# New Scientist

**WEEKLY** April 1 - 7, 2023

**ULTIMATE TILING**
The tessellating shape that never repeats

**BLACK HOLES FROM A PREVIOUS UNIVERSE**
Could some have survived the big bang?

**WILD IDEA**
The animals that could solve climate change

## THE SURPRISING TRUTH ABOUT WRINKLES

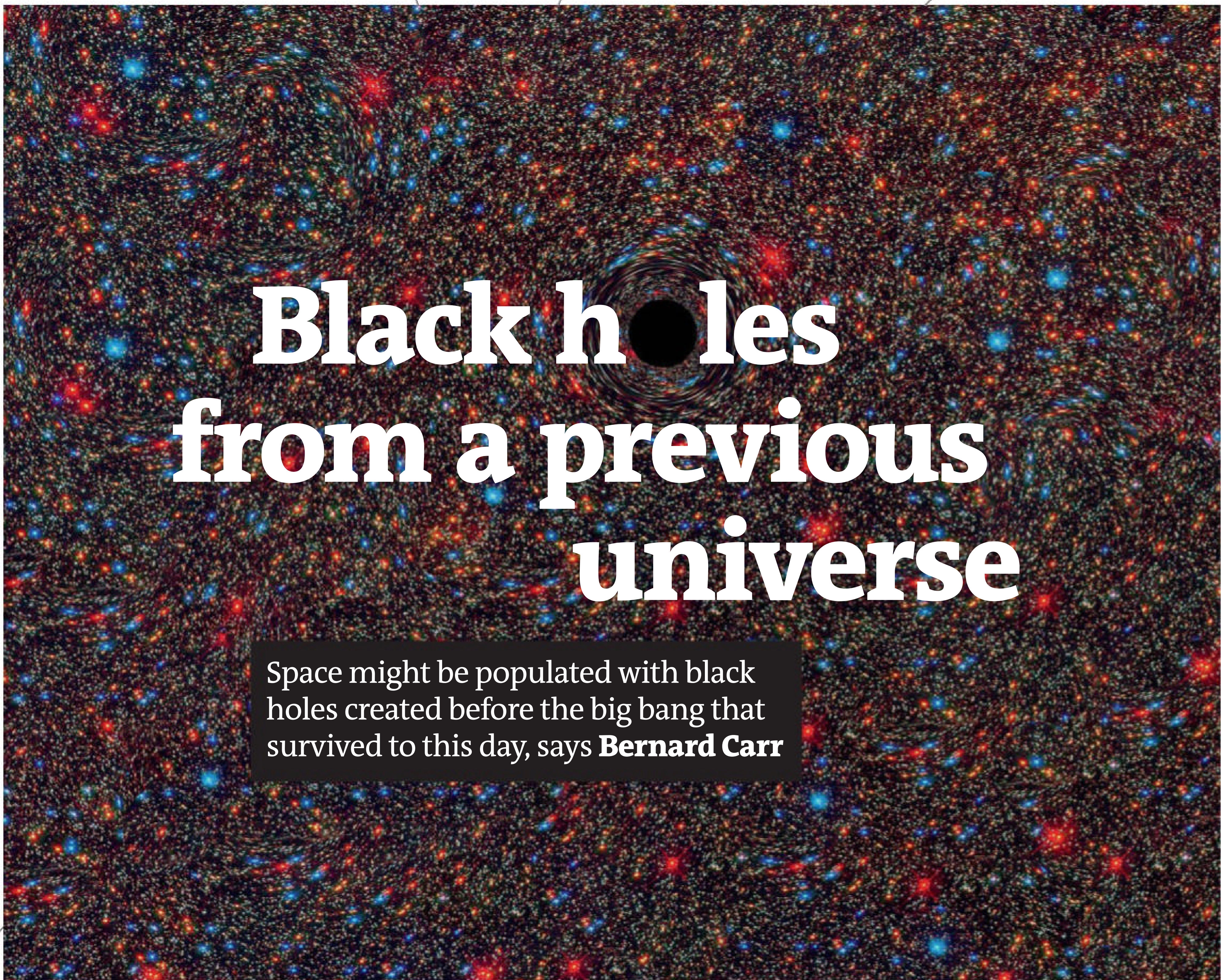
How banishing them could slow ageing in your body and brain

No3432 US$7.99 CAN$9.99

**PLUS** FIRST SNAIL-EATERS / **DOES PROTEIN HELP YOU SLEEP?** / GLOWING DORMICE / **3D-PRINTED CAKE** / **IS GPT-4 THE FIRST TRULY INTELLIGENT CHATBOT?**

Science and technology news **www.newscientist.com**

GSFC/NASA



# Black holes from a previous universe

Space might be populated with black holes created before the big bang that survived to this day, says **Bernard Carr**

ALMOST exactly 50 years ago, when I was a PhD student, I wrote an article in this magazine about the mounting evidence for black holes, regions of space in which gravity is so strong that light can never escape. Today, there is no longer any doubt about their existence. We know they form from collapsing stars and that supermassive ones sit at the centres of galaxies. We have even taken a picture of two of them. But in my article I also mentioned a more speculative possibility: that smaller black holes might have formed in the early universe, shortly after the big bang.

I was working on this idea under the supervision of Stephen Hawking, who had started to think about such a possibility just a few years earlier. Our work together set the trajectory of my career, much of which has been dedicated to studying what we now call primordial black holes. We still don't know if they formed, but there are good reasons to think they might have. Some of them could still be around today and, excitingly, they could be the answer to a whole range of cosmological conundrums.

Recently, however, I have become interested in an even more exotic possibility: that some black holes could be older than the universe itself. It is a wild idea, but not inconceivable. And new research suggests that we might one day be able to positively identify them, a breakthrough that would radically change our understanding of cosmology.

Most cosmologists would claim that all the matter and energy that permeates our universe today came into existence in a single moment 13.8 billion years ago that we call the big bang. After that, there was a period when the universe grew exponentially fast, called cosmic inflation, before it settled down to a gentler expansion.

One problem with this picture is that we don't know for sure what happened at the big bang. It is often described as a singularity – a point of infinite density – and Albert Einstein's general relativity, our best description of gravity, breaks down at a singularity. As a result, we can't describe it with the usual equations that make sense of reality.

This has led some cosmologists to speculate that the universe started with a big bounce. Instead of everything springing into existence in one moment, a big bounce would be the result of a previous, collapsing universe starting to expand again. This is a kind of big bang, but without a singularity, as the universe always has a finite density. The bouncing scenario is compatible with certain attempts at uniting the laws of physics, such as some models of quantum cosmology, loop quantum gravity and some alternative theories of gravity.

If our universe came from a bounce, it might end in one too. This kind of recurring bounce, where the universe goes through periods of expansion and compression, is called a cyclic universe. It only applies if the universe is destined to recollapse and this, in turn, depends on the nature of dark energy, the mysterious force causing the universe to fly apart faster and faster. Nevertheless, if we found evidence for these bouncing and cyclic models, it would have huge implications, both for how the universe began and how it might end.

Finding this evidence is tricky, partly because everything that would have existed in the previous universe is likely to have been destroyed when it collapsed. Or would it? I think there is a chance that some black holes from a previous universe may have survived the big bounce and still be around today.

The idea that black holes may have formed in the early universe dates to the early 1970s. Stephen and I had been considering whether black holes could form from density fluctuations near the big bang. From our calculations, that did indeed seem possible. ›

But there was a snag. A few years earlier, Russian researchers Yakov Zeldovich and Igor Novikov had shown any black holes formed in the early universe would grow rapidly, reaching an enormous mass today. This was ruled out with observations – we would have seen the effects of such black holes, so they concluded that primordial black holes never formed.

My first paper with Stephen showed this result was wrong. After many days of calculation, I rushed excitedly to his office to give the good news: because of the expansion of the universe, which the pair hadn't considered, primordial black holes wouldn't grow much at all. I was rather deflated to find Stephen had just come to the same conclusion, independently, by doing the calculation in his head. Nevertheless, we agreed: primordial black holes may have existed, after all.

Fifty years later, we still haven't seen any of these black holes for certain, although some people think there are hints of them in detections of ripples in space-time called gravitational waves. What we can say for certain, at least, is that thinking about them prompted Stephen to discover the radiation that black holes give off, which we call Hawking radiation, and the black hole information paradox (see "Black hole candy", right).

Of course, it would be much more interesting if primordial black holes did form, and in recent years there has been a growing interest in the idea. We know that any black holes weighing in at less than 1 trillion kilograms, roughly the mass of a mountain, but the size of a proton, would have evaporated by now because of Hawking radiation. But any black holes bigger than that would exist today.

However, there is an even more intriguing possibility. Around 10 years ago, Alan Coley at Dalhousie University in Halifax, Canada, and I became interested in whether we live in a cyclic universe. We started to consider whether black holes might have formed in a previous cosmic cycle and realised there were two possibilities.

The first is that they formed due to the high density of the previous universe in the final moments of its collapse. This "big crunch" is just like the high-density phase in the big bang, but running backwards in time. So if black holes can form in the big bang, they might also form in the big crunch. In this case, they would have a minimum mass determined by the density of the universe at the bounce, the time at which the universe is at its most dense. If this density is small enough, the black holes could be large enough to potentially explain dark matter, the mysterious stuff that keeps galaxies from flying apart, or the origins of supermassive black holes.

Later work investigated this in more detail. In 2016, Jerome Quintin and Robert Brandenberger, both at McGill University in Montreal, Canada, calculated the quantum and thermal fluctuations of a collapsing universe. They found that black holes can indeed form, albeit only if the universe is dominated by matter, not radiation.

The second possibility is that black holes formed in an earlier phase of the previous universe – just like the black holes that form from the collapse of stars or galactic nuclei in our universe. In either case, our next question was whether the pre-big bang black holes would survive the bounce and persist into the current cycle. This depends on the fraction of the volume of the universe occupied by black holes at the bounce. We reasoned that one could expect black holes to persist if their separation at the bounce was greater than their typical size, because they wouldn't be squeezed together and merge. We concluded that this should be possible in many situations.

In 2015, Timothy Clifton, my colleague at Queen Mary University of London, along with Coley and myself, made a stab at tackling this question in a more mathematically rigorous way. We derived some exact solutions to Einstein's equations of general relativity, describing a regular lattice of black holes in a universe that undergoes a bounce. Our results indicated there are indeed solutions in which

## BLACK HOLE CANDY

**Perhaps the most important offshoot from the idea of primordial black holes (see main story) was that it motivated Stephen Hawking to consider the quantum effects of black holes. In particular, he discovered that black holes emit Hawking radiation.**

**Only primordial black holes can be small enough for this radiation to cause them to disappear in the lifetime of the universe. Thinking about this also led Hawking to the black hole information paradox: quantum theory says information cannot be destroyed, but he argued that information would be lost when a black hole evaporates. He later changed his mind about this and we are still pondering the resolution of this paradox today.**

**Hawking radiation is one of the most important discoveries in 20th-century physics. It unifies three previously disparate areas of physics: quantum theory, general relativity and thermodynamics. It is such a beautiful result that physicist John Wheeler – who coined the term black hole – once told me that talking about it was like "rolling candy on the tongue".**

**As Stephen Hawking's collaborator, I was fortunate to have a ringside seat when he was working on these developments. Even if primordial black holes never formed, the discovery of Hawking radiation shows that it has been important to think about them.**

**"If black holes can form in the big bang, they might also form in the big crunch"**

multiple black holes persist through a bounce.

Later, we also looked into some cosmological consequences of this proposal, arguing that pre-big bang black holes in different mass ranges could explain dark matter, provide seeds for galaxies and perhaps even cause the bounce itself. In the standard big bang scenario, primordial black holes generated before inflation would be exponentially diluted, so any present today are usually assumed to form after inflation, but there is no inflation in some bouncing models.

Other researchers subsequently elaborated on those ideas. In 2018, Carlo Rovelli at Aix-Marseille University in France and Francesca Vidotto at Western University in Ontario, Canada, investigated the possibility that dark matter is made up of the remnants of pre-big bang black holes. They argued only a tiny fraction of the volume of the universe would be outside these black holes at the bounce, though observers in these regions would see a homogeneous universe at later times.

An even more exotic possibility is that the bounce squeezes the universe so tightly that all the black holes merge. Even the supermassive black holes we know exist today could lead to this situation, if our universe eventually recollapses. These progressive mergers would generate black holes with a hierarchy of increasing mass until, eventually, the whole universe would be turned into a black hole.

Nobody knows what would happen in this situation, but work by two groups has recently thrown light on the problem. Last year, Daniela Pérez and Gustavo Romero at the Argentine Institute of Radio Astronomy and, independently, a team led by Maxence Corman at the Perimeter Institute in Canada, calculated the behaviour of a single black hole during a bounce. Although the details of their calculations differ, both groups agree the black hole could survive through the bounce and that its size may shrink for some period. This shrinking also raises the possibility that black holes may never completely merge.

All of which is well and good, but what about finding evidence? Interestingly, another recent study offers some hope that we might one day be able to identify pre-big bang black holes, meaning that we could distinguish them from black holes formed in our universe. It was led by Yi-Fu Cai at the University of Science and Technology of China, who is interested in the idea that primordial black holes might have generated the supermassive black holes at the centres of galaxies.

ESA/HUBBLE, DSS, NICK RISINGER, N. BARTMANN

**We're not certain how supermassive black holes formed**

## Too big, too fast

These huge black holes range from 1 million to 10 billion times the mass of the sun. We know from looking at the distant universe that they already existed very early on – possibly too soon for them to have been created by standard astrophysical processes. It isn't clear how they could grow so big, so fast. One possibility, although not the mainstream view, is that they were seeded by primordial black holes. In which case, is there some way to figure out if these primordial black holes came from a big bang or a big bounce?

Cai and his colleagues modelled the density fluctuations in the inflationary and bounce scenarios, to compare the two models. They predict that the number of supermassive black holes would fall off more steeply with increasing mass in the case of a bounce. At the moment, we don't have enough data to discriminate between the two scenarios. But future observations by the James Webb Space Telescope could provide this.

The existence of primordial black holes formed in this universe is speculative, so the notion of black holes from a previous universe might seem doubly speculative. Nevertheless, it is important to explore this possibility, not to mention exhilarating. Just as thinking about primordial black holes has led to important insights into quantum gravity, thinking about pre-big bang black holes may lead to further physical insights, even if it turns out that the universe isn't cyclic.

I have recently retired, and I find it strangely appropriate that my career, which began with the study of black hole formation at the start of this universe, is finishing with the study of their formation at the end of the last one. My article 50 years ago concluded that "black holes are as pervasive in theory as they are evasive in observation", but I am now more optimistic about finding primordial black holes, whether or not they formed in a previous universe. ▮

Bernard Carr is emeritus professor of mathematics and astronomy at Queen Mary University of London