Gravitational waves and black holes

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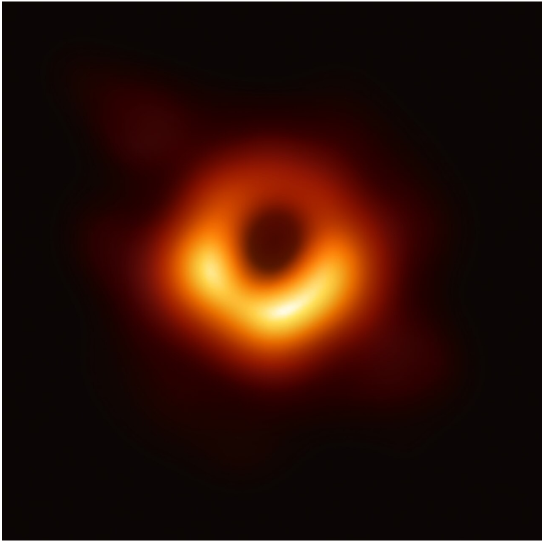
Plan

1. Black holes
   - Black holes as a discovery in steps
   - Some features of black holes
2. Gravitational waves
   - The theory
   - The observations

Black holes



Event Horizon Telescope image of the supermassive black hole at the centre of galaxy M87.

Newtonian escape velocity

Definition (Escape velocity)

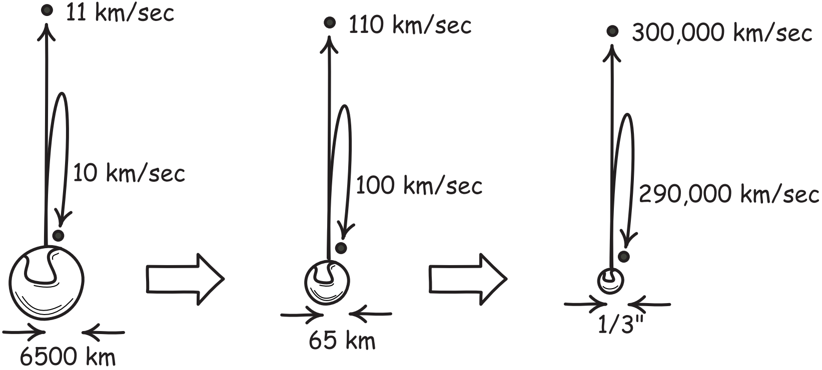
In Newtonian physics, the escape velocity v_e *for a body hurled straight up from the planet's surface is the sufficient velocity for it to escape the planet's gravitational field and is given by*

$$v_e = \sqrt{\frac{2GM}{R}},$$

where M *and* R *are the planet's mass and radius and* G *is Newton's gravitational constant.*

- For Earth, $v_e = 11.2$ km/s.
- Now imagine a much more massive and compact body. Then M/R and so v_e will be much larger.
- If $v_e > c$ (speed of light), the planet would appear to be completely dark when viewed from large distances (in Newtonian physics).

Newtonian escape velocity



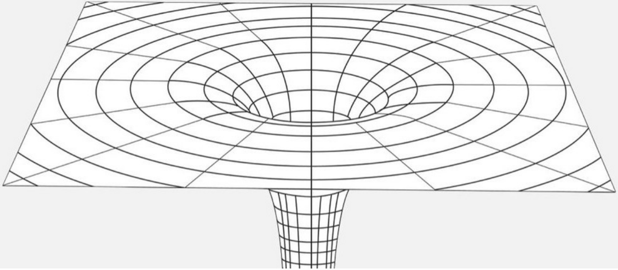
Source: John Norton, Einstein for Everyone

`https://sites.pitt.edu/~jdnorton/teaching/HPS_0410/chapters/black_holes/index.html`

Karl Schwarzschild's 1916 discovery

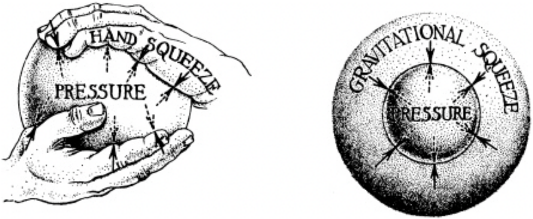
- In general relativity, we expect that there are such situations, resulting in what is called a black hole.
- Since no signal or moving body can exceed the speed of light, for a given mass M, this defines a maximum radius R_S (Schwarzschild radius) from which anything can escape the gravitational pull of M:

$$R_s = \frac{2GM}{c^2}$$



Gravitational collapse

📄 Kip S Thorne (1995). *Black Holes and Time Warps: Einstein's Outrageous Legacy*. New York and London: Norton and Company.



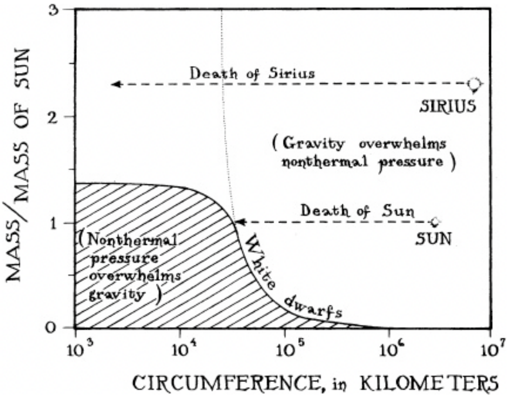
4.2 *Left:* The balance between the squeeze of your hands and the pressure inside a balloon. *Right:* The analogous balance between the gravitational squeeze (weight) of an outer shell of stellar matter and the pressure of an inner ball of stellar matter.

- What counteracts gravitational pull: nuclear fission, thermic pressure, electron and neutron degeneracy pressure (Pauli principle).

⇒ a white dwarf (solar mass concentrated into size of Earth) is held apart by electron degeneracy pressure

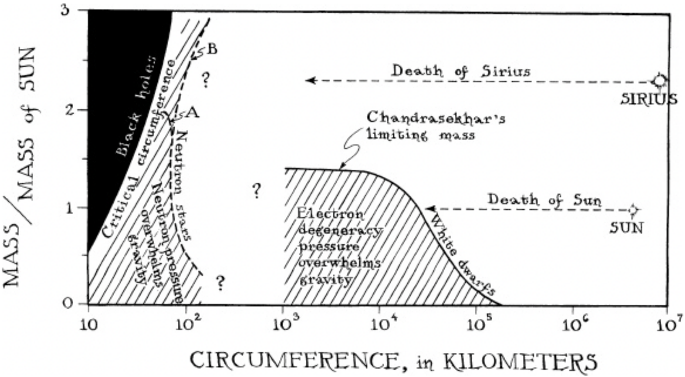
⇒ a neutron star (solar mass concentrated into radius of 10km) is held apart by neutron degeneracy pressure

Subrahmanyan Chandrasekhar's 1931 discovery



4.4 When a normal star such as the Sun or Sirius (not Sirius B) starts to cool off, it must shrink, moving leftward in this diagram of mass versus circumference. The shrinkage of the Sun will stop when it reaches the edge of the shaded region (the white-dwarf curve). There degeneracy pressure balances gravity's squeeze. The shrinkage of Sirius, by contrast, cannot be so stopped because it never reaches the edge of the shaded region. See Box 4.2 for a different depiction of these conclusions. If, as Eddington claimed, white-dwarf matter's resistance to compression were always 5/3, that is, if relativity did not reduce it to 4/3 at high densities, then the graph of mass versus circumference would have the form of the faint dotted curve, and the shrinkage of Sirius would stop there.

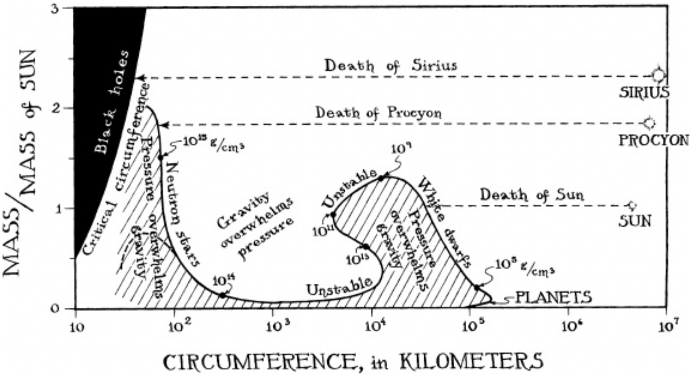
Fritz Zwicky 1934: neutron stars



5.3 The ultimate fate of a star more massive than the Chandrasekhar limit of 1.4 Suns depends on how massive neutron stars can be. If they can be arbitrarily massive (curve *B*), then a star such as Sirius, when it dies, can only implode to form a neutron star; it cannot form a black hole. If there is an upper mass limit for neutron stars (as on curve *A*), then a massive dying star can become neither a white dwarf nor a neutron star; and unless there is some other graveyard available, it will die a black-hole death.

Robert Oppenheimer et al’s 1940s discovery:

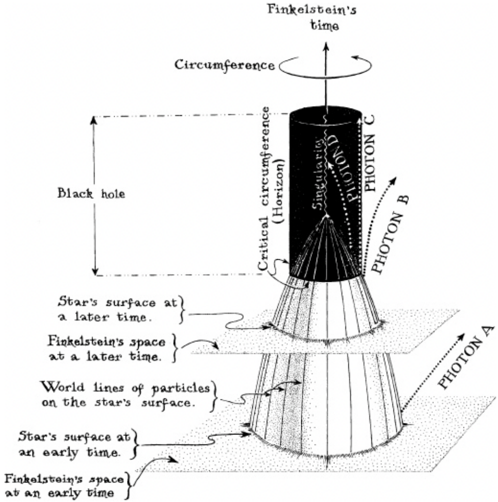
Collapse to black hole in highly idealised and symmetric situations



5.5 The circumferences (plotted horizontally), masses (plotted vertically), and central densities (labeled on curve) for cold, dead stars, as computed by Masami Wakano under the direction of John Wheeler, using the equation of state of Box 5.5. At central densities above those of an atomic nucleus (above 2 x 1014 grams per cubic centimeter), the solid curve is a modern, 1990s, one that takes proper account of the nuclear force, and the dashed curve is that of Oppenheimer and Volkoff without nuclear forces.

Roger Penrose and Stephen Hawking's 1967 discovery:

Black holes as generic end states of gravitational collapse



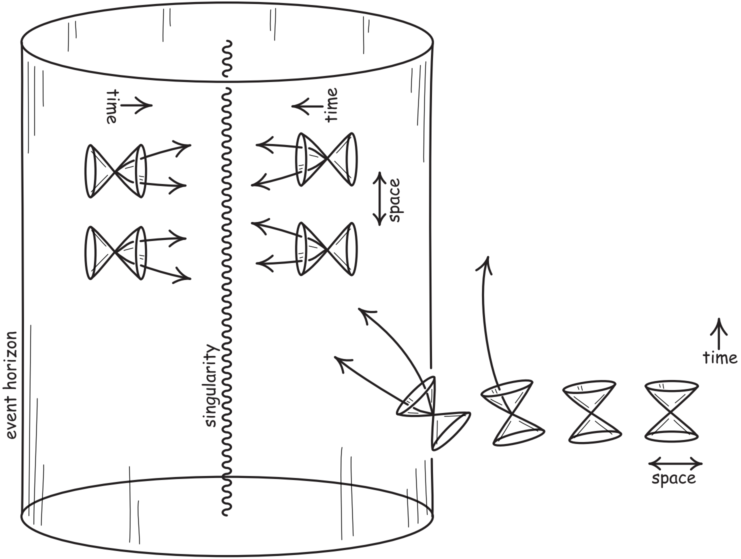
6.7 A spacetime diagram depicting the implosion of a star to form a black hole. Plotted upward is time as measured in Finkelstein's reference frame. Plotted horizontally are two of the three dimensions of that frame's space. Horizontal slices are two-dimensional "snapshots" of the imploding star and the black hole it creates at specific moments of Finkelstein's time, but with the curvature of space suppressed.

The 2020 Physics Nobel Prize

`https://www.nobelprize.org/prizes/physics/2020/summary/`

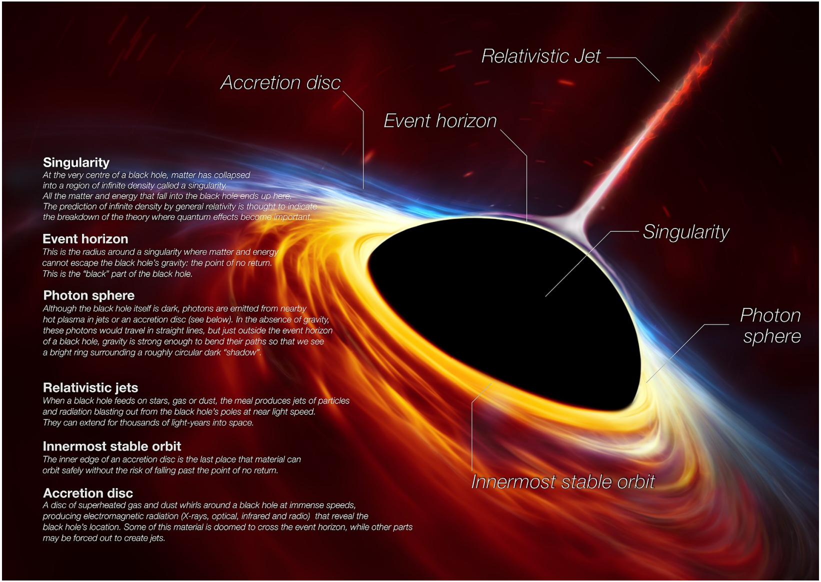
The Nobel Prize in Physics 2020 was divided, one half awarded to Roger Penrose "for the discovery that black hole formation is a robust prediction of the general theory of relativity", the other half jointly to Reinhard Genzel and Andrea Ghez "for the discovery of a supermassive compact object at the centre of our galaxy".

The lightcone structure of a black hole



Source: John Norton, Einstein for Everyone

The features of a black hole



Singularity
At the very centre of a black hole, matter has collapsed into a region of infinite density called a singularity. All the matter and energy that fall into the black hole ends up here. The prediction of infinite density by general relativity is thought to indicate the breakdown of the theory where quantum effects become important.

Event horizon
This is the radius around a singularity where matter and energy cannot escape the black hole's gravity: the point of no return. This is the "black" part of the black hole.

Photon sphere
Although the black hole itself is dark, photons are emitted from nearby hot plasma in jets or an accretion disc (see below). In the absence of gravity, these photons would travel in straight lines, but just outside the event horizon of a black hole, gravity is strong enough to bend their paths so that we see a bright ring surrounding a roughly circular dark "shadow".

Relativistic jets
When a black hole feeds on stars, gas or dust, the meal produces jets of particles and radiation blasting out from the black hole's poles at near light speed. They can extend for thousands of light-years into space.

Innermost stable orbit
The inner edge of an accretion disc is the last place that material can orbit safely without the risk of falling past the point of no return.

Accretion disc
A disc of superheated gas and dust whirls around a black hole at immense speeds, producing electromagnetic radiation (X-rays, optical, infrared and radio) that reveal the black hole's location. Some of this material is doomed to cross the event horizon, while other parts may be forced out to create jets.

Source: Wikipedia

Einstein's general relativity (GR)

Core of GR: Einstein field equation

$$G_{ab}[g_{ab}] = 8\pi T_{ab}$$

$G_{ab}[g_{ab}]$: functional of the metric g_{ab} and its first and second partial derivatives; contains complete information about the geometrical structure of spacetime.

T_{ab}: energy-mass-density; describes the distribution of (energy and) masses in the spacetime.

‘Disembodied’ gravitational energy

Roger Penrose (2004). *The Road to Reality: A Complete Guide to the Laws of the Universe*. New York: Vintage Books.


(a) (b)

Fig. 19.8 Non-locality of gravitational potential energy. Imagine two planets (which for simplicity we may suppose to be instantaneously relatively at rest). If (a) they are far apart, then the (Newtonian) negative potential energy contribution is not so great as (b) when they are close together. Thus the total energy (and hence the total mass of the whole system) is larger in case (a) than in case (b) despite the total energy densities, as measured by the energy–momentum tensors, being virtually the same in the two cases.

Gravitational waves

Penrose (2004, 465)

> *[L]et us consider that the bodies are in motion, in orbit about one another. It is a consequence of Einstein's field equation that gravitational waves—ripples in the fabric of spacetime—will emanate from the system and carry (positive) energy away from it. In normal circumstances, this energy loss will be very small. For example, the largest such effect in our own solar system arises from the Jupiter–Sun system, and the rate of energy loss is only about that emitted by a 40-watt light bulb! But for more massive and violent systems, such as the final coalescence of two black holes that have been spiralling into each other, it is expected that the energy loss would be so large that detectors presently being constructed here on Earth might be able to register the presence of such gravitational waves at a distance of 15 megaparsecs or about* 4.6×10^{23} *metres.*

Gravitational waves as ripples in spacetime

- Similar to electromagnetic waves, gravitational waves are transverse waves oscillating perpendicular to the direction of propagation.
- They can oscillate at any frequency, depending on their source.
- They propagate at the speed of light.
- They propagate in spacetime as ripples in the geometry of spacetime.
- Their amplitude is tiny and inversely proportional to the distance of the source, which makes their direct detection challenging.

Example of the effect when looking straight at the source of the wave:

`https://commons.wikimedia.org/wiki/File:Quadrupol_Wave.gif`

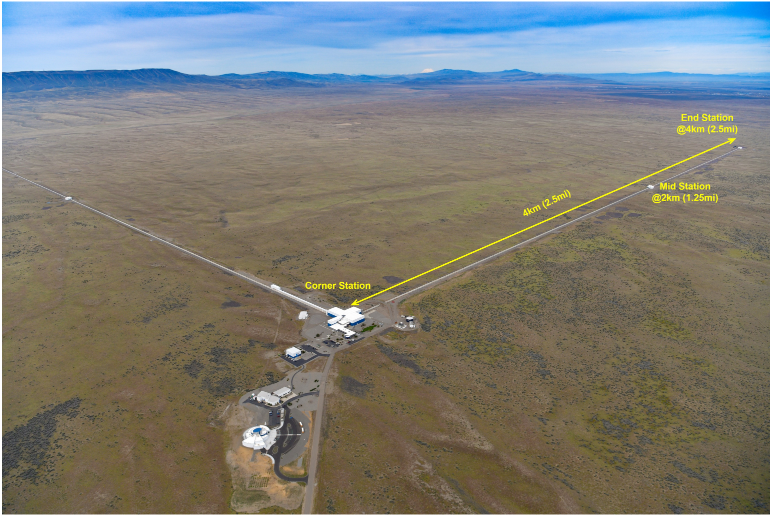
Indirect detection: Hulse-Taylor double neutron star system

Fig. 19.9 The Hulse–Taylor double neutron star system PSR 1913 + 16. One member is a pulsar which sends out precisely timed electromagnetic signals that are received at Earth, enabling the orbits to be determined with extraordinary accuracy. It is observed that the system loses energy in exact accord with Einstein's prediction of energy-carrying gravitational waves emitted by such a system. These waves are ripples in the spacetime vacuum, where the energy–momentum tensor vanishes. (Not to scale.)

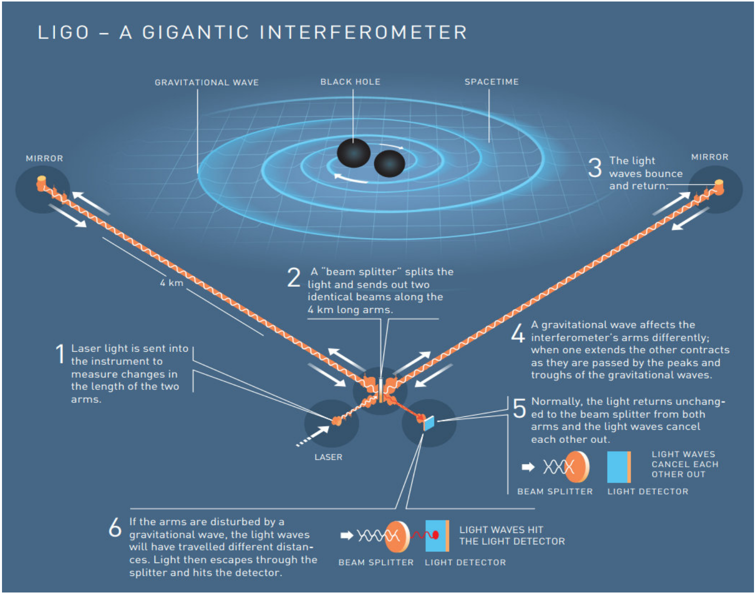
Direct detection: LIGO

Laser Interferometer Gravitational-Wave Observatory

Two locations in US-states of Louisiana and Washington built between 1994 and 2002:



LIGO: How interferometry works



LIGO – A GIGANTIC INTERFEROMETER

1 Laser light is sent into the instrument to measure changes in the length of the two arms.

2 A "beam splitter" splits the light and sends out two identical beams along the 4 km long arms.

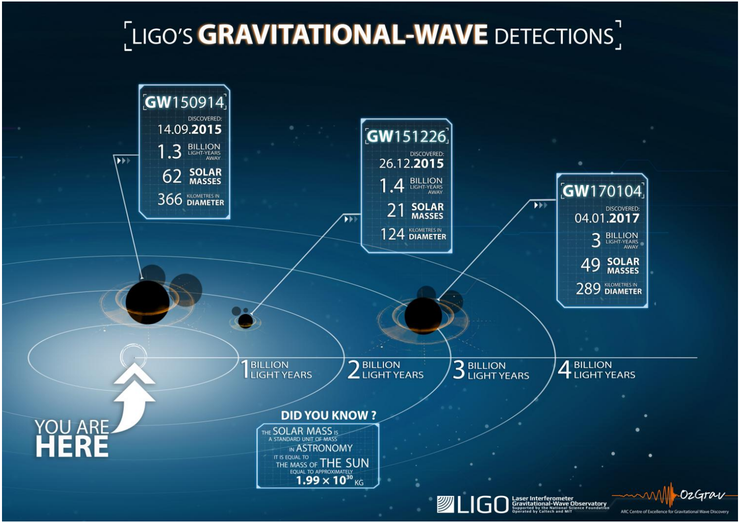
3 The light waves bounce and return.

4 A gravitational wave affects the interferometer's arms differently; when one extends the other contracts as they are passed by the peaks and troughs of the gravitational waves.

5 Normally, the light returns unchanged to the beam splitter from both arms and the light waves cancel each other out.

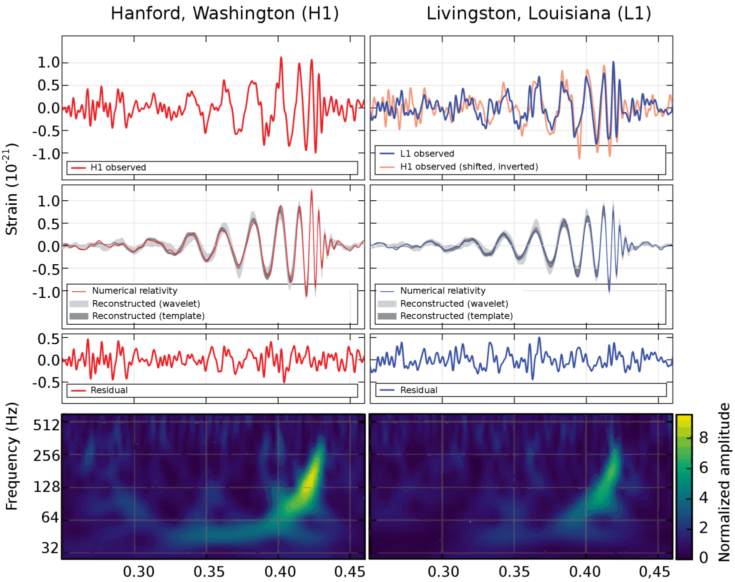
6 If the arms are disturbed by a gravitational wave, the light waves will have travelled different distances. Light then escapes through the splitter and hits the detector.

LIGO detections

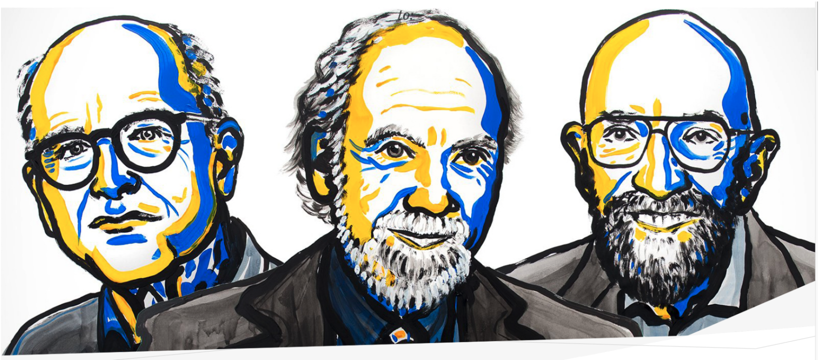


- The first detection occurred on 14 September 2015 (GW150914).
- As of May 2024, LIGO has 90 confirmed detections of gravitational waves.

GW150914: observed and compared with numerical relativity



The 2017 Physics Nobel Prize



https://www.nobelprize.org/prizes/physics/2017/summary/

The Nobel Prize in Physics 2017 was divided, one half awarded to Rainer Weiss, the other half jointly to Barry C. Barish and Kip S. Thorne "for decisive contributions to the LIGO detector and the observation of gravitational waves".