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Cosmic curveballs

We may be on the cusp of finding a new kind of gravitational wave signal that can reveal many of the universe's secrets, finds **Jonathan O'Callaghan**

DID you hear the one about the star that died twice? In 2014, astronomers saw the explosion of the Refsdal supernova. Then, 360 days later, it went bang again.

This bizarre sequence of events was down to a phenomenon called gravitational lensing, in which massive objects warp the fabric of space enough to cause light to bend. The path of the flash from the supernova was changed in this way on its journey to us, so that portions of it took different routes and arrived at different times – almost a year apart in this extreme case.

As that story shows, gravitational lensing has been around for a while, but now it is about to enter a compelling new chapter. Scientists know it isn't just light that can be lensed, but gravitational waves too. It is a mind-bending concept: ripples in space-time themselves being distorted by the curvature of space. It is also a deeply important phenomenon that could illuminate the secret interiors of neutron stars, settle a mystery about the power of dark energy and test gravity itself more keenly than ever. And here is the best part: we may be on the cusp of spotting our first lensed gravitational wave.

No one is under any illusions that this will be anything other than fiendishly difficult. Still, there is a sense it will happen sooner or later – and there are tricks we can pull to expedite the discovery. "It's exciting, and it's going to happen," says Simon Birrer at Stony Brook University in New York. "There's no way [these waves] don't exist."

When we gaze at space, it looks like empty nothingness. But for the purposes of cosmology, scientists think of it as space-time, which is as a bit like a stretchy sheet of fabric. Albert Einstein's theory of general relativity tells us that the more massive an object is, the more it warps this underlying fabric of the universe. Sudden, dramatic changes in mass – like when black holes collide – make the fabric ripple, an effect we call a gravitational wave.

These ripples were first directly detected by the Laser Interferometer Gravitational-Wave Observatory (LIGO) in the US in 2015. Its detectors work their magic by firing laser beams along two perpendicular arms, each 4 kilometres long. The detectors can sense a passing gravitational wave because it squashes and expands the space the arms occupy by a tiny amount, altering the distance the beams travel with respect to each other. That first detection was heralded as a huge breakthrough; a Nobel prize soon followed.

Since then, about 90 confirmed detections have been made in three observing campaigns. Each arose from a collision, or merger, between two neutron stars, two black holes or one of each. Some of the neutron star mergers are followed by super bright visible explosions called kilonovae. Observing the gravitational waves generated by the mergers has taught us much about the objects that cause them, including the distribution of their sizes. We have even detected the so-called gravitational wave background, a low-level hum of such ripples that emanate from the early universe.

LIGO is now in its fourth observing run, complemented by an additional detector in Italy, called Virgo, and another in Japan, the Kamioka Gravitational Wave Detector (KAGRA). We expect that hundreds of additional mergers will be detected in this run, which lasts until February 2025. There is even another detector, LIGO-India, set to open later this decade. In short, gravitational

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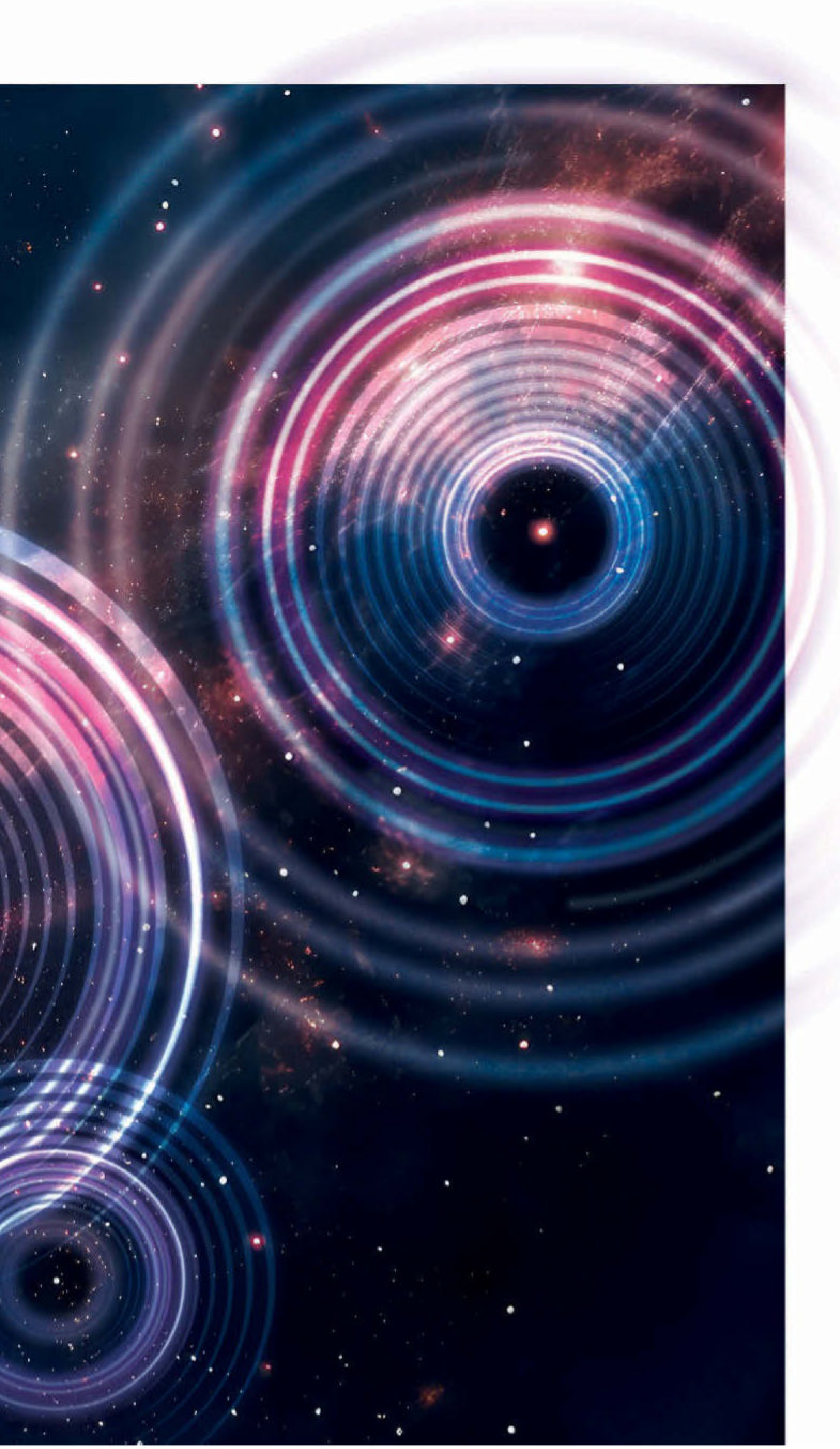


wave sightings are becoming routine.

But routine in this case is the opposite of boring. The more of these waves we see, the better the chance we have of snaring rare varieties. Like ornithologists waiting patiently in a hide, gravitational wave watchers feel they might soon catch a glimpse of a really uncommon bird.

In principle, a lensed gravitational wave works very much like a lensed ray of light (see diagram, page 42). A merger produces ripples in space-time that spread out in all directions. If there is some massive object like a galaxy cluster between the source of the ripples and Earth, it warps space-time and acts like a lens. This can bend some of the waves travelling roughly towards Earth, focusing them on us. With light, this can result in distorted or repeated images. Rarely, it can form an "Einstein ring", where the resulting image is a circle, which occurs when the source, lensing object and observer are all perfectly aligned.

With gravitational waves, the same applies – the wave can be distorted, magnified or even repeated, like an echo. "And that's just incredibly powerful for the science we can do," says Graham Smith at the University of Birmingham, UK.

Wait for it

How frequently should we expect to detect these strange echoes? In 2023, Smith and his colleagues ran the numbers and estimated that, at best, we might expect 1 in 1000 detected gravitational waves to be lensed. Given that we are expecting to see hundreds in the current observing run, we could, if we are lucky, see one at any moment. At a recent scientific meeting to discuss this, the consensus was that we will see a lensed gravitational wave within a few years. "You probably need a few hundred gravitational wave events before you're likely to get [a lensed one], which is kind of the ballpark we're getting into now," says Tessa Baker at the University of Portsmouth, UK.

It will be a big moment. Observing lensed gravitational waves should open up at least three new avenues in science. The first involves measuring the speed of gravity.

According to general relativity, gravitational waves should travel at the speed of light. Observing lensed waves would enable us to check this with unprecedented precision. Physicists are hunting for clues that might lead to a quantum theory of gravity, and deviations from general relativity could point the way. ›

"Seeing a lensed gravitational wave may help us with several cosmological mysteries"

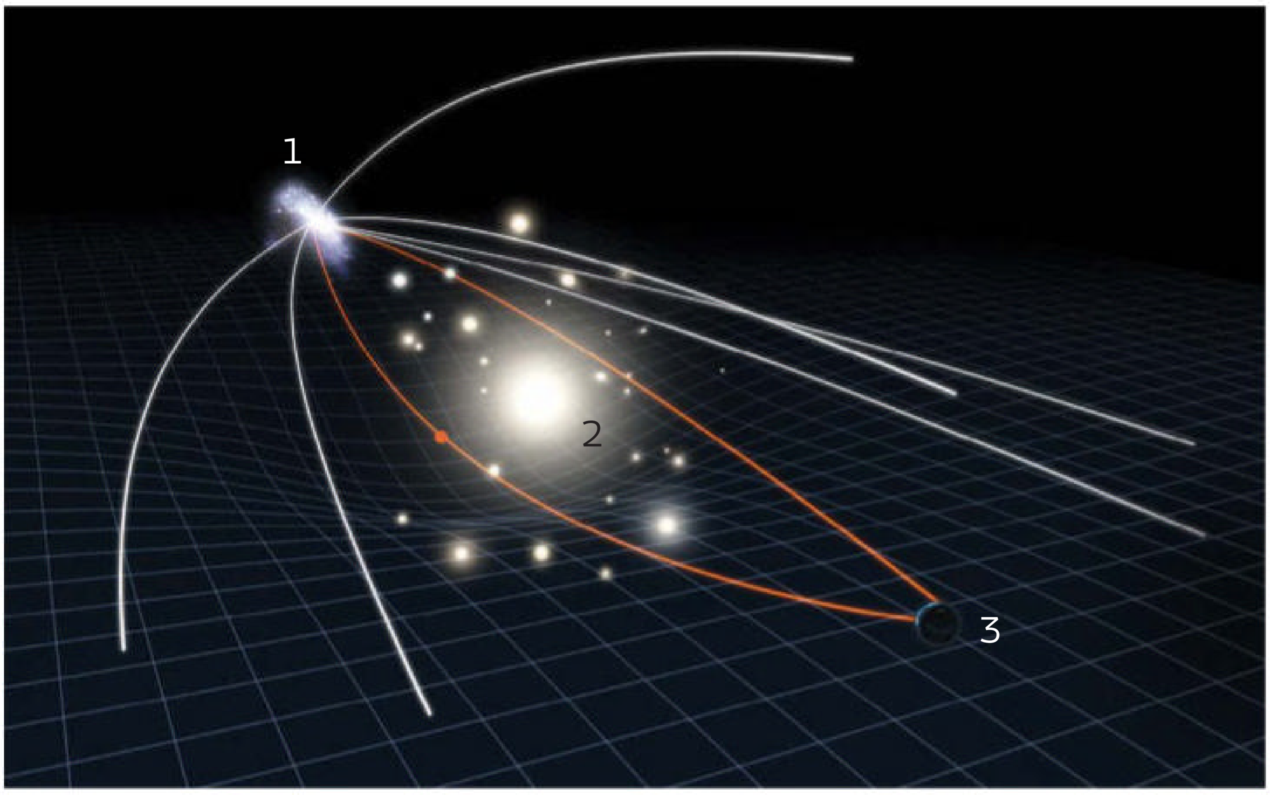
The amount that the incoming gravitational wave signals are distorted could also give us key information about dark matter, the unexplained stuff thought to make up 85 per cent of the universe's material. Any intervening galaxy cluster would contain substantial amounts of dark matter, perhaps even in the form of clumps with the mass of planets, says Birrer. "Depending on how dark matter is structured, it will create an imprint in these waveforms." This could help us distinguish between different hypotheses for what dark matter is and how it behaves.

Even more excitingly, certain types of lensed gravitational wave may help resolve a persistent problem in cosmology known as the Hubble tension. We know the universe is expanding at an increasing pace, driven by a mysterious force called dark energy. Astronomers can measure this rate, known as the Hubble constant, in two ways. One involves analysing large-scale fluctuations in the cosmic microwave background radiation, which permeates the universe. The other looks at supernovae explosions that are relatively close to us. However, these methods give conflicting values for the expansion rate: about 73 kilometres per second per megaparsec (a megaparsec is about 3 million light years) in the local universe, but 67km/sec/Mpc on larger scales.

Observing a lensed gravitational wave would give us another way of measuring cosmic distance and therefore a third, independent measure of the Hubble constant that would have far less uncertainty than the other methods. "We know our current standard cosmological model is a bit broken," says Baker. "Either there's something that's been mismodelled or there's new physics." Observing a lensed gravitational wave wouldn't solve the Hubble tension overnight, but it would "add a very complementary measurement", says Birrer, helping us move towards a solution.

How gravitational lensing works

(1) Light rays from a bright object such as a galaxy spread in all directions; (2) These rays are bent by the gravity of a massive object, like a galaxy cluster; (3) Some rays (orange) arrive at Earth at different times or angles, creating distorted images. A similar process can affect gravitational waves (see main story)



That is the good news. The bad news is that identifying a lensed gravitational wave just from the signal that LIGO detects will be taxing in the extreme. Searches for one in LIGO's back catalogue of detections have found nothing so far.

When light is bent around a gravitational lens, the resulting effect is obvious. The Refsdal supernova, named for Norwegian astronomer Sjur Refsdal, literally appeared in the sky twice. Not the sort of thing astronomers are likely to miss. A lensed gravitational wave will be subtle by comparison. The signals detected by LIGO are "chirps": a wave that sharply increases in amplitude and then tails off. Lensing could affect these in a few ways.

First, the lens could increase the amplitude, or strength, of the wave. The trouble is, that wouldn't be conclusive: there is no surefire way to distinguish between a lensed gravitational wave and one that just comes from a bigger or closer merger. "There are certainly scenarios where there is gravitational wave lensing, but the result would be inconclusive," says Otto Hannuksela at The Chinese University of Hong Kong.

Except there might be a workaround. We can deduce from LIGO signals the mass of the two objects involved in a merger that produces the gravitational wave seen. Based on all the confirmed LIGO detections so far, we think there is a "mass gap" between the heaviest neutron stars, at 2.2 times the mass of the sun, and the lightest black holes, which start at about five times the solar mass. If we spot a merger with progenitor objects that appear to be in this mass gap, we might be looking at a neutron star merger event that has been magnified by a lens to look bigger than it really is. "Some of them will get boosted [by lensing] and fall into this mass gap," says Anupreeta More at the Inter-University Centre for Astronomy and Astrophysics in India.

The second way lensing could affect gravitational waves is just to distort them in hard-to-anticipate ways. But the third way is much more promising. In special cases, the wave could repeat. In this case, we would get two almost identical chirps arriving one after another, with the delay depending on the mass of the lens. This would be much more of a smoking gun. Yet detecting any of these will rely on complex signal processing and interpretation. Which is why the gravitational

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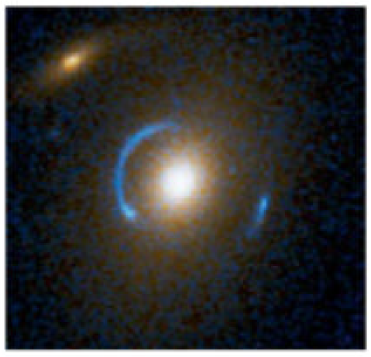

NASA, ESA, A. BOLTON, SLACS TEAM

An Einstein ring (above) is a telltale sign of the gravitational lensing of visible light. The Vera C. Rubin Observatory (left) could help us find the source of a lensed gravitational wave

echo hunters have another card up their sleeve.

To provide bulletproof evidence of a gravitational lens, astronomers would ideally find the lens itself – usually a galaxy cluster – and show that it lines up with the source from Earth's perspective. But LIGO's detectors can only narrow down the origin of space-time ripples to a fairly broad area of sky. So they want to recruit some help from a new telescope.

The plan is to try to spot the visible kilonova explosion emanating from the merger that produced the ripples. This arrives at Earth typically within about a day of the gravitational wave. Scanning the sky to find this in such a short time would be a tall order. But the Vera C. Rubin Observatory at the summit of Cerro Pachón in Chile is one of the world's most advanced telescopes. It is due to switch on at the start of 2025 and will use its 8.4-metre-wide mirror and a massive digital camera to snap vast images of the whole sky.

Catch the flash

Rubin's primary goal is to perform our most detailed survey of the night sky. Over 10 years, it is expected to image 40 billion cosmic objects. But in March, Smith met with the Rubin team to discuss whether the telescope could occasionally take a short break from its survey and try to find the visible counterpart of a lensed gravitational wave signal. Federica Bianco at the University of Delaware, Rubin's deputy project scientist, is keen on the idea and actively exploring it with Smith.

If and when Smith and his colleagues spot a likely looking lensed gravitational wave, they plan to notify the Rubin telescope. It will scan the sky to find the corresponding flash, then send the coordinates to space observatories, including the powerful James Webb Space Telescope, which can then watch in detail. The hope is that this whole process will be automated, with the multi-billion-dollar telescopic dance lasting just minutes.

Doing all this would help identify the lens itself, confirming the lensed gravitational wave was genuine. But it would also be crucial for unlocking some of the scientific possibilities of such a detection. For example, measuring the speed of gravitational waves will only be possible if we can pinpoint the source of those waves using Rubin. But beyond that, it would open up even more science.

Only one definitive kilonova has been seen before . That was in August 2017, when LIGO picked up a gravitational wave known as GW 170817 and astronomers managed to find and see the visible explosion that followed 11 hours later. "This first detection confirmed the origin of kilonovae can be these binary neutron stars," says More.

One reason studying kilonovae matters is because these explosions may be the only events powerful enough to create half the elements on the periodic table, those heavier than iron. That 2017 kilonova was the first and only time we have seen such elements being made – analysing the light given off showed us the individual signatures of each element.

But we only caught the tail end of the explosion. For Smith and his colleagues, the dream is that a lensed gravitational wave could give us early warning of a kilonova, which we could then watch from start to finish with telescopes. That could paint a complete picture of element synthesis and potentially answer the important questions we have about how it works, including whether kilonovae produce enough of the heavier elements to account for the amounts we see in the universe or if there must be another source.

The same visible signal could contain answers to fundamental questions about how nuclear material behaves at extremes. A neutron star, as the name suggests, is a blob composed almost exclusively of neutrons compressed to incredible pressure. Elsewhere, neutrons are normally embedded in atoms, and physicists have hypotheses to describe how they behave – but it is usually impossible to test them beyond standard atomic pressures and arrangements.

Neutron stars are the one place we can push far beyond this. Again, studying the flash from a kilonova could show us how the neutron stars react as they slam together, by extension telling us about the neutrons within. "They are about the only place in the universe where this is possible, so it is a big deal," says Matt Nicholl at Queen's University Belfast in the UK.

To see both the lensed kilonova and the lensed gravitational waves from the same merger requires both LIGO and Rubin to operate simultaneously, which may not happen for a few years yet. "We will be waiting till around 2027 or 2028," says Smith. Still, there is always the possibility we might see hints of a lensed gravitational wave before that just in the LIGO data. If this does arrive, ambiguous though the detection might be, it would be a thrilling moment of potential scientific discovery. "We need to be ready," says Smith. ▮

Jonathan O'Callaghan is a reporter focusing on space, based in the UK