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10^{12} DEGREES IN THE SHADE

The primeval fire that once filled the universe has cooled, leaving matter "frozen" in an arbitrary state. Now particle accelerators can recross that high-temperature frontier by "thawing" heavy atomic nuclei.

BY FRANK WILCZEK

STRANGE THINGS HAPPEN AT HIGH TEMPERAtures. You need not look far for examples. When a pot of cold water is heated on a stove, the temperature rises steadily until the boiling point is reached. Then, counterintuitively, the temperature gets stuck. To unstick the temperature and raise it beyond the boiling point requires strenuous effort, in the form of a large amount of heat that must be supplied to the pot. Or consider one of the little bar magnets you might find in a toy store. Such a magnet is called permanent because under ordinary conditions it keeps its magnetism indefinitely. But at high temperatures something surprising takes place. Extensive studies by the "other" Curie—Pierre, Marie's husband—showed that magnetic materials that are heated past a certain critical temperature, the so-called Curie temperature, lose their magnetism.

The unusual behaviors of the pot of water and the bar magnet are rooted in the same underlying principle: during a transition between a low temperature and a high one matter can undergo a basic reorganization. The temperature of the water gets stuck because, on the microscopic scale, to change liquid water into steam you must supply energy to rip apart clusters of water molecules. The energy needed to rearrange the molecules does not go into producing faster motion, and so it does not raise the temperature of the water. The temperature thus remains constant until the boiling is complete. A bar magnet, on a submicroscopic scale, is really a collection of iron atoms, each acting as a little elementary magnet. At low enough temperatures the magnets all are aligned with one another. Above the Curie temperature, however, the thermal energy available to the atomic magnets is enough to enable them to rotate freely, ignoring the efforts of their neighbors to bring them in line.

That basic principle of the reorganization of matter is richly intertwined with the history of physics, and it continues to enthrall physicists today. Indeed, it may even apply on the grandest scale imaginable: the universe itself. One of the most exciting frontiers of current research arises out of the possibility that the universe may have undergone a kind of reorganization shortly after the big bang exploded the universe into being. To test the theory, physicists at the Brookhaven National Laboratory in New York and at CERN, the European center for particle that will seek to mimic the high temperatures and extreme conditions of the universe in the first fraction of a second following the big bang. The temperatures in those experiments will reach a few times 10^{12} degrees Kelvin—a few thousand billion degrees Kelvin (10^{12} is a one followed by twelve zeros). To put such a temperature in perspective, the temperature at the surface of the sun is a few thousand degrees Kelvin, a billion times less.

According to modern cosmological ideas, the first few moments after the big bang were crucial for determining the structure of the present universe. To date, however, there have been few chances to test theoretical ideas about the properties of matter during that gestational period. Thus the new experiments afford physicists and cosmologists the prospect of checking their own understanding and, perhaps, of finding some surprises. In fact, surprises have already emerged from theoretical investigations. One is the strong possibility that new stable forms of matter (so-called strange matter) will arise; another is that the extreme conditions will give rise even to new forms of vacuum—a physical state that is commonly, but inaccurately, thought of as empty space. As compelling as those prospects are, however, the real attraction of the high-temperature frontier may be the simple challenge of exploring it "because it's there." Perhaps you will agree there is a certain intrinsic grandeur to the question of what takes place as things get hotter and hotter.

BEFORE PLUNGING INTO WILD AND POORLY charted territory, it seems prudent to consult the experience of previous explorers. Twice before in this century the opening of new frontiers of high temperature has profoundly affected both physics and cosmology.

The first great divide affecting the basic properties of matter as the temperature rises occurs at about 10,000 degrees Kelvin. Below that, roughly speaking, is the usual domain of chemistry; above it is the realm of plasma physics. Below 10,000 degrees most atoms and many kinds of molecule retain their basic integrity. The thermal energies available to particles at those temperatures are not enough to tear electrons away from neutral atoms or to break strong chemical bonds.

But although the change is not abrupt, as temperatures approach and exceed 10,000 degrees, the typical energies available to electrons are enough to overcome the forces that normally bind them into orbits around positively charged atomic nuclei. Once the thermal velocity of electrons exceeds their "escape velocity" from atoms, the electrons break loose from their orbits and roam free. The presence of freely moving electrons is the defining characteristic of a plasma.

Plasmas at roughly 10,000 degrees are actually a familiar sight: both the interior of a fluorescent light and the surface of the sun are good examples. And it is no accident that both of those plasmas are excellent emitters of light. The Scottish physicist James Clerk Maxwell and other nineteenth-century physicists showed that light is a disturbance in the electromagnetic field. Disturbances in the field are generally caused by the motion of charged particles. When charged particles of opposite sign are tightly bound into atoms that are electrically neutral overall, their effects tend to cancel one another. Hence the coupling of ordinary atoms to the electromagnetic field is relatively weak. But when, on the contrary, the temperatures are so high that atoms are torn apart into charged nuclei and free electrons, their ability to radiate light is much enhanced. Thus plasma glows.

Max Planck, Albert Einstein and other physicists early in this century made it clear that light can be regarded as being made up of particles, now known as photons. From that perspective, to say that hot plasma glows is to say that the plasma contains, besides freely moving electrons and atomic nuclei stripped bare, a large number of photons. Thus supplying heat to a gas of atoms not only causes them to break apart into more elementary pieces; it also induces them to create something new: a gas of photons. The photon gas is every bit as real and tangible as an ordinary "material" gas. Indeed, as the temperature is further raised, the importance of the photon gas, by almost any measure, increases relative to the material gas that created it. The number of atomic nuclei and electrons is fixed, but the number of photons increases as the cube of the temperature.

Large atomic nuclei, *smashed together in accelerators, will create intensely hot nuclear matter for* 10^{-22} *second.*

What especially intrigued Planck about the photon gas (which, of course, is not what he called it) was its profoundly universal character. The properties of the gas, which Planck and his contemporaries called blackbody radiation, are almost independent of the matter used to create it. Just as light is created in the collisions of charged particles, so it can also be absorbed. Eventually a dynamic equilibrium is established, characterized by a certain distribution of intensities of light of different colors, or, equivalently, densities of photons with different energies.

When he began his quest, Planck could show that the blackbody distribution was independent of such details as the density of atoms. (More atoms would mean more emission, but also more absorption, leading to the same net result.) He realized that one could even abstract the matter away altogether—or employ, as the old books quaintly put it, "a tiny speck of dust" as a catalyst—to arrive at the idea of a pure radiation gas. In its properties Planck, who was a deeply religious man, explicitly sought an absolute, an entity perfectly reflecting the fundamental laws of nature, uncontaminated by the accidents of matter. But his many attempts to determine the distribution theoretically, based on the physics known in his day, failed.

The importance of the blackbody distribution of energy was not lost on experimenters, and Planck's colleagues, the German physicists Ferdinand Kurlbaum and Heinrich Rubens, obtained exquisitely accurate experimental data on its energy spectrum. With the new data in hand, Planck sought to fit them to various mathematical formulas; in 1901 he stumbled upon what is now known to be the correct formula describing the blackbody radiation. Working backward, he supplied a suggestive though unsound derivation of his empirical formula, in the course of which he introduced a new physical constant, h—now known as Planck's constant. That work triggered a cascade of revolutionary developments in physics, including Einstein's invention of the photon, and culminated in modern quantum mechanics, the theory of atomic physics, in which h plays a central role.

Planck could hardly have imagined that his quest would lead not only to a new mechanics but also to a new cosmology, yet that is precisely what happened. In the 1930s the American astronomer Edwin Powell Hubble discovered that distant galaxies are receding from the earth with velocities proportional to their distance. If you make a straightforward extrapolation of that motion backward in time, you find that the greater distance of the farthest galaxies is exactly compensated for by their greater velocities; hence, all of them appear to originate in the same place at the same time. On the basis of that extrapolation, the Belgian astrophysicist and Jesuit seminarian Georges-Henri Lemaître and others began to speculate that the universe originated in a much hotter, denser state—and that the expansion evident in the present Hubble motions is just what it looks like, the aftermath of an initial universal explosion. Lemaître called his model universe the primeval atom, but the term coined somewhat later by the English astrophysicist Fred Hoyle to mock that kind of theory has become standard: the big bang.

As Hoyle's term of derision implies, most physicists in the 1940s and 1950s regarded such ideas as speculations at or perhaps even beyond the border between science and mythology. Then, in 1964, Arno A. Penzias and Robert W. Wilson, working at the Bell Telephone Laboratories, somewhat accidentally observed a startling relic of those early times. In a large microwave receiver, they detected unexpected noise that seemed to come from all directions in space. A remarkable interpretation of the noise was immediately supplied by Robert H. Dicke and Philip James Edwin Peebles, both of Princeton University, who, along with their Princeton colleagues Peter G. Roll and David

T. Wilkinson, had been planning a search for it. Dicke and Peebles proposed that Penzias and Wilson had discovered Planck's absolute—a perfect blackbody radiation that fills the universe.

IN THE LIGHT OF THE PREVIOUS DISCUSSION ONE can appreciate the logic of the interpretation. If the material content of the universe was much hotter and denser early on, it must have existed in a plasma state at high temperatures, with an associated photon gas. As the material expanded and cooled to below 10,000 degrees Kelvin, the electrons and the nuclei must have combined into neutral atoms, which interact feebly compared with the free charged particles. The effect was that the universe rather suddenly became transparent. The photons did not suddenly disappear, however. The photon gas, though it too became cooler as the universe expanded, remained in existence. And it can be observed with suitable instruments, such as Penzias and Wilson's original microwave antenna. The existence of the blackbody radiation is one of the major supporting pillars of big bang cosmology.

Physicists learned an important lesson from that episode: to understand crucial events in the early history of the universe, they would do well to explore the high-temperature frontier.

Indeed, they soon realized that the passage of the universe through an earlier frontier, at still higher temperatures, had left a permanent imprint on its basic structure. That transition, the next big qualitative change in matter, occurs at about 10^{10} degrees Kelvin. It might be described as the boundary between nuclear chemistry and nuclear plasma physics. For just as atoms dissociate into their constituent electrons and nuclei at 10,000 degrees Kelvin, nuclei in turn dissociate into their constituent protons and neutrons at temperatures roughly a million times hotter. At temperatures higher than that the universe harbored none of the familiar nuclei observed today (other than lone protons, which are the nuclei of hydrogen). Those nuclei had to form later, as the hot stuff expanded and cooled.

Because physicists had gone to great lengths to understand the basic processes that occur at the relevant high energies, it was straightforward, at least in principle, to calculate how much of each kind of nucleus gets produced as the universe cools to below 10^{10} degrees Kelvin and the protons and neutrons begin to stick together. The nuclear abundances, calculated under the assumption that the material content of the universe at one time reached temperatures above 10^{10} degrees Kelvin, agree well with what is observed. The success of that calculation is the second pillar of big bang cosmology.

THOSE PAST SUCCESSES GIVE ADDED IMPETUS to the push to study ever higher temperatures. Can one make sensible predictions about what might take place at higher temperatures? Are there additional frontiers, beyond which qualitatively new things take place?

In fact, one can form reasonable expectations about what might take place at what I call the third frontier, at temperatures far beyond any that have been observed directly. Those theoretical expectations build on the results of much previous work devoted to pushing back the high-energy frontier. In particle accelerators at such laboratories as Brookhaven and CERN, the traditional goal has been to study the results of energetic collisions between simple projectiles—protons colliding with protons, for instance. To study conditions at high temperatures, however, one really must study how collections of particles behave, because the concept of temperature applies only to ensembles and not to individual particles. The complexity of that study dictates that the elementary processes up to a given energy scale be understood first; once that is done, the behavior of ensembles of large numbers of particles with that energy, interacting with one another repeatedly, can be explored.

The two laboratories will pursue the same basic strategy to push back the high-temperature frontier. Two beams made up of large atomic nuclei, each containing roughly 200 protons and neutrons, will be accelerated to velocities close to that of light in opposite directions around a ring. The paths of the particles will be controlled by cunningly designed magnetic fields, and at a few spots the beams will be focused and allowed to cross. When they cross, a few of the nuclei will collide head-on. Each collision will create a minute fireball, and inside the fireballs nuclear matter will be heated, for an unimaginably fleeting instant lasting about 10^{-22} second, to temperatures of a few times 10^{12} degrees Kelvin.

THE NEW WORK WILL BUILD on the old. One of the great triumphs of physics in the past fifty years has been the discovery and verification of theories that supply a detailed and rather complete picture of interactions up to energies corresponding to temperatures of 10^{15} degrees Kelvin. The most significant interactions in fireballs at 10^{12} degrees Kelvin are described by a theory known as quantum chromodynamics, or QCD. Physicists' understanding of QCD leads them to suspect that the coming high-temperature frontier will mark the passage from ordinary nuclear physics, with recognizable protons and neutrons, to something quite different—a state of matter in which the weird inner workings of QCD will be exposed.

QCD had its beginnings in the 1930s with the study of the interactions that hold protons and neutrons together in atomic nuclei and that govern the transformations of nuclei that take place inside stars and in nuclear reactors. Those forces are the most powerful ones known in nature, and that explains their name: the strong forces.

As often happens in science, deeper investigation has altered the framework of discussion. Experiments done since 1950 have shown that protons and neutrons are not elementary at all but are made up of simpler and more basic entities known as quarks and gluons. It appears from experiment that the forces among quarks and gluons, in contrast to the forces among protons and neutrons, are governed by simple, mathematically beautiful laws. QCD is precisely that body of laws.

There are several flavors, or species, of quark, which differ in mass and charge. The lightest quarks are the "up" quark, u, the "down" quark, d, and the "strange" quark, s; there are three heavier kinds as well. Only the u and d

quarks are important constituents of ordinary matter. Each quark also has an antiquark: a quark that has the same mass but opposite electrical properties.

Each species of quark and antiquark in turn comes in three varieties. Patriotic American physicists have labeled them red, white and blue, but they have nothing whatever to do with ordinary color. What the three varieties really resemble, physically and mathematically, are three kinds of charge, analogous to electric charge. To highlight that fact, I have chosen the British spelling *colours* for the three kinds of quark (and antiquark). And just as photons respond to ordinary electric charges, the colour gluons of QCD respond to colour charges.

When analyzed at the level of quarks and gluons, the strong force is fundamentally simple—only a little more complicated than the corresponding electromagnetic force. Ultimately those simple forces affecting quarks and gluons hold atomic nuclei together and give rise to all the other manifestations of the strong force.

A key theoretical property of QCD is known as asymptotic freedom: the interactions between quarks and gluons become weaker in a precisely calculable way at high energies or temperatures. Conversely, at low temperatures or energies, that is, under ordinary terrestrial conditions, the strong interaction is so strong that objects carrying unbalanced colour charges cannot exist in isolation. The energy associated with the unbalanced colour field is always sufficient to produce a neutralizing particle of the opposite charge. In particular, at low temperatures neither quarks nor gluons can exist in isolation. This peculiarity of QCD—that the basic entities of the theory cannot be isolated—is called confinement. It is, as you might imagine, one main reason the theory took so long to find.

WITH THOSE BASIC IDEAS IN MIND, I CAN return to the discussion of the transformations of matter at high temperature. At 10^{10} degrees Kelvin the atomic nuclei have dissociated into individual protons and neutrons. But according to QCD, each proton is made of two *u* quarks and one *d* quark, one of each of the three colours; similarly, each neutron is made of one *u* quark and two *d* quarks. As the temperature approaches 10^{12} degrees Kelvin, the third frontier of high-temperature physics, another group of particles made up of quarks is produced in great numbers, just as photons are produced in great numbers in a plasma: the pi mesons, or pions.

The proliferation of pions is, however, merely the prelude to a change yet more profound. Asymptotic freedom predicts that the interaction among quarks and gluons gets weaker at high energy, and the detailed theory enables physicists to make a fairly precise estimate of the temperature at which thermal motion is sufficient to rip quarks and antiquarks apart. At the same time it becomes possible for single gluons to propagate freely, and they too are produced in great abundance. Thus, at temperatures above approximately 10^{12} degrees Kelvin, matter should take the form of a radically new kind of plasma, a quark–gluon plasma. In such a state of matter the basic entities of QCD, hitherto confined, roam free.

A plasma of free quarks, antiquarks and gluons differs in many ways from the gas of protons, neutrons and (mainly) pions from which it arises. One of the simplest and most basic differences is sheer density. When it is appropriate to describe things in terms of pions, there are basically only three kinds of particle to worry about, namely, the positively charged, the negatively charged and the electrically neutral pions. When the temperature rises just a little and it becomes appropriate to describe things in terms of free quarks and gluons, there are *u* and *d* quarks and their antiquarks, each of which comes in three colours, plus gluons that come in eight colours. And so suddenly there is a large proliferation of particles.

In equilibrium the distribution of energies for each kind of particle is roughly the same as the blackbody distribution Planck discovered for photons. But since those energies must now be distributed over so many more particles, it will suddenly cost a lot of energy to produce the small change in temperature over which the transition from the pion gas to the quark–gluon plasma takes place. In fact, the energy density must increase by more than tenfold. The situation in QCD is conceptually similar to what takes place when the pot of cold water is heated on the stove, but it takes place at a much higher temperature and energy scale. Pions, instead of clusters of water molecules, get ripped apart.

A second new effect in the quark–gluon plasma is that in the plasma it becomes much easier to create *s* (strange) quarks, together with their antiquarks. The mass of a free strange quark or its antiquark is about the same as that of a pion. Because of Einstein's equivalence between mass and energy, and because the energy density of the quark–gluon plasma is equivalent to the mass of a pion, strange quarks can simply materialize out of the energy background.

FINALLY, THERE IS A MORE SUBTLE DIFFERENCE between the low- and high-temperature regimes of QCD—probably the most profound and interesting difference of all. The concept is a bit much to swallow in one gulp, so I will introduce it by way of analogy.

Think once more about the little bar magnet from the toy store. From a microscopic perspective, magnetism arises because the total energy of all the atomic magnets is lower when the magnets are aligned in the same direction (whatever that may be) than it is when they point in different directions (whatever they may be). Because any material tends to assume its lowest-energy state, all the atomic magnets tend to point in the same direction; energetically, it does not matter what that common direction is. Small external influences, or random events that take place when the magnet is formed, determine the direction in which its magnetic field points.

The random nature of the direction of the magnetic field is easily seen when a magnet is heated past its Curie temperature and then cooled down again. Notice that when the magnet is heated and the individual atomic magnets point in many directions, the lump of metal is perfectly symmetrical in the sense that no direction is preferred. But when the magnet is cooled it generally settles down with its poles pointing in a direction different from the one they started with. Thus the original symmetry of the situation is broken by the emergence of a preferred direction; in physics one says that spontaneous symmetry breaking has taken place. Perhaps nothing could demonstrate more plainly the somewhat accidental character of the most obvious feature of a magnet: the direction of its magnetic field.

In QCD there is also a form of spontaneous symmetry breaking that is both conceptually and mathematically similar to the case of the magnet. I have already mentioned that the *u* and *d* quarks are the lightest quarks. For a moment let me adopt the convenient fiction that their masses are exactly zero. At zero mass, if the quarks and antiquarks did not interact with one another, it would cost no energy to fill space with them. The real situation is more dramatic: there is an attractive interaction among the quarks and antiquarks, and so one can achieve lower energy in a volume of space by filling it with quarks and antiquarks than one can by leaving it “empty.”

Thus according to QCD, what people ordinarily think of as a vacuum—the state of lowest energy, or what remains when you take away everything that is takable—is actually a highly populated, complicated state. The “no-particle” state, devoid of the condensate of quarks and antiquarks, has a much higher energy than the true vacuum. If the no-particle state were produced it would immediately decay into a true vacuum containing a nonzero density of quarks and antiquarks, and large amounts of energy would be released in the process. That is not to say that the true vacuum has an indefinitely large number of quark–antiquark pairs: in fact, if too many pairs are crammed close together, they start to repel one another. Thus there is a definite best choice of the density of pairs that gives the lowest overall energy; that is the density of the vacuum.

There are four possible ways to pair off a quark and an antiquark: *u,* anti-*u*; *u,* anti-*d*; *d,* anti-*u*; and *d,* anti-*d.* The vacuum must be filled with a certain overall density of such pairs, but how much of each? The answer is, It does not matter. There is a perfect symmetry between the different kinds of quark and antiquark, in that the energy of the vacuum with one mix of relative densities is the same as the energy of any other vacuum. But here is the rub: to get the lowest possible energy you must choose some definite fixed ratio of densities, the same throughout all space.

NOW YOU CAN BEGIN TO APPRECIATE THE sense in which the vacuum, according to quantum chromodynamics, is much like a magnet. Just as the magnet must “choose” one direction, spontaneously breaking the intrinsic symmetry of the atomic magnets, the pairs of quarks and antiquarks must “choose” some definite mix, a process that breaks the intrinsic symmetry among all the possible mixes of pairings. The process whereby the QCD vacuum acquires less symmetry than the intrinsic symmetry of the physical laws is called spontaneous chiral symmetry breaking.

One big difference between the QCD vacuum and a magnet, of course, is that one can get outside the magnet and see that it is a complicated object that spontaneously breaks a symmetry of the world—the equivalence of all directions. If there were creatures that lived inside a magnet and thought of it as their world, however, they would not perceive that anything was unusual or wrong about their surroundings. They would be accustomed to the idea that not all directions are equivalent: it would be the most obvious thing in their world. For such creatures to realize that the true symmetry of physical laws might be larger than what they perceive would require an enormous act of imagination. Perhaps then they would be inspired to try to create a state of higher symmetry than that of their vacuum, by exploring their own high-temperature frontier—beyond the Curie temperature.

That, in essence, is the prospect that lies before physicists at Brookhaven and CERN. The temperatures in prospect are beyond the “Curie temperature” of the QCD vacuum. There will be more than enough thermal energy to tear apart the quark–antiquark pairs abundantly present in the ordinary vacuum. A more perfect vacuum, exhibiting more nearly the full symmetry of physical law, will be established.

> AT “LOW” TEMPERATURES—
> *below about 10^{12} degrees Kelvin—*
> *neither quarks nor gluons*
> *can exist in isolation.*

The theoretical ideas I have just discussed suggest that remarkable things will take place just beyond the third frontier of temperature. Quarks, antiquarks and gluons will occur in great abundance and move freely. A generous sample of the ordinarily rare *s* quarks and antiquarks will be produced. The quark–antiquark pair condensate that ordinarily fills the vacuum will vaporize, and the vacuum will regain its symmetry. But theoretical ideas, however beautiful and well motivated, become science only when one uses them in concrete ways to elucidate events in the natural world.

IS THERE ANY HOPE OF GAINING DIRECT EVIDENCE that these extraordinary concepts describe reality? It is a challenge, because the extreme conditions of temperature needed to test them are generated only fleetingly and in a small volume. Fortunately, it does seem likely that experimenters will be able to find, through intelligent and diligent searching, signs of the remarkable goings-on in the early moments of the fireball. Each of the three qualitatively new features of the quark–gluon plasma mentioned above suggests something quite concrete for experimenters to look for.

First, the great increase in the number of kinds of particle excited in the quark–gluon plasma should cause the temperature to stick and thus drastically affect the evolution of the fireball. That evolution, however, is quite complicated and hard to model precisely; only if the effect is large and qualitative is it likely to be discernible at all. Fortunately the evolution of the temperature can be traced from the energy of particles at the surface of the fireball as it cools. The higher the temperature of the fireball, the higher the energy of its emanations. If the temperature of the fireball sticks at a certain value, the emitted particles will bear the stamp of that temperature.

Second, the superheated plasma will give rise to many more *s* quarks and antiquarks than are produced at even slightly lower temperatures. The *s* quarks and antiquarks will eventually decay, but the processes responsible for their decay are relatively slow, and many of them will escape the fireball. They will escape inside particles such as K mesons and lambda particles, which experimenters are eminently equipped to observe.

An intriguing possibility, analyzed recently by Robert L. Jaffe of the Massachusetts Institute of Technology, is that new, long-lived quasi-atomic nuclei may exist, which contain many *s* quarks in the place of the *u* and *d* quarks in ordinary atomic nuclei. Jaffe calls the objects strangelets. He estimates that strangelets containing roughly equal numbers of each species—*u*, *d* and *s* quarks—are particularly favorable energetically. The quark–gluon plasma produced by a collision between two heavy ions, with its rich population of *s* quarks, provides for the first time an environment in which samples of that new form of matter, if it exists, might be produced.

FINALLY, THE VAPORIZATION OF THE QUARK–ANTIquark condensate and the resultant loss of symmetry of the vacuum may have spectacular aftereffects. Recall that the poles of a magnet can change direction when the magnet is heated past its Curie temperature and then cooled. Similarly one might expect that the QCD vacuum, heated above the temperature at which its condensate of quark–antiquark pairs vaporizes, will generally recondense with a different mix of pairs.

At this point I must correct the convenient fiction I introduced earlier, namely, that the masses of the *u* and *d* quarks are zero. If those masses were actually zero, the analogy I made between the possible mixes of pairs in the QCD vacuum and the possible directions of the poles of a magnet would have been mathematically precise. But the effect of the real nonzero masses is also straightforward to visualize via the magnet analogy. It is as if there exists, in addition to the atomic magnets whose directions are arbitrary, a small additional magnetic field, external to the magnet itself. The additional external field defines a definite preferred direction, and to minimize its energy the bar magnet will eventually align with it. If the external field is weak, however, a heated lump of iron might cool and realign its poles at some angle to the external field, in the “wrong” direction. Such a magnet, suspended from a flexible string in a weak external field, could oscillate many times before settling down to point along the direction of the field.

The situation for the QCD vacuum may be closely analogous to the one for the magnet, according to recent work by Krishna Rajagopal of Harvard University and me. As the Russian physicist Aleksei A. Anselm of the Saint Petersburg Institute of Nuclear Research in Russia, among others, has pointed out, oscillations of the QCD vacuum as it seeks its true minimum value could lead to quite dramatic effects. Those oscillations, remember, are changes in the relative numbers of different kinds of quark–antiquark pairs in the condensate. As the wrong pairs in the misaligned condensate are converted into correct pairs, some pairs escape. They would be detected by experimenters as special, coherent collections of pions. The misaligned vacuum, in other words, creates a pion laser.

I HAVE NOW DESCRIBED IN SOME DETAIL THE HIGH-temperature frontier on the immediate horizon, the frontier between the nuclear plasma and the quark–gluon plasma. It is likely the exploration of that frontier will be an important part of physics in the twenty-first century. But there are two even more remote frontiers, the first of which perhaps will be ripe for exploration in the twenty-second century—and the second. . . . Who knows?

Those frontiers are associated with other episodes of spontaneous symmetry breaking, with the vaporization of other condensates. The fourth frontier, whose outlines can at least dimly be perceived, occurs at approximately 10^{15} degrees Kelvin. Above that temperature the force responsible for nuclear decay and for the energy of the sun, known as the weak interaction, is profoundly changed in character: the condensate responsible for making the weak interactions weak vaporizes. Under such conditions many processes that are rare or forbidden in the ordinary low-temperature vacuum become possible. Some recent theoretical work suggests that those processes, which would have unfolded in the moments immediately following the big bang, were responsible for generating the imbalance between matter and antimatter that characterizes the present universe. That is an imbalance without which human beings would not exist.

The fifth high-temperature frontier may occur around 10^{30} degrees Kelvin. Above that temperature theoretical calculations indicate that the condensate responsible for the differences among the strong, weak and electromagnetic interactions vaporizes. It is possible that events associated with the formation of that condensate in the moments immediately following the big bang induced a rapid inflation of the universe, as first proposed by the astrophysicist Alan H. Guth of MIT. If it were possible to reproduce such conditions—which would unfortunately require a technology that is not in immediate prospect—it might be possible to grow new universes.

Such ideas go well beyond other frontiers: the frontier of knowledge and perhaps even the frontier of reasonable scientific speculation. But big questions about the origin of the universe will not be solved by a refusal to consider them. The successes so far make physicists optimistic that further progress on those big questions is possible. ●

FRANK WILCZEK is a professor of physics at the Institute for Advanced Study in Princeton, New Jersey.