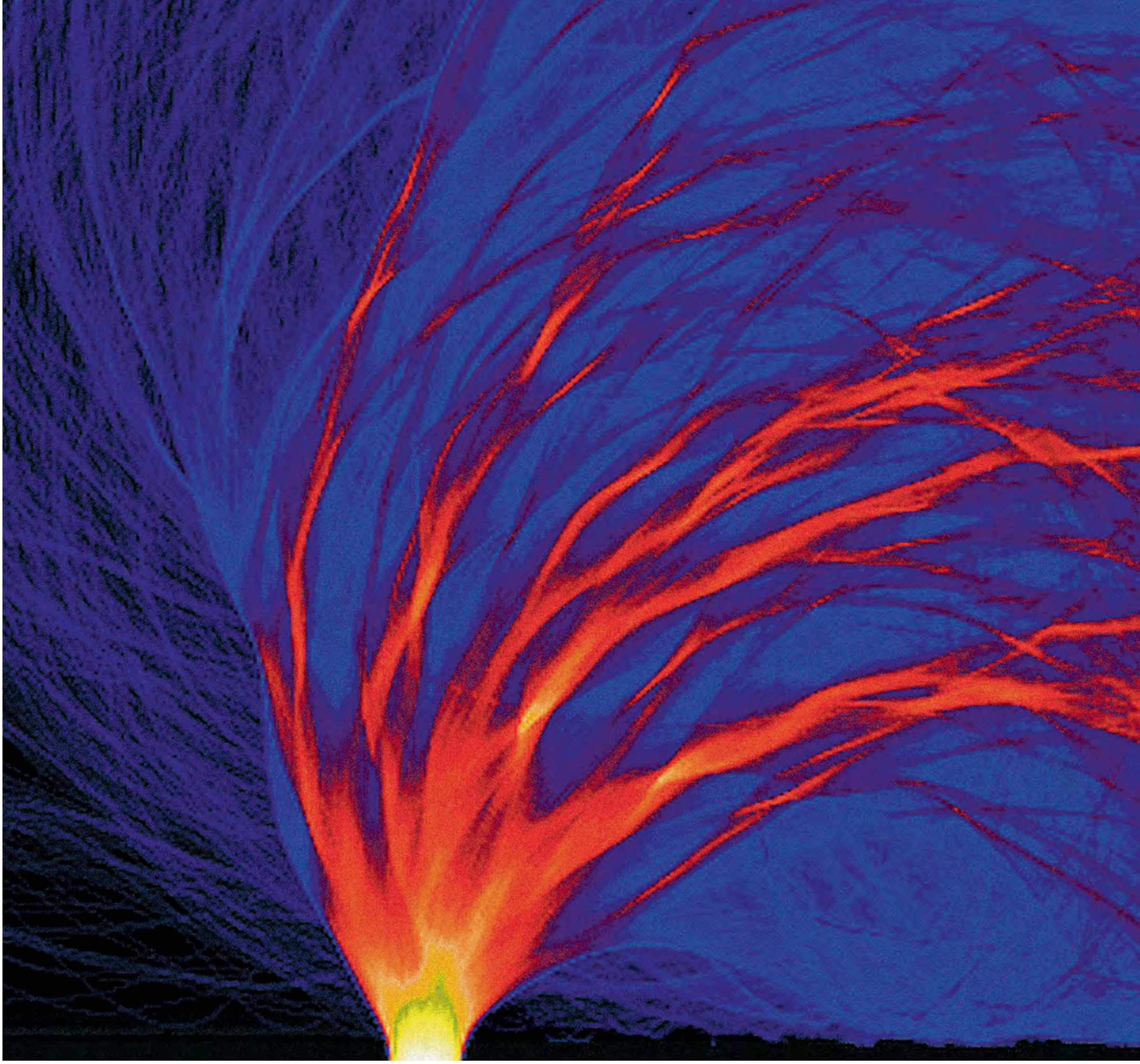
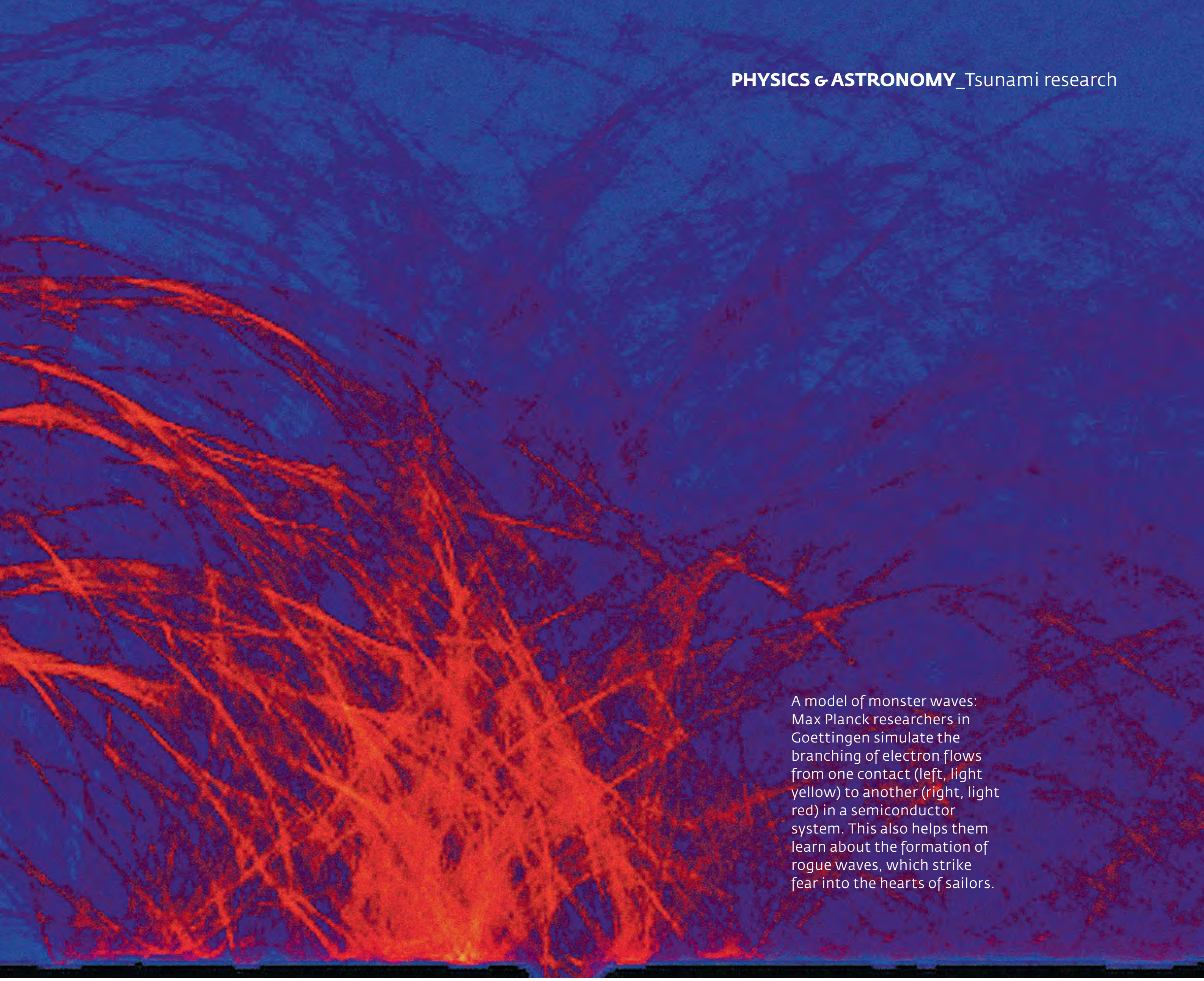


Atoms **make waves**

For **Ragnar Fleischmann**, it was a surprising discovery: in simulations depicting the flow of electrons in semiconductors, he observed behavior resembling that of tsunamis and rogue waves on the open sea. Today, his team at the **Max Planck Institute for Dynamics and Self-Organization** in Goettingen is researching electronic processes with a view to improving forecasts of destructive waves.

TEXT **KLAUS JACOB**

Photo: MPI for Dynamics and Self-Organization – Ragnar Fleischmann



A model of monster waves: Max Planck researchers in Goettingen simulate the branching of electron flows from one contact (left, light yellow) to another (right, light red) in a semiconductor system. This also helps them learn about the formation of rogue waves, which strike fear into the hearts of sailors.

For anyone who was still unaware of it, the destructive force of tsunamis became abundantly clear over Christmas in 2004. A powerful earthquake struck off the coast of Indonesia, triggering a wave that raced halfway around the world and killed in excess of 200,000 people. The tsunami traveled for hours before slamming into distant coastlines, claiming the lives of unsuspecting beachgoers even thousands of kilometers away.

Since then, German scientists have installed an early warning system in the Indian Ocean. This is based on the principle that seismic waves move much faster through rock than water waves can cross the ocean, meaning there are often several hours in which to issue a warning. From the seismic waves, scientists can determine not only the strength of the earthquake but also its epicenter – that is, the place from which the wave originates. Based on this information, software is used to model the path of the tsunami and to calculate when it is expected to arrive at the various coasts. People on the ground are then warned via radio announcements, sirens, or other signals.

But the modeling of the wave's course can be misleading, as demonstrated by Ragnar Fleischmann and his team at the Max Planck Institute for Dynamics and Self-Organization in Goettingen. According to their calculations, these monster waves are even more deceptive than previously assumed. To understand this, we must turn our attention away from the great ocean for the time being and instead consider the world of tiny nanostructures, which can only be accessed using highly sensitive techniques such as atomic scanning probe microscopy.

A MOMENTOUS DISCOVERY IN SEMICONDUCTOR SYSTEMS

Indeed, Fleischmann is not an oceanographer but rather a theoretical physicist, and his research focuses primarily on complex dynamics and quantum phenomena, such as those in electronic semiconductor structures. While he was studying systems of this kind as a postdoc with the physicist Eric Heller in Harvard 18 years ago, he and two colleagues made a discovery with far-reaching consequences. They were seeking to explain an experiment that delivered beautiful images but that is also difficult for non-experts to understand. It concerned how electrons move in a two-dimensional electrical conductor.

A conductor of this kind is formed at the interface between two different semiconductors – a semiconductor heterostructure. Here, electrons are trapped in a "potential well", rather like water in a trough. Their freedom of movement is therefore limited to the two dimensions parallel to the interface.

IMPURITY ATOMS FORCE ELECTRONS ONTO NEW PATHS

Two tiny metal contacts on the surface of the crystal are separated from one another by a narrow slit, forming a bottleneck that the electrons have to squeeze through. This is known as a quantum point contact. Since the semiconductor material used in the experiment was highly pure, the scientists expected the electrons to fan out from the quantum point contact in all directions like light from a streetlamp.

After all, the particles should be able to move freely and have only negligible obstacles to overcome: the adjacent semiconductor is doped with impurity atoms that affect the flow of current. However, because these impurities are relatively far from the interface, they should only deflect the electrons slightly, and their effect should be barely noticeable – or so the researchers assumed.

Instead, the experiment produced a completely different result. The image from the atomic scanning probe microscope showed that the electrons did not fan out evenly, but rather were focused into filaments. What the researchers saw was more reminiscent of a "cat o' nine tails" than a uniform beam of light. "At first, we feared that the mea-

Photo: dpa

suring technique was at fault," says Fleischmann. However, he and his colleagues produced detailed models showing that the method worked perfectly, except that physicists had considerably underestimated the influence of the imperfections. Although the impurity atoms were not located on the interface between the two semiconductors, they were forcing the electrons onto new paths.

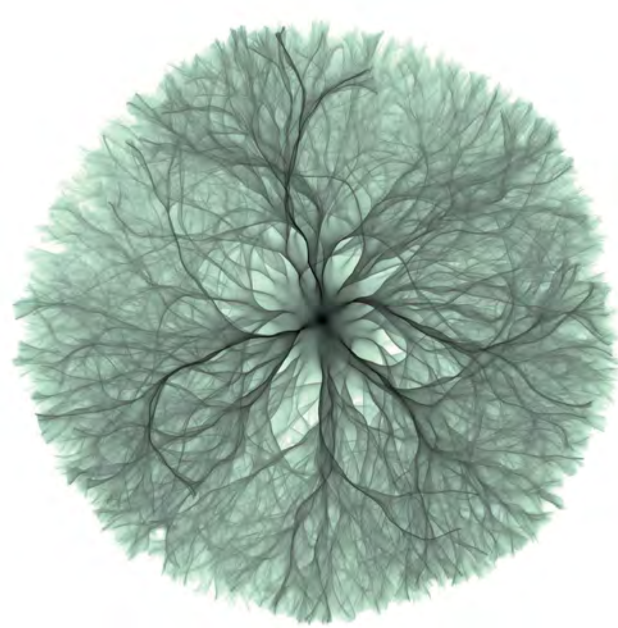
Together, the many small imperfections created a focusing effect, which led to the flow branching that the researchers observed under the microscope. The structures of these focusing patterns have long been known to science and go by the technical term "caustics". The term comes from the study of optics, where it is used for specific aberrations produced by lenses.

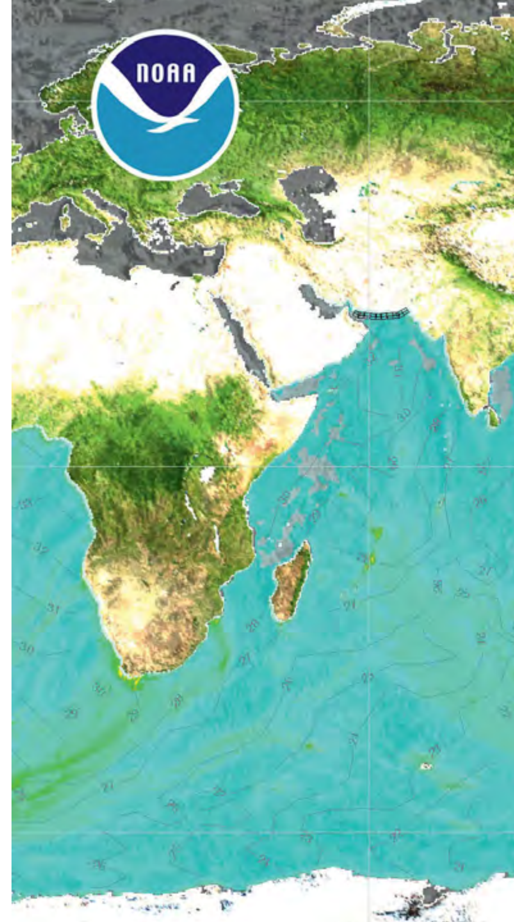
Caustics can be observed in many everyday situations. For example, when the sun shines on the surface of an outdoor swimming pool, you often see a grid of bright lines on the bottom of the pool. Here, the sunlight is being focused into caustics, which are also known as focal lines. With their calculations, Fleischmann and his colleagues showed that even minimal imperfections are enough to produce this phenomenon. In other words, small causes can have a big effect – this had simply been overlooked so far.

This brings us back to tsunamis, and more precisely to the catastrophic tsunami of 11 March 2011, which destroyed several nuclear power plants in Japan and ultimately spelled the end of nuclear power in Germany. Scientists from the NOAA Center for Tsunami Research reconstructed how the wave spread across the Pacific and how its height varied. For this, they used data from sensors that had recorded the wave height at a number of locations in the open ocean. When they adapted this measurement data to the modeled course of the tsunami, the resulting pattern was astonishingly similar to that of the electrons in the semiconductor. Ragnar Fleischmann immediately thought to himself: "The two

Left The tsunami of 2004 completely destroyed this part of the city of Banda Aceh, in northern Indonesia. Here we compare two aerial photographs: one taken six months before the disaster (top) and one taken two days after (bottom).

Right Electrons radiating from a point source can be used to simulate how seabed relief focuses waves that were originally triggered by seaquakes. Small defects in the conducting layer concentrate the flow of charge carriers into small branches.





things might be related." Here too, there was no homogeneous wavefront, and the wave energy was instead concentrated in individual bands that branched out – as Fleischmann had observed in the nanostructures. The wave reached a far greater height in the bands than in the surrounding area. Although the values only differed by a few decimeters, this can eventually have major consequences in the case of a tsunami.

SEABED RELIEF INFLUENCES TSUNAMIS

After all, a tsunami is a highly unusual wave. It is rarely more than a meter high in the open ocean, but it is also incredibly long, with successive wave troughs often separated by a distance of several hundred kilometers. Its shape is more like a gently sloping plane than a steep hill and is best imagined as a tidal bulge instead of wind waves. Indeed, ships' crews generally don't even notice when they pass over a tsunami. The ship just gently rises and falls.

Experts call this a shallow water wave, because the wavelength is much larger than the water depth. To put it another way: for the tsunami, the sea is nothing more than a puddle. The key thing to note is that shallow water waves have completely different properties from those of the short waves whipped up by the wind. Their character is essentially determined by the seabed.

For a start, the speed at which a tsunami rolls across the ocean depends solely on the water depth: at a water depth of 5,000 meters, a tsunami reaches speeds of around 800 kilometers an hour – as fast as a jet aircraft. At a depth of 3,000 meters, it still travels at approximately 600 kilometers an hour. Only when it reaches the coast does the wave undergo rapid deceleration, rising steeply to reach catastrophic proportions. At this point, the few-decimeter height difference in a tsunami moving across the open sea grows to many meters.

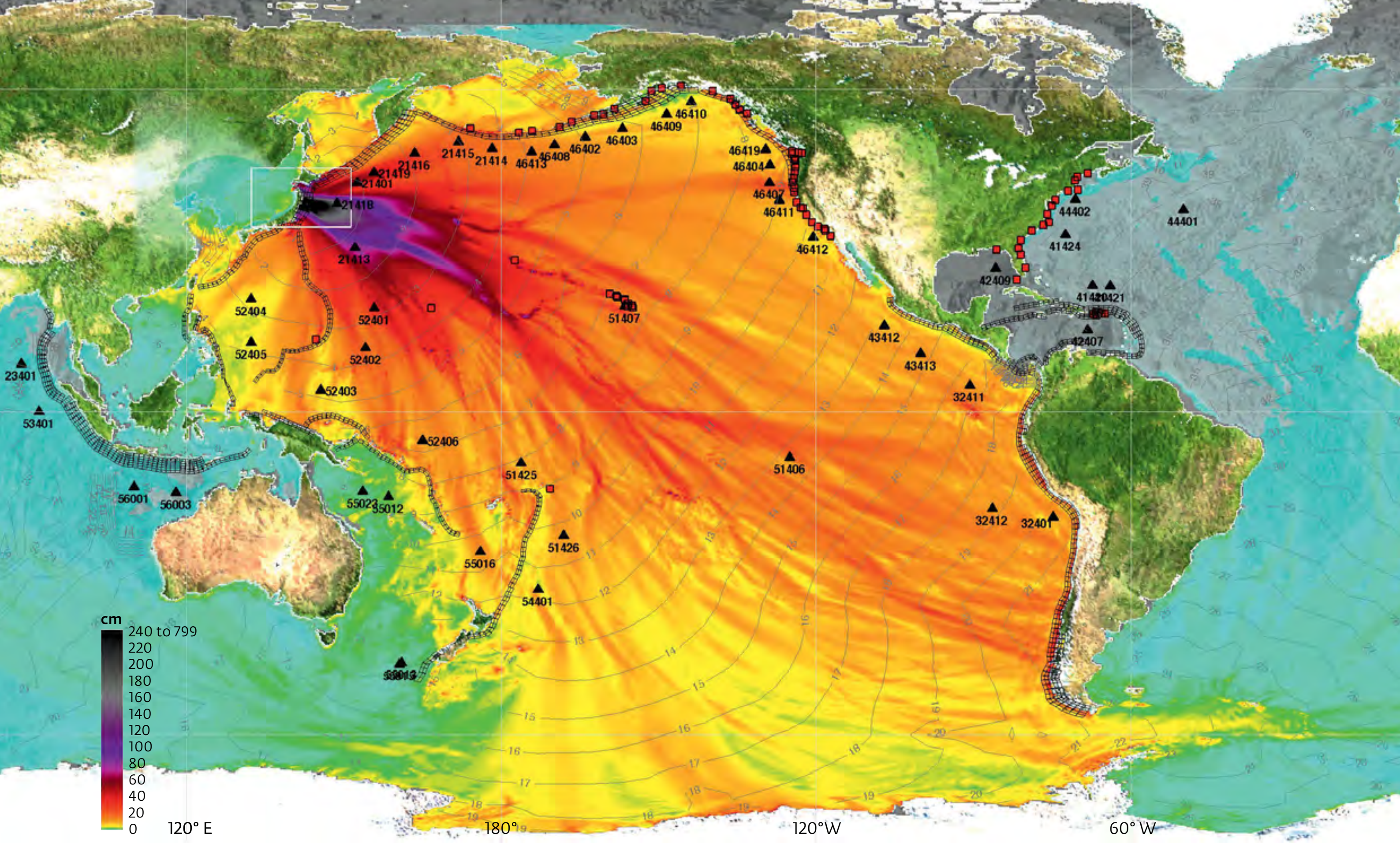
However, seabed relief not only determines the wave's speed but also its course and shape. For example, an underwater mountain acts like a converging lens and focuses the energy, whereas depressions act like diverging lenses and long trenches behave like guide rails. Islands also leave their mark on the wavefront, and experts take all of this into account when modeling the path of a tsunami. Until now, however, they had only considered larger structures. Smaller disturbances with elevations of just 100 or 200 meters were not included in the calculations – which potentially leads to significant errors, as Fleischmann and his colleagues have now demonstrated.

They selected a 1,500-kilometer square of the Indian Ocean with no interfering islands or major underwater mountains. The depth was around 4,000 meters plus or minus seven percent, and the seabed relief was taken from the official data pool. Based on this, they used a computer to model how a tsunami – triggered by a fictitious event – passed over the relief in order to observe how the wave changed in response to the seabed.

In a second run, they varied the seabed relief slightly. Small changes should not make a great deal of difference. After all, the existing data is anything but exact, providing depth measurements that are accurate to within a few hundred meters. The researchers therefore incorporated a few hills whose heights were less than the error tolerance. This

Top The tsunami formed in 2011 following a quake off the coast of Japan raced across the Pacific and exhibited significant differences in height. At some points, the wave stood just 20 centimeters above mean sea level (yellow), while at others it reached a height of 8 meters (black).

Bottom When electrons from a point source flow through the boundary layer between two semiconductors, they are focused by impurity atoms in the material, as this simulation demonstrates. These so-called caustics can also be observed on the open sea, where currents can focus waves to reach over double the height of the waves around them.



Photos: Ragnar Fleischmann (left); NOAA (top)

second relief therefore still corresponded to the real topography. Again, they simulated a tsunami moving across it – but this time they obtained a completely different pattern. At some points, the wave energy differed by a factor of ten between the two calculations – and a power of ten results in enormous height variations that could mean the difference between life and death. As with the semiconductor mentioned earlier, small causes can have a big effect.

But what does this finding mean for tsunami forecasts? Unfortunately, it won't be possible to predict caustics reliably until accurate maps exist of the ocean floor. Whether we like it or not, the models are still imperfect. "But we have to realize that this effect exists," says Fleischmann. For example, warning services could examine how their calculations are affected by small depth variations to get a better idea of the reliability of their forecasts.

Of course, these services also have a completely different set of problems to deal with. Above all, they must ensure that their warnings reach even the smallest fishing villages and that they are actually taken seriously once they get there. False alarms undermine their efforts because they desensitize people. Anyone who has sought refuge unnecessarily three times simply won't bother when the fourth warning comes. The problem is that not every earthquake produces a tsunami; it is only when the sea floor moves in a vertical direction that it causes the water to surge.

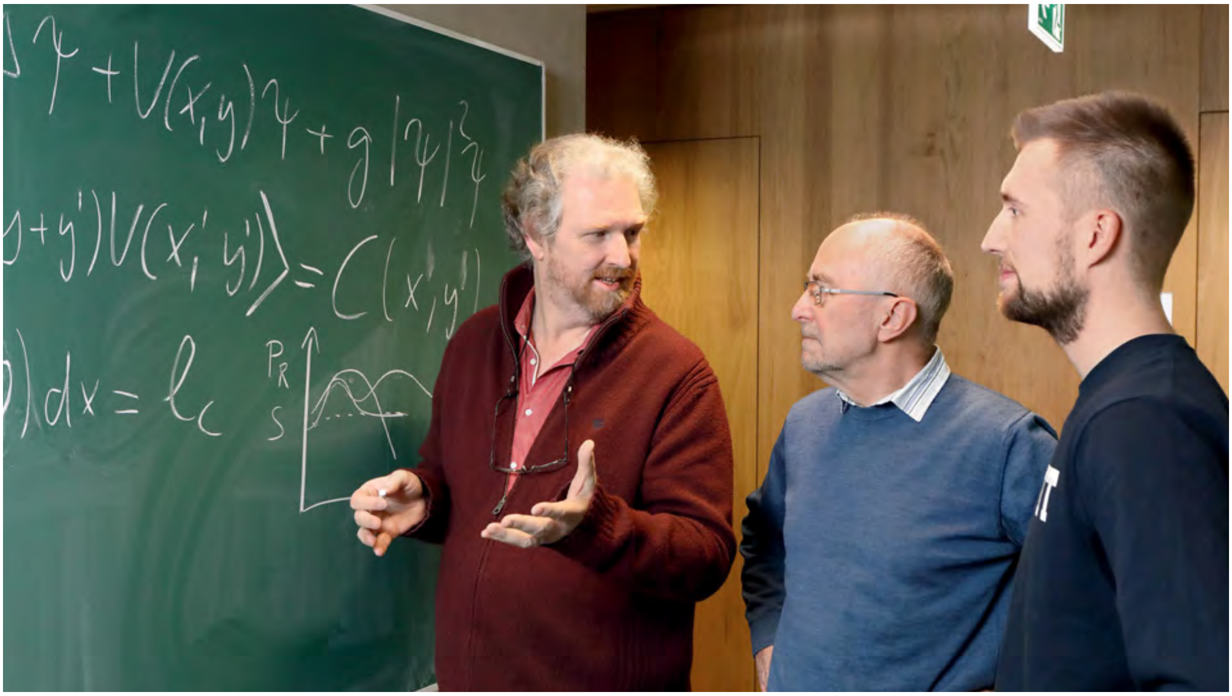
MANY EXAMPLES INVOLVING THE SAME MECHANISM

These two phenomena – a tsunami that races halfway around the world and the electron flow in a semiconductor – are separated by about twelve orders of magnitude, but they both involve the same mechanism. Indeed, the relationships that Fleischmann identified in the semiconductor are universally applicable. Wherever a wave propagates though a disordered medium, small imperfections can have major consequences, focusing the energy into branched structures.

Of course, this is subject to certain prerequisites. Firstly, the medium must only cause relatively weak deflection in the waves. The effect would not occur if every encounter with an imperfection scattered the waves in every direction. Secondly, the medium must be disordered, because a sea floor structured as regularly as an egg carton would have no impact on a wave. That being said, landscapes with an irregular distribution of elevations and depressions represent the rule rather than the exception.

It is no wonder, then, that there are many other examples involving this mechanism, such as the twinkling of stars. Of course, stars do not twinkle in reality – but they appear to do so if you look at them for a long time. This is also due to caustics: before the light reaches our eyes, it must pass through the atmosphere, which is littered with small disturbances that produce a focusing of the light. For the observer, the starlight therefore seems to vary in intensity. When a caustic reaches the eye, it resembles a small flash of light – the star appears to twinkle. This also explains why stars twinkle particularly strongly when there is turbulence in the atmosphere.

One particularly impressive example of this are monster waves, which are also referred to as rogue or freak waves. These actually have nothing to do with tsunamis – they are just unusually high,



wind-driven waves that suddenly tower up in the middle of the ocean. They are at least twice as high as surrounding waves and are said to have engulfed many a ship over the years. Until a few decades ago, however, these stories were dismissed as seamen's yarns.

CURRENTS CAN FOCUS WIND WAVES INTO ROGUES

Our knowledge has advanced since then – or at least we now give credence to the observations of seafarers. In fact, they actually know several categories of monster waves: in addition to the unusually high wave, there is also the "white wall", which rises at an especially steep angle and lights up due to its covering of foam. Sailors have also learned to fear the "three sisters" – three giant waves in quick succession that slow ships down so sharply that they can no longer climb the final crest.

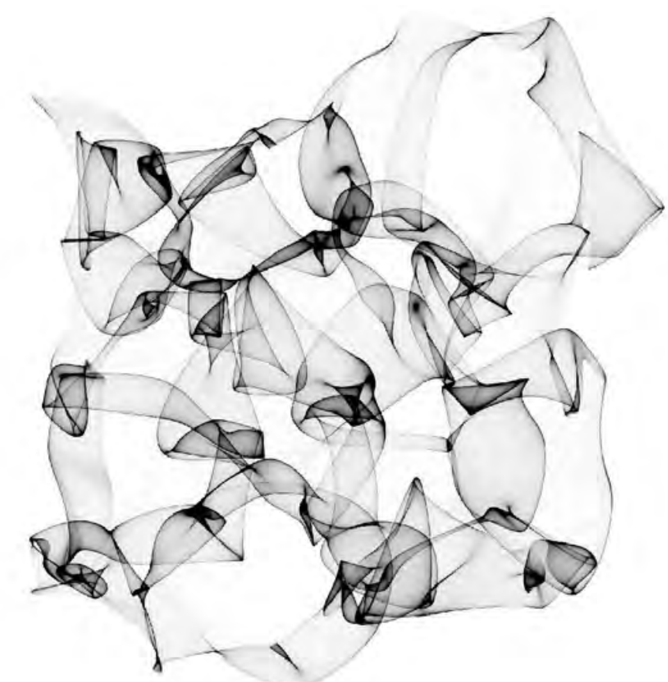
If these eerie encounters far out at sea are no longer dismissed as myths, it is partly because shipping traffic has increased enormously and almost no section of the sea remains unobserved. Oil platforms also record wave movements, and some satellites are able to detect these gigantic breakers. In February 1995, a laser system on the Draupner drilling platform in the North Sea recorded a 26-meter surge, and in November 2007, a 21-meter wall of water rushed toward the Ekofisk platform, also in the North Sea. This is said to be the steepest wave ever measured. At the time, it was only a force-nine storm, and the wave simply appeared out of nowhere.

Every year, ships are lost with no explanation – many of them presumably due to an encounter with a killer wave. In 2001, the cruise liner MS Bremen had a lucky escape off the east coast of Argentina when it was caught by a breaker reportedly measuring 35 meters in height. The force of the impact smashed windows on the bridge, which normally towers high above the waves. As water rushed in, the resulting short-circuit caused the engines to cut out, leaving the ship in a precarious situation, listing parallel to the wavefront. It took the crew half an hour to start the auxiliary diesel engine.

Science has taken a serious interest in monster waves for around 20 years, but it has yet to provide a convincing explanation of how they are formed. According to basic wave models, they shouldn't even exist. But what does all of this have to do with caustics and experiments on semiconductors? The answer becomes clear when you enter the mouth of a river on a ship. The river's current alters the waves rolling in from the sea and can cause them to build up into dangerous breakers.

The current therefore corresponds to the impurity atoms in the semiconductor, or to the underwater hills affecting a tsunami. It influences the wave and changes its course, focusing the energy at certain locations. This effect, which is clearly visible in river estuaries, also occurs on the open sea. After all, the water is moving in every direction – if you plotted the near-surface currents on a map, they would produce a disordered pattern of spirals.

The greatest danger arises where currents intersect. This can also produce a focusing of the wave energy, causing a vast wave to appear out of nowhere. Eric Heller, the scientist with whom Fleischmann once modeled the electron experiment, has undertaken a particularly intensive study of monster waves. His conclusion is that if you take account of branches in wave flow due



Left Ragnar Fleischmann talks to Max Planck Director Theo Geisel and doctoral student Gerrit Green (from left to right) about mathematical laws that apply to both electron dynamics and ocean waves.

Right Ragnar Fleischmann's team simulated how water with a moving surface focuses light into a web of caustics. The researchers created an inverted image of the effect, representing the bright focal lines as areas of dark shading.

to currents, the number of freak waves is 50 times higher than without this assumption. That sounds feasible, especially since other studies have now confirmed that rogue waves are far more numerous than once assumed.

USING TWO THEORIES TO MAKE REALISTIC PREDICTIONS

However, there is another theory of how freak waves are formed. This is based on special properties of the wave equation, so-called nonlinearities, which are used to describe water waves. Fleischmann is convinced that only a combination of the two theories will permit realistic statistical forecasts of freak waves. This is therefore one of the research projects he is currently working on.

In addition, he is particularly committed to gaining a deeper understanding of branched flows and to producing a statistical description of this phenomenon, as caustics are merely its most striking feature. Indeed, a branched flow contains a complex interplay of chaotic stretching, compression, and folding of wavefronts, creating not only caustics but also interference phenomena. Only by understanding the interaction between these factors can scientists make reliable forecasts of how often monster waves occur and where tsunamis will deliver their greatest destructive force. ◂

SUMMARY

- **Impurity atoms in tiny semiconducting structures cause an electron flow to branch out as it passes through the system. By analogy, Max Planck physicists draw conclusions as to why tsunamis hit different sections of coastline with varying degrees of force. In the same way as impurity atoms alter the course of electrons, these destructive waves are focused by irregularities in the seabed.**
- **By analyzing nanosystems, researchers can gain a better understanding of why monster waves repeatedly occur on the open sea, where waves are whipped up by the wind before being focused by ocean currents.**
- **These findings could help improve early warning systems for tsunamis and allow more accurate statistical forecasts of how often ships might encounter rogue waves.**

GLOSSARY

Branched flow: The flow of electrons or water waves can be focused by disturbances.

Caustic: In this effect, which is known from the field of optics, light is focused into lines – for example, when it passes through moving water. In a similar way, electrons and water waves can also be focused into caustics.

Monster wave: Ocean currents can focus wind-driven waves, causing them to grow to over twice the height of surrounding waves. Monster waves are also referred to as rogue waves.

Quantum point contact: A nanoscopic constriction in a conductor. When electrons flow through a bottleneck of this kind, quantum effects occur that are not observed in ordinary conductors.

Tsunami: A wave triggered by a seaquake.

Photo: Ragnar Fleischmann