Listening to the Universe

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Ten years ago, one of the greatest scientific discoveries of modern times took place. On September 14, 2015, the LIGO detectors in the states of Louisiana and Washington (USA) struck gold. Both detectors – so-called laser interferometers – picked up extremely small but significant variations in space along their 4-kilometer-long arms. The variations were thousands of times smaller than the diameter of a proton. They were caused by gravitational waves: ripples in the fabric of space and time resulting from extremely violent events in the universe. In this case, the source of the gravitational wave was a merger of two black holes, each several dozens of times more massive than the Sun and located more than a billion light-years away from Earth.

Before merging, the black holes spiralled toward each other, warping space enough to produce a wave detectable here on Earth. They did so with their colossal masses, because according to Einstein's theory, the gravitational pull of massive moving objects causes the space around them to ripple. The signal picked up by the LIGO detectors showed the final stage of the approach of the black holes as they spun faster and faster around each other. When converted into an audio signal, this spinning could be heard as a "chirp" which lasted only a second. The chirping signal of the first detected gravitational wave – a historic event only announced in February 2016, after physicists were absolutely certain they had indeed measured a gravitational wave – captured the world's attention. From that moment on, astronomers and cosmologists could not only observe the universe but also listen to it.

That the signal from two merging black holes sounded like a chirp was no surprise. It had already been predicted and simulated using solutions to Einstein's equations – the theoretical framework of general relativity, which describes the curvature of spacetime under the influence of gravity. A significant part of this preparatory work was completed around 2000 by Italian (now naturalized American) theoretical physicist

Alessandra Buonanno and French theorist Thibault Damour. The duo devised a way to analytically solve Einstein's complex equations for two spiralling and eventually merging black holes. For this "effective one-body formalism", Buonanno and Damour were awarded the 2021 Balzan Prize for Gravitation: Physical and Astrophysical Aspects.

Their work was crucial for the first observation, and more importantly, for the interpretation of the gravitational wave. The chirp signal revealed that two black holes about 1.3 billion light-years from Earth and weighing 29 and 36 solar masses had merged. The resulting black hole had a mass of 62 Suns. But what had happened to the three solar masses? They had been emitted as energy, in the form of gravitational waves.

The merger of the two black holes aligned beautifully with the effective one-body formalism, Buonanno and Damour's theoretical work that uses mathematical equations to analytically describe two objects as if they were a single one. Their formalism was completed around 2000, but it wasn't until 2005 that the first full numerical simulation of two merging black holes was successfully conducted. A supercomputer had to work on it for a month, and Buonanno and Damour used the results as input for their formalism, sifting through the data to make highly accurate predictions of the gravitational waves that the LIGO and Virgo detectors would eventually pick up. However, it took another ten years for the first detection to occur.

That first historic detection in 2015 was just the beginning. Since then, nearly 300 gravitational waves have been detected and measured. This was done not only with the LIGO detectors but also with Virgo and Kagra, two second-generation gravitational-wave detectors located in Italy and Japan, respectively. Most of these waves were produced by merging black holes, but some were caused by the merger of two neutron stars (extremely compact stars so dense that a teaspoon of their material would weigh a billion tons) or by a neutron star merging with a black hole. Unlike black holes, neutron stars emit electromagnetic radiation, a property which led to another historic detection on 17 August 2017. This time, the gravitational wave did not come from a pair of black holes but from a pair of neutron stars. Again, the signal was a "chirp", but this time it lasted much longer, over a minute and a half.

With these developments, astronomers were not only able to listen to the merging neutron stars but also to observe them. The LIGO-Virgo detector network made it possible to localize the event in the sky and consequently allow telescopes to be pointed in that direction to detect the electromagnetical radiation produced by the merging neutron stars. In the days and weeks that followed, dozens of ground- and space-based telescopes recorded the afterglow of the cosmic merger. In the meantime, it became clear that one space-based telescope had picked up a bright burst of gamma radiation from the event - this radiation had reached Earth only seconds after the gravitational wave. In the days and weeks that followed, dozens of ground- and space-based telescopes recorded the electromagnetic afterglow of the cosmic merger.

The observation of a neutron star merger via both gravitational and electromagnetic waves marked the first milestone of multi-messenger astronomy. The event was observed using two very different methods, giving astronomers the opportunity to gather much more information. This has already led to improved insights. For example, the electromagnetic radiation from the neutron star merger contained "fingerprints" of heavy elements like gold and platinum, providing evidence that such elements are indeed formed during these violent events. And gamma-ray bursts (GRBs) – short but extremely powerful bursts of gamma radiation – are in fact partly caused by merging neutron stars. However, a new question arose: although the resulting GRB occurred at a relatively close distance of "only" 130 million light-years, it was surprisingly weak – much weaker than the theoretical models predicted. Thus, multi-messenger astronomy not only answers questions but will also raise new ones.

In any event, 300 gravitational waves detected in just over ten years is a relatively small number, and not really enough for truly robust astronomical and cosmological research. That's why there are concrete plans for third-generation gravitational-wave detectors. These will again be laser interferometers, but with much longer arms. They may also be built underground, shielded from environmental vibrations, thus making them ten times more sensitive than current second-generation ones like LIGO. That means they would only need one day to detect a few hundred gravitational waves – not ten years. Moreover, they could observe wave-producing events located much farther away in the universe. While current detectors have a detection horizon of about 600 million light-years, third-generation detectors could practically cover the entire cosmos, detecting mergers of black holes or neutron stars in very distant galaxies, or even going back so far as to detect events that occurred shortly after the Big Bang, 13.8 billion years ago. In other words, it would be as if the entire universe has suddenly come within earshot.

One of the proposed third-generation detectors is the Einstein Telescope. The name may seem odd for a gravitational-wave detector, which is more of a listening post than an observatory and this one will be built underground to tell us about what's happening out there, far away in outer space. Furthermore, what does Einstein have to do with it? Einstein predicted the existence of gravitational waves over a century ago. Gravitational waves follow directly from his general theory of relativity, which dates all the way back to 1916 but still perfectly describes the behaviour of space and time and the influence of gravity on it. The historic first detection of a gravitational wave in 2015 came almost exactly a century after Einstein conceived of it, so the name fits.

The Einstein Telescope is planned to be built in Europe and should be operational by 2035. Its exact location has not yet been decided. Currently, there are three candidate regions to host the detector: the area near the tri-border between Belgium, Germany, and the Netherlands; the Italian island of Sardinia; and the eastern German state of Saxony. A decision on the location of the site is expected in 2026 or 2027. After that, construction on the tunnels where the Einstein Telescope's laser interferometers will be housed can begin.

The exact design of the Einstein Telescope is also still under consideration. Two different designs are being studied. One is a triangle with sides that are ten kilometres long and form the arms of six nested interferometers: three for higher-frequency gravitational waves and three for lower-frequency ones (the heavier cosmic objects are, the lower their gravitational waves are in frequency). A benefit of the triangular design is that only one excavation site is needed. The other design consists of two L-shapes, similar to the LIGO, Virgo, and Kagra detectors but with much longer arms – each 15 kilometres long – and also underground. A benefit of this design is that the sources of gravitational waves can be more easily localized in the sky, allowing conventional telescopes to quickly capture electromagnetic radiation. A drawback is that two separate sites would be needed.

Regardless of its final design or location, the Einstein Telescope is set to elevate the still-young field of gravitational-wave research to new heights. Daily, it will detect and measure many waves coming from all over the universe. This will allow us to unravel the mysteries of the cosmos not only with our eyes but also with our ears.