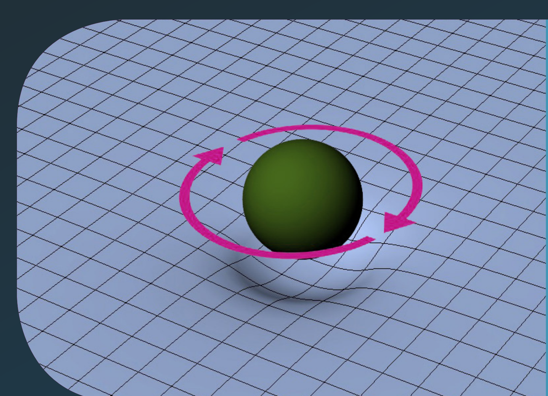
The Science of Gravitational waves

General Relativity and Gravitational Waves

In 1915, Albert Einstein breathed new life into the study of gravitation with his theory of general relativity. In this theory, space and time are unified into a single entity – 'spacetime' – which interacts with massive bodies.
Highly dense and massive celestial bodies curve spacetime considerably. Einstein understood that the resulting curvature produces the effects that we attribute to the force of gravity.
The waves that propagate across this 'spacetime fabric' are called gravitational waves. They arise from the dynamics of large mass distributions that lack spherical symmetry or are axially deformed. Our bodies generate gravitational waves as we move, but it is only the waves from astrophysical phenomena that are powerful enough to be detected by our experiments.
A perfectly spherical rotating body in a non-viscous fluid does not generate waves.



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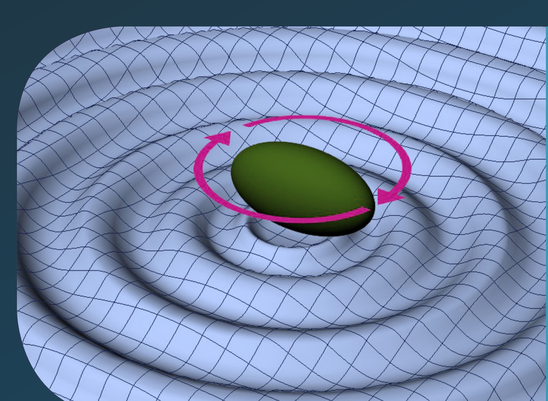

An elongated rotating body in a non-viscous fluid does generate waves.

Sources of Gravitational Waves

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Neutron Stars:

Neutron stars are remnants of supernova explosions, with masses close to 1.4 times the mass of the Sun and radii of about 10 km. A typical neutron star is one hundred billion times denser than water and rotates about 10 times per second. Any departure from spherical symmetry, even wrinkles as small as a few centimeters on the star's surface, can produce gravitational waves that are emitted at twice the star's rotation frequency. Some neutron stars shine light from their polar regions and their rotation can beam this light towards Earth at regular intervals. These stars are called 'pulsars' and we expect their emission (both electromagnetic and gravitational) to be very long-lasting; lasting even for millions of years.

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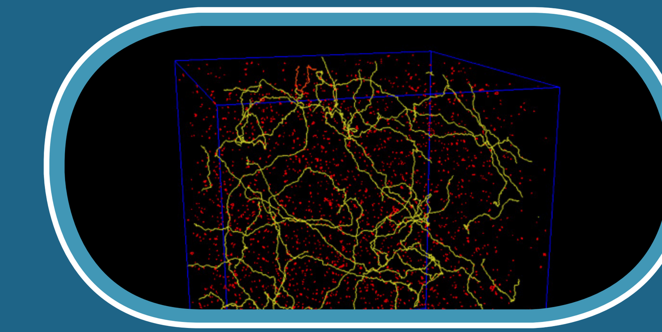
Supernovae:

When stars heavier than 8 solar masses exhaust their nuclear fuel, they become unstable and finally undergo an extremely fast gravitational collapse, with a concurrent, powerful neutrino emission, which carries away much of the star's energy. The collapse produces shock-waves that rip away the outer shells of the star and push them towards outer space at very high speed. This is a very energetic phenomenon with a luminosity 5 billion times greater than that of the Sun.
Again, if the explosion lacks spherical symmetry, it can generate gravitational waves.

© Event Horizon Telescope

Black Holes:

A black hole is a heavenly body with such an intense gravitational field that not even light can escape it. This is why these objects do not emit light and appear totally black. There are different types of black holes, such as those with star-like mass, which are the terminal stage of massive stars, and often follow a neutron star stage. In their core, many galaxies hide supermassive black holes with masses that may be as large as millions or even billions of solar masses. The gravitational waves detected by LIGO and Virgo have revealed the existence of black holes that weigh tens of solar masses, the existence of which was previously only conjecture.



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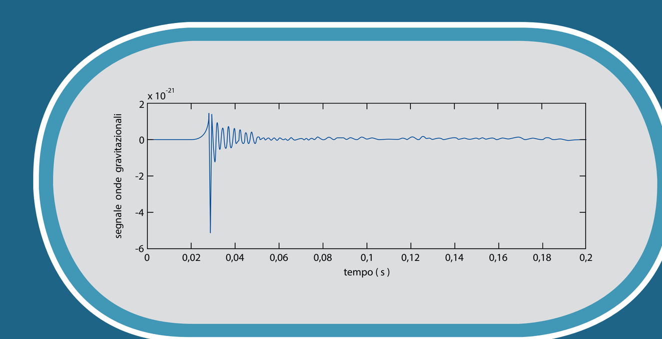
Exotic Sources:

Gravitational astronomy is a powerful tool with which to discover exotic sources such as: exotic stars, where even neutrons dissolve into their quark components, which are no longer joined in triplets, so that the star becomes a strange 'quark soup'; cosmic strings, that can be open or closed and which are wiggling threadlike defects in the structure of space-time; and clouds of ultralight bosons, such as axions, which may be the basic constituents of dark matter, circling around black holes.

Types of Detectable Signals



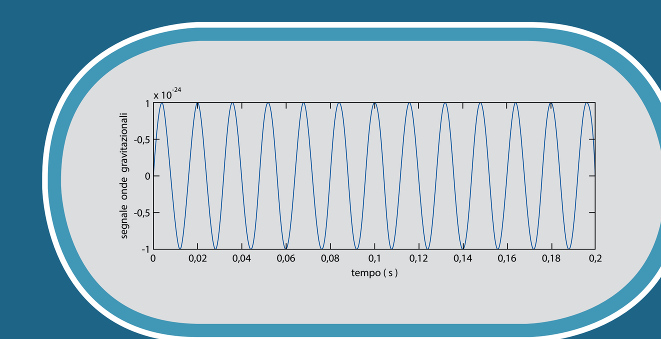
Transient Signals:

Some astrophysical sources produce bursts of gravitational waves that last no more than a few seconds. These are of two types:

- Coalescence of black holes and/or neutron stars: after endless spiraling orbits, two compact and massive bodies finally merge into a single object that can be either a neutron star or a black hole. The final mass determines whether the burst of gravitational waves is accompanied by electromagnetic waves or not.

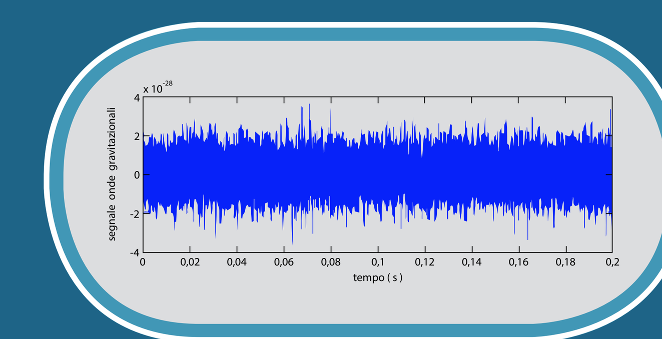
The observation of one such burst produced the first detection of a gravitational wave – called GW150914 – which was emitted by the coalescence of two black holes about 30 times heavier than the Sun. Another burst – associated with the gravitational wave GW170817 – came from the merger of two neutron stars.

- Bursts from supernova explosions, which are emitted when massive stars die. The detection of gravitational waves from these explosions will be all-important in the testing of the many existing theoretical models and to clarify the mechanisms of supernova explosions.



Periodic Signals:

These signals are associated with the continuous emission of gravitational waves from astrophysical sources, such as isolated neutron stars, or neutron stars in a binary system with another star. An isolated neutron star can emit gravitational waves only if it is distinctly non-spherical. These signals last much longer than the typical data-taking time of the detectors and from them one can derive precious information on the nature and dynamics of the source.
The electromagnetic signals emitted by pulsars determine the precise rotation frequency and can be of great help in the search for gravitational waves.



Stochastic Background:

- The astrophysical stochastic background is the ensemble of signals produced by innumerable sources of different natures and positions. It covers a huge range of intensities and frequencies. It is a kind of cacophony of signals that are randomly superposed upon one another.
- The cosmological astrophysical background is also due to the superposition of gravitational waves, but in this case, the independent sources are the physical processes that took place in the early history of the Universe. This background is similar to the cosmic microwave background and it permeates the Universe to this day.

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