AT THE FRIGID DEPTHS NEAR ABSOLUTE ZERO TEMPERATURE, THE FAINT CRACKLING OF COLLIDING NEUTRALINOS COULD MAKE ITSELF HEARD.

Long Island worked on designing axion detectors through the mid-1980s. The basic idea was to get as many axions as possible to change into photons and somehow prevent this small harvest of photons from being swamped by the countless photons of other frequencies that are constantly ricocheting throughout space and matter. No matter how well you seal the detectors, the noise problem is intractable—especially when you're dealing with a particle as elusive as the axion.

The designs the two physicists settled on were essentially the same: a powerful magnet surrounding a microwave cavity—essentially a large box with reflective interior walls. An axion passing through the box should turn into a photon under the influence of the magnetic field; the photon would bounce back and forth off the walls. After a while, another passing axion would disintegrate in the box, providing another photon to join the first. Eventually, enough photons might join the parade to create an ultratiny microwave signal that could be picked up by a receiver tuned to resonate at precisely the right frequency. It would have to be a sensitive receiver, indeed; as Lawrence Krauss of Yale has pointed out, if this setup were enlarged to the size of the sun, it would produce an axion signal just energetic enough to power a single light bulb. "It was sort of like *Field of Dreams*," says Turner. "Build a microwave cavity and a magnet, and they will come." The two physicists put their detectors together and waited, but of course, things usually don't work out the way they do in the movies. "The magnets just weren't big enough," Turner says, "so the axions didn't come."

Unfortunately, further calculations suggested that even the biggest magnet conceivable wouldn't be likely to snag axions. In April 1989 Turner went to a meeting intended to put the project to rest. Also present were Sikivie, Melissinos, and Karl van Bibber of the Lawrence Livermore National Laboratory. "It was supposed to be a requiem for the axion," recalls Turner. "But over a last lunch we got to talking about what would happen if we tried to find axions that had one-tenth the energy of the axions we had been looking for. We were all surprised to figure out that life suddenly got a lot easier." The group's original estimates had been based on calculations of a hypothetical "typical" axion, but there was no reason, the group decided, why the axion might not also turn up in a less energetic version—a version far more easily turned into a photon when nudged by a magnet. Suddenly, the lure of capturing the axion and clearing up the dark matter problem captured Turner himself.

The magnet would still have to be a great deal larger than the ones they had been using. In fact, the group realized that only one available magnet in the world was powerful enough: a minivan-size, donut-shaped superconducting "tin can" gathering rust at Lawrence Livermore. The government-run lab had acquired the magnet for a nuclear fusion test facility but promptly abandoned the idea. "It was one of the great embarrassments of all time, a half-billion-dollar project decommissioned the day after it was commissioned," says Turner. But fu-

Dark Matter . . . Not?

In 1933, in the midst of the Great Depression, Caltech astronomer Fritz Zwicky noticed that galaxies within the Coma cluster, a rich assembly some 300 million light-years away, were circulating far too fast for comfort. Zwicky reported to a Swiss journal that the cluster had to be filled with large amounts of *dunkle Materie,* or dark matter. The unseen matter—up to ten times more stuff than the luminous stars and gas clouds visible to the eye—would be the gravitational glue required to keep the spirited cluster from breaking apart.

At the time of Zwicky's discovery, the very notion of galaxies was still wet behind the ears; these "island universes" situated far beyond the shores of the Milky Way had been discovered just nine years earlier. Astronomers naturally assumed that a better understanding of galactic motion would eventually expose Zwicky's dark matter as a mirage. Instead, by the 1980s, most astronomers had become convinced that *dunkle Materie* is all too real. Extensive radio and optical evidence—much of it cataloged by astronomer Vera Rubin—suggests that diffuse halos of hidden matter surround most galaxies and perhaps pervade the entire universe.

To this day, however, a handful of holdouts remain skeptical. Dark matter, they're trying to prove, may be nothing more than an illusion. "The cosmologically important 'missing mass' problem may not be related to mass," says radio astronomer Gerrit Verschuur of Rhodes College in Tennessee. "It may be a missing-the-point problem."

Part of the disillusionment stems from the failure of dark matter enthusiasts to turn up a suitable suspect. Looking outward with their telescopes, observers have been scanning the Milky Way's borders for MACHOs, a hard-to-see host of Massive Astrophysical Compact Halo Objects such as faint stars, black holes, Jupiter-like planets, and faint brown dwarfs, objects just short of providing the mass needed to sustain a stellar nuclear fire. Meanwhile, physicists, convinced that dark matter is subatomic in nature, have turned inward, setting up exquisitely sensitive detectors to look for WIMPs, Weakly Interacting Massive Particles that might be slipping through the Earth as if our planet were an insubstantial mist. But so far, herds of brown dwarf stars have not been sighted, and underground detectors have yet to catch one WIMPy particle.

Some maverick scientists have begun to wonder whether the cherished theories that predicted dark matter in the first place might be flawed. A leading renegade is Israeli astrophysicist Mordehai Milgrom. For more than ten years he has been making the rounds of dark matter conferences and urging his fellow astronomers to consider a rather radical remedy for their dark matter problems: a completely new law of gravity.

Almost all arguments supporting the existence of dark matter turn on the laws of gravity and motion formulated by Sir Isaac Newton. It was Newton who first described the relationship between gravity and the orbital velocity of celestial objects such as stars and planets. Imagine an object (say, Earth) orbiting close to a massive source of gravity (say, the sun). Earth "falls" toward the sun, pulled by gravity. But the sun's surface curves away underneath it. Thus the constant falling, caused by gravity, is transformed into circular sion's loss could be the axion's gain: the group quickly put in a bid for the magnet.

With the innards of the experiment in place, all that's needed now is a strong enough magnetic field. If the physicists get their magnet—along with the modest $2 million grant they've requested—Turner thinks they stand a decent shot at finding the axion, their earlier experience notwithstanding. "That's the way physics is," he says. "You start with something impossible, then try to do a piece of it, and then keep improving your efforts."

Standing in a baggage check-in line at San Francisco International Airport, Bernard Sadoulet is complaining about having to make yet another trip to Washington to discuss the progress of his work with funding agencies. "I hate spending all my time on administration," he sighs. But the government is not likely to ease up on its questions. When you give someone millions of dollars, you can't help being curious about what exactly it is that you're getting for your money.

What Sadoulet hopes to deliver to his funders, and to the rest of us, is the neutralino. It's something he's been seeking, in a sense, most of his life. Sadoulet received his physics degrees from the Ecole Polytechnique in Paris and in 1970 landed a fellowship at CERN in Geneva, the world's preeminent facility for finding exotic particles. When his fellowship ended in 1973 (CERN has a rule against offering a permanent position to anyone under the age of 30), Sadoulet went to Berkeley; here he joined the team, led by Burton Richter, that discovered the J/psi particle, for which Richter won the Nobel Prize. On Sadoulet's thirtieth birthday, CERN offered him a contract.

Back in Geneva, Sadoulet joined Carlo Rubbia in the search for the *W* and *Z* boson particles—a search that was ultimately successful and that again resulted in a Nobel Prize for Sadoulet's boss. But by 1984 Sadoulet had grown discontented with the CERN scene, a contentious one by any standards. "It is well known that this was not the most peaceful environment," he says. "Rubbia and I argued a lot, and I finally decided it would be best to separate our trajectories."

That year, Sadoulet took a sabbatical at Berkeley and began to poke around in cosmology. He liked what he saw. "There are a number of questions about particle physics for which the answers are out of the reach of accelerators because of the high energies that are involved," he says. "We must rely on other hints to see what physics looks like at those energy scales. The cosmology of the early universe is one of the ways to observe those kinds of effects." In addition, he says, he preferred the small teams of six or so people that are the norm in cosmology to the giant accelerator groups of several hundred that dominate particle physics. Berkeley offered him a professorship and he accepted.

The dark matter problem drew him immediately. "I was particularly fascinated by the possibility that there is stuff out there making up 99 percent of the universe," says Sadoulet, "and we just don't understand what it is." Even better, the puzzle called for doing what he had always done best: finding a new particle.

Sadoulet is an experimentalist, but his understanding of underlying concepts is on a par with that of most theorists, an unusual capability in this age of specialization. "He teaches general relativity," marvels Tom Shutt, a graduate student in physics at Berkeley and a member of Sadoulet's group. "I don't know many other experimentalists who could teach that kind of subject at that level." In addition, says Shutt, Sadoulet isn't the obsessive leader often found at the head of top research teams. "I think after his experience at CERN he decided to make a real effort to make things different here," Shutt says. "He's created a very healthy atmosphere."

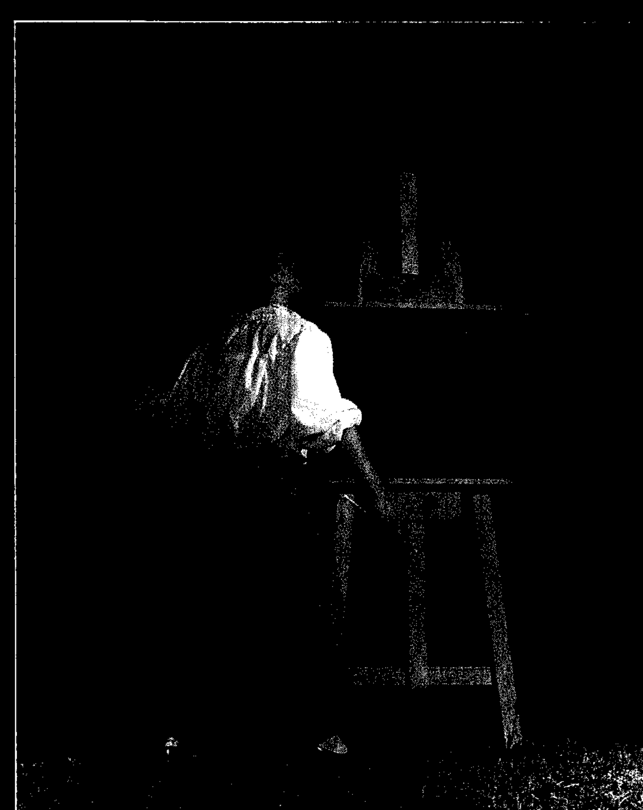
Not that Sadoulet isn't focused. From the moment he got hooked on the dark matter problem, he's kept his eye

motion—an orbit. The stronger the pull of gravity, the faster the orbital speed; and the closer the object, the stronger the pull. So Mercury, the planet closest to the sun, whips around at a racy 107,000 miles per hour, while faraway Pluto orbits at a sedate 10,500 miles per hour. Similarly, stars at the remote edge of a spiraling galaxy, far removed from its massive core, were expected to circulate at a relatively slow pace.

But in hundreds of spiral galaxies, stars and gas at the spiral's edge appear to travel just as fast as matter closer in. Like well-matched sprinters racing around a circular track, those in the outer lanes move as fast as those in the inner lanes. Not wanting to give up on Newton, astronomers can only conclude that each galaxy is embedded in a vast sphere of extra material that extends the gravitational pull to the far reaches of the galaxy.

To Milgrom, though, the unusually fast velocities of a galaxy's outlying stars could be a sign that Newton's law, so reliable in our immediate environs, breaks down in a realm where gravity is so thinned out that its force is barely a whisper. He has written several papers showing how Newton's equations can be altered to account for the curious galaxy rotations.

The idea that Newton's laws could be wrong is hardly heresy. After all, Einstein showed that Newton's law of gravity is incomplete and fails under special circumstances. "Newton's law fails when objects approach the speed of light," points out Milgrom. "For that we need Einstein's theory of relativity. What I am suggesting is that Newton's law must also be amended when gravitational accelerations are very, very small, as they are in a galaxy's outer fringes." Milgrom's adjustment to Newton's law is, in fact, very successful in re-



on the neutralino. And he thinks he knows how to get one.

Far more weighty than the axion, the neutralino belongs to a category of particles collectively known as WIMPs (Weakly Interacting Massive Particles, a term invented, ironically, by Turner). It comes from yet another conjectural extension to the standard model. Known as supersymmetry, the theory is innately appealing because it presumes that all the various kinds of forces and particles in the universe are the same if you melt down their differences at an extremely high temperature—the temperature of the universe in the instant following the Big Bang. Only as the universe cooled did particles and forces freeze into their current state. (Imagine a snowman, an igloo, and an ice-sculpture swan; under a hot enough sun, they all transform into puddles of plain water. In the same way, electrons, protons, axions, neutralinos, and what have you are all just differently configured forms of frozen energy.)

Reworking the laws of physics to accommodate a universe that was supersymmetric also produced a new family of particles, most of which would have been transformed almost immediately into ordinary matter. But the neutralino could have persisted into today's lower-energy universe. Supersymmetry predicts roughly how many of these survivors are floating around; when you add up their mass, you end up with a number that fits the estimate of the total quantity of missing dark matter in the universe. "This could be a numerical coincidence," says Sadoulet. "But nature had such a large range of numbers to play with; why would it pick exactly the right one?" To put it another way, if you lose a bag of 12,000 pennies, and then find a bag of 12,000 pennies, it *could* be someone else's pennies, but . . .

When Sadoulet first started mulling over how he might catch a neutralino, he realized he would have to build a far more sensitive particle trap than any that existed. A standard way to grab an elusive particle is to get it to smash into a target, knocking out electrons. The booted electrons are easy to detect because they're electrically charged and therefore interact with just about everything. The most sensitive detectors use silicon or germanium crystals as targets because electrons in these materials are loosely bound to the atoms around them; an ordinary particle of even the most sluggish variety is able to kick out hundreds or even thousands of electrons from such a target.

But a neutralino is not an ordinary particle. It would have only about one-tenth the energy needed to bust a single electron out of silicon or germanium—assuming, of course, it could be enticed to interact at all. And even if a detector could be persuaded to pick up the rare electrons set loose in a neutralino collision, it couldn't reliably distinguish them from electrons produced by other sources—in particular, the incessant rain of high-energy particles streaming in from the sun, the cosmos, the surrounding Earth, even the detector itself.

Sadoulet needed a detector that was more than merely sensitive: it had to be discriminating as well. "The problem was that we didn't have enough information about the events," explains Sadoulet. "We were just trying to measure one number, and it's easy to pick up lots of disturbances that make this one number fluctuate. We needed some redundancy."

Three years ago, Sadoulet figured out how to get a second signal that would provide that redundancy and confirm the sighting of a neutralino. When a neutralino plowed into the silicon or germanium target, it would plunge directly into the nucleus, knocking the whole atom out of its neat crystal lattice. The atom would rip through the crystal, setting up vibrations and producing a minuscule rise in temperature of about one millionth of a de-

producing the observed galaxy spins, a point that has been acknowledged by dark matter specialists. However, his tinkering cannot yet be reconciled with general relativity, a far more detailed theory of gravity that has so far passed every test. Until that happens, Milgrom's idea remains suspect.

Caltech biophysicist Roy Britten, too, has been wondering if dark matter is more theory than substance. Noted for his work on DNA sequences, Britten started thinking about the dark matter problem in his spare time when he worked at the Carnegie Institution of Washington, where Vera Rubin was compiling her all-important data. In a recent paper, Britten suggests that certain interactions involving particles known as gravitons might cause the strength of gravity to vary in a way that only becomes noticeable on the vast scales of galactic distances.

Gravitons are still hypothetical, but particle physicists believe they are responsible for conveying the force of gravity, just as photons convey electromagnetism. Britten proposes that some gravitons, after they are emitted by a mass, may get deflected or scattered off the vacuum of space itself. Since these gravitons are not immediately absorbed by another mass, they start diffusing over the galaxy like perfume molecules wafting across a dance floor. Over time the gravitons build up, and consequently the galaxy develops a stronger gravitational field. This boost in gravity then allows the external parts of a galaxy to spin faster without the need for extra matter. In Britten's scheme, gravitons, not dark matter, provide the extra gravitational glue.

At this stage, Britten thinks of his effort as no more than a thought experiment. "This is all supposition," he readily admits. "No one yet knows if gravitons would even be capable of scattering in this way."

Other scientists think that the need for dark matter may disappear simply when other forces at work within galaxies and clusters are considered. Gerrit Verschuur, whose studies have demonstrated the role magnetism plays in creating and maintaining the structure of interstellar gas clouds, wonders if magnetism might also somehow mimic the effects of so-called dark matter, although so far he hasn't any idea how.

Dark matter enthusiasts are not persuaded by any of these arguments. As proof that dark matter is real, they point to convincing observations made recently by Anthony Tyson and his colleagues at AT&T Bell Laboratories. These researchers have been looking at a large number of dim blue galaxies at the edge of the visible universe. When light rays from these far galaxies pass by an intervening galaxy cluster on their way to Earth, the rays are gravitationally diverted by the cluster's immense mass. The entire cluster acts like a giant gravitational lens. Using computer programs to keep track of this bending of light, Tyson can directly assess the amount of matter in the cluster. Most of it, some 90 percent, turns out to be dark.

Besides, the observed dynamics of galaxies aren't the only reasons for believing in dark matter—at least not for everyone. In fact, two quite separate dark matter issues coexist within the scientific community, only occasionally overlapping. The first—the dark matter around galaxies and clusters—is now accepted by almost all serious astronomers. The second is far more controversial: it suggests that as much as 99 percent of the entire universe may be hiding. This second dark matter scenario comes from cosmologists, who gree. Unfortunately, such a wimpy signal would be undetectable at room temperature; random shaking of the crystal target could easily generate that much heat. "It'd be essentially like throwing a match into a huge vat of molten steel," says Shutt.

So Sadoulet started to make plans for a new type of detector, one that would lower the target material to temperatures near absolute zero (about −460 degrees). At those frigid depths, random shaking would be effectively stilled and the faint crackling of colliding neutralinos could make itself heard.

AN AXION CONVERTS into a photon inside the microwave cavity (above); a properly tuned cavity will ring like a bell.

Jeffery Newbury

Neither the presence of loose electrons nor the presence of this vibrational energy alone would be sufficient to determine that a neutralino, and not some impostor, had crash-landed. But only a neutralino—with its 200-miles-per-second cruising speed and inability to interact electrically—would set up relatively strong vibrations while dislodging a small number of electrons. That combination of signals would be the neutralino's unique signature.

In 1990, Sadoulet and his collaborators got to work on a prototype detector. Now on-line, the prototype contains 60 grams of germanium, a chunk barely big enough to snare an average of one neutralino every three months, despite the fact that millions would be moving through it every second. Even with the redundancy scheme, a count that small would still be swamped by background radiation.

Thus Sadoulet's group is currently designing a larger detector, incorporating 500 grams of germanium, to be operational by next year. Housed in a small underground facility at Stanford, it will be capable of upping the neutralino count to about one every ten days. In addition, the group is working to improve the sensitivity of the vibration detection scheme to eliminate false triggerings. "We have a rejection rate of 90 percent now," says Sadoulet, "and we hope to improve it to 99.9 percent." That would mean that only one out of a thousand bogus signals would be mistaken for a neutralino—an acceptable noise level. However, it may not be possible to achieve that. If too many spurious signals are still fooling the detector, the group may end up burying the experiment in a deep mine to take advantage of the natural shielding provided by the surrounding rocks. Sadoulet hopes that won't be necessary. "I may be bragging," he says, "but I think we're close to the threshold of sensitivity and rejection we need."

For now, the identity of dark matter remains an open question. "To me, it doesn't matter whether it is the axion, the neutralino, or something else," shrugs Sadoulet. "I don't think there is any room for parochialism."

Turner expresses the same commitment to placing the quest for scientific truth above personal accomplishment—though he also points out that equanimity has its limits. "When you have a lot of ideas to pursue, taste is important. And I like the axion."

Only time will tell whether either of the two physicists has the right kind of taste, the taste to reveal, at long last, the true nature of the hidden universe. ◘

worry about the universe's grand structure and fate. They have reason to suspect that the expanding universe is coasting to an aesthetically pleasing balance point, poised exactly on the brink between expanding outward forever and collapsing in on itself. The unseen mass would provide the gravitational muscle needed to lasso the speeding galaxies from hurtling outward forever. The theory is appealing because it would mean that neither galaxies nor their inhabitants (including us) are doomed to continue riding the wave of space-time's expansion into an endless void for all eternity.

The idea got a tremendous boost in 1980 when Alan Guth, now at MIT, suggested that our universe began not only with a bang but with a sudden burst of space-time that traveled faster than light—a cosmic sneeze known as inflation, when space-time exploded like a science fiction starship on warp drive. Guth's theory provided a plethora of answers to long-standing puzzles about the evolution of the universe, including a mechanism for bringing the universe to this critical balance point. In the process, however, it predicted that dark matter would outweigh luminous material by 100 to 1. If inflation truly happened, where is all that extra matter?

The lack of substantial observational evidence for this much vaster pool of dark matter has caused some cosmologists to wonder whether something fundamental is awry with our understanding of the universe. A few have gone so far as to reconsider a concept that Einstein introduced decades ago but then quickly abandoned, calling it the greatest blunder of his scientific life. And of all the alternative explanations for the missing matter, this one is taken most seriously.

In 1917, shortly after introducing his general theory of relativity, Einstein tacked one more term onto his equations. He made the adjustment out of desperation. Astronomers at the time believed the universe was eternally static and unchanging. But general relativity predicted that the universe should be in some kind of motion. To bring his theory in line with observations, Einstein jury-rigged his own equations by adding an extra term, which he called the cosmological constant. It did not define a material substance per se, but rather an added energy in empty space, exerting an outward "pressure" that exactly balanced the inward gravitational attraction of the galaxies toward each other. The term, as Einstein used it, described a kind of antigravity, a repulsive force that ultimately served to preserve the status quo. Once Edwin Hubble revealed in 1929 that our universe was indeed rapidly ballooning outward, though, Einstein quickly (and gladly) dropped the term.

Reinserting a small cosmological constant (today also known as "vacuum energy") back into the universe's clockwork, however, could produce some interesting consequences. Since energy and mass are equivalent (by the familiar formula $E = mc^2$), this added energy would behave exactly like mass, making the universe appear to contain much more material than it really does. Missing matter isn't necessary to keep the universe from flying apart; vacuum energy gets the job done equally well.

For the moment, though, the astronomical community seems to prefer good old dark matter to messing up its favorite models with complications like a cosmological constant or a new law of gravity. Dark matter substitutes will likely remain on the theoretical back burner, at least until future evidence forces astronomers to reconsider. —*Marcia Bartusiak*