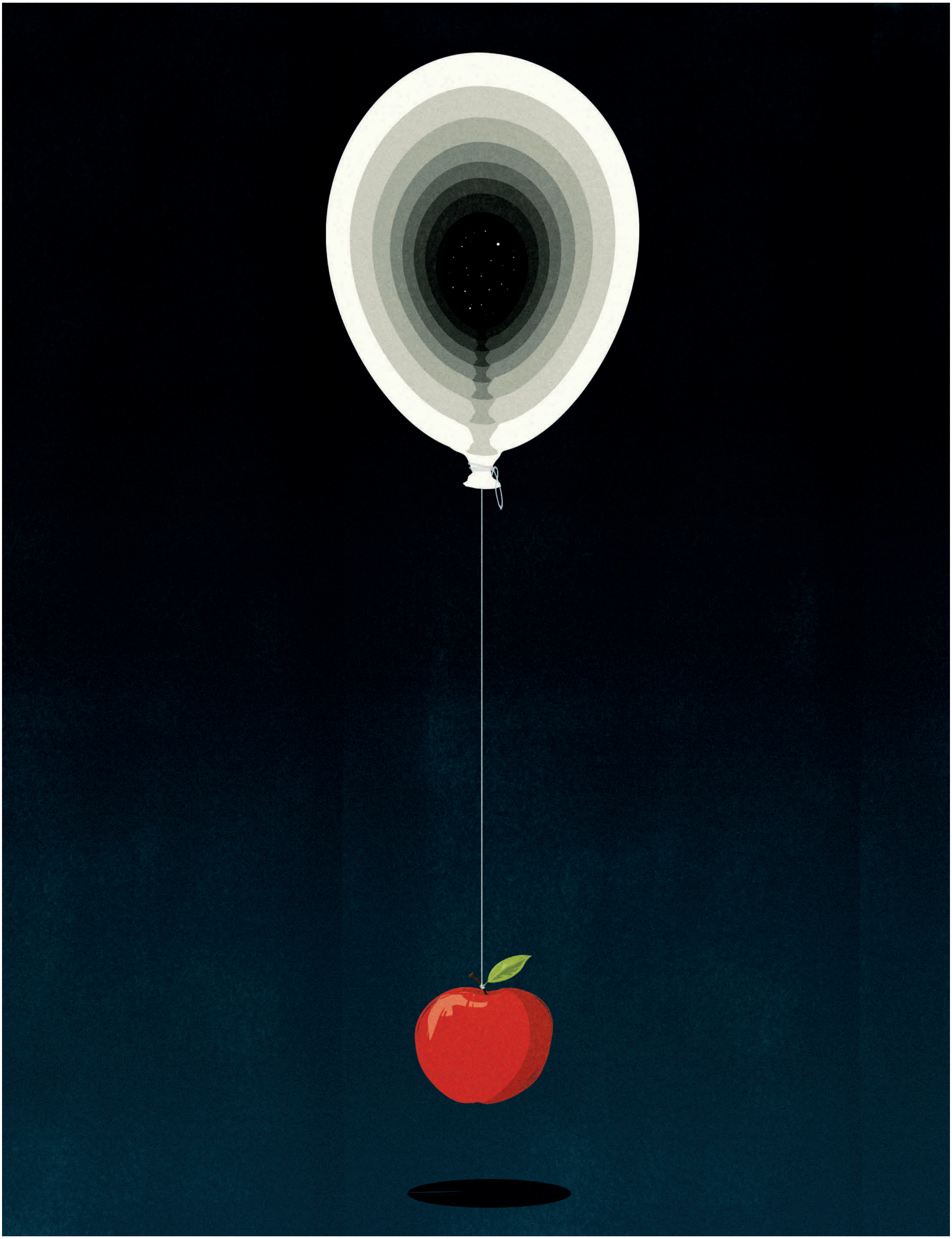
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Perfect disharmony

Gravity is stalling attempts to unify nature's forces. Is peaceful cohabitation a more realistic goal, asks Anil Ananthaswamy

GRAVITY just doesn't play ball. It is the odd one out, the square peg in the round hole. It is a party pooper, a stick-in-the-mud, an old fuddy-duddy: unreformed and, seemingly, unreformable.

Its crime, in the eyes of many fundamental physicists, is that it refuses to kowtow to quantum theory's claim to be the one true theory. Our understanding of every other phenomenon under the sun – and indeed the burning of the sun itself – is underwritten by models with quantum particles at their heart. Gravity is the eternal refusenik.

Our current picture of gravity is painted by Einstein's general theory of relativity. Einstein is one of many who have attempted, forlornly, to broker an understanding between the two theories. But gravity has resisted any attempt to force it into a quantum straitjacket.

Now a bunch of physicists are advocating a gentler approach: let gravity be gravity, and look instead at how quantum theory might change its ways to accommodate it. Their thinking is that perhaps then quantum theory and gravity might join, if not in perfect union, then at least in amicable cohabitation. With a first few theoretical successes already ticked off, now it is time to put the idea to the test.

The cosmologist John Wheeler came up with probably the best way of visualising how general relativity works: "space-time tells matter how to move; matter tells space-time how to curve", he wrote. A large agglomeration of matter (Earth, say) curves space-time around it. Other matter (a falling apple, for example) moves along those curves and so feels gravity.

The other three forces of nature, electromagnetism and the strong and weak nuclear forces, are all transmitted very differently, by the exchange of quantum particles. General relativity works very well on scales where classical physics rules the roost, with large masses and large distances. It predicts surprising effects, confirmed by experiment, such as the bending of distant starlight as it passes the sun, caused by its warping of space-time.

The problem comes when the matter causing space-time to warp is made of quantum particles. Quantum theory is a probabilistic theory: it doesn't tell you definitively how things are now, just how they are likely to turn out when you make measurements. That unleashes mind-boggling apparitions such as Schrödinger's cat, seemingly both dead and alive until you look to find out.

> "Gravity refuses to kowtow to quantum theory's claim to be the one true theory"

Unsettling it may be, but this fuzziness has been verified to astonishing precision in the lab. One consequence is that quantum particles don't appear to have definite positions before you measure them. But if they don't have definite positions, you can't predict how they will curve space-time. So with current theories as your starting point, you can't make a workable model of quantum gravity. And that means in situations where both gravitational and quantum effects hold sway, such as the big bang or within black holes, answers will elude you.

It is a roadblock with no obvious diversionary route – and that bothers a lot of physicists. "One expects some kind of fundamentally unified description of nature," says Daniel Sudarsky at the National Autonomous University of Mexico. Whole research programmes into areas such as string theory and loop quantum gravity aim to find a way through, but so far have had little success.

We have been working on the problem for some time. In fact, back in the 1960s, physicists came tantalisingly close to finding a fix that combines general relativity with quantum mechanics. It is called the semi-classical Einstein equation.

Einstein's original theory consists of a series of equations in which the left-hand side represents the curvature of space-time. The right-hand side, meanwhile, encapsulates how the distribution of matter and energy changes continuously over time, creating that curvature. In the equations, this distribution appears as a solidly classical mathematical term known as the energy-momentum tensor. In the semi-classical Einstein equation, this is replaced by a quantum "expectation value" that represents the average matter distribution you would › expect to obtain from many measurements. It is the equivalent of shrugging and saying, we don't know exactly where the matter is, but this is our best guess.

This trick allows matter to remain quirkily quantum while its gravitational effects are predictably classical. It has proved immensely useful in many astrophysical calculations. Stephen Hawking used the method in the 1970s, for example, in his seminal work showing that black holes emit Hawking radiation. "As long as we don't have fully quantised gravity, which we might never have, this is a very, very powerful tool," says Lajos Diósi of the Wigner Research Centre for Physics in Budapest, Hungary.

"Nowhere are the problems of quantum theory more acute than at the big bang"

Powerful – but defective. The thing is, the semi-classical Einstein equation can't cope with that all-important moment when you measure the position of quantum matter, "collapsing" it to a localised point in space and time. This abrupt jump causes the equation to blow up, with its two sides providing different answers – a mathematical nonsense.

Similar defects plagued Diósi and, independently, Roger Penrose at the University of Oxford in the 1980s, when they attempted to combine quantum mechanics and Newtonian gravity. Newton's simpler picture of gravity has been superseded by general relativity, but is still a good description for objects moving at significantly less than light speed.

But all these semi-classical theories ended up having discomfiting effects. They predicted, for example, that even something as classically dependable as the moon could end up in a quantum "superposition" state with half its mass in one place and the other half elsewhere – a truly loony version of Schrödinger's cat. Similar superpositions could infect space-time itself, creating a new layer of confusion that might, in theory, enable signals to travel faster than light speed. Not only that, but the equation resulted in a breakdown of the quantum world's predictably probabilistic nature, going against decades of experiment.

As practical descriptions of reality, then, these hybrid theories seemed implausible. Penrose was among the first to suggest the blame for this impasse lay not with gravity, but with quantum theory.

Specifically, it came from that moment of collapse. The standard interpretation is that the act of measurement causes the quantum world to shift into classical certainty. But this leaves many unanswered questions, such as how big a measuring device must be to collapse a quantum state, and whether the process requires a human observer or some other form of consciousness.

Nowhere are such questions more acutely unanswerable than at, and soon after, the big bang. Collapsing quantum states in the infant cosmos are thought to have played a pivotal part in its subsequent development, determining how stars, galaxies, planets – everything, in fact – eventually formed. But how did they collapse with nothing around to measure them? "In ordinary quantum mechanics, measurement involves an external device," says Sudarsky. "What's playing this role in cosmology? If I don't want to invoke God or something external to the universe, which I don't, I have no place to locate this measuring device."

In recent years, Sudarsky and others have begun working with a mathematically equivalent alternative to standard quantum theory known as the spontaneous collapse model (*New Scientist*, 16 July 2016, p 30). This contends that quantum states collapse randomly without the need for an explicit measurement. The average time it takes for a single quantum particle in a collection to collapse is very long – about the age of the universe – but if one goes, they all go. As an object's size and the number of particles it contains increases, the likelihood grows – indeed reaches certainty – that the quantum state of the entire object will collapse. This explains why microscopic quantum systems remain quantum, while macroscopic objects have definite, classical forms.

Bridging the divide

The first collapse theory, called Ghirardi–Rimini–Weber or GRW theory, was formulated in 1985. It didn't catch on, partly because of entrenched views about the correctness of standard quantum mechanics, and also because the equations didn't explain why spontaneous collapse happens. "They are ad hoc and I understand when people say that they are ugly modifications," says Antoine Tilloy at the Max Planck Institute of Quantum Optics in Garching, Germany.

So it certainly never occurred to anyone that collapse theories might help bridge the gap between quantum theory and gravity. "People could have tried this 35 years ago, if they had been more open to alternatives to standard quantum theory," says Maaneli Derakhshani of Utrecht University in the Netherlands.

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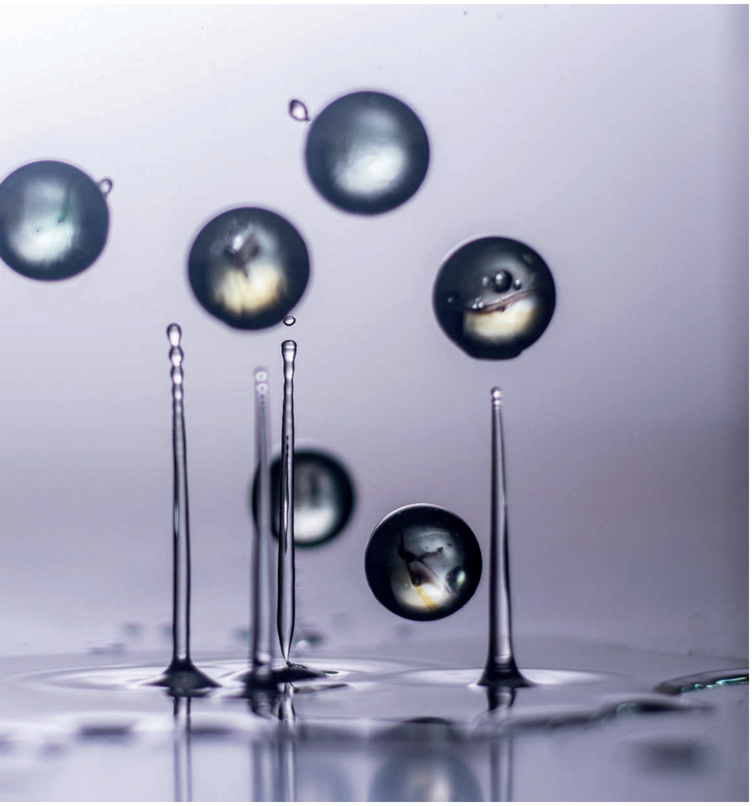
In 2013, Derakhshani made the first attempt to incorporate GRW collapse theory into equations seeking to combine quantum theory and Newtonian gravity. He found a marked improvement. The quantum world remained fuzzy and quantum just as experiments required; and the weird Schrödinger's cat states for macroscopic objects such as the moon went away, as common sense demanded.

But the theory still allowed signals to travel faster than light, a no-no for those who believe in standard ideas of cause and effect. That problem has only been solved over the past few years by Tilloy. Working first with Diósi and then on his own, he incorporated a slightly different collapse model into a theory of semi-classical Newtonian gravity. This model calls individual collapse events "flashes", and proposes that they happen randomly at specific points in space-time, causing matter to end up in definite positions and so give rise to gravity. Space-time itself remains classical and can never enter into a



Gravity works: why change a winning formula?

quantum superposition of states, removing the potential for faster-than-light influences. "This is what saves you," says Tilloy.

It is still early days, he cautions: this work is just a proof of concept showing that you can formulate semi-classical theories of gravity without all the paradoxes. "Basically, my main objective was to destroy the counterarguments," he says.

Sudarsky thinks that Diósi and Tilloy's work is an important step. But he agrees there is more to be done, not least in moving beyond Newtonian gravity to the Einsteinian picture. "Now the question is how to make that all compatible with general relativity," he says.

That's just what he and his team are now attempting to do, using yet another variant of the spontaneous collapse model. So far, they have shown how semi-classical gravity can describe matter and its effects on space-time before and after collapse. They are also making significant progress with the mathematics at the actual point of collapse.

One of the most appealing aspects of such work is the growing potential for experiments to confirm or deny its results. Take collapse theories themselves. If spontaneous collapse really occurs, we should be able to see it happening. Double-slit experiments, for example, are used to test the quantum nature of matter: single quantum objects pass through the slits, creating an interference pattern that shows they are in a superposition of being in two places at once. We could see if molecules larger than a certain size collapse spontaneously into a classical object by pushing larger and larger molecules through double slits, watching for the point at which the quantum interference stops. "Until five to 10 years ago, it was absolutely impossible to propose any experimental tests," says Diósi. "Now, the situation is completely different."

"If gravity is ultimately a quantum force, it should create entanglement"

Then there is the gravity side of things. If gravity is ultimately a quantum force, it should do something that the other forces can do: create entanglement. This is when the state of particles that have interacted via a quantum force remain forever intertwined, however far apart they might subsequently be.

In November 2017, Sougato Bose of University College London and his colleagues proposed an experiment to test gravity's entanglement-giving powers. The idea is to let two masses, each of them in a separate quantum superposition of states, fall freely. The experiment is designed such that the only possible interaction between these masses as they fall is gravitational. At the end, you can test whether the quantum states of the two masses are entangled with each other. If they are, gravity must be a quantum force, and there must be an as-yet-unknown route to describing it with quantum theory. "If that's the case, then we are toast," says Tilloy. Alternatively, if gravity cannot create entanglement, semi-classical gravity remains a viable proposition.

Tilloy's own work suggests other experimental tests. Usually, the strength of Newtonian gravity falls in step with the square of the distance from the source. Tilloy's equations predict that this standard force law will break down at length scales of about 10^{-10} metres, around the size of an atom. "It's not super, super small. But still, it's very small for gravity," says Tilloy. "The behaviour of gravity beyond micrometres is not known." In the future, more sensitive experiments should be able to detect any deviation.

Carlo Rovelli at Aix-Marseille University in France thinks such experiments will only show us we still need a quantum theory of gravity. According to general relativity, the dynamics of gravity are not unlike those of other fields, such as the electromagnetic field. "I see no reason why it should not behave like any other dynamical entity in nature, and be a quantum field," says Rovelli. "I bet 99 to one that the outcome will be consistent with gravity having quantum properties."

Despite working on theories of semi-classical gravity himself, Sudarsky sounds a similarly sceptical note. At its most fundamental, he thinks, gravity probably is quantum mechanical, and when it emerges from a deeper, as-yet-obscured layer of reality, we get Einstein's classical space-time.

All the researchers are well aware that they are treading on uncertain ground in their search for a theory of semi-classical gravity. But the potential prize is too great to ignore: gravity that works as Einstein predicted, but also in the quantum world. A square peg sitting comfortably in a round hole. "It may not have anything in common with reality, but we must explore," says Diósi. "It might have some seeds of truth." ■

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