Unweaving the cosmic web: Relativity goes large

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*We're on the verge of being able to see the structure of the entire universe. That could help us go beyond Einstein's masterwork, says **Pedro Ferreira***

AS WE near the centenary of Einstein's general theory of relativity, a quiet revolution is under way. A number of groups around the world are attempting to test the validity of general relativity on the scale of the universe. So far the tests are inconclusive, yet they herald a striking shift in the way that Einstein's theory is perceived. And testing general relativity is rapidly becoming one of the core endeavours for some of the most powerful satellite and ground-based experiments being developed.

Einstein's general theory of relativity has served us well. Yet what if he was off the mark? Don't get me wrong, the theory is remarkably successful at explaining many different phenomena: it allows us to calculate the orbits of all the planets of the solar system with extraordinary accuracy. It also enables us to work out how light is deflected by the deformed space-time around stars and planets. But could we have taken general relativity too far in attempting to predict the evolution of the universe?

It is a striking fact that general relativity has remained unchanged since Einstein first proposed it in 1915. At its heart is our understanding of the force of gravity. Einstein put forward the idea that there is no force of gravity per se. Instead, what we perceive as gravity results from the geometry of space-time. If we place an object - a planet or a star, or indeed anything with mass - into space, it will deform it. Einstein's general theory of relativity gives us unique and exact rules for calculating the extent of this deformation.

Those same rules are with us today, and we have long been mining them, extracting predictions that range from black holes to the big bang. One of the first predictions to emerge was the notion that the universe is expanding. Distant galaxies are moving away from us, and each other, at speeds of tens or hundreds of thousands of kilometers per second. The expansion of the universe was spectacularly confirmed by Edwin Hubble in 1929 and, since then, ever improving observations have enabled us to unravel the history of the expanding universe with increasing precision.

But there's the rub. If general relativity is correct, it has some explaining to do. That's because observations seem to indicate that the universe is not just expanding, its expansion is actually accelerating. This is not at odds with relativity: Einstein's theory suggests that there is something else out there, a "dark" form of energy that is pushing space apart. According to calculations based on the theory, two-thirds of the total energy budget of the universe must be made up of this elusive dark energy.

Suspicious minds

The problem is, our observations so far have found no indication of what dark energy is and what it was doing at different times in the history of the universe. New missions are being planned to address these issues. But until we have such knowledge, it is possible that the concept of dark energy is concealing something fundamentally wrong with our notions of gravity.

So is it just possible that we have reached the limits of Einstein's tremendous insight and that some new theory is needed? It would not be the first time that suspicions have been raised about general relativity's accuracy and completeness; luminaries such as Paul Dirac and Andrei Sakharov have questioned it (see "Replacements for relativity").

Despite the plethora of alternatives, Einstein's theory has remained the favourite. It is still by far the simplest and most elegant proposal for how space-time behaves. Furthermore, dark energy does seem to fit the wealth of cosmological data that we have accumulated over the past few decades.

The thing is, for the first time in almost 100 years there is now a real possibility that we may actually be able to test Einstein's theory on the scale of the universe. In doing so, we might have to find a more powerful theory that subsumes general relativity or take one of the alternatives more seriously.

The idea is to study in detail how large and complex structures grow in the universe. The current paradigm is that they are driven primarily by gravitational collapse, which is itself explained by general relativity: in areas where there are more galaxies, space will warp in such a way as to pull even more galaxies towards it, leading to massive concentrations of light and energy, in the form of clusters and super clusters. Conversely, empty regions of space will tend to become even emptier, resulting in cosmic voids of gigantic proportions. The tapestry of full and empty regions form what has become known as the cosmic web.

The last few decades have seen an explosion in our understanding of the cosmic web. Huge surveys of galaxies, such as the 2-degree-Field Survey and the Sloan Digital Sky Survey, have constructed detailed maps of the structure of the universe, carefully identifying how the clusters, walls, filaments and voids are distributed around us. What's more, maps of the universe made at different wavelengths, including those supplied by the WMAP satellite and the Herschel space telescope, show how the cosmos looked at different times. So these should allow us to see how gravitational collapse has played a role at different epochs in the universe's history (see "instant expert: The unseen universe", *New Scientist*, 4 September).

Given that the primary driver behind the cosmic web is gravity, it isn't surprising that the fine details of the web's structure and history may be used to search for deviations from general relativity. By studying how quickly it is evolving and by mapping out how the space-time around it distorts light rays, it should be possible to tease out even small discrepancies in how gravity behaves. That is what has begun to happen.

A crucial first step was taken by Luigi Guzzo and his team at the Brera Astronomical Observatory in Merate, Italy, in 2008. The researchers took a catalogue of 10,000 faint galaxies, measured when the universe was approximately half its current age, and studied how these galaxies moved relative to each other. The team calculated how fast gravitational collapse seemed to be happening at those early times and then used it to show that some proposed alternatives to Einstein's theory simply didn't work. Guzzo's research showed that such detailed studies of the cosmic web could be remarkably effective at probing gravity *(Nature*, vol 451, p 541).

Rachel Bean and her collaborators at Cornell University in Ithaca, New York, took this idea a step further in September 2009. She abandoned the idea that general relativity is sacrosanct and instead placed modifications to relativity on an equal footing with all other cosmological parameters. She then looked for evidence in the data that would single out, or disprove, Einstein's theory.

Unlike Guzzo's team, who considered only one catalogue of galaxies, Bean combined a series of observations. They included WMAP's measurement of the cosmic microwave background radiation, distant bright supemovae being dragged along with the cosmic expansion, and traces of light from distant galaxies being distorted by the intervening cosmic web.

Tantalizingly, the team's preliminary analysis suggested tentative evidence for deviations from Einstein's theory *(New Scientist*, 24 October 2009, p 8). However, further work by the group showed that Einstein's theory was still very much in the game and consistent with all the cosmological measurements. What is clear from Bean's work is that a large number of high quality observations will allow us to place very tight constraints on Einstein's theory, or uncover deviations.

Bean's findings have been followed by a flurry of results from other groups. For example, Reinabelle Reyes of Princeton University and her collaborators have gone a step further and used a method particularly attuned for teasing out modifications to general relativity *(Nature*, vol 464, p 256). Her team, too, found that Einstein's theory prevails, and the results also rule out a class of alternative theories that Guzzo had not tested, although they still allow a range of other modifications.

Einstein's theory is merely one hypothesis within a vast range of possibilities that encompasses alternative theories

Reyes's conclusions are echoed by two more recent analyses of even greater amounts of data. General relativity is still the front runner as a theory of gravity, according to teams led by Scott Daniel of Ewha Womans University in Seoul, South Korea, and Levon Pogosian of Simon Fraser University in Burnaby, British Columbia, Canada.

But not so fast. Although Einstein's theory seems to be passing these tests with flying colours, we can't rule out all of the alternatives. Very much like in other fields of physics, Einstein's theory can be viewed as one hypothesis within a vast range of possibilities that encompass alternative theories. With today's experimental tests we are finding out how far we can deviate from general relativity.

For now, the results can only be said to weakly favour general relativity. But we are at a turning point in how we study the physics of the universe. For the first time we can genuinely test one of our most profound and basic theories, one that has guided and fuelled the development of cosmology.

Such tests of general relativity are driving major astronomical projects. The European Southern Observatory's VIPERS survey is mapping the positions of over 100,000 galaxies out to when the universe was less than half its current age. Meanwhile Simon Driver at the University of St Andrews in the UK is leading the GAMA survey, which collates observations of 250,000 galaxies from telescopes around the world. Assembling these detailed maps will allow us to reconstruct the history of gravity and how it has shaped the complexity of our universe. On a far more ambitious scale is the Euclid mission, a satellite observatory being considered by the European Space Agency. If approved, it will launch around 2018 and will map the positions of up to a billion galaxies, leading to a stunning chart of the heavens.

We have entered a truly exciting era as we start to look critically at one of the pillars of modern physics. Einstein's general theory of relativity underlies almost all modern discoveries in cosmology. But we can now step back and check if we have been right all along or if the ideas of heavyweights like Paul Dirac, Andrei Sakharov, Theodor Kaluza and Oskar Klein could actually have a real bearing on how the universe is put together on the largest scales.

Replacements for relativity

British theoretician Paul Dirac devoted a large part of his later life to cracking the complex structure of general relativity. He was puzzled by the extraordinary similarity between certain large numbers in the universe, such as why the size and total energy of the visible universe seemed to be related to the strength of gravity on the Earth's surface. To Dirac, Einstein's theory was incomplete because it was unable to explain these coincidences; he felt there might be something more to gravity.

So in 1938, he proposed a change to general relativity. Although it would still be a theory of space and time, its strength could vary from place to place - as if the actual fabric of space-time had a different stiffness depending on where you were sitting. So a star in one place would bend space around it by a certain amount, while an identical star in a different area might warp space much more or less.

Dirac was able to do what very few have managed since - to sow the seeds for an alternative theory. It was later taken up by some researchers in the 1960s as a counterfoil to general relativity. Known as the scalar-tensor theory of gravity, it is actively studied to this day.

An altogether different idea was brewing in the Soviet Union in the 1960s. Physicist Andrei Sakharov conjectured that space and time would be much more warped and deformed on microscopic scales than predicted. His idea was simple: when we look at atomic and subatomic scales, quantum physics comes into play and this means that, much like children on a long car journey, nothing can keep still. Sakharov reasoned that we can apply the same principle to space-time itself and that if we were able to look at it on subatomic scales, it wouldn't look smooth but more like a froth, or a quantum foam.

Sakharov suggested that Einstein's theory would have to be changed if one took into account the frothy nature of space-time. While he was motivated by what happens on small scales, the past few years has seen a resurgence of the idea applied to all scales, even the very largest.

Another recent major development has been the idea that the universe may have more than three spatial dimensions. Although this was first suggested by Theodor Kaluza and Oskar Klein in the 1920s, it has been given a new lease of life thanks to developments in the field of string theory.

In 2001, New York University physicists Gia Dvali, Gregory Gabadadze and Massimo Porrati proposed that we live on a three-dimensional surface, known as a brane, within a higher-dimensional world called the bulk. All the fundamental forces we experience would be confined to the brane except gravity, which can leak out. Dvali and colleagues-- reasoned that gravity would be affected by what happens on the brane and in the bulk.