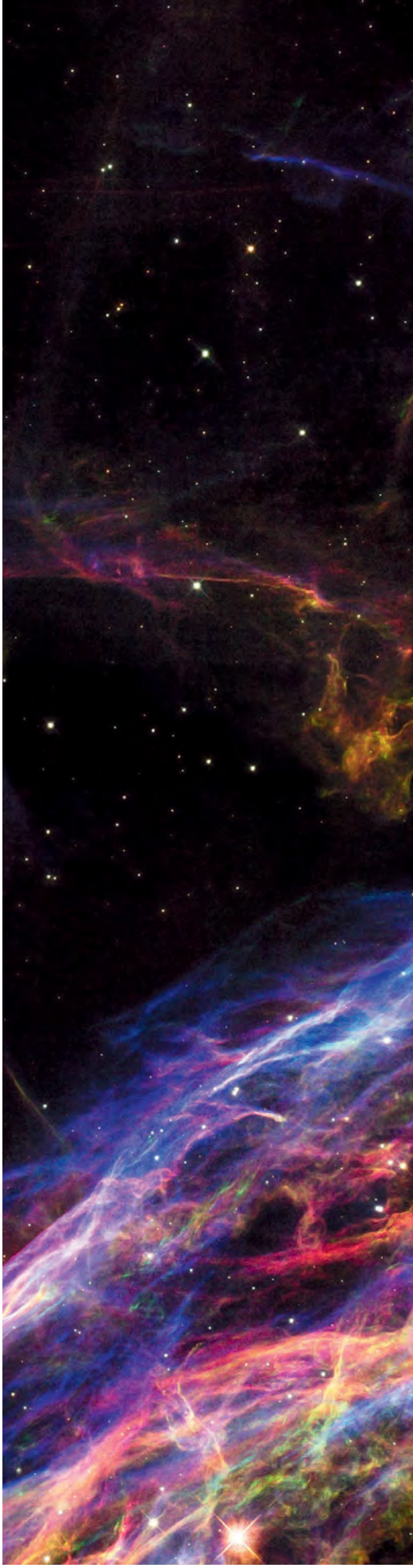


Frantic **Finish**

Supernovae portend cosmic catastrophes. When a massive star slides into an energy crisis at the end of its life, or a sun that has already died is overfed with matter, the end is an explosion of unimaginable proportions. What exactly happens here? **Hans-Thomas Janka** from the **Max Planck Institute for Astrophysics** in Garching wants to get down to the nuts and bolts. He simulates supernovae on the computer and makes them explode in the virtual world – meanwhile even in three dimensions.

TEXT **HELMUT HORNUNG**

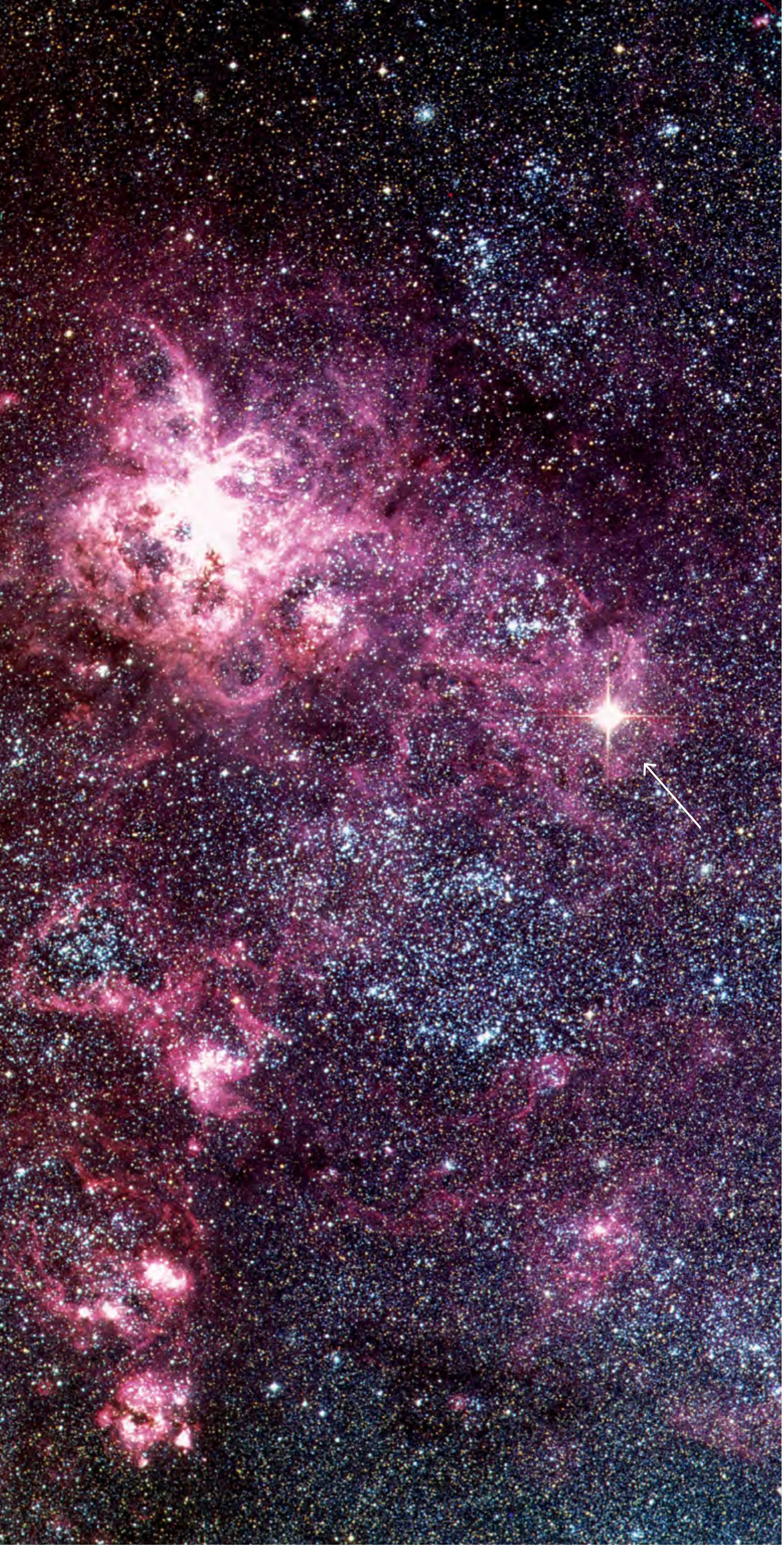
On February 24, 1987, shortly after midnight, Ian Shelton is sitting in the darkroom of the Las Campanas observatory near the city of La Serena in Chile. The Canadian astronomer is developing pictures of the Large Magellanic Cloud, a neighboring galaxy of our Milky Way. As the images in the fixing solution become clearer and clearer, he immediately recognizes a bright star that doesn't belong there. Shelton goes outside into the clear night, looks up to the sky and discovers the spot of light in the Large Magellanic Cloud with his naked eye. The scientist knows immediately: what he is observing is a supernova, the closest one in 383 years.

"Supernova 1987A opened up a new chapter in research," says Hans-Thomas Janka. The scientist at the Max Planck Institute for Astrophysics has been studying this astronomical phenomenon for many years. It is by no means as far removed from our daily life as some would think, because the calcium in our bones and the iron in our blood originate from the nuclear melting pots deep in the interiors of the stars. These elements were released during large numbers of supernovae, and mixed with others to form the stuff that life on Earth was ultimately made on. Our existence is therefore closely connected with the cosmos via the most violent explosions since the Big Bang.

The zoo of supernovae is very diverse and confusing to the layperson. Astronomers have classified around a dozen different types of supernovae. However, "fundamentally, we differentiate between thermonuclear and core-collapse supernovae," Janka says. The criteria used are the lines of hydrogen, helium and silicon that occur in the spectra – that is, in the decomposed light – and also the shape of the light

Photo: NASA/ESA/Hubble Heritage Team

The end of a star: Around 18,000 years ago, a massive sun exploded. At the site of the disaster, astronomers now observe the Cirrus nebula – gas that was once released by the supernova. The image shows a section of this cosmic web.



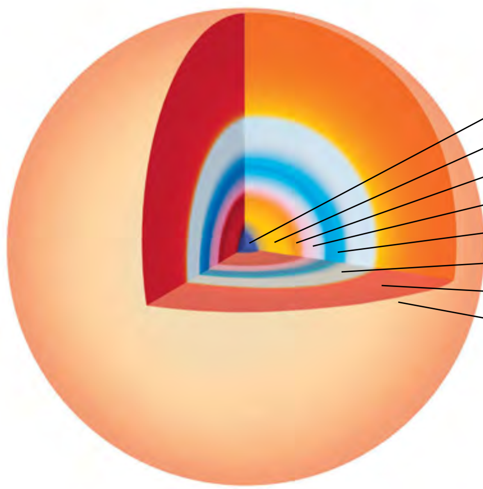
curves. The spectra of thermonuclear supernovae (Type Ia) have no hydrogen and no helium lines, but strong lines of the element silicon. According to one conceivable scenario, the explosion is caused by the "overfeeding" of a white dwarf, the burnt-out core of a sun of relatively low mass.

Such a stellar remnant sometimes has a partner star to which it is bound by gravitational forces. It is also gravity that enables the white dwarf to extract large amounts of gas from the surface of its partner. The matter flows onto the white dwarf, where it accumulates. This process, called accretion, causes the dwarf to constantly increase in mass. At some stage, its mass reaches around 1.4 solar masses.

If this limit, which is named for astrophysicist Subrahmanyan Chandrasekhar (1910 – 1995), is exceeded, the worst-case scenario becomes reality: the white dwarf begins to contract. This contraction releases gravitational energy, which heats the crystal-like mix of carbon and oxygen; in this phase, the star resembles an extremely compressed

Light shows in the sky: Supernova 1987A (arrow), taken shortly after its flare-up as a bright star in the Large Magellanic Cloud. The small image shows the remnant of the explosion just over ten years later; three bright rings are clearly visible.

Photos: ESO; Robert P. Kirshner and Peter Challis, Harvard University, STScI, NASA



Layers full of energy: Different nuclear burning processes occur in a massive sun. After the fusion of sulfur and silicon to iron, production stops. The sphere of iron in the core finally collapses further into a dense object – a neutron star or a black hole.

Illustration: Christoph Schneider based on a diagram by Achim Weiss – MPI for Astrophysics

diamond. In its interior, the first step is the formation of islands in which thermonuclear reactions occur. Silicon and nickel are formed. The ignition sources spread at subsonic speed (deflagration) and burn from the center of the star outward toward its surface.

This causes instabilities, leading in turn to turbulence, which interacts with the thermonuclear flame and rapidly increases its surface area. Finally, a detonation wave builds up that propagates at supersonic speed and blows the ball of gas to pieces – a supernova explodes. "Unfortunately, it has not yet been possible to observe even a single precursor system of such an explosion directly, which is why we are still speculating about other possibilities," says Hans-Thomas Janka.

This type represents only around one quarter of all supernovae observed, whereas most violent stellar deaths can be attributed to a single massive star (Type II). This means the precursor star has at least eight or nine times the mass of our Sun. The giant first spends several million years quietly and unspectacularly fusing hydrogen to helium. When the supply of fuel is exhausted, this is not the end by a long shot. Although the intense radiation means the star continuously loses energy, it compensates this deficit through the contraction of its interior – which results in a massive increase in pressure and temperature.

THE STAR BALLOONS INTO A GIANT

In this phase, the star increases its surface area: it balloons into a giant with a radius measuring a hundred to a thousand times that of the Sun. Its luminosity also increases considerably, now shining several million times brighter than the Sun. "The subsequent fate of the star is now decided," says Janka. "If the temperature in the stellar core increases sufficiently, the ash from the previous fusion process can ignite." Helium, for example, burns at around 200 million degrees Celsius to form carbon and oxygen.

At the end of this chain, stars with the stated eight or nine solar masses develop temperatures of 800 million degrees at their centers. The carbon fuses to sodium, neon and magnesium; neon to oxygen and magnesium; oxygen to sulfur and silicon. The star literally has a warmer and warmer glow around its heart. Above three billion degrees, the subsequent fusion steps follow one another at an ever-increasing speed. Within only a few months and then after only a few days, nickel, cobalt and finally iron are forged.

Now the end has been reached: since iron has the highest binding energy per nucleon, no more energy can be generated from its fusion. The structure of the star now resembles that of an onion: the core of iron slag is surrounded by layers of silicon, oxygen, neon, carbon and helium, with the hydrogen layer at the very outside.

The Chandrasekhar limit mentioned above, which the iron core now approaches, again plays a role in how the story continues. The density of the core has increased to 10,000 tons per cubic centimeter. Electrons are squeezed into the protons to form neutrons. This reduces the pressure inside the core, which now collapses in fractions of a second to an object of 10,000 times greater density: a neutron star. But it can get even denser still. If the core has a large initial mass, a black hole forms at the center of the dying star.

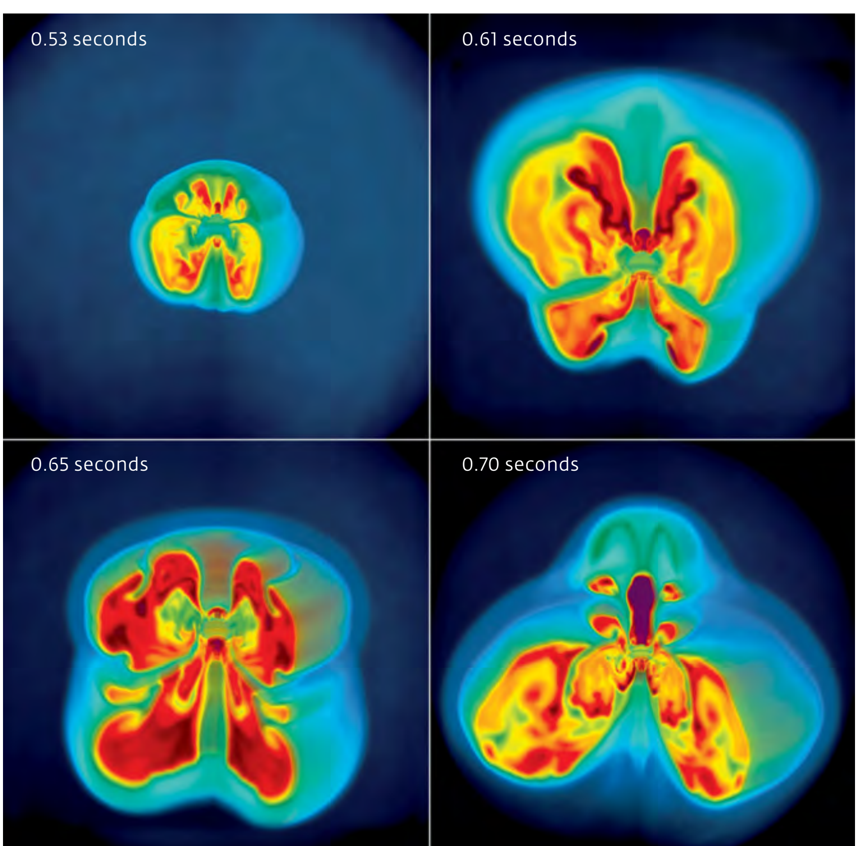
THE FRAGILE EQUILIBRIUM IS SEVERELY DISTURBED

In any case, the inner layers of the star plunge unceasingly onto the massive central object. The delicate hydrostatic equilibrium has already been severely disturbed for some time – the interplay between the outwardly acting gas and the radiation pressure, and the inwardly directed gravitational pressure. The latter inevitably compresses the star even further. The impact of the matter at supersonic speed does not go well for long: a shock wave builds up and travels from the inside to the outside and rips apart the stellar gas envelope with speeds of up to tens of thousands of kilometers per second – a supernova flares up.

Or maybe not? “If only it were that simple,” says Hans-Thomas Janka. When the astronomers considered the scenario in greater detail, they found that there is no way the shock wave can cause the explosion directly by means of a purely hydrodynamic rebound mechanism. “Such a shock alone turns out to be much too weak. It isn’t able to balance the massive energy loss from the center on the long journey through the collapsing stellar layers,” explains the Max Planck researcher. In short, “after only 100 to 200 kilometers, the shock loses its power, it gets stuck in the star’s iron core.”

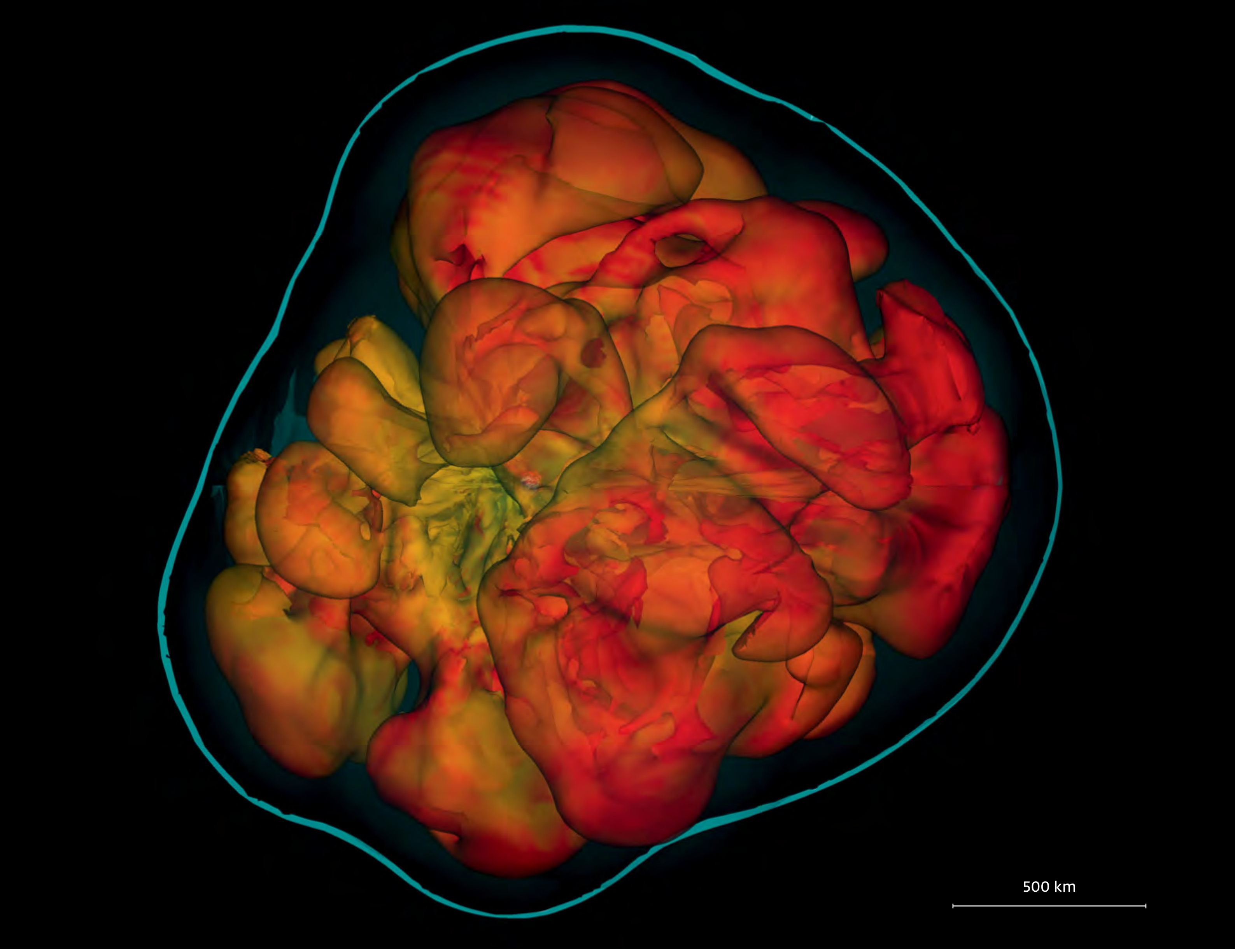
So what acts as the driving force? As early as the mid-1960s, scientists were bringing another engine into play: neutrinos. These nearly massless particles succeed almost effortlessly in penetrating practically anything that gets in their way – like our thumbnail, through which more than 66 billion of these elusive phantoms race every second. That they also play a role in supernovae has been known since the events of February 24, 1987. That was the day the explosion of a star called Sanduleak -69° 202 with a mass of 15 to 20 solar masses was observed from a distance of some 166,000 light-years. Around three hours before the visible light flash from the Large Magellanic Cloud, several neutrino observatories around the world registered two dozen of these ghost particles.

Although all later supernovae were much too distant to measure such neutrinos, this finding bolsters the theoretical assumption. “After a decade of development work, the 1980s saw researchers succeed in describing the mechanism of neutrino transport,” says Janka. It was found that the particles manage to leave the interior of the star at the speed of light after stumbling about in it for several seconds. And, according to Janka, they are able to carry vast amounts of energy with them.



Explosion on the computer: A star of 15 solar masses is disrupted and gives rise to violent turbulence in the process. There is already a neutron star at its center; the seconds in the four partial images refer to the time after its formation. The explosion is asymmetric and is driven by the energy transfer of neutrinos. The diameters of the bubbles of matter (yellow, orange, red) range from 300 in the first to 600, 800 and 1,500 kilometers in the last image.

Computer graphic: Andreas Marek, Hans-Thomas Janka – MPI for Astrophysics



Seething ball of gas: This computer simulation from 2015 shows the end of a star of 20 solar masses in three dimensions – and with it, the progress that has been made in research: the sequence on page 22 is around ten years older and was still a two-dimensional computation. The outer, bluish line in this image indicates the shock wave of the supernova.

Computer graphic: Elena Erastova and Markus Rampp, Max Planck Computing and Data Facility (MPCDF)

As the stellar core collapses to a neutron star, the gravitational energy converts into internal energy of the matter, which in turn produces vast numbers of neutrinos. These heat the electrically conductive gas (plasma) around the neutron star and give the shock wave renewed power. The efficiency of this process is surprising: "American astrophysicists Stirling Colgate and Richard White argued that only 1 percent of the neutrino energy needs to be deposited by neutrino heating to ignite a supernova," says Hans-Thomas Janka.

In the 1980s, theoreticians began to simulate supernovae on the computer – and were disappointed. The stars simply wouldn't explode properly. Was the neutrino heating inefficient after all? It was soon suspected that the failure was more likely due to the models used – Janka's specialty. "At that time, they still had spherical symmetry – that is, they were one-dimensional." But then came Supernova 1987A. "We learned from observations that a high degree of asymmetry had to be present when it exploded," the scientist recalls.

GAMMA LIGHT BECOMES VISIBLE AFTER ONLY A FEW WEEKS

A thorough mixing evidently must have taken place during the explosion. This means that elements that had been deep inside the dying star suddenly moved toward the outside – nickel, for example, which was ejected far into the outer layer and radioactively decayed into cobalt. "We had actually expected that it would be more than a year after the explosion before we would observe gamma quanta, which originate from the decay of cobalt. But they turned up after just a few months," says Janka. We then knew that, in reality, it isn't as simple as the idea of layers of onion flying away.

As computers became ever more powerful, the theoretical scenarios, too, became increasingly complex: in the early 2000s, Janka and his colleagues worked meticulously on two-dimensional models whose stars possessed axial symmetry. The researchers now took very accurate account of interactions between the neutrinos and the stellar plasma, as well as convective mass motions and turbulence. "In fact," says Hans-Thomas Janka, "in these simulations, the symmetry is destroyed as soon as the explosion begins. Hydrodynamic, turbulent fluctuations occur, similar to convective flows in the Earth's atmosphere."

Janka's then-doctoral student Andreas Marek generated the first complete two-dimensional supernova model at the Max Planck Institute for Astrophysics between 2003 and 2006. The Institute purchased a 128-core computer especially for this purpose and installed it at the neighboring Garching computing facility, where it was used solely for this simulation – which was successful: "The supernova exploded!" says Janka. The effort had paid off – as had the efforts of Janka and his doctoral student Markus Rampp: the researchers wrote the extremely complex program codes for the computer simulation. These algorithms were intended to improve the neutrino transport. Janka doesn't want to go into detail, but when he talks of "three-dimensional equations with spatial coordinate and momentum space," even the layperson quickly realizes that these matters are fairly complicated.

This is all the more true for three-dimensional simulations that only became part of the scientists' repertoire in the last few years. The computing power required is enormous – 16,000 processors have to work in parallel for months to compute one model. This would take a single, modern PC 8,000 years. What it boils down to, according to Janka, is this: explosions driven by neutrinos also occur in 3-D. But the astrophysicist states two clear objectives that he and his colleagues will be striving to achieve in the future with the three-dimensional computations: "We want to use fully self-consistent simulations and all relevant microphysics to confirm the explosion mechanism quantitatively for many stellar masses. And we want to compare the models with the observations."

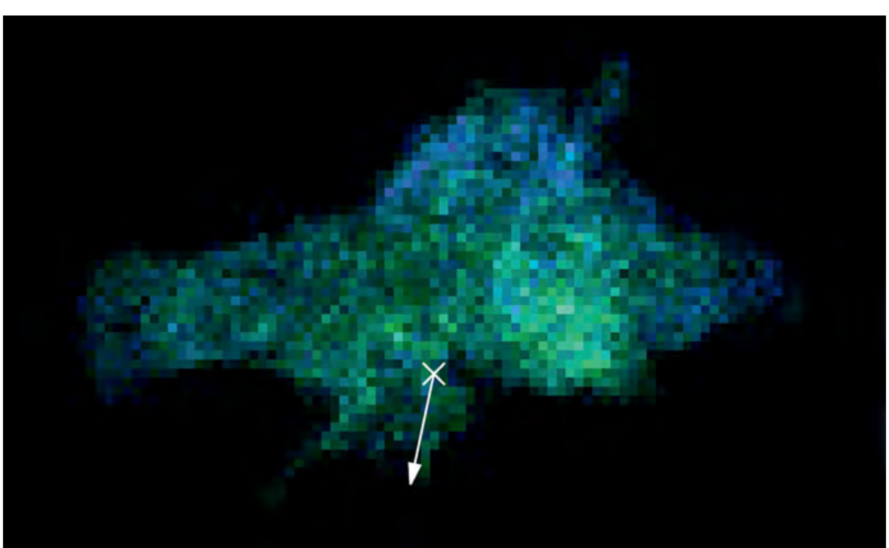
ULTRABRIGHT EMITTERS KEEP THE ASTRONOMERS GUESSING

It could then also be possible to solve a mystery that has increasingly moved into the research spotlight in recent years: ultrabright supernovae, or superluminous supernovae, as astronomers call them. The scientists observed the first example of this type in 2010. Although they sight more than 1,000 stellar explosions in total every year, only a few dozen of these tremendously bright emitters are known, which are up to 100 times as bright at their maximum as conventional Type II supernovae. The problem is: "These objects are all extremely far away. We can often register only the light curves, and the spectra are not conclusive in detail," says Hans-Thomas Janka.

What causes these supernovae? The researchers can only speculate. After an initial explosion, a magnetar, for example – a neutron star with an extremely strong magnetic field (MaxPlanckResearch 1/2017, page 26 ff.) – could become involved to drive this explosion further and amplify it enormously. The second possibility is that the shock wave of the supernova propagating outward interacts with dense matter shed by the star before the explosion.

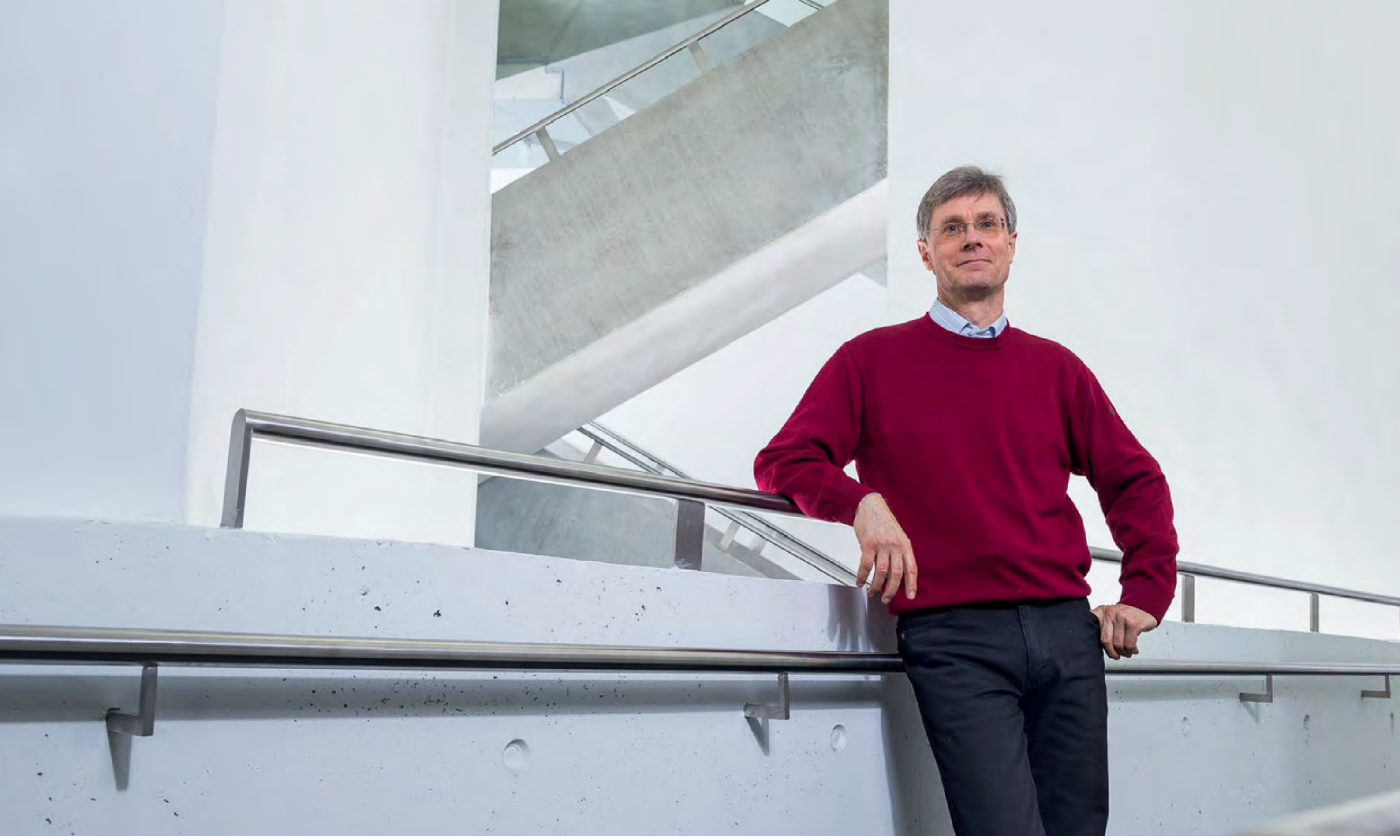
As a further alternative, the scientists consider so-called pair instability supernovae. This scenario is based on a star with 100 to 200 solar masses or even more. Such a heavyweight has a brief life and collapses as soon as it reaches the stage at which carbon fuses in the center. At temperatures of one billion degrees, photons with very high energies start to spontaneously convert into electrons and their antiparticles, the positrons. This "pair formation" leads to a rapid drop in radiation pressure – gravitation gains the upper hand, the nuclear combustion of carbon and oxygen accelerates at an explosive rate and the star could become a supernova.

Astronomers still don't know which of the three scenarios is the right one. They know from investigations of the light curves that superluminous supernovae apparently don't always release the incredibly large quantities of nickel – several tens of solar masses – that would be expected from pair-instabil-



Stellar kick: The neutron star (white cross) left behind by the supernova experiences a kick in the direction (arrow) opposite to the stronger side of the asymmetric explosion. Elements such as titanium and nickel (blue and green) are produced in greater amounts in the hemisphere that points away from the direction of neutron star motion. The astronomers observe this geometry for supernova remnants in space – in perfect agreement with theoretical models such as this simulation.

Computer graphic: Annop Wongwathanarat et. al, arXiv: 1610.05643



Supernovae in his focus: Hans-Thomas Janka from the Max Planck Institute for Astrophysics in Garching studies the largest explosions in the universe since the Big Bang. To investigate the physics that determines these events, Janka develops theoretical models based on complex computer programs.

ity supernovae. A viable theory must provide an adequate explanation of this fact.

Nickel is also the topic of Janka's most recent work, which has just been published in the ASTROPHYSICAL JOURNAL. It deals with what dying stars leave behind – supernova remnants. Observations and measurements of high-energy radiation at X-ray and gamma wavelengths with satellite telescopes such as NuSTAR and Integral show that radioactive elements such as titanium-44 and nickel-56 contained in the ejected material are not distributed symmetrically around the remnant neutron star.

According to the theory, this is because the compact stellar object receives a kick into the opposite direction of an asymmetric explosion – with consequences for the immediate cosmic environment: "The radioactive elements should have been explosively produced predominantly in the hemisphere of the massively deformed gas remnant that is opposite to the direction of motion of the neutron star," says Hans-Thomas Janka. That is what the theoretical 3-D models forecast. And that is precisely what the telescopes have discovered in nature, to the delight of the researchers: in the Cassiopeia A remnant and, so the prediction, probably also in what remains of Supernova 1987A. The latter therefore still turns out to be a lucky break for science, even though it is now 30 years since it flared up. ◂

Photo: Axel Griesch

TO THE POINT

- **Some stars meet a spectacular end as supernovae. The dozen or so different types that have been observed can be classified into two theoretical groups.**
- **In the case of supernovae of Type Ia, the probable scenario is that a white dwarf fed by a companion explodes; in the case of all other types, it is a massive star whose core collapses.**
- **The researchers found that the neutrino-heating mechanism plays a crucial role in the explosion of core-collapse supernovae.**
- **Astronomers today use complex three-dimensional models to simulate the physical processes in supernovae and can put several aspects of the theory to a test with the aid of actual observations.**

GLOSSARY

Antiparticles: As far as is known, nearly every particle has an antiparticle that is identical in terms of mass, lifetime and spin. In contrast, electric charge, magnetic moment and all charge-like quantum numbers are equal in magnitude, but have the opposite sign. The positron, for instance – the antiparticle of the electron – has a positive charge.

Plasma: A mixture of neutral and charged particles (partially ionized) or only charged particles, such as electrons and atomic nuclei (completely ionized), that is also called the fourth state of matter. Plasmas frequently occur at high temperatures. Stars consist of hot gas and plasma, for example.