In his 1916 article [1] predicting the existence of gravitational waves, Einstein wrote that they were too weak to be of any consequence. A century later, the world’s attention was captured by the February 11th announcement, demonstrating how wrong this was. In a landmark publication in Physical Review Letters [2], an international team reports the first direct detection of the gravitational waves emitted by a pair of black holes (29 and 36 solar masses) during their final few orbits before merging to form a single 62 solar-mass black hole.

Physicists love extremes, because pushing the limits leads to insight and understanding. This discovery, a short chirp lasting about a quarter-second (see Fig. 1, adapted from [2]), pushes the limits in many different directions.

Let’s start with the human side. The first unsuccessful attempts to detect gravitational waves were small-investigator experiments made about fifty years ago. In contrast, the discovery paper had about 1000 authors (20% are from the Max Planck Institute for Gravitational Physics, for which I am the Managing Director). Some of these authors have worked towards the discovery for more than forty years.

The detector technology also pushes the limits. The advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) instruments are located 3000 km apart, in Hanford, Washington and Livingston, Louisiana. The effect of the gravitational waves is to distort the effective path length between pairs of mirrors hanging 4 km apart in a seismically-isolated high-vacuum system. At the peak of the signal the measured length change in each detector arm is about 0.002 femtometers, 1/1000 the diameter of a hydrogen nucleus. This is a fractional precision of a part in \(10^{21}\); analogous to measuring the distance to the nearest star (Proxima Centuri) to an accuracy of 40 \(\mu\)m. I don’t know of any other measurement done with comparable precision.

The binary system we observed was about one billion light years distant from earth; over some tens of milliseconds it converted about three solar masses of gravitational binding energy into gravitational waves. During that brief time, the system emitted more power than the optical luminosity of every star in every galaxy in the visible universe. My kids, jaded by generations of Star Wars movies, were unimpressed until I told them that in comparison with this, the “Death Star”, capable of vaporizing entire planets, is child’s toy, a harmless plaything. Three solar masses is enough energy to vaporize every planet in many galaxies!

Binary black hole systems like this one could not have been detected in any other way, because (being black!) they do not emit any light or electromagnetic energy. But there are intriguing reports [3] that a team analyzing data from the Gamma-ray Burst Monitor (GBM) detector on board NASA’s Fermi satellite observed a gamma-ray burst 0.4 seconds after the merger. So Nature might still surprise us. Could such systems be surrounded by clouds of gas or dust? We can’t be sure now, but within a few years, I am confident that we will know the answer to this and to many other questions.

The rate at which our knowledge will now increase is breathtaking. In their first observing run the advanced LIGO detectors were a factor of three below their final design sensitivity. That doesn’t seem like much, but keep in mind that the expected number of sources/detections is proportional to the observable volume of space, which scales like the cube of the sensitivity. So the second observing run, starting this September and lasting six months, should observe about a dozen black hole mergers, and the third observing run, starting in 2017, should see about one hundred.

It’s going to be quite a ride – a golden age of gravitational wave astronomy. By the end of it, we’ll know the mass distribution and spatial density of these stellar-mass black hole binary systems. And perhaps our catalog of observations will include new extremes, such as systems with high spin, or neutron-star/black-hole binaries, or other surprises.
Fortunately, the development of the theoretical tools has kept pace with the experimental progress. Decades of beautiful analytic work on the two-body problem, including the effects of gravitational-wave back-reaction, has given us the means to calculate the expected waveforms with high precision. Some of these calculations include parameters which cannot be determined ab-initio, but progress in numerical relativity (solving the Einstein field equations on supercomputers) now allows them to be measured with experiments performed on computers. And so far, in comparison with the advanced LIGO data, Einstein's theory of general relativity, the complete description of which was first published in *Annalen der Physik* [4], has passed every test with flying colors.

The construction of the advanced LIGO instruments was led by an MIT/CALTECH consortium, but included in-kind contributions from several international partners. Remarkably, it was completed on budget and ahead of schedule. Other ambitious projects are underway to observe gravitational waves in other frequency regimes. At cosmologically-low frequencies, via their polarizing effect on the electromagnetic cosmic background radiation, in the nano-Hertz regime by long-term precision timing of a number of stable millisecond radio pulsars, and with space-based interferometers at milli-Hertz frequencies. I am optimistic that all of these efforts will eventually succeed.

This discovery was the result of decades of hard work and careful management, but luck still played an important role. The signal was detected four days before the observing run was scheduled to start, but happily the instruments were calibrated and stable, and the on-line detection systems were operating properly and being monitored. Moreover the signal was significantly stronger than needed. Had the black hole binary been 70% farther away from Earth it could still have been confidently detected. In fact the signal was so strong that the analysis teams could only set an upper limit on the false alarm probability. One would have to wait more than 200,000 years before detector noise could produce similar chirp signals at both detector, coincident within the light travel time between them.

Humanity can now observe gravity in an entirely new regime, where the gravitational fields are strong, the gravitational sources are moving at a substantial fraction of the speed of light, and dynamical effects dominate. Within the coming decade, as new instruments like VIRGO, LIGO-India and the Japanese KAGRA join our international network, our picture of the universe will broaden and deepen.

Einstein also didn’t really believe that black holes were real, but when he found mistakes in his published work, he corrected them gracefully. So I don’t think he would have minded being wrong!

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