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Gravitational waves: a new window to explore the Universe

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The last two years saw the opening of a new window for exploring the Universe thanks to the first direct detection of gravitational waves. Gravitational waves have been predicted by Albert Einstein himself in the framework of his theory of general relativity. He first mentioned them in a paper appeared in 1916 and then in 1918 he wrote a paper with the title: "On gravitational waves" [1, 2]. Einstein, however concluded that it would be impossible to detect them. Einstein proved to be wrong: gravitational waves were detected in 2015 and on 3 October 2017 it was announced that the this year Nobel prize for physics will be awarded for their discovery to Rainer Weiss, Barry Barish and Kip Thorne.

In the sixties, Joseph Weber started designing and building the first gravitational wave detectors now known as Weber bars. However, their sensitivity was far too low to see any signal. The first indirect evidence for the existence of gravitational waves came with the discovery in 1974 of the first binary pulsar by Hulse and Taylor. In 1979, results were published detailing measurement of the gradual decay of the orbital period of the pulsar, which fitted precisely with the loss of energy and angular momentum in gravitational radiation (through gravitational waves) predicted by general relativity.

After many decades in developing bar detectors and then later on interferometers to detect gravitational waves, the first direct detection has been made in 2015 by the two Advanced LIGO (Laser Interferometer Gravitational Wave Observatory) detectors. LIGO was founded in 1992 by Kip Thorne (Professor at Caltech, born in 1940) and Ronald Drever (who passed away in March 2017), both at Caltech and Rainer Weiss (Professor emeritus at MIT, born in 1932) of MIT. LIGO consists of two observatories in the US which are some 3000 km apart: one near Hanford (in Washington state) and the other in Livingston (state of Louisiana). Barry Barish (Professor emeritus of Caltech, born 1936) has been the principal investigator of LIGO from 1994 till 2005 and director of the LIGO Laboratory from 1997 till 2005. He was instrumental in bringing the project to completion. Indeed, the construction of the observatories ended in 1999 and the first measurements started in August 2002 and lasted till 2010. Afterwards the detectors have been substantially upgraded and started again in February 2015. Meanwhile, hundreds of scientist in more than 40 Institutes worldwide are involved in the project, and are member of the LIGO Scientific Collaboration (LSC). On 14 September 2015 the two LIGO detectors simultaneously observed a transient gravitational wave signal, which has been interpreted as due to the merger of two black holes with masses of about 36 $M_\odot$ and 29 $M_\odot$, respectively, some 1.3 billion light-years away, which formed a new black hole of 62 $M_\odot$ with the energy equivalent of 3 solar masses emitted as gravitational waves. The announcement of the first detection followed then on 11 February 2016 [3].

On 15 June 2016, the LSC announced the detection of a second signal of gravitational waves, which was observed on 26 December 2015 [4]. Analysis of the signal indicated that this event represented the merger of two black holes about 1.4 billion light years distant, with masses of 14.2 and 7.5 solar masses, yielding a combined black hole of approximately 20.8 solar masses, with one solar mass radiated away.

On 1 June 2017, the LIGO scientific collaboration announced the discovery of a third event, which took place on 4 January 2017 and which was due to the coalescence of two black holes with 31.2 and 19.4 solar masses, respectively, and produced a black hole of 48.7 solar masses, with about 2 solar masses radiated away [5].

LIGO will operate for many more years, and in the meantime it has been joined by VIRGO, which is a detector located nearby Pisa, built mainly by Italy and France. From 1 August 2017 on all three second generation interferometers (LIGO Hanford, LIGO Livingston, and Virgo) were simultaneously taking science quality data for the first time. On 27 September 2017 VIRGO and LIGO announced the first three detector observation on 14 August 2017 of a gravitational wave due to the coalescence of two black holes of 30 and 25 solar masses, respectively, located at a distance of

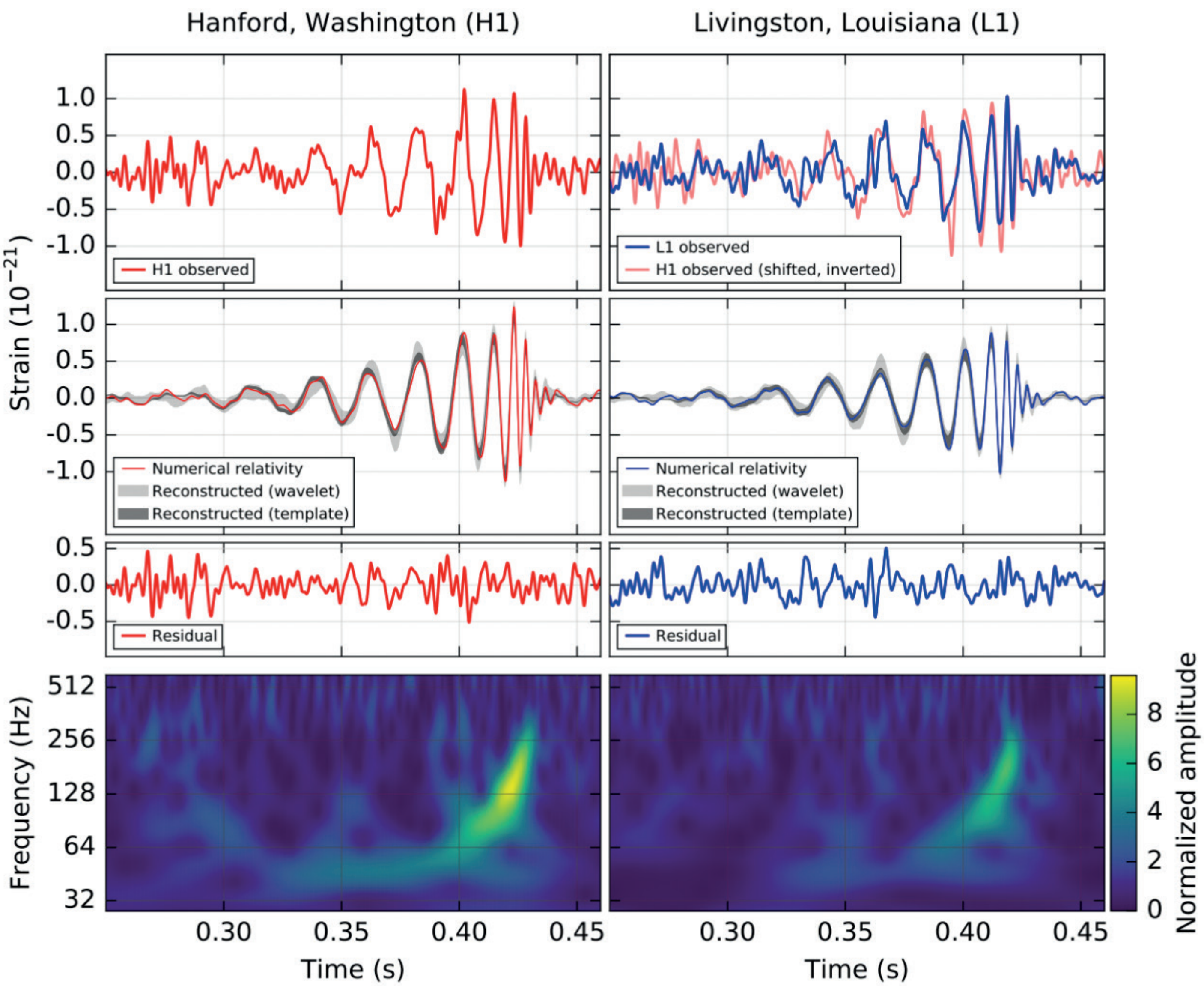

Figure 1: LIGO measurement of the gravitational waves at the Hanford (left) and Livingston (right) detectors, compared to the theoretical predicted values (From [3]).

about 540 Mpc, and leading to the formation of a black hole of about 53 solar masses. Thanks to the observation with VIRGO as well the position in the sky could be determined much better and allowed to probe, for the first time, the polarization content of the signal. The data strongly favor pure tensor polarization of gravitational waves, as expected from general relativity [6].

In few years the interferometric detector KAGRA, using cryogenic technology, will become operational in Japan. This way there will be several *antennas* operating in different locations on Earth, which will allow a much better localization of gravitational wave sources enabling the observations in electromagnetic bands.

There are plans to build a gravitational wave detector in space: the LISA project (Laser Interferometric Space Antenna) which is an ESA mission in collaboration with NASA. In December 2015 the satellite LISA Pathfinder (LPF) by the European Space Agency (ESA) has been launched successfully. Following six apogee-raising manoeuvres, the spacecraft reached its final science orbit around the first Sun-Earth Lagrange point L1, 1.5 million km from Earth, on 22 January 2016.

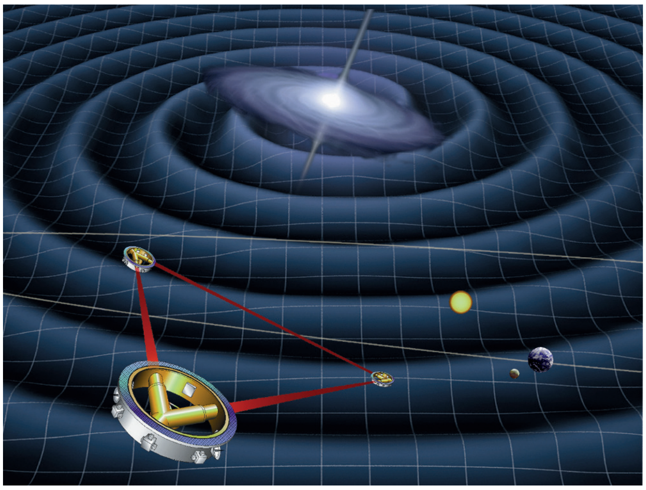

Figure 2: LISA (Laser Interferometre Space Antenna).

LPF goal was to place two test masses in a nearly perfect gravitational free-fall, and control and measure their relative motion with unprecedented accuracy, at the level required for a future space-based gravitational wave observatory, such as LISA. This requirement was achieved through innovative technologies comprising inertial sensors, an optical metrology system, a drag-free control system and micro-Newton thruster system. The LPF mission ended very successfully on 18 July 2017. Indeed, its performances were far better than expected [7, 8] and as a consequence ESA and NASA are pushing forward the LISA mission, which will be capable of detecting gravitational waves (GW) emanating from a wide range of objects in the Universe.

In November 2013 ESA has selected *The Gravitational Universe* [9] as the science theme to be explored by ESA's Large class mission L3. On 20 June 2017 ESA selected LISA [10] as the realization of the L3 mission, which at present is scheduled to be launched in 2034, but with the possibility left open for an earlier launch. The scope of LISA is to detect and study low-frequency GW from about 0.1 mHz to 1 Hz, and thus to complement ground-based gravitational observatories. LISA opens new possibilities for astrophysical studies by allowing, for instance, to detect supermassive black holes (typically of 10^6 –10^7 $M_\odot$) merging at cosmological distances. Mergers of a supermassive black hole with another compact object (such as another black hole or a neutron star) produce a very clean GW signal which LISA will be able to measure with high precision. Alternative gravity theories influence the dynamics of such mergers and hence LISA is expected either to directly see the imprints of certain alternative theories or to put severe constraints on them. Another class of objects, which will be observed by LISA, are ultra-compact binaries, in particular of white dwarfs in our Galaxy. They are important sources of gravitational waves in the mHz frequency range. Moreover, it will be possible to detect or put strong constraints on the primordial gravitational wave background, which is just, as the cosmic microwave background, a leftover from the Big Bang. For LISA, the test masses will consist, similarly to LPF, of cubes of about 2 kg weight, housed in separate spacecrafts, according to present day plans, some 2.5 million km apart.

The discovery of gravitational waves has definitively opened a new window to explore the Universe. We are just at the beginning of using this new window and the prospects are bright to make important progress and new discoveries. Following all these rapid and successful developments the fact that the this year Nobel prize in physics has been awarded for the discovery of gravitational waves came no longer as a surprise.

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