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 by Camille M. Carlisle

Unmasked

The first image of our galaxy's central black hole gives us a peek at a bizarre object.

Enthroned in the Milky Way's heart sits the cowardly lion of black holes. Known as Sagittarius A*, this object holds the equivalent of 4 million Suns squashed into a region less than 20 times as wide as our star. A diffuse tulle of hot gas skirts the beast, fueling a glow about 100 times brighter than the Sun — so feeble that, if it lay in another galaxy, it would probably be undetectable.

Astronomers first discovered Sgr A* (pronounced "Sadj-ae-star") in 1974 as a "compact radio source," just as the realization was dawning that big black holes might sit in most galaxies' cores. Over the decades, observers have tiptoed closer to its lair. By the late 1990s they'd realized the radio signal had structure, but it would take another decade before they confirmed this structure was on the scale of the event horizon, a black hole's infamous point of no return.

> Sgr A*'s "shadow" spans about 50 microarcseconds on the sky, roughly the size of a grapefruit seen at the distance of the Moon.

Even with these advances, Sgr A* has remained just out of reach, crouched 26,000 light-years away. But on May 12, 2022, astronomers with the Event Horizon Telescope Collaboration jumped the distance and brought us face-to-face with our black hole. The EHT image, reconstructed from data taken at radio telescopes across the Western Hemisphere, shows a luminous ring encircling a dark center: the black hole's silhouette, marking where light from surrounding gas is either bent around the hole or comes too close and is swallowed.

Three years ago, the EHT team gave us a similar image of the much larger, plasma-jet-shooting black hole in the elliptical galaxy M87 (*S&T:* Sept. 2019, p. 18). With two images in hand of very different beasts — one extraordinary, one ordinary — astronomers can now say that M87*'s ring of light was no fluke; we are indeed seeing extreme gravity at work. But Sgr A*'s blurry visage also carries the beginnings of deep physical insight into our black hole and others like it, insight that already challenges some of our expectations.

As the World Turns

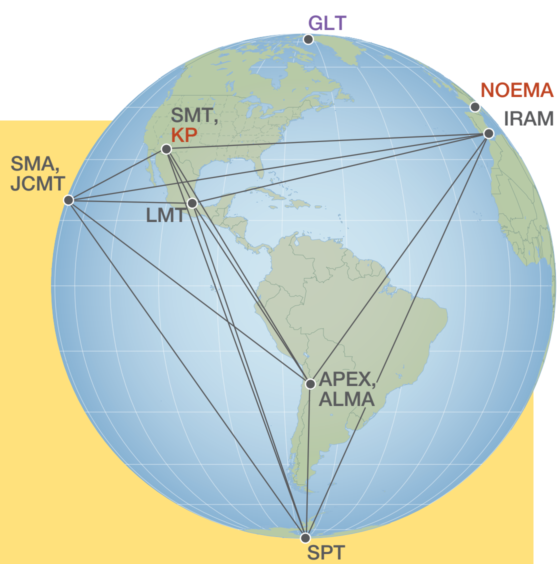
Sgr A*'s "shadow" spans about 50 microarcseconds on the sky, roughly the size of a grapefruit seen at the distance of the Moon. To espy such a minuscule sight, astronomers need an Earth-size radio telescope. They "build" this telescope by observing simultaneously with dishes spread across the planet, then flying data-filled hard drives back to supercomputers in Massachusetts and Germany, where they carefully sync the observations to within trillionths of a second. This technique is called *very long baseline interferometry*, or VLBI.

VLBI combines data from pairs of telescopes; more telescopes give you more combinations. Each pair probes a different scale, with close-together dishes sensitive to large-scale structure and dishes separated by thousands of kilometers picking up small structure. As the planet turns, different stations have different views, and their positions relative to one another change as seen from the target's perspective, filling in bits of the virtual telescope's dish.

◀ **HELLO** This is the first image of the black hole at the center of the Milky Way Galaxy. Scientists created it by averaging thousands of possible reconstructions, built with data from eight radio observatories.

OBSERVATORIES

Atacama Large Millimeter/submillimeter Array (ALMA)
Atacama Pathfinder Experiment (APEX)
IRAM 30-meter Telescope (IRAM)
James Clerk Maxwell Telescope (JCMT)
Large Millimeter Telescope (LMT)
South Pole Telescope (SPT)
Submillimeter Array (SMA)
Submillimeter Telescope (SMT)
Greenland Telescope (GLT)
Kitt Peak 12-meter Telescope (KP)
Northern Extended Millimeter Array (NOEMA)



▶ **PLANET-SCALE DISH** Eight stations participated in the EHT's 2017 observing campaign. All eight successfully observed Sgr A* on April 7th, collecting data over about 12 hours. In 2018 the Greenland Telescope joined the array, and in 2021 NOEMA and Kitt Peak did as well. (LMT sat the 2021 run out but returned in 2022.)

SGR A* SHADOW: EHT COLLABORATION; TELESCOPE ARRAY: LEAH TISCIONE / *S&T*, SOURCE: EHT COLLABORATION / *ASTROPHYSICAL JOURNAL LETTERS* 930:L12 (2022)

But VLBI's reliance on Earth's rotation comes with a downside: To gather enough information to construct the image, astronomers must observe the target continuously for several hours. That's fine for sources that change their appearance gradually over days or months, like M87*. But smaller Sgr A* flickers constantly and flares daily, and its light travels to us through our galaxy's gas and dust, scattered like a quivering candle flame seen through frosted glass. VLBI smears out all these changes in its single, hours-long exposure.

Unveiling Sgr A*'s shadow thus proved a formidable task. As they had with M87*, EHT members split into multiple teams, each using its own computer algorithms. But while the teams quickly produced remarkably similar images for M87*, this time they were stumped. It was so unclear what the right shape was that people didn't even want to show their images, says computer scientist Katie Bouman (Caltech), who co-led the imaging effort. "That's really what we have spent years trying to figure out," she explains. After intense scrutiny, they were finally confident: There's a ring.

It's important to stress what we can and cannot believe about this shadow image. The image is the average of more than 11,000 different reconstructions, each using data gathered on April 7, 2017. Trust the ring's width and the presence of a central darkness — the ring not only appears in more than 95% of the reconstructed images, but its size also matches the prediction from Einstein's theory of gravity. Yet be cautious with the ring's bright knots. Knots are natural, due to the tangled magnetic fields threading the hot gas and constricting its flow. But the positions of the knots in the Sgr A* image move slightly depending on which reconstruction you use, and they tend to line up along directions with more telescopes, warns Feryal Özel (University of Arizona). "We don't trust the knots that much," she says.

We also must be wary in concluding what the image tells us about the black hole. The team compared more than 5 million simulated images with the data, in order to interpret the underlying physics. Each simulated image makes specific assumptions, not just about the black hole's size and distance (which we knew) but about how fast it spins, its orientation, and the nature and behavior of the gas it eats (which we don't). Combined with multiwavelength observations from a large parallel campaign, EHT data rule out vast swaths of interpretations. What's left suggests a tentative picture: Sgr A* has a smoother gas skirt than predicted, it spins pretty fast, it leans nearly on its side, and it eats from a magnetized flow with properties that, 20 years ago, no one thought were physically possible.

Fair-Weather Friend

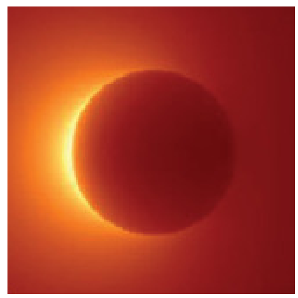
Think of watching waves from a beach. The speed at which the tide comes in depends on planet-scale gravitational forces, but the individual waves' heights depend on wind and sea conditions.

Something similar happens with a black hole's glow, explains theorist Dimitrios Psaltis (University of Arizona). There are two kinds of variation: how fast and how much.

TERRI DUBÉ / S&T, ADAPTED FROM R. FRAGA-ENCINAS / E. ROS / BLACKHOLECAM / EHT / FIKSFILM

▼ **A BRIEF HISTORY OF SAGITTARIUS A*** Since the 1970s, astronomers have been edging closer to our galaxy's black hole, using both theory and observation. This graphic focuses on advances at radio wavelengths.

1974



2000

1974
Discovery of Sagittarius A* (Sgr A*)
Astronomers find an unusual, very compact, bright structure at the center of the Milky Way.
BALICK & BROWN 1974
11 cm & 3.7 cm

1985
Sgr A* is small
Observations show that its size is only about 166 light-minutes wide.
LO ET AL. 1985
1.4 cm

1993
First VLBI image at 7 mm
A network of four radio telescopes shows Sgr A* has a slightly elongated structure.
KRICHBAUM ET AL. 1993
7 mm

1994
First image at 3.5 mm
Obtained using a network of four radio telescopes
ROGERS ET AL. 1994
3.5 mm

1998
First Sgr A* size measurement at 1.3 mm
The IRAM radio telescopes in Spain and France study Sgr A* at the same frequency as the future EHT.
KRICHBAUM ET AL. 1998
1.3 mm

2000
"Shadow" calculated for Sgr A*
Astronomers predict that a dark region surrounded by a bright ring should be detectable.
FALCKE ET AL. 2000
1 mm

2008
Size at 1.3 mm
Early EHT measurements show Sgr A*'s size is comparable to the predicted size of the black hole shadow.
DOELEMAN ET AL. 2008
1.3 mm

Gravity determines how fast gas moves around Sgr A*; plasma conditions determine how that flow brightens and fades.

It's the latter that surprised the team. Simulations forecasted big changes for Sgr A* — perhaps so big that researchers wouldn't be able to take a decent long-exposure picture. But Sgr A* proved calmer than any simulated image in the library. "It's like making weather predictions for a planet that you've never seen — you do your best, but you have no idea what the conditions there are," Psaltis says. "We predicted the storm, and we got a beautiful sunny day."

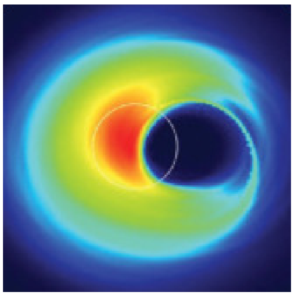
The discrepancy means we're missing something in our understanding of what's happening in the gas flow. Some team members (including Psaltis) think this is one of the most intriguing results. Others are unperturbed. "It is true, not a single model was able to reproduce the variability," says Ramesh Narayan (Center for Astrophysics, Harvard & Smithsonian), who has studied black hole accretion for decades. "For some reason that doesn't bother me, and I can't even tell you why," he adds, laughing.

Myriad solutions abound. Perhaps the gas is less turbulent or thicker than we expected, its magnetic fields are less tangled, or its electrons and ions behave in ways we haven't fully grasped. Adjusting where the light we see comes from — perhaps there's a jet as well as the accretion disk? — might solve the conundrum, too.

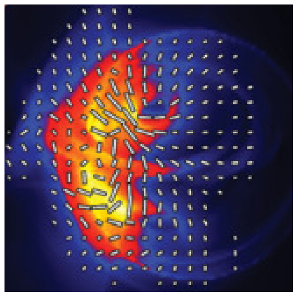
One possibility lies in how gas falls onto the black hole. Sgr A* eats only a billionth as much as a beast of its size is capable of, fed by a trickle of gas blown off as winds from the bright, hot stars that encircle the black hole. These stellar winds billow toward Sgr A* in a disorderly breeze, coming in from all directions, explains Sean Ressler (University of California, Santa Barbara), who studies how such wind-fed accretion works.

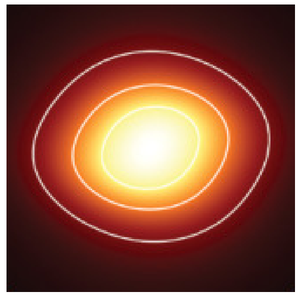
I Dub Thee Sagittarius A*

Codiscoverer Robert Brown (1943–2014) coined the name Sagittarius A* several years after finding the black hole. He later explained, "Scratching on a yellow pad one morning I tried a lot of possible names. When I began thinking of the radio source as the 'exciting source' for the cluster of H II regions seen in the VLA [radio] maps, the name Sgr A* occurred to me by analogy brought to mind by my PhD dissertation, which is in atomic physics and where the nomenclature for excited-state atoms is He*, or Fe*, etc."


2009


2011


2015


2019

2009 → **Extensive theoretical work**
Models built to explain the emission observed from Sgr A*.
MOSCIBRODZKA ET AL. 2009, DEXTER ET AL. 2009, YUAN ET AL. 2009, BRODERICK ET AL. 2006 AND 2009
1.3 mm

2011 → **Feeding black hole**
Comparison of observations with simulations shows that Sgr A* is consistent with a crescent of the right size and shape to be an accreting black hole.
BRODERICK ET AL. 2011, 2016
1.3 mm

2015 → **Magnetic fields detected**
Quickly varying polarization patterns suggest tangled, writhing magnetic fields near the event horizon.
JOHNSON ET AL. 2015
1.3 mm

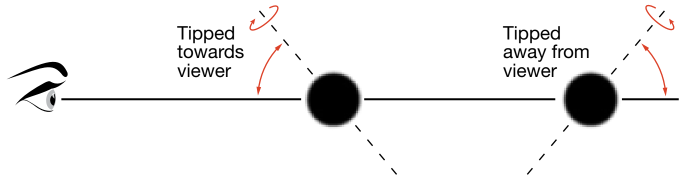
2016 → **Sgr A* is not symmetric**
Detection of asymmetric shape
FISH ET AL. 2016
1.3 mm

2018 → **Ultra-compact and asymmetric structure**
APEX telescope in Chile detects structure in emission from Sgr A*
LU ET AL. 2018
1.3 mm

2019 → **Scattering removed**
Astronomers map and subtract the scattering effect of clumpy interstellar gas on Sgr A*'s light.
ISSAOUN ET AL. 2019
3.5 mm

2022 **First EHT image of Sgr A***
Shadow provides first direct evidence of the supermassive black hole at the center of our galaxy.
EHT COLLABORATION 2022
1.3 mm

Simulations normally assume gas falls in toward a black hole from a fat surrounding donut called a *torus*, which would feed the accretion disk in an orderly way. But this is a solution of convenience, Ressler says — he doesn't know of a torus ever forming in simulations with realistic initial conditions. Winds, on the other hand, create a diffuse flow with less turbulent motion, and thus less variability. In fact, Ressler and two colleagues recently tested the wind-fed scenario against other observations of Sgr A*'s behavior and found that it matched how the brightness changed with time.



▲ **INCLINATION ANGLE** The spin axis of Sgr A* appears to partially point toward us, angled at most 50° away from our line of sight. It's unclear whether the tilt is toward or away from us (both options shown). Additional data favor an angle of roughly 30° and an axis tipped away from us.

Navigating Oz

If EHT astronomers set aside Sgr A*'s variability — which busts every model tested — then they are left with an interesting subset of findings about the black hole. But there's no yellow-brick road here: We're traveling in shadowy territory, and any of these inferences might be wrong.

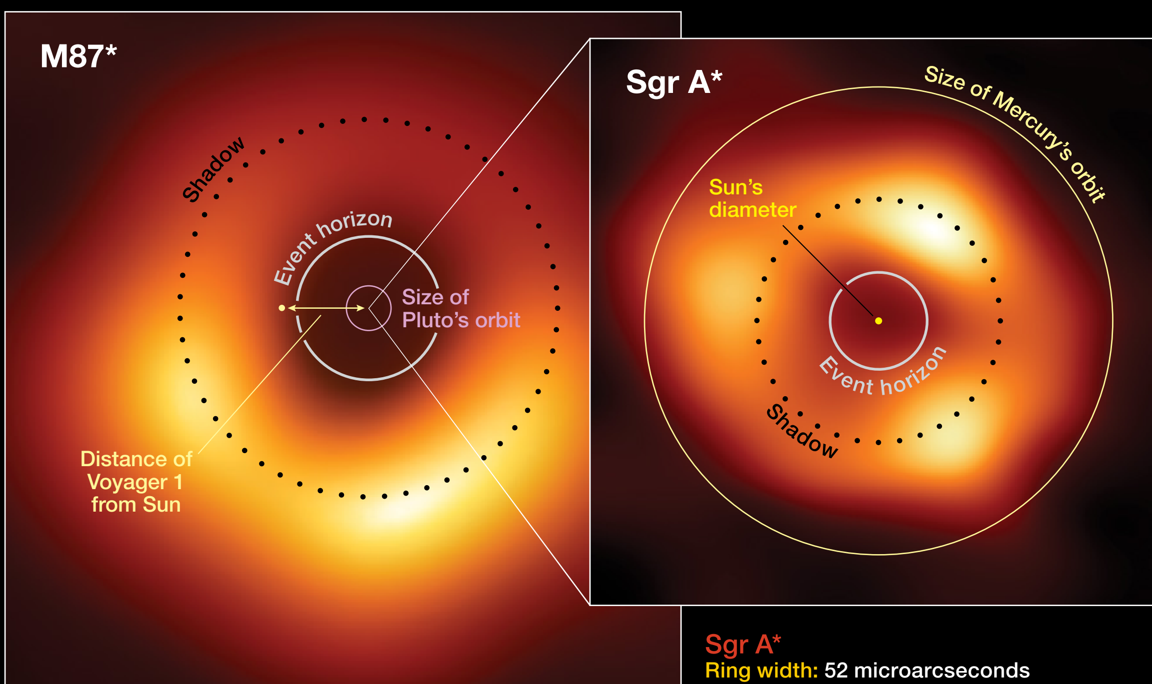
First, the spin. Astronomers define a black hole's spin as a fraction of how fast the object can whirl. The few measurements we have of supermassive black holes similar to Sgr A*'s heft are gas gobblers that spin nearly as fast as they can, likely spun up by a steady stream of gas.

If we rely on the subset of simulations that fit most of what's seen, then Sgr A* also spins fast, at least 50% of its max. But there's reason to doubt that number. Many theorists think that black holes power jets with their spins, and Sgr A* shows no definite sign of shooting jets. Some astronomers have also suggested that if our beast spins quickly, then it should drag spacetime around with itself so much that it would disrupt the orbits of the stars closest to it, which doesn't appear to be the case.

From a galactic-evolution standpoint, Sgr A* perhaps shouldn't spin at all, says Angelo Ricarte (Center for Astrophysics, Harvard & Smithsonian). The Milky Way hasn't

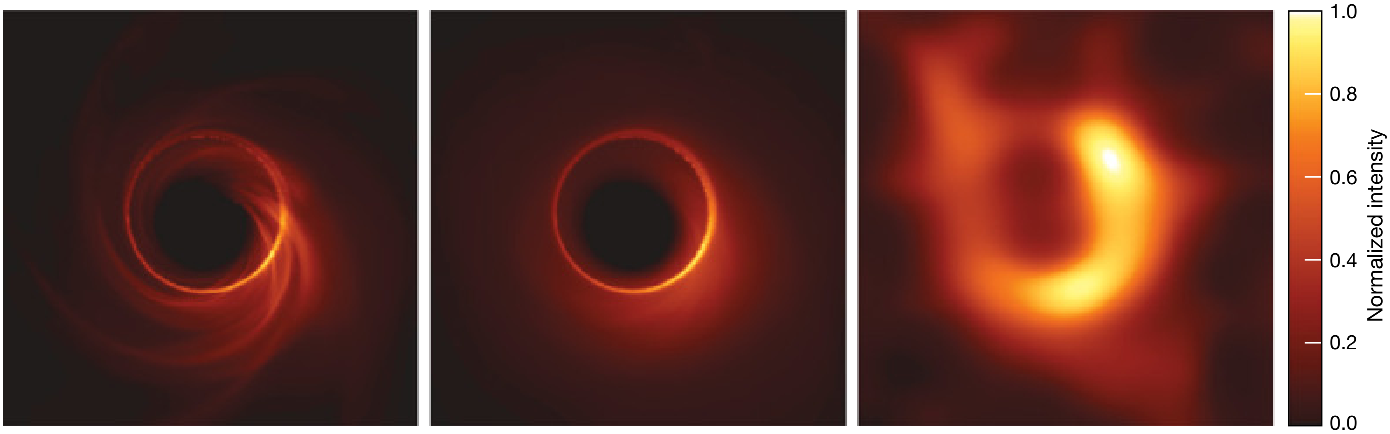
INCLINATION ANGLE: GREGG DINDERMAN / S&T; BLACK HOLE COMPARISON: GREGG DINDERMAN / S&T; IMAGES: EHT COLLABORATION (ACKNOWLEDGMENT: LIA MEDEIROS, XKCD)

▶ **M87* VS. SGR A*** A black hole's shadow is larger than its event horizon: The innermost stable photon orbit lies just outside the event horizon, and the black hole's gravity lenses this light to create an oversized silhouette. If we had perfect resolution, the light would form a narrow ring where the dotted circles are. Because the black hole M87* is 1,500 more massive than Sgr A*, its event horizon is much bigger — the whole solar system would easily fit inside.



M87*
Ring width: 42 microarcseconds
Black hole mass: 6.5 billion Suns
Distance: 55 million light-years
Jet? Yes
Spin axis's inclination to our line of sight: 17°

Sgr A*
Ring width: 52 microarcseconds
Black hole mass: 4 million Suns
Distance: 26,000 light-years
Jet? Unknown
Spin axis's inclination to our line of sight: <50°



▲ **THE RING** Radio photons whizzing around the black hole just outside the event horizon draw a thin circle called the photon ring. *Left:* This snapshot from a simulation shows one possibility for what the photon ring around Sgr A* would look like with perfect resolution. *Center:* The same simulation, averaged to match the cadence of EHT observations. *Right:* What the EHT's reconstructed image of this ring might look like, combining various methods' results.

EHT COLLABORATION / *ASTROPHYSICAL JOURNAL LETTERS* 930:L12 (2022) / CC BY 4.0

suffered many dramatic mergers with other galaxies, which funnel gas into galactic centers. If Sgr A* has grown by eating a random assortment of clouds, then there's been nothing to spin it up, he explains.

The second EHT inference is that Sgr A* leans on its throne. Instead of pointing straight up along the rotation axis of our galactic pinwheel, the black hole's spin axis lies more sideways, angled at most 50° from our line of sight. (An angle of around 30° looks likely.) Researchers can't tell whether it's leaning toward us or away — we're either looking down at its forehead or up at its chin.

Astronomers already had reason to suspect this result: Infrared observations of hotspots looping around Sgr A* at breakneck speed also suggest the black hole cants away from us (*S&T:* Feb. 2019, p. 11). That two different experiments give us a similar result is consoling.

Nor is Sgr A* the only supermassive black hole listing sideways. Observations of accreting black holes in spiral galaxies have revealed a range of orientations, says Geoff Bower (Academia Sinica Institute of Astronomy and Astrophysics, Hilo), who coined the cowardly lion moniker. The varied tilts are unsurprising, he explains, because a black hole's orientation depends on how it grew. Mergers with other black holes could cause a jumble of spin tilts, and for less active black holes like Sgr A* there may have been no hefty gas stream to force the black hole into a particular orientation. Thus there's no reason Sgr A* ever had to point straight up.

Some have wondered what this orientation means for the Fermi bubbles, the giant dumbbell-shaped outflows that extend up and out from the galactic center for tens of thousands of light-years (*S&T:* Feb. 2021, p. 60). Many astronomers suspect that a fantastic roar from the black hole blew the bubbles a few million years ago. Hsiang-Yi Karen Yang (National Tsing Hua University, Taiwan), who uses computer simulations to investigate the bubbles' formation, says that outflows from tilted jets would still be funneled up and out of the Milky Way's disk by the dense surrounding gas, creating bubbles that align with the galaxy's rotation axis rather than that of the black hole. She's currently working to simulate this scenario, although preliminary results suggest that creating the bubbles this way doesn't as easily explain the lobes' appearance, she says.

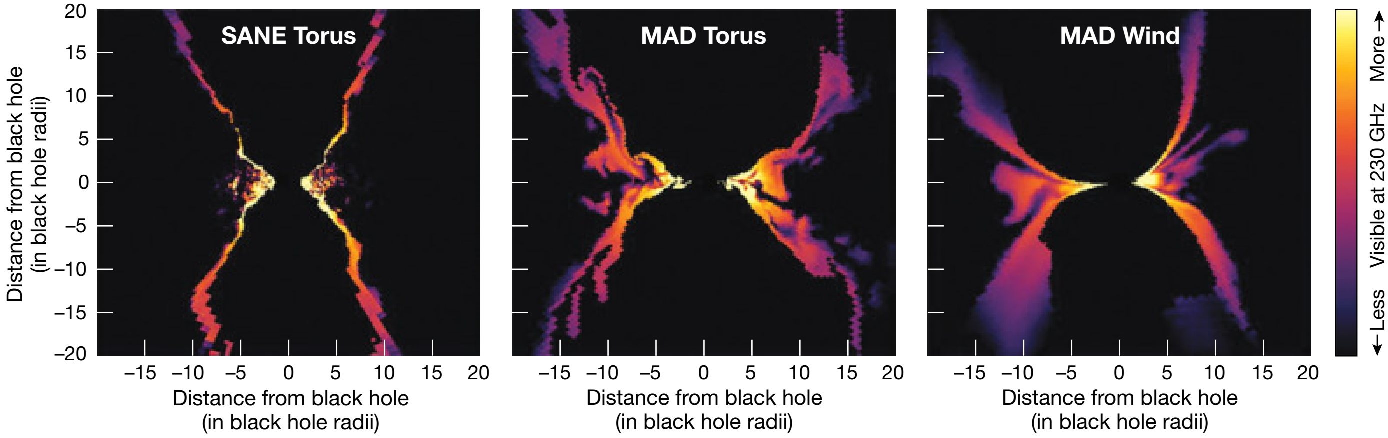
The Lion's Mane

Then there's the inflowing gas itself. The gas in the disk feeding a black hole drags magnetic fields with it as it spirals in toward the event horizon. Scenarios for the conditions in the disk fall into two categories: SANE and MAD. *Standard and normal evolution* (SANE) disks are more turbulent, with weak and messy magnetic fields threading them. *Magnetically arrested disks* (MADs) are packed with fields all stuck upright, which can choke the gas flow and serve as a highway for magnificent jets.

Twenty years ago, MADs were astrophysical insanity. Narayan and his collaborators fought to publish the scenario in scientific journals against referees' complaints that magnetic field lines would never behave like this. Even Narayan didn't think they'd happen in the real universe. "I thought it was just a cute idea," he says.

But younger scientists in his group saw the idea's potential, particularly Sasha Tchekhovskoy (now Northwestern University), who as a graduate student demonstrated that a MAD with a "booming jet" would arise naturally. Even so, Narayan didn't expect MADs to be common.

The EHT results might indicate otherwise: Overall, the EHT team favors a MAD feeding Sgr A*. "That's huge!" exclaims Michael Johnson (Center for Astrophysics, Harvard & Smithsonian). "People generally expected that it was SANE, turbulent, and nonspinning, because we don't see powerful jets. We're saying it's MAD, strongly magnetized, and spinning." The same holds for M87*, but given its jet, that's expected. "If this is true, then MAD systems are everywhere."



▲ **GAS INFALL** A black hole might eat from a thin, weakly magnetized stream of gas *(left)* or a flow choked with magnetic fields *(center and right)*. Many of the EHT team's simulations used a MAD torus to feed the accretion disk, but a trickle from stellar winds *(right)* might be smooth enough to explain the calm glow from Sgr A*.

Tchekhovskoy says that, on reflection, maybe it makes sense that a MAD feeds Sgr A*. The key factor that determines the flow's nature is whether magnetic fields can dominate the gas motions.

As gas streams into the black hole in a MAD, the black hole binges on the magnetic fields in the material, stuffing itself. There are so many field lines threading the black hole that they're like a handful of uncooked spaghetti. And like uncooked spaghetti, magnetic fields don't like to be squeezed or shoved into place: Loosen your fingers, and strands will pop out of the bunch. In an accretion disk, the only thing keeping the fields stuck in the black hole's throat is the gas pouring in. Concentrate enough fields together, though, and they'll fight back, buoyant against the gas. They'll form a dam or even shoot out and rip through the disk, creating hotspots and flares.

Given how little Sgr A* eats, even a relatively small magnetic buildup could control the gas flow, Tchekhovskoy says. "Maybe this is not such a big surprise, that it is MAD," he says. "What's surprising is that it pretends to be *not* MAD." For example, if the accretion flow is MAD and the black hole spins quickly, then there should be a jet, if only a stubby one, Tchekhovskoy and Narayan agree.

Perhaps the jet has been stifled. A jet will stream out along the black hole's spin axis while it's still close to the black hole, but if enough gas flows in along that axis, then the flow will re-route the jet in a completely different direction. "Through that process [the jet] loses a lot of power, and so it fizzles out much more easily," Ressler says. Stellar winds could potentially quash the jet this way, because they can feed the black hole from any direction.

The Quest Continues

The picture drawn so far might be confusing, and it should be. Although this work involved collecting 3½ petabytes of data — equivalent to one-seventh of the entire digital collection of the Library of Congress — it's only a first look.

"We've done the best job we can," Narayan says. But the inferences are self-contradictory: For example, how can we have a rapid spin and MAD flow with no jet? "I'm a little nervous," he admits.

The EHT team has plenty of data to keep exploring these questions: Observations from 2018, 2021, and 2022 all remain to be studied, as well as Sgr A*'s 2017 polarization data. The light's polarization will reveal the magnetic fields' orientation and, potentially, a more precise spin estimate if the black hole drags everything around with it enough to affect the pattern. The team is still discussing which data set to attack next.

But what several members of the collaboration are turning their eyes to is the next-generation EHT (ngEHT). No matter how good the algorithms, the EHT's true limits are the number of radio dishes and their locations. M87*'s image used data from seven stations at five sites; Sgr A*'s image involved eight at six sites (the eighth being the South Pole Telescope, for which M87* lies below the horizon). The team has continued adding telescopes to the array, and in 2022 eleven stations at nine sites participated in the campaign.

But it's not enough. "Right now we're on the edge," says EHT founding director Shep Doeleman (Center for Astrophysics, Harvard & Smithsonian). "We lose one of these antennas, it's very difficult to recover the image. . . . If we have a weather pattern that takes two of our antennas out in key locations, we're done for the night. Might as well not even observe."

The ngEHT could change that. Phase I aims to rope in five additional dishes, three grabbed and refurbished from a former National Science Foundation project and shipped to new locations. Proposed to be up and running in 2026, Phase I will increase the number of baselines by a factor of eight compared with 2017. It will also observe in both the existing 230 GHz band and a new 345 GHz one, which will not only

ACCRETION SCENARIOS: L. MURCHIKOVA ET AL. / *ASTROPHYSICAL JOURNAL LETTERS* 2022 / CC BY 4.0; FORECAST: EHT COLLABORATION (2)

effectively change the image from monochrome to color but also improve resolution by 50%. Even without resolving shadows (only possible for a handful of objects), the enhanced array could enable astronomers to "weigh" dozens of supermassive black holes and clock spins for about 10 of them.

Then comes Phase II, which by 2030 would add another five dishes (this time custom-built) as well as potentially partnering with proposed observatories in Namibia and Argentina. That would increase the number of baselines to more than 200, substantially filling in the virtual dish and revealing features 100 times fainter than the 2017 observations could pick out.

That kind of observing power will reveal M87*'s shadow and jet in exquisite detail. Astronomers don't fully understand how black holes make jets: Either the accretion disk powers jets, or the spin does. Observations favor the latter.

In this scenario, the magnetic field is like an eggbeater, twirled around by the black hole's spin, explains Doeleman. These fields are sweeping through charged particles, and the particles drag on the fields like pancake batter drags on the eggbeater when you dip it into the mixing bowl. The fields strain against the resistance, sucking energy from the black hole's spin like the eggbeater does its motor.

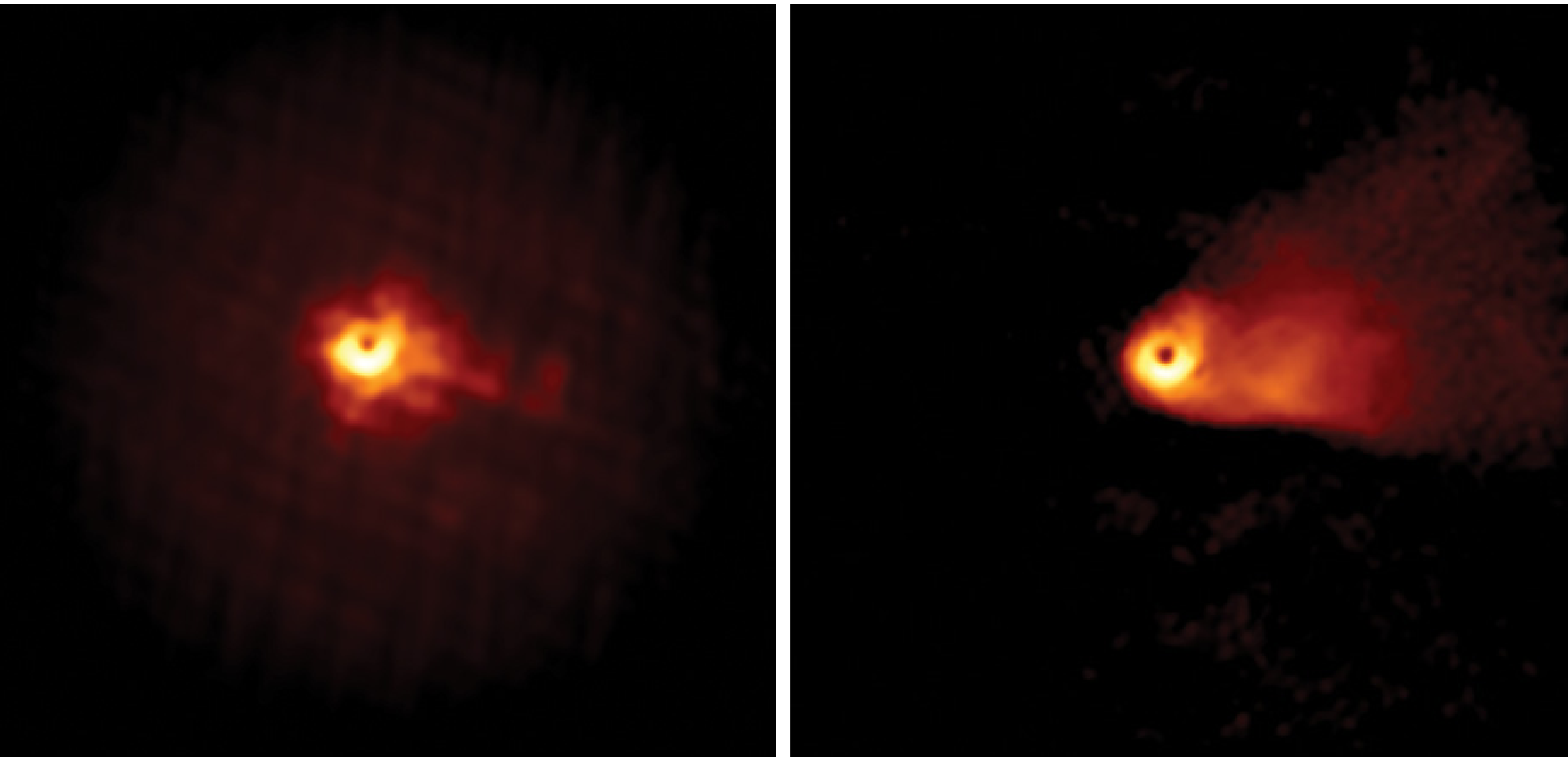
Charged particles corkscrew around magnetic field lines, but they also have to follow where a magnetic field leads, so

Astronomers don't fully understand how black holes make jets: Either the accretion disk powers jets, or the spin does. Observations favor the latter.

as the fields whip around, the particles whip around, too. "They're orbiting and they're going on this Tilt-A-Whirl, all at the same time," Doeleman says. "They're very dizzy particles." This whipping about accelerates the particles and flings them out along the field lines, making the jet.

By decade's end, EHT scientists hope to have full-blown movies of both M87* and Sgr A*. The measurements will show M87*'s jet-launching process in action and reveal whether this eggbeater picture is true, as well as tell us whether Sgr A* has a jet. The Sgr A* movie will take longer than the M87* one, for the same reasons that the portrait took longer. But the lion no longer lies hidden in its lair — the safari is under way.

■ Science Editor **CAMILLE CARLISLE** wrote part of her master's thesis about the EHT's quest to image Sgr A*. Now that the team has succeeded, her career has come full-circle. (Alas, the editor in chief won't let her retire early.)



▲ **OBSERVING FORECAST** These are simulated images of what the Event Horizon Telescope would see of M87* using seven stations (as in 2017) and 20 stations (as in Phase 2 of the ngEHT). Both are based on the same computer simulation of conditions around the black hole, not real data, so that they can be easily compared. In the seven-station version *(left)*, we see the black hole's shadow surrounded by a haze of radio emission from the surrounding gas. But with additional baselines, we're able to resolve larger scales and dimmer features, revealing the black hole's jet (swath extending rightward in the 20-station image).