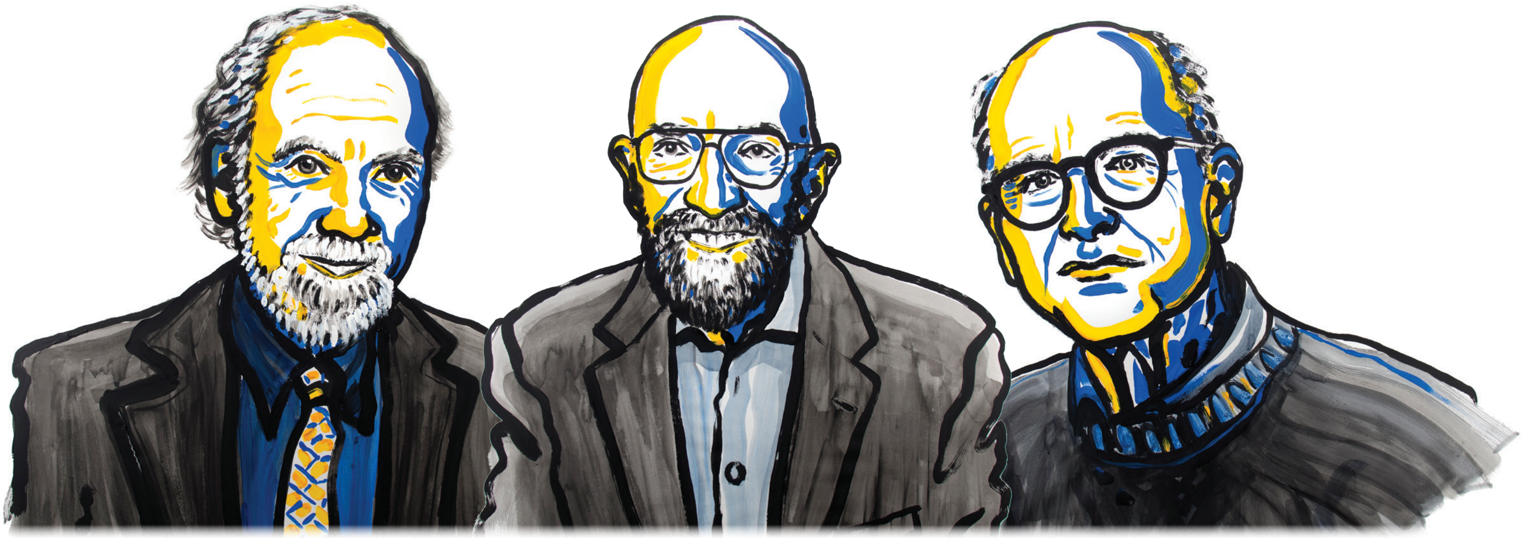

Nobel Prize laureates Barry Barish, Kip Thorne and Rainer Weiss. Illustration: Niklas Elmehed. © Nobel Media AB 2017.

Nobel Prize for Detecting Gravitational Waves

The 2017 Nobel Prize in Physics has been awarded to three US researchers, Rainer Weiss, Barry C. Barish and Kip S. Thorne 'for decisive contributions to the LIGO detector and the observation of gravitational waves'.

The first direct detection of gravitational waves on 14 September 2015 was an event that, quite literally, shook the world. The two LIGO detectors registered a tiny vibration, first in the detector in Louisiana, and then, seven milliseconds later, in the other detector in Washington State. This tiny vibration was caused by a ripple in spacetime itself, known as a gravitational wave, a consequence of Einstein's theory of General Relativity.

Analysis of the signal showed that it came from the inspiral and merger of two black holes orbiting one another in a binary system, more than 1.3 billion light years from Earth. The black holes had masses of around 29 and 36 times that of the Sun, and formed a single spinning black hole of mass 62 times that of the Sun, with the 'missing' three solar masses being liberated as gravitational wave energy.

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LIGO is an acronym: Laser Interferometer Gravitational Wave Observatory. A laser beam is split in two, with each half being sent up one of two orthogonal vacuum tubes, where it is reflected by a suspended mirror at the end. The two beams are then recombined, with shifts in the interference pattern indicating changes in lengths of the arms, caused in part by a passing gravitational wave.

It was Weiss that, while at MIT, formulated the basic ideas underlying these detectors, making estimates of the main sorts of noise that would compete with the gravitational wave signals themselves. This led to the co-founding of the LIGO project by Weiss, Thorne and the Scottish physicist Ron Drever. Drever lived to see the announcement of the first detection, but sadly passed away soon after.

It became clear that the construction and running of LIGO would be a major undertaking. In 1997 Barish became Director of the LIGO Laboratory, and played a key role both in organising the project, and, crucially, securing the funding required from the National Science Foundation. He founded the LSC (LIGO Scientific Collaboration), the international network of more than 1,000 researchers that work on the project.

Mathematical modelling played a key role in developing the science case for building the LIGO detectors, an area where Thorne played a leading role. This included the development of many ideas in relativistic astrophysics, such as the theory of relativistic stellar pulsation, laws governing how black holes move and precess, and the formalism for how one computes the gravitational wave emission from a given source. Thorne was also instrumental in developing the data analysis techniques required to extract the weak gravitational wave signals from the noisy detector data, and in the analysis of quantum effects in the optical components of the detectors.

There is a sense, however, in which the mathematical side of this story can be traced back much further. In a wonderful historical resonance, the basic theory underlying gravitational waves, namely Einstein's theory of General Relativity, was finalised in 1915, one hundred years before the eventual detection of gravitational waves. In 1916, a century before the announcement of the detection, Einstein himself realised that, by looking at the weak field linearisation of his equations, gravitational wave solutions existed, propagating at the speed of light. There was in fact controversy about the physical reality and relevance of both gravitational waves and black holes in the decades that followed, eventually put to rest through the careful calculations of many researchers in the field of general relativity.

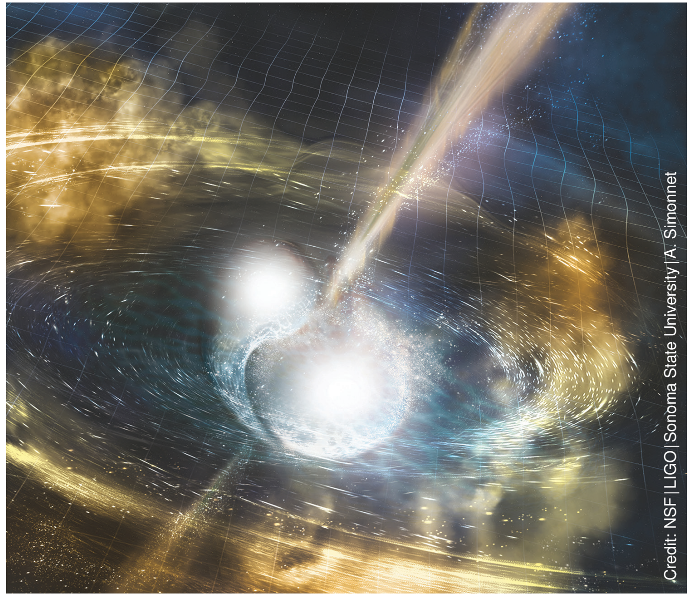
The Nobel prize was awarded not just for the 2015 detection of gravitational waves from black holes, but for the promise of what was to come. Gravitational wave physicists have long promised to 'open a new window' on the Universe, using gravity, not light, as the probe. In a spectacular and remarkably rapid fulfilment of this promise, just weeks after the award of the Nobel prize, the LIGO detectors, together with the European Virgo detector, announced the observation of gravitational waves from two inspiralling and merging neutron stars.

Neutron stars are small ultra-compact objects, formed in the death throes of some main sequence stars. With masses comparable to that of the Sun, crammed into a sphere of radius of around 10 kilometres, neutron stars represent ready-made laboratories for testing the behaviour of matter under extreme conditions. And sure enough, the gravitational wave signal was followed within two seconds by the detection of a flash of light, known as a gamma ray burst. In the hours, days and weeks that followed, the aftermath of this catastrophic collision was observed throughout the electromagnetic spectrum, heralding the birth of *multi-messenger astronomy*.

The detection of this new sort of source, with all of the complicating effects of matter, requires a whole new set of tools, in terms of the mathematical modelling. Even before the two neutron stars come into contact, each produces a tidal deformation on the other, subtly accelerating the inspiral. Perturbation theory, originally developed in the Newtonian context to describe the tides of the Earth, is being extended into the relativistic regime, to quantity the importance of finite-size effects on the gravitational waveform.

The late stages of the inspiral and the coalescence itself requires full-blown numerical simulation, to capture the behaviour of the neutron star fluid. There are reasons to believe that magnetic fields may be important too, so in reality the equations of *general relativistic magnetohydrodynamics* need to be evolved. Efforts to carry out such simulations are already well advanced, but much work needs to be done to make them accurate enough, and to evolve long enough, to carry out a full comparison between theory and observation.

The award of the 2017 Nobel Prize in Physics to Weiss, Barish and Thorne was richly deserved. The birth of gravitational wave astronomy stands to revolutionise the way we learn about the universe around us. And the new theoretical challenges it presents us with will certainly keep mathematical modellers busy for many year to come.



Artist's illustration of two merging neutron stars.

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For a review of gravitational wave physics, and the mathematical modelling involved, see my *Mathematics Today* article, Oct 2017, p. 235, ima.org.uk/7430/gravitational-waves-new-window-universe