

## *A Brief History of LIGO*

One hundred years ago, using his recently formulated general relativity theory, Albert Einstein predicted the existence of gravitational waves and described their properties. To Einstein these waves seemed too weak ever to be detected, even for the strongest sources that he could conceive. Over the subsequent decades, our improving knowledge of the universe (black holes, neutron stars, supernovae ...) and the march of technology (lasers, computers, solid state electronics, low loss optics...) have changed that.

In the 1960s, Joseph Weber at the University of Maryland pioneered the effort to build detectors for gravitational waves, using large cylinders of aluminum that vibrate in response to a passing wave, an approach which broke the ground for the field of gravitational-wave searches.

LIGO's approach, using laser interferometry to monitor the relative motion of freely hanging mirrors, was proposed as a theoretical concept form in 1962 by Michael Gertsenshtein and Vladislav Pustovoit in Moscow Russia, and independently several years later by Weber and by Rainer Weiss in America. In 1967, Weiss investigated a laser interferometer limited at some frequencies by quantum shot noise, and in 1972 he completed the invention of the interferometric gravitational wave detector by identifying all the fundamental noise sources that such a detector must face, and conceiving ways to deal with each of them, and by showing that — at least in principle — these ways could lead to detector sensitivities good enough to detect waves from astrophysical sources.

Prototype interferometric gravitational wave detectors (“interferometers”) were built in the late 1960s by Robert Forward and colleagues at Hughes Research Laboratories (with mirrors mounted on a vibration isolated plate rather than free swinging), and in the 1970s (with free swinging mirrors between which light bounced many times) by Weiss at MIT, and then by Hans Billing and colleagues in Garching Germany, and then by Ronald Drever, James Hough and colleagues in Glasgow Scotland.

In the late 1970s and 1980s, elegant new ideas to improve the interferometers' sensitivity were developed by Ronald Drever, Brian Meers and the Glasgow Group as well as by Roland Schilling, Lise Schnupp, Albrecht Ruediger and the Garching Group.

In 1968, Kip Thorne created a research group at Caltech working on the theory of gravitational waves and their astrophysical sources, and later on noise in interferometers. In collaboration with a Russian experimental group, led by Vladimir Braginsky, Thorne's group recognized that advanced gravitational wave interferometers would operate in an entirely new technological regime, in which heavy mirrors behave like quantum particles, and they went on in the 1980s – 2000s to formulate techniques for dealing with this.

In the late 1970s Thorne triggered the creation of an experimental gravitational wave group at Caltech, led by Drever (imported from Glasgow in 1979) and Stan Whitcomb (1980).

In 1980 the US National Science Foundation (NSF) funded the construction of a Drever-Whitcomb 40 meter prototype interferometer at Caltech and Weiss's 1.5 meter prototype at MIT,

and funded Weiss to design and lead a technical and cost study for a several-kilometer-long interferometer. With this study demonstrating the feasibility of long interferometers and the MIT, Caltech, Garching and Glasgow prototypes showing success, in 1984 Caltech and MIT signed an agreement for the joint design and construction of LIGO, with administrative headquarters at Caltech, and with joint leadership by Drever, Weiss and Thorne.

Prototype research and the planning for LIGO's long interferometers continued through the mid 1980s, and was capped in November 1986 with a week long, in depth investigation by a hard nosed external committee, appointed by NSF. After examining the planning for LIGO and the state of the entire world-wide field of gravitational wave science (prototype research, knowledge of astrophysical sources and industrial capabilities as well as costs), the committee enthusiastically endorsed LIGO's scientific case and its technical feasibility. The committee recommended that NSF entertain a construction proposal for LIGO, but only after the creation of a new LIGO leadership structure under a single director.

In 1987 Caltech's Rochus Vogt was appointed Director of LIGO, and in 1989, Vogt, Drever, Fred Raab, Thorne and Weiss submitted a joint Caltech/MIT proposal for LIGO construction to the NSF. The proposal envisioned building LIGO facilities at two sites, and then operating in them a pair of *initial interferometers* based on proven technology, with a sensitivity where gravitational waves might be detected, followed by *advanced interferometers* based on more advanced technology, with a high probability of detecting waves. This two-stage approach has been essential to LIGO's 2016 success. The technological leap from prototypes to advanced interferometers was too great to be carried out in a single step.

In 1990 the National Science Board, which oversees NSF, approved LIGO construction, and in 1991 Congress appropriated LIGO's first year of funding. In 1992 Hanford, Washington and Livingston, Louisiana were chosen as the sites for LIGO's interferometers, and a cooperative agreement for the management of LIGO was signed between NSF and Caltech. In 1994 Caltech's Barry Barish was appointed the principal investigator for LIGO, and in 1997, the LIGO Director. He served in both roles through 2005. Barish organized LIGO's construction phase, then oversaw construction of its facilities (1994-1998) and then the installation and commissioning of LIGO's initial interferometers (1999-2002) and its first few gravitational wave searches (2002-2005).

In 1997, with the facilities construction nearly finished, Barish conceived and led a major change in LIGO's organization — establishing two entities: (1) The LIGO Laboratory at Caltech, MIT, Hanford and Livingston, responsible for LIGO operations and advanced interferometer R&D, and (2) the LIGO Scientific Collaboration (LSC), responsible for organizing and coordinating LIGO's technical and scientific research and data analysis, and for expanding LIGO to include scientists elsewhere, beyond Caltech and MIT.

In 2017 the LSC Collaboration has grown to include approximately 1200 scientists at approximately 100 institutions in 19 nations. Barish appointed Weiss as the LSC's first spokesperson (1997-2003); in subsequent years, Weiss has been succeeded by elected spokespersons: Peter Saulson (Syracuse University 2003-2007), David Reitze (University of Florida 2007-2011), Gabriela González (Louisiana State University 2011-2017), and then David

Shoemaker (2017-). Barish was succeeded as LIGO Director by Stan Whitcomb (acting director, 2005-2006) and Jay Marx (2006-2011), who led LIGO through the end of the initial interferometer era, and then by David Reitze (now at Caltech, 2011- ) in the advanced interferometer era.

In 2007 the LSC established a collaboration with the European Virgo project — a collaboration of CNRS (France), INFN (Italy), NIKHEF (Netherlands), POGRAW (Poland), and RMKI (Hungary) that had constructed and was operating a long initial interferometer in Cascina, Italy. The LSC and Virgo scientists combine and jointly analyze all data that come from their interferometers. The combined data, American and European, improves measurements of source locations on the sky and improve confidence in detected waves.

Using the initial LIGO interferometers, the LSC carried out a sequence of gravitational wave searches, partly in collaboration with Virgo, with ever improving sensitivities (from minimum strain noise of  $10^{-19}$  in 2002 to design sensitivity,  $1.5 \times 10^{-22}$ , in 2010). In 2005-2010 the initial LIGO searches placed astrophysically interesting limits on gravitational wave sources, but did not find any waves.

In the 2000s, in parallel with these initial searches, the LIGO Laboratory planned and prepared for the next generation, advanced interferometers. In 2008 NSF funded the construction of the advanced interferometers (“Advanced LIGO”). In 2008-2010 the components for Advanced LIGO were constructed by the LIGO Laboratory, with significant contributions from the Scottish and German GEO Collaboration and the Australian ACIGA collaboration. After installation and commissioning in 2010-2014, the advanced interferometer at Livingston achieved “first lock” (began to operate) in May 2014 and within several months its sensitivity exceeded that of the initial interferometers. Hanford followed with first lock and better-than-initial sensitivity in early 2015. By September 2015 both interferometers had reached minimum noise level of  $7 \times 10^{-23}$  and had made improvements of a factor 10 or more over initial LIGO at low frequencies, and the LIGO and Virgo scientists together were analyzing the LIGO data.

On September 14, 2015, shortly before the beginning of Advanced LIGO’s first official gravitational wave search and nearly 100 years after Einstein first postulated gravitational waves, LIGO’s two interferometers achieved their first detection of a gravitational wave: a detection with a very strong and unambiguous signal. The measured waveform matched the predictions of Einstein’s general relativity for waves from two black holes spiraling together, colliding and merging. A few days later there appeared in both detectors a weaker second signal consistent with the merger of two lower mass black holes. During the second observing run, from November 2016-August 2017, more signals were seen, and with Virgo joining on 1 August 2017, signals were seen in all three interferometers. This allows far better localization of sources and will be of great value in pointing traditional astronomers to possible sources for multi-messenger astrophysics.

During these first searches, the interferometer noise is about three times worse than the Advanced LIGO design. Over the next several years, interspersed with subsequent searches, LIGO’s and Virgo’s interferometers will be brought to design sensitivity with a 30-fold increase

in the rate of detection of waves, followed by the addition of an advanced Japanese interferometer called KAGRA. Major further improvements are envisioned in the 2020s, including the addition in the mid-2020's of a third LIGO Observatory in India.