AstroTalk: Behind the news headlines of September 2015

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Einstein revisited: Searching for the elusive 'gravitational waves'

The *Advanced LIGO Project*, a major upgrade of the Laser Interferometer Gravitational-Wave Observatory, is completing its final preparations before the initiation of scientific observations. Designed to observe gravitational waves—ripples in the fabric of space and time—*LIGO*, the Laser Interferometer Gravitational-Wave Observatories, which was designed and is operated by the California Institute of Technology (Caltech) and the Massachusetts Institute of Technology (MIT) in the USA, consists of identical detectors in Livingston (Louisiana, USA) and Hanford (Washington, USA). Although the upgraded facility was officially dedicated during a ceremony on 19 May 2015, scientists and engineers have been working around the clock until now to get it up and running.

> "*We've spent the past seven years putting together the most sensitive gravitational-wave detector ever built. Commissioning the detectors has gone extremely well thus far, and we are looking forward to our first science run with Advanced LIGO beginning later in 2015. This is a very exciting time for the field,*" says David Reitze, the executive director of the *LIGO* programme at Caltech.

Gravitational waves were predicted by Albert Einstein in 1916 as a consequence of his general theory of relativity, and are emitted by violent events in the Universe, such as exploding stars and colliding black holes. Gravitational waves are emitted by accelerating masses much in the same way as radio waves are produced by accelerating charges, such as electrons in antennas. As they travel to Earth, these ripples in the space-time fabric bring with them information not only about the objects that produce them, but also about the nature of gravity in extreme conditions that cannot be obtained by other astronomical tools.

> "*Experimental attempts to find gravitational waves have been ongoing for over 50 years, and they haven't yet been found. They're both very rare and possess signal amplitudes that are exquisitely tiny*," Reitze says.

Originally proposed in the 1990s, *LIGO* began observing in 2002, but no gravitational waves were detected. Since it was first conceived, a major rebuild, *Advanced LIGO*, was planned, which would increase sensitivity by more than a factor of ten, resulting in a thousand-fold increase in observable candidate objects, to the point where predicted signals would be detectable about forty times per year.

> "*To achieve this improvement, we took many lessons learned from initial LIGO, put them together with the results of worldwide research and development, and made a complete redesign and replacement of the*

> *detectors*," says David Shoemaker of MIT, the project leader for *Advanced LIGO*.

Included in the upgrade were changes in the lasers (180 Watt highly stabilized systems), optics (40 kg fused-silica 'test mass' mirrors suspended by fused-silica fibres), seismic isolation systems (using inertial sensing and feedback), and in how the microscopic motion (less than one billionth of one billionth of a metre) of the test masses is detected.

> "*The first Advanced LIGO science run will take place with interferometers that can 'see' events more than three times further than the initial LIGO detector*," adds David Shoemaker, the MIT *Advanced LIGO* project leader, "*so we'll be probing a much larger volume of space*."

Each of the 4-kilometer-long L-shaped *LIGO* interferometers uses a laser beam split into two beams that travel back and forth through the long arms, within tubes from which the air has been evacuated. The beams are used to monitor the distance between precisely configured mirrors. According to Einstein's theory, the relative distance between the mirrors will change very slightly when a gravitational wave passes by.

The original configuration of *LIGO* was sensitive enough to detect a change in the lengths of the 4-kilometer arms by a distance one-thousandth the diameter of a proton; this is like accurately measuring the distance from Earth to the nearest star—over four light-years—to within the width of a human hair. *Advanced LIGO*, which will use the infrastructure of *LIGO*, is much more powerful.

While earlier *LIGO* observing runs did not confirm the existence of gravitational waves, their influence on the binary pulsar system called PSR B1913+6 has been measured accurately and is in excellent agreement with the predictions. The system consists of two objects, both neutron stars—the compact cores of dead stars—that orbit a common centre of mass. The orbits of these two stellar bodies have been observed to be slowly contracting owing to the energy that is lost to gravitational radiation. Binary star systems such as these that are in the very last stages of evolution—just before and during the inevitable collision of the two objects—are key targets of the planned observing schedule for *Advanced LIGO*. Based on observations like these, scientists have great confidence that gravitational waves exist. But a direct detection will confirm Einstein's vision of the waves and allow a fascinating new window into cataclysms in the cosmos.

> "*Ultimately, Advanced LIGO will be able to see 10 times as far as initial LIGO and, based on theoretical predictions, should detect many binary neutron star mergers per year*," Reitze says.

The improved instruments will be able to look at the last minutes of the life of pairs of massive black holes as they spiral closer together, coalesce into one larger black hole, and then vibrate, much like two soap bubbles becoming one. *Advanced LIGO* also will be able to pinpoint periodic signals from the many known pulsars that radiate in the range of 10 to 1,000 Hertz (frequencies that roughly correspond to low and high notes on an organ). In addition, *Advanced LIGO* will be used to search for the gravitational cosmic background, allowing tests of theories about the development of the Universe only 10^{-35} seconds after the Big Bang.

> "*We expect it will take five years to fully optimize the detector performance and achieve our design sensitivity*," Reitze says. "*It has been a long road, and we're very excited to resume the hunt for gravitational waves*."
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> "*The initial detectors were sensitive enough to detect events up to a distance of about 50 million light years*," says Professor David Blair from the University of Washington. "*But even in that volume, we only expected one event every hundred years. If you can make your detector ten times more sensitive then it can see ten times further into the Universe, which is a volume increase of a thousand times*."

The researchers used facilities at the Gingin Gravitational Research Centre to carefully heat *Advanced LIGO*'s mirrors in order to make tiny changes to its shape, thus increasing the detector's sensitivity to sense gravitational waves from approximately 200 million light-years away.

In 2005, David Blair's team predicted a problem known as 'parametric instability,' in which the laser light bounces off thermal vibrations in the mirrors, creating unwanted oscillations. The phenomenon was indeed discovered when *Advanced LIGO* was switched on in November 2014.

> "*It's a bit like the feedback whistles you get in a public-address system, so we've developed a whole suite of tools to control the instabilities in the detectors, and we'll be carrying on with that for the next few years*," according to David Blair.

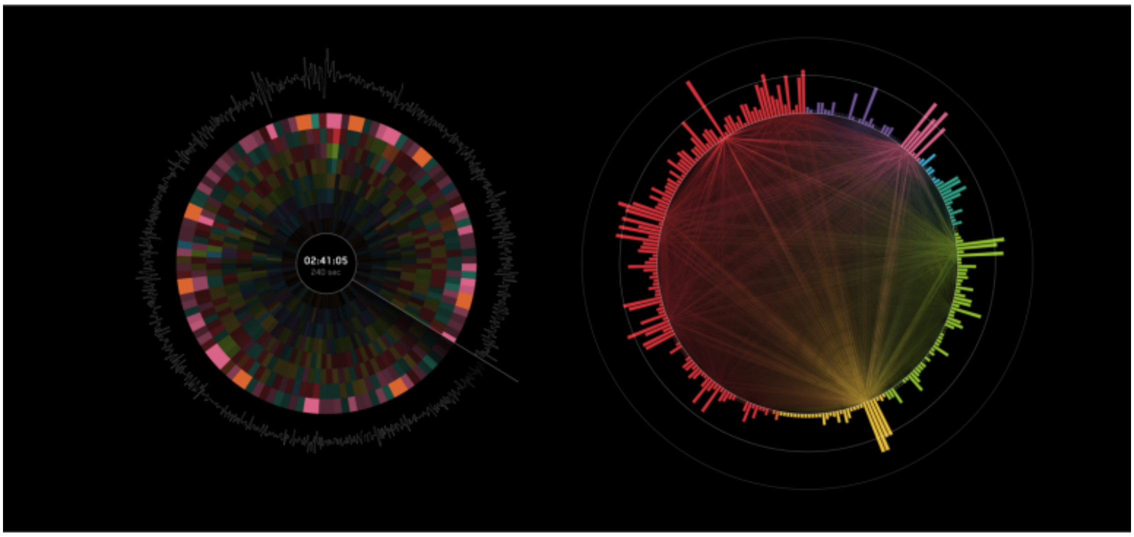
Another team at the same university, led by Professor Linqing Wen, has developed a method of picking out the signals in the detectors in real time, instead of the weeks or months it has taken in the past. The researchers have developed an electronic (software) 'ear' that will vastly improve the ongoing search for gravitational waves.

The software picks out and adds up the pattern of frequency changes in the same way the human brain takes signals from hair cells in the cochlea and creates pattern recognition for all the complex sounds we hear. The *LIGO* detectors operate in the frequency range between 10 Hertz and 3 kilo-Hertz. The vibrations concerned are a few parts in 10^{20}, which is about 100,000 times smaller than a proton. When detected, each signal will be like a 'chirp'—a rapidly rising tone a bit like an ambulance siren— and so it can be instantly identified and reported. If the same signal is identified in two or more detectors, spread across the continental USA, it will constitute evidence of a gravitational wave.

The idea for the 'ear' came from work done by Professor Yanbei Chen at Caltech, but was made into a working system by Linqing Wen and his team of three PhD students. David Blair says, "*The system is installed in a computer graphics card, so we have benefited from the enormous processing power developed for computer games.*"

To be effective, the sensitive instruments have to be shielded against nearby noises, from earthquakes anywhere on Earth to scientists riding bicycles on the *LIGO* site, strong winds, or the sounds of a passing truck. Only when these noises are neutralized can *LIGO* hope to detect the incredibly small vibration caused by gravitational waves from supernovae or colliding black holes coming from many light-years away. These waves carry vital information about their origin and about the nature of gravity itself, so their detection will create an entirely new form of astronomical study.

Students from the Data Visualization Summer Internship program—operated by faculty members from Caltech, the Jet Propulsion Laboratory, and the Art Center College of Design—were tasked with determining if a blip on the detector is a gravitational wave or instead just a signal from ordinary bumps and shakes. To do this, they developed colourful visualizations to represent how signals are related to known events, as shown in the graphic below:



The dial on the left marks the time at which each event was recorded; on the right, the height of the bars indicates the strength of each event, while the lines connecting the bars indicate how strongly these events are correlated to one another. Coupled with the existing analytical methods used by *LIGO*, this new way of looking at 'events' will help researchers identify and eliminate terrestrial noise sources, directly improving the astrophysical reach of the *LIGO* detectors—and making those elusive gravitational waves just that much easier to detect.

> "*The world will be watching as the Advanced LIGO detectors begin to take data, joined next year by Virgo and in the future by other detectors in an international network,*" says Gabriela González, professor of physics and astronomy at Louisiana State University (USA). "*The LIGO Science Collaboration is preparing for analyzing data from gravitational wave detectors thoroughly and promptly to advance astrophysics, expecting significant results in a few years.*"

> "*I have been involved in the experimental search for gravitational waves for many years and, on the basis of my personal experience, I can state that these days are crucial for the whole international community, which is pursuing the goal of the first direct detection*," says Virgo consortium spokesperson Fulvio Ricci, professor of experimental physics at Sapienza University of Rome (Italy). "*The beginning of the Advanced LIGO operation is the most important step in the process leading to the deployment of an international network of advanced detectors. Virgo and LIGO previously collected data and produced interesting physics results. Now the time is mature for a discovery and for writing a new chapter in fundamental physics and astronomy books.*"
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> "*It is inspiring to be part of a collaborative worldwide effort that has built the most sensitive detector ever, now 'listening' for the weakest signals in the Universe generated by its most violent events*," says David McClelland, professor of physics and head of the Department of Quantum Science at the Australian National University. "*It has been exciting to see LIGO mature as a research endeavour, and as each year has passed, the generation of new knowledge and technology has become more and more significant*," adds Aidan Byrne, chief executive officer of the Australian Research Council.

Indeed, these are exciting times for astrophysicists and fundamental physicists alike. We are on the verge of being able to peer into a largely ignored part of the electromagnetic spectrum, which promises to deliver a fundamental overhaul of the basic principles governing the physics of gravity.

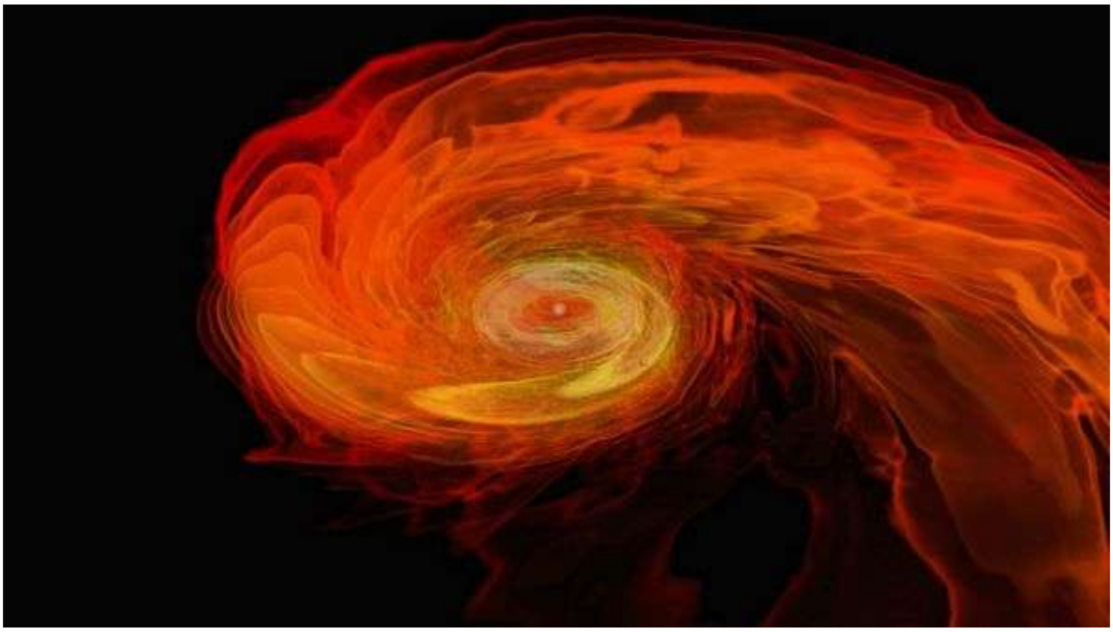

Figure 1: These waves carry vital information about their origin and about the nature of gravity itself, so their detection will create an entirely new form of astronomical study.

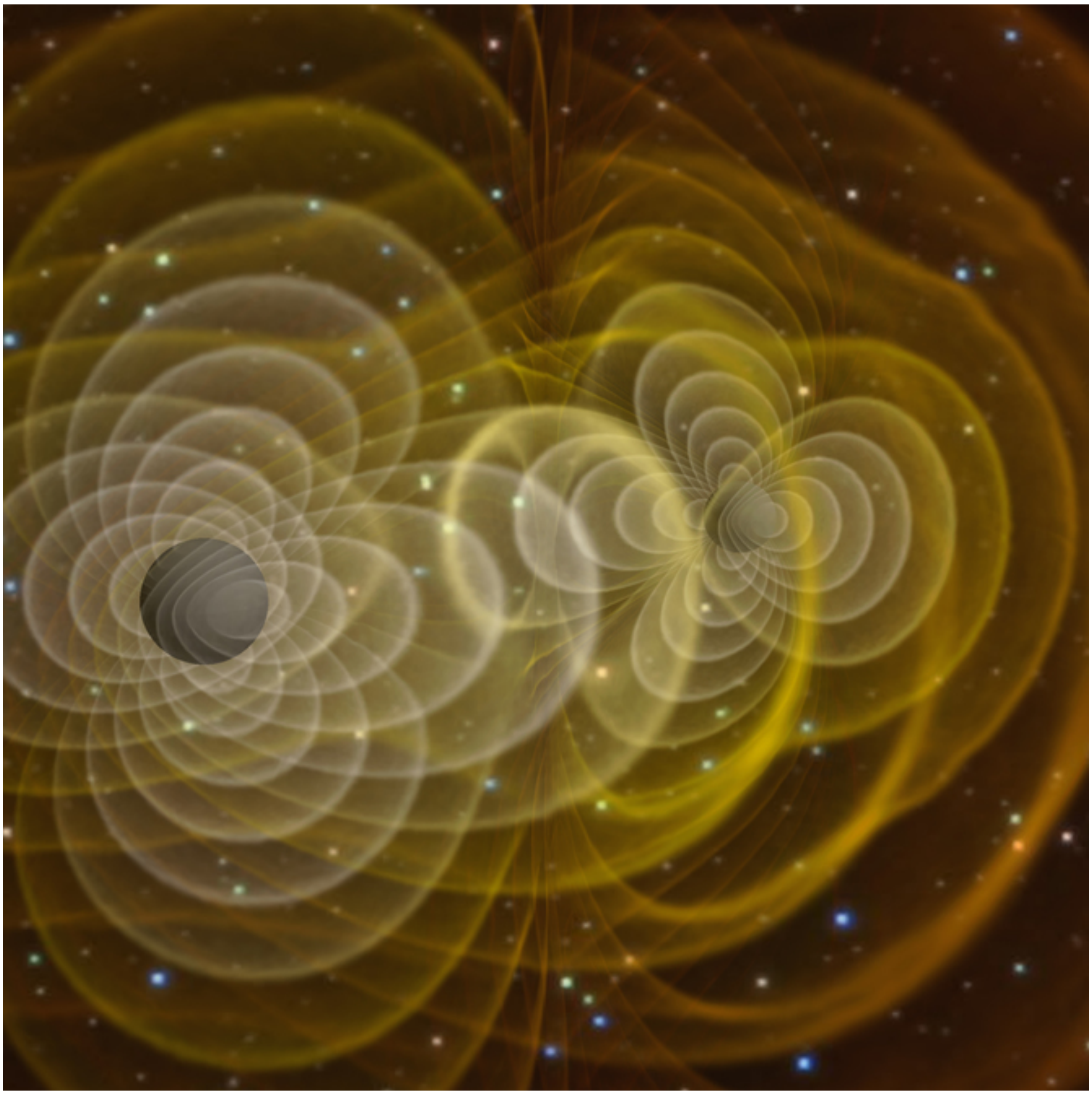

Figure 2: Elegant but elusive. Simulation of merging black holes showing gravitational waves. (*Credit: NASA/ESA/Wikimedia*)

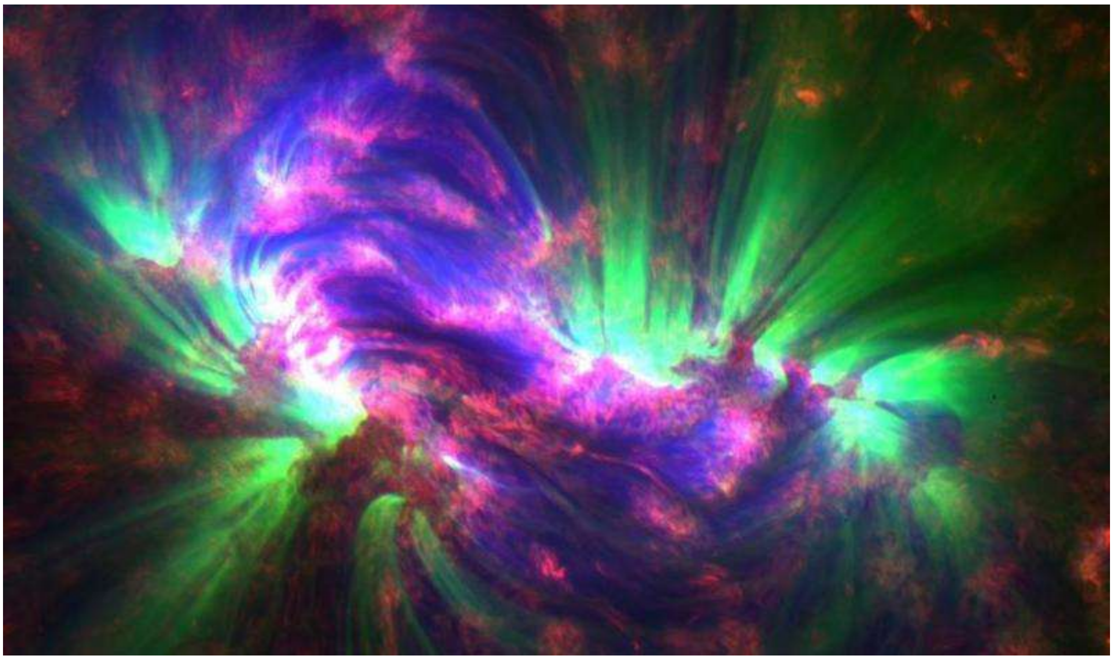

Figure 3: "*The initial detectors were sensitive enough to detect events up to a distance of about fifty million light years*," David Blair says. (*Credit: NASA Goddard Space Flight Center*)

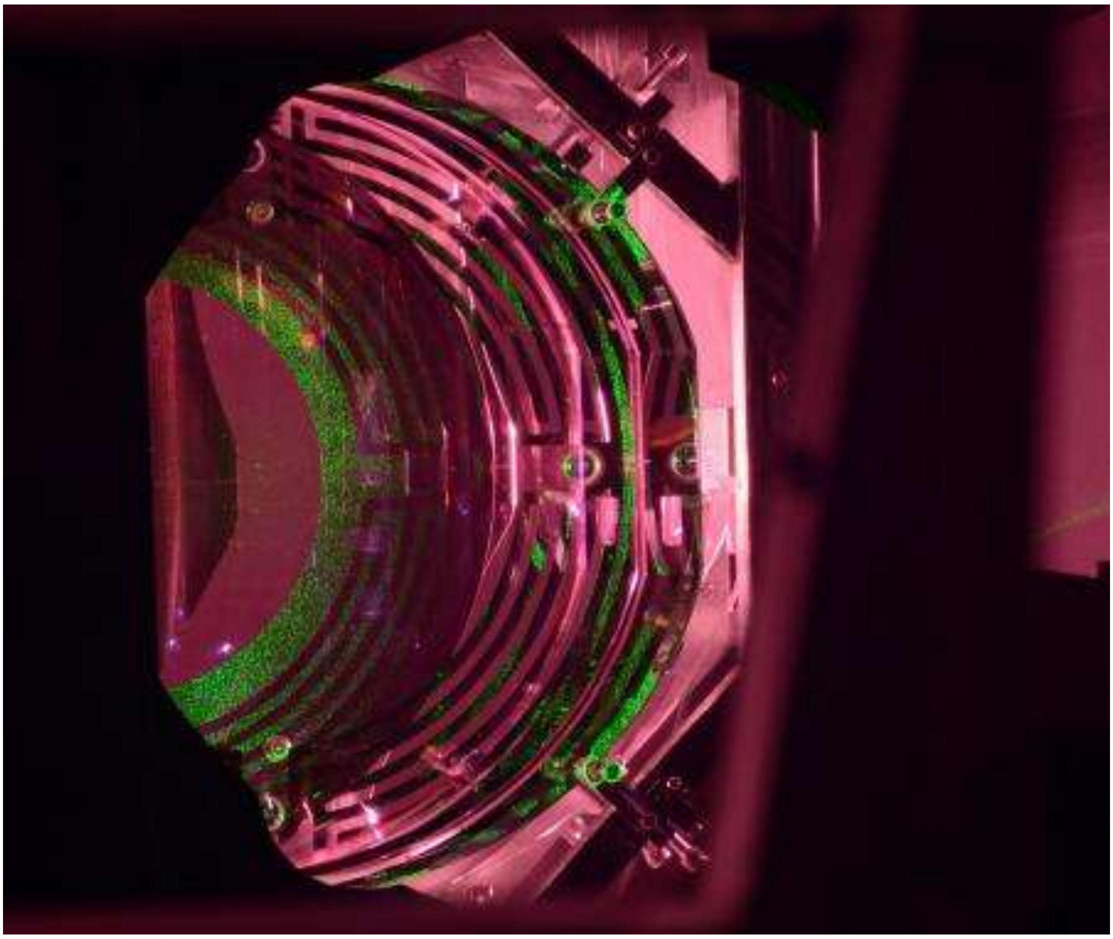

Figure 4: An *Advanced LIGO* optic that senses gravitational waves. About half of the 100 pound cylindrical optic can be seen. The green light comes from a laser used to help bring the system into an operational state. The maze-like pattern is part of the system to push, twist, and tilt the optic to hold the system in alignment. (*Credit: Caltech/MIT/LIGO Laboratory*)

Figure 5: Technicians in *Advanced LIGO*'s Hanford (Washington, USA) control room prepare for its first full-scale operational run. (*Credit: Caltech/MIT/LIGO Laboratory*)

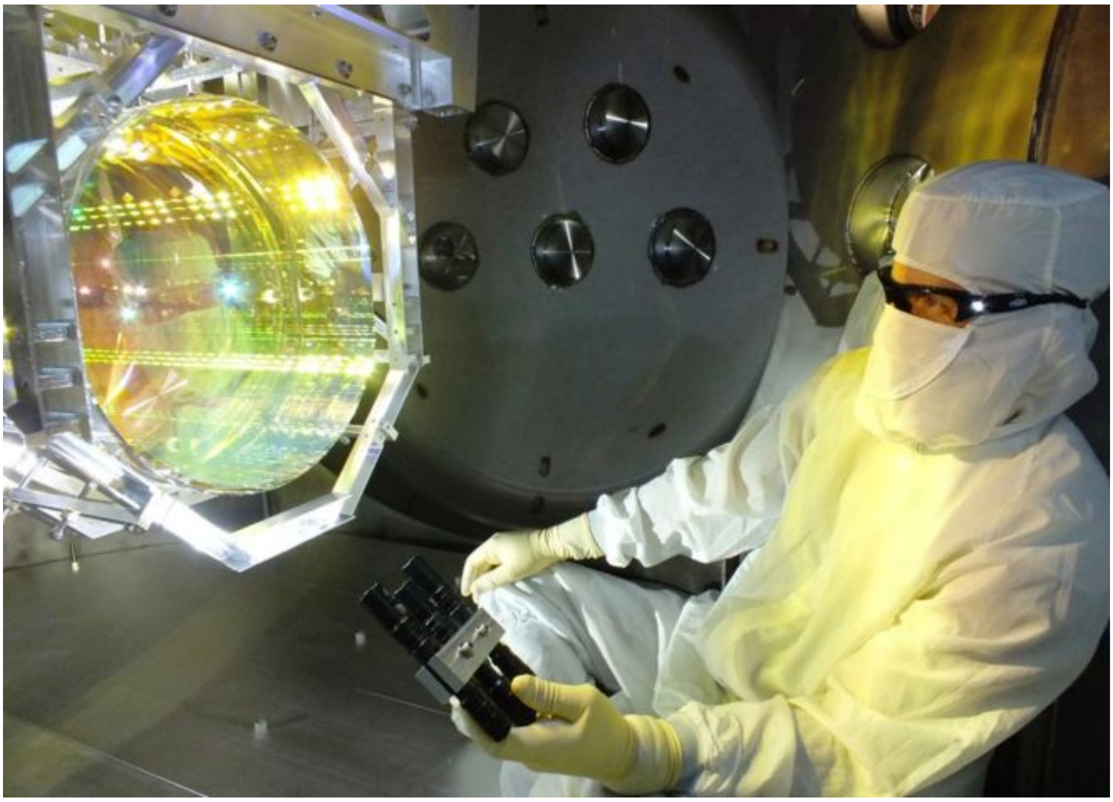

Figure 6: *Advanced LIGO* represents one of the most sensitive measuring systems ever devised. (*Credit: Advanced LIGO*)

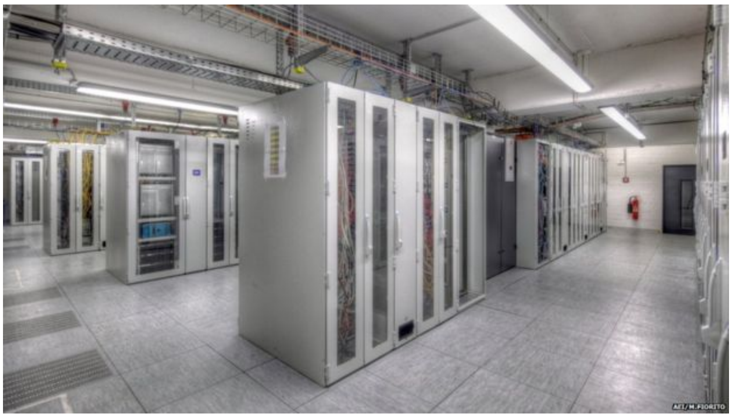

Figure 7: Supercomputers are being used to sift the data for gravitational wave signals (*Credit: AEI/M. Fiorito*)

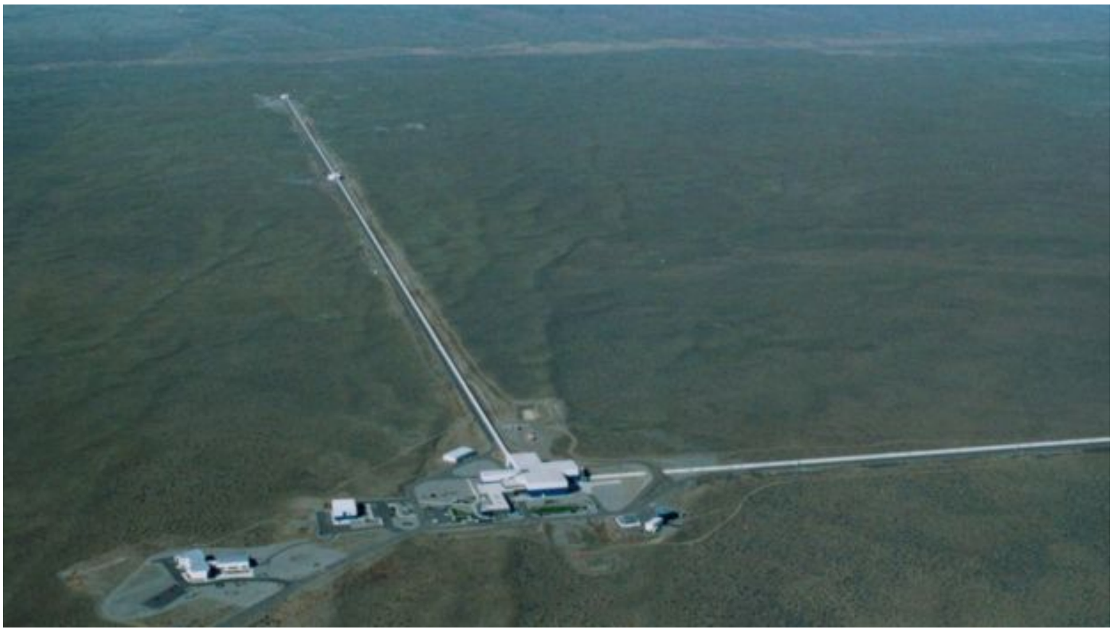

Figure 8: The LIGO labs have an L-shaped configuration (*Credit: Advanced LIGO*)

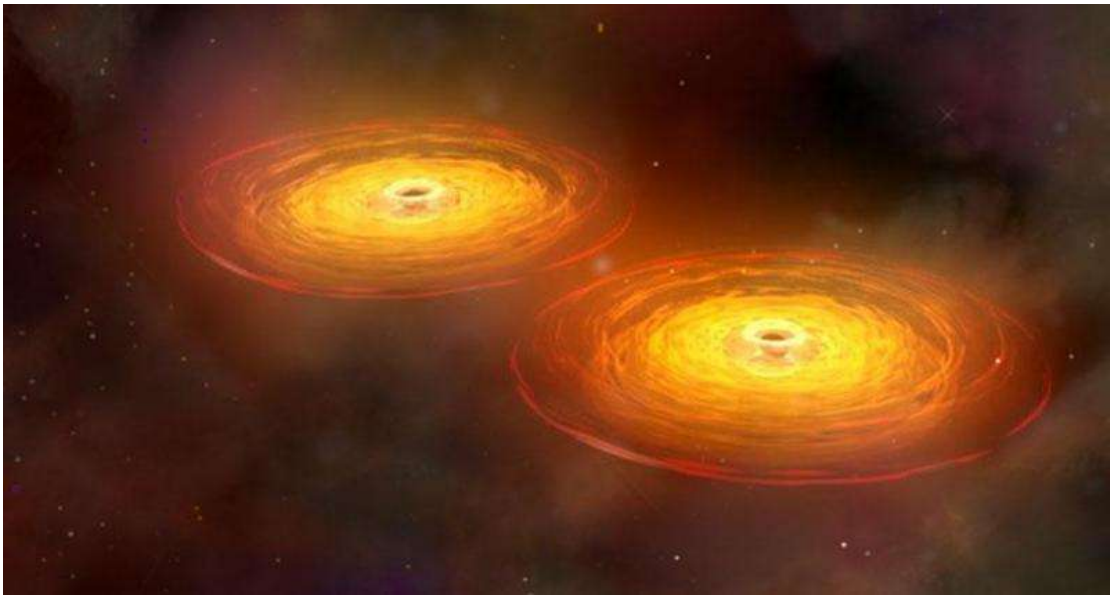

Figure 9: The coalescence of black holes (*Credit: NASA*)