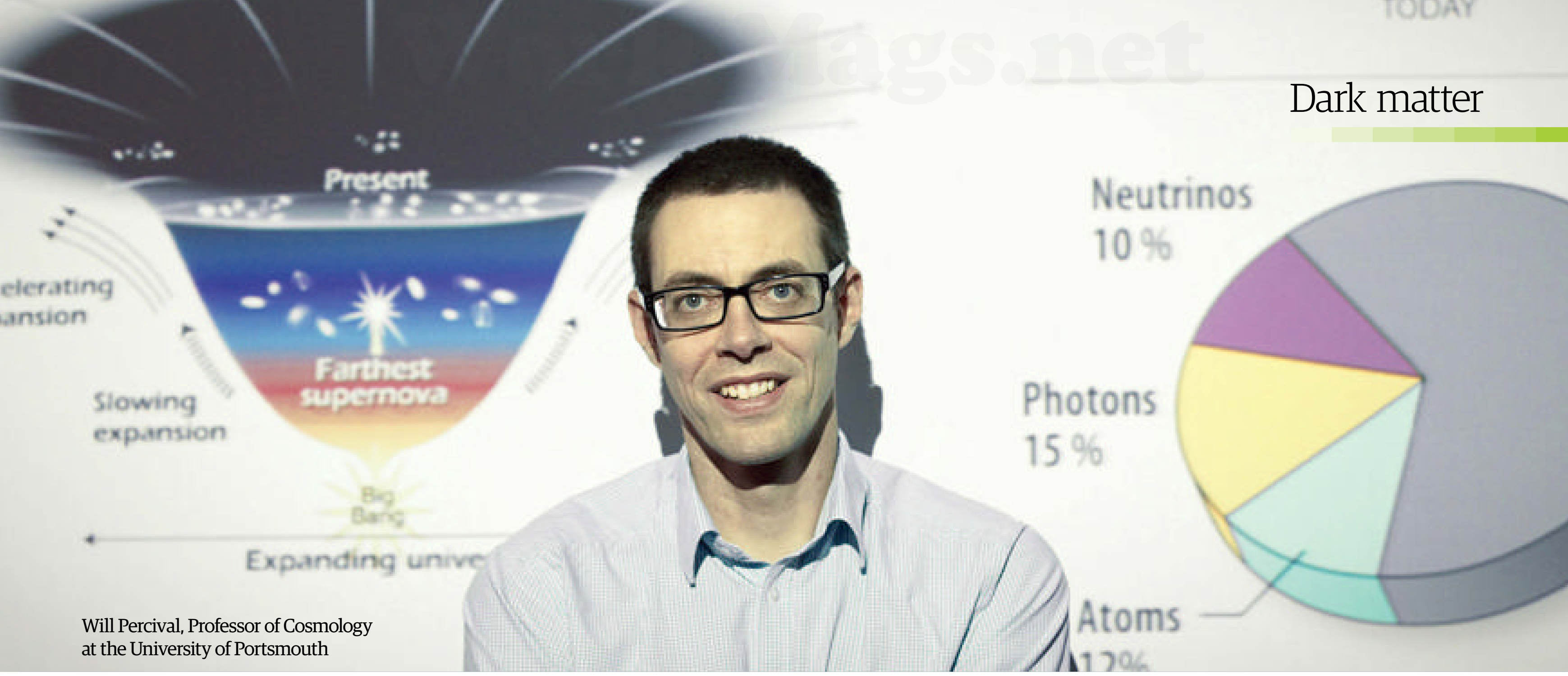
The quest for DARK MATTER

Written by Giles Sparrow

96 per cent of our universe is missing... **All About Space** explains how science is attempting to solve this cosmic mystery



Will Percival, Professor of Cosmology at the University of Portsmouth

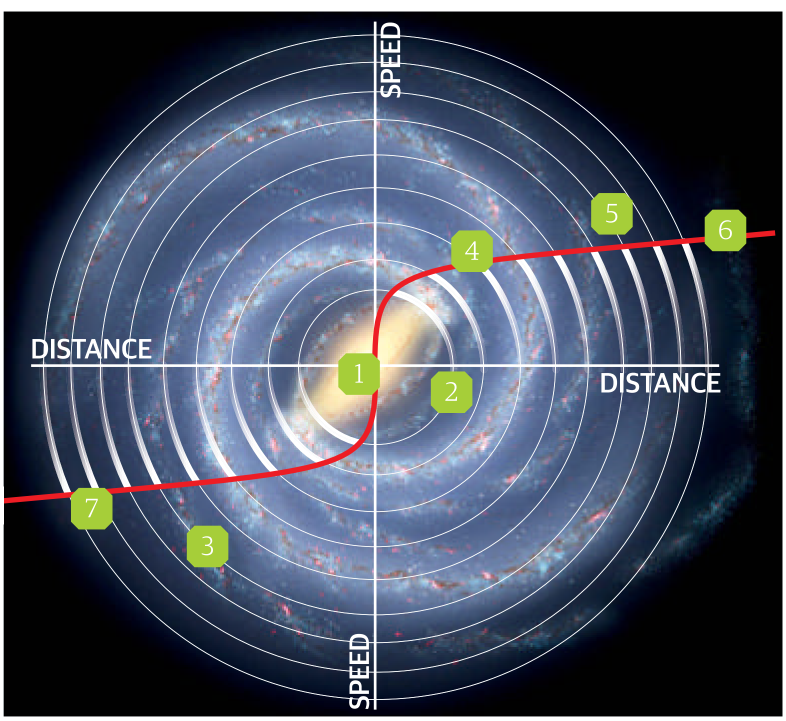
Cosmology, the study of the history and large-scale structure of the universe, has a way of putting you in your place. It's hard enough getting to grips with the fact that our entire complex world is little more than a speck of rock orbiting an insignificant Sun, and that even our galaxy is just one among hundreds of billions in the universe. But now it seems that all the visible matter in the cosmos is vastly outweighed by an unseen 'shadow universe' – a strange realm filled with heavyweight particles that are invisible through the most powerful telescopes, pass straight through normal matter as if it wasn't there, and only reveal their presence through the influence of gravity.

This 'dark matter' is one of the greatest mysteries of modern astronomy – permeating and surrounding the normal 'baryonic' universe of matter that interacts through electromagnetic forces, it is frustrating but also tantalising. Because, despite its unsociable nature, dark matter has had an enormous influence on the history and development of the universe. In fact, it is probably fair to say that if it weren't for dark matter, we wouldn't be here today.

"There is an incredible amount of evidence for an increased gravitational force pulling the baryonic material that we can see together," explains Will Percival, Professor of Cosmology at the University of Portsmouth, "and this can most simply be explained by having this dark matter component, basically an excess amount of this material which interacts through gravity but doesn't interact through the electromagnetic force. It's the simplest explanation for a huge number of phenomena."

Percival is one of the UK's leading researchers into dark matter, and is involved in a number of groundbreaking galaxy surveys that aim to map its changing influence throughout the history of the universe. "We are currently going through a very interesting time in astronomy," he explains, "where a large fraction of the energy density in the universe is unknown. We think that's dominated by a force called dark energy [see boxout on page 42], but even out of the 30 per cent that we think interacts gravitationally – the matter component of the universe – we think only a small fraction of that is baryonic, and the rest is dark matter."

So what's the evidence for this mystery matter? It turns out to come from a surprising number of sources, and taken in combination is enough to convince the most sceptical scientists. The first signs that something was wrong with traditional models of matter in the universe came as early as the Thirties, but were explained away for more than four decades before being resurrected. In 1932, Dutch astronomer Jan Oort undertook an ambitious project to map the rotation of our galaxy from the movement of individual stars and clusters within it. He expected to find that stars were moving at slower speeds the further away they were from the centre of the Milky Way (just



The galactic curve

The first clues to the existence of dark matter came from studying the orbital speeds of stars within spiral galaxies, and discovering that they did not behave as simply as planets orbiting a star.

1. Galactic hub
In traditional models of galaxy structure, most of a spiral galaxy's mass was thought to be concentrated in this central region, with other objects orbiting around it.

2. Inner stars
Stars close to the hub move around their orbits at high speeds, in accordance with the established laws of orbital motion.

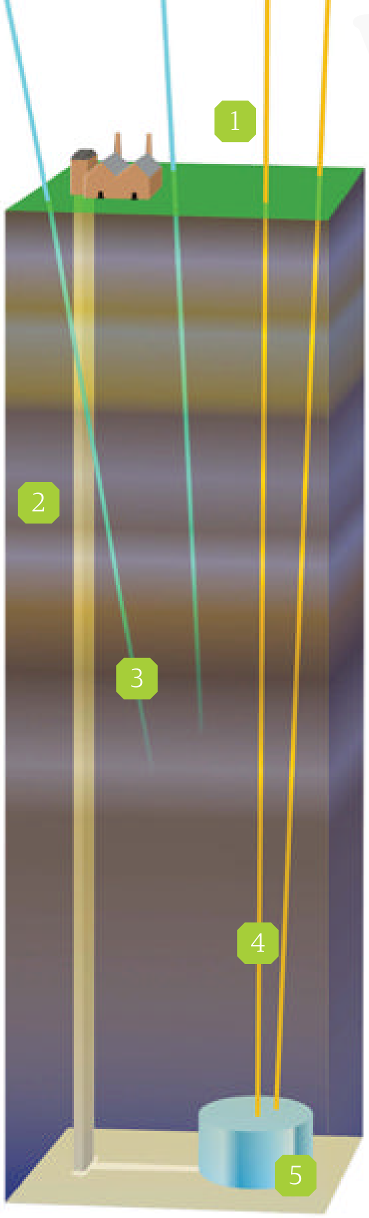
3. Spiral arms
The movement of different regions in the galaxy's disc at different speeds helps to create its beautiful pattern of spiral arms.

4. Slower orbits
Stars a little further away from the hub not only have larger orbits, but also move more slowly along them, matching again with established orbital motion theories.

5. Keeping pace
Stars at greater distances from the galaxy's hub move at almost the same speed as those closer in – they do not behave as they should if the galaxy's mass is all concentrated in the hub.

6. Dark matter halo
Instead, astronomers think that the galaxy's mass is much larger and more evenly distributed. Huge amounts of dark matter form a halo that extends beyond the visible disc and influences the orbits of its stars.

7. Rotation curve
By plotting the speeds of stars in different parts of a spiral galaxy, astronomers can measure the amount and distribution of its dark matter.



WIMPS

The UK Dark Matter Collaboration's laboratory at Boulby Mine beneath the North York Moors hosts some of the world's first dedicated WIMP detectors. Scientists hope they will reveal direct evidence for WIMPs, and perhaps even some of their properties.

1. Bombardment from space
Particles from space raining down on Earth include cosmic rays from the Sun and other sources, as well as neutrinos and WIMPs

2. Going down
Sited 1,100m (3,600ft) below ground in one of Europe's deepest mines, the DRIFT detectors are only accessible via deep mine shafts.

3. Soaked up
Layers of dense rock absorb even the highest-energy cosmic rays, ensuring that none can reach the experiments.

4. Passing through
Lightweight neutrinos and mysterious WIMPs pass through the rock as if it wasn't there, because they are only weakly interactive with normal matter.

5. DRIFT detector
This experiment looks for rare collisions between WIMPs and molecules in a low-pressure gas, and hopes to measure the recoils they create in the gas particles.

measured, then it might be enough to make a significant contribution to dark matter. In 1998, astronomers at Japan's Super-Kamiokande neutrino observatory confirmed a phenomenon called oscillation (in which neutrinos 'flip' between different types) that is only explicable if neutrinos do in fact have a tiny mass – less than 1/100,000th that of an electron.

However, even with the largest plausible maths, neutrinos could only contribute around ten per cent of the universe's missing mass. What's more, their properties don't necessarily match what little we can work out about the likely behaviour of WIMPs.

The most productive way of studying WIMPs is through computer modelling – assigning various different properties to the hypothetical particles in a complex simulation of the early universe, and seeing how these properties affect the way that structure develops in the simulated baryonic matter. The most important property cosmologists assign to their model WIMPs is similar to temperature, and indicates how far and how fast the particles could travel in the early universe before slowing down. This in turn affects the scale of density variations that WIMPs could seed in the early universe – the 'cooler' the dark matter, the smaller the fluctuations it creates.

Neutrinos are a form of 'hot dark matter', but as the level of detail in our maps of the CMBR has increased thanks to satellites such as the Wilkinson Microwave Anisotropy Probe (WMAP) and the European Space Agency's Planck Telescope, we've discovered more and more fine structure in the early universe, suggesting that cold dark matter or 'CDM' is the dominant type. Another important characteristic of CDM is that it tends to gather in the same regions as baryonic matter, which helps explain why it is largely associated with galaxy clusters and individual galaxies.

"Neutrinos can't make enough of a contribution to dark matter, and all the observational evidence that we have fits within what's called a 'Lambda CDM universe' – a fairly simple model of the universe in which the dark matter is cold, relatively slow moving, and has absolutely no interactions with electromagnetic

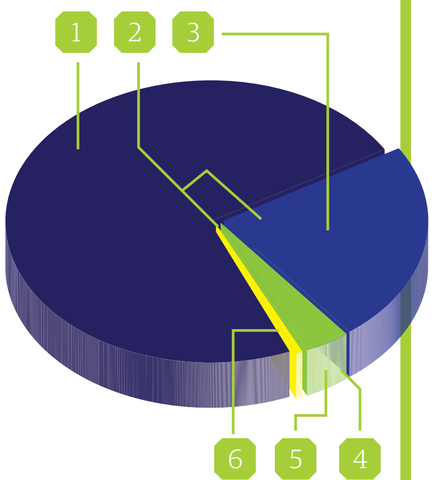
Portsmouth University's Institute of Cosmology and Gravitation


The team recently announced a remarkable measurement of the scale of the early universe


Percival is one of the UK's leading researchers into dark matter

Discovering dark matter

According to the latest research, luminous objects such as stars and galaxies make up just a tiny proportion of the matter in the universe, vastly outweighed by dark matter.



1. Dark energy
This newly discovered phenomenon, which causes space to expand at an increasing rate, accounts for 72 per cent of all energy in the universe.

2. Mass or energy?
The mass within baryonic and dark matter together binds up 27 per cent of all the energy in the universe. Until the late-Nineties, it was thought to account for 100 per cent of cosmic energy.

3. Dark matter
Studies of galaxy rotation and galaxy clusters reveal the gravitational influence of dark matter, accounting for 85 per cent of all the mass in the universe and 23 per cent of all energy.

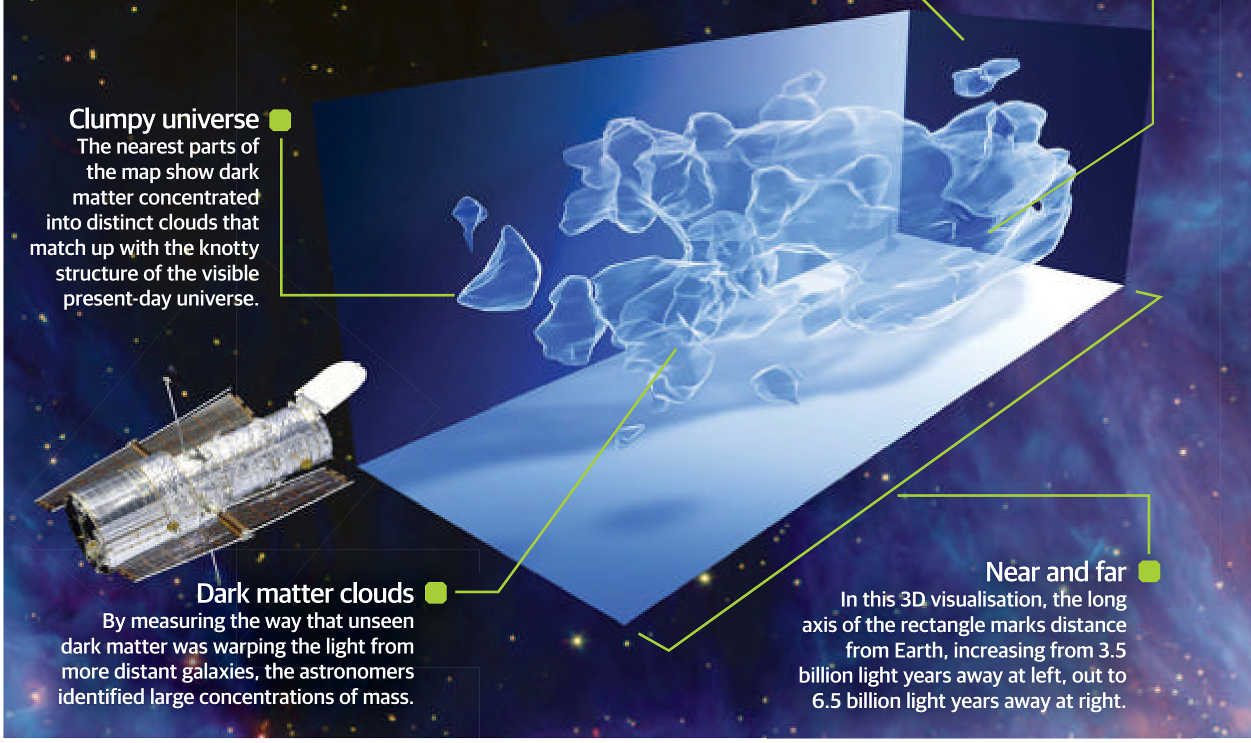
4. Intergalactic gas
X-ray-emitting intergalactic gas is now thought to account for 4.6 per cent of all the universe's energy, or 13 per cent of its mass.

5. Other radiations
Not all 'baryonic' matter produces visible light – objects such as interstellar dust and intergalactic gas clouds emit invisible, but still detectable, radiations such as infrared and X-rays.

6. Visible matter
Stars, galaxies, and other objects that glow in visible light account for just 0.4 per cent of all the energy in the universe, or 1.5 per cent of all the mass.

Hubble's dark matter map

In 2007, astronomers published the first three-dimensional map of dark matter in a small section of the universe. Using gravitational lensing – the way that large concentrations of mass bend the path of light – they mapped the distribution of dark matter between 3.5 and 6.5 billion light years from Earth.



forces," explains Percival. "So we're looking for an unknown, massive, and 'non-relativistic' particle."

Most of the current suggestions for exactly what these particles might be originate not from astronomical observations, but from the musings of theoretical physicists. They bear exotic names such as axions and supersymmetric particles, and arise naturally from various 'unifying theories' of physics that are themselves so far unproven.

Could such a particle ever be discovered through astronomical observations? Professor Percival is doubtful: "Unless these particles prove to have some 'non-cold' features that we could pick up, we're probably more likely to discover them using particle accelerators than using telescopes. You should never say never, but it would take something outside of the current bounds of mainstream astronomy to pick it up."

So, if dark matter is so hard to detect and so reluctant to interact with the everyday universe, why should we worry about it? One long-standing reason is that it could affect the fate of the cosmos itself. The amount of matter in the universe, and the gravity it exerts, was thought to determine whether cosmic expansion, powered by the enormous explosion of the Big Bang, would keep going forever, or eventually slow to a halt. With enough matter in the universe, the expansion might even go into reverse, pulling everything back to a cataclysmic 'Big Crunch' at some point in the unimaginably distant future. Attempts to measure the density of the universe repeatedly came up with figures on the tantalising borderline between these three scenarios, which only made the mystery of dark matter all the more intriguing.

In the late-Nineties, however, the future of the cosmos was thrown into further doubt with the shocking discovery that cosmic expansion is actually accelerating, driven by an unknown force that was soon named 'dark energy'. This force seems to account for some 72 per cent of all the energy in the universe, with dark matter accounting for 23 per cent and baryonic matter around 4.6 per cent. At face value, it seems to ensure that the universe will keep expanding forever, but there's growing evidence that the story is more complicated than that.

"There's a race on at the moment to get more information about dark energy, with a whole series of upcoming and ongoing experiments designed to fill in different pieces of the puzzle," explains Professor Percival. Most recently, he and his colleagues have announced a remarkable measurement of the scale of the early universe, showing how cosmic expansion was initially slowed by matter and gravity, and dark energy only became the dominant force after several billion years.

His University of Portsmouth colleague Dr Matthew Pieri draws an interesting comparison to the ups and downs of cosmic history: "If we think of the universe as a rollercoaster, then today we are rushing downhill, gaining speed as we go. Our new measurement tells us about the time when the universe was climbing the hill – still being slowed by gravity. It looks like the rollercoaster crested the hill just about seven billion years ago, and we're still going."

And where do we go from here? Is it possible that dark energy could fade away again and the pull of dark matter could reassert itself after a relatively brief cosmic 'growth spurt'? Or are we doomed to accelerate forever, perhaps at an ever-increasing rate? Nobody can say for certain, but it seems clear that these twin unknowns, dark matter and dark energy, ultimately hold the fate of the universe in their hands.