Einstein and the Universe

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Today's talk is very much motivated by the fact that this year is the 100th anniversary, the centenary of Einstein's famous papers on 'Relativity and the Photoelectric Effect' and 'Brownian Motion'. But I'm going to talk primarily about work that he did ten years later on Cosmology and Relativity.

Einstein is a nightmare for modern public relations people who work so hard to promote books and individuals and records and films. Einstein is the most recognised face in the world, the most photographed person… but on reflection you probably realise that you've never seen a colour picture of him, you've never seen any movie film of him and you've never heard his voice. And if you talk to an audience of specialist scientists and physicists, none of them, you would find, have heard his voice or seen a piece of film of him either.

He managed to become an icon of science without having any research group, without having any research student, without having an agent, without having a fashion advisor and, God help us, he didn't even have a web site. When Einstein died, a famous cartoon appeared by Herb Block in the USA and it rather summarised this overall view of his scientific contribution to the 20th century… a picture of the universe and the human contribution to its understanding.

The development of science that Einstein made such an important contribution could be summarised in a nutshell as 'changing perspective on the universe from one that's human centred to one that has no specific observer at all. If you look back to the most ancient picturesque views of the universe, you'll see a cosy picture in which human existence lies completely at the centre of the world. That was a rather paternalistic, theistic perspective on the human position.

Jump forward to the time of Copernicus, and you find a view that's a little less anthropocentric. The sun now sits located at the centre of the universe and the earth is in its particular orbit, a little further out from the sun. So, the position has changed; we're no longer located in a special position in the universe. Our view of objects in the universe is not necessarily special.

What Einstein began to do was to remove any special view that we had of the laws of nature, not just the locations of things in the universe. When you're in school - or at least when I was in school - you learned things called 'Laws of Motion' which Newton first taught us. The Newtonian view of the world is based on a picture in which there is some fixed space, rather like this stage I am walking around on, on which things move and happen. And as time moves forward, it does so in a uniform, straight line.

Nothing that goes on in the universe can change the rate at which time passes, in the Newtonian World, or can change the shape or nature of the stage of space on which everything is played out. And, we learn, there are certain rules which govern how things move around in that space: things like 'Newton's 2nd Law', 'F = MA', force is equal to mass x acceleration. So, if a body is acted upon by force, it will accelerate. If a body is being accelerated, it is being acted upon by force. This is a typical and most famous example of one of Newton's Laws.

There's something very strange about this law that you learn first at school and that is, it's only a law seen in the universe by special classes of observers. So, you have to be moving in a very particular way in order that your scientific observations will deduce that this is the Law of Motion. Why is that?

Newton himself was perfectly aware of these limitations. Suppose you are sitting inside a rocket and for some reason or another it starts to spin relative to the very distant stars. And you look out of the window - or whatever they have instead of windows on spacecraft - what will you see? Well, as the rocket spins in a clockwise direction, you will see all the distant stars spinning in the opposite direction past your window.

Things that rotate, that spin, are accelerating. So, what is happening as a result of you being in a spinning spacecraft is that you are seeing objects that are accelerated but they're not acted upon by any forces that are causing them to accelerate. So, if you are in a rotating spaceship, you do not observe Newton's Second Law, F=MA. The only people who observe that law are people who are moving in systems, in rocket ships that are not accelerating, which are not rotating and they're not accelerating relative to the distant stars. So, those simple forms of the Laws of Nature that Newton deduced are only seen by very special observers that have a very simple type of motion.

Einstein recognised that this is a rather unacceptable state of affairs. The complete formulation of the Laws of Nature shouldn't only be available or only be simple to some class of special observers who only happen to be moving a particular way. Everyone should discover the same Laws of Nature no matter how they are moving. And this is one of Einstein's motivations for extending Newton's picture of the universe and his Laws of Motion.

Einstein did it, really, in two ways. The first thing that he did away with was the old idea that space and time were just things that were fixed, like this stage: unchanged by the events that go on on top of it. Instead of thinking of space like a flat tabletop or this stage, Einstein's conception of space was more like a trampoline. It was elastic, malleable - as objects moved around on it, they changed the space of the surface, the space in which they were embedded. The motion that they have locally, the mass that they have, determines the shape of the space and so dictates how they are going to move in their next step.

If there's a very heavy mass sitting here, it will create a big distortion of the shape in space. If you were to throw another object like a planet, as it were, past here, it will move so it gets from this point to this point in the shortest possible time. And the way to do that on a curved surface is to take a curved path.

You give up the idea that there is some mysterious force pulling a planet towards an object. There are no forces at all. There's simply a distortion of the shape in space: everything moves to go along the straightest line it can possibly take on a curved surface.

In case you might think this is just another way of looking at things and there's nothing really different about this, there really is. If an object were to jump up and explode, ripples would spread out from it through the trampoline surface. Something that was sitting a long way away would eventually get hit by them and move in response to it. These are called gravitational waves and astronomers are just beginning their experimental search for those waves in the last year.

Another nice example is if we have an object that is spinning. If space is a flat stage on which the space remains flat and unchanged by things that go on, and if we spin something on it like a ball, then it doesn't affect anything elsewhere. But if space is really a malleable sheet, and if you spin something, it twists the trampoline surface of the space and that tends to drag objects far away around in the same direction. In the last year or two, the Gravity Probe B space probe has looked for and seen this effect as a result of the rotation of the earth on gyroscopes being flown around the earth. They are dragged around in the same direction that the earth is rotating.

Einstein's mathematical contribution was to find the equations that enable us to work out what that kinky geometry is for any distribution of material and mass and energy moving around in any way you like. You could work out the shape and then you could figure out how the shape makes objects, like planets, move around.

Those equations are very nasty; they are very, very difficult: there are not very many solutions of them known, and even to attack them with very large computers is very awkward. Those equations have a very, very wonderful mathematical form that solves the problem of the rotating rocket. They have a form such that however you moved, however you located yourself in the universe, you would always see those equations to have the same form.

They solve this problem of the democracy of observers of the Laws of Nature. So, all observers in the universe, no matter what gravitational fields they're subjected to, how fast they are spinning, how fast they are accelerating, they will always see the same Laws of Nature. In this respect, you could regard Einstein as having completed the Copernican Revolution that did away with special places and special viewpoints of the universe. The extraordinary thing about Einstein's equations is that every solution of them describes an entire possible universe. There has never been a theory of physics before which has had that remarkable property. Every solution of Einstein's equations describes a whole possible universe, and the name of the game is to find out which of those solutions describes best our universe.

What does the solution look like? Well, as a cartoon, you could view it as rather like a movie: one of those trampoline sheets that describes the state of the whole of space and the universe at this moment. And then the solution tells you, as time goes forward, how does the movie change, how does the shape of the space change as objects orbit, move around, expand, contract, explode? Each solution describes what physicists call 'Space-time'. A whole time unfolding of the shape of space: a map of the whole of space for ever in the future and forever in the past.

Well, Einstein's equations - there are ten of them - are much more complicated, much more difficult to solve than Newton's equations were. Newton had just one equation. And if you drew a picture of the domain, as it were, of possible universes that Einstein's theory predicts and describes, and overlaid a picture of the worlds and gravitational situations that Newton's theory described, you would see some overlap.

So, some of Newton's theory is part of Einstein's theory. When things move slowly, when gravity is very weak, Einstein's theory reduces to Newton's theory. You often find rather widely publicised and somewhat erroneous philosophies that talk about great revolutions, and how new theories replace old ones. This is not what happens in subjects like physics. New theories tend to extend the domain of applicability of the old theories. And if you take weak gravitational fields, low pressure, something like that, the new theory will reduce to the old one. So, it's contained within the new one.

The theories of Newton's which are not contained in Einstein's theory arise because Einstein's theory contains the proviso that nothing can spread information or send signals faster than the speed of light and Newton's theory allows signals to be sent at any speed you like, even at infinite speed. And it's instructive to see one of these forbidden universes, which are not allowed by Einstein's theory, but which are allowed by Newton's theory. And, they are very, very strange because people for centuries regarded Newton's theory as extremely simple and predictable and deterministic, and nothing unusual could happen; whereas Einstein's theory allows time travel and all sorts of counter-intuitive things to occur.

But strange things can happen in Newton's theory as well and here's one of them. There's a solution of Newton's Theory of Gravitation which describes the following situation: we have two planets, both of the same mass, big 'M', and they're orbiting around their common centre of mass, rather like the earth and the moon would if they had the same masses. And parallel to that plane, we have exactly the same thing: two other planets with the same mass orbiting around their common centre, some orbit in one direction and others orbit in the other direction, so there's no overall directional pull of the orbit. In between, there's a much smaller mass which is released to move on a straight line between the two centres of the orbits. What happens when you do that?

Well, when a third mass enters into a gravitational system where there are already two masses present, there is something of a crisis. What happens is that one of the masses gets kicked out very quickly and the other two recoil and this situation exploits this fact when the third mass comes up. It moves around and very quickly gets kicked back out and it comes back down and enters the world of the two masses, and they kick it out straight back up, and this process continues. The recoils make the two objects move away from one and other.

The extraordinary thing about the solution of this situation is that the size of the system, the distance between the two pairs of planets, goes to infinity in a finite time and the particle goes back and forth an infinite number of times in a finite amount of time on our watches as we're looking at it. This is completely counterintuitive; rather extraordinary.

Let's move on to look at some of Einstein's universes. From a human and cultural perspective, what's interesting is that almost all the great discoveries in the early days of cosmology, the solving of Einstein's equations to find some of these possible universes his theories describe, were made by four people. They were very different; they came from different countries and they had very different backgrounds.

Einstein himself was born in Switzerland and most of his work was done the early days in Berlin, the later part of his life spent at Princeton in the USA. Another instrumental figure was Willem de Sitter, a Dutch astronomer and Alexander Friedman, who was a meteorologist from St. Petersburg who died at a very young age after finding the most important solutions of Einstein's equations. He died as a result of his scientific work: he was a mathematical meteorologist, and for a period held the world altitude record for ballooning.

He would go up to very high altitudes, to make measurements of temperature and pressure and so forth in rather extraordinary, bizarre circumstances. He would deliberately allow himself to go into a state of unconsciousness having calculated that he would come around when the balloon dropped below a certain altitude so that he could make more measurements. His instruments would have been taking measurements while he was unconscious. Well, as you might imagine, this was not something that Health and Safety Regulations would recommend today, and eventually he died as a result of pneumonia contracted as a result of these draconian experiments.

The last actor in the drama is Georges Lemaître who was a Belgium Catholic priest who came as a student, after he was ordained as a priest, to Cambridge to work with Arthur Eddington. After that he went to the USA to take his Ph.D. at M.I.T. and then returned to Belgium. He, probably more than anybody, is responsible for the picture of the 'Big Bang', the hot, dense, expanding universe, that expands and cools from some apparent beginning.

The last important thing we have to know, the only equation we have to look at today, is that Einstein's theory gave one other new ingredient to our perspective of the universe. It created a new type of gravitational force, or a new piece of the force of gravity. So, if we had a particle that was being acted upon by the gravitational field of some mass 'M', then Newton taught us that it would feel an attracted force, and that force would fall off.

But Einstein's theory allowed another part of the gravitational force to exist, and we usually just call this the lambda term or refer to it as the lambda term. It's a term that's quite different, has a positive sign, so it's repulsive. Two objects would be repelled from each other because of this force, and it increases with the distance between them - this is very strange. This is an attractive force; this is a repulsive force. The equation shows the first universe to be found and it's sometimes known simply as 'Einstein's Universe' or the 'Einstein Static Universe'.

Einstein, in 1915. had never encountered the idea of an expanding universe that's rather familiar to us. No one had ever had the idea that the universe might be expanding or contracting. So, when Einstein saw that his theory allowed universes to expand, he thought this was really something you ought to suppress, it's not going to be realistic. In 1915 people didn't even know for sure there were other galaxies. Most people's conception of the universe amounted to our own galaxy and there was an argument that would continue for another thirteen years about whether some objects you saw in the sky really were other galaxies or just objects inside our own galaxy.

So, Einstein produced this conception of the universe that had motionless matter, things just stood still, it had a fixed size and nothing ever changed. Mr. de Sitter, just one year later, thought 'suppose we just try to find universes where only that strange lambda term is present, and we don't have the ordinary attracting force of gravity. And he found a universe that usually bears his name, 'de Sitter Universe', and it's very unusual. It expands forever but it never has a beginning.

So, this is an exponential curve, it's always increasing but it never reaches zero. So, this universe has no beginning, it has no end and its always increasing in size. Distant galaxies are moving away from each other, they're accelerating. That's why I call this 'matterless motion', so it doesn't have the ordinary gravitational forces of matter in it. This was the first time that someone ever represented the idea of an expanding universe.

Well, Einstein's 'Static Universe' soon became rather controversial. Lots of people started to look at this, tried to solve his equations again and they realised that, although this static universe was a solution of his equations, it wasn't a stable solution. It's rather like balancing a needle on its point: under perfect conditions you could make it stand vertically, but if you nudge it in any way it will fall in one direction or another. Einstein's universe is like that: if anything moves in it, any planet or comet or star, then the universe will start to expand, so it's unstable - not the sort of solution that you would expect to exist.

Eddington and Lemaître, who had worked earlier as his student, found new solutions to Einstein's equations which made explicit this instability. You could have a universe that was static from a past eternity but at some stage it would begin to expand. When it did so, it would eventually end up expanding like de Sitter's Universe. This was the next step in thinking about these universes, that you really had to have an expanding universe if you're interested in physically realistic ones.

Our friend Alexander Friedman in St. Petersburg, where nobody knew what he was doing, made the biggest step. He managed to solve Einstein's equations for pretty much all the interesting cases: universes which expand at the same rate in every direction and are, on average, the same everywhere. He found three sorts of universes.

There are universes that start expanding at some time in the past and they expand and keep on expanding forever. But he discovered that universes, rather like shares, can go down as well as up and there are universes which start with a slower expansion speed, they reach a maximum and then they start to contract. These are usually called 'closed universes' and they have a finite total lifetime. In between there is a sort of 'British-compromise' universe that just manages to keep on expanding to infinity doing the least possible amount of work.

Einstein and de Sitter got their names attached to this universe not because they found it but because they emphasised that this was the simplest and probably the most astronomically relevant universe, because our own universe expands tantalisingly close to that critical Einstein-de Sitter case. Today, cosmologists refer to these universes usually as 'Friedman Universes' or the 'Friedman Models'. To a first approximation they provide a beautiful description of the possible things that could go on in our universe. Astronomers use their observations to try to tell whether we have a long-range forecast that looks like that perhaps or perhaps like that, and to try to work out how far we're expanding, how old the universe is, its apparent beginning and so on. But this was a first approximation.

Lemaître wasn't content with finding just one universe: he found another one. He looked at situations like Friedman's and he included that lambda force again, which Friedman had excluded in those pictures, and he found that what happened then was you start expanding from a beginning, as though you're going to be in a universe that keeps going for ever or comes back to a crunch, but then after a while the lambda force takes over and starts to accelerate the universe by its repulsive force. So, you have a model which expands forever but has a change of gear from deceleration to acceleration.

Meanwhile, over in the United States, a rather different type of perspective was being adopted by Richard Tolman at Caltech. Tolman was the first person to try and inject real physics into what was going on in these possible universes. He was interested in universes which were closed, so they had a 'big bang' and a big crunch. He noticed that it was possible for there to be oscillating universes, so a universe would start to expand, hit a crunch, expand again and so on ad infinitum.

At first, he thought that all these cycles - rather like a Buddhist cosmology of things rising Phoenix-like from the ashes - would all be the same on the average: the same size, the same lifetime. But then he started to think about what would be the impact of the Second Law of Thermodynamics, the fact that things always go from bad to worse - as we know in practice. There are so many more ways for things to go from being good to being disordered than vice versa. And that's why, on average, why you do tend always to see things becoming more disordered rather than less. So, your children's bedrooms do not spontaneously become tidy, but they often spontaneously become untidy - because there are so many more ways for them to become untidy than there are to become tidy. So, it's much more probable that you will find that they become untidy.

In the case of the universe, what that un-tidying means is that energy tends to form - preferentially move from ordered forms into rather disordered forms and the most disordered form you can have is dust radiation. So, when you put your brakes on on your bicycle, the rather ordered rotational energy of the rotating wheel gets transformed into heat motion which heats up the brake locks and is in a rather random form.

Now, when this was applied to this oscillating universe, Tolman discovered it had a dramatic consequence. It made each cycle of the oscillating universe get bigger and last longer than the previous one. So it looked as though if you wanted to live in one of these oscillating universes, you have to pick your cycle rather carefully. It has to last long enough for stars to be able to form rather than to be one of these very short-lived, rather transient bounces.

Well, all these universes we've talked about so far are ones that expand rather like a spherical ball, the same rate in every direction and they're the same everywhere. There was a mathematician called Edward Kasner in the USA who, in 1925 - actually before those solutions we just looked at - discovered another remarkable solution of Einstein's equations which has since proved to be one of the most important in understanding how our universe got to be as it is, and we call it the Kasner Universe or Kasner's Universe and it expands in different rates and different directions.

If you imagine that there are three radii, it's rather like an expanding ellipsoid, this solution has a very strange property. The volume of the ellipsoid keeps getting bigger and bigger but although two directions expand and get bigger, the third direction gets smaller, it implodes. So, this universe is rather like an expanding pancake: it's getting flatter and flatter in one direction but bigger and bigger in the other two.

Kasner found out that if you looked at almost any type of very irregular universe that it was very well approximated by this type of behaviour. And soon afterwards, people like Einstein himself and Lemaître started to think about different types of universes that expanded in complicated ways; so, universes that were distorted, different rates of expansion in different directions, universes that rotated, spun around and universes that had those great ripples of curvature going through the shape of space because of violent events.

And people discovered that there were only nine varieties of universes of that sort, universes that different things in different directions but no matter where you were you would see the same things going on The most unusual of those universes was one discovered by the famous magician Kurt Gödel, who was at Princeton in the period after the war. He spent his lunch times talking with Einstein, usually about general relativity and matters of mathematical physics.

And, in 1952, Gödel found a very unusual new solution of Einstein's equations which rather shocked Einstein. It was a universe that was not expanding like all the other ones so it wasn't astronomically relevant. By this time, we knew that our universe was expanding, but this universe was spinning so it was a universe that was rotating, it had matter in it, it had that lambda force, but it was not expanding. But the dramatic feature of this universe was that it allowed time travel to occur.

Einstein and everybody else thought that this was impossible, that his equations couldn't allow something like time travel to happen. Surely it must be contrary to the Laws of Physics. But what Gödel was in effect showing was that Einstein's equations, which had all the Conservation Laws of Physics built into them, allowed time travel to occur. There was nothing paradoxical or contradictory about it.

Characteristically, Gödel published the solution but never showed anybody quite how he found it. It took a long, long time for other people to sort of find the mathematical root that would allow you to find this remarkable solution.

How could you have time travel, what does it mean, does that mean you can go back and kill yourself in the past and things like this? Well, in a universe where there is no time travel, you can regard the passage of time rather like soldiers marching one behind the other, in a straight line. Everybody is either in front or behind everybody else, so there is no ambiguity in where you are with respect to other people.

But in a universe with time travel, the timeline is closed and so now the soldiers march in a circle and everybody is both in front and behind everybody else. So, there is no well-defined ordering of events, there are just closed loops of history. All you have is self-consistent loops, self-consistent orders of history. You're not allowed to go into the past and kill yourself when you're a child. That doesn't produce a contradiction with your existence now. If you had been killed as a child, you would not exist now. The situation where you were killed but you exist now is not admitted as one of these self-consistent histories.

As an example of a self-consistent history, imagine I go back in time and I decide I'm going to shoot myself as a baby when I'm being held in my mother's arms, thinking this will create a contradiction with my own existence now. And so, I raise the rifle, take aim and just as I go to pull the trigger I feel a spasm in my shoulder because of an old injury and that causes the gun to jump in the air, there's a bang which startles my mother who drops the baby who injures its shoulder. That's a self-consistent history.

This discovery, though, was quite a shock - Einstein's equations contained the possibility of time travel. If you members of the Gresham community are interested in time travel - since many of you have great a interest in financial affairs in the City of London - time travel offers wonderful investment opportunities. If I say 2001 here to make the numbers right, you were to invest your €1 and come back in 1000 years and you'll find that it's grown 4% interest to €108,000,000,000,000,000… probably just enough to buy a Tube ticket back to Chancery Lane.

While these unusual types of universes that expand at different rates and different directions, and rotated and did other complicated things, created a very interesting puzzle because, in 1967 for the first time astronomers were able to measure the shape of the universe to very high precision and what they discovered was something of a shock. The universe is expanding at the same rate in every direction, they found, to better than 1 part in 1,000. Today we know, with most better observations, the answer is actually 1 part in 100,000. And, if you measure the sort of graininess of the universe, the lumps and bumps and irregularities in it, its level is about the same. The irregularity is only about 1 part in 100,000.

So, the universe is extraordinarily smooth and almost perfectly spherical in its expansion. That's a big puzzle because if you were just to pick solutions of Einstein's equations out of a hat, it's much more likely that you'll pick an irregular one. And it turned out if you picked a regular one, just like balancing the needle on its point, if you nudged it a little bit, the irregularities tended to grow, and the expansion tended to go at different rates, in different directions and the effects snowballed.

So, there was a big mystery: why is it that the universe is so uniform and so spherical in its shape today when the most common type of universe, the most likely type of universe that's a solution of Einstein's equations, behaves completely differently? This gave rise to a programme of work which I worked on while I was a student long ago, and the programme of work was called 'The Chaotic Cosmology Programme' and created lots of chaotic cosmologists.

The idea was, you wanted to try and explain why the universe was orderly today by the following idea: You imagine that it starts in some very complicated, chaotic way - you don't even need to know precisely what it is. Then you try to show that there are physical processes like friction, dissipation, smoothing of irregularities that steadily eradicate all those asymmetries and non-uniformities so that if you wait billions of years, you always end up with a highly ordered universe, no matter how you began.

It's rather like having a big bucket full of oil. If you stir it in a very chaotic way, you can even put a blindfold on, come back in 30 seconds and you know exactly what the surface of the oil will be like. It doesn't matter how you stirred it. The friction in the oil will damp out all the irregularities and motions, and it will just be smooth and uniform.

So, it's exactly the same idea. Well, unfortunately this didn't work. One of the things I did as a graduate student was to show that there was an awkward price to pay for this, that you could indeed contemplate damping out lots of irregularity, but the Second Law of Thermodynamics means that you have to create entropy and radiation in the process. So, if you measure the total amount of radiation in the universe today and do the right calculations, you can put a limit on the maximum amount of this eradication that could have gone on in the past. It turned out that you're only allowed a tiny, tiny amount of removal of irregularity in the whole past history of the universe. And this process could not explain why the universe was so regular today from very chaotic starting conditions.

The next step in trying to understand this process, to try to stir up the universe, was to find what was the most complicated solution to Einstein's equations that have ever been found. And it has the name of the 'Mixmaster Universe'. Mixmaster is a sort of a food blender on the American market and the Mixmaster Universe acts a bit like a food blender. It's like our Kasner Universe expands in two directions, implodes in the other but every so often it keeps permuting the imploding direction around. It oscillates; it's rather like an expanding, wobbling jelly. In one direction the jelly expands in two directions, and it implode in the other and then it keeps oscillating in two directions for a while, then the imploding direction swaps over, oscillates with the other direction for a while, swaps over and so on forever.

This was a universe which might mix up irregularities very efficiently and then smooth them out. Again, the price we paid was too much radiation. The solution to this problem, the regularity of the universe, only came in 1981 and it was the result of something that's become known as the 'Inflationary Universe'.

The Inflationary Universe explained why our universe looked so smooth and uniform, not by doing away with irregularities, dissipating it, but by sweeping it away where you can't see it. Imagine that there is a little bubble of the universe, close to the beginning of its expansion, and there is a dramatically fast expansion of that bubble very, very early on for some short period. As a result, it can expand so much that by the present it would encompass the whole of what we now call our 'Visible Universe' 14,000,000,000 light years away.

The whole of our Visible Universe has been grown from the expanded image of one region that's so tiny it can be kept smooth just by simple statistical processes without any dissipation. If we could look beyond our horizon 14,000,000,000 years away, we would see lots of irregularities in the universe behaving very differently to how it seemed to behave inside our horizon. So, all the non-uniformities and irregularities have been inflated and swept beyond our horizon. They're still there but our whole visible universe is the expanded image of a region that's so small, it's essentially smooth and uniform.

This inflation process is produced essentially by that lambda force that Einstein introduced all those years ago. Physicists discovered it's possible when the universe is very young and very hot, for physical processes to produce a temporary addition of that lambda force. So, for just a brief period, the force appears, accelerates the expansion, the forms of matter that do it then decay away, and normal service is resumed, and the universe has just become much bigger than it would have otherwise have become.

This picture of the universe makes our conception of the geography of the universe much more complicated then when we did geography at school. You see, the universe may be very smooth and uniform within our visual horizon 14,000,000,000 light years away but if we could see beyond that, it predicts that we should find that the universe would be very, very different, both in structure and perhaps in the nature of some of its laws because those regions beyond our horizon will inherit the properties of other tiny bubbles which expand and are never seen by us. This is sometimes called the ‘Chaotic Inflationary Universe’.

It was then generalised into the most modern picture we have of universes of this sort. They’re sometimes called the ‘Eternal Inflationary Universes’ and the Eternal Inflationary Universe is a consequence of that last picture that people were rather surprised by. The Eternal Inflationary Universe involves these little bubbles again which inflate and eventually encompass the whole of our visible universe.

It was discovered that they have a particular property, that having inflated they necessarily create within themselves conditions for little pieces of themselves to inflate again. And those pieces that inflate to produce new large bubbles will create within themselves conditions for further inflation. So, the inflationary process is self-reproducing, eternal to the future, probably eternal to the past.

We see ourselves as inhabiting one of these inflated bubbles - we’re part of a grand process that we might call a ‘Multiverse’. Inside this bubble where we live is an apparent beginning to and there may be an end, there may not; however, the whole process, the multi-verse of all the bubbles is a process that has no end at all. It’s well described by that first expanding universe solution that Willem de Sitter found. It’s a process that increases exponentially in size as time goes on - there is no beginning and there is no end. So, the question ‘did our universe have a beginning?’ - the present has a rather unusual answer. Our bit of it probably did have a beginning but it is part of something that’s much larger and much more complex that probably did not have a beginning.

Well finally, what’s the best view then of what’s going on inside our little piece? We have what we might call ‘the puzzling universe’. It’s the type of universe we seen before – it is Mr. Lemaître’s other universe. Just a few years ago, astronomers using the capability of the Hubble space telescope were able to observe the expansion of the universe out at unprecedented distances…quite close to the 14,000,000,000 edge of our visible universe, our horizon.

What they discovered from those observations was that the expansion of the universe had rather recently begun to accelerate, it has changed gear. So, when the universe was about 75% of its present age the expansion started to accelerate as though it had indeed become dominated by this lambda force, which Einstein taught us could exist. It almost started to inflate again.

We don’t know in detail what is the cause of the lambda term. Why did it suddenly set in at that particular time? It’s puzzling because, had it set in when the universe was about 65% of its present age or 70% of its present age, then we wouldn’t be here because there wouldn’t be any stars, there wouldn’t be any galaxies and there wouldn’t be any planets because the universe would have started accelerating so early, material would be whipped apart at high speed, it could never coagulate and condense and beat the expansion by forming galaxies and stars. So, it’s rather crucial for our own existence that this acceleration did not start earlier than it did.

It’s the biggest unsolved problem in modern cosmology to try to understand the source of that lambda term creating acceleration. Perhaps to understand why it took over the expansion when it did and whether its always going to accelerate the expansion or whether it will one day fade away and the universe revert to its old trajectory.

The acceleration really does away with the option that the universe might one day be heading for a big crunch in the future. If this lambda force is a permanent feature, our universe is destined to expand and last for ever. This lecture, you’ll be relieved, will not.