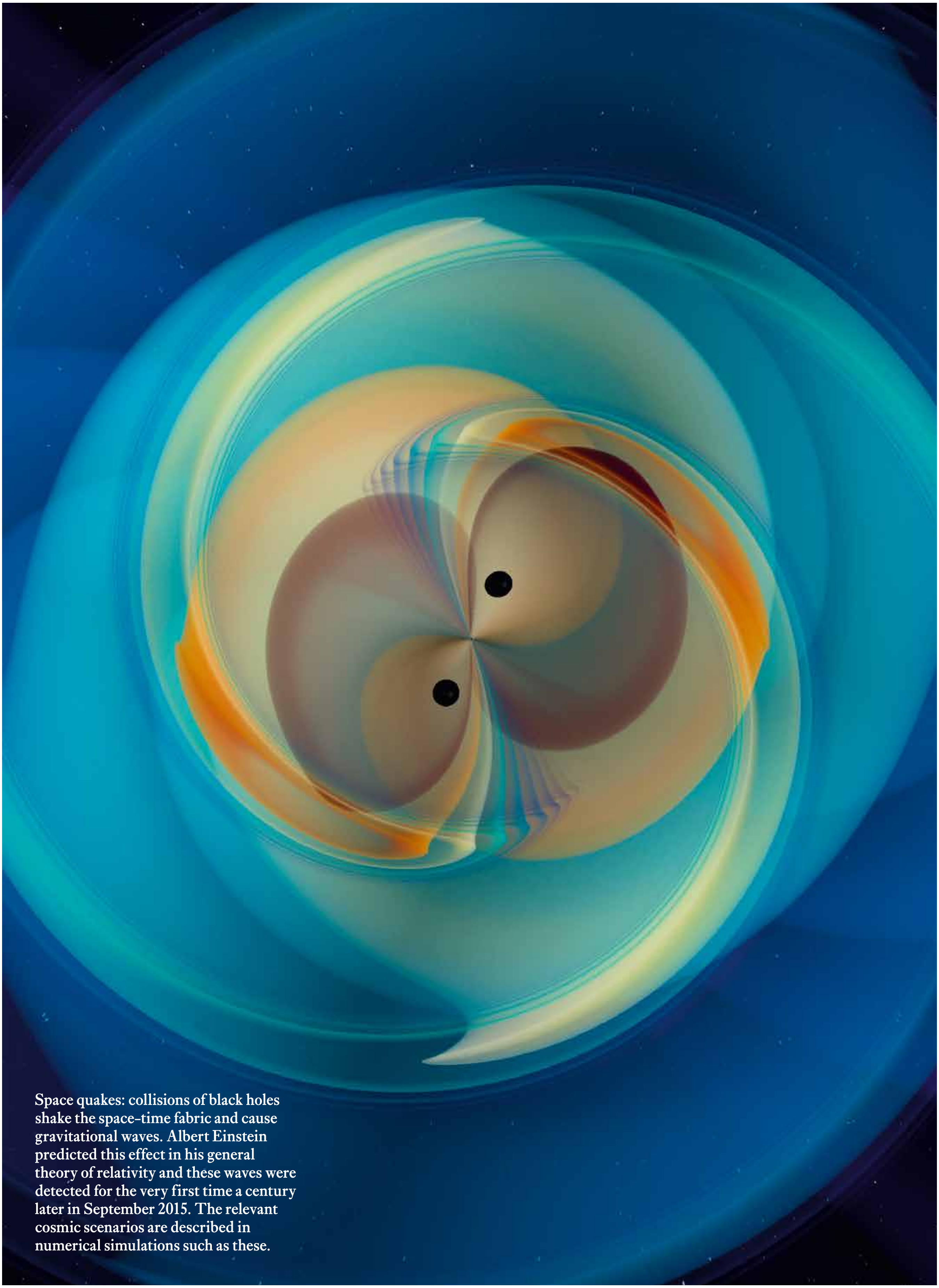

Space quakes: collisions of black holes shake the space-time fabric and cause gravitational waves. Albert Einstein predicted this effect in his general theory of relativity and these waves were detected for the very first time a century later in September 2015. The relevant cosmic scenarios are described in numerical simulations such as these.

IMAGE: N. FISCHER, H. PFEIFFER, A. BUONANNO/MPI FOR GRAVITATIONAL PHYSICS, SIMULATING EXTREME SPACETIMES (SXS) COLLABORATION

A BIG FISH IS MAKING BIG WAVES

TEXT: HELMUT HORNUNG

It should not actually exist – a black hole with a mass 85 times that of our sun. But that is precisely what astronomers have discovered. Apparently, this heavyweight used to be part of a binary star system before it merged with its equally massive partner. The resulting space-time quake unleashed gravitational waves that are posing many a puzzle for researchers at the Max Planck Institute for Gravitational Physics in Potsdam and Hanover.

Gravitational waves are messengers from the dark universe. Albert Einstein described them in two papers published in 1916 and 1918 respectively, but temporarily came to doubt their existence during the 1930s. In any case, he considered these waves – whose existence is predicted by his general theory of relativity – to be immeasurable. However, they became entangled in the scientists' finely spun web for the first time on September 14th, 2015, and shook the two Advanced LIGO detectors at the Hanford and Livingston sites in the U.S.

But what lies behind this cosmic quiver? In the ultimate analysis, general relativity is a field theory, according to which the accelerated motion of masses within the gravitational field results in disturbances that propagate at the speed of light. These disturbances are referred to as gravitational waves. It sounds incredible, but they stretch and compress the space through which they pass. Theoretically, they occur when, for example, a child bounces around on a trampoline. But humans have a small mass and bounce comparatively slowly, so the gravitational waves the child causes are immeasurably minuscule.

By contrast, masses out in the universe are large and there is even a "trampoline", i.e. space-time itself, in which everything is in constant motion, because there isn't a single celestial body that remains motionless in one place. The Earth creates a bulge in the fabric of space-time too as it orbits the Sun, emitting gravitational waves with a power of 200 watts. But even these waves are too weak to be detected. However, there are some extremely large masses and super high velocities out in the universe. The signal detected on September 14th, 2015, for example, was caused by two black holes that merged in a fraction of a second following a turbulent dance of death. Each of the objects, which were about 1.3 billion light-years from Earth, had a mass around 30 times that of the sun.

By the time this issue of *Max Planck Research* went to press, scientists had reliably detected 50 gravitational wave events since their initial discovery five years ago. The majority of these events were caused by colliding black holes, and such discoveries had gradually become a matter of routine. But something powerful occurred on May 21st, 2019. Rather than detecting a "chirp" in the LIGO (U.S.) and Virgo (Italy) detectors, what the astronomers perceived was, as it were, a plop! It lasted just a tenth of a second and reached a maximum frequency of only 60 Hertz – the lowest observed so far.

"Right from the beginning," says Alessandra Buonanno, Director at the Max Planck Institute for Gravita-

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tional Physics in Potsdam, “this extremely short signal presented a challenge when it came to identifying its origin. But we were able to match the signal to one expected of black-hole mergers.” Based on the recently analyzed data, the scientists conclude the event involves two true heavyweights of around 85 and 65 solar masses, respectively. This event, referred to as GW190521, also broke another record: the merger happened about seven billion years ago when the universe was just half its current age. And because looking into the universe’s past also entails a journey into the distance, the signal is the most distant ever observed.

What’s more, eight solar masses were converted into gravitational energy during that cosmic collision, resulting in the creation of a colossus with 142 times the mass of our home star. “We realized we had witnessed, for the first time, the birth of an intermediate-mass black hole,” says Alessandra Buonanno. Scientists had only ever suspected the existence of such objects, which are heavier than the lighter black holes with masses of up to 65 times that of the Sun, and less massive than the extremely heavy ones at the centers of galaxies. In short, their masses equate to around 120 to 100,000 solar masses.

All of this sounds very plausible. Yet one of the protagonists involved in the GW190521 event confounds expectations: “According to our understanding of how stars age and evolve,” says Frank Ohme, group leader at the Max Planck Institute for Gravitational Physics in Hanover, “we would expect to find black holes with masses of either less than 65 solar masses or greater than 120 solar masses, but none in between.” However, this is precisely the gap into which the black hole of 85 solar masses falls. “Either our understanding of stellar evolution is incomplete, or something fundamentally different took place here,” Ohme concludes.

According to astronomers’ models, black holes of up to about 65 solar masses form when heavy stars reach the end of their lives. When the nuclear fuel in the interior is depleted, the stellar gas spheres first enter an energy crisis phase and then become unstable before finally exploding as supernovae, leaving behind a lightweight black hole. At the other end of the weight range of these gravity traps, scientists suspect the presence of extremely heavy stars that, rather than exploding as supernovae at the end of their lives, immediately collapse with no such fireworks, to form intermediate-mass black holes of over 120 solar masses.

SUMMARY

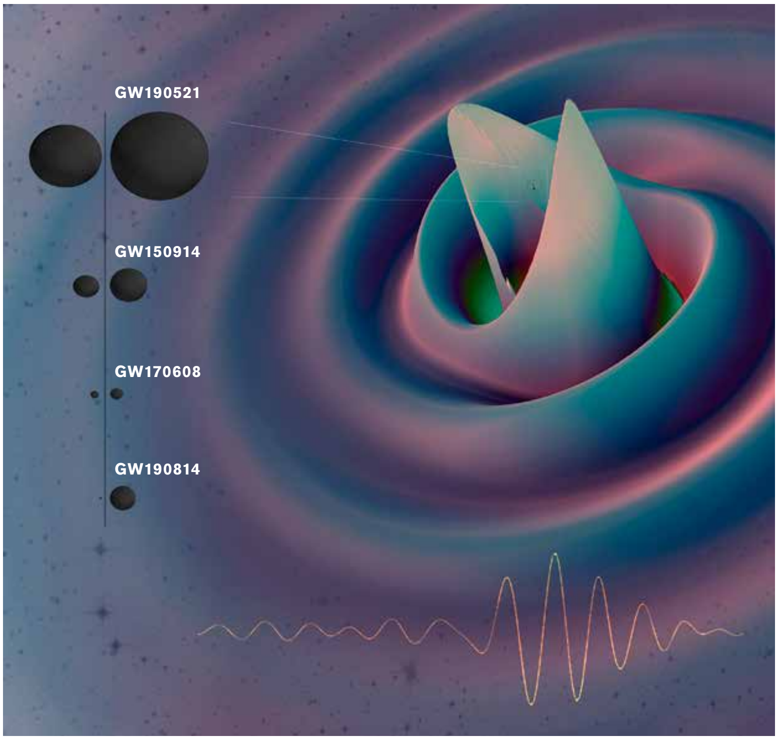
Astronomers used gravitational wave detectors to observe the coalescence of the most massive black holes to date.

This event was the first time the scientists had witnessed the formation of an intermediate-mass black hole.

Prior to the merger, one of the two black holes had had a mass equivalent to 85 solar masses and – in theory – should not exist.

PHOTO: SVEN DÖRING FOR MPG

Light into the dark: Alessandra Buonanno is developing theoretical models to identify and interpret gravitational-wave signals. The work being carried out by the Director at the Max Planck Institute for Gravitational Physics is helping to decode the secrets of black holes and neutron stars and allows conclusions to be drawn about the physical properties of these exotic objects.



GRAPHIC: D. FERGUSON, K. JANI, D. SHOEMAKER, P. LAGUNA, GEORGIA TECH, MAYA COLLABORATION

Heavyweights: this graphic shows a freeze frame from a numerical relativity simulation of the GW190521 event. About seven billion years ago, two black holes with about 85 and 65 solar masses had merged – a record! For comparison, the image on the left shows a schematic representation of the masses involved in other gravitational wave events.

This gives rise to the mass gap of around 65 to 120 solar masses mentioned by Frank Ohme, in which no stellar black holes ought to exist because, theoretically, those stars from which black holes could form within this range fail to explode as supernovae and therefore do not collapse into black holes. Instead, these stars undergo one or more brief episodes of instability, during which they eject significant quantities of their matter. Only following this radical weight loss will a star remain, which then explodes in a supernova to produce a black hole, but this will have a mass of less than 65 solar masses.

So how was the black hole with 85 solar masses created in the GW190521 event? One possibility is that our current evolutionary models of stars are flawed or incomplete, and that certain supernovae may still spawn black holes with masses in excess of 65 solar masses. However, the researchers consider this rather unlikely, as Alessandra Buonanno explains: “My assumption is that this object emerged from an earlier merger of a binary system, probably as the result of a coalescence of two smaller black holes or of two massive stars.”

In fact, according to the general theory of relativity, the signal could be well described as a merger of two black holes. Nevertheless, the scientists are also investigating other potential explanations for their observation, for example that the signal may be the result of an interaction between cosmic strings, i.e., hypothetical objects that may have formed in the early universe. Or could it be the result of a supernova after all? Could GW190521 ultimately be not nearly as distant as it seems, and the event thereby involves less massive black holes, which in fact merged at a shorter distance from Earth, and their waves were subsequently distorted by a gravitational lens? And finally, could the signal have been generated by primordial black holes that formed in the infancy of the universe before the first stars appeared? However, in the final analysis, none of these scenarios quite fits the data.

“We don’t yet know whether the GW190521 event represents an entirely new class of binary black holes, or just the high-mass end of the source spectrum we’ve observed so far,” says Karsten Danzmann, Director at the Hanover-based Max Planck Institute. “Hopefully, we’ll know more once we’ve analyzed all binary black hole mergers seen by LIGO and Virgo during their third observation run (O3).” The scientists certainly have no shortage of data to work with. During the O3, which lasted from April 1st, 2019 to March 27th, 2020, they recorded data from no fewer than 56 potential gravitational wave candidates.

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GLOSSARY

GRAVITATIONAL WAVE DETECTOR
The largest facilities currently in operation are LIGO in the U.S. and Virgo in Italy. Their working principle involves interferometry: laser light travels in two vacuum tubes, or arms, arranged at right angles to one another. These arms lengthen or shorten whenever a gravitational wave passes through the detector, which causes the laser light waves to get out of sync, thereby altering the intensity of the measured light. The LIGO sites in Hanford and Livingston each have arms that are four kilometers long, while the Virgo site in Tuscany uses tubes that are three kilometers long.