LISA: Simulating a Space-based Gravitational Wave Detector

Jean-Baptiste Bayle
APC, Université Paris-Diderot, CNRS/IN2P3-CNES

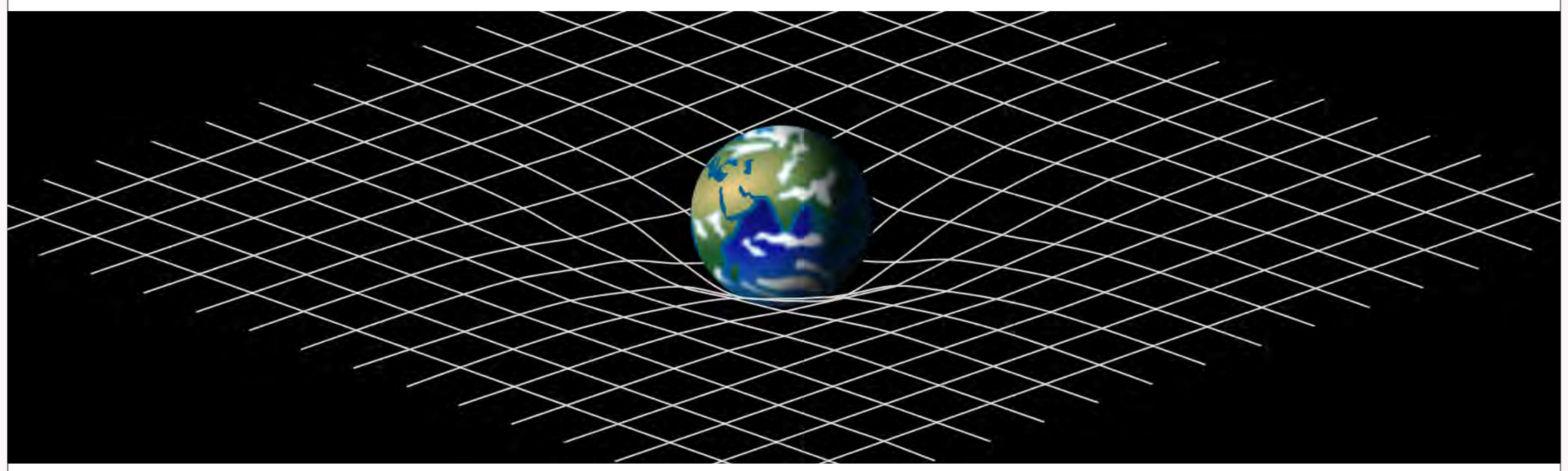
Opening a new window on the Universe...

Einstein's theory of General Relativity describes gravity as a geometrical deformation of our space and time, much like apples would deform a taut blanket. Einstein's famous equation simply relates masses to the curvature:

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

When a very dense object moves asymmetrically at near the speed of light, deformations of spacetime propagates through spacetime at the speed of light, in the manner of waves at the surface of a lake. Those **gravitational waves** travel almost unimpeded by the matter they cross and therefore bring us precious information about their sources.

They are an exciting **new way of observing our Universe** and detecting events that remain invisible to the usual electromagnetic spectrum, such as black-hole or neutron star mergers, cosmic strings, etc.



2-dimensional representation of a spacetime curved by the mass of the Earth. © Wikipedia Commons.

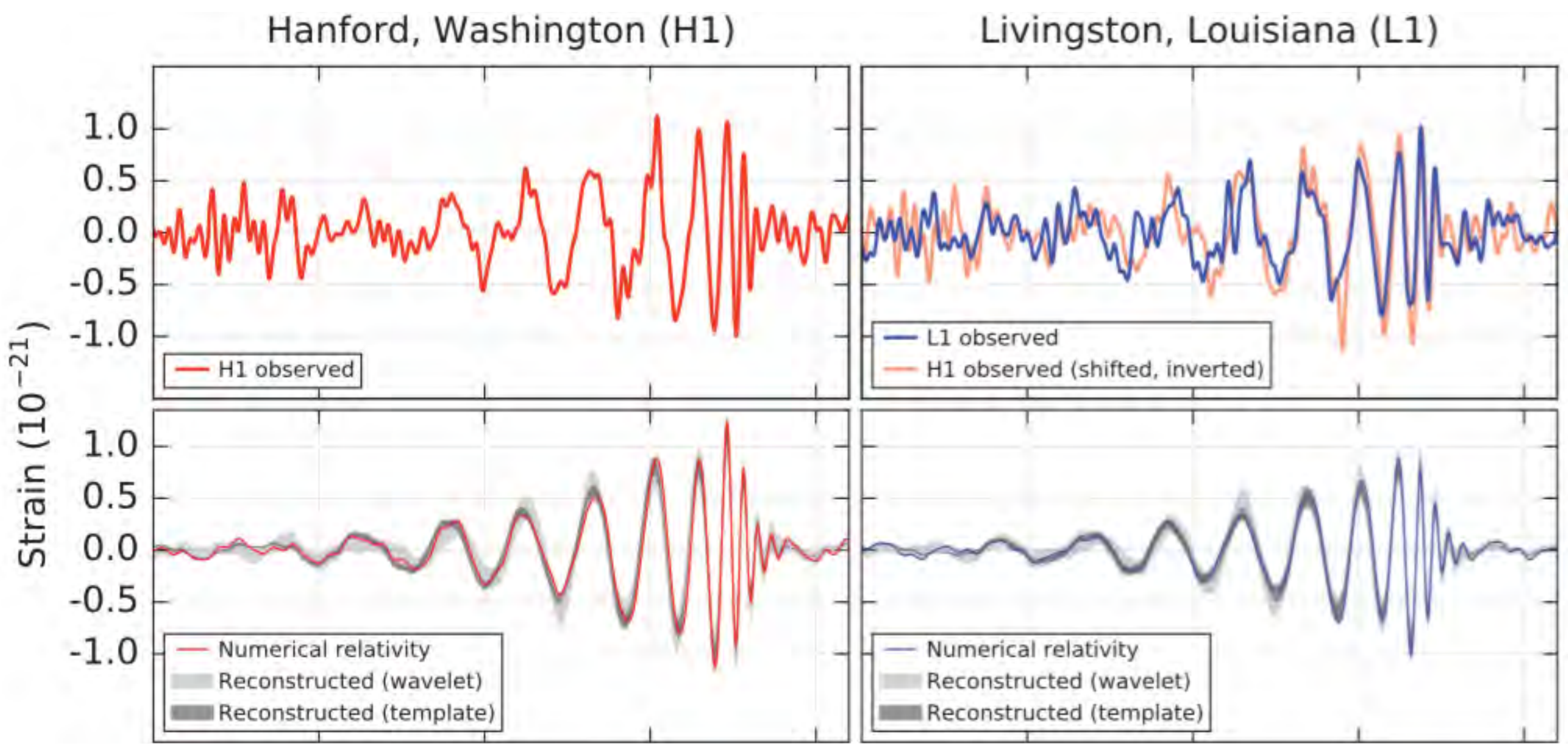
Interferometric detection on Earth

A gravitational wave affects the dimensions of an object, compressing the lengths in one direction and expanding them in the perpendicular direction. Unfortunately the effect is very small and the length difference is of the order of 10^{-18} m for an initial length of a few kilometres.

Today's best-known technique to measure such tiny differences is **optical interferometry**: a laser beam is split and guided through two perpendicular arms, at the end of which they are reflected on mirrors. The intensity at the recombining point is a function of the optical path length difference. When a gravitational wave passes, we can detect a modulation of the light signal.

Virgo interferometer near Pisa, Italy. © Wikipedia Commons.

Earth-based detectors, such as LIGO (Hanford and Livingston, USA) and Virgo (Pisa, Italy as part of a French-Italian collaboration) are currently running. In September 2015 **gravitational waves were detected**[1] for the first time by the LIGO-Virgo collaboration, corresponding to the merger of two black-holes.



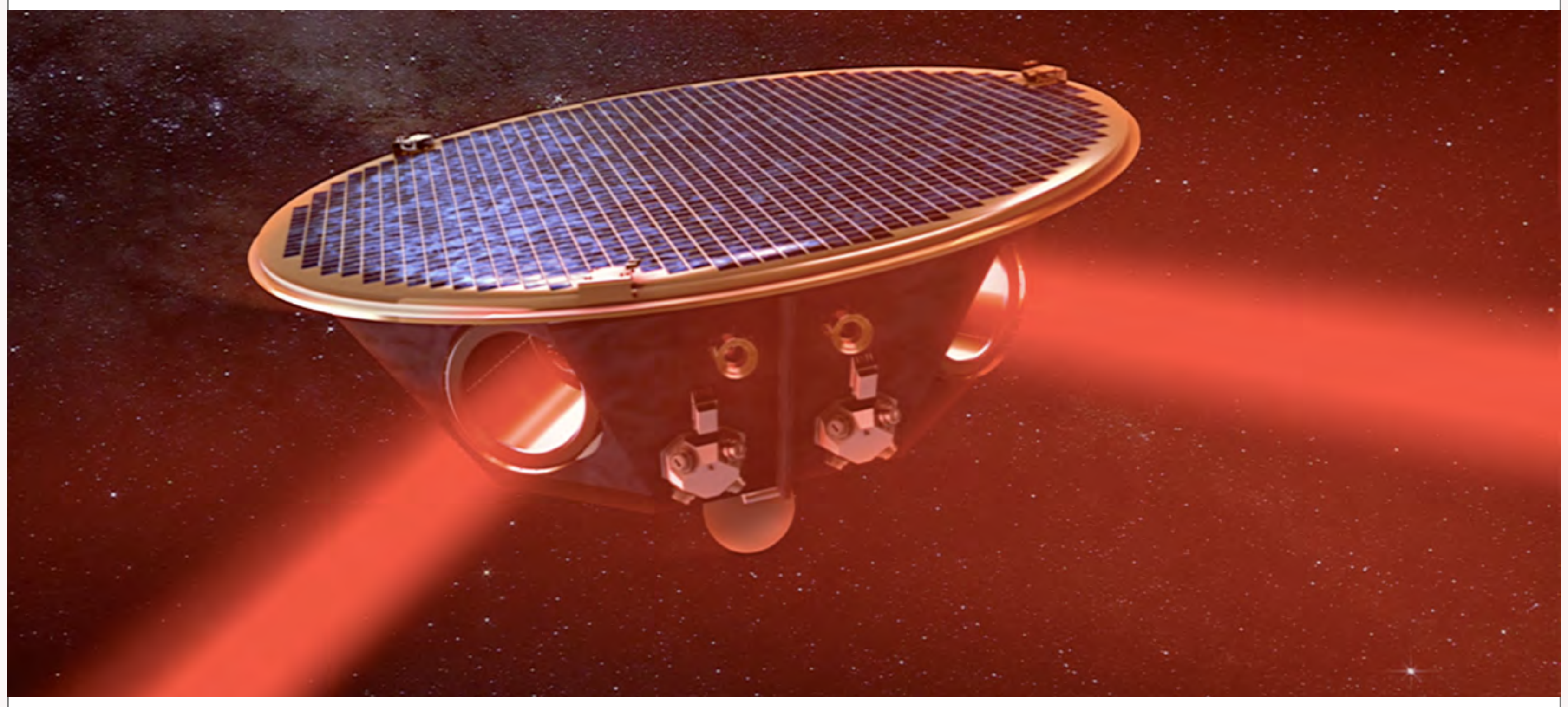
Signals from the first gravitational wave detection by LIGO.

[1] *LIGO Scientific Collaboration and Virgo Collaboration, T. V. (2016, February 11). Observation of Gravitational Waves from a Binary Black Hole Merger. arXiv.org. American Physical Society. DOI: 10.1103/PhysRevLett.116.061102.*

Towards space: the LISA mission

Gravitational wave signals are faint and buried in noises. LIGO and Virgo for example are limited at low frequencies by seismic vibrations. Many sources of high scientific interest however generate waves of frequencies below 0.1 Hz: supermassive black-hole (that we suspect at the center of most galaxies) binaries, extreme mass-ratio objects that allow to probe General Relativity in strong gravity regime, binary systems in our galaxy, etc. To detect their signal we have to... **go to space**!

This is what the European Space Agency mission "**Large Interferometer Space Antenna**" aims at in the horizon 2030. LISA relies on the same interferometric detection principle: three spacecrafts separated by millions of kilometres exchange laser beams. They are reflected on inertial reference masses, protected from external perturbations. These gold-platinum cubes are kept in **free-fall** and control systems adjust spacecraft positions accordingly. Since test-masses are submitted only to gravity their separation is therefore modified if a gravitational wave passes.



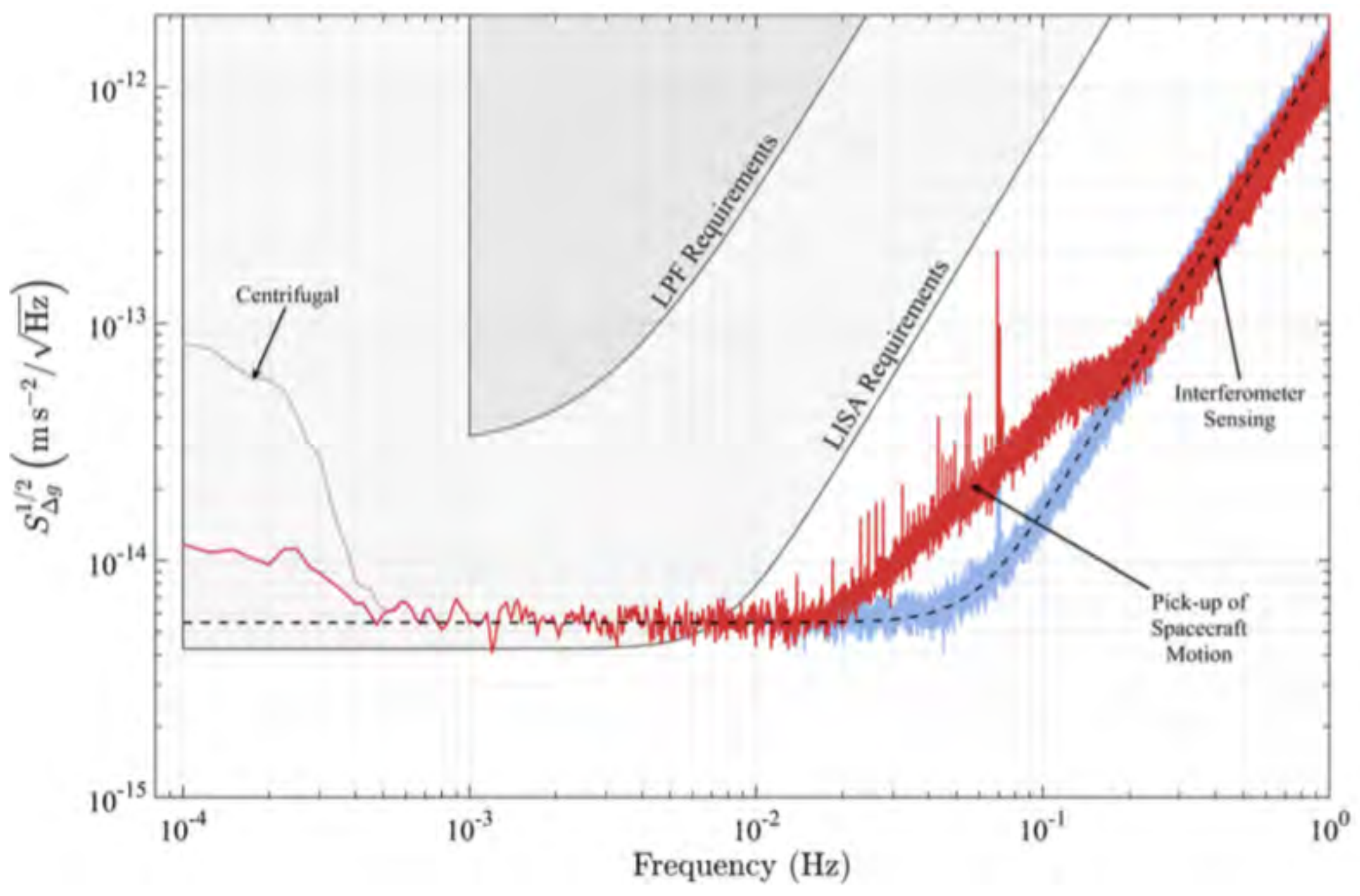
Artist view of what one of the LISA spacecraft would look like. The laser beams would connect it to the rest of the constellation. © ESA.

LISAPathFinder: a flying laboratory

To confirm the feasibility of the mission, many new technologies including the drag-free system must be tested in-flight. ESA has therefore lead the **proof-of-concept mission LISAPathFinder**, launched last September from Kourou, French Guyana.

One LISA arm has been shrunk down to fit in a single spacecraft, containing two test masses. The science team carries out experiments to characterise the behaviour of the instrument and prepare for the full LISA mission. In particular, one of the goals is to understand all the sources of noise and explain their levels observed in the sensitivity curve.

The first results[2] published in June 2016 exceeded expectations, turning on the green light for the LISA mission.



LISAPathFinder's Gravitational Reference Sensor and Optical Bench.

[2] *Armano et al. (2016). Sub-Femto-g Free Fall for Space-Based Gravitational Wave Observatories: LISA Pathfinder Results. Phys. Rev. Lett., 116(23), 231101. DOI: 10.1103/PhysRevLett.116.231101.*

Simulating LISA

A large part of my PhD project will be connected to **computer simulation**. The existing simulator LISACode needs to be updated so we can implement new designs and transfer our knowledge from LISAPathFinder.

The consortium must provide an end-to-end simulation of the LISA mission to ESA and the industrials to help them **optimise the final design** maximising the scientific returns. I also plan to use this tool to contribute to the consortium efforts in **preparing for data analysis**.

Contact: Jean-Baptiste Bayle, APC, Université Paris-Diderot, CNRS/IN2P3-CNES, bayle@apc.in2p3.fr.