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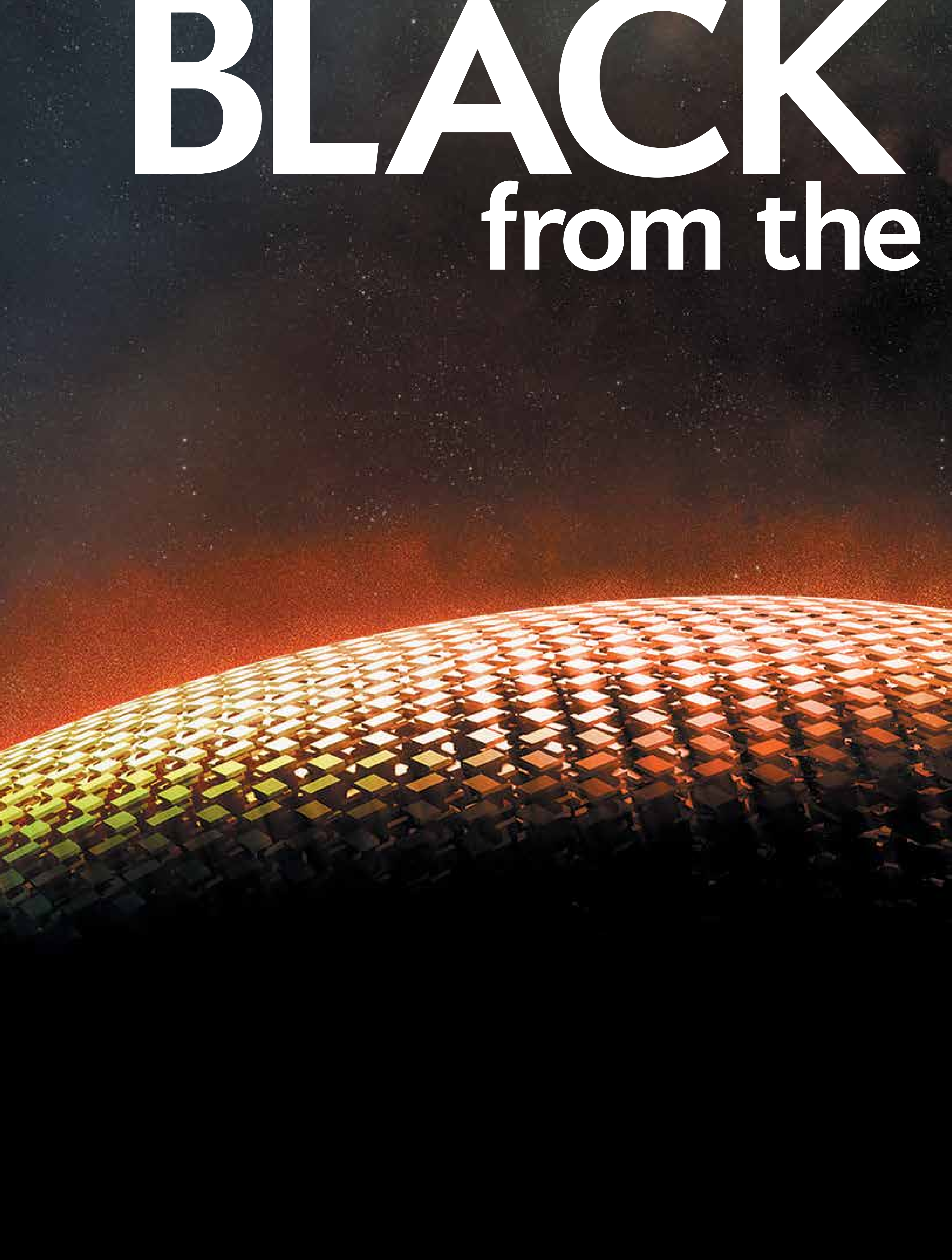


HOLES

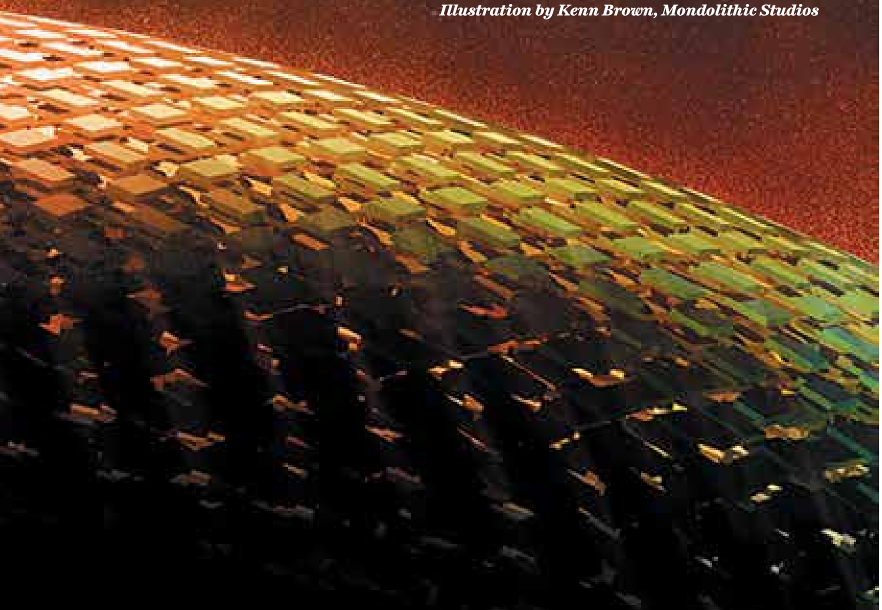
Beginning of Time

COSMOLOGY

A hidden population of black holes born less than one second after the big bang could solve the mystery of dark matter

By Juan García-Bellido and Sébastien Clesse

Illustration by Kenn Brown, Mondolithic Studios



IN BRIEF

The nature of dark matter—the invisible material that holds galaxies together by its gravity—is a deep cosmic enigma.

Many researchers suspect dark matter is made of weakly interacting massive particles and seek them in experiments. But to date, no such "WIMPs" have been found.

"Primordial" black holes that may have formed shortly after the big bang are an alternate candidate for dark matter. Yet these, too, have so far eluded detection.

More evidence for primordial black holes may emerge in new data from gravitational-wave detectors and other observatories. If confirmed to exist, these objects could solve the mystery of dark matter and several other cosmic conundrums.

More than a billion years ago two black holes in the distant universe spiraled around each other in a deathly dance until they merged. This spiraling collision was so violent that it shook the fabric of spacetime, sending perturbations—gravitational waves—rippling outward through the cosmos at the speed of light. In September 2015, after traveling more than a billion light-years, those ripples washed over our planet, registering as a "chirp" in the sensors of the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO).

This was the first direct detection of gravitational waves, and the observation confirmed Albert Einstein's century-old prediction of their existence. Yet the chirp revealed that each of the merger's progenitor black holes was 30 times heavier than the sun. That is, their masses were two to three times larger than ordinary black holes born from supernova explosions of massive stars. These black holes were so heavy, it is hard to explain how they formed from stars at all. Furthermore, even if two such black holes did independently form from the deaths of very massive stars, they would have then had to find each other and merge—an event with an exceedingly low probability of occurring within the current age of the universe. It is thus reasonable to suspect that these massive black holes formed via some other, more exotic pathway that might not involve stars at all. Beyond its detection of gravitational waves, it may be that LIGO has unveiled something even more extraordinary: black holes that predate the formation of the stars themselves.

Although such "primordial" black holes have never before been seen, some theoretical models suggest they could have formed in astronomical numbers from the hot, dense plasma that filled the cosmos less than one second after the big bang. This hidden population could then solve several of the most outstanding mysteries in modern cosmology. In particular, primordial black holes could constitute some, if not all, of dark matter—the invisible 85 percent of the matter in the universe that acts as gravitational glue to hold galaxies and galaxy clusters together. Further studies with LIGO and other facilities will soon test these ideas, potentially unleashing a new revolution in our understanding of the cosmos.

THE FALL OF MACHOS, THE RISE OF WIMPS

BLACK HOLES would initially seem to be ideal candidates for dark matter because they emit no light. Indeed, along with other dark objects such as planets and brown dwarfs, they make up one long-proposed solution to the dark matter problem: MACHOs, short for *ma*ssive *c*ompact *h*alo *o*bjects. Found both in spherical halos surrounding each galaxy and near each galaxy's luminous center, MACHOs would create the gravitational pull responsible for the otherwise anomalous motions of stars and gas that astronomers observe in the outskirts of galaxies. Simply put, galaxies seem to be rotating too fast to be held together by the visible mass in stars that we observe. Dark matter provides the extra pull to prevent spinning galaxies from flinging off their stars.

If MACHOs make up most of the universe's dark matter, they must also account for other observations. Whatever dark matter is, it shapes the universe's largest structures, determining the origin and growth of galaxies as well as clusters and superclusters of galaxies. These objects coalesce from the gravitational collapse of clumps of gas inside dark matter halos. Cosmologists have precisely mapped the spatial distribution of these clumps through deep and wide galaxy surveys and correlated them with tiny temperature fluctuations present in the cosmic microwave background (CMB), the big bang's all-sky afterglow. The diffuse mass of dark matter in large galaxies and clusters also bends space to distort the light from far distant background objects—a phenomenon known as gravitational lensing.

The MACHO hypothesis, however, fell from favor a decade ago when MACHOs did not turn up in tentative, indirect searches for their existence. Most notably, astronomers looked for them via microlensing, a variety of gravitational lensing in which a black hole, a brown dwarf or even a planet passes in front of a background star and temporarily magnifies the star's light. Several multiyear microlensing surveys of millions of stars in the Large and Small Magellanic Clouds, the main satellite galaxies of the Milky Way, found no evidence that MACHOs made up the entirety of our galactic halo. These results were conclusive enough to rule out MACHOs up to around 10 solar masses as the primary constituent of dark matter. As these surveys took place, theorists built the case for an alternative hypothesis—WIMPs, or weakly interacting massive particles.

WIMPs are predicted by certain extensions of the Standard Model of particle physics, but they remain at least as elusive as MACHOs. To date, no evidence of their existence has been found despite decades of searches using particle accelerators, underground detectors and space telescopes. As null results piled up in the search for WIMPs, some researchers began reconsidering the MACHO hypothesis, focusing particularly on primordial black holes. But what process could have seeded these strange objects throughout the observable universe, and how could they have eluded detection for so long?

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BLACK HOLES FROM THE BIG BANG

PHYSICISTS BERNARD CARR AND STEPHEN HAWKING proposed the idea of primordial black holes in the 1970s, although they considered only black holes with masses smaller than that of a mountain. Such minuscule black holes would have already evaporated and vanished within the age of our nearly 14-billion-year-old universe, via a quantum-mechanical process discovered by Hawking and appropriately called Hawking radiation. Consequently, Carr and Hawking's primordial black holes would have a negligible contribution to the universe's current amount of dark matter.

The possibility that massive primordial black holes could actually be most or even all of the dark matter hinges on an idea known as cosmic inflation, first proposed by physicist Alan Guth in the early 1980s. Inflation is a hypothetical phase of prodigious expansion immediately after the big bang. In 10^{-35} second, two points separated by less than an atomic radius would have become separated by four light-years, a distance comparable to that of the closest stars. Moreover, during inflation tiny quantum fluctuations are magnified to macroscopic scales by the rapid expansion, seeding the growing universe with underdense and overdense regions of matter and energy from which all cosmic structures subsequently emerge. As bizarre as it may seem, the theory of inflation is strongly supported by observations of such density fluctuations in the CMB.

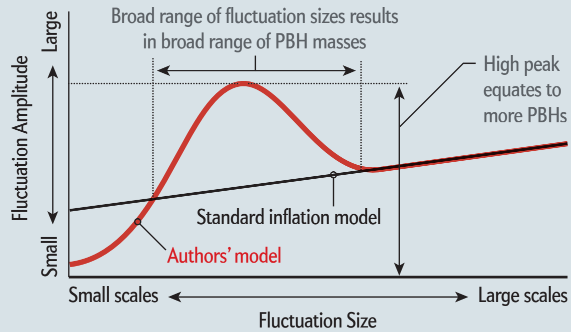
In 1996 one of us (García-Bellido), together with Andrei Linde of Stanford University and David Wands of the University of Portsmouth in England, discovered a way for inflation to form sharp peaks in the spectrum of density fluctuations in the early universe [*see box on opposite page*]. That is, we showed how quantum fluctuations enormously magnified by inflation would naturally produce particularly dense regions that would collapse to form a population of black holes less than one second after inflation ends. Such black holes would then behave as dark matter and would dominate the matter content of the present-day universe.

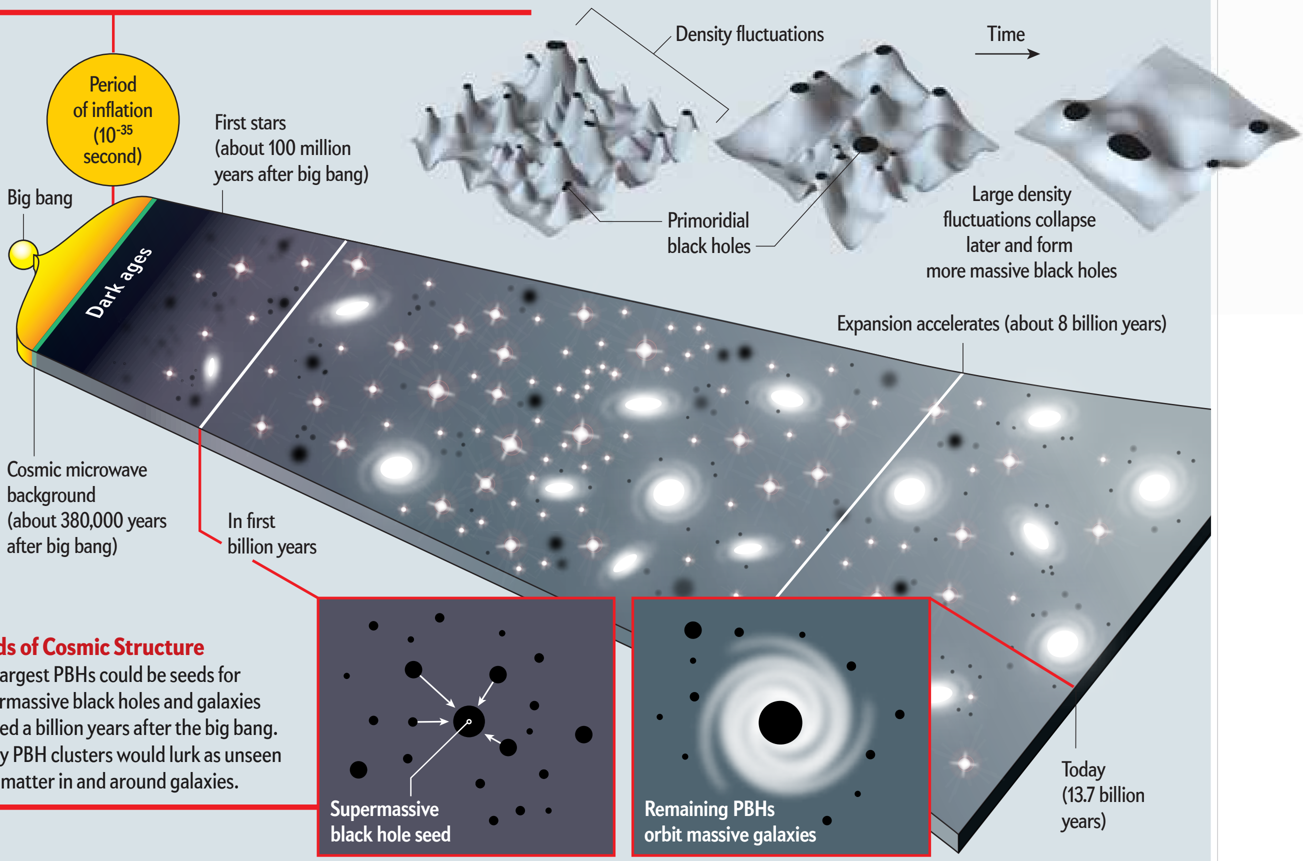
Black Holes Birthed by the Big Bang

The universe's first black holes may have been born in the earliest moments of cosmic time, when all was a seething, thick fog of fundamental particles. In the 1970s theorists realized that dense regions of that fog could collapse under their own gravity just a second after the big bang, forming so-called primordial black holes (PBHs) that would then shape the structure of the evolving, expanding universe. Emitting no light, PBHs would be a natural—albeit difficult to detect—candidate for dark matter.

Primordial Black Holes Form in Clusters

Inflation—a proposed acceleration to the universe's expansion less than a second after the big bang—would form PBHs by magnifying quantum fluctuations to immense scales. As inflation ended, these fluctuations would create density perturbations that then form PBHs. Larger, more powerful fluctuations would create more massive and numerous PBHs. The authors' inflationary model predicts a broad peak of magnified fluctuations and a wide range of density perturbations, producing PBHs in clusters, with each PBH ranging from 100th to 10,000 times the mass of our sun. Half a million years after the big bang, a cluster might span hundreds of light-years and contain millions of PBHs. As the PBHs within such clusters merged together, scattered apart, and fed on ordinary gas and dust, they would guide the growth of galaxies and galactic clusters.





Seeds of Cosmic Structure

The largest PBHs could be seeds for supermassive black holes and galaxies formed a billion years after the big bang. Today PBH clusters would lurk as unseen dark matter in and around galaxies.

This model generated a population of black holes with the same mass, determined by the amount of energy within the collapsing region. Many other groups then started exploring these ideas within different models of inflation.

In 2015 the two of us (Clesse and García-Bellido) proposed a scenario, similar to that of 1996, in which these primordial fluctuations exhibit a broad peak in their energy densities and spatial sizes, giving rise to primordial black holes with a wide range of masses. A key consequence of this scenario is the fact that large density fluctuations collapse in close spatial proximity to one another, generating clusters of black holes of different masses—from 100th to 10,000 times the mass of our sun. Within half a million years of the

Illustration by Jen Christiansen and George Retseck (density fluctuation panels) big bang, each growing, evolving cluster could contain millions of primordial black holes in a volume just hundreds of light-years across.

Such clusters of primordial black holes would be sufficiently dense to explain LIGO's mysterious black hole mergers, which one would not otherwise expect to occur with regularity. From time to time, the trajectories of two primordial black holes within a cluster can cross, so that both objects become gravitationally bound to each other. They would then spiral closer together for up to millions of years, radiating gravitational waves until they merge. In January 2015 we actually predicted that LIGO would detect gravitational waves from such massive mergers—waves identical to those LIGO then detected later that year. Our estimates for the rate of merger events within primordial black hole clusters fit perfectly within the limits set by LIGO. If LIGO and other similar facilities detect many more mergers within the next few years, it may be possible to determine the range of masses and spins for all the progenitor black holes. Such a statistical analysis of black hole mergers would provide crucial information for testing their potentially primordial origins.

A key aspect of this scenario is that it evades the constraints on MACHOs previously set by gravitational microlensing experiments—constraints that ruled out black holes of up to about 10 solar masses as the main constituent of dark matter. If primordial black holes exist and possess a wide range of masses, only a small fraction would be visible to these microlensing experiments, with the bulk remaining invisible. Moreover, if primordial black holes are grouped in clusters, this arrangement suggests a probability of less than one part in 1,000 that a cluster would happen to be along the line of sight of the stars in the nearby satellite galaxies monitored for microlensing events. To avoid this effect, one could search for microlensing events elsewhere in the sky, looking for the magnified light from stars in the Milky Way's neighboring Andromeda galaxy or even from quasars in far distant galaxies. In this way, one could probe a much larger volume of galactic halos for signs of MACHOs—that is, for primordial black holes. Recent observations suggest that whereas MACHOs of up to 10 solar masses may not make up the entirety of an average galaxy's halo, MACHOs between one tenth and a few solar masses could easily account for about 20 percent of the mass in a typical galactic halo. This value is consistent with our broad-mass primordial black hole scenario.

Simply put, we cannot yet rule out the possibility that dark matter is mostly made up of primordial black holes. Indeed, this proposed scenario could decipher several other cosmic mysteries related to dark matter and galaxy formation.

Is Dark Matter Made of Primordial Black Holes?

These observations will make the difference:

1. Detecting more gravitational waves
Gravitational-wave detectors such as the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) in the U.S. and Advanced Virgo in Italy should detect more black hole mergers. The detection of an unexpectedly large number of massive black hole mergers would be a hint for a primordial origin but would not by itself prove that primordial black holes constitute dark matter. Such proof will have to emerge from corroboration via other observations. Ultimately, detecting a black hole with a mass lower than the so-called Chandrasekhar limit (1.45 solar masses), below which stars cannot produce a black hole, would be the undeniable sign of a primordial origin. Fortunately, LIGO may very soon reach the sensitivity to detect such a black hole if its companion is more massive (greater than 10 solar masses). Finally, on cosmological scales, abundant black hole binaries should induce a diffuse background of gravitational waves, which could be detected by the future space-based Laser Interferometer Space Antenna (LISA) and by ground-based pulsar timing arrays.

2. Discovering more ultrafaint dwarf galaxies
In 2015 astronomers using data from the Dark Energy Survey collaboration discovered dozens of ultrafaint dwarf galaxies in the galactic halo, a finding that suggests hundreds of such dark matter–dominated dwarf galaxies could orbit around the Milky Way. If dark matter is made of primordial black holes, most of them should reside in such dwarf galaxies, a large number of which could be detected with future space-based facilities such as the European Space Agency's Euclid mission and NASA's Wide-Field Infrared Survey Telescope (WFIRST).

3. Measuring variations in the position of stars
The ESA's ongoing Gaia mission is measuring the positions and velocities of about one billion stars in the Milky Way with unprecedented precision. These measurements may reveal the presence of numerous isolated massive black holes via the tiny variations those objects have on the motions of neighboring stars.

4. Mapping neutral cosmic hydrogen
Before and during the formation of the first stars, the universe was mostly composed of neutral hydrogen, which emits characteristic radiation at a radio wavelength of 21 centimeters. As early as 2020, the Square Kilometer Array (SKA), planned to be the largest radio telescope ever built, will begin making an all-sky map of this 21-centimeter signal. The accretion of matter by primordial black holes creates intense x-ray radiation, ionizing the surrounding neutral hydrogen and imprinting signatures on this 21-centimeter all-sky map. SKA should thus detect the presence of massive primordial black holes, if they account for the dark matter.

5. Probing distortions of the cosmic microwave background
X-rays from primordial black holes gorging on gas and dust in the early universe should also induce distortions on the spectrum of the cosmic microwave background. The importance of this effect is still controversial, in particular in models where primordial black holes are grouped in dense clusters. Nevertheless, NASA's Primordial Inflation Explorer (PIXIE) mission concept has been proposed to accurately measure such distortions, which should strongly constrain models of primordial black hole dark matter.

MANY PROBLEMS, ONE SOLUTION

CLUSTERS OF PRIMORDIAL BLACK HOLES could clear up the so-called missing satellite problem—the apparent lack of "dwarf" satellite galaxies that should form around massive galaxies such as our Milky Way. Current simulations modeling the cosmic distribution of dark matter accurately replicate the universe's observed large-scale structure, in which halos of dark matter pull galaxy clusters into giant filaments and sheets surrounding great voids of lower density. On smaller scales, however, these simulations predict the existence of numerous subhalos of dark matter orbiting around massive galaxies. Each of these subhalos should host a dwarf galaxy, and hundreds should surround the Milky Way. Yet astronomers have found far fewer dwarf galaxies than predicted.

Many potential explanations for the missing satellite problem exist, mainly the notion that simulations fail to fully account for the influence of ordinary matter (hydrogen and helium in stars) on the formation and behavior of the predicted dwarf galaxies. Our scenario suggests that if clustered primordial black holes made up most dark matter, they would dominate the subhalos surrounding the Milky Way, absorbing a fraction of ordinary matter and reducing the rate of star formation in the subhalos. Moreover, even if these subhalos vigorously formed stars, these stars could easily be ejected by close encounters with massive primordial black holes. Both effects would greatly reduce the brightness of the satellites, making them very hard to detect without wide-field cameras of exquisite sensitivity. Fortunately, such cameras now exist, and astronomers have already used them to discover dozens of ultrafaint dwarf galaxies surrounding the Milky Way. These objects appear to host up to hundreds of times more dark matter than luminous stars, and our model predicts that thousands more should orbit our galaxy.

Simulations also predict a population of galaxies intermediate in size between dwarf galaxies and massive galaxies. Such objects are said to be too big to fail because they would be sufficiently large to readily form stars and be easily seen. Still, they have not turned up in astronomers' searches of the Milky Way's vicinity. This too-big-to-fail problem has a solution similar to that of the missing satellite problem: massive primordial black holes in the cores of intermediate-sized galaxies could eject stars and star-forming gas from these objects, rendering them effectively invisible to most surveys.

Primordial black holes could also resolve the origin of supermassive black holes (SMBHs). These monsters weigh from millions to billions of solar masses and are observed at the centers of quasars and massive galaxies very early in the universe's history. Yet if these SMBHs formed and grew from the gravitational collapse of the universe's first stars, they should not have acquired such gigantic masses in such a relatively short time—less than a billion years after the big bang.

In our scenario, although most primordial black holes have just tens of solar masses, a very small fraction will be far heavier, ranging from hundreds to tens of thousands of solar masses. Born less than a second after the big bang, these monstrous objects would then act as giant seeds for the formation of the first galaxies and quasars, which would rapidly develop SMBHs at their centers. Such seeds could also account for the existence of intermediate-mass black holes possessing 1,000 to a million solar masses, observed orbiting SMBHs and at the centers of globular clusters of stars. In short, primordial black holes may be the missing link between conventional stellar-mass black holes and SMBHs. The observational case for this scenario is building rapidly: recent detections of unexpectedly abundant x-ray sources in the early universe are most easily explained by large numbers of primordial black holes producing x-rays as they gorge on gas less than one billion years after the big bang.

SEEING IN THE DARK

EVEN THOUGH massive primordial black holes could solve the mystery of dark matter, as well as many other long-standing problems of cosmology, the game is not yet over. Other models and explanations are still possible, and future observations should allow us to distinguish among the alternatives. Indeed, within the next few years several observations could test the primordial black hole scenario [*see box on opposite page*]. They include the detection of ultrafaint dwarf galaxies, the influence of massive primordial black holes on the positions of stars in the Milky Way, the mapping of neutral hydrogen during the first epoch of star formation and the study of distortions in the cosmic microwave background.

Beyond these experiments, we also now possess a completely new tool to unravel the mysteries of the universe in the form of Advanced LIGO and other gravitational-wave detectors. If indeed LIGO has detected merging members of a hidden population of massive primordial black holes, we should expect many more to be detected in coming years. In June 2016 Advanced LIGO scientists presented to the community a second detection of gravitational waves, emitted during the merging of two black holes, of 14 and eight solar masses, respectively, as well as a tentative hint of another merger of black holes of 23 and 13 solar masses. As we finalized this article, they claimed to have detected six additional merging events. These detections suggest that binary black holes are much more frequent than expected and that they are broadly distributed in mass, in agreement with our scenario of massive primordial black holes.

All together these new experiments and observations could confirm the existence of primordial black holes and their possible linkage to the universe's missing matter. Soon we may no longer be in the dark about dark matter. SA

MORE TO EXPLORE

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