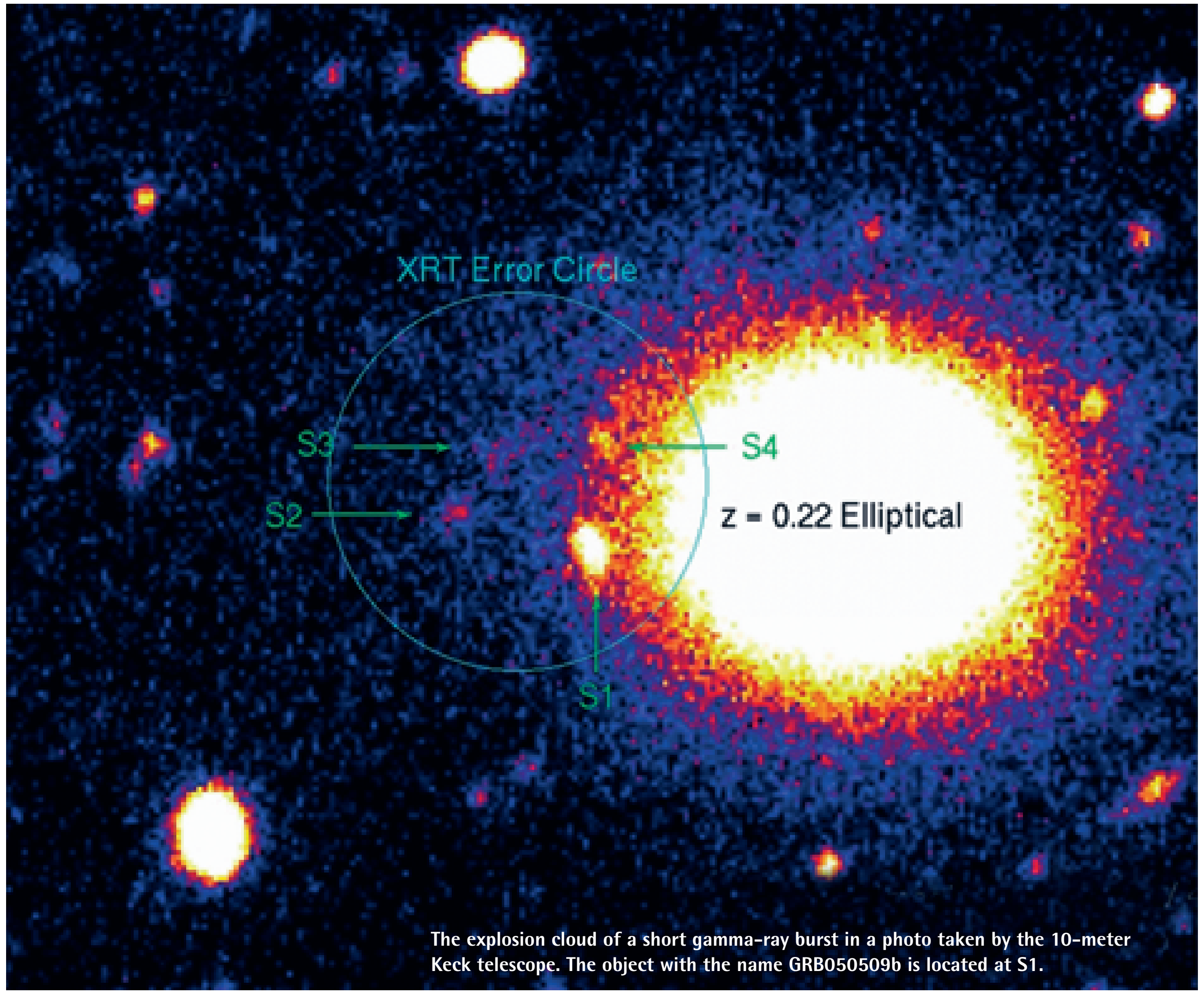


The explosion cloud of a short gamma-ray burst in a photo taken by the 10-meter Keck telescope. The object with the name GRB050509b is located at S1.

Photo: Keck Observatory

Only the **Big Bang** Was More Powerful

For around 40 years now, astronomers have been registering flashes in the gamma-ray spectrum that abruptly appear in the sky. Some 10 years ago, it was discovered that these are the most powerful explosions in the universe. Since then, the field of research into these gamma-ray bursts has experienced more turbulent development than nearly any other in astrophysics. At the invitation of the **Max Planck Institute for Astrophysics** *in Garching, more than 50 researchers met at Ringberg Castle to discuss the topic.*

Curiously, this chapter of modern astrophysics began with a discovery by the American military. In the 1960s, surveillance satellites orbited the Earth to search for gamma radiation emitted by aboveground atomic bomb tests. In 1969, one of these instruments did, indeed, register a flash of gamma radiation. However, it had not come from the Earth, but rather from space. Further such bursts followed and soon aroused the curiosity of a few astronomers. But detailed studies were difficult, because the Earth's atmosphere swallows up the gamma radiation. Space-based telescopes were needed.

The situation changed significantly when, in 1991, the American space agency NASA sent the *Compton* Observatory, in which physicists from the Max Planck Institute for Extraterrestrial Physics in Garching were also involved, into orbit. The result was absolutely astounding: *Compton* registered a cosmic flash somewhere in the sky about once per day, the duration varying between a few hundredths of a second and a few minutes.

There were absolutely no clues as to the cause. The *Compton* telescope could determine the positions only very imprecisely, so it was not possible to subsequently track down the outbursts with optical telescopes. Since then, the astrophysicists have proposed more than a hundred theories regarding the nature of the bursts, including the – naturally not entirely serious – idea of exploding warp engines of the spaceships of intelligent beings.

Then the Italian-Dutch space telescope BeppoSAX came to the rescue. It was able to precisely localize the Gamma bursts and automatically sent the celestial coordinates to a network of astronomers who, as quickly as possible, pointed their – in some cases robotically operated – telescopes at the indicated spot in the sky. Thus, 1997 saw the first success in observing, in the visible spectrum, the afterglow of two gamma-ray bursts.

A spectral analysis then showed that these celestial bodies were in galaxies located billions of light-years away. This makes them the most extreme explosions in the universe – only the Big Bang was more powerful. The record holder so far, named GRB050904, was some 13 billion light-years away. If it had exploded at a distance of about 4,000 light-years, it would have radiated on our terrestrial sky as brightly as our Sun for a few seconds.

In some cases, a supernova was discovered at the location of the gamma burst, and occasionally, evidence of these exploding stars was seen in the late afterglow. After this, the theory became popular that these were very massive, rapidly rotating stars that burst at the end of their life and collapse to form a black hole. In this process, matter heats up to several hundred billion degrees and shoots into space in two collimated beams, so-called jets, along the rotation axis, emitting gamma radiation like two gigantic headlights. When the particles zipping along at nearly the speed of light strike surrounding matter, it heats up and then also glows in the X-ray and visible spectra.

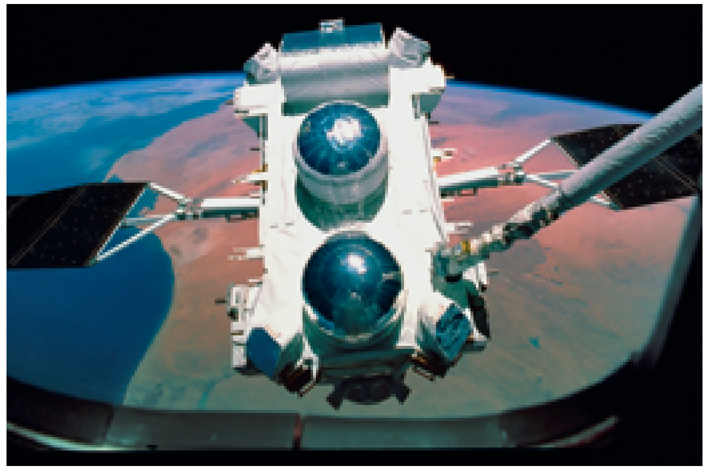


Photo: NASA

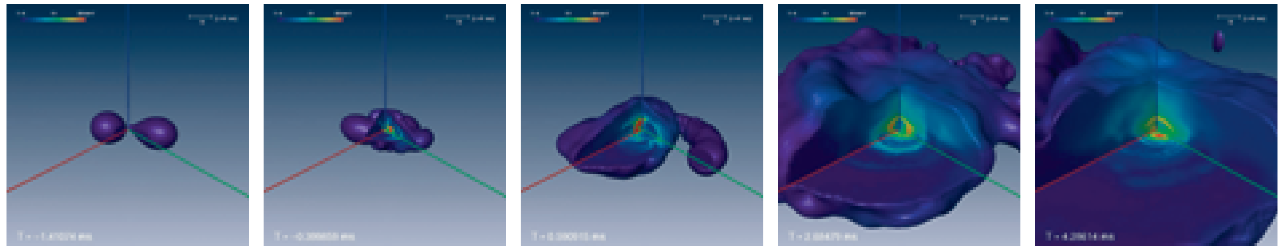
Compton's **success story began in 1991. The satellite discovered more than 2,700 gamma-ray bursts until its crash nine years later.**

A Telescope Sets Its Sights on the Afterglow

These fireballs were observed with the terrestrial telescopes. Since the stellar explosions are even more violent than normal supernovas, they were called hypernovas. "We suspect that, among several hundred supernovas, only one hypernova occurs," explains Thomas Janka from the Garching-based Max Planck Institute for Astrophysics, which co-organized the Ringberg workshop.

It appeared that a decades-old mystery of astrophysics had finally been cleared up. But, as is so often the case in celestial research, things turned out differently. Even with the *Compton* telescope, the astronomers had noticed that there are apparently two classes of gamma-ray bursts: long flares that can last up to several minutes, and short ones with a duration of up to about three seconds. The latter account for no less than one-third of all bursts, but they fade so quickly that, for years, it was not possible to locate their afterglow with optical telescopes. This changed with the American space telescope *Swift*, launched in November 2004, heralding the beginning of a new era for this research field. In the two years following its commissioning, the number of publications on gamma-ray bursts quadrupled. As NASA project manager Neil Gehrels reported at Ringberg Castle, in the best case, this instrument can notify the astronomers by e-mail or text message within 15 to 20 seconds.

In this way, two years ago, the first observation of short bursts succeeded with large telescopes or sensitive X-ray detectors on satellites. The surprise was great when the bursts were localized in elliptical galaxies. Supernovas almost never occur in these star systems – and thus certainly not the far less common hypernovas. In the few cases in which the afterglow could be observed with an optical telescope, there were also



Sophisticated computer simulations illustrate how neutron stars coalesce within a few thousandths of a second.

Photos: Roland Oechslin and Hans-Thomas Janka, MPI for Astrophysics

none of the signatures that are typical of supernovas.

Do, perhaps, the two classes of gamma-ray bursts have two different causes? This was one of the questions the experts discussed at Ringberg Castle, often until late into the night. To date, the luminescent fireball has been spectroscopically observed for just five short gamma-ray bursts, and in additional new cases, the afterglow was registered in the visible spectrum as well as in the X-ray and radio ranges. As Gehrels explained, these few cases show that the short gamma bursts radiate only about a thousandth of the energy of the long ones. But that is still about as much as is released in the form of light in a supernova, and corresponds approximately to the energy our Sun emits over the course of several billion years.

Since the fireballs of the short bursts appear much more weakly than those of the long ones, and also fade faster, the largest telescopes are needed to observe the handful of fireballs shortly before they die out. As Sylvio Klose of the Thueringer Landessternwarte (State Observatory) Tautenburg reported, among the large telescopes in the visible spectrum, the Very Large Telescope of the European Southern Observatory (ESO) holds the world record for speed: in the past year, it was able to track down a short flash just seven and a half minutes after the gamma burst.

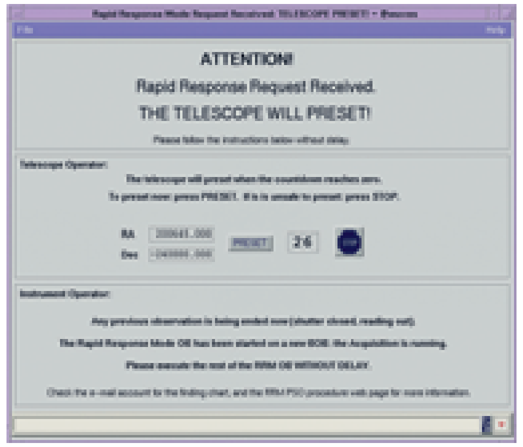
For short gamma-ray bursts, the evidence is still very meager, but one thing seems clear: when such a huge amount of energy is emitted within just a few seconds, only very compact celestial bodies come into question as the cause. The existing observational evidence of such a link was reviewed and evaluated by Ehud Nakar (Caltech, USA) and Edo Berger (Carnegie Observatory, USA). Two neutron stars that coalesce and collapse to form a black hole are considered the most probable explanation. Using computer simulations, Maximilian Ruffert from Edinburgh University, Roland Oechslin and Miguel Aloy (Max Planck Institute for Astrophysics), Emmanuela Rantsiou (Northwestern University, USA) and William Lee (UNAM, Mexico) demonstrated what happens in such a process.

Death Throes of Dying Stars

Neutron stars are the most compact celestial bodies whose existence is observationally established. They are created when a massive star has used up the nuclear fuel in its interior at the end of its life. Then the internal energy production stops and the star that was once larger than the Sun collapses into itself. When it has reached a diameter of about 20 kilometers, the collapse stops – and a neutron star is born. The matter is then so dense that a piece the size of a sugar cube would weigh several hundred million tons on Earth. Since generally more than half of all stars belong to double systems, there must also be double neutron stars that circle each other. When this happens, they emit gravitational waves, which withdraws energy from the pair. As a result, the two bodies slowly draw closer to one another on a spiral pathway. At the moment their surfaces touch, they merge within a few thousandths of a second. The new body then becomes so massive that it collapses into a black hole under the force of its own gravity. A portion of the matter, in which temperatures of up to one hundred billion degrees and densities of up to one million tons per cubic centimeter prevail, continues to race around the black hole in the form of a ring-shaped torus for a short time before, finally, it is likewise swallowed up. Thus, the matter of two to three Suns disappears within a few seconds.

In this cataclysmic process, a profusion of nuclear and particle reactions takes place that Reiner Birkl (Max Planck Institute for Astrophysics) studied in depth. A burst of high-energy matter in two concentrated gas jets occurs in the direction of the rotation axis and thus perpendicular to the dense torus. Magnetic fields are also discussed as the reason why energy shoots into space in such jets with a beam semi-opening angle of just 10 to 20 degrees. “According to our knowledge, this matter has a speed of around 99.9995 percent of the speed of light,” says Thomas Janka.

At distances of 10 to 100 million kilometers, the jets then produce the short flash of energetic radiation that is visible as a gamma burst. If the jet matter subsequently collides with surrounding interstellar matter (gas and dust), this matter, too, heats up and glows. That is the luminescent fireball that astronomers observe with X-ray and optical telescopes, and whose light reveals, for example, how far away the object is located.



ATTENTION!

Rapid Response Request Received.

THE TELESCOPE WILL PRESET!

Photos: ESO

Alarm in space: The *Very Large Telescope* of the European Southern Observatory (ESO) in the Chilean Andes is integrated in the warning system of the *Swift* space telescope. A notification arriving by e-mail (right) indicates the celestial coordinates of the gamma-ray burst.

In principle, current computer models can explain the observation results of the short gamma-ray bursts. Nevertheless, much is still unclear: What role do magnetic fields play in creating and accelerating the jets? How, exactly, do two neutron stars coalesce? When does the resulting object collapse to form a black hole and how much matter remains in the torus for some time afterward? The latter questions depend, as James Lattimer (Stony Brook University, USA) and Madappa Prakash (Ohio University, USA) explained, on the as yet insufficiently known properties of dense neutron star matter, and determine which double-star systems can emit gamma bursts in the last moment of their existence.

So, basically, it is not just merging neutron stars that could be the cause of the short gamma bursts. It could likewise be mixed systems in which a black hole and a neutron star circle each other. These two objects eventually also merge and release energy much like an explosion.

Ghost Particles with Extremely High Energies

The observable energy emission of a short gamma-ray burst is enormous. Nevertheless, up to a thousand times more energy goes into the emission of invisible particles: the neutrinos. They are also created in great numbers in normal supernovas. The first and, to date, only detection of such neutrinos, when the – astronomically speaking – nearby supernova 1987A in the Large Magellan Cloud exploded, was a sensation and was rewarded with the Nobel Prize. New underground detectors with which it is hoped that it will also be possible to detect neutrinos from future gamma-ray bursts are currently under construction. However, the measurable neutrinos in this case are expected to occur with extremely high energies, as theoretical models for their creation in the jets predict.

Neutrino telescopes have nothing in common with known telescopes for photons. Currently, the largest instrument, named *IceCube*, is being built in the Antarctic and is designed especially to capture such extremely high-energy neutrinos. It consists essentially of many sensitive light detectors that are sunk into the ice at depths between 1,400 and 2,400 meters. These electronic eyes monitor the ice mass located between them. If a neutrino approaching from the cosmos collides with an atomic nucleus here, a charged particle is created that produces a short flash of light that the instruments register. In this way, since the direction of the neutrinos' origin can also be determined, the causative source in the heavens can be localized. As Marek Kowalski from Berlin's Humboldt University

Photos: Maximilian Ruffert, The University of Edinburgh

When a black hole with 2.5 solar masses and a neutron star with 1.6 solar masses collide in the computer, an enormous vortex results and the matter heats up.

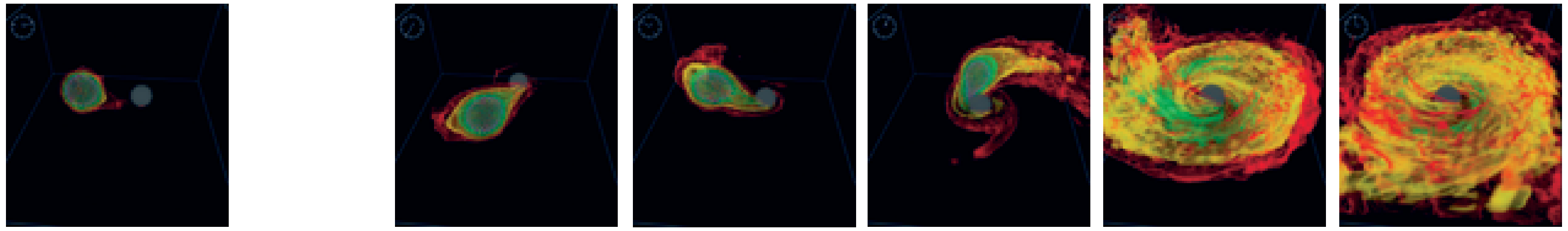


Photo: University of Wisconsin

Researchers in Antarctica are currently building a case for neutrinos. The detectors of the *IceCube* observatory are buried 1,400 to 2,400 meters deep into the ice and are expected to detect the cosmic ghost particles.

reported, neutrinos should reach the Earth 10 to 100 seconds after the observed gamma burst. This neutrino flash could easily be matched to its source and the astrophysicists would have entirely new avenues through which to observe this phenomenon. One part of the *IceCube* is already in operation, with overall completion expected in 2010. The 4,800 sensors will monitor one cubic kilometer of ice.

Gravitational Waves as Touchstones for Theory

Gravitational wave researchers, too, have a strong interest in studying gamma-ray bursts. This was also expressed by the fact that the German Research Foundation (DFG) co-financed the Ringberg workshop through its Transregional Collaborative Research Center 7 “Gravitational Wave Astronomy.” Merging neutron stars and black holes are among the most intense sources of gravitational waves and thus among the top candidates for detection.

Einstein’s general theory of relativity predicts the existence of gravitational waves, but to date, it has not been possible to detect them directly. They are thus considered a major touchstone for the current theory of gravitation, which holds that every body produces a depression in space, similar to a ball on a rubber blanket. If another body enters into this curved area, its path follows the curvature of space. This gives the impression that the two bodies exert an invisible pull (gravity) on each other. Light, too, travels on a curved path through a gravitational field.

Gravitational waves are always created when a distribution of matter rapidly changes its shape. Then the curved space is overlapped by a ripple-like structure that propagates at the speed of light. This can be imagined as something similar to waves on the surface of a body of water. If two massive objects merge, a gigantic gravitational wave distorts the fabric of space-time.

If the gravitational wave passes over the Earth, it briefly compresses space – in other words, the distances between all objects change. To date, it has never been possible to detect this phenomenon directly, because it is unimaginably small: compression and expansion of only a fraction of the diameter of an atom’s nucleus have to be measured. For the first time, with the German-British gravitational wave antenna *GEO 600* in Ruthe near Hannover and the two *LIGO* facilities in the US, researchers have achieved the immense sensitivity needed to capture this rhythmic compression of space.

A successful detection would mean, for one thing, that Einstein’s general theory of relativity could be tested; for another, gravitational waves contain information about astrophysical processes that cannot be obtained in any other way. Only in this way will it be possible, for example, to positively prove the connection between short gamma bursts and merging double stars.

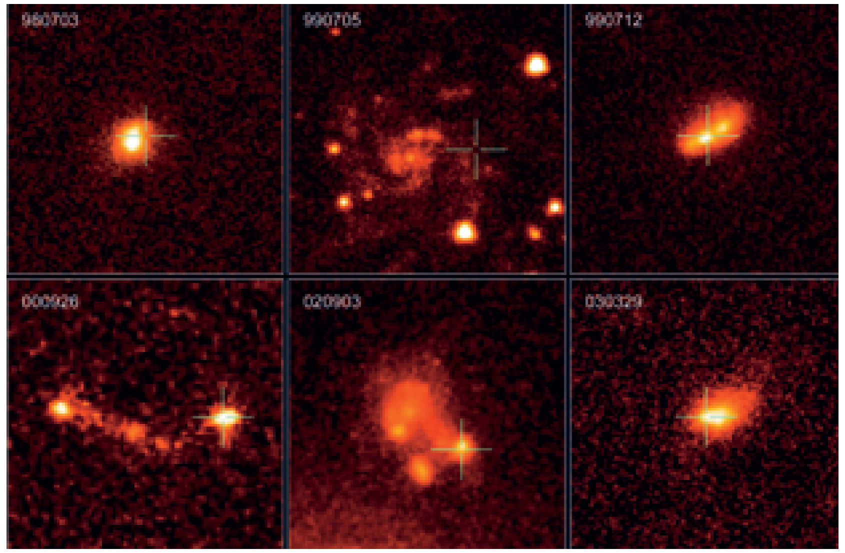
“At present, with GEO 600, we can measure changes in length of 10^{-19} meters, which is one ten-thousandth of the diameter of a proton. This allows us to detect coalescing neutron stars and black holes up to the edge of the Virgo Galaxy Cluster,” says Peter Aufmuth of the Max Planck Institute for Gravitational Physics (Albert Einstein Institute) in Golm. Improving the sensitivity by a factor of two would bring GEO 600 into the range of the Virgo Cluster, some 70 million light-years away, and increase the number of galaxies in the measurement range by well over a thousand.

The question of how frequently short gamma-ray bursts occur is of major importance to the success of the gravitational wave detector, as well as to cosmology research. The figures presented by several astrophysicists, such as Chris Belczynski (New Mexico State University, USA) and Richard O’Shaughnessy (Northwestern University, USA), demonstrated how far the astronomers still are from a comprehensive understanding of these processes. For an average galaxy like the Milky Way, between 3 and 200 collisions of two neutron stars are expected every one million years. Composite systems comprising a neutron star and a black hole are somewhat less common, but can be detected at greater distances.

Pushing Computers to Their Limits

Thus, the chances for *GEO 600* and *LIGO* are not yet very good for a detection. Only after about 2014, when the instruments have been equipped with new technology, should a few dozen events be detectable each year. In view of the uncertainty of the predictions, however, Aufmuth was unperturbed.

In any case, the gravitational wave detectors in Germany and the US are in operation and are becoming ever more sensitive. When the instruments detect a wave, theoreticians will analyze its time curve and compare it with computer models that they are currently making of colliding objects. At present, these calculations are pushing available computers to their limits. If, namely, a black hole or a neutron star moves, these bodies relentlessly bend the fabric of space and, moreover, change the course of time. Space-time thus itself becomes a variable physical quantity that must be recalculated for every step of the simulation.



Photos: NASA/ESA, A. Fruchter (STScI), GOSH Collaboration

With the *Hubble* space telescope, it has been possible to record the afterglows of several long gamma-ray bursts. Here, the galaxies in which they exploded also become visible.

Thus far, the calculations have regularly crashed after just one revolution of the bodies, or delivered meaningless results. But as Luca Baiotti and Bruno Giacomazzo from the Max Planck Institute for Gravitational Physics reported, particularly recent months have seen astonishing progress. Now the calculations remain stable throughout several revolutions, and also the form of the gravitational wave upon collision can be calculated. These computer simulations will allow conclusions to be drawn about the properties of the celestial sources based on the measured signals. This would usher in the beginning of gravitational wave astronomy.

Thomas Bührke