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Ripples in Spacetime

The development of gravitational wave detectors has made it possible for astronomers to penetrate the deepest corners of the universe in search of black holes and neutron stars.

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In astrophysics, the concept of space is far more complex than our intuitive sense of our everyday surroundings. Gravitational waves – tiny disturbances or ripples in the curvature of spacetime – were detected for the first time in 2016, opening up a revolutionary new way of studying space. The signal denoted as GW150914 originated from a merger of a pair of black holes of around 29 and 36 solar masses. Travelling at the speed of light, the signal reached the Earth from a distance of approx. 400 Mpc (1 Mpc = 3×10^{19} km!). The discovery marked a breakthrough moment in contemporary science, following decades of work on developing gravitational wave theory and improving the sensitivity of state-of-the-art detectors. Rainer Weiss, Barry Barish, and Kip Thorne were awarded the Nobel Prize in Physics for decisive contributions to the LIGO detector and the observation of gravitational waves.

The existence of gravitational waves, or propagating ripples in spacetime, was predicted over a century ago by Albert Einstein as one of the effects of his General Theory of Relativity. In the early days, physicists – including Einstein himself – were rather skeptical that humankind would ever develop technology sufficiently advanced to detect them. However, through the development of gravitational wave theory, with significant contribution from the Polish astrophysicist Prof. Andrzej Trautman, and with great progress made in state-of-the-art technologies, humankind has attained this once impossible goal. In simplified terms, the LIGO (USA) and Virgo (Italy) detectors operate based on laser Michelson interferometers. Each detector comprises two long arms through which the laser beam is directed. When a gravitational wave passes through the arm, its length changes. Since the speed of light is a constant, the interference allows researchers to calculate the difference between the lengths of the paths of the two beams. Extremely sensitive instruments and advanced algorithms make it possible to detect changes with a precision on the order of a thousandth of the width of a proton, as well as locating the source of the signal (if registered by more than one detector) and measuring its parameters.

The gravitational waves that can be detected by LIGO and Virgo are radiated by tight compact binary systems – such as pairs of black holes, a black hole paired with a neutron star, or pairs of neutron stars. Before such systems merge fully, their components gradually lose orbital energy by radiating gravitational waves. Since this mechanism operates very slowly, for a given system to merge fully within a sufficiently short time (i.e. within the age of Universe – approx. 13.77 billion years) – the pairs of objects must have been on a sufficiently tight orbit since their formation.

Binary systems

Around 90 gravitational wave signals have been officially detected by July 2022. Where possible, each publication also identifies whether the emitting system consisted of black holes or neutron stars. Scientists have also estimated their mass, rotational parameters, and approximate distance from Earth. The list of detected objects is dominated by signals from binary black hole systems, due to their considerably greater mass than neutron stars. Just two signals have been classified as originating from pairs of neutron stars, and another two as systems combining a neutron star with a black hole.

The database of around 90 signals with their parameters is being used by scientists to improve our understanding and eliminate uncertainties in many

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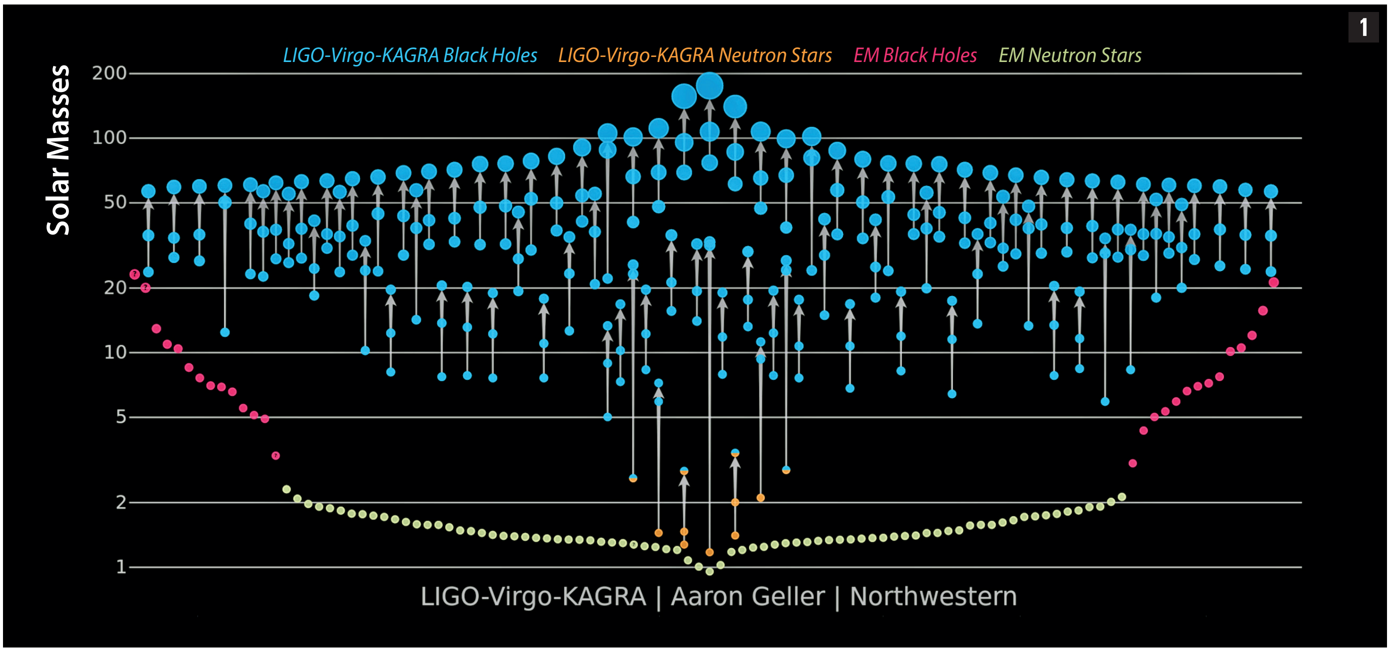
Artistic vision of a compact system of two black holes

spheres of contemporary astrophysics based on theoretical models. For example, it is a priceless source of information for researchers studying the evolution of massive stars or mechanisms by which neutron stars and black holes form (supernova explosions). The detection of gravitational waves has also served as a test of the General Theory of Relativity and helped verify the origins of heavy elements such as gold and platinum.

The mechanisms behind the formation of the binary systems of masses that have been registered by LIGO and Virgo have yet to be studied in depth. The literature proposes several theories concerning the formation of sources of gravitational waves. The two most popular ones posit the formation of tight compact object binary systems following the isolated evolution of binary massive stars, or the capturing of a compact object as a result of dynamic multibody interactions within dense star clusters. Massive stars forming binary systems, at various stages of their evolution, may exchange mass. Such transfer of mass between components of binary systems has a major impact on the final mass of the resulting compact objects (neutron stars or black holes) and the system's orbit. The processes involved remain poorly understood, and studying them requires a comparison of theoretical models developed by observations of massive stars at various stages of evolution and the resulting com-



SOURCE: HTTPS://LIGO.NORTHWESTERN.EDU/MEDIA/MASS-PLOT/INDEX.HTML

Fig. 1
Known masses of compact objects. A popular illustration summarizing the currently known masses of black holes and neutron stars of stellar origin. The masses are known from detected gravitational waves (black holes in blue, neutron stars in orange) or observations in the electromagnetic spectrum (black holes in red, neutron stars in yellow)

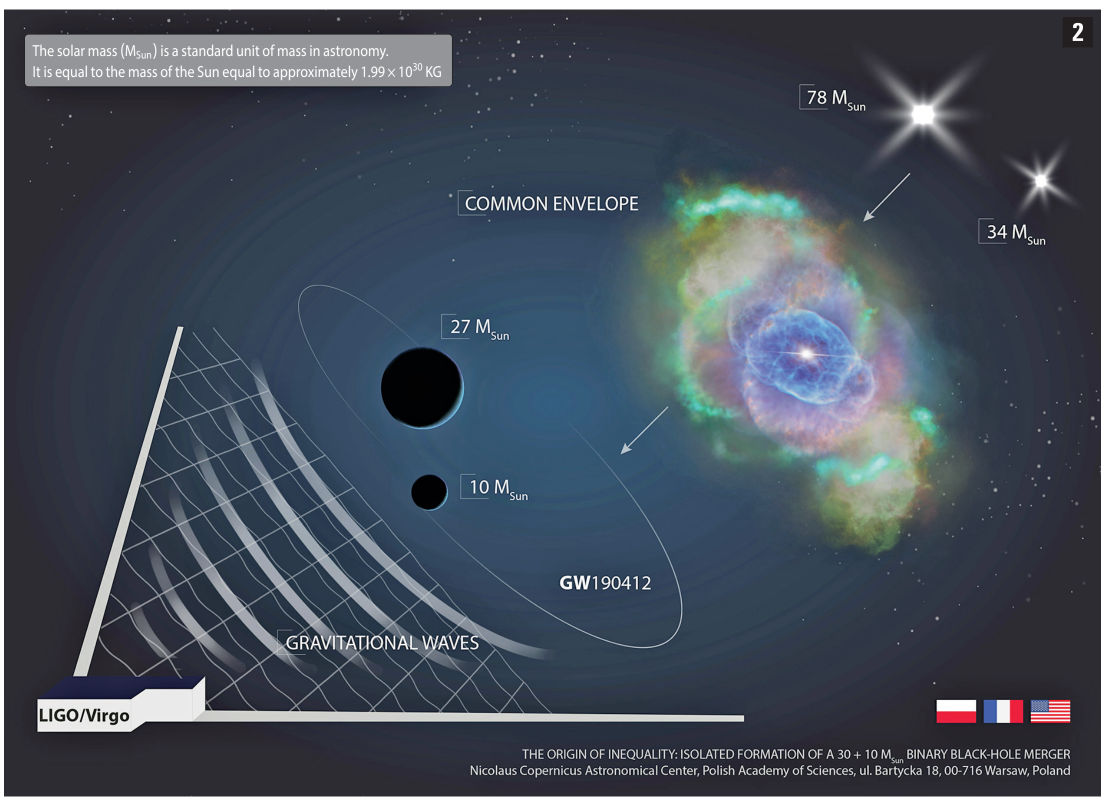


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Fig. 2
A simplified diagram of the evolution of two massive stars leading to the formation of an asymmetric black hole system similar to that known as GW190412

pact object systems. One of the scientific groups with expertise in studying the evolution of isolated binary systems of massive stars leading to the formation of sources of gravitational waves – in other words, contact binary systems – works at Nicolaus Copernicus Astronomical Centre of Polish Academy of Sciences, and is headed by Prof. Krzysztof Belczyński.

Everything indicates that these are just early days for the emergent and rapidly developing discipline of gravitational wave astrophysics. The proposed third-generation ground-based detectors (the Einstein Telescope and the Cosmic Explorer facility) will be more sensitive, allowing scientists to detect events from the early stages of the expansion of our universe, soon after the Big Bang. This will allow us to verify numerous theories about the evolution of the universe, the rate of star formation and the formation of merging binary systems of compact objects. ■

Further reading:

Gubser S.S., 2017. *The Little Book of Black Holes* (Princeton: Science Essentials, 29).

"Gravitational waves: A three minute guide" nature video, https://www.youtube.com/watch?v=hhbMpe17fzA