BLACK HOLES: New Webb Discoveries PAGE 20

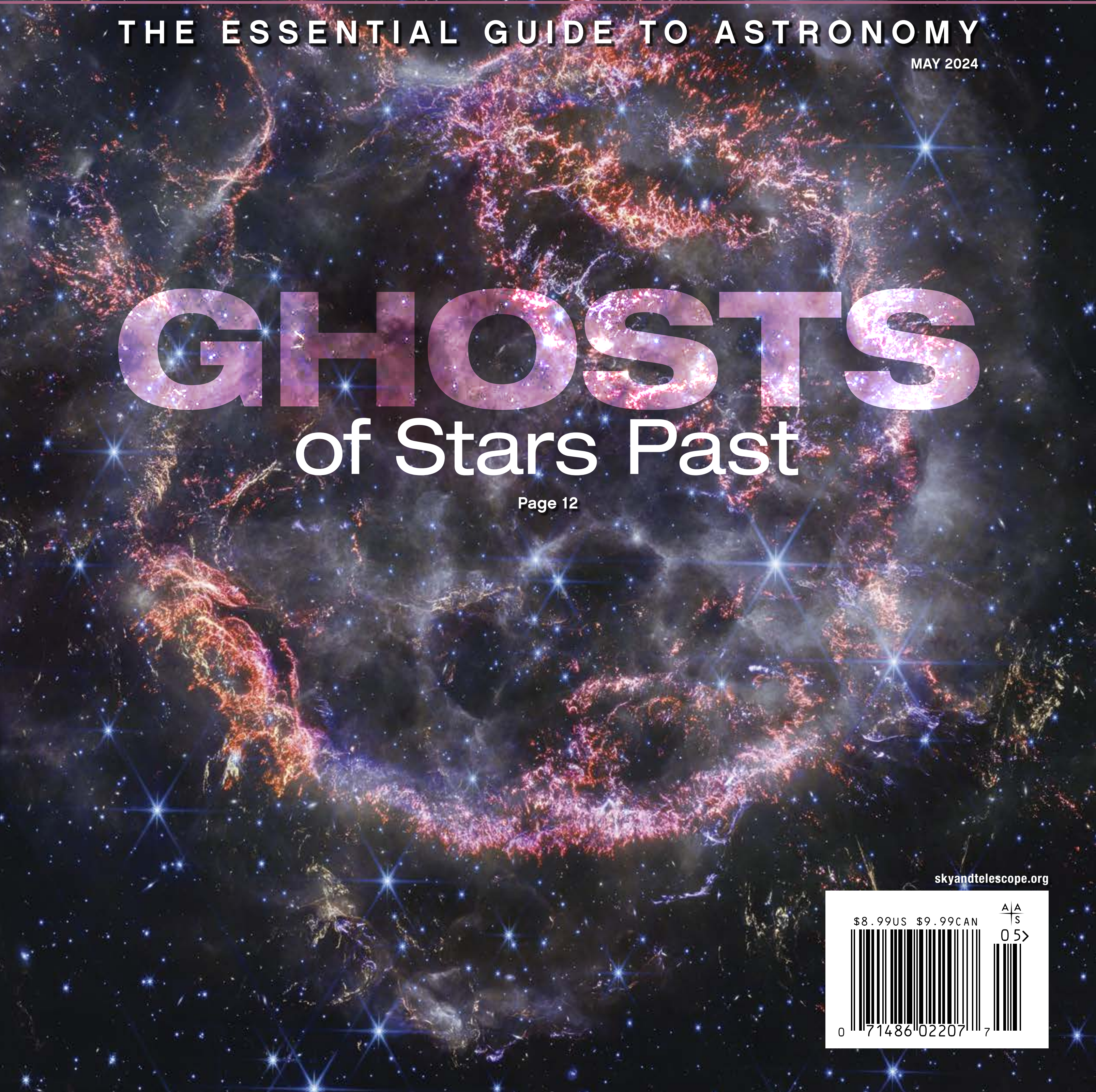
OBSERVER'S CHALLENGE: Track Barnard's Star PAGE 60

ASTRO ADVENTURE: Capture Elusive Aurorae PAGE 26

SKY & TELESCOPE

THE ESSENTIAL GUIDE TO ASTRONOMY

MAY 2024



GHOSTS of Stars Past

Page 12

skyandtelescope.org

$8.99US $9.99CAN

05

0 71486 02207 7

DAVID CURTIS

Distant Lights in the Darkness

The James Webb Space Telescope has revealed a surprisingly rich treasure-trove of black holes in the early universe.

Imagine entering a dark cavern. Everything appears pitch black. You venture forth carefully, feeling the location and shapes of the walls. Each step could reveal a cliff in the floor.

Then, your eyes begin to adapt to the environment. You realize that a soft, shy starlight shines from the cracks in the ceiling. After some time, everything becomes clear. The size and shape and oddities of the cavern are not mysterious anymore. Those obstacles you found while wandering around are no longer dreadful traps. Everything makes sense.

Astronomers analyzing the first data from the James Webb Space Telescope (JWST) have stepped inside a similar cavern. JWST, launched on Christmas Day in December 2021, has opened up an immense, unexplored, dark discovery space. We are now inundated daily by new JWST results. Some are expected. Others are revolutionary. As

astronomers' eyes and minds adjust to the new environment, some of these oddities will align with our previous theories. Others instead will remain disruptive and radically change our understanding of how the universe formed and evolved. Eventually, enough light will pierce the darkness, and everything will make sense.

This is especially true — we hope — of black holes. The first black holes formed during the first few hundred million years of the universe. Over billions of years, they and their host galaxies grew larger, developing in a still-mysterious lockstep that has left a supermassive black hole at the center of nearly every large galaxy today. But how did the first black holes form? And what did they and their environments look like in their earliest years?

What follows is the story of JWST's revolutionary findings regarding faraway black holes in its first year of operations. It is a story of giant black holes furiously swallowing gas near the beginning of time; a tale of smaller black holes that are much more numerous than we expected; and a chronicle of how astronomers, serving as modern-day Dantes and Virgils, "came forth to see again the stars" in primordial galaxies.

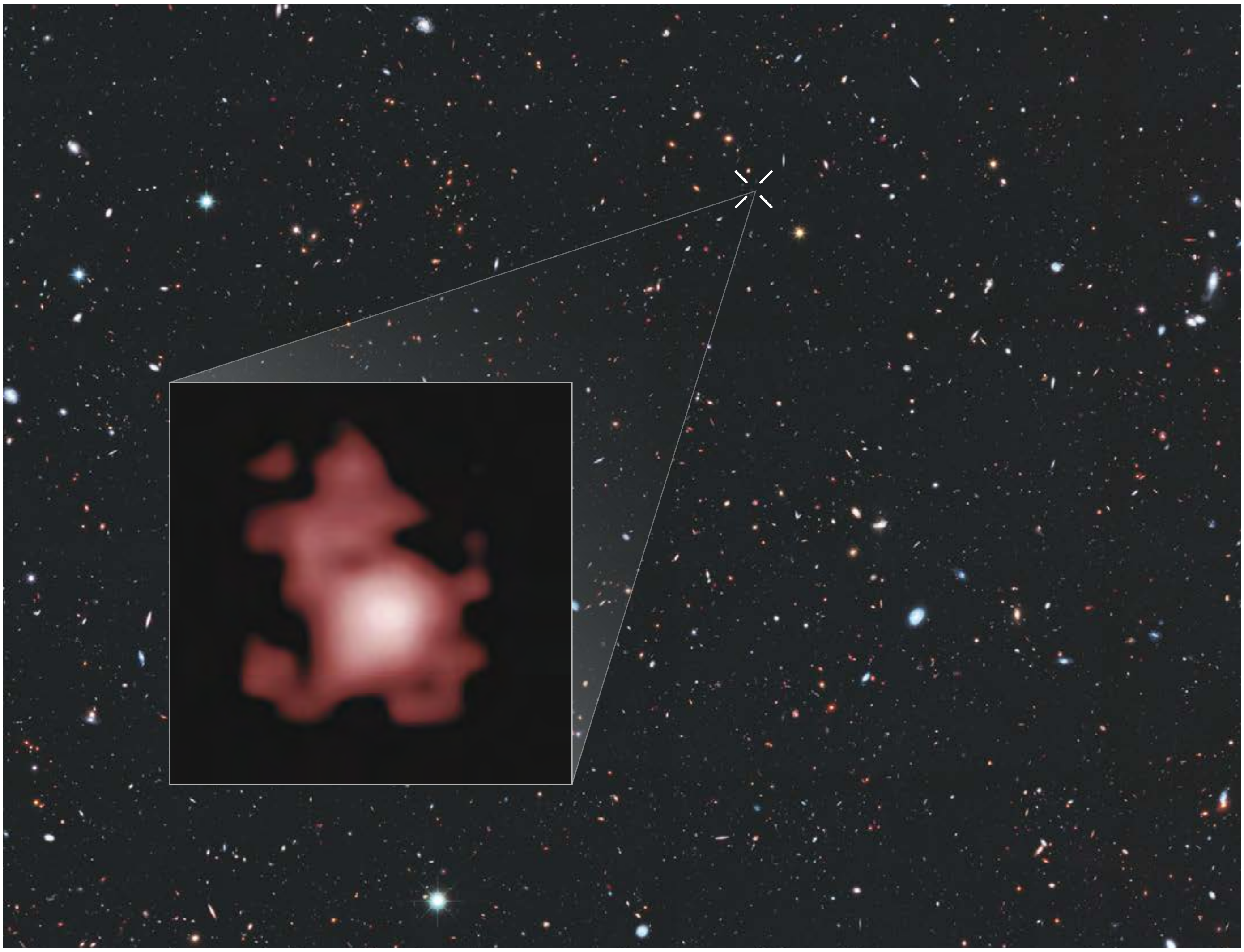
Lighthouses in the Distant Darkness

Black holes, counterintuitively, are some of the brightest objects in the cosmos. A supermassive black hole frantically accreting matter will radiate large amounts of light — not from itself but from the extremely hot gas that it's trying to swallow from the surrounding environment. Typically, astrophysicists use the name *quasar* to refer to a supermassive black hole that's accreting so much gas that it becomes bright enough to outshine its host galaxy. Although there is no clear-cut definition of a quasar, they are very massive — generally more than a billion times the mass of the Sun.

These cosmic lighthouses had their heyday about 2 to 3 billion years after the universe's birth, but we've seen them much earlier than that. The most distant quasars observed were already shining when the universe was only several hundred million years old, an infant compared to today's age of 13.8 billion years. The rays of light originating from those quasars have traveled billions and billions of years to reach our telescopes. Along the way, their wavelengths stretched due to cosmic expansion, and the light became much redder, in the well-known *redshift* phenomenon. Astronomers use how much a source's light is redshifted to estimate how much the universe has expanded since those photons were emitted and, consequently, how long the light has been traveling: the higher the redshift, the older and more distant the source.

Before JWST, the *black hole horizon*, defined as the farthest black hole we could observe with our telescopes, stood at a redshift of 7.6, or 690 million years after the Big Bang. With JWST, astronomers have (so far) pushed 250 million years earlier, detecting a supermassive black hole in a faraway galaxy at a redshift of 10.6, or just 440 million years after the Big Bang. The host galaxy is named GN-z11.

This remote galaxy, which appears to the sight of our mightiest telescopes as an unremarkable red blob, has a mar-



▲ **GN-Z11** This unassuming blob is the host galaxy of the current record holder for the farthest supermassive black hole detected, seen as it was nearly 13.4 billion years in the past, just 440 million years after the Big Bang. Bright, young, blue stars suffuse the galaxy, but its light has been stretched to redder wavelengths by the universe's expansion. The field image is from the Hubble Space Telescope Great Observatories Origins Deep Survey (GOODS), which contains tens of thousands of galaxies stretching far back into time.

NASA / ESA / P. OESCH (YALE UNIVERSITY), G. BRAMMER (STSCI), P. VAN DOKKUM (YALE UNIVERSITY), AND G. ILLINGWORTH (UNIVERSITY OF CALIFORNIA, SANTA CRUZ) velous story of its own. Astronomers discovered GN-z11 in 2016 with the Hubble Space Telescope. For nearly seven years, until the advent of JWST, GN-z11 held the record for the most distant object known. In late 2022, it lost its place to another galaxy named JADES-GS-z13-0 (*S&T:* Oct. 2023, p. 12).

But GN-z11 still had a story to tell. In 2023, astronomers used JWST to study the galaxy's spectrum in detail. A spectrum not only breaks apart the light seen from an astronomical object into its constituent wavelengths, much like a rainbow, but it also reveals how the material producing the light is moving with respect to the observer. The spectrum of GN-z11 showed that the gas in the innermost region of the galaxy was moving at roughly 1,000 km/s (more than 2 million mph) — the fingerprint of a massive, central black hole.

Using this information, the researchers estimated the mass of this "small and vigorous black hole in the early universe," as they called it, was some 1.5 million solar masses. That makes it one-third as massive as the black hole at the center of the Milky Way today — a tiny object to be detected so far away.

In another plot twist, astronomers discovered that the central black hole in GN-z11 is probably swallowing gas furiously, turning itself into a floodlight. The rate at which a black hole can accrete gas from its environment has a speed limit, the so-called *Eddington limit*, whose namesake, Sir Arthur Eddington, was a renowned 20th-century English astronomer. Above the Eddington limit, the infalling gas's own glow pushes material out and away from the black hole, controlling how much the black hole can accrete.

In the high-redshift universe, with abundant gas to be accreted, the Eddington limit is like the speed limit on a highway: generally obeyed but not unbreakable. Most black holes accrete around the speed limit. Some accrete somewhat higher or lower than that. GN-z11, however, seems to be accreting at about five times its Eddington limit. This rate is remarkable: If, billions of years ago, GN-z11 continued growing at this pace, it would reach the superlative mass of 1 billion solar masses by redshift 9.5, more than 13 billion years ago. We are unaware of such extremely massive objects at those redshifts; they must be scarce if they exist. Super-Eddington accretion might also be an episodic event, turning on and off and keeping black hole growth in check.

The tiny supermassive black hole in GN-z11 became visible to our telescopes because it's radiating away a vast amount of energy. What we see in its spectrum also suggests that we may be staring down at the accretion disk from above, hence observing the black hole from its most luminous side.

GN-z11 is not the only remarkable black hole that JWST has discovered in the very early universe. For example, the crown for the farthest black hole known belonged previously to CEERS 1019, a 10-million-solar-mass object shining at redshift 8.7, 13.1 billion years ago. Astronomers discovered this remarkable source in the Cosmic Evolution Early Release Science (CEERS) JWST survey. CEERS 1019 also accretes slightly above the Eddington limit, indicating that violating the speed limit could be common in this early population of compact objects.

When your eyes adjust to darkness, you begin to discern a more numerous population of dimmer stars. Astronomers are having the same experience with the early universe.

Countless Feeble Candles

GN-z11 and CEERS 1019 are relatively midsize when it comes to supermassive black holes. Astronomers have found dozens of giant quasars a little later in cosmic history, roughly 1 billion years after the Big Bang. Before the advent of JWST, black hole hunters' focus was on finding these extremely massive — and bright — objects as far away as possible.

Yet the giant quasars discovered at very high redshift are rare, extraordinary objects. Consider the distance between the Milky Way and the Andromeda Galaxy, some 2.5 million light-years. Multiply this distance by 1,000 and construct a cube from this side. In the early universe, at redshift 6 (12.8 billion years ago), we estimate that there is just a single, bright quasar in this immense volume. At redshift 10 (13.2 billion years ago), these objects are so rare that there may only be one in the entire universe.

But there are other things in that great expanse besides the majestic quasars. When you look up at the sky on a clear and dark night, your eyes immediately see the brightest stars. Then, when your eyes adjust to darkness, you begin to discern a more numerous population of dimmer stars. Astronomers are having the same experience with the early universe: They are now discovering a population of smaller, fainter supermassive black holes.

When analyzing the first deep images obtained by JWST, different teams started to notice tiny red dots popping out everywhere. These sources were distinctively crimson compared to other sources in the field, because their emission at longer, redder wavelengths was stronger. They also appeared small in physical and angular size — so small, in fact, that although the dots emitted as much light as a whole galaxy does, that light came from a region that's between the size of a large star cluster and the smallest dwarf galaxies.

After a careful spectral analysis, researchers discovered that some of these peculiar sources were young galaxies hosting black holes at their centers. Most were observed between redshift 4 and 7, when the universe was between 770 million and 1.6 billion years old. Astronomers discovered tens of specimens of this large population and lovingly named them "little red dots" or "hidden little monsters."

Instead of billions of solar masses, these little monsters commonly are black holes of 10 to 100 million solar masses. If accreting at their Eddington rates, then these somewhat smaller black holes generate a luminosity of about 100 billion times that of our Sun; the most massive quasars we know of blaze with a luminosity of almost 1,000 trillion times that of our Sun.

The discovery of a population of fainter, less massive black holes is not surprising. In the universe, it is typical for small things to be more numerous than big things. Small galaxies are more frequent than big ones; Sun-like stars are more common than massive ones. Hence, astronomers expected that JWST, with its larger light-gathering power, would find plenty of smaller black holes in faraway galaxies.

The astonishing part is the sheer number of smaller black holes found. According to the first estimates, JWST has detected 10 to 100 times more black holes than previously expected from the census of giant quasars. One of the main conclusions of JWST's first year of observations is, therefore, that the young universe was fertile ground for forming massive, hungry black holes — many more than expected when we observed only the brightest among them.

The discovery of such a large and enigmatic population of little red dots is one of the main breakthroughs in JWST's first year of observations. These black holes are not quite quasars. But at least some of them may *become* quasars. JWST is showing us the population of quasar precursors, on their way to becoming the majestic lighthouses we observe at later cosmic epochs.

We See Again the Stars

In the 14th-century classic "The Divine Comedy," Dante and his guide, Virgil, finally exit the depths of Hell to emerge onto Earth's reassuring surface. The end of this stage of the journey to Paradise, which symbolizes the march from darkness to enlightenment, is marked by the words, "And thence we came forth to see again the stars." In a very different context, JWST is also illuminating our path toward understanding how galaxies and black holes co-evolved in time — by allowing us to see the host galaxies' starlight again.

We compared the giant quasars observed in the high-redshift universe to lighthouses. Once the light beam dazzles your eyes, it is hard to see anything else. High-redshift supermassive black holes discovered in the pre-JWST era were too bright for us to detect the starlight coming from the host galaxy. This is not the case for the smaller, numerous, and fainter population of high-redshift black holes that JWST is now showing us. These black holes are candles instead of lighthouses: We can detect the surrounding starlight and measure the mass in stars held by the host galaxies. What results is among the most surprising discoveries yet.

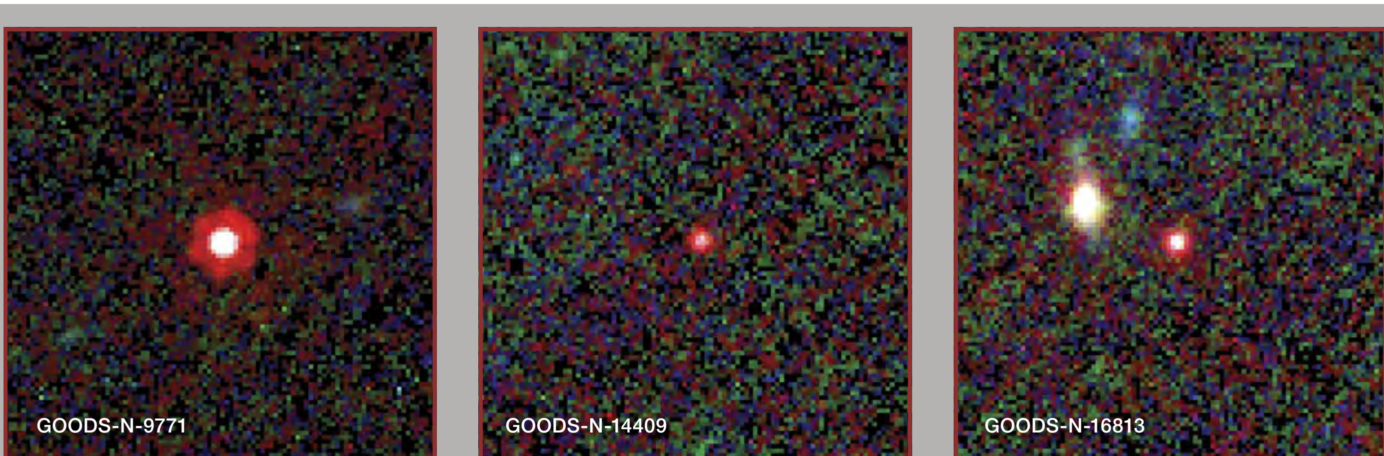
In the local universe, we have known for decades that the mass of a galaxy's central black hole correlates with some properties of the host galaxy (*S&T:* Feb. 2017, p. 18). For example, the mass of the black hole is typically about 0.1% of the stellar mass of the host. In other words, big black holes are in big galaxies, and small black holes are in small galaxies. High-energy phenomena within the galaxies explain these correlations, as they regulate both star formation and black hole growth. Central black holes and their galaxies thus co-evolve through cosmic time by interchanging mass and energy.

But we have no idea if these relations hold up in the early universe. Maybe the ratio between black hole and stellar mass was very different back then.

Indeed, JWST observations show us oddities in the evolutionary waltz between black holes and galaxies. Tens of galaxies detected so far by JWST, especially above redshift 4, conclusively have black holes that are significantly overmassive with respect to their galaxy's stellar mass. Instead of their mass being about 0.1% of the stellar mass of their hosts, these early behemoths are 1%, 10%, or even close to 100%. For example, thanks to the combined power of JWST and the Chandra X-ray Observatory, astronomers recently found a supermassive black hole at a redshift 10.3 (13.3 billion years ago) that seems to be as massive as its host galaxy. We are thus facing an early universe in which the relation between black holes and host galaxies is far from the ones in the familiar local universe, pointing us toward a better understanding of how black holes and galaxies evolve together.

JORRYT MATTHEE ET AL. (6)

▼ **LITTLE MONSTERS** These false-color infrared images reveal "little red dots," which likely include the glow of gas accreting onto midsize supermassive black holes. The objects appear as they were about 1 to 1.5 billion years after the Big Bang. Some images also show bluish galaxies.



Lighting Up the Cavern: The Path Forward

JWST's first year has revolutionized our view of the early universe. First, we have significantly expanded the black hole horizon: The most distant supermassive black hole we've detected, that in GN-z11, lies only 440 million years after the Big Bang. Second, we've observed a vast population of smaller black holes actively accreting inside young and small galaxies; these objects are 10 to 100 times more numerous than expected, based on the number of observed giant quasars. Perhaps many of them will stay "small" and never reach billion-solar-mass proportions. Third, these smaller black holes seem to be 10 to 100 times more massive than expected with respect to the stellar mass of their hosts.

What are the consequences, thus far, for our theories of the early universe? By detecting more distant supermassive black holes, the expansion of the black hole horizon will eventually allow us to pinpoint the formation mechanism of the first black holes, also known as seeds (*S&T:* Nov. 2022, p. 16). These seeds were either heavy, with an initial mass on the order of 100,000 solar masses, or light, with a mass up to a few thousand — or a combination of both types. Light seeds would have had to grow furiously to match the early supermassive black holes we've found; heavy seeds would slowly pace their race to greatness.

To understand how the first population of black holes formed, we have two pathways: Either we discover incredibly massive black holes at even higher redshifts, impossible to explain with the light-seed scenario, or we obtain a better census of quasar precursors and their galactic hosts and determine how their masses evolved with time. JWST is well under way on both pathways.

The little red dots also highlight tensions between observations and theoretical work. In the pre-JWST era, theorists predicted many more black holes than observers did, based on the number uncovered so far. Some theorists have welcomed the discovery of the little-red-dots population as bringing theory and reality closer together. But some observers worry that we may now have swung too far the other way. For now, it remains unclear how many of the little red dots are in fact black holes.

Some early JWST observations also suggested that the universe became full of massive galaxies earlier than expected, based on how bright these galaxies are (*S&T:* May 2023, p. 9). This tension has already eased thanks to modifications in how astronomers measure the stellar mass of galaxies at high redshift, by improving the estimate of the masses with which stars form and by better accounting for the role of interstellar dust. Possibly, the presence of glowing, overly massive black holes will reduce estimates of the stellar content of these galaxies even further, better reconciling them with our expectations.

Furthermore, over-massive early black holes may be the best indication yet that they formed from heavy seeds. When a heavy seed forms, the galaxy may take a while to build up its stars and catch up, size-wise, either through mergers with other galaxies or via in situ star formation. Thanks to these combined processes, the system would slowly progress toward the familiar 0.1% ratio of masses in our cosmic neighborhood. If this picture is accurate, then many galaxies may undergo a "hidden little monster" phase.

To conclude, JWST's first year of operations has revealed a mother lode of faraway black holes. Some of the observations obtained thus far are puzzling and in conflict with what we thought the early universe would look like. Remember — we are still in the phase of exploring a dark cavern, barely lit by starlight. Our eyes — and minds — are still adjusting to the entirely new environment that JWST is showing us.

Some of these oddities will probably be re-incorporated into our previous expectations. Others will disrupt our vision of the cosmos. Reassuringly, in this dark and damp cavern, we have not yet found something truly bizarre, like water flowing uphill. But the magnificent young cosmos that JWST is showing us is already changing the history of astronomy forever.

■ **FABIO PACUCCI** is an astrophysicist at the Harvard & Smithsonian Center for Astrophysics, where he holds the Clay and Black Hole Initiative fellowships.