allowed by mathematics corresponds to a real universe. Taken to this extreme, mathematics is reality.

If some or all of the mathematics that has compelled us to think about parallel worlds proves relevant to reality, Einstein's famous query – whether the universe has the properties it does simply because no other universe is possible – would have a definitive answer: no. Our universe is not the only one possible. Its properties could have been different, and indeed the properties of other member universes may well be different. If so, seeking a fundamental explanation for why certain things are the way they are would be pointless. Statistical likelihood or plain happenstance would be firmly inserted in our understanding of a cosmos that would be profoundly vast.

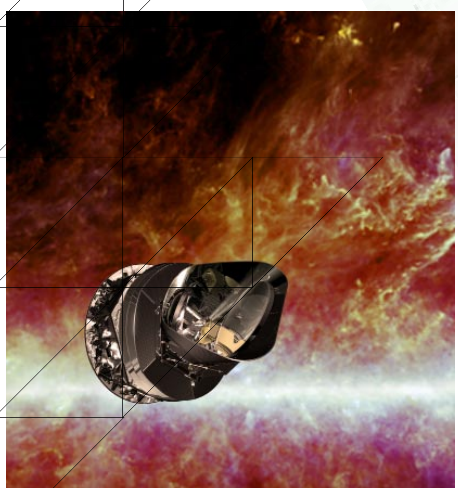
I don't know if this is how things will turn out. No one does. But it is only through fearless engagement that we can learn our limits. Only through rational pursuit of theories, even those that whisk us into strange and unfamiliar domains – by taking the mathematics seriously – do we stand a chance of revealing the hidden expanses of reality.n

Brian Greene is a theoretical physicist at Columbia University, New York. This article is adapted from his book *The Hidden Reality* (Allen Lane, 2011)

Experiment

2. Planck

The cosmic microwave background radiation contains vital clues about the early universe. The most detailed whole-sky maps are coming from the European Space Agency's Planck satellite, launched in 2009. It can capture the CMB precisely enough to measure cosmological quantities without making many theoretical assumptions, detect the rippling of gravitational waves and test various models of the inflation thought to have occurred at the big bang. It will even let us explore ideas outside our standard cosmology, such as higher-dimensional brane worlds. **Valerie Jamieson**



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Big bang cosmology

The dark side

Our established picture of the universe is supremely successful – if you ignore that we have to make most of it up, says **Stephen Battersby**

TO OUR eyes, stars define the universe. To cosmologists they are just a dusting of glitter, an insignificant decoration on the true face of space. Far outweighing ordinary stars and gas are two elusive entities: dark matter and dark energy. We don't know what they are... except that they appear to be almost everything.

These twin apparitions might be enough to give pause, and make us wonder whether all is right with the model universe we have spent the past century so carefully constructing. Would that they were the only thing. Our standard cosmology also says that space was stretched into shape just a split second after the big bang by a third dark and unknown entity called the inflaton field. That might imply the existence of a multiverse of countless other universes hidden to our view, most of them unimaginably alien – just to make models of our own universe work.

> "We don't know what these dark apparitions are... but they seem to be almost everything"

Are perhaps these weighty phantoms too great a burden for our observations to bear – a wholesale return of conjecture out of a trifling investment of fact, as Mark Twain put it?

The physical foundation of our standard cosmology is Einstein's general theory of relativity. Einstein began with a simple observation: that any object's gravitational mass is exactly equal to its resistance to acceleration, or inertial mass. From that he deduced equations that showed how space is warped by mass and motion, and how we see that bending as gravity. Apples fall to Earth because Earth's mass bends space-time.

In a relatively low-gravity environment such as Earth, general relativity's effects look very like those predicted by Newton's earlier theory, which treats gravity as a force that travels instantaneously between objects. With stronger gravitational fields, however, the predictions diverge considerably. One extra prediction of general relativity is that large accelerating masses send out tiny ripples in the weave of space-time called gravitational waves. While these waves have never yet been observed directly, a pair of dense stars called pulsars, discovered in 1974, are spiralling in towards each other just as they should if they are losing energy by emitting gravitational waves.

Gravity is the dominant force of nature on cosmic scales, so general relativity is our best tool to model how the universe as a whole moves and behaves. But its equations are fiendishly complicated, with a frightening array of levers to pull. If you then give them a complex input, such as the details of the real universe's messy distribution of mass and energy, they become effectively impossible to solve. To make a working cosmological model, we make simplifying assumptions.

The main assumption, called the Copernican principle, is that we are not in a special place. The cosmos should look pretty much the same everywhere – as indeed it seems to, with stuff distributed pretty evenly when we look at large enough scales. This means there is just one number to put into the equations: the universal density of matter.

His greatest blunder

Einstein's own first pared-down model universe, which he filled with an inert dust of uniform density, turned up a cosmos that contracted under its own gravity. He saw that as a problem, and circumvented it by adding a new term into the equations by which empty space itself gains a constant energy density. Its gravity turns out to be repulsive, so adding the right amount of this "cosmological constant" ensured the universe neither expanded nor contracted. When observations in the 1920s showed it was actually expanding, Einstein described this move as his greatest blunder.

It was left to others to apply the equations of relativity to an expanding universe. They arrived at a model cosmos that grows from an initial point of unimaginable density, and whose expansion is gradually slowed down by matter's gravity.

This was the birth of big bang cosmology. Back then, the main question was whether the expansion would ever come to a halt. The answer seemed to be no; there was just too little matter for gravity to rein in the fleeing galaxies. The universe would coast outwards forever.

Then the cosmic spectres began to materialise. The first emissary of darkness put a foot in the door as long ago as the 1930s, but was only fully seen in the late 1970s when astronomers found that galaxies are spinning too fast. The gravity of the visible matter would be too weak to hold these galaxies together according to general relativity, or indeed plain old Newtonian physics. Astronomers concluded that there must be a lot of invisible matter to provide extra gravitational glue.

The existence of dark matter is backed up by other lines of evidence, such as how groups of galaxies move, and the way they bend light on its way to us. It is also needed to pull things together to begin galaxy building in the first place. ›

VIEWPOINT: GRAVITY REDUX

Cosmology's dark apparitions raise the question whether general relativity is the right theory, says Jacob Bekenstein

The success of general relativity is embedded in our modern world. True, most solar system and astronomical phenomena are still calculated with Newton's hoary theory of gravitation; but we would be nowhere without our GPS gadgets, which work only once corrected for the effects of general relativity.

General relativity has been tested with great precision within the solar system, and in binary pulsar systems where gravitational fields are very strong, but never on large scales where gravity's pull is weak. Might the twin embarrassments of dark matter and energy mask general relativity's failure there?

Supporters of this idea have chalked up some successes. Modified Newtonian dynamics (MOND), proposed by Mordehai Milgrom of the Weizmann Institute in Israel in the early 1980s, relates mass to the gravity it generates in a slightly different way. It describes galaxies better and more parsimoniously than general relativity with dark matter. Cosmological models constructed from alternative "f(R)" gravitational theories manage to behave as if they contain dark energy, even though they don't.

But no one theory holds all the cards. MOND does not handle motions of individual galaxies within clusters well. Neither does Tensor-vector-scalar (TeVeS) gravity, a relativistic version of the theory I proposed in 2004. The f(R) theories do not adequately describe the anomalous galactic rotations that first led dark matter to be proposed.

We might yet strike lucky. If dark energy is the venerable cosmological constant that Einstein shoehorned into his equations of general relativity, its favoured source is vacuum energy. Gravitational fields might conceivably perturb the vacuum enough that concentrations of energy appear in and around galaxies and galaxy clusters, mimicking dark matter. It is impossible to magic up concentrations large enough from current quantum field theories – but perhaps one day the mystery of the two dark stuffs may be dispelled by judicious application of known quantum physics.

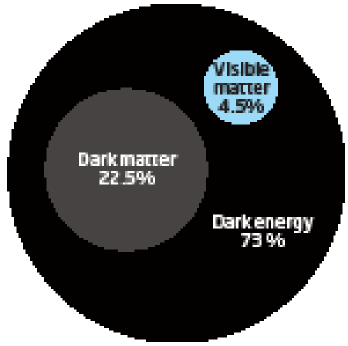
Jacob Bekenstein is a theoretical physicist at the Hebrew University of Jerusalem, Israel

Overall, there seems to be about five times as much dark matter as visible gas and stars.

Dark matter's identity is unknown. It seems to be something beyond the standard model of particle physics, and despite our best efforts we have yet to see or create a dark matter particle on Earth (see "Flawed genius", page 45). But it changed cosmology's standard model only slightly: its gravitational effect in general relativity is identical to that of ordinary matter, and even such an abundance of gravitating stuff is too little to halt expansion.

The second form of darkness required a more profound change. In the 1990s, astronomers traced the expansion of the universe more precisely than ever before, using measurements of explosions called type-1a supernovae. They showed that the cosmic expansion is accelerating. It seems some repulsive force, acting throughout the universe, is now comprehensively trouncing matter's attractive gravity.

Seeing in the dark



Precise recipe

This could be Einstein's cosmological constant resurrected, an energy in the vacuum that generates a repulsive force, although particle physics struggles to explain why space should have the rather small implied energy density. So imaginative theorists have devised other ideas, including energy fields created by as-yet-unseen particles, and forces from beyond the visible universe or emanating from other dimensions.

Whatever it might be, dark energy seems real enough. The cosmic microwave background radiation, set loose when the first atoms formed just 370,000 years after the big bang, bears a faint pattern of hotter and cooler spots that reveals where the young cosmos was a little more or less dense. The typical spot sizes can be used to work out to what

Experiment

3. Advanced LIGO

General relativity predicts ripples in space-time should constantly be passing through Earth. From 2014 Advanced LIGO, an upgrade of an existing gravitational wave detector in the US, will use laser "rulers" several kilometres long to spy spatial disturbances equivalent to Earth moving one-tenth of an atomic diameter closer to the sun.

If it sees something, it will be the crowning triumph of Einstein's relativity. If it doesn't, it's back to the drawing board with our theories of gravity. **Richard Webb**

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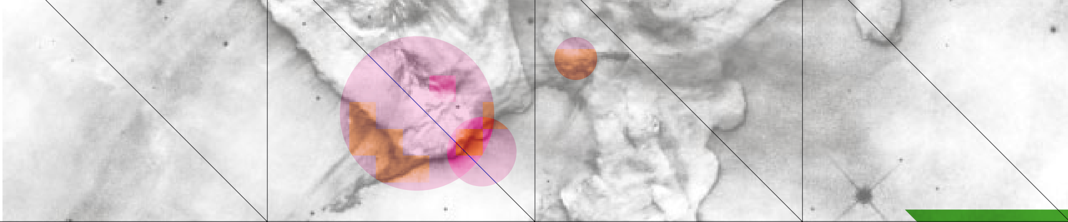


extent space as a whole is warped by the matter and motions within it. It appears to be almost exactly flat, meaning all these bending influences must cancel out – again requiring some extra, repulsive energy to balance the bending due to expansion and the gravity of matter. A similar story is told by the pattern of galaxies in space.

All of this leaves us with a precise recipe for the universe. The average density of ordinary matter in space is 0.426 yoctograms per cubic metre (a yoctogram is 10^{-24} grams, and 0.426 of one equates to about 250 protons), making up 4.5 per cent of the total energy density of the universe. Dark matter makes up 22.5 per cent, and dark energy 73 per cent. Our model of a big bang universe based on general relativity fits our observations very nicely – as long as we are happy to make 95.5 per cent of it up.

Arguably, we must invent even more than that. To explain why the universe looks so extraordinarily uniform in all directions, today's consensus cosmology contains a third exotic element. When the universe was just 10^{-36} seconds old, an overwhelming force took over. Called the inflaton field, it was repulsive like dark energy, but far more powerful, causing the universe to expand explosively by a factor of more than 10^{25}, flattening space and smoothing out any gross irregularities.

When this period of inflation ended, the inflaton field transformed into matter and radiation. Quantum fluctuations in the field became slight variations in density, which eventually became the spots in the cosmic microwave background, and today's galaxies. Again, this fantastic story seems to fit the observational facts.

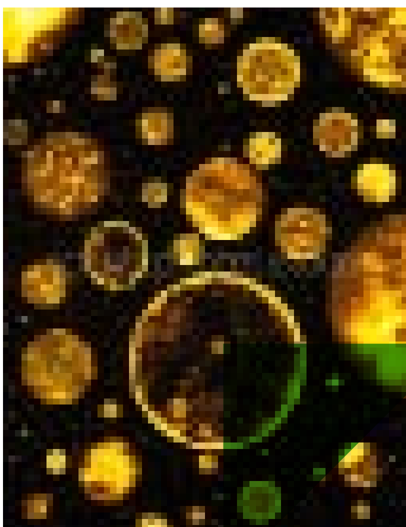
And again it comes with conceptual baggage. Inflation is no trouble for general relativity – mathematically it just requires an add-on term identical to the cosmological constant. But at one time this inflaton field must have made up 100 per cent of the contents of the universe, and its origin poses as much of a puzzle as either dark matter or energy. What's more, once inflation has started it proves tricky to stop: it goes on to create a further legion of universes divorced from our own. For some cosmologists, the apparent prediction of this multiverse is an urgent reason to revisit the underlying assumptions of our standard cosmology (see "Viewpoint: Inflation or bust?", page 44).

The model faces a few observational niggles, too. The big bang makes much more lithium-7 in theory than the universe contains in practice. The model does not explain the possible alignment in some features in the cosmic background radiation, or why galaxies along certain lines of sight seem biased to spin left-handedly. A newly discovered supergalactic structure 4 billion light years long calls into question the assumption that the universe is smooth on large scales.

A shady triumvirate

It is quite likely that these niggles will disappear with more data, or revised calculations. But the bigger problem remains. "We don't know what dark energy is and we don't know what dark matter is, and that should be a little bit embarrassing," says Robert Kirshner, a cosmologist at Harvard University and a member of one of the supernova teams that first exposed dark energy.

The underlying maths has not changed since the days of Einstein's dust-filled universe, but the added components make today's model cosmos more dynamic and etched in far more detail. Its age and constituents are precisely known. Dark matter seems to have created



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Our universe might be just one of myriads

VIEWPOINT: **DARK ILLUSIONS**

Assumptions about our place in the cosmos could be skewing our view of it, says Chris Clarkson

In all directions we look, we see a cosmos that appears broadly the same. Since we are nowhere special, the same is probably be true of everywhere else.

This is the sensible assumption known as the Copernican principle. But it is hard to confirm what aliens in faraway galaxies see. What if it is not true? Observations of supernovae at different distances convinced us that the universe's expansion is accelerating, and dark energy must exist. But thanks to light's finite speed, the further we look in space, the further back we look in time. Variation in space can be surprisingly easily confused with evolution over time. Dark energy might conceivably be an illusion.

Imagine a spherical universe a bit like an onion, made of layers of different density. Gravity's cohesive force will hold back expansion in denser areas. If we are sitting in a central void with a low density and high expansion rate, and looking outwards in all directions to regions of higher density and slower expansion, this would look to us very like a universe whose expansion has been accelerating in recent times.

Such a universe could be produced with a change in the inflationary conditions during the first split second to produce areas of such colossal under-density. But it would violate the sacred Copernican principle: others less advantageously situated in the onion would see a distinctly inhomogeneous cosmos.

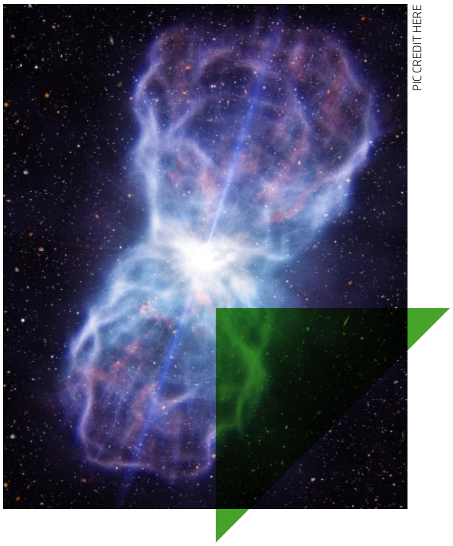
The chance of 1 in a few million that we are at the centre of a void isn't that unlikely to anyone who plays the lottery. But studying variations in the temperature of the cosmic microwave background around distant galaxy clusters allows us to "see" the universe from distant locations and tell whether it is homogeneous or not - and the latest observations suggest it is. A model that abandons the Copernican principle will need a lot of fine-tuning to fit reality, if it works at all.

Chris Clarkson is a cosmologist at the University of Cape Town, South Africa galaxies and other structures; dark energy implies the cosmos will accelerate away into a cold and lonely future; inflation suggests a violent birth. Each member of the shady triumvirate points to new physics.

Kirshner sees that as a challenge. “It doesn’t mean there is any flaw in our arguments. It gives a sense not of desperation, but inspiration.” But as long as we have no evidence of dark matter in the lab, or a proven physical basis for dark energy, the possibility remains that we are living under some profound misapprehension – an unknown unknown, something so basic awry in our mathematical model of the universe that as yet we have not been able to imagine the form of our mistake. Might a quantum theory of gravity show us the way forward? Or might some new observation lead us to reformulate our general relativistic cosmology again?

We have only the most tenuous of indications where we might look for alternatives. But perhaps if we only discard an unheeded assumption about reality, then a veil will be lifted, all the darknesses banished and the starry night restored. n

Stephen Battersby is a *New Scientist* consultant based in London



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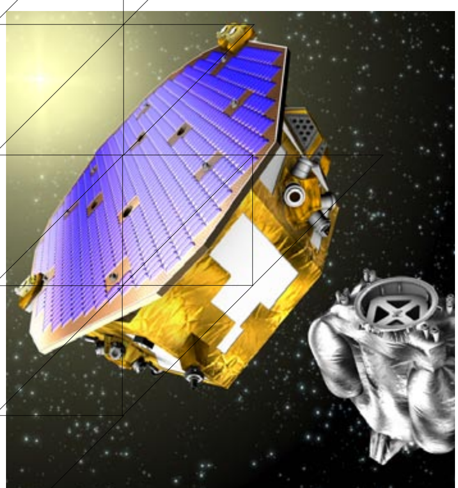
“Our lack of answers gives us a sense not of desperation, but inspiration”

Experiment

4. LISA-Pathfinder

The European Space Agency’s LISA Pathfinder mission will primarily test gravitational wave detectors, but from next year it could also confirm whether gravity is all general relativitysays it is. By flying through the “saddle point” where the Earth and the sun’s gravity cancel out, the craft might probe whether Einstein’s theory still holds when gravitational accelerations are incredibly small. If it does, these gravitational lacunae will be the last resting place of other occasionally fashionable theories, such as Modified Newtonian dynamics (MOND). **Stuart Clark**



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VIEWPOINT: INFLATION OR BUST?

The best theory of our big bang has logically self-destructed, argues Max Tegmark

Inflation got off to a great start: beginning with a subatomic speck of a novel, hard-to-dilute substance, it predicted that this stuff would repeatedly double during a split second to create our big bang and our nearly uniform, flat space.

It got even better: inflation also produced random quantum fluctuations which grew into today’s stars, galaxies and large-scale structures. The theory makes spectacularly accurate predictions: for example, the quantity “Omega”, which quantifies the flatness of space, should equal 1 – and it has been measured as 1.003 ± 0.004. Bingo!

But like a tenacious ageing professor, inflation refuses to retire. The theory predicts that the process continues forever in distant parts of our cosmos, producing a space that isn’t just huge but truly infinite, with infinitely many galaxies, stars, planets – and even people like us. Its random fluctuations distribute matter differently in different places, so infinitely many of these people observe an Omega near 1, infinitely many an Omega near 2 – and indeed any other value.

So what’s the probability that we’re among those people who observe what we do? The useless, formal answer is infinity divided by infinity. We cosmologists still haven’t reached consensus on how to turn this into something useful. Thanks to inflation, we can predict the probability of virtually nothing any more. I’ve called this the “measure problem”, and view it as one of the deepest crises facing physics today. The way I see it, inflation has logically self-destructed, destroying the predictions that made us take it seriously in the first place.

In fairness to inflation, I don’t feel that any competing theory does better. My guess is that once we solve the measure problem, some form of inflation will still remain – but perhaps not the eternal kind. All the problems stem from infinity, specifically the assumption that space can be stretched forever without somehow breaking down. We tend not to question this radical assumption – but we should!

Max Tegmark is a cosmologist at the Massachusetts Institute of Technology