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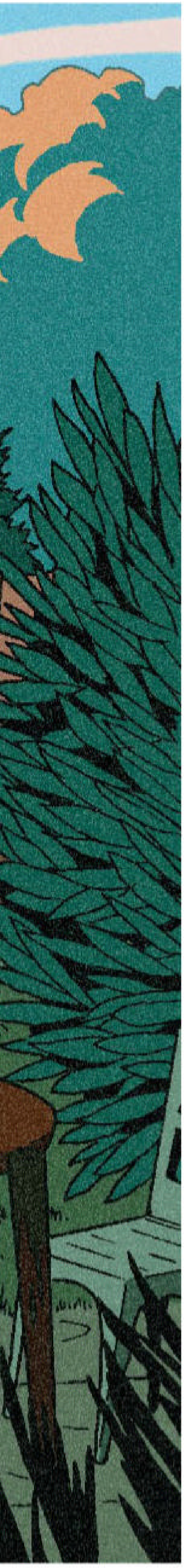

A black hole in our backyard

Black holes born in the big bang could transform our view of the universe. Is there one lurking on the fringes of the solar system, asks **Stuart Clark**

BEYOND the giant planets of the outer solar system lies a vast wilderness. Most astronomers think it is inhabited by a population of small, icy worlds similar to Pluto, and several groups have dedicated themselves to tracking down these dwarf planets. In the process, some have come to suspect that something bigger is lurking out there: a planet several times the mass of Earth.

They believe that this hypothetical world, known as Planet Nine, betrays its presence by the way its gravity has aligned the orbits of a group of these small, icy bodies. The problem is that no one can imagine how a planet big enough to do that could form so far from the sun. "All we know is that there's an object of a certain mass out there," says Jakub Scholtz, a theorist at Durham University in the UK. "The observations we have can't tell us what that object is."

But if not a planet, then what? Scholtz suspects it could be something even more exotic: a primordial black hole, one forged in the big bang.

If he is right, it would be a stunning discovery. Primordial black holes would give us a new window onto the early universe. They might even comprise dark matter, the mysterious substance that holds galaxies together. All of which explains why cosmologists have been scouring the universe for them. But no one had dared to dream we might find one in our own backyard.

The question now is, how can we determine what the mysterious source of gravity lurking at the fringes of our solar system really is?

Black holes are regions of space-time so warped that their gravity becomes irresistible; nothing can escape their pull, not even light. They were predicted based on Albert Einstein's general theory of relativity in 1915. Exactly a century later, they were directly detected for the first time when the Laser Interferometer Gravitational-Wave Observatory (LIGO) spotted faint ripples in space-time, or gravitational waves, caused by the collision and merger of two black holes.

LIGO has since reverberated to the tune of 50-odd more detections, many of which aren't what we were expecting. The black holes previously inferred from theory, and from their influence on nearby matter, fall into two categories. The largest are the supermassive black holes found at the centre of every galaxy in the universe, including our own. These grow by merging with other black holes, becoming behemoths that are millions or even billions of times the mass of the sun.

Then there are stellar black holes. These are created in the gigantic explosions that end the life cycles of massive stars, and the closest to Earth is around 1,000 light years away. They tend to weigh in at between five to 15 solar masses, and they were the black holes that most astronomers had assumed LIGO would pick up. But the 2015 discovery only made sense if one of the colliding black holes was roughly 35 times the mass of the sun, while the other was around 30 times this mass.

Subsequent detections threw up more seemingly inexplicable black hole masses. The GW190814 signal involved one black › hole that was too heavy, at around 23 solar masses, and one that was too light, at about 2.6 solar masses. Then there was GW190521, from a collision between black holes of 85 and 66 solar masses. "These observations are very hard to explain with astrophysical scenarios and they are quite easily explained with primordial black holes," says Sébastien Clesse, a cosmologist at the University of Brussels in Belgium.

Little and large

That is because primordial black holes are thought to form across a wide range of masses, even down to that of planets and asteroids. In theory, they formed in the early universe, a shifting maelstrom of matter and energy squeezed together so tightly that any disturbance could tip a given region over the critical density at which it collapses into a black hole. The size of each would depend on the conditions from which it sprang. So there should be lots of primordial black holes of all different sizes.

Still, it seems a stretch to propose that Planet Nine is one when its mass is dramatically smaller than the black holes revealed by LIGO. At present, the conventional story is that the mysterious source of gravity beyond Pluto is a planet between five and 15 times the mass of Earth. That was the estimate Scott Sheppard at the Carnegie Institution for Science in Washington DC and Chad Trujillo at Northern Arizona University first came up with in 2014.

And yet the more Scholtz and his colleague James Unwin at the University of Illinois thought about the logistics of Planet Nine, the more comfortable they were speculating about a more exotic scenario. Unwin had heard about Planet Nine at a planetarium show in Chicago. "I think he was pretty excited," recalls Scholtz, "because he calls me and he's like, 'You know, OK, maybe it's a planet and that's great, but what if it's something else? What could it possibly be?'"

Their thinking was fuelled by the theoretical problems involved in forming a large planet that far from our star. The planets of the solar system coalesced from a disc of matter surrounding the sun. The difficulty is that the matter thins out the further you get from the sun. At the distance Planet Nine would be sitting, there simply isn't enough raw material to build something that large.

There is a hybrid scenario in which Planet Nine formed much closer and was then hurled into the darkness by the gravity of Jupiter or Saturn. But that quickly becomes problematic because a single interaction can't do the job. Instead, a string of interactions is needed to make sure Planet Nine never returns to where it was originally formed – and that all sounds like too much coincidence to Scholtz, or at least grounds to consider alternatives.

"When you look at the formation scenarios for Planet Nine, I think they pose a lot of issues," says Scholtz. What drew him to the possibility that the mysterious mass at the edge of the solar system could instead be a primordial black hole was another intriguing observation from astronomers looking much further afield.

The Optical Gravitational Lensing Experiment (OGLE), operating primarily out of Las Campanas Observatory in Chile, watches stars in the centre of the Milky Way for unexpected increases in brightness caused by gravitational microlensing. This is when light from background sources is bent by the passage of intervening objects that would otherwise be too small or too faint to be seen. They reveal themselves because their orbits happen to temporarily line up between Earth and a star in the galactic centre such that their gravity focuses the light, making the star appear to brighten. The shorter the time span of this increase, the lower the mass of the intervening object.

Out of 2600 microlensing events that OGLE detected between 2010 and 2015, six turned out to be "ultrashort", lasting less than half a day. Przemek Mróz at Warsaw University Observatory in Poland and his colleagues suggested that they were planets orbiting freely in interstellar space rather than bound to a solar system. But in a 2019 paper, Hiroko Niikura at the University of Tokyo in Japan and his colleagues showed that these signals could just as easily be produced by primordial black holes of a few Earth-masses.

When Scholtz saw this paper, he noticed something curious: the alignment of mini-worlds in the outer solar system was

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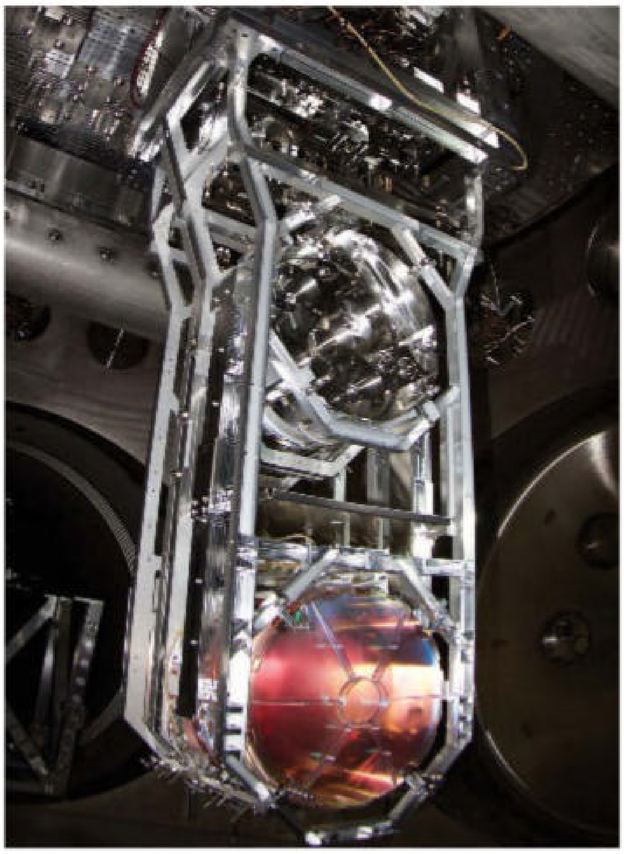
"This ancient black hole would be roughly the size of a grapefruit"



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One of LIGO's detectors (left) and one of the mirrors that reflect laser beams along the detector arms

indicative of an object of similar mass to those behind this series of anomalously short microlensing events. It could just be a coincidence, of course. But for Scholtz and Unwin, it hinted at a wider population of previously unseen celestial objects. And if they aren't planets, then the only other things that fit the bill are primordial black holes.

In 2019, Scholtz and Unwin put out a paper titled "What if Planet 9 is a Primordial Black Hole?". It revealed that such a black hole would be just 9 centimetres in diameter, roughly the size of a grapefruit. It also went into detail as to why the suggestion is plausible, and it all comes down to the way you would have to get Planet Nine – if it were actually a planet – into its orbit.

If Planet Nine didn't form in our solar system, the only other way to get it there is to capture a free-floating planet that was made in another solar system and just happened to be passing. Different groups have come up with estimates, each showing that this is unlikely, but not impossible. In their paper, Scholtz and Unwin demonstrated that it was no less improbable to capture a primordial black hole.

What is in no doubt is that finding a primordial black hole anywhere in the cosmos would be absolutely massive, if you can pardon the pun. If they are still distributed across the universe, as expected, these ancient objects could solve several of cosmology's biggest problems in one gulp.

Dark secrets

Take dark matter, the catch-all term for the gravitational glue that holds galaxies together and accelerates their formation in the first place. For much of the past half century, researchers have been convinced that it must be made of undiscovered particles: not the stuff we know, but weird stuff that generates gravity and doesn't interact with light. The trouble is that no one has been able to detect a single dark matter particle, despite having spent billions on experiments over the years.

In recent years, researchers have argued over whether it could be comprised of primordial black holes. Clesse, working with Juan Garcia-Bellido at the Autonomous University of Madrid, used the rate of black hole mergers seen by LIGO to figure out how many ancient black holes there could be. Their estimates suggest that the total population might indeed contain a significant fraction of the universe's mass. "Primordial black holes could be the dark matter," says Clesse.

Having formed in the first few moments of the universe, primordial black holes would also encode information about what was happening just fractions of a second after the big bang. This was a crucial time: the forces of nature were taking on their final forms; matter, antimatter and dark matter were coalescing into their respective proportions; and space itself was engulfed by a bout of exponential inflation that blew it up to a vast size.

Yet investigating this era is incredibly difficult. Optical and radio telescopes can never see that far back. They hit a barrier at around 300,000 years after the big bang, when the density of matter increases so much that it fogs the view. An attempt to extract a subtle gravitational wave signal created in this era also met with failure, when researchers were fooled by the effects of dust in the Milky Way.

As relics from the birth of the universe, primordial black holes would change everything. "We would suddenly have a way to search back in time, to events that we have no other way to explore," says García-Bellido.

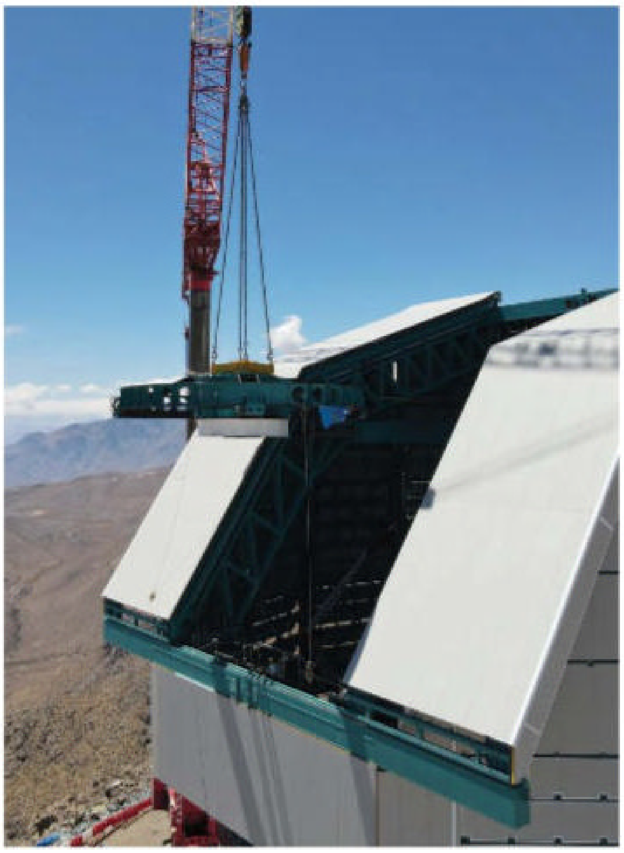
Such events took place at different times and so, according to theory, would be associated with a different primordial black hole mass. Furthermore, each event would have influenced the number of primordial black holes forming at that instant. So comparing the number of black holes of different masses should tell us about what was going on back then. Planet Nine's mass, for example, suggests that, if it is indeed an ancient black hole, it was probably produced during the electroweak transition, when electromagnetism separated from the weak nuclear force.

But we aren't about to start peering through this window onto cosmic history quite yet. First, we have to show that there really is a black hole in our solar system, and that means mounting a fresh search that requires a different approach to the hunt for a hinted-at planet. ›

Optical telescopes will never see a black hole. X-ray telescopes do stand a chance because anything falling into a black hole would heat up and give off a burst of light in the X-ray wavelength. The catch is that these flashes would be fleeting, so we would have to be looking in exactly the right direction at exactly the right time to spot one. There is one other possibility that would give a steady X-ray signal, and that is if dark matter really is made up of exotic particles that annihilate each other on contact. The dark matter would tend to cluster around the black hole. As a result of the annihilation, it would emit a steady beam of X-rays or gamma rays that would drift across the sky as the black hole followed its orbit.

Mission possible

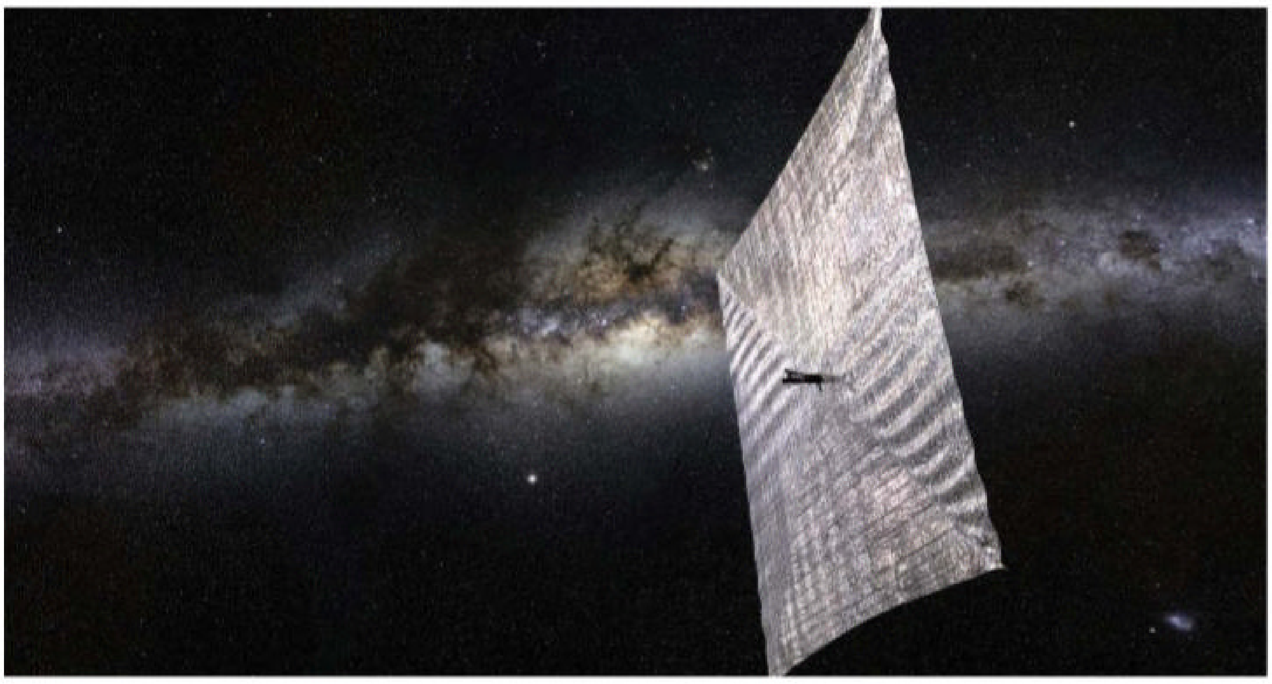
Perhaps the best way to catch a primordial black hole is to look for the thing it produces in abundance: gravity. This is where Slava Turyshev at NASA's Jet Propulsion Laboratory in California comes in. He has suggested probing whatever this source of gravity is with a fleet of small spacecraft. The idea is that deviations in their expected trajectories could reveal any massive object lurking out there – be it planet or black hole. It would provide a precise location on which to train our telescopes. If we see a speck of light, it is a planet; if not, it is a black hole.



RUBIN OBS/NSF/AURA

The Vera C. Rubin Observatory in Chile and (below) an artist's impression of a solar sail

"We could prove this mysterious gravity source using a fleet of tiny craft"



NASA

In a recent paper, Turyshev and several colleagues point out that the miniaturisation of satellites and the use of solar sails now make such missions possible. Solar sails require no fuel: they propel a spacecraft simply by the momentum imparted by the pressure of sunlight falling on the sail. By first diving close to the sun, they can receive a mighty push, sufficient to send them sailing serenely out to the orbit of Neptune in about a year. "This is about 10 times faster than can be achieved with chemical propulsion," says Turyshev.

For now, such a mission remains firmly on the drawing board. Indeed, some astronomers are unconvinced that a Planet Nine of any description is out there. Earlier this year, Kevin Napier at the University of Michigan and his colleagues published an analysis making the case that the alignment of smaller dwarf planets suggesting the existence of a ninth planet is simply a statistical artefact that will fade away with more and better data.

For the moment, the state of the art is to return to where we started: charting the small, icy worlds of the outer solar system to determine whether Planet Nine – or something else – is out there. That will soon become less of a slog thanks to the Vera C. Rubin Observatory in Chile, due to start operating this year. It is expected to find tens of thousands of mini-worlds in the remote reaches of the solar system, vastly increasing the sample size. Their orbits will prove once and for all whether there is a planetary-mass object out there. They will even allow astronomers to precisely predict its location, at which point the telescope can take a closer look.

If it sees a planet, it will be a huge deal. If it doesn't see anything and yet the anomalous gravitational pull remains, it will be time to launch the solar sails. ■

Stuart Clark is a consultant for *New Scientist*. His latest book is *Beneath the Night: How the stars have shaped the history of humankind*