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...THE CLOSER WE LOOK, THE WEIRDER IT GETS

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SOMETHING IS WRONG WITH OUR MODEL OF THE UNIVERSE

OUR PICTURE OF THE COSMOS IS INCREDIBLY DETAILED. BUT IT'S BY NO MEANS COMPLETE. THERE ARE CRUCIAL PIECES MISSING IN THE COSMIC JIGSAW. AND WITHOUT THEM THE PICTURE JUST DOESN'T MAKE SENSE

by MARCUS CHOWN

"Cosmologists are often wrong, but never in doubt," remarked the Russian Nobel Prize-winning physicist Lev Landau. Perhaps he had a point. Perhaps cosmologists should have a little more humility. After all, in their investigations of the Universe, they've missed some pretty enormous things.

Dark energy, for example. Although it accounts for 68.3 per cent of the mass-energy of the Universe, this invisible stuff that fills all of space and whose repulsive gravity is speeding up cosmic expansion, wasn't discovered until 1998. Imagine not noticing the major mass component of the Universe until barely a generation ago!

Then there's dark matter, which makes up the lion's share of the remaining 31.7 per cent of the Universe's mass-energy. Although its existence was initially suspected in the 1930s, this second kind of invisible stuff – which outweighs the visible stars and galaxies by a factor of about six – wasn't confirmed until the late 1970s.

Given cosmologists managed to overlook these two things for so long, is it possible they could have missed any other major pieces of the cosmic jigsaw? The answer, as of 2024, is a definite maybe. Several cosmic anomalies are creating a buzz in astrophysics and hinting that new ingredients may need to be added to the cosmic mix. Here are three of the biggest… →

ILLUSTRATION: MAGIC TORCH

THE HUBBLE TENSION

THE UNIVERSE IS EXPANDING, AND WE CAN MEASURE THE SPEED OF ITS EXPANSION. THE TROUBLE IS, DEPENDING ON HOW WE MEASURE THAT SPEED, WE KEEP GETTING DIFFERENT RESULTS

The first anomaly concerns the speed at which the Universe is expanding. Astronomers determine this in two ways and herein lies the problem: the two methods yield different values.

The obvious method is to observe galaxies (the basic building blocks of the Universe) in the nearby Universe and measure how fast they're moving away from us. They're scattering like pieces of cosmic shrapnel in the aftermath of the Big Bang, the titanic explosion in which the Universe was born 13.82 billion years ago.

A second way of determining the expansion rate is to deduce it in the early Universe and extrapolate it to today. The primordial expansion rate is encoded in the cosmic background radiation, the 'afterglow' of the Big Bang, which is still around us today and accounts for 99.9 per cent of the photons, or particles of light, in the Universe.

The problem is that the expansion rate measured locally is eight per cent greater than deduced by extrapolating from the early Universe. There are those who believe there is a cosmic ingredient we've overlooked which has speeded things up over the past 13.82 billion years. But extraordinary claims require extraordinary proof. Does the evidence stack up?

The first thing to say is that measurements of the cosmic background radiation by the European Space Agency's (ESA) Planck satellite have ushered in the age of precision cosmology and are considered the gold standard of astronomical observations. Thanks to Planck, not only have we learnt that the Universe is 13.82 billion years old, but also that it consists of 68.3 per cent dark energy, 26.8 per cent dark matter and 4.9 per cent ordinary atoms.

Given astronomers' faith in Planck, all attention has focused on the local expansion measurements. These, however, are fraught with difficulties.

The expansion rate is characterised by the so-called Hubble constant. In 1929, the American astronomer Edwin Hubble discovered that the further away a galaxy is from us, the faster it's moving away. The Hubble constant (H_0) connects these two quantities, so that a galaxy that's D megaparsecs more distant than another galaxy (where one megaparsec, or Mpc is equal to 3.26 million light-years) is receding

1 The Hubble Space Telescope above Earth

2 Precise details of the cosmic background radiation are observed by the Planck satellite, seen here in the Netherlands before its launch

3 A dark matter map for a patch of sky based on gravitational lensing

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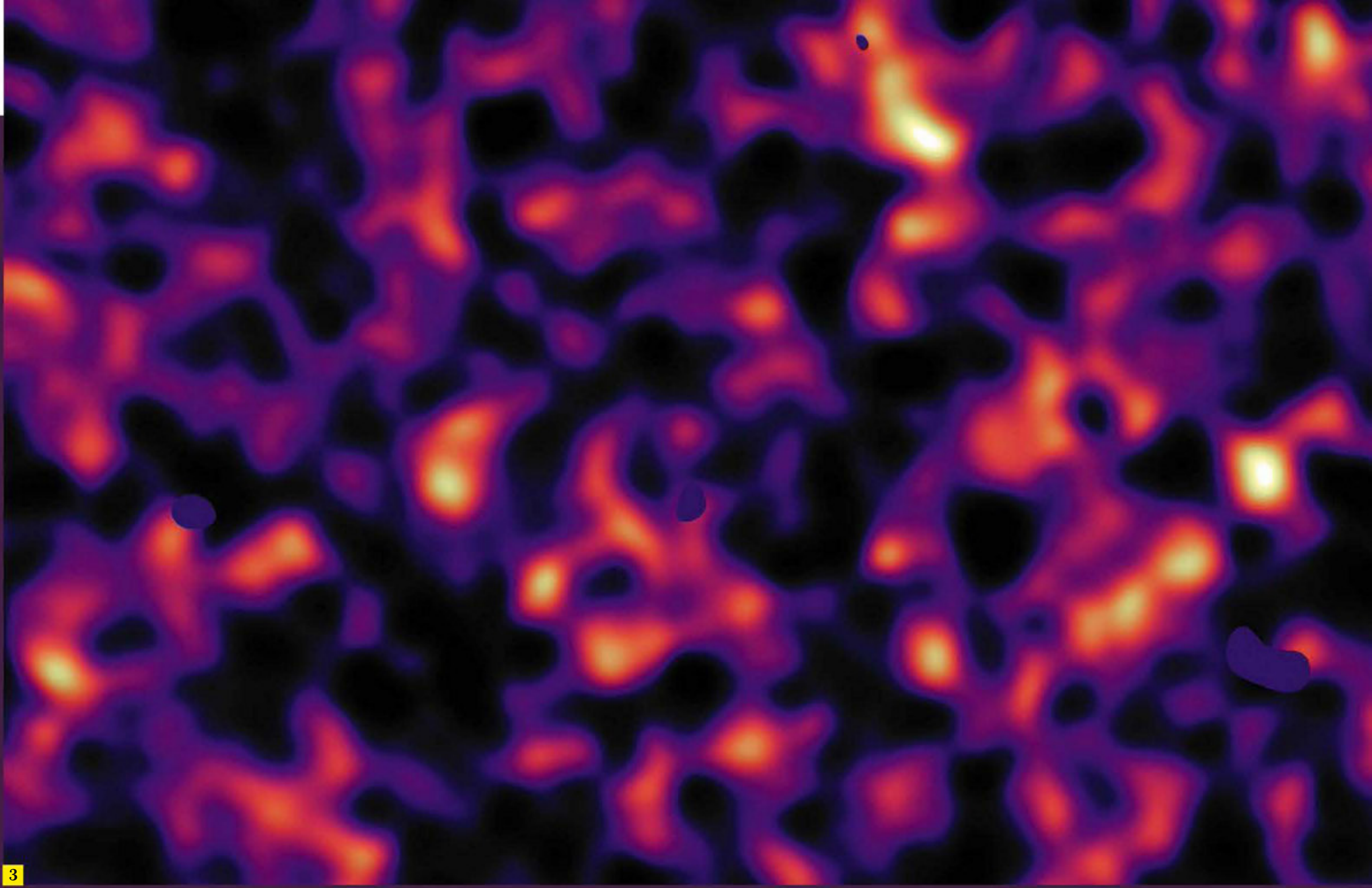

ESO, GETTY IMAGES, NASA

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at H_0 x D kilometres per second faster. The speed a galaxy is moving away is encoded in its spectrum – the way the intensity of its light varies in frequency. Specifically, the velocity of a galaxy can be deduced from the shift in pitch, or frequency, of its light, an effect similar to the shift in pitch of the sound of the siren on a passing police car. The difficult thing is determining the distance to a galaxy.

For 'nearby' galaxies, astronomers observe Cepheid variables, extremely luminous pulsating stars whose pulse rates are related to their intrinsic luminosity. It means that, if astronomers see a Cepheid that's four times as faint as another, they know it's twice as far away – and not simply a fainter star at the same distance.

Cepheid variables are known as 'standard candles.' Astronomers use them to establish the first rung on the cosmic distance ladder, in the process determining the distance to galaxies that contain Type Ia supernovae. These detonations of a super-dense white dwarf in a binary star system are believed to all be of similar luminosity. This makes them an even more luminous type of standard candle than a Cepheid and enables the determination of distances to even more remote galaxies.

For 25 years, the Hubble constant was determined from Cepheids observed by NASA's Hubble Space Telescope. But there were concerns. When observing Cepheids at great distances, even Hubble's sharp eyesight couldn't be sure of picking out a lone Cepheid. There was always the chance of a Cepheid being smeared together with a star close to the line of sight, causing astronomers to overestimate the Cepheid's brightness.

Enter NASA's James Webb Space Telescope (JWST). Launched on Christmas Day 2021, the 6.5m (23ft) →

→ infrared telescope has sharper vision than Hubble. Using it, a team led by Nobel Prize-winner Prof Adam Riess of Johns Hopkins University in Baltimore determined that Hubble's estimate of the Hubble constant was correct. The eight-percent discrepancy between expansion rates remains.

This 'Hubble tension' could still be a mirage. There could be unrecognised measurement errors. Prof Joseph Silk of the University of Oxford suspects so. "I admire the detailed, painstaking attempts at calibration by Prof Adam Riess and his colleagues," he says. "However, I'm still not completely convinced."

Silk points out that the stellar environments in which Type Ia supernovae are born have changed over time. This change potentially makes these supernovae in distant galaxies a different luminosity to those in nearby galaxies (more distant galaxies allow us to see further back in time because of the finite speed of light). "And perhaps more worrying," says Silk, "is that an alternative approach to determining the distance scale, led by Prof Wendy Freedman and colleagues, systematically finds a lower value of the Hubble constant than the supernova method."

Freedman, of the University of Chicago, and her colleagues look for giant stars at the tip of the red giant branch. Here, stars make an abrupt transition from burning hydrogen in their cores to burning helium and have a remarkably consistent luminosity. "They're the best understood distance indicator in astronomy," says Silk. Freedman's group has yet to publish its own results from using the JWST, but Silk suspects they'll shrink – or perhaps even remove – the Hubble tension.

"DARK ENERGY OR DARK MATTER COULD HAVE MORE EXOTIC PROPERTIES THAN THE MOST 'VANILLA' ASSUMPTIONS"

But say the Hubble tension is real, what missing ingredient could have sped up the expansion of the Universe? "I wish I knew," says theorist Prof Marc Kamionkowski of Johns Hopkins University. "It's really puzzling."

Prof Ian McCarthy of Liverpool John Moores University adds: "The implication is that something about the Standard Model of Cosmology is incorrect. That would be very exciting."

Riess has a theory. "Dark energy or dark matter could have more exotic properties than the most 'vanilla' assumptions we make for them in the Standard Model," he says. The Standard Model is the Big Bang + dark matter + dark energy + an 'inflation', a period of super-fast expansion in the first split-second of the Universe.

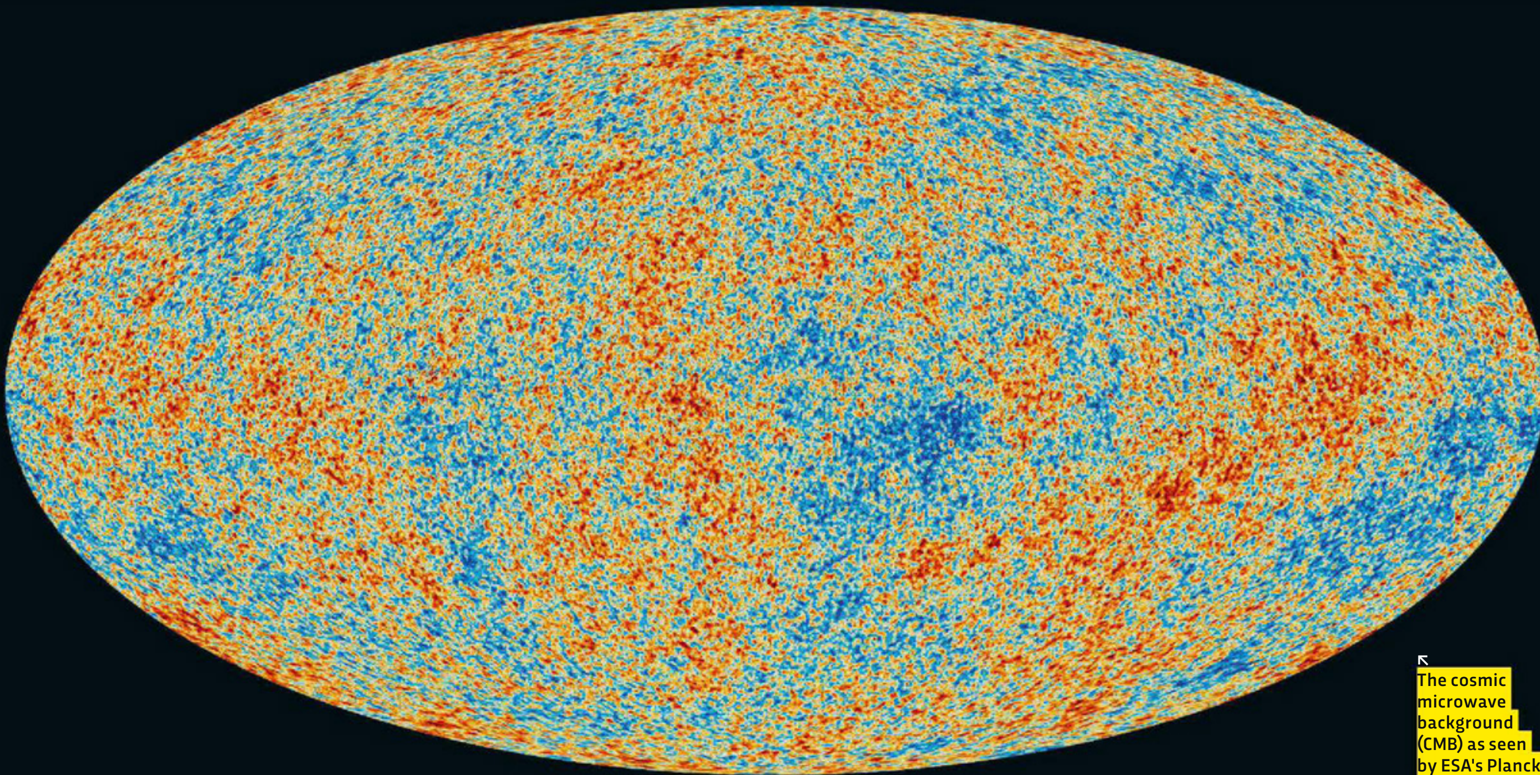
The vanilla assumption about dark energy is that it's a so-called 'cosmological constant' that maintains a constant energy density as the Universe expands. It means the dark energy and its effect grows as space grows. Although unimportant early in cosmic history, eventually it dominated the Universe, putting a rocket under cosmic expansion. But, given we don't understand the nature of dark energy, it's entirely plausible that its energy density has evolved with time.

According to Kamionkowski, the energy density of dark energy may have increased recently, boosting cosmic expansion. Alternatively, there might have been early dark energy, which boosted cosmic expansion in the first few hundred thousand years of cosmic history. By overlooking it, astronomers would have underestimated the cosmic expansion rate they deduced from the cosmic background radiation. "Early dark energy is promising, but not quite as easy to get to work as we initially thought," he says. It's testable, however, because it would have left a fingerprint on the way the cosmic background radiation varies over small regions of the sky. How dark energy evolved with time is due to be tested by a host of experiments, such as ESA's Euclid satellite, currently in orbit, and the Vera C Rubin Observatory, which is being built in Chile.

Another way the Universe could have sped up is if Einstein's theory of gravity breaks down on the largest scales. Is the gravity that's trying to slow the expansion of the Universe weaker than expected? Silk, however, remains sceptical of all the proposals. "To date, all attempts to introduce new physics ingredients to fully resolve the Hubble tension have failed," he says.

↙ Euclid lifts off from Cape Canaveral, Florida, last July

ESA/PLANCK COLLABORATION, ESA



The cosmic microwave background (CMB) as seen by ESA's Planck satellite

THE SMOOTHNESS PROBLEM

HUBBLE TENSION ISN'T THE ONLY COSMIC ANOMALY. THERE MAY ALSO BE A PROBLEM WITH HOW CLUMPED TOGETHER GALAXIES ARE, ALTHOUGH THE EVIDENCE IS NOT QUITE AS STRONG

Cosmic background radiation plays a role in the smoothness problem. Variations in its brightness over the sky tell us how clumped matter was when radiation broke free of matter, 380,000 years after the Universe's birth. Theorists can run the history of the Universe forward and see how gravity and dark energy amplify the primordial clumpiness into today's clumpiness. When they do and compare the results to reality, however, they discover that today's Universe is about 10 per cent smoother than expected.

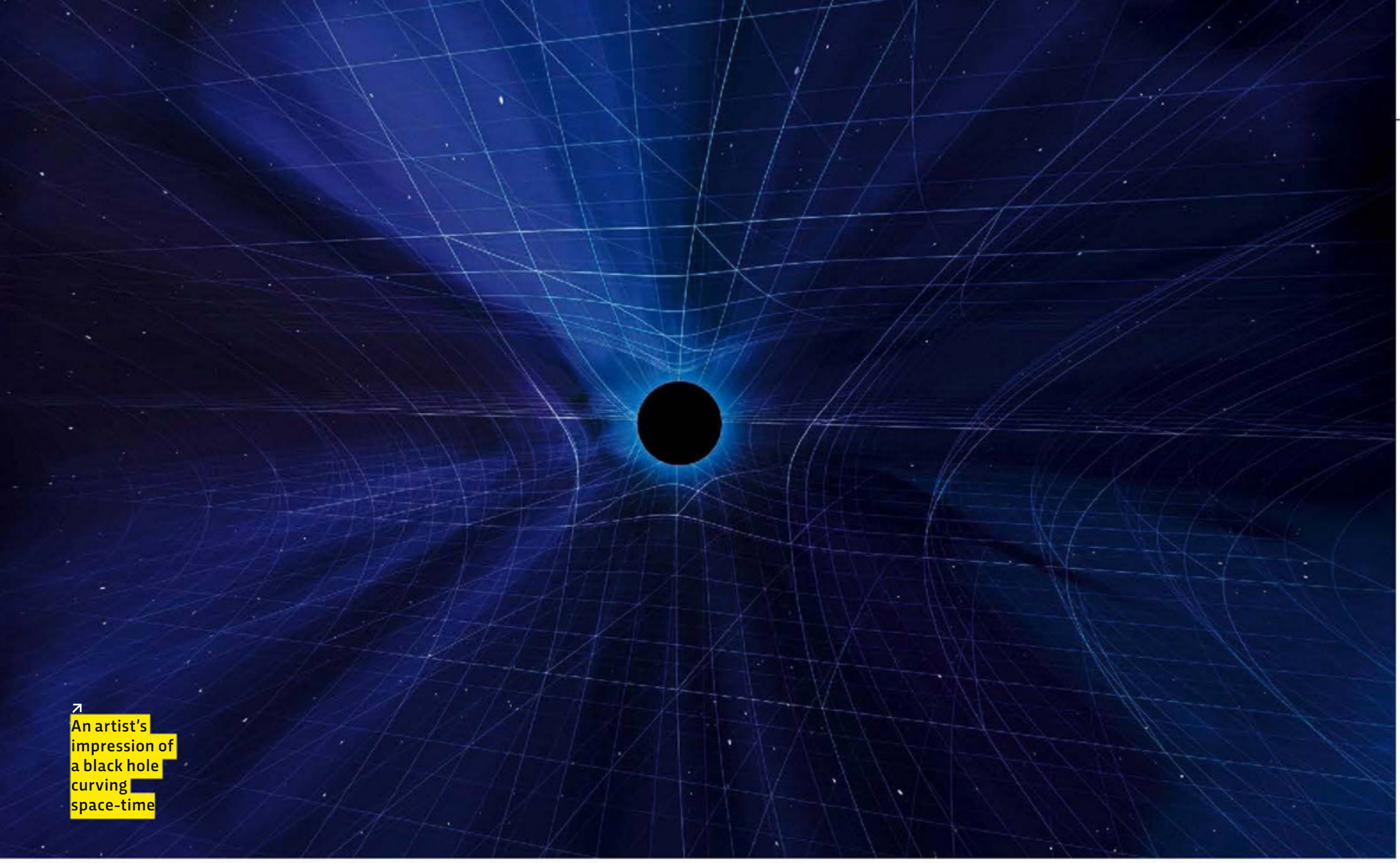
Observing clumping in the local Universe isn't easy. This is potentially because so much material is hidden from view in the form of dark matter. Astronomers have overcome this by exploiting gravitational lensing, where light from distant galaxies is bent and distorted on its way to Earth by the gravity of intervening matter. The shapes of distant spherical galaxies, for instance, are distorted into ellipses and those ellipses are subtly aligned with each other. The problem is that distant galaxies appear as mere blobs in the biggest telescopes, so determining distortion and alignment is hard. It's one reason scientists are more uncertain about whether matter today is distributed more smoothly than they are about the Hubble tension. If the result holds, however, what has smoothed out that matter?

"DISTANT GALAXIES APPEAR AS MERE BLOBS IN THE BIGGEST TELESCOPES, SO DETERMINING THE DISTORTION AND ALIGNMENT IS HARD"

There are a number of possibilities. One, according to Prof Ian McCarthy, is that dark energy smooths things out. "If the effect of dark energy grows faster in time than for a cosmological constant, then its associated anti-gravity effect will slow the clumping of matter," he says.

Another theory is that dark matter interacts with itself. This would enable energy to spread more evenly throughout the dark matter. "Essentially, it's like a form of thermal conduction that heats the densest regions, providing an outward force to oppose the gravity trying to shrink them," says McCarthy. It's also possible that the dark matter is a mixture of cold, sluggishly moving particles and hot, relatively fast-moving particles. "Hot dark matter would resist gravitational collapse," he says.

Yet another possibility is that jets from supermassive black holes in the hearts of some of the Universe's most active galaxies are responsible. These stab outwards for millions of light-years and could smooth matter out. Certainly, the JWST is seeing big galaxies with big supermassive black holes earlier in cosmic history than anyone expected.



THE COSMOLOGICAL CONSTANT PROBLEM

AS TROUBLING AS THE HUBBLE TENSION AND THE SMOOTHNESS PROBLEMS ARE, THEY'RE NOT THE BIGGEST COMPLICATIONS FACING OUR COSMOLOGICAL MODELS. THE MOTHER OF ALL HEAD-SCRATCHERS IS THE COSMOLOGICAL CONSTANT PROBLEM

In November 1915, Einstein presented his revolutionary theory of gravity – The General Theory of Relativity – in which he showed gravity to be the warpage of space-time by energy, most obviously mass-energy. Einstein recognised that space-time itself might be intrinsically warped and, to describe this, in 1917, he inserted the cosmological constant into his theory. By opposing the gravity pulling matter together, he believed it could create an unchanging, or 'static', Universe.

Actually, it didn't. And when Edwin Hubble discovered the Universe was expanding, Einstein discarded the cosmological constant, calling it his biggest blunder. But it resurfaced in 1998 in the guise of dark energy – a hypothetical energy in the vacuum of space. And herein lies the problem.

According to quantum field theory, our best description of the subatomic realm, space is permeated by 'fields'. A localised hummock in a field is a subatomic particle – for instance, a hummock in the electron field is an electron.

Each field is in fact a superposition of an infinite number of waves, from sluggish oscillating 'modes' to frenetic ones. However, in quantum theory, nothing is ever still. Therefore, each field mode jiggles with a minimum energy. When they're all added up, the energy is enormous. In fact, the energy density of the vacuum is estimated to be 10^{120} times bigger than the dark energy.

The Nobel Prize-winning physicist Prof Steven Weinberg proposed a desperate explanation in 1987. Say there are many different values of the cosmological constant in many different parts of the Universe (or multiverse). In most regions, the cosmological constant is so big it blasts matter apart, preventing it from forming galaxies and stars. We find ourselves in a region where the cosmological constant is small enough to permit the existence of stars because, well, how could we not? This 'anthropic' reasoning enabled Weinberg to predict a cosmological constant within a factor of 10 or 100 of the magnitude of the dark energy.

Since few people are happy with Weinberg's solution, the cosmological problem represents the biggest discrepancy between a prediction and an observation in the history of physics. The previous biggest concerned how an electron can orbit in an atom before spiralling into its nucleus. Theory

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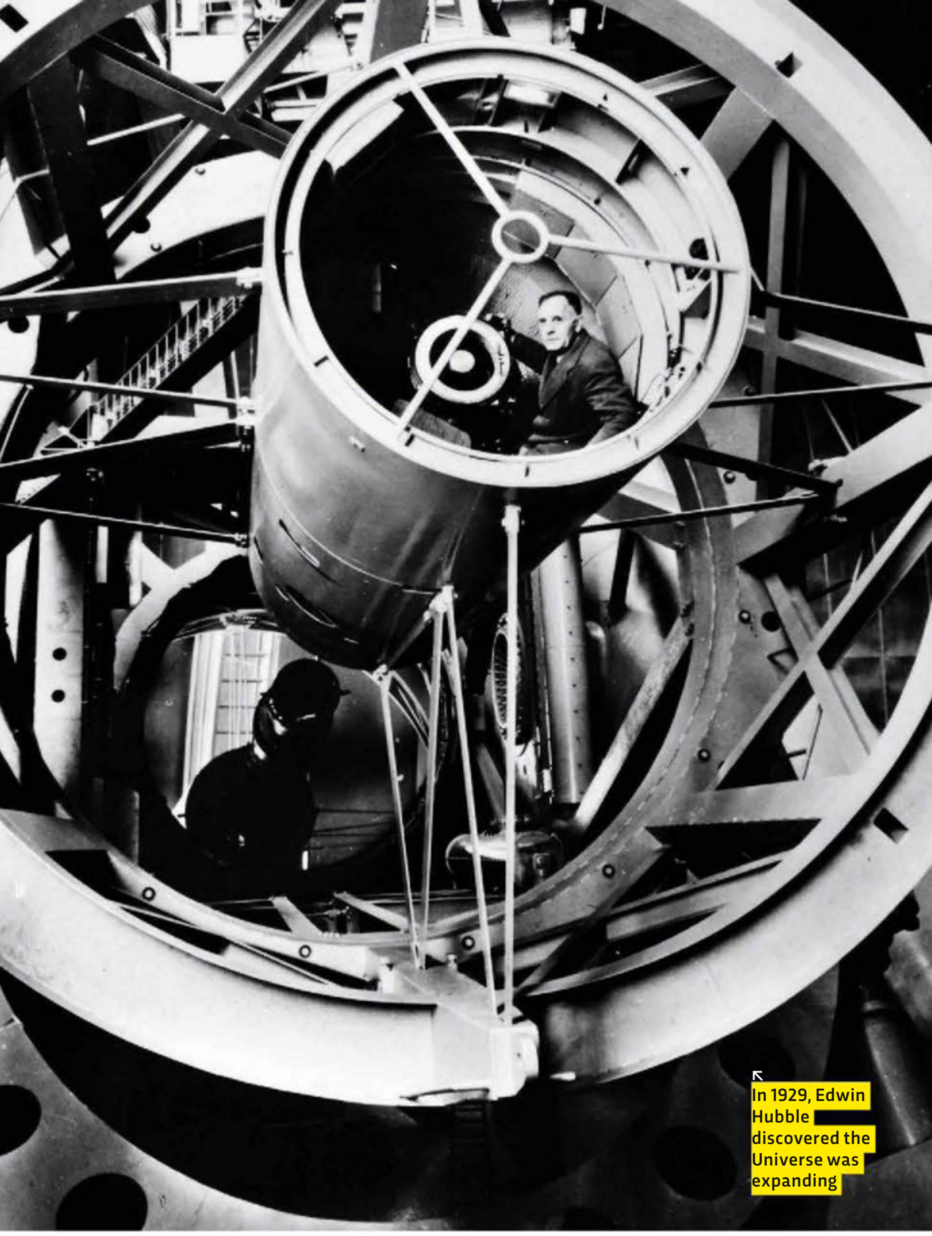

In 1929, Edwin Hubble discovered the Universe was expanding

Steven Weinberg tried to solve the cosmological constant issue

"IT MAY BE THAT WITHIN THE NEXT COUPLE OF YEARS WE'LL HAVE RULED OUT THE STANDARD MODEL OF COSMOLOGY AND LEARNED SOMETHING NEW, EITHER ABOUT THE NATURE OF MATTER/ENERGY IN THE UNIVERSE AND/OR THE FORCES ACTING ON IT"

predicted that atoms should collapse in a split-second, yet atoms are known to have persisted for the age of the Universe: 10^{40} times longer. The discrepancy was resolved in the 1920s by a revolutionary new theory: quantum theory.

Similarly, it's possible that resolving the cosmological constant problem will require a revolution in physics. Specifically, a theory that unites quantum theory (the theory of the very small) with Einstein's theory of gravity (the theory of the very big). Such a theory, dubbed quantum gravity, has so far proved elusive.

As for whether cosmology really is in crisis, the jury is still out. Theorists like Prof Joseph Silk remain sceptical. Others like McCarthy dare to hope for new physics. "It may be that within the next couple of years, we'll have ruled out the Standard Model of Cosmology and learned something new, either about the nature of matter/energy in the Universe and/or the forces acting on it," he says. "Very exciting times ahead." SF

by MARCUS CHOWN

Marcus is an award-winning writer and formerly a radio astronomer at the California Institute of Technology. His latest book is A Crack in Everything: How black holes came in from the cold and took cosmic centre stage *(Head of Zeus, released on 6 June 2024).*