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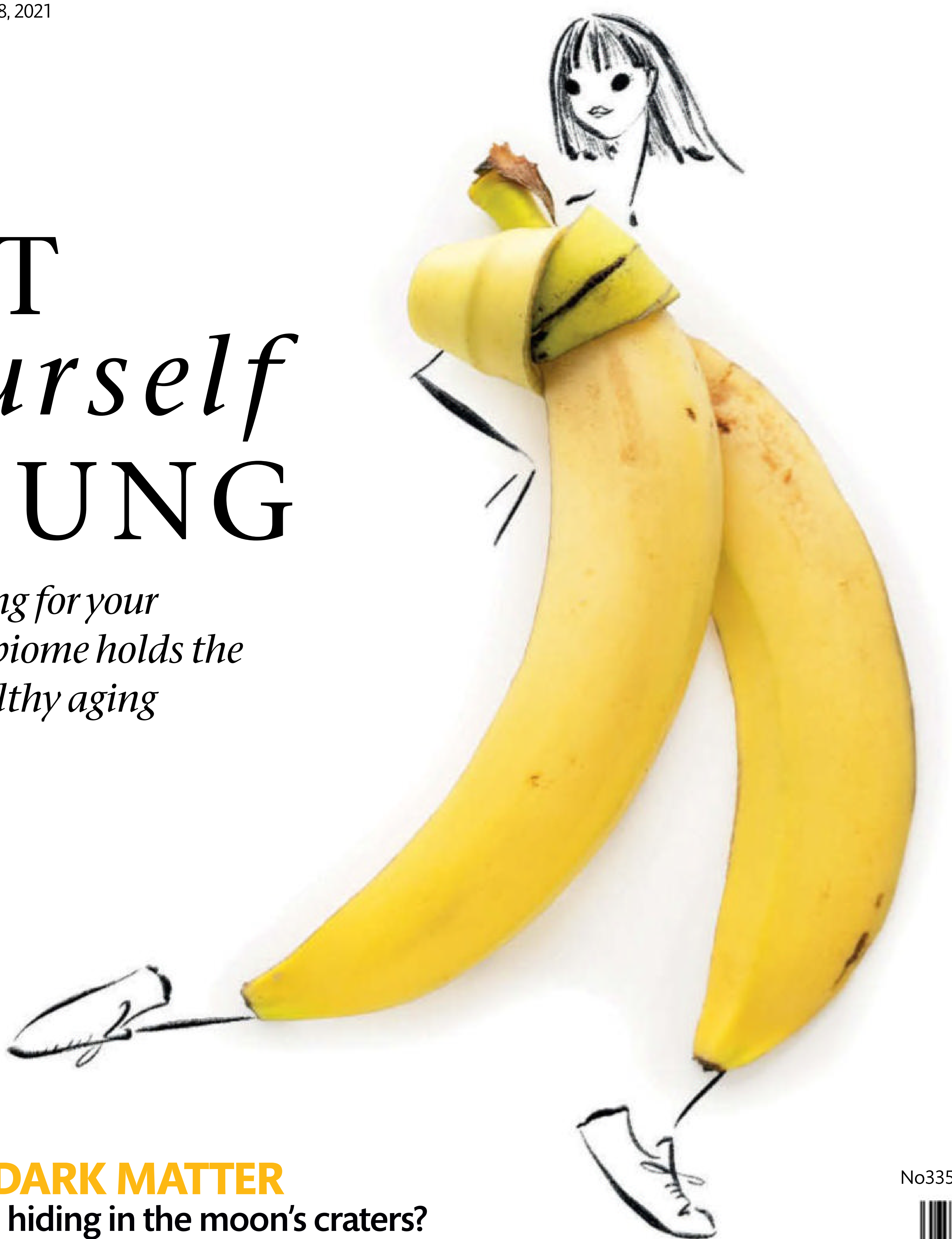

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Curious craters

Could scars left by ancient black holes smashing through the moon finally provide evidence for elusive dark matter? **Jonathan O'Callaghan** investigates

IF YOU hovered above the surface of the moon and studied it up close, you wouldn't necessarily see anything special. There would be craters, of course, some dusty slopes and a few featureless, ancient volcanic plains. If you were in the right place, you might get a glimpse of Neil Armstrong's footprints. But if you knew what to look for, you may find something much more extraordinary than all of this. Hiding on the lunar surface could be a scar left behind by a tiny black hole.

We aren't talking about any old black holes, but remnants from the dawn of the cosmos. Known as primordial black holes, these theoretical beasts are thought to range in size from the width of a single atom to that of our entire solar system. If they exist, they may explain some of our universe's greatest mysteries, from the origins of supermassive black holes found at the centres of galaxies to the mysterious planet-like mass at the edge of our solar system. They might even account for dark matter – the roughly 85 per cent of the universe's mass that we are unable to see, but know must be there in some form.

As yet, there is no evidence that these black holes exist. But now, two physicists have come up with an audacious plan to change that. They want to scour the lunar surface in search of craters left behind as these black holes slammed into – and indeed through – the moon. "It sounds a little bit wild," says Matthew Caplan at Illinois State University. "But you never know until you check."

The idea of primordial black holes dates back to the 1970s, when Bernard Carr, now at Queen Mary University of London, was working alongside Stephen Hawking. The pair suggested that in the early moments of the universe, shortly after the big bang, some pockets of space became so dense that they collapsed and formed black holes, in much the same way that we believe some stars explode and collapse into black holes today.

In 1974, Hawking put forward the notion that came to be known as Hawking radiation, the idea that black holes might lose mass and evaporate over time. As they get smaller, the theory says, they lose mass more quickly until they end their lives in an explosion. "That's why there was such interest in primordial black holes, because if they exist, we might see them exploding in the present epoch," says Carr. Evidence wasn't forthcoming, however, so interest dwindled.

Black hole revelations

In recent decades, the idea has been renewed as larger primordial black holes – which could have persisted to the present day – were proposed as possible answers to a few of the questions that keep astronomers and cosmologists up at night. A primordial black hole crashing into Earth has been touted as an explanation for the famous 1908 Tunguska event, for instance, which saw a large explosion over Siberia that many believe was due to a meteor. Another idea is that the elusive Planet Nine, which is thought to reside at the edge of our solar system, might not be a planet at all, but a black hole.

Perhaps the most intriguing notion is that dark matter could be made of these primordial black holes. So far, efforts to detect possible dark matter particles, such as the proposed weakly interacting massive particles (WIMPs), have come up empty. "A lot of people have spent their lives looking for some form of elementary dark matter › particle," says Carr. "But the fact is we haven't found those particles."

Primordial black holes offer an intriguing alternative. "What's nice about them is you don't need any new particles," says Charles Horowitz at Indiana University Bloomington. "It's just normal matter and density fluctuations when the universe was very young."

Primordial black holes could also explain the detection of about 20 unknown lensing objects – unexplained clumps of mass causing light from distant stars to bend around them – studied by the European Space Agency (ESA)'s Gaia satellite. They seem like stars, but aren't visible. "We are slowly getting glimpses that primordial black holes might really be there," says Günther Hasinger, director of science at the ESA.

At the same time, evidence from the detection of gravitational waves has hinted that black holes could exist in a wider variety of masses than we had thought, raising the possibility that others – potentially with lower masses – could be found. While studying black hole mergers in its hunt for gravitational waves, the Laser Interferometer Gravitational-Wave Observatory (LIGO) has detected black holes that seem to be as low as 2.6 times the mass of our sun, an unexpectedly low mass for black holes. "If LIGO sees black holes that are smaller than the mass of the sun, that will be pretty convincing evidence of something primordial," says Maya Fishbach, a LIGO team member at Northwestern University in Illinois. "We don't know of any evolution process that can create a compact object that small."

While this is promising, none of it is concrete evidence. But this is where Caplan and his colleague Almog Yalinewich at the Canadian Institute for Theoretical Astrophysics in Toronto come in. "Our idea is to use the moon as a detector," says Yalinewich.

"It sounds a little bit wild, but you never know until you check"

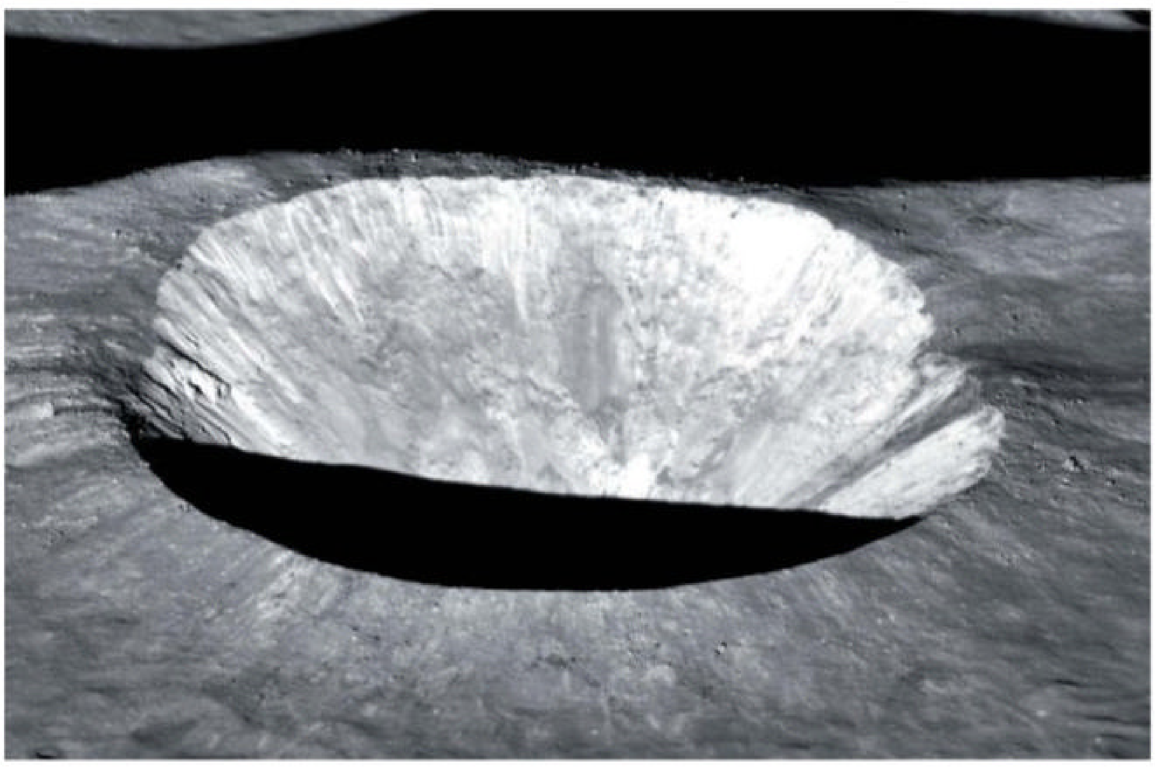
This is undoubtedly a bizarre idea, but the science behind it seems sound. If our universe produced copious amounts of primordial black holes in its infancy, it is plausible that some have persisted to the present day, pervading the universe and perhaps regularly passing through our solar system. If so, they may have hit some of our celestial bodies, such as the moon, leaving a telltale crater behind.

But how big would such a crater be? That depends on the size of the black hole. Astronomers searching for primordial black holes have mostly ruled out certain masses – too small and they would have evaporated by now, too large and we would see the effects of their gravity on distant stars. In a study published in July, Yalinewich and Caplan considered those in the middle – roughly the mass of an asteroid, between about 10^{16} and 10^{19} kilograms, but with the radius of an atom.

In this scenario, up to a few hundred primordial black holes would be expected to pass through our solar system every year, some hitting celestial bodies. For worlds such as Earth that have been resurfaced by weathering and geological activity, any evidence of an impact would have been erased. But for airless bodies like the moon, scars could remain – even after billions of years.

What would these scars look like? If such a black hole hit the moon, it would temporarily create a small molten tunnel through its 3500-kilometre-wide bulk, which it would cross in seconds, with temperatures of maybe 100,000 degrees kelvin, Yalinewich calculated. "They're going at incredible speeds, 200 kilometres a second," says Caplan. "It's like a bullet punching through cotton candy." These tunnels would quickly cool, leaving only small,

The surface of the moon is littered with craters of many shapes and sizes



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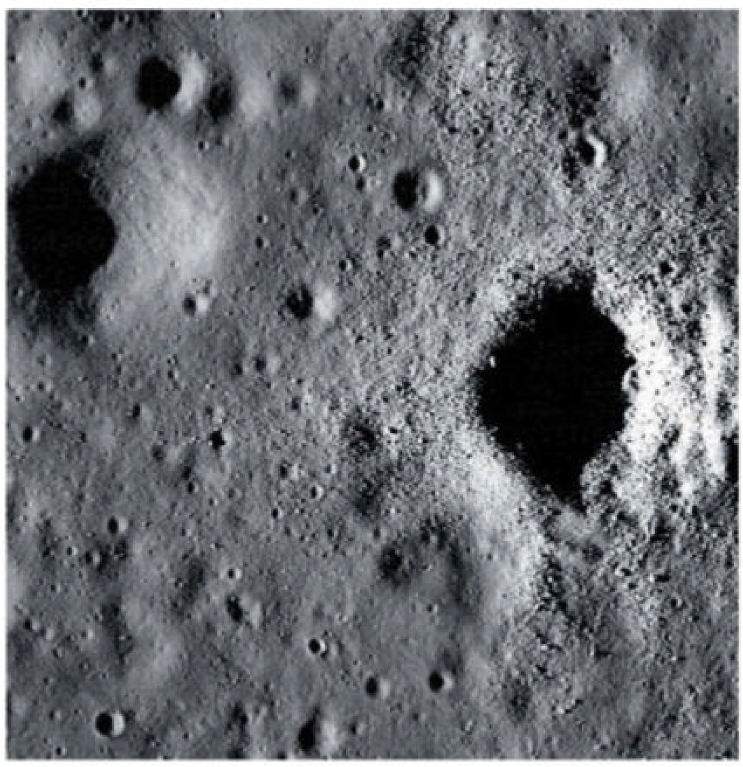

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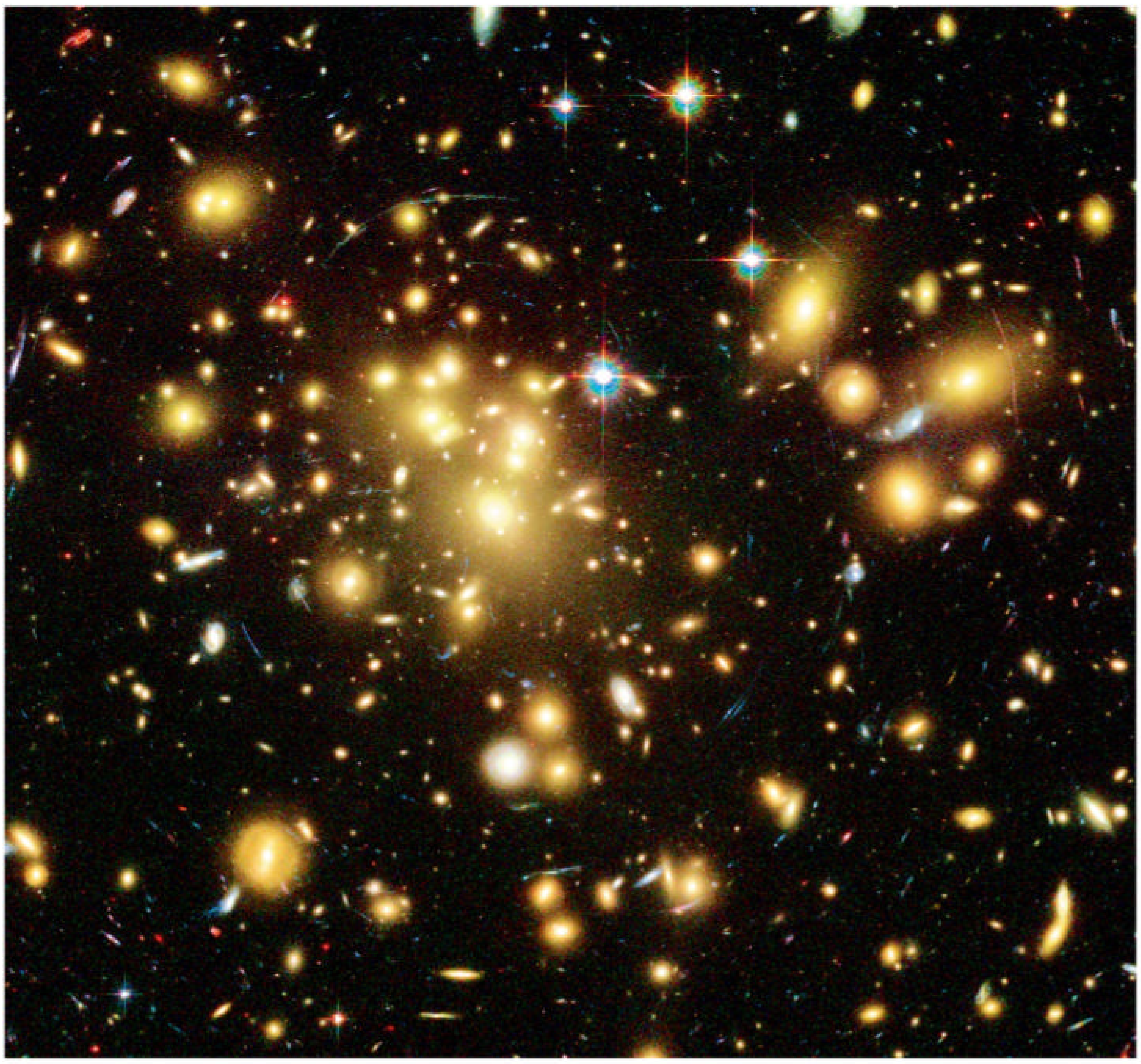
Studying the movement of galaxies like these could reveal if dark matter exists



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detectable entry and exit points on the surface in the form of a small crater 1 metre wide.

While there are millions of craters this size on the moon, a black hole crater would have a noticeable difference: the ejected debris, which would extend several metres around the crater, would form a much steeper slope than a regular crater. This is a result of the black hole being a million times denser than the moon and passing clean through without slowing down. "Because the object doesn't decelerate, it imparts a different velocity onto the ejecta," says Yalinewich.

By scouring through high-resolution images of the lunar surface from orbiting spacecraft, such as NASA's Lunar Reconnaissance Orbiter, we might be able to spot such a crater. Given there are millions of other metre-wide craters, that could take some time if done by hand, so Yalinewich and Caplan plan to use machine learning tools. "If we are successful in training a machine to find them, I expect to see results within three years," says Yalinewich.

If these craters do exist on the moon, there will be two implications. Firstly, they could provide tantalising evidence that primordial black holes do exist after all. "That would be a Nobel prize I'm sure," says Christian Byrnes at the University of Sussex, UK. Secondly, they could help prove whether primordial black holes are responsible for dark matter. According to Yalinewich, if a primordial black hole turns up on the moon, despite the relatively slim odds, it suggests they are abundant enough in the universe to account for at least some of the dark matter we have observed. But we would need to find them elsewhere to be completely sure.

Yalinewich and Caplan know their chances of success are remote. Even in this best-case scenario, where all primordial black holes are roughly the mass of an asteroid, there is only a 10 per cent chance one would have hit the moon. In reality, it is much more likely that they span a wider range of masses, which reduces the chances of us finding a crater.

There may be another hurdle. David Minton at Purdue University in Indiana says the pair have overestimated how long small craters would remain on the moon. Rather than persisting for billions of years, Minton thinks a crater 1 metre in size would probably be erased within just 13 million years as the lunar surface is reshaped by frequent meteorite impacts. "The constant bombardment of small meteoroids causes a constant churning of the surface of the moon," he says.

Yalinewich agrees that this could make the identification of such craters more complicated. But his simulations found that the ejecta around the impact, which would persist for longer, should still be noticeably different than one formed by a meteorite impact.

"A black hole impact would be like a bullet punching through cotton candy"

Such identification might be exceedingly difficult due to the sheer number of craters on the moon, says Mohamad Ali-Dib at New York University Abu Dhabi, who has developed his own machine learning tools to study lunar craters and uses them to probe the history of the solar system. "You can probably find whatever properties you want, but it's not necessarily due to a black hole," he says.

To truly confirm if a crater with suitable properties were formed by a black hole, it would need to be studied up close. An astronaut with ground-penetrating radar, for example, could look for a column of "messed-up matter" beneath the crater, says Caplan. The surface of the centre of the crater, meanwhile, could be sampled. With a primordial black hole punching through, "it gets hilariously hot, enough to make new phases of silica and quartz you could look for", he says.

And if nothing turns up on the moon, that doesn't mean the search is over. The same technique could one day be applied to other airless bodies, if we get sufficiently good imagery. Mercury could make a good target, as could Mars and Pluto, or even the rocky moons of Saturn and Jupiter. For each, the chances of seeing a crater ranges from 5 to 23 per cent, say Yalinewich and Caplan, but taken together, the odds increase. "If you look at the combined surface area of all these," says Yalinewich, "you should expect at least one of these exotic craters to appear." ■

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