As far back as the 1930s, astronomers began to suspect that every galaxy and every cluster of galaxies was surrounded by a massive haze of “dark matter”—an utterly invisible ectoplasm that held these photogenic yet fragile structures together with the stabilizing force of its gravity. These early observers were right: Not only does dark matter seem to be real, but it outweighs the visible universe—meaning stars, planets, nebulae, galaxies, and anything else made of ordinary atoms—by a factor of five (1).

Yet the nature of dark matter remains one of the biggest mysteries in cosmology. One favored theory is that it’s made of weakly interacting massive particles (WIMPs) that barely interact with normal matter, except gravitationally. Also popular is a theory that dark matter is made of lighter but equally hypothetical particles called axions.

But over the past half-decade or so, some researchers have become more open to an older idea: Dark matter consists of primordial black holes (PBHs) that emerged from the Big Bang. “If you’d asked me in the early days I would have said primordial black holes are interesting, but there’s maybe only a 10% chance they really exist,” says Bernard Carr, a physicist at Queen Mary University of London, UK. Carr is referring to the early 1970s, when he and his thesis advisor, the late Stephen Hawking, did the first detailed calculations for how the infant universe could have produced black holes, which are gravitational singularities in which the fabric of space and time curves in on itself so tightly that not even light can escape (2–5).

But today, says Carr, who recently coauthored a recent review of PBHs as dark matter (6), “I would bet you at least 50% that they exist, maybe even more.”

Carr cheerfully admits that a PBH pioneer like himself is hardly a neutral observer on this subject—and he is quick to acknowledge that PBH formation requires a fine-tuning of cosmological parameters that many researchers find implausible. Still, his cautious optimism can also be heard from other cosmologists. They point to three primary reasons for the shift: first, attempts to find WIMPs or the other hypothesized dark matter particles have come up empty; second, results from gravitational wave experiments looking for ripples in space-time are surprisingly consistent with the PBH idea.

And third, the next decade or two could bring observational evidence that either confirms the existence of PBH dark matter or rules it out.

Where Are the WIMPs?

Even though there are strong theoretical motivations for believing in WIMPs, this idea faltered in the 2010s. Despite decades of looking for them at accelerators, in ever-more-sensitive detectors located deep underground, and even with telescopes searching for gamma rays that could ostensibly be produced by dark-matter annihilations in deep space, researchers have yet to see an unambiguous signal (7).
This has led some researchers to start taking a more serious look at alternative dark-matter candidates—including primordial black holes, which have at least one compelling advantage over hypothetical particles like axions. Black holes are known to exist, whether or not they formed in the Big Bang, and require no new physics to explain them.

In our own galaxy, for example, astronomers have detected "stellar" black holes with masses between roughly five and 20 times that of our sun. The origins of such black holes are well-understood: They are the remnants of very large stars that blew apart in explosions called supernovae.

Crucially, astronomers have also detected many examples of the much larger black holes that are thought to exist at the core of virtually every galaxy, including ours. These behemoths all weigh in at millions or billions of times the mass of the sun. Because it is hard to explain how such monsters could have formed from ordinary stars, some researchers have argued that they grew from PBHs. "They would be the seeds," explains New York University physicist Yacine Ali-Haimoud. "You would start with a pretty massive primordial black hole in the early universe, perhaps 10,000 solar masses," and then this black hole would quickly grow to millions or billions of solar masses by swallowing all the stars and gas around it.

Clues from LIGO

The second, more dramatic development in the PBH story came in February 2016, when the US-based Laser Interferometer Gravitational-Wave Observatory (LIGO) collaboration announced its first detection of gravitational waves: space-time ripples created, in this case, by the merger of two black holes in a distant galaxy.

Perhaps the biggest surprise was that both of these black holes were around 30 times the mass of our sun—a value on the ragged upper edge of what astrophysicists thought a supernova could produce (although later calculations have raised that limit somewhat.) But the masses were consistent with the PBH picture.

Years before the LIGO announcement, in fact, theorists had used modern particle physics to redo Hawking and Carr's calculations of PBH formation rates in the early universe (8, 9). And they had found that the primordial plasma would have experienced a series of abrupt changes at a cosmic age around \(10^{-5}\) seconds, when free-ranging quarks started condensing into protons, neutrons, and related particles. Each of these changes would have triggered a corresponding surge in PBH production and a peak in the distribution of PBH masses seen today. The biggest predicted peak would be at 1 to 2 solar masses. But a substantial, if smaller, peak would occur around 30 to 50 solar masses—exactly the mass range of the black holes seen by LIGO.

Although this was hardly proof of anything, says Carr, the LIGO result was tantalizing enough to trigger a surge of interest in PBHs. Nowadays, he says, "it's hundreds of articles every year. I can't keep up."

Much of this recent work deals with the steadily increasing number of gravitational-wave detections coming out of LIGO and its Italian partner observatory Virgo, which is named after a cluster of galaxies in that constellation. Together, LIGO and Virgo have now cataloged dozens of mergers between black holes that lie in this surprisingly large mass range of 30 solar masses or more. Although this is still not enough to make an ironclad statistical case for PBHs, says Christian Byrnes, a cosmologist at the University of Sussex, UK, that could change as LIGO is upgraded for much higher sensitivity. So a few years after it starts observing again in December 2022, "we'll have statistics on close to 1,000 black holes," says Byrnes. One telling indicator will be the spins of these objects. If they were created in supernovae, astronomers expect that on average they'll be rotating very rapidly. But if they are PBHs born in the Big Bang, then their average rotation rate should be much slower—and slower spins is the case for most of the black holes detected so far by LIGO-Virgo. The larger sample size will be crucial to telling the two explanations apart.

Another focus of the new work is to examine the latest observational constraints on the numbers and sizes of PBHs in today's universe. If the Big Bang had managed to make PBHs as massive as a typical galaxy, for example—
even a substantial fraction of a galaxy—their gravity would have violently disrupted the star clusters and spiral arms of any other galaxy they encountered. Because astronomers find no evidence of such disruption, truly gargantuan PBHs must be very rare.

Astronomers also have shown that there can’t be a large population of PBHs at intermediate scales—a few solar masses or less. These medium-sized PBHs would have shown up in “microlensing” surveys: multyear observations that look for a characteristic twinkling in the light of distant stars caused by the gravity of massive objects when they come between the stars and Earth (10, 11).

And at the very low end, there can’t be any PBHs at all. As Hawking famously showed in 1974 (12), the very smallest PBHs would have long since turned their mass into radiation and disappeared in a final burst of gamma rays. Any PBH left today would have to exceed about $10^{17}$ grams: the mass of Mount Everest compressed into a black hole with a radius less than that of a hydrogen atom. The upshot is that PBH dark matter is still possible, but only if the black-hole masses are distributed very broadly, with very low numbers in any given value.

Finally, yet another focus of the current work grapples with a problem that bothered Hawking and Carr back in the 1970s, and that remains by far the most serious drawback to the PBH idea: The equations that describe their formation are balanced on a knife edge.

Even if PBHs now dominate the universe as dark matter, Carr explains, they could have accounted for only about a billionth of the total energy during the first fraction of a second after the Big Bang. (Most of the rest would have been ultra-high-energy photons.) “If the fraction is even a little bit bigger, then too much of the universe collapses and everything is black holes. There’s no visible matter left,” he says. But if the fraction is even a little bit too small, “you don’t form any PBHs.”

Unfortunately, says University of Nottingham, UK, physicist Anne Green, no one has yet explained why the PBH abundance should be sitting right at that one-in-a-billion tipping point. The problem, explains Green, who is coauthor of another recent review of the PBHs-as-dark matter idea (13), is that PBHs must have formed from random fluctuations in the infant universe’s mass and energy density. Such primordial density fluctuations are well understood on the largest scales, where they are thought to have triggered the formation of today’s galaxies. But the fluctuations that were extreme enough to collapse into a black hole must have been small, rare, and far above the average density. Hence, they’d be “way out in the tail of the distribution,” says Green, where theorists can only guess at what is going on.

But Byrnes points out that new experiments may provide data to help the theorists. The violent density fluctuations required to produce PBHs in the early universe would have also generated gravitational waves. These waves would be exceedingly faint today, says Byrnes, and undetectable by LIGO-Virgo. But the much bigger and more sensitive Laser Interferometer Space Antenna (LISA), which the European Space Agency plans to launch in 2037, should be able to detect them.

All this means that the mystery is, in principle, solvable. If primordial black holes actually did form in the very early universe, says Byrnes, “sometime in the 2030s, we’ll have an answer.”

1. G. Bertone, D. Hooper, History of dark matter. Rev. Mod. Phys. 90, 045002 (2018).
2. S. Hawking, Gravitationally collapsed objects of very low mass. Mon. Not. R. Astron. Soc. 152, 75 (1971).
3. B. Carr, The pervasive black hole. New Sci. 59, 316–318 (1973).
4. B. J. Carr, S. W. Hawking, Black holes in the early Universe. Mon. Not. R. Astron. Soc. 168, 399–416 (1974).
5. B. J. Carr, “Primordial black holes,” PhD dissertation, Cambridge University, Cambridge, United Kingdom (1975).
6. B. Carr, F. Kuhnel, Primordial black holes as dark matter: Recent developments. Annu. Rev. Nucl. Part. Sci. 70, 335–394 (2020).
7. G. Bertone, T. M. P. Tait, A new era in the search for dark matter. Nature 562, 51–56 (2018).
8. K. Jedamzik, Primordial black hole formation during the QCD epoch. Phys. Rev. D Part. Fields 55, R5871–R5875 (1997).
9. B. Carr, S. Clesse, J. Garcia-Bellido, F. Kuhnel, Cosmic concordia explained by thermal history and primordial black holes. Phys. Dark Universe 31, 100755 (2021).
10. C. Alcock et al., The MACHO Project: Microlensing results from 5.7 years of large Magellanic Cloud observations. Astrophys. J. 542, 281–307 (2000).
11. P. Tisserand et al., Limits on the MACHO content of the Galactic Halo from the EROS-2 Survey of the Magellanic Clouds. Astron. Astrophys. 469, 387–404 (2007).
12. S. W. Hawking, Black hole explosions? Nature 248, 30–31 (1974).
13. A. M. Green, B. J. Kavanagh, Primordial black holes as a dark matter candidate. J. Phys. G Nucl. Part. Phys. 48, 043001 (2021).