BANG, BOUNCE OR ETERNAL BUDDING?

There is no bigger, more profound topic: **JASMIN FOX-SKELLY** explores the myriad models and mysteries that make up our multitude of scientific explanations of the origin of the Universe.

AROUND fourteen billion years ago there was nothing. No atoms, no gravity and no time. Then a Universe burst into existence. An infinitesimally tiny particle suddenly inflated to a huge size in a fraction of a second. Thus states the Big Bang theory, first put forward in 1931 by Georges Lemaître, a Belgian cosmologist and Catholic priest. Met at first with incredulity, the theory is now scientific dogma, accepted as being incontrovertibly true, but is there more to the story? Over the years other models have been proposed to explain how the Universe came to be, although almost all have a variation of the Big Bang at their core.

What caused the birth of the Universe? AN artwork by Greg Smye-Rumsby.

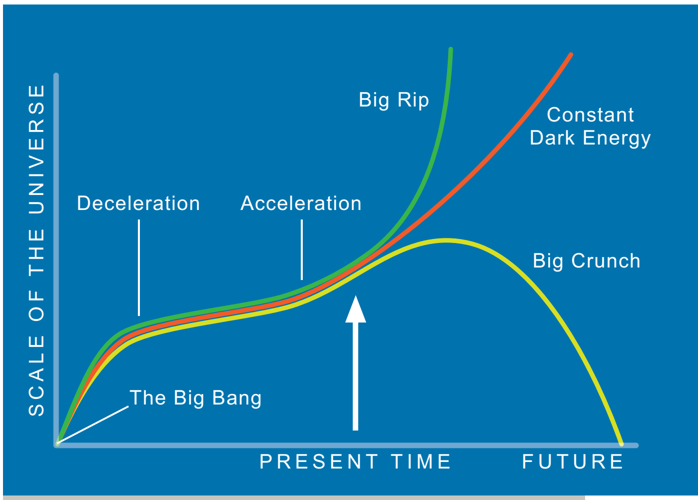
THE BIG BANG

IF we assume that the laws of physics are universal and do not change with time or location in space, and that we do not observe the Universe from a privileged location such as at its centre should such a place exist (it doesn't), then the Big Bang theory says that the Universe should have certain properties that can be objectively measured. We should be able to see that the Universe is expanding and that it was once hotter and denser than it is now. If the Universe began in a burst of radiation, a prehistoric trace of that radiation should also still linger in today's cosmos.

Evidence for all these properties have been found. In 1929 Edwin Hubble was busy measuring the distances and motions of galaxies when he surprised everyone, including Einstein, by discovering that the Universe is expanding. Hubble found that the galaxies he looked at were moving away from us at very high speeds. This shifted the colour of their light towards the red end of the colour spectrum. Hubble also found that the further away a galaxy was, the bigger its 'redshift'.

His observations suggested that the cosmos is expanding away from a single point, the fabled Big Bang. As astronomers' abilities to measure the distance of galaxies improved over the years, Hubble's discovery that the Universe is expanding was confirmed. Not only that, but by measuring the rate of expansion (called the 'Hubble flow') it was possible to determine the age of the Universe by extrapolating backwards and calculating when all the galaxies would have been in one place at the Big Bang. The latest measurements set this date as 13.81 billion years ago.

In the moments after the Universe came into being, the Big Bang would have released phenomenal amounts of energy. If the Big Bang theory is correct, then we should still be able to detect that energy today, cooled to microwave wavelengths by the expansion of the Universe. The existence of the Cosmic Microwave Background radiation, or CMB, was first predicted by Ralph Alpher and George Gamow in 1948, and was inadvertently discovered in 1965 by Arno Penzias and Robert Wilson at the Bell Telephone Laboratories in Murray Hill, New Jersey. The cosmic radiation was interfering with a radio receiver they were building, causing a strange static noise. When researchers at nearby Princeton University, who happened to be devising an experiment to find the CMB, heard about the problem with the radio they immediately realised that the CMB had been found. Penzias and Wilson shared the 1978 Nobel prize in physics for their discovery.

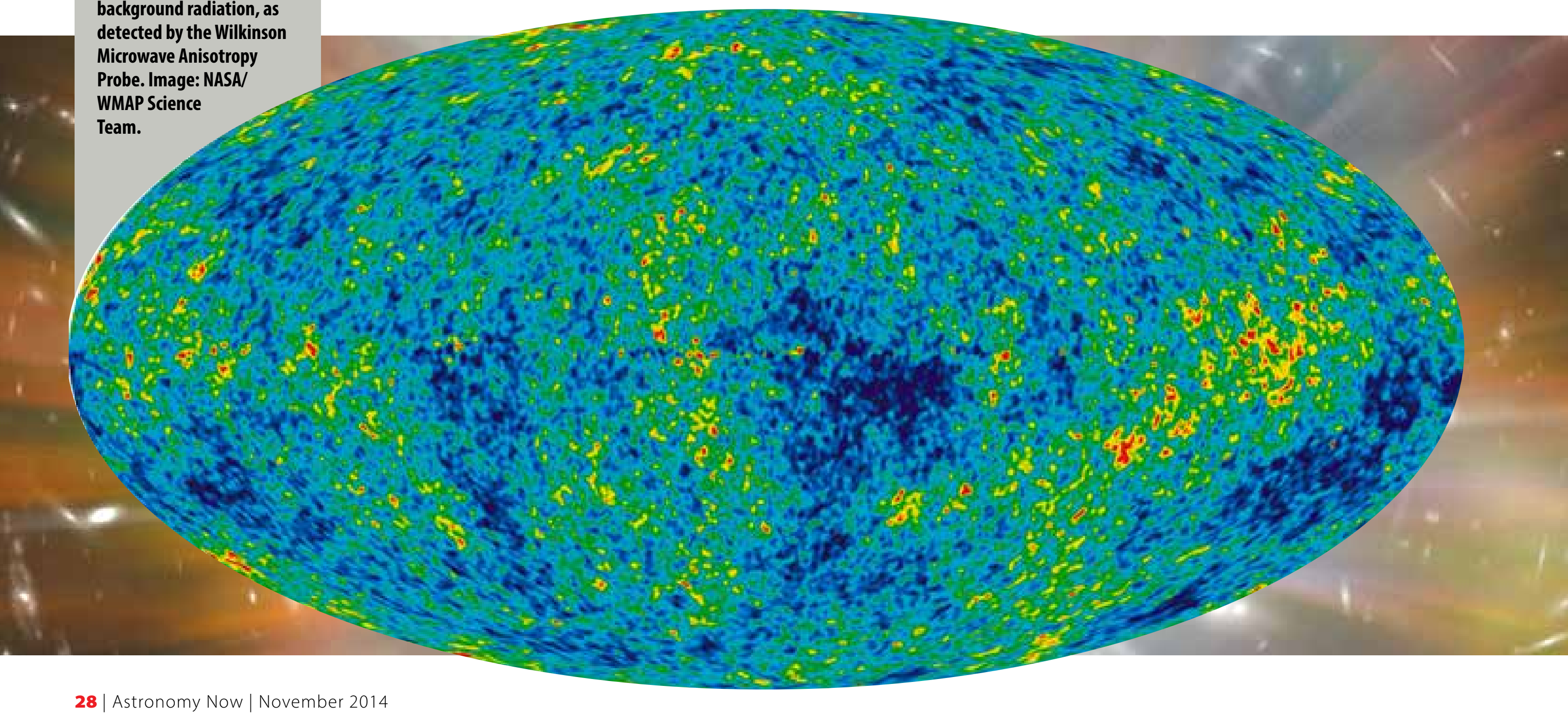


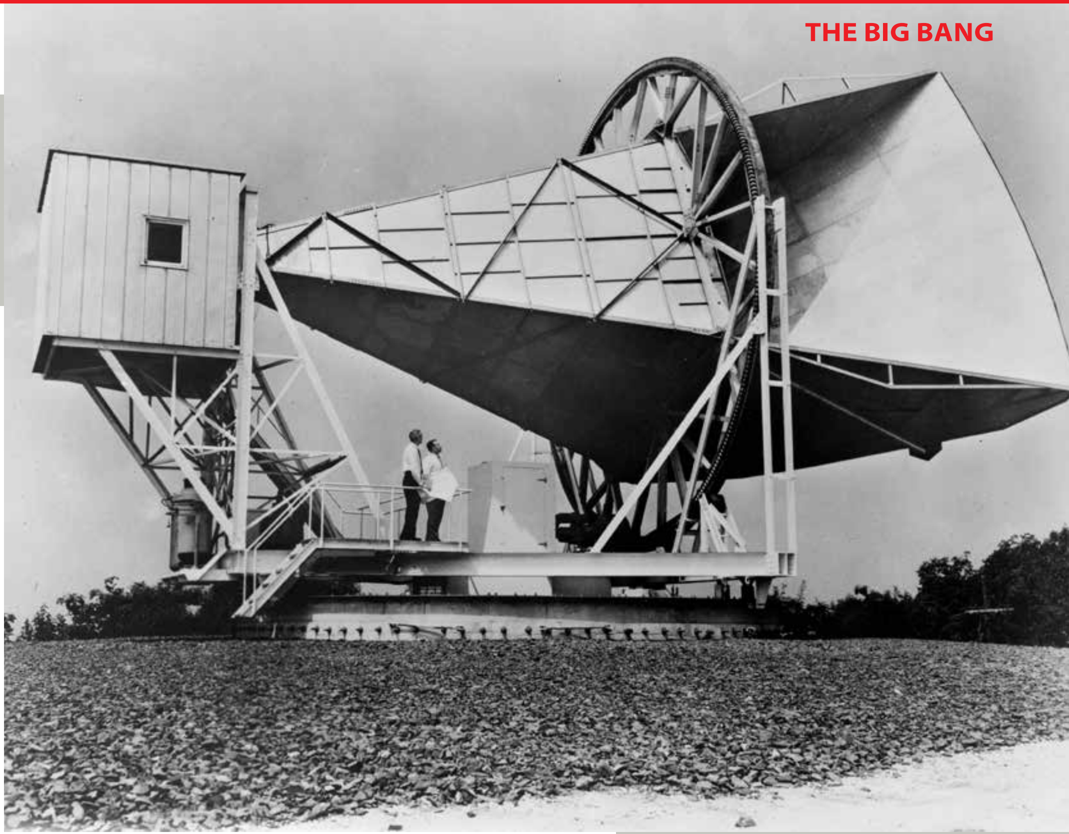
Various scenarios of the fate of the Universe following the Big Bang. The Universe could continue to expand forever and if dark energy is strong enough, even rip apart. On the other hand, if the mass density of the Universe is great enough, gravity will eventually cause the Universe to collapse into a 'big crunch' or, perhaps, a 'big bounce'. AN graphic by Greg Smye-Rumsby.

AMENDMENTS TO THE BIG BANG THEORY

Although many observations of the Universe support the Big Bang theory, there are aspects of the cosmos that have been a bit of a stumbling block. For example, the Big Bang theory predicts that the distribution of stuff in the Universe should be even, with no clumps of matter or any large spaces in between. However, today we see clumps of matter in the shape of individual stars, galaxies and clusters of galaxies, while there are huge voids between them. If the matter in the Universe had started out smooth, there would have been no regions of stronger gravity to start to pull material together into denser clumps. So how did they form? Cosmologists believe that there were tiny fluctuations in the nearly-uniform density of the early Universe, like ripples, which under the pull of gravity grew into the chains of galaxies that we see today. These fluctuations can be detected in hot and cold spots found in the cosmic microwave background.

The cosmic microwave background radiation, as detected by the Wilkinson Microwave Anisotropy Probe. Image: NASA/WMAP Science Team.





Arno Penzias and Robert Wilson stood underneath their giant radio 'horn' antenna with which they discovered the CMB. Image: NASA.

Another problem is why deep space looks broadly the same on all sides of the sky, and why the Universe is so flat. In order to incorporate all of this into the Big Bang model, some additional theories were needed. The idea of inflation – that the cosmos experienced an exponential growth spurt in its first trillionth of a trillionth of a trillionth of a second of life – was proposed in the early 1980s in an attempt to fill in these gaps. If the Universe quickly expanded this process would smooth out space–time, making the Universe flat. It would also explain why different sides of the sky look the same, as regions of space that were once close to each other would be spread far apart today, on opposite sides of the visible Universe.

Although inflation would seem to be the answer to many puzzles of the Universe, until recently there was little direct evidence that it took place. However, the theory of inflation makes one prediction that is testable: if it happened then waves of gravitational energy would have left ripples in the fabric of space that we should be able to detect by looking at the Universe's ancient light, the CMB. This year astronomers thought they had finally detected these telltale ripples (see *Ripples from the early Universe*, *AN* April 2014), but since then other researchers have cast doubt on the findings, suggesting that the imprint of the ripples they found could just be interfering noise from dust within our own Milky Way.

When Hubble discovered that the Universe was expanding, astronomers assumed that gravity would eventually cause the expansion to slow down. However, in 1998 it was discovered that the rate of expansion was actually speeding up – the Universe had begun to increase its rate of expansion about five billion years ago. As a result, the Universe is now bigger and emptier than we previously thought. Two teams of Nobel Prize-winning cosmologists had measured the distance to type Ia supernovae – exploding white dwarfs that all reach the same maximum brightness, allowing us to determine how far away they are based on how bright they appear to us. The researchers found that the more distant the supernovae, the further away from us than expected they were, as though a mysterious force, subsequently called dark energy, was causing the expansion of the Universe to accelerate, not slow down.

Physicists now believe that in the first phase of the Universe, matter dominated the agenda and, under the attractive force of gravity, progressively larger and more complex structures were formed, from stars to galaxies to clusters and superclusters of galaxies. It seems that five billion years ago we entered a new phase where dark energy became the dominant energy in the Universe. Unlike gravity, dark energy is self repulsive, which means that as the Universe pushes away from itself it will expand even more rapidly, heading into a period of increasing emptiness.

So how sure are we that the Big Bang took place? According to Paul Steinhardt, the Albert Einstein Professor of Science at Princeton University and a professor of theoretical physics, it depends on what you mean by 'the Big Bang'.

"Cosmologists and the public mean different things when they talk about the Big Bang theory," he says. "To cosmologists, the idea is simply that the Universe was once hotter and denser in the past and is becoming cooler and less dense in the future. There is overwhelming evidence that this is so.

"The public thinks of the bang itself – the beginning of space and time. Yet cosmologists are less sure about the bang itself. The Big Bang picture is incomplete because it does not explain why the Universe is so uniform and flat on large scales, or how large scale structures such as galaxies came about, or why there are hot and cold spots in the microwave background. Inflation was invented as an improvement to explain these features. However, inflation itself requires very special initial conditions, which makes it incredibly unlikely; and, once started, it continues forever."

Edwin Hubble, who discovered that the galaxies were moving away from us in an expanding Universe.

If cosmologists are unsure about what happened in the beginning of time and space then perhaps there is room for alternative theories. For example, what if the Universe did not actually begin 13.8 billion years ago, but rather 'rebounded' from the collapse of a previous existence?

THE BIG BOUNCE

THE 'Big Bounce' theory suggests that the Universe is like a looped woven fabric that gives space itself an atomic structure just like matter. The theory relies upon something known as loop quantum gravity (LQG), which says that if the Universe becomes more dense, gravity begins to repel itself, in the same way that a spring that is squashed is harder to compress. This means that if the Universe collapsed, it would become more dense, gravity would begin to repel itself and, after it reached a critical small size, the Universe would then rapidly expand again.

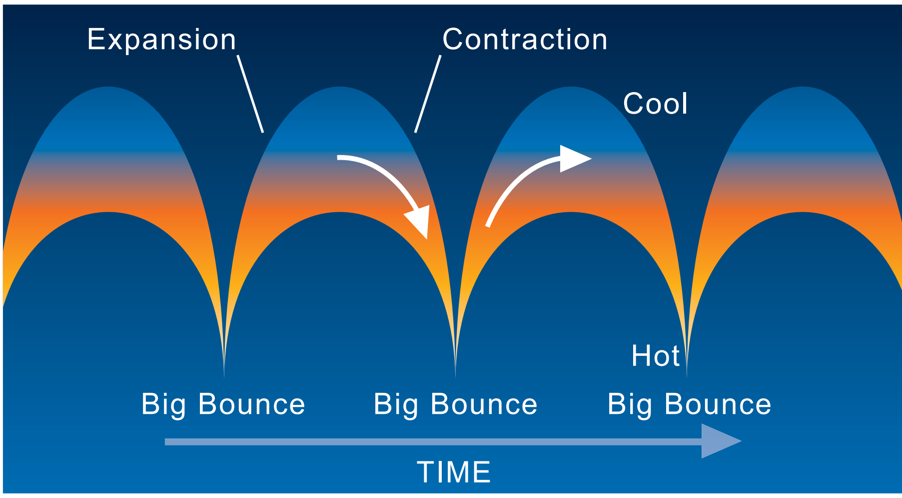
The Big Bounce theory would solve the problem of what came before the Big Bang, as it would simply have been the Universe contracting before reaching its smallest possible size and then expanding again, like a recycled cosmos. It would also provide a credible explanation as to why inflation occurs. Indeed, the Big Bounce theory actually fits more with the idea of inflation than the Big Bang theory. This is because Einstein's General Theory of Relativity states that for inflation to have happened a specific set of conditions in the early Universe, with an unlikely probability of 6×10^{-92} of occurring, would have to be present. However, with the Big Bounce model, where the Universe emerged from the remnants of an earlier Universe that had been squeezed by gravity, the probability of inflation happening increases to almost one.

"Although the Big Bang is often portrayed as the event at which our physical Universe was born, the equations that this idea is based on – Einstein's General Theory of Relativity – do not apply at the very high densities of matter that would have been present at the beginning of the Universe," says Abhay Ashtekar, a theoretical physicist and Director of the Institute for Gravitational Physics and Geometry at Pennsylvania State University.

"To obtain a more reliable account of what happens at the very high densities and space-time curvature, one needs a deeper theory that unifies general relativity with quantum physics. A leading approach to this goal is loop quantum gravity, in which the the fabric of space is woven by 'quantum threads'."

The equations for this theory predict that a huge repulsive force halts the formation of a singularity – the Big Bang – and the Universe bounces.

In the Big Bounce scenario, the Universe expands and cools, before eventually contracting and heating up again until it reaches a point where it bounces back again, expands, contracts and repeats the cycle. AN graphic by Greg Smye-Rumsby.



THE STEADY STATE UNIVERSE

IN the 1940s Sir Fred Hoyle developed an alternative mathematical model of the Universe. He stated that instead of all of the matter of the Universe being created in one moment, it is created continuously. Hoyle accepted that the Universe was expanding, but said that if all the matter in the Universe was created in the Big Bang then as it spreads out it should become less dense and yet the Universe continued to look the same in all directions. How could the Universe continue to look the same when observations showed it to be expanding, which should thin out its contents? Hoyle said that the answer must be that matter is continually being created between galaxies as they spread out, at a rate that keeps the average density of the Universe the same as it expands. The amount required would be undetectably small — about a few atoms for every cubic mile each year.

A 'Steady State' Universe would be infinite, with no end and no beginning, therefore avoiding the awkwardness of a Universe coming from nothing – interestingly, it was Hoyle who coined the term Big Bang in 1949 during a discussion about the subject on the radio. Along with the Big Bang theory, the Steady State Universe would also explain the outward rush of the galaxies discovered by Edwin Hubble in the 1920s. However, although it avoided the problem of a Universe that seemed to come from nowhere, it replaced it with the problem of matter continuously appearing from nothing.

The theory has been largely discredited today as a result of significant evidence to the contrary. First, when astronomers discovered quasars in 1962, which are the black hole-powered bright cores of mostly very distant galaxies, they realised that the Universe did not actually look the same in all directions. Because the vast majority of quasars lie exceedingly far away and hence a long time ago, their existence disproved the idea that the Universe looks essentially the same from every position at every time. The distant and therefore ancient Universe is not the same as the younger Universe nearby. Then the nail in the Steady State coffin was really hammered in when Penzias and Wilson discovered the CMB, which the Steady State theory had no way to explain.

"The Steady State model was initially rejected because it cannot explain the existence of the cosmic microwave background or the existence of quasars," says Steinhardt. "Today there is much more evidence against the Steady State picture. Hubble Space Telescope images show us that the Universe was a very different place in its past than it is now."

Sir Fred Hoyle's 'Steady State' Theory did not stand the test of time.

ETERNAL INFLATION

Alan Guth, the father of inflation. Image: Kulvinder Singh Chadha.

ANOTHER competing theory for the origins of the Universe is the 'Eternal Inflation' theory. As we have seen, in 1981 physicist Alan Guth suggested that the young universe had undergone a brief period of runaway expansion, which he called inflation. He pointed out that when the Universe grew exponentially in the first tiny fraction of a second after the Big Bang, some parts of space-time could have expanded more quickly than others. This could have created 'bubbles' of space-time that could have grown into individual universes, each governed by their own unique laws of physics. In the late 1980s Guth and other physicists suggested that this inflation could be happening over and over again in an eternal process, where pocket universes much like our own pop out of an un-inflated parent Universe all the time.

Some of these pocket universes would eventually collapse into black holes, while others would expand forever, eventually thinning out and becoming the new empty space from which more inflation could start, beginning the process again. If a multiverse of parallel universes exists then there would be no need for a single Big Bang. Instead new universes would be constantly budding off. Many cosmologists believe that the theory of inflation lends itself perfectly to a multiverse scenario. Yet one problem with the theory of internal inflation is that it is – at least at present – scientifically untestable.

"In eternal inflation the Universe becomes an endless sea of patches of space that exhibit every conceivable cosmological property," says Steinhardt. "This creates a problem because it makes inflation scientifically untestable, since literally any outcome can occur in eternal inflation and does so an infinite number of times."

Quasars are common in the distant Universe, proving that the Universe is not the same as seen from any location at any time. Image: ESO/M Kornmesser.

THE BRANE UNIVERSE

STEINHARDT has his own theory about what happened at the beginning of the Universe. Along with physicists Justin Khoury, Neil Turok and Burt Ovrut, he suggests that there is no beginning of time, but that instead our Universe exists on one of two three-dimensional membranes, or 'branes' floating in a four-dimensional space. One analogy would be how a sheet of paper blowing in the wind is like a two-dimensional membrane inhabiting our three-dimensional world. In Brane theory our entire Universe is just one sheet, a 3-D brane, moving through a four-dimensional background called 'the bulk'. The two branes are locked in an endless oscillatory motion in which they get closer to one another, 'bounce' through each other, withdraw and then creep together again. Each bounce is like a fresh Big Bang, sending ripples of phenomenal amounts of energy through the Universe, which would, from the inside, look like a tremendous explosion.

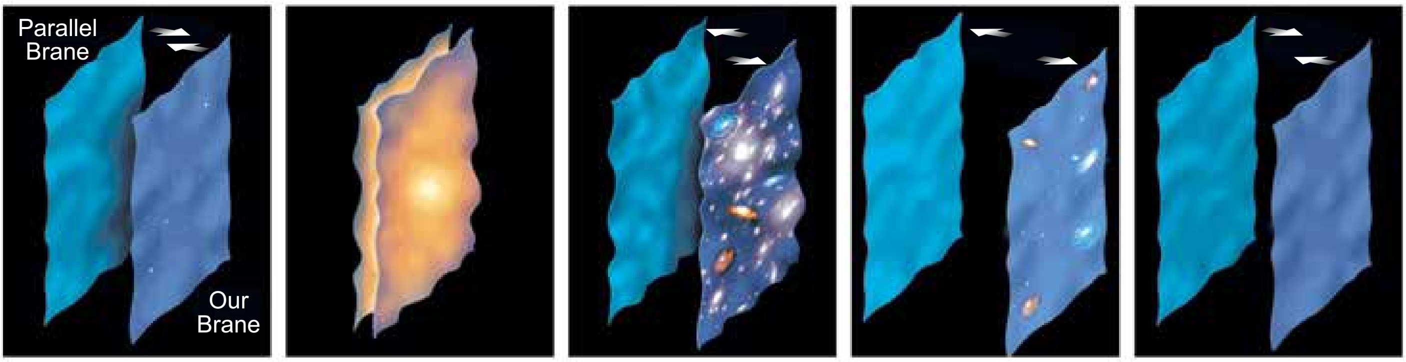
Steinhardt and Turok have since revised their brane theory into a new 'cyclic theory', also known as the 'ekpyrotic universe'. In this theory our Universe is still thought of as one of two 3D branes separated by an extra dimension which, over the course of trillions of years, bounce off each other. However, in the cyclic model, dark energy plays an essential role.

At first, matter and radiation are dominant in a newly formed Universe. However, accelerating dark energy gradually drives the expansion of the Universe to such an extent that the cosmos becomes virtually empty. Then a weak force starts bringing the branes back together in the extra dimension, setting the stage for another bounce that fires up the next Big Bang.

Owing much to String Theory – the idea that minuscule strands of energy vibrating in 11 dimensions create every particle and force in the Universe – it also mathematically answers many of the questions thrown up by the Big Bang theory.

"Our theory replaces the Big Bang with a bounce in which all the smoothing, flattening and generation of hot spots and cold spots is generated before and during the bounce, so the Universe enters the current expanding phase with all the properties we want. The only real issue in this theory is that we do not have a complete theory of the bounce, but there are good reasons, supported by some solid mathematics, to suggest that this is possible," says Steinhardt.

The real test for brane theory lies in gravitational waves, in particular those waves left over from the Big Bang, which the European Space Agency's Planck spacecraft has been searching for and which scientists working on the BICEP 2 experiment earlier this year claimed to have found. If that discovery, hotly contested at present, turns out to be true then it would put an end to the cyclic theory.



In Brane Theory, the Universe is a three-dimensional 'brane' that exists in something called 'the bulk'. When it collides with another brane it sets off a 'Big Bang'. The branes gradually move apart, the Universe expands, then they begin to move together again and the Universe contracts and the cycle repeats. AN graphic by Greg Smye–Rumsby.

THE WINNING THEORY

SO which theory wins? Well, to decide this, first of all we need to explain what is meant by the word 'theory'. When used in a non-scientific context, the word 'theory' implies that something is unproven or speculative. However, in science, a theory is an explanation or model based on observation, experimentation and considerable evidence.

WHAT WE KNOW FOR SURE

We know that the Universe is expanding at an ever-increasing rate and that it was hotter and denser in the past and is now becoming colder and sparser in its old age. The cosmic microwave background is also solid evidence that radiation from the beginning of the Universe surrounds us today.

WHAT WE THINK WE KNOW

To make the standard Big Bang story fit with what we see in the cosmos, we have had to introduce a few amendments. Inflation, a force that made the Universe 10^{60} times bigger in a tiny fraction of a millisecond just after the Big Bang, solves the problem of why the Universe today has the geometry it does, but explaining what triggered inflation is tricky. Inflation also lends to the idea of parallel universes popping up, an idea that is scientifically untestable, at least at present. Meanwhile, dark energy is the mysterious force in the Universe that drives the accelerating expansion of the Universe, but where did it come from?

WHAT WE REALLY JUST DO NOT KNOW

What astronomers disagree on, and what we just do not know, is what happened at the very beginning. Could the Universe really have expanded from a singularity – a particle of zero volume and infinite density where the laws of physics as we know them would have broken down? If so, what caused the singularity to exist and why did it suddenly expand?

Models such as eternal inflation, the ekpyrotic universe and the Big Bounce theory avoid the embarrassing problem of a Universe popping up from nowhere and have more to say about where the Universe came from. However they are based on unproven ideas and theoretical mathematics. It would seem that the Universe is going to hang onto its deepest secrets for some time to come.

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