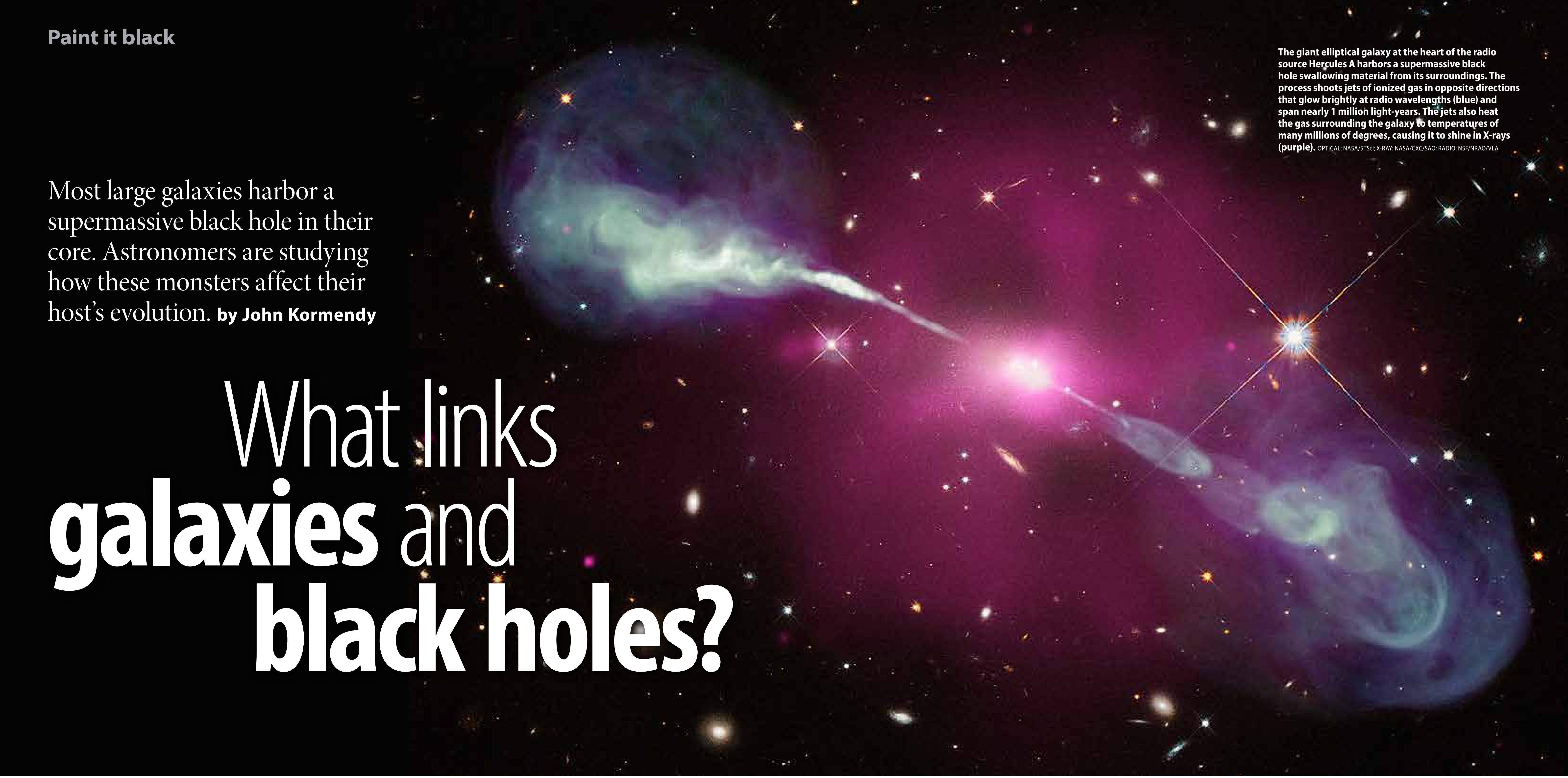
What links galaxies and black holes?

Most large galaxies harbor a supermassive black hole in their core. Astronomers are studying how these monsters affect their host's evolution. **by John Kormendy**



The giant elliptical galaxy at the heart of the radio source Hercules A harbors a supermassive black hole swallowing material from its surroundings. The process shoots jets of ionized gas in opposite directions that glow brightly at radio wavelengths (blue) and span nearly 1 million light-years. The jets also heat the gas surrounding the galaxy to temperatures of many millions of degrees, causing it to shine in X-rays (purple). OPTICAL: NASA/STScI; X-RAY: NASA/CXC/SAO; RADIO: NSF/NRAO/VLA

Do supermassive black holes control how their host galaxies evolve? Recent research gives a nuanced answer to this fundamental question. Beginning in the mid-1990s, astronomers came to believe that these objects grew together and controlled each other. The reasons were compelling, and the conclusion seemed to make it easier to understand galaxy evolution.

But first conclusions often turn out to be oversimplified. Early hints a decade ago have now turned into a flood of studies that clarify how and when galaxies and black holes affect each other — and when they do not.

The first inkling

Supermassive black holes entered the astronomy lexicon soon after 1963. That year, California Institute of Technology astronomer Maarten Schmidt discovered that the enigmatic radio source 3C 273, which coincides with a 13th-magnitude starlike object, was not a star at all. Its optical spectrum exhibited an astonishing redshift that implied it is receding from Earth at 16 percent the speed of light, making it the second-farthest object then known.

Hundreds more of these "quasars" soon turned up. Many shine brighter than whole galaxies. But rapid variations in their brightness — sometimes in less than a day — imply that the "engines" driving these emissions must be smaller than our solar system. Although it took years to prove that quasars reside at galaxy centers, it was immediately clear that their engines have to be extremely efficient. Many spew jets of ionized gas (plasma) millions of light-years into space.

These jets give researchers a way to calculate a lower limit on how much energy a quasar emits. Cambridge astronomer Donald Lynden-Bell first showed that the nuclear reactions that power stars could not produce such huge energies without also making 10 times more energy through gravitational contraction. Evidently, gravity powers quasars. After a Darwinian struggle among competing theories, astronomers settled on supermassive black holes that swallow any gas that comes too close. As the gas falls in, it speeds up to nearly the speed of light. Friction then heats the gas so much that it emits the ferocious radiation we see.

Indirect evidence for supermassive black holes grew stronger from the 1970s to the 1990s. The most compelling observations were of many compact knots in galaxy jets that appear to move outward at five to 10 times the speed of light. This is an illusion that results when a jet points almost directly at us and travels at nearly the speed of light. It then looks like the knots move faster than they really do because they almost keep up with the light that

▲Astronomers first thought that 3C 273 was an odd star that emitted radio waves. Starting in the 1960s, however, they came to understand such objects as the active cores of distant galaxies powered by supermassive black holes. The wavy line to the upper left is a jet of high-energy particles fired from the quasar's central engine. ESA/HUBBLE AND NASA

◄Amplified microwave emission from water molecules in a gaseous disk at the center of spiral galaxy M106 helped astronomers prove that it contains a black hole with a mass of 38 million Suns, and not a dense cluster of failed or dead stars. NASA/ESA/THE HUBBLE HERITAGE TEAM (STScI/AURA)/R. GENDLER (FOR THE HUBBLE HERITAGE TEAM)

they emit. Flinging clumps of plasma at close to light-speed essentially requires a black hole.

By the 1980s, most astronomers were convinced that accreting black holes with masses of millions to billions of Suns powered quasars and their weaker cousins, active galactic nuclei (AGNs). But there still was no direct evidence that such hefty masses exist at galaxy centers. Direct searches for black holes through their effects on surrounding stars and gas became a hot topic in the 1980s. This situation was dangerous: It's easy to believe you have proved what you expected to find. For this reason, scientists set the standards of proof very high.

Starting in 1988, astronomers detected supermassive black holes in the Andromeda Galaxy (M31), the Sombrero Galaxy (M104), and several other nearby galaxies. Ground-based spectra of each of these objects resolved the small volume near the galaxy's center where the black hole makes stars move faster than they would if they felt only the gravity from other stars.

Meanwhile, the Pinwheel Galaxy (M33) hinted that at least some galaxies — those without a bulge (a dense, spherical collection of stars surrounding its center) — contain no supermassive black hole. After astronauts fixed the Hubble Space Telescope's optics in 1993, its observations confirmed the ground-based discoveries. By the early 2000s, Hubble had turned up about 30 dark objects in the centers of more distant galaxies. But were any of these bodies truly black holes?

To answer this question, researchers had to rule out alternative hypotheses that the central dark objects might be clusters of failed or dead stars. They managed to do so in two high-profile cases. In the spiral galaxy M106, astronomers used radio telescopes to discover a tiny, central molecular gas disk in which water molecules emit amplified microwave radiation. These observations provided unprecedented resolution and showed that the central dark object, which contains 38 million solar masses, is too small to harbor the necessary number of failed or dead stars.

John Kormendy, *one of the world's leading experts on galaxies and on black holes, is professor of astronomy at the University of Texas in Austin. In the late 1980s, he and astronomers Alan Dressler and Douglas Richstone were the first to discover supermassive black holes in galaxies.*

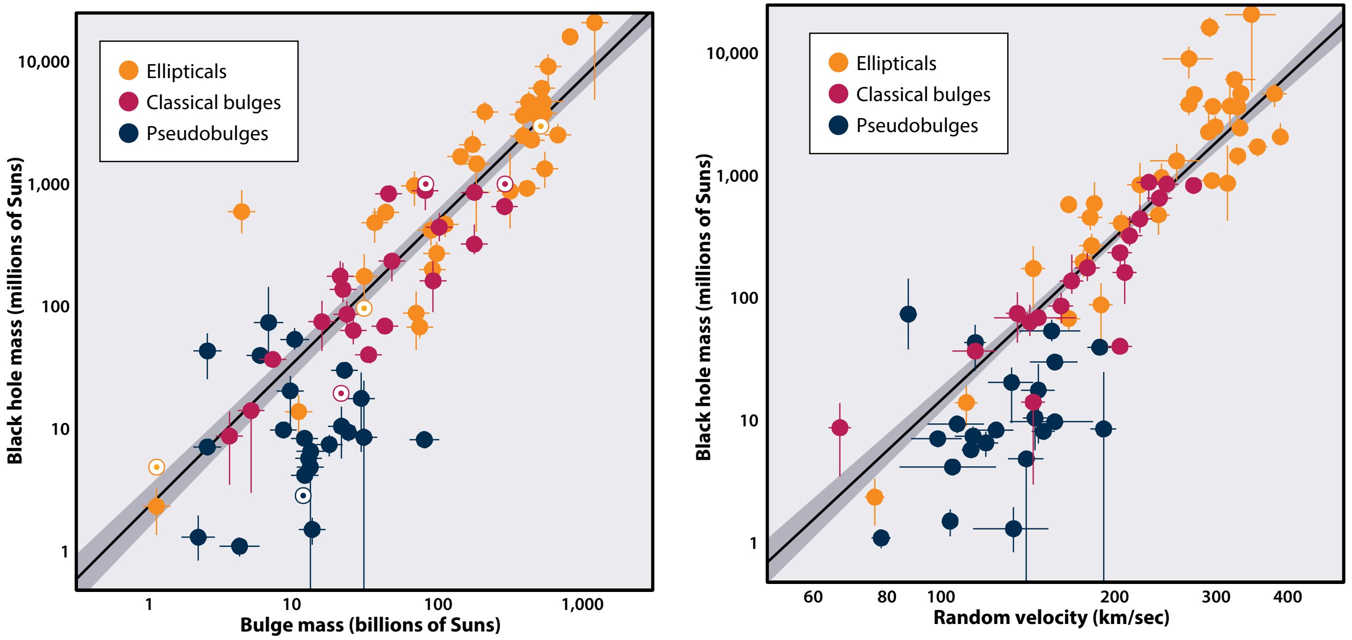
But our galaxy makes the best black hole case. In 2002, scientists started observing the motions of individual stars in the core and proved that the central 4.3 million-solar-mass dark object is too small to be anything other than a black hole. By 2005, Hubble observations excluded black hole alternatives for the central object in the Andromeda Galaxy. In this way, astronomers grew progressively more certain that they were discovering supermassive black holes.

Do black holes control galaxy evolution?

A number of results in the 1990s led researchers to the idea that supermassive black holes and galaxies grow in lockstep, controlling each other's evolution. It began with the discovery that the mass of the central black hole correlates tightly with both the luminosity and mass of the host galaxy's bulge. Although the first version of this correlation from 1993 included only seven galaxies, the results agree nicely with the best current values for these seven plus a host of new galaxies.

More convincing evidence came with the 2000 discovery that a black hole's mass seemed to correlate even more tightly with the typical speeds of stars in the outer, main part of the galaxy. In this region, it is the gravity of the galaxy's stars and not of its black hole that controls the objects' movements. With a larger sample of galaxies and more accurate masses available today, the two relationships appear to have the same scatter. Astronomers find such correlations extremely compelling — they suggest that the two phenomena influence each other.

The black hole-galaxy connection



These diagrams compare the mass of a central black hole to the mass of its host galaxy's bulge (left) and to the random velocities of stars that are in the bulge but far enough out so that the black hole doesn't affect them (right). In both cases, the black hole's mass correlates tightly for elliptical galaxies and for the classical bulges of disk galaxies (those that form quickly during mergers) but not with "pseudobulges" that form slowly out of disks. The dotted open circles in the left panel are the seven galaxies from the first published black hole correlation. *ASTRONOMY*: ROEN KELLY, AFTER JOHN KORMENDY AND LUIS HO

Meanwhile, several astronomers had pointed out that it takes a lot more energy to gravitationally bind the central black hole than to bind the host galaxy. Could some of the energy radiated away during the black hole's growth affect galaxy formation? The radio lobes and jets seen in radio galaxies such as Hercules A (see p. 46–47) show how the central engines in AGNs can deliver energy to the hundred-million-degree gas that fills the galaxy's host cluster.

If the gas that goes into forming the galaxy absorbs only a tiny fraction of the energy produced as the quasar's black hole feeds, then that gas can reach temperatures too high for star formation.

The Pinwheel Galaxy (M33) in Triangulum is the third-largest member of our Local Group. It has a disk but no bulge, and it does not harbor a supermassive black hole in its core. ESO

In some cases, the gas can get blown completely away. No leap of the imagination is required to guess that black holes might, in this way, control galaxy evolution. Astronomers also observe that the history of quasar activity in the universe parallels the history of star formation. This adds icing to a beguiling cake.

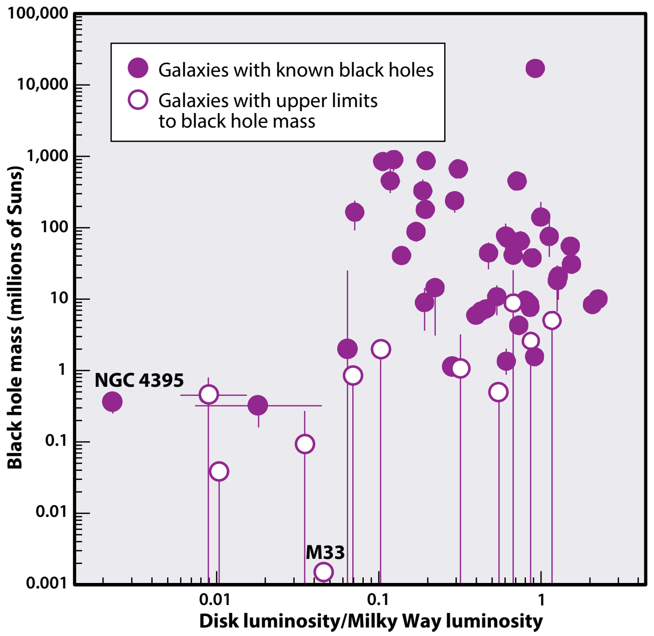
The idea that black holes control galaxy formation proved a welcome addition for scientists who develop computer simulations of how galaxies form. It is now straightforward to model how density fluctuations in dark matter — the still-mysterious stuff that gives off no light and interacts with normal matter only through gravity — grew from tiny perturbations in the early universe into today's galaxy halos. But modeling how atoms make visible galaxies inside these halos requires extra energy beyond what they can get from gravitational collapse. AGN feedback looked like the ideal solution. This simple picture in which black holes and their host galaxies control each other's evolution dominated astronomers' work from the mid-1990s until about 2010.

Not the final answer

Spiral galaxy M33 provided the first hint that this scenario is oversimplified. As the third-biggest galaxy in our Local Group, M33 was a natural target for black hole searches. It is a pure-disk galaxy — it does not contain a bulge. In the mid-1990s, I showed that if it harbors a central black hole, that object cannot be as massive in proportion to the galaxy's disk mass as bulge black holes are in proportion to their host bulges. By 2001, two independent groups used Hubble to show that M33 can't have a black hole much more massive than a paltry 1,500 Suns. In contrast, other galaxies having disks with the same mass as the one in M33 but with giant bulges contain black holes as massive as one billion Suns.

In general, the mass of a central black hole does not correlate with the mass of the host galaxy's disk, even when it does correlate

The black hole-disk connection



The mass of a central black hole doesn't bear much relationship to the infrared luminosity of its host galaxy's disk (which is approximately proportional to the disk's mass). Although there's a hint that the smallest black holes live in the tiniest disks, which would have the least amount of fuel to feed a black hole, there is no tight correlation, which suggests black holes influence disk evolution. The labels highlight two well-known bulgeless galaxies. *ASTRONOMY*: ROEN KELLY, AFTER JOHN KORMENDY AND LUIS HO

with the mass of the galaxy's bulge. From this, astronomers conclude that black holes do not affect disk growth. Instead, they affect — or coevolve with — only the bulge components of their host galaxies.

M33 is unusual because it does not harbor a supermassive black hole. Many disk galaxies — including those that have no bulge — do contain black holes, though they do not influence disk evolution. One of the best examples is the low-surface-brightness spiral NGC 4395 in Canes Venatici. This galaxy has a well-defined disk of spiral arms and no bulge. It also contains the smallest supermassive black hole astronomers have been able to measure reliably. In a tiny galaxy with a gentle formation history and little gas to act as fuel, it's not surprising that NGC 4395's black hole has grown slowly and reached a mass of only 360,000 Suns. Despite the black hole's small size, it does generate a faint AGN.

A group of researchers led by Luis Ho of the Kavli Institute for Astronomy and Astrophysics at Peking University, Jenny Greene at Princeton University in New Jersey, and Aaron Barth of the University of California, Irvine, has shown that such black holes are common. They conclude that classical bulges are not necessary to create central black holes.

Black holes in bulgeless disks are the least-evolved versions of the black hole seeds that grew into the monsters we see in giant bulges. The best current theory is that they got their start when the universe's first stars died, and some of them left behind fairly high-mass black holes. Subsequently, tens or hundreds of such black holes merged as protogalactic fragments collided, joined with one another, and eventually grew into today's galaxies. (For more details on how black holes form, see "Why are there so many black holes?" in the August 2016 *Astronomy*.)

The case for pseudobulges

A more-nuanced analysis of galaxies helps astronomers better understand how black holes and their galaxy hosts coevolve, or not. If a black hole lies at the center of an elliptical galaxy or the classical bulge of a disk galaxy, its mass correlates tightly with that of its host. The Andromeda Galaxy and M81 both have classical bulges.

But recent research has led astronomers to realize that some disk galaxies possess a kind of dense center created by a different mechanism. Galaxy mergers make classical bulges and ellipticals. But isolated disks can evolve, too, and they can grow high-density centers that until recently researchers often confused with classical bulges. Astronomers call them "pseudobulges" — fake bulges that develop slowly out of disks and not rapidly via mergers.

Two other galaxies provide good examples. In the barred spiral NGC 1300, the dark dust lane in the bar lies on the leading edge of the galaxy's rotation. The lanes mark the sites where gas flows toward the center and fuels star formation there, which grows the pseudobulge. NGC 3945 shows a mature version of this evolution. Here, disk gas has formed an outer ring but little gas remains in the inner parts of the galaxy, so the pseudobulge has stopped growing.

Pseudobulges form differently from classical bulges, and they behave differently, too. The diagrams on p. 49 show this clearly. The blue dots representing pseudobulges scatter widely, showing that black holes correlate tightly only with the old merger remnants of elliptical galaxies (orange dots) and classical bulges (red dots).

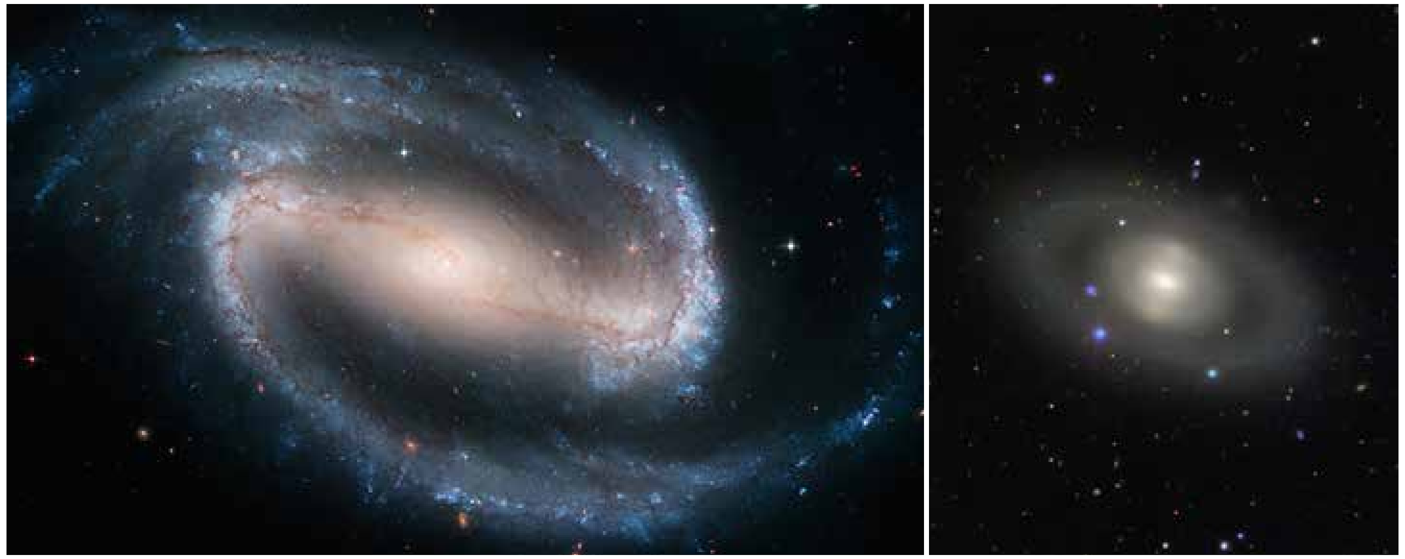
Supermassive black holes and their hosts

These and other galaxy properties give astronomers a new picture of how supermassive black holes and their host galaxies do and do not control each other's evolution. Based on new observations, Luis Ho and I have concluded that such coevolution takes three main forms.

First, disk galaxies without classical bulges can contain black holes, but they don't accrete much gas and thus grow slowly. Any resulting AGN activity puts out too little energy to affect the host galaxy. While the galaxy controls black hole feeding, the black hole does not control galaxy evolution. In the nearby universe, most supermassive black holes fall into this category.


ADAM BLOCK/MOUNT LEMMON SKYCENTER/UNIVERSITY OF ARIZONA

The small, low-surface-brightness disk galaxy NGC 4395 in Canes Venatici lacks a bulge. Still, it holds a 360,000-solar-mass black hole that powers a faint active galactic nucleus (visible as a blue dot at the galaxy's center). M33, a much bigger disk galaxy without a bulge, does not contain a black hole more massive than 1,500 Suns. Astronomers see no signs that the black holes in pure-disk galaxies affect disk evolution.



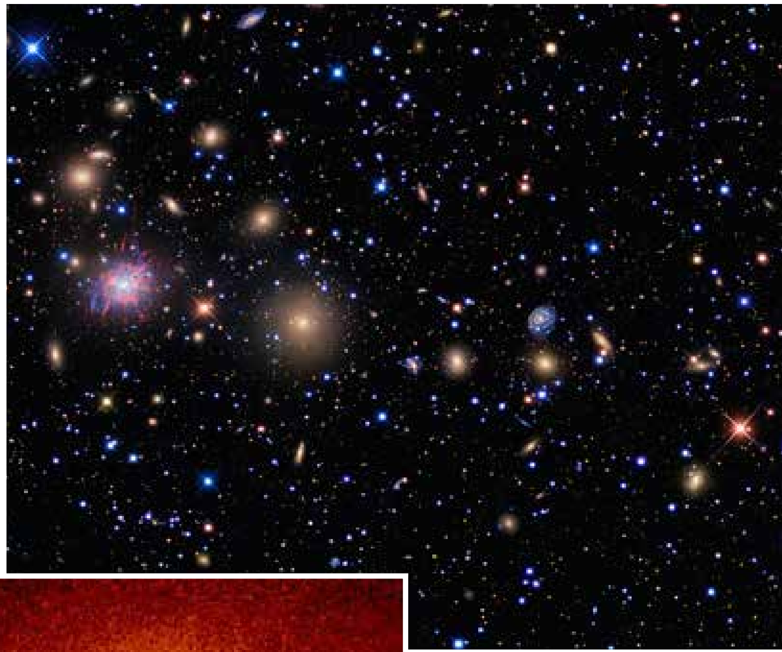
The disk galaxies NGC 1300 (left) and NGC 3945 (right) both contain pseudobulges. In NGC 1300, material funnels into the core where new stars form and the pseudobulge grows. NGC 3945 is further along in its evolution. An outer gaseous ring surrounds a core region with negligible gas and a fully formed pseudobulge. Astronomers can recognize pseudobulges because they tend to appear less spherical than classical bulges. For example, although the bright center in NGC 3945 may resemble a small elliptical galaxy, it looks as flat as the outer ring. NGC 1300: NASA/ESA/THE HUBBLE HERITAGE TEAM (STScI/AURA); NGC 3945: DAVID W. HOGG/MICHAEL R. BLANTON/THE SLOAN DIGITAL SKY SURVEY COLLABORATION

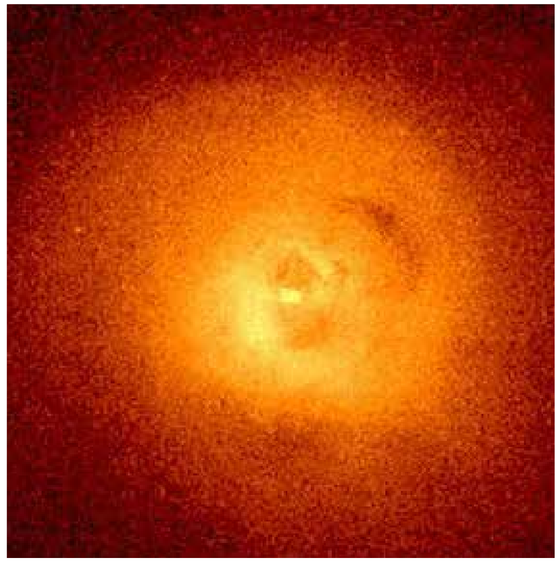
Second, AGN energy feedback helps to establish the tight correlation between black holes and their hosts during the mergers that make classical bulges and similarly low-luminosity ellipticals. These mergers are what astronomers call "wet" — the progenitor galaxies contain cold gas, and that gas falls to the center of the remnant during the merger, feeds enormous starbursts, and builds the high densities seen in classical bulges and ellipticals. The lion's share of such mergers happened during the quasar heyday when the universe was 2 billion to 6 billion years old.

In the local universe, ultraluminous infrared galaxies like Arp 220 are the prototypes for this process. The properties of such galaxies are just right to form ordinary, low-luminosity ellipticals once the starburst is finished. Astronomers don't know for sure what clears the galaxy of its residual gas, but our best guess is that energy feedback from the starburst starts to blow away the leftover gas and AGN feedback finishes the process. In this way, we believe that black holes help to control galaxy formation by helping to stop its late stages.

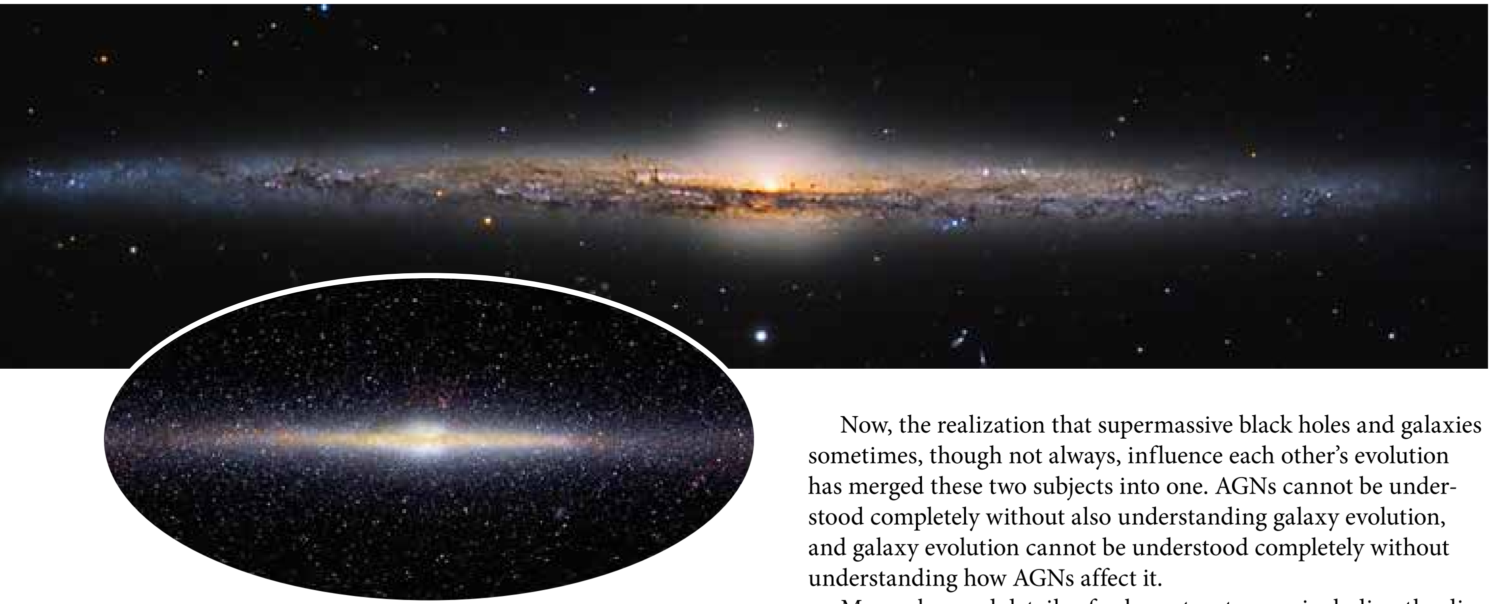
Third, giant elliptical galaxies have lower-density centers and differ in other ways from their smaller cousins. The only galaxies massive enough to create these behemoths are the ellipticals mentioned above, which must merge themselves. So, it is only natural that the giants inherit the black hole-host galaxy correlations from their progenitors. After the mergers, AGN feedback stops galaxy formation from "going to completion" by keeping normal matter locked up in hot gas and thus preventing subsequent star formation and black hole accretion.

The controlling factor is that these galaxies are massive enough to hold onto hot gas. In some giant ellipticals and in the rich clusters of galaxies where such monsters tend to live, the hot gas accounts for two to 10 times as much mass as the stars. If a galaxy rich in cold gas falls into one of these giants,





Galaxy NGC 1275 sits near the center of the massive Perseus Cluster of galaxies. The filamentary structures seen in visible light (at far left, above) represent cool gas suspended by magnetic fields; hot gas shows in a close-up of the galaxy in X-rays (left), where brighter and yellower colors indicate higher densities. The X-ray image shows several lower-density regions, which suggest that energy from radio jets fired by an active galactic nucleus blows bubbles that rise through the gas and help to heat it. TOP: R. JAY GABANY; LEFT: NASA/IOA/A. FABIAN ET AL.



Both the Milky Way Galaxy (above, seen in infrared light with the Cosmic Background Explorer satellite) and its close analog, NGC 4565 (top, seen in visible light), possess boxy pseudobulges. In each case, the pseudobulge is a bar viewed nearly end-on. Dust hides a second, flatter pseudobulge that is disk-shaped and actively forms stars. In galaxies like these, there is no evidence that a central black hole affects galaxy evolution. TOP: ADAM BLOCK/MOUNT LEMMON SKYCENTER/UNIVERSITY OF ARIZONA; ABOVE: NASA/MICHAEL HAUSER (STScI)/THE COBE/DIRBE SCIENCE TEAM

the hot gas strips away the cold gas and heats it into more hot gas. Any subsequent merger will be "dry" — it will involve negligible cold gas and star formation.

What keeps the hot gas hot? This question puzzled astronomers throughout the 1990s, because hot gas naturally cools, and calculations showed that many hot-gas halos would cool far faster than observations suggested. But thanks to orbiting X-ray telescopes that can measure the temperature profiles of these halos, we now know that the gas doesn't cool much.

The Perseus Cluster is a typical case. NGC 1275, the cluster's brightest galaxy and a strong AGN, fires radio jets into its surroundings that help create a halo of hot gas that glows brightly in X-rays. Although scientists don't yet know exactly how the AGN heats the gas, they know it plays a key role in the process. Most of the cluster's ordinary matter is in the form of hot gas, and thus unable to make new stars, and likely will remain so for a long time.

Where does the Milky Way fit in? Our galaxy contains a pseudobulge, a boxy structure akin to the one in the similar Needle Galaxy (NGC 4565). Astronomers now know that such structures are not really bulges — they are bars seen almost end-on. They are one kind of pseudobulge. The Milky Way thus contains our best case of a central supermassive black hole, one with a mass of 4.3 million Suns, that shows no sign of having affected the evolution of its host galaxy beyond the inner few hundred light-years.

A mature picture of coevolution

My theme has been the confluence of two major research movements in astronomy. For decades, hundreds of astronomers studied quasars and other AGNs and concluded that their engines are supermassive black holes that produce prodigious energies when they swallow stars and gas. Hundreds of mostly different astronomers studied galaxy structure and came to understand, in a general way at least, how various kinds of galaxies evolved. For many years, these movements proceeded independently.

Now, the realization that supermassive black holes and galaxies sometimes, though not always, influence each other's evolution has merged these two subjects into one. AGNs cannot be understood completely without also understanding galaxy evolution, and galaxy evolution cannot be understood completely without understanding how AGNs affect it.

Many observed details of galaxy structure — including the distinctions between the two kinds of bulgelike components and the differences between ordinary and giant ellipticals — suddenly make sense within the new AGN story. When so many details in our comprehension get connected with conceptual "bonds of steel," then our picture of AGNs and galaxy evolution gets much more reliable. This is a sign of the growing maturity of the subject. Well understood, mature subjects, such as the evolution of stars, went through the same transition from isolated cottage industries to multiconnected theories.

It reminds me of a quote from John Muir, published in 1911 in *My First Summer in the Sierra*: "When we try to pick out anything by itself, we find it hitched to everything else in the Universe."

NASA/ESA/THE HUBBLE HERITAGE (STScI/AURA)-ESA/HUBBLE COLLABORATION/A. EVANS (UNIVERSITY OF VIRGINIA, CHARLOTTESVILLE/NRAO/STONY BROOK UNIVERSITY)

The prominent loops and shells in Arp 220 are signatures of a "wet" merger of two disk galaxies. Gas from both progenitors is concentrated near the center where it feeds one of the most vigorous starbursts in the nearby universe. In this visible-light image, dust blocks our view of Arp 220's center. But the dust absorbs light from the young stars and reradiates it at infrared wavelengths, making this an ultraluminous infrared galaxy. Wet mergers create low-luminosity elliptical galaxies after star formation has finished.