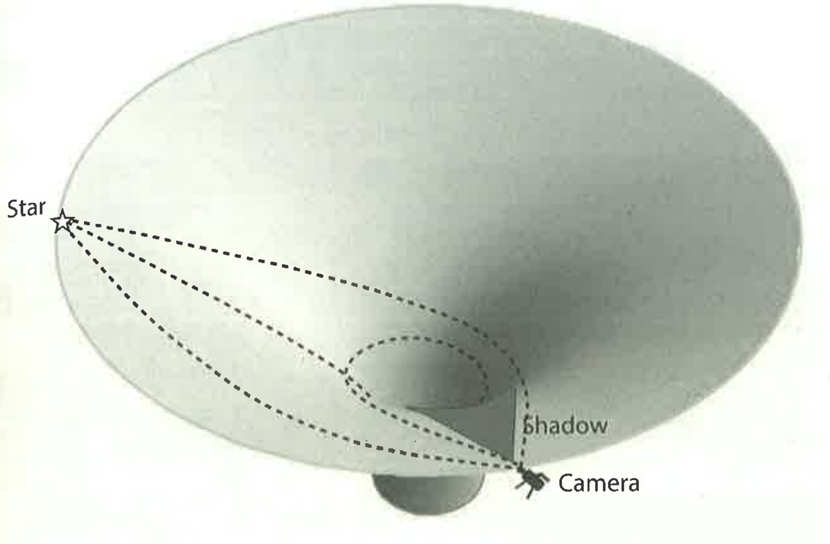

FIGURE 3.5. Three light rays that travel along three different paths though the warped space of a black hole, from a star to a camera. Adapted from an image in *The Science of Interstellar* by Kip Thorne. See color plate 8.

Particularly iconic in the movie is the appearance of a black hole as seen by human eyes (or an iMax camera). To understand this, begin with a camera looking at images of a star that is far from the hole, as depicted in figure 3.5. If spacetime were not warped, there would be just one light ray from the star to the camera: the straight line between them. But because of the warping, there are many such light rays; the figure depicts three of them. The camera sees an image of the star coming in along each light ray, so three images in the figure, but a huge number in reality. This is called gravitational lensing, and when there are many stars, and many images for each star, it gives rise to a remarkable pattern of swirling stellar images as the camera orbits around the black hole. A snapshot from a movie[1] of those swirling images is shown in figure 3.6. The pitch black, nearly circular region in the center is the shadow that the black hole's horizon makes in front of the field of stars that are being gravitationally lensed. The strange flattening and thin striations on the left side of the shadow are caused by the whirling motion of space, which is toward the camera on that left side.

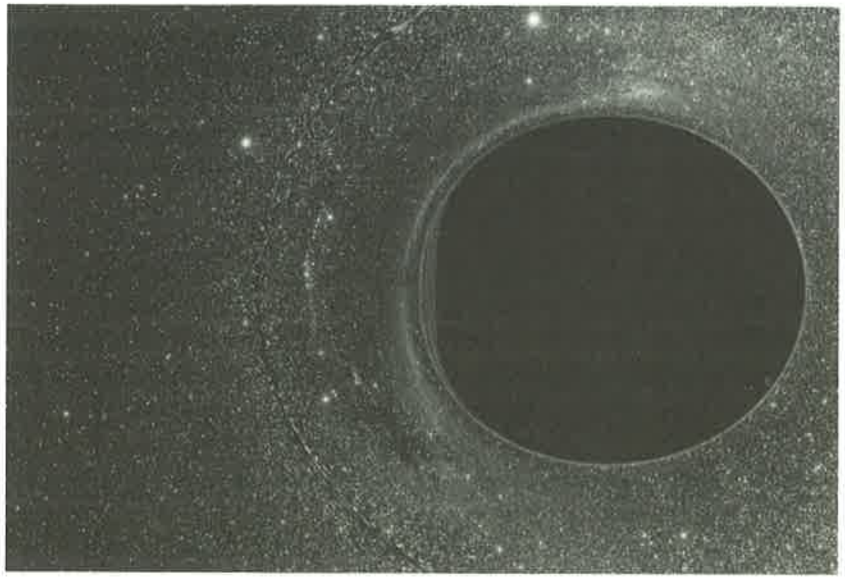

FIGURE 3.6. A field of many stars gravitationally lensed by a fast-spinning black hole. Courtesy DNEG. See color plate 9.

Accretion Disks around Black Holes

But figure 3.6 is not what we saw in *Interstellar*. What we saw was the black hole Gargantua surrounded by a disk of hot gas that gradually accretes onto the black hole, a disk so bright that it blinds us to the stars (figure 3.7). This has since become the iconic black hole image in popular culture.

How does this image come about? The disk of hot gas is thin and lies in Gargantua's equatorial plane (upper right of figure 3.8). The iMax camera is a bit above the disk's plane, as shown in the figure. Light rays from the upper back face of the disk, for example ray A, travel up over the black hole and down to the camera; they are pulled around the hole and down by the hole's intense gravity. These light rays produce the upper piece of the disk image (piece A in the lower left of the figure). Similarly, light rays from the disk's lower back face, for example ray B, travel under the black hole, which pulls them upward to the camera, producing the lower piece of the disk image (piece B in the lower left of the figure). And rays such as C, from the front of the disk, travel directly to the camera, producing the central bar in the image (piece C in the lower left of the figure). So it's all very simple: again, the culprit is gravitational lensing—a natural result of the warping of space and time, and of the gravity that the time warp produces.

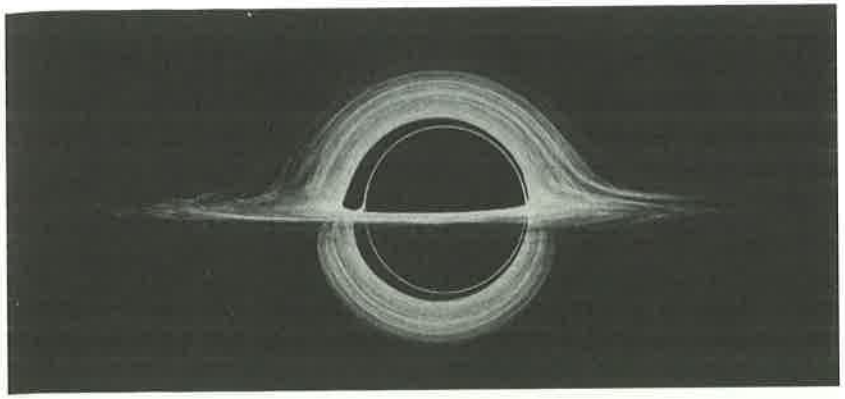

FIGURE 3.7. A variant of the image of the black hole Gargantua with a thin disk of hot gas in its equatorial plane, as seen in *Interstellar*. From James, Von Tunzelmann, Franklin, and Thorne (2015), © 2015 IOP Publishing Ltd. under CC BY 3.0 License. See color plate 10.

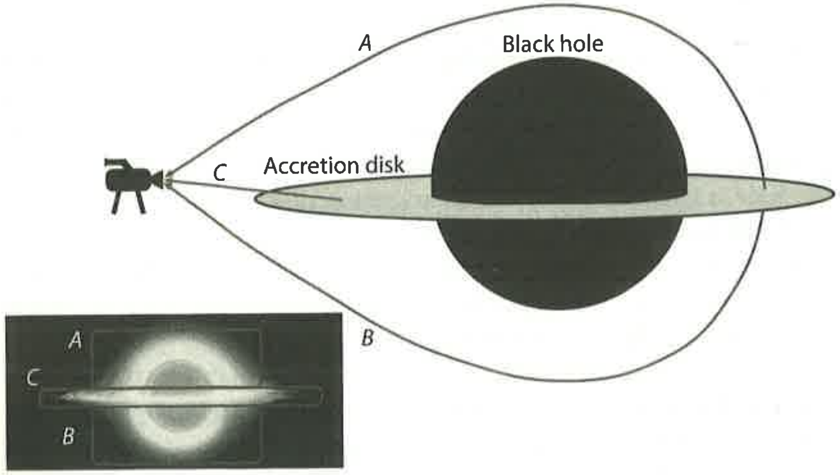

FIGURE 3.8. The iconic image of the black hole Gargantua is produced by gravitational lensing of light from its thin, equatorial accretion disk. Adapted from *The Science of Interstellar* by Kip Thorne, using the variant of Gargantua's image shown in figure 3.7.

Where do accretion disks like this one come from? Many are produced when the tidal gravity of black holes tears apart stars that stray too close. Figure 3.9 is an image from a movie of such a *tidal disruption*—a movie made by astrophysicist postdocs James Guillochon (University

FIGURE 3.9. Hot gas from tidal disruption of a star by a black hole. Courtesy of James Guillochon. See color plate 12.

of California at Santa Cruz) and Suvi Gezari (Johns Hopkins University), based on a computer simulation that solves Einstein's equations. The black hole is the tiny black spec in the upper left crook of the gas stream. The orange gas stream is the remnant of the disrupted star. The gas near the hole is beginning to form an accretion disk. The gas farther from the black hole is escaping into interstellar space.

There is a black hole in the center of our Milky Way galaxy. It has only a very weak accretion disk. It hasn't been fed recently. Someday, it will get fed and will have a nice rich disk for a while.

Andrea Ghez at UCLA and her team have been mapping the orbits of stars in the vicinity of this black hole for more than twenty years; see figure 3.10. The black hole is at the location of the star . . . the focus of all the approximately elliptical orbits. From the details of the orbits, Ghez and her group deduce that the black hole weighs four million times what the Sun weighs—a relatively light black hole compared to the one in Gargantua. By contrast, the black hole at the center of the nearest big galaxy to our own, the Andromeda galaxy, weighs 100 million times more than our Sun: the same as *Interstellar*'s Gargantua.

For the black hole at the center of our Milky Way galaxy, radio astronomers are likely to actually image the accretion disk and the black hole's shadow in the next several years. They will do so using a set of radio telescopes that are linked together to make a single near-Earth-sized telescope, called *the event horizon telescope*. This is a marvelous collaboration of hundreds of astronomers from thirty-four universities and institutes. Note added in proof: In 2019, the event horizon telescope successfully imaged a far larger black hole in the more distant galaxy M87.

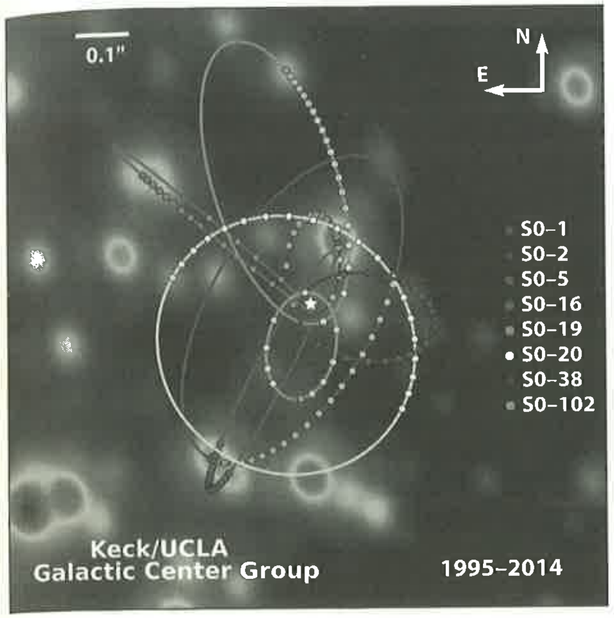

FIGURE 3.10. Orbits of stars around the black hole at the center of our Milky Way galaxy as mapped by Andrea Ghez. Courtesy of Keck / UCLA Galactic Center Research Group, Andrea Ghez. See color plate 13.

Inside a Black Hole: The Flow of Time, Three Singularities, and the Laws of Quantum Gravity

What is inside a black hole? Let me approach this gradually. Suppose, first, that you are at the surface of a black hole, its event horizon, hovering there, not falling in (left spacecraft in figure 3.11). Then time will stop for you, whence gravity there is infinitely strong, so you can only hover momentarily; you are pulled inexorably into the hole and cannot escape.

As you plunge into the hole, you might expect the time you feel to be slower than stopped time. That, of course, is nonsensical. So, what really happens to your time? The answer is that inside the black hole, time flows in a direction you would have thought was a space direction: It flows downward, toward the hole's center and toward *singularities* that reside there. Once you cross the horizon, you are dragged downward by the forward flow of time (right spacecraft in figure 3.11). That's another explanation of why you can't get out of a black hole: neither you nor

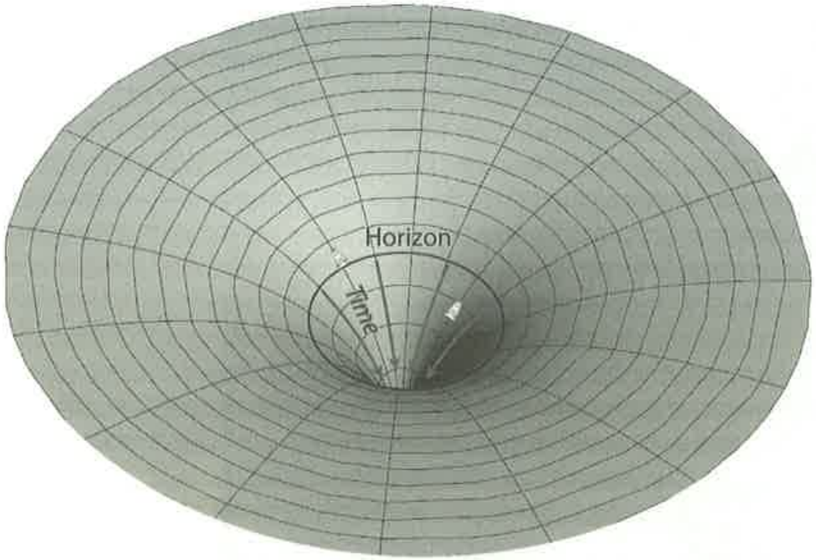

FIGURE 3.11. A black hole as seen from the bulk. Time slows to a halt in a spacecraft hovering at the horizon. Inside the black hole, time flows downward. Drawing by Kip Thorne.

anything else can travel against the forward-and-downward flow of time, according to Einstein's general relativity theory.

In *Interstellar*, Cooper, played by Matthew McConaughey, plunges into Gargantua. Nothing special happens to him as he crosses the horizon. He feels no infinite gravity, because he is falling. Tidal gravity does not suddenly become huge; it changes only slowly, gradually. When he looks upward, he sees the universe above, and the accretion disk. He can see out of the hole because light from above falls through the horizon and onto him. But people outside the hole cannot see him, since he cannot send signals upward against the flow of time.

Deep inside the black hole, according to general relativity, there is a chaotic singularity (left side of figure 3.12): a region where tidal gravity becomes infinitely strong in a chaotic way, stretching first in one direction then another, and then another, faster and faster, in a chaotic pattern. This is called the BKL singularity, so named for the three Russians who discovered it by solving Einstein's field equation: Belinsky, Khalatnikov, and Lifshitz. If Cooper hits the BKL singularity, he will be killed by the infinitely growing tidal forces, and then the atoms of which his body are made will be torn apart and destroyed.

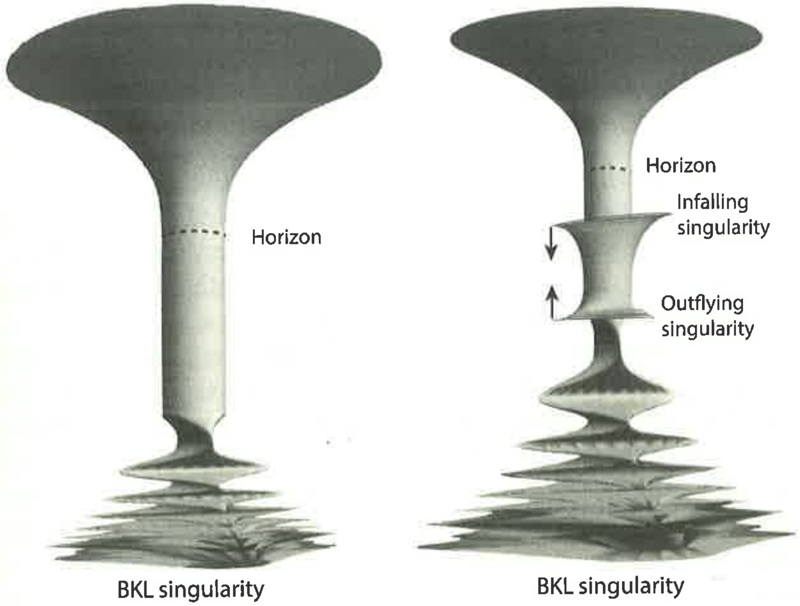

FIGURE 3.12. *Left:* Heuristic drawing of the chaotic BKL singularity inside a black hole, as seen from the bulk. *Right:* The infalling and outflying singularities produced by stuff that falls into the black hole. From *The Science of Interstellar* by Kip Thorne. See color plate 15.

Now, it turns out there are actually three singularities inside a black hole. In addition to the chaotic BKL singularity, there are two others that are more gentle (right side of figure 3.12). When Cooper falls into Gargantua, he gets caught between the other two. One is falling inward toward him. It is created by everything that will fall into the black hole in the future, over billions of years. Time is so screwed up inside the black hole, that all that infalling stuff gets compressed into a thin sheet, with infinite tidal gravity, that descends toward Cooper at near light speed. The other singularity is flying upward toward Cooper. It is created by small portions of the stuff that fell into the black hole in the past, portions that got scattered back upward. That outflying singularity also has tidal gravity that grows infinitely strong, though in a much more benign way than the BKL singularity.

In *Interstellar*, just before Cooper hits the outflying singularity, he gets scooped up by an alien spacecraft with four space dimensions, called the *tesseract*, and carried into the bulk; and he survives. If you want to understand the weird things that happen after that, you'll have to read my book, *The Science of Interstellar* (Thorne 2014). Christopher Nolan so admires Stanley Kubrick's film, *2001: A Space Odyssey*, that he chose to make his own movie's ending as inscrutable as Kubrick's—and invited me to explain the ending in my book.

Physicists are eager to understand the singularities inside black holes, because the singularities' ultimate behaviors, as their tidal gravity becomes infinitely strong, are controlled by the laws of quantum gravity. (Cooper's goal in plunging into Gargantua is to extract information about these quantum gravity laws through measurements that he and the robot Tars make near the outflying singularity.) These laws arise from some sort of synthesis of general relativity and quantum theory, and the quest to learn them has been the Holy Grail of theoretical physics since about 1960.

The laws of quantum gravity not only control the singularities inside black holes; they also controlled the birth of our universe. So, once we understand the laws of quantum gravity, we should be able to use them to understand how the universe was born, and whether there are other universes besides our own, and what if any are the connections between universes. The quantum gravity laws also control, I think, whether you can build a machine to take you backward in time. We physicists suspect that every time machine, no matter how it is designed, will self-destruct when it is activated; see, for example, Hawking et al. (2002). This is Stephen Hawking's *chronology protection conjecture*. Of course, building time machines and activating them is far beyond our technological capabilities today. But Hawking and I and others have struggled to figure out what general relativity predicts for the fates of time machines that are made by infinitely advanced civilizations. Hawking and I like to make bets with each other, but in this case we made no bet, because we came to agree that a time machine's fate is controlled by the laws of quantum gravity, and will remain inscrutable until physicists understand those laws with confidence.

Gravitational Waves

Gravitational waves are another prediction of general relativity. These waves, like black holes, are made wholly and solely from warped spacetime. I have devoted much of my career to gravitational waves, and so for the remainder of this chapter I shall discuss them from my own personal, historical perspective.[2] This book of written lectures contains three other chapters about gravitational waves, one by Barry Barish, whose leadership of LIGO was crucial to the discovery of these waves, another by Alessandra Buonanno, whose contributions to theory and data analysis were also crucial, and a third by the sociologist of science Harry Collins. My lecture and this chapter are complementary to theirs.

Gravitational waves can be thought of as ripples in the shape of space that travel at the same speed as light. They exert tidal-gravity forces on any object through which they pass, for example Miller's planet (figure 3.13). They have no influence along the direction in which they propagate (into the page in the figure), but they stretch the planet along one transverse direction and squeeze it along the other. The stretch and squeeze are oscillatory, and the pattern of oscillations—the waves "waveform" (figure 3.14)— contains information about the waves' source.

Gravitational waveforms are rather like those for sound. You can feed sound into an oscilloscope and watch, on a screen, the sound's oscillating waveform; and similarly, you can feed the output of a gravitational-wave detector into a computer to produce an image of the gravitational waveform. And just as the sound waveforms from a symphony carry rich information about the orchestra, what its various instruments are doing,

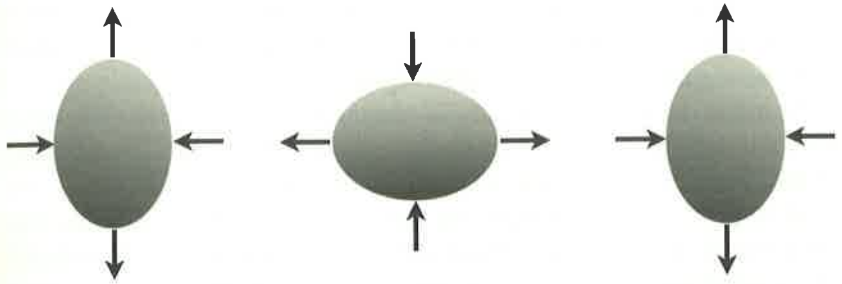

FIGURE 3.13. A gravitational wave propagating perpendicular to the plane of this picture oscillates between horizontal squeeze and vertical stretch, and horizontal stretch and vertical squeeze.

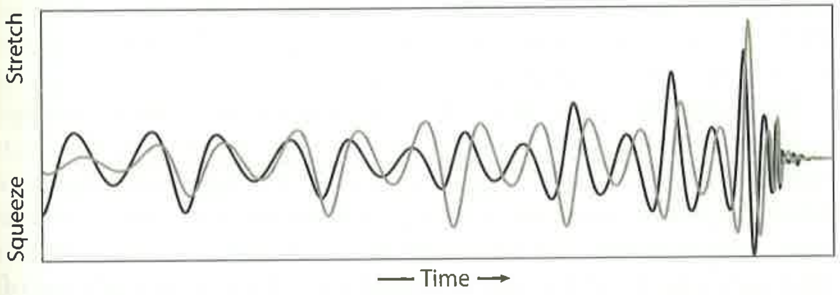

FIGURE 3.14. Two gravitational waveforms, one red and one black, produced by black holes that orbit each other and then collide. Courtesy SXS Collaboration.

and the emotions of the composer, so also the gravitational waveforms can carry rich information.

Gravitational waves were predicted and elucidated by Albert Einstein in 1916, using his general relativity theory. For the first half century after Einstein's prediction, theorists struggled to understand them (and also struggled to understand black holes). Are they real, physical phenomena, or are they figments of the mathematics that have no true physical reality? For some details of this struggle, see Barry Barish's lecture in this volume, and also see Daniel Kennefick's beautiful book, Kennefick (2007).

And during that first half century most physicists, including Einstein, thought the waves coming to Earth from the astrophysical universe would all be so weak that they might never be detected.

Joseph Weber, at the University of Maryland, in the late 1950s and 1960s was the first physicist to have the courage and inventiveness to design and build gravitational-wave detectors, and search for waves from the astrophysical universe, but he did not find any. See Barish's chapter for details. I met Weber in 1963 at a summer school in the French Alps, where I was a student and he lectured. Through his lectures and through conversations as we hiked together, I became enamored of gravitational waves. And through John Wheeler, my PhD thesis advisor, I became enamored of black holes and neutron stars.

So it was natural that when I joined the Caltech faculty in 1966, I created a research group that focused on black holes, neutron stars, and gravitational waves. Most important for this chapter, in 1972, with my PhD student Bill Press, I began to develop a vision for the science that might be done with gravitational waves, if they could be detected: the kinds of information that might be extracted from the waves, and what astrophysicists might do with that information.

In parallel, also in 1972, Rainer (Rai) Weiss at MIT was developing a design for a new type of gravitational-wave detector—a *gravitational-wave interferometer* of the sort that would ultimately be implemented in LIGO. In a remarkable technical paper dated April 15, 1972, Rai described his interferometer's design (figure 3.15).

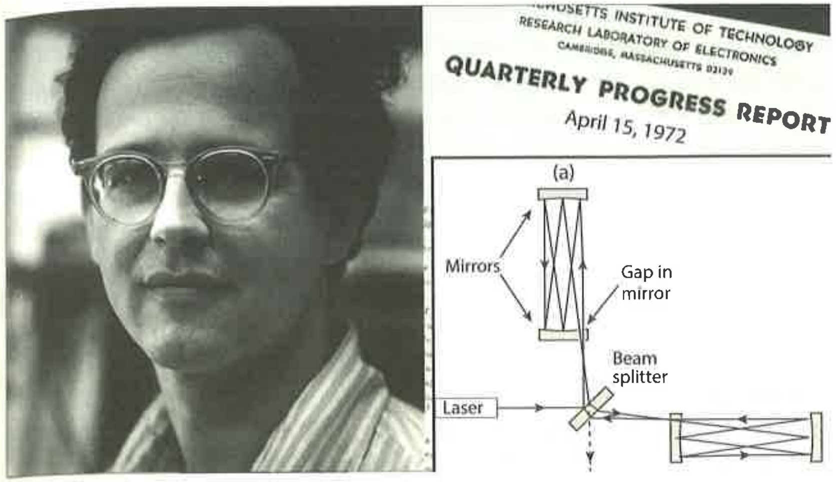

FIGURE 3.15. *Left:* Rai Weiss ca. 1972. *Lower right:* The bare bones of Rai's proposed gravitational interferometer, as seen from above. *Upper right:* The beginning of Rai's technical paper about this interferometer. Courtesy Rainer Weiss.

Four mirrors hang from overhead supports in an L-shaped configuration: two at the ends of the L and two at the corner. A gravitational wave stretches one pair of mirrors apart ever so slightly and squeezes the other pair together, and a laser beam (shown red) measures that stretch and squeeze. The laser light is split in two at a beam splitter. Each resulting beam bounces back and forth between the mirrors of its arm. Then the beams recombine and interfere with each other at the beam splitter. The interfered light going downward in the picture enters a photodetector that measures its intensity. As the arms stretch and squeeze, that intensity rises and falls due to the changing difference in the travel distance of the interfering beams. The multiple bounces in each arm increase the difference in travel distance, thereby increasing the light intensity's rise and fall.

In Rai's technical paper, he identified all of the major noise sources that such an interferometer would have to face, explained ways to deal with each and every one of those noise sources, and estimated how big the resulting total noise would be. By comparing with the strengths of the waves that my astrophysicist colleagues and I were predicting, he concluded that, if the interferometer were a few kilometers in size, it would have a real possibility to detect the predicted waves. His analysis was an amazing tour de force.

Rai did not publish this technical paper in a standard scientific journal such as *Physical Review* or the *Astrophysical Journal,* where the rest of us were publishing. No. Rai, being Rai, thought he shouldn't publish until he had built his interferometer and shown it would work, and perhaps even detected gravitational waves! So instead, he put his paper in an internal MIT technical report series (upper right of figure 3.15), and then sent copies to many colleagues around the world, including me.

When I first perused his paper, I was highly skeptical. Rai proposed to use light to measure a stretch and squeeze of the interferometer's arms that was nearly a trillion times smaller than the light's wavelength! Ten million times smaller than an atom! a hundred times smaller than the nucleus of an atom! This seemed crazy to me—until I discussed it at length with Rai and studied his paper in depth. Then I became enthusiastic and vowed that I and my theory students would do whatever we could to help Rai and his experimenter colleagues succeed.

In 1976, at about the same time as I was making this vow, Ronald Drever at the University of Glasgow became enamored of Rai's ideas, and following Rai's lead, started building an interferometer. In the process he invented some important improvements on Rai's design. Most important, he proposed a different way to bounce the light back and forth in each arm—a way that is more compact and has turned out to be more versatile, but that is much more difficult to implement, technically (figure 3.16). In technical language, he made each arm into a Fabry Perot cavity. In other words, he made the round-trip distance in each arm be an integer multiple of the light's wavelength, so the light can bounce back and forth resonantly inside the arm. The light gets "sucked" into each arm, gets trapped there for many bounces, then leaks back out and interferes at the beam splitter.

In 1976, having become convinced that gravitational-wave detection was likely to succeed, I proposed that we create an experimental effort at Caltech to build and perfect these gravitational-wave interferometers, in parallel with Rai's effort at MIT, Drever's new effort at Glasgow, and an effort recently initiated near Munich, Germany by Heinz Billings. My proposal was embraced enthusiastically by Caltech's faculty, provost, and president; and I was even invited to talk to the Caltech trustees about it. The trustees didn't have to approve it, but they were enthusiastic. The entire Caltech community embraced our gravitational-wave quest and stuck with us enthusiastically right up to our ultimate success, forty years later.

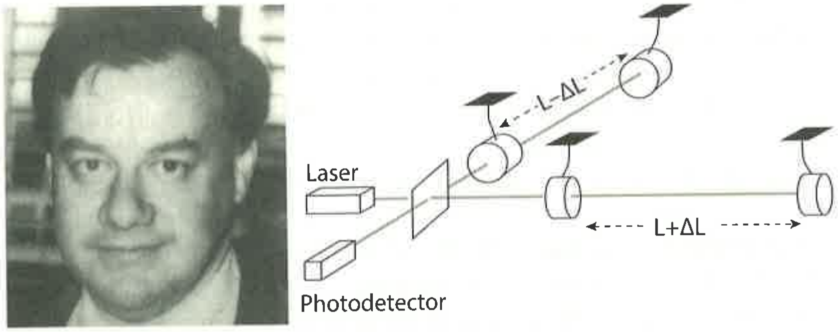

FIGURE 3.16. Ronald Drever (photo) and his version of Rai Weiss's gravitational interferometer. Courtesy Caltech Archives.

In 1979–80 we brought Ronald (Ron) Drever to Caltech, from Glasgow, to lead our effort, and brought Stan Whitcomb from Chicago as an assistant professor to co-lead it. The Caltech administration provided approximately $2 million (in 1979 money!) to get the effort off the ground, and I think that played a large role in convincing the US National Science Foundation (NSF) to begin investing substantial sums. Under Ron's oversight, Stan led the Caltech experimental team in building a prototype interferometer with 40-meter-long arms (just 1% of the arm length that we would ultimately use in LIGO); figure 3.17. (Stan went on to become chief scientist in the LIGO Laboratory and one of the several most effective and influential LIGO experimenters in our 40-year quest.) In parallel, in 1980–83, the NSF funded Rai to continue work on his smaller prototype, and most important, to do a feasibility study for the kilometer-sized interferometers that we knew we would ultimately need.

In 1984, Rai, Ron, and I presented to a key NSF committee the results of Rai's feasibility study, and the achievements of the prototypes at Caltech, MIT, Glasgow, and Munich. Our progress was great enough that NSF encouraged us to initiate plans for 4-kilometer-long LIGO interferometers.

For three years, 1984–1987, Rai, Ron, and I led this planning effort. Ours was among the most dysfunctional leaderships that the physics community has ever seen, so in late 1986 our NSF program officer

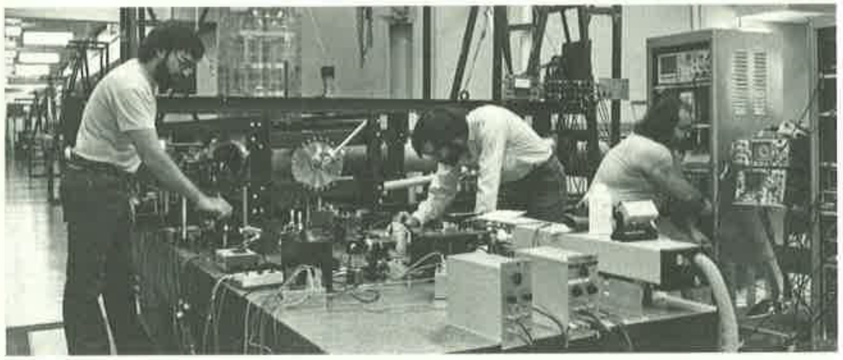

FIGURE 3.17. Stan Whitcomb (middle) and colleagues working on the Caltech 40m prototype interferometer ca. 1982. Courtesy Caltech Archives.

(an amazing physicist named Richard Isaacson who had made major contributions to the theory of gravitational waves) told us that, in order to move forward we must get a strong, single leader: a single director for LIGO. And so, with the help of the Caltech and MIT administrations, we recruited Rochus (Robbie) Vogt to lead us.

Robbie had created Caltech's Space Radiation Laboratory to conduct cosmic ray research and had made a major personal mark on that field. He had been the first chief scientist at Caltech's Jet Propulsion Laboratory, and he had been Caltech's chair of Physics, Mathematics and Astronomy, and Caltech's provost—and he was tough. He "knocked heads together" in the Caltech and MIT LIGO teams, making them truly merge and work together effectively for the first time. And he led us in writing a superb construction proposal for LIGO. Our proposal contained a detailed vision and plan for first building LIGO's facilities—the vacuum system and so forth in which our interferometers would operate—and then building two generations of interferometers. The first interferometers would be at a sensitivity where we would have to be awfully lucky to see anything, but they would give the experimental team enough experience and insights to then build the far more complex second generation: advanced interferometers that are sensitive enough to likely see lots of gravitational waves.

Our proposal was reviewed by several hard-nosed NSF committees and got high marks, so NSF seemed ready to move forward. But then we ran into a buzz saw. LIGO was being funded out of the Physics Division of NSF. It was being designed and built by physicists for whom our two-generation approach is quite natural. But our ultimate goal was to do astronomy. And there were a number of eminent members of the astronomy community who could not accept the idea that you build something costing nearly $300 million that's unlikely to see anything, and then you spend more money on second-generation instruments that you claim will have success. For $300 million, you could create a fabulous optical telescope, or several. As a result, we got blindsided in congressional testimony by an attack from eminent astronomers and were driven into an intense political battle.

FIGURE 3.18. Me, Ron Drever, and Robbie Vogt ca. 1988. Courtesy Caltech Archives.

NSF, Caltech, and MIT stood firmly by us through this battle, as did a significant portion of the astronomy community, and Robbie led us with wisdom. Finally, after two years of struggle to educate key members of Congress and their staffs, Congress bought in and provided our first major funding for LIGO. Congress has stood by us firmly from then (1992) through the detection of our first gravitational waves (2015)—for twenty-three years—and beyond, regardless of who was in power, Democrats or Republicans.

As we moved forward toward construction, NSF and Caltech got cold feet over the very lean management structure that Robbie was planning, and so Robbie stepped down as LIGO director and was replaced by Caltech's Barry Barish, who had extensive experience in leading large, high-energy physics projects. Barry, in fact, is widely viewed as the most effective leader of large projects that the physics community has ever seen, and LIGO's success is due in very large measure to his leadership. In his chapter in this volume he describes in detail the history of LIGO from 1994, when he became LIGO director, up to the present.

In extreme brevity, beginning in 1997, Barry expanded LIGO from about fifty scientists at Caltech and MIT to about a thousand at about eighty institutions in fifteen nations. This expansion was critical to success, as the LIGO interferometers are so complex that

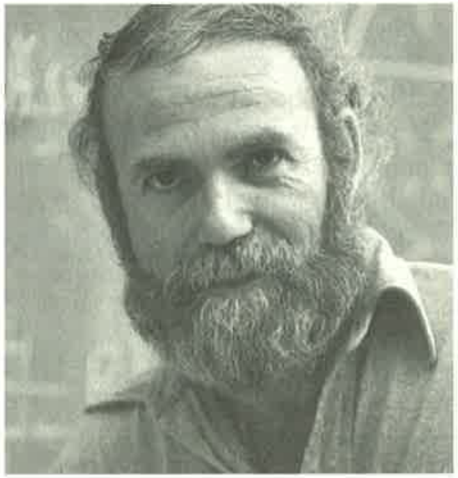

FIGURE 3.19. Barry Barish. Courtesy Caltech Archives.

building and operating them successfully requires far more skilled scientists and engineers than Caltech and MIT alone could provide. Barry led us in building the first generation of interferometers and carrying out their first searches (2000–2005), and then turned over LIGO's leadership to Jay Marx and then David Reitze, who steered us through subsequent gravitational-wave searches with the initial interferometers (2005–2010), and the construction and installation of the advanced interferometers (2010–2015).

In parallel with this major experimental effort, theorists were working hard to predict the gravitational waveforms that LIGO was likely to see, particularly the waveforms from colliding black holes, which I was pretty sure would be LIGO's strongest source. These waveforms would be long (many cycles of oscillation) and could be complex and difficult to find in LIGO's noisy data. To find them with confidence, we needed a large catalog of their possible wave shapes, which would underpin the analysis of LIGO's data. And to extract the information carried by the waves, we would need to compare the observed waveforms with the waveforms predicted for black holes with various masses and spins.

In her chapter in this volume, Alessandra Buonanno sketches how the required waveform catalog was, in the end, built and then used in the data analysis. The black holes in a binary gradually spiral together emitting oscillatory waves, then collide in a great cataclysm, producing a huge final burst of waves. During the gradual inspiral, the waveforms can be computed using so-called post-Newtonian techniques (largely with pencil and paper). But the only way to analyze the collision and its huge final burst of waves is by solving Einstein's field equation numerically, on a very large computer. This is called numerical relativity.

Theorists began working on numerical-relativity simulations of colliding black holes in the 1950s, at about the time that Joseph Weber was planning his first gravitational-wave detector. But progress was very slow. In the early 2000s, I became worried that the simulations would not produce the needed waveforms in time for LIGO's first wave detections. Fortunately, by then I had trained a number of young theorists who could take over the roles that I was playing in LIGO, so I left day-to-day involvement with the LIGO project to focus on building a numerical relativity effort at Caltech, as an adjunct to an already existing effort at Cornell University led by Saul Teukolsky. We called our effort the *SXS collaboration*, for *Simulating eXtreme Spacetimes*. Under Saul's leadership, it has now been expanded to several other universities, it includes roughly fifty computational physicists, and it has had great success. Saul is now a joint professor at Caltech and Cornell.

By September 2015, when LIGO captured its first gravitational waves, our SXS team had built a catalog of several hundred waveforms from black hole collisions—each waveform produced by a pair of black holes with a specific ratio of the holes' masses, and specific values of the holes' vectorial spins; see figure 3.20. (The magnitude of the stretch and squeeze and the duration of the waves are both proportional to the holes' total mass, so we don't have to specify the total mass in the simulations.) Our catalog was used to underpin the LIGO data analysis, as Alessandra Buonanno describes in her chapter.

This brings me to September 14, 2015. The LIGO team was preparing for its first gravitational-wave search with the advanced LIGO interferometers, when, unexpectedly, a strong burst of gravitational waves arrived—a burst that the LIGO team has named GW150914 after the date it arrived. In their chapters in this book, Barish and Buonanno describe that first gravitational-wave discovery from the viewpoint of LIGO scientists. I will describe it from the viewpoint of the waves themselves and their source—the source that the LIGO team identified with the aid of the SXS simulations.

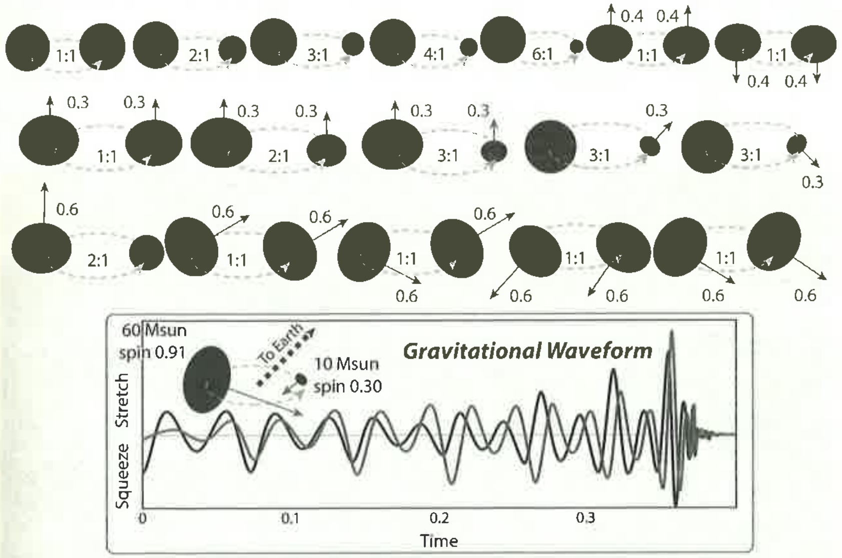

FIGURE 3.20. *Top:* Seventeen of the black hole binaries whose waveforms are in the SXS catalog; 4:1 means a mass ratio of 4 to 1, the red arrows indicate the directions and magnitudes of the black holes' spins, the red numbers are the spin magnitudes as a fraction of the maximum possible spin, and the green arrows depict the orbit. *Bottom:* The two waveforms for a specific example of the binary's parameters. (A gravitational wave has two waveforms, just as light has two polarizations; LIGO measures only one of them.) Courtesy SXS Collaboration. See color plate 17.

Approximately 1.3 billion years ago, when here on Earth multi-celled life was just spreading around the globe, but in a galaxy far, far away, two black holes spiraled around and around each other, emitting gravitational waves. Figure 3.21, based on an SXS simulation, shows what those black holes would have looked like to you, if you had been nearby. This is an analog of figure 3.6: it shows the shadows of the two black holes' horizons in front of a field of many stars and shows the swirling pattern of stellar images produced by the holes' gravitationally lensing the stars' light rays.

As they lost energy to gravitational waves, the two holes gradually spiraled inward and then collided, creating a veritable storm in the shapes of space and time. Figure 3.22 depicts that storm, as seen looking in on our universe from the bulk; this is an analog of figures 3.2 and 3.3. The top picture shows the binary black hole (BBH) 60 milliseconds before collision. The space around each black hole dips downward like the water surface in a whirlpool, and the color shifts from green to red (time slows) as one moves down the tube. The middle picture shows the BBH at the moment of collision. The collision has created a veritable *storm* in the shape of spacetime: Space is writhing like the surface of the ocean in a weather storm, and the rate of flow of time is changing rapidly. The bottom picture shows the BBH after the storm has subsided. It has produced a quiescent, single, merged black hole; and far from the hole, a burst of gravitational waves (depicted only heuristically as water-wave-type ripples) flows out into the universe.

FIGURE 3.21. The black hole binary that produced LIGO's first gravitational-wave signal, GW150914, as your eyes would have seen it if you had been nearby. Image produced by Andy Bohn, Francois Hébert, and Will Throwe from an SXS simulation. Courtesy SXS Collaboration. See color plate 18.

The initial black holes weighed 36 and 29 times as much as the Sun, for a total of 65. The final black hole weighed only 62 times the Sun, so the collision converted three solar masses of black hole mass into gravitational waves. It was as though Nature had annihilated three suns and converted their masses entirely into gravitational-wave energy. And this was done so quickly, in less than a tenth of a second, that the total power output during the collision (the total energy emitted per unit time) was fifty times larger than the total power output of all the stars in the universe put together! It was the most powerful explosion that astronomers have ever seen.

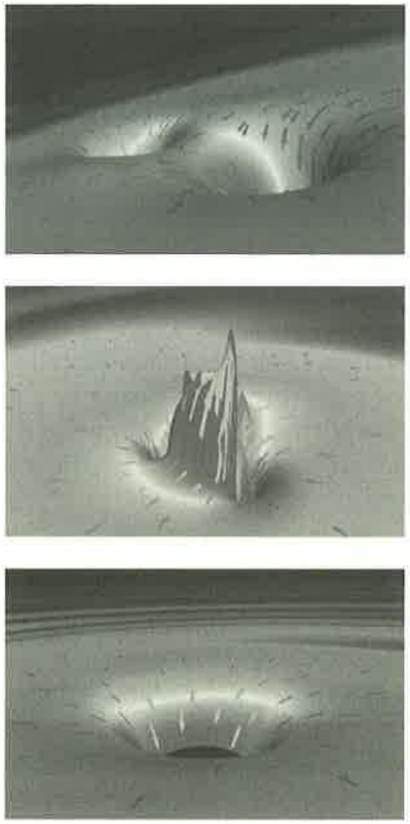

FIGURE 3.22. Snapshots from a movie depicting the geometry of spacetime around the GW150914 binary black hole, as seen from the bulk, 60 ms before collision, at the moment of collision, and 12 ms after the collision. Movie generated by Harald Pfeiffer from an SXS simulation. Courtesy SXS Collaboration. See color plate 19.

The gravitational waves traveled out of the galaxy in which the black holes lived, into the vast reaches of interstellar space. For 1.3 billion years they traveled, until 50,000 years ago, when our ancestors were sharing our Earth with the Neanderthals, the waves reached the outer reaches of our Milky Way galaxy. They traveled onward for 50,000 years, arriving at Earth on September 14, 2015. They arrived first near the tip of the Antarctic peninsula, then traveled upward through the Earth, unscathed, emerging at Livingston, Louisiana, where they stretched and squeezed one LIGO interferometer, and then 7 milliseconds later emerging at Hanford, Washington, where they stretched and squeezed the other LIGO interferometer.

Our LIGO team, assisted by members of the European Virgo gravitational-wave team, analyzed the signal for about four months to be absolutely sure it was truly produced by a gravitational wave and to deduce the details of its source, and then, on February 11, 2016, we announced our discovery: humans' first encounter with a gravitational wave. For far more detail, see the chapters by Barish and Buonanno in this book.

GW150914 is just the beginning. Over the next decade, as LIGO's sensitivity improves, it will see many hundreds of binary black holes, hundreds of colliding neutron stars, and perhaps hundreds of black holes tearing apart companion neutron stars—and also perhaps the core of a supernova explosion, and defects in the structure of space called cosmic strings. LIGO is searching for all of these. But most interesting of all will be huge surprises: Whenever a new method has been devised for observing the universe, surprises have come; and gravitational waves are so radically different from other ways of observing that huge surprises are almost guaranteed.

LIGO observes gravitational waves with periods of 1 to 100 milliseconds. Over the next two decades, three other types of gravitational-wave detectors operating in three other period ranges will reach maturity and begin probing the universe. Space-based gravitational-wave interferometers such as the European Space Agency's LISA mission will observe waves with periods of minutes to hours. Radio telescopes, by monitoring arrays of pulsars, will observe gravitational waves with periods of roughly three to thirty years. And by mapping the polarization patterns of cosmic microwaves over the sky, astronomers will indirectly observe gravitational waves from the earliest moments of our universe with periods today of hundreds of millions of years. By the middle of this century, I expect gravitational-wave astronomers to be exploring our universe's birth and, with the aid of their observations, physicists will be mastering the laws of quantum gravity that governed our universe's birth.

Four hundred years ago Galileo built a small optical telescope, pointed it at Jupiter, and discovered Jupiter's four largest moons—and thereby initiated instrument-based electromagnetic astronomy. In 2015, the LIGO team turned on its advanced interferometers and discovered gravitational waves from colliding black holes—and thereby initiated gravitational- wave astronomy. Over the four hundred years since Galileo, electromagnetic astronomy has totally revolutionized our understanding of the universe. I invite you to speculate about what gravitational-wave astronomy will bring over the next four hundred years.