LIGO and Gravitational Waves

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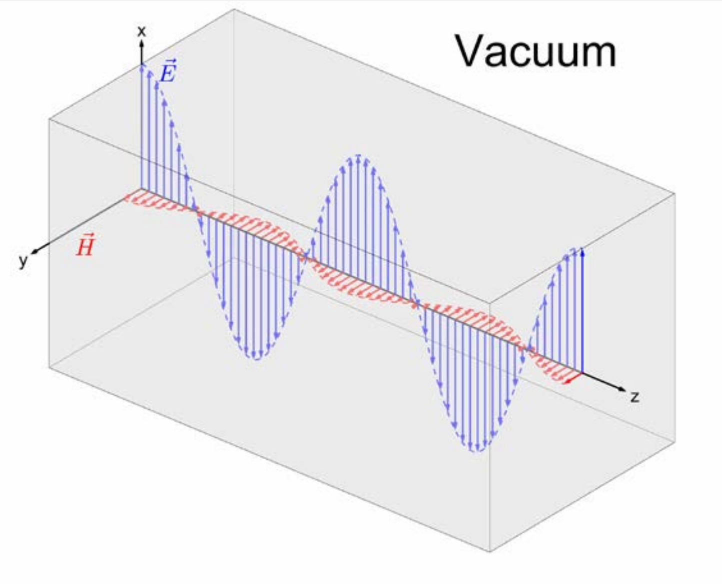
From Kip S. Thorne's "LIGO and Gravitational Waves III" for the Nobel Prize in 2017

Outline

- What are Gravitational Waves?
- Theory, Timeline, & Experiment
- Future work
  - Short- and long-term predictions

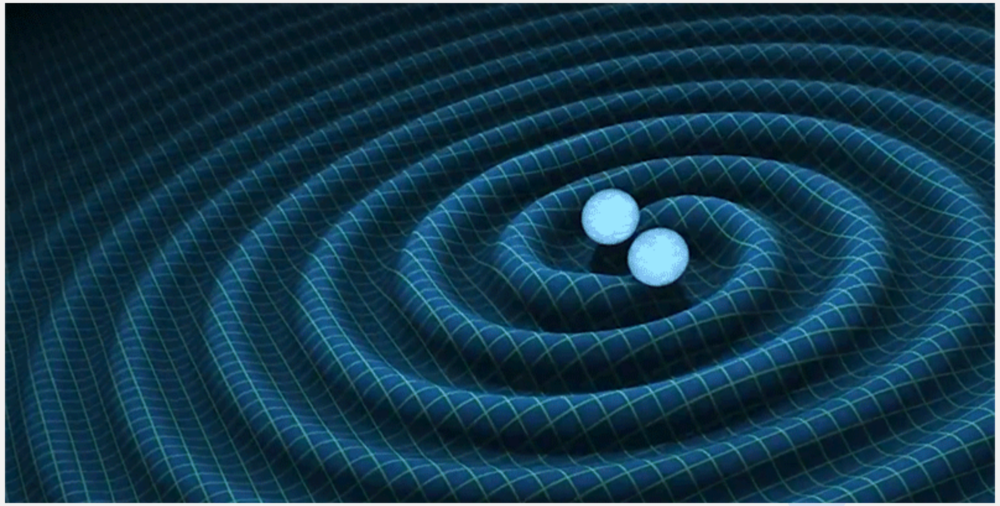
Electromagnetic Waves

- Oscillations of electromagnetic field propagating through spacetime
- Incoherent superposition of waves from particles, atoms, and molecules
- Easily absorbed and scattered



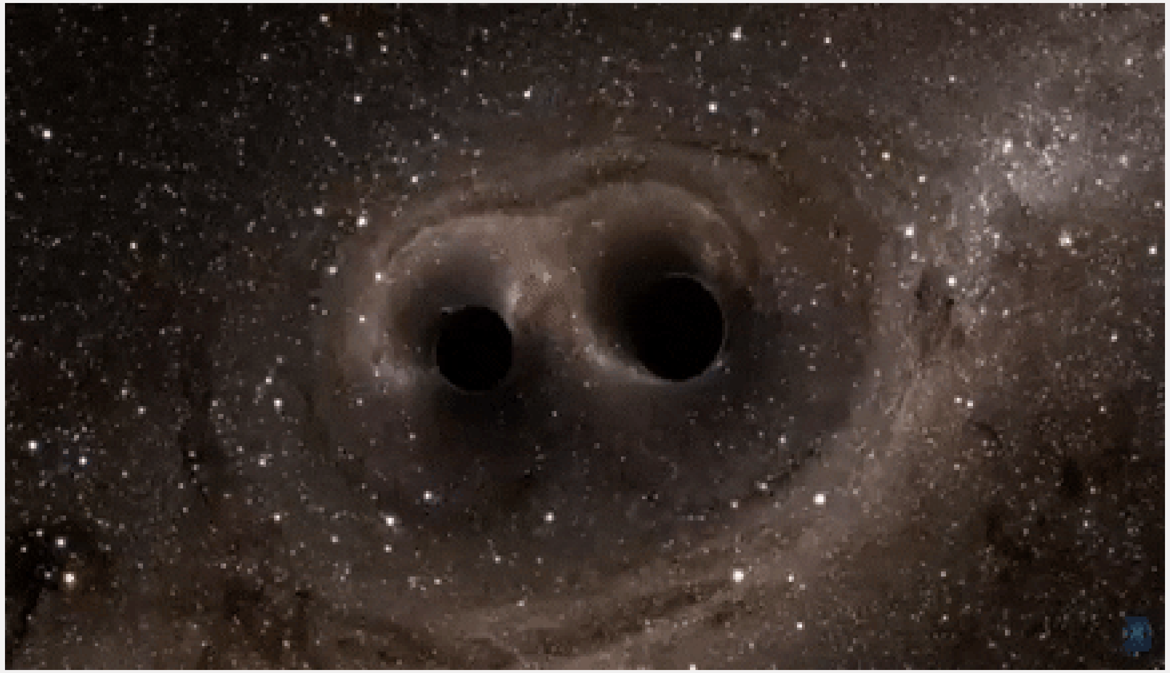
Gravitational Waves

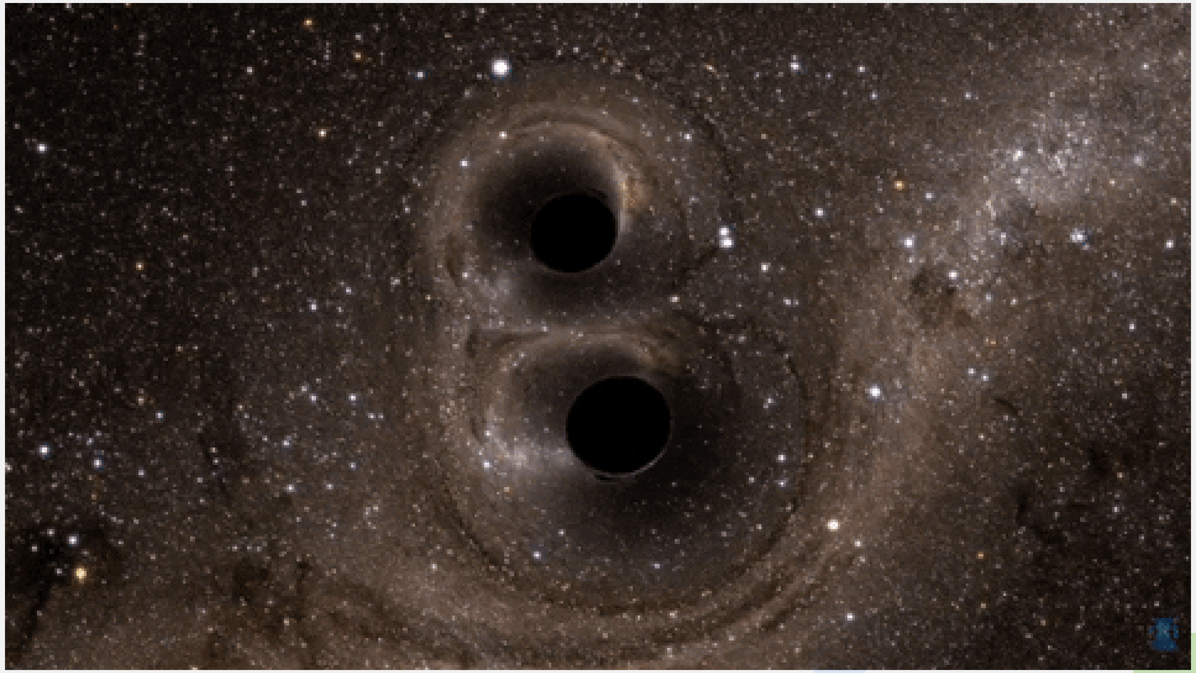
- Oscillations of spacetime itself
- Coherent emission by bulk motion of mass and energy
- Not significantly absorbed or scattered



Gravitational Wave Implications

- Many gravitational waves won't be seen electromagnetically
- Surprises are likely
- Could revolutionize our understanding of the universe





Main Challenge

Classical simulations

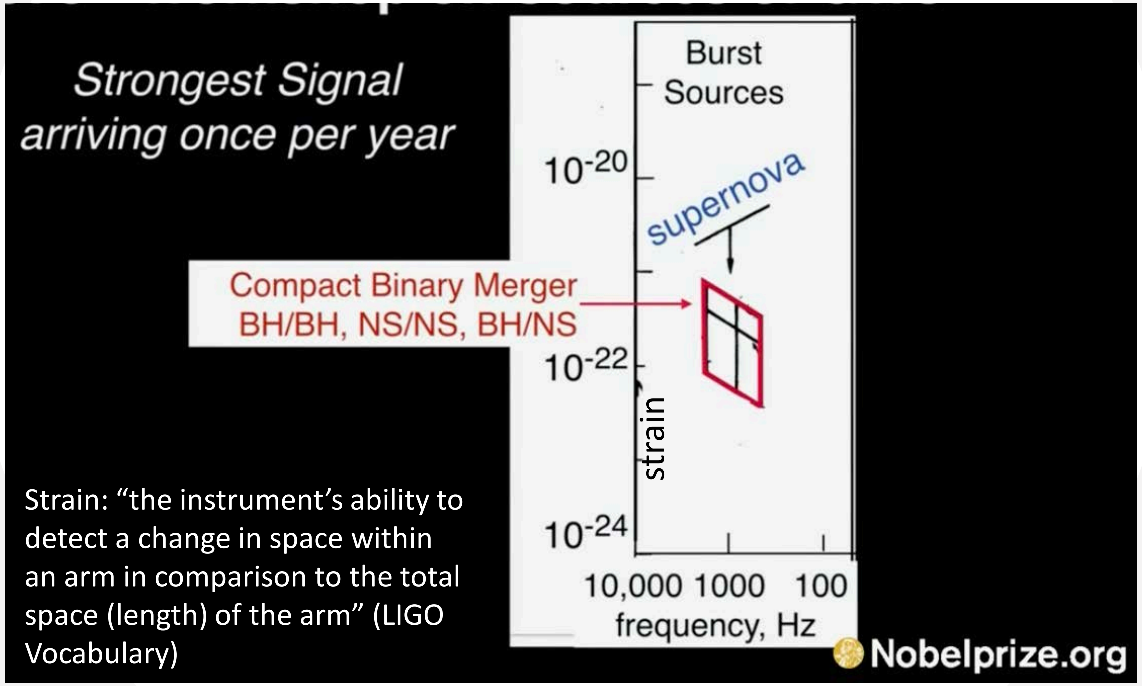
- Working with two objects that collide in space and time
- Simulating objects in an arena

GW simulations

- Working with warps in space and time itself colliding with each other
- Simulating the arena itself changing

First GW Signal Expectations

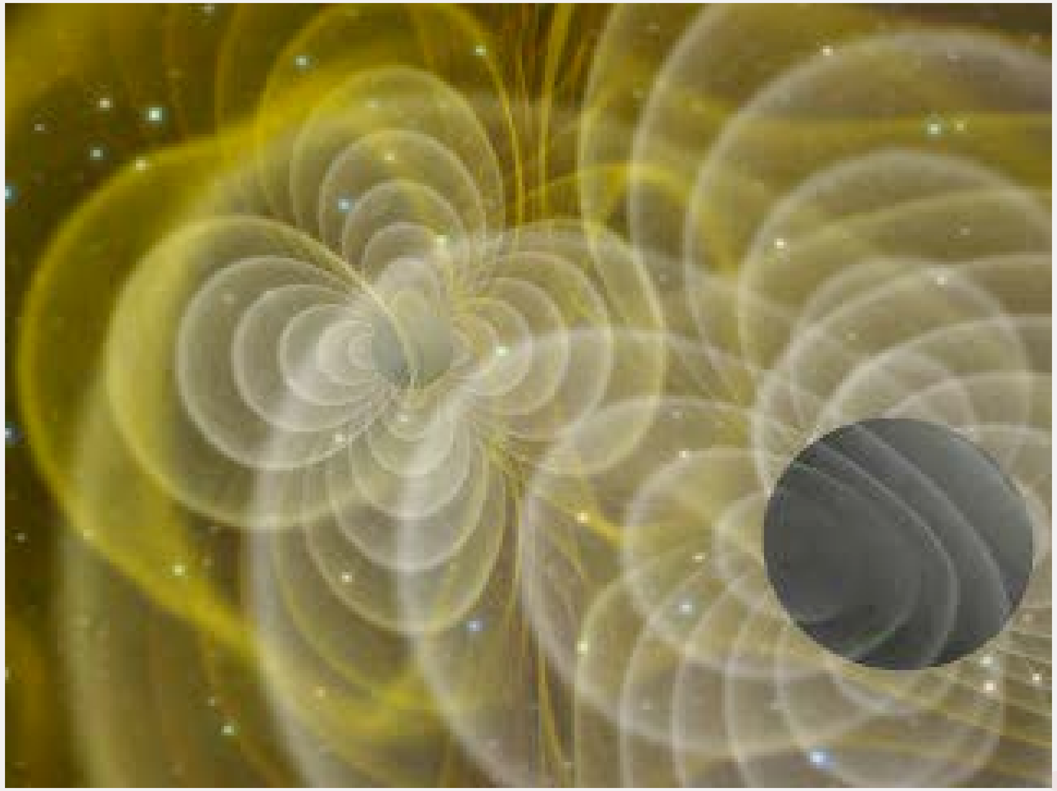
- 1978: Workshop on Sources of GW
  - “10^{-21} or bust”
  - Strain sensitivity at this upper limit
  - Compact binary merger
- 1983: planning LIGO
  - Expecting first detection being between two black holes (as opposed to two neutron stars or a neutron star and a black hole)
    - Black holes are heavier and greater in volume than neutron stars
  - Numerical simulations necessary to solve Einstein’s equations to compute shapes of waves post-collision



First GW Simulation

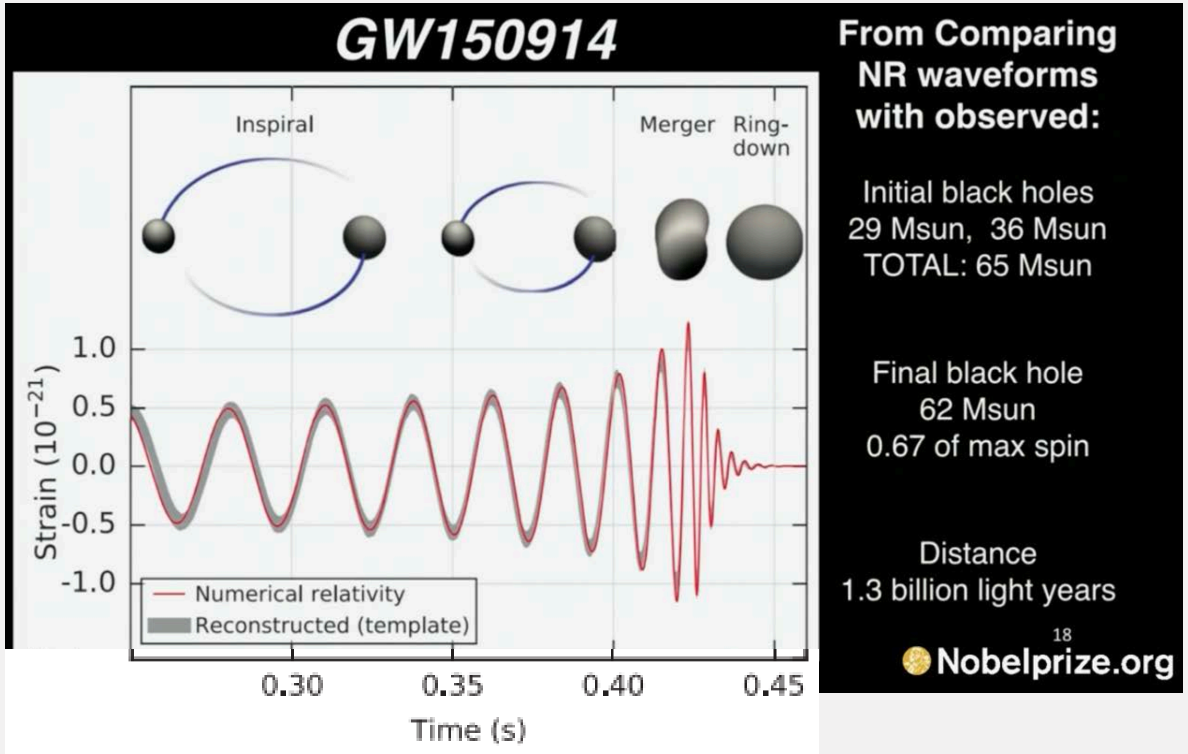
- 1990s: Binary Black Hole Grand Challenge Alliance
  - World-leading experts collectively working on one goal
- Early 2000s: simulation progress is much slower than experimental progress
- 2004: first simulations of orbital collision achieved
- 2014: simulations advanced enough for the first LIGO observations

On the right: Shows Einstein’s vision of two black holes merging. It was the largest astrophysical calculation ever performed on a NASA supercomputer (as of April 2006)
Credit: Henze, NASA



First GW LIGO Detection

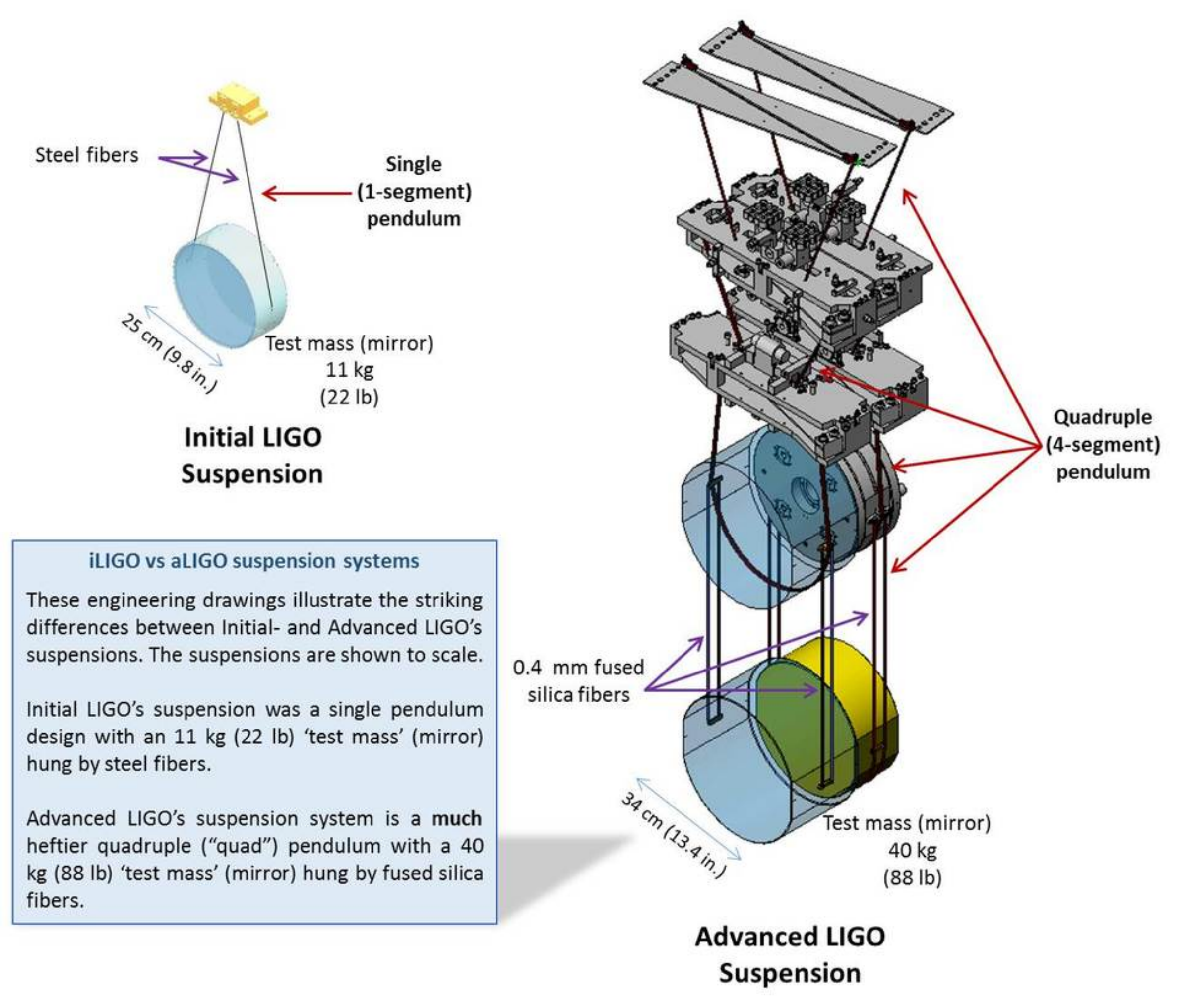
- September 14, 2015: first detection of GW with LIGO
  - Red: simulated waveform
  - Gray: observed waveform
  - Comparing red and gray, can infer properties of the black holes
- 2020: Advanced LIGO
  - Challenge with Advanced LIGO: dealing with quantum fluctuations of the mirrors themselves to circumvent the Heisenberg uncertainty principle
  - "quantum nondemolition" (QND technology) required to monitor motions of 40kg mirrors
    - QND: requires the measurement process preserves the integrity of the measured system
    - Described as the "most classical and least disturbing" type of measurement in quantum mechanics
    - Does *not* imply that the wave function fails to collapse
  - Humans see human-sized objects behave quantum mechanically for the first time



GW with strain around 10^{-20} distort the shape of the Earth by 10^{-13} meters, or about 1% of the size of an atom. In comparison, the Moon raises a tidal bulge of about 1 meter on the Earth's oceans.

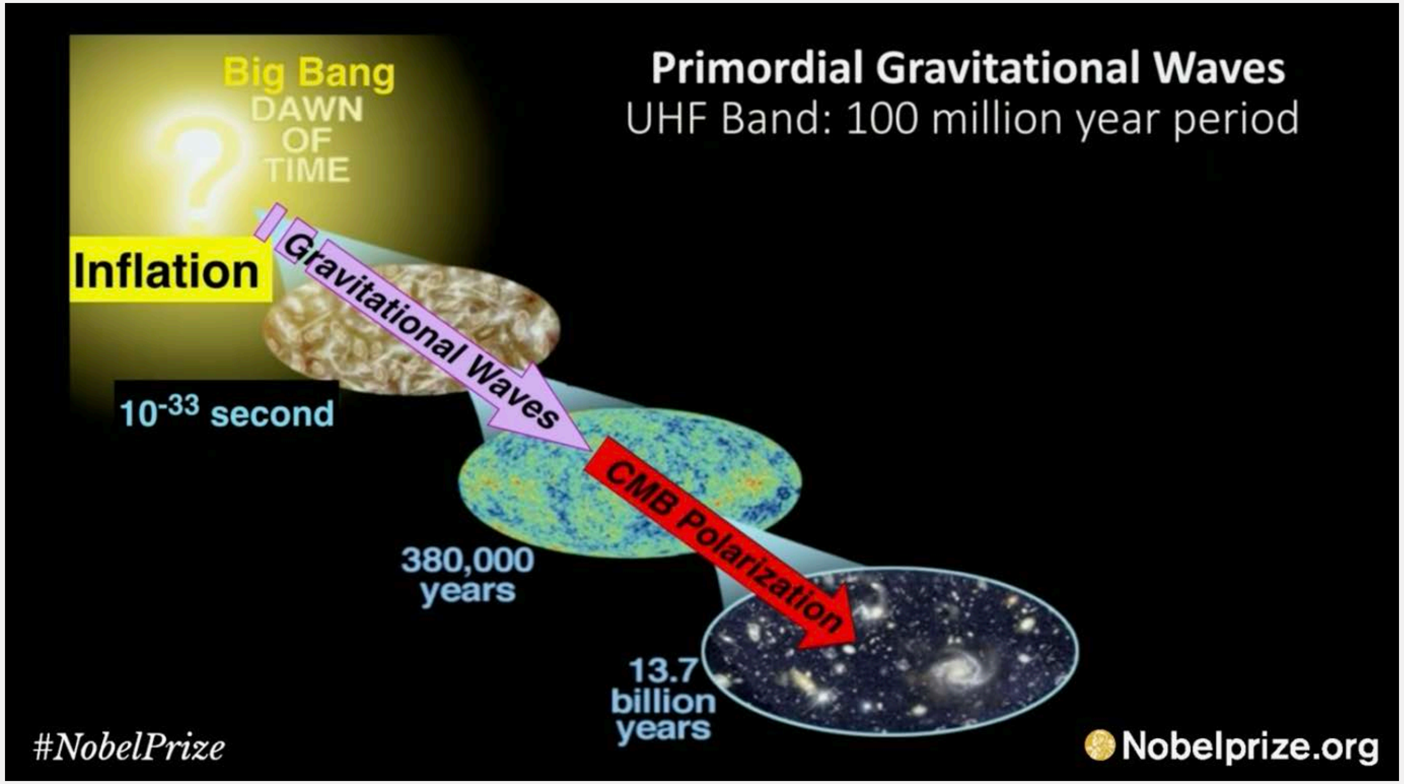
Advanced LIGO Mirrors

- aLIGO reduces the recoil effect due to laser photons hitting the mirrors
- Increased size and mass of the mirrors decreases overall noise detection
- Larger mirrors can also absorb more heat before distorting the mirror



Future work

- By 2050: detect primordial gravitational waves
  - Vacuum fluctuations
- Measure polarization of CMB to infer gravitational waves that came off the Big Bang convolved with the effects of inflation
- Prediction by Kip S. Thorne: there will not be agreement between the gravitational waves with a period of about 1 second and those with periods of 100 million years
  - What really came off the Big Bang will largely be a mystery

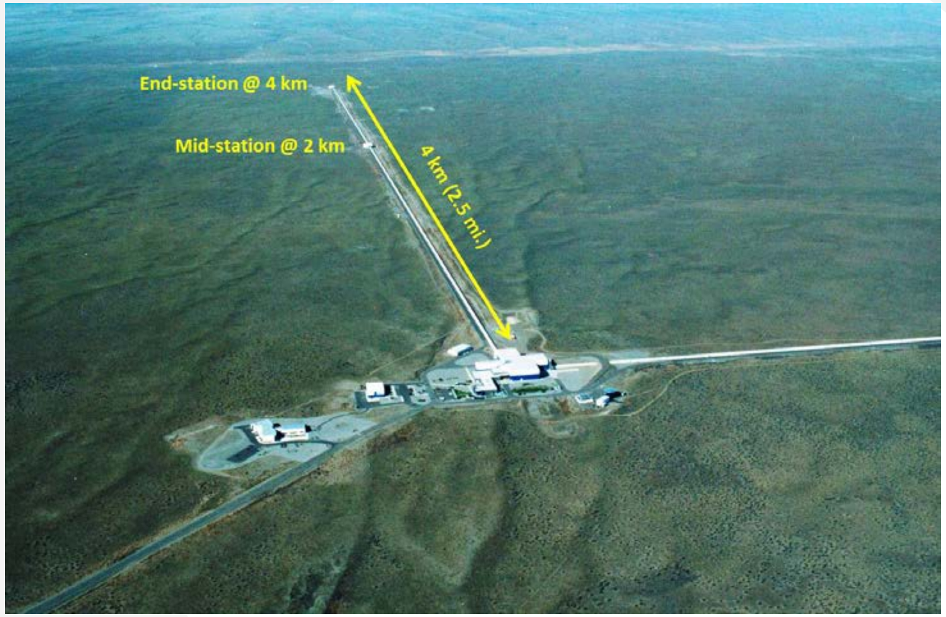


Perspective

- Over 400 years ago: Galileo created modern electromagnetic astronomy
  - Small object telescope → saw moons of Jupiter
- Only within the last 5 years has LIGO detected gravitational waves from the collision of two black holes
- 400 years from now, with 400 years of gravitational astronomy and the progress of electromagnetic astronomy, the future of the field holds much excitement

Left: Galileo's telescope used to see Jupiter's moons

Image credit



Above: overhead view of LIGO Hanford

Image credit

Sources

- The Binary Black Hole Grand Challenge Alliance
- Kip S. Thorne Nobel Lecture
- NASA History: Galileo Discovers Jupiter’s Moons
- LIGO Detectors
- NASA Black Hole Simulation
- Gravitational Waves, Caltech
- LIGO Vocabulary
- Quantum Nondemolition Measurement
- aLIGO Mirrors