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TESTING THE THEORY OF GENERAL RELATIVITY AT THE GALACTIC CENTER

INTERVIEW WITH DR. REINHARD GENZEL

BY SABRINA WU, YI ZHU, AND ELETTRA PREOSTI

Reinhard Genzel, PhD, is a German astrophysicist, co-director of the Max Planck Institute for Extraterrestrial Physics, an honorary professor at the Ludwig Maximilian University of Munich, and an emeritus professor at the University of California, Berkeley. He also sits on the selection committee for the Shaw Prize in Astronomy. Dr. Genzel has received numerous honors and awards, including the Herschel Award and the Harvey Prize. Most notably, in 2020, he was awarded the Nobel Prize for the discovery of a supermassive compact object at the center of our galaxy. In this interview, we discuss Dr. Genzel's decades-long work developing ground and space instruments to study physical processes at the center of galaxies that led to his groundbreaking discovery.

BSJ: What were some of your early, memorable experiences that led you to work in "extraterrestrial physics"?

RG: My father was a physicist. In particular, he was an experimentalist working in solid-state physics, so I essentially grew up in physics. Why extraterrestrial physics? After high school, I began to explore a number of fields when I discovered that there was a new Max Planck Institute in Bonn conducting research in radio astronomy. At the time, they had the largest single dish radio telescope, almost one hundred meters in diameter, in the world. That seemed like a terrific opportunity!

BSJ: What is the theory of general relativity?

RG: In his theoretical work on special relativity, Einstein started to take into consideration a very important experiment, called the Michelson-Morley experiment, which demonstrated that there is a speed limit to communication. We can only communicate at the speed of light or less. Using this limit, Einstein developed a theory that explained how to communicate between reference frames moving at high speeds relative to each other. This is known as the theory of special relativity.

Einstein's next step was to take into account gravity, as he knew that gravitational fields affect the motions of photons (i.e., particles of light). It was very clear to Einstein that light is bent by masses in its vicinity and that light loses energy when escaping from regions of mass. Einstein then put these discoveries into a proper theory known as the theory of general relativity. Overall, general relativity takes into account both the consequences of special relativity as well as the effects of mass on spacetime.

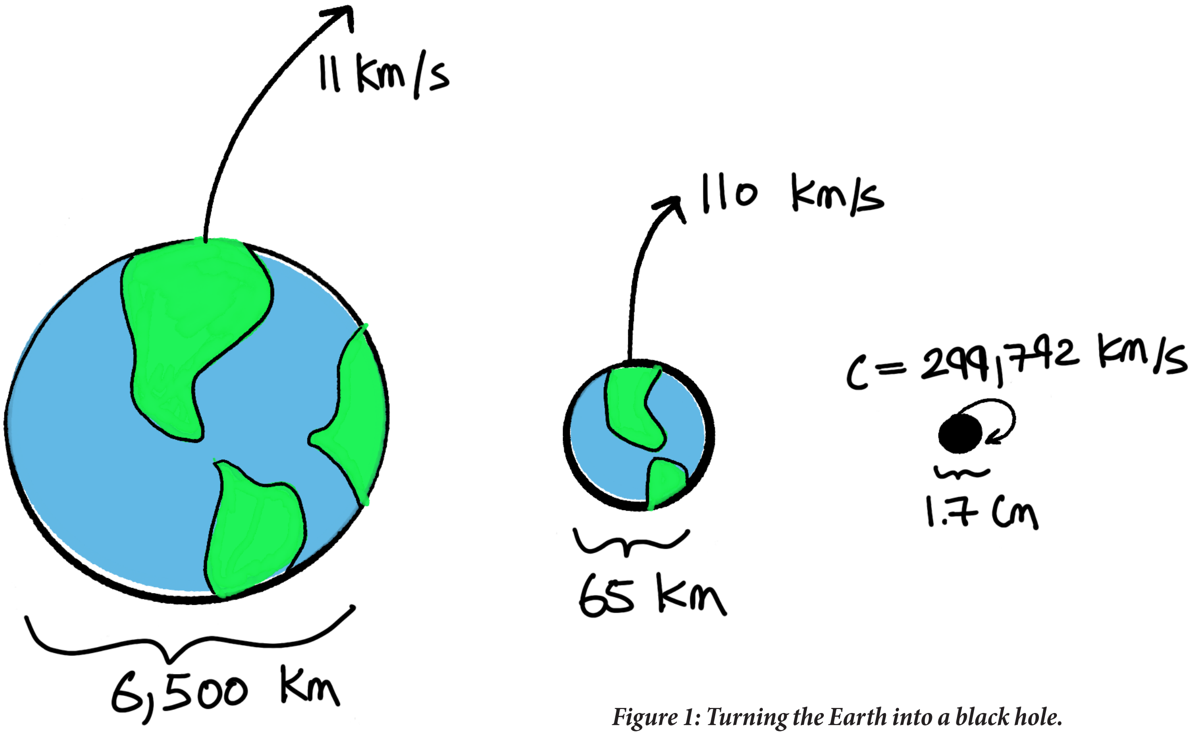

Figure 1: Turning the Earth into a black hole.

BSJ: What is a black hole?

RG: We can determine from Newtonian mechanics that the escape speed of a rocket launched from the Earth's surface is approximately eleven kilometers per second. Next, if we take the Earth and shrink it to one centimeter in diameter without changing its mass, the rocket's escape speed is determined to be the speed of light. Then, if we shrink the Earth even further, the rocket's speed will become faster than the speed of light. However, no object can travel faster than the speed of light, so this means that neither the rocket, nor anything else—not even light—can escape from this shrunken Earth. Thus, we have transformed Earth into a superdense object called a black hole.

BSJ: How are black holes created?

RG: In order to understand how black holes are created, we must first examine stellar black holes. At some point, stars much more massive than the Sun run out of fuel, allowing gravity to pull the stars' material inward. Since there is no longer any radiation pressure from the star to resist the pull of gravity, the star collapses inwards on itself, resulting in a supernova—a powerful and luminous stellar explosion. What remains becomes a stellar black hole.

BSJ: How can we prove the existence of a black hole?

RG: In our solar system, the Sun, which is hundreds of times more massive than all of the planets, lies at the center. Then, by Kepler's laws, we know that all of the planets in the solar system orbit around the Sun in ellipses. Let us now do a gedanken experiment—a thought experiment—and switch off the light of the Sun. What happens to the planets? They will still orbit around the Sun because their motion has nothing to do with the radiation from the Sun, only the force of gravity. That is how we can make visible something which is not: we look at the effect it has on its environment.

BSJ: Why did researchers theorize the existence of a supermassive black hole at the center of our galaxy?

RG: Another species of black holes which we now know to exist are supermassive black holes. They were first discovered in 1963, when Martin Schmidt, a professor at Caltech, used the Panama Telescope to observe a "star" and found that its optical spectrum consisted of emission lines (from hydrogen, helium, neon, etc.) that were all redshifted by sixteen percent. He then realized that if the redshift of these emissions lines was caused by the expansion of the universe, this little "star" must actually be over two billion light years away. And if he could see this "star" when it is so far away from him, then what looked like a faint star must actually be very luminous. In fact, it must be about two thousand times more luminous than the entire Milky Way Galaxy. We call this "star" a quasar, an object that emits large amounts of energy. The question then becomes: how can we perform the same thought experiment we used to prove the existence of black holes on quasars? We cannot; quasars are too far away!

More recently, inspired by the discovery of quasars, theoretical physicists from the UK began to propose that every galaxy contains a black hole. That is in fact what we now believe: every galaxy has a massive black hole, and it is just during certain phases of activity that these black holes show up in such spectacular ways as quasars. That would also mean that there is a black hole at the center of our very own Milky Way.

BSJ: How, then, did you try to show the existence of the black hole Sagittarius A* at the center of the Milky Way?

RG: Initially, we thought that we would be able to detect some sort of motion at the Galactic Center, or the rotational center of the Milky Way Galaxy, to indicate the presence of a supermassive black hole just through observation. But, we faced a major obstacle: it is not possible to optically observe the Galactic Center. This is because there exists an immense amount of dust in the interstellar space between the Earth and the Galactic Center, twenty-seven thousand light years away, which completely extinguishes the visible radiation emitted by the Galactic Center. To overcome this challenge, we realized that while we may not be able to optically observe any motion due to the visible waves radiated by the potential massive black hole, any radio waves it emitted would be able to penetrate the dust and thus be detected.

That is exactly what Charles Townes did. In collaboration with his research group, which included myself as a postdoc, we started building infrared spectrometers to measure the motions of gas clouds near where we thought the Galactic Center was located. Sure enough, the gas clouds we observed moved at enormous speeds, about one hundred times faster than the speed of the Earth. Now, since the Galactic Center is much closer to the Earth than the quasar discovered by Schmidt, we can use Kepler's laws to find that there must be a concentration of a few million solar masses at the Galactic Center. This could be a supermassive black hole!

BSJ: What kind of new technologies have improved our observations of the Galactic Center where the supermassive black hole is?

RG: Gas is not a perfect tracer of gravity as it can be influenced by many other factors such as magnetic fields or stellar winds, so we instead have to observe the behavior of stars. In fact, by measuring the positions of nearby stars in the sky and tracking how they change over time, we can actually derive more information about a possible supermassive black hole at the Galactic Center. So, how then are we able to obtain these measurements? To accomplish this, we need very sharp images as we are looking at motions on the scale of milliarcseconds (2.78×10^{-7} degrees) per year. That is not something a normal telescope can help us observe. In fact, because Earth's atmosphere distorts starlight, not even a really big telescope would be able to help us in observing these tiny motions.

So, to remedy this, we initially took very fast snapshots of the stars' motion to avoid any distortion from wind. Afterwards, using a computer, we added these images together to make them as sharp as possible. We then used what is called "adaptive optics," a method used to measure and correct for distortions in the atmosphere by utilizing a deformable mirror before even taking an image. Adaptive optics is able to improve the resolutions of images by factors ranging from ten to twenty.

BSJ: With a more precise understanding of the stars' motion at Galactic Center, your group was able to use a technique called orbit fitting to constrain the mass of Sagittarius A*. Can you

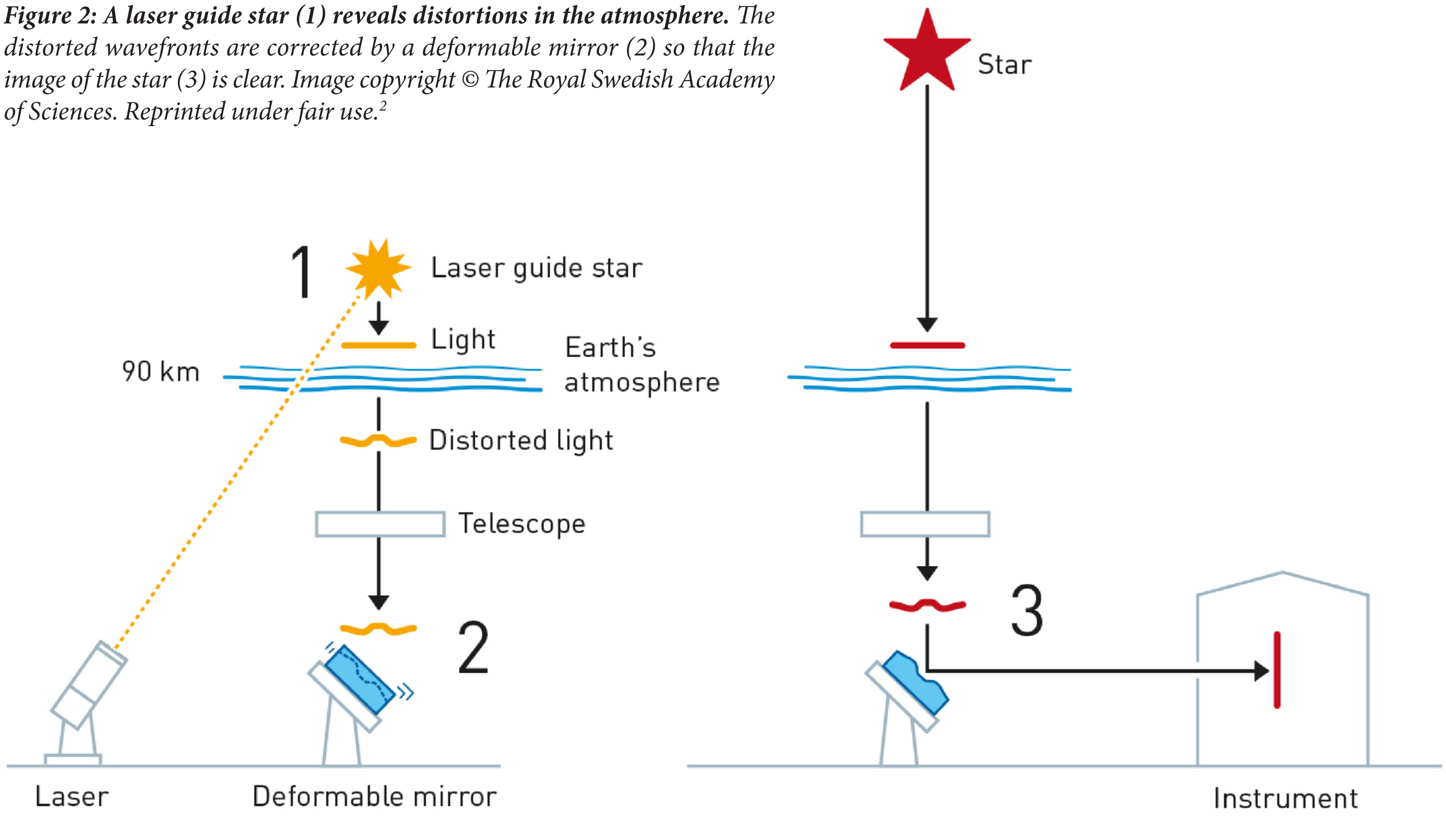

Figure 2: A laser guide star (1) reveals distortions in the atmosphere. *The distorted wavefronts are corrected by a deformable mirror (2) so that the image of the star (3) is clear. Image copyright © The Royal Swedish Academy of Sciences. Reprinted under fair use.*[2]

describe the process of orbit fitting?

RG: We know that by Kepler's law, if we have a dominant mass, then the stable orbits of nearby bound test particles, such as stars or gas particles, will be elliptical. So, first we collected data on the velocities and separations of objects close to the Galactic Center in order to determine the curvature in their motions. Next, we used statistical techniques to fit Keplers' ellipses to the curvatures that we had calculated. We were then able to directly use these orbit fits in order to determine the mass of the nearby black hole.

BSJ: Why is the star S2 such a good candidate for orbit fitting?

RG: When observing the movement of stars around black holes, we wanted to track a bright star that travels as close to the black hole as possible. The general wisdom at the time, however, was that we should not expect to have bright stars very close to a black hole. This is because near a black hole, interstellar gas clouds are pulled by the black hole's tidal forces. As a result, they are not able to collapse under their own gravity to form bright stars.

But from pictures taken in the 1990s, we already had evidence that there are bright stars at angular distances of approximately half an arcsecond away from the Galactic Center. Moreover, when we actually took measurements using the spectral technique, we were able to find a number of stars near the Galactic Center that are actually quite bright. There seemed to be a trick that nature was playing to bring bright stars next to black holes.

In fact, we now know that binary stars formed way outside of the Galactic Center can, by chance, move inwards towards the Galactic Center where the supermassive black hole Sagittarius A* lies. Once close enough, the binding energy between the two stars becomes smaller than the kinetic energy from their motion relative to the massive black hole, meaning that the stars no longer want to stay bound together. When this happens, only one of the stars remains near the black hole while the other one gets flung out of the Milky Way. We believe that, using this mechanism S2 has been able to remain near the black hole while its companion was lost. At perigee (closest approach), S2 comes close to 14 milliarcseconds from Sagittarius A*.

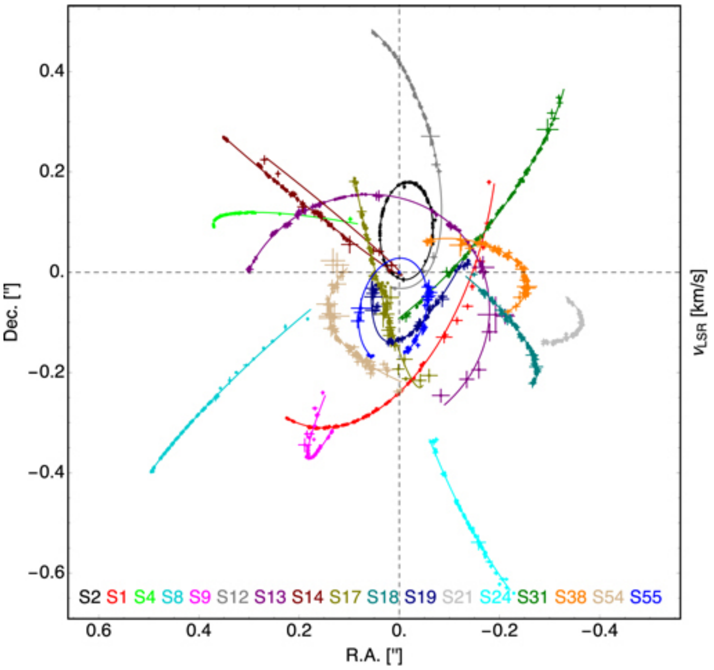

*Figure 3: **Observation of the orbits of 17 stars surrounding Sagittarius A* from data collected over a 25-year period.** Image copyright © The American Astronomical Society. Reprinted under fair use.*[3]

BSJ: You use both a Newtonian orbit fit and a relativistic fit in your calculations. Can you explain the difference between the two?

RG: There are various ways of approaching relativistic orbit fitting, one of which is using parameterised post-Newtonian approximations. Essentially, the post-Newtonian approximation method performs orbit fits by adding more and more terms, on the order of v/c2, to the model of the orbit shape without the need to solve the Einstein field equations. The first term that is added represents the Roemer effect, which accounts for the finite speed of light. The next term accounts for the gravitational redshift, the reddening of light due to the fact that clocks tick slower near big masses. The third term represents the Schwarzschild precession, which describes the precession in the direction of orbit of ellipses traced by orbiting stars. The final term accounts for the precession of stars about the spin of a black hole. That is, if a black hole has a spin and the orbit of the stars around the black hole makes an angle relative to the spin, then over time, the orbit of the star starts to wobble—to precess about the spin of the black hole.

On the other hand, the relativistic fit method directly solves the field equations numerically using a computer. In the relativistic method, we formulate the fitting problem as a Newtonian fitting problem and add a fudge factor multiplied by the aforementioned terms (Roemer effect, gravitational redshift, etc.). We then perform the fit using the computer and solve for the fudge factor. If Einstein's theory of general relativity is correct, the fudge factor will be one. Otherwise, the factor will deviate from one.

BSJ: The orbit of S2 has revealed the existence of a supermassive black hole at the galactic center. How else has S2 improved our understanding of general relativity?

RG: At perigee, when S2 is closest to Sagittarius A*, the effects of general relativity are most visible. We know that S2 has an orbital period of sixteen years, so when we observed S2 at perigee in 2002, we began preparing for its return in 2018.

Our goal was to do something which had never been done before: to use the Galactic Center as a laboratory to test general relativity. Indeed, we developed a completely new instrument called GRAVITY with four eight-meter (in diameter) telescopes separated by as much as one hundred and thirty meters.

GRAVITY has milliarcsecond resolution, and we can measure distances of about ten to twenty microarcseconds. This advancement in precision enabled us to observe several effects of general relativity when S2 came back around in 2018. One particularly exciting result

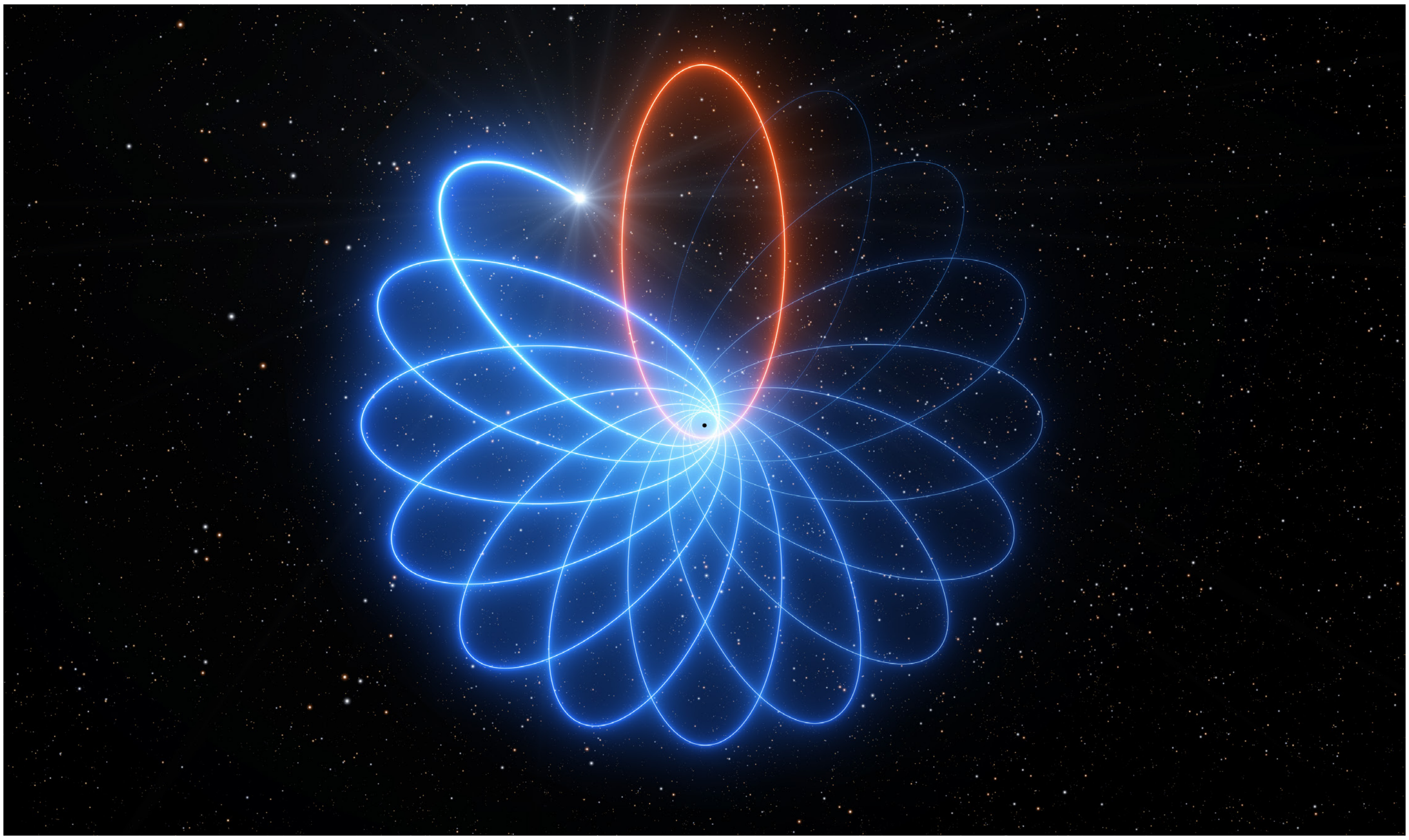

Figure 4: Artist's rendition of the Schwarzschild precession of S2's orbit. *Image licensed under CC BY 4.0.*

is that we detected Schwarzschild precession of the orbit of S2 [1].

BSJ: What is the advantage of GRAVITY over adaptive optics?

RG: Using adaptive optics, we are typically able to measure the position of a star at a precision of approximately 0.4 milliarcseconds. For example, let us say we have fifty statistically independent measurements. So, the accuracy to which we can measure apogee (the point in the orbit farthest from Sagittarius A*) should be 0.4 milliarcseconds divided by the square root of fifty, which is about 0.06 milliarcseconds. We also know that everytime S2 returns to apogee, the apogee is moved by about 0.6 milliarcseconds. Since 0.06 is much less than 0.6, by using adaptive optics, we should have already been able to measure the Schwarzschild precession of S2 ten years ago. Why were we not able to? What had we done wrong?

Well, the problem with adaptive optics is that we are not able to image Sagittarius A* directly—it is not visible in the optical band—so we can only see S1, S2, and the surrounding stars. Because the systematics of the telescope can change day-to-day due to slight variations in temperature and other environmental factors, it is difficult to obtain a stable reference for the location of Sagittarius A*. If we do not know the location of the Galactic Center, we have to acquire its value as a fit parameter, and that then destroys the available information to a considerable extent.

Now GRAVITY employs radio astrometry to pinpoint the location of Sagittarius A* and S2 at the same time. With both objects visible, finding their distance becomes simple triangulation and we can make full use of our data.

BSJ: How does GRAVITY use interferometry to improve resolution?

RG: The resolution of a telescope at a given wavelength is specified by the ratio of the size of the telescope and the wavelength of the light we are observing. However, in terms of interferometry, if we have two telescopes, instead of thinking of them as two individual telescopes, we can think of each telescope as the edge of an even bigger telescope. So, now, instead of four eight-meter telescopes, we have one large telescope that is one hundred and thirty meters. This alone improves our resolution by a factor of about fifteen to twenty.

Of course, if you have a complex image, such as a galaxy or a planet, it is not yet possible to image them well without dozens of telescopes. However, you can do very good astrometry on point sources such as S2.

BSJ: What are the future plans for the GRAVITY instrument?

RG: The GRAVITY instrument has been a major breakthrough, not only for understanding what is happening at the Galactic Center, but for astrophysics research in general. So far, GRAVITY has allowed us to resolve the broad line region around our

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active galactic nucleus. We now hope to improve the sensitivity of GRAVITY by another factor of, hopefully, one hundred. This upgrade would make GRAVITY approximately one hundred thousand times more sensitive than interferometric telescopes designed even just a few years ago. Improving sensitivity by factors this large would be an absolute game changer. In fact, with GRAVITY, we have been able to obtain the best exoplanet spectra to date.

In addition to improving our detectors, we are also looking to equip all four of our eight-meter telescopes with laser guide stars so that we can use these stars as reference points (Figure 2). This will allow us to look at faint, high redshift quasars and take broadline measurements for cosmology experiments for the first time.

But these experiments take a long time. In my case, forty years have passed since I have worked on the early stages of this experiment with Charles Townes, and the work is still ongoing. While it is fantastic to see all of this, it requires a lot of patience.

BSJ: In your Nobel Lecture, you describe you and your team's work on proving the existence of a black hole at the galactic center as a 40 year journey. What has been the most rewarding part of this decades-long endeavor?

RG: I would say that the most rewarding part of my decades of work is how much we have learned. This route that my fellow researchers and I have taken, which has largely been made possible due to the generosity of the Max Planck Society, has been very long, risky, and ambitious. Over time, we have been able to improve our work and enhance it, which is not always possible in science. I hope that this work will continue even after I retire.

I now have the chance to continue my research for some time, not only exploring the Galactic Center, but also looking at time travel. In fact, most of my research is actually in time travel. That sounds crazy, but astronomers are actually time travelers in the sense that when we look through a telescope at far away objects in space, due to the finite speed of light, we are actually seeing the galaxy as it was billions of years ago.

BSJ: What advice do you have for undergraduates still early in their career?

RG: There is a German phrase that translates to 'nothing comes from nothing.' What that means is, if you do not work hard, it will be very unlikely that you will be successful. To be successful in research, you need to work hard, try hard, and be excited about your work. So, go ahead, pursue your interests, and have fun!

This interview, which consists of one conversation, has been edited for brevity and clarity.

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