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**Was Einstein Right?**

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It is a pleasure to give this lecture on the eve of the 100th anniversary of one of the greatest scientific achievements of the last century: Albert Einstein’s General Theory of Relativity. In a month of frantic activity, culminating on the 25th of November 1915, Einstein presented 4 short papers to the Prussian Academy of Science, one per week, developing his ideas. Quite remarkably, his thinking was still changing during this month and it was not really until the final instalment that the theory as we know it emerged.

Today, we tend to think of Einstein’s theory as a spectacular success. General Relativity is (along with quantum mechanics) one of the cornerstones of modern physics. It provides us with an understanding of gravity - both how it works and why - that allows us to explore and explain the universe.

However, as I will discuss in this lecture, the recognition of Einstein’s theory was far from immediate. For more than half a century General Relativity was considered an esoteric construction that had little to do with the real world. Its practitioners made use of mumbo-jumbo mathematics (tensor calculus) to describe gravity in terms of a curved space-time. Few people – even leading scientists – were able grasp the actual meaning of the theory. As late as the 1960s, young researchers were advised to stay away from General Relativity because it had very little to do with actual astronomy. Fortunately, some of them did not listen.

The fortune of Einstein’s theory changed dramatically in the second half of this first century. Increasingly precise measurements of space and time put the theory to the test, and it passed every challenge with flying colours. In this lecture, I will try to give you an idea of the scope of these developments.

But maybe we had better start from the beginning. What exactly is Einstein’s theory of gravity?

To set the scene, let us to go back to 1905 when the young Albert Einstein published his first ground breaking theory. With Special Relativity, Einstein resolved a well-known problem concerning electromagnetism and motion. The theory clarifies the relationship between space and time. It builds on a single, very simple, assumption; the speed of light (in vacuum) is the same according to all observers, no matter how they move relative to one another (as long as they do not accelerate). The consequences of this assumption are at odds with our everyday reality. Moving clocks appears to run slow, moving rods appear short, and then we have the most famous equation of all physics, E=mc2. Even the tiniest speck of dust harnesses an enormous amount of energy.

Special Relativity was an immediate success, possibly because a number of other people were thinking along similar lines and were close to the same conclusions. Einstein received recognition for the theory, but this was pretty much it. He remained a clerk at the Bern patent office. In 1906 he was promoted to Technical Assistant Level I, but I guess this had little to do with relativity.

Einstein was well aware that his theory was incomplete. It described bodies in uniform relative motion. It did not account for acceleration. And the idea that no information can travel faster than the speed of light was in direct conflict with one of the main theories of physics: Newton’s inverse square law for gravity.

This problem would bother Einstein for the next couple of years. Then one day in 1907, he was working at his desk in the patent office. Perhaps a bit bored, he looked out the window and saw window cleaners at work. All of a sudden he imagined one of them falling. It struck him that the falling man would not actually feel the effects of gravity. In a beautiful leap of logic, Einstein realised that the situation would be exactly the same if there were no gravity - if the man floated freely - and he himself sitting at his desk were accelerated upwards. He concluded that acceleration and gravity must be equivalent.

The next step tied in the fixed speed of light from Einstein’s first theory. He realised that, if he were in a lift accelerating upwards to near the speed of light then a beam of light entering the lift would appear to curve towards the floor. Now, a key aspect of Einstein’s thinking was that light is lazy. It prefers to take the shortest path between two points. Under normal circumstances this is a straight line. But this would not be the case in this thought experiment. In order to allow light to be lazy and follow the shortest possible path, Einstein had to assume that space was curved.

With these ideas – the equivalence principle and the curved space-time - Einstein had the foundation for his gravity theory. But sometimes there is a long way from physics insight to a complete theory. Einstein spent the next eight years trying to learn to work with the mathematics of a curved space-time. This was the effort that he completed in that frantic month of November 1915.

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Einstein’s General Relativity explains gravity in term of geometry, the “shape” of space and time. The mathematical equations of the theory can be written in a neat form, giving the impression that we are dealing with something quite simple. In essence, we have an equation where the left-hand side depends on the geometry of space-time and the right-hand side accounts for all matter, where it is and how it moves. In practical situations, Einstein’s equations can be horrendously complicated but for the present purposes we do not need to understand them beyond John Wheeler’s famous summary: “Matter tells space how to curve and space tells matter how to move”.

Einstein’s theory describes a universe far from our everyday experience. Not only does gravity move mass, it also bends light and warps time. Clocks run slow in a gravitational field. Gravity makes waves and creates black holes. Ultimately, gravity also helps us explain the cosmos by providing a glimpse of the beginning of it all – the big bang. There are some very exciting ideas here, but how do we know they are right? How do we put Einstein to the test?

Einstein himself was convinced the theory had to be correct. He had good reasons for thinking this because he knew the curved space-time description reproduced many features of Newtonian gravity (in the appropriate weak gravity limit). In fact, he had managed to resolve a long-standing problem concerning the motion of the planet Mercury. The conundrum dated back to 1859 when Urban Le Verrier tried to work out the influence of the other planets on the perihelion precession of Mercury. He worked out the rate at which the point of closest approach to the sun marches forward due to the presence of other bodies in the solar system. When he added everything up, he found that something was missing; 43 arcseconds per century, about 1/3 of the effect due to Jupiter. This led to suggestions of a missing planet and a discussion that lasted until Einstein solved the problem.

That gravity bends light – apparently displacing the stars in the sky – is a direct consequence of the equivalence principle. Einstein first calculated the effect already in 1911, well before he completed the theory. He managed to convince astronomers that the prediction could be tested during a solar eclipse. Luckily – for Einstein – a number of proposed expeditions fell through. This was fortunate, because the first calculation was wrong. The 1915 theory corrected this mistake, but by then the world was at war. It was not until 1919 that a British eclipse expedition, led by Arthur Eddington, confirmed the light bending. The result propelled Einstein to fame and made him a household name. But the measurement was actually not totally convincing. The observations agreed with Einstein’s calculated value with an error of about 30%. This level of uncertainty would remain for a long time.

When Einstein died in 1955, he left a desk full of unfinished calculations and unanswered questions. Many of the predictions of his theory remained untested. The effects were simply too small and there was no serious interest in testing the theory, anyway. Most scientists simply found it “too complicated”.

The eventual renaissance of relativity in the decade that followed Einstein’s death was driven by three developments: First, atomic clocks allowed precision measurements of space and time. Second, a new generation of telescopes – building on technology developed during World War II - opened new windows to the universe, driving a revolution in astronomy. Third, a generation of talented physicists revisited Einstein’s theory, leading to a much better understanding of the implications.

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For thousands of years astronomers studied the night sky, tracking stars gliding gently across the firmament, trying to understand a gradual evolution over eons. But our universe is actually not like that at all. As soon as radio telescopes were turned to the skies it became clear that the universe is a violent place.

In 1963 Maarten Schmidt discovered the first quasar (the radio source 3C 273), an object so bright that it had been mistaken for a star, but it turned out to be a billion light years away. What could possibly fuel such a spectacular display? The answer, as it turns out, is gravity. We now know that these distant active galaxies can be thousands of times as luminous as an ordinary galaxy. In some cases, like Cygnus A, matter is ejected at relativistic speed in powerful jets that extend for thousands of light years away from the galaxy core.

In this dramatic new universe, stars explode in supernovae when they run out of nuclear fuel. This can lead to the formation of neutron stars, often seen as radio pulsars. These spinning radio lighthouses, first detected by Jocelyn Bell in 1967, are some of nature’s most extreme objects. With a mass of a bit more than that of the sun compressed inside a radius of about 10 km (the size of the core of London, half the way to the M25), they often spin at an astonishing rate. For example, the Crab pulsar, which is associated with a supernova explosion recorded by Chinese astronomers in 1054AD, spins around 33 times every second, and it is by no means the fastest one. These objects test our understanding of much of modern physics. They require Einstein’s General Relativity and, as we will see, provide us with unique ways of testing the theory.

Vastly improved technology – and a wider range of astrophysics – has led to many impressive tests of General Relativity. For example, NASAs MESSENGER (in orbit from 2011) measured Mercury’s perihelion shift to a precision of a fraction of a percent. The same effect is also tested in the much stronger gravity setting of the Binary Pulsar (PSR B1913+16), discovered by Richard Hulse and Joseph Taylor in 1974. For this system the perihelion advances about 4 degrees per year, which means that the relativistic effect accumulates much faster and therefore provides a better test of the theory.

When it comes to the bending of light, arrays of radio telescopes have used distant quasars passing behind the sun to confirm Einstein’s prediction to the 0.01% level. ESAs GAIA mission, which aims to track the motio n of 1% of the stars in the galaxy, is expected to test the light bending to the level of one part in a million. This will not leave much wriggle room for alternative models…

Light bending has, in fact, become an important tool for modern astronomy. Gravity can lens distant sources in different ways, forming multiple images, arcs or in some cases complete circles. After matching to detailed calculations, the distortion of light originating in the distant universe (way back in time!) provides clues of the presence of unseen matter between us and the source. Combined with data from, for example, the Sloan Digital Sky Survey this has given us one of the best handles we have on dark matter in the cosmos.

Quite naturally, the development of atomic clocks was key to a number of precision tests of General Relativity. The theory says that gravity makes clocks slow down. But in our everyday life, this effect is tiny. However, it has a number of repercussions. Einstein himself noted that the frequency of light should shift toward the red as it struggled to escape from the gravitational pull of the sun. Basically, the light gets a little bit “tired”, loses some of its energy and shifts towards a lower frequency. The first attempt to measure this effect took place already in 1917, but the experiment was simply difficult for the available technology (the surface of the sun is “messy”). The solar redshift would not be measured until 1962. By then the first precision test of the redshift of light had already been carried out by Robert Pound and Glen Rebka at MIT. In 1959 they compared the energy shift for photons dropped down a 23 m tower to that of photons launched upwards the same distance. In essence, this was the first measurement of the mass of the photon.

A few years later, in 1964, Irwin Shapiro discovered a related effect; a fourth test of Einstein’s theory. Light slows down as it passes through a gravitational field, leading to a signal arriving a little bit later than it would otherwise have done. The Shapiro time-delay has by now been measured very precisely. As an example, in 2003 the delay of signals from NASAs Cassini spacecraft were found to agree with the theory to the 0.001% level.

The obvious way to use atomic clocks to test Einstein is to keep one clock in the laboratory and fly another one at high altitude. If the theory is correct, the flying clock should tick faster than the one left behind. But this experiment is not as “straightforward” as it may seem because one has to weigh in the fact that Special Relativity says that a moving clock slows down.

The first successful experiment of this kind was carried out by Joseph Hafele and Richard Keating in 1971. They brought one of their atomic clocks on a round the world trip – and back again – on commercial airliners. The clock took up two seats, but scientists had to settle for one each. When they returned and worked out the combined effects of both relativity theories they found the experiment to be in good agreement with the expectations.

The slowing down of clocks has obviously been tested at much higher precision since those pioneering days, mainly by going into space. The trailblazer for this was Gravity Probe A, a rocket experiment launched in 1976 carrying a hydrogen maser (the microwave equivalent of a laser) clock. When it splashed down in the Atlantic after a short 1 hour and 55 minute flight, it had tested the theory prediction to better than 0.01%.

The efforts to reach higher precision are continuing. In 2016 the ACES/Pharao clock experiment will fly on the International Space Station. This will be the most accurate measurement of time yet.

Before moving on, it is worth mentioning Gravity Probe B. After a very long time in preparation, this experiment was finally launched in 2004. It successfully used sensitive gyroscopes to measure how the earth drags space and time along with it as it rotates, confirming the predictions of Einstein’s theory with a precision better than 1%.

The fact that gravity makes your head age faster than your feet may not have a huge effect on your life, but many of us are regularly making use of technology that simply would not work if we did not account for relativity.

The multi-billion dollar GPS system has 24 satellites orbiting the earth, each carrying a precise atomic clock, allowing navigation with a precision of 15 meters and local time determination to 50 billionths of a second. The satellites move at 14,000 km per hour in orbits that circle the earth twice a day, much faster than clocks on earth. Special Relativity says that moving clocks move slower and if we work it out we find that this amounts to 7 millionths of a second per day. However, in the curved space-time the clocks on the ground move slower. This effect, in turn, makes the orbiting clocks move faster by 45 millionths of a second per day. Combining the effects, the moving clocks move faster by 38 millionths of a second every day. The upshot of this is that, if we ignored relativity, navigational errors would accumulate at the rate of more than 10 km per day. More than enough to make Satnav driving dangerous...

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The rebirth of relativity owed much to the effort of a few dedicated individuals, like John Wheeler at Princeton. Wheeler was intrigued by the apparent contradiction of gravitational collapse; the notion that gravity could drive the collapse of a massive object, wrapping space and time around it like a dark cloak, hiding it from view. Until the 1960s the discussion of such objects – what we now, thanks to Wheeler, call black holes – was confused. And there was no real evidence that such objects existed in the Universe.

The situation changed dramatically with the first detection of x-rays from outside the solar system in 1962. As soon as one of the strongest sources, Cygnus X1, was found to be varying on very short timescales it was suggested that it might be a black hole. The case for this strengthened with the data from the Uhuru satellite, launched in December 1970. From the Uhuru observations it was inferred that most of the galactic x-ray sources were compact objects accreting matter from a binary companion. One can use the orbital data to “weigh” the dark companion in these systems, and we are now convinced that Cygnus X1 is a black hole with about 15 times the mass of the sun, far too massive for any (reasonable) alternative explanation. The evidence eventually became so overwhelming that Stephen Hawking conceded his famous bet with Kip Thorne…

Since the 1970s we have learned that black holes come in vastly different sizes. Absolute giants lurk at the heart of many galaxies.

In May 1994 NASA announced that the Hubble Space Telescope (HST) had “seen” a black hole at the centre of M87. The gas in the central parts of the galaxy was whirled around rapidly. Spectrographic measurements pointed towards an unseen mass of more than 2 billion times that of the sun. Another impressive case for a supermassive black hole was presented a year later when emission lines from water masers were used to accurately map the gas motion in the spiral galaxy NGC 4258. The Very Long Baseline Array resolved a disk surrounding a compact dark mass, and the associated rotational velocities indicated a black hole nearly 40 million times as heavy as the sun. There is now plenty of similar evidence, and we are beginning to understand how these large black holes influence galaxies and large scale structure formation.

Perhaps surprisingly, the best evidence for the existence of massive black holes comes from close to home. Since the early 1970s we know that an unusual radio source is located at the dynamical centre of our own galaxy. This source, Sagittarius A\*, has long been regarded a prime candidate for a supermassive black hole. The best evidence for this, which continues to strengthen, is based on remarkable infrared observations that trace the proper motion of stars near the galactic centre over more than a decade. The detected motion is consistent with a black hole weighing about 3 million times as much as the sun.

It has been a remarkable transformation. In little over two decades, we have seen black holes jump from speculation to mainstream astronomy.

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According to Einstein, space and time are flexible. They may stretch to the point where clocks appear to stop completely – as in the case of a black hole horizon. But the flexibility has more general implications. The theory predicts that all changes in gravity propagate as waves, tiny ripples in space-time moving at the speed of light.

These gravitational waves have proved elusive. For a long time scientists debated if they were even real – Einstein himself argued both for and against. As soon as the issue was settled in the 1950s – as a result of arguments by Hermann Bondi at King’s College and others - the first attempts were made to catch the waves. This effort, which was pioneered by Joseph Weber in the United States, has been going on for four decades without success, but we have every reason to expect that this is about to change.

First of all, there is strong indirect evidence that the theory is correct. Long term tracking of the orbital change of binary neutron star systems agree with the predictions. In the celebrated case of the Binary Pulsar, the rate of gravitational emission agrees with Einstein to a fraction of a percent.

Secondly, the detector technology has now reached the level where sources from beyond our galaxy should be detectable. We have instruments that are able to measure a change smaller than the size of the atomic nucleus over a length of several kilometers – an astonishing engineering achievement. In parallel, the quality of our supercomputer simulations – of, for example, colliding black holes – has improved to the point where we can be confident that we know what we are looking for.

There are good reasons to think that we are (finally) about to enter the age of gravitational-wave astronomy.

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As we have seen, General Relativity has been tested to high precision both in the solar system and stronger gravity regimes, like neutron stars. We have convincing evidence that black holes exist. But what about the cosmos on the large scale? What happens if we try to weigh the universe?

In order to understand the context of modern cosmology; let us take another look at Einstein’s equations, the shape of space balancing the presence and motion of matter. In principle, each and every solution to these equations is a universe. It may not be the one we live in, but it is a universe nevertheless.

When Einstein formulated his theory, the general belief was that the universe was static – it did not evolve. However, General Relativity pointed in a different direction, towards a universe that expanded or contracted. In order to fix this “problem”, Einstein added a term to his equations. The role of this term - which we now call the cosmological constant - was to make gravity push instead of pull. This way Einstein managed to reinstate the static universe.

Of course, history tells us this was a mistake. Edwin Hubble’s 1929 discovery that distant galaxies move away from us showed that the universe is expanding. The cosmological constant was dropped, but it never quite went away.

If the universe is expanding then it must have been smaller in the past. If you trace this evolution back far enough, do you reach a time when it all began? The first evidence for an initial explosion - the big bang - came when Arno Penzias and Robert Woodrow Wilson found a mysterious noise in their radio antenna in 1964. The noise was more intense than expected, evenly spread over the sky, and present both day and night. The noise suggested a uniform radiation from the universe, corresponding to a temperature of about 3 degrees Kelvin. This cosmic microwave background is a whisper from the big bang.

In the last couple of decades, cosmology has become a science of precision measurements. With space instruments, like COBE in the 1980s and more recently WMAP and Planck, we are probing the fine structure of the universe when it was about 400,000 years old. What we see are tiny variations that have their origin in quantum fluctuations in the very early universe.

These impressive experiments allow us to test our theories.

When different sets of data are put together we find that we need three components to explain the universe. Only a small fraction, less than 5%, is made up of normal stuff; atoms, molecules, the stars, you and me. About a quarter is dark matter, which we do not see, but which we know has to be there from, for example, gravitational lensing. The rest, more than 70% of the universe, is dark energy - the cosmological constant – required to explain the fact that the expansion of the universe is accelerating. Something keeps pushing.

The recent advances in cosmology are impressive but our current understanding is not satisfactory. Basically, we can explain only a small fraction of the universe (the matter). We have some idea of a larger part (the dark matter) but are utterly clueless about most of it (the dark energy). This is one of greatest challenges for physics today. It is not just a test of Einstein’s theory of gravity – although a plethora of alternative theories are being proposed to explain the data – it is a problem for fundamental physics.

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We have reached the end of the journey through the first century of Einstein’s curved space-time universe. Was Einstein right? Of course he was. Even in ways he would never have imagined. But this does not mean that our understanding of gravity is complete. It only means that we understand the universe a little bit better. General Relativity is not the final answer.

To finish, let us look ahead. What happens next? I obviously do not know when any breakthroughs may come, but I think we can be pretty certain that we will soon catch gravitational waves. This will be very exciting, and should help us explore the dark side of the universe. We may find out if the black holes we see in the sky are exactly the black holes of Einstein’s theory. In the future a gravitational-wave experiment in space (like eLISA, due to launch in the 2030s) may be able to provide a detailed map of the geometry of a black hole. Other experiments, like the Event Horizon Telescope, will provide complementary information. On the much larger scale, future experiments will continue to improve our understanding of cosmology. Hopefully we will make progress on the question of dark energy. What exactly is it? Perhaps the answer will require a connection between the very large and the very small; the elusive quantum theory of gravity.

We are struggling to develop a theory that reconciles the curved space-time of general relativity with the uncertainties of quantum theory. This quest is approaching its own centenary and I’m afraid we are still far from the answer. If this were a “popularity contest” then the answer would simply be “string theory”. But reality is a little bit more complicated than that. At the moment, string theory is a bit like an empty vessel. We can fill it with anything we want, all our hopes and dreams, but we have not (yet) managed to make string theory predictive. There are too many possibilities and no experiments to constrain our imagination. At least not yet…

During this first century of Einstein’s curved space-time universe we have seen many remarkable discoveries and insights, but we still have a lot of work to do. There are a lot of challenges to overcome. I suspect there will still be things to figure out in another 100 years’ time.

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