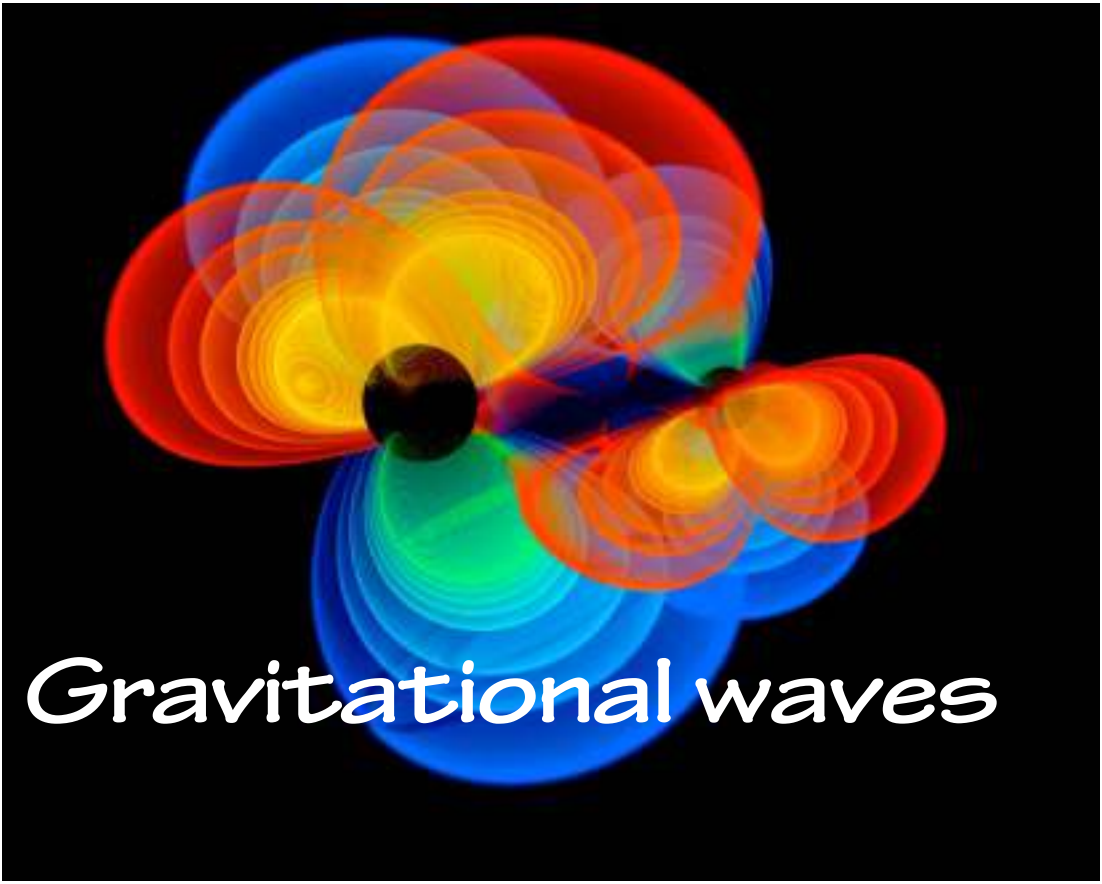
The Universe in my pocket



Gravitational waves

Nº 18

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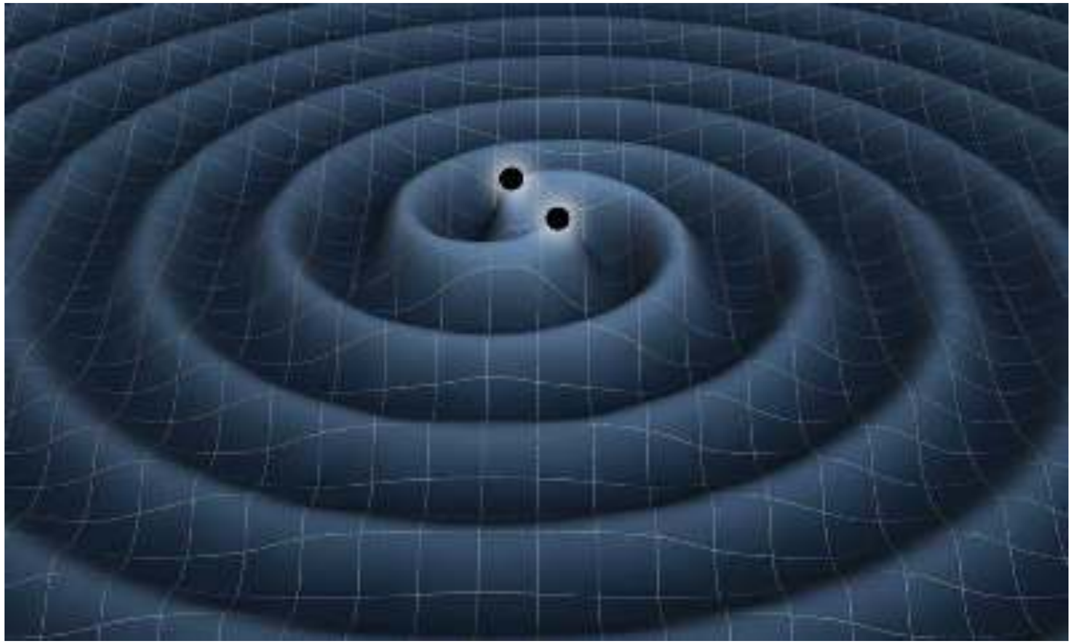
Alexandre Le Tiec
Paris Observatory

An artistic depiction of two black holes orbiting each other under the effect of their mutual gravitational attraction. Their orbital motion generates gravitational waves.



[Credit: NASA]

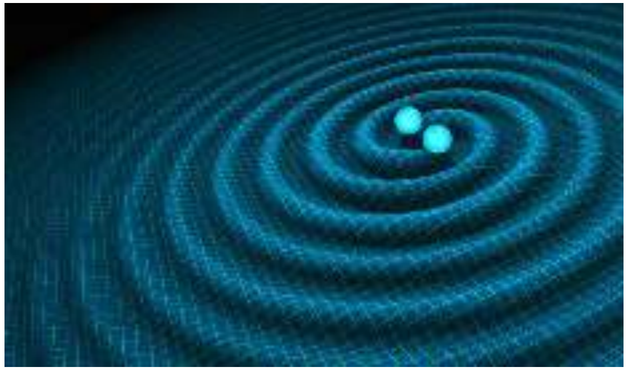
What are they?

Gravitational waves are small vibrations in the structure of space-time that propagate at the speed of light. They are transverse waves which means that the displacement in space-time is perpendicular to the direction of propagation.

They were predicted by general relativity, the theory of gravitation formulated by Albert Einstein in 1915.

The first indirect evidence of their existence was the observation by Hulse and Taylor in 1974 of their effect on the orbital period of a pair of neutron stars.

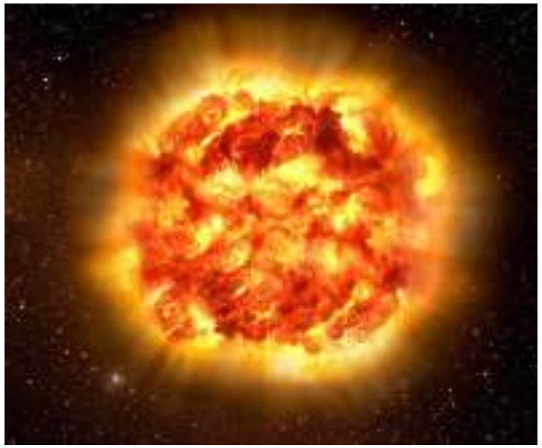
The first instrumental detection of a gravitational wave took place in 2015 using the LIGO detectors. This gravitational wave came from the coalescence of two black holes of about thirty solar masses each.



Representation of a pair of neutron stars [Credit: R. Hurt/Caltech-JPL]

Artist's depiction of a pair of white dwarf stars [Credit: ESO]

Artist's view of an isolated neutron star [Credit: NASA].



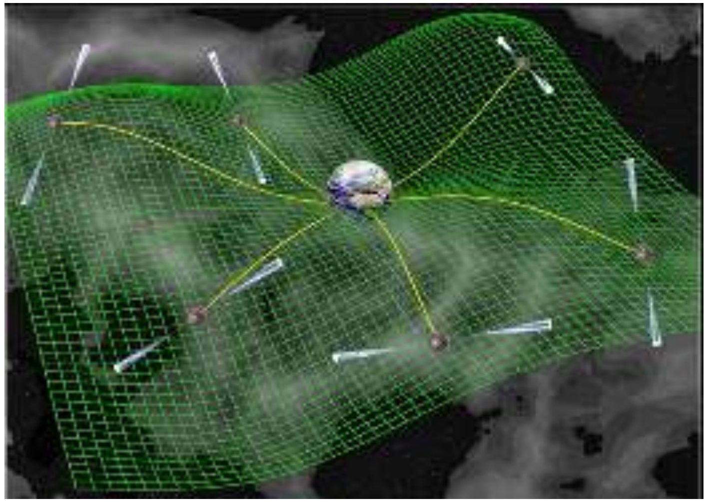
Artist's view of a Type Ia supernova [Credit: ESO].

Local sources

The main sources of gravitational waves are massive, compact stars (see TUIMP No. 9), such as black holes, neutron stars and white dwarfs, either singly or in pairs.

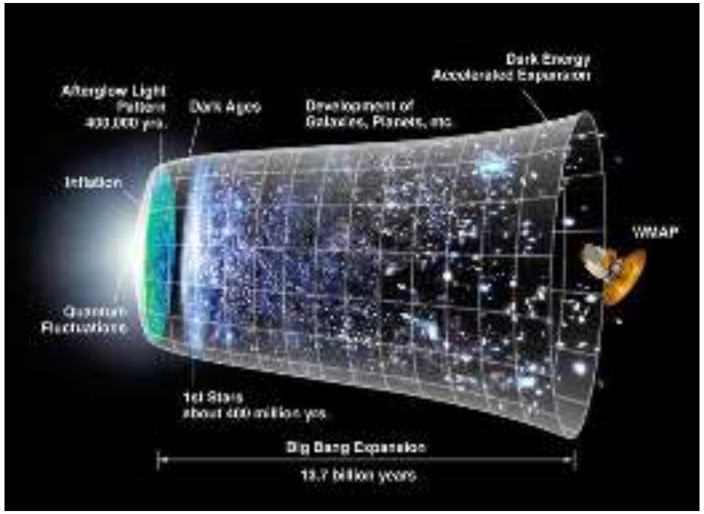
The following localised sources can be distinguished:

- Binary systems of compact objects such as spiralling and merging black holes or neutron stars, either galactic or extra-galactic;
- Binary white dwarf stars in the Milky Way ;
- Isolated, slightly asymmetric, rotating neutron stars in the galactic neighbourhood;
- Explosion of massive stars (supernovae) in our galaxy, leading to the formation of neutron stars or black holes.



[Credit: D. J. Champion]

Depiction of an array of pulsars. Each line of sight to a pulsar acts as an arm of the interferometer on which the passage of a gravitational wave is measured.



[Credit: NASA]

Representation of the expansion of the Universe from the period of inflation to the present day.

Diffuse sources

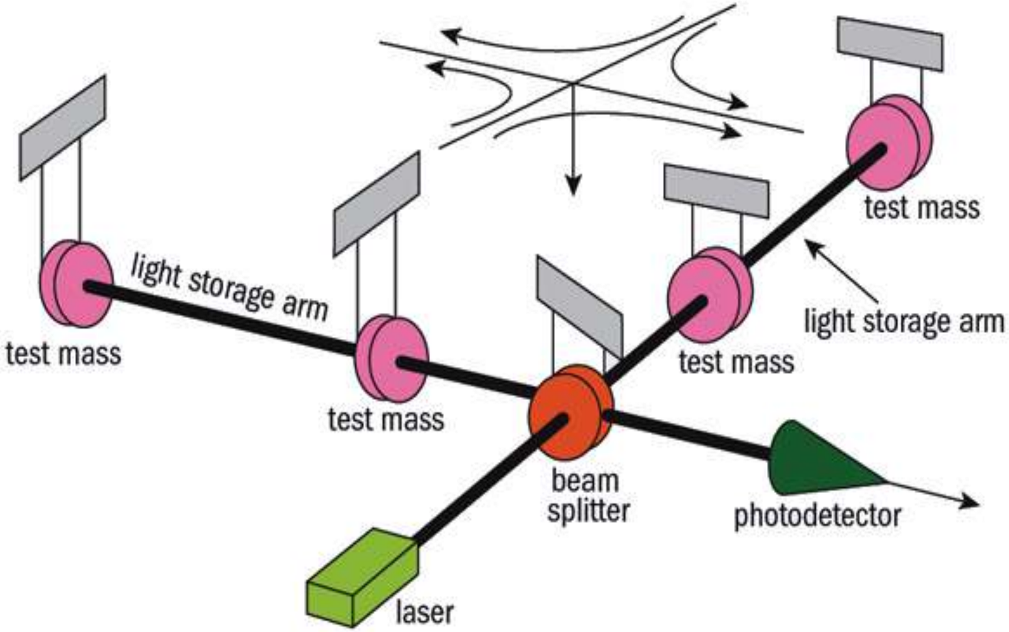
When gravitational waves generated by a very large number of localised sources are superimposed, they can no longer be distinguished from one another. The result is a stochastic astrophysical background.

In addition, various more speculative physical phenomena produced shortly after the Big Bang (see TUIMP n°12) might generate a cosmological stochastic background. These include :

- cosmic strings, resulting from a sudden change of state in the energy and material content of the primordial Universe;
- primordial black holes, which are thought to have formed as a result of large fluctuations in the energy density of the early Universe;
- inflation, a period of rapid cosmic expansion that took place a fraction of a second after the Big Bang.

The Virgo detector in Cascina, near Pisa (Italy).

The LIGO detector in Livingston (Louisiana, USA).



Operating diagram of an interferometric gravitational-wave detector.

Current detectors

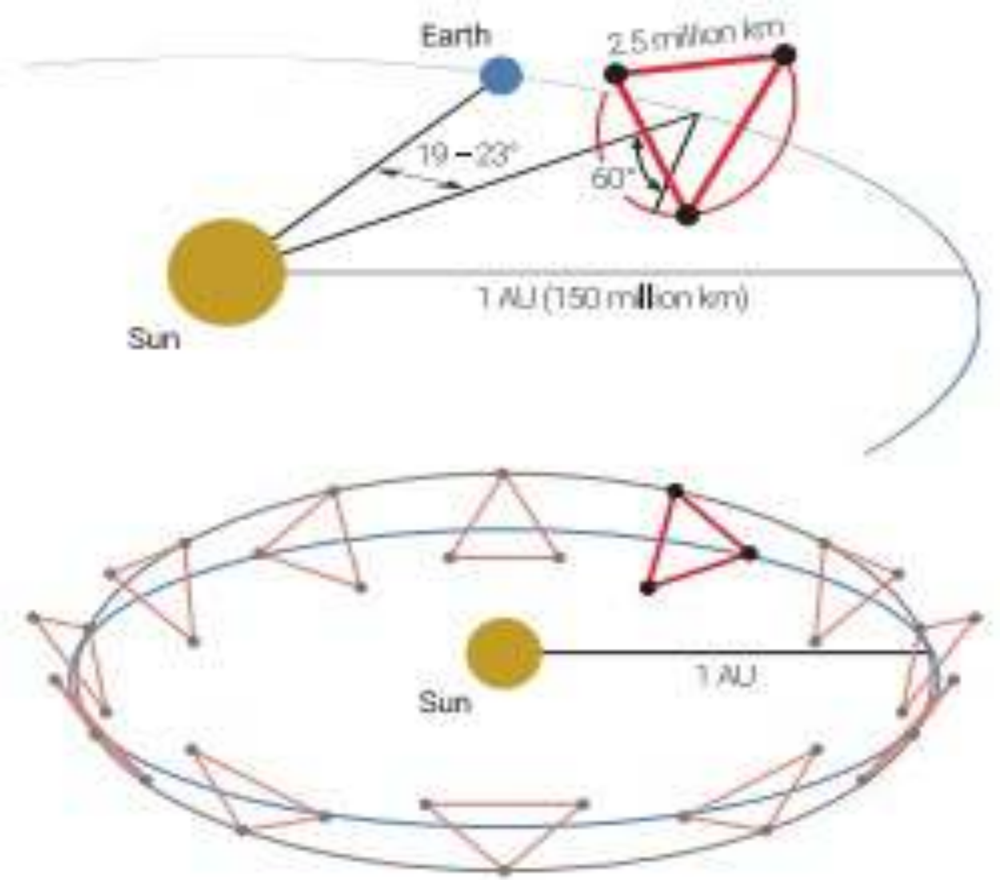
Existing gravitational-wave detectors are based on the principle of optical interferometry: they measure tiny variations in length by superimposing laser light on itself.

They consist of two perpendicular arms, each about a kilometre long, through which light travels. When a gravitational wave passes through them, the difference in length between the two arms varies slightly. This variation is of the order of one thousandth of the size of an atomic nucleus, or 0.000000000000000001 metres.

Four detectors are in operation:

- the two LIGO instruments in the United States (at Livingston and Hanford);
- the Franco-Italian Virgo observatory, near Pisa in Italy;
- the KAGRA detector in Japan.

Image of the future European Telescope, the Einstein detector.

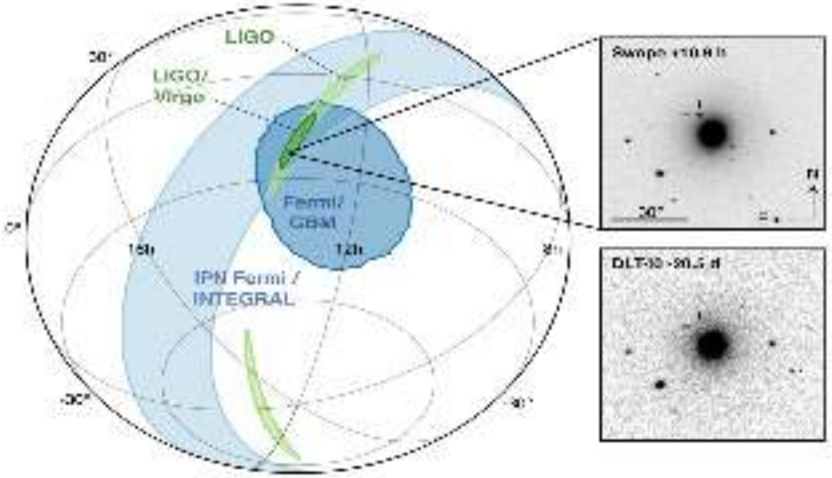


The future LISA space detector. The three satellites in triangular configuration follow the Earth's orbit.

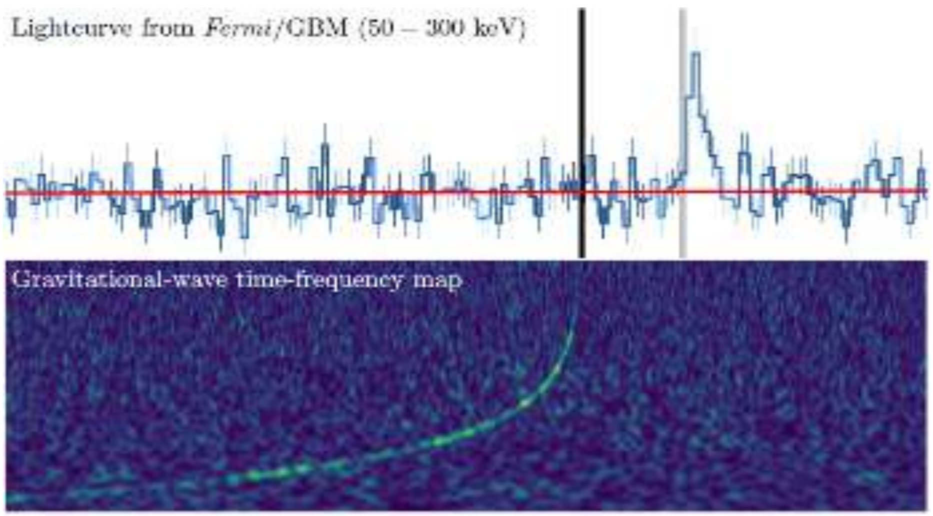
Future gravity wave detectors

Following on from existing detectors, the European Union plans to build the Einstein Telescope, a new gravitational wave observatory. It will have a triangular configuration, greater vibration isolation because it will be placed underground, and cryogenic cooling technology for the mirrors.

The European Space Agency is developing LISA, a space-based gravitational-wave detector, to eliminate terrestrial disturbances such as seismic noise. It will consist of three satellites several million kilometres apart, enabling it to observe particularly massive sources, complementary to those seen from Earth.



The gamma-ray signal observed by FERMI and the position of the source predicted by LIGO-Virgo (in green) [Credits: LIGO-Virgo, FERMI].



Signals from the merger of two neutron stars: top, gamma ray; bottom, increase in the frequency of the gravitational wave.

[Credits: LIGO-Virgo, FERMI]

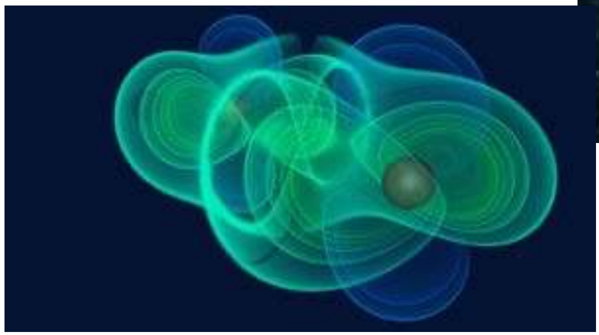
Multi-messenger astronomy

In August 2017, the coalescence of two neutron stars was observed for the first time. Almost simultaneously, LIGO and Virgo measured the gravitational wave signal emitted as the two compact bodies spiralled, and the FERMI satellite detected the gamma-ray burst (see TUIMP No. 9) resulting from their merger. In the days that followed, numerous telescopes observed the various electromagnetic counterparts (visible, infrared, radio, etc.) of this event.

This historic observation inaugurated what is known as multi-messenger astronomy, with not only electromagnetic waves being detected but also gravitational waves and high-energy particles. It led to a number of breakthroughs, confirming the propagation of gravitational waves at the speed of light, the suspected link between short gamma-ray bursts and the coalescence of neutron stars, and the mechanism of gold synthesis.

Quiz

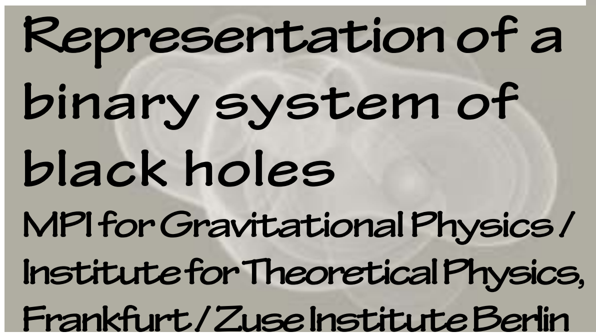
Which of these objects do not emit gravitational waves?



Answer on overleaf

Response

All these objects are (or have been) sources of gravitational waves, with the exception of the planetary nebula.



The Universe in my pocket N° 18

This mini-book was written by Laura Bernard and Alexandre Le Tiec from Paris Observatory (France).

Cover image: Numerical simulation of a pair of black holes and visualisation of the gravitational waves generated when they merge [credit: Michael Koppitz/Albert Einstein Institute].

To find out more about this collection and the themes presented in this mini-book, visit http://www.tuimp.org.

Translation: Stan Kurtz