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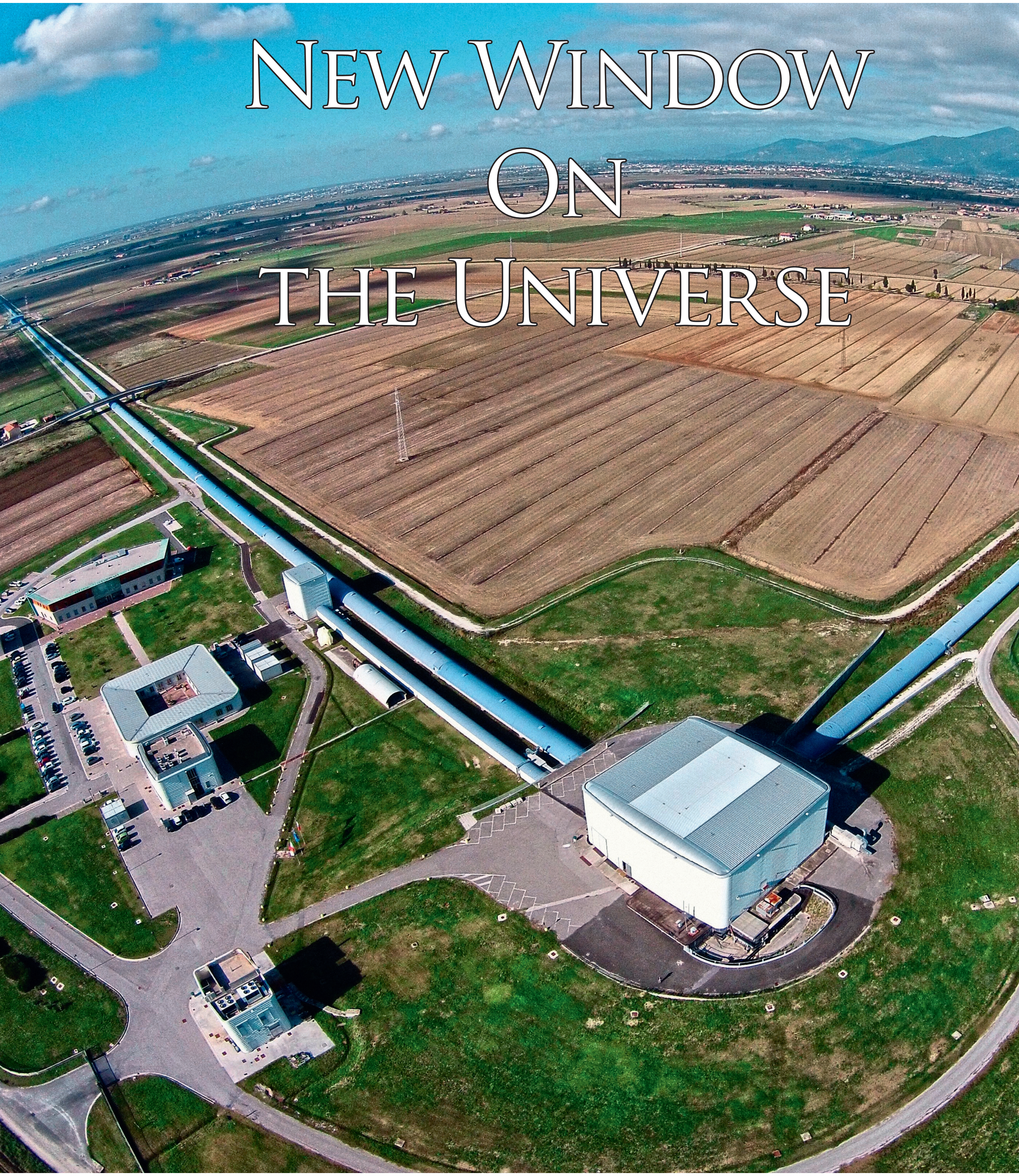

New Window On the Universe


VIRGO PROJECT

The first direct observation of gravitational waves was a major breakthrough in contemporary astronomy – and Polish scientists made major contributions to the discovery.

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From the mathematical perspective, gravitational waves – much like black holes – are a solution to Einstein's equations. Those equations lie at the foundation of the General Theory of Relativity, posited by Albert Einstein in 1915. They form a set of ten coupled nonlinear partial differential equations of an elliptical-hyperbolic type, for components of a metric tensor dependent on time and three spatial dimensions. Einstein predicted gravitational waves as early as 1916, by linearizing his equations. However, the following decades were overshadowed by doubt as to whether gravitational waves are an observable physical effect or simply a mathematical artefact. Finally, a precise analysis of Einstein's equations in the late 1950s and early 1960s revealed that gravitational waves should indeed carry energy and have an observable impact on the relative motion of particles in their gravitational field. The Polish physicist and relativity expert Prof. Andrzej Trautman made huge contributions to this research, which eventually led to the first-ever direct observations of gravitational waves.

Two gravitational-wave detectors built as part of the American Laser Interferometer Gravitational-Wave Observatory (LIGO) project were upgraded to enhance sensitivity from their first phase of operation (between 2002 and 2010); the modernized instruments started a new detection campaign in September 2015.

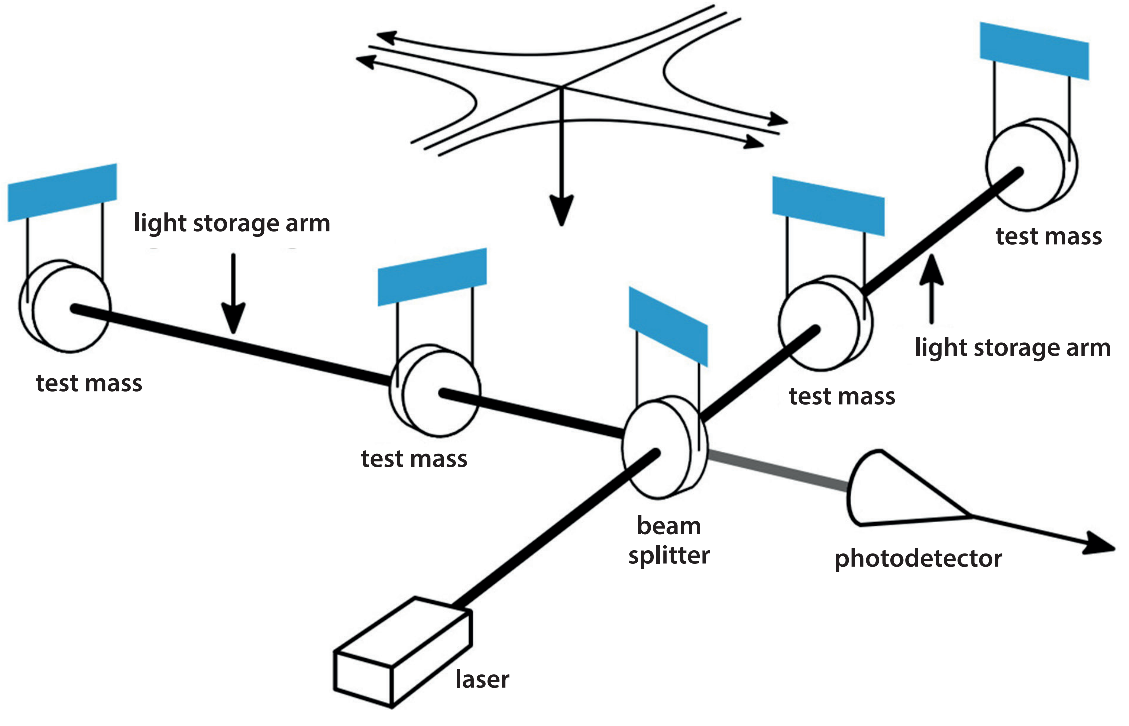
Bird's-eye view over the Virgo gravitational-wave detector near Pisa in Tuscany, Italy

This campaign ran until January 2016. LIGO recorded the first direct detection of gravitational waves on 14 September 2015; the waves in question had been generated by a merger of two black holes in a distant galaxy. This was the very first time gravitational waves had been detected by humans, and at the same time the very first detection of two black holes merging into a single black hole. The waveform of the detected signal, designated GW150914, matched the predictions of General Theory of Relativity. Three American scientists – Rainer Weiss, Kip S. Thorne, and Barry C. Barish – were awarded the 2017 Nobel Prize in Physics for decisive contributions to the LIGO detector and the successful observation of gravitational waves.

In November 2016, LIGO launched a new campaign, which was then joined by the Virgo gravitational-wave detector in Italy on 1 August 2017. Much like LIGO, Virgo is a laser interferometer with two perpendicular arms, each 3 km long. The interferometer is similar to the device used by Albert A. Michelson and Edward W. Morley in 1887 to conduct their famous experiment attempting to establish the possible dependence of the value of the speed of light on the Earth's daily and yearly motion (the arms of the Michelson-Morley interferometer were approx. one meter long each). The modern devices are incredibly sensitive: LIGO-Virgo detectors can measure differences in length between their arms that are smaller than 1/10,000th the size of a proton. They are constructed using state-of-the-art laser and optics technologies, as well as precision mechanics, electronics, and materials physics.

String of pearls

During the 2016/17, LIGO and Virgo conducted joint observations until 25 August 2017, when the detectors were switched of for upgrading. Between 14 and 17 August, the observatories detected two more gravitational-wave signals. The first, denoted GW170814, was the result of a merger of two black holes and was similar to the first signal detected in 2015. The second signal, GW170817, was the result of a merger of two neutron stars. It was an extraordinary discovery, accompanied by a gamma-ray burst (GRB 170817A), detected by the Fermi and INTEGRAL satellite telescopes just 1.7 seconds after the gravitational wave. The Virgo detector made it possible to pinpoint the exact location of the source of the signal in the sky. The location was transmitted to the numerous astronomical observatories working with LIGO-Virgo. The observations have led to the discovery of another phenomenon resulting from collisions of neutron stars, called a "kilonova." It was originally predicted by the legendary Polish astrophysicist Bogdan Paczyński. The location of the source, made more precise by subsequent observations, made it possible to identify the galaxy NGC 4993 as the location where the two neutron stars had collided. Observations of the source of GW170817 were a global campaign, covering the entire spectrum of electromagnetic radiation and conducted by myriad telescopes on Earth and in orbit. This ushered in a new era of observational astronomy, known as "multimessenger astronomy." The next breakthrough following the detection of GW170817 was a new, independent



LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY (LIGO)

Operational diagram of a laser interferometer as a gravitational-wave detector. Monochromatic light emitted by the laser is split into two beams. The beams then follow perpendicular arms where they travel back and forth between two mirrors. The interferometer arms comprise optical cavities where multiple reflections of light off mirrors increase its optical path (around 300-fold) thus improving the sensitivity of the device. A low proportion of light from each arm is directed towards the photodetector; the beams from both arms merge along the way and – if the distances they have travelled are different – they exhibit interference patterns. Gravitational waves passing through the detector, e.g. perpendicular to the plane marked by its arms, cause varying changes to the length of each arm which leads to a relative phase shift of the beams interfering with one another. As a result, the intensity of light registered by the photodetector changes measurement of the Hubble constant, which describes the rate of expansion of the Universe. This cycle of observations and measurements made possible by the original detection of gravitational waves following the collision of neutron stars – the gamma-ray burst, the kilonova, and the measurement of the Hubble constant – has been dubbed the "string of pearls."

Poland's contribution

The paper announcing the first detection of gravitational waves was published in 2016. Its list of authors included nine Polish researchers from the Polgraw team, working as part of the European project Virgo related to the gravitational-wave detector of the same name. Polgraw is led by Prof. Andrzej Królak from the PAS Institute of Mathematics. The group currently comprises thirty members from nine institutions: the PAS Institute of Mathematics, PAS Nicolaus Copernicus Astronomical Centre, Jagiellonian University in Kraków, University of Warsaw, University of Białystok, University in Zielona Góra, University of Wrocław, AGH University of Science and Technology in Kraków, and the Polish National Centre for Atomic Research in Świerk. The team analyzes data obtained by the LIGO and Virgo detectors, studies astrophysical sources of gravitational waves, develops theoretical models of gravitational-wave signals, and works on upgrading the Virgo detector. Polish authors have developed the foundations of numerous algorithms and methods used to detect and estimate the parameters of gravitational waves from binary systems, contributed to the development of a precise model of gravitational-wave signals from such systems, conducted simulations showing that binary systems of black holes are the sources of gravitational waves most easily detectable by LIGO-Virgo detectors, and searched for optical flashes likely to accompany detections of gravitational waves.

The involvement of Poland's Polgraw group in gravitational-wave observations conducted at the Virgo observatory means that their discovery – a watershed moment for humankind's understanding of science – is, in part, a Polish achievement. Joint observations conducted by the LIGO and Virgo detectors have opened up a new window onto our Universe through the development of the field of gravitational-wave astronomy. Polish researchers have had, and continue to have, a major input in the development of the discipline. Additionally, the planned Polish contribution to the upgrade of the Virgo detector by providing apparatus is certain to bolster the development of state-of-the-art technologies in Poland.

Observations of gravitational waves bring us incredibly valuable information about the Universe, its creation and evolution. Such information is frequently impossible to gather by conducting observations of electromagnetic radiation, and it helps researchers study parts of the universe impenetrable to such radiation. Gravitational-wave astronomy provides unique insight into merging binary systems of neutron stars or black holes and the gravitational waves emitted during the process. In the future, we expect to detect gravitational waves originating from rotating single neutron stars (including pulsars) and supernova explosions, and to register background gravitational radiation residual from the earliest stages of the evolution of our Universe. The successful detection of gravitational waves has opened up brand-new possibilities for research into the very foundations of contemporary physics and astronomy by robustly testing Einstein's gravitational theory vs. alternative theories, obtaining data allowing us to gain a better understanding of the laws governing very dense matter inside neutron stars, and conducting independent tests of cosmological models. Gravitational-wave astronomy should help us unravel the mysteries that still remain about the formation of black holes, test whether Einstein's gravitational theory truly is correct, and learn more about the behavior of matter inside neutron stars and during supernova explosions. The state-of-the-art methods of data analysis developed during our search for gravitational waves, involving machine learning and AI, are highly likely to find applications in other scientific and technological fields. ■

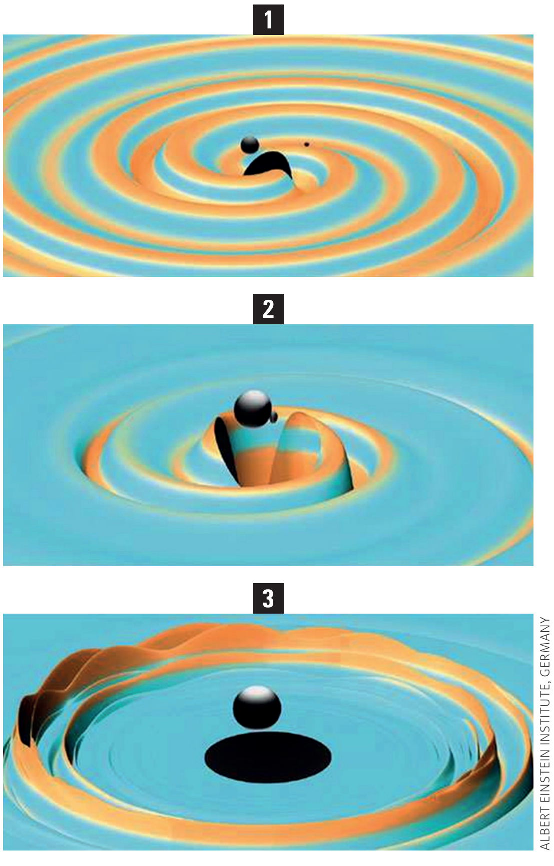


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Illustration of the results of a numerical simulation of the motion and emission of gravitational waves from the binary black hole system GW150914 – the source of the first detected gravitational-wave signal. There are three steps in the system's evolution:
1) the inspiral stage, resulting from the loss of energy of the system carried by gravitational waves – orbiting their joint center of mass, the black holes get closer to one another and take on spiral orbital paths;
2) the merger stage, when the black holes combine to create a single "resultant" black hole;
3) vibrations of the newly-formed black hole itself, which give rise to a final pulse of gravitational waves with a rapidly diminishing amplitude

Further reading:

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The Nobel Prize in Physics 2017, https://www.nobelprize.org/uploads/2018/06/popularphysicsprize2017-1.pdf.