The difficult birth of gravitational wave astronomy

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What?

This chapter traces the sequence of discoveries which led to our current best theory of space, time, and matter. The presentation starts with special relativity and the foundations of general relativity and discusses some of the key tests of the theory before focusing on the century-long quest to detect one of the most spectacular predictions of Einstein – gravitational waves.

For whom?

Readers who want to understand the historical development of relativity, and the key ideas that led to gravitational wave astronomy which is allowing us to listen to the gravitational sounds of the universe.

Introduction

This chapter tells the story of Albert Einstein’s theory of relativity, the “greatest feat of human thinking about nature, the most amazing combination of philosophical penetration, physical intuition, and mathematical skill” as physicist Max Born (1968) described Einstein’s achievement. Our story begins in 1905, the miraculous year in which Einstein established the foundations of a new scientific worldview. Our story ends more than a century later. This story encompasses the struggle with ideas that preceded Einstein’s theory, the difficulties in understanding the theory, the experiments that validated its predictions, and the heroic struggle that culminated in the detection of gravitational waves in 2015. This quest has given us a new reality; a reality in which space is not only curved but rippling unpredictably; a reality in which we can listen to the gravitational sounds of the cosmos, hear black holes colliding, and catch neutron stars coalescing. Gravitational waves have opened a new frontier of our knowledge and mark the beginning of a new astronomy in which we explore the universe with gravitational waves.

Special relativity and Einstein's happiest thought

In 1905, the same year that he predicted photons, Einstein published his special theory of relativity. Special relativity is a theory of the structure of space and time, and its development took place in the context of intense investigations by some of the most brilliant mathematicians and physicists of the late 19th and early 20th century, among them Henri Poincaré, Hendrik Lorentz, and Hermann Minkowski. Shortly before his death, Einstein said, "*There is no doubt that the special theory of relativity, if we regard its development in retrospect, was ripe for discovery in 1905.*" (Einstein as cited in Born, 1968) Indeed, the formulation of special relativity is a direct consequence of Maxwell's theory of electromagnetism. Maxwell's equations describe the propagation of electromagnetic waves. These equations predict that light propagates at a constant speed (c) in vacuum.

Einstein took the constant speed of light as the first postulate of special relativity and combined it with a second postulate, the principle of relativity. According to this principle, the laws of physics are the same for all inertial observers. Albeit radical, Einstein embraced the implications of his two postulates: absolute motion, absolute space, and absolute time do not have any physical significance; it depends on the observer and the choice of coordinates whether or not two events occur at the same time.

Einstein's theory became quickly accepted, especially after a series of lectures on the mathematical formalism of special relativity that Minkowski gave in 1908. Minkowski (1909) famously proclaimed "The views of space and time which I want to present to you arose from the domain of experimental physics, and therein lies their strength. Their tendency is radical. From now onwards space by itself and time by itself will recede completely to become mere shadows and only a type of union of the two will still stand independently on its own."

Despite its success, Einstein's special theory of relativity did not include the physics of gravity. It was clear that Newton's law of gravity was in direct conflict with special relativity. According to Newton, the force of gravity acts instantaneously; according to Einstein, there exists a universal speed limit in our universe. Nothing can move faster than light, not even gravity! Besides, there was experimental evidence that Newton's force model might be incomplete. In the 19th century, astronomers observed tiny deviations in the orbit of planet

Mercury around the Sun that they could not explain. Despite many attempts, astronomers were not able to match observational data to Newton's theory.

In 1907 Einstein had his "happiest thought": "I was sitting in a chair at the patent office in Bern, when all of a sudden, a thought occurred to me: If a person falls freely, he will not feel his own weight. I was startled. This simple thought made a deep impression on me. It impelled me toward a theory of gravitation." (Einstein as cited in Pais, 1982) Although his happy thought put him on the right track, it would take eight more years and help from his friends and colleagues for Einstein to develop his new theory of gravity.

Einstein recognised that in free fall weight disappears, just like an astronaut floating freely and weightlessly in outer space. If an astronaut's rocket accelerates, the astronaut feels a force towards the floor, just like gravity. The *equivalence principle* captures the observation that locally, it is not possible to distinguish between gravity and acceleration. A freely falling observer feels weightless, measuring no local effect of gravity at all.

During his struggle to combine special relativity with a theory of gravity, Einstein had to grapple with conceptual obstacles as well as mathematical difficulties. Einstein received enormous assistance from his friend and former classmate Marcel Grossmann who had become a professor of mathematics (Einstein & Grossmann, 1913). General relativity, the theory that eventually emerged, is considered by many to be one of the most beautiful and elegant human creations. In a stroke of genius, Einstein identified gravity as arising from changes in the shape of spacetime. Seeing that the shape of spacetime changes geometry, we can say that gravity is geometry: the curvature of spacetime explains gravitational phenomena.

The idea that space could be curved was not new to mathematicians at the turn of the 20th century. A century before Einstein and Grossmann linked gravity to the geometry of curved spacetime, mathematician and geometer Carl Friedrich Gauss realised that the shape of three-dimensional space need not follow the two-dimensional geometry of flat paper, which is the geometry set out in Euclid's book Elements. Indeed, Euclidean geometry, in which parallel lines never meet, could be seen as a postulate, rather than an established fact. Gauss suggested that the geometry of our world should be experimentally tested. This suggestion led to a paradigm shift in geometry, and inspired by Gauss' work, mathematician Bernhard

Riemann developed the mathematics of curved spaces during the first half of the 19th century. It was this geometry that Grossmann had studied extensively, and that provided the mathematical tools to develop a geometric theory of gravity.

General relativity has a conceptual simplicity, and yet, it stretches our minds and completely changes our view of the universe. The conceptual simplicity is married to sophisticated mathematical notation and abstraction. Einstein's field equations are at the heart of the theory and describe the dynamic interplay between matter and spacetime. The mathematics is necessary for theoretical investigations but is entirely unnecessary for teaching the theory in schools.

The interplay between matter and spacetime is summarised by the aphorism "*matter tells spacetime how to curve, spacetime tells matter how to move*". For spacetime to be able to curve, it must be elastic. For this reason, we often see deformed elastic membranes being used to represent curved spacetime. These images are deceptive because they do not emphasise the enormous stiffness of spacetime. The stiffness is represented by a constant of nature made up from the speed of light to the 4th power (a huge number), divided by the constant of gravitation G (a tiny number): stiffness of space is $\frac{c^4}{8\pi G}$, a number equal to about 10^{43}. Einstein's theory then resolves into a set of equations of the form mass-energy = stiffness of spacetime x curvature of spacetime.

The equations tell us that though being flexible and able to curve, spacetime is the stiffest thing in the universe. That is why many effects of general relativity are tiny and difficult to measure. Even your muscles, weighing just a few kilograms, can easily overcome the gravitational pull of our planet with a whopping mass of 6×10^{24} kilograms! Table 1 summarises the fundamental ideas that make up special and general relativity.

<INSERT TABLE 4.1 HERE>

Predictions of general relativity

Einstein’s field equations describe how massive objects curve space and how the gravitational field influences the flow of time. In our solar system, the deviations from flat-space geometry are extremely small but sufficient to demote Euclidean geometry from being an exact description to a mere approximation of reality. Equipped with his field equations, Einstein was able to solve the riddle of Mercury’s orbital pattern. Orbits in Newtonian gravity are defined by the area an orbiting body sweeps out, and by the perimeter of the orbit. In flat space, for a circular orbit, the area to perimeter ratio is exactly equal to half the radius, but in curved space, you can fit extra area within the same circle, so the perfect ratio is violated. Without the perfect ratio, orbits cannot stay fixed in the sky: they *precess* and create a daisy petal pattern (Figure 1). The correct description of the orbit of Mercury was an early triumph of general relativity, but it was the next test of general relativity that made Einstein truly famous.

<INSERT FIGURE 4.1 HERE>

The bending of light

Since the early 1800s, astronomers had suggested that starlight might be deflected by the Sun, thinking that gravity should deflect light as if it was a stream of bullets. A bullet travelling at light speed and passing the Sun in flat Euclidean space would be deflected by 0.87 arc seconds. Since the 1890s, astronomers had searched unsuccessfully for this effect by trying to photograph stars near the Sun during a solar eclipse. If they had succeeded, they would have been surprised because if space is curved, there are two separate effects: the Newtonian effect that many had expected, and an equal-sized effect due to the straight-line motion of light through curved space. This combined effect doubles the prediction to 1.75 arc seconds.

An eclipse in 1919 provided an ideal opportunity to test Einstein’s prediction. Overcoming many difficulties, Sir Arthur Eddington led an expedition to the west coast of Africa and succeeded in photographing a group of stars close to the Sun. Eddington and his team measured the changed position of the stars, not with great accuracy, but sufficient to proclaim that Einstein was correct: space is curved by the Sun. (Chapter 11 discusses this topic in detail.)

Eddington's expedition was the turning point in Einstein's career. The curvature of spacetime was no longer just a mathematical curiosity; it explained fundamental phenomena in nature. The proclamation on the front page of the New York Times stated: *"Lights askew in the heavens….men of science agog"* and finally *"A book for 12 wise men…no more in the whole world could comprehend it, said Einstein…*" Almost overnight, Einstein had become an international celebrity. Although this observational confirmation of general relativity was a scientific triumph for Einstein, the "twelve wise men" claim marked the beginning of the widespread perception that Einstein's theory was almost incomprehensible to laypeople.

Singularities and waves: the first solutions of Einstein's equations

In early 1916, within months of the publication of Einstein's theory, physicist and astronomer Karl Schwarzschild had found a solution to the field equations of general relativity in the simple case of spherical symmetry. Schwarzschild's solution describes the curvature of space and the warping of time around a spherical mass. However, if the density of the central mass is high enough, Schwarzschild's solution features a singularity, a point of infinite density (Box 1), surrounded by an event horizon that marks the region of space in which the gravitational field is so strong that no light can escape. Physicists found it impossible to believe that such a solution could represent reality. It was considered to be a weird mathematical artefact and physically meaningless.

Box 1: The Schwarzschild radius of a black hole

The Schwarzschild radius is the physical parameter r_S that appears in the Schwarzschild solution of Einstein's field equations: $r_s = \frac{2GM}{c^2}$

This parameter describes the event horizon of a spherically symmetric, non-rotating and electrically neutral black hole with mass M; here, G is the gravitational constant and c the speed of light.

In mid-1916, months after Schwarzschild's solution, Einstein found another solution to his field equations. This solution predicted gravitational waves, fluctuations in spacetime, that would travel at the speed of light. However, Einstein was not the first to propose the existence of gravitational waves. In 1905, the year that Einstein published his special theory of relativity, Henri Poincaré proposed the existence of gravitational waves, while Oliver Heaviside had suggested the same thing 12 years earlier. Much like Einstein in the development of his spacetime formalism, Heaviside and Poincaré had been inspired by Maxwell's theory of electromagnetism. In analogy to accelerating electrical charges that emit electromagnetic waves, they hypothesised that accelerated masses could produce gravitational waves. For example, a pair of stars orbiting each other could create these ripples in space. However, any source of gravitational waves that Einstein could imagine would emit utterly negligible gravitational wave power (Box 2) because the immense stiffness of spacetime means that ordinary masses like stars and planets make only tiny amounts of curvature. Einstein concluded that the waves were of academic interest only.

Box 2: Gravitational wave power

Gravitational wave power from two masses M (in kg) orbiting each other at a distance L (in meters), with orbital frequency ω measured in radians per second:

$$\text{Power} \approx G/c^5\ M^2L^4\omega^6$$

Imagine trying to create gravitational waves by placing huge masses (say 10^5 kg) on a large turntable (say 100m diameter) and spinning it to the point of destruction (say 10 radians per second): the output power would be less than 10^{-30} Watts, an utterly negligible amount of power.

Not only did the effects of gravitational waves seem too tiny to be ever measurable, but Einstein also started to doubt the validity of the mathematical derivations. The mathematical complexity of the theory led people to ask whether gravitational waves were not merely ripples in the curved coordinates, like ripples in lines of longitude, rather than ripples in space itself. In 1922, Eddington was able to show that Einstein, indeed, had misinterpreted parts of his solution. It seemed that some forms of gravitational waves could propagate at any speed, which led to Eddington’s famous joke that gravitational waves "propagate at the speed of thought” (Eddington, 1922). Einstein himself was confused, and in 1935, he submitted a paper proposing the non-existence of gravitational waves. To Einstein’s consternation, the paper was rejected by the editor. The confusion around gravitational waves remained for a further two decades.

It was not until 1957, two years after Einstein’s death, that Richard Feynman settled the question of the reality of gravitational waves with a simple thought experiment (DeWitt & Rickles, 2011). Feynman described two masses A and B spaced some distance apart, with gravitational waves passing. *“Let one mass A carry a stick which runs past touching the other [mass] B. I think I can show that the second, in accelerating up and down, will rub the stick, and therefore by friction make heat.”*

Feynman then went on to demonstrate this effect using an equation derived by theoretical physicist Felix Pirani. Finally, Feynman concluded *“In view therefore of the detailed analysis showing that gravity waves can generate heat… I conclude also that these waves can be generated and are in every respect real.”*

<INSERT FIGURE 4.2 HERE>

Feynman had shown that gravitational waves make real measurable changes in the distance between objects (Figure 2). We can think of this change in distance in terms of inertia. Inertia is the coupling of matter to space. Usually, we think of space as unchanging. Then inertia is experienced as resistance to acceleration through space – heavy masses like cars are difficult to accelerate when you push them! But what if space expands or contracts? Then the coupling of matter to space acts the other way - the matter experiences an acceleration provided by the expanding space. This is a real acceleration creating real changes in distance between objects. This phenomenon can be measured by light; just like light is used to measure the speed of cars on a road or even the expansion of the universe, which is also an expansion of space.

The quest to validate general relativity

With the conceptual difficulties of the reality of gravitational waves overcome, physicists began to take a much greater interest in general relativity after a long hiatus, partly caused by the second world war. Full validation of general relativity would require evidence of objects with event horizons in line with Schwarzschild's solution (black holes) and observation of gravitational waves. Physicists and astronomers were inspired by Fritz Zwicky's prediction in the 1930s that ultra-compact *neutron stars* might be formed in supernova explosions. Neutron stars consist mostly of neutrons, and their density is comparable to that of an atomic nucleus. Robert Oppenheimer, who went on to become a father of the atom bomb, combined quantum mechanics with relativity to predict a *critical mass* for such balls of neutrons. Oppenheimer and his colleague George Volkoff concluded that "*actual stellar matter after exhaustion of thermonuclear sources of energy will, if massive enough, contract indefinitely"*(1939, p. 374). It seemed that nature allowed the existence of neutron stars, but the greater their mass, the smaller they became, and at a certain point, they would collapse. A few people imagined that such things might actually exist, but there was no evidence. It was not until 1964 that the evocative name *black hole* first appeared in print in Science News, a year after theoretical physicist Roy Kerr had found an exact mathematical solution to spinning black holes. Kerr's solution was immensely important because all black holes are likely to spin.

Besides, Kerr's solution predicts a new type of gravitational phenomena, called *gravitomagnetism*. Gravitomagnetism is analogous to magnetism, the force that is created when electric charges move. In Einstein's theory, we can think of mass as the gravitational charge of gravity in analogy to the electric charge of the electromagnetic force. Following this reasoning, we expect spinning objects to create a gravitomagnetic force. Massive spinning objects seem to drag space around them similar to the way a floating spinning ball drags water into rotation, and electrons flowing in loops of wire create magnetism. Kerr's solution also provided a mechanism for energy to be extracted from black holes: the rotational energy of the hole can be extracted because it brings surrounding matter into rotation. All future observations of black holes would be measured against Kerr's solution.

Even before neutron stars were discovered, Freeman Dyson showed that enormous amounts of gravitational wave power would be emitted if two neutron stars were to collide. If only Einstein had believed in the reality of Schwarzschild's solution! If he had, he might have considered two black holes orbiting each other, instead of two average stars. Then, few lines of algebra would have shown him that the wave power produced when two black holes coalesce is roughly c^5/G, a vast number representing a power greater than that of all the stars in the universe combined! The algebra just needs substitution of the Schwarzschild radius and orbital speeds into Einstein's formula for the power of gravitational waves (Box 2). School students can do this calculation. The result tells us how nature can convert the mass-energy of black holes into pure gravitational energy in the form of ripples of space. In the 1960s, these insights provided optimism about the detectability of Einstein's waves. They motivated a growing band of gravitational wave physicists for the next 50 years.

During the 1960s to 80s, general relativity was investigated separately in three different domains:

a) Astronomers discovered strange new objects - X-ray stars, pulsars and quasars that needed either neutron stars or black holes to explain them.
b) Space scientists conducted experiments to test general relativity in the solar system.
c) Experimental physicists in the USA and Russia began to consider how to build sensitive gravitational wave detectors.

Astronomers discover pulsars

Pulsars are rapidly spinning magnetised neutron stars. In 1967, astrophysicist Jocelyn Bell was the first to detect a pulsar as a pulsing radio signal. Pulsars emit narrow beams of radio waves and rotating quickly, they sweep the sky like lighthouses to create a pattern of pulses. Each pulsar can act as an extraordinarily precise clock. By timing when the pulses arrive, radio astronomers can probe changes in the pulsar's motion. In 1974, Russell Hulse and Joseph Taylor discovered the first *binary pulsar*. This binary system of a pulsar and another neutron star orbiting around a common centre of mass was a veritable laboratory for probing general relativity.

The pulses came faster when the pulsar was approaching and slower as it receded. Using this periodic pattern in the arrival time of the pulses, Hulse and Taylor could map the orbit of the binary system. The two stars were orbiting each other once every eight hours, inside a volume a bit larger than the size of the Sun. The orbital precession due to the curvature of space around the stars was enormous compared with the tiny precession of Mercury that first helped prove general relativity.

The precession caused by curved space has quite far-reaching effects in astronomy. The geometric perfection of orbits in Newtonian physics limits what can be learnt from observation of pairs of orbiting stars because it is complicated to distinguish between circular orbits seen obliquely and elliptical orbits seen face on. When the orientation is unknown, the masses and distance are ambiguous. This ambiguity makes it extremely difficult to make precision measurements in astronomy.

The binary pulsar quickly showed how observations of systems where spacetime is strongly curved resolve this ambiguity. Suddenly, just one observation and knowledge of Newton's constant of gravitation measured in a laboratory on Earth enable the critcial properties of distant star systems to be determined. The physics of strongly curved spacetime also means that gravitational wave signals carry with them distance information. Bernard Schutz, the author of the first chapter of this book, proved this point which we discuss below.

Box 3: The first binary pulsar

The precession caused by curved spacetime allows the masses of the two neutron stars to be determined to four significant figures, very close to the precision that we know the gravitational force constant. This level of precision had been unprecedented in astronomy up to the discovery of the first binary pulsar:

$M_1 = 1.441 M_\odot$, $M_2 = 1.387 M_\odot$

Here, M_1 is the mass of the pulsar, $M_2$the mass of its companion, and $M_\odot$ the mass of our Sun.

The binary pulsar allowed the first precise measurements of the masses of stars (Box 3). Besides, Hulse and Taylor were able to measure the pulse delays due to the radio pulses passing through the curved spacetime of the other unseen neutron star, and the gravitational time dilation as the pulsar moves closer and further from its companion. Most importantly, the measurements of Hulse and Taylor showed that the orbital radius was shrinking by 3.1mm every orbit exactly as predicted by Einstein's formula for gravitational wave emission. This observation was a triumph for general relativity for which Hulse and Taylor won the 1993 Nobel prize. The shrinking orbit was indirect evidence that gravitational waves exist in accordance with general relativity.

Moreover, simple extrapolation of the orbital decay implied that in 300 million years, these two stars would be brought together by gravitational waves. The stars would spin about each other faster and faster, until in their last minute, they would emit a rising tone of gravitational waves from 50 Hz to 1kHz in a waveform called a *chirp*. It would be an extremely powerful source. Freeman Dyson had hypothesised such a source in 1962 before neutron stars were even discovered. The proof of energy loss from the binary pulsar was the first proof that powerful gravitational wave sources *must* exist in the universe. Yet, it would still be a long way to the direct detection of gravitational waves, when such chirps became a regular occurrence.

Space scientists test general relativity in the solar system

While general relativity could be tested in distant astronomical systems, space scientists wanted to probe general relativity in the solar system directly. In 1971, Irwin Shapiro reported an experiment in which he bounced radar pulses off planets when their line of sight passed close to the Sun. The warping of time in the Sun's gravitational potential should cause the pulses to be increasingly delayed as the line of sight moved closer to the Sun. This, he duly observed (Shapiro, Ash, Ingalls, & Smith, 1971). A few years later, as discussed above, Hulse and Taylor found the same phenomenon in the binary pulsar.

NASA planned two projects designed to test general relativity around the Earth that would test the warping of time, the curvature of space, and gravitomagnetism. The latter would confirm the second necessary component of general relativity for gravitational waves to exist. All types of waves involve an exchange of energy between two components: an elastic component (like the stretching of a spring), and a dynamic component (like the movement of mass). In electricity, the dynamic component is magnetism, and because of its existence, we have electromagnetic waves. If gravitational waves exist, both the elastic and dynamic components of gravity must exist, too. Thus, we should be able to measure gravitomagnetism, the dynamic component of gravity that occurs in the Kerr solution.

The two NASA space experiments would use the mass and rotation of the Earth to probe both of these components. Schwarzschild's solution predicts the static effect of the Earth's mass: mass distorts both space and time. Kerr's solution predicts the dynamic effect from a rotating mass. NASA's first experiment, called Gravity Probe A, was led by Robert Vessot. Gravity

Probe A consisted of an atomic clock launched into a 10,000 km trajectory above the Earth. The warping of time, or *gravitational time dilation,* was clearly observed. This observation confirmed that time speeds up as you leave the Earth's gravitational potential per Schwarzschild's prediction (Box 4).

Box 4: Gravitational time dilation near the surface of the Earth.

The fractional change in time Δt is given by

$$\Delta t/t = g/c^2 \text{ per meter of height}$$

where g is the acceleration due to gravity.

Gravity Probe B was to be an exquisite quartz gyroscope that would maintain its spin axis so precisely that it could discern the static curvature of space around the Earth (Figure 3) which causes the 40,000 km length of the orbit to differ from its Euclidean value by 28mm. More importantly, this gyroscope would measure the dynamic gravitomagnetic component from the Earth's rotation. This experiment, led by Francis Everitt, was a marathon. It took 40 years and more than 100 PhD researchers to complete. Eventually, it confirmed both the curvature of space and that the spinning Earth creates the predicted "magnetic" component of gravity that is needed if gravitational waves are to exist. The results were published in 2011. By this time binary pulsar observations meant that few physicists doubted the existence of gravitational waves.

<INSERT FIGURE 4.3 HERE>

Meanwhile, in the height of the cold war, the US military launched the Vela satellites, designed to pick up secret nuclear weapons tests in space. The satellites did not detect any tests, but instead, they discovered powerful bursts of gamma rays hitting the Earth about once a day. The source of these bursts was a mystery. Over many decades, it became clear that there were two types of bursts, called long and short bursts. While the long ones seemed to be associated with the collapse of massive stars into black holes, it took 40 years to discover the nature of the short bursts. Eventually, the observation of gravitational waves solved the mystery of the short bursts quite dramatically as we shall see below.

Experimental physicists design gravitational wave detectors

The third domain of investigation was the quest to detect the gravitational waves that Einstein had thought to be of academic interest only. In the 1960s, Joseph Weber was the lone pioneer of gravitational wave detection. He investigated two types of detectors that closely followed Feynman's thought experiment of a pair of masses joined by a sliding stick. The key idea was to measure the energy imparted when the spacing between two masses was changed by a passing gravitational wave (see Figure 2). Weber's plan was to treat the two masses as two halves of a solid bar. Then the gravitational wave would squeeze and stretch the bar, leaving behind a tiny amount of acoustic energy. The second idea, first put forward by Russian scientists Gertsenshtein and Pustovoit (1963), was to use a laser-powered Michelson interferometer that could measure tiny changes in the spacing of widely spaced mirrors caused by gravitational waves. Such devices could be arbitrarily large. Weber's student Robert Forward tried out this idea and discovered the enormous technical challenges to make such a device have high sensitivity.

Weber used a pair of widely spaced detectors and searched for simultaneous excitations that could indicate gravitational wave signals arriving from space. In 1969, Weber announced that he had discovered gravitational waves. Within a few years, at least ten similar detectors had been built in research centres across the world. But nobody could repeat Weber's results. His results were statistical, and like many other researchers across many fields, Weber deceived himself with the statistics. The shame of Weber's false reports overshadowed the inspiration and the two key ideas he introduced:

- Detectors must be near perfect oscillators with minimum *energy dissipation* because dissipation is always connected to noise and measurement uncertainty.
- Widely separated detectors are needed to suppress the effects of interference from other sources such as earthquakes which travel slowly compared to the light speed of gravitational waves passing through the Earth.

Weber's ideas underpinned the entire research program that eventually created billion-fold improved detectors that detected gravitational waves. Detectors were always widely spaced on the planet. They all involved innovative new technologies that enabled every component to be an almost perfect oscillator with such low energy dissipation that it would ring for millions or billions of cycles.

The idea of improved technologies for building better and better gravitational wave detectors emerged before Weber's work had been discredited. Detectors had to be able to measure minuscule stretching and shrinking of space due to gravitational waves because the enormous stiffness of spacetime means that vast amounts of energy correspond to tiny motions. Space is perhaps thirty orders of magnitude stiffer than steel. Even for the most optimistic sources – the colliding black holes - the stretching and shrinking would be tiny, vastly smaller than the size of an atom.

Concepts for greatly improved detectors were put forward by William Fairbank at Stanford University and Rainer Weiss at the Massachusetts Institute of Technology. Fairbank proposed cooling huge metal bars to near absolute zero and use superconductivity to make extremely sensitive microphones to pick up vibrations induced by gravitational waves. Weiss proposed building laser interferometers kilometres in length. Theoretically, both approaches offered sensitivity billions of times better than Weber's detectors.

In the 1970s, Vladimir Braginsky pointed out something that shocked the small community of detector designers. Braginsky realised that the huge instruments they were designing, consisting of tonnes of cryogenic, superconducting metal bars or tens of kilograms of mirrors were actually ruled by quantum mechanics. Simple calculations proved that the Heisenberg uncertainty principle that physicists imagined being relevant only to the realm of atoms would also apply to the planned measurements of mirrors and metal bars. This insight required a re-evaluation of all proposed detectors because the uncertainty principle would limit their sensitivity. This, in turn, led to a new field of research in quantum measurement and quantum engineering.

By the 1990s, physicists had created cryogenic metal bars with superconducting sensors that were able to measure motions approaching 10^{-20}m. Five widely spaced detectors listened for bursts of gravitational waves for many years, but the universe was silent. The signals they could have detected would have had to come from the Milky Way, and by this time, astronomers were fairly certain that the Milky Way could not have sufficiently frequent events involving black holes or neutron stars.

In the meantime, another community had created 10-40m length prototype laser interferometers. Like all the detectors, these devices had taken years to understand and bring into sensitive operation. For laser detectors, the teams had to discover how to create, suspend and control near-perfect mirrors and noise-free lasers, and detect tiny motions. The laboratory-scale instruments were not in themselves nearly sensitive enough but proved the possibility of high sensitivity if expanded from meters to kilometres in length.

Kip Thorne championed the development of the kilometre-scale detectors, showing how these detectors could specifically detect the only type of gravitational wave source known to actually exist: coalescing pairs of neutron stars like the binary pulsar. The logic of the design follows simple mathematics: Knowing that the binary pulsar in our galaxy will coalesce in 300 million years, how many galaxies like our own would we need to listen to, to hear on average one binary pulsar coalesce every year? The answer is easy: 300 million galaxies! To reach so many galaxies would require enough sensitivity to detect neutron stars coalescing hundreds of millions of light-years away. In fact, the numbers are not quite so pessimistic because subsequently, many more binary pulsars were discovered in the Milky Way, including one pair that will coalesce in about 80 million years. The careful analysis allowed the necessary sensitivity to be specified and gave the laser interferometers a clear sensitivity target.

Two groups, the Virgo collaboration and the LIGO collaboration, obtained funds for enormous observatories in Europe and the USA. The detectors in these observatories were remarkably complex instruments, needing huge teams to design and operate them. It took many years, intense effort by hundreds of physicists, and a billion dollars first to construct the detectors, and then to learn how to operate them and make them sensitive. The first large scale LIGO detectors began to operate in 2002, but it took eight years of excruciating efforts to bring them to design sensitivity. Yet, even at full sensitivity, the universe was again silent. No signals were detected. Although disappointing, this silence did not come as a surprise., By this time, there were estimates of the rates of coalescence of neutron stars, and the chance of one occurring close enough to be detectable was rather small.

A new astronomy

The Virgo and LIGO teams had been careful to emphasise that the first interferometer detectors had only a small chance of success. They had always foreshadowed the need for another step in sensitivity, called Advanced LIGO and Advanced Virgo. Only these detectors would have a high chance of success. Nevertheless, the joke spread that "*gravitational wave detection is always ten years in the future*." The Advanced LIGO detectors came into operation in September 2015. They were better isolated from seismic vibrations and had mirrors that had much lower acoustic losses, as well as more powerful lasers, making them about three times more sensitive than the previous detectors, and able to measure signals at lower frequencies.

On the fourteenth of September 2015, just before the official start of observations, but when all systems were operating, the rising tone of a chirp suddenly appeared in the two LIGO detectors. It was the unmistakable sound of two objects spiralling together faster and faster. The strength of the signal, the rate of frequency increase, and the wave pattern are enough to define the masses and the distance. The teams had been expecting pairs of neutron stars, but the frequency rose much too rapidly for neutron stars. It had to be a pair of huge black holes, each more than thirty times the mass of the Sun. The signal seemed just too good to be true! No black holes of this mass had ever been identified.

It took the collaboration months from the first detection to announce the results, because of fear that it could have been a fake signal injected into the data, or some form of interference. The memory of Weber's false announcements still haunted the community. When it was announced in February 2016, it brought worldwide headlines, and in 2018 Weiss, Thorne and Barish received the Nobel Prize for the discovery that had taken a team of 1000 physicists several decades to accomplish.

The gravitational wave detectors were the most sensitive quantum instruments ever created. The clear gravitational wave signal from the two coalescing black holes represented a power output in gravitational waves 50 times larger than the power output of all the stars in the universe! The waves had travelled for a billion years, and yet when they reached the Earth their power per square meter represented *the most powerful burst of energy ever detected from outside the solar system – pure gravitational energy.* Yet the signal captured by the detectors was *the smallest amount of energy ever recorded*, corresponding to a motion ten thousand times smaller than the diameter of a proton! The signal precisely described the moment that two black holes merged into one, followed by the faint ringing of the newborn black hole. At the point of coalescence, the two holes were travelling at a good fraction of the speed of light. They had emitted three solar masses of energy in less than one second. The chirp had travelled for a billion years while life was steadily evolving on Earth. Finally, it arrived just at the time that the life forms on Earth had invented detectors able to hear it! Since that momentous day, similar signals have been detected frequently.

In 2017, 55 years after Freeman Dyson's prediction of gravitational waves from pairs of neutron stars, two such stars in their final minute of inspiral were detected. The signal arrival time at each of three detectors located the burst in the sky, and optical telescopes were soon able to pinpoint the flash of a *kilonova* in the galaxy NGC4993. This time the gravitational waves had travelled for 130 million years to reach the Earth. Remarkably, the gravitational wave distance estimate of the event, which ultimately depends only on the laboratory measurement of the gravitational force constant G, matched the distance estimate from the recession speed of the galaxy due to the expansion of the universe. The remarkable ability of gravitational waves to map and measure the universe, first predicted by Bernard Schutz, was demonstrated.

Equally exciting was the detection of a burst of gamma-ray photons by the Fermi gamma-ray observatory satellite, which arrived 1.7 seconds after the gravitational wave chirp. Given that the journey time of both signals was 130 million years, the difference in speed between light and gravity had to be less than 4 parts in 10^{16}. Assuming that the "magnetic engine" that created the burst took a second or so to form, we can treat this as clear confirmation that gravitation travels at the speed of light to quite extraordinary precision. Einstein was right again!

The discovery of radio waves marked the beginning of a century in which humanity explored the enormous breadth of the electromagnetic spectrum. The recent discoveries mark the start of a similar exploration of the gravitational wave spectrum. Gravitational waves allow us to listen to the birth and death of black holes, and to know them from the way they create gravitational waves. In 2019, we were able to identify a black hole from how it interacts with background light. A set of microwave telescopes called the Event Horizon Telescope imaged the hole in spacetime created by the supermassive black hole in galaxy M87 (Figure 4)

<INSERT FIGURE 4.4 HERE>

The next significant steps in gravitational wave astronomy will be detectors in space (https://lisa.nasa.gov/) designed to measure much lower frequency gravitational waves, and new detectors on Earth. Both are designed to listen to gravitational waves from the entire universe. We expect to hear black holes coalescing every five minutes, and neutron stars coalescing even more often, as well as stellar-mass black holes spiralling into supermassive black holes. The evolving and slowly dying universe will be audible in real-time, thanks to general relativity and gravitational waves.

Conclusion

A century of studying Einsteinian physics has given us a deep understanding of general relativity and quantum physics that has allowed us to create instruments to hear the universe in gravitational waves. Before the first observation of two merging black holes in 2015, gravitational waves had been the last prediction of general relativity that had not been tested directly. We now know that spacetime is dynamic, continually rippling and vibrating, and carrying vast amounts of energy like invisible and harmless tsunamis travelling at the speed of light.

Gravitational-wave astronomy is a still-young field of research that gives scientists insights into cosmic regions not accessible by conventional telescopes. The combined measurement of gravitational waves and electromagnetic waves opens up exciting new possibilities in multi-messenger astronomy, in which objects are observed simultaneously by different forms of radiation or other messengers from the universe. Besides, gravitational waves promise new insights into the nature of spacetime because they allow us observing black holes very close to the singularities where the theory of relativity might break down. We have just begun this brand-new exploration of a brand-new spectrum. We are at a frontier, facing the unknown.

Einsteinian physics is a triumph for humanity that everyone deserves to share. Besides its enormous scientific potential and ongoing discoveries, Einsteinian physics and the emerging discipline of gravitational wave astronomy have the opportunity to motivate students and encourage interest in STEM topics. While scientists listen ever deeper into space, we hope that Einstein's ideas will entice students and instil an appreciation for the astonishing story of our existence, a story that can only be told in the language of Einsteinian physics.

References

Born, M. (1968). *Physics in My Generation* (2nd ed.). New York: Springer.

DeWitt, C. M., & Rickles, D. (Eds.). (2011). *The Role of Gravitation in Physics: Report from the 1957 Chapel Hill Conference* (Open Acces). Berlin: Communicated by Jürgen Renn, Alexander Blum and Peter Damerow. Max Planck Research Library for the History and Development of Knowledge.

Eddington, A. S. (1922). "The Propagation of Gravitational Waves." *Proceedings of the Royal Society A*, *102*(716), 268–282.

Einstein, A., & Grossmann, M. (1913). "Entwurf einer verallgemeinerten Relativitätstheorie und einer Theorie der Gravitation [Outline of a Generalized Theory of Relativity and of a Theory of Gravitation]." *Zeitschrift Für Mathematik Und Physik*, *62*(225).

Gertsenshtein, M. E., & Pustovoit, V. I. (1963). "On the detection of low frequency gravitational waves." *Soviet Physics JETP*, *16*(2), 433–435.

Minkowski, H. (1909). "Raum und Zeit [Space and Time]." *Jahresbericht Deutscher Mathematischer Verein*, *18*, 75–88.

Oppenheimer, J. R., & Volkoff, G. M. (1939). "On massive neutron cores." *Physical Review*, *55*(4), 374–381.

Pais, A. (1982). *Subtle is the Lord : The Science and the Life of Albert Einstein*. Oxford University Press.

Shapiro, I. I., Ash, M. E., Ingalls, R. P., & Smith, W. B. (1971). "Fourth Test of General Relativity: New Radar Result." *Physical Review Letters*, *26*(18).