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OUR UNBELIEVABLE UNIVERSE

Why the final truth about the cosmos has yet to be revealed

By Nobel prizewinner Jim Peebles

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Have we got the universe right?

Nobel prizewinner **Jim Peebles** contributed more than most to our standard model of cosmology – but it's unlikely to be the final answer, he says

IF SUCCESS is measured in Nobel prizes, we have got something right with our standard model of cosmology. In the past two decades, three prizes have been awarded for advances in the study of the large-scale nature of the universe. Our picture of a cosmos that some 13.8 billion years ago was in a hot, dense state and has been expanding and cooling ever since is in close agreement with a considerable variety of observations.

But you can argue it the other way, too. Our cosmology assumes that most matter comes in a "dark" form that hasn't yet been detected. It relies on Albert Einstein's cosmological constant, a seemingly arbitrary addition, to explain why the universe's expansion is apparently speeding up. Even if you are prepared to overlook these difficulties, there is the unsolved question of what the universe was doing before it was expanding.

A sceptic might view complications such as dark matter and dark energy, the current incarnation of the cosmological constant, as today's equivalent of the Ptolemaic epicycles, the convoluted tweaks made to the model of the planets' motions to maintain the fiction that they were all revolving around Earth.

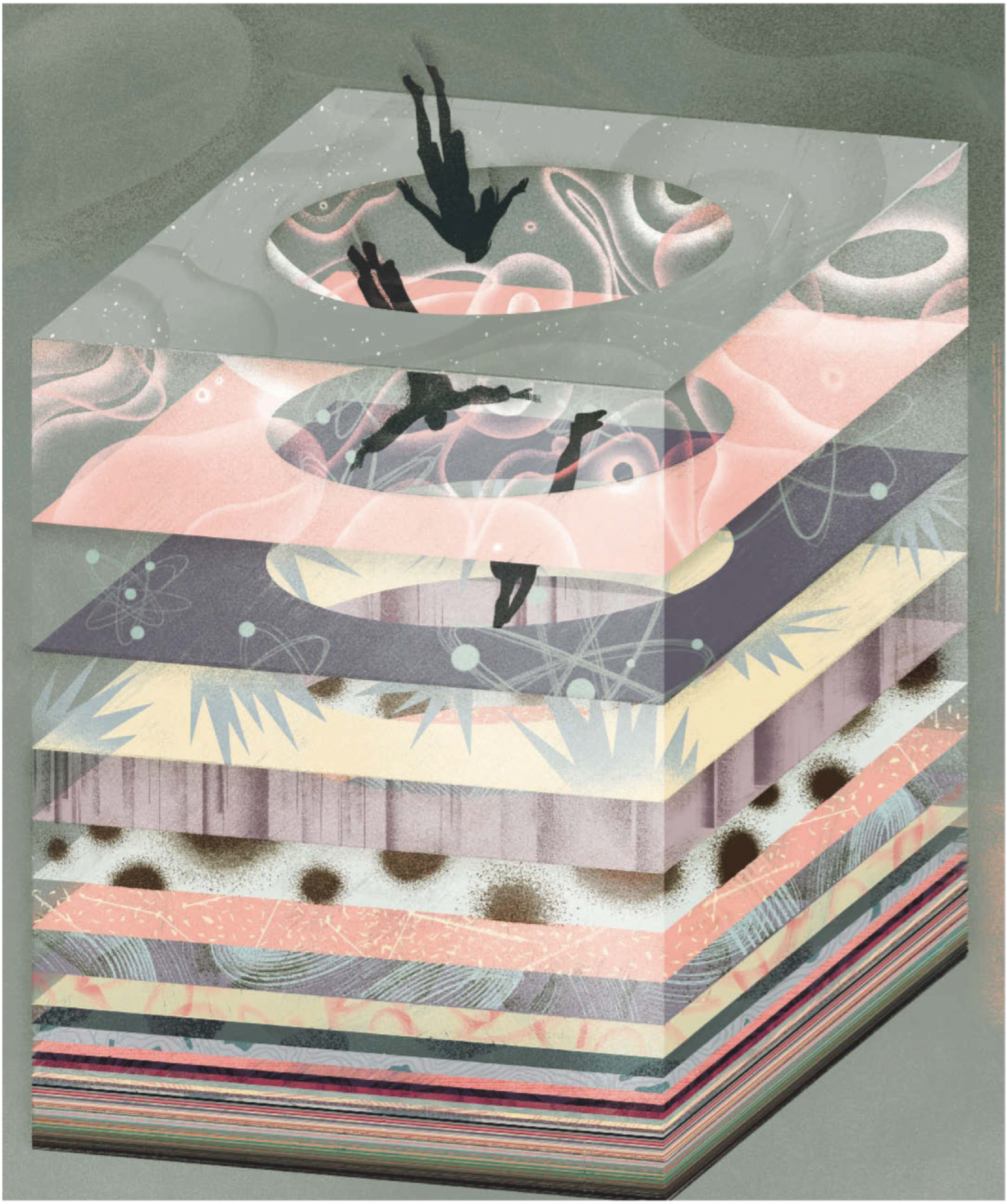
I have more skin in this game than most: I introduced the mystery elements of dark matter and dark energy into our standard cosmology. So is the model I helped construct right; is our cosmology a true reflection of reality? In what follows, I will strongly argue yes – but only as far as that goes.

Fossil footprints

The evidence for a universe that began in a "big bang" is serious. The chief witness is a close-to-uniform sea of microwave radiation of wavelengths from millimetres to centimetres that fills all of space. As a postdoc with my adviser and mentor Bob Dicke more than half a century ago, I explored the idea that the early universe may have been hot, and left behind a background of such long-wavelength radiation as it expanded and cooled. Shortly after, in 1964, this "cosmic microwave background" was accidentally discovered by Arno Penzias and Robert Wilson as the by-product of experiments testing telecommunications equipment.

In 2006, John Mather was awarded a share of the physics Nobel prize for his leadership in showing, with measurements from the Cosmic Background Explorer satellite (COBE), that the spectrum of the cosmic microwave background radiation – its energy density at different wavelengths – is that of radiation that has entered thermal equilibrium. This process will occur only if the density of the surrounding matter is sufficient to trap the radiation, forcing it to relax to thermal equilibrium. This isn't the case in the present-day universe, through which microwave radiation can travel freely. I countthe spectrum of the cosmic microwave background, preserved as the universe expanded and cooled, as tangible evidence that our universe really evolved from a different state, just as dinosaur footprints show us that massive creatures once roamed Earth.

The other half of the 2006 Nobel prize went to George Smoot, who led the demonstration that the cosmic microwave background isn't completely smooth. The tiny variations of its intensity across the sky, which have been mapped out in detail in later measurements, are consistent with what would be expected in an expanding big bang universe with ›



ELENI DEBO

those two additional, hypothetical components: dark matter and dark energy.

When I added the first of these into the mix in the early 1980s, my motivation came in part from early measurements of the cosmic microwave background, which were already good enough to show us that the radiation is quite smooth. Yet we could see that matter came in great clumps: galaxies and groups and clusters of galaxies. This led to talk of a crisis in cosmology. How could matter have been pulled together in great concentrations without pulling the radiation with it?

My proposal was that most matter isn't the "baryonic" matter of the kind you and I and stars and planets are made of. The non-baryonic dark matter I had in mind wouldn't interact with normal baryonic matter, except through gravity, or with radiation. As it clumped under the influence of gravity, it would slip through the radiation of the cosmic microwave background, leaving it largely undisturbed.

> **"You have to be careful not to build a cosmological just-so story"**

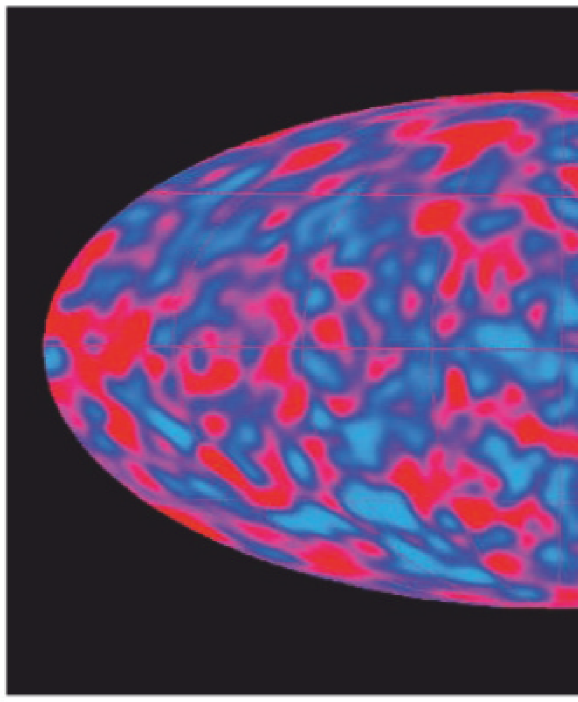
You have to be careful with this sort of adjustment of a hypothesis to fit what is wanted, lest you build a "how the leopard got its spots" just-so story. But I had two other hints to go on. First, there was astronomical evidence that most of the mass on the outskirts of galaxies isn't very luminous. If the visible matter were all that existed, the galaxies would fly apart, based on the speed at which they are rotating.

The second hint came from particle physics. Back then, there were two confirmed families of the fundamental particles known as leptons: the electron and its neutrino, and the muon and its neutrino. There was also growing evidence of a third family, made up of what became known as the tau and its neutrino. So why not a fourth?

The attraction of this idea was that if this fourth neutrino were heavy, with a mass about three times that of a proton, a sea of them left from the hot early universe would provide about the matter density required for the universe to be expanding at "escape speed". This is the name given to the rate of expansion at which the gravity pulling together the universe's matter is just enough to slow expansion down, but never quite stop it or reverse it back to a "big crunch", by analogy to the speed a rocket must attain so it can just escape Earth's gravity, rather than fall back to the ground.

At the time, it looked like the average matter density of the universe was smaller than this critical number, by enough that the expansion rate was around twice escape speed. That would point to a curious coincidence: that we are currently observing the universe just around the time when the expansion rate has beaten gravity and started to expand freely. This problem would be solved if the universe contained just the right matter density. In that case, whenever in the history of the universe we happened to flourish and take an interest in its expansion, it would always be growing at escape speed. The thought is comforting somehow, and many argued for it, including me, but it is wrong.

I think for the particle physicists who were theorising a fourth, massive type of neutrino, it was just an interesting idea. They may have been vaguely aware of the escape speed argument, but they knew little of the evidence for invisible extra mass around galaxies. Putting the two hints together with the need to account for the quite smooth sea of thermal radiation resulted in the cold dark matter model. The "cold" refers to the fact that the particles making up the dark matter would be moving slowly relative to the general expansion of the universe, an important property in the model to ensure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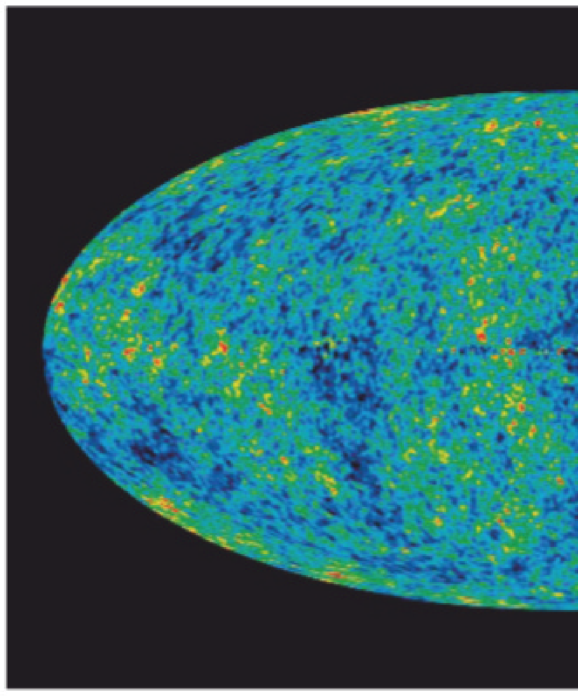
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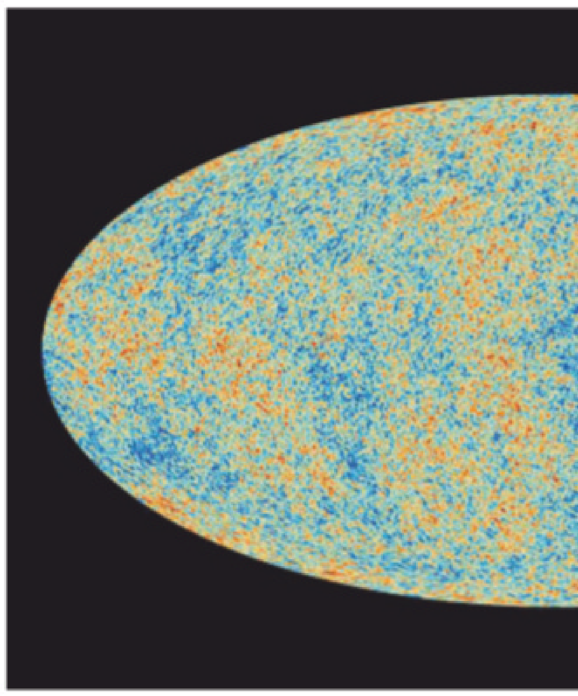
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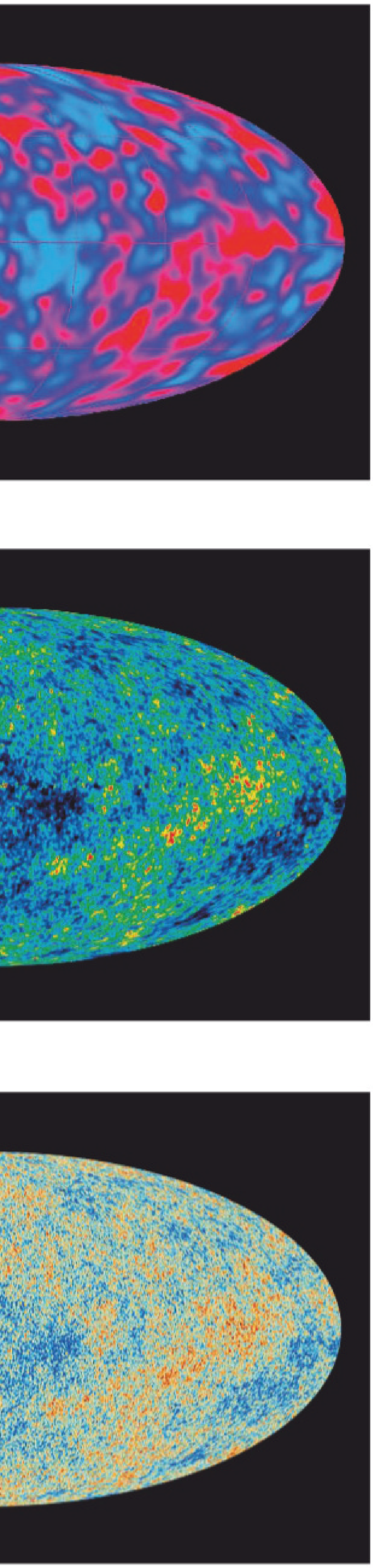


Maps of the big bang's microwave afterglow from three generations of probes. Top to bottom: COBE (operational 1989-1993), WMAP (2001-2010) and Planck (2009-2013)

the formation of galaxies and clusters of galaxies of the sort we observed.

I offered just one prediction with this proposal when I made it in 1982: that the cosmic microwave background temperature would vary in different parts of the sky by about four parts in a million. This agrees with the measurement accomplished some two decades later by COBE. The prediction came about partly through educated guesswork, and partly because I had spent a lot of time measuring the large-scale distribution of matter across the universe, so had a guide as to its expected gravitational effect on the radiation.

Meanwhile, I had also been working on measures of the universe's average matter density. Such efforts had left me pretty sure that this density is small enough that the expansion of the universe would actually be faster than escape speed, fourth neutrino or no fourth neutrino. This wasn't welcome: expansion at escape speed seemed so right. But to me, it seemed to call for the reintroduction of a cosmological constant into the model.

"The tiny value for Einstein's constant is preposterous – but it works"

Einstein had introduced this constant back in 1917 with the intention of maintaining a static universe that was neither expanding nor contracting, a situation he seemed to have taken for granted. He came to dislike it when observations in the following decade proved the static model wrong. Particle physicists today really dislike it because its natural value, the quantum vacuum energy density, is ridiculously large compared with what is required to fit the evidence.

When, in 1984, I first argued for the cosmological constant's reintroduction, at a tiny value that looks preposterous but works, I remember a capable younger physicist saying to me something along the lines of the quote from *Alice's Adventures in Wonderland*: "He only does it to annoy, because he knows it teases." I knew it was annoying, but I was serious. Vindication came almost two decades later, when results from three great experimental programmes in cosmology arrived during a half-decade stretch around the year 2000.

The first set of results came from a thoroughly cross-checked array of feasible, though difficult, methods to measure the average cosmic matter density, which by 2000 had produced a good case that the universe is indeed expanding faster than escape speed. The coincidence argument I mentioned meant that many continued to feel this must be an error, but the measurements certainly influenced me, and I think others.

The second confirmation came from measurements of the universe's changing rate of expansion by detection of the light from supernovae exploding in distant galaxies. Far-off galaxies are seen as they were in the past because of the time light takes to travel to us, and the Doppler shift also changes the wavelength of that light according to the galaxy's motion relative to us. By 2000, the data from supernovae in galaxies at different distances pretty convincingly showed that the rate of expansion is not only greater than escape speed, but is also growing over time. The measurement led to the rebranding of the cosmological constant as dark energy, and later to the 2011 Nobel prize being awarded jointly to three members of two competing teams: Saul Perlmutter, Adam Riess and Brian Schmidt.

The third vindication for the cosmological constant hypothesis came from the precise measurement of the variation in the temperature and polarisation of the cosmic microwave background radiation across ›

CHRIS GUNN/NASA

The James Webb Space Telescope, due to launch in 2021, will be the next big probe of the cosmos. A full-scale model (left) is on display in Austin, Texas

NASA/ESA/NRAO/AUI/NSF AND G. DUBNER

the sky, which yielded a tight constraint on the effects of dark energy and dark matter.

Why did these three great efforts reach the required precision to make these measurements at close to the same time? I suppose it was, in part, simple coincidence. But all three relied on technological advances in the detection of radiation, from X-rays to optical light to radio waves, and great improvements in computing power and storage to deal with the vast amount of data they produced. The technology was by and large developed for other purposes – it is what gave us people walking about looking at their smartphones instead of where they are going – and was adapted by inventive astronomers for cosmological tests.

The consistent case from these three different ways of probing the universe convinced most cosmologists that the model with dark matter and dark energy is almost certainly on the right track. Since then, measurements have tightened the evidence. But I had assembled this cosmology out of the simplest assumptions I thought I could get away with. I can't have consistently guessed right. Indeed, precise measurements have shown that the initial conditions I assumed – for instance in the detail of how matter warps space-time – were a little out.

Surely there are more adjustments to come. An example may be the current 10 per cent discrepancy in the rate of the universe's expansion derived in two different ways. One, like the supernova measurements honoured by the Nobel committee in 2011, uses measurements of the distances to galaxies and their rates of motion away from us derived from Doppler shifts. The other comes from adjusting the parameters of the cosmological model to fit the precise measurements of how the cosmic microwave background varies across the sky. If the model is right, the two measurements ought to give the same answer. Maybe the difference is down to a subtle systematic error, which wouldn't be surprising for these difficult measurements.

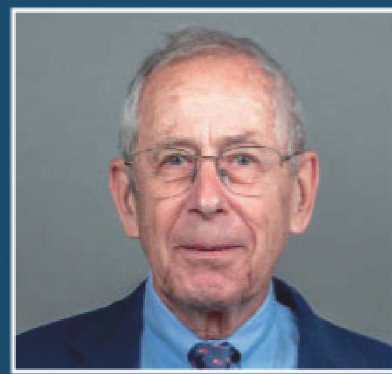
> **"Despite all our searching, dark matter is still a hypothetical substance"**

Or maybe it is evidence of something new. I haven't joined the search for what that something new may be, but I will be fascinated to see what people come up with.

There are other cross-checks we can do to test the standard cosmological model, for example on the abundance of helium. We have three ways to estimate this. First, the measured relative abundances of hydrogen and deuterium allow us to predict how much helium formed in thermonuclear reactions in the hot early stages of the universe's expansion, when the cosmic microwave background had a temperature a billion times its current level of 3 kelvin above absolute zero. This prediction assumes our cosmological model is a good approximation all the way back to that very early time, of course.

Second, we can estimate the helium abundance from the distributions of matter and radiation when the background temperature of the universe was a thousand times its present value, hot enough that baryonic matter was ionised and the resulting

Data and images from the Hubble Space Telescope, such as this shot of the Crab Nebula, have guided cosmological discoveries since its launch in 1990



RICHARD SODEN

PROFILE

Jim Peebles is Albert Einstein professor of science, emeritus, at Princeton University. He was awarded one half of the 2019 Nobel prize in physics "for contributions to our understanding of the evolution of the universe and Earth's place in the cosmos". His book *Cosmology's Century* is out this month.

plasma tightly bound to the radiation. Helium is denser than hydrogen, so its presence affects the way that the plasma moves in response to the pressure of surrounding radiation.

Third, astronomers can measure how much helium there is in nearby stars and plasma. All three methods provide consistent results so far, which is really impressive. Surely they will continue to do so as the measurements improve in accuracy? Maybe, but wouldn't it be exciting if they didn't?

Yet even if continued agreement further bolsters our confidence in the accuracy of the model, the central mysteries of dark matter and dark energy remain. Cold dark matter is still a hypothetical substance, despite laboratory experiments since the 1980s of ever-increasing sensitivity looking for its occasional predicted interactions with normal matter. Detection would be really exciting. But it is possible that dark matter is completely decoupled from the baryonic matter and radiation we are familiar with, never to be detected, apart from through its gravitational effect holding galaxies together that we already know of.

And what should we make of dark energy? A great deal of work is now focused on discovering whether its value changes as the universe expands. That would mean it isn't a cosmological constant with a really odd value, but rather that it plays a role in the universe's dynamics. Working out that role would be both a great challenge and a great opportunity.

Then there are those other great challenges for modern cosmology, such as explaining precisely what happened at the big bang. The elegant idea of ballooning cosmic inflation smooths out some otherwise inexplicable wrinkles in that story, and suggests the big bang may have spawned a multiverse of universes beyond our own. But again, that idea lacks evidence.

Messy and incomplete

We haven't been issued a guarantee that we can make sense of the physical world around us, or detect things such as dark matter. But lest there be doubt about how well physics has been doing so far, consider how successfully scientists and engineers can command the behaviour of electrons, atoms and molecules, as well as electric and magnetic fields, in cellphones. All of this has been done based on incomplete approximations.

The theory of electric and magnetic fields that James Clerk Maxwell put together in the 19th century is still used in designing cellphones, electric power grids and so much more. But Maxwell's theory is only a limiting case of quantum electrodynamics. That larger theory in turn emerges as a consequence of a broken symmetry in the standard model of particle physics, which is in turn a messy confusion of seemingly arbitrary parameters. Surely there is something better, maybe some variety of superstring theory to be discovered? And after that?

My point is that all of physics is incomplete. I certainly don't mean wrong, I mean that it can all be improved. Maybe there is a final theory of physics, or maybe it is approximations all the way down. And so it is with cosmology.

When I started my cosmological research all those decades ago, I was uneasy at first because the subject then really was a kludge of ideas supported by pathetically little evidence. The evidence is now vastly more abundant and instructive, yet there, still, is the kludge of those hypothetical components. I don't expect our current model will prove to be false. But I do expect we can do better – allowing future cosmologists to garner their continued share of Nobel prizes. ▮