Exploring Gravitational Waves
in the Classroom

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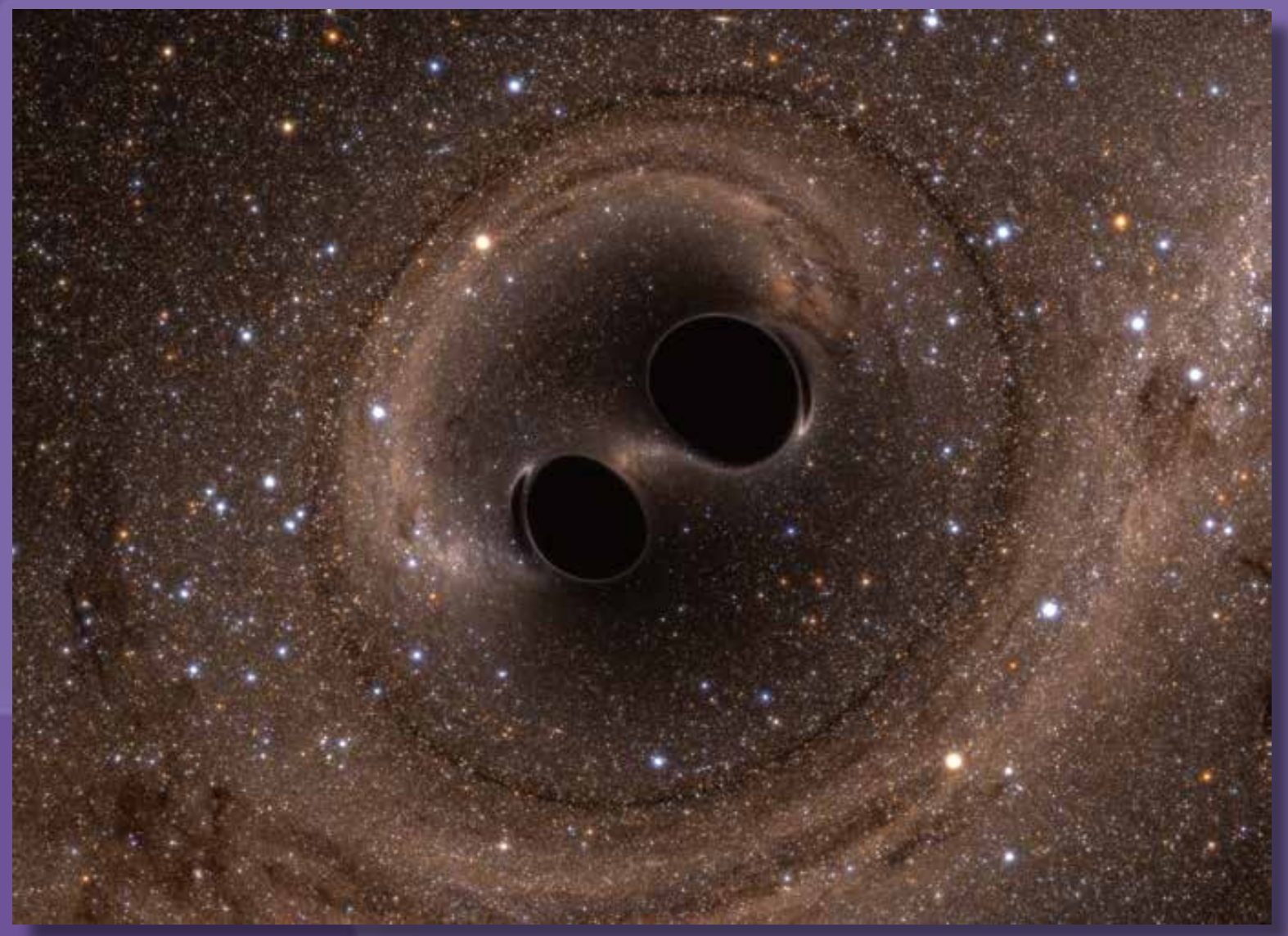
Introduction

On September 14, 2015, the Laser Interferometer Gravitational-wave Observatory (LIGO) received the first confirmed gravitational wave signals. Now known as GW150914, the event represents the coalescence of two black holes that were previously in mutual orbit. LIGO's exciting discovery provides direct evidence of the last major unconfirmed prediction of Einstein's General Theory of Relativity.

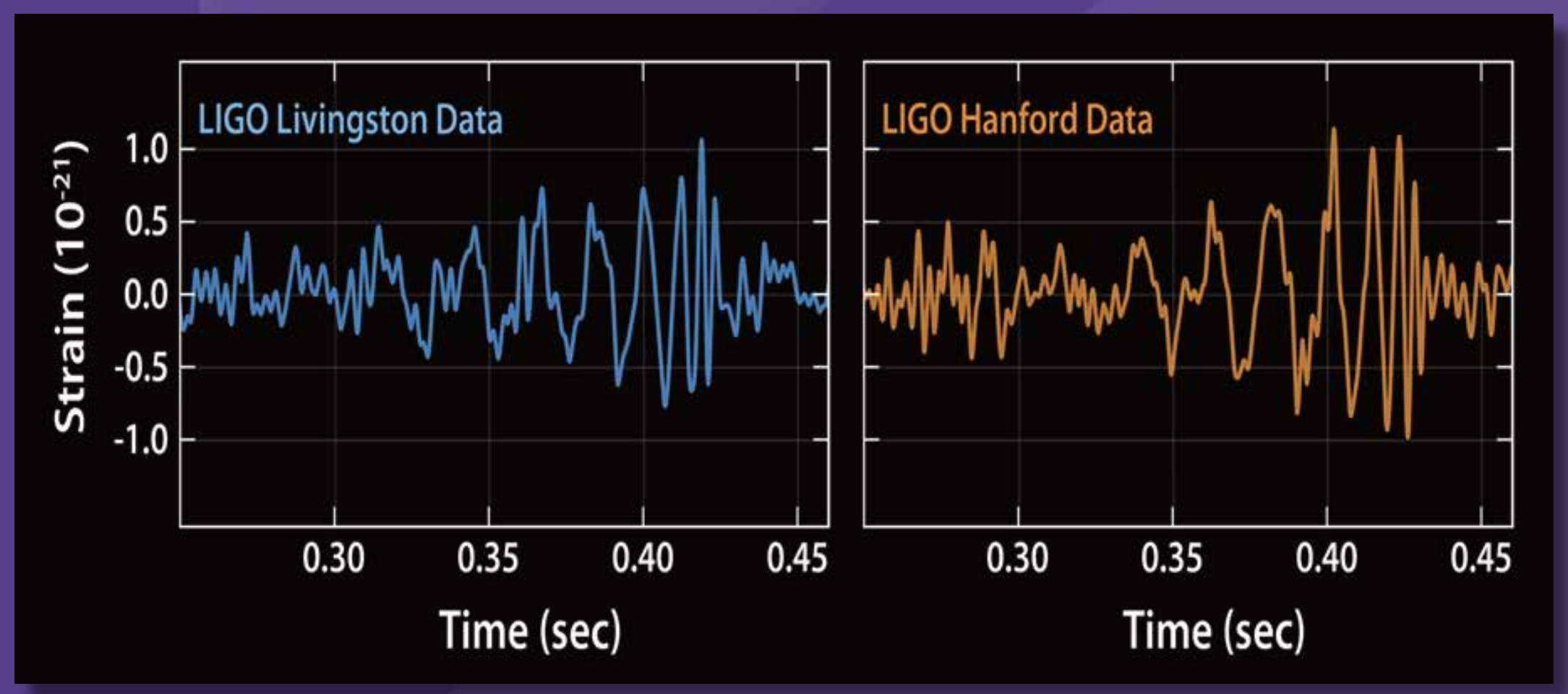


Numerical simulation of two merging black holes. Credit: SXS.

150914

Gravitational Waves as Signals from the Universe

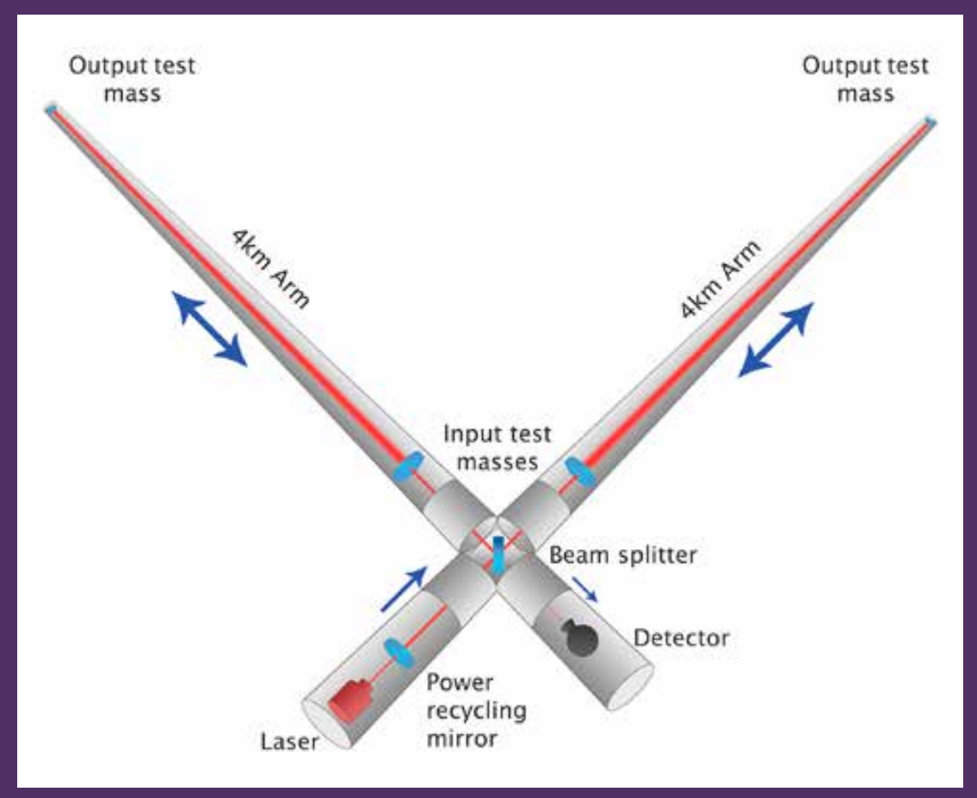
Gravitational waves are 'ripples' in the fabric of spacetime caused by accelerating masses such as colliding black holes, exploding stars, and even the birth of the universe itself. Albert Einstein predicted the existence of gravitational waves in 1916, derived from his General Theory of Relativity. Einstein's mathematics showed that massive accelerating objects would disrupt spacetime in such a way that waves of distorted space would radiate from the source. These ripples travel at the speed of light through the universe, carrying information about their origins, as well as clues to the nature of gravity itself. Two black holes in mutual orbit will revolve around each other emitting gravitational waves and losing orbital energy. Over time, the energy loss causes the stars to move closer together and orbit around each other faster and faster until they eventually merge together, or coalesce. This type of merger has never before been directly observed, and it is the type of event that emitted the gravitational waves detected by LIGO on September 14, 2015 as shown in the figure below.

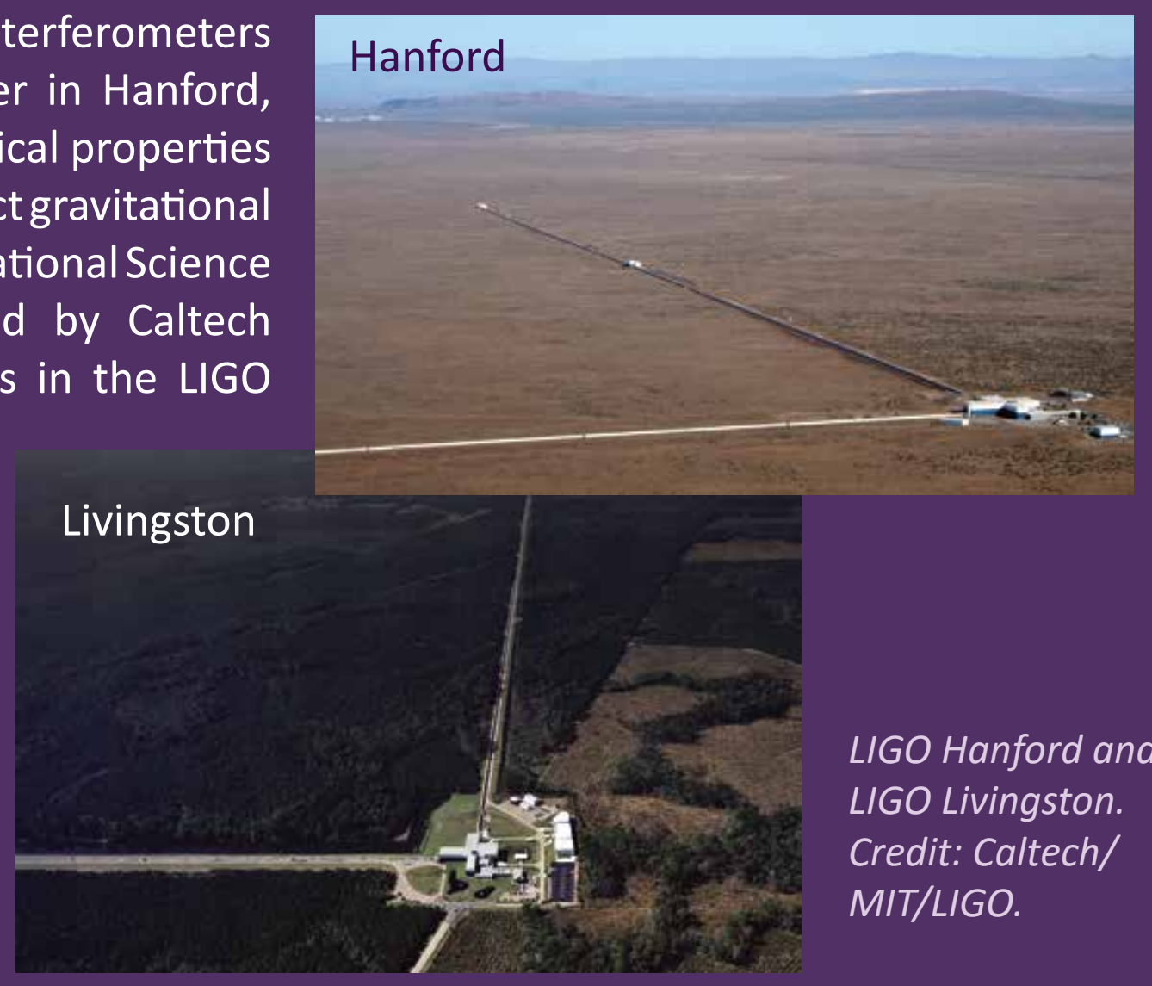


Strain data recorded at LIGO Livingston and LIGO Hanford detectors on September 14, 2015. The Hanford data were received about 7 ms later than Livingston, due to the light travel time between the two facilities. Credit: LIGO Scientific Collaboration.

LIGO and Direct Observation

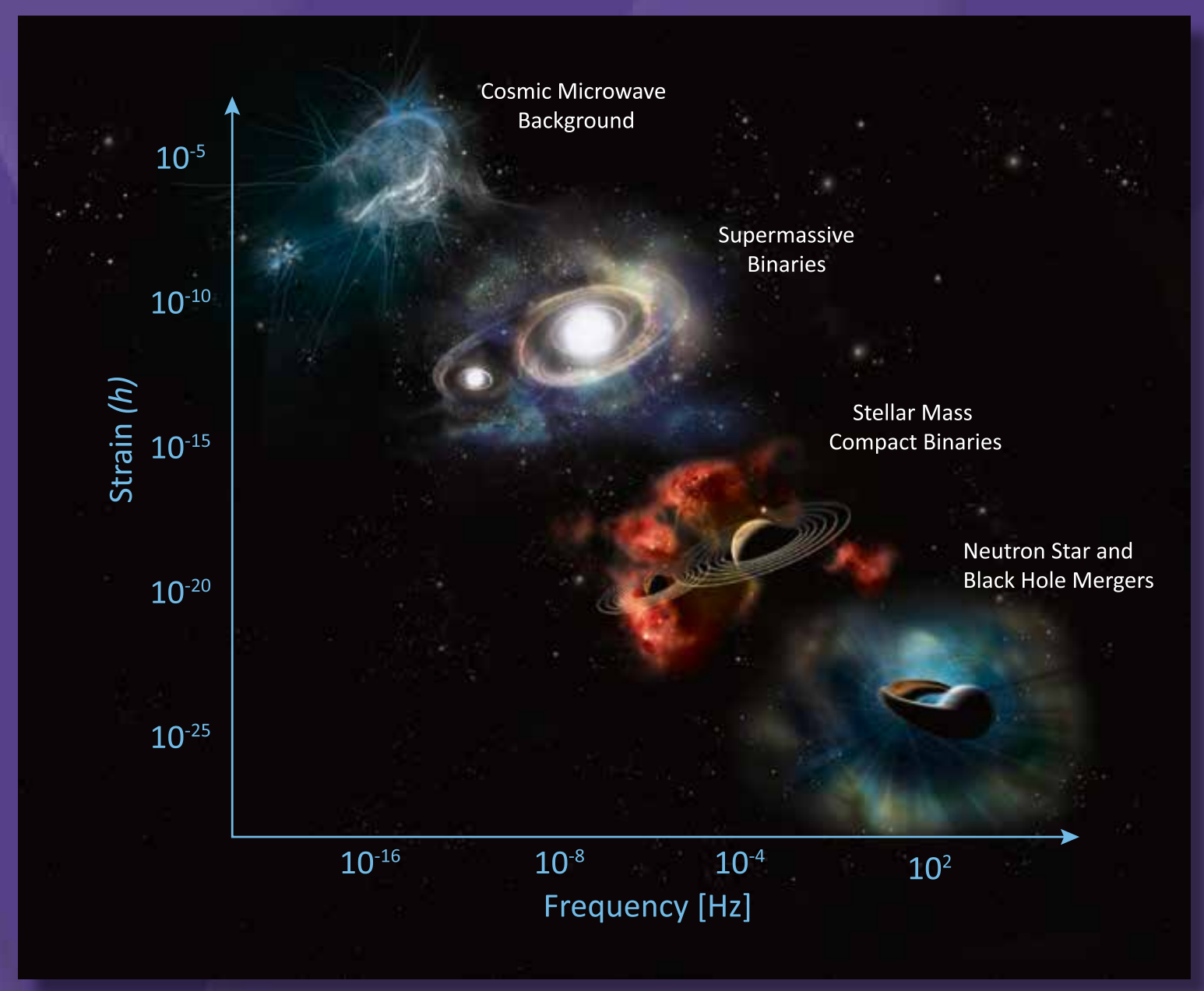
LIGO is the world's largest gravitational wave observatory. LIGO consists of two laser interferometers located thousands of kilometers apart, one in Livingston, Louisiana and the other in Hanford, Washington. LIGO uses the physical properties of light and of space itself to detect gravitational waves. It was funded by the US National Science Foundation, and it is managed by Caltech and MIT. Hundreds of scientists in the LIGO Scientific Collaboration, in many countries, contribute to the astrophysical and instrument science of LIGO. There are also other gravitational wave observatories in the world, including Virgo in Italy and GEO 600 in Germany.





LIGO Hanford and LIGO Livingston. Credit: Caltech/MIT/LIGO.

LIGO consists of two perpendicular, 4-km "arms". A laser beam is fired into a beam splitter that sends half the light down one of these arms, and half down the other. The mirrors then reflect the light back the way it came, and the beam splitter combines the two beams back into one, sending the combined beam to a detector. LIGO carefully tunes the lengths of the detector arms so that the light from the arms almost completely cancels out, or undergoes destructive interference, when the reflected beams recombine back at the beam splitter. However, if the arm lengths change slightly due to a passing gravitational wave, then the differences in length will introduce a small difference in phase between the beam from different arms. The waves that would have cancelled each other at the beam splitter will now travel different path lengths and end up producing some light at the detector.

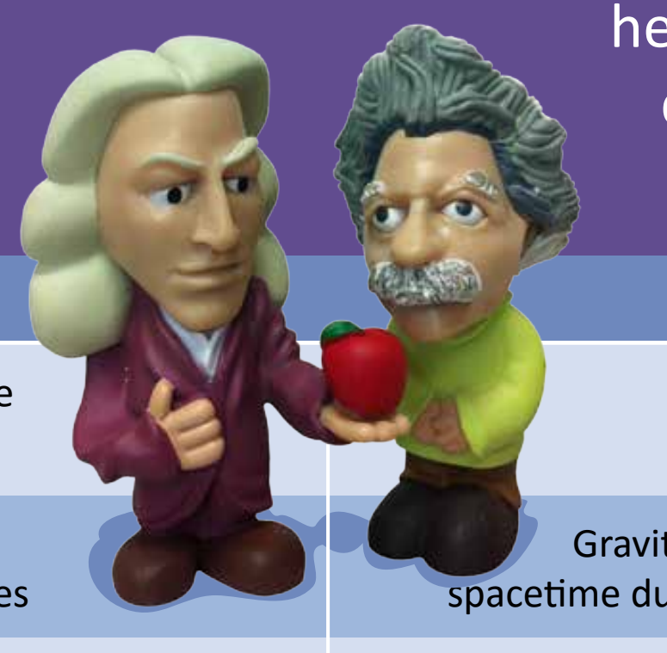


Gravitational Wave Spectrum. This figure plots the predicted strain (h, y-axis) vs. the frequency of expected gravitational waves in Hz (x-axis) for different types of cosmic objects. Credit: SSU E/PO/Aurore Simonnet.

Just as different cosmic objects generate different wavelengths across the electromagnetic spectrum, different physical systems are expected to generate different wavelengths of gravitational waves. These in turn can be observed by different types of observatories. The figure to the left illustrates the expected strengths of the gravitational wave, usually called *h* or strain, wavelength bands and types of sources expected in each band. LIGO (and other similar-size ground-based interferometers such as Virgo in Italy) are sensitive to gravitational waves with frequencies in the range 10 - 2000 Hz.

From Newton to Einstein to the Classroom

Legend has it that Isaac Newton discovered gravity when he was hit on the head by an apple which fell from a tree under which he was sitting. Today, he is credited with the mathematical expression that explains how the force of gravity depends on the mass of the two objects and their mutual distance - it is called Newton's Law of Gravitation.



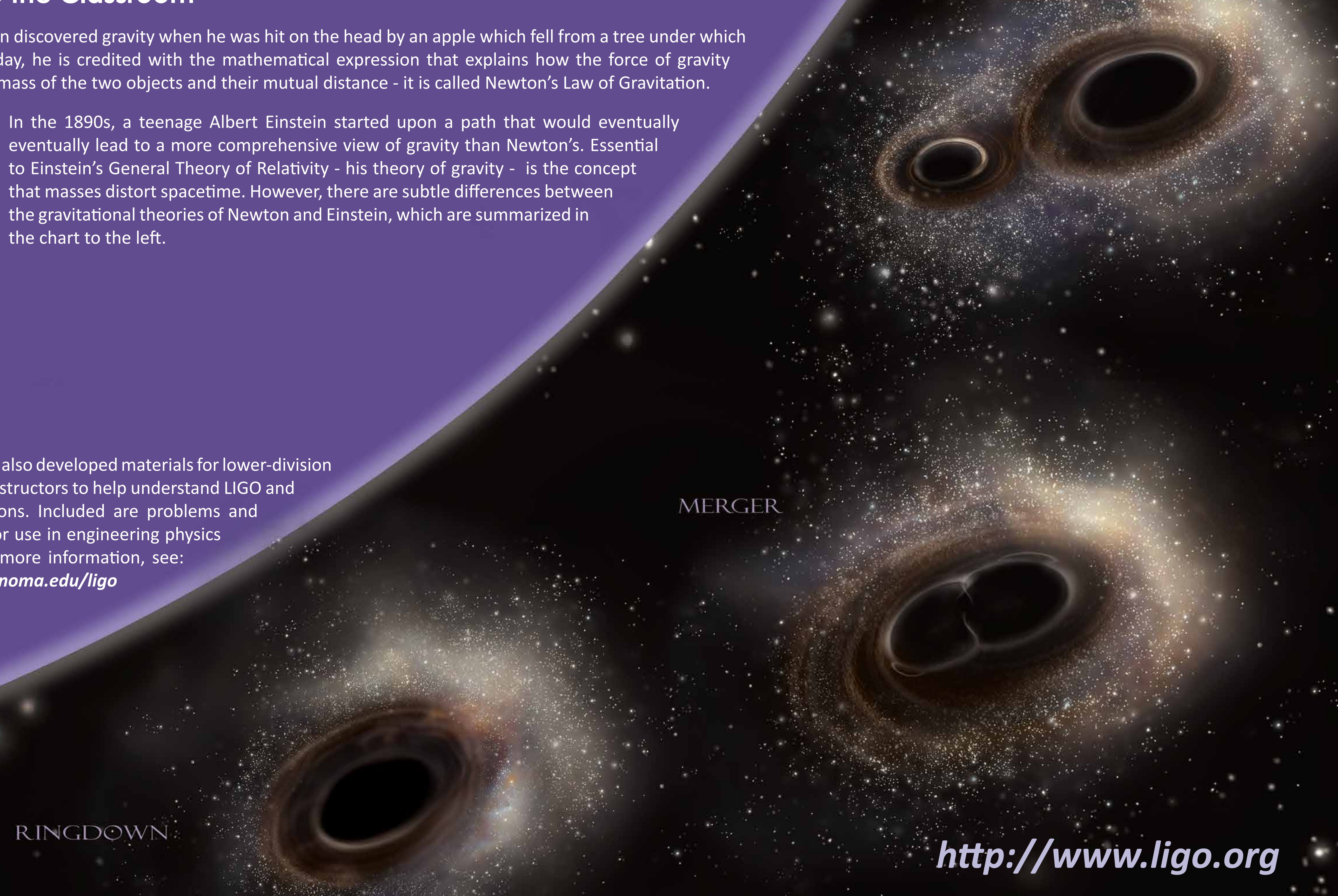
Newton	Einstein
Space is flat, time is constant	Space and time are intertwined
Gravity is a force between 2 masses	Gravity is curvature of spacetime due to single mass
Force of gravity is instantaneous	Gravitational waves travel at c
Light travels in a straight line	Light follows shortest path through curved spacetime

In the 1890s, a teenage Albert Einstein started upon a path that would eventually eventually lead to a more comprehensive view of gravity than Newton's. Essential to Einstein's General Theory of Relativity - his theory of gravity - is the concept that masses distort spacetime. However, there are subtle differences between the gravitational theories of Newton and Einstein, which are summarized in the chart to the left.

We have developed an educator's guide in which we present two simple demonstration activities *"Coalescing Black Holes "* and *"Warping of Spacetime"* that you can do in your classroom to engage your students in understanding LIGO's discovery.

Download:
https://dcc.ligo.org/LIGO-P1600015/public

We have also developed materials for lower-division college instructors to help understand LIGO and its detections. Included are problems and resources for use in engineering physics courses. For more information, see: ***http://epo.sonoma.edu/ligo***



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