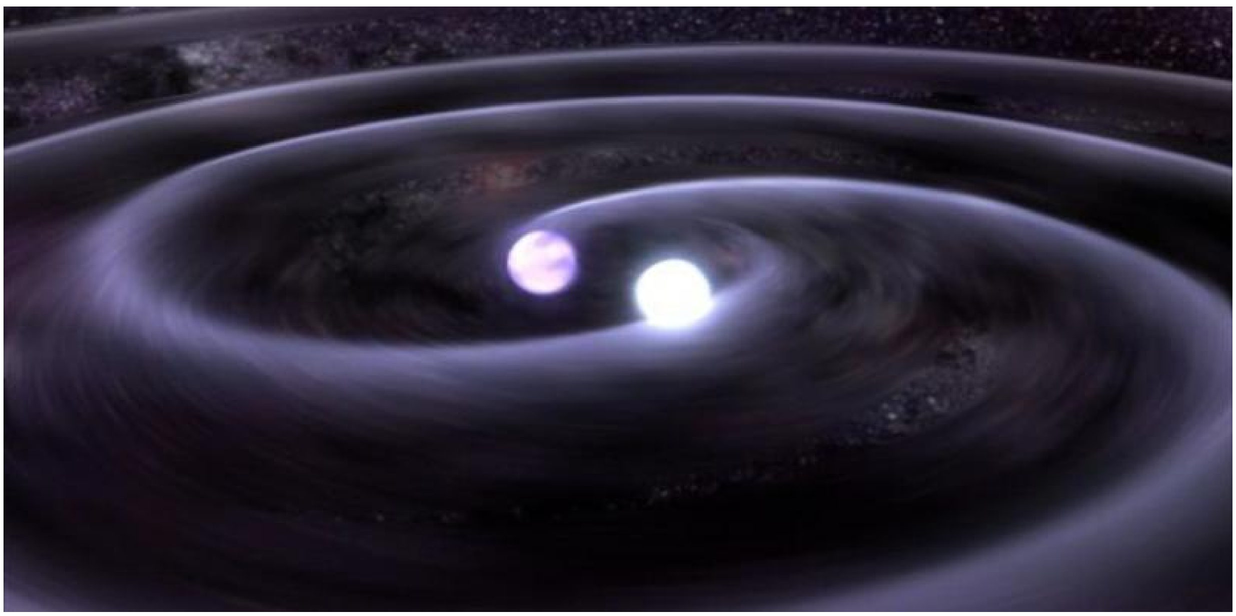
Gravitational waves discovered—top scientists respond

February 12 2016, by Keith Riles, Alan Duffy, Amanda Weltman, Daniel Kennefick, David Parkinson, Maria Womack, Stephen Smartt, Tamara Davis, And T



Massive bodies can send ripples through space time in the form of gravitational waves. Credit: NASA

One hundred years ago, Albert Einstein published his general theory of relativity, which described how gravity warps and distorts space-time.

While this theory triggered a revolution in our understanding of the *universe, it made one prediction that even Einstein doubted could be confirmed: the existence of gravitational waves.*

Today, a century later, we have that confirmation, with the detection of gravitational waves *by the Advanced Laser Interferometer Gravitational-Wave Observatory (*aLIGO*) detectors.*

Here we collect reactions and analysis from some of the leading astronomers and astrophysicists from around the world.

Keith Riles, University of Michigan

Einstein was skeptical that gravitational waves would ever be detected because the predicted waves were so weak. Einstein was right to wonder – the signal detected on September 14, 2015 by the aLIGO interferometers caused each arm of each L-shaped detector to change by only 2 billionths of a billionth of a meter, about 400 times smaller than the radius of a proton.

It may seem inconceivable to measure such tiny changes, especially with a giant apparatus like aLIGO. But the secret lies in the lasers (the real "L" in LIGO) that are projected down each arm.

Fittingly, Einstein himself indirectly helped make those lasers happen, first by explaining the photoelectric effect in terms of photons (for which he earned the Nobel Prize), and second, by creating (along with Bose) the theoretical foundation of lasers, which create coherent beams of photons, all with the same frequency and direction.

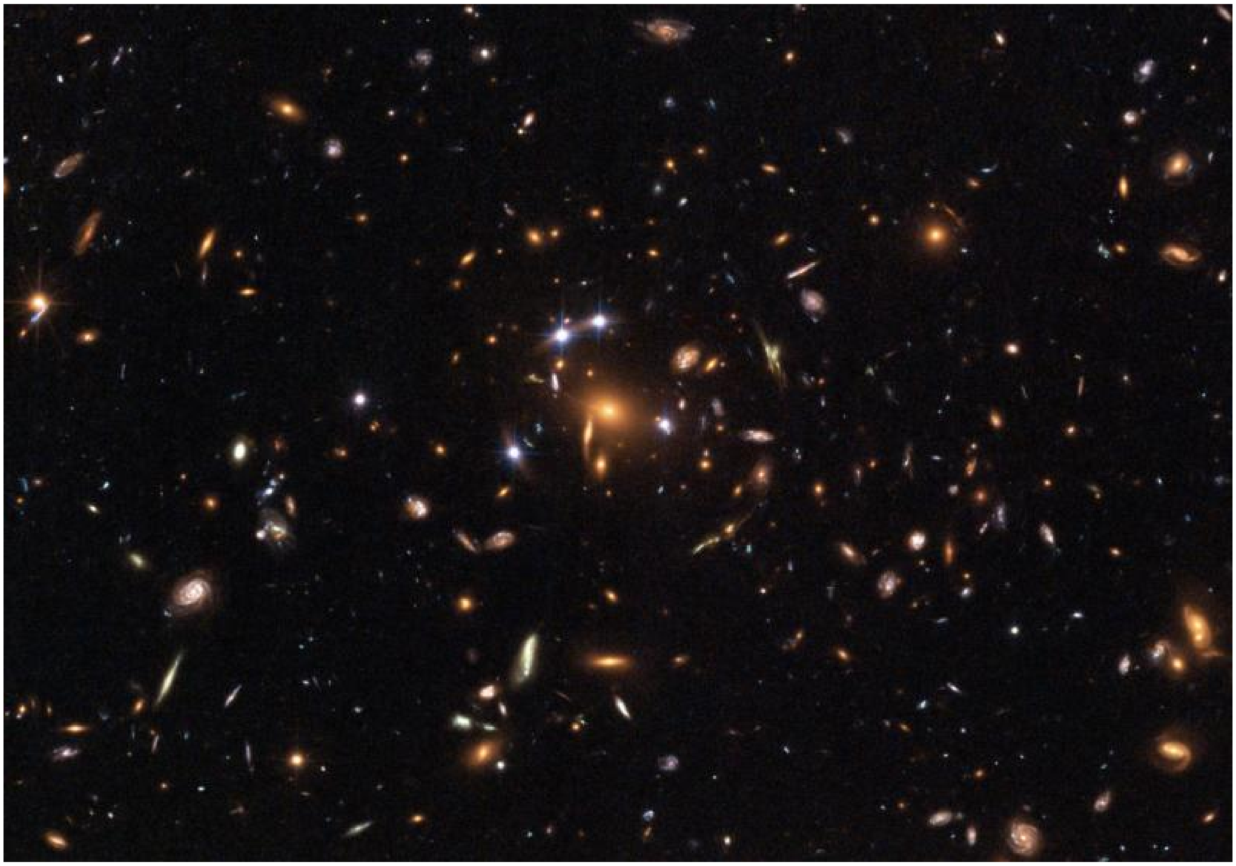
In the aLIGO arms there are nearly a trillion trillion photonsper second impinging on the mirrors, all sensing the precisepositions of the interferometer mirrors. It is this collective,coherent sensing that makes it possible to determine that one mirror has moved in one direction, while a mirror in the otherarm has moved in a different direction. This distinctive,differential motion is what characterizes a gravitationalwave, a momentary differential warp of space itself.

By normally operating aLIGO in a mode of nearly perfect cancellation of the light returning from the two arms (destructive interference), scientists can therefore detect the passage of a gravitational wave by looking for a momentary brightening of the output beam.

The particular pattern of brightening observed on September 14agrees remarkably well with what Einstein's General Theory of Relativity predicts for two massive black holes in the final moments of a death spiral. Fittingly, Einstein's theory of photons has helped to verify Einstein's theory of gravity, a century after its creation.

Amanda Weltman, University of Cape Town

The results are in and they are breathtaking. Almost exactly 100 years ago Einstein published "Die Feldgleichungen der Gravitation" in which he laid out a new theory of gravity, his General Theory of Relativity. Einstein not only improved on his predecessor, Newton, by explaining the unexpected orbit of the planet Mercury, but he went beyond and laid out a set of predictions that have shaken the very foundations of our understanding of the universe and our place in it. These predictions include the bending of light leading to lensed objects in the sky, the existence of black holes from which no light can escape as well as the entire framework for our modern understanding of cosmology.



NASA's Hubble Space Telescope captured gravitational lensing of light, as predicted by Einstein. Credit: NASA, ESA, K. Sharon (Tel Aviv University) and E. Ofek (Caltech), CC BY

Einstein's predictions have so far all proven true, and today, the final prediction has been directly detected, that of gravitational waves, the tiniest ripples through space; the energy radiated away by two massive heavenly bodies spiralling into each other. This is the discovery of the century, and it is perhaps poetic that one of the places it is being announced is Pisa, the very place where, according to legend, 500 years ago, Galileo dropped two massive objects to test how matter reacts to gravity.

As we bathe in the glory of this moment it is appropriate to ask, what is next for astronomy and physics and who will bring about the next revolution? Today's discovery will become tomorrow's history. Advanced LIGO brings a new way of testing gravity, of explaining the universe, but it also brings about the end of an era of sorts. It is time for the next frontier, with the Square Kilometre Array project finally afoot across Africa and Australia, the global South and indeed Africa itself is poised to provide the next pulse of gravity research.

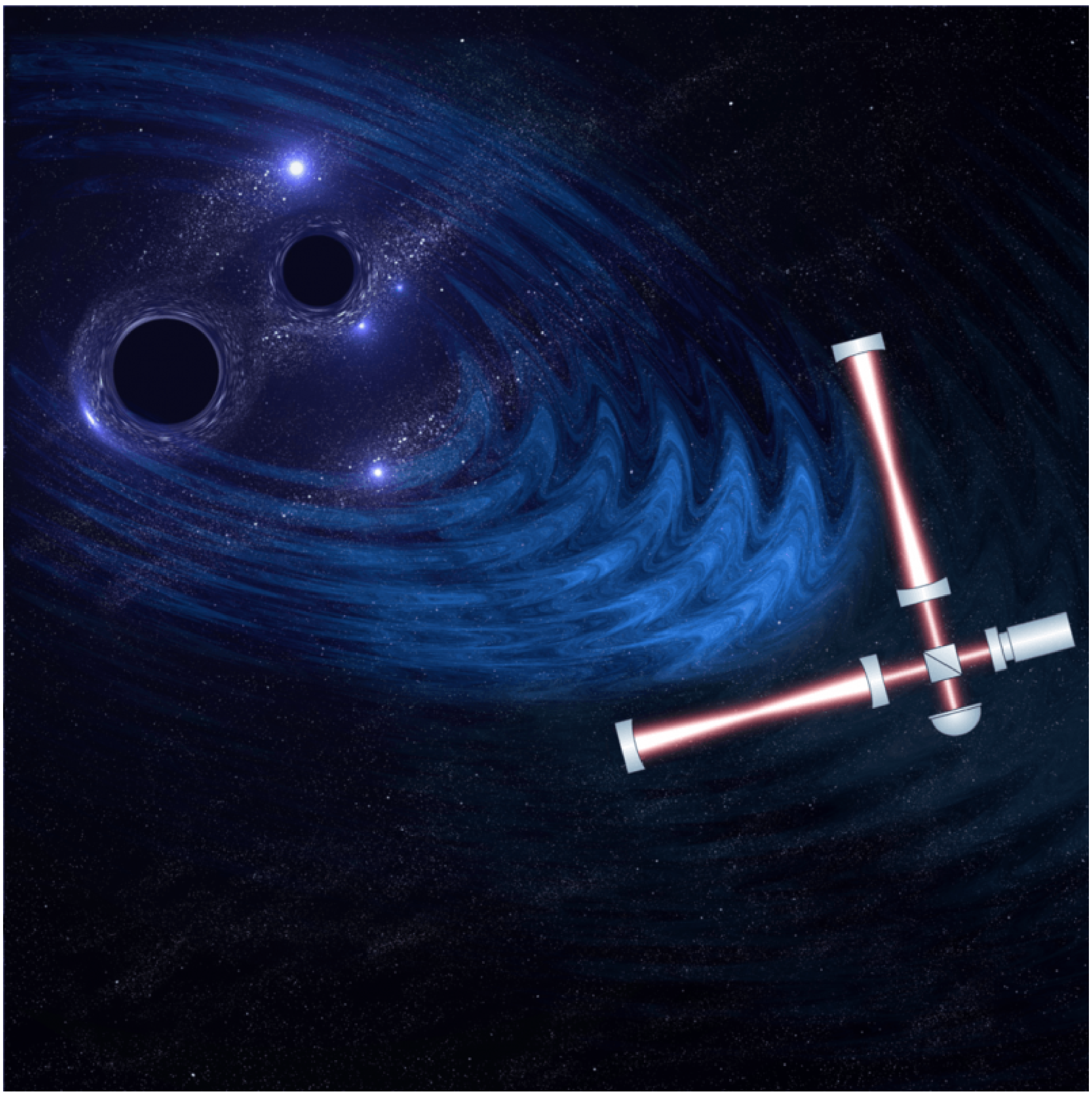
Stephen Smartt, Queen's University Belfast

Not only is this remarkable discovery of gravitational waves an extraordinary breakthrough in physics, it is a very surprising glimpse of a massive black hole binary system, meaning two black holes that are merging together.

Black holes are dark objects with a mass beyond what is possible for neutron stars, which are a type of very compact stars – about 10 km across and weighing up to two solar masses. To imagine this kind of density, think of the entire human population squeezed onto a tea spoon. Black holes are even more extreme than that. We've known about binary neutron stars for years and the first detection of gravitational waves were expected to be two neutron stars colliding.

What we know about black hole pairs so far comes from the study of the stars orbiting around them. These binary systems typically have black holes with masses five to 20 times that of the sun. But LIGO has seen two black holes with about 30 times the mass of the sun in a binary system that has finally merged. This is remarkable for several reasons. It is the first detection of two merging black holes, it is at a much greater distance than LIGO expected to find sources, and the total mass in the system is also much larger than expected.

This raises interesting questions about the stars that could have produced this system. We know massive stars die in supernovae, and most of these supernovae (probably at least 60%) produce neutron stars. The more massive stars have very large cores that collapse and are too massive to be stable neutron stars so they collapse all the way to black holes.



The LIGO detectors are sensitive to the minute ripples in space-time caused by the merging of two black holes. Credit: University of Birmingham Gravitational Waves Group, Christopher Berry

But a binary system with two black holes of around 30 solar masses is puzzling. We know of massive binary star systems in our own and nearby galaxies, and they have initial masses well in excess of 100 suns. But we see them losing mass through enormous radiation pressure and they are predicted, and often observed, to end their lives with masses much smaller – typically about ten times the sun.

If the LIGO object is a pair of 30 solar mass black holes, then the stars that formed it must have been at least as massive. Astronomers will be asking – how can massive stars end their lives so big and how can they create black holes so massive? As well as the gravitational wave discovery, this remarkable result will affect the rest of astronomy for some time.

Alan Duffy, Swinburne University

The detection of gravitational waves is the confirmation of Albert Einstein's final prediction and ends a century-long search for something that even he believed would remain forever untested.

This discovery marks not the end, but rather the beginning, of an era in which we explore the universe around us with a fundamentally new sense. Touch, smell, sight and sound all use ripples in an electromagnetic field, which we call light, but now we can make use of ripples in the background field of space-time itself to "see" our surroundings. That is why this discovery is so exciting.

The Advanced Laser Interferometer Gravitational-Wave Observatory (aLIGO) measured the tiny stretching of space-time by distant colliding black holes, giving them a unique view into the most extreme objects in general relativity.

The exact "ringing" of space-time as the ripples pass through the detector test this theory and our understanding of gravity in ways no other experiment can.

We can even probe the way galaxies grow and collide by trying to measure the gravitational waves from the even larger collisions of supermassive black holes as the galaxies they are contained in smash together.

Australia in particular is a leading nation in this search, using distant pulsars as the ruler at the Parkes telescope.

Tara Murphy, University of Sydney

In addition to binary black holes, aLIGO will detect gravitational waves from other events such as the collision of neutron stars, which are the dense remnants left over when a massive stars collapse.

Astronomers think that two neutron stars colliding may trigger a gamma-ray burst, which we can detect with "regular" telescopes.

In Australia, we have been using the Murchison Widefield Array and the Australian Square Kilometre Array Pathfinder) to follow-up aLIGO candidates.

aLIGO is an incredibly sensitive instrument but it has very poor ability to determine where the gravitational waves are coming from. Our radio telescopes can scan large areas of sky extremely quickly, so can play a critical part in identifying the event.

This project has been like no other one I have worked on. When aLIGO identifies a candidate, it sends out a private alert to an international network of astronomers. We respond as quickly as possible with our telescopes, scanning the region the event is thought to have occurred in, to see if we can detect any electromagnetic radiation.

Everything is kept top secret – even the other people using our telescopes are not allowed to know where we are pointing them.

To make sure their complex processing pipeline was working correctly, someone in the aLIGO team inserted fake events into the process. Nobody on the team, or those of us doing follow-up, had any idea whether what we were responding to was real or one of these fake events.

We are truly in an era of big science. This incredible result has been the work of not only hundreds of aLIGO researchers and engineers, but hundreds more astronomers collaborating around the globe. We are eagerly awaiting the next aLIGO observing run, to see what else we can find.

Tamara Davis, University of Queensland

Rarely has a discovery been so eagerly anticipated.

When I was a university undergraduate, almost 20 years ago, I remember a physics lecturer telling us about the experiments trying to detect gravitational waves. It felt like the discovery was imminent, and it was one of the most exciting discoveries that could be made in physics.

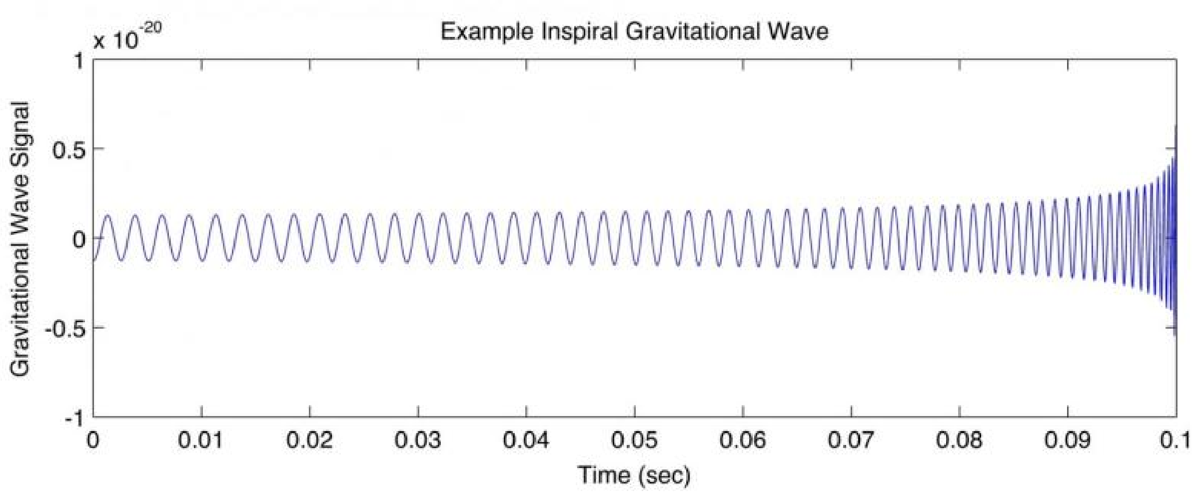
Mass and energy warping the fabric of space is one of the pieces of general relativity that most captures the imagination. However, while it has enormous explanatory power, the reality of that curvature is hard to grasp or confirm.

For the last few months I've had to sit quietly and watch as colleagues followed up the potential gravitational wave signal. This is the one and only time in my scientific career that I wasn't allowed to talk about a scientific discovery in progress.

But that's because it is such a big discovery that we had to be absolutely sure about it before announcing it, lest we risk "crying wolf".

Every last check had to be done, and of course, we didn't know whether it was a real signal, or a signal injected by the experimenters to keep us on our toes, test the analysis and follow-up.

I work with a project called the Dark Energy Survey, and with our massive, wide-field, half-billion pixel camera on a four metre telescope in Chile, my colleagues took images trying to find the source of the gravitational waves.



An example signal from an inspired gravitational wave source. Credit: A.

The wide-field is important, because the gravitational wave detectors aren't very good at pinpointing the exact location of the source.

Unfortunately if it was a black hole merger, we wouldn't expect to see any visible light.

Now that we're in the era of detecting gravitational waves, though, we'll be able to try again with the next one.

Maria Womack, University of South Florida

This is a momentous change for astronomy. Gravitational-wave astronomy can now truly begin, opening a new window to the universe. Normal telescopes collect light at different wavelengths, such as Xray, ultraviolet, visible, infrared and radio, collectively referred to as electromagnetic radiation (EM). Gravitational waves are emitted from accelerating mass analogous to the way electromagnetic waves are emitted from accelerating charge; both are emitted from accelerating matter.

The most massive objects with the highest accelerations will be the first events detected. For example, Advanced LIGO, funded by the U.S. National Science Foundation, can detect binary black holes in tight, fast orbits. GWs carry away energy from the orbiting pair, which in turn causes the black holes to shrink their orbit and accelerate even more, until they merge in a violent event, which is now detectable on Earth as a whistling "chirp."

The gravitational-wave sky is completely uncharted, and new maps will be drawn that will change how we think of the universe. GWs might be detected coming from cosmic strings, hypothetical defects in the curvature of space-time. They will also be used to study what makes some massive stars explode into supernovae, and how fast the universe is expanding. Moreover, GW and traditional telescopic observing techniques can be combined to explore important questions, such as whether the graviton, the presumed particle that transmits gravity, actually have mass? If massless, they will arrive at the same time as photons from a strong event. If gravitons have even a small mass, they will arrive second.

Daniel Kennefick, University of Arkansas

Almost 100 years ago, in February 1916, Einstein first mentioned gravitational waves in writing. Ironically it was to say that he thought they did not exist! Within a few months he changed his mind and by 1918 had published the basis of our modern theory of gravitational waves, adequate to describe them as they pass by the Earth. However his calculation does not apply to strongly gravitating systems like a binary black hole.

It was not until 1936 that Einstein returned to the problem, eventually publishing one of the earliest exact solutions describing gravitational waves. But his original sceptical attitude was carried forward by some of his former assistants into the postwar rebirth of General Relativity. In the 1950s, doubts were expressed as to whether gravitational waves could carry energy and whether binary star systems could even generate them.

One way to settle these disputes was to carry out painstaking calculations showing how the emission of gravitational waves affected the motion of the binary system. This proved a daunting challenge. Not only were the calculations long and tedious, but theorists found they needed a much more sophisticated understanding of the structure of space-time itself. Major breakthroughs included the detailed picture of the asymptotic structure of space-time, and the introduction of the concept of matched asymptotic expansions. Prior to breakthroughs such as these, many calculations got contradictory results. Some theorists even got answers that the binary system should gain, not lose, energy as a result of emitting gravitational waves!

While the work of the 1960s convinced theorists that binary star systems did emit gravitational waves, debate persisted as to whether Einstein's 1918 formula, known as the quadrupole formula, correctly predicted the amount of energy they would radiate. This controversy lasted into the early 1980s and coincided with the discovery of the binary pulsar which was a real-life system whose orbit was decaying in line with the predictions of Einstein's formula.

In the 1990s, with the beginnings of LIGO, theorists' focus shifted to providing even more detailed corrections to formulas such as these. Researchers use descriptions of the expected signal as templates which facilitate the extraction of the signal from LIGO's noisy data. Since no gravitational wave signals had ever been seen before, theorists found themselves unusually relevant to the detection project – only they could provide such data analysis templates.

David Parkinson, University of Queensland

Gravitational waves can be used to provide a direct probe of the very early universe. The further away we look, the further back in time we can see. But there is a limit to how far back we can see, as the universe was initially an opaque plasma, and remained so even as late as 300,000 years after the Big Bang.

This surface, from which the cosmic microwave background is emitted, represents the furthest back any measurement of electromagnetic radiation can directly investigate.

But this plasma is no impediment for gravitational waves, which will not be absorbed by any intervening matter, but come to us directly. Gravitational waves are predicted to be generated by a number of different mechanisms in the early universe.

For example, the theory of cosmic inflation, which suggests a period of accelerated expansion moments after the Big Bang, goes on to predict not just the creation of all structure that we see in the universe, but also a spectrum of primordial gravitational waves.

It is these primordial gravitational waves that the BICEP2 experiment believed it had detected in March 2014.

BICEP2 measured the polarisation pattern of the cosmic microwave background, and reported a strong detection of the imprint of primordial gravitational waves. These results turned out in fact to be contamination by galactic dust, and not primordial gravitational waves.

But there is every reason to believe that future experiments may be able detect these primordial gravitational waves, either directly or indirectly, and so provide a new and complementary way to understand the physics of the Big Bang.

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