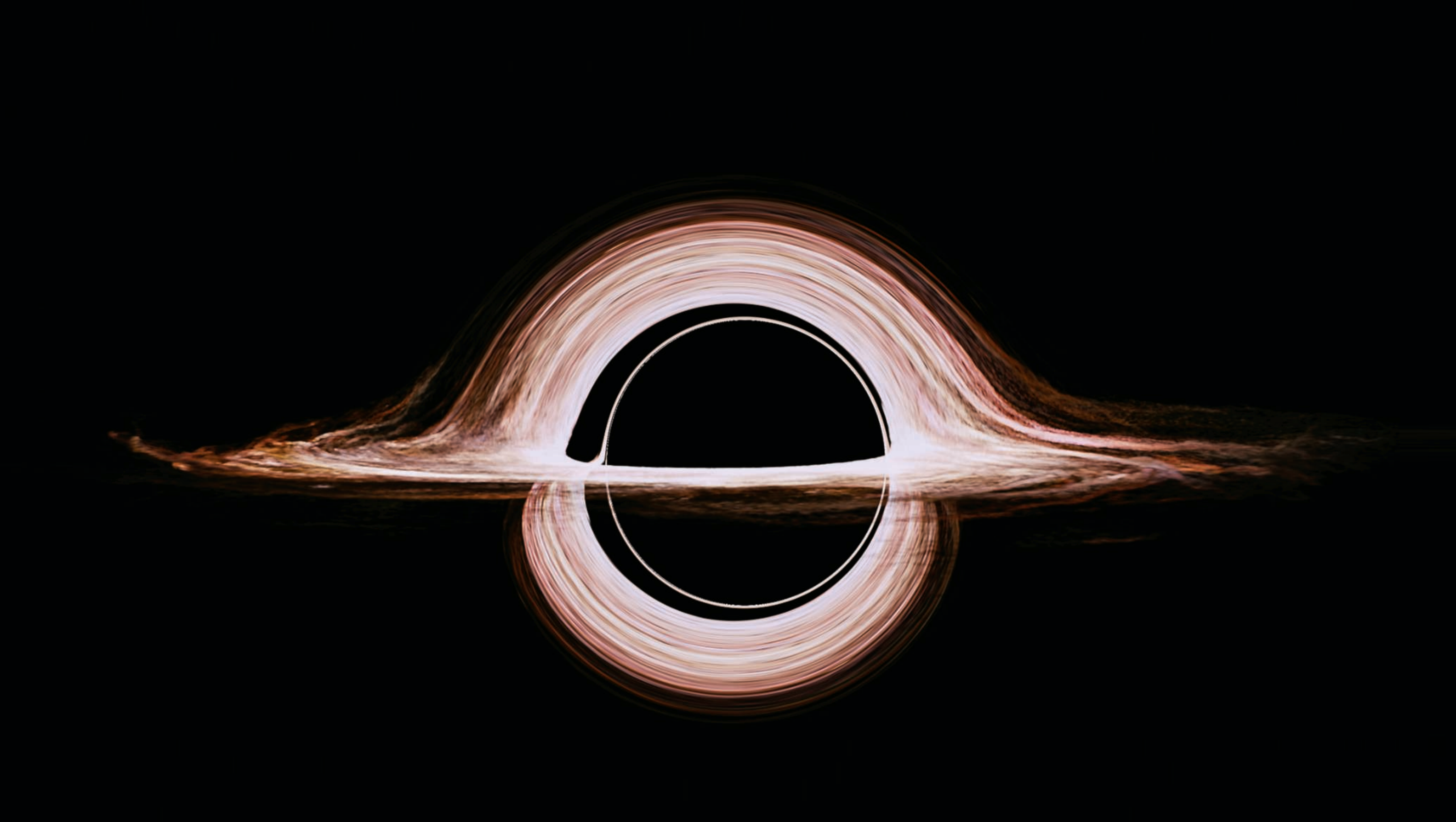

THE DARK LAB

To put general relativity to the acid test, researchers are looking inward—toward the supermassive black hole at the center of the Milky Way

By **Daniel Clery**

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A black hole distorts the image of a disk of dust and gas around it, courtesy of the special effects team for the film *Interstellar*.

Like an Olympic athlete, the general theory of relativity has passed many tests in its century-long career. Its string of successes began in 1915, when Albert Einstein's picture of gravity as curved spacetime neatly explained shifts in the orbit of Mercury that had vexed astronomers for more than half a century. In recent decades it has faced more exotic and extreme tests, such as explaining why pairs of superdense neutron stars whirling around each other appear to be gradually spiraling toward collision. Here, too, general relativity triumphed: The stars are losing energy at exactly the rate expected if, as the theory predicts, they emit gravitational waves (see p. 1097).

Yet physicists remain unsatisfied. The tests so far have been too easy, they say. The gravitational fields involved have been fairly weak, coming from single stars and bending or slowing light only very slightly. If the theory is going to show cracks, it will be under more extreme, high-field conditions. That matters because—on paper, at least—general relativity isn't the only game in town. Theorists have put forward alternative models for gravity, but in low fields they look identical to Einstein's theory. In strong fields, they begin to change.

Now, searching for a tougher test, researchers are looking toward the center of our galaxy. There, shrouded in dust, lurks a bright, compact source of radio waves known as Sagittarius A* (Sgr A*) for its position in the sky, near the edge of the constellation Sagittarius. Because of the way stars move in its vicinity, astronomers think that Sgr A* marks the dark heart of the Milky Way: a supermassive black hole weighing as much as 4 million suns but crammed into a space smaller than the distance between the sun and Mercury. That black hole produces the most intense gravitational field in our galaxy and so provides a unique laboratory for testing the predictions of general relativity. Over the next few years, using a range of new instruments tuned to infrared light and radio waves—radiation capable of penetrating the clouds of dust and gas around the galaxy's core—astronomers are hoping to see whether Sgr A* is bending relativity beyond the breaking point.

Two teams of astronomers—one led by Andrea Ghez of the University of California, Los Angeles (UCLA), and the other by Reinhard Genzel of the Max Planck Institute for Extraterrestrial Physics (MPE) in Garching, Germany—are staring at the center of the galaxy more intently than anyone before them. They are tracking a handful of

PHOTO: ESO/Y. BELETSKY

stars that swoop close to the center—one of them to a distance equal to that between the sun and the edge of the solar system. Meanwhile, a unique new radio telescope array—still being assembled—is gearing up to carry the scrutiny right up to the edge of the putative black hole itself. In each case, the mission is the same: to spot discrepancies that Einstein's formulae cannot explain.

General relativity has "never before been tested at the high-field limit," says astrophysicist Abraham Loeb of the Harvard-Smithsonian Center for Astrophysics (CfA) in Cambridge, Massachusetts. Elsewhere in the galaxy, astronomers have observed stars apparently caught in the grip of smaller black holes. But the stars close to Sgr A* "are 100 times closer to the event horizon [the boundary of a black hole] and the mass scale is a million times greater," Ghez says. "Does general relativity work down at scales 100 times closer? You're getting into the realm of basic physics: What is gravity? That's why people care."

Testing general relativity in this distant laboratory isn't easy. The black hole at Sgr A* is a small object, by galactic standards, and it emits no light. What radiation we do see is from superheated dust and gas falling in toward the event horizon. Once material passes that boundary, no trace of it remains. All astronomers can observe is the effects of the black hole's gravity on things around it. The UCLA and MPE teams aim to do just that.

Both groups began work in the early 1990s, when the current generation of 8- to 10-meter optical and infrared telescopes was coming online. At first, it was very difficult to pick out the movement of individual stars. The teams first determined that the stars were moving very fast (consistent with orbits around a very large mass) and then that they were

By peering through the glowing gas and dust that hides the galactic center, the Atacama Large Millimeter/submillimeter Array in Chile may help image the black hole and find pulsars around it.

accelerating around something. In 2002, the brightest of the near-in stars appeared to make its closest approach to the black hole and swing away again, essentially allowing the researchers to calculate its full orbit. It was following an ellipse so tight and so fast—5000 kilometers per second at closest approach—that it had to enclose an enormous, compact mass. "Then the community began believing in the supermassive black hole," says astronomer Stefan Gillessen of the MPE team.

Observations stepped up a gear during the 2000s, thanks to adaptive optics: systems that rapidly deform a telescope's mirror to compensate for the blurring effect of Earth's atmosphere. The sharper images that resulted enabled the teams to see more stars and to track them more accurately. Now the researchers could start looking for signs that relativity was making the stars' orbits deviate from a classical Newtonian course. So far, the effects of relativity have not emerged.

Both teams expect that to change starting in 2018, when that same bright star from 2002—known as S2 in Europe and S0-2 in North America—has its next close encounter with the black hole and the gravitational field it experiences is at a maximum. By then, both the W. M. Keck telescope in Hawaii, which the UCLA team uses, and Europe's Very Large Telescope in Chile, used by the MPE team, will have been upgraded. "We're trying to line up all the tools and methods ready for 2018," says UCLA's Gunther Witzel.

The teams will be looking for two telltale relativistic effects during and after the close approach, Ghez says. First, they expect to see the star's light shift toward longer, redder wavelengths as the photons strain against the black hole's intense gravity.

A more subtle effect they hope to see is precession. A star moving in a Newtonian orbit would trace out an unchanging elliptical path through space, so long as no other object perturbs it. General relativity, however, predicts that after S2/S0-2’s closest approach, warped space will make the star overshoot its previous orbit very slightly, shifting the axis of its ellipse by 0.2°. The change should become apparent gradually, as the star diverges from its earlier orbit. “By 2019 we should start to see the difference,” Ghez says.

With two teams after the prize, there’s bound to be a race. “Everyone will be trying to get it. It’s a question of when do you believe your own measurements,” says Ghez, who adds that systematic errors could easily swamp the effect. But she welcomes the competition from Germany. “It’s good for getting confirmation of your results. We push each other.”

Invisible attractor

Stars tightly orbiting the galaxy’s central black hole may soon show relativistic effects. (Dots mark observed positions; ellipses, inferred orbits.)

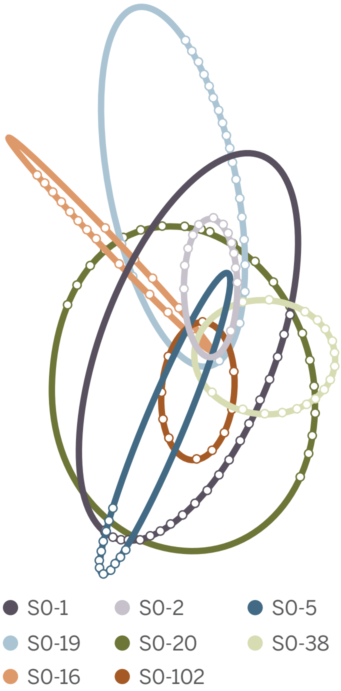


DIAGRAM: UCLA GALACTIC CENTER GROUP, W. M. KECK OBSERVATORY LASER TEAM/ADAPTED BY G. GRULLÓN/SCIENCE

SOME OBSERVERS would like an even more stringent test of relativity. The orbiting stars don’t get *that* close to the galactic center, after all. S2/S0-2’s nearest approach is still four times the distance between the sun and the planet Neptune. If general relativity is correct, the galactic black hole’s event horizon stretches only 1/1500 that far out. An international team of researchers is preparing to look right to that edge, beyond which no photons can escape, by building a telescope array as wide as Earth itself.

The Event Horizon Telescope (EHT), as the array is called, will use short-wavelength radio waves to peer through the dust veiling the galactic center. Conventional radio telescopes can’t get a detailed image of Sgr A* because their centimeters-long wavelengths limit their resolution. But shorter radio waves, with wavelengths measured in millimeters or less, yield sharper images. Combining waves from far-apart radio telescopes can further boost the resolution. About 15 years ago, astrophysicists calculated that by combining signals from millimeter-wave observatories separated as widely as Earth allows, they could image the area around Sgr A*. Then scientists could tackle three basic questions: Do the black hole and its event horizon really exist? If so, are they shaped the way that general relativity says they should be? Or does some other theory give a better description?

There are only a handful of millimeter-wave observatories around the world, but the EHT team is attempting to link as many as possible into a single array. The technique used, known as very-long-baseline interferometry, involves making observations with the different scopes simultaneously and recording the data with very accurate time stamps. Later, a computer can merge the separate observations as if they were all taken at once by one huge dish. To create the planet-wide array, the EHT team has had to equip some of the individual telescopes with better receivers, recorders, and highly accurate atomic clocks. Early this year a team was doing so at the South Pole Telescope in Antarctica. “This is what gets me out of bed in the morning: fashioning a new type of telescope out of a few bits and pieces,” says team leader Shep Doeleman of the Massachusetts Institute of Technology’s Haystack Observatory in Westford and CfA.

Over the past few years, the EHT team has been testing the system with just a few dishes—in Hawaii, Arizona, and California—and has seen structures at the galactic center of about the right size but not with enough detail to probe relativity. Later this month they will try again after adding new, more distant dishes to the array: Mexico’s Large Millimeter Telescope and the Atacama Pathfinder Experiment in Chile. With this extra receiving area and longer baselines, the team hopes to see the first definitive sign of the black hole: its shadow.

The black hole should block out light from stars behind it, casting a visible shadow. Its intense gravity should also bend—or “lens”—light from stars behind it, producing a ring of distorted starlight around the edge of the shadow. That starlight is too faint to be seen from Earth. But

MILESTONE: 1936

Einstein eschews peer review

Albert Einstein was not infallible, and sometimes his pride made him slow to acknowledge mistakes. A notable example took place in 1936, when he butted heads with the editor of the journal *Physical Review* over a process that modern scientists take for granted: peer review.

Einstein, then at the Institute for Advanced Study in Princeton, New Jersey, and collaborator Nathan Rosen had submitted an article titled “Do Gravitational Waves Exist?” Their answer, surprisingly, was “no.”

At the time, peer review by anonymous outside experts was beginning to take hold among journals in the United States. Einstein, however, wasn’t used to it: Until he left Germany 3 years earlier, he had regularly published in German journals without external peer review. He was indignant when he learned that his paper had received a critical review, and he withdrew it in a huff. “We (Mr. Rosen and I) … had not authorized you to show it to specialists before it is printed,” he wrote to the editor. “I see no reason to address the—in any case erroneous—comments of your anonymous expert.” He and Rosen submitted the paper to another journal, the *Journal of the Franklin Institute*, without change.

Yet before it was printed, Einstein revised the manuscript, retitling it “On Gravitational Waves.” It now came to the opposite conclusion: that gravitational waves were possible. The unidentified referee had pointed out a legitimate flaw in the original paper. Historians have recently confirmed that the referee was Howard Percy Robertson of Princeton University. After his anonymous criticisms were ignored, Robertson had delicately approached Einstein and convinced him of his error.

Even though peer review had helped Einstein save face, he stuck to his guns and never published another scientific paper in the *Physical Review*. ■ –E.C.

theorists say the EHT should see a bright ring of lensed radio waves from another source: the glowing, superheated gas and dust swirling around the black hole. A dark circle—the black hole's shadow—should blot out the very center of the glow.

Detecting the shadow, just outside the black hole's event horizon, will be a major validation of general relativity. "Just seeing the shadow as an image will be proof of the existence of a black hole," says astrophysicist Michael Kramer of the Max Planck Institute for Radio Astronomy (MPIfR) in Bonn, Germany. It would finally give astrophysicists something more than circumstantial evidence of these objects—pure creatures of general relativity. "There is no direct evidence that [a black hole] exists; everything is from theory. First we must show it is there, and then does it deviate from general relativity," says EHT collaborator Heino Falcke of Radboud University in Nijmegen, the Netherlands.

The shadow "would look different if there was no event horizon," Kramer says. Theorists say that if general relativity holds, the shadow should be roughly circular; alternate theories of gravity predict slightly different shapes, such as prolate, like a cigar, or oblate, like an M&M. EHT might be able to tell the difference when it reaches full power, researchers say. The array will really come into its own when other key instruments are added in the next few years, in particular the South Pole Telescope and the Atacama Large Millimeter/submillimeter Array (ALMA). ALMA is the world's largest observatory at millimeter wavelengths; adding its 66 dishes will double EHT's resolution and boost its sensitivity 10 times, Doeleman says.

As radio astronomers sharpen their scrutiny of the galactic center, they might stumble on something that could give Einstein's theory the most stringent test of all: a pulsar, a spinning neutron star that emits clocklike radio pulses, orbiting close to the black hole. It would amount to a precise clock, probing the structure of spacetime around the black hole with undreamed-of precision, says theorist Norbert Wex of MPIfR. By tracking variations in the pulsar's timing, Wex says, researchers could measure the black hole's mass to better than one part in a million and its spin. From those two quantities, they could calculate a quality of its gravitational field known as the quadrupole moment, predicted by general relativity. Using the pulsar again, they can then directly measure the quadrupole moment to see if relativity got it right.

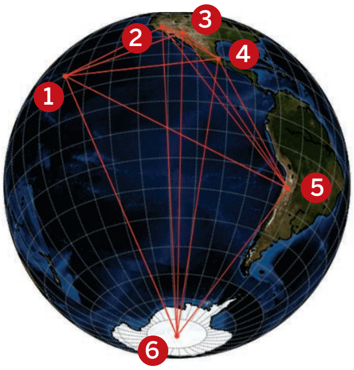
For theorists, that raises a tantalizing possibility: Even a slight difference in the two values would imply that the black hole is nonspherical. But according to general relativity, the shape of a black hole is forbidden knowledge. According to the oddly named "no-hair" theorem of relativity, the only things that it is possible to know about a black hole are its charge, its mass, and its spin. All other information about it (its "hair") has disappeared below the event horizon, never to be seen again.

Unfortunately, despite a couple of decades of searching, the galactic center seems to be devoid of pulsars. "There should be thousands. We're completely puzzled," Falcke says. In 2013, European radio astronomers did find one magnetar—a rare type of high-magnetic field pulsar—orbiting Sgr A*, but not close enough to probe the black hole's spacetime. The finding did raise hopes, though, because "it shows the pulsar mechanism can work [at the galactic center] and that they are being made," Falcke says. Bigger telescopes, like the upcoming Square Kilometre Array, or higher frequencies, such as those used by ALMA, might pierce the gloom and spot the coveted natural probe.

One way or another, researchers are looking forward to exploiting the extraordinary laboratory at the galactic center. "The next decade will be very exciting. We'll get much more data … and hopefully an image of a black hole," Loeb says. Says Falcke: "It's about space and time. It can't be more fundamental than this." ■

The long view

To image the galaxy's central black hole requires a telescope array that spans the globe.



1. Submillimeter Array and James Clerk Maxwell Telescope, Hawaii

2. Combined Array for Research in Millimeter-wave Astronomy, California

3. Arizona Radio Observatory/ Submillimeter-wave Telescope, Arizona

4. Large Millimeter Telescope, Mexico

5. Atacama Pathfinder Experiment, Chile

6. South Pole Telescope, Antarctica

PHOTO: LAURA VERTATSCHITSCH/HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS

MILESTONE: 1959

Bringing general relativity down to Earth

General relativity mostly reveals itself on cosmological scales, but its effects also show up closer to home—even in our pockets. The GPS that so many smart phones use to orient and guide users would be useless if the system did not account for relativity.

According to general relativity, time slows in a gravitational field; as a result, clocks closer to a gravitational mass run slower than those farther from it—an effect known as time dilation. Time dilation results in a subtle reddening of light moving up from Earth's surface, as the weakening gravity causes the light's electromagnetic fields to oscillate at a lower frequency.

Researchers first definitively detected that "gravitational redshift" in 1959, in an experiment at a 23-meter tower at Harvard University. Physicists Robert Pound and Glen Rebka set up a source of light with a known frequency at the bottom of the tower and a detector at the top. The photons changed frequency in transit by an amount that agreed with Albert Einstein's theory. In 1977, scientists laying the foundation for GPS navigation confirmed the underlying effect, time dilation, by launching a satellite with a highly precise cesium clock. Sure enough, the clock quickly went out of sync with its Earth-bound counterparts, in agreement with Albert Einstein's theory.

For GPS to function, clocks on satellites and on the ground have to stay in sync, allowing your smart phone to measure the exact travel time of radio signals from multiple satellites. The relative timing of the signals allows the phone's GPS receiver to calculate position. If engineers failed to account for gravity's time dilation, the weaker gravity in orbit would nudge the clock in each GPS satellite ahead of ground-based clocks by tens of microseconds per day—an error that would quickly make the navigational system useless. ■ –E.C.