NOBEL PRIZE WINNERS

How Artificial Stars Guide Andrea Ghez Towards Her Next Discoveries

TOPTICA

Revealing the Center of our Galaxy

If you look up to the sky on one of the cloudless nights, you might see our galaxy. You might be impressed by the hugeness of the Milky Way and get the humble feeling about how little we know how it all works.

Thanks to ambitious researchers like Andrea Ghez, Reinhard Genzel, and Roger Penrose, we gain increasingly more knowledge about the mysteries of the universe. The three scientists dedicated their work to one of the current century‘s burning questions of astronomy and astrophysics: What is in the center of our galaxy?

For their work providing the theoretical prediction and experimental evidence for a massive black hole, called Sagittarius A*, in the center of our galaxy, they finally have been rewarded with the 2020 Nobel Prize in physics.

INTRODUCTION

Some time ago, in the 1960s, Roger Penrose, a British mathematician and theoretical physicist, and Stephan Hawking developed a theory that predicted the shape and motion of galaxies in line with Einstein's general theory of relativity. They proposed the existence of massive black holes in the center of galaxies, including our Milky Way.

Two groups independently tried to prove this hypothesis, one around Andrea Ghez from UCLA and one around Reinhard Genzel from the MPI for extraterrestrial physics. To find experimental evidence for this prediction, large telescopes are necessary. And if you don't build such telescopes in space, sophisticated techniques to fight atmospheric distortions are required. Otherwise, these distortions blur the images and limit the observation of distant stellar motion.

In the last 30 years, the two groups gathered experimental evidence for the existence of a supermassive black hole in the center of our Milky Way. And with that, could, in the end, rule out alternative theories and hypotheses.

MEASURING THE UNMEASURABLE

But how to prove the existence of a black hole? As the name already suggests, black holes are not observable straight away. They consist of a huge concentration of mass containing some million solar masses.

This mass is condensed in a small volume because of its massive gravitational pressure. For such an object, general relativity predicts that all things within a specific event horizon can’t escape the black hole - including light.

Thus, the best way to observe a black hole is to look at its effects on objects nearby the event horizon. But what seems like an easy task, in the end, is not trivial at all: In general, the mirror size limits the resolution of a telescope. For two stars to still be distinguishable, the dimmer and closer to each other they are, the larger the telescope‘s mirror must be. And since the center of our galaxy is 25’000 light-years away from us, the visible light of stars from this region is entirely obscured by space dust. Even in the near-infrared regime, which is less sensitive to scattering at this dust, only one in 10 stellar photons can make it through.

Thus, astronomic researchers use large ground-based telescopes with mirrors of 8 meters and more in diameter and try to observe stars in the crowded center of the Milky Way. But even for such giant telescopes, another challenge massively limits the imaging of distant stars: The blurring by the atmosphere.

SPECKLE IMAGING

To fight this blurring, researchers used a technique called speckle imaging. It is a method where instead of taking one image with a long exposure time, several hundred short-time images are recorded.

Each of those images represents an instant of atmospheric blurring. And those images are then superposed in a nonlinear image processing procedure to obtain an image with better resolution. Using this technique, Genzel’s group at the 8-meter Very Large Telescope (ESO VLT) in Chile and Ghez’s group at the 10-meter Keck telescope in Hawaii independently measured the motions of stars and gas near the center of the Milky Way in the late 1990s.

By analysis, they gained the first estimations of orbital motions that strongly indicated a supermassive black hole at the center of our galaxy. But with the short exposure times of this method, the dimness of objects again became a bottleneck, and for imaging fainter stars, the resolution and signal to noise had to be improved.

ADAPTIVE OPTICS AND NATURAL GUIDE STARS

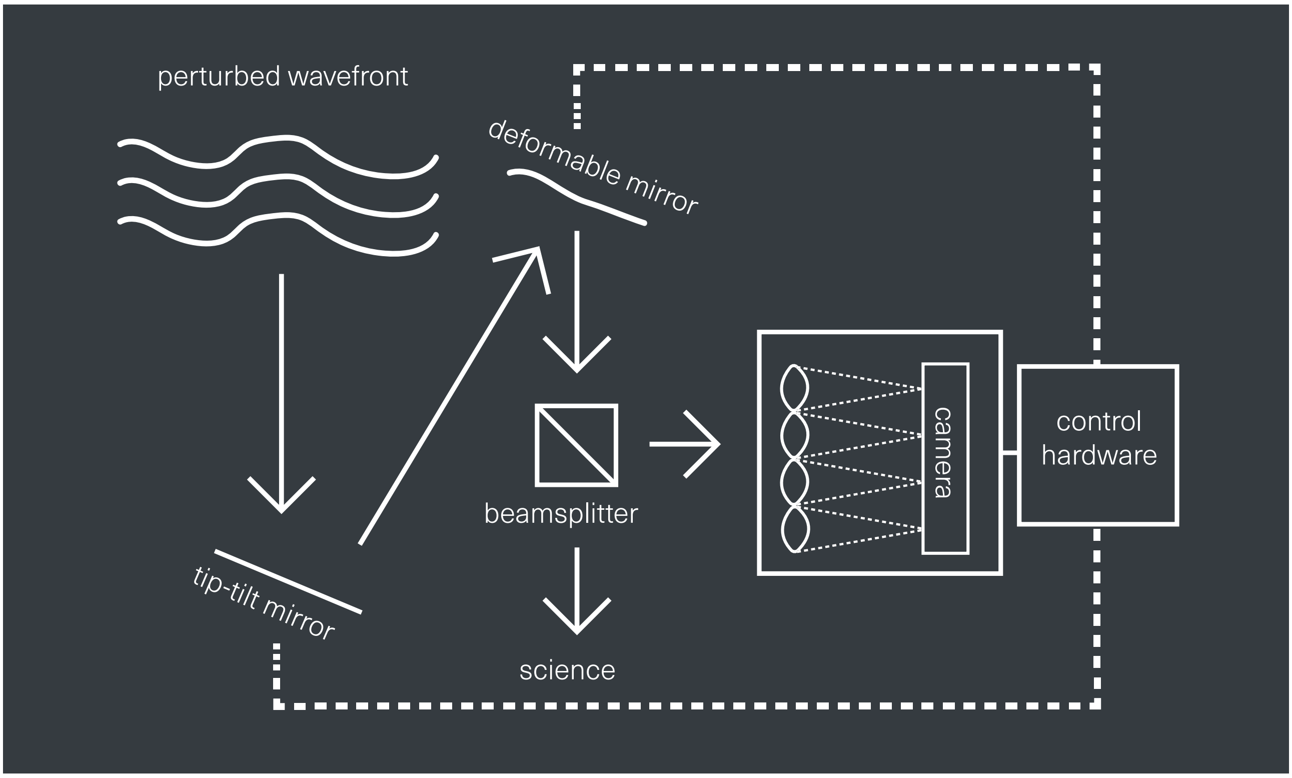
An advanced approach to imaging stars at the galactic center is adaptive optics (AO). The technique uses an auxiliary mirror in the optical path to correct for optical distortions like atmospheric turbulences.

The auxiliary mirror is deformable by several hundred actuators at its backside and is used to measure the incoming wavefront of a bright point-like reference source with a sensor. The sensor information is analyzed and used to continuously adapt the mirror by the actuators in a feedback loop. This way, a real-time corrected image of the reference source is created.

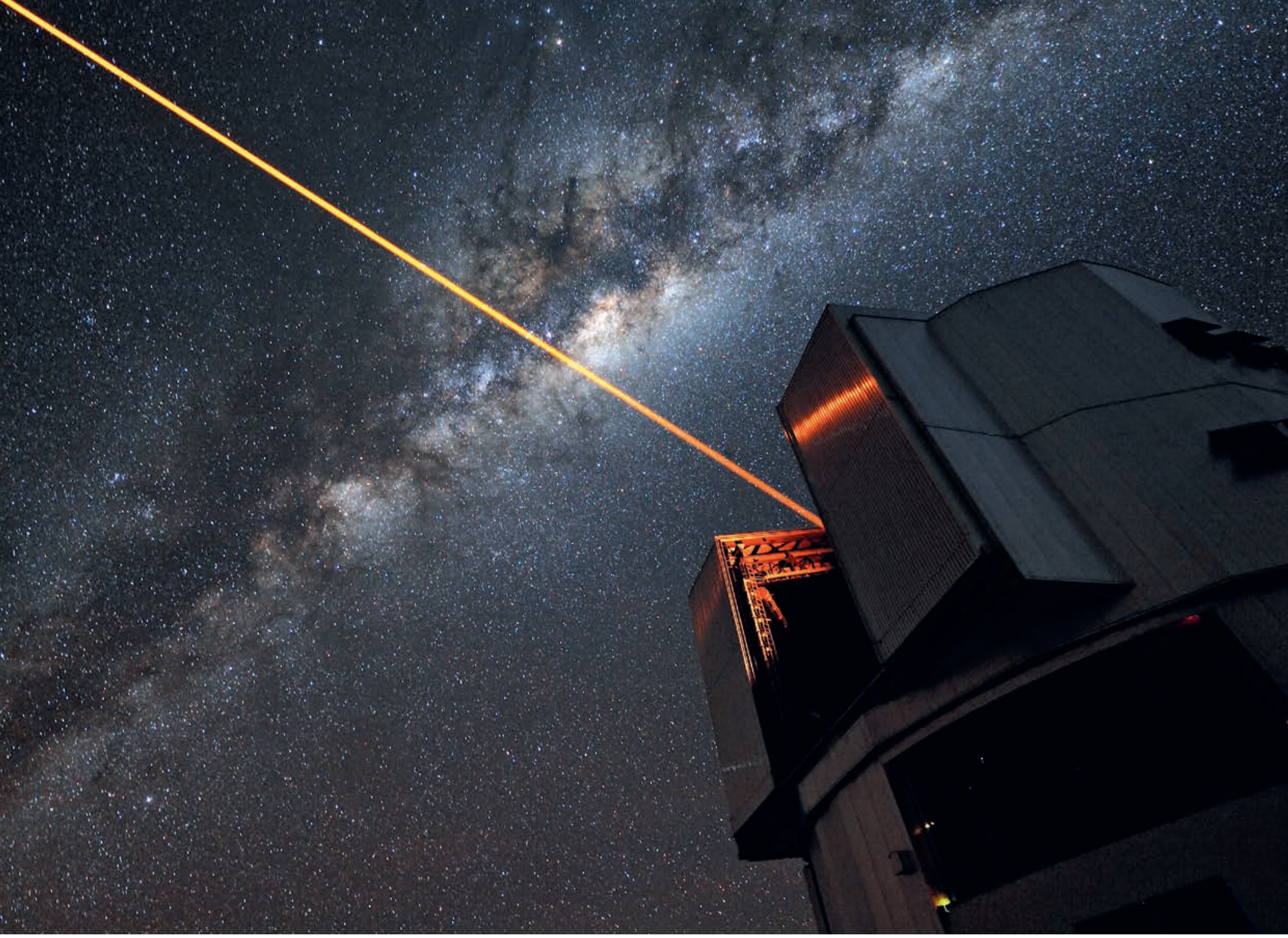
Since astronomical objects are often quite faint, brighter stars near the object to be observed can be used as a reference source, the so-called natural guide stars. With such an AO system, Ghez and Genzel gained significantly higher resolution and succeeded in measuring the orbit of the rapidly moving star S2 near the center of our galaxy.

These measurements ruled out all alternative assumptions of what might be in the galactic center apart from a supermassive black hole. A discovery worth the 2020 Nobel Prize in physics.

But what if natural guide stars are not available next to the objects of interest? Could you use an artificial guide star, and what could it look like?



Schematics of an adaptive optics system. The perturbed light first hits a tip-tilt mirror and then a deformable mirror. With a beamsplitter, some light is diverted to a wavefront sensor that creates a signal to adapt the mirrors.



Creation of an artificial guide star for ESO's Very Large Telescope (VLT) in the Atacama Desert of northern Chile. A laser at 589 nm is exciting sodium atoms in the outer atmosphere. (ESO G.Hüdepohl -atacamaphoto.com-)

SODIUM ATOMS AS ARTIFICIAL GUIDE STARS

Natural guide stars are rare and limit AO systems to investigations of only small segments of the sky. Thus, if it is possible to create artificial guide stars at any position in the sky, this means much more flexibility for the experiments.

The idea of an artificial guide star is to excite an object in or around the earth's atmosphere and collect its emitted light. Because the emitted light of the excited object is exposed to the same turbulences as a distant astronomical object, it can be used as a reference.

To generate such artificial guide stars, the sodium layer of the outer atmosphere is well suited. Because it is a distant atmospheric layer, it essentially obtains the same atmospheric distortions as a natural star.

However, to excite sodium atoms in the outer atmosphere high power lasers are required with narrow bandwidth at 589 nm (yellow-orange color) and tunability to match the hyperfine structure of sodium.

Therefore, Artificial Guide Stars were not as widespread as they could be because older laser systems based on dye lasers or solid state lasers hardly met the requirements and were quite large and demanding with respect to maintenance.

SODIUMSTAR DIODE LASER FOR NEW EXPERIMENTS

This changed some years ago, when the W. M. Keck Telescopes and most other large observatories installed a new laser system: the “SodiumStar” developed by TOPTICA Projects and MPB Communications in collaboration with ESO and Keck. Thanks to the ESO Fiber Raman Amplification approach, a robust diode laser of 1178 nm can be used and is subsequently converted to the resonance frequency of 589 nm.

This new approach results in a high power, narrow linewidth tunable laser system, which can be run under rough environmental conditions and offers the possibility of remote control. These features are precious for further investigations on black holes in the next couple of years since they enable a standby-operational mode.

Such a mode is necessary for the researchers’ ambitious goal: Observing how a star is torn and/or swallowed by a black hole. This significant incident is expected to happen in the next couple of decades. And to capture such a rare moment in astronomy and gather as much measurement data as possible, Ghez, Genzel, and other leading astronomers need to rely on large telescope systems that can be activated and aligned quickly. And this is where the artificial guide stars created by TOPTICA’s SodiumStar laser make the difference.

After her nobel prize, Andrea Ghez is still looking into the sky for answers. And at W. M. Keck Observatory near the summit of Mauna Kea in Hawaii, artificial stars made by TOPTICA lasers help her to see clearly.

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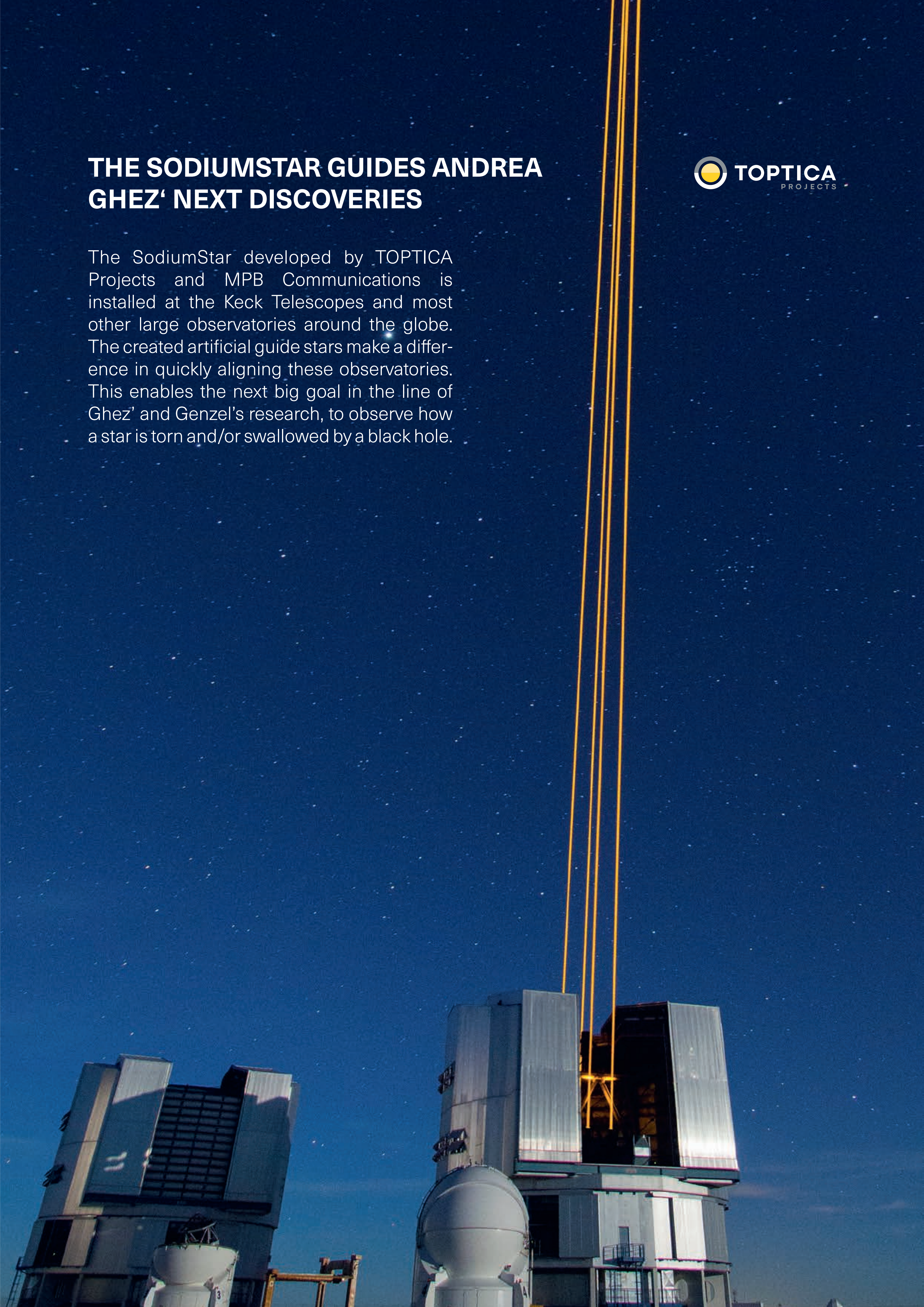
THE SODIUMSTAR GUIDES ANDREA GHEZ‘ NEXT DISCOVERIES

TOPTICA PROJECTS

The SodiumStar developed by TOPTICA Projects and MPB Communications is installed at the Keck Telescopes and most other large observatories around the globe. The created artificial guide stars make a difference in quickly aligning these observatories. This enables the next big goal in the line of Ghez’ and Genzel’s research, to observe how a star is torn and/or swallowed by a black hole.



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