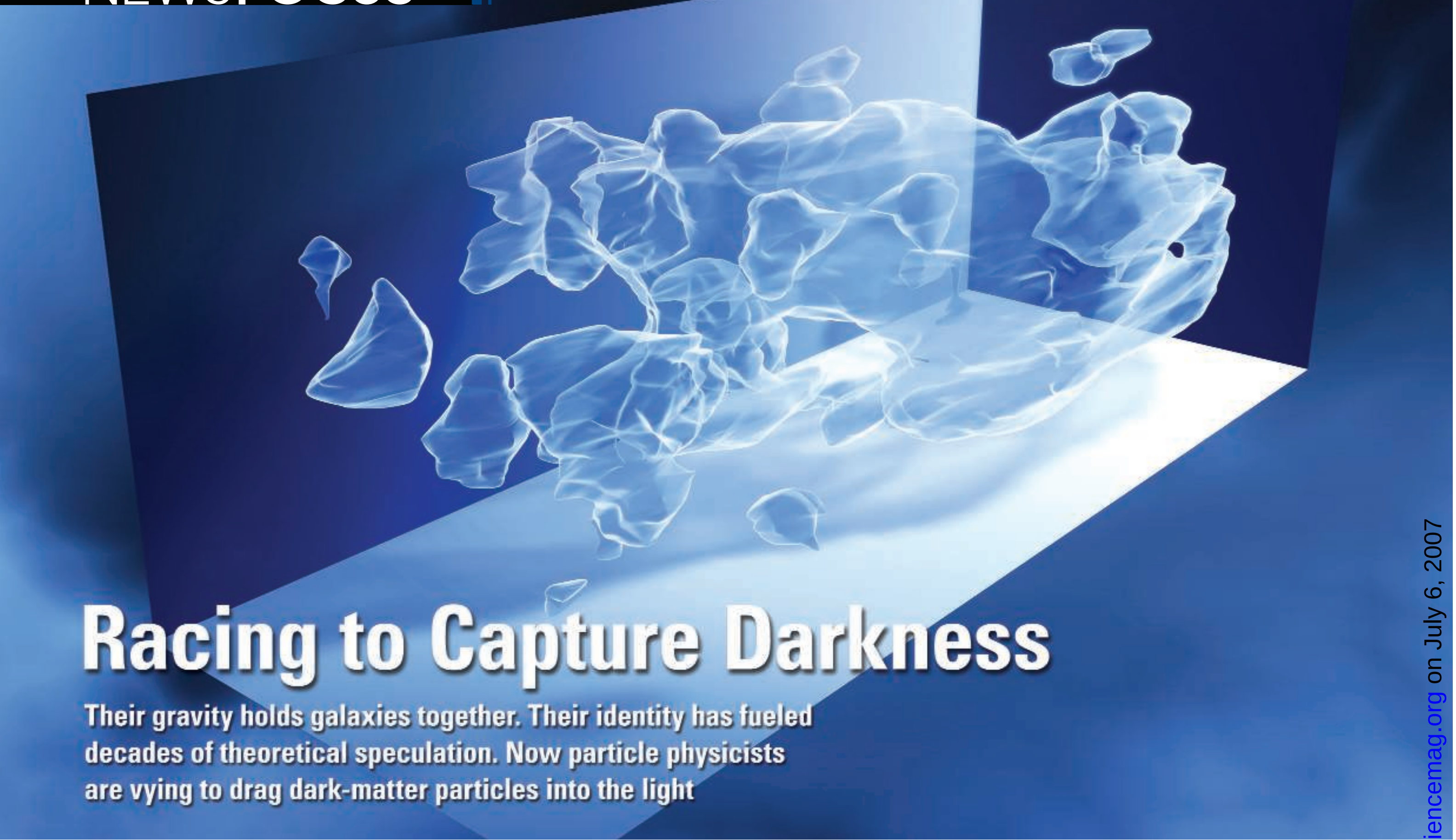


Racing to Capture Darkness

Their gravity holds galaxies together. Their identity has fueled decades of theoretical speculation. Now particle physicists are vying to drag dark-matter particles into the light

YANGYANG, SOUTH KOREA, AND BATAVIA, ILLINOIS—Deep inside Korea's Jeombong Mountain, in a vault suffused with an eldritch red glow, a giant black cube begins to unfold. One thick, lead-lined wall filled with mineral oil, along with the box's base, inches away from the rest of the structure to reveal a smaller cube of shimmering copper. A young man steps up and pulls a chain, hand over hand, and gradually, amid the clatter of steel, the face of the copper cube rises. The rarest of coins or the relics of a saint might be accorded such sanctity, but here, in an anteroom to a tunnel delved for a hydropower station in northeastern Korea, the treasure is precious only to a particle physicist. Inside the copper cube are a dozen blocks of crystalline cesium iodide, doped with thallium and wired with electronics that will register the tiniest scintilla of light produced inside the crystals. Researchers are making a few final tweaks to their crystal array before sealing it up again and beginning an otherworldly quest.

The 15 centimeters of gamma ray–blocking lead and neutron-quenching oil in the black cube, the 10 centimeters of copper that absorb x-rays from the lead, the nitrogen piped into the copper box, the red light, and the 700 meters of rock between the chamber and the outdoors all have a singular purpose: to minimize the number of spurious flashes inside the crystals. Here at the Korea Invisible Mass Search (KIMS) experiment, researchers are hoping to be the first to spot what no one—indisputably—has seen before: particles of dark matter.

After years of preparation, physicist Kim Sun Kee of Seoul National University and his KIMS colleagues began taking data here last month with a 100-kilogram array of crystals. Each day they hope to record one or two instances of weakly interacting massive particles (WIMPs)—prime candidates for dark matter—tickling cesium and iodine nuclei in a way that liberates a flash of light. That's assuming dark particles tangle with ordinary particles as many models predict. "If they don't interact with matter, we have no hope to find them," says Kim.

The KIMS experiment is one of a few dozen experiments racing to detect dark-matter particles. Like Kim's team, groups in several countries are engaged in so-called direct searches, striving to spot the particles jostling ordinary atomic nuclei. Others are turning to the skies in indirect searches that seek signs of dark-matter particles annihilating one another in the hearts of galaxies. Meanwhile, the world's most powerful atom smasher, the Large Hadron Collider (LHC) near Geneva, Switzerland, could make dark matter as soon as it turns on next spring.

"This is the epoch in which the central theoretical predictions are finally being probed," says Blas Cabrera of Stanford University in Palo Alto, California, who for a decade has stalked dark matter as the co-spokesperson of the Cryogenic Dark Matter Search (CDMS) project. "The best guess is within reach." That prospect thrills researchers. At a recent workshop* at Fermi National Accelerator Laboratory (Fermilab) in Batavia, Illinois, more than half the 170 attendees wagered that dark-matter particles will be detected within 5 years.

Discovery is not guaranteed. The favored theoretical models suggest that experimenters should soon have dark matter in their grasp, but others predict the ghostly particles will be so elusive that researchers can never hope to snare them. It's a make-or-break situation, predicts Rocky Kolb, a cosmologist at the University of Chicago in Illinois: "Either in 5 years we will know what dark matter is, or we will never know."

The WIMP miracle

Astronomers first sensed dark matter's shadowy presence more than 70 years ago.

---

* The Hunt for Dark Matter: A Symposium on Collider, Direct, and Indirect Searches, 10–12 May

CREDIT: NASA, ESA AND R. MASSEY (CALIFORNIA INSTITUTE OF TECHNOLOGY)

Unseen clouds. Astronomers can infer where dark matter lies in space, but nobody knows what it is.

In 1933, Fritz Zwicky of the California Institute of Technology in Pasadena calculated that the Coma Cluster of galaxies contains too little visible matter to hold itself together. Some unseen matter must supply the extra gravity that keeps the galaxies from flying into space, he reasoned. That maverick idea gained credence about 4 decades later when astronomers found that individual galaxies also lack enough luminous matter to hold on to their stars, suggesting that each galaxy is embedded in a vast clump, or "halo," of dark matter.

Evidence continues to mount. In 2003, researchers with NASA's orbiting Wilkinson Microwave Anisotropy Probe (WMAP) measured the big bang's afterglow—the cosmic microwave background—the temperature of which varies ever so slightly across the sky (*Science*, 14 February 2003, p. 991). The pattern of hot and cold spots reveals much about how the universe evolved, and researchers found they could explain the observed pattern if the universe consists of 5% ordinary matter, 22% dark matter, and 73% weird space-stretching "dark energy," all interacting through gravity.

Researchers have never captured a speck of dark matter, however. Like a cosmic Cheshire Cat, the stuff hides in plain sight, presumably floating through our galaxy and the solar system and showing only its gravity as its grin. That coyness vexes physicists, who assume that dark matter must consist of particles. "This is the best evidence we have of new physics," says Jonathan Feng, a theorist at the University of California, Irvine. "It's simply a fact that there is dark matter, and we don't know what it is."

Theorists have dreamed up dozens of possibilities. Dark matter could be particles that would exist if space has minuscule extra dimensions. Or it could be particles called axions that have been hypothesized to patch a conceptual hole in the theory of the strong force that binds the nucleus.

Most promising may be the idea that dark matter consists of particles predicted by supersymmetry, a theoretical scheme that pairs every known particle with a heavier, undiscovered superpartner. The lightest superpartner, expected to be a few hundred times as massive as a proton, could be the long-sought WIMP. And if it interacts with ordinary matter as anticipated, then a simple calculation shows that roughly the right amount of WIMPy dark matter should remain from the big bang. That uncanny coincidence, or "WIMP miracle," suggests that supersymmetry is more than another stab in the dark, Feng says.

Detecting is believing

The proof is in the particles. The most obvious way to find them is to catch them bumping into ordinary matter, and the KIMS experiment joins more than a dozen experiments that are hunting for collisions with ever greater sensitivity—including one that claimed a signal. Spotting dark matter is easier said than done, however. The particles should interact with ordinary matter even more feebly than do neutrinos, which can zip through Earth unimpeded. Researchers must also shield detectors from cosmic rays and other ordinary particles so that they may perceive the soft cries of dark particles amid the din of ordinary collisions.

Darkest desires. Kim Sun Kee hopes his cesium iodide array will register one or two WIMPs a day.

CREDIT: MUTSUMI STONE

In the race to capture darkness, the front-runner for the past few years has been an experiment called CDMS, which runs in the Soudan Mine in northern Minnesota. Its 5-kilogram "cryogenic" detector consists of stacks of germanium and silicon wafers cooled to within a fraction of a degree of absolute zero. If a WIMP crashes into a nucleus, it should knock loose several electrons and produce a tiny pulse of heat. Analyzing both the charge and heat signals, researchers can look for dark-matter particles and weed out neutrons and other red herrings.

Now, another experiment has taken the lead in sensitivity. The XENON10 experiment, which resides in a tunnel in Gran Sasso, Italy, consists of a tank filled with 15 kilograms of liquid xenon. When pinged by a WIMP, a xenon nucleus should rebound through the liquid to produce a flash of light and knock free a handful of electrons. In April, the XENON10 team, led by Elena Aprile of Columbia University, reported that it had searched with five times the sensitivity of CDMS—and found nothing.

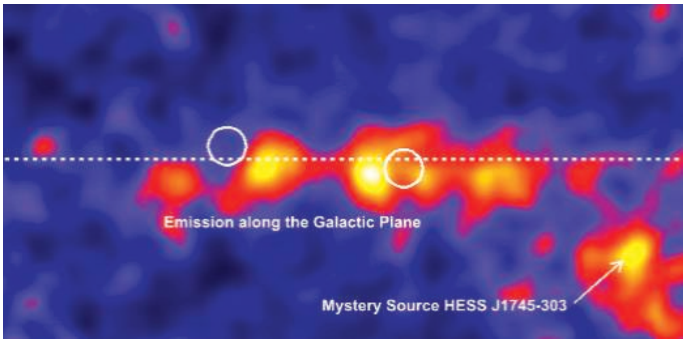
To go head to head with such efforts, the KIMS team had to start from scratch. A decade ago, Korea did not have a particle physics facility. "We always had to go abroad for research and training," says Kim, who cut his teeth at Japan's KEK accelerator laboratory in Tsukuba in the 1980s. When South Korea's science ministry launched a Creative Research Initiative in 1997, Kim, with colleagues Kim Hong Joo of Kyungpook National University in Daegu, South Korea, and Kim Yeong Duk of Sejong University in Seoul, pounced. Thrice the trio of Kims submitted their aptly named KIMS proposal, and thrice they failed. Finally, in 2000, they opted for a novel cesium iodide detector—and got funded. They caught a second break when during construction of the Yangyang Pumped Storage Power Plant, a small section off one tunnel caved in, and plant officials were amenable to hosting the experiment. "We were very lucky," says Kim Sun Kee. The collapse "opened up just enough space for the experiment."

Since then, the most arduous task has been to develop a detector largely free of trace radioactive isotopes. The KIMS team has also spent 3 years studying the scintillation signals of gamma rays and stray cosmic rays, which cause chain reactions in the atmosphere that give rise to a background "noise" of hurtling neutrons. "The neutron signal is very similar to what we expect a WIMP signal to look like," Kim explains, so the experimenters must find ways to screen it out. So far they have reduced it by 99.999%, he says.

KIMS won't immediately rival CDMS and XENON10 for overall sensitivity. But KIMS will excel in one important regard: If the WIMP-nucleus interaction depends on how each particle spins, KIMS will have a better chance of seeing the effect. "That makes KIMS complementary with CDMS and XENON10," Kim says.

KIMS can also test one of the more spectacular recent claims in physics. In 1997 and

Published by AAAS



Too bright? HESS's maps of gamma rays at the center of the Milky Way may leave clues to dark matter lost in the glare.

CREDIT: H.E.S.S.

again in 2000, researchers with the Italian DAMA experiment at Gran Sasso reported evidence of WIMPs in a 100-kilogram array of sodium iodide crystals (*Science*, 3 March 2000, p. 1570). The team found that the rate of flashes went up and down with the seasons. That would make sense if the galaxy turns inside a cloud of WIMPs so that the solar system faces a steady WIMP wind. As Earth circles the sun, it would alternately rush into and away from the wind, causing the collision rate to rise and fall.

No other experiment has reproduced the DAMA signal, however, and most physicists dismiss the sighting. Because KIMS employs a similar detector array—with cesium iodide instead of sodium iodide—many experts say it can provide an unambiguous test of the DAMA results. DAMA group leader Rita Bernabei, a physicist at the University of Rome Tor Vergata, disagrees. "No direct comparison will be possible," she argues, because cesium iodide is less sensitive to low-mass dark-matter particles than DAMA's detectors were. In 2003, Bernabei's group fired up an upgraded 250-kilogram detector called DAMA/LIBRA. Its initial findings are due to be released next year.

The competition among dark-matter experiments is heating up. The CDMS team has already collected enough data to retake the sensitivity lead this summer. Meanwhile, researchers in North America, Europe, and Asia are deploying or planning a gaggle of ever more ambitious detectors, including XMASS, an 800-kilogram spherical liquid xenon detector that won funding this year and will be built in Kamioka, Japan. "For the first time, the direct detection experiments are moving into a regime where theorists would say that *a priori* you would expect to see something," says Lawrence Krauss, a theorist at Case Western Reserve University in Cleveland, Ohio.

Other ways to skin a cat

Meanwhile, astronomers are searching for signs of dark-matter particles in the heavens. When two WIMPs in a galactic halo collide, theory says they can annihilate each other to produce high-energy gamma ray photons or other ordinary particles. The emerging generation of gamma ray "telescopes" should be well-suited to search for such signs. Since 2004, the European-funded High Energy Stereoscopic System (HESS) in Namibia, Africa, has used its four detectors to look for light created when a gamma ray smashes into the atmosphere and triggers an avalanche of particles. Similarly, the Very Energetic Radiation Imaging Telescope Array System (VERITAS) at the base of Mount Hopkins in Arizona began taking data earlier this year. "The gamma ray observations are really the only way to measure the halo distribution and tie this all together," says James Buckley, an astronomer at Washington University in St. Louis, Missouri, who works on VERITAS.

HESS has already mapped the gamma ray glow coming from the heart of our Milky Way galaxy, the most obvious place to look for dark matter. Unfortunately, those gamma rays come overwhelmingly from more mundane sources, such as hot gas. So researchers may have to turn away from the central glare and look at so-called dwarf spheroidal galaxies that orbit our galaxy. Those galaxies should come into fuller view when NASA's Gamma-ray Large Area Space Telescope (GLAST) blasts into orbit, perhaps as early as this winter.

Dark-matter annihilations would produce other particles, too. The Russian-Italian satellite PAMELA is looking for antiprotons and other antiparticles born in the process. And IceCube, an array of 4200 light sensors being lowered into the South Pole ice, could spot neutrinos from annihilations in the sun. Zipping along with tremendous energy, measured in billions of electron volts or GeV, a few would interact with the ice to create flashes of light. A stream of 100 GeV neutrinos coming out of the sun would be a sure sign of dark matter huddling there, says Francis Halzen, a physicist at the University of Wisconsin, Madison. "How else do you get a 100 GeV neutrino out of the sun?"

Before researchers find dark-matter particles, they may be able to manufacture them. The European LHC will smash protons together at energies seven times greater than any previous collisions, recreating, in billions of tiny explosions, conditions that haven't existed since the big bang. If superpartners exist, the LHC should crank them out by the thousands, says Alex Tumanov of Rice University in Houston, Texas, who works on an LHC particle detector. "Most of these models predict that we will find or exclude the dark matter particles within 1 or 2 years," he says. "That's why everyone is so excited. We're on the doorstep."

Even if the LHC spews out new particles, however, it might not reveal enough about them to nail down which of the many versions of supersymmetry nature plays by, says Michael Schmitt of Northwestern University in Evanston, Illinois. That would require another collider that could study particles in greater detail: the proposed 40-kilometer-long International Linear Collider.

Putting it all together

Ultimately, all three methods—direct detectors, telescopes, and colliders—may have to strike pay dirt before scientists can say what dark matter is. "It's really going to require that we detect the particles in our galaxy and produce them in the lab, and that we convince ourselves that they are the same thing," says Edward Baltz, a theorist at Stanford University. In the race to spot dark matter, he says, "You don't win until everybody finishes."

Of course, the efforts may not come together so harmoniously. Direct searches might spot particles so massive that the LHC can't generate them. Or, in spite of the "WIMP miracle," dark matter might turn out to comprise several different types of particles. Researchers also face a psychological challenge if they do see something. "The first thing that you would say would be, 'Is this real?' " says Daniel Akerib, a CDMS team member from Case Western. "The first thing we would have to do is to try to make it go away" and prove it was a spurious signal, he says. That could be tricky, as it would require checking every conceivable way an ordinary particle might mimic a WIMP.

Still, that's a problem most researchers, including Kim Sun Kee, would love to have. Kim hopes that within a year, his team members will have accumulated enough data in their Korean crypt to reveal a convincing WIMP signal. The form of a WIMP behind that Cheshire grin is another question. "We don't know what a WIMP will look like," says Kim. They may soon find out—and solve one of the bigger mysteries in physics.

–ADRIAN CHO AND RICHARD STONE