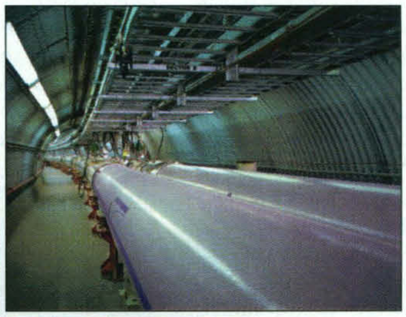
Starting this fall, a machine called RHIC will collide gold nuclei with such force that they will melt into their primordial building blocks

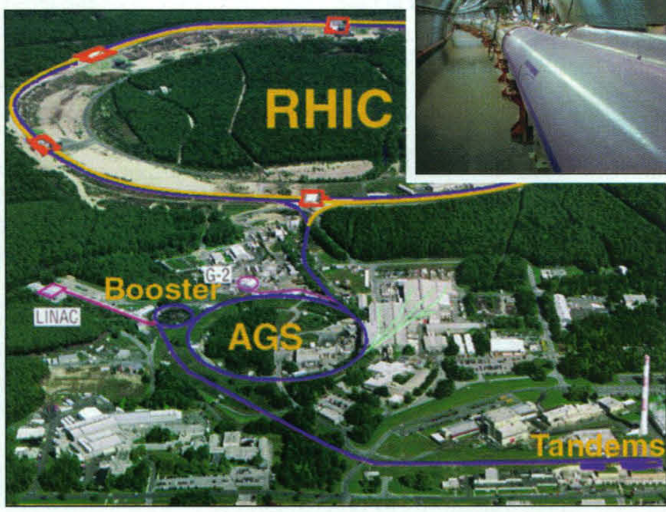
Making the Stuff of The Big Bang

BROOKHAVEN NATIONAL LABORATORY—If all goes well later this year, physicists here in the pine barrens of eastern Long Island will create miniature copies of the big bang by smashing together the bare nuclei of gold atoms traveling at nearly the speed of light. Reaching temperatures a billion times hotter than the surface of the sun, the protons and neutrons in the nuclei will melt into their bizarre building blocks: quarks and the gluons that hold them together. Out of this inferno will come an exotic form of matter called quark-gluon plasma, primordial stuff that may have been the genesis of all the normal matter we see around us. And most profoundly, the very vacuum, what we think of as empty space, will be ripped apart, revealing its underlying fabric.

Brookhaven's subatomic demolition derby will take place at RHIC, the Relativistic Heavy Ion Collider, a superconducting racetrack in a tunnel 3.8 kilometers around. A decade in the making, costing $600 million, RHIC is the first collider designed specifically to create and detect this primordial soup. This racetrack is itself in a race, however. CERN, the European particle physics laboratory near Geneva, hopes to collide heavy nuclei to create the same quark concoction sometime around 2005 in the Large Hadron Collider, a giant accelerator now under construction. Already, one of CERN's existing accelerators may have spotted hints of the quark-gluon plasma (QGP). The traces are fleeting, however, and physicists hunger for confirmation. At RHIC, says director Satoshi Ozaki, "we can reach a completely new range of temperature and density," where the signs of quark-gluon plasma should be unmistakable.

Just this past June, technicians at RHIC started flowing liquid helium through the accelerator's superconducting magnets for the "big cooldown" and testing the machine with beams of gold nuclei. By this fall, providing the inevitable gremlins have been shooed away, the search for quark plasma will begin in earnest. It won't be easy. Each collision will last for only 10^{-23} second and emit thousands of particles of nuclear debris, from which physicists will try to pick out the subtle signatures expected of QGP. But if captured, QGP would be a new and exciting plaything for physicists, holding clues to how quarks and gluons bind together in normal matter, and how the stuff around us first took shape.





Golden rings. RHIC will accelerate gold nuclei in stages (*labels*), culminating in the main ring, 3.8 kilometers around, where a pair of tubes holds the counterrotating beams.

Now you see them

RHIC physicist Bill Zajc likes to say that he and his colleagues are replaying the first moments of creation. "The first attempt to create this quark-gluon plasma was successful, about 10 billion years ago," he says. It lasted just 10 microseconds after the big bang; then, as the universe expanded and chilled, the quarks paired up to form particles called mesons and combined in threes to form the protons and neutrons of everyday stuff. They have rarely emerged since—and never for earthly physicists. Try as they might, physicists have never been able to coax a naked quark into the spotlight.

The theory developed to explain how quarks interact via the strong force, quantum chromodynamics (QCD), accounts for this behavior. Just as electromagnetic theory endows particles with electrical charge, QCD describes quarks as having a charge whimsically called "color," either red, green, or blue. And just as electrically charged particles attract or repel each other by exchanging photons, quarks interact by tossing gluons back and forth.

When quarks are close together in "hadrons" (mesons, protons, and neutrons), they almost totally ignore each other. But try to separate them by any distance, and the force carried by the gluons goes to infinity, much as a piece of string that is limp when its ends are close together goes taut when it is stretched. If stressed too far, the string snaps. Likewise, as quarks are pulled apart the energy between them rises until something snaps, and the energy is transformed into new quarks and antiquarks. A lone quark quickly couples with the new quarks to form regular matter again, so that single quarks can never be taken captive. But QCD also predicts that at the temperatures and densities that existed just after the big bang, quarks and gluons become "deconfined"—released from their imprisonment and free to move around in a kind of quarky broth.

So run the movie backward, say the researchers at RHIC. Slam together lumps of quark-rich matter, such as heavy nuclei, with enough energy to heat the nuclei way past where atoms are ionized, even beyond where the nuclei themselves break apart into protons and neutrons. Crank it up to a trillion kelvin, where quarks and gluons become free again.

Physicists studying heavy-ion collisions at CERN say they may already have achieved this feat. CERN's venerable Super Proton Synchrotron (SPS) has been circu-

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lating beams of lead nuclei and smashing them together within a detector called NA50, which is tailor-made to detect the so-called J/psi mesons that flee the scene of a collision between heavy nuclei. The behavior of these ghostly hit-and-run mesons is leading researchers at SPS to claim a sighting of QGP.

In nuclear collisions, the pure energy of the interaction can produce many pairs of quarks and antiquarks. Often, these matter-antimatter partners just annihilate each other, but occasionally they get locked in a sort of particle tango. They can dance away from the collision, separating and then rejoining their original partners to form a new particle—a meson—that survives just a moment. J/psi particles are exactly this kind of particle pas de deux executed by charm quarks, one of the six quark flavors, and their matching antiparticles.

When a QGP forms, theorists predict that the immense energies in the collision volume should create quark-antiquark pairs of all possible flavors—up, down, charm, strange, top, and bottom—in large numbers, a process called "nuclear democracy." Now conditions resemble those in a crowded ballroom. With a huge number of pairs dancing close together, the separating dancers are likely to bump into someone who is not their original partner and whirl away as a new pair. Similarly, any charm quarks produced in the collision have many more partners to choose from; they don't have to run away with an anticharm partner, which causes the number of J/psi mesons to drop. "I am convinced that J/psi suppression is the gold-plated signature for QGP detection," says NA50 spokesperson Louis Kluberg.

He and his colleagues presented their latest results at the Quark Matter conference this past May in Torino, Italy. The data show that J/psi particle production in the energetic lead-lead collisions drops far below the level seen in collisions of lighter nuclei like oxygen, sulfur, and hydrogen. CERN's collegial competitors at Brookhaven are intrigued by the findings but aren't completely sold. "It is tantalizingly close to a real effect," says RHIC associate project director Tom Ludlam, "but you cannot really make the statement yet" that CERN researchers have produced QGP.

Even if they have created QGP, this fleeting glimpse provides little information about this exotic state of matter. Among other things, physicists would like to know what kind of phase transition separates ordinary matter from QGP. The appearance of the plasma could either be a first-order transition—a sharp change like water turning into steam—or a continuous second-order transition with no sharp change in properties. The answer has deep implications for theories about what happened to the big bang as it cooled and for understanding QCD. As theorist Frank Wilczek of the Institute for Advanced Study in Princeton, New Jersey, puts it, "We know QCD is correct, and it gets boring to prove that. … We can play the notes, and now we want to play some chords."

One chord might be heard during "freeze-out" of the QGP, when the excess strange quarks populating the short-lived nuclear democracy might coalesce into "stranglets," tiny clumps of matter made up only of strange quarks. Another might come when the droplet of free quarks and gluons created in each collision interacts with the surrounding vacuum, which QCD pictures not as empty space but as a sea of "virtual" quark pairs that wink into and out of existence. Doing all that will take a machine capable of creating generous quantities of QGP, equipped with instruments that can go well beyond detecting J/psi suppression to pick up a dozen other subtler signals of the quark plasma's life and death. That's where RHIC comes in.

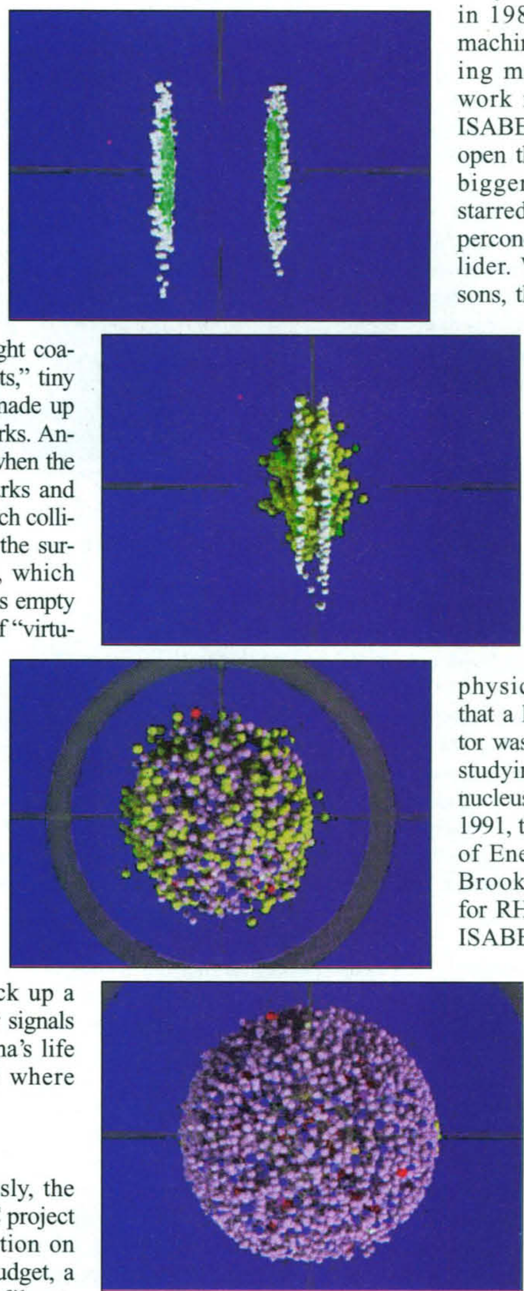
Ring of ice

Almost miraculously, the $600 million RHIC project is nearing completion on schedule and on budget, a feat the rank and file attribute to director Ozaki's deft management. Not only has he juggled the construction of a massive piece of scientific instrumentation, but he's had to run a kind of United Nations of physicists. The list of collaborators fills an entire viewgraph with fine print: more than 800 scientists from 19 countries, including India and Croatia.

For Brookhaven it is sweet compensation for perhaps the most painful episode in the lab's history, the cancellation of ISABELLE, a huge proton collider intended as the successor to the Tevatron accelerator at the Fermi National Accelerator Laboratory in Illinois. ISABELLE's builders broke ground in 1979, only to see it killed in 1983. Some say the machine's superconducting magnets never did work right, others that ISABELLE got the ax to open the way for an even bigger but equally ill-starred machine: the Superconducting Super Collider. Whatever the reasons, the cancellation left ISABELLE's massive concrete tunnel empty except for the occasional jogger or Rollerblading physicist on lunch break.

Coincidentally, at about this time a separate tribe of scientists—the nuclear physicists—concluded that a heavy-ion accelerator was a high priority for studying how the atomic nucleus is put together. In 1991, the U.S. Department of Energy (DOE) chose Brookhaven as the site for RHIC, and the empty ISABELLE tunnels, just north of the main campus, offered a natural home.

The Alternating Gradient Synchrotron, a small, existing heavy-ion accelerator, will be put to work as a booster stage, generating ion beams for injection into RHIC's two counterpropagating rings, nestled close together in the tunnel. The beams will contain needlelike bunches of gold nuclei, each about 100 micrometers in diameter and less than a meter long. At six points around the ring, strong magnets will steer the beams so that they cross and collide, yielding something like 1000 gold-on-gold collisions every second at energies of some



Little big bang. This computer simulation charts the collision of two gold nuclei, which appear flattened (*top frame*) because they are moving at nearly the speed of light.

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RHIC Physicists Go to Media School

Last month, the tiny big bangs Brookhaven National Laboratory (BNL) researchers hope to ignite this fall in the Relativistic Heavy Ion Collider (RHIC) caused a flutter outside the laboratory. The *Sunday Times* of London ran a story with the headline "Big Bang machine could destroy Earth," based on speculations that the atom-scale collisions within the accelerator could create clumps of "strange" matter that might catastrophically transform normal matter into something, well, strange—or make black holes that would suck up the planet. Already unsettled by reports of chemical and radioactive leaks from Brookhaven facilities, Long Island residents feared the worst—and Brookhaven caught another glimpse of public-relations Armageddon.

E-mails from alarmed residents began flying around when the *Times* story appeared, according to lawyer Scott Cullen of Standing for Truth About Radiation (STAR), a local organization that has been a steady critic of Brookhaven's environmental record. Most physicists discount the disaster scenarios. As lab spokesperson Mona Rowe puts it, the energy of the collisions is like that of a "mosquito hitting a screen door." But these days Brookhaven officials, stung by past public-relations debacles, realize they can't simply brush off public fears. "Whenever any scientist suggests a disaster scenario, we are obligated to take it seriously enough to decide if there is an issue," says lab director John Marburger.

In the past, BNL has provided plenty of ammunition to its critics, who include celebrity environmental activists summering nearby at the Hamptons. The lab was declared an Environmental Protection Agency Superfund site in 1989 owing to a history of contamination going back to its early days as an Army camp. Tritium leaks from the High Flux Beam Reactor, a flagship source of neutrons for research, were a public-relations disaster, and the reactor has been padlocked since January 1997. Brookhaven's Graphite Reactor, built 30 years ago and decomissioned in 1969, has turned out to be a Pandora's box of leaking radioactivity and bad publicity. In May 1997, Associated Universities, the contractor that ran the lab for the Department of Energy, was fired; it was replaced in November 1997 with Brookhaven Science Associates. Stringent new regulations have been put into place at BNL, and researchers now attend mandatory seminars in environmental health and safety.


Big Bang machine could destroy Earth

by Jonathan Leake Science Editor

Firing line. Brookhaven officials were quick to respond to this story in the 18 July London *Sunday Times.*

Brookhaven staffers are now reaching out to the public, speaking at local schools and community events. The lab promptly countered the London *Sunday Times* story with a statement posted on the Web (*Science*, 23 July, p. 505), and Rowe says that several RHIC physicists have taken public speaking courses to prepare them for dealing with the public and the media. RHIC director Satoshi Ozaki says even seemingly small things can make a big difference in mending fences with the facility's neighbors. "One of the people living nearby complained about the noise from one of our compressors," he says, "and I insisted that it be fixed by the end of the day. At the next town meeting, that same person said how delighted she was that the problem had been fixed," notes Ozaki. "So we had gained a friend."

The legacy of mistrust will be hard to overcome, however. A survey the laboratory conducted late last year showed that a full 60% of the 766 residents polled still felt that Brookhaven was not doing enough to keep the community informed about its activities. And organizations like STAR are still convinced that the lab poses serious dangers and that the environmental impact review for RHIC has been inadequate. The outreach effort "has been mostly a PR shift," says Cullen. "A lot of times they're willing to sit down and talk, but whether they are willing to actually do anything is another matter."

–D.V.

200 billion electron volts per proton or neutron. Temperatures will reach a trillion degrees. Under those conditions, say theorists, the colliding nuclei should explode into an almost pure quark-gluon plasma.

They will do so in full view of four detectors, designed to collect as many different kinds of information as possible about the collisions to prove that QGP exists. "It's a funny business," says RHIC researcher Tim Hallman. "Usually in particle physics, people are looking for one decay, and they've designed a whole experiment around it. In our case there are lots of different signatures but no one thing that sticks out that is unambiguous. So we're in the business of measuring many different signals and correlating them to give an airtight case."

Two of the detectors, STAR and PHENIX, are the kind of grand-scale hardware normally associated with a place like CERN or Fermilab. Each costing $100 million, they are massive steel skeletons supporting a fine filigree of sensors, wiring, and high-speed optical fiber. To illustrate the capabilities of STAR (the Solenoidal Tracker at RHIC), Hallman, the detector's spokesperson, holds up a simulated collision that looks like a fireworks display on steroids. "STAR is a tour de force in keeping track of particle trajectories," he says.

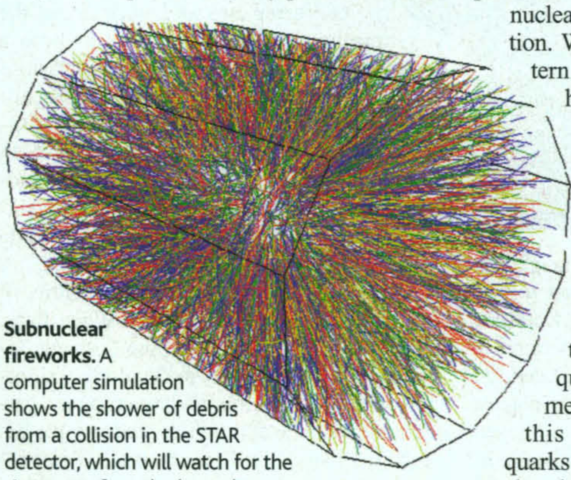
As particles zing through STAR's central chamber, basically a giant can of gas with high-voltage electrodes spidering through it, they will leave trails of ionized molecules. Big, charged collecting plates at each end of the STAR chamber will suck up the ionized gas, carefully recording how much ionization is collected over time. By projecting this record back into space coordinates, a computer can reconstruct the path of the particles in the three-dimensional volume of the detector—thousands from every collision.

The filigree of tracks should include telltale signs of QGP. One is a shower of unusual particles spawned in the rich quark soup. Strange critters like K mesons (kaons), lambdas, and omegas will shoot out, for example. And just as molecules in a gas scatter off their neighbors, energetic quarks zipping through the plasma would slow down as they bang into other quarks and gluons. STAR should be able to detect this attenuation with its spectrometers and so learn something about the stuff the quarks are traversing.

PHENIX, so named "because it has risen from the ashes of three separate detector proposals," says Zajc, the experiment's spokesperson, will track fewer particles than STAR—hundreds rather than thousands—with higher precision. It will concentrate on the lighter and more evanescent escapees—photons and leptons (electrons and muons). Because the photons and leptons are unaffected by the strong force, they can escape the dense quark matter and report back about conditions right in the thick of the collision, such as the temperature of the quark soup. Tipping the scales at about 4000 tons, "PHENIX is about the mass of a good-sized naval destroyer," says Zajc—in part because of the 100-ton, 20-centimeter-thick steel plates that flank the collision point. The plates, which act as filters for the detectors that identify muons, are so big that few steel mills in the world could have fabricated them. Part of Russia's in-kind contribution to RHIC, they were made at a plant in St. Petersburg and sold to DOE at half price.

RHIC also sports two smaller experiments, BRAHMS and PHOBOS, each built for a tenth the cost of STAR or PHENIX. BRAHMS (for Broad Range Hadron Magnetic Spectrometers) will measure the energy of charged hadrons flying away from the collision, another clue to the temperature and density at the very point where the nuclei are fragmenting and blowing apart. And PHOBOS is specifically designed to watch for the appearance of the plasma as the collision energy is ratcheted up. "We are looking for a phase transition to quark-gluon plasma," explains Massachusetts Institute of Technology (MIT) physicist Wit Busza, the project spokesperson.

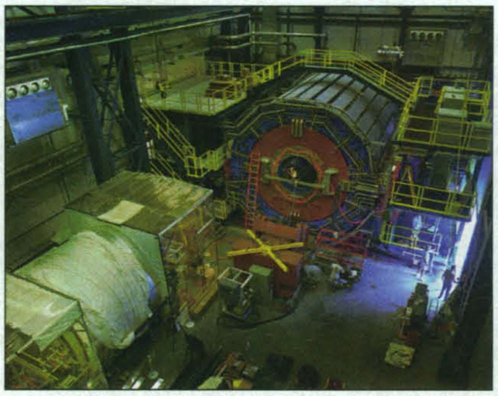
Because material passing through a phase transition exhibits huge fluctuations in density, like water at a rolling boil, PHOBOS is designed to look for unusual variations in the total number of particles created in the collision. An array of relatively inexpensive silicon detectors surrounding the collision point, lithographically engineered with pixels to register particle hits, will allow it to do a gross head count of debris particles. A second component of the detector, a set of low-cost silicon spectrometers, will keep watch for any peculiar fluctuations in particle momentum as the gold nuclei get cooked into quark soup.



Subnuclear fireworks. A computer simulation shows the shower of debris from a collision in the STAR detector, which will watch for the signature of quark-gluon plasma.

CREDIT: BROOKHAVEN NATIONAL LAB

These instruments will generate a torrent of data—about a petabyte (10^{15} bytes) every year, according to Barbara Jacak, a physicist who coordinates computing for PHENIX. "Think about the multigigabyte hard drive on your PC," she says. "The raw data rate from RHIC would fill that in a few minutes." To handle the particle track reconstruction and detector signal processing, RHIC will host a $7 million computing facility outfitted with a high-performance tape library and a computer farm of 1000 Linux workstations. Theorists, who are trying to wrest predictions of how the quark plasma should behave from the complex equations of QCD, are getting some major computing muscle too: a 600 gigaflops supercomputer, one of the most powerful outside military and corporate labs, that is the product of a collaboration between Brookhaven and the RIKEN research center in Japan.



STAR's eye. The detector will track thousands of debris particles from each nuclear collision.

Set your pion lasers on stun

"RHIC was built with the specific purpose of looking for the quark-gluon phase transition," says Ozaki, "but once you build a machine of this size, you want to do other things too." One is searching for the basis of proton "spin," a quantum mechanical property that causes particles to act like tiny magnets. Ozaki convinced physicists at RIKEN to kick in about $20 million to outfit RHIC for experiments in which the gold beams will be replaced with protons. The protons will be polarized, so that each little nuclear magnet is lined up in one direction. When the protons collide, the pattern of debris should hold clues about how much of the proton's spin comes from quarks and how much from gluons.

Many earlier experiments have studied nuclear spin, but RHIC will be a pioneer in probing another mystery: the vacuum and the sea of short-lived up and down quarks and antiquarks thought to fill it. Because pairs of quarks and antiquarks make up pi mesons, or pions, physicists refer to this sea as a pion condensate. But quarks can pair up in various ways, and theorists believe that in the vacuum as it exists today, they are paired up in only one of many equally likely arrangements.

In the early stages of the big bang, however, the up, down, antiup, and antidown quarks in the vacuum flitted about, refusing to adopt any fixed pairing. Then, as the universe cooled, the condensing quarks had to pick a particular arrangement, or orientation, and stick with it. Magnets offer a good analogy, says Wilczek: "When you raise the temperature of a magnet above a temperature called the Curie point, all the spins become randomized and the magnetism disappears." And when the material cools back down below the Curie temperature, the spins all line up in some direction—the symmetry of the material is broken.

If the magnet is cooled in an externally imposed magnetic field, the spins would probably lock together in a direction different from the external field. After a time, though, the spins might all suddenly jump to align with the external field. When they did, the system would release coherent waves of spin energy called magnons.

Like the magnet, theorists predict, the hot quark matter created in RHIC will shun any particular arrangement, but as it cools, it should lock into a specific mixture. This mix is unlikely to be identical to the mix in the surrounding cool vacuum, however, and Wilczek and Krishna Rajagopal (now at MIT) have predicted that eventually that little smudge of disoriented condensate will suddenly reorient, releasing energy in the form of pions moving in lockstep, like the photons in a laser. RHIC researchers hope to catch a glimpse of this "pion laser," in the form of unusual ratios of neutral to charged pions. Even if no pion laser technology is likely to come out of such experiments, the signal would carry a profound message about the physical nature of the vacuum.

But as Dan Beavis, project manager for BRAHMS, puts it, "I don't know how kind nature will be to us." For RHIC is entering largely unknown territory. Predictions that some kind of transition to quark-gluon plasma will take place are so strong that everyone expects RHIC to see something. But beyond that, "theoretical guidance has been diffuse," says Zajc. "So experimentalists are in the driver's seat on this one."

–**David Voss**