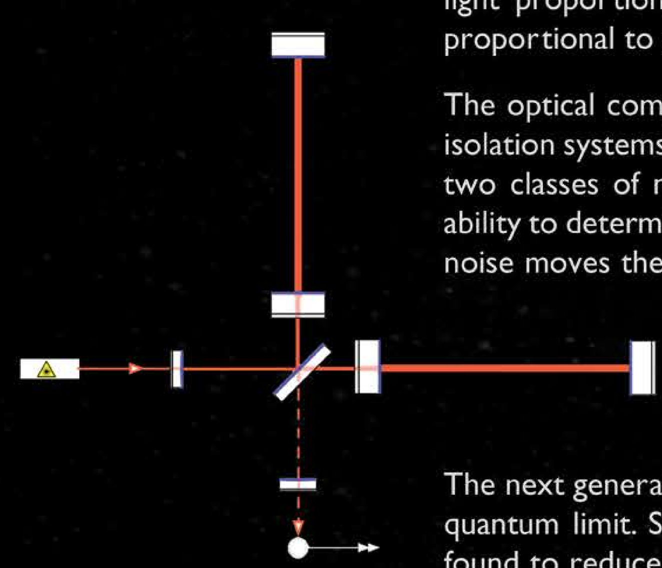
GRAVITATIONAL WAVE DETECTORS

{LISTENING TO THE UNIVERSE}

Interferometer Detector

Interferometric detectors are designed to compare the time it takes light to travel in two orthogonal directions. The interferometer works by dividing a laser beam at the beam splitter so that each beam travels along one arm. When the beams return to the beam splitter, they are redirected to the photodetector. If the two beams have taken equal times (or time differences that are multiples of the period of optical oscillation), there is destructive interference of the light (dark fringe) at the photodetector. A gravitational wave propagating through the detector causes the time difference to vary by stretching spacetime along one arm of the interferometer and compressing spacetime along the other, causing an amount of light proportional to the time difference to appear at the photodetector. This signal is proportional to the gravitational wave strain ***h***.



(credit: Jeff Kissel)

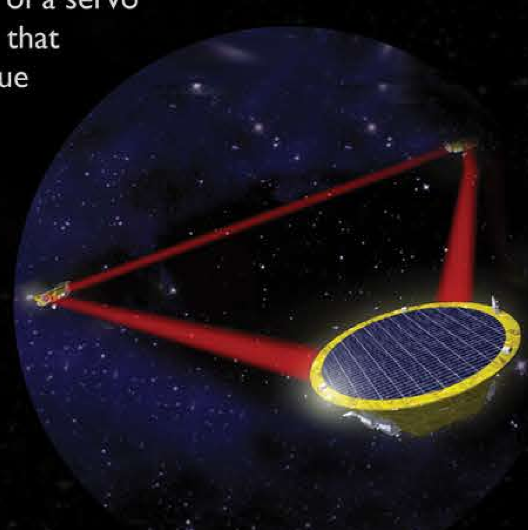
The optical components of the detector are suspended by pendula mounted on vibration isolation systems to reduce the disturbance from seismic noise. Within the interferomenter, two classes of noise interfere with the measurements: photon counting noise limits the ability to determine the time difference (the ability to split the fringe), and radiation pressure noise moves the mirrors. The noise is reduced by regulating the amplitude, frequency and beam jitter of the laser source. However, laser adjustments which reduce the photon noise also increase the pressure noise and vice versa. The standard quantum limit is the lowest noise level achieved by balancing these effects.

The next generation of interferometric detectors is expected to be limited by the standard quantum limit. Squeezing the state of light is a promising new technique which has been found to reduce noise caused by quantum effects. The injection of squeezed states of light into the output port of the interferometer will reduce photon and pressure noise, improving sensitivity beyond quantum limits.

Interferometers in Space

Operation of a very long baseline interferometer (5 x 10^6 km) in solar orbit would make the low frequency (10^{-4} to 1 Hz) gravitational wave band accessible. The gravitational field gradients from seismic compression of the ground and density fluctuations in the atmosphere limit the sensitivity of terrestrial detectors below frequencies of a few Hz. The Laser Interferometer Space Antenna (LISA) is a proposed ESA mission for a space-based gravitational-wave detector.

The mission will place three identical spacecraft in a triangular configuration. The spacecraft consist of an outer shield and an inner proof mass. The shield will follow the proof mass by means of a servo system that uses ion engines as controllers and that protects the proof mass from random forces due to fluctuations in the solar wind and radiation pressure. The motions of the proof masses relative to each other are measured by heterodyne interferometry which can detect the gravitational-wave signal.



(credit: ASTRIUM)

LIGO - A Long Baseline Interferometer

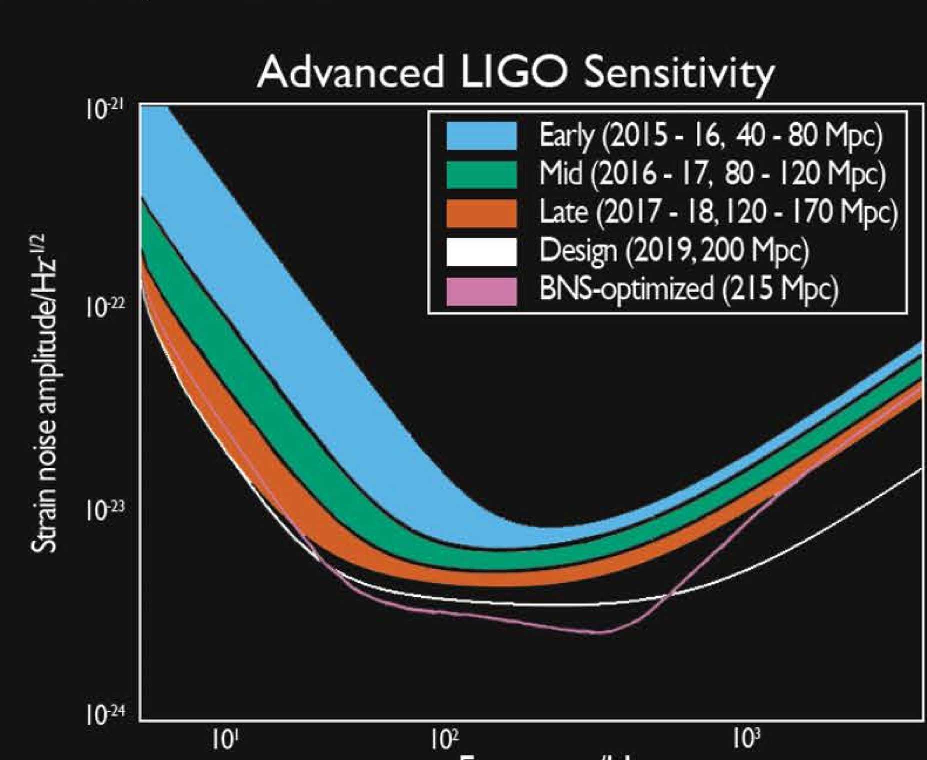
In recent decades, large baseline interferometers have begun operations in the United States (LIGO), Italy (VIRGO), Germany (GEO), and in Japan (KAGRA). Such an international network provides detection confidence and information to determine source position and wave polarization, and thereby a means to attach gravitational wave observations to electromagnetic and neutrino astronomy.

Long baselines gain sensitivity because gravitational wave displacements grow in proportion to the arm length while most random force noise is independent of the arm length. LIGO (Laser Interferometer Gravitational-wave Observatory) is a joint project of the California Institute of Technology and the Massachusetts Institute of Technology, sponsored by the National Science Foundation.

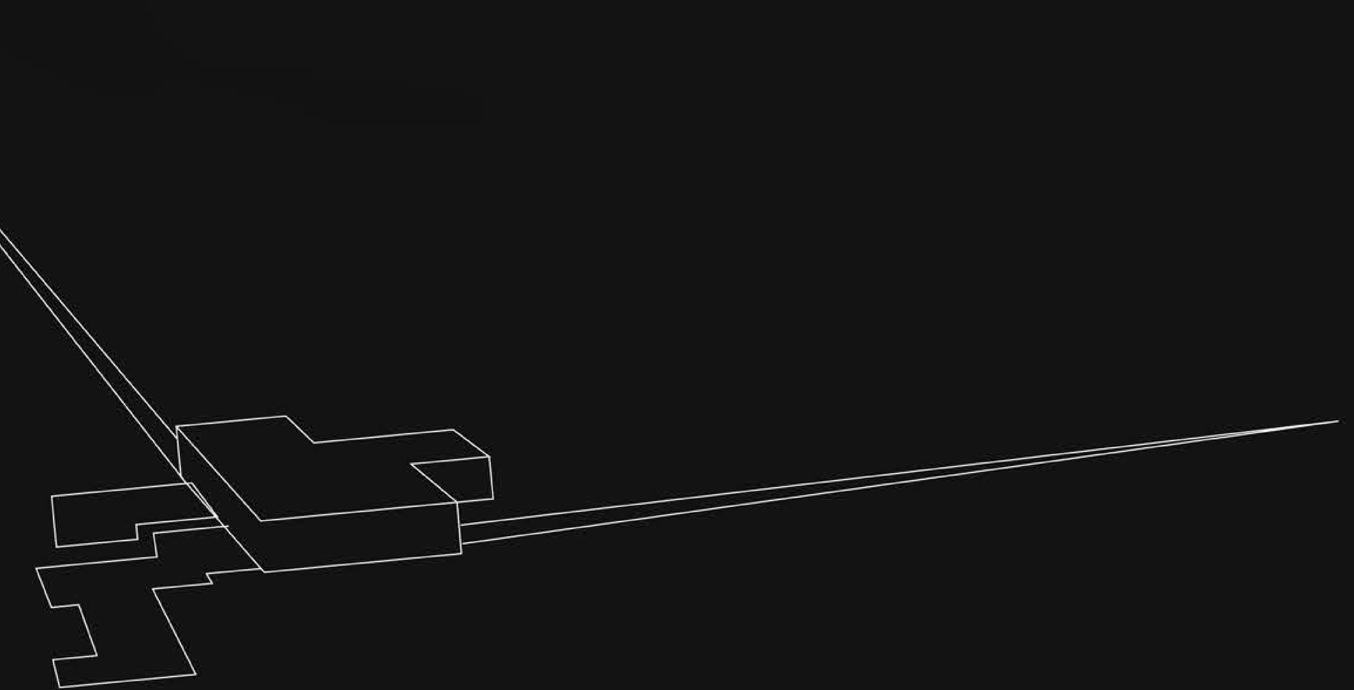
Between 2002 and 2010, LIGO operated three detectors that achieved sensitivities of h = 10^{-21} near 100 Hz. The 4-kilometer L1 detector is located near Livingston, Louisiana, and the 4km H1 detector and a companion 2km H2 detector shared a facility near Hanford, Washington. All three LIGO interferometers were upgraded in the Advanced LIGO program, and the upgraded L1 and H1 interferometers are now completely installed. The subsystems for the second Hanford instrument currently rest in storage, waiting for transport to a new detector location in India rather than undergoing installation at the location of H1 in Washington.

All three interferometers were run in coincidence to search for gravitational-wave bursts as well as in correlation to search for a stochastic background of gravitational waves and periodic gravitational-wave sources. The detection of gravitational waves by LIGO would have required an observation at both sites, a 2/1 ratio (within statistics) in the 4 km/2 km interferometers and no detection in a host of environmental and apparatus monitors.

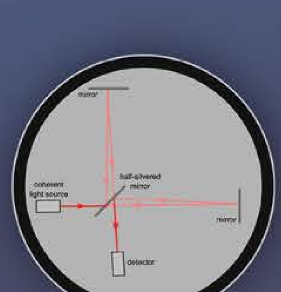
The initial interferometers did not detect any gravitational waves. However, they established upper limits on the flux of gravitational waves. The Advanced LIGO detector is designed to achieve more than a factor of 10 improvement in strain sensitivity over the initial interferometers, resulting in sensitivities which should make the detection of gravitational waves a routine occurrence.



(credit: Keita Kawabe)



(background credit: Gareth Johnson)



1962

A paper is published by Gertsenshtein and Pustovoit proposing the use of interferometers for the detection of gravitational waves. (credit: Stannered)

1964

Weber, unaware of the previous suggestion, proposes detecting gravitational radiation using a laser to measure differential motion of two isolated masses in phone conversation to Forward. (credit: University of Maryland)

1971

Moss, Miller, and Forward construct the first prototype interferometric detector with an arm length of 2m. (credit: UAH Library Robert L. Forward Collection)

1972

Weiss publishes detailed report on the design of gravitational-wave antennae. (credit: Bryce Vickmark)

1980s

Interferometer detectors become operational at Caltech (40m), MIT (30m), and in Munich (30m), Glasgow (10m), and Japan (100m). (credit: LIGO)

1989

Proposals are submitted for LIGO in the USA (2 x 4km, 1 x 2km), VIRGO in Italy (3km), and GEO in Germany (600m). (credit: Institute for Gravitational Research, University of Glasgow)

1992

A NSF Cooperative Agreement initiates the construction of LIGO and funds related research and development.

1995

Construction begins on the TAMA detector in Japan (300m). (credit: Kestral)

2000

LIGO achieves "first lock" of its three first-generation detectors. (credit: LIGO)

2010

The first-generation LIGO detectors cease operations. No gravitational wave detections are made with these interferometers; however, data from Initial LIGO establishes upper limits on the flux of gravitational waves. (credit: LIGO)

2015

The Advanced LIGO detectors begin operations.

LIGO's advanced instruments should achieve a factor of ten improvement in sensitivity over their first-generation predecessors, eventually making gravitational wave detections a routine occurence. (credit: R. Powell and B. Berger)

LIGO Scientific Collaboration

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