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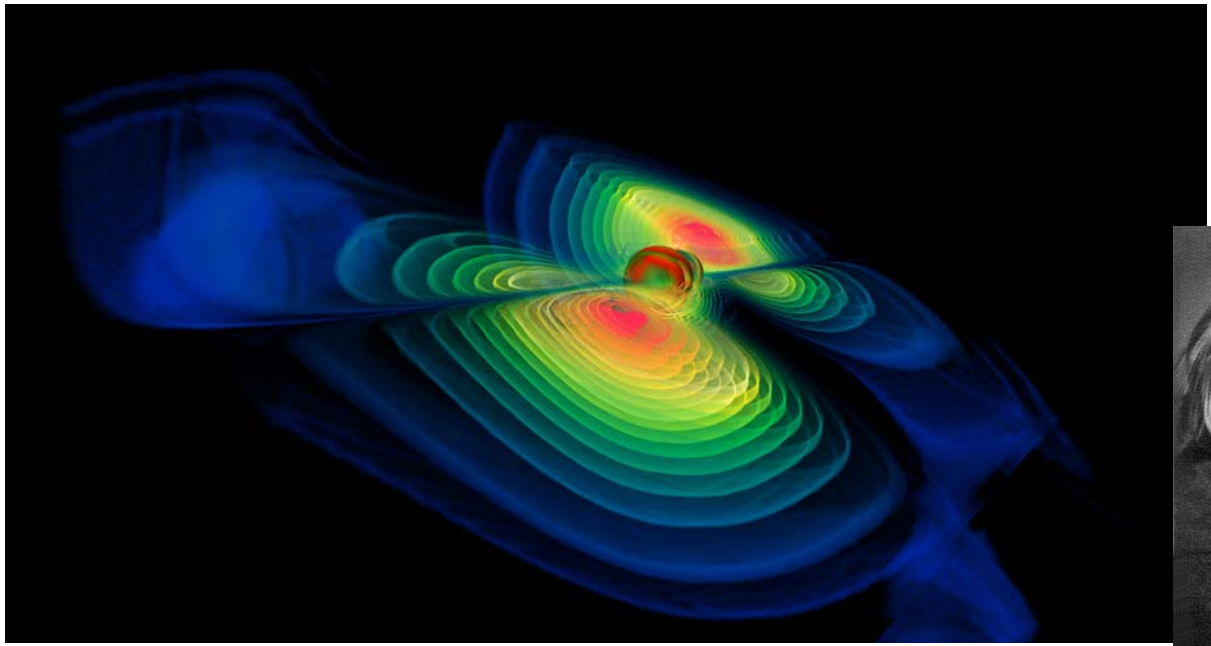
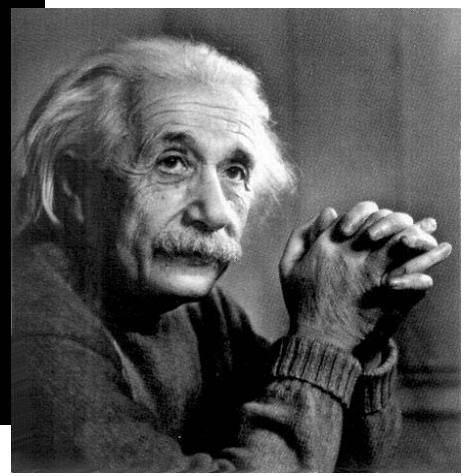
Relativity



"Colliding Black Holes"

Credit:
National Center for Supercomputing Applications (NCSA)



Fred Raab,
LIGO Hanford Observatory

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The Origins of Relativity

- Relativity describes how things move through space and time
- Galileo (1564-1642) first realized that uniform (constant velocity) motion was relative
  - » Consider two canoes on a placid lake, one of which is moving relative to the other. How do we establish which canoe is moving? We can only decide if an object is moving if we can relate that motion to some frame (Shoreline? Water surface? Canoeist?)
  - » Motion of either canoe is ***relative*** to a reference frame
- Isaac Newton (1643-1727), the master of motion, codified Galilean relativity into his laws of mechanics
  - » space and motion were defined relative to a reference frame
  - » time was an absolute quantity $\Rightarrow$ all clocks ticked at the same rate
  - » law of universal gravitation

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Fast Forward 200 Years

- About 100 years ago, Albert Einstein (1879-1955) began to explored anew the concepts of space and time
  - » Theory of electromagnetism had correctly described motors, generators, radio and light transmission
  - » Newton's mechanics had correctly described motion of neutral matter
  - » But the two theories were incompatible in the description of moving electrical charges
- Einstein eventually discovered that the incompatibility was caused by the presence of "absolute" time
  - » Two travelers in relative motion, not only cannot define who is moving, if they move fast enough they also disagree on the time between events

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Special Relativity

- Einstein's *Special* Theory of Relativity (1904) described motion of matter *in the absence of gravity*
  - » Everything is relative, except the speed of light, which is absolute, in agreement with electromagnetism
  - » There is a special symmetry between space and time, mass and energy
  - » All observers in relative motion observe the same laws of physics but they disagree on the definitions of time and space that they use to describe those laws
- Theory was controversial at the time
  - » Nobel committee did not mention Relativity in Einstein's Nobel Prize citation, which was for the explanation of the photoelectric effect
- Predictions:
  - » Moving rulers contract
  - » Moving clocks tick slower
  - » Matter is just a "frozen" form of energy (e.g., nuclear power industry)

e.g., explanation of muon flux at surface of earth

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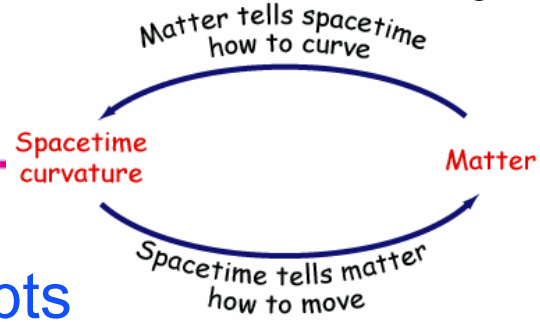
The Dawn of General Relativity

- Einstein struggled another decade to discover how to incorporate gravity into relativity
- The big clue was known by Newton and often observed by us since the dawn of the space age
  - » "Microgravity" as we often view it on video of astronauts aboard the Space Shuttle or the Space Station was predicted by Newton's law of *universal* gravitation, which showed that all objects fall exactly the same under gravitation, and confirmed by Newton's pendulum experiments
  - » Einstein eventually realized that these objects all followed the same *path* through space and time and that *gravitation was the consequence of geometrical properties of space and time*

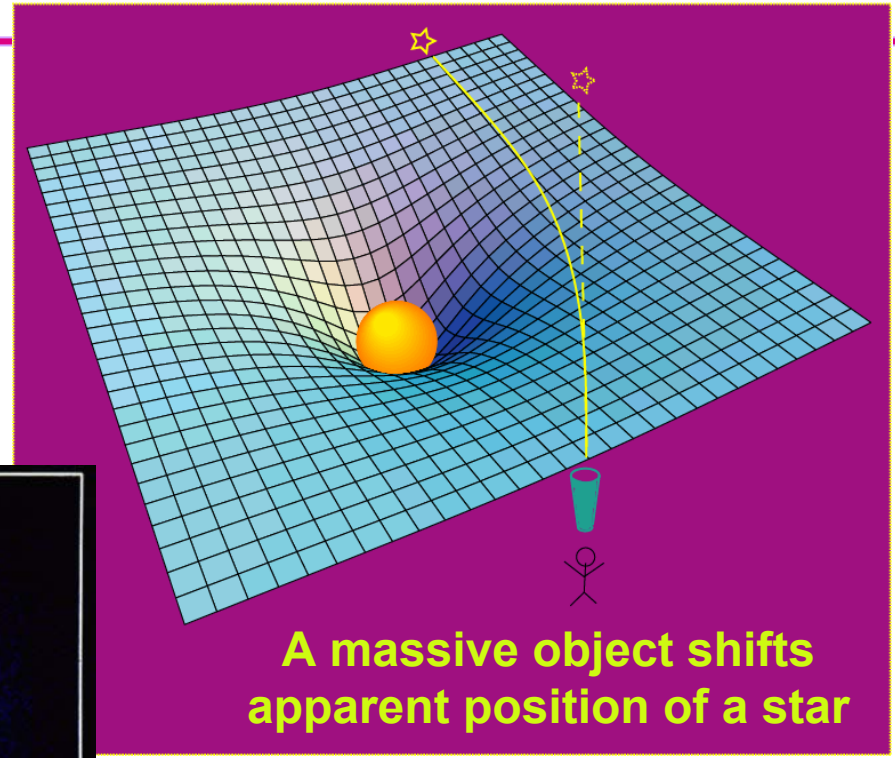
The Essence of General Relativity



- Space and time are things, not concepts
  - » Space and time affect the motion of objects and objects affect the character of space and time
- Things move along the shortest path through the four dimensions of space and time
  - » The presence of matter (or energy) warps space and time, changing their geometrical properties
  - » For example, a flat sheet of space can be warped into a curved sheet, like the surface of the earth; parallel lines remain a fixed distant apart on flat sheet, but converge on earth's surface (lines of longitude)
  - » The paths of all objects naturally follow the curvature of space and time
  - » In flat spacetime, General Relativity reduces to Special Relativity

Mass Warps Space, Affecting Paths of Objects and Light

- Presence of mass gives space the appearance of lumpy glass as evidenced by the bending of light
- First observed during the solar eclipse of 1919 by Sir Arthur Eddington, when the Sun was silhouetted against the Hyades star cluster



Einstein Cross
Photo credit: NASA and ESA

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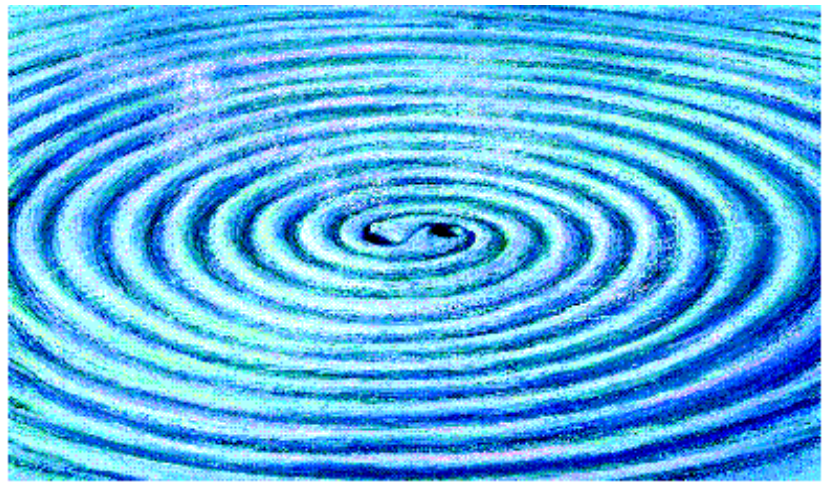
Was Einstein Right?

- Remarkably so, but it took time to appreciate how right he was!
- Checking relativity needed good rulers and clocks, and measurements over large expanses of space and time
- Golden age of experimental relativity began in late 1950's
  - » Radar had become an excellent ruler
  - » Atomic timekeeping came of age
  - » Space flight allowed controlled measurements over large distances
- Dozens of new effects predicted by relativity have been confirmed to accuracies between 0.1% to 0.0001%
- No test of general relativity has ever found a discrepancy!

The Frontier of Relativity: Gravitational Waves

Gravitational waves are ripples in space when it is stirred up by rapid motions of large concentrations of matter or energy

Rendering of space stirred by two orbiting black holes:

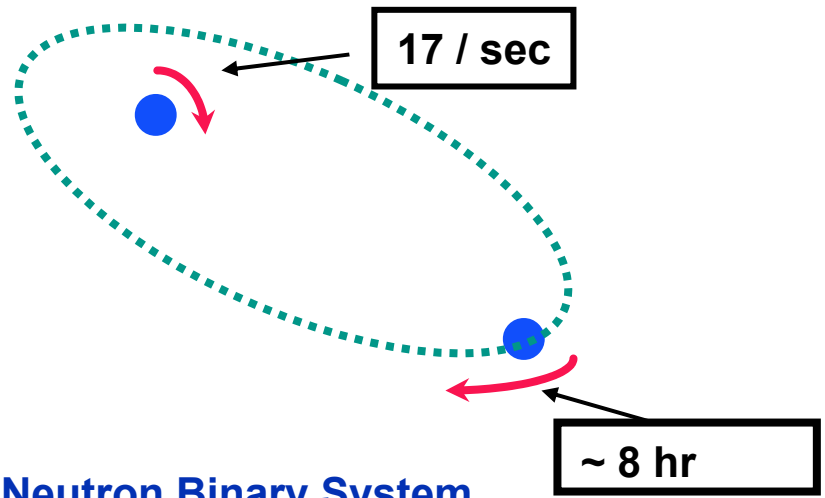


Emission of Energy by Gravitational Waves Has Been Observed

Emission of gravitational waves

Neutron Binary System – Hulse & Taylor

PSR 1913 + 16 -- Timing of pulsars

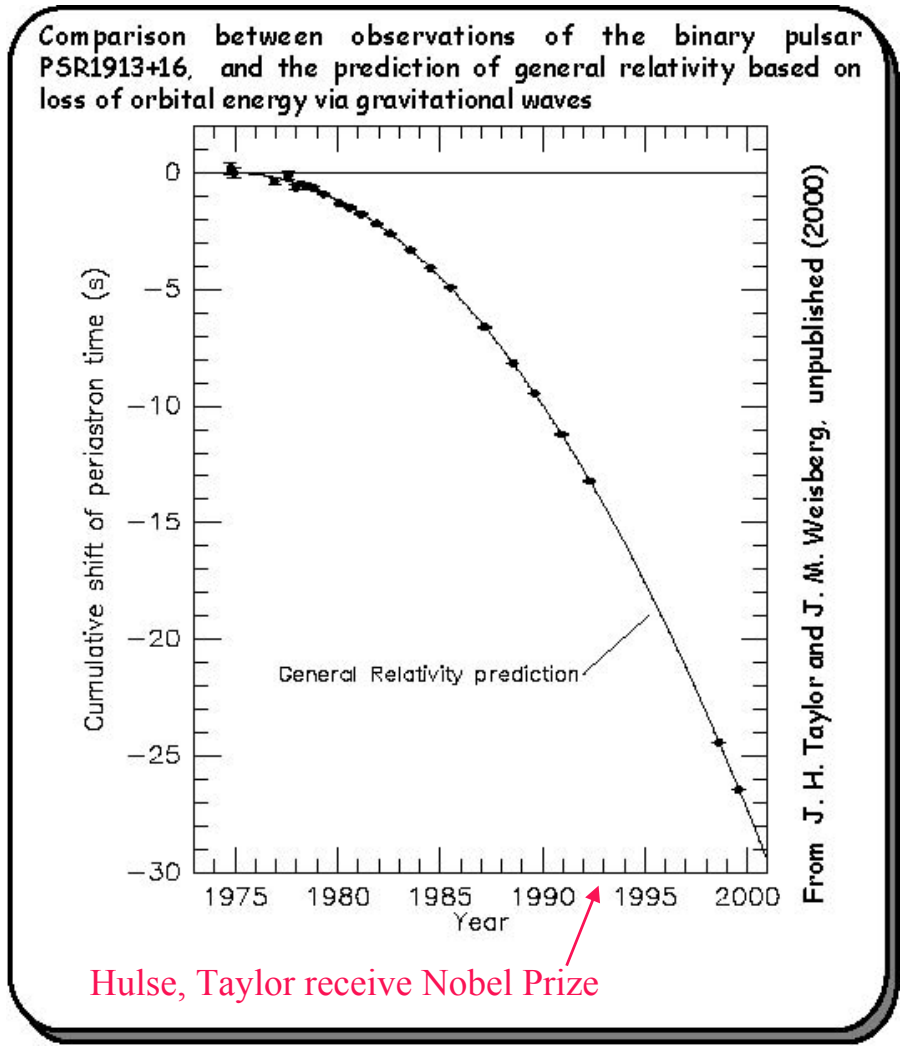


Neutron Binary System

- separated by 10^6 miles
- $m_1 = 1.4m_\odot$; $m_2 = 1.36m_\odot$; $\varepsilon = 0.617$

Prediction from general relativity

- spiral in by 3 mm/orbit
- rate of change orbital period



The Laser Interferometer Gravitational-Wave Observatory

LIGO (Washington)

LIGO (Louisiana)

Brought to you by the National Science Foundation; operated by Caltech and MIT; the research focus for more than 400 LIGO Scientific Collaboration members worldwide.

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Recommended Reading

- “Was Einstein Right”, by Clifford Will. A bit ancient (more than 10 years old) accounting of progress in verifying Einstein’s theory.
- “Black Holes and Time Warps: Einstein’s Outrageous Legacy”, by Kip Thorne. From basics to time travel in a long, but rewarding read.
- “Einstein’s Unfinished Symphony”, by Marcia Bartusiak. A highly readable account of the search for gravitational waves.