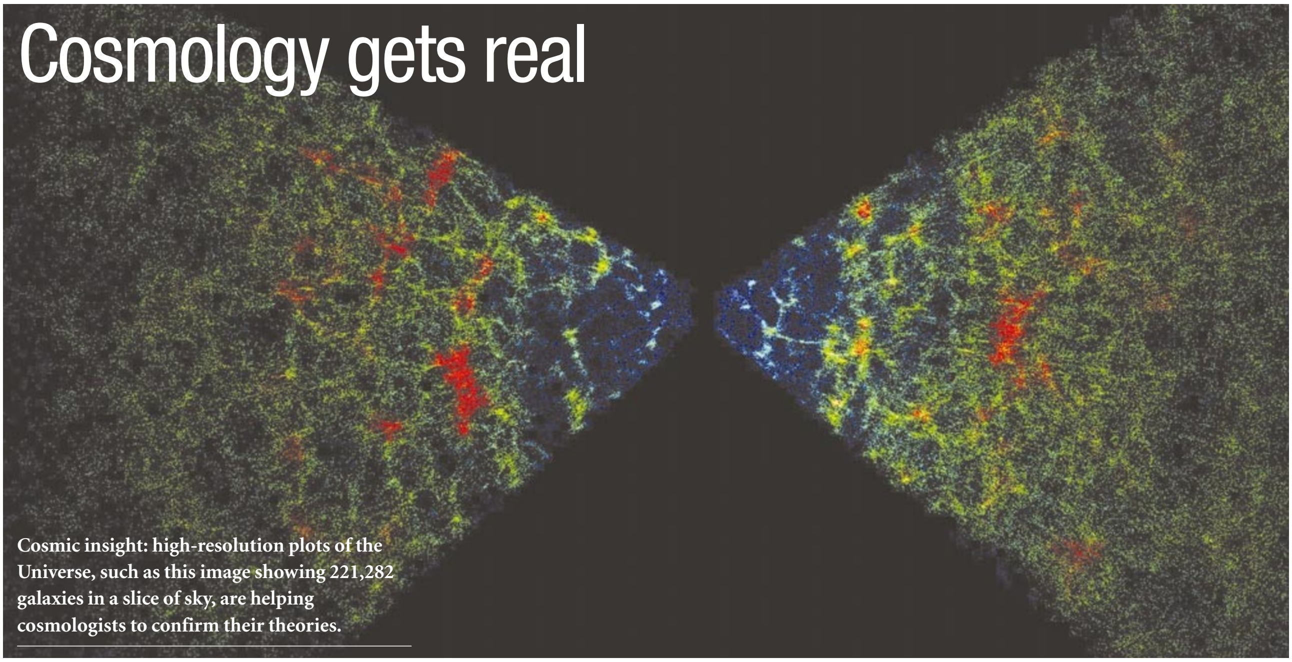
Cosmology gets real



Cosmic insight: high-resolution plots of the Universe, such as this image showing 221,282 galaxies in a slice of sky, are helping cosmologists to confirm their theories.

2DF GALAXY REDSHIFT SURVEY TEAM

By clarifying the age and make-up of the Universe, researchers have ushered in an era of precision cosmology. Now they are preparing to probe the mysteries of dark matter and dark energy. Geoff Brumfiel reports.

The history of cosmology is full of deep thoughts and unlikely ideas. Early European star-gazers thought that Earth was at the centre of a Universe filled with concentric crystalline spheres, whereas their counterparts in America believed that the cosmos sat on the back of a giant tortoise. Much modern cosmology has been similarly speculative, with theorists using fractal patterns to describe the Universe, or modelling its evolution on the behaviour of a giant ball of very cold fluid.

Such cosmological guesswork flourished because important parameters of the Universe, such as its age, could not be measured precisely. But over the past two decades, astronomers have quietly been measuring these details with ever greater precision, verifying and discarding theories along the way. With a crucial new map just in showing the cosmic microwave background (CMB) — radiation left over from the early Universe — the field is rapidly converging on a single picture of the cosmos.

But that picture is extremely odd. A mysterious force, known as dark energy, is pushing the heavens apart. Most of the mass in the cosmos remains unseen, and researchers are unsure what form this 'dark matter' takes. The two theories that describe the Universe — quantum mechanics and general relativity — remain incompatible. So to plug these gaps in the Universe's narrative, researchers are gearing up with a new generation of precision instruments.

Many aspects of our current picture of the Universe date from the early 1980s, which was a difficult period for astronomers. By studying the large-scale structure of the Universe — such as how galaxies are aligned — and the way in which it is expanding, researchers reached some basic, if shaky, conclusions.

Level-headed approach

Most believed that the geometry of our Universe is flat, meaning that it will continue to expand forever. For this to be true, the mass density of the Universe must have a particular value. But estimates of the visible mass in the Universe fell well short of this figure. Researchers knew that there was mass out there that they couldn't see — this dark matter revealed itself by the gravitational pull it exerted on nearby galaxies. Even so, calculations that combined the inferred dark matter with the observed luminous matter had error margins of 25–30%, making it hard to tell if the Universe really was flat.

The theorists, by contrast, were having a field day. Their ranks had been swelled by high-energy physicists, who realized that the knowledge gleaned from particle accelerators could be applied to the high-energy conditions of the early Universe. "In those days it was a theorist's paradise because there were hardly any data to go on," says Peter Coles, a theoretical astrophysicist at the University of Nottingham, UK. "You had a lot of freedom to work on theoretical ideas without any real prospects of them being tested."

The most popular of these theories was inflation, developed in part by Alan Guth of the Massachusetts Institute of Technology. This suggests that the Universe expanded rapidly 10^{-35} seconds after the Big Bang, and it makes specific predictions about the distribution of matter and energy in the Universe immediately after this expansion. The theory says that the Universe was then a sea of high-energy particles, such as electrons and photons, which would have contained small areas of low and high density. These areas should have left their mark in the form of temperature variations in the CMB, which has had little interaction with matter since about 300,000 years after the Big Bang. By verifying these predictions, observational astronomers began to catch up with the theorists.

Temperature fluctuations in the CMB were first spotted in 1990 by NASA's Cosmic Background Explorer satellite[1], and a finer plot of these variations was provided by BOOMERANG, a small balloon-based telescope that was first flown over Antarctica[2] in 1998. Both maps seemed to show the temperature variation predicted by inflation. "The results had a sense of rigour that gave people confidence in where they were going," says Saul Perlmutter, an astronomer at Lawrence Berkeley National Laboratory in California.

Other measurements have since provided more support for inflation. The uneven dis-

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Studying supernovae (lower left) has convinced Saul Perlmutter that cosmic expansion is accelerating.

tribution of matter in the early Universe, detected by the CMB studies, seeded the formation of the first stars. This allowed theorists to predict where and when stars and galaxies should have formed. These predictions have now been tested, thanks to two surveys — the Anglo–Australian Two-Degree Field Galaxy Redshift Survey[3] and the Sloan Digital Sky Survey[4], based at Apache Point Observatory in New Mexico — which have taken the best-ever large-scale images of the Universe. These images detailed the ways in which galaxies are aligned and provided additional information about the distribution of dark matter. The results fitted nicely with the idea of inflation and its effect on the CMB, but still left about two-thirds of the mass in the Universe unaccounted for.

In with a bang

As evidence for inflation piled up, a solution to this problem was proposed. In 1998, a group led by Perlmutter[5] and a second team headed by Brian Schmidt[6] of the Mount Stromlo Observatory near Canberra, Australia, measured the distance from Earth to exploding stars in far-off galaxies using two separate techniques. First they measured the colour of the light emitted by the explosions. In most cases, the farther away an object is, the redder it appears. This 'redshift' is the most common measure of distance used in modern astronomy. But astronomers also know that the explosions have very similar luminosities, so they can infer distance by measuring how bright the explosions appear.

Perlmutter and Schmidt's teams found that the brightness measurements placed the explosions, commonly called supernovae, farther away from Earth than did the redshift readings. Redshift is based on the assumption that the rate of the Universe's expansion is slowing down, so this finding led them and others to make an extraordinary suggestion: that the expansion of the Universe is accelerating, pushed outwards by some kind of phantom force for which there was no explanation.

This phenomenon of dark energy seemed odd. But according to the general theory of relativity, mass and energy are equivalent. And when cosmologists looked at the amount of energy needed to create the mysterious force, they found that it accounted perfectly for the mass still missing from their picture. "It's like a funny-looking jigsaw piece that just happened to fit," says Michael Turner, a cosmologist at the University of Chicago. "People were quick to accept it."

With the addition of the latest data on the CMB[7,8], courtesy of NASA's Wilkinson Microwave Anisotropy Probe, our picture of the Universe is now clearer than ever. Combined, the various CMB studies have confirmed that the Universe is indeed flat. The Wilkinson probe has now set ratios for the composition of the cosmos: 23% dark matter and 73% dark energy, leaving only 4% for galaxies, stars and people. The Universe's age has also been nailed to within 1% of 13.7 billion years. And the total mass density matches that predicted by inflation to within a 2% margin of error. "This is a giant leap forward in credibility for cosmology," says Max Tegmark, a cosmologist at the University of Pennsylvania in Philadelphia. "It has been transformed into a real, hard science."

Although that leap has left cosmological theory on a surer footing than ever before, the holes in our knowledge are still considerable. Researchers are confident that dark energy and dark matter are out there, but they don't know what kind of entities they are or how to find them. "Ninety-six per cent of the Universe is stuff that we've never seen," says Turner.

Hidden depths

Dark matter is the older, and perhaps easier, problem to address. The key to understanding it lies in its effects on stars and galaxies. According to general relativity, all mass distorts the space around it. When light from distant objects passes close to dark matter, it should be bent — a process called gravitational lensing. In the past, astronomers could detect only the largest clumps of dark matter, which create dramatic lensing effects. But with the aid of computer algorithms, they can now pick up much weaker distortions.

These lensing projects are only just under way, but they should produce results in the next few years, says Nicholas Kaiser, an astronomer at the University of Hawaii in Manoa. He predicts that the number of lenses identified will increase by a factor of ten. The hope is that these will allow astronomers to determine the distribution of dark matter in the present-day Universe. Those measurements won't say much about what dark matter actually is, but they should provide tighter constraints on the role it played in the evolution of the Universe.

Cosmologists also know a little about how dark matter interacts with other matter. The faster a particle moves, the more energy it transfers to any particles that it collides with. If, during the early Universe, dark matter was moving at close to the speed of light, it would have left its mark on the process by

W. COUCH/R. ELLIS/NASA

Invisible touch: the Universe's dark matter reveals its presence through gravitational lensing — the distorting effect it has on the light from galaxies.

Let's be precise

A new generation of experiments promises to provide a wealth of data against which cosmologists can test their theories. They include:

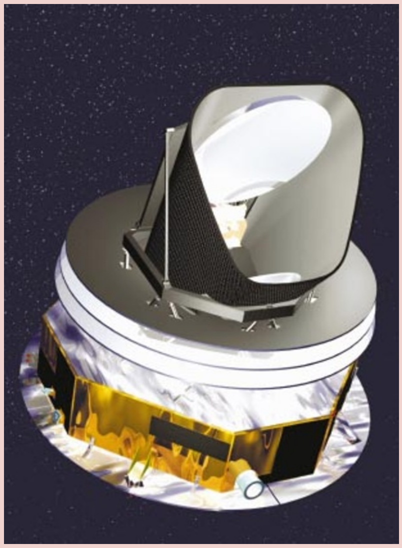
Planck A cosmic-microwave-background satellite with better spatial resolution and temperature sensitivity than the Wilkinson probe. Scheduled to launch in 2007.

James Webb Space Telescope The successor to the Hubble Space Telescope, it will allow astronomers to view younger galaxies than is currently possible. Scheduled to launch in 2011.

Supernova/Acceleration Probe Designed to take measurements of distant supernovae to see if the strength of dark energy has changed over time.

Large Synoptic Survey Telescope A giant ground-based telescope that would improve maps of large-scale galactic structure and probe dark matter using gravitational-lensing techniques.

Laser Interferometer Space Antenna Three satellites that would look for gravitational waves generated by inflationary expansion, an important but unchecked prediction of the inflation theory.



ESA

Planck: set to improve our picture of the cosmos.

which matter clumped together to form stars and galaxies. But astronomers can watch star and galaxy formation occurring in very distant parts of the Universe, and so far they have not seen any evidence of the influence of fast-moving dark matter.

This has led many cosmologists to speculate that it is made up of heavy and relatively slow-moving particles that seldom interact with visible matter. This prescription interests high-energy physicists, who may be able to help. Although nothing that fits the bill has yet been created in a particle accelerator, researchers at CERN, the European Laboratory for Particle Physics near Geneva, should have a new and more powerful device — the Large Hadron Collider — up and running in 2007. Theoretical calculations indicate that the collider may create candidate dark-matter particles, which would help to constrain cosmologists' models.

Dark energy is a more vexing problem, but the solution could lie in the nature of empty space. According to quantum theory, particles and their antiparticle equivalents are continually being created and annihilated, even in a vacuum. Some researchers have speculated that this vacuum energy could be what is accelerating the Universe's expansion. But theoretical predictions for vacuum energy are up to 120 orders of magnitude greater than the strength of dark energy seen today.

Another idea, says Paul Steinhardt, a theoretical physicist at Princeton University in New Jersey and one of the originators of inflation theory, is that dark energy may be a cousin of inflation. Like dark energy, the inflationary force resisted gravity, pushing everything outwards. But inflation was many times the strength of the current outward-acting force, and seemed to switch off moments after the Big Bang. Theorists are now experimenting with weaker versions of the equations for inflation to see if they can describe dark energy. So far, few solid conclusions have emerged. "Those models raise more questions than they answer," says Turner.

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Highly strung

Other theoretical ideas may come from attempts to combine the worlds of quantum mechanics and general relativity. Known broadly as string theory, these models suggest that all elementary particles are made of tiny strings and loops vibrating in multiple dimensions. The theory might be able to explain how tiny quantum fluctuations, such as vacuum energy, could interact with gravity on larger scales to create the effect of dark energy. "String theory might give you answers," says Lisa Randall, a theorist at Harvard University who is working on a version of inflation that involves extra dimensions. "But I don't think anything has come close to doing it yet."

As in the past, experimentalists might eventually provide the additional data needed to constrain these models. In 2001, Adam Riess, an astronomer at the Space Telescope Science Institute in Baltimore, Maryland, led a Hubble Space Telescope team that helped to confirm dark energy's existence by looking at older supernovae[9] than those studied by Perlmutter and Schmidt. Riess is now looking for even older supernovae to see if dark energy changes with time, although his results will only be able to detect large deviations in the force's behaviour.

Apart from supernovae, there are no other bright and distant objects that lend themselves to distance measurements, so astronomers are wracking their brains for new methods of probing dark energy. One of the most promising is the Deep Extragalactic Evolutionary Probe 2 at the Keck Observatory on Mauna Kea in Hawaii. The study is trying to establish what types of object — most probably certain kinds of galaxy — are evenly distributed throughout the Universe. By monitoring collections of these objects at different distances from Earth, and hence at different stages in the evolution of the Universe, the survey will reveal how dark energy pushes them apart, which should help to verify the supernovae results.

A new generation of precision instruments, planned for the next decade and beyond, should provide a slew of extra data (see 'Let's be precise', left). The Supernova/Acceleration Probe (SNAP) satellite would, for example, continually monitor patches of sky, searching for new supernovae. The probe's backers, based across several US institutions, say it could gather data on 2,000 supernovae a year — 20 times the number obtained by a decade of ground-based searches.

Such data would allow astronomers to tell whether dark energy is constant, as the vacuum-energy explanation would suggest, or changing, as its inflationary cousin did in the early Universe. But researchers working on SNAP are still seeking funding for the project, and the probe is unlikely to be launched before the end of the decade. "It could take us a long time to figure out the nature of the dark energy," says Steinhardt.

For many astronomers, the CMB map generated by the Wilkinson probe is a milestone in cosmology. The data capped a long effort to measure the basic properties of the Universe. And despite the unexplained phenomena of dark matter and energy, astronomers are more confident than ever of their ability to understand the cosmos. "We've flushed out the basic features of the Universe," says Turner. "What we need now is a good story." ■

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Wilkinson Microwave Anisotropy Probe
➧ **map.gsfc.nasa.gov**