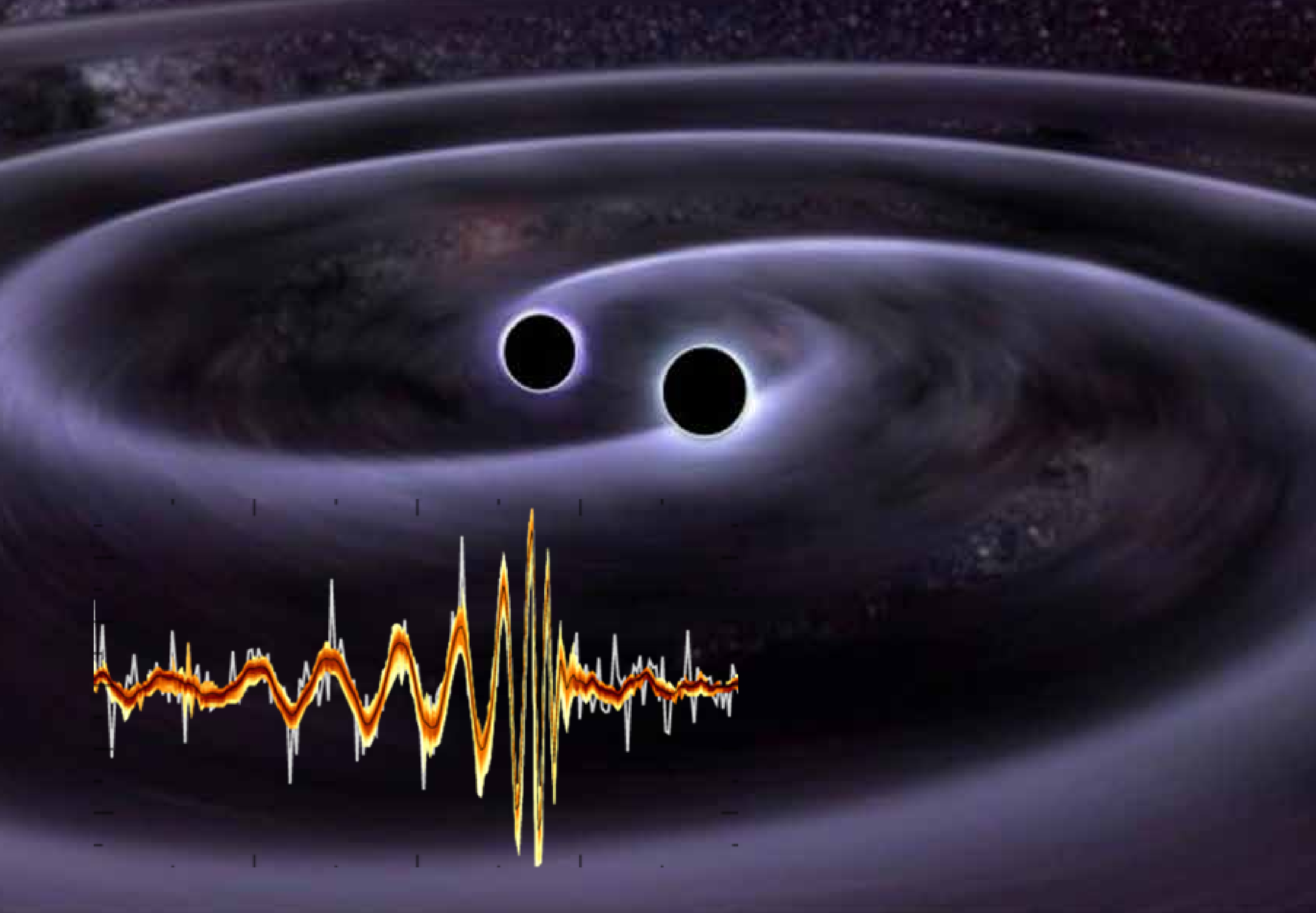
The Century Quest for Gravitational Waves

Gravitational Waves Discovered

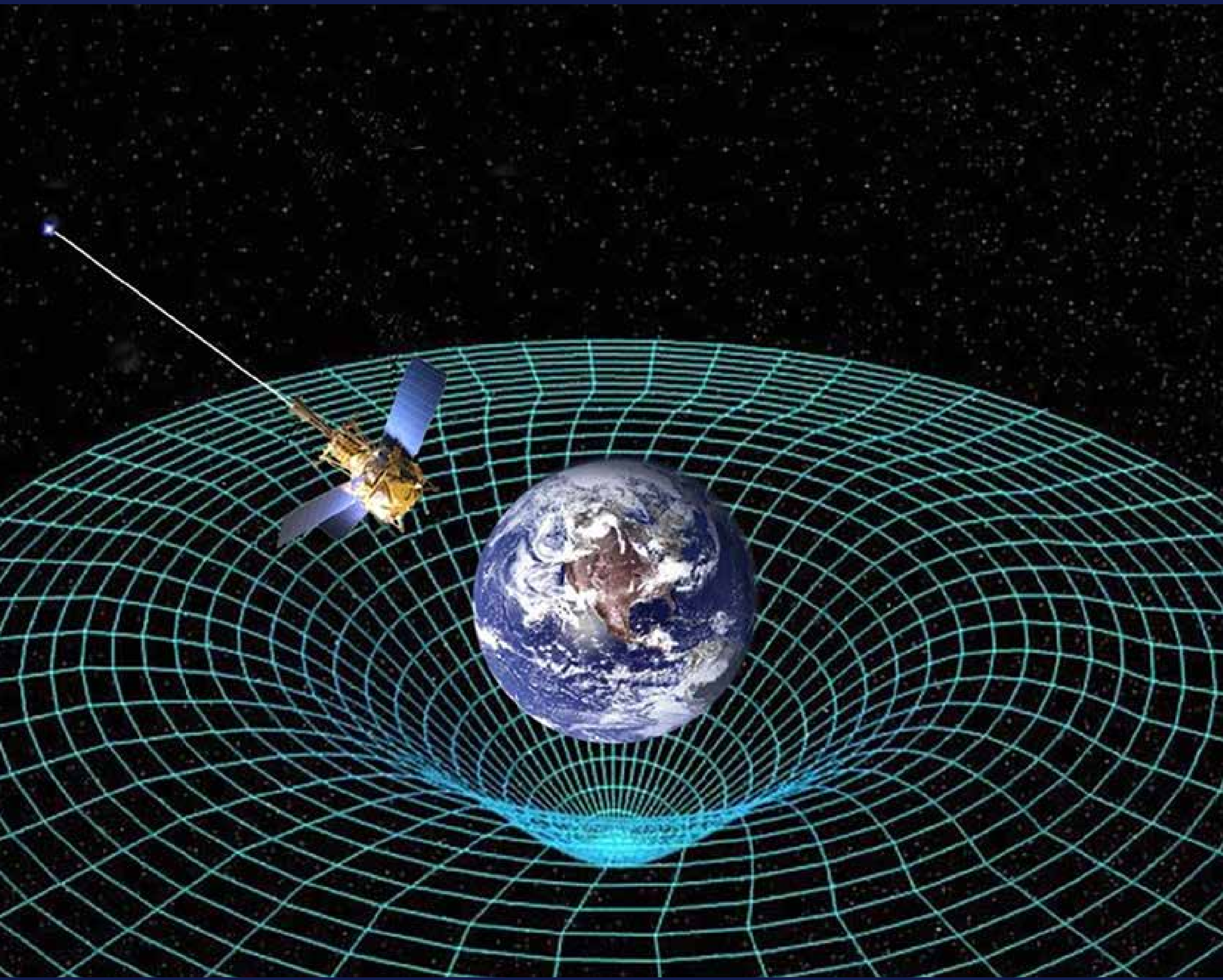


gravity DISCOVERY CENTRE

ACIGA

Australian Consortium for Interferometric Gravitational Astronomy

Curved space around the Earth



Curved space around the Earth as measured by NASA's Gravity Probe B spacecraft. Navigators in our mobile phones today must correct for the time warp created by the Earth's gravity.

Einstein's theory predicts not only that space can warp, but that it can carry ripples of gravitational waves.

Einstein's Revolutionary Theory

1916: Einstein Predicts Gravitational Waves

In 1915 Einstein published his revolutionary theory of general relativity that explained gravity as the curvature of space and time. A few months later in early 1916 Karl Schwarzschild found the first mathematical solution for Einstein's equations of general relativity that predicted *spacetime singularities* that today we know as black holes.

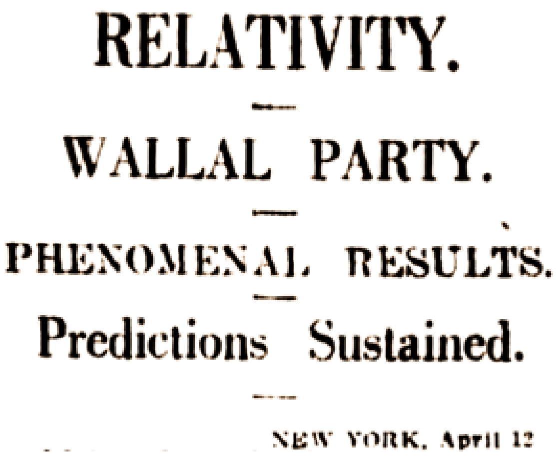
On June 22, 1916, Einstein published another paper showing that his theory predicted ripples in the curvature of spacetime which he called (in German) *gravitationswellen* or gravitational waves. He gave a simple formula for calculating energy emitted in gravitational waves and commented that *"in all thinkable cases"* the energy has *"a vanishing value"*. He thought gravitational waves were of academic interest only.

1922: Australia Tests Einstein

Einstein's theory of gravity was beautiful, but mathematically difficult, and difficult to test. Weak evidence for curved space around the Sun had been found in 1919, but many physicists were unconvinced.

In 1922 an eclipse of the Sun over Australia was a perfect opportunity to test Einstein's theory. Warped space near the Sun should skew the position of the stars.

Professor Alexander Ross, foundation professor of physics at the University of Western Australia instigated an international expedition to Wallal, a remote and desolate location south of Broome. Here the eclipse would last the longest. This heroic expedition proved that starlight was deflected exactly as predicted. Einstein passed the test.



RELATIVITY.

WALLAL PARTY.

PHENOMENAL RESULTS.

Predictions Sustained.

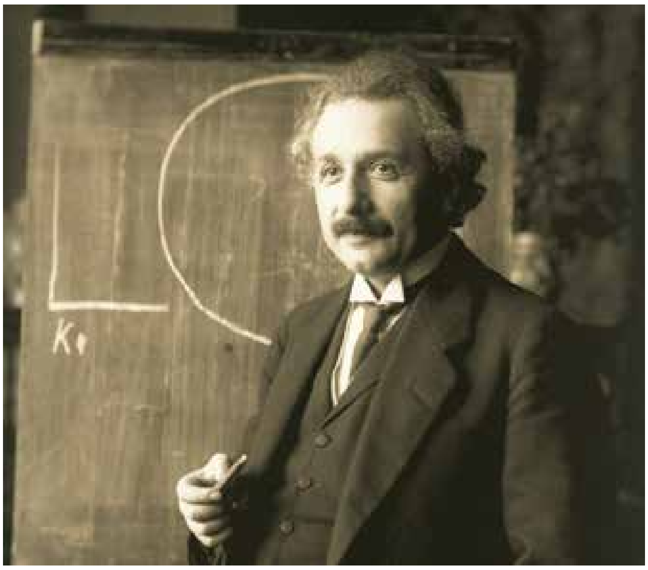
NEW YORK, April 12

Top: Wallal eclipse expedition loading their donkeys on 80 mile beach in Western Australia, 1922.

Bottom: A Lick Observatory telescope at Wallal, on the day of the eclipse.

From Confusion to Clarity

1936: Einstein's Doubts, Theoretical Confusion

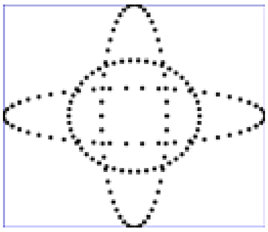


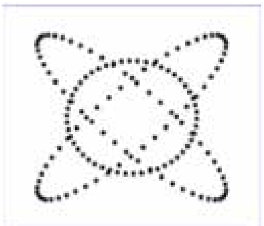
Twenty years later Einstein began to question some of the consequences of his earlier work. In 1905 he had proved that light consists of photons. The theory of quantum mechanics, that underpins almost all modern technology, including gravitational wave detectors, came out of this discovery.

Yet in 1935 (with Podolski and Rosen) he proved that quantum theory predicts weird quantum entanglement. It was an attempt to disprove quantum mechanics, but it actually served to prove the weirdness of the quantum world. Quantum entanglement later came to be harnessed by gravitational wave physicists.

Despite Einstein's elegant prediction of gravitational waves in 1916 and 1918 they were not properly understood. Eddington, a leading astronomer, said that they *"travelled at the speed of thought"*.

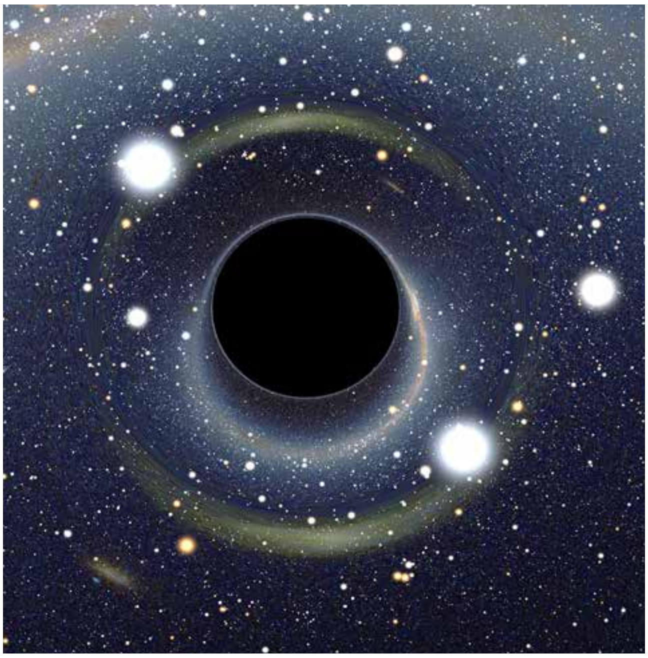
Astonishingly, in 1936, Einstein came up with a proof that gravitational waves do not exist! His paper, submitted to Physical Review, was criticised by referees and he angrily withdrew it. About the same time, with Rosen, he came up with an amazing concept originally called an Einstein-Rosen Bridge, but now known as a wormhole. While appearing to be theoretically possible it is not known if wormholes exist, but they do power many science fiction stories!



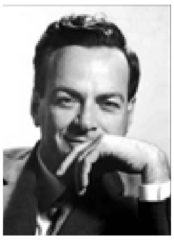


Gravitational waves are shape changing waves that alternately stretch in one direction and shrink in the other.

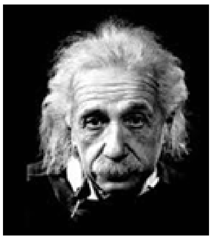
1957: Gravitational Waves Exist in Theory



Confusion about gravitational waves continued until the 1950s. Finally Richard Feynman, Herman Bondi and others settled the question of the theoretical reality of gravitational waves, proving Einstein's original conclusion. The waves of Einstein's theory are real waves that carry energy at the speed of light. They are waves of geometry. They ripple the shape of objects, leaving behind tiny sound vibrations. Because light and matter are affected differently by gravitational waves, the waves can also be detected using laser beams reflected off mirrors.



Richard Feynman



Possibilities and a False Start

1960-69: The First Gravitational Wave Detectors

If two black holes merge together to become a single black hole, they can emit a gravitational wave explosion vastly more powerful than any other known process in the universe.

Joseph Weber began to build the first gravitational wave detectors in the 1960s. He obtained huge blocks of aluminium, and monitored their tiny vibrations. His idea was to search to see if any cosmic sources of gravitational waves might exist. Given the *vanishing* smallness of gravitational waves this seemed like a pursuit of the impossible.

Joseph Weber with one of his resonant bar detectors

Impossible or Possible?

Einstein thought that gravitational waves could never be measured for two reasons. Firstly all the stars known to astronomers in 1916 had gravity far too weak to be able to make strong gravitational waves. Secondly the waves only cause tiny vibrations even if they carry enormous energy.

In 1939 Einstein published a paper claiming to prove that *"Schwarzschild singularities (i.e. black holes) do not exist in physical reality"*. Not believing in their existence, he never took the next step of proving, from his theory, that if two black holes merge together to become a single black hole, they can emit a gravitational wave explosion vastly more powerful than any other known process in the universe. This possibility was known to Weber, and provided a cause for optimism that helped sustain 45 years of searching.

A False Start and a New Beginning

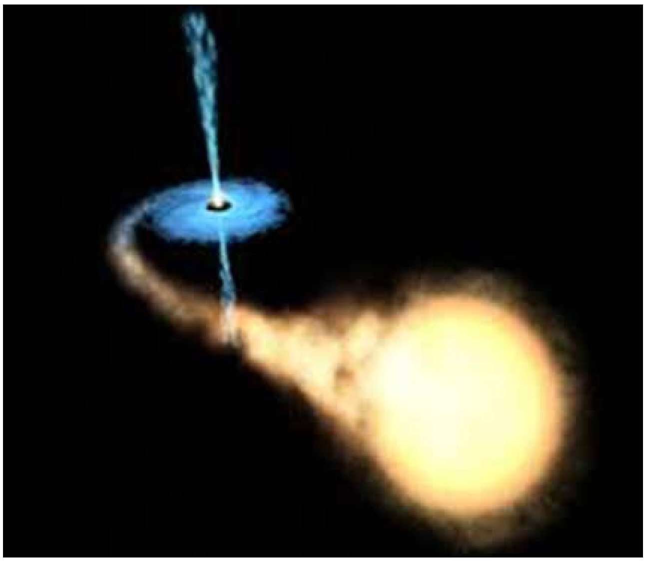
Weber pioneered gravitational wave detection technology, but made the mistake of *believing* he had detected waves. He knew that the birth of black holes could make enormous bursts of gravitational waves, but he lacked the skepticism necessary to find his mistakes. Others proved he was wrong.

Astronomers pointed out that if Weber was right, then all the stars in the universe would need to be turned into black holes in a very short time to account for all the gravitational waves energy.

Amongst the skeptical physicists a few of them took Weber's work as a challenge to design detectors a billion times more sensitive. This was the beginning of a 45 year struggle to detect Einstein's waves.

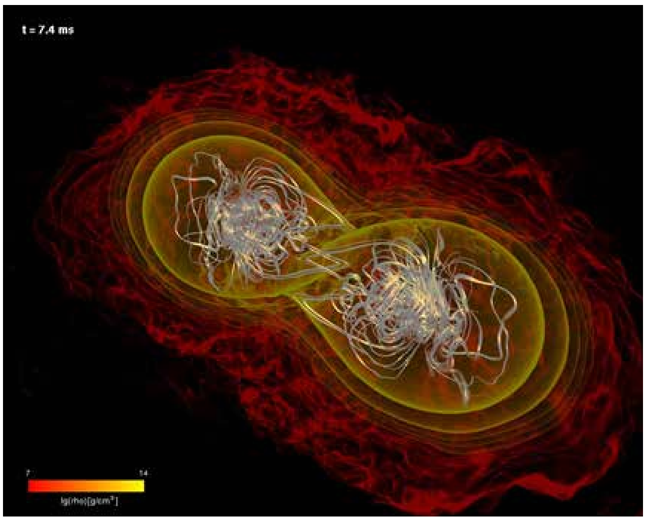
Gravitational Waves Exist

1962-74: Neutron Stars and Black Holes Discovered



An x-ray star consists of a normal star losing gas to a black hole or neutron star.

Artist impression of the binary pulsar.



The final coalescence of two neutron stars is thought to create a simultaneous burst of gamma rays and gravitational waves.

In the same period that Weber was developing his first detectors astronomers began to discover phenomena that could only be explained by the existence of enormously dense and compact objects – black holes and neutron stars.

Neutron stars are the last stable form of matter before collapse to a black hole. According to theory, neutron stars heavier than three times the mass of the Sun are unstable and must collapse to form black holes.

In 1962 the first x-ray telescopes on high altitude rockets found strange new stars emitting rapidly fluctuating x-rays. It was soon realised that we were seeing gas from normal stars falling into neutron stars.

In 1971 a very bright x-ray emitting star was discovered called Cygnus X-1. This system is thought to consist of a huge star orbiting a black hole about 15 times as massive as the Sun. The black hole is thought to exist but cannot be seen directly.

In 1974 a pair of neutron stars orbiting each other three times every day was discovered by radio astronomers Russell Hulse and Joseph Taylor. This famous system called the *binary pulsar* was soon found to be *spiralling* slowly together. Its loss of energy exactly matched Einstein's prediction for emission of energy via gravitational waves. The discoverers won the Nobel Prize in 1993.

Joseph Taylor

Russell Hulse

Australia's Involvement

1995: Australia Joins the Laser Teams

In 1995 physicists at Australian National University, University of Western Australia, University of Adelaide and CSIRO set up a national consortium to develop laser interferometer technology for a future Australian detector. An Australian detector is needed to allow triangulation across the planet for pinpointing the direction of incoming waves.

The Australian team began collaborating with huge projects planned for the USA and Europe: The Laser Interferometer Gravitational Observatory (LIGO) detectors in the USA, and the Virgo detector in Italy. Later Australia became a partner in the *Advanced LIGO* project.

The Australian teams focused on technology for the advanced detectors that would be needed to detect frequent signals. At Gingin, innovative vibration isolation systems gave the world's best performance. ANU provided a length stabilisation system and developed technology that uses quantum entanglement of the photons to reduce the noise in the laser light. At University of Adelaide, sensors were created to allow errors in laser light beams to be corrected at the level of 1/20,000th of the wavelength. At UWA the team predicted that in Advanced LIGO the powerful laser light would create sounds in the mirrors, which would cause the detectors to become unstable. The team went on to develop methods for controlling the instabilities once they occurred. These predictions were proved by Advanced LIGO in 2014, and UWA has since then been closely involved in stabilising the new detectors.

All the Australian technologies made critical contributions to the discovery of gravitational waves.

1999: Gingin Site for Gravitational Astronomy

In 1999 the Western Australian Government provided a site for a future large scale detector, the Australian International Gravitational Observatory. The Australian Consortium developed the Gingin Research Centre on this site to develop technology for Advanced LIGO. The WA Government proposed and supported the development of the Gravity Discovery Centre as a centre for promoting science education and for involving the public in the discovery of the new spectrum of gravitational waves. Public and corporate donations allowed the Gravity Discovery Centre Foundation to create its exciting and innovative centre. With UWA, the centre has tested a new high school physics curriculum called *Einstein First.*

The Gingin Gravity Precinct showing the high optical power interferometer (far side) and the Gravity Discovery Centre.

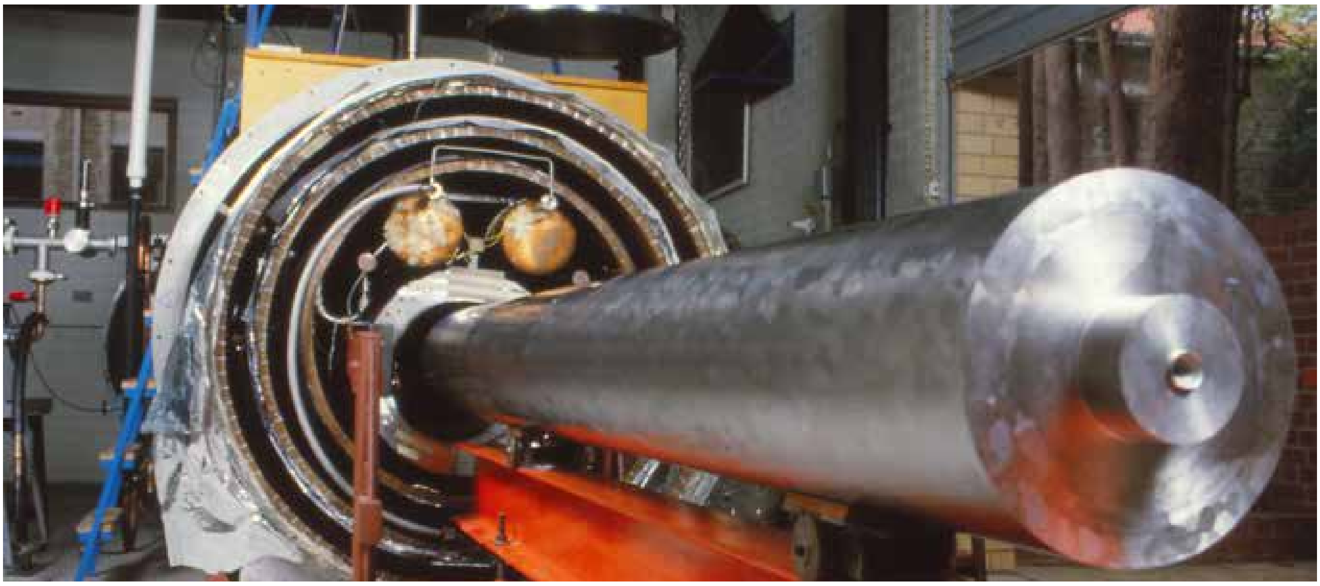
The leaning tower of Gingin at the Gravity Discovery Centre.

The Tower is used for school gravity experiments.

The Advanced LIGO detectors: LIGO Livingston in Louisiana (above) and LIGO Hanford in Washington State.

The Quest for Sensitivity Begins

1970-2000: Competing Technologies



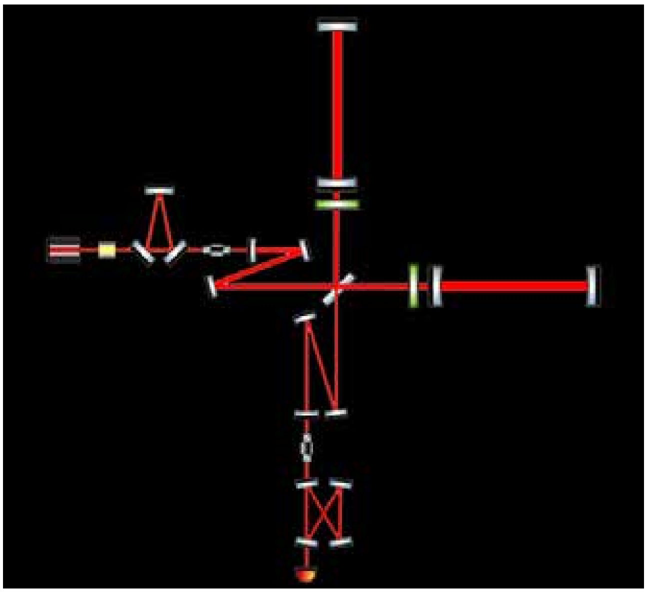
The UWA resonant bar detector NIOBE, made from the world largest ingot of the superconducting metal niobium, now on display at the Gravity Discovery Centre.

In the 20 years after Weber's spurious announcement, physicists set about designing detectors for gravitational astronomy. They needed to make sensors a billion times better than Weber's. They had to be able to detect vibrations a billion times smaller than the size of an atom. These unimaginably small vibrations had to be detected in the presence of natural vibrations one billion times bigger.

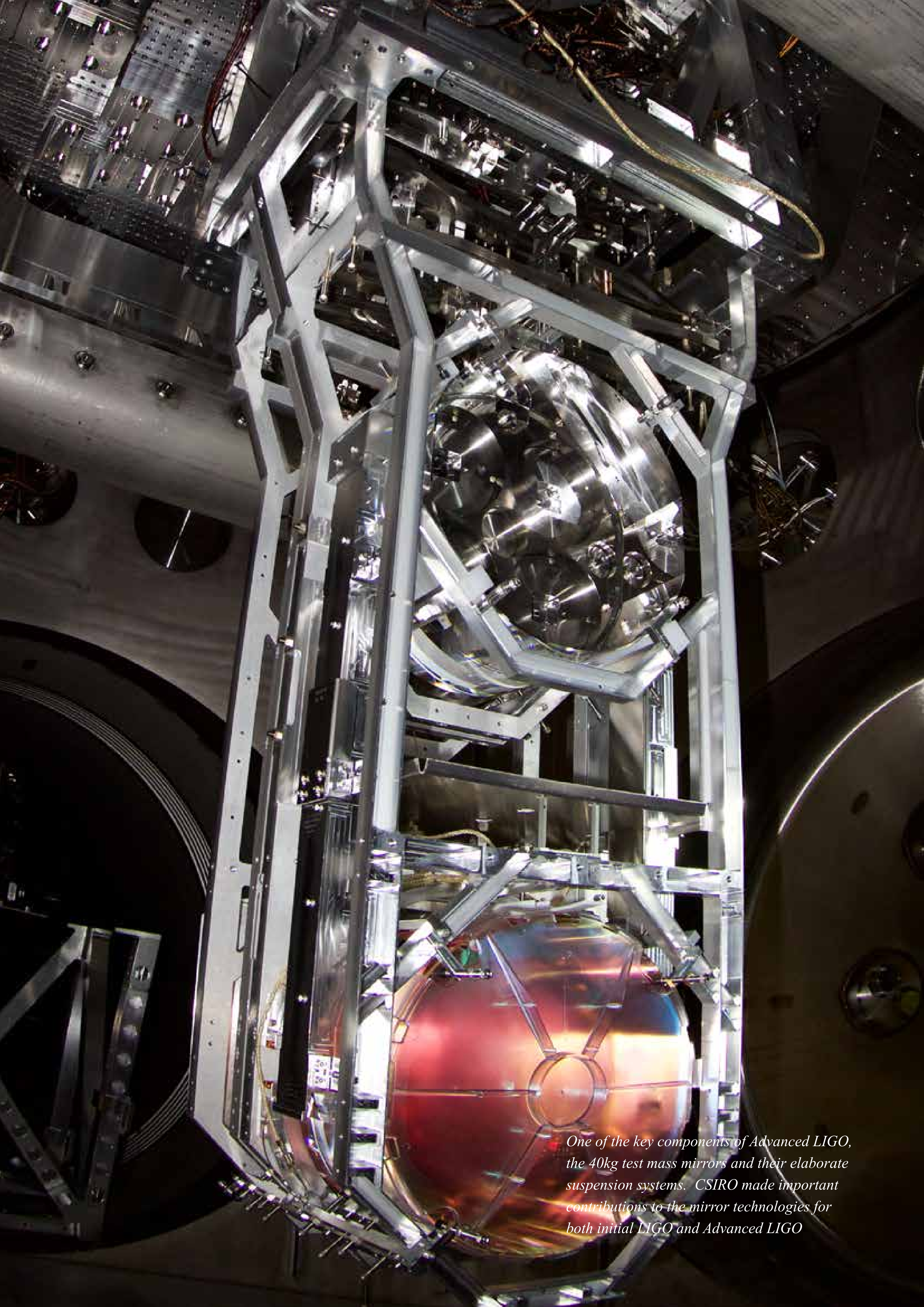
One group of physicists, mainly at Stanford University, Louisiana State University, The University of Rome and The University of Western Australia developed cryogenic resonant bars: these were huge metal bars cooled to cryogenic temperatures. Gravitational waves would induce tiny vibrations and superconductors were used to create the most sensitive vibration sensors ever created.

The second group began to develop systems called laser interferometers, in which lasers are bounced between carefully suspended mirrors at right angles to each other. The mirrors follow the vibrations of space and the laser measures their vibrations. The advantage of this technology was that you could increase sensitivity by putting the mirrors kilometres apart. The disadvantage was that the devices need to be kilometres in size, and they are extremely complicated.

Both groups faced enormous challenges, and multiple setbacks. All were exploring the unknown, creating brand new technologies, and discarding many that failed. At UWA the sapphire clock was invented to provide the pure microwave signals needed to measure the tiny vibrations in a huge superconducting bar. In Glasgow the recycling of laser light was invented to multiply the sensitivity of laser measurements. In France and Germany supermirror optical cavities and super stable lasers were created to allow high sensitivity laser measurements. Decade by decade detectors improved by leaps and bounds, about 1000-fold every 10 years.



Simplified optical layout of a laser interferometer gravitational wave detector



One of the key components of Advanced LIGO, the 40kg test mass mirrors and their elaborate suspension systems. CSIRO made important contributions to the mirror technologies for both initial LIGO and Advanced LIGO

25 Years, Wonderful Technology But No Detections

2000: No Detections with Cryogenic Bars

The cryogenic bar Auriga at Legnaro, Italy

Five cryogenic bar detectors around the world (including NIOBE at UWA) reached high sensitivity in the 1990's, and monitored the Milky Way for several years, searching for simultaneous signals in all the detectors. No signals were found.

The lack of signals proved that black hole births are rather rare in our Milky Way galaxy. Unfortunately the bars did not have enough sensitivity to detect signals from more distant galaxies. It needed the much bigger laser detectors for this.

2006: Huge Laser Interferometers reach initial design sensitivity

Small optical systems suspended inside a LIGO vacuum chamber.

The first step for the laser detectors was to prove that the enormously complicated instruments could be built on kilometre scales and could operate at predicted sensitivity. Two 4km LIGO detectors were built in the USA, and the 3km Virgo detector was built in Italy.

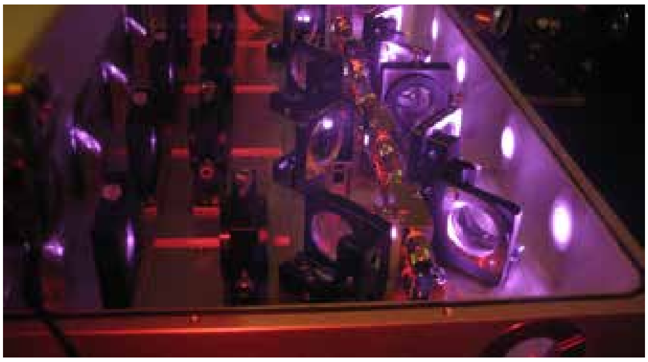
It took many years to learn how to drive the detectors. Hundreds of mirrors and laser beams had to be controlled with nanometer precision. Eventually after years of effort by hundreds of physicists, full sensitivity was achieved in 2006.

At this sensitivity they could in principle see neutron stars coalescing at about 50 million light years distance, far beyond our Milky Way galaxy. But to see frequent signals, they needed to be able to pick up events at least three times further away.

The Virgo 3km interferometer in Italy.

Advanced LIGO, Aiming for Detection

Advanced LIGO and Australia's Role



The pre-stabilised laser made by the German partners provides frequency and intensity stabilised light for the Advanced LIGO detectors.

A system developed at ANU being installed at Advanced LIGO.

A LIGO control room.

The next step in the quest for gravitational waves was Advanced LIGO. This project was designed to achieve a ten-fold increase in sensitivity compared with initial LIGO. Led by California Institute of Technology and Massachusetts Institute of Technology, the project was a partnership between USA, Britain, Germany and Australia.

For Advanced LIGO, Australia provided certain key components and technologies. These included technology for measuring distortions in the light waves passing through the mirrors, technology for aligning the output beams, technology for preventing the detectors from becoming unstable, and supercomputer-based data analysis systems to dig signals out of the noise.

Advanced LIGO is a collaboration of almost 1000 physicists across the world. Every university and research institute provided state of the art know-how, expertise and equipment. The final result was the two 4km × 4km laser interferometers and several data processing centres.

More than 60 research organisations participate in the LIGO Scientific Collaborations (see the logos on the back page). The search for gravitational waves has cost more than $1billion. The development of know-how, spin-off technologies and training is certain to provide benefits that vastly outweigh the costs.

Advanced LIGO is a collaboration of almost 1000 physicists across the world.

Detetected at Last

14 September 2015: a Date to Remember

On 14 September 2015, Advanced LIGO was being readied to begin long term observations. Australian students Carl Blair from The University of Western Australia and Eleanor King from The University of Adelaide were among the small teams operating the detectors. In the early hours of the morning a signal came in almost simultaneously at both LIGO observatories 3002km apart.

When the wave passed through Australia it would have made the distance between Perth and Sydney oscillate by the diameter of an atomic nucleus.

The signal at first seemed too good to be true and for many months mundane explanations were sought. Could it be hacking? Could it be lightning? Could it be a computer glitch or accidental vibrations?

All the mundane explanations were ruled out.

The waveforms from coalescing binary black holes are highly specific. They rise in frequency and rise in amplitude. The signal size tells the distance of the source, the frequencies tell the masses of the two black holes and the final ringing tells the spin and mass of the final black hole.

The incoming signals fitted perfectly to gravitational waveforms calculated by supercomputers.

We are now confident.

The Signal

The first detected gravitational wave signal came from a pair of black holes spiralling together and merging. Their masses, 29 and 36 times the mass of the Sun, tell us that they were born from enormous stars made from the primordial gases hydrogen and helium when the universe was very young.

The gravitational wave explosion detected in September 2015 was the most energetic event ever observed by astronomy – more than three solar masses of pure gravitational energy were emitted in less than 1/10th of a second.

When first detected, the black holes were orbiting each other 25 times per second. As they got closer, the orbit sped up to 100 times per second. At this point they merged into a single vibrating black hole.

The new black hole is spinning 100 times per second. Its mass is 62 times the mass of the Sun. Its rotational energy alone has a mass four times the mass of the Sun. Its surface area is about four times the area of Tasmania.

Most likely the two black holes had been spiralling towards each other for billions of years. Then just over one billion years ago they finally merged. The waves rippled towards us for a billion years, expanding like ripples in a pond, to pass through the solar system on 14 September 2015.

From Speculation to Reality

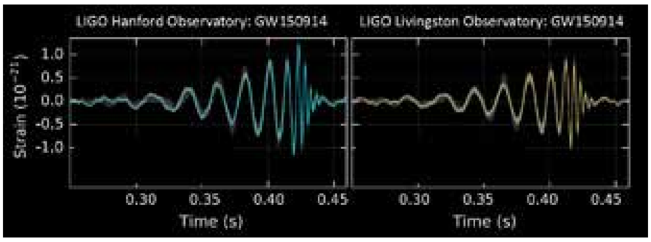
For many years black holes have been needed to explain many astronomical phenomena, but they have never been directly observed. With gravitational wave detection we have directly observed the vibrating event horizon of a black hole.

Suddenly we know that the black holes of Einstein's theory exist and are out there in the universe.

Suddenly we know that gravitational waves interact with detectors the way physicists had deduced. The theory of detection is correct.

Suddenly we know that space is populated by black holes, some in the form of binary pairs slowly spiralling together, many more in the form of lone black holes that never formed into binaries, and other lone black holes formed in past mergers.

Binary black holes are time capsules from our stellar ancestors. They are a direct link to the first stars in the universe. Suddenly the earliest ancestors of our Sun are revealed.



Gravitational wave signals detected at the two LIGO sites 3002km apart. The wave arrived at the Hanford detector 6.9 milliseconds after it arrived at Livingston.

The Future of Gravitational Astronomy

Gravitational Wave Detection and the Future

Gravitational waves are akin to sound waves that travel through empty space at the speed of light. The first detections mark the birth of gravitational wave astronomy. The first discovery marked the start of our exploration of a brand new spectrum.

The universe has spoken!

Humanity can now begin to listen to the sounds of the Universe.

The first detection marks the beginning of the exploration of the gravitational wave spectrum. We will be able to answer many questions:

- How many black holes are there in the universe?
- Where are the black holes located: in the cores of galaxies, in globular clusters or drifting through intergalactic space?
- How much of the baryonic matter and how much of the dark matter in the universe has been lost into black holes?
- Does the total surface area of black holes in the universe always increase, as predicted by Stephen Hawking and Jacob Beckenstein?
- Is the singularity inside a black hole always hidden as proposed by Roger Penrose, or could it emerge at the moment that two black holes turn into one?
- How often do neutron stars coalesce? Are neutron star mergers the origin of gamma ray bursts?
- Can we measure dark energy with gravitational waves? What happens when dark matter falls into black holes?

As detectors improve there are many more sources of gravitational waves to be discovered, from neutron star quakes to signals from the big bang in which the universe began.

Gravitational wave detectors have intrinsically poor directional sensitivity, but excellent distance sensitivity (for coalescence signals). Signals from binary black holes encode their distance as well as their masses and spin rates.

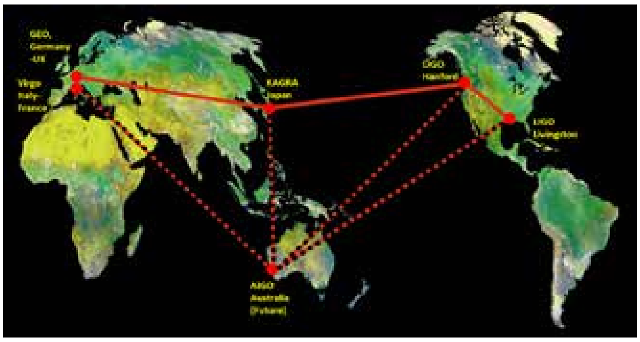
To determine the direction of gravitational wave sources many widely spaced detectors are required. There is a special need for an Australian detector. This would bring a dramatic improvement to the global array capability.

With a southern hemisphere detector we will be able to map the signals, identify the galaxies or galaxy clusters they came from, and tell radio, optical and x-ray telescopes where to look. This is essential if we are to understand where the black holes are located and where they came from, and to find answers to many new questions.

The addition of a southern hemisphere detector improves the sensitivity of the world array, roughly doubling the number of accessible sources.

Accidental false positives from interference are suppressed by the power of the number of detectors in the array. The addition of an Australian detector reduces such interference to a negligible level.

Thus Australia has an important future role in gravitational astronomy. We have 40 years of experience, innovations and technologies, and a dynamic young team that was part of the first discovery, who are ready to build Australia's future in gravitational astronomy.



The world network of gravitational wave detectors is currently confined to the northern hemisphere. A detector in Australia will greatly improve the network, allowing the direction of gravitational wave sources to be determined.

Applications and Benefits from Detector Technologies

A Pinnacle of Technological Innovation

To build gravitational wave detectors we had to learn how to make quantum measurements on masses ranging in size from tonnes to micrograms. We had to learn how to make mirrors precise to atomic dimensions, and able to reflect light with unsurpassed perfection. We had to learn how to suppress the natural vibrations of atoms caused by heat, and vibrations caused by earthquakes, cars and walking people. We had to learn how to cut out vibrations one billion times bigger than our signals. We had to learn how to program supercomputers to mimic the human ability of picking complex sounds out of background noise, and learn how to prevent the detectors from creating spurious noises from the enormous power of the laser light that drives them.

Australian scientists played a pivotal role in all these breakthroughs. Fifty six Australian scientists contributed to the first discovery.

Today we have exposed the tip of the iceberg. In the next decades the dark side of the universe will be revealed by gravitational wave astronomy.

Gravitational wave detectors are the first gravity radios. By eliminating most ordinary sources of noise and interference, we have created pure quantum instruments.

Gravitational wave detectors are the most sensitive instrument ever created. The detectors are quantum objects, like single atoms, and one wrong photon of laser light can cause a disturbance.

Physicists had to learn how to obtain exquisite control of laser light to enable delicately suspended mirrors to be measured without disturbance.

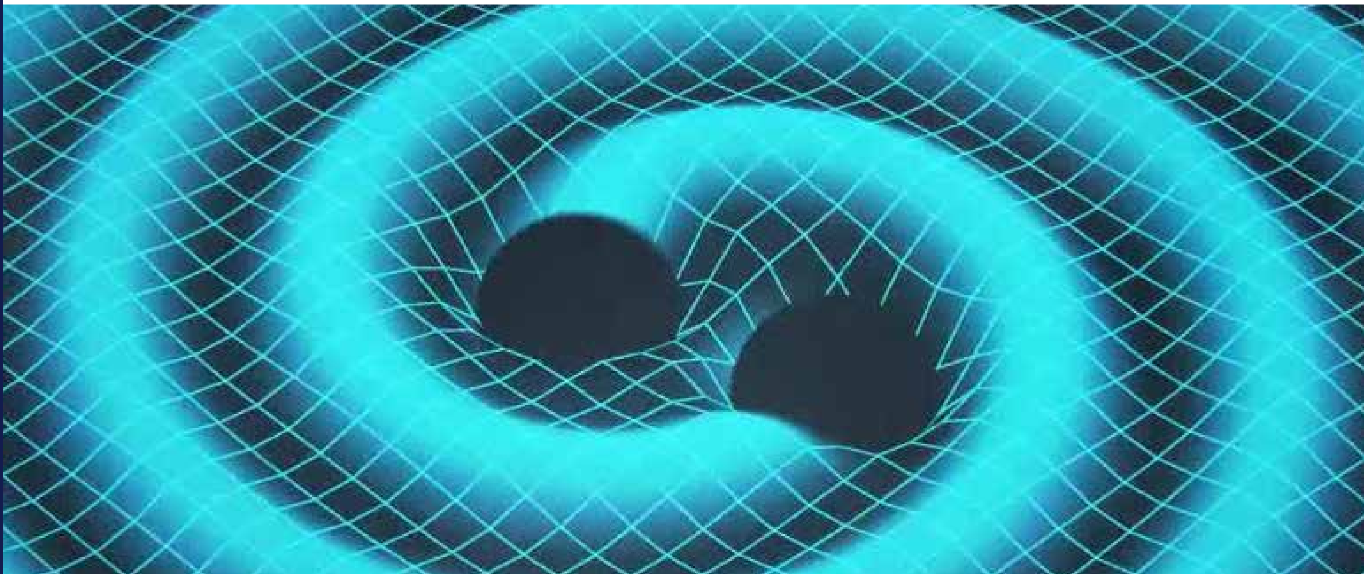
Enormous innovations were needed to get this far. Many more innovations are in the pipeline. They are being developed so that the detectors can take another ten-fold leap in sensitivity over the next decade.

Gravitational wave technology is already being applied to "useful things" like mineral exploration, time standards, quantum computing, precision sensors, ultrasensitive radars and pollution monitors.

Across the Australian community industry-funded projects are underway to exploit the innovations that were driven by the need to discover gravitational waves.

Heinrich Hertz had no idea of the revolution he began when he created the first radio transmission in 1886. When he was asked about the use of his discovery, his reply was "of no possible use whatsoever".

Where will gravitational waves take us? Only time will tell.



LIGO

LIGO Scientific Collaboration

LSC

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Andrews University
Washington State University
California State University Fullerton
The University of Alabama in Huntsville
Sonoma State University
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Montclair State University
University of Glasgow
Australian National University
Whitman College
American University Washington DC
University of the West of Scotland UWS
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