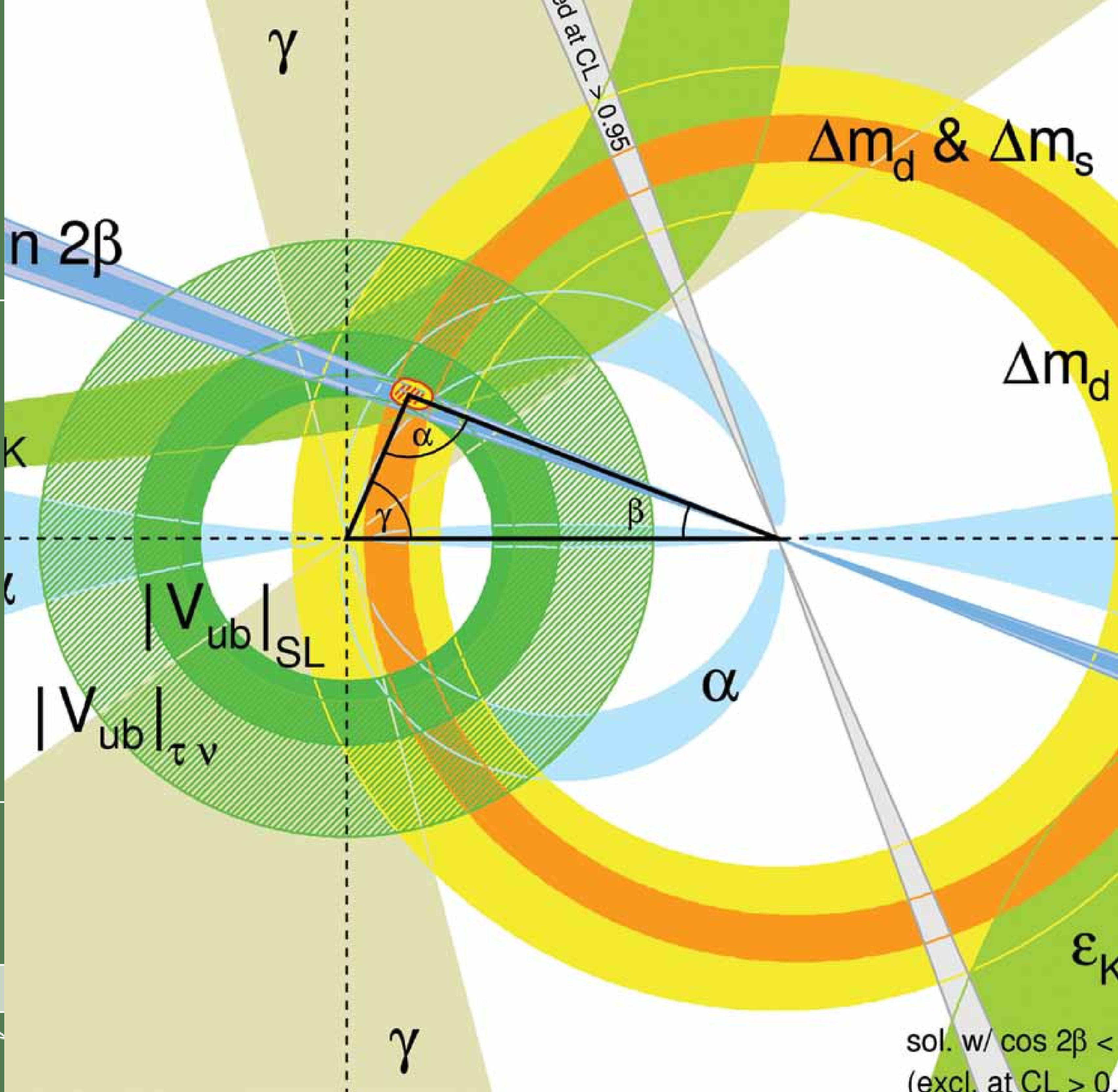
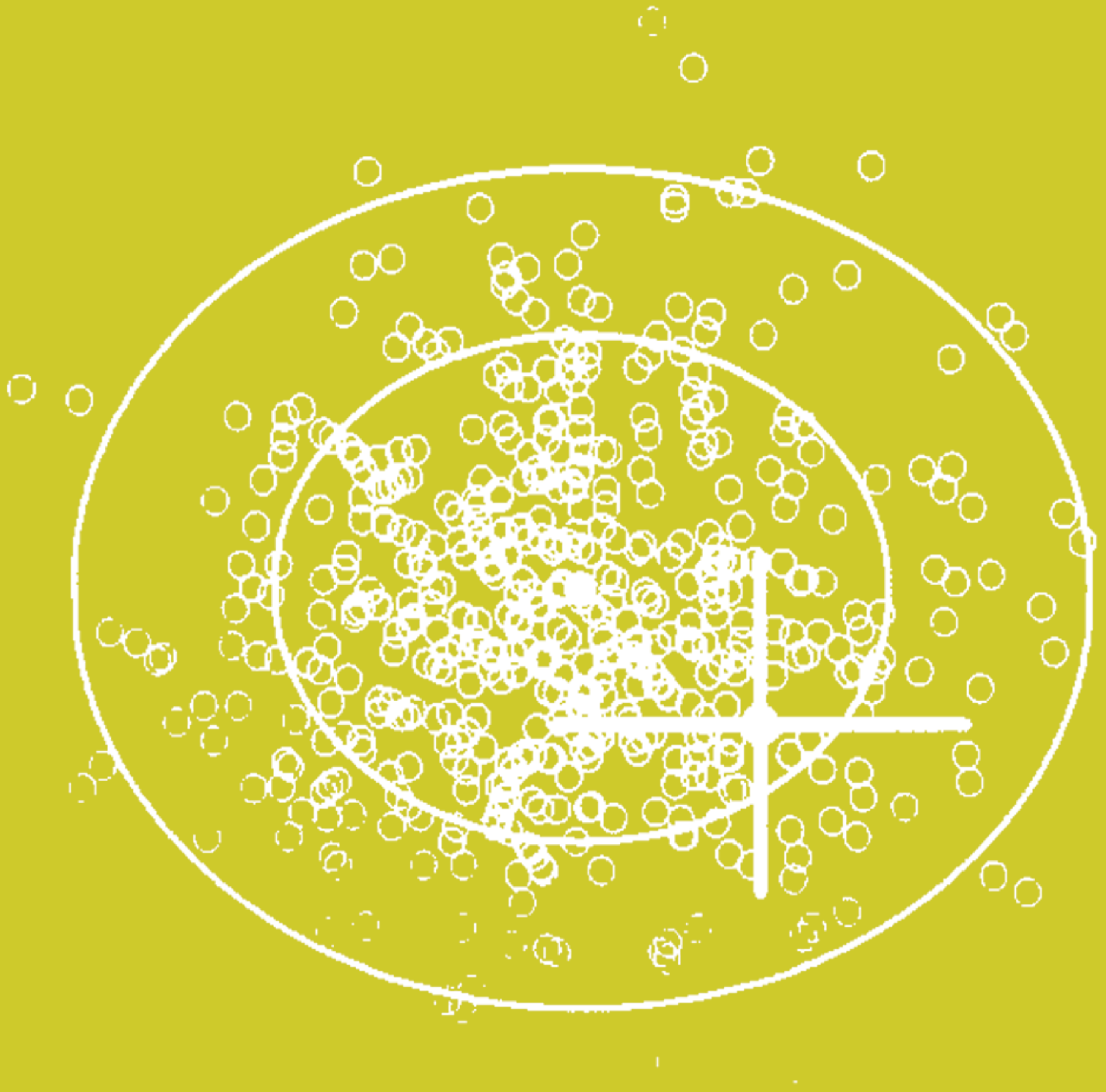
48

1994 The Riddle of Flavor

The elementary particles in nature come in three versions. These versions have identical charges, but each has a different mass. An electron, for instance, also comes in two heavier versions, called muon and tau. Physicists say that electron, muon and tau are three “flavors.” The values for the masses of the different flavors reveal a surprising pattern: The muon is some 200 times heavier than the electron, while the tau is about 3,500 times heavier than the electron. A similar hierarchy exists for the masses of other fundamental particles. A “top”-flavored quark, for instance, is 100,000 times heavier than an “up”-flavored quark. The Standard Model – the accepted theory for the structure of matter – has no explanation for the hierarchical pattern of these masses, leaving particle physicists faced with the “flavor puzzle.”

The mystery deepens when we look at such extended versions of the Standard Model as the theory of supersymmetry. Such models predict the existence of new particles, which also come in several flavors. Other factors compound the mystery – for example, the suppressed rate measured for certain particle decay processes. To account for this situation, one must assume very specific properties for new flavors, including nearly exact degeneracy between their masses. Institute scientists and their colleagues proposed a new type of symmetry that compels the properties of the different flavors to take on surprising arrangements. This symmetry not only explains the relationships between the masses of the different flavors in the Standard Model, but also “aligns” the supersymmetric flavors so that they don’t enhance the suppressed decays previously measured. This theory opened an important new research direction, so that the discovery of new particles and measurement of their properties could shed new light on – and possibly even solve – the flavor puzzle.





49

1994

The Mystery of the Sun's Neutrinos

Institute scientists contributed to the solving of the mystery of the neutrinos missing from the sun. The mystery stemmed from the fact that various measurements had turned up fewer of these particles than expected, to the point that certain physics theories were cast into doubt, including the accepted view of the sun's structure and the way it produces energy.

The difficulty in such measurement arises from the extreme weakness of neutrinos' interactions with matter. In effect, the particles leave practically no trace of their passage. Most of the neutrino particles that reach Earth pass through the planet in a fraction of a second, never slowing down or producing any reaction.

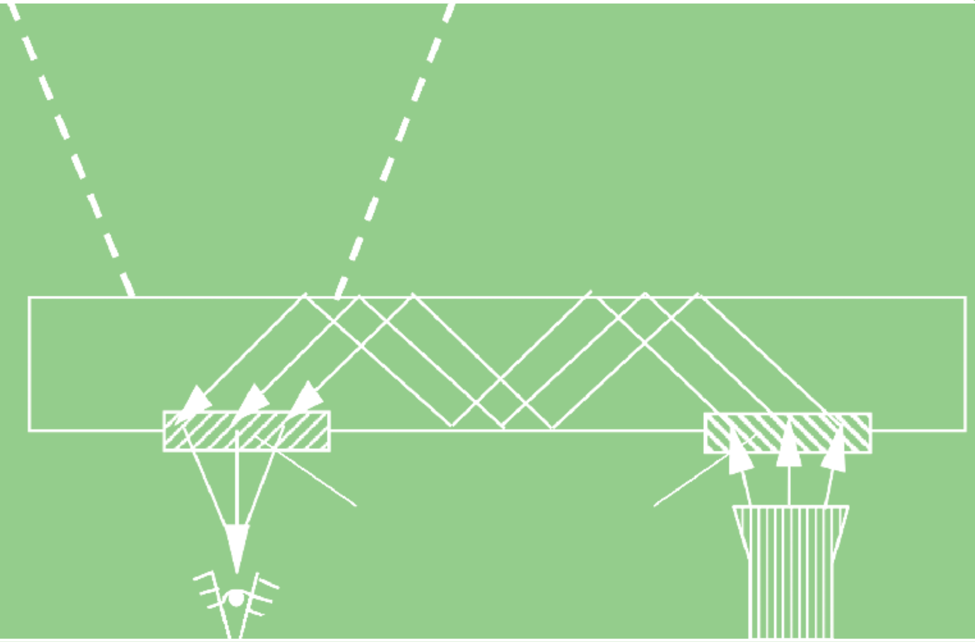
To obtain a better measurement, an international group of scientists, including several from the Weizmann Institute, designed and constructed a detector to measure the flow of neutrino particles from the sun. The detector contains 30 tons of the element gallium. When a gallium nucleus of mass 71 reacts with a neutrino particle, it produces one nucleus of the radioactive isotope germanium 71. Approximately one such event occurs in the detector per day. The Institute scientists developed a method to separate out the relatively small amount of germanium 71 atoms from the 30 tons of gallium every few weeks.

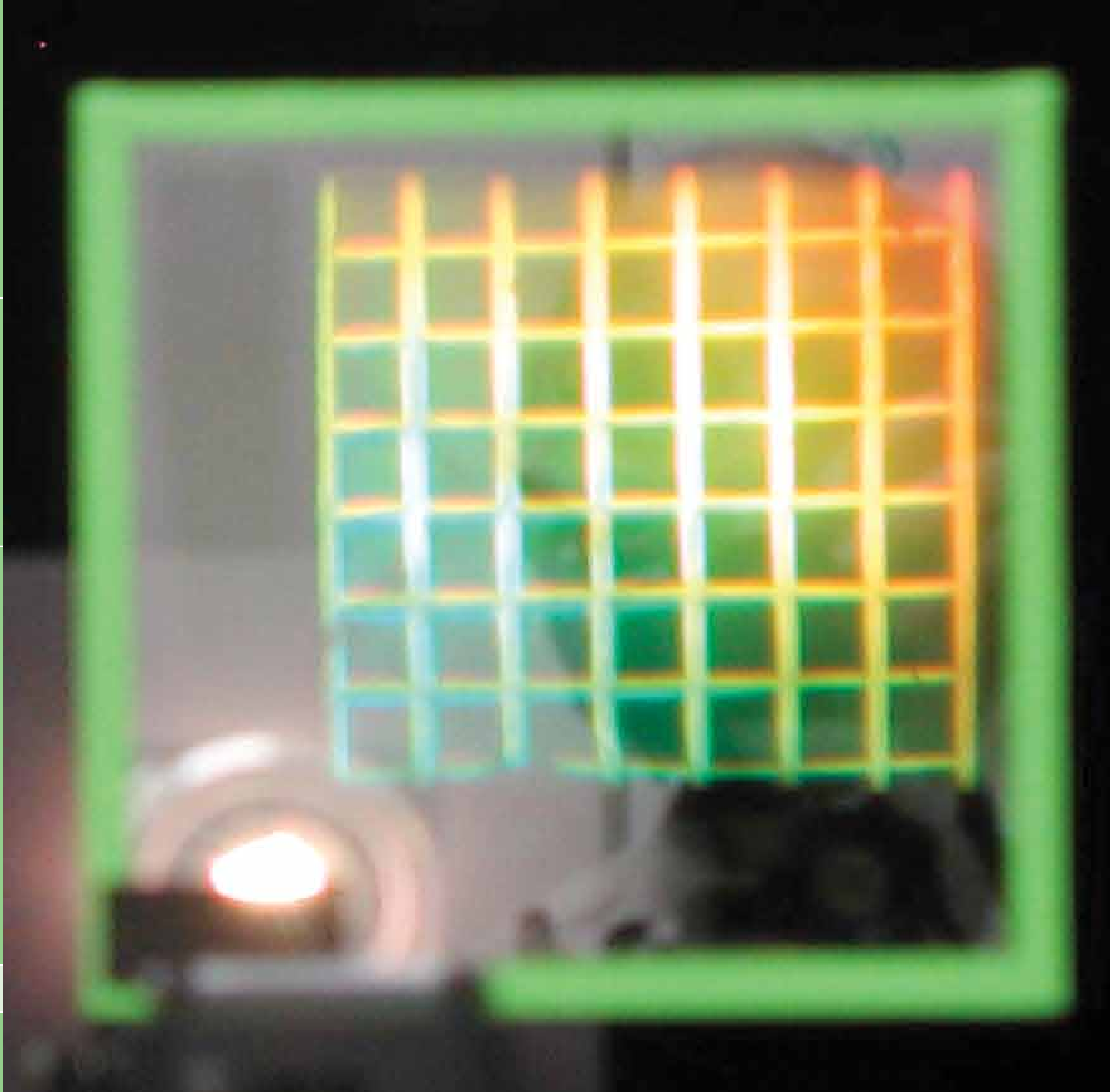
The results obtained so far in the experiment fit the hypothesized amounts of energy reaching Earth from the sun and verify the theory of the nuclear nature of the sun's energy. Nevertheless, the results point to basic discrepancies in our understanding of the neutrino.

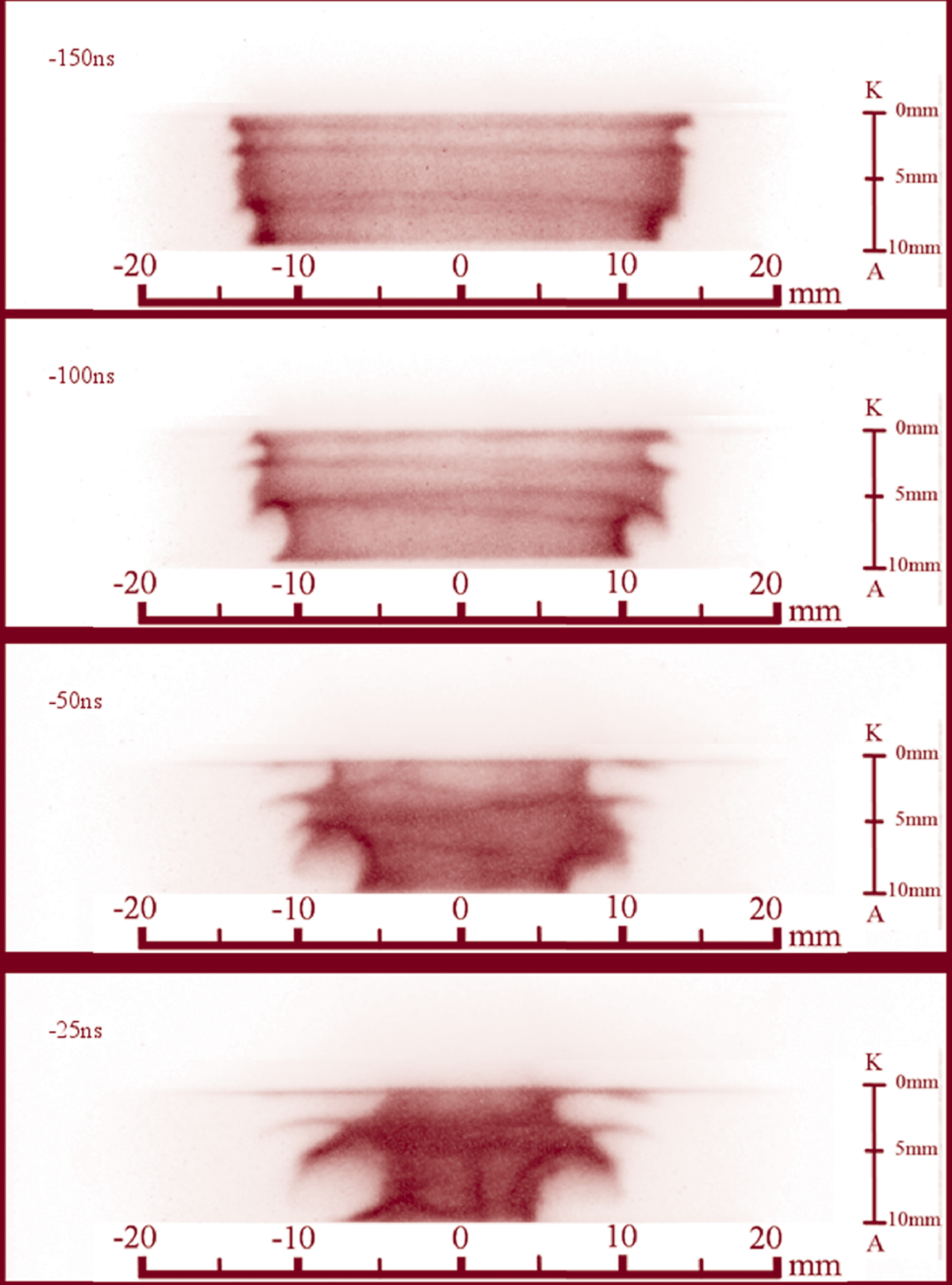
50

1994 Paths of Light

Weizmann Institute scientists were among the first in the world to develop “planar optics” technology. In such systems, several holographic optical components are combined on one substrate, enabling the formation of a complete optical system mounted on a single thin transparent plate. These systems are compact, lightweight, resistant to environmental erosion and suitable for mass production (which means they can be advantageously exploited in a wide range of applications). Several systems using this technology have been developed at Weizmann: compact head displays for pilots or doctors, as well as virtual reality systems; systems for multiplexing and separating wavelengths in optical communications; optical pattern recognition for parallel data processing in robotics; and optical interconnects between electronic circuits in computers and communications systems.







51

The Fourth State of Matter

1994

Weizmann Institute scientists developed unique spectroscopic methods to measure various properties of plasma under high-density energy, generally plasma under intense electric and magnetic fields. Plasma is the fourth – and the least understood – state of matter, a state in which highly energized particles are ionized (and thus carry an electric charge). These particles are generally either ions or electrons. The most common methods for creating plasma in the lab involve lasers or short-duration, high-power electric discharges. Institute scientists used these methods to produce plasmas of different densities and temperatures that simulated certain plasmas found in interstellar space and in stars (as well as in research facilities and industry).

Research into plasmas may greatly assist in understanding various processes in the stars and in the Universe. It may also be useful for a long list of industrial applications, including nuclear fusion. (For nuclear fusion to take place in hydrogen gas, it must be in a plasma state.)

In developing their unique measurement methods, the Institute scientists made use of the different properties of light emitted and absorbed by the plasma, as well as the reaction of its ions and electrons to excitation by light irradiation. These novel techniques enable various reactions in the plasma to be measured over very short time periods, down to a billionth of a second. The scientists then used these measurements to map a number of physical processes in the plasmas.

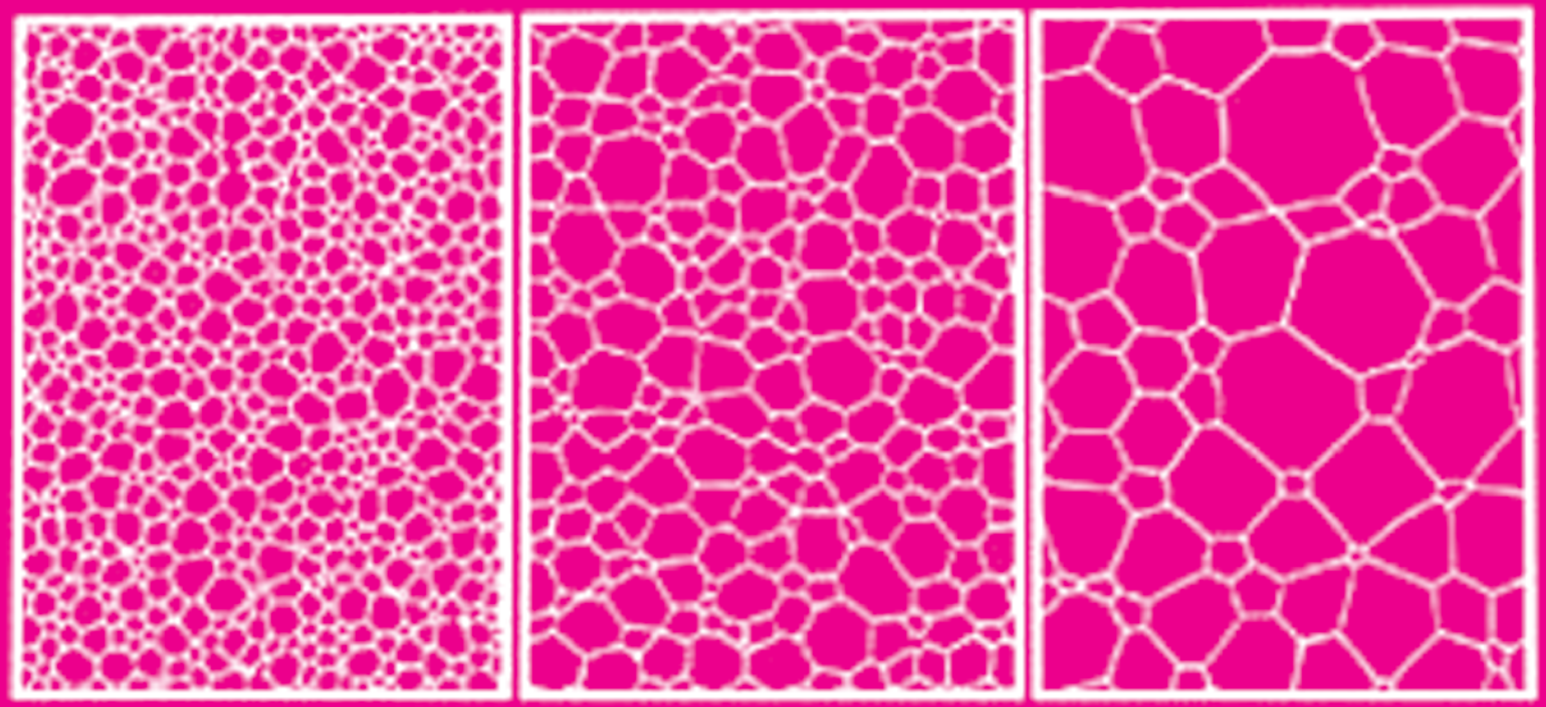
52

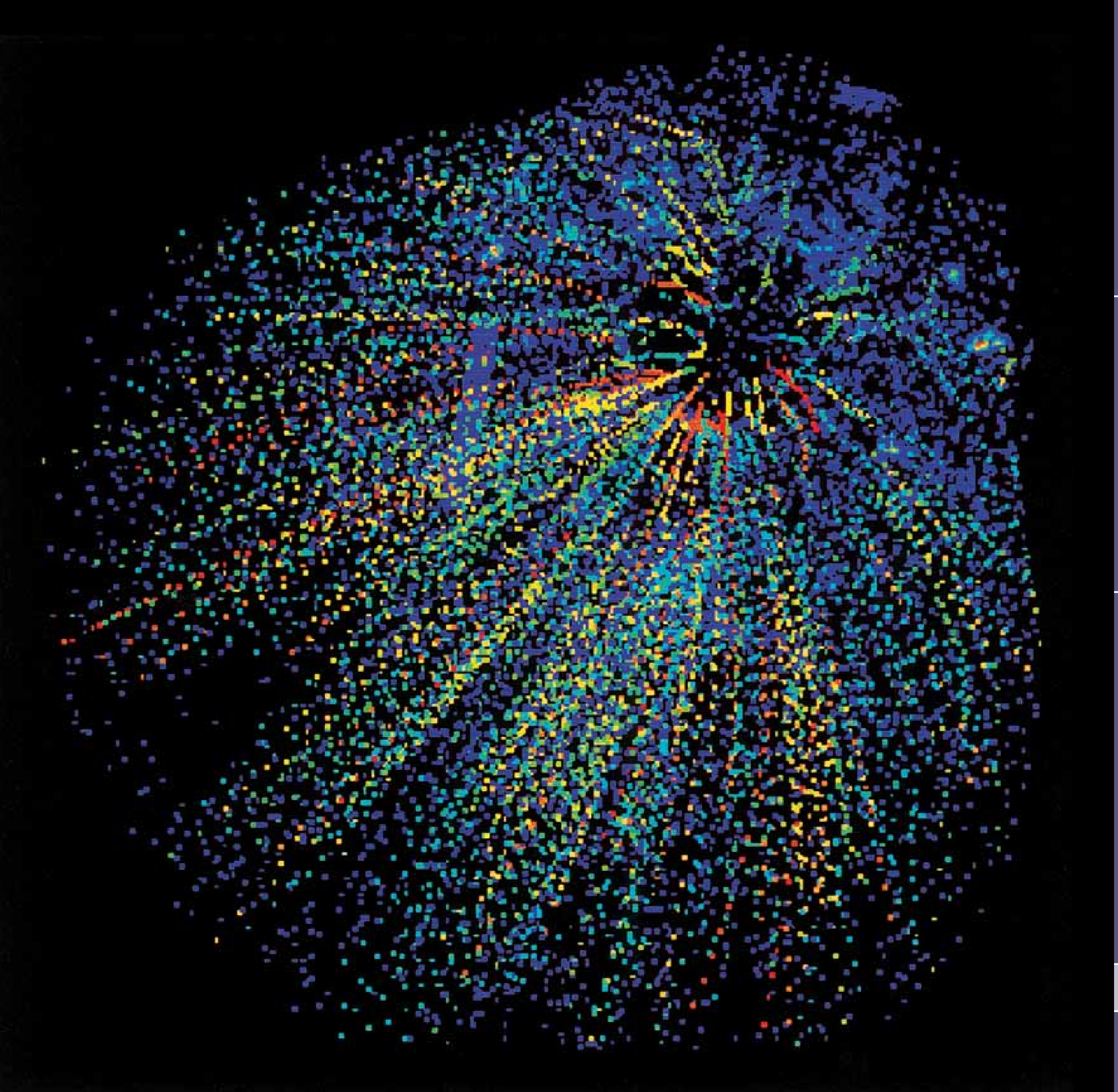
1994 Like Soap Bubbles

When molten metal is cooled and begins to solidify, little crystals of solid material form throughout. These crystals grow larger, while the overall volume of the molten metal decreases as it solidifies. But when the crystals are observed under a microscope, one can see that their development does not cease with complete solidification. Rather, the larger crystals continue to grow at the expense of the smaller ones, which eventually disappear.

Weizmann Institute scientists discovered that the statistical and geometric processes that describe the growth of crystals in metals or other cellular materials are similar to those that describe the growth of soap bubbles in foam. In other words, soapy froth can serve as a simple, inexpensive and convenient model for studying crystal growth.

Similar phenomena take place in systems that contain a mixture of liquid and solid. Weizmann Institute scientists showed that development of the solid regions depends on their close surroundings: A region of solid matter will grow or diminish according to what's happening in its neighborhood. This discovery confirmed, for the first time, predictions made by theoretical models.

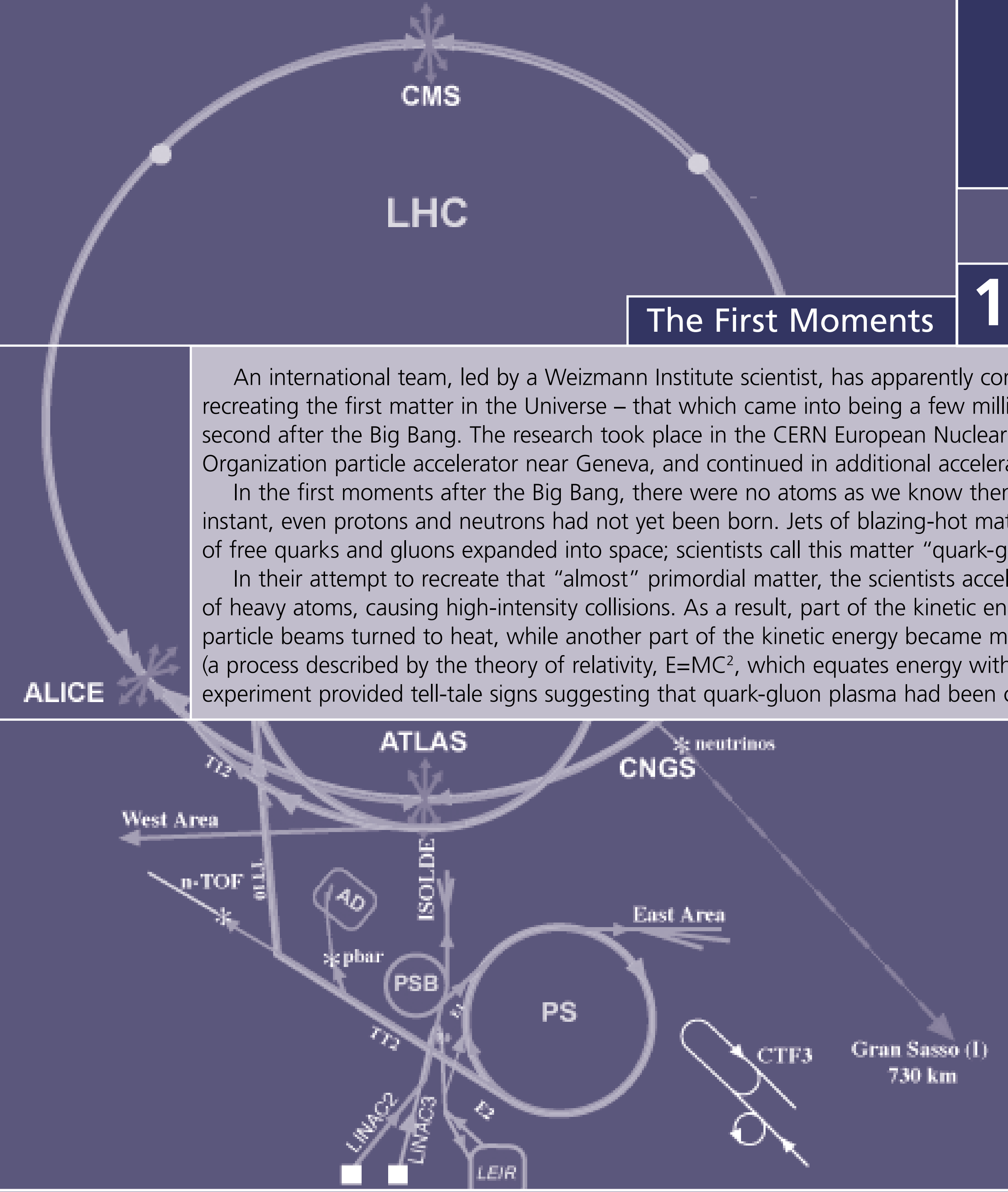




53

The First Moments

1995



An international team, led by a Weizmann Institute scientist, has apparently come close to recreating the first matter in the Universe – that which came into being a few millionths of a second after the Big Bang. The research took place in the CERN European Nuclear Research Organization particle accelerator near Geneva, and continued in additional accelerators in the US.

In the first moments after the Big Bang, there were no atoms as we know them. At that instant, even protons and neutrons had not yet been born. Jets of blazing-hot matter composed of free quarks and gluons expanded into space; scientists call this matter "quark-gluon plasma."

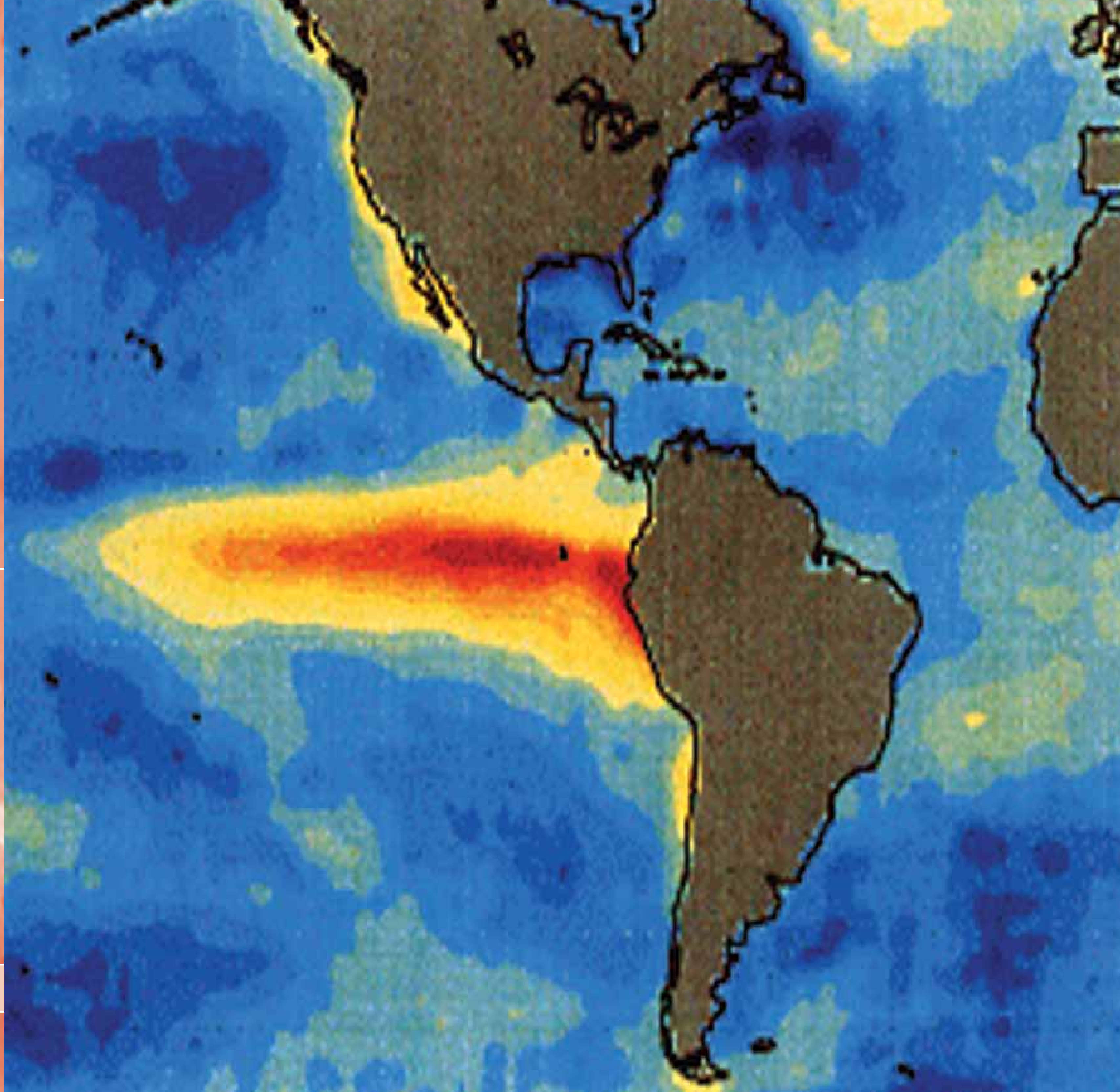
In their attempt to recreate that "almost" primordial matter, the scientists accelerated the nuclei of heavy atoms, causing high-intensity collisions. As a result, part of the kinetic energy of the particle beams turned to heat, while another part of the kinetic energy became matter particles (a process described by the theory of relativity, $E=MC^2$, which equates energy with matter). This experiment provided tell-tale signs suggesting that quark-gluon plasma had been created.

54

1995 Speaking of the Weather

Institute scientists proposed an explanation for the seemingly random nature of the climate phenomenon known as El Niño in the Pacific Ocean. El Niño involves higher-than-usual warming of the ocean surface every three to four years, generally around Christmas time. (El Niño is Spanish for "the child," referring to the infant Jesus.) The proposed explanation states that the yearly cycle of seasons (including winds, changes in water and atmospheric temperature, etc.) periodically affects the Pacific deep ocean waves. This, in conjunction with various non-linear effects, can lead to the chaotic occurrence of El Niño and surface warming.

El Niño disrupts weather worldwide, causing storms, floods and droughts, and affecting large populations, as well as causing huge economic losses in many countries. The ability to understand the changing cycles of El Niño might help in predicting its appearance and ameliorating some of its worst effects.



55

The Purest Semiconductor in the World

1995

Institute physicists developed the purest semiconductor (made of gallium arsenide) in the world. This means the electrons in it can travel quite far without hitting other particles. The achievement put Institute scientists in the lead in the global race to develop the purest semiconductor material.

The speed at which electrons move through a particular material depends on the material's purity. The more "impurities," the more likely are electrons zipping through the material to collide with the foreign particles, slowing their progress. Therefore, the purer the material, the farther an electron can go before hitting another particle. This translates into a higher average speed for the electrons.

The scientists who created the ultra-pure semiconductor produced it using a unique vacuum system installed and upgraded in the Institute's Joseph H. and Belle R. Braun Center for Submicron Research.

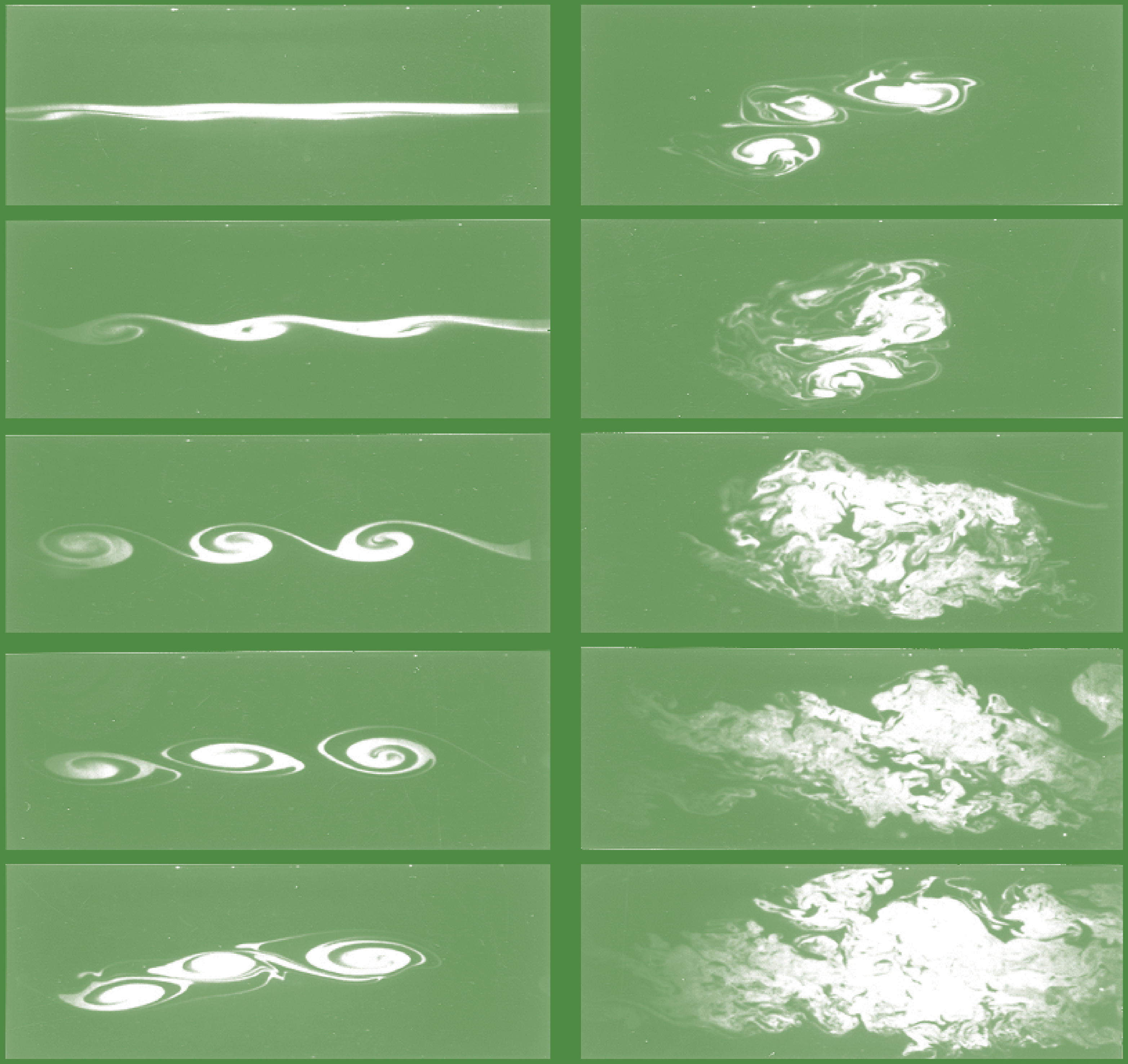
56

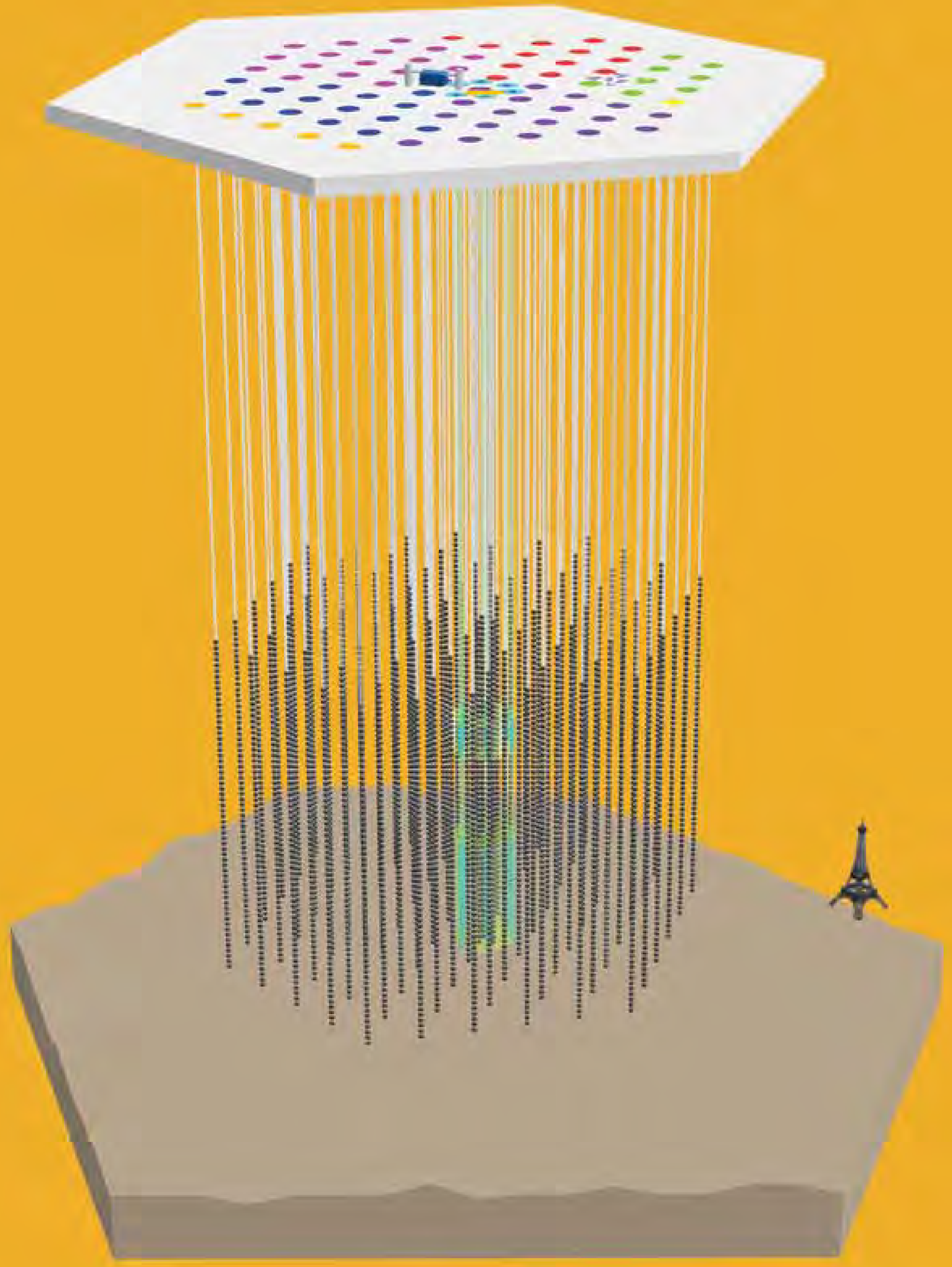
1995 Go with the Flow

Institute scientists made significant progress in understanding the statistical nature of turbulent flow, a question defined as one of the last and most puzzling of the open problems in statistical physics.

Chaotic turbulent flow is a universal phenomenon that occurs in gases and in liquids moving in pipes or channels or on surfaces. To observe turbulence, one need only open a kitchen tap and watch the water run into the drain. At first, the flow appears orderly, but soon, especially if we open the tap fully, it swirls chaotically. The flow of air around a moving vehicle is also turbulent, and this is one of the main drags on a car’s forward movement. But no one has yet attained perfect comprehension of the phenomenon. A partial theory had managed to predict turbulent flows to some extent. A mathematical formula proposed by Institute scientists greatly improves the prediction capability of this theory, and this should give scientists the building blocks they need to construct a complete theory of turbulent flow.

A comprehensive theory of turbulence might, among other things, enable designers to modify the air turbulence around cars and airplanes, which would reduce their fuel use significantly.





57

The Source

1996

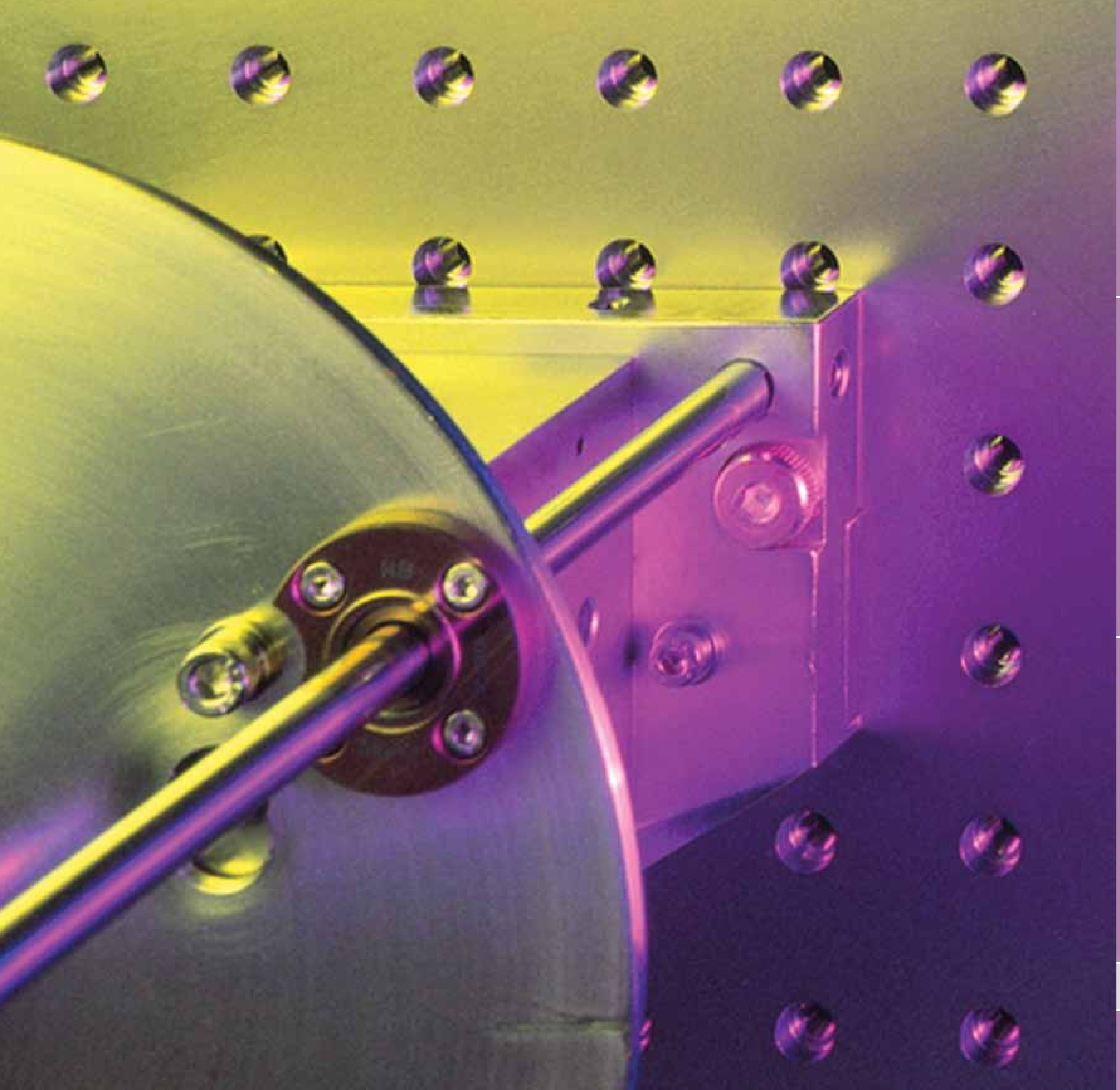
Extremely-high-energy particles, with energy of over one hundred billion gigavolts (ten million times the energy of the most energetic particles produced in labs) are constantly striking Earth's atmosphere. The sources of these particles and the way in which they are produced are still unknown. Institute physicists proposed that these particles are created near young black holes, whose mass is similar to that of our sun, and which are believed to be responsible for powerful bursts of gamma radiation. This model also predicts the creation of high-energy neutrinos – particles with no electric charge and almost no mass that rarely interact with other types of matter. Giant detectors under construction deep in the sea and under the Antarctic ice will enable scientists to evaluate the validity of the model. Detecting the predicted neutrinos would also enable scientists to test the principles underlying the special and general theories of relativity with unprecedented accuracy.

58

1996 Working Backwards

Institute scientists, working with American colleagues, developed a novel mathematical approach to assimilating ocean observations into a model of the global ocean. The method, which borrows from robotic control systems, is known as "optimal control." With this particularly efficient method, large quantities of oceanographic observations may be combined with state-of-the-art models, improving our understanding of the ocean circulation and its effects on climate.

The usual ocean modeling approach uses data on the winds that drive ocean flows to calculate the ocean's temperature and salinity. But the existing wind data are not reliable, whereas temperatures and salinity are relatively well known. So the scientists built a model that could "work backwards," calculating the winds and other unknown factors from the known measurements of temperature and salinity. The new method makes possible the creation of a more detailed, more accurate picture of ocean circulation, and it may improve our ability to predict possible climate change.



59

Replacing the Ring

1996

Institute physicists designed and built a sophisticated trap for storing ions. This trap enabled them to conduct many experiments that until then had been possible only in gigantic ion storage rings. These experiments use ions that are cooled to their base temperatures – the lowest energy in which a particle can exist, in which it ceases almost all movement. When molecular ions are in this "frozen" state, it is easier to investigate such properties as structure and dynamics.

There were five large ion storage rings in the world prior to the Weizmann development. These costly facilities are in such high demand by researchers from all over the world that experiment times are strictly allotted. This situation meant that scientists had to make the most of their precious ring time, often leading them to perform "safe" experiments whose outcome was more or less assured, rather than more "adventurous" ones. Unfortunately, it is often the high-risk experiments that lead to true scientific breakthroughs.

The ion trap built at the Institute was much more modest than the giant rings, but it allowed the scientists to perform adventurous experiments that could lead them into unknown territory.

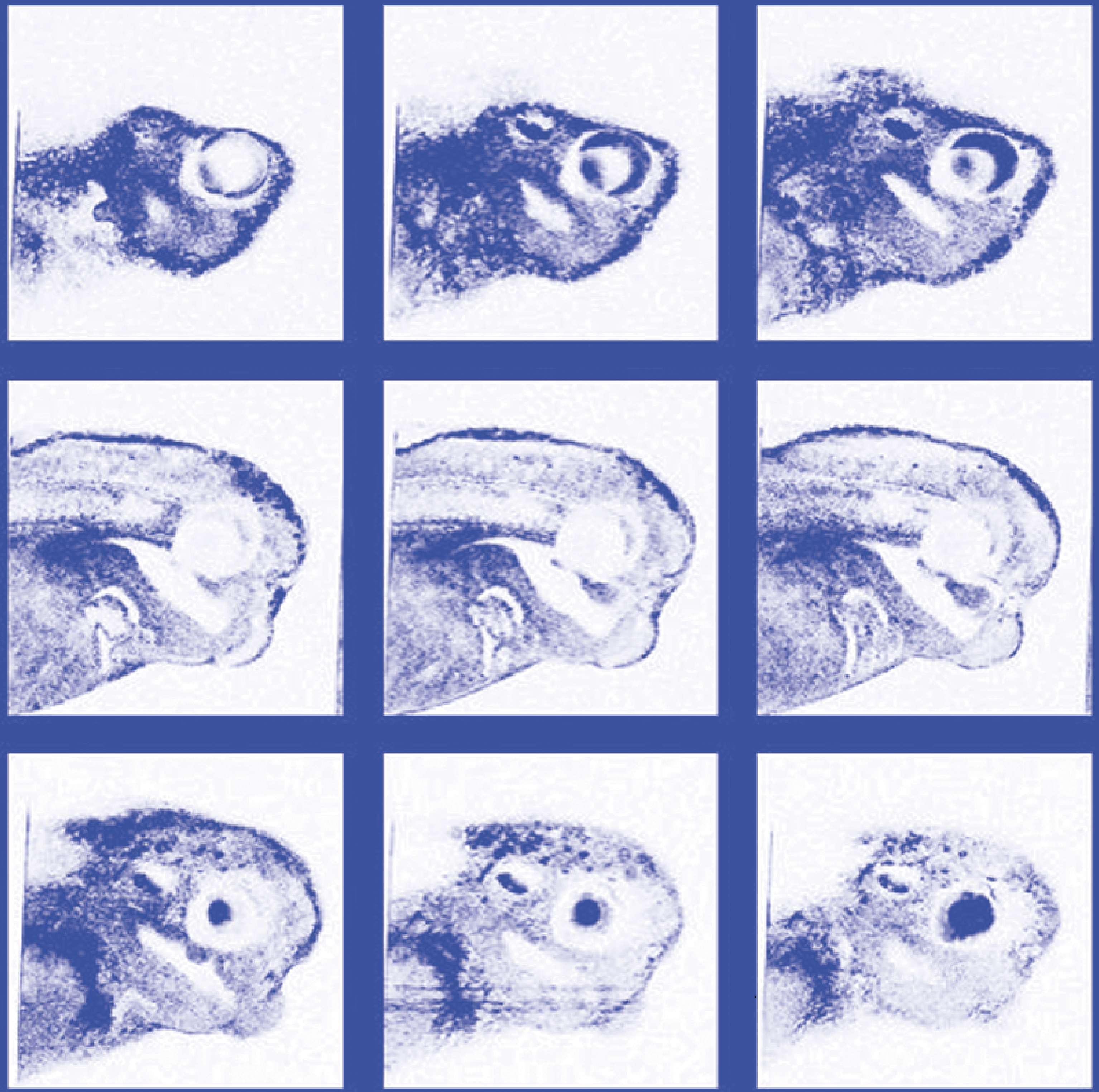
60

1997 Nella and Leon Benoziyo Physics Library

The Nella and Leon Benoziyo Physics Library was designed by Zarhy Architects in 1996. Placing a library on columns and thus disconnecting it from the ground is characteristic of Modernism. Beams projecting from the plane of the ceiling are attached to wide circular columns on the sides of the library, leaving a column-free interior occupied only by bookshelves. The ground-floor columns have a unique design: The capital of each column is rotated at 45 degrees to the base, creating a series of triangular facets from the base to the capital.

The Institute's physics buildings have undergone substantial development over the years. Not only have numerous buildings been added alongside the library, but its split-level plan has come to serve as a general lobby leading in several directions. In other words, the Modernist idea of space flowing underneath a building has been fully realized here.

Beneath the library is a lobby that serves as a work area for students; it is partitioned by wavy etched glass that creates a dynamic feeling reminiscent of an airport.



61

Secrets of the Third Harmonic

1997

Institute scientists developed innovative optical microscope methods based on the use of incredibly short pulses of laser light – lasting only a few femtoseconds (a femtosecond is to a minute as a minute is to the age of the Universe). The scientists use the fact that when a very short flash of extremely high-intensity laser light passes through transparent material, a small part of it is converted to light of a different color – in harmony. The wavelength of the converted light waves (their color) is exactly either two or three times the original wavelength. For instance, a small part of a light beam with a wavelength of 1.5 microns (in the infrared range) passing through transparent material at very high intensity will be converted to a frequency three times as large: green light. This is the third harmonic that the scientists used to create their non-linear microscope method. In this method, it is possible to observe one plane in a three-dimensional object (an "optical slice") by controlling where the light beam focuses, so that the third harmonic occurs only at the required depth. Scientists can use this method, for instance, to observe processes deep inside a cell or a tissue without marking or staining them.

62

1997

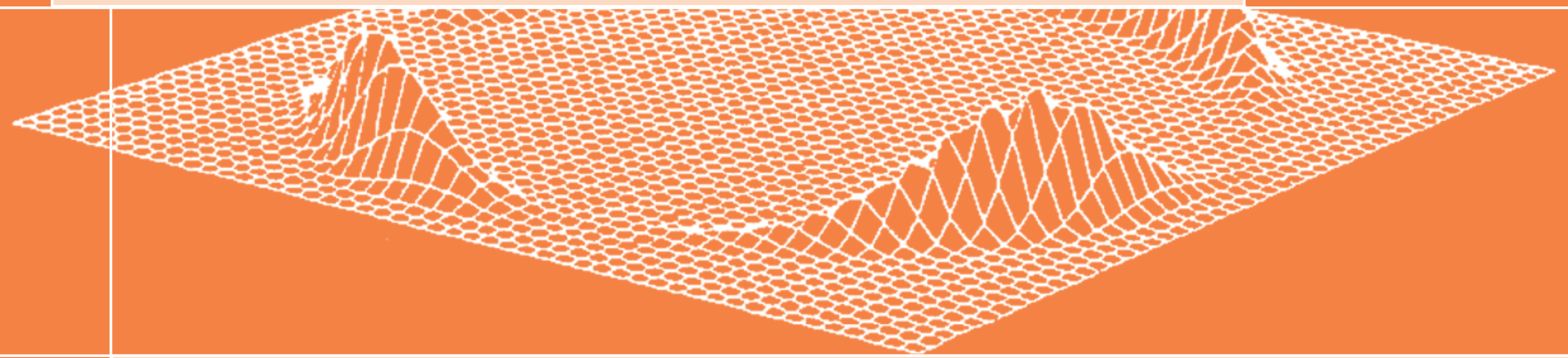
Wave Packets

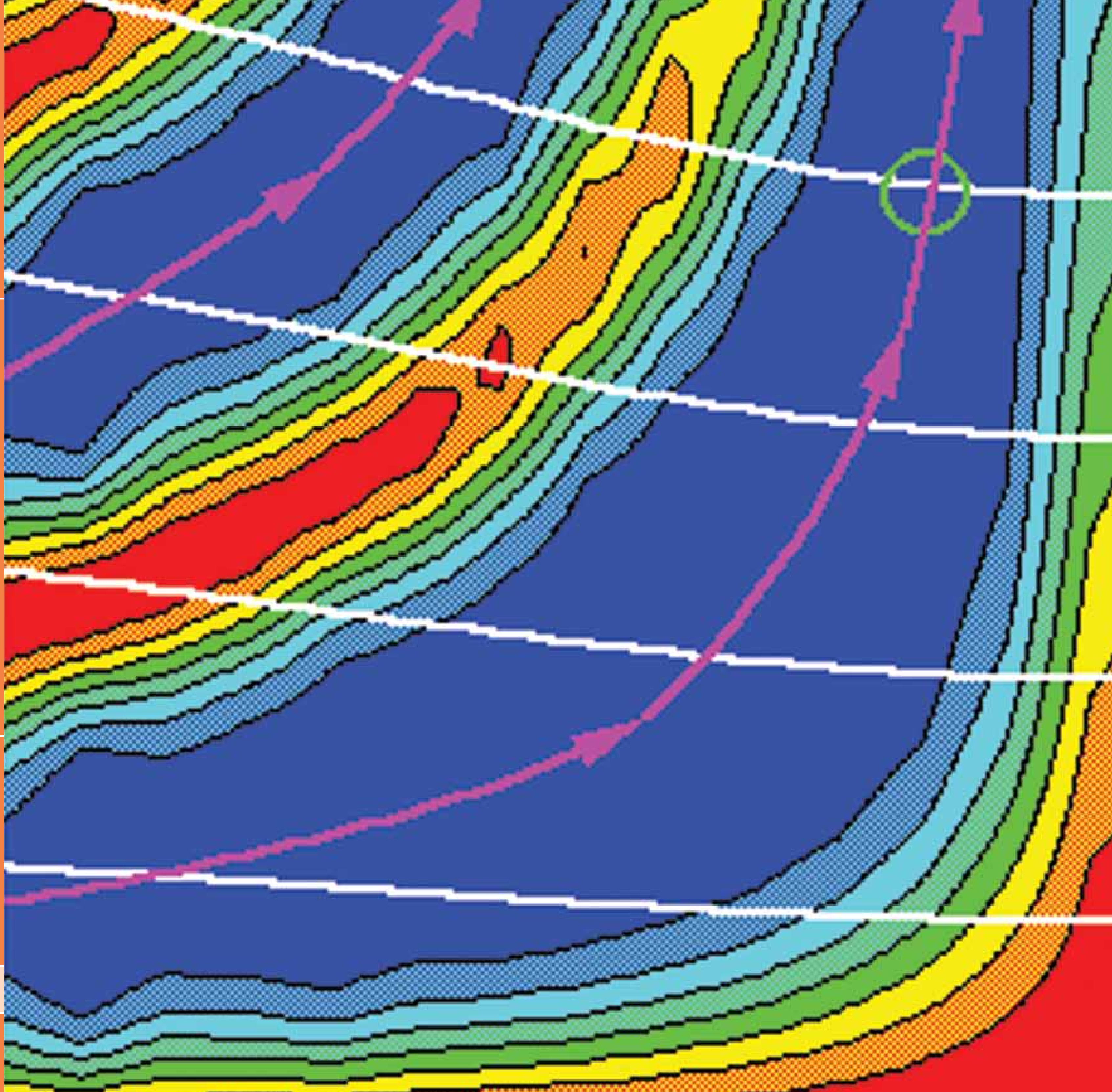
An original method of separating isotopes based on the principles of quantum mechanics was developed at the Weizmann Institute. The ability to separate isotopes is widely valued in advanced chemical industries, biotechnology and genetic engineering, the pharmaceutical and medical device industries, scientific research and many other fields.

The method is based on a fundamental law of quantum mechanics which states that it is impossible to know both the location and the velocity of a quantum particle at the same time. Thus the question of whether a particle is or isn't in a certain spot is not an incontrovertible fact but a matter of probability. In effect, an electron orbiting an atomic nucleus looks, through the lens of quantum physics, like a "probability cloud."

The probability cloud itself undergoes periodic shape changes. It shrinks, disperses, revives and appears as two smaller probability clouds, or as four or six or even more so-called "wave packets." The periodicity of the changes in the appearance of probability clouds (or wave packets) is unique and different for each isotope.

Institute scientists developed a way to use laser beams to manipulate isotopic probability clouds in different ways. The method enables a sort of "wave packet engineering" that allows one to control the progression of the probability that a quantum particle will be found in a particular location at a particular time. Because the periodicity is unique for each isotope, the method can distinguish between them.





63

How Stars are Born

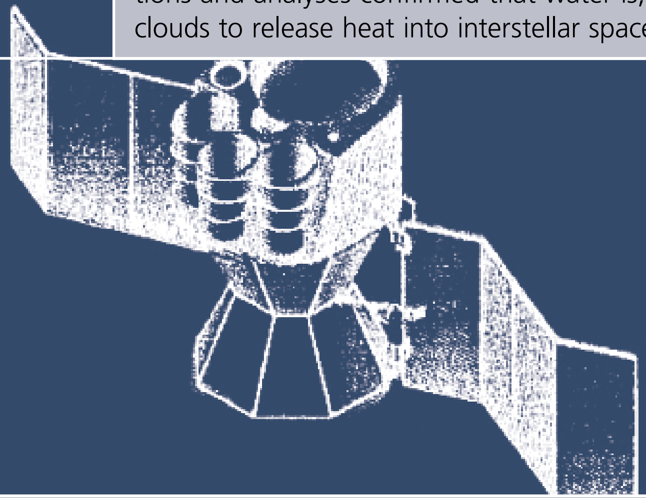
1997

On the one hand, compressing a gas causes it to heat up. On the other, material that heats up tries to expand. But if the gas in space behaved only according to these principles, the Universe as we know it would never have come into existence. So how were all of those billions of stars created?

Institute scientists investigating this question came to the conclusion that in gas clouds that become stars there is a sort of cooling system that reduces the temperature of the compressed material. It can therefore stay compressed until the material's gravity can overcome its tendency to expand.

The main approach to this matter says that part of the cooling system of a condensing star is based on a process in which water molecules play an important role. But is this really what happens? Is water actually produced when stars form?

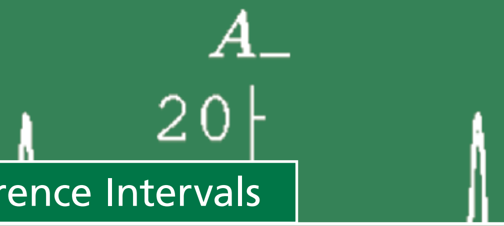
The researchers planned and carried out a simulation of the physical and chemical conditions in interstellar clouds. The experiment showed that water is created in interstellar clouds in a chemical reaction taking place between a lone electron and hydronium (H_3O^+). Further observations and analyses confirmed that water is, indeed, one of the factors that allow condensing gas clouds to release heat into interstellar space as they become stars.



64

1997

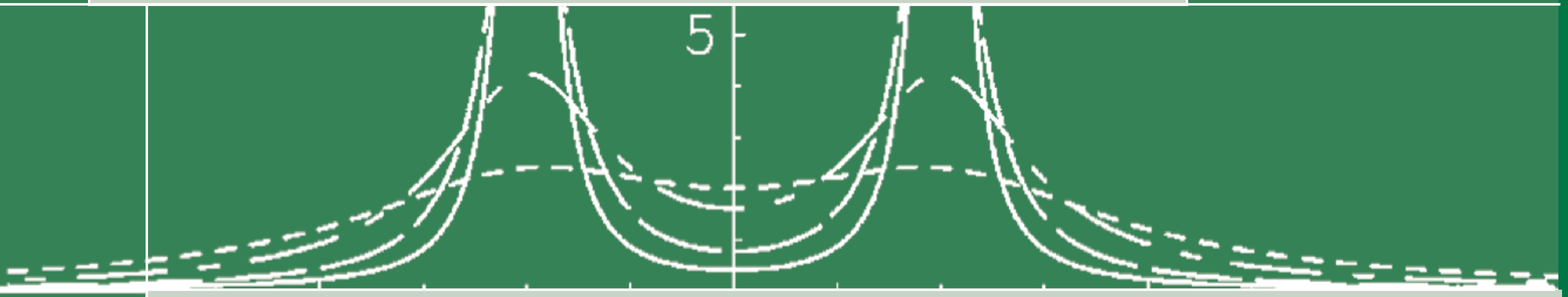
Interference Intervals

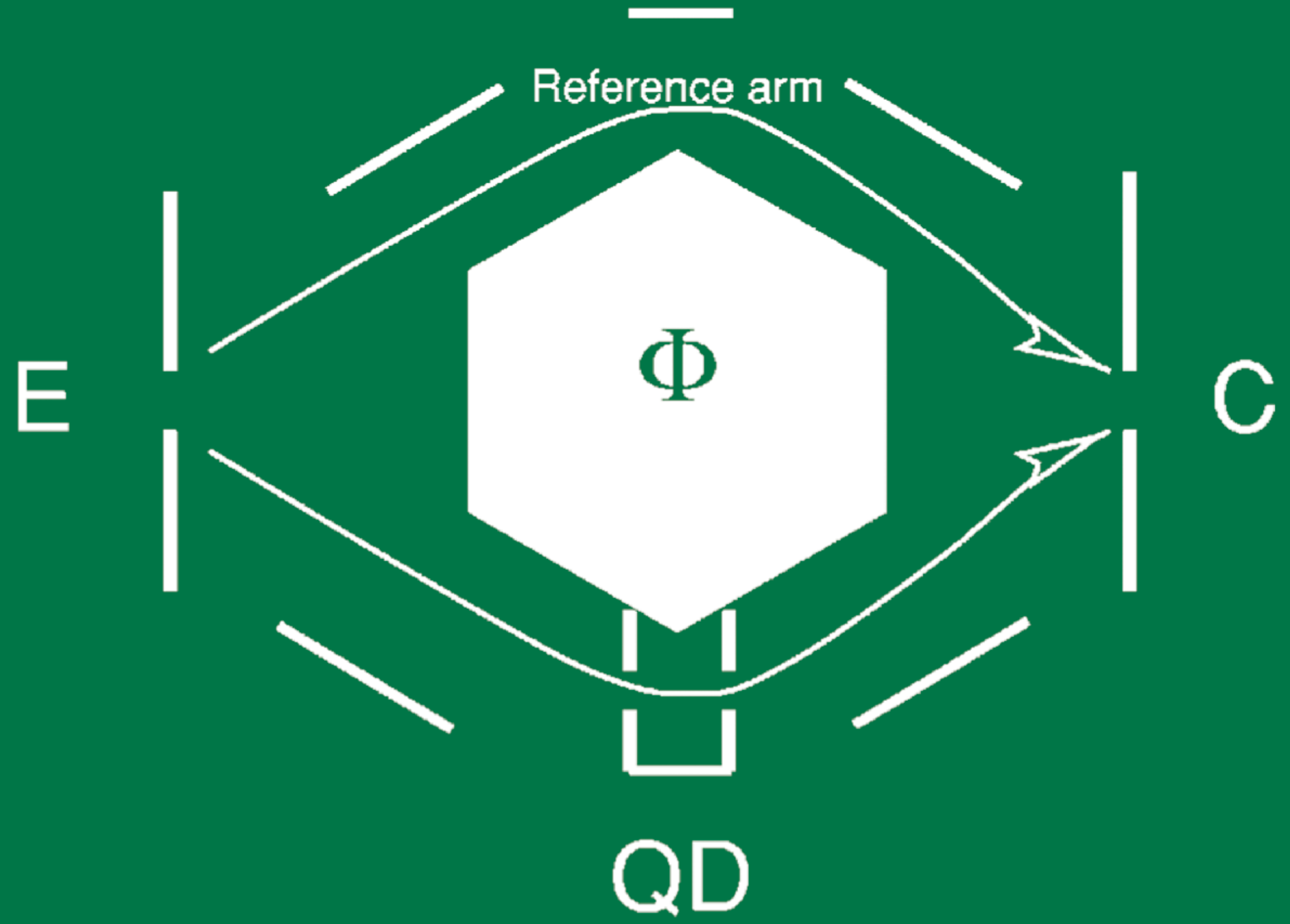


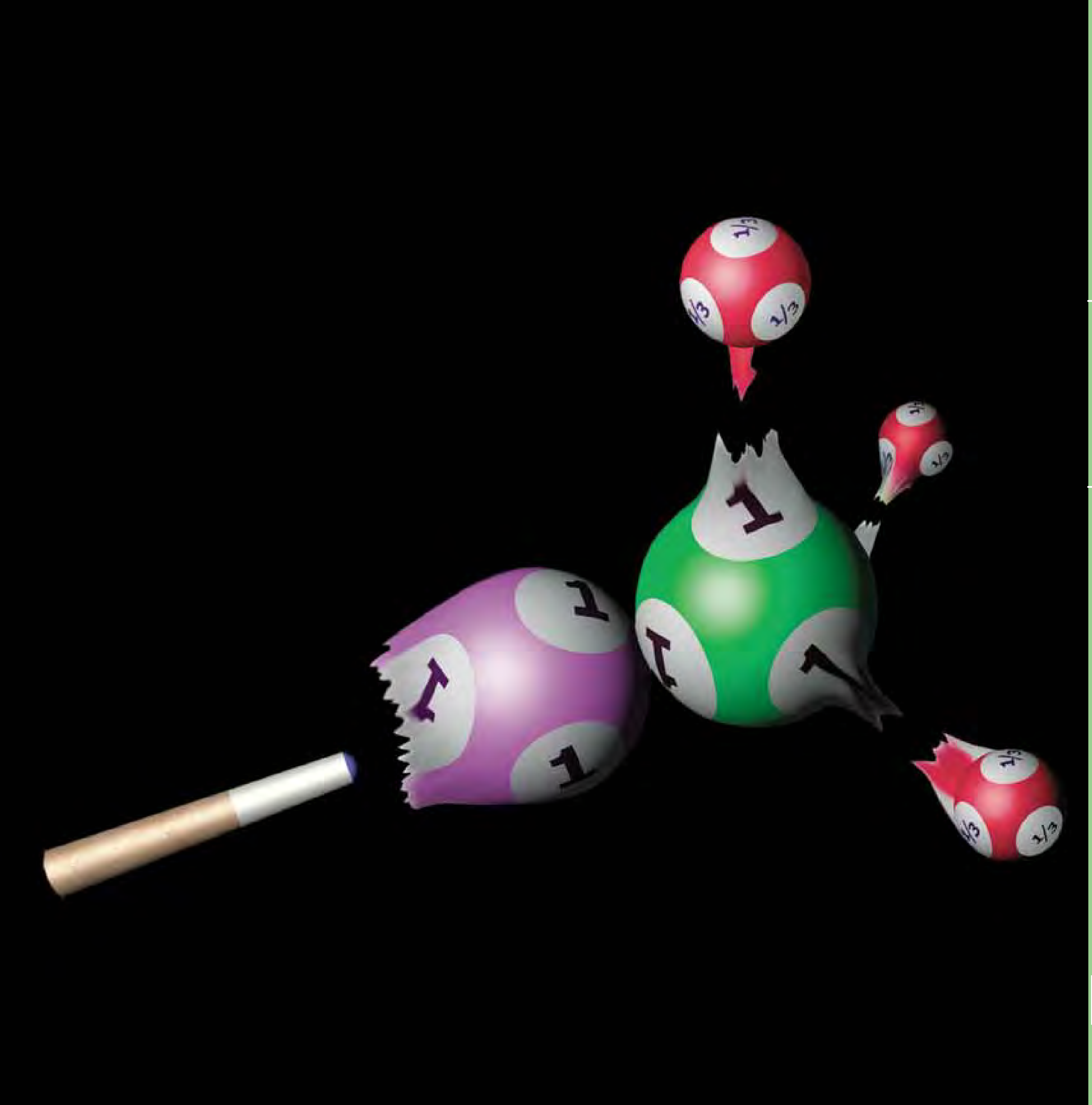
Physicists at the Institute conducted an experiment in which they were able to demonstrate, for the first time ever, both the wave and the material properties of the same particle simultaneously. Quantum mechanics states that subatomic particles can appear in two ways – as matter particles or as waves. To prove this statement, scientists often place a physical barrier on a particle's path. If particles are really only "grains of matter," they either come to a stop at the barrier or are repelled backwards. But particles acting as waves can get around the barrier (a phenomenon called "tunneling"), and these show up in interference patterns on the other side.

The researchers planned and built an experimental system to test the interference abilities of a single electron. They placed a barrier on one of the possible paths of a tunneling electron wave. This barrier was a sort of "quantum box"; in order to cross it, the electron was obliged to reveal its particle nature. But, at the same time, another part of the wave-electron, which chose a different tunneling path, continued on as a wave. Thus, in effect, in this experimental system an electron showed itself to be both a wave and a matter particle at the same time.

At the end of the tunneling pathway, the two met up and interfered with each other. The scientists discovered that this interference takes place at regular intervals and the transition between these intervals is quite sharp. They proposed an explanation for this sharp transition between interference intervals and later developed a theoretical model in which such periodicity arises. Does this model describe the process observed in the experiment? Why does this periodicity occur in nature? These questions are now being investigated.







65

1997

Proof for Imaginary Particles

Institute scientists were the first to observe “imaginary particles,” in which the electric charge is one-third of the charge of a standard electron. Until that time, it was thought that the charge of an electron, which was first measured in the 1920s, was a basic, indivisible unit. But in 1982, a theory was proposed that was meant to explain a particular electronic phenomenon; and this led to the possibility that under certain conditions, electrons form structures that act as imaginary particles, each carrying a fraction of a normal electron’s charge. These fractional charges can be one-third, one-fifth, one-seventh, etc., of a standard electron’s charge.

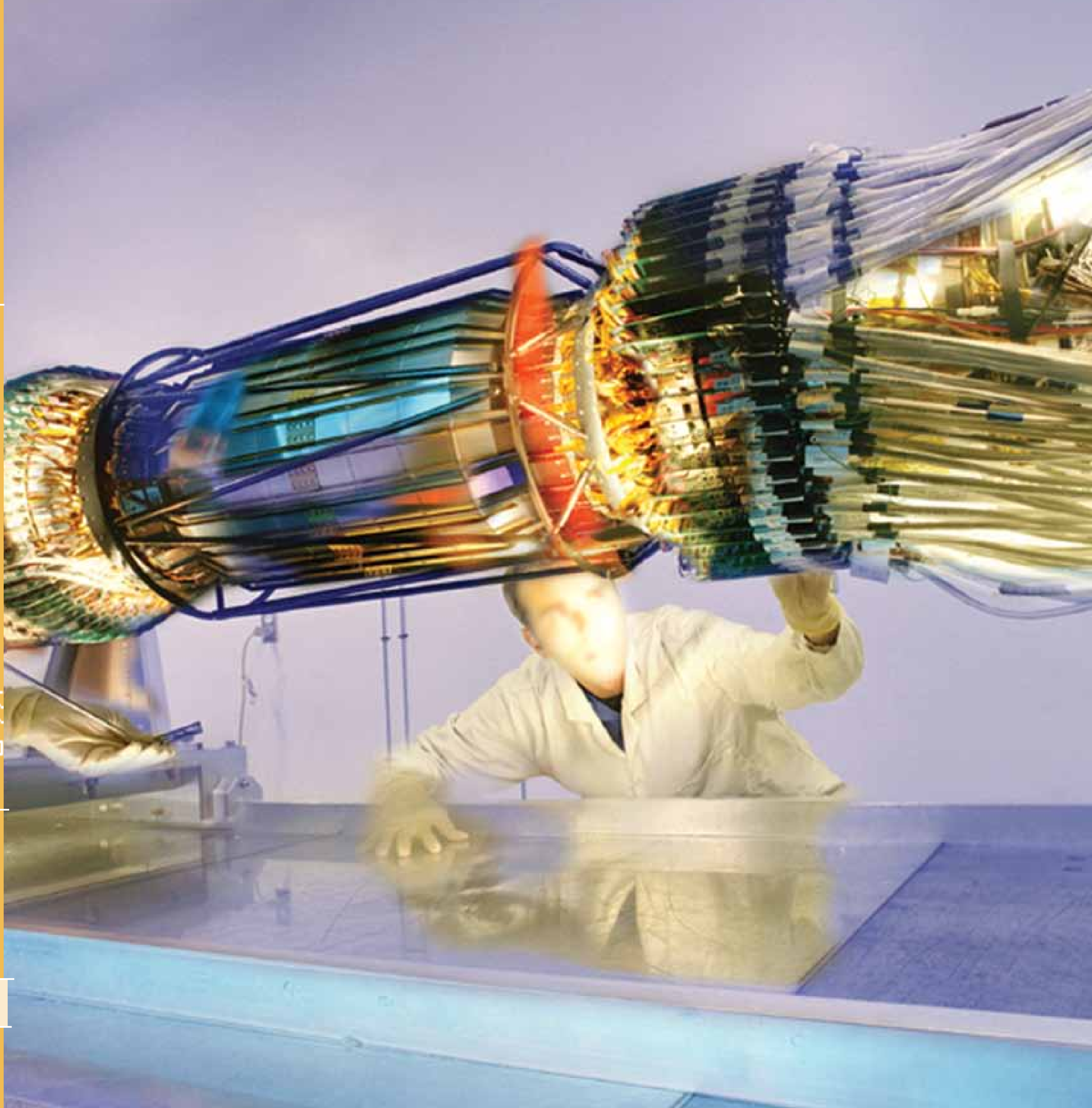
66

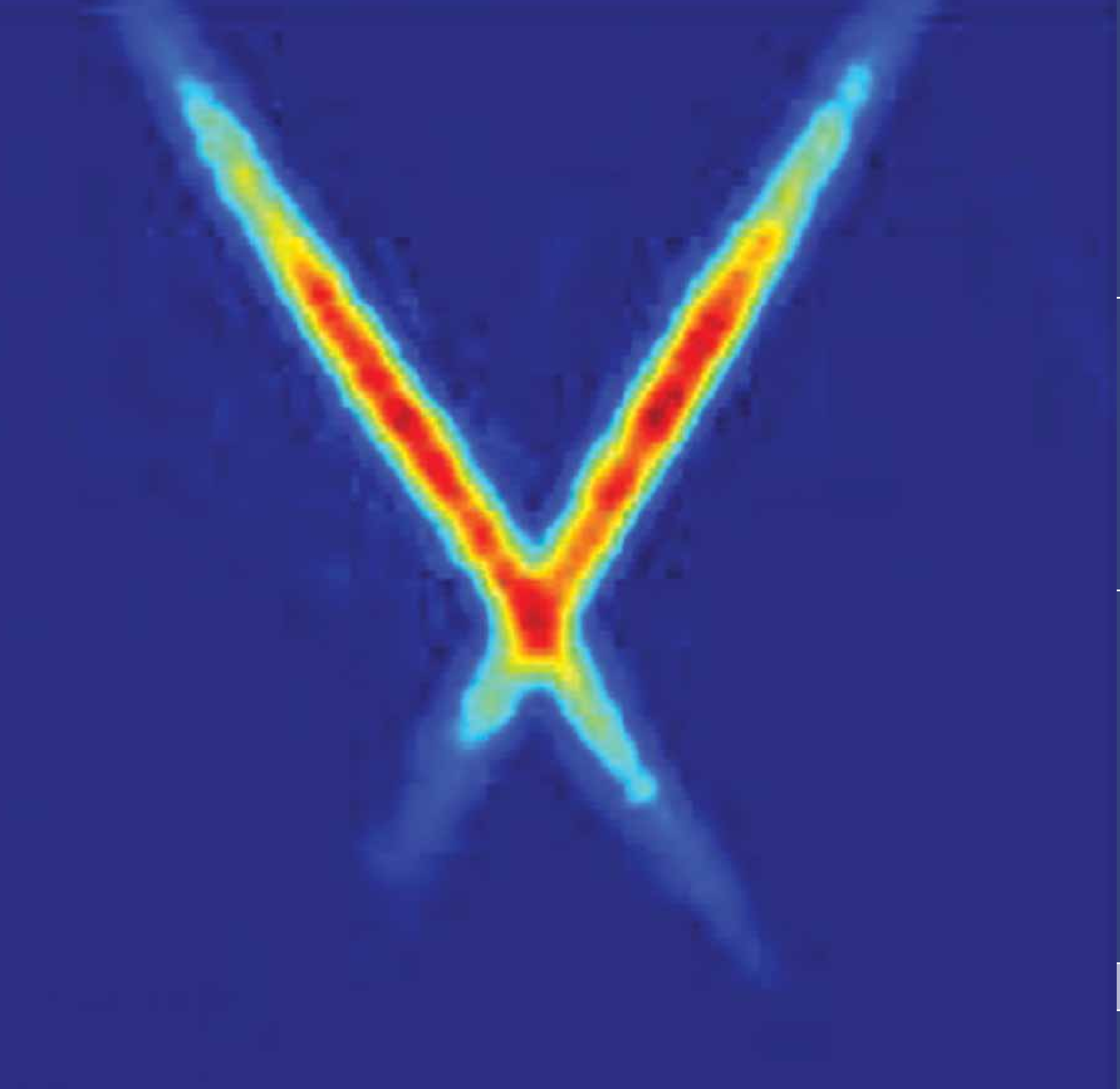
1998 Opposite Twins

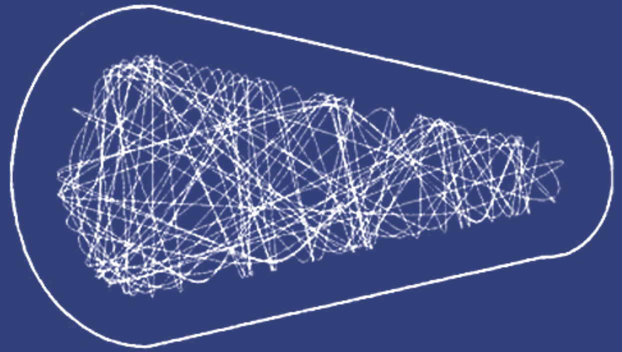
The elementary particles we're familiar with have "twin brothers" – particles with the exact same mass but opposite charges. These are the antiparticles. Thus, for instance, the proton, which carries a positive charge, has an antiproton twin with an identical mass but a negative charge. The anti-electron, on the other hand, has a mass that is identical to that of an electron but with a positive charge. Scientists can create antiparticles in the lab, and even use them in experiments, as well as in medicine; but as far as we know, all structures in the Universe, from the living cell to clusters of galaxies, are made up of matter (protons, neutrons, electrons) and not antimatter (antiprotons, antineutrons, anti-electrons).

The fact that the forces of nature act differently on matter and antimatter, something that was proved experimentally in 1964, enables us to understand why antimatter disappeared from the Universe. But the Standard Model, the accepted theory of the structure of matter in the Universe, predicts that most of the Universe's matter should have disappeared together with the antimatter, leaving behind barely enough matter for a single medium-sized galaxy. Scientists around the world conducted experiments in an attempt to find an unknown force that might be able to distinguish in a more dramatic way between matter and antimatter. The discovery of such a force might explain why so much matter has remained in the Universe.

Weizmann Institute scientists proposed some possible measurements that could be carried out in these experiments, as well as new ways of analyzing them, so that it would be possible to detect such a new force or to constrain its strength. An analysis of experimental results in this field led to the conclusion that all the measurements fit the predictions of the Standard Model and that the contribution of any new force to the measured process, if it exists, is very small.







67

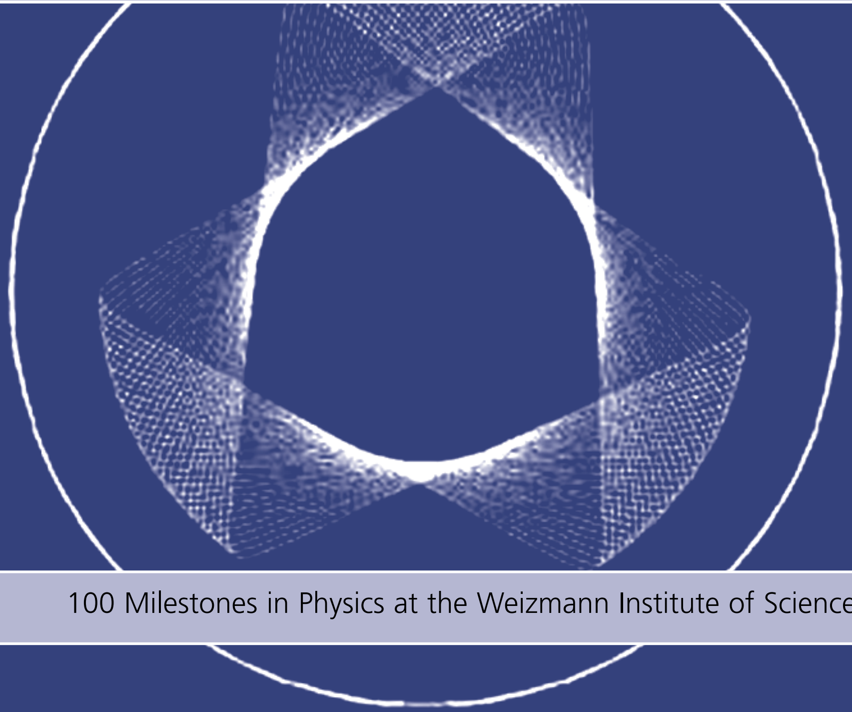
Trapped in the Dark

1998

Gas atoms constantly fly around at great speeds. Only at the very low temperature of around a millionth of a degree above absolute zero do atoms calm down a bit and float at a pace that allows scientists to observe their properties. To cool and slow down gas atoms, scientists use lasers that “bombard” groups of atoms from all sides and “trap” them so they can barely move. This is how Institute scientists succeeded in cooling atoms to nearly absolute zero.

These scientists were the first to demonstrate a “dark trap” in which cold atoms are repulsed by light and caught in the dark area of the trap. In this way, the cold atoms can be stored without disturbing them and then investigated in detail.

In practical research fields, cold atoms could be used, for instance, to build extremely accurate atomic clocks. In basic research, they might be used to probe such laws of nature as symmetry and symmetry breaking, for measuring various atomic constants and for confirming or disproving various additions to quantum theory.



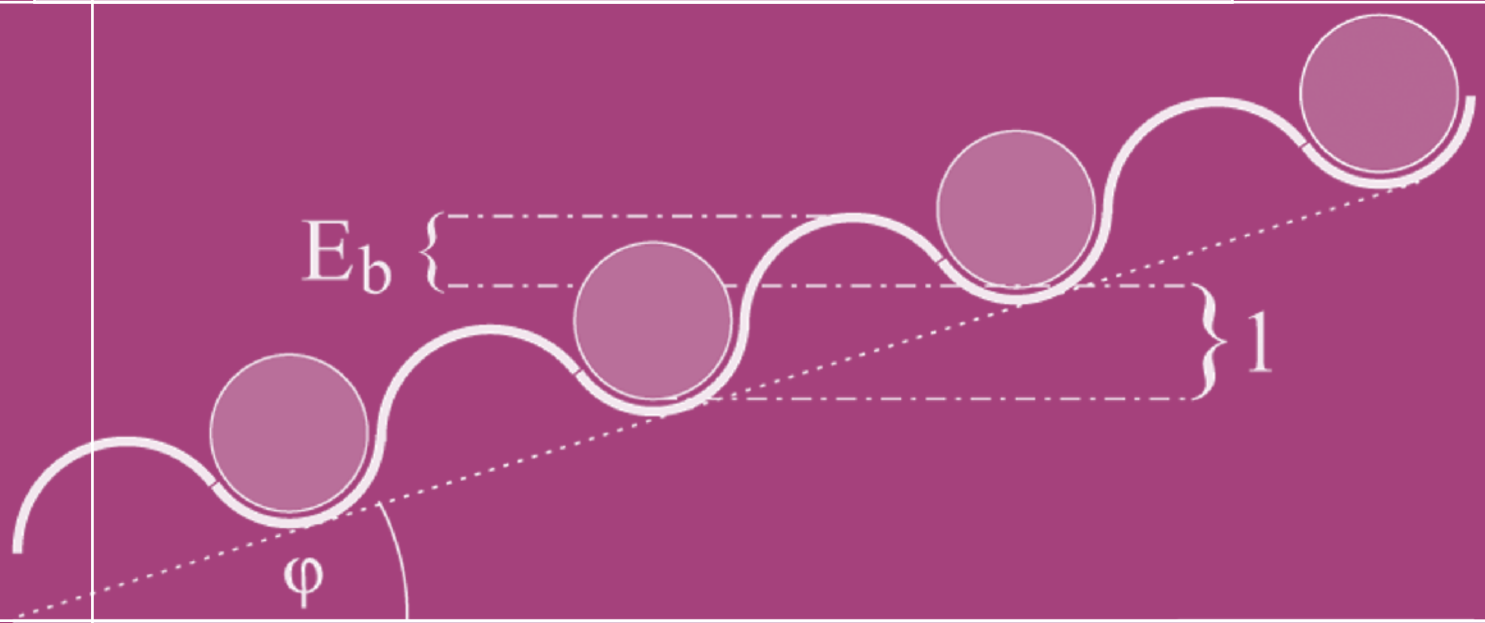
68

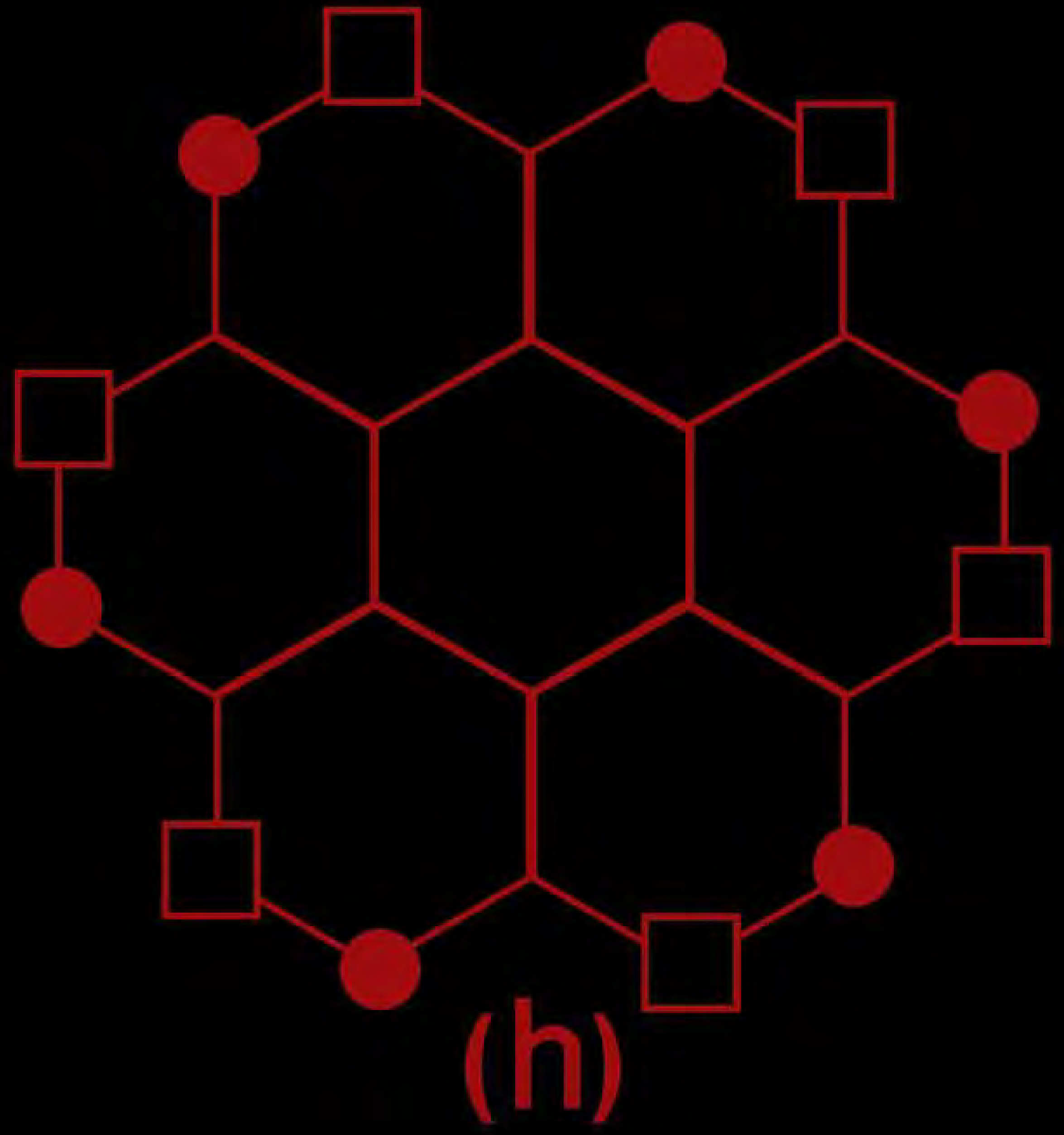
1998 Traffic Jams and Non-Equilibrium

Institute scientists developed models that explain phase transitions taking place in systems out of equilibrium (systems that develop and change over time). Systems that contain fluid flow, electric current or heat (a category that includes plants, animals and humans) are non-equilibrium systems, as are growing cities, the stock market and roadway traffic patterns.

These models have been used to describe traffic on road networks, which enable researchers, among other things, to understand what conditions can lead to "natural" traffic jams (i.e., those not caused by accidents or roadwork).

The scientists contributed to the development of computational methods based on statistical mechanics; these methods could be applied, for instance, to the process of learning in a neural network and more, and they may find use in many different types of research.





69

Transitions in Two Dimensions 1999

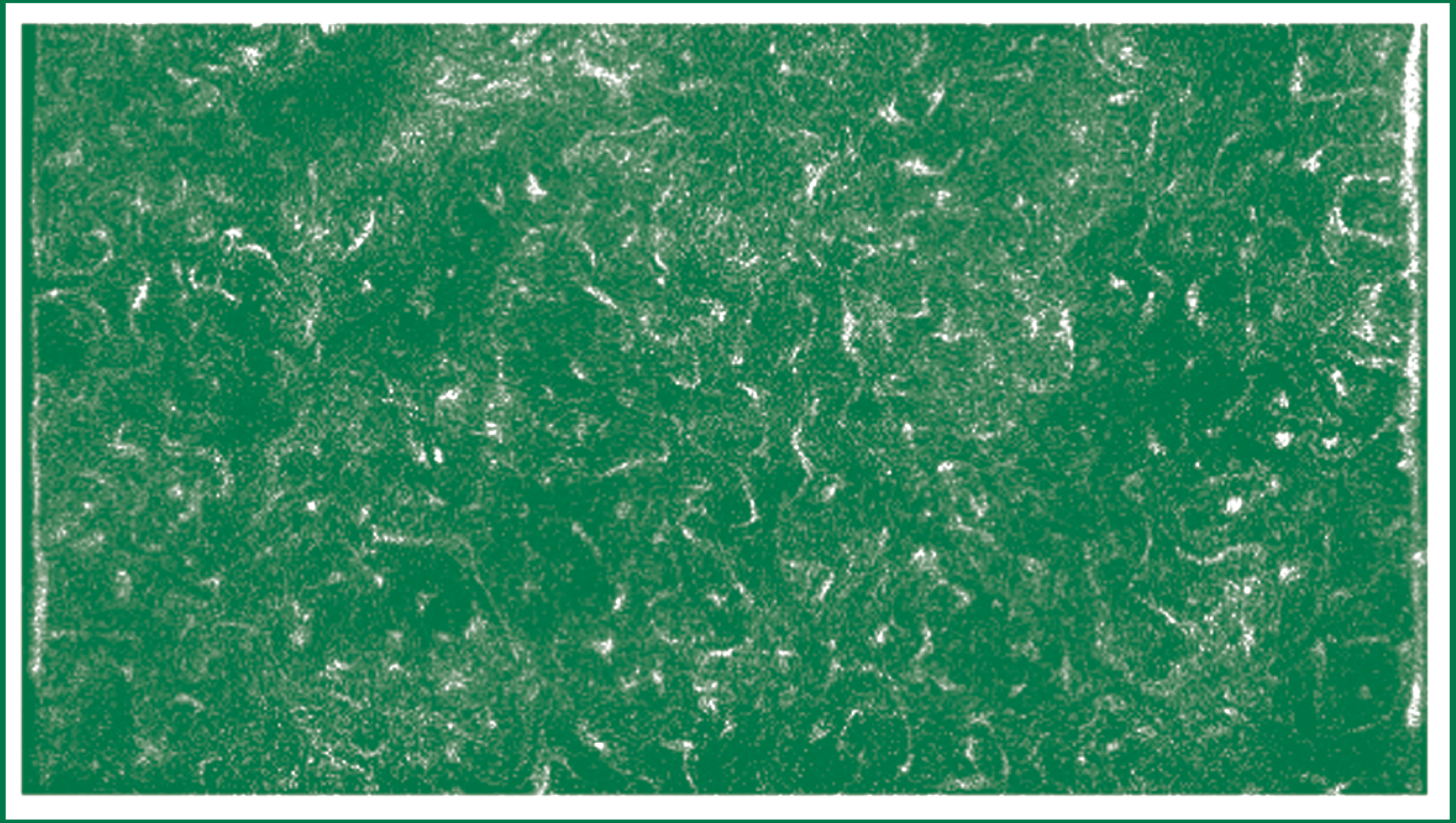
Institute scientists investigated what happens when a layer of material only one atom thick – that is, a two-dimensional material – undergoes phase transition. They found that phase transitions in two dimensions are characterized by fixed properties, and that these are different from the properties of phase transitions that take place in three-dimensional systems. These scientists made a significant contribution to the understanding of the relationship between the physical properties of a phase transition and the dimensionality of the system.

70

1999 Two-Dimensional Whirlpool

A physicist at the Institute developed a mathematical model for the behavior of eddies in turbulent, two-dimensional systems of liquid or gas. The two-dimensional model is able to describe large, real-life systems that are wide but not deep (flat, for all practical purposes). Thus, for instance, the model can predict the behavior of certain thin dust clouds that extend for thousands of kilometers, like those created in volcanic eruptions.

In the past, various hypotheses had been put forward concerning the laws for the developments taking place within such eddies, but Institute scientists produced the first mathematical description of these laws. In subsequent research, the scientists developed a model that enabled them to predict the eruption of chaotic jets inside volcanic clouds. Such jets can cause disturbances quite far from the sites of volcanic eruptions.



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The Neutrino Limit 1999

Institute scientists, working with a colleague in the US, showed that cosmic radiation sets an upper limit to the flow of high-energy neutrinos that appear to be created by objects outside our galaxy. This upper limit implies that detectors for indentifying neutrinos from beyond the galaxy would need a mass of over a gigaton. Such giant detectors, which aim to identify those out-of-galaxy objects that generate neutrinos, are now being built at the South Pole and the Mediterranean Sea.