What if there was no big bang?

Cosmologist **Anna Ijjas** is developing a startling new idea about the origins of everything

REFLECTING on the question of what God was doing before creation, Saint Augustine is said to have quipped: "He was preparing hell for those who pry into mysteries." Apparently the idea of hell doesn't scare today's scientists. As a matter of fact, many of us are trying to understand how our universe came to be.

You might think that the universe started with a big bang. Ten years ago, that is what I thought too. But then I came to realise that the issue is far from settled. Pursuing this question prompted me to change the tack of my career and become a cosmologist, even though I had just completed a PhD in the philosophy of quantum physics. What I have discovered since then supports a radically new response to the question that irked Augustine – what came before the beginning? The answer, thrillingly, may be that there never was a big bang, but instead a universe with no beginning or end, repeatedly bouncing from an epoch of contraction to expansion, and back again.

In the 1920s, the Russian physicist Alexander Friedmann and the Belgian priest and astronomer George Lemaître independently proposed that the universe was expanding. Extrapolating backwards in time, Lemaître reasoned that it ought to have started off as a small "primeval atom". When Edwin Hubble provided compelling empirical evidence in favour of cosmic expansion based on his observation of the motions of distant galaxies, the case was settled. The expansion theory implied that the cold, vast universe we see today had once been a tiny, hot patch of space. Keep going further back, assuming the same laws apply, and the hot patch shrinks to a pinpoint containing an ultra-high concentration of energy. This hypothetical state came to be dubbed the big bang. But there is no evidence that this simple extrapolation is valid or that the universe began this way. Nevertheless, it has become the standard view, so ingrained that many of us learned about it as children, as I did.

There is one very good reason to be suspicious of this extrapolation, and it is to do with quantum theory. By the time the big bang entered the popular lexicon, the rules governing the subatomic realm were pretty clear, albeit extremely strange. Among other things, they say that particles can pop into and out of existence all the time, as long as they don't stick around too long. This constant fizz is important at small scales such as the big bang, when the universe was the size of a pinpoint. Whatever this speck contained would have been constantly and randomly fluctuating in energy so that, as space expanded, those differences should have been spread out, resulting in huge imbalances in the amount of energy in different parts of the universe. But here's the thing: we see no such imbalance.

"There never was a big bang, but instead a universe with no beginning or end"

Although matter in the universe randomly coalesces in clumps that we call galaxies, when we look at the universe on the largest scales, the distribution of all forms of matter is remarkably smooth over space. This uniformity calls for an explanation. Furthermore, those same quantum fluctuations at the big bang ought to have caused space to twist, curve and warp. As the universe expanded, these deformations would have expanded too, and would produce wild distortions in the path of light travelling across the cosmos. Yet

RUBY FRESSEN

astronomers see no trace of these distortions.

In the early 1980s, theoretical physicists Alan Guth, Andrei Linde, Andreas Albrecht and Paul Steinhardt introduced an idea designed to resolve the big bang theory's problems. They proposed that just moments after the big bang, the universe underwent a brief epoch of extremely rapid expansion, known as inflation. Their concept was that inflation would stretch the universe so quickly that any twists, curves and warps in the fabric of space-time would be ironed out and the distribution of all matter smoothed.

But inflation creates problems of its own. For example, it requires a hypothetical field called the inflaton. This needs to have switched on at just the right time and with just the right strength – and remained nearly constant over time – in order to account for the smoothness of the universe. In the big-bang scenario, this is unlikely to have occurred, because the strength of the inflaton field would differ in different regions of space due to large quantum fluctuations. As a result, it is more likely to have no inflation or not enough to smooth the universe, or inflation that would lead to a universe different from what we observe.

What is more, in places where there is substantial inflation, those same troublesome quantum fluctuations take over and prevent inflation from ending, except perhaps in a few rare patches of space. In those regions, cosmological properties differ randomly and unpredictably. Instead of the uniform universe we see, the outcome of inflation is that space is ultimately divided into an infinite number of patches with an infinite variety of different properties. This uncontrollable diversity is called the inflationary multiverse, an ensemble in which any number of different universes are possible and yet nothing is probable.

"The current phase of the universe expanding will end and it will enter a new contracting phase"

The majority of cosmologists and astrophysicists today tend to neglect these issues. But ever since I first heard about these problems, I haven't been able to ignore them. My original plan was to explore ways of fixing inflation, but then something else happened that changed my mind.

A generic feature of inflation, again due to quantum fluctuations, is that there should be small distortions in the fabric of space-time wherever inflation ends that evolve to become a curious phenomenon known as primordial gravitational waves. These aren't the same ripples in space-time spotted by the LIGO collaboration in 2015, which are usually created by colliding black holes. Primordial gravitational waves have much larger wavelengths – so large that the only way to detect them is by their imprint on the cosmic microwave background radiation. This radiation pattern is sometimes called the baby picture of the universe because it provides an image of what the universe looked like when it was about 400,000 years old. This might sound old, but if applied to a human life, it would correspond to a picture taken of a day-old baby.

The European Space Agency's Planck satellite had long been mapping this radiation

Neither bang nor bounce?

Think the universe must have had a beginning? Physicists are not short of far-out ideas

STEADY STATE

We know from observations that the universe is expanding, so it may seem logical to conclude that it expanded from a single point. But there is another way to think about it, as proposed by cosmologist Fred Hoyle in 1948. If new matter is continually created as space expands, then each new region of space would look the same. Under this view, there need not be a beginning or an end to the universe. Hoyle coined the phrase big bang in derisory reference to astronomer George Lemaître's ideas on expansion, but the joke was on him when the term was picked up.

THE NO-BOUNDARY PROPOSAL

The physicists Stephen Hawking and James Hartle thought rather differently. They suggested that as you go back in time towards the big bang, and things get smaller and smaller, the three dimensions of space and one of time would essentially transform into four dimensions of space. This means that the universe had no time boundary to it and the question of a beginning, or of what came before the big bang, is meaningless.

THE ANTIMATTER UNIVERSE

Latham Boyle and Neil Turok at the Perimeter Institute for Theoretical Physics in Canada think the no-boundary proposal is flawed and came up with an alternative, using similar mathematical tools. They propose that our universe could be the mirror image of another. This antiuniverse would extend backwards in time before the big bang, getting bigger as it does so, and would be dominated by antimatter.

STRING GAS COSMOLOGY

Inspired by string theory, Cumrun Vafa at Harvard University and Robert Brandenberger at McGill University in Canada proposed that the current universe emerged from a hot, dense gas of excited superstrings, which are thought to be the fundamental components of matter.

CHANGE OF PHASE

Some physicists think that space-time itself must be made of tiny, atom-like particles. One implication, according to Daniele Oriti, a physicist at the Max Planck Institute for Gravitational Physics in Germany, is that just as atoms can organise themselves into a solid, liquid or gas, particles of space-time can coalesce into different phases. Maybe the beginning of the universe was the point these particles condensed. As to what things were like before that point – who can say.

Joshua Howgego

in exhaustive detail, with the goal of finding evidence of primordial gravitational waves. But in 2013, the researchers behind it announced that they had failed to find them at the expected level. When I heard this news, I realised that this meant the simplest versions of inflationary theory were eliminated. I felt that inflation was losing its appeal as a simple explanation of what happened after the big bang, so I chose to abandon my initial plan and explore a different approach to cosmology.

The idea I decided to pursue was first put forward by the same Steinhardt who co-proposed inflation. He pointed out that there was a logical alternative to the big bang. It could be that our universe began not by bursting forth from nothing, but after a previous universe slowly contracted down to a small patch of space and then bounced, whereupon it began to expand as we observe it today.

The main appeal of this scenario was the long phase of ultra-slow contraction before the bounce. Just as inflation required a special form of energy (the inflaton field) to drive rapid expansion, ultra-slow contraction requires a special form of energy that exerts extraordinarily high pressure. The high pressure slows contraction by resisting compression and, at the same time, tends to smooth out any irregularities in the distribution of energy and in the fabric of space-time. But, unlike an inflationary phase, a slowly contracting phase doesn't require special starting conditions. It can be triggered in various ways, for example, by decaying dark energy.

And there was another perk: in a slowly contracting, cold universe, quantum fluctuations remain small at all times. That means the outcome of the bouncing scenario is definite, unlike the messy multiverse produced by wild quantum fluctuations during inflation.

Missing from the scenario was evidence that a bounce with these properties was actually possible. Last year, I published the first theoretical account of how a bounce could happen. Simply put, I describe a putative source of energy that halts the contraction and smoothly reverses it to expansion long before the universe shrinks to the point where quantum gravity effects are important. A universe that emerged from such a bounce would have exactly the smooth distribution of energy and flat untwisted geometry of space-time that we observe.

Today, together with Steinhardt and Frans Pretorius at Princeton University,

BRIAN KEATING, UC SAN DIEGO

The Simons Observatory in the Atacama desert will hunt for primordial gravitational waves

"We could be living in a cyclic universe with bounces every 100 billion years or so"

I am modelling the evolution of the universe to search for novel distinctive signatures of the contraction-and-bounce process. One prediction is that the ultra-slow contraction doesn't produce detectable primordial gravitational waves. This is in agreement with the Planck data and subsequent observations.

More sensitive experiments are under construction, such as the Simons Observatory in the Atacama desert of Chile and the LiteBIRD satellite to be launched within a decade by Japan's space agency. If they detect primordial gravitational waves, the idea of slow contraction must be wrong. I am often asked if it worries me that my idea could be eliminated by a single experiment. But to me this is what real science is all about. I wouldn't want it any other way.

If we do see signs of a bounce, however, the implications would be profound. A natural extension of the concept is that we could be living in a cyclic universe with bounces occurring every 100 billion years or so.

It is even possible to imagine a cyclic universe with no beginning or end. Each period of ultra-slow contraction would erase any fine details of the previous cycles and bring the universe to the bounce point with the same conditions as it had the cycle before. As a result, all the features of the universe would be the same on average during each cycle, including the temperature, the concentration of dark matter, ordinary matter and dark energy, and the number of observable stars and galaxies. In other words, if you had lived on a planet like Earth in the cycle before our own, you would observe roughly the same basic properties of the universe as we do.

This, in turn, leads to a dramatic prediction: the current phase of the universe in which its expansion rate is slowly accelerating will come to an end and the universe will enter a new contracting phase. It will then head towards a new bounce and new phase of expansion. Consequently, the dark energy that is driving the current accelerated expansion must decay away, which may be detectable in future experiments.

This, together with the search for primordial gravitational waves, means it may soon be possible for us to know if the universe really did begin with a bang. My guess is that the story is a little more circular. ▮

Anna Ijjas is a group leader at the Max Planck Institute for Gravitational Physics in Germany