RED ALERT

Our tried and tested way of sussing cosmic distance is struggling to keep up with the latest generation of galaxy surveys, says cosmologist ***Andrew Pontzen***

"ONE last time," says Father Ted, patiently holding up a tiny model cow to a clearly baffled Father Dougal. "These are small. But the ones out there are far away."

Astronomers don't have to be fans of the classic UK sitcom *Father Ted* to recognise they have a similar problem with perspective – one that is becoming ever more acute as we look further and deeper into the cosmos. Over the coming decade, a new generation of telescopes will be taking petabytes of data to map out the night sky in unprecedented detail. This comprehensive three-dimensional picture of what's where will help us better understand the forces that have shaped the universe.

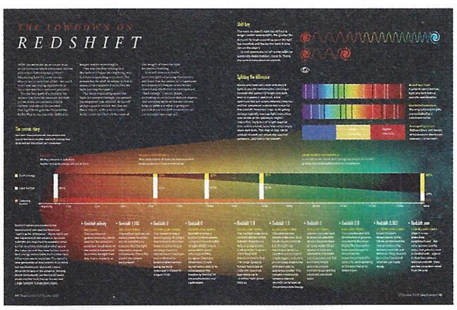
But creating a 3D picture from a telescope's 2D images means accurately gauging distance – and unlike cows, galaxies vary enormously in shape and size. Is this one small, or just far away? Big, or close by? In this modern era of astronomical precision, it's rapidly becoming clear we need to rethink how we answer those questions.

When telescopes peer across distances of billions of light years, they are looking back in time towards the big bang. The first hints of our universe's origins in a hot, dense pinprick of infinitesimal size came in the late 1920s, when the astronomer Edwin Hubble and others noted an effect known as redshift: far-flung galaxies have redder tints than those closer by. Hubble realised that Einstein's general theory of relativity provides a remarkable explanation, that the space between galaxies is expanding, stretching passing light to longer, redder wavelengths. The degree of redshift depends on the amount of expanding space the light traverses – and thus on the distance of the light source. Since Hubble, accurate colour vision has proved to be the best way to estimate cosmic distance.

Studies in the 1990s of distant supernovae provided another unexpected twist, however. The furthest supernovae surveyed were consistently fainter than you would expect for bodies with their measured redshift – suggesting they were further away than predicted by Einstein's description of the cosmic expansion. It was as if some mysterious agent had popped up in the last few billion years and accelerated the expansion. Today, we're still no clearer what this "dark energy" is or how it works – but we now know it makes up more than two-thirds of the total mass and energy in the cosmos.

Since looking back to different distances provides us with snapshots of the universe at different times, a detailed 3D map of cosmic structures would allow us to begin to see how these forces have driven its evolution. Since 2013, the Dark Energy Survey (DES) has been using a 570-megapixel camera attached to a telescope high in the Chilean Andes to map, over five years, 300 million galaxies covering an eighth of the sky. Euclid, a European Space Agency project due to blast off in 2020, is a space telescope that will pinpoint a billion galaxies over an area of sky three times that size. The Large Synoptic Survey Telescope, again on a Chilean mountain, will top them all for sheer output of data: once complete in 2022, it will begin surveying an expected 10 billion galaxies.

Redshift tells the story of an expanding, accelerating universe **(see graphic, page 44)**



These projects entail an awful lot of distance measurements. "The two dimensions you have from measuring position on the sky aren't enough," says Dragan Huterer, a cosmologist at the University of Michigan, Ann Arbor. "All these surveys hinge on having depth information to see how the universe has developed over its life."

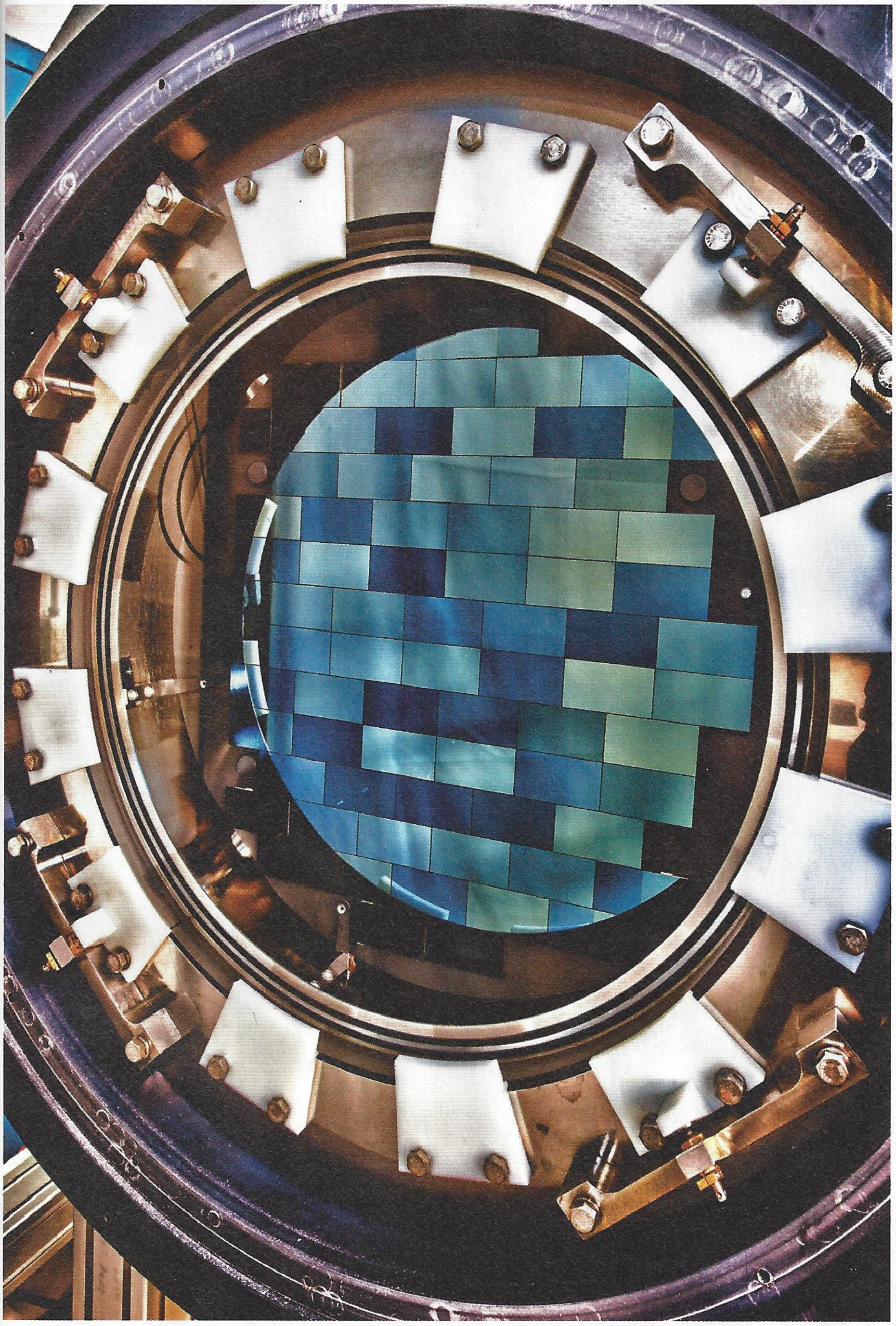
Lost in space

And that's where the small/big cow problem is really kicking in. As well as coming in a range of sizes and shapes, galaxies vary enormously in intrinsic colour. "This is when science turns into art. You need some way of working out how much the colour has changed, even when you don't know what the original looked like," says Huterer.

One way is to look at the full spectrum of a galaxy's light. Atoms and molecules in a galaxy emit and absorb specific wavelengths of light, forming a distinctive "barcode" of light and dark lines. Work out how far this pattern has moved along the spectrum, compared with a nearby, stationary light source, and that should tell you the redshift.

But this sort of forensic reconstruction is beyond the new large-scale surveys. The DES, for example, takes five snaps of every field of view, each time through a different colour filter. These exposures measure light levels averaged across a portion of the spectrum, but not the position of spectral lines. "We work with a tiny fraction of the information you ideally want," says Stephanie Jouvel of University College London, who is part of the DES team. "We can tell a lot, but we only end up with a probable answer rather than the certainty you get from a spectrum."

Getting even that requires a lot of highly educated guesswork, using tried-and-trusted galaxies for calibration, or simulations that model the expected light levels under each filter for galaxies at different redshifts, and



REIDAR HAHN/FERMILAB

The Dark Energy Survey's 570-megapixel camera aims to map the cosmos

then trying to find a match. But this tends to yield several possible matches, creating uncertainties that smudge the final map.

If that were the end of it, we wouldn't be too worried. "It's fine to be uncertain," says Huterer. "So long as you are certain about your uncertainty, you're good to go." But the universe isn't regular enough to give us that confidence: a strange galaxy emitting an unexpected colour combination can end up in entirely the wrong place. That's enough to skew our view of the universe, rather as an outsider's view of Earth would be skewed if a data blip showed just a few cows roaming the wastes of the Antarctic. "If you put even a few galaxies in a catastrophically wrong place, you get the wrong answer about the universe. It's as simple as that," says Huterer.

One solution the DES team is investigating involves neural networks: chunks of code that process data in a way loosely inspired by the interlinked cells of the human brain. The network's sensory inputs are the five raw numbers representing the filtered colour intensities, and its output is a single number for the redshift. Just as a baby's brain learns with repeated exposure to react appropriately to familiar stimuli, and then progresses to unfamiliar ones, the network's algorithm is trained by showing it pictures of galaxies with surer redshifts, and allowing it to run until it makes sense of things. "The computer learns to get an answer for itself," says Jouvel.

Faced with the complexity of the real universe, these self-taught systems often pick up on subtle hints that the models miss. So far they're also five to 10 times as fast – a significant improvement when dealing with hundreds of millions of galaxies.

Yet the neural network still fails catastrophically on some objects emitting strange colours, and does even worse with things that aren't conventional galaxies. Quasars are extremely luminous sources of light thought to be powered by supermassive black holes. They shine so brightly that they can be seen tens of billions of light years away, so are essential for filling out our map to the farthest possible distances. They also have few identifiable colour traits, meaning their chance of being put in completely the wrong place is even greater than normal.

Not all is lost. Cosmic objects aren't scattered at random, but tend to lie along a relatively well-defined web of structures. Galaxies and quasars with accurate redshifts can be placed with confidence in this web, providing a clue as to where others must slot in. "We think of it like a puzzle; we can slide the troublesome objects around until the whole thing locks together," says Matt McQuinn at the University of Washington in Seattle. He and his colleagues have been developing heavy-duty statistical methods to make that happen. "The fundamental goal is to get probabilities that each redshift assignment is correct, so that we at least know how wrong things are going," he says. Several studies show that this improves on the accuracy of the output from neural networks significantly.

Although enthusiastic about these innovations, Huterer is clear that more are needed. "It's part of the solution, but on its own it's still insufficient," he says. Getting to grips with dark energy and the story of cosmic evolution means measuring billions of distances to an accuracy of 0.1 per cent, he says, and that will require a whole battery of tricks from statistics and astrophysics. We cosmologists may be needing a little more time to sort out our cows. ■

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For more on redshift, see graphic on next page ›