A century of correct predictions

General relativity was first experimentally verified in 1919. On the centennial of this occasion, we celebrate the scientific progress fuelled by subsequent efforts at verifying its predictions, from time dilation to the observation of the shadow of a black hole.

When we think back to the beginnings of Einstein's general theory of relativity, we consider the measurements obtained during the solar eclipse in 1919 as rock-solid proof. However, things weren't as clear cut back then. In 1921, the editorial introducing the special issue on general relativity in *Nature* (<https://go.nature.com/2uZCo4E>) betrayed a certain level of caution: "In two cases predicted phenomena for which no satisfactory alternative explanation is forthcoming have been confirmed by observation, and the third is still a subject of inquiry."

The first success of general relativity dates back to 1915 when Einstein provided a theoretical footing for the motion of Mercury's perihelion — a phenomenon at odds with Newton's theory of gravitation. Four years later, the theory was experimentally tested for the first time. During the solar eclipse on 29 May 1919, two British expeditions detected the predicted deflection of light rays travelling past the Sun, which was found to be in line with Einstein's predictions. A century later, that event marked the first of many tests of general relativity that would follow.

Einstein had hoped for general relativity to be experimentally confirmed already during the solar eclipse on 21 August 1914. A team led by the astronomer Erwin Freundlich travelled to Crimea from where the eclipse would be visible. Two weeks into the trip, however, Germany declared war on Russia, and the scientists were imprisoned under charges of espionage. This may have been scientifically fortuitous, however: Einstein later realized that the curvature of space-time near the Sun would cause an additional deflection, resulting in a correction to his original prediction. The next chance to test the theory was in 1919 — an event now remembered as a resounding scientific success. As Luís Crispino and Daniel Kennefick explain in a [Comment](#) in this issue, however, it very nearly didn't happen.

The third prediction mentioned in the 1921 *Nature* editorial would have to wait until the 1960s to be verified. It concerned light propagating near the Earth's surface, which should exhibit a $10^{-12}\%$ shift in frequency for an altitude difference of 100 m — the effect known as gravitational redshift. Despite numerous attempts, experimental techniques required

Credit: Event Horizon Telescope Collaboration

to conduct such precise measurements took decades to become available.

In 1971, physicist Joseph Hafele and astronomer Richard Keating took the tests of general relativity a step further, aiming for a direct proof of time dilation. They flew twice around the world with two atomic clocks strapped in the adjacent seats. The times of the atomic clocks that had been travelling around the world were then compared to atomic clocks that had stayed at the US Naval Observatory. The precision of the time dilation measurement markedly improved with the Gravity Probe A experiment in 1976. The times measured by an atomic clock on board the spacecraft and a ground-based clock were compared via radio signals, achieving a precision of 70 ppm.

While 100 years ago experimental tests of general relativity focused mostly on the Sun, in recent years we have seen a clear trend emerging towards the study of neutron stars and black holes — extending not only the scope of the tests but also redefining what is technically feasible. Among the most impressive tests of general relativity is the first direct detection of gravitational waves on 14 September 2015. The event was recorded a few days before a scheduled scientific run, but the Advanced LIGO detectors at both sites were already fully operational. The arms of the interferometers are around 4 km long, and when a gravitational wave sweeps through, their length changes by approximately 10^{-19} m, meaning that gravitational-wave observatories are among the most sensitive instruments

ever built. A complementary approach relies on high-precision observations of the sky, checking for changes in the travel time of pulsar signals to Earth.

We've also seen two further important confirmations of general relativity in the past three years: firstly, in 2018, the GRAVITY Collaboration measured stellar orbits near the supermassive black hole candidate in the centre of our galaxy. Secondly, the first image of a black hole — located at the centre of the galaxy Messier 87 (M87) — revealing the form of its shadow was presented by the Event Horizon Telescope on 10 April 2019 (pictured), to huge public acclaim.

The detection of gravitational waves and the observation of M87 have rekindled the world's fascination with general relativity, and scientists are now devising instruments that can test Einstein's predictions with even greater accuracy. The most ambitious of these is the space-borne gravitational-wave observatory LISA: scheduled to launch in the 2030s, its arms will be a staggering 2.5 million km long.

Einstein's general theory of relativity is, alongside quantum electrodynamics, the most precisely tested physical theory. Yet it never ceases to intrigue our scientific curiosity. Or, as Einstein put it, "The important thing is not to stop questioning. Curiosity has its own reason for existing." The continuing efforts to test general relativity with increasingly sophisticated methods prove him right. □

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