 by Camille M. Carlisle

Of Black Holes *and* Galaxies

How much influence do supermassive black holes have on their galaxies, or vice versa?

Black holes might seem like control freaks. A gaping maw in the fabric of spacetime, devouring anything fool enough to come close, inexorable in its dominance — that's basically the dictionary entry for a tyrant.

But in fact, these objects have surprisingly tiny spheres of influence. Their gravitational reach is small, only a few light-years. Stars can even come within a few thousandths of a light-year and survive unscathed. As far as a galaxy should be concerned, its black hole could just as well not be there.

Yet that's not the case. In the 1990s and 2000s, astronomers noticed some unexpected correlations between galaxies and the supermassive beasts enthroned in their hearts. The black holes' masses increased or decreased in tandem with other galaxy properties: the more massive the black hole, the bigger and brighter the galaxy's central bulge of mature stars, and the faster those stars zipped around.

"[These connections] tell us that either the black hole cares about the galaxy that it lives in, or the galaxy cares about the black hole that's in it," says Kayhan Gültekin (University of Michigan), who has been one of many to investigate the link with star speeds, called the *M-sigma relation* (*M* for the black hole's mass, *sigma* for the range of stellar velocities).

But bulges can easily span 10,000 light-years, far beyond the black hole's presumed reach. In other words, these correlations shouldn't exist. Yet preliminary data showed relations that looked so good, they appeared to have "no scatter": all the systems tightly hugged a straight line on a graph.

"That seemed like it had to be magic," says Jenny Greene (Prince-

▶ **MONSTER WITHIN** The galaxy M106 has a pair of "anomalous arms" that intersect with its spiral disk. Astronomers suspect that the jets of the active black hole at the galaxy's heart are creating shock waves in the interstellar gas, thereby heating the gas and shoving it out of the galaxy. This outflow appears as the arms, which glow in radio, optical, and X-ray wavelengths.

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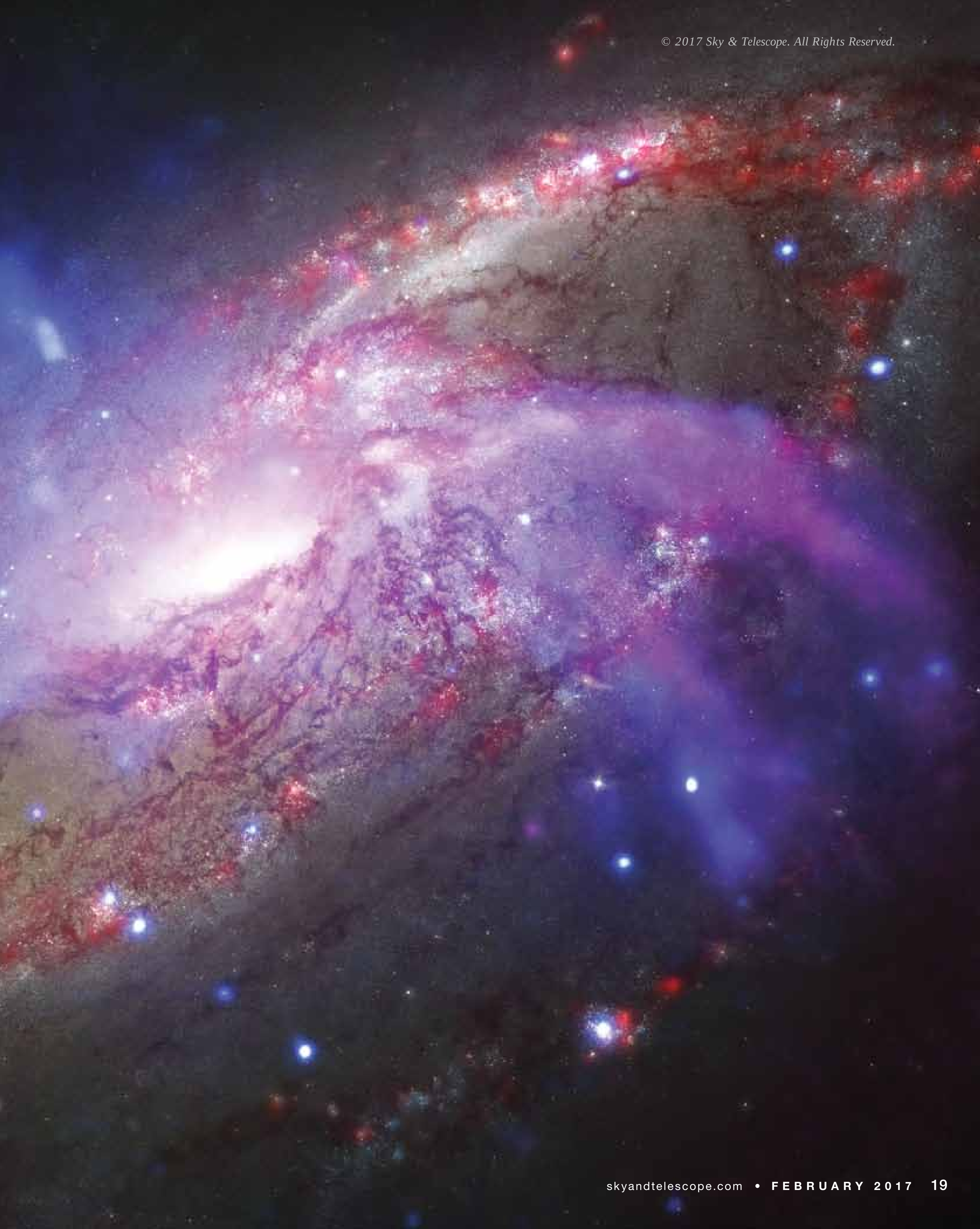
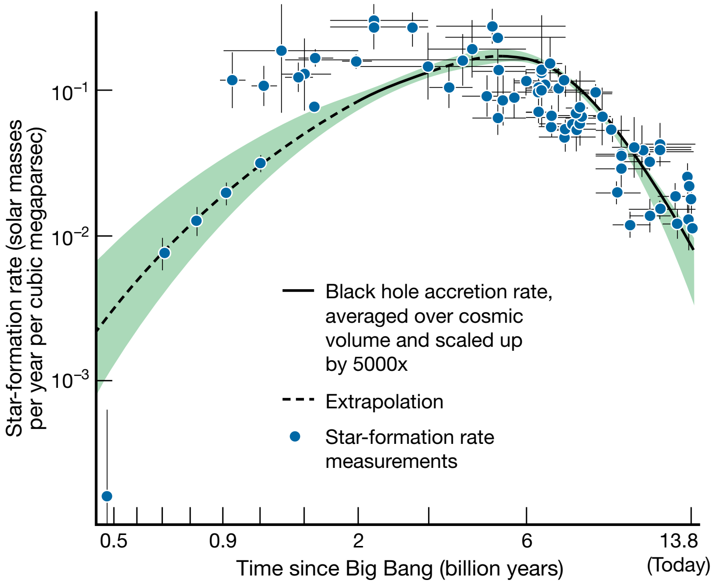




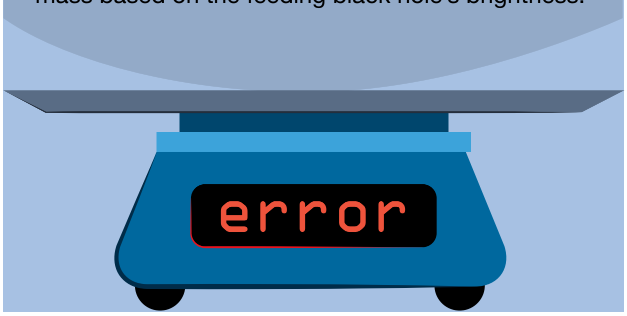
STARS AND BLACK HOLES This figure tracks the growth of black holes and of galaxies (manifested as star formation) over cosmic time. At first glance, the graph appears to show that black holes and galaxies co-evolve. But while black hole accretion and star formation rates do track each other closely in the last 10 billion years, that might arise if they're controlled by the same thing — for example, the gradual decline of fuel as the universe's cold gas supply is used up. Another explanation is that, if both black holes and galaxies grow early on thanks to galaxy mergers, then the rates might decline in recent cosmic times because galaxy mergers are increasingly rare as the universe expands.

How We "Weigh" Black Holes

Obviously astronomers can't put a black hole on a bathroom scale. (It's impolite.) So to measure the mass of one of these objects, observers clock the speed of stars or gas whirling around it in a galaxy's core. These velocities depend on the mass of the black hole that the stars or clouds are orbiting. When observers can also see how far away this stuff is from the black hole, they can then directly measure the beast's mass.

When it's impossible to see how large these orbits are directly, astronomers turn to the accreting material's glow. Active black holes are notorious for their flickering. The delay between flickers corresponds to how long light took to travel from one side to the other of the accreting gas — and since light travels at a finite speed, the travel time tells us the distance crossed. That distance, plus the gas's orbital speed, corresponds to how massive the black hole is.

When all else fails, astronomers estimate the mass based on the feeding black hole's brightness.



ton University). Astronomers immediately started speculating that galaxies and black holes grow in lockstep. "It had to be some kind of feedback loop between the black hole and the galaxy," she says, describing what scientists thought at the time.

Many suspected that the black hole dominated the relationship. If so, these little spacetime monsters controlled not just unlucky, passing stars but galaxy formation across the universe, serving as invisible masterminds in the development of cosmic structure. Black holes were suddenly the most important object in the cosmos. When I wrote my master's thesis on these objects in 2010, one astronomer told me that "understanding the whole history of the universe is locked up in understanding black holes."

But with more data, astronomers are realizing that the tale isn't so magically simple. The saga may not have the black hole as its all-powerful hero. Instead, the hole might just be along for the ride.

Messed-up M-sigma

At first, astronomers thought all galaxies obeyed M-sigma and the other correlations. But soon they realized that wasn't the case. True, the correlations did hold in typical elliptical galaxies, those big bulbous balls of old stars. But the trends show up only weakly, if at all, in disk galaxies. In such systems, none of the galaxies' properties — their total mass in stars, their bulge mass, the range of star speeds, or the mass of the dark matter clouds they sit in — closely aligns with the central black hole's mass.

If the M-sigma rule applied to every galaxy, then disk galaxies should have black holes much beefier than they do. Instead, several astronomers have seen a "lightweight" trend in recent years, including Greene's team.

"The only population left where there is a tight relationship between the black hole and the galaxy are these typical ellipticals," Greene says. Even the most massive ellipticals don't follow it well, she adds.

But spreading the message that there's no universal, tight coevolution has taken time. "We're terribly human people, and the psychology kind of took over," says John Kormendy (University of Texas at Austin), one of the first to suggest a relationship between black holes and their galaxies — and, with Luis Ho (Peking University, China), one of the first to raise the red flag against the lockstep growth many astronomers came to believe in. "Scientists get very sure of the things that they think they're very sure of. And sometimes they've been wrong — and when they are, it's a hell of a job to change the folklore."

CHART: *S&T*: LEAH TISCIONE, SOURCE J. KORMENDY AND L. HO / *ANNUAL REVIEW OF ASTRONOMY AND ASTROPHYSICS* 2013; ILLUSTRATION: *S&T* / GREGG DINDERMAN

That's not to say stellar beauties and their beasts aren't connected. Observations reveal that for at least the last 11 billion years, black hole growth and starbirth rates have risen and fallen together in a roughly constant ratio (see graph on the facing page). So there *might* be a link between them, but it could exist merely because the same factors influence the growth of both, not because they're tightly coevolving.

Thus the main question is, what is driving the apparent relationship? And that's where the real debate begins.

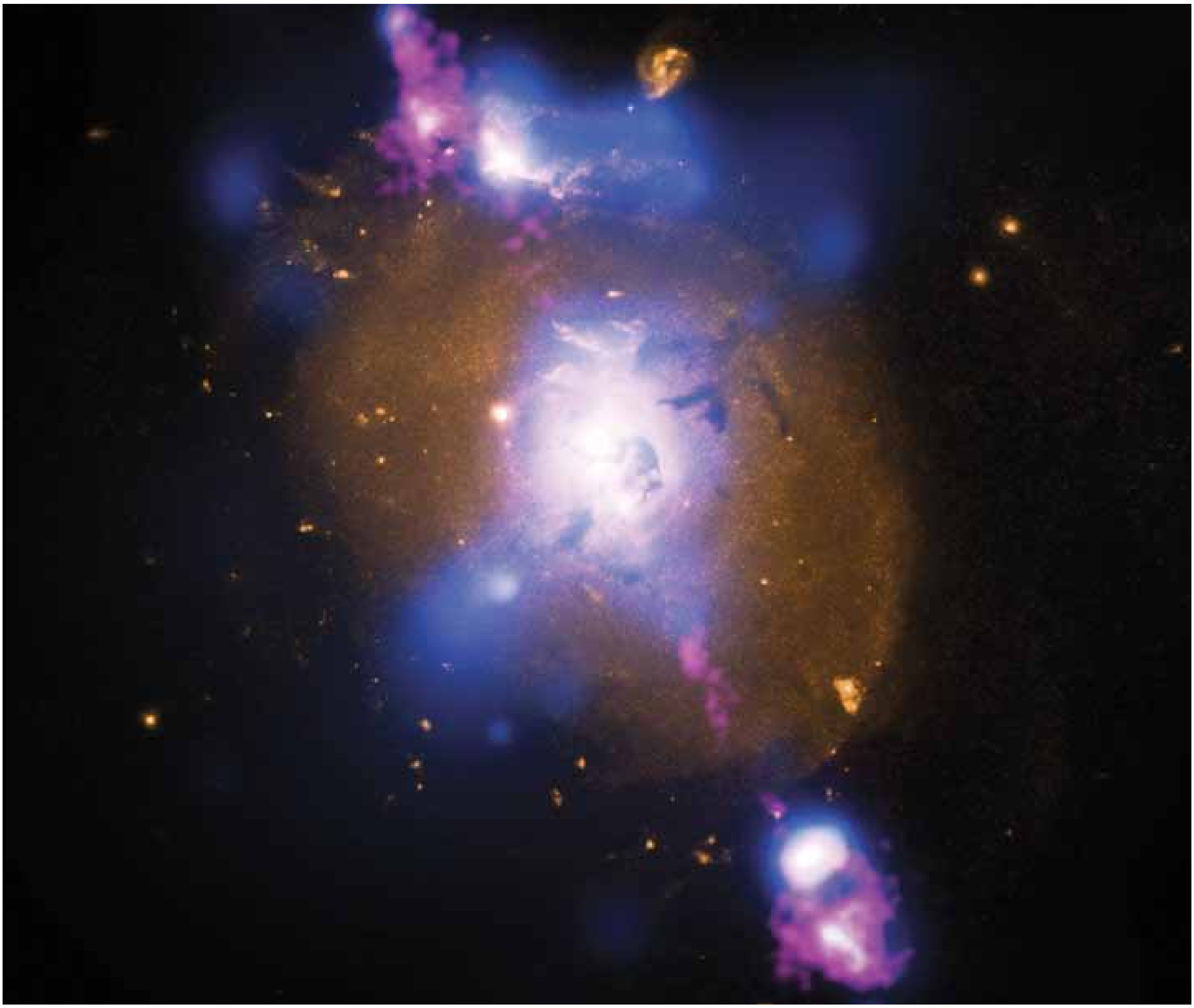
Option A: Black Hole Tyrant

Astronomers have good reason to suspect the black hole pulls the cosmic strings. The energy radiated during the hole's accretion can be 2,000 times greater than the binding energy of all the gas in the galaxy's central bulge. By the numbers, a madly gobbling black hole would be able to wreak havoc on its host. It could easily control the galaxy.

Throwing that possibility to astronomers was like throwing candy to trick-or-treaters. The major motivation for its popularity came from answering a different question: why are big ellipticals red and dead, when they're replete with gas?

Stars form from cold gas, and the gas surrounding these galaxies in big, X-ray-emitting halos is hot. But it shouldn't be: it should have enough time to cool and rain back down, fueling starbirth. Astronomers have detected a few precipi-

▼ **ON A RAMPAGE** The jets shot out by the black hole in the galaxy 4C+29.30 blaze in this composite image, which combines observations in X-ray (blue), optical (gold), and radio (pink) wavelengths. The optical light is from the galaxy's stars; the X-rays reveal million-degree gas, much of it appearing to pool around the black hole. The radio emission comes from particles accelerated by the jets. Because jets can carry so much energy into (and beyond) the surrounding galaxy, many astronomers suspect that they're the mechanism that controls star formation and black hole growth.



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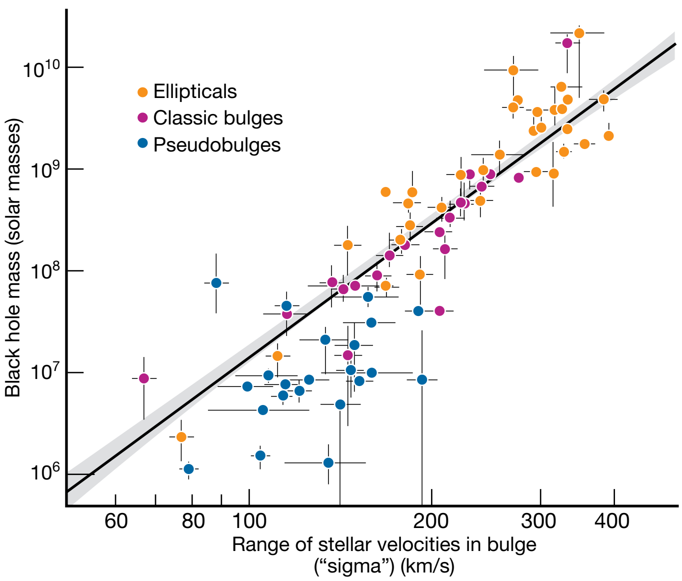
tating clouds (*S&T:* Nov. 2016, p. 11), but nothing like the downpour that should exist if the gas were left to cool on its own. Something is heating it.

One solution is black hole feedback. Dribble some gas on the beast, and it'll rouse like an angry dragon, shooting jets and inflating gigantic bubbles as it powers an *active galactic nucleus*, or AGN. The rising bubbles drag surrounding gas with them, creating eddies and turbulence. These motions heat the gas, preventing star formation.

Observers see signs of jet activity in more than 70% of the galaxies in clusters' centers — generally the biggest, brightest galaxies with the most hot gas. Many have cavities in their X-ray-emitting gas, too. Black holes thus serve as "cosmic thermostats," as one 2014 review article put it, modulating gas temperatures and closely regulating starbirth and, therefore, galaxy growth.

"I don't think anyone disagrees with that," Kormendy says. "I would be very surprised if we were barking up the wrong tree."

Spurred on by its utility in heating gas, feedback became *the* thing in astronomy. Many suspected that the hole forced its host to adhere to its own growth rate as the beast haphazardly chomped on gas, explaining the trends. "At some black hole conferences you'll still see people show the M-sigma correlation and say, 'This is evidence for AGN feedback,'" says Chien Peng (Giant Magellan Telescope Organization) told me



▲ **M-SIGMA** As astronomers gathered more observations, it became clear that the masses of all galaxies' black holes do not tightly trend with the galaxies' other properties. In their 2013 review John Kormendy and Luis Ho divvied up galaxies based on their shapes and concluded that, although elliptical galaxies and those with classical bulges still follow the trend (black line), galaxies with pseudobulges do not. Not all astronomers are convinced by this distinction, but this result helped astronomers recognize that all black holes and galaxies don't grow in lockstep. This figure only includes black holes for which astronomers have direct mass measurements, not indirect ones (see sidebar, p. 20).

▲ **BULGES** M87 *(above left)* is the classic example of a massive elliptical galaxy. Distinguishing between classical bulges like the one in M81 *(center)* and pseudobulges like that of M77 *(right)* is tougher — knowing the stars' orbital paths helps, because those in classical bulges are less orderly.

in 2012. "People often say that black holes have to grow by accretion and that feedback must happen. To that I usually respond by saying, 'All those things could happen but still have no bearing on a correlation.'"

That's because, although the black hole is no doubt partly responsible for heating galaxies' halos of gas, the thermostat effect would preserve a correlation that was already there — it wouldn't necessarily create it. And AGN feedback is too weak to control growth in most galaxies. There are plenty of active galaxies that don't follow the trends, Kormendy says, including the two spirals NGC 1068 and NGC 4151, whose black holes astronomers have studied for decades.

"It's still thought that the black hole has an influence on the galaxy, but it may not be as dominant as was thought," Gültekin sums up. Nowadays the question is what *kind* of feedback is important — maybe jets, or winds driven out by the accreting black hole's glow (called *quasar feedback*). Generally jets get the attention, says Gültekin.

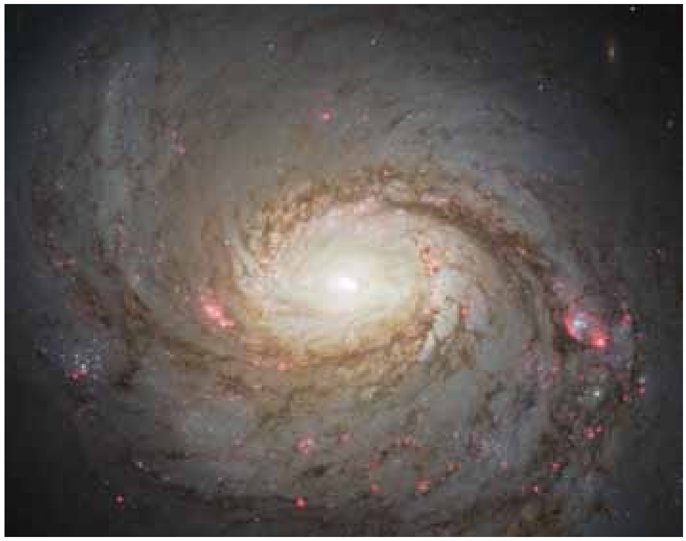
"I'm actually probably in the minority now in thinking that quasar feedback is still an important component," he says. "But there's been no vote on this, this is just my informally taking the temperature of the community."

Option B: Mergers

Peng was among the first to say that the apparent connection between galaxies and their black holes could simply be a matter of math. Take any two galaxies and merge them, then do it again and again and again, and the correlations will arise naturally, no feedback needed. It's an inevitable outcome of adding big numbers together.

But when Peng first suggested the idea, feedback was "a super-hot topic," he says. "You can imagine the excitement, and fear, I had to potentially start a controversy," he says,

M87: CHRIS MIHOS (CASE WESTERN RESERVE UNIV.), ESO; *S&T:* LEAH TISCIONE / SOURCE: J. KORMENDY AND L. HO / *ANNUAL REVIEW OF ASTROPHYSICS* 2013



M81: NASA / ESA / HUBBLE HERITAGE TEAM (STSCI / AURA); M77: NASA / ESA / A. VAN DER HOEVEN

recalling when the scenario first popped into his head. "The merger idea was so exciting to me that I almost missed my flight to Germany that morning in 2007 from a lack of sleep."

Kormendy also thinks mergers are the answer, but in a different way. He explains that the correlations don't just appear in ellipticals: they're also in spiral galaxies with *classical bulges*, which are essentially little ellipticals skirted by a big disk. Mergers with other galaxies made both these systems.

But the trends show up only weakly — if at all — in disk galaxies that have *pseudobulges*. Pseudobulges look similar to classical bulges but probably didn't grown via galactic crashes. (The Milky Way has a pseudobulge.) Instead, astronomers think that these central spheroids arise thanks to internal dynamics that reorganize stuff in the galaxy. Pseudobulge stars tend to follow more orderly, disk-like orbits, ostensibly because they've developed slowly over several billion years as gas trickled to the galaxy's core and fed star formation. In contrast, classical bulges would have grown suddenly, when a merger dumped a bunch of gas into the galaxy's center and triggered a starburst, Kormendy says.

Given that the correlations are tighter in galaxies with violent histories, the mergers must somehow be connected, he argues.

"If you're not making classical bulges, you're not making the correlations," he sums up. "You may be growing black holes, but you're not making the correlations."

Mergers in of themselves aren't enough in this picture, though; the intermingling galaxies also have to be full of cold gas. Cold gas makes stars and feeds black holes, and without it, mergers can only preserve a galaxy–black hole trend that's already there, not create one, he says. That could only happen in the early universe, 10 to 12 billion years ago. Back then galaxies were half gas, whereas nowadays a typical big galaxy has only 5 to 15% of its mass in cold gas, he explains. Observations confirm that mergers in today's universe aren't producing the correlations. "The magic that happened in the early universe that allowed this coevolution can't now be recreated," he says.

Despite Kormendy's confidence, other astronomers doubt that a galaxy's merger history explains everything. "Unfortunately in elliptical galaxies, *everything* is tightly correlated — the sizes, the masses, and the black hole," Greene says. "But once you open up to the entire galaxy population — which we have very painstakingly done over the last decade — it gets much messier."

At lower masses, the galactic population is dominated by spirals. These galaxies mostly have pseudobulges, not merger-made classical bulges, she explains. Although there are a few ellipticals at lower masses, she doesn't think there are *enough* merger-created structures at all scales to prove that the trends' driver is galactic history.

Option C: The Galaxy Reigns

If a galaxy were the size of Earth, its central black hole would be the size of a penny. Our planet certainly doesn't notice its pennies. So perhaps galaxies don't notice their black holes, either; the beasts just grow when their hosts deign to feed them.

Although cold gas feeds both starbirth and black holes, astronomers have found that, when a burst of star formation begins — say, due to a collision with another galaxy — AGN activity doesn't blaze up for another 250 million years. That suggests the black hole has to wait for gas to make its way to the center.

Perhaps the delay is one the galaxy itself imposes. This time frame matches a stellar switch point, specifically the stage at which the most massive stars in the galaxy's center have all died in supernovae. The remaining suns would be much smaller and evolve more slowly, with no violent outflows to stem the gas raining down into the core and onto the black hole. Thus, it could be that stellar feedback prevents the black hole from accreting, forcing the beast to grow when the galaxy does and thereby creating the M-sigma trend.

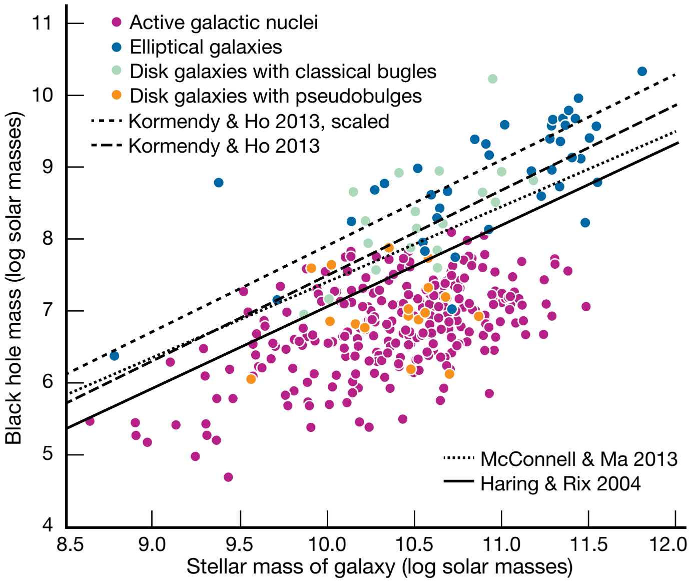
The details of this scenario are still unclear, and the stellar switch is just one option. But in big-picture terms, the black hole depending on the pleasure of the galaxy makes sense: the galaxy is *much* bigger than the black hole, and it serves as the fuel reservoir for both star and black hole growth.

That might explain why astronomers sometimes find weak echoes of a trend across other segments of the galactic population. Marta Volonteri (Paris Institute of Astrophysics) and Amy Reines (NOAO) recently looked at 341 nearby galaxies, 262 of which contained an actively accreting black hole. The

> "Even if there's no real coevolution going on, it would be a little surprising if there wasn't a crummy correlation."

duo found that the black hole's mass did increase with the galaxy's total stellar mass. But for a given galactic weight, the accreting beasts were roughly one-tenth as massive as those that weren't feasting on gas.

Volonteri and Reines couldn't see the shape of the galaxies they studied, because the accreting black hole acts as a floodlight, blinding telescopes to the stellar metropolis that contains it. But today's active galaxies are usually spirals, with small bulges and smaller black holes than ellipticals have. If these AGN are spirals, then the result hints that there is some sort of trend governing black hole masses in these galaxies.



▲ **GALAXIES AND THEIR BLACK HOLES** This graph shows the relationship between galaxies' masses in stars and the masses of their central black holes. The straight lines are possible relations between black hole mass and the mass of the galaxy's *bulge* (ellipticals are essentially all bulge). The active galactic nuclei (AGN) shown have had their masses measured in a more indirect way (so they're more uncertain) and include many dwarf galaxies. For many AGN shown here, it's unclear what shape the host galaxies have. But today's AGN usually appear in spiral galaxies, so *if* most of these galaxies are spirals, then this graph confirms that spirals generally have less massive black holes than ellipticals do.

That makes sense, Kormendy says. "Even if there's no real coevolution going on, it would be a little surprising if there wasn't a crummy correlation between the gas reservoir and how much you could feed a black hole," he says. "It would be completely unnatural if there weren't."

Perhaps all the correlations are crummy. All of the astronomers interviewed for this article noted that, because feedback and lockstep evolution were such popular ideas, they're now entrenched far more deeply than the data justify. "I tend to be a little more cynical," Greene says. "I was a kid when the M-sigma relation got everyone excited," so she doesn't have a lifetime of work riding on its defense.

Volonteri also doesn't believe in lockstep growth. "I strongly believe that there is a coevolution, but the way I mean coevolution is very different," she says. "To me, coevolution means simply big black holes, big galaxies; small black holes, small galaxies."

Both galaxy and black hole depend on something much bigger, though: the cosmic gas supply. Recent simulations by Tiziana Di Matteo (Carnegie Mellon University) and others follow the growth of galaxies and their black holes across the early eons of cosmic time. The researchers found that the biggest black holes tend to grow in spheroidal galaxies, not those dominated by disks — which matches what astronomers see observationally. But, Di Matteo's team explains, this is because such galaxies form at the nodes of several filaments in the cosmic web, where cold gas pours straight in instead of coming in at an angle, as it does for disk galaxies. That could explain why a galaxy's shape is connected to its black hole's mass. The simulations also suggest that whether a galaxy is a ball or a disk depends on where it's born and how the cosmic web feeds it, not on whether it merges with something else.

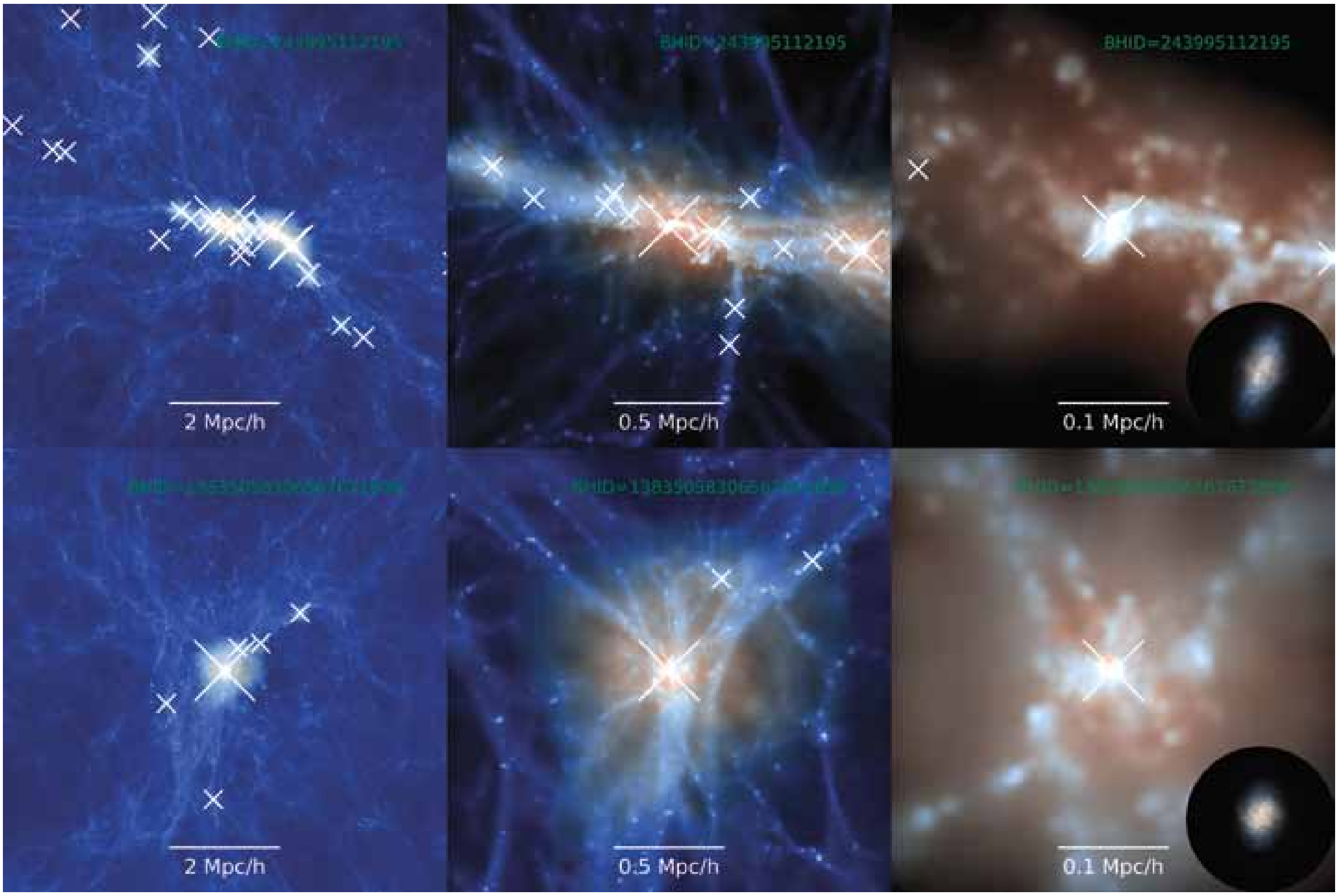
Finding the Culprit

Astronomers do not agree on which of these scenarios is true. They might all be, to some extent. Part of the problem is that we don't know when the correlations arose or what they looked like early on. Studying galaxies from the universe's first couple billion years requires valiant struggle. The systems are far away, so they're small and faint, plus cosmic expansion shifts their light to longer wavelengths, making them harder to study. Not to mention the universe was smaller and more crowded, and things were rowdy; a big galaxy back then was much smaller — or in pieces — compared with now, with gas pouring in from the cosmic web to boot. "Life back then was really seriously messy," Kormendy says.

Astronomers see hints that the M-sigma relation is looser in the early universe, with bigger black holes for a given range of star speeds. But they're wary of trusting that impression. The AGN detectable in that cosmic era are the brightest ones, and they might be the basketball players of the population, far larger than the norm, Volonteri cautions.

Kormendy agrees. "I wouldn't want to stick my neck out terribly far on our understanding" of what was happening 11 or 12 billion years ago, he admits.

S&T: LEAH TISCIONE, CHART SOURCE: A. REINES & M. VOLONTERI / *ASTROPHYSICAL JOURNAL* 2015 (813:2:82)



▲ **COSMIC WEB** These snapshots from the BlueTides simulation show the gas environments of the most massive disk galaxy that formed in the simulation (top row) compared with the most massive black hole and host galaxy. These stills are from about 650 million years after the Big Bang; the rightmost, circular inset in each row is a zoom in on the host galaxy. Hotter gas appears redder. Large crosses mark the positions of black holes, and their sizes are proportional to each hole's mass. Although massive disk galaxies did grow big black holes in the simulation, they generally didn't contain the most massive ones. The simulation also confirms that spheroidal (elliptical) galaxies grow at the crossroads of many filaments in the cosmic web, whereas disk galaxies form along more isolated filaments. The results suggest that a galaxy's shape depends on where it forms in the cosmic web, not on whether it merges with another galaxy.

TIZIANA DI MATTEO ET AL. / *ARXIV.ORG* 2016

Dwarf galaxies may help. Greene and others have been tracking down the black holes at the centers of these galactic runts because dwarfs are the primordial crumbs of galaxy formation, left more or less unscathed since they first formed. "There's something interesting to learn by looking specifically at galaxies that don't really have mergers and didn't really undergo that kind of growth," she says. If they and their black holes follow any trends today, it will be because they were born with them.

Gültekin agrees that galaxies shirking M-sigma, whether barely or flagrantly, are an important place to look. "Things that don't follow the relation are important clues for telling us what's not important for driving the relationship," he says.

His team is investigating gas outflows from a range of galaxies. If researchers can pin down how fast this material moves, then they can determine how much energy must be launching the flows and whether the black hole is to blame.

What astronomers really need is a census, Greene says. What is the full distribution of black hole masses across the entire galaxy population? ALMA and the next-gen superscopes should enable observers to peer out to 60 or 70 million light-years, detecting all types of galaxies and measuring black holes down to a million solar masses, the same size as the Milky Way's (relatively puny) supermassive beast, she predicts.

"Then we'll be able to see the full range of black hole masses," she says. "We'll be able to slice and dice the sample into things that are round and things that are flatter and things that evolved slowly and things that are more like bulges and ask whether they're different."

At that point, astronomers will finally discover just what the connection between black holes and galaxies is. Maybe they'll exonerate the poor little beasts of cosmic guilt. Or maybe the objects will prove just as ruthless as the sci-fi stories claim.

■ Every time she writes a story about these spacetime potholes, Science Editor **CAMILLE M. CARLISLE** resists the urge to cry out, "BWAHAHAHA BLACK HOLES!"