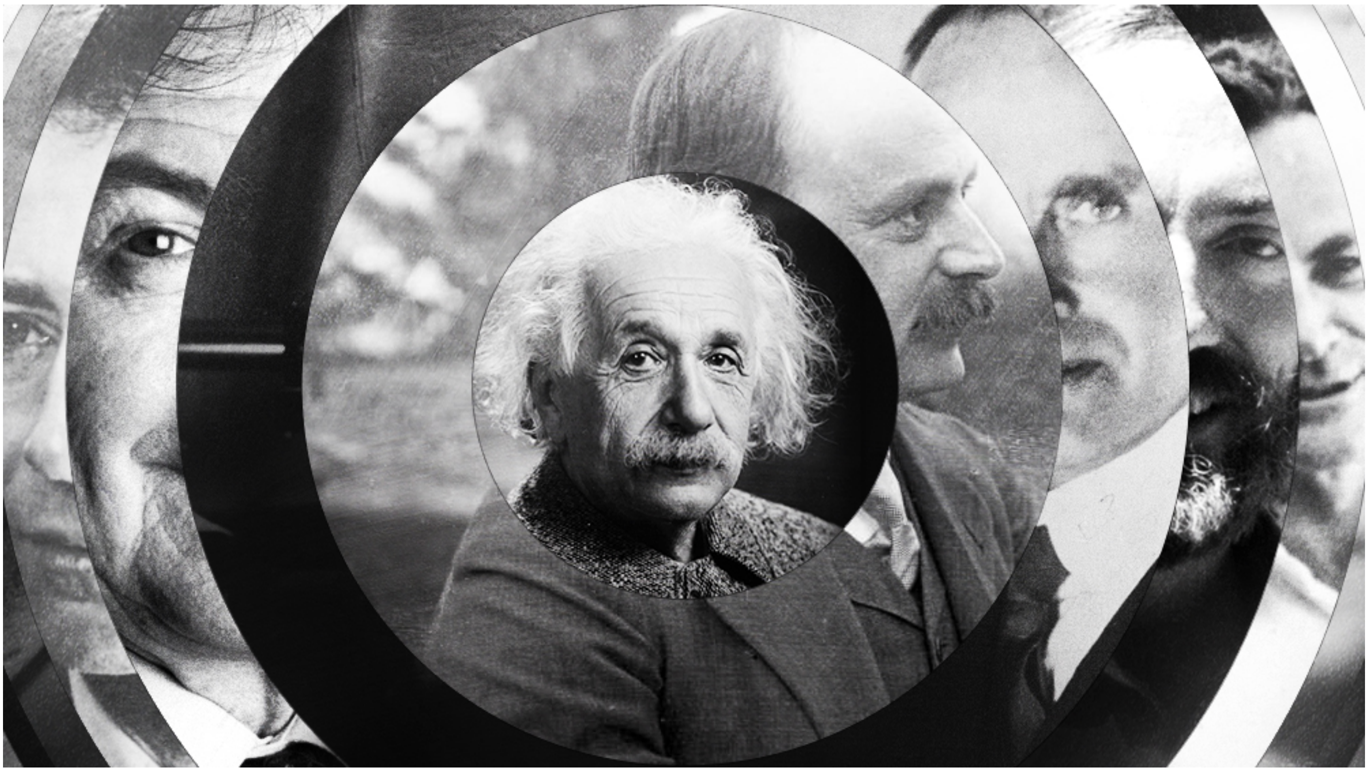
From Einstein’s Theory to Gravity’s Chirp

The path from a revolutionary set of equations to the detection of gravitational waves was strewn with obstacles and controversy, explains the physicist Daniel Kennefick — and the struggle continues.

By Natalie Wolchover



Gravitational-wave theorists (left to right) Robert Oppenheimer, Roger Penrose, Albert Einstein, Karl Schwarzschild, Arthur Eddington, Kip Thorne and Richard Feynman, whose work helped pave the way for LIGO’s big announcement last week.

“There are no gravitational waves … ” … “Plane gravitational waves, traveling along the positive *X*-axis, can therefore be found … ” … “ … gravitational waves do not exist … ” … “Do gravitational waves exist?” … “It turns out that rigorous solutions exist … ”

These are the words of Albert Einstein. For 20 years he equivocated about gravitational waves, unsure whether these undulations in the fabric of space and time were predicted or ruled out by his revolutionary 1915 theory of general relativity. For all the theory’s conceptual elegance — it revealed gravity to be the effect of curves in “space-time” — its mathematics was enormously complex.

The question was settled once and for all last week, when scientists at the Advanced Laser Interferometer Gravitational-Wave Observatory (Advanced LIGO) reported that they had detected gravitational waves emanating from the violent merger of two black holes more than one billion light-years away. Picking up the signal — a tiny flurry of contractions and expansions in space-time called a "chirp" — required extraordinary technical finesse. But it also took 100 years for scientists to determine what, exactly, Einstein's theory predicts: not only that gravitational waves exist, but how they look after crossing the cosmos from a coalescing pair of black holes — inescapably steep sinkholes in space-time whose existence Einstein found even harder to swallow.

Daniel Kennefick, a theoretical physicist at the University of Arkansas, began his career as a graduate student working with LIGO co-founder Kip Thorne to unravel the predictions of general relativity. Fascinated by the contentious history of gravitational-wave research, Kennefick began a sideline as a historian; he is the author of the 2007 book *Traveling at the Speed of Thought: Einstein and the Quest for Gravitational Waves*, and last year he co-authored *An Einstein Encyclopedia*. In discussions before and after Thursday's big announcement, Kennefick recounted the journey leading up to it and explained where theorists must go from here. An edited and condensed version of the conversation follows.

QUANTA MAGAZINE: How exciting was last Thursday's announcement for you?


Daniel Kennefick, a theoretical physicist and Einstein scholar at the University of Arkansas.

DANIEL KENNEFICK: I couldn't believe how exciting it was. It's great, given the very controversial history of the field, that it's such an incontrovertible detection. They didn't have to dig the signal out of the noise as many of us expected they would; you could really see it in the data with your own eyes. And from a theorist's point of view, one is thrilled that the theoretical predictions were so close to reality. There was the signal, and there was their prediction of what the waveform from the merger of two black holes would look like overlying it.

How would you characterize the history of gravitational-wave research that led up to this moment?

There's no doubt that a big characteristic has been controversy — a series of controversies. Controversy over whether gravitational waves exist. Do they really exist? Do they carry energy? Do they exist in a way that we can hope to detect? Even just ontologically: What is reality? Are you measuring something here or are you kidding yourselves?

And that's been true from the very beginning. The first mention of gravitational waves that we have from Einstein is of him saying they don't exist. Gravitational waves were a very bold, daring idea that started to enter people's heads 100 years ago, and yet there's always been that sense of uncertainty. One question will be answered but a new question will come up.

How does the phrase in your book title — "traveling at the speed of thought" — capture this uncertainty?

When Einstein wrote his paper [predicting gravitational waves] in 1916, he thought he had discovered three different kinds of gravitational waves. Earlier that year, when he thought the waves didn't exist, he had been using the wrong coordinate system. He changed to a different coordinate system at the suggestion of a colleague, and that allowed him to see more clearly that there were waves. But this coordinate system is itself kind of wavy, and so it turned out that two of the waves he thought he was looking at were really just flat space seen in a wavy coordinate system; they're not real waves at all.

[The English astronomer and physicist] Arthur Stanley Eddington responded to Einstein's paper in 1922, and he was interested in the question: Do gravitational waves travel at the speed of light? The answer is that they do, as we now know for sure. Eddington did his calculation to show that, and he realized that the two other types of waves, the spurious ones, could travel at any speed depending on what coordinate system you use, and so he said these fake waves "travel at the speed of thought." It's a charming phrase because on the one hand it shows the skepticism — "traveling at the speed of thought" as something that's not real. And on the other hand it shows the importance of skepticism, because after all, there aren't three types of gravitational waves; there's only one kind.

And then Einstein changed his mind again in 1936 and said gravitational waves don't exist. What happened?

Einstein and his assistant Nathan Rosen set out to find an exact [rather than approximate] gravitational-wave solution, and they discovered a problem. No matter how they tried to set up their coordinate system, they always found a "singularity" somewhere in space-time. A singularity means a place where we can't assign a number to how big the wave is there. Now the truth is, this singularity was only a coordinate singularity; it's not a real problem with gravitational waves.


Einstein on the beach in Santa Barbara, Calif. (undated).

Think about the North Pole. If I ask you what is the longitude of the North Pole, you'll say, "Well, all lines of longitude run through the North Pole." Our system of measurement breaks down there, but that doesn't mean the North Pole doesn't exist or you can't go there. Physically, it exists. So Einstein and Rosen were confused. They thought that since there was a singularity there, this provided a proof that gravitational waves couldn't exist. So they wrote this paper and they sent it off to the *Physical Review*. And the referee wrote a 10-page report pointing out the possibility of a mistake, and that was sent back to Einstein. He reacted very angrily and just withdrew the paper.

And some people started arguing that even if gravitational waves did exist, it wouldn't be possible to feel them.

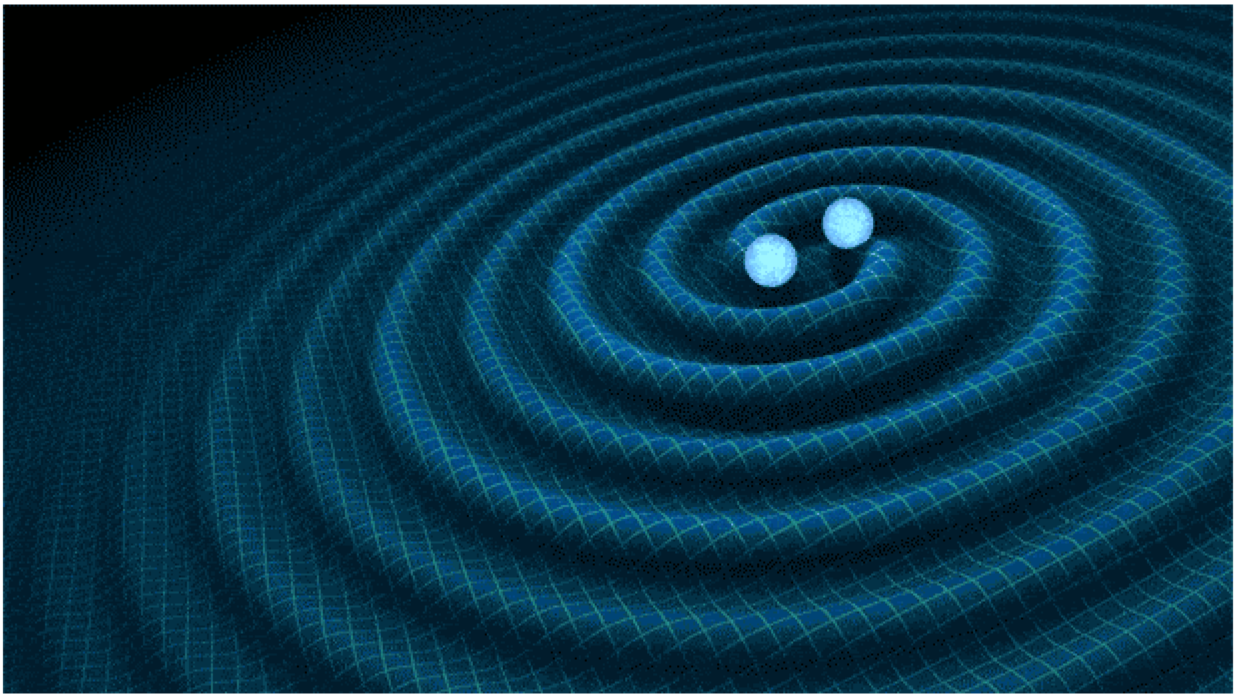
In 1955, Nathan Rosen tried to argue that gravitational waves don't carry any energy, so they're just a formal mathematical construct with no real physical meaning. A good way to think about that is, if I'm out in the ocean and there's an enormous ocean swell, I might not even be aware that it's there, because I'll rise up with the wave and then sink back down with it, and so will everything around me. If gravitational waves are like that deep ocean swell, do they really interact with us or do we all just move together up and down in the swell? That was a big debate in the '50s.

How did that question get resolved?

Rosen's argument was brought up at a conference in 1957 in Chapel Hill, N.C., and very fortunately a man named Felix Pirani, who sadly just passed away, came to the conference. He had decided to look at how general relativity works, using a very practical approach that got around this whole problem of the coordinate system, and he showed that the waves would move particles back and forth as they pass by.

Richard Feynman heard Pirani's talk and said, in essence, "Well, since we know that the particles move, all we have to do is imagine a stick, and on the stick we can put some beads. As the wave passes by, the beads will move back and forth, but the stick will stay rigid because the electromagnetic forces in the stick will try to keep the atoms and electrons in the same positions as they were previously. So the beads will drag against the stick, and the friction will produce energy. And the energy must have come from the gravitational wave. So I conclude that the wave has energy." So this famous "sticky bead" thought experiment convinced a lot of people that there wasn't any reason for the skepticism that Rosen had advanced. And then people like Joe Weber started trying to detect gravitational waves shortly after.

But people still didn't know whether there would be any astrophysical sources of gravitational waves strong enough to detect, right?



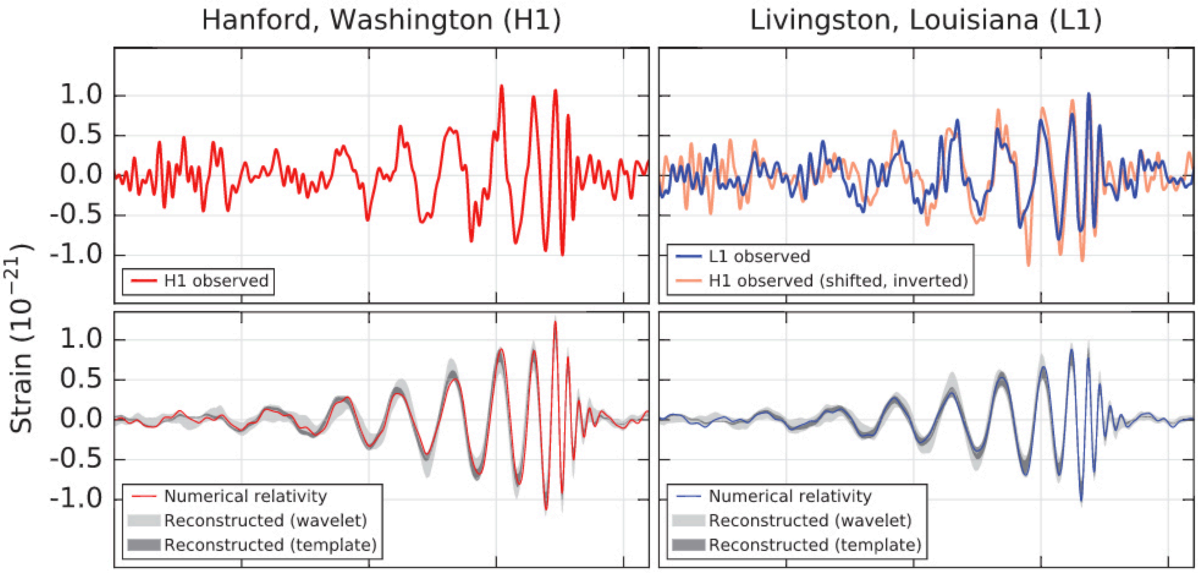
Einstein showed in 1918 that dumbbell-like systems that rotate about two axes at once, such as binary stars, radiate gravitational waves.

Right. Einstein wrote that it was unlikely that anyone would ever find a system whose behavior would be measurably influenced by gravitational waves. He was pointing out that the waves from a typical binary star system would carry away so little energy, we would never even notice that the system had changed — and that is true. The reason we can see it from the two black holes is that they are closer together than two stars could ever be. The black holes are so tiny and yet so massive that they can be close enough together to move around each other very, very rapidly. Since Einstein didn't believe in the existence of black holes, he just couldn't conceive of a system that could behave in such a way that you would be able to see the gravitational waves.

Karl Schwarzschild found the black-hole solution to Einstein's equations in 1916, the same year Einstein predicted gravitational waves. Why didn't Einstein believe in black holes after that?

Black holes themselves have a very controversial and complex history, and LIGO's detection was the first really complete proof of the existence of black holes. In 1916 Einstein thought Schwarzschild had just discovered a physical simplification: Just as one would treat the Earth as a point mass [with its mass concentrated to a point] for simplicity, they thought the “Schwarzschild solution” — what we now call a black hole — treated the sun as a point mass just for convenience. They didn’t think it would ever be a real thing, where you would have the mass concentrated to a point. They thought that was impossible, outrageous. By the 1930s it was beginning to dawn on people, “You know, it’s not entirely clear to us that the theory prevents that from happening.” Gradually, people like Robert Oppenheimer, the famous director of the Los Alamos Laboratory for the Manhattan Project, began to show that it was possible for a star to collapse into itself until it actually created something that really did look like the Schwarzschild solution. And that work was taken up in the 1960s by John Wheeler’s group, of which Kip Thorne was one of the students, and they and others developed the theory of black holes.

How did people then figure out what the gravitational waves produced by merging black holes would look like on Earth?



The gravitational-wave “chirp” observed by Advanced LIGO’s Hanford (top left) and Livingston (top right) detectors, compared to theoretical predictions (bottom row) of the chirp from two black holes of 29 and 36 solar masses, respectively, merging 1.3 billion light-years away.

A key problem was imposing the condition that there are no waves coming into the binary black hole system from infinitely far away, only waves going out to infinity. But that’s actually very hard to do, because you usually need a completely different mathematical formalism to describe the very distant gravitational field —at “infinity” or out here at Earth — than you need to describe the black holes themselves. People would try to do this calculation in the 1950s and ‘60s and they would get wrong answers. In some cases, they would get an answer that the black holes were gaining energy rather than losing it, because they made a mistake and had incoming waves bringing energy in from infinitely far away. So what happened in the course of the 1960s was that people like Roger Penrose, the great English relativist, did research on the structure of space-time. And Penrose discovered that there’s more than one infinity at the edge of space and time, and you have to pick the right infinity on which to impose your conditions. And then other people introduced techniques from fluid dynamics. These are just examples of many different conceptual and formulaic breakthroughs that had to be made.

And then the next step was predicting the particular signals that LIGO's detectors might pick up.

At one of my very first group meetings in Kip's group as a young student — this was 1991 or so — he came in with a big sheet of paper, and he had typed up everything that needed to be done on the theory side if LIGO was going to work. Because the whole reason you can detect the signal is that it has this characteristic sweep, and you filter the data against it. But you can only filter if you know what the signal looks like, and since you've never seen it before, you can only know what it looks like if the theorists tell you. And so Kip said, I want everybody in the group to work on this. And that's what we did.

You'd like to have a prediction of the waveform from the beginning of where LIGO could conceivably see the signal to the final stage where the black hole has settled back down again and is not emitting any more waves. But there's no single method that can give you the whole thing. For the first stage, you can use approximation methods that were already around at that time, but it was realized that several orders of magnitude more levels of approximation would be needed, and this was very daunting. And then when the black holes are merging, the gravity is insanely strong, and so you need numerical methods, where you do the calculation on a supercomputer. There were a whole bunch of groups who were trying to do that, and they were confronted with serious challenges. They couldn't evolve the two black holes over more than a tiny amount of time, which wouldn't help at all. And so a few years ago, they basically decided, "We just don't have a choice. We'll keep changing our coordinate systems until we find something that works that doesn't crash on us." And a guy called Frans Pretorius found a way to do it, and the methods took off from there.

There's this hope that LIGO will "open up a new window on the universe" by detecting gravitational waves from previously unknown astrophysical objects. Considering the effort that went into recognizing the signal from a black-hole merger, how will we be able to see the unexpected?

Yes, the real excitement would be to find something we didn't expect. One possibility is that the unexpected might help us out by being a very large signal. Our hopes for that have been dampened somewhat, because the original LIGO was online for quite a while and if the signal were very large it might have seen it. It does look like the unexpected is not going to be easy, so how do we dig the signal out of the noise?

One answer is that there are certain kinds of techniques that people have been looking at where you don't commit yourself to knowing precisely what the signal looks like, but you just look for certain kinds of regularities — for instance, maybe this unexpected signal is at least a periodic signal. And LIGO is certainly doing that. They even have an "Einstein@Home" project, where they'll send a piece of LIGO data to your home computer if you sign up for this, and your computer will help look for simple things like that. Another approach is to use machine learning to try to teach machines to look for signals. You start with what you know, but there is some hope that over time these techniques might grow and develop to where they become sufficiently flexible to catch things that aren't what you expect.

What do you take away from this story?

I am struck by the collective nature of the endeavor. It had to be a collaborative effort; each step was sufficiently difficult that it had to link to the next step. And collective efforts come with vitriol and disputes. People shouted at each other. But the finer qualities of human nature won out. People got over their anger. Einstein got over his anger. People admitted they were wrong. And eventually, as a community, we got there.

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