Listening to Space with LIGO

The 2005 World Year of Physics was dedicated to Albert Einstein, on the centennial of the 'miraculous year' when his breakthrough papers on Brownian motion, light quanta and special relativity were published, reshaping modern physics. The year 2005 also marked a major step towards the fulfillment of Einstein's vision, as scientists at the Laser Interferometer Gravitational-wave Observatory (LIGO) delivered high precision instruments that are now listening for gravitational waves, elusive distortions of space-time predicted by General Relativity. To understand the nature of gravitational waves and why an army of physicists and engineers is trying to detect them, it is useful to review how Einstein's theory of General Relativity redefined our understanding of the Universe.

From Newton to Einstein

Sir Isaac Newton's theory of universal gravitation (Principia Mathematica, 1687) was brilliant. Inspired by the works of Kepler and Galileo Galilei, Newton observed that any two objects are attracted to each other by a force proportional to their masses and inversely proportional to the square of the distance between them. This observation, combined with the laws of classical mechanics, explained several puzzling phenomena, like the orbits of planets and moons and the oceans' tides. Newton depicted a peaceful universe where all celestial bodies know about each other's presence and move in a harmonious balance of forces. In all of its elegance, though, Newton's theory has two fundamental problems. First, it does not explain what mechanism is behind the force of attraction between masses. Second, it declares that gravity performs "action at a distance": whenever something changes in the position of a celestial body, all other stars and planets instantly know about it and readjust their positions and orbits accordingly, with the uncomfortable consequence that information travels faster than light.

About 300 years passed before the open issues in Newton's model were addressed by General Relativity. According to Einstein, there are no invisible wires pulling bodies towards each other. What we experience as a force of attraction is rather a geometrical property of the four-dimensional universe we live in (the "space-time"). To visualize this, a classical two-dimensional analogy can be drawn between space-time and a rubber sheet. A bowling ball on the sheet will deform it and a smaller object in its vicinity, like a golf ball, will move towards the larger mass not because it is pulled by some invisible force, but simply because it is sitting on a curved surface. In the four-dimensional extension of this picture, Earth's orbit is a geodesic in the space-time deformed by the Sun, clocks run slower near a black hole and space-time behaves like a glob of gelatin whose shape, or curvature, is determined by the presence of massive bodies: "mass tells space-time how to curve, space-time tells mass how to move" (J. A. Wheeler). The theory of General Relativity is, in essence, a mathematical formulation of this geometrical view of the Universe.

Ripples in space-time

Einstein's model offers an elegant solution to the philosophical dilemma of Newton's "action at a distance". When a mass accelerates, its contribution to the underlying space-time also changes; like waves in a pond where a stone is thrown, this change propagates outward at the speed of light as ripples in the fabric of space-time: gravitational waves.

Everything produces gravitational waves: children playing a soccer game, cars on the highway, jet planes taking off and landing, volcanic explosions, they all induce vibrations in space-time, but these effects are extremely small. Only the dramatic acceleration of massive astrophysical objects could produce gravitational waves large enough to be detected on Earth. In this sense, the business of gravitational wave detection is poised to open new paths in the exploration of the universe. Our current knowledge of the universe is based on the observation of electromagnetic radiation, but gravitational waves are space itself changing its configuration, in response to the most violent rearrangements of mass and energy. Gravitational waves travel virtually undisturbed, unimpeded by intervening clouds of dust, and, if we learn how to listen, they can tell us tales of what happens in the core of a supernova or during the collision of two stars. Gravitational waves can teach us about the most mysterious astrophysical objects, such as black holes and neutron stars, and conceivably bring us information from the very beginning of the Universe.

Indirect evidence of gravitational waves is already available, thanks to the observation of binary systems of neutron stars rotating around each other, where one of the neutron stars is a pulsar emitting regular pulses of radio waves, similar to the beacon of a lighthouse. The first such system to be observed was PSR 1913+16, whose discovery earned Russel Hulse and Joseph Taylor the 1993 Nobel Prize. Monitoring the radio pulses over 20 years, they observed that the pulsar's 8-hour period of rotation sped up by 14 seconds, in beautiful agreement with General Relativity's prediction that the two stars are spiraling towards each other and shedding energy and angular momentum by emitting gravitational waves. The Hulse-Taylor pulsar tells us they exist, but gravitational waves have never been seen directly. As they travel through the Earth, they stretch and compress space in directions perpendicular to their propagation, locally altering the distance between free masses. This warping of space-time can be detected, if we can construct an instrument that can measure tiny changes in distance (strain) of the order of one part in 1,000,000,000,000,000,000,000.

A laser fishnet

The first attempt to directly measure gravitational waves dates to the 1960s, when Joe Weber, at the University of Maryland, connected a transducer to a 3-meter-long aluminum cylinder to monitor the changes in its length induced by the passage of gravitational waves. Through the years, a number of similar "resonant bar" detectors have been operated around the world, but none has yielded a confirmed detection of gravitational waves.

LIGO (the Laser Interferometer Gravitational-wave Observatory) is adopting a radically different approach. The LIGO project is sponsored by the National Science Foundation and jointly hosted by the California Institute of Technology and the Massachusetts Institute of Technology, in collaboration with a worldwide network of some 500 scientists (the LIGO Scientific Collaboration). LIGO uses laser light to measure changes as small as 10^{-18} m in the distance between mirrors that are suspend several kilometers apart. To achieve this sensitivity, one thousand times smaller than the size of a proton, LIGO scientist have worked at the frontiers of technology in optics, precision lasers, vacuum science and mechanical systems for more than 20 years.

The two LIGO observatories are located in Livingston, LA and in Hanford, WA. Each LIGO detector is an interferometer, similar to the one used by Michelson and Morley in their 1887 ether experiment. The interferometer is laid out in an L-shape, with arms that are 4 km long, a compromise between construction costs and the need for a long baseline to measure small strains.

A laser beam is split in two by a semi-transparent mirror, the beam splitter. The two components travel along the two perpendicular arms, are reflected from freely suspended mirrors at the far end, and are recombined when they return to the beam splitter. In normal conditions, the device is tuned so that the two recombining waves exactly cancel, with the peaks of one aligning with the valleys of the other in destructive interference. If the distance between the mirrors changes for any reason, the two beams accumulate different phase delays. Peaks and valleys lose their alignment and a photodetector measures interference light, signaling the passage of a gravitational wave. There are some additional design subtleties that increase the interferometer's sensitivity, such as bouncing the beams between the end and near mirror some 50 (100?) times in order to increase the length of travel and amplify the effect of a change in distance.

Fighting the odds

An interferometer is essentially a complex machine that measures the distance between two mirrors. There are several sources of noise competing with gravitational waves to perturb the position of the mirrors, but seismic vibrations are LIGO's principal nemesis.

The interferometers are built in isolated locations, in the woods of Louisiana and in the desert of Washington State, but they are so sensitive they can be affected by construction works, trains, trucks on the nearby highways, jet planes flying overhead, windstorms, ocean waves, and earthquakes around the globe. To isolating them from these low-frequency vibrations (below a few Hz), the mirrors are suspended by wires that are themselves cushioned by a system of masses and springs that absorb ground vibrations; the Louisiana facility is protected by an additional active insulation system, where hydraulic pressure is used to cancel the tremors coming from falling trees during logging in nearby forests.

The laser beams travel in vacuum enclosures, in order to avoid distortions due to scattering on molecules of air. The LIGO interferometers have one of the world's largest ultra-high-vacuum systems, with a volume of nearly 300,000 cubic feet at one-trillionth of atmospheric pressure; evacuating and "baking out" the tunnels requires more than XXX months. The mirrors are polished and coated to reduce the thermal vibration of the atoms on their surface. Tiny magnets attached to the mirrors can be driven electromagnetically to adjust the mirrors' position and orientation; more than thirty different control systems combine to hold all lasers and mirrors in proper alignment to within a fraction of a wavelength over the four kilometer lengths of both arms of the interferometers. The laser itself is state-of-the-art: the beam must be so well regulated, that over one hundredth of a second, the frequency fluctuates by less than a few millionths of a cycle.

The result is a device with broadband high sensitivity: it can detect a strain of 10^{-21} over a range of 100Hz. At low frequencies, below 10Hz, the sensitivity is limited by the seismic shaking of the mirrors. In the mid-range of frequencies, between 100 and 200 Hz, it is limited by thermal noise, the motion of atoms in the suspension fibers. At larger frequencies, it is limited by quantum "shot" noise, as individual photons hit the photodetector and the mirrors like raindrops on a roof.

Finding gravitational waves in the midst of all this noise requires understanding both the device and the expected signal. The latter is not always possible: there are no good waveform predictions for most of the sources the LIGO data analysis is pursuing. The ultimate defense for LIGO from the pollution of environmental and instrumental transients in the signal is the requirement of a coincident measurement in multiple detectors. The observatory is comprised of three interferometers, two of them co-located in Hanford (one of them with a shorter, 2km baseline) and the other in Louisiana. A gravitational wave will appear in both sites within 10 milliseconds (the time it takes a gravitational wave to travel from one to the other site at the speed of light) and with the same calibrated amplitude and at the same time in the two Hanford interferometers.

From development to exploration

In the fall of 2005, the LIGO detectors reached their sensitivity design goals and began long-term data acquisition, listening for gravitational waves produced by sources at distances of tens of million light-years. Astrophysicists, hardware experts and data analysts are sifting through the daily generated Terabyte of LIGO data, digging in the noise to identify gravitational wave signatures. The data they use includes the information on the distance between mirrors (the “gravitational wave channel”), sampled at 16,384 Hertz, and signals from hundreds of data acquisition channels for diagnostics of the machine and monitoring of the environmental noise.

LIGO is listening to space, searching for the chirp wave produced by the death spiral of neutron stars before they collide and merge into a black hole, for the sound of an exploding star in a supernova, for the first cries of nascent neutron stars and their instabilities, for the periodic humming of pulsars, for the murmurs of the relic gravitational radiation from the Big Bang and the primordial universe, and for all serendipitous sources that may be out there. LIGO scientists, like early explorers, are open to the unexpected, probing the universe in ways that were not done before.

When will LIGO find its first gravitational wave, and what will its source be? There are too many uncertainties in current astrophysical models to give a good answer to this question – we do not know how many black-hole or neutron-star binary systems are in the nearby galaxies, what happens during a stellar core collapse or whether spinning neutron stars have blemishes on their surfaces. Any asymmetry in the evolution of these systems causes dramatic changes in the pattern and amplitude of gravitational wave emission. Super-computers are hard at work to provide answers and models, using numerical General Relativity, but there are no firm answers yet. Since no one has ever listened for signal this faint, we cannot know beforehand what we will hear.

LIGO may not yield detection for a few more years, but an upgraded LIGO should hear waves from in-spiraling binary neutron stars within days. Advanced LIGO will be ten times more sensitive and will listen to sources in a thousand time larger volume of space; the installation of a new laser, new optics suspensions and isolation systems that will allow this enhanced sensitivity should start within the next five years.

And LIGO is not alone in this quest: other interferometers are operating or about to start in Europe (GEO and VIRGO) and in Japan (TAMA). Protocols for data exchange and joint analysis are being tested on short duration runs, proving this is truly a worldwide cooperative effort. The LISA experiment will launch a laser interferometer into space – the ultimate cure for seismic noise. A growing community of scientist is now committed to the quest for gravitational waves: the first discovery will only be the beginning for a new branch of science that may take us beyond General Relativity and unveil a whole new universe.

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Preliminary pictures – these are placeholders – working on copyright statements for usage

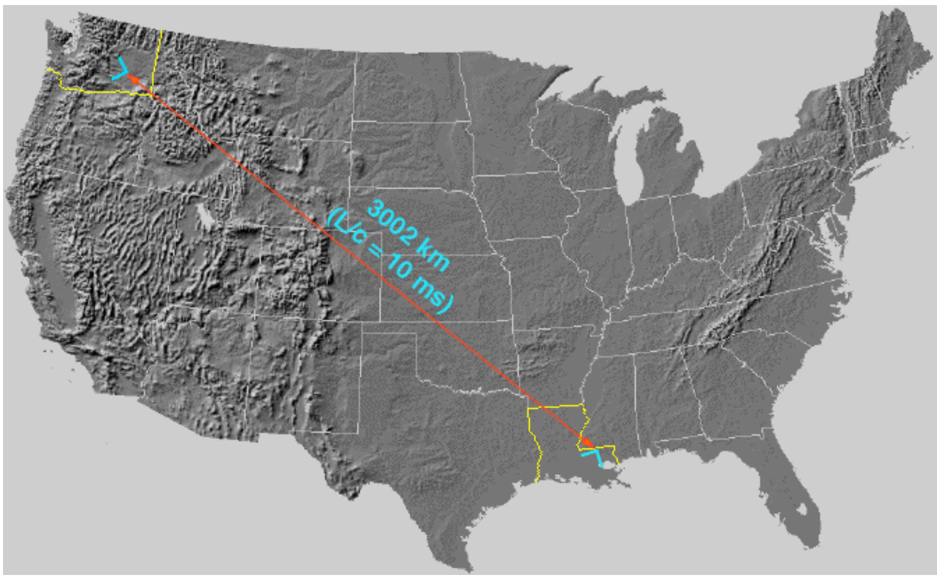

Figure XX: Photographs of the LIGO Observatories in Livingston, LA (right) and in Hanford, WA (left). The Hanford facility comprises two co-located interferometers, sharing the same vacuum enclosure but otherwise independent, with 2 and 4 km baselines.
Credits – LIGO lab

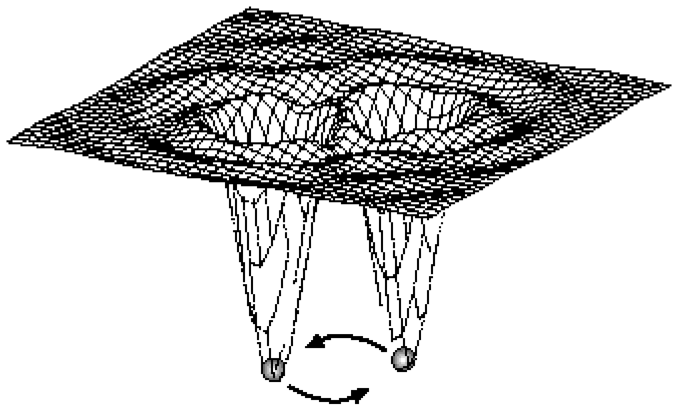

Figure XX: a binary system of compact massive objects, such as neutron stars or black holes, curves space-time. Additional ripples propagate outwards from the system, due to the rapid orbiting of the two objects. These perturbations are gravitational waves; their amplitude diminishes in inverse proportion to the distance from the source.
Credits: www.astronomynotes.com

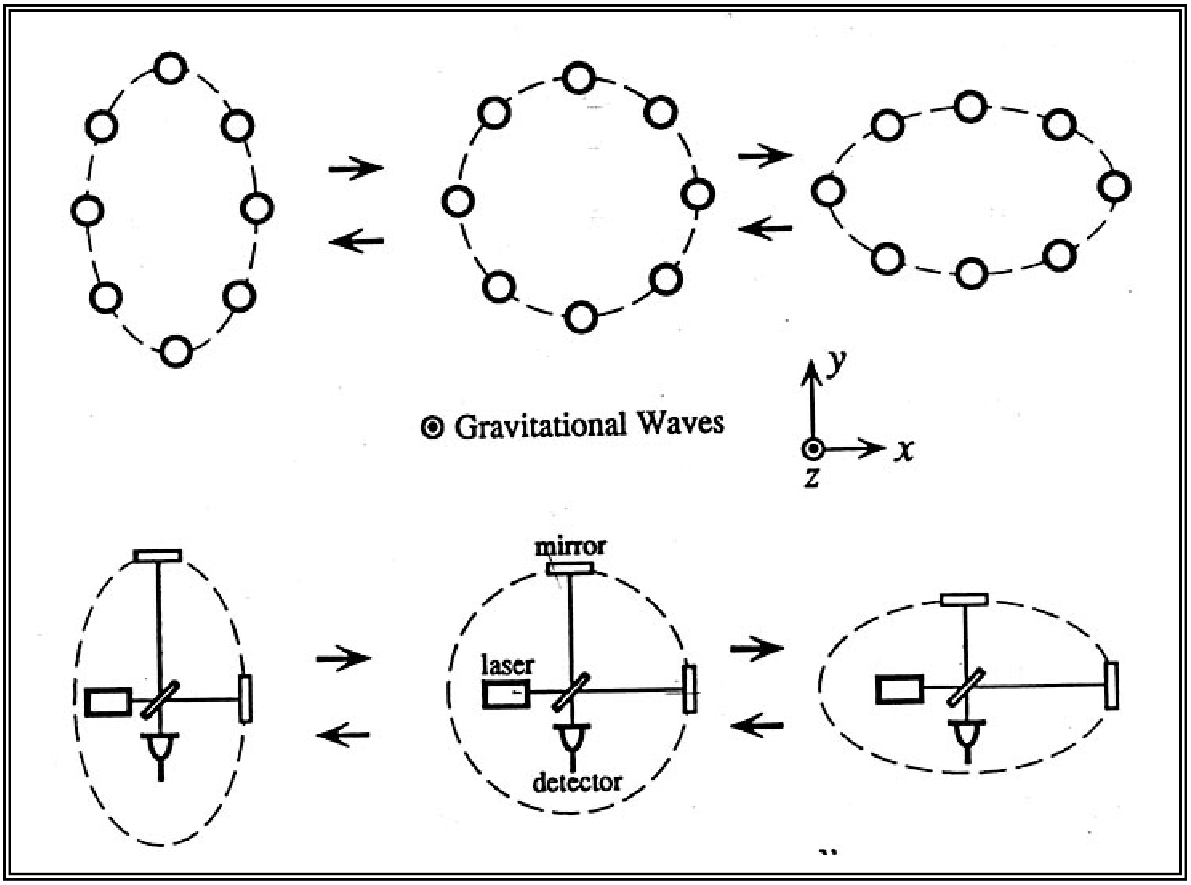

Figure XX: Placeholder for new graphics
Top: effect of the passage of a gravitational wave that travels in a direction perpendicular to the plane of the paper: the distance between free masses laid in a circle changes with the wave cycles; the circular shape is stretched and compressed into an oval.
Bottom: in a laser interferometer like LIGO free masses are replaced by suspended mirrors and the arms change their length with the passage of the wave. The effect is extremely small: if the interferometer arms stretched from earth to Proxima Centauri, (the closest star, 4.2 ly away), the length change of the two arms would be the thickness of a hair. In more realistic units. LIGO is now detecting changes of the order of 1/1000 of the size of a proton over a 4-kilometer baseline.

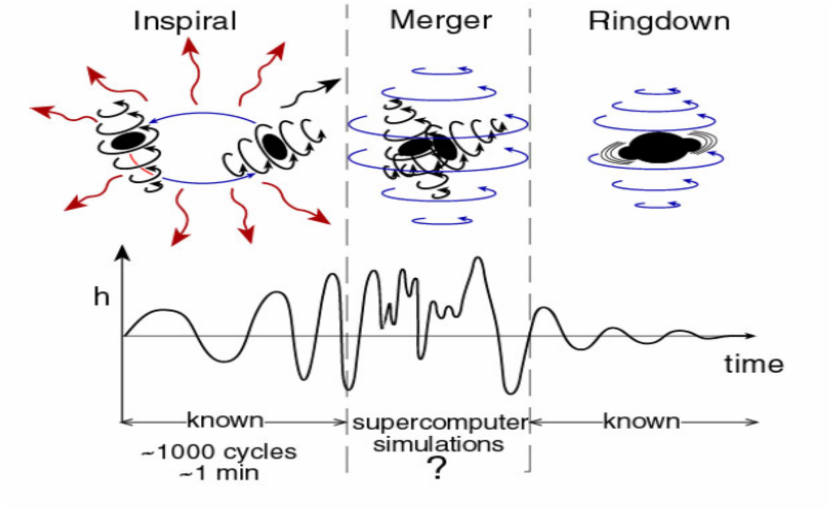

Figure XX: gravitational-wave emission from a compact binary system in the last few minutes of its life. This class of sources has a distinct signature and it is the one for which most predictions are formulated. The two massive object spiral faster and faster around each other, losing more and more energy to gravitational waves. The two bodies then collide and merge, leaving behind a black hole that vibrates to equilibrium. While "inspiral" and "ringdown" phases are well modeled, the merger phase is still being studied with supercomputer simulations. If the two objects are neutron stars, LIGO stands a good chance at detecting GW emitted in the inspiral phase. If they are more massive black holes, the gravitational wave frequency is lower in inspiral phase and LIGO is more sensitive to what happens in merger and ringdown phase. Different analysis techniques have been implemented to identify these classes of signals, which are to date the most studied and best understood. According to current computations, LIGO stands a non-null chance to see one of these objects in its initial configuration and will see several within days in its advanced design.

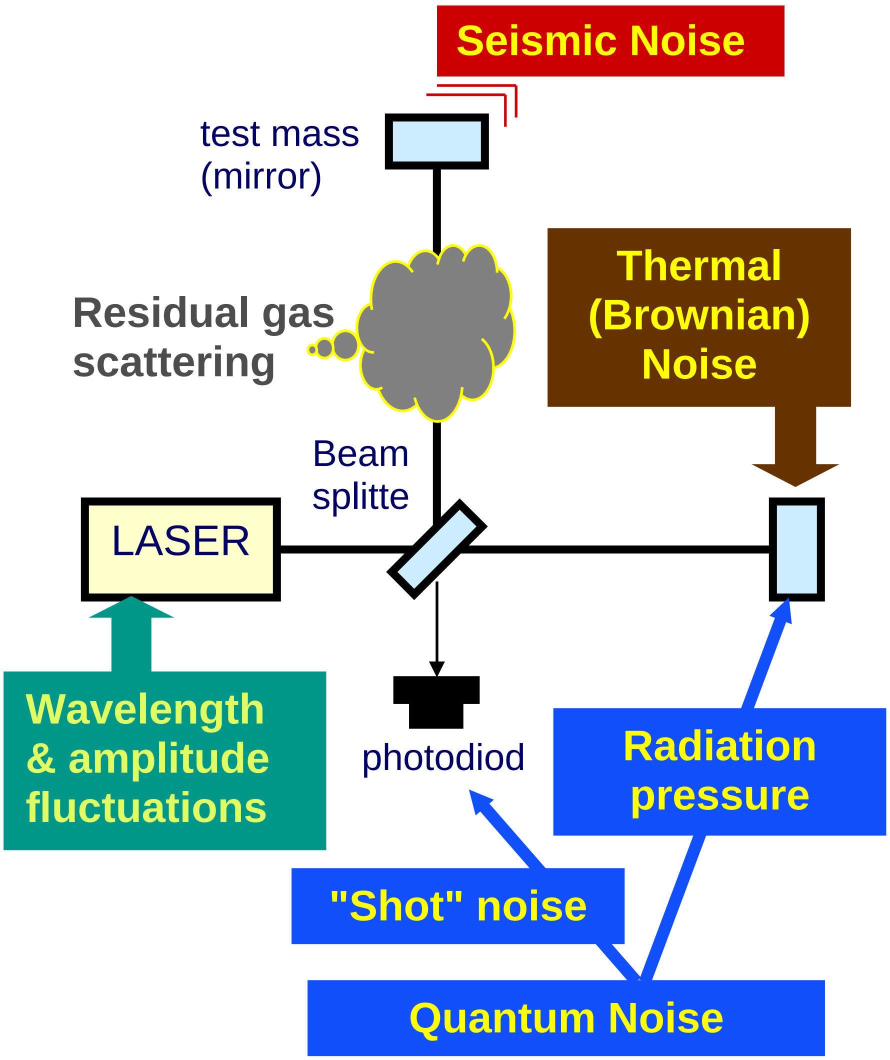

Figure XX – **placeholder for new graphics**. Noise sources in LIGO.

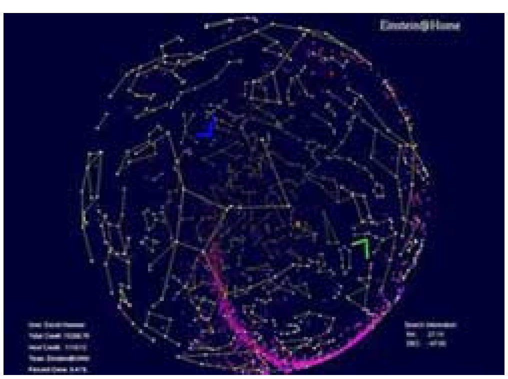

Figure XX: the Einstein at home project: computer users from around the world are contributing to the search for gravitational waves from pulsars and supernova remnants – for more information, see www.einsteinathome.org
Credits: