Mercury

2022 • Issue 2, Volume 51

ASTRONOMICAL SOCIETY of the PACIFIC

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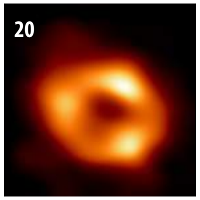
Space News

A rundown of some of the most notable discoveries and need-to-know news in space and time.



Supermassive Success

STEVE MURRAY

After five years of data analysis and simulations, astronomers revealed their first image of the monster black hole at the center of our Milky Way Galaxy.

A New View

LIZ KRUESI

Last month, the James Webb Space Telescope team showed the world the observatory's first views of the cosmos.

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on the cover

Front: The James Webb Space Telescope captured the interacting galaxies of the Cartwheel Galaxy. The pink-red streaks that look like wheel spokes are mid-infrared radiation, and they reveal hydrocarbon-rich dust. The other colors show data from a different instrument aboard the telescope, the Near-Infrared Camera. Every blue point is a star or a spot of star formation. Astronomers think the collision responsible for this striking interaction occurred some 400 million years ago. *[NASA/ESA/CSA/STScI/Webb ERO Production Team]*

Back: The Hubble Space Telescope has also imaged the Cartwheel Galaxy. This image, released in 2010, comes from reprocessing data collected using the telescope's Wide Field Planetary Camera 2, which operated from 1993 to 2009. *[ESA/Hubble & NASA]*.

perspectives

Astronomy's Success Stories

These past few months have seen several astronomical successes, and this issue of *Mercury* magazine focuses on those.

First up, freelance science journalist Steve Murray dives into recent results from the Event Horizon Telescope (EHT) on pages 20–27. While the EHT's first-ever image, released three years ago, of a black hole was of the one at the center of massive galaxy M87, this new result is a lot closer to home — it's humanity's supermassive black hole. He describes the complexities involved to combine and understand the imaging data from disparate observatories around the globe that act as one EHT.

And as we saw in May, the result is a beautiful orange doughnut, or rather, the photon ring surrounding the event horizon of that supermassive black hole.

This issue of *Mercury* also includes a feature article focusing on another incredible imaging feat: the first images released from the James Webb Space Telescope (JWST). This observatory, certainly the most complex (and expensive) to ever fly, works better than expected. Every place where something could go wrong instead went right, and the fantastic data from the telescope's four instruments display that.

Those images (see pages 28–38) and this issue's cover photo hold an incredible amount of detail, and yet they only took days to capture. I look forward to the many more views and discoveries from this great telescope.

There's one other exciting development I want to mention in this issue, and that's the summer symposium the Astronomical Society of the Pacific (ASP) is hosting later this week. The theme is science communication of all varieties. I am leading a panel about reporting about the big astronomy news, with some stellar science journalists and editors. For more information about this event, please read Linda Shore's column on page 4 or visit our website.

Liz Kruesi
Editor, *Mercury*

Mercury
THE MAGAZINE OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC
astrosociety.org
2022 • Issue 2, Volume 51

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Mercury (ISSN 0047-6773) is published quarterly by the Astronomical Society of the Pacific, 390 Ashton Avenue, San Francisco, CA 94112
Telephone (415) 337-1100; Fax (415) 337-5205

Yearly membership rates are: $35 (seniors), $55 (individual), $175 (supporter's circle).
Technical and Institutional memberships are also available.

The Astronomical Society of the Pacific increases the understanding and appreciation of astronomy by engaging scientists, educators, enthusiasts and the public to advance science and science literacy.

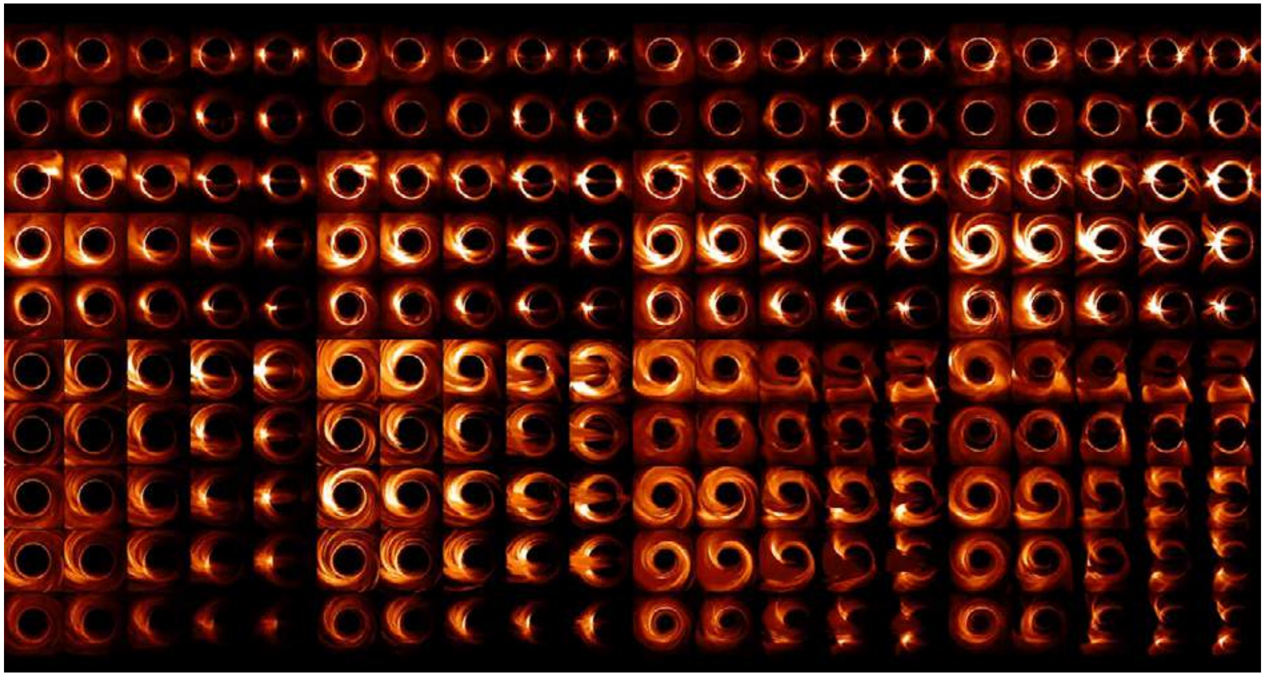
Supermassive Success

After five years of data analysis and simulations, astronomers revealed their first image of the monster black hole at the center of our Milky Way Galaxy.

By Steve Murray

We now know what our galaxy's supermassive black hole looks like, and it's a beauty. *[EHT Collaboration]*

The Event Horizon Telescope (EHT) collaboration is now two for two. Their first image of Sagittarius A*, the supermassive black hole at the heart of our galaxy, was revealed to the public three years after their groundbreaking image of galaxy M87's black hole, dubbed M87*. Although the size and shape of these objects conform to physics predictions, Sgr A* (pronounced "Sag-ay-star") yielded some surprises. It looks like our theoretical models still need work, and the next round of EHT observations is already underway to fill in the missing pieces.



Researchers generated millions of images from the Event Horizon Telescope data and physics predictions. This is a sample of some of them. *[Ben Prather/EHT Theory Working Group/Chi-Kwan Chan]*

While both black hole images were developed from 2017 observations, the science team was able to include data from the South Pole Telescope (SPT) at Amundson-Scott South Pole Station for Sgr A*. The SPT wasn't in a position to see M87* but was perfectly located to continuously observe Sgr A*.

"Astronomers are always working right at the cutting edge of technology," says Jessica Lu, an associate professor of Astronomy at the University of California, Berkeley. "Our ability to learn something new about the universe is only confined to what we can imagine and what we can build." Lu follows EHT developments closely, but uses other instruments to examine smaller black holes near the galactic center.

Matching models to reality

Imaging these black holes was incredibly difficult. It's important, then, to appreciate the role that simulation modeling played in interpreting the first results for both M87* and Sgr A*. The EHT is the world's most comprehensive network for doing very long baseline interferometry (VLBI), a method that uses telescopes around the world to create a planet-sized radio "dish." The parts of such a dish, however, can only be filled where telescopes are located, so the EHT team had to optimize this incomplete information through a series of imaging and modeling steps.

The team generated tens of thousands of different images of Sgr A* based on EHT observation data, and a variety of different methods were applied to fill aspects of the missing information for each. The resulting images were then "averaged" to highlight which features were common in most of them. Other teams generated five million simulated images using physics models that reflected different parameters for Sgr A* such as orientation, spin, and magnetic field strength. These two image sets were then matched, and simulation products that didn't agree with observation products were discarded. The end result was a small family of likely representations of what EHT saw, and it's this family of models that astronomers used as the basis for the final Sgr A* image.

"That's a crazy amount of data," says Lia Medeiros, a National Science Foundation Astronomy and Astrophysics Postdoctoral Fellow at the Institute for Advanced Study in Princeton, New Jersey, and an EHT scientist. "But remember that we can't run every possible simulation. That's way too expensive. All of the results from the simulations should be taken seriously, but all of our results depend on the set of simulations that we chose to include." Therefore, although the approach yielded robust results, future observations might still require revisions in both models and theories.

Opportunities and challenges

The hard work needed to realize these images was assisted by some fortunate circumstances. Both M87* and Sgr A* are just the right size and just the right brightness to make the project possible. M87* is one of the largest black holes known at 6.5 billion times the mass of our Sun. Sgr A* checks in at a much smaller 4.3 million solar masses.

Comparisons are telling. The M87* "shadow" is larger than our Solar System, while the Sgr A* shadow wouldn't quite span the orbit of Mercury. But M87* is 55 million light years from Earth while Sgr A* lies only 27,000 light years away. This size-distance trade off results in both objects having about the same angular subtense as seen from Earth telescopes: 50 *micro*arcseconds (that's equivalent to the size of an atom held at arm's length). Happily, this falls just within the resolving capabilities of the EHT array but, at this performance extreme, both images appear blurred. "We're just getting to the point where we can do this at all," says Richard Anantua, Assistant Professor of Physics and Astronomy at the University of Texas at San Antonio and also an EHT scientist. "You're pushing the instrument to the limit with current technology. Any other instrument would show much blurrier results, and likely no results at all."

The accretion rates of these black holes also worked in favor of the EHT observation effort. If they were not accreting, they'd be invisible to any instrument (at least directly), but if they were accreting too rapidly, telescopes couldn't peer through the glowing material to detect their event horizons. In a sense, M87* and Sgr A* are in a golden zone of conditions for black hole astronomers, the only ones in our sky that offer the possibility of seeing their shadows.

The location and behavior of Sgr A* also explain why the EHT science team required an additional three years to develop its

The supermassive black holes at the center of M87 and our Milky Way Galaxy span the same area on the sky, but it's all a result of perception. M87's central black hole is much larger and much farther away than our galaxy's. *[ESO/M. Kornmesser, EHT Collaboration]*

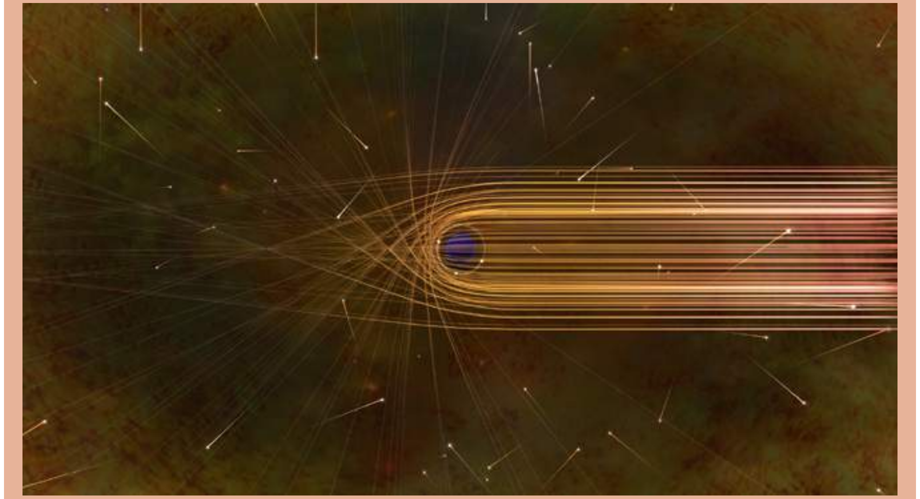
Decoding black hole speak

Doppler beaming: Glowing gas in the accretion disk appears brighter as material moves toward us versus away from us.

Event horizon: Every black hole has this boundary beyond which its gravitational force holds anything that approaches.

Shadow of a black hole: If light gets close but doesn't quite fall into a black hole's event horizon, it can circle, creating a bright ring. Inside that region is the black hole's shadow, which is what the Event Horizon Telescope has imaged at M87★ and Sgr A★.

Very Long Baseline Interferometry: A technique to mimic a large single telescope by combining data from separate radio telescopes observing one celestial target at the same time. The observational data is later combined by software algorithm. — *Liz Kruesi*



In the vicinity of a black hole's gravity, light particles (shown as the orange streaks in this illustration) change direction. They can even loop around the black hole's "event horizon" boundary. *[Nicolle R. Fuller/NSF]*

image. We see Sgr A★ through the plane of the Milky Way, so there's plenty of gas and dust to penetrate just to collect a signal. M87★, sitting at the center of the more-distant M87 galaxy in the Virgo cluster of galaxies, didn't give us that problem. Sgr A★, being closer to Earth, also moves more quickly across the sky during EHT observations. But that's not the only movement scientists had to contend with.

While gas moves at almost the speed of light around both black holes, it takes substantially less time to circle around the much smaller Sgr A★. Material takes days to complete one orbit in the accretion disk around M87★ but only minutes to follow the similar journey around Sgr A★. Imaging Sgr A★ was therefore like trying to photograph a fast-moving sports event with a long duration camera exposure, and the EHT team had to develop new data analysis methods to deal with this variability.

First findings

Sgr A★ features both confirmed many of the astronomers' expectations but offered up a few surprises, too. The initial studies of Sgr A★ have been published in a special issue of *The Astrophysical Journal Letters*.

First, Einstein's theory of general relativity is still on solid footing. The theory predicts the size of a black hole shadow based on its mass. Astronomers had already calculated a mass for Sgr A★ from years of tracing the orbits of stars around it. This allowed them to make a precise prediction of the diameter of its shadow, and their EHT results fit the prediction almost perfectly.

"I was one of the coordinators for our recent paper on testing general relativity," says Medeiros. "It's the most comprehensive paper we've ever put out on the topic. We used the size of the black hole shadow and confirmed it against prediction to within

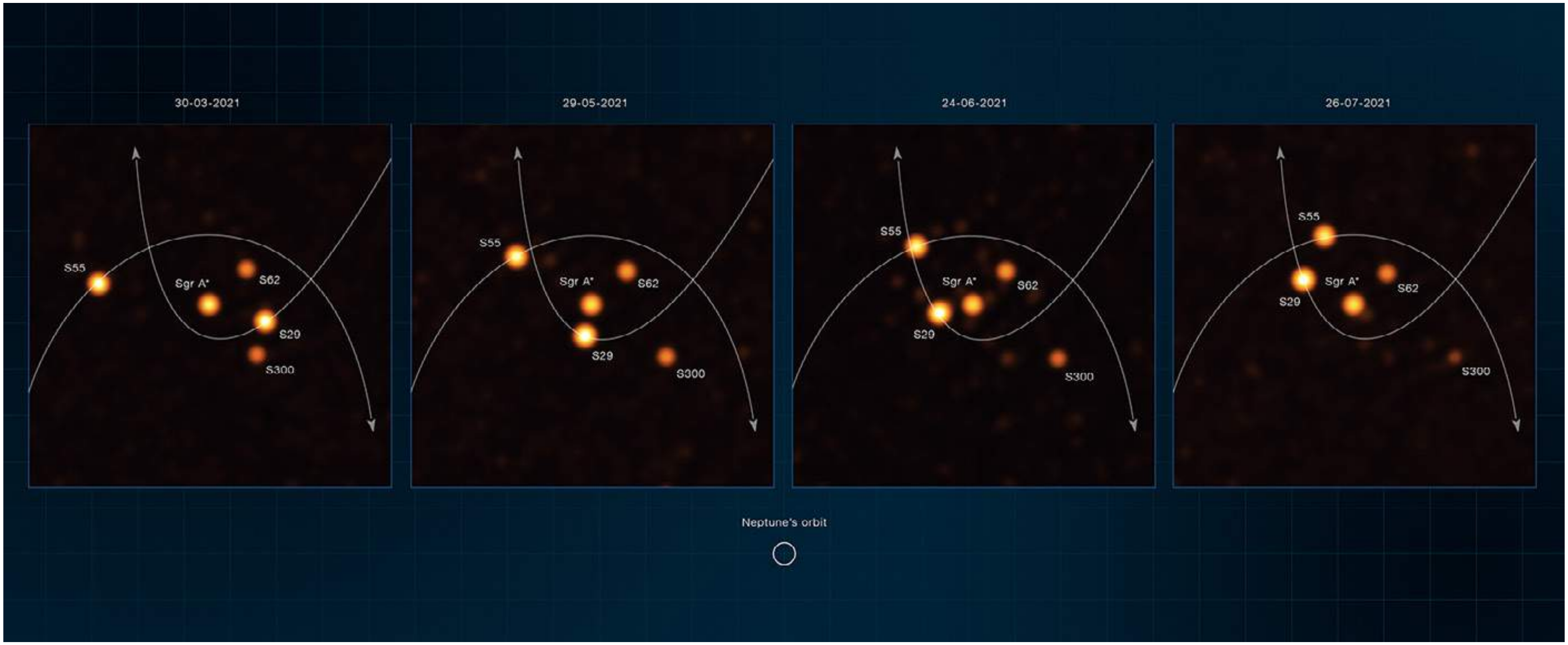
10 percent, and that's a powerful result because we're testing in such a strong gravitational field."

The general theory of relativity also predicts that the shadow will be perfectly circular to within tight limits. Although none of their current models indicate a deviation from that circularity, EHT researchers intend to test this explicitly in the future.

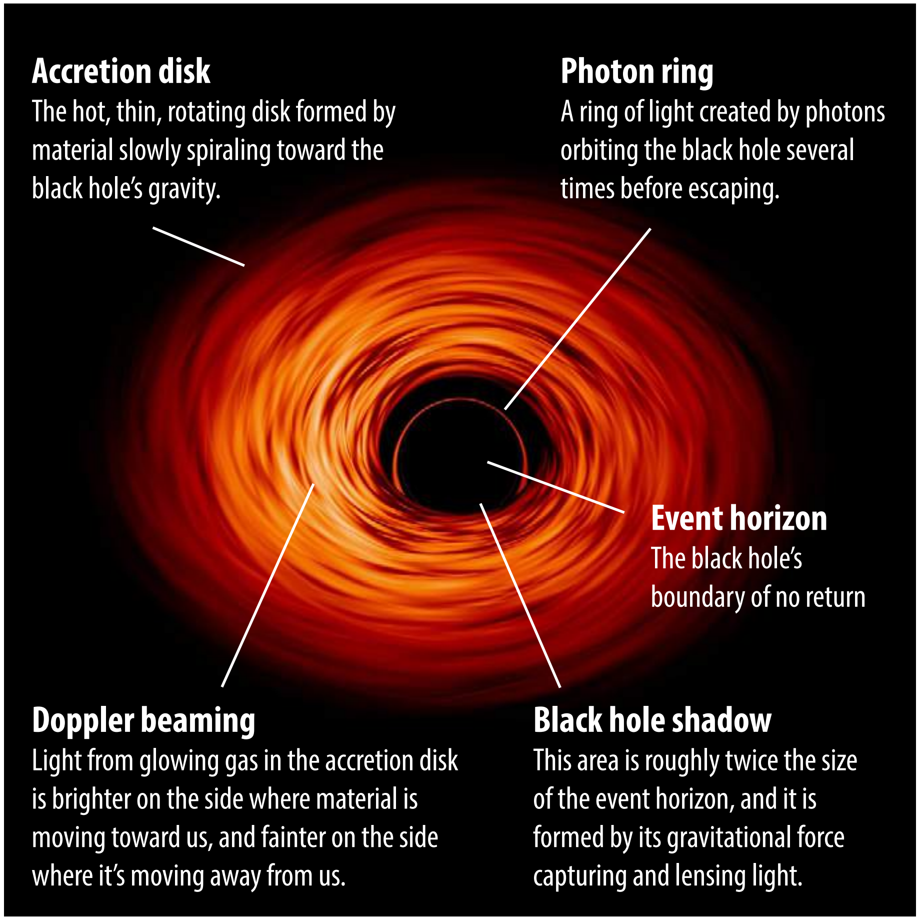
"What I find so remarkable about black holes is that they're unbelievable simple," says Medeiros. "Their shape is exactly the same regardless of mass. You just change the scale, and that's a fundamental prediction of general relativity. There are so few things in our everyday lives that don't change their shape when you change their scale like this." The new image of Sgr A* supports this scaling prediction.

The EHT models currently indicate that Sgr A* has a non-zero spin, and that this spin is likely positive — in the same direction as its accretion disk — although the rate of any spin still has to be determined. The disk also appears to contain strong magnetic fields and material with temperatures running into the trillions of Kelvins.

The orientation of the accretion ring appears to show that the axis of Sgr A* is tilted slightly toward us and not aligned with the plane of



In 2021, astronomers captured these images of stars orbiting supermassive black hole Sgr A*. From these and similar observations, astronomers can calculate the black hole's mass. *[ESO/GRAVITY collaboration]*



Accretion disk
The hot, thin, rotating disk formed by material slowly spiraling toward the black hole's gravity.

Photon ring
A ring of light created by photons orbiting the black hole several times before escaping.

Event horizon
The black hole's boundary of no return

Doppler beaming
Light from glowing gas in the accretion disk is brighter on the side where material is moving toward us, and fainter on the side where it's moving away from us.

Black hole shadow
This area is roughly twice the size of the event horizon, and it is formed by its gravitational force capturing and lensing light.

Black holes are incredibly dense, and their gravitational force alters how light behaves near them. *[NASA's Goddard Space Flight Center/Jeremy Schnittman]*

the galaxy. "It's somewhat surprising that we suddenly see that this very innermost ring around the black hole, which may align with the black hole spin, is likely pointing toward us," says Anantua. "It's not perpendicular like the large-scale arrangement of the galactic disk." This phenomenon depends, of course, on whether the spin of the black hole is aligned with the spin of the ring. Although astronomers have reasons to believe that they're aligned, they've never really been able to test it, and it remains an active area of research.

Sgr A★ also has a surprisingly low accretion rate, consuming very little of the material around it. Astronomers already expected this, but their measurements establish new, lower bounds on the activity. As some EHT astronomers have described, Sgr A★ gives us a view of a more standard state for black holes, one that is quiescent.

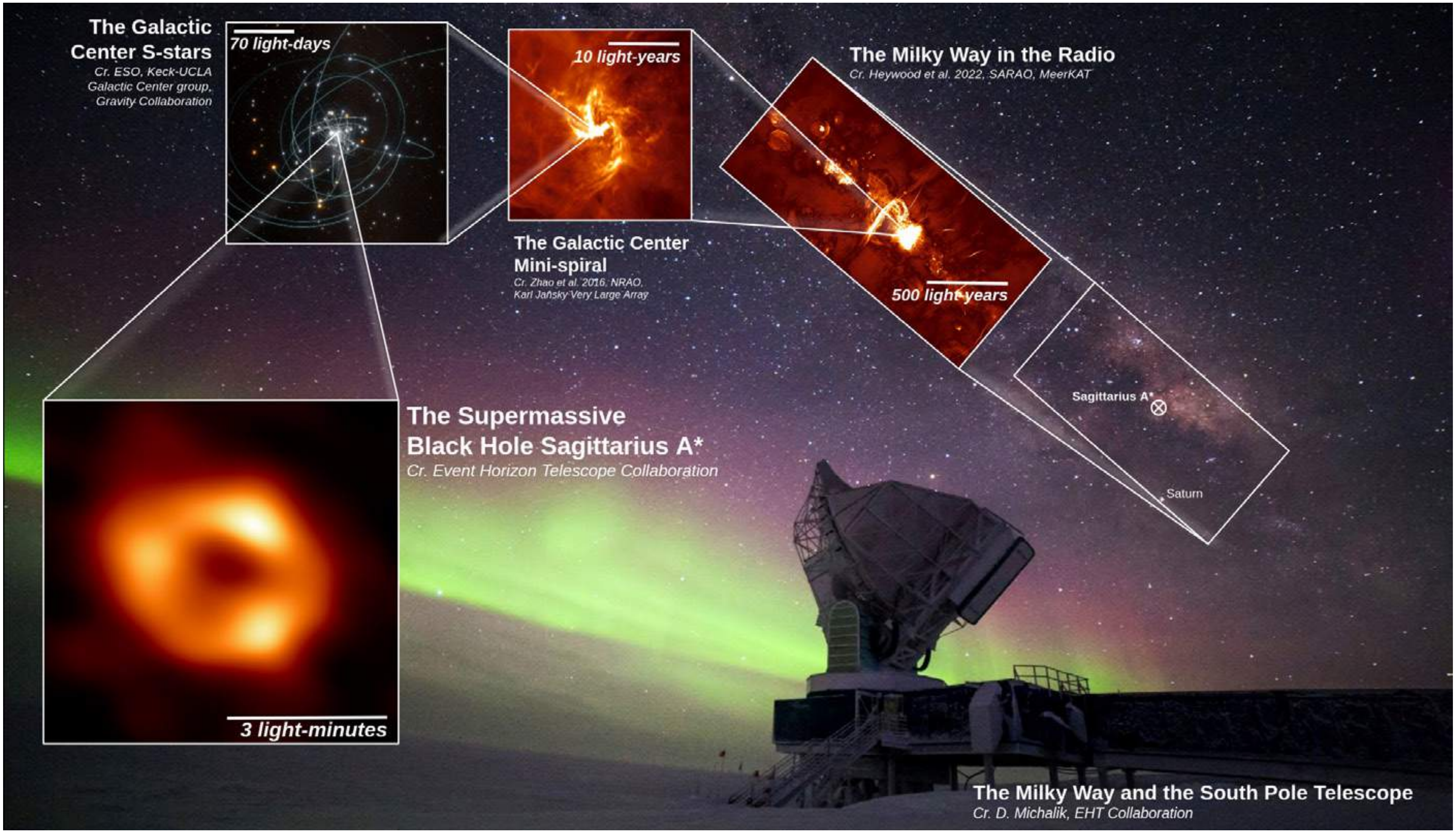
Sgr A★ has shown the EHT team that there's still a way to go to simulate turbulent accretion behavior around supermassive black holes. In particular, their models tend to predict significantly more variability than they observe. The differences in accretion disk brightness of Sgr A★ may also require revisions to their physics models. "The disk is different from [that of] M87★," says Anantua. "We don't see the same kind of Doppler boosting, where the part of the disk moving toward you is much brighter than the rest. And it's not nearly as variable as it could be, given that the material moves around it at such fast timescales."

The accretion ring also appears more disturbed than the one around M87★ and contains distinct bulges or "knots" that surprised astronomers. While it's reasonable to expect some brightness changes in the ring, collaboration members also suggest that these could be data artifacts, as the locations of the specific knots tend to correspond to where more telescopes were observing. More analysis may show that they're not real.

Astronomers are also looking for any evidence of a jet from Sgr A★. Although they haven't detected one yet — certainly nothing like the enormous relativistic jet of M87★— there is circumstantial evidence to support the search. These and other studies of Sgr A★ are still in their earliest stages and, given the rough resolution of the May 2022 image, any number of explanations are still possible for many of the phenomena it contains.

New work on the (event) horizon

The EHT collaboration's March 2022 observations included additional telescopes in Greenland, France, and the US that expanded its network to 11 instruments — up from 8 telescopes that made up the original array in 2017. They're also observing at higher frequencies, which will reduce the effects of scattering. "That should allow us to constrain the circularity of the shadow," says Medeiros, who is co-coordinator of the EHT Gravitational Physics Working Group. "That



This composite image shows just how small of a spot on the sky Sagittarius A* spans, and how much detail the Event Horizon Telescope can reveal. *[Sara Issaoun, Smithsonian Astrophysical Observatory]* will be a new powerful test of general relativity." Observations scheduled for 2023 will search at an even shorter wavelength that could double the current resolution of the array.

At the same time, other observations are filling in the environmental context around Sgr A★. "The galactic center is an incredibly rich environment," says Lu, "It's messy, it's complex. So I think other telescopes have a role to play." Lu is currently preparing to study the gas and stars around Sgr A★ using the James Webb Space Telescope (JWST). "There are strong connections between the bigger picture that JWST will show us and the very small, high-resolution picture that EHT reveals."

A next generation EHT (ngEHT) is also in the works that will double the number of telescope dishes. Observations from this new network will allow the team to make movies of these supermassive black holes that should offer more precise insights into the physics of how material moves around them.

The yellow dots mark the telescopes that were part of the Sgr A★ 2017 observations. The three blue dots are the additional sites that have since joined the observatory. *[ESO/L. Calçada]*

The EHT consortium has now given astronomers two laboratories to study supermassive black holes, each with a different story to tell. As Harvard & Smithsonian Center for Astrophysics scientist Michael Johnson pointed out during the EHT's May 12 press announcement, M87★ is exciting because it's extraordinary; Sgr A★ is exciting because it's common.

Anantua is looking forward to a time when even more objects come within the capabilities of advanced telescope imaging. He hopes eventually astronomers will have something akin to an organizational data base of black holes. "There could be very different morphologies out there, very different physics in the matter that's swirling around them," he says.

In the meantime, it seems that the public is still absorbing the magnitude of this achievement. At an astronomy conference immediately following the Sgr A★ image release, Anantua encountered a frequent but surprising question among his astronomy colleagues. "Why is the image so blurry?"★

STEVE MURRAY is a freelance science writer & NASA Solar System Ambassador. A former research engineer, he follows developments in astronomy, space science, & aviation.