 by Camille M. Carlisle

The *First* Black Holes

Astronomers are laboring to discover how the universe's first supermassive black holes were born.

Birth Stories Matter. When I was a kid, every year on my birthday my mom would regale me with the tale of the day I took my first breath. She'd include all the gory details — and as a nurse practitioner, she could get pretty specific — to ground me in who I am by telling me how I came to be here.

Astronomers would like to do the same thing for the universe's supermassive black holes. These gargantuan spacetime potholes lurk at the center of most large galaxies. They can have the mass of millions or even billions of Suns. Like potholes, most of them go unnoticed until they throw something out of whack — say, by shredding a star or projectile-vomiting a jet of plasma.

Black holes have been around since nearly the beginning of cosmic time. Astronomers see the glow of their superheated gas shining at us from about the same time that galaxies began churning out stars with abandon. But we don't know exactly when they arrived on the scene. Their birthday matters, because how and when they formed determines how much of an impact they had on their host galaxies and the early universe at large — and that impact might have been severe.

◀ **IN THE BEGINNING (ALMOST)** This artist's concept depicts the quasar ULAS J1120+0641, powered by one of the earliest supermassive black holes detected. Astronomers see this system as it was 750 million years after the Big Bang (redshift 7.1). The black hole contains roughly 2 billion Suns' worth of mass, and scientists have long wondered how the object grew to be so big so early.

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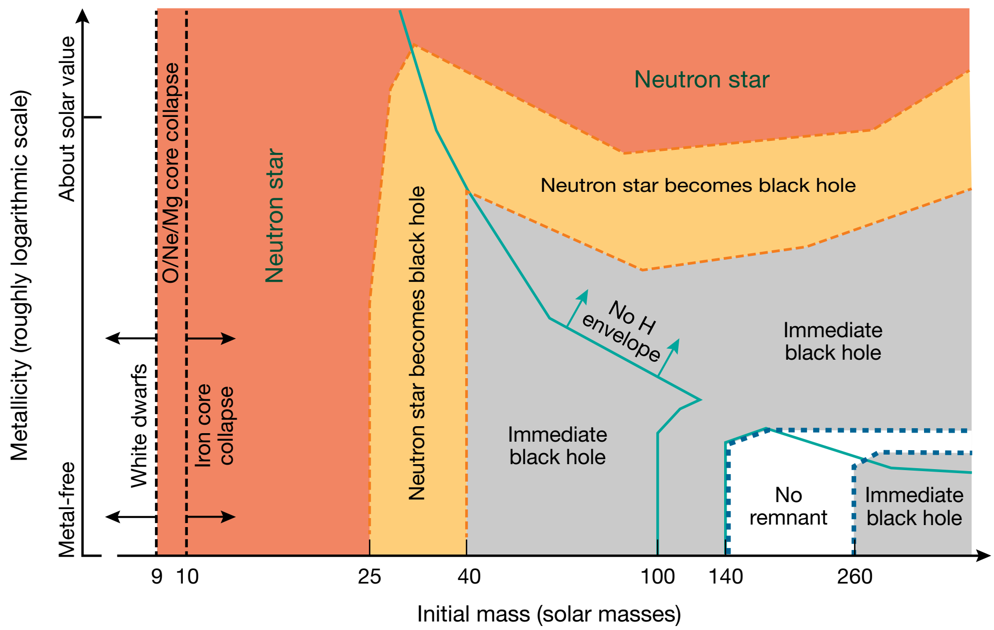


REMNANTS OF MASSIVE STARS When stars die, what they become next depends on their masses and how tainted their gas is with heavy elements, called metals. The most massive stars create black holes (gray regions) — except for a subset that have just the right characteristics to die in a so-called *pair-instability supernova*, which leaves no remnant. The cores of less massive and/or more metal-tainted stars become neutron stars, some of which then convert into black holes when too much material from the star's layers falls back on them and triggers runaway gravitational collapse (yellow regions). The green line separates stars that keep their outer hydrogen layer (left and lower right) from those that lose it in winds. Many of the universe's first stars should have fallen in the black hole regions of this diagram.

Surveys have uncovered roughly 50 *quasars*, brilliant hot-gas beacons powered by supermassive black holes, blazing only a billion years after the Big Bang. The black holes have masses of billions of Suns, comparable to the heftiest black holes we see today. To be so big so early, these titans must have grown to full size within 900 million years of the Big Bang.

But that's nonsensical. Black holes usually eat like obstinate toddlers — a little food goes down the throat, but most is left on the plate, dropped on the floor, or flung away. If the earliest objects adhered to this grazing strategy, they'd never have beefed up in time.

Still, these black holes came from *somewhere*; there's no cosmic stork. Astrophysicists have been grappling for years with the questions of how these objects were conceived and how they grew so fast. And thanks both to some high-powered simulations and to observations of dwarf galaxies, it's finally looking like the problem is not as intractable as it once seemed.

Creating Seeds

Astronomers have three main ideas for black hole genesis. The basic question boils down to whether stars stick their noses into the affair or not. For two of the theories, they do; the third circumvents them.

The first scenario starts with star clusters. Stars in clusters can sometimes bonk into each other and merge. If a cluster is compact enough, its stars could suffer runaway collisions, growing like The Blob into a single star a few hundred to a few thousand times as massive as the Sun. This superstar would then collapse into a black hole.

Calculations suggest that such cluster dynamics could produce black hole "seeds" of several hundred to a couple thousand solar masses. But this process is grossly inefficient, and it's hard to explain why a dense enough cluster would exist to enable this chain of events. Of the three theories, this one is the least talked about among astronomers.

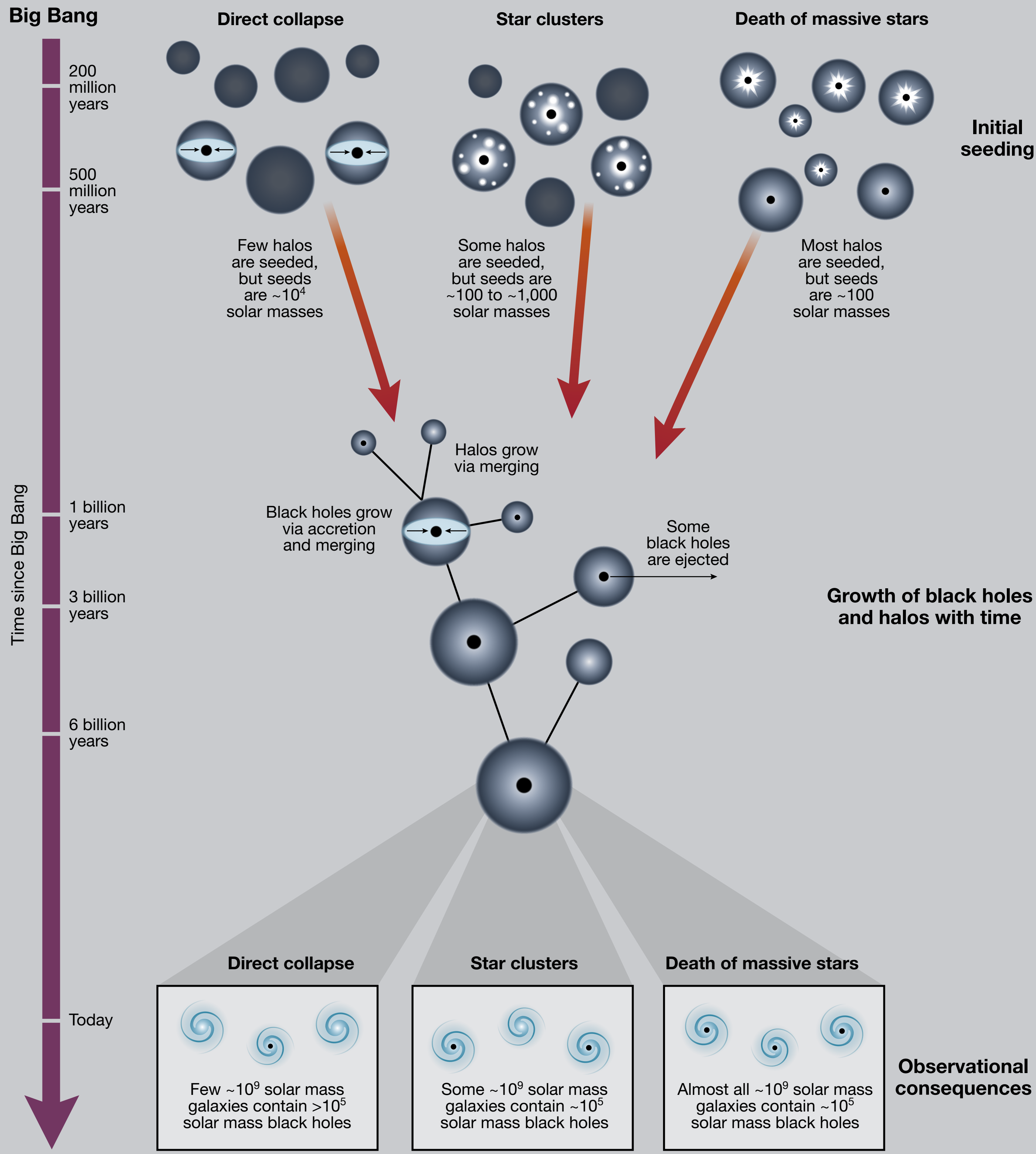
The second (far more popular) star scenario is a souped-up version of "normal" black hole creation. When a single, massive star dies catastrophically, its core can collapse and become a black hole. The first generation of stars to form in the universe, called Population-III stars, would have often died this way. These stars probably weighed in at a couple hundred Suns.

The universe can't easily create stars that big anymore, because of a little thing astronomers call *metals*. In astronomers' parlance, these are all the elements heavier than helium. Stars fuse hydrogen and helium into metals, and when the stars die they spread these heavier elements into the galaxy around them.

Metals make things difficult for star growth, for two reasons. First, metals cause gas to cool faster. Cooler gas fragments into smaller star-forming clumps than warmer gas, meaning metal-rich stars will generally start smaller than metal-poor ones. Second, metals make gas more opaque. A star's light actually pushes on its outer gas layers, balancing the inward pull of gravity. If a star has a lot of heavy elements in its makeup, its gas will be less transparent. Instead of passing through the outer layers, light will shove on them, the pressure driving the layers away as massive winds. This process curtails the star's growth and exacerbates stellar weight loss.

Population-III stars didn't have this problem, because they contained no metals: there were no stars before them to pollute the gas that made them. Those that later collapsed into black holes could have retained at least half of their original mass, or about 100 solar masses (see graph above). High-end exceptions might weigh in at 10 times that. Planted at the center of a growing galaxy and fed by gas that sank there, these seeds would have then grown into supermassive black holes.

S&T: LEAH TISCIONE, SOURCE: HEGER ET AL. / *ASTROPHYSICAL JOURNAL* 2003



S&T: LEAH TISCIONE, SOURCES: J. GREENE / *NATURE COMMUNICATIONS* 2012 & MARTA VOLONTERI

EVOLUTION OF SEED BLACK HOLES Astronomers suggest three main avenues for creating the universe's supermassive black holes: direct collapse of gas (left), runaway collisions in star clusters (center), and the death of the first, massive stars (right). The gray circles represent the dark matter halos in which each process takes place. These halos, and the protogalaxies in them, then grow through merging (center of diagram). Black holes themselves grow both by merging with each other and by accreting gas. Occasionally a merger is violent enough to kick the black hole out of the galaxy. The fraction of small galaxies that have massive black holes will depend on which of these scenarios dominated. (The Small Magellanic Cloud is 10^9 solar masses.)

Many astronomers — and particularly those who specialize in black holes — are huge fans of this scenario. John Kormendy (University of Texas at Austin), one of the first astronomers to establish that black holes sit at the centers of most massive galaxies, describes the Population-III picture as "the only game in town."

"It's enormously natural," he says. "It's essentially inevitable that by the time the universe was half a billion years old, quite a lot of these 100-ish-solar-mass black holes would have merged, and then you've got 1,000-ish-solar-mass black holes, and that's what we need."

Not everyone agrees with Kormendy's assessment. The problem is that at these masses, the black hole seeds would need to grow continuously at their maximum feeding limit in order to become the titan quasars that existed 13 billion years ago.

This limit exists because of the same light pressure problem that curtails stars' masses. As gas falls onto a black hole, it heats up and glows. If you dump too much gas on, the glow will be so strong that the pressure of photons radiating out will actually overcome the gravity pulling in and cut the black hole's fuel line. This balance point between accretion in and radiation out is called the *Eddington limit*.

Keeping up Eddington-level growth is exceptionally hard. Not only does it mean that the galaxy must have fed its central black hole with a steady supply of gas for several hundred million years, but also that the black hole kept its mouth at the straw. That's a tall order.

Populations I, II, and III

Astronomers talk about three populations of stars, based on Walter Baade's work in the 1940s studying the Milky Way. These are:

- **Pop I:** usually young and in the galaxy's spiral disk. Metals make up about 2–4% of their total composition. Includes both the Sun and *O*- and *B*-type, bluish massive stars.
- **Pop II:** older (often 10 billion years or more), in the galaxy's bulge and halo. Metal content much lower, down to maybe a thousandth that of the Sun. Only the least massive ones survive today.
- **Pop III:** the fabled first stars. Would have formed with only hydrogen and helium (no metals). None yet conclusively detected — either they've died off or are masked by heavy-element "pollution" they've picked up over time.

Just Get to the Point

So other astronomers turn to the third scenario, direct-collapse black holes. In this scenario, warm, metal-free gas collapses under its own gravity to form a black hole of tens to hundreds of thousands of Suns. (The gas might or might not first form a supermassive star.) With masses so much greater than those created by Population-III stars, direct-collapse seeds offer an attractive alternative, explains Muhammad Latif (Paris Institute of Astrophysics).

But if growing a Pop-III seed into a titan is hard, making direct-collapse black holes can seem almost impossible.

"It's the opposite of Occam's razor," she says, sighing. "It's such a series of events to occur all at the same time that I'm like, 'Seriously?' I'm a *scientist*.'"

To make one of these objects, you need a large influx of gas. In the standard direct-collapse picture, this gas needs to stay warm (tens of thousands of kelvin) so that it doesn't fragment too early. Thus the gas must be pristine, with essentially no metals. The gas also needs to be basking in enough ultraviolet radiation to stifle the formation of molecular hydrogen, which also cools it.

Here's where things get complicated. These ultraviolet photons must come from stars. But the gas forming the black hole seed can't have been tainted by stellar-made metals. To avoid contaminating the gas but still bathe it in ultraviolet rays, the stars would need to lie in a massive protogalaxy just 10,000 light-years or so away, or less than half the span between our solar system and the Milky Way's center. Furthermore, these stars would likely be Population-II stars (which means they'd contain some metals), because such stars live longer and are more common, Latif says. So to protect the black-hole-birthing gas from the stellar winds or supernovae, either the stars' outflows must be precisely timed with the black hole's formation, or they must all aim away from where the black hole is forming.

The universe's metal enrichment did proceed patchily, and observations show that pockets of pristine gas survived even to the time that we see the titan quasars. But many astronomers have trouble swallowing the complexities of the direct-collapse scenario. Although Marta Volonteri (Paris Institute of Astrophysics) contributed to its theoretical groundwork, she's become increasingly skeptical of direct collapse in the last couple of years. "It's the opposite of Occam's razor," she says, sighing. "It's such a series of events to occur all at the same time that I'm like, 'Seriously?' I'm a *scientist*.'"

Despite her reservations, Volonteri remains agnostic. She and others recently suggested that a clump of bright, pristine gas in the protogalaxy CR7 might contain a direct-collapse black hole. Others have also found potential sources in the

CANDELS/GOODS-S survey. Astronomers are still arguing over whether any of these sources could indeed be a direct-collapse seed.

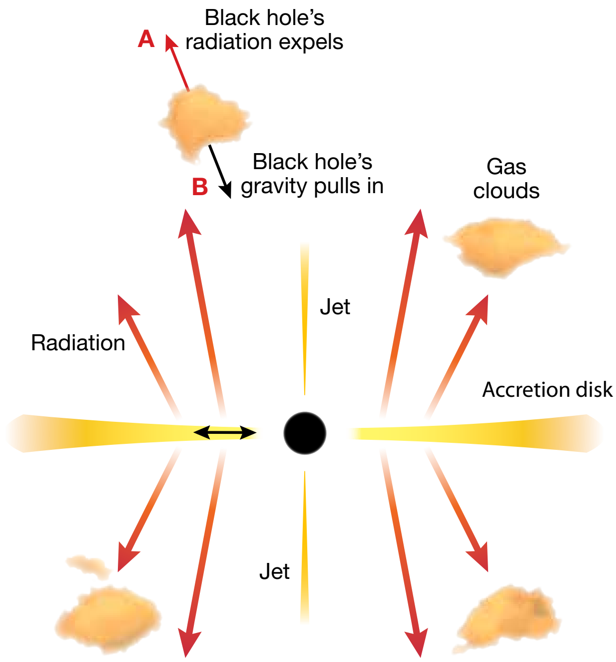
Some claim that the direct-collapse process is not as complicated as we think. Even if it is, Latif says, his team's simulations show that sufficient seeds would form to explain the titan quasars we see in the infant universe.

Overcoming Eddington

But even a 10,000-solar-mass seed is a far cry from the 2 billion solar masses of the black hole powering the quasar ULAS J1120+0641, whose light left it 12.9 billion years ago. To reach that size in less than a billion years, the black hole must have accreted gas at its Eddington limit for roughly 60% of the time if it began as a direct-collapse seed. If the seed was a stellar one of 300 solar masses, then it had to eat at the limit for *all* of those 900 million years. Either way, somehow the galaxy shoves tens of thousands to tens of millions of solar masses' worth of gas down the black hole's throat, all within a few hundred million years.

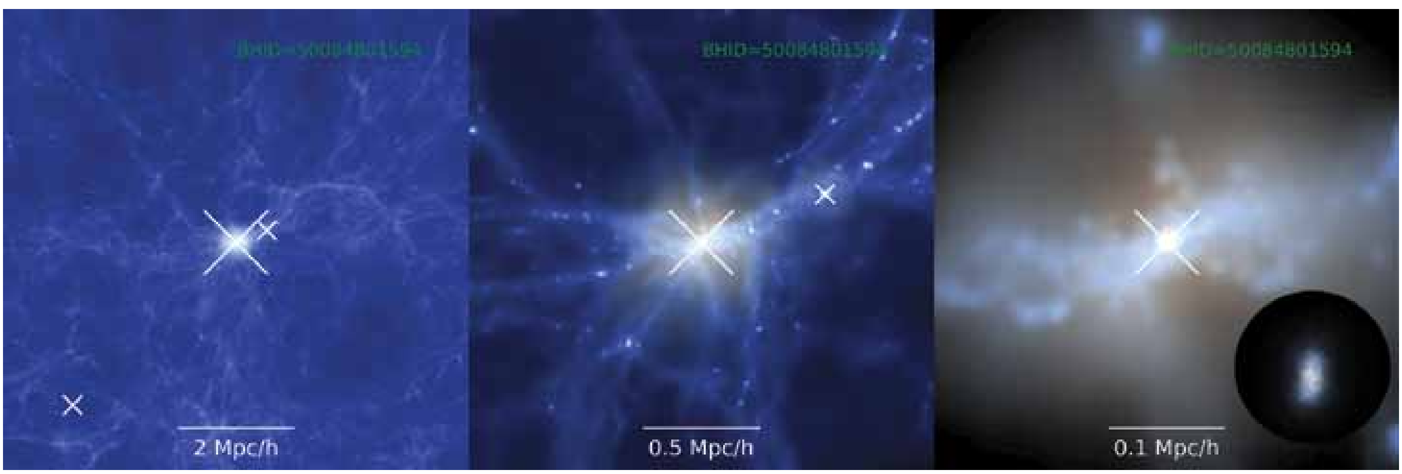
It's at this point that the accretion ceiling begins to feel more like a straitjacket than physics. "I'm not a believer in the Eddington limit," Volonteri said flatly in a recent talk at the Harvard-Smithsonian Center for Astrophysics. "If the accretion rate can be higher, then building the biggest black holes is not crazy."

But overcoming the Eddington limit is no easy task, she admits. The super-Eddington inflow of gas must trap the gas's glow well enough that the radiation doesn't launch the gas away. Nor can the black hole shoot material away in jets, unless the jets reach far enough away from it that the plasma doesn't heat the nearby accretion flow and stifle the downpour onto the hole. Galactic centers are also hotbeds of starbirth, and the stars mustn't do anything to disrupt the pipeline — no cataclysmic antics allowed. Not to mention that the violent glare from the accreting black hole can "damage" the galaxy, heating up ambient gas and preventing it from funneling into the core and feeding the beast. "Aaaah," Volonteri groans. "There are so many variables that they're driving me nuts."



▲ **SUPER-EDDINGTON ACCRETION** There are two conditions to consider when talking about whether a black hole can accrete faster than it's theoretically capable of doing. One is the balance between the gravitational pull inward and the pressure outwards, caused by the glow from the accreting black hole (red arrows). The radiation can push and shove away gas clouds (A) that would otherwise fall toward the black hole (B). The other condition is what happens inside the accretion disk itself — the disk's own glow and internal pressure work against it, limiting how much material can drain down onto the black hole (black arrow). On the other hand, when the black hole is fed at rates much higher than the theoretical limit, the disk can become so dense and thick that some of the radiation becomes trapped inside, suppressing the push on nearby gas. Regardless of the theoretical limit, the hot and powerful radiation from an accreting black hole, as well as the jets it sometimes has, would eventually stifle accretion and stymie growth by pushing or shredding the surrounding gas clouds.

▼ **SIGN OF THE TIDES** *(below)* These snapshots from the BlueTides simulation show the gas environment of one of the most massive black holes about 650 million years after the Big Bang. Hotter gas appears redder. Large crosses mark the positions of black holes, and their sizes are proportional to each hole's mass. The inset in the rightmost panel is a zoom 10 times closer than the panel it's in and shows the host galaxy.



S&T ILLUSTRATION: LEAH TISCIONE; SOURCE: MARTA VOLONTERI; SIMULATION: TIZIANA DI MATTEO ET AL. / *ARXIV.ORG* 2016

It's more natural for black holes to grow in spurts. In some recent simulations of growing protogalaxies, the black hole seemed to be "breathing," its accretion rate rising and falling as feedback from nearby exploding stars turned on and off, Volonteri says. But once the galaxy reached maybe a hundredth the Milky Way's mass, there was enough gas coming in that material built up and shoved into the black hole. Growth then took off like a rocket.

The key is to shovel enough gas into one place, says Tiziana Di Matteo (Carnegie Mellon University). For several years her team has been crafting computer simulations to explore how galaxies and black holes grow together. Their most recent simulation, BlueTides, follows the formation of galaxies and their black holes in a volume 1.3 billion light-years on a side. That's roughly 300 times larger than the largest observational survey to date of the universe in this early cosmic era. Such a sweeping simulated view enables astronomers to make testable predictions about what we should and shouldn't see in the real universe.

It's this work that has solved the mystery of how the titan quasars formed, Di Matteo declares. The problem was that previous simulations didn't have the resolution or volume coverage to probe the rarest, highest density regions of the universe. In some of these regions, the gas can plunge inward directly instead of settling into disks and draining in more slowly. In these places, "black holes can grow at their maximum rate pretty much since the time they are seeded," she explains. Such fast growth is "virtually unstoppable."

Locations where this kind of infall is possible are few and far between. "In the simulations we see hundreds of thousands of black holes — in every newly forming galaxy in the early universe," she says. "But the fast growth is induced in only a handful of regions." That's in keeping with observations, she explains: the several dozen early quasars detected are a drop in the bucket of the nearly 1 billion galaxies uncovered by surveys. Other teams' recent simulations also support this conclusion.

Delving into Dwarfs

Simulations cannot yet tell us what kind of seed was planted in these rare, dense quasar regions: Di Matteo's code plops a 50,000-solar-mass black hole into place whenever the mass of the growing galaxy surpasses about a hundredth that of the Milky Way. But given the BlueTides results, the fantastic growth rate should make the seed mass irrelevant, she says. "You can pretty much start from anything, and still end up close to what you need at a redshift of 7," she says. (A redshift of 7 corresponds to 13 billion years ago; this era is when astronomers see the enigmatically large black holes.)

Unfortunately, that means that the titan quasars tell us nothing about what type of seed they formed from. Nor do most supermassive black holes seen today. These objects have

S&T: SEAN WALKER

▲ **EMPTY NEST** The Triangulum Galaxy (M33) is the third largest galaxy in the Local Group, roughly a tenth as massive as the Milky Way and Andromeda. Yet this spiral contains no supermassive black hole in its core, and astronomers aren't sure why. (There's no sign of it having been ejected.)

grown so much over cosmic time through both accretion and mergers that they essentially suffer from amnesia: they've forgotten where they came from.

That's not true for the runts. The smallest massive black holes, and the dwarf galaxies they inhabit, have changed little since their creation. These galaxies are so small that their stars ravage them, the stellar winds and supernovae ousting the cold gas needed to feed the black hole. Thus, black holes in dwarf galaxies should be about as big today as they were when they first formed.

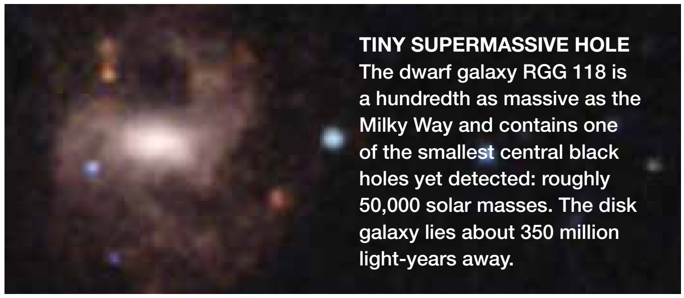
Amy Reines (NOAO) and others are ferreting out these dwarf supermassive black holes. So far, they've turned up more than 150 of them. Of the couple dozen that they've weighed, the smallest contains roughly 50,000 solar masses. Right now the sample is small, and observations aren't sensitive enough to detect black holes much lighter than this. But if as they keep digging astronomers find that there's a "plateau" in how low black holes go, the limit could serve as a paternity test: if the masses peter out around tens of thousands of solar masses, that would favor direct collapse; if they keep plunging past our observational reach, that would favor stellar sources.

Jenny Greene (Princeton) wants to go further: she wants a census of all galaxies, to see how often they contain big black holes. Direct-collapse seeds are harder to make than stellar ones, so if supermassive black holes are normally born through direct collapse, there should be fewer of them — they'd occupy only about 60% of galaxies whose masses are at least a billion Suns (comparable to the Small Magellanic Cloud), she estimates. If massive black holes came from stellar seeds, on the other hand, basically all galaxies of this mass would have them.

We already know of exceptions to the latter. For example, there's no sign of a central black hole in the Triangulum Galaxy (M33), the spiral satellite of the larger Andromeda Galaxy. "M33 is the whole reason we get to ask whether all galaxies have black holes," Greene says. "Because we know that, when you get to a low enough stellar mass, they don't *all* have black holes."

Based on observations, she says, the best estimate is that galaxies with more than 100 million Suns contain a black hole at least 50% of the time. "We've ruled out below 20%," she says. "So it's looking like it's not so uncommon, even at these relatively low [galaxy] masses, to host a black hole above 100,000 solar masses." But if this fraction doesn't go up with more data, it could be a strike against the Population-III scenario.

On the other hand, recent simulations by Volonteri and her colleagues warn against thinking that building black holes is ever easy. The team followed black hole formation in a wide range of galaxies but took a more individual approach than Di Matteo. For each clump of gas, the team's simulation took into account its unique conditions and calculated how massive a black hole could form there, assuming it arose from Population-III stars or stellar-cluster dynamics.



TINY SUPERMASSIVE HOLE The dwarf galaxy RGG 118 is a hundredth as massive as the Milky Way and contains one of the smallest central black holes yet detected: roughly 50,000 solar masses. The disk galaxy lies about 350 million light-years away.

SDSS

The resulting seeds spanned a wide range of masses, but most had on the order of a thousand Suns — within an order of magnitude of the teeniest known massive black hole. Plus, supernova feedback stunted black hole growth in the smallest galaxies, and stellar cities with only a tenth of the Magellanic Clouds' mass were unlikely to form a central beast. So even with a stellar seed, massive black holes might be fairly rare.

LIGO and Beyond

Dwarf galaxies are the most promising lead for answering the genesis question, but they're not the only one. Kormendy also points to gravitational wave research. "It's really interesting and a little surprising that the first binary black hole detected by LIGO didn't involve 5-solar-mass black holes," he says. "It involved 30-solar-mass black holes. I really perked up when I saw that." If gravitational wave observatories regularly turn up black holes of several tens of solar masses, that would favor Population-III seeds, he says (see sidebar below).

Future observations of the early universe may also shed some light on the matter, pushing to within a billion years of the Big Bang. NASA's proposed WFIRST spacecraft should detect 10,000 supermassive black holes this early, Di Matteo estimates. Projects such as NASA's James Webb Space Telescope and ESA's Athena X-ray observatory (both upcoming) should also be able to detect accreting black holes with millions of solar masses in this era. So it's feasible that, in the next decade, we'll be able to answer for black holes what my mother answered for me, and definitively dismiss the cosmic stork.

■ *Sky & Telescope*'s Science Editor **CAMILLE M. CARLISLE** thinks black holes are adorable.

eLISA's Gravitational Waves

Slated for launch in 2035, the European space mission eLISA will "listen" for gravitational waves from merging black holes and other astrophysical phenomena. The experiment will be able to detect spacetime ripples from black holes with masses of 10,000 to 10 million solar masses from across the universe. If black holes with such masses existed, and merged, even just a few million years after the Big Bang, eLISA will find them.

