May the *fifth* force be with you

The universe increasingly seems to be telling us there is an unexplained presence on the cosmic stage, says **Daniel Cossins**

TASKED with telling the universe's epic story, cosmologists have put on a compelling show. The curtain rises with a bang before a sweeping, unstoppable narrative unfolds. Stars form and explode, galaxies swirl their way into existence. Black holes munch and merge, sending out ripples through the auditorium.

It is a ripping yarn – but the longer we watch it, the more it seems not quite to add up. The story is inconsistent. The pace changes arbitrarily. Some of the characters are ill-drawn, do inexplicable things or are just plain not there on cue. All in all, there is enough in this play that goes wrong to make you think someone has lost the plot.

Increasingly, we think we know how. We had assumed that just four fundamental forces keep the cosmic action bowling along. But hints from theory and experiment are combining to suggest it might not be just four, but five, six – or maybe even more. Sketchy though these indications are, even one new force would be a turn-up for the books. "It would be absolutely momentous," says Philippe Brax at the Saclay Institute of Theoretical Physics in France.

Forces drive the cosmic narrative. They tell its various actors, from particles to planets, how to move and behave – things that would otherwise seem inexplicable (see "What is a force?", page 32). The four fundamental forces we know of are gravity, electromagnetism, the weak nuclear force and the strong nuclear force (see "The familiar four", page 35). Of these, gravity is the outlier, the only one with no quantum field or particle attached to it and which can't be described by the "standard model" of particle physics. Yet gravity, described by Albert Einstein's space-and-time-warping general theory of relativity, determines the universe's overarching plot lines.

The problems with the story of the cosmos begin at the beginning. The big bang theory suggests that temperature and matter density in the universe should now be a hotchpotch, the result of early random quantum fluctuations being amplified as the cosmos expanded. But viewed at the grandest scales, galaxies and the like seem remarkably evenly spread. To square that circle, in the 1980s cosmologists invented cosmic inflation, a split-second burst of growth during which the primordial cosmos ballooned exponentially, flattening out its surface

WHAT IS A FORCE?

By holding this magazine, or swiping down a smartphone screen, you are exerting a force: one that operates between two objects that are physically touching. Drag forces such as friction and air resistance are also such "contact forces", which influence movement and acceleration, and can be described by Isaac Newton's laws of motion.

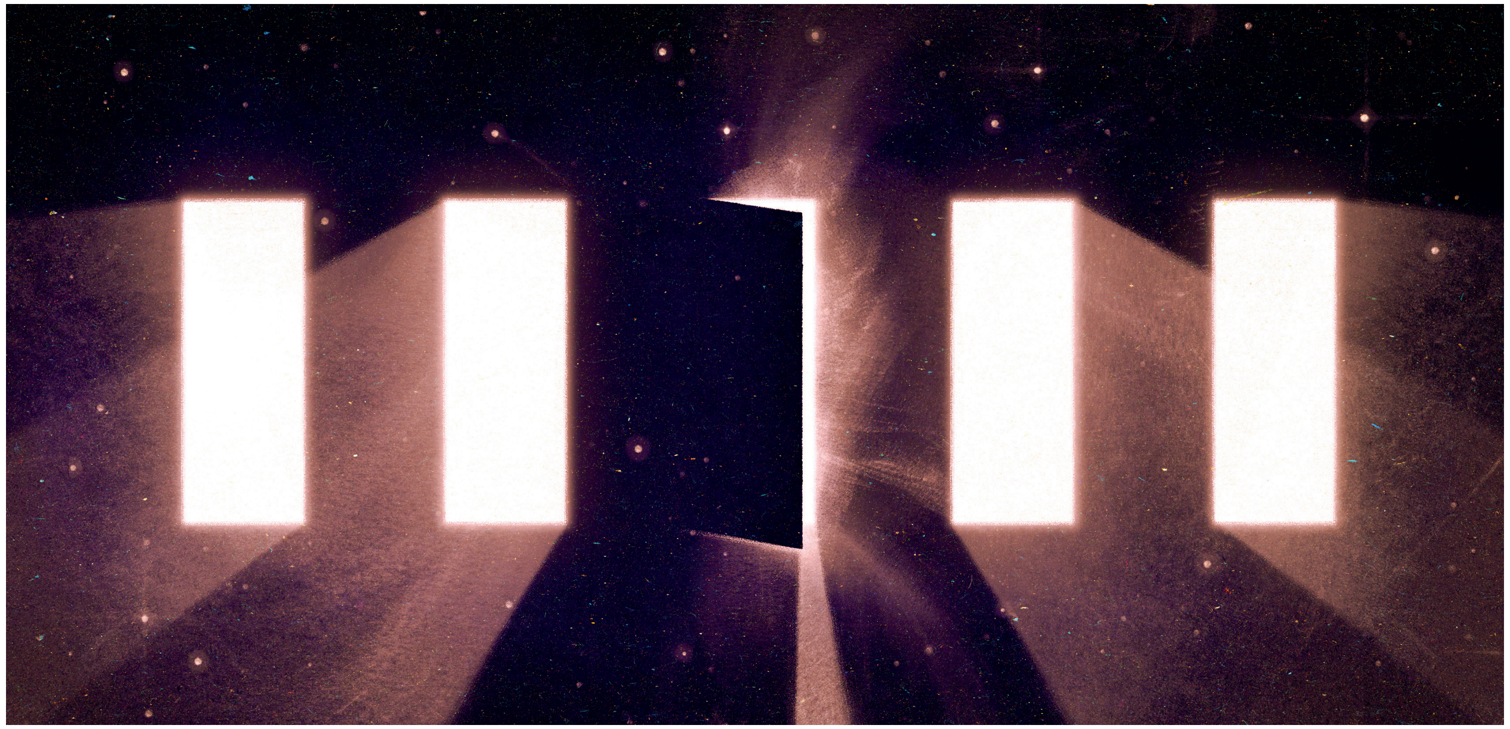
When physicists talk about fundamental forces, it is something rather different: influences between things that are apparently not in contact. This "action at a distance" perplexed Newton when his universal law of gravitation first suggested it. It was, he wrote, "so great an absurdity that I believe no man who has in philosophical matters a competent faculty of thinking can ever fall into it".

These days, we ascribe such mysteries to the action of fields that fill empty space. "In the modern understanding, the most basic things in the world are fields," says theorist Frank Wilczek at the Massachusetts Institute of Technology.

So what are fields? They are, says Matt Strassler at Harvard University, "a fundamental intermediary between two objects". For three of the four fundamental forces we currently know of, they are quantum fields that come with accompanying particles, called bosons, that pop in an out of existence to mediate influences across various ranges: the massless photon, for instance, mediating the electromagnetic force.

The odd one out is the gravitational field. According to Albert Einstein's general theory of relativity, which superseded Newton's universal law, gravity is the product of mass warping space-time. The strength of the gravitational field at any point is essentially the degree to which a massive object is curving space-time around it.

In all cases, what separates the fundamental forces from the common-or-garden ones we tend to notice is that they can't be reduced to another force or field, as for example friction or air resistance can ultimately be reduced to electromagnetic interactions between different bits of matter. But the question of how many of these fundamental intermediaries exist remains unanswered (see main story).



"We don't know what new actor to expect, other than it must be a quantum force"

wrinkles. A grand plot twist – but one that is currently entirely inexplicable.

Problem number two really became apparent around the same time – the 1980s, not the dawn of time – with the observation that there isn't enough visible matter in most galaxies to exert the gravitational pull required to stop them flying apart as their components whirl around. Cosmologists' second big invention was some additional invisible stuff, dark matter, to glue galaxies together – stuff we have failed to find.

The third implausible turn of events came in the late 1990s, when observations of far-off exploding stars known as supernovae revealed that the universe's expansion is accelerating. Naively, with only gravity pulling things together, you might expect it to be slowing. Our best stab at explaining the "dark energy" we think is responsible for accelerated expansion invokes the power of quantum particles popping in and out of empty space. But this comes up with an answer for the size of the effect roughly 120 orders of magnitude too big. "The universe would have expanded so rapidly, everything would have been ripped apart," says Clare Burrage at the University of Nottingham, UK.

The simplest solution to these problems might be just to say that gravity doesn't work how we think it does. But general relativity has proved maddeningly difficult to edit, passing every test we have ever thrown at it, including the recent detection of gravitational waves produced when black holes and other massive cosmic objects collide. Meanwhile, ideas that try to alter gravity, such as modified Newtonian dynamics or MOND – a popular way to explain away dark matter – don't square with all cosmic observations.

That adds to the yearning for a new character on the stage, and the belief that a fifth fundamental force of nature must be waiting in the wings. "We have several indications," says Brax. "There's definitely something there."

The dark side

But we don't know what new actor to expect, other than a quantum force. This tallies with the idea that even if gravity can't yet be described in quantum terms, most physicists believe it eventually will be, in a long sought after marrying of relativity and quantum field theory. "Any sensible physicist believes gravity's force-carrying particle exists," says Frank Wilczek, a particle theorist at the Massachusetts Institute of Technology who won a share of a Nobel prize in physics for the quantum theory behind the strong nuclear force. Follow that logic and any fifth force has to be quantum, too.

The tricky part is finding a force that fits the bill. For inflation, a one-off event some 13.8 billion years ago, whatever caused it might have long since left the stage – not that this has stopped people from coming up with inventive new plot lines, even involving particles and forces we already know (see "The Higgs force awakens", page 34).

When it comes to the other cosmic inexplicables, dark matter and dark energy, however, we seem to have some hot leads. Perhaps the hottest, although controversial, lead dates from 2015, when a team led by Attila Krasznahorkay of the Institute for Nuclear Research at the Hungarian Academy of Sciences spotted anomalies in the decay of short-lived nuclei of the unstable isotope beryllium-8. These seemed to indicate the interference of an even shorter-lived, slow-moving particle. Its mass was about 17 MeV, a little more than 30 times the mass of an electron, and nowhere near that of any known particle. It also happened to look like a boson, a force-carrying particle like the photon, but one that interacts very weakly – just the thing for explaining dark matter's diffident interaction with the rest of the cosmos. The researchers speculated that it might be a "dark photon", a new particle that might transmit a force between dark matter particles.

Like most observers, theorist Jonathan Feng at the University of California, Irvine, found this hard to believe when he first heard it. Similar anomalies crop up from time to time, and are almost always down to experimental error. "But when I went through the paper trail, looking at how they did the experiment, I couldn't see anything wrong," says Feng.

The plot thickened late last year, when the Hungarian team reported a similar anomaly in the decay of helium nuclei. Feng reckons both results are consistent with the existence of a "protophobic X boson" that interacts over short distances with the neutrons within the atomic nucleus in a new way. That would be a startling find. "It would be huge," he says. "We're talking about a once every half-century sort of discovery."

The idea has its critics. Matt Strassler, a theorist at Harvard University, points out that making Feng's proposed new force coexist with the ones we know about "requires some complicated and not entirely plausible trickery". The properties of the particle, with an intermediate mass and a short range of interaction, are certainly surprising given what quantum field theory suggests we should expect. "There are two kinds of things you can add to the standard model that have not been observed, but would be consistent with everything we have observed," says Wilczek: very heavy particles, which would carry a short-range force, or very light particles that would mediate a long-range force.

The new particle seems to be neither. Still, Feng says, we need to keep an open mind. "New physics doesn't have to come from the place you expect it." To really get theorists' pulses racing, the result needs first to be corroborated in an independent experiment. That could come soon, or not: researchers at PADME, the Positron Annihilation into Dark Matter Experiment in Frascati, Italy, for example, have been collecting data for over a year now and expect to have results sometime in 2021.

If confirmed, the particle would count among the great surprises that experiments occasionally throw at theorists – a new force that interacted so weakly with ordinary matter that we just hadn't spotted it. Brax and Burrage, meanwhile, are investigating the possibility of a type of fifth force that adopts a different disguise: it has large effects, but those effects are screened by gravity.

It is known as a chameleon force, and the idea is that the particle transmitting it changes its mass depending on the local density of matter. Chameleon particles would be heavier where the average matter density is high, as for example around Earth, meaning the force ›

THE HIGGS FORCE AWAKENS

As physicists close in on the discovery of a fifth fundamental force of nature (see main story), a pedant might counter that we have already found it. And they would be right, sort of.

Discovered in 2012 at the Large Hadron Collider – CERN's powerful atom smasher near Geneva, Switzerland – the Higgs boson and its underlying field is famous for giving all other known particles their masses. But the Higgs field isn't only a mass-giver. Under the right conditions, it can create a push and pull between two particles, too, which would make it another fundamental force of nature to add to the four we already know.

You won't often hear physicists refer to it as such, however, because the Higgs force operates at such a short range that it is practically irrelevant – and possibly undetectable. That is why we had to find the Higgs particle to confirm the existence of the field. "If we define the Higgs field as the interaction, then we've already discovered it," says theorist Matt Strassler at Harvard University. "But if we mean the pull between two objects it induces, then we've not seen it."

All of which makes it a bit surprising that theorists have suggested the Higgs field could be the cause of cosmic inflation, the split-second burst of mega-expansion at the time of the big bang invoked to account for the perplexing uniformity of the universe at the largest scales. But it is possible to tweak the properties of the Higgs field, such that it could have been temporarily strong enough to suddenly inflate everything in that first moment, before settling down to the barely detectable strength it has now.

On further inspection, though, it turns out the Higgs works in this way, as an "inflaton", only if you invent at least one other field to regulate its strength. So although the Higgs force alone probably can't explain inflation, it might plausibly serve as a portal to new forces that could.

associated with them would have a smaller range in our neighbourhood and so would be practically invisible to us. The mass of these particles would be much smaller in the vast swathes of empty space between galaxies, where they would have a larger range of influence – just the ticket to explain the dark-energy effect of distant galaxies racing away from us ever faster.

"It is not quite as strange as it sounds," says Burrage, pointing out that the massless photon undergoes a similar metamorphosis when passing through a plasma of charged particles, experiencing a drag and effectively gaining mass. Wilczek agrees in principle, while being sceptical of the models themselves. "That sort of thing is allowed by the rules of quantum field theory," he says.

And it might just work. In 2018, a group led by Baojiu Li at Durham University, UK, ran simulations that showed that a universe with a chameleon force would form galaxies like those we see. The challenge now is to identify subtle differences in those galaxies compared with general relativity's predictions, so that next-generation telescopes, such as the European Space Agency's EUCLID satellite, set for launch in 2022, can look for them.

"A 'chameleon' force would be invisible to us where matter density is high, like on Earth"

It's a trap!

Burrage thinks we don't need to wait. Even if a chameleon force is a master of disguise, it can still be exposed here on Earth, she says. "You just need to come up with a situation where it can't hide."

That situation is housed in a basement lab at Imperial College London, where Burrage has collaborated with experimentalists to craft a bowling-ball-sized vacuum chamber with a marble-sized metal sphere at its centre designed to cancel out the effects of the known forces. It is a trap for chameleons. A chameleon field would be suppressed around the central sphere and the walls of the chamber but active between them – so drop atoms into the vacuum and any acceleration of them in this region would betray its presence.

The team reported its first results last year. It was a bust, there was no sign of the chameleon. "That is obviously disappointing," says Burrage. But so far, the researchers have ruled out only one particular chameleon model, and there is plenty of room for an upgraded experiment to uncover the real deal: a weaker force ever so slightly stronger than gravity that might explain dark energy.

THE FAMILIAR FOUR

We currently know of four fundamental forces governing the basic workings of matter in our universe today.

ELECTROMAGNETISM: Explains why atoms hold together and how light behaves
GOVERNING THEORY: Quantum electrodynamics (QED)
MEDIATOR: Photon (predicted by Albert Einstein in 1905)
MAXIMUM RANGE: Infinite

WEAK NUCLEAR FORCE: Accounts for radioactive beta decay and the nuclear fusion that fuels stars
GOVERNING THEORY: Electroweak theory (unified theory with QED at high energies)
MEDIATOR: W and Z bosons (predicted in 1968, discovered in 1983)
TYPICAL RANGE: 10^{-18} metres

STRONG NUCLEAR FORCE: Holds protons and neutrons together within the atomic nucleus
GOVERNING THEORY: Quantum chromodynamics (QCD)
MEDIATOR: Gluons (predicted in 1962, discovered in 1979)
TYPICAL RANGE: 10^{-15} metres

GRAVITY: Keeps galaxies together, the planets moving around the sun and our feet on the ground
GOVERNING THEORY: General relativity
MEDIATOR: None; gravitons if it were found to be quantum
RANGE: Infinite

Given the changeable nature of chameleons, it may not even be such an outrageous stretch to think that a chameleon force might, under certain circumstances, change its strength so it assists gravity, rather than counteracting it – and so bag two birds with one stone by also addressing dark matter. "There have been some attempts to see if the chameleon can play a role on galaxy and galaxy cluster scales, maybe replacing some of the need for dark matter," says Burrage. Indications so far, however, seem to suggest that chameleon forces can't explain all the effects we ascribe to dark matter, she adds.

Anyhow, rather than a unification of forces, the smart money is on diversification. With the four fundamental forces we already have, we have contrived to explain only normal atomic matter, which appears to make up only 5 per cent of the matter and energy in the universe. "It seems unlikely that all the vast majority of the universe would be made of just one or two components," says Brax. "I wouldn't be surprised if we find more than one new force."

Wilczek agrees, sort of. "I wouldn't be scandalised," he says. "I don't know what to expect, but certainly it would be nice to have more than one." Indeed, he is pursuing another candidate for an additional fundamental force: one associated with hypothetical, light, long-lived particles called axions. These would have many of the properties associated with dark matter, as well as helping to explain some other thorny problems in particle physics, such as why events at the subatomic level look the same whether they run backwards or forwards in time. "This is the fifth force that I think is most compelling," says Wilczek.

All these efforts speak to a wider truth, says Brax: that what we have now with our standard cosmological model is akin to a rough draft of the script for the story of the universe. "To embed our model in something larger, something we could call a theory, usually that involves new particles or fields, and those are going to give you new forces," he says.

Or to put it another way, even a smash hit like our cosmological model starts to look a little tired after a while. A sprinkling of new players to add to the established figures is starting to look like the best way to reaffirm why everyone found the story so compelling in the first place. ∎

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