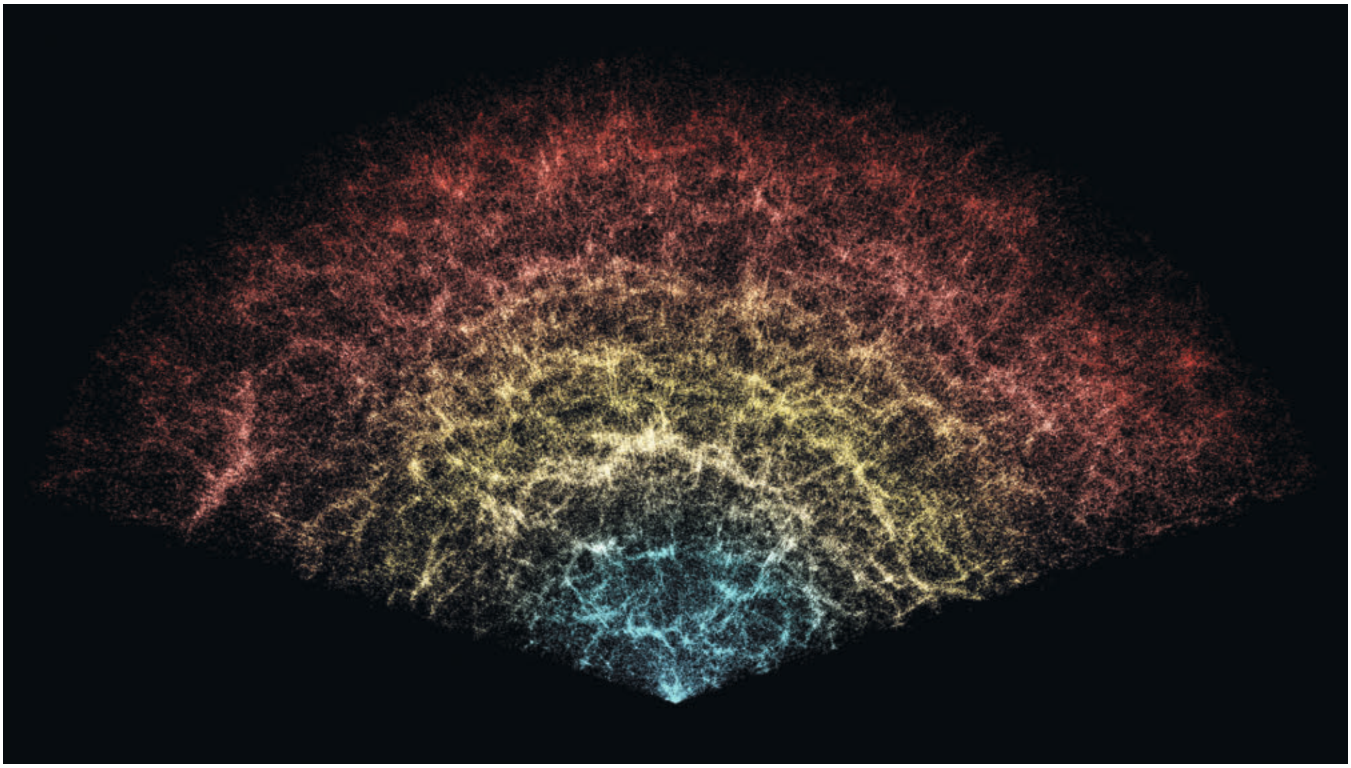
Science & technology



Cosmology

Cracks in the heavens

New observations hint dark energy may break scientists' best model of the universe

IN ARIZONA, AT Kitt Peak National Observatory, a telescope has spent three years building a three-dimensional map of the heavens. In examining the light from tens of millions of galaxies, the Dark Energy Spectroscopic Instrument (DESI) may have found something astounding.

DESI, as its name suggests, is a tool to investigate the nature of dark energy, a mysterious entity that accounts for 68% of everything in the universe and which pushes space apart in a repulsive version of gravity. Though they do not know what it is, scientists have hitherto assumed that the density of dark energy has been the same since the start of the universe, 13.7bn years ago. But DESI's initial results suggest that this assumption may have been wrong. Perhaps, say DESI's scientists, the density has been changing over time. "It's so bizarre," says Dragan Huterer from the University of Michigan, who was involved with the work. If the findings prove true, it would catapult cosmology into a crisis.

The study of dark energy is surprisingly new. Direct evidence for its existence was not detected until 1998, when scientists discovered that extremely bright exploding stars called supernovas were moving away from Earth much more quickly than they ought to. Their conclusion: not only was the universe expanding, but that expansion was accelerating. "People did not expect that," says Adam Riess of Johns Hopkins University, who shared a Nobel prize in physics for the discovery in 2011.

Because it is hard to study directly, the true nature of dark energy remains poorly understood. The leading hypothesis is that it is energy intrinsic to the vacuum of empty space. Per quantum theory, a vacuum is not really empty, it fizzes with countless pairs of particles and antiparticles that emerge from nothing, only to annihilate each other. These interactions produce a "vacuum energy" that, over the scales of the cosmos, could push space apart. This idea is not without its problems—when physicists try to calculate what this vacuum energy density would amount to, they get a value between 60 and 120 orders of magnitude larger than what observational evidence currently supports—a fiasco known as the vacuum catastrophe. "The general consensus is that resolving the [catastrophe] will require fundamental new insight," says Dr Huterer.

Vacuum catastrophe aside, dark energy now forms one of two central pillars of the standard model of cosmology, the best scientific description of the universe's evolution. The other pillar is dark matter, an invisible form of matter that makes up 27% of the universe. Regular matter, which constitutes stars and galaxies, accounts for a measly 5%. The standard model says that, after the Big Bang set the universe's expansion in motion, the gravitational attraction between atoms first led to the formation of stars and galaxies, while also acting as a brake on the universe's overall growth. As the amount of empty space increased, however, so did the amount of dark energy and, eventually, it took over as the primary influence on the evolution of the cosmos, driving the accelerated expansion that Dr Riess observed a quarter of a century ago.

This expansion of the universe is expected to go on for ever, with galaxies eventually drifting out of each other's sight, a fate known as the Big Freeze. But if, as DESI suggests, the density of dark energy can change, other scenarios come into play: ever-denser dark energy could one day cause atoms and even the fabric of spacetime itself to burst apart, a scenario known as the Big Rip. Conversely, a dark energy of decreasing density could cause matter and gravity to take over the universe once again, recollapsing the cosmos into an inverse Big Bang, known as the Big Crunch. (Earthlings need not worry overmuch—the Sun will swallow up the innermost planets of the solar system long before either fate occurs.)

DESI's preliminary findings were announced at the American Physical Society's annual meeting in California in April, swiftly after a series of papers were published on arXiv, a preprint server. The papers contained the data from the first year of DESI's five-year survey. Tasked with capturing an invisible target, DESI has had to find creative, indirect methods to hunt for the signs of dark energy. The instrument's main task is to map the distribution of galaxies in space. Buried in this map are imprints of sound waves that travelled through the early universe. These patterns have grown as dark energy has caused the universe to expand. Analysing the most distant imprints in effect gives cosmologists a way of looking back in time, allowing them to chart the evolution of dark energy over the course of billions of years.

Big crunch time

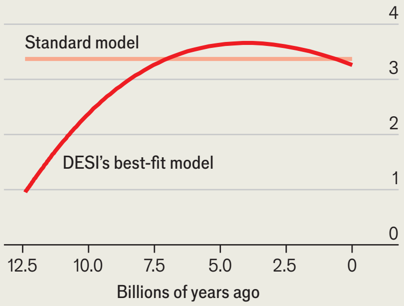
DESI's results suggest not only that dark energy's density has changed over time. According to Dr Huterer, what happened is even stranger than that: the density increased until around 4bn years ago and then it began decreasing (see chart). Nobody can explain why.

If the DESI team's results are right, it would mean a complete re-evaluation of what dark energy could be. "The moment [dark] energy changes in time, it is no longer vacuum energy," says Bhuvnesh Jain, a cosmologist at the University of Pennsylvania. Alternative proposals already exist, centring on a dark-energy field called quintessence, which pervades all space and can change with time. However, Dr Jain says, the DESI results as they stand now indicate something more complex than the simplest quintessence models.

Next top model?

Density of dark energy through cosmic history

Giga electron-volts per cubic metre



Sources: Dark Energy Spectroscopic Instrument; Dragan Huterer

It would also mean that the standard model of cosmology, in its current form, is toast. It is no wonder, then, that DESI's results are causing consternation. But these are not the only vexing cracks in the model. For example, some astronomers have observed that matter in the nearby universe clumps together less than the standard model says it ought to and that the early universe does not seem to have been as uniform a place as the standard model's predictions say it should have been.

What's more, over the past decade different teams have measured differing values for the Hubble constant, the rate at which the universe is currently expanding (named after Edwin Hubble, an American astronomer, who worked out that galaxies were moving away from Earth at a velocity proportional to their distance from it). This would imply that cosmologists do not really understand the universe's historical expansion—or, by extension, how dark energy has behaved in that time. Recent observations from the James Webb Space Telescope, however, collected by Wendy Freedman of the University of Chicago and her team, seem to suggest these values can be reconciled, implying nothing unexpected in dark energy's behaviour. The results have yet to be published in a scientific journal, though, so not all sides in the debate are convinced.

All these problems have led some cosmologists to advocate for radical solutions—adopting more flexible notions of dark energy, for example, or working on an alternative to the standard model of cosmology. Some even go so far as to suggest that Albert Einstein's general theory of relativity, on which the model is based, may have reached its limits. "We know that sooner or later, it will fail. It happened to Newton, it will happen to Einstein," says Andreu Font-Ribera, a cosmologist at the Institute of High Energy Physics in Barcelona and another member of the DESI team. That would not mean that Einstein was wrong but only—small consolation though it may be—incompletely right. Just as Isaac Newton's law of universal gravitation was shown to be an approximation of general relativity under the right conditions (ie, across the relatively small distances and low gravitational fields on and around Earth), general relativity may also turn out to be the limiting case of some deeper, as-yet-undiscovered theory.

For now, all talk of replacing the standard model of cosmology, let alone general relativity, is motivated by hints and guesswork. But as the next generation of telescopes and observatories begins to generate data, a new, more complete picture of dark energy's role in the universe may emerge. The Vera Rubin Observatory in Chile, for example, will also chart the universe's expansion over time and map the universe's evolution over the past several billion years. That will start watching the heavens next year. The European Space Agency's Euclid, a space telescope, is already in orbit and building its own map of galaxies. It is likewise aiming to track dark energy through measurements of the universe's expansion. "You feel like the clues are almost there," says Dr Riess. "I keep waiting for a really smart person to put these puzzle pieces together." ■

Football

On the spot

Augmented-reality headsets could help players take better penalties

ARE YOU reading this, Gareth Southgate? As the England football manager prepares for his team's next match in this year's European championship, a Swiss neuroscientist is offering some help with their Achilles heel: penalty shoot-outs. (As a player, Mr Southgate is perhaps best remembered for missing a decisive spot-kick in a shoot-out against Germany in 1996.)

Penalty kicks are used at the knockout stage of major tournaments to determine

The goal looks so small