Research Topics

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One Hundred Years of Gravitational Waves

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The search for gravitational waves has entered a new era. The MPIWG, CalTech and the Hebrew University have studied the long way from Einstein's prediction to observation.

Albert Einstein submitted the first publication on gravitational waves within the general relativity framework in June 1916. Yet for many decades afterwards, Einstein himself, and many others, remained uncertain about the actual, physical existence of these waves.

Collaborative work by the Einstein Papers Project at Caltech (EPP), the Hebrew University of Jerusalem, and the Max Planck Institute for the History of Science (MPIWG) has recently shown that the prediction of gravitational waves emerged as early as February 1916 from an exchange of letters between Einstein and the astronomer Karl Schwarzschild. In these letters, Einstein expressed skepticism about their existence. After Schwarzschild's death in May 1916, Einstein returned to the subject of gravitational waves after the astronomer Willem de Sitter had pointed out how to overcome a mathematical obstacle in Schwarzschild's line of investigation. Einstein then predicted the existence of gravitational waves within his newly formulated gravitational theory. The 1916 paper contained a significant error, which Einstein corrected in 1918, when he derived a formula for the emission of gravitational waves that, apart from a factor of 2, is still considered to be correct. His calculations showed, however, that these waves were too weak to be observed with the technology then available.

Einstein's calculation involved a linear approximation, which was criticized by many. Over time, Einstein himself came to doubt the existence of gravitational waves and, in 1936, he and his collaborator Nathan Rosen wrote a paper purporting to demonstrate the point. After a referee spotted a mistake in their argument, the paper was published with a conclusion that left open the original question. This fascinating episode is investigated in Daniel Kennefick's book Traveling at the Speed of Thought, which gives an excellent overview of the history of gravitational waves.

Gravitational waves were hardly a hot topic at the time. Indeed, the period from the mid-1920s until the mid-1950s has been called the "low water mark of general relativity." As has been made clear by recent historical investigations jointly undertaken by the MPIWG, the Hebrew University, and the EPP, those few physicists working on the subject at the time were more interested in finding a new theory to replace general relativity that might encompass or even explain the new developments in quantum theory. And even these few physicists only rarely exchanged results or ideas. There was, in other words, no recognized field

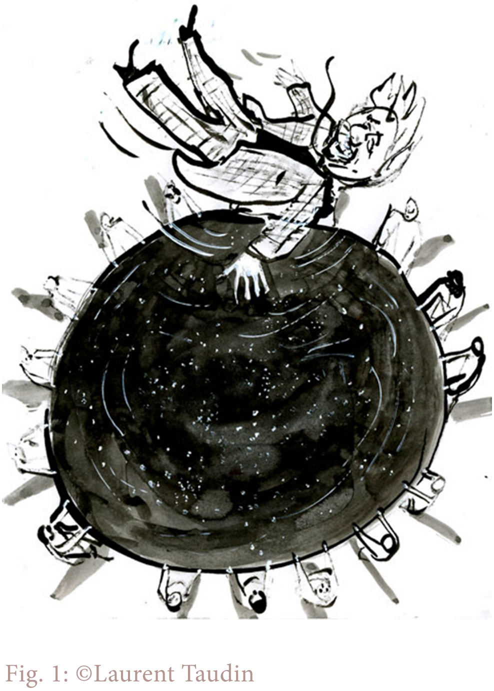

Fig. 1: ©Laurent Taudin

of research called "general relativity (and gravitation)" as there is today, with entire scientific institutions (such as the MPI for Gravitational Physics) devoted to it.

This began to change in the mid-1950s. During the period called the "renaissance of general relativity" the physicists recognized the potential for establishing a vibrant community interested in the many aspects of Einstein's theory. Conferences, journals, and an international society dedicated specifically to general relativity were the result. Among the most pressing of the questions that could now be pursued were the existence and properties of gravitational waves.

Heated discussions about gravitational waves took place at the first international conference entirely dedicated to general relativity in Bern in 1955. Two years later a follow-up conference was held in Chapel Hill (the report of the which was first published in 2011 in the Edition Open Sources Series of the MPIWG), where a broad consensus began to form that gravitational waves were real and carry energy.

The first attempts to observe the tiny effects produced by such waves were made by Joseph Weber of the University of Maryland. Weber began his experimenting around 1960; after nearly a decade he announced that he had collected convincing evidence. Weber's work had a significant impact, sparking other experiments designed to test his results. None of these confirmed his findings, leading to a long and heated controversy. Although a consensus eventually emerged that no gravitational waves had been observed in Weber's experiments, new techniques and methodologies were developed that later constituted the basis

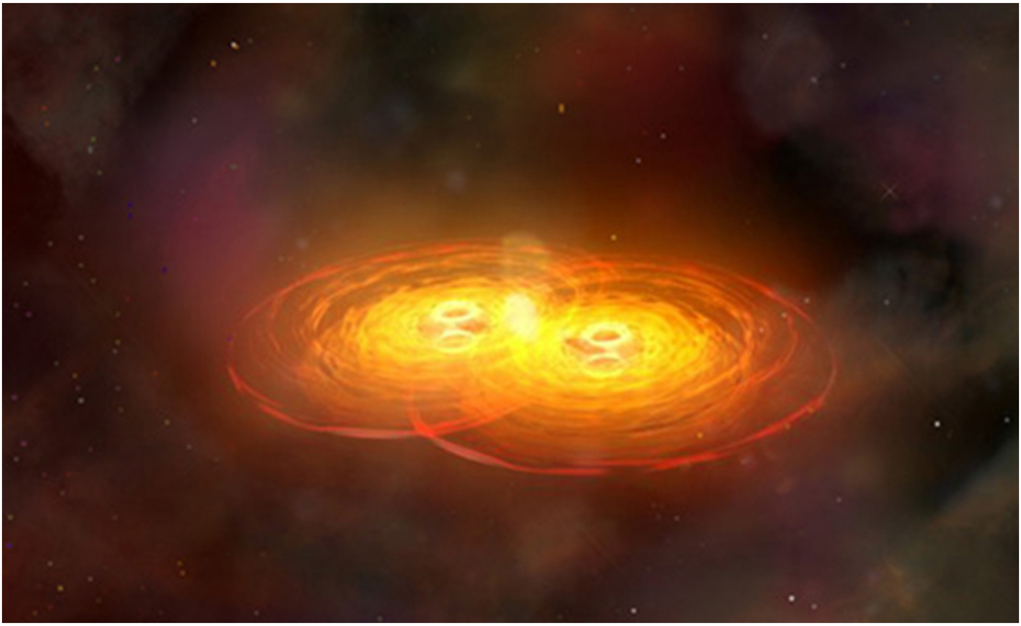

Fig. 2: Black Hole Merger; http://chandra.harvard.edu/photo/2002/0192/bh_merger_still3.jpg, NASA.

of larger machines, including LIGO.

In addition to advances in technology, a second prerequisite for the direct detection of gravitational waves in 2015 was a better understanding of their astronomical sources. Indeed, an "indirect" detection of gravitational waves had already been performed by closely observing a binary system of two massive stars circling each other which slowly lost energy by emitting gravitational waves, with the result that the stars move faster and ever closer to each other. This observation was made possible by the discovery of the first binary pulsar in 1974 by Joseph Taylor and Russell Hulse. The energy loss of this system, measured by Taylor, Joel Weisberg and their collaborators in a long series of observations, precisely matched theoretical calculations, which significantly contributed to the 1993 Nobel Prize awarded to Taylor and Hulse "for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation."

The source of the gravitational waves now detected by LIGO is novel, for it involves the collision of two black holes. The actual existence of black holes only began to be taken seriously in the 1960s, when observations made in the newly established field of radio astronomy indicated that such extreme objects really existed in distant galaxies.

Being able to qualitatively explain the properties of such distant, yet incredibly luminous radio sources (quasars) was one of the great successes of general relativity in the renaissance years. Numerical simulations for the behavior of black holes had to be made in order to reach actual predictions. Simulations of this sort required advances in computing technology as well as theoretical developments in order to follow the evolution of a system over time. The result was the birth of an entirely new field of research: numerical relativity.

While the discovery of gravitational waves is now rightly heralded as the confirmation of a prediction Einstein made 100 years ago, the concept really only started to gain traction from the 1950s, when the great technological, conceptual, and organizational advances of the renaissance of general relativity laid the groundwork for this year's discovery, and initiated a lasting boom that made possible large-scale, international projects such as LIGO. The groundwork for the establishment of LIGO was prepared close to forty years ago by Rainer Weiss, Ronald Drever, and Kip Thorne. It took more than two decades after the project's start to obtain significant signals that confirmed ripples in the spacetime structure of the universe.

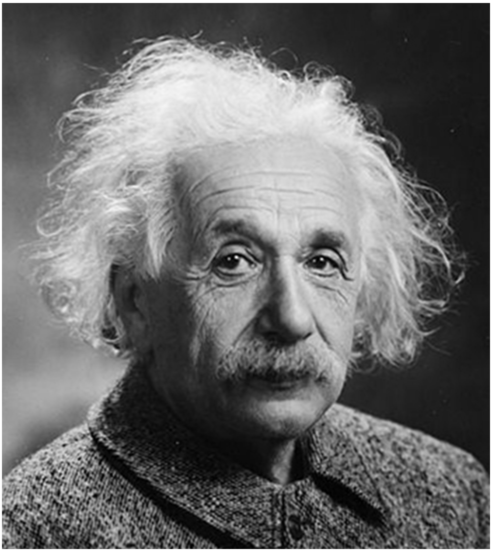

Fig. 3: Albert Einstein 1947; Wikimedia Commons.

In 2015, the MPIWG initiated a collaborative research project with the EPP and the Hebrew University on the multifaceted renaissance period of general relativity and the important role of gravitational waves. So, while gravitational waves, after having been discovered, also promise to provide a new tool with which to observe the universe, the history of this long-controversial subject will be further illuminated as well.

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