To Catch a WIMP

These heavy, secretive particles—if they exist—could make up the bulk of the universe. Around the world, physicists are setting traps to find out

If Secretary of the Treasury Robert Rubin announced one day that he could not account for 90% of the $6 billion worth of gold held at Fort Knox, he would have some explaining to do. The world's astronomers have a roughly equivalent problem, only theirs is about mass, not money. For the past 20 years, astronomers have had compelling evidence that there is more to the universe than meets the eye: About 90% of the mass of the universe seems to be invisible. This "dark matter" could consist of dim stars, not bright enough to be seen from Earth. It could simply be neutrinos, infinitesimal particles that zip around the universe in great profusion, rarely interacting with matter. But there is a more exotic alternative, harder to prove but increasingly appealing: that the dark matter is made up of massive particles yet to be discovered, collectively known as WIMPs (weakly interacting massive particles).

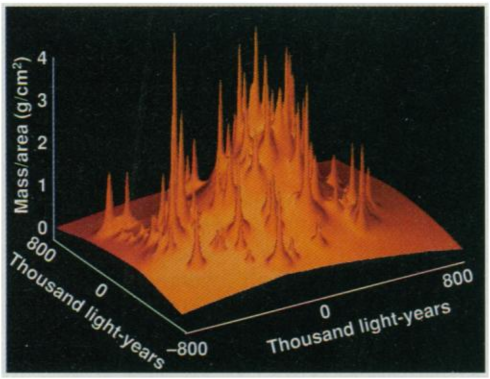
This is not just the stuff of theoretical debate. Astronomers are scouring the perimeter of our galaxy for unseen stars and scrutinizing the neutrino to see whether it could make up the mass deficit. But as such searches look less and less likely to offer a full answer to the dark-matter puzzle, researchers are also setting traps for WIMPs, which might be drifting continuously through Earth. This year, what was a trickle of WIMP-hunting experiments will swell to a respectable stream as a new generation of high-technology WIMP detectors joins the effort. A U.S.-based experiment that monitors crystals at close to absolute zero temperature for the tiny pulse of heat that might signal a WIMP was expanded last month, and this month a more sensitive competing experiment will debut at Italy's underground Gran Sasso laboratory. Some 20 other WIMP searches are on their way, aiming to snare these phantoms in everything from grains of tin to tiny droplets of Freon.

Success is a long shot, the researchers concede. WIMPs are, as their name implies, loath to interact with ordinary matter, and their properties—and thus the best way to trap them—are largely unknown, all of which makes WIMP-hunting "a very difficult business," says Oxford University physicist Susan Cooper, a leader of the Gran Sasso project. "[A WIMP] doesn't have a clear signature," she laments. "It's not the kind of experiment that you really like to do, because it is so hard, but I feel we are forced to try because the question is so big."

Where's the mass?

Dark matter may be elusive, but the evidence that it exists is strong. About 2 decades ago, astronomers first began measuring the speeds at which hydrogen clouds orbit the centers of spiral galaxies. The velocities turned out to be too high for the gravitational pull of the visible stars in the galaxies to hold the clouds in their orbits. Astronomers concluded that a large but invisible source of gravitational pull in the outer reaches of these galaxies must also be at work.

Gravitational lensing provides even more persuasive evidence. Light reaching Earth from distant galaxies is sometimes distorted by the gravitational pull of a cluster of galaxies that lies in the path of the light. By analyzing the distorted image, astronomers can "weigh" the cluster, and "that very convincingly shows that there's lots and lots of dark matter in the cluster," says Oxford astronomer Will Sutherland.



Lighting up dark matter. Each spike represents a galaxy in a cluster in Pisces; the mound around them is dark matter with a mass 250 times more than all the galaxies combined.

G. KOCHANSKI ET AL./LUCENT TECHNOLOGIES' BELL LABS

At least some of that dark matter, says Sutherland, could consist of the so-called massive compact halo objects (MACHOs), a catchall term embracing brown dwarfs, old white dwarfs, neutron stars, and any other massive and invisibly dull star. Sutherland and colleagues in Australia and the United States are part of the MACHO Collaboration, one of several teams looking for changes in the brightness of distant stars caused by gravitational lensing due to MACHOs in the halo of our own galaxy.

The MACHO Collaboration announced its discovery of a handful of MACHO candidates last year, but most researchers, even those actively hunting MACHOs, expect that these objects will only make a modest contribution to the total of dark matter, given the dictates of cosmology. Current theories of how matter formed after the big bang limit the amount of normal or "baryonic" matter—the protons and neutrons that make up both normal stars and MACHOs—to about 10% of the mass required to gradually slow the universe's expansion—the type of universe cosmologists currently favor.

If the cosmologists are to be believed, this means that the rest of the matter must be something more exotic. Neutrinos are one possibility for this nonbaryonic matter. Some theorists speculate that they are endowed with a minute mass, tens of thousands of times smaller than the mass of an electron. Yet, despite decades of trying, experimenters have yet to pin a mass on the neutrino. And cosmological models based on neutrino dark matter predict large groupings of galaxies not seen in the real universe. So many are now turning to WIMPs—heavyweight relics of the big bang—which may match particles predicted by some exotic theories in particle physics such as supersymmetry.

WIMPs have fewer strikes against them so far than the other dark-matter candidates—except that they are entirely hypothetical. They also provide a unique challenge for experimentalists: building a detector for a particle you do not know for certain exists, with unknown properties. To make matters worse, WIMP detectors risk being flooded with known particles, such as cosmic rays and debris from radioactive decays of atoms around the experiment and in the apparatus itself. Says Cooper: "Any signal that is seen is liable to be a bit shaky, and it's very important to have the possibility of confirming it with different techniques."

One technique has already been tested over the last several years in an earlier generation of WIMP searches. It relies on scintillation: the tiny pulse of light given off when an incoming particle strikes an atom in certain crystals, such as sodium iodide. The U.K. Dark Matter Collaboration (UKDMC) runs a scintillation detector in Europe's deepest mine, the Boulby salt and potash mine in northern England, where spurious signals from cosmic rays are at a minimum. The experiment, led by Peter Smith of the Rutherford Appleton Laboratory, consists of a 6-kilogram crystal of sodium iodide watched by a pair of light-detecting photomultipliers. Running since

1994, the detector has established upper limits on the frequency with which WIMPs of various masses knock into the detector.

Meanwhile, in the Gran Sasso laboratory beneath the Apennine mountains of central Italy, the DAMA group, led by the University of Rome's Rita Bernabei, has a similar 115.5-kilogram sodium iodide detector. To improve their chances of capturing a WIMP, the team is planning to scale up to 1 ton of sodium iodide in the near future. And both DAMA and the U.K. group are currently working on new detectors with liquid xenon in place of the sodium iodide crystals, which is expected to improve sensitivity.

WIMP SEARCHES

Experiment in Progress	Location	Detector Type
Baksan	Prielbrusye, Russia	Ge ionization
Canfranc-NaI	Canfranc, Spain	NaI scintillator
COSME	Canfranc, Spain	Ge ionization
DAMA	Gran Sasso, Italy	NaI scintillator, liquid Xe scintillator, CaF_2 scintillator
DEMOS	Sierra Grande, Argentina	Ge ionization
Milan	Gran Sasso, Italy	Cryogenic TeO_2 bolometer
UKDMC	Boulby mine, U.K.	NaI scintillator
Starting		
CDMS	Stanford, U.S.	Cryogenic Ge/Si bolometer with ionization
CRESST	Gran Sasso, Italy	Cryogenic sapphire bolometer
EDELWEISS	Fréjus, France	Cryogenic Ge bolometer with ionization
ELEGANT VI	Oto cosmo obs, Japan	CaF_2 scintillator
Tokyo	Nokogiri-yama, Japan	Cryogenic LiF bolometer
Under Construction		
HDMS	Heidelberg, Germany	Ge ionization
PICASSO	Montreal, Canada	Superheated Freon droplets
ORPHEUS	Bern, Switzerland	Superconducting transition in tin granules
ROSEBUD	Canfranc, Spain	Cryogenic sapphire bolometer
SALOPARD	Canfranc, Spain	Superconducting transition in tin granules
SIMPLE	Paris	Superheated Freon droplets
UKDMC	Boulby mine, U.K.	Liquid Xe scintillator

NOTE: This list does not claim to be definitive. Several significant experiments that have run to completion have been omitted. The listed experiments differ widely in their ability to distinguish background radiation, in their sensitivity, and in their potential for detecting WIMPs.

Small is beautiful

Many of the new detectors, however, are based on a different strategy which should raise the odds of catching a WIMP: detecting an incoming WIMP not by scintillation but by the energy it deposits in the detector material. "The amount of energy, by room temperature thermal standards, is absolutely insignificant," explains Tom Shutt of the University of California, Berkeley. But if you cool your crystal to a temperature of 0.020 kelvin, a single particle depositing a few kiloelectron volts will cause a millionth-of-a-degree temperature rise, "which, it turns out, is quite measurable," Shutt says.

One set of these detectors, called bolometers, is already keeping watch for WIMPS. The Cryogenic Dark Matter Search (CDMS) experiment, headed by Berkeley's Bernard Sadoulet, has had two detectors stationed a few meters underground at an old particle-accelerator complex at Stanford University since last September and added a third detector just weeks ago. Running at a temperature of a few tens of millikelvins, they consist of between 100 and 200 grams of crystals of germanium or silicon. An incoming WIMP knocks into a crystal nucleus, which recoils and creates heat.

To distinguish between WIMPs and cosmic rays, particles that constantly rain down on Earth from space, the CDMS detectors can also detect the charged particles—electrons or nuclei—dislodged in the crystal by a particle impact. "That's very important, because essentially all the radioactive background interacts with the electrons, and the signal that we are looking for interacts with nuclei," says Sadoulet. "In the end, we identify the amount of charge produced by each particle that strikes our detector, and thus distinguish WIMPs from background [gamma-ray] photons," adds Shutt. Soon, says Sadoulet, the experiment will move to the Soudan mine in Minnesota, where it will be better shielded from cosmic rays.

By the time it does, a host of other cryogenic experiments should be under way. Makoto Minowa and his colleagues at the University of Tokyo are building a WIMP detector based on measuring the temperature rise in ultracold lithium fluoride. "An array of eight pieces of 20-gram lithium fluoride bolometers is now ready for measurement," says Minowa, and it will soon be installed in the Nokogiri-yama underground laboratory in Tokyo. And the French EDELWEISS (Experience pour Detecter les Wimps en Site Souterrain) collaboration, is building a germanium bolometer in the Fréjus underground laboratory in the Alps, which, like the Berkeley device, will be sensitive to both the charge signal and the temperature rise from an impinging particle.

Telltale transitions

Lighter, slower WIMPs would deposit less heat in a bolometer, a possibility that has encouraged some groups to develop new, more sensitive thermometers. One is the closest competitor to the Berkeley experiments, the CRESST (Cryogenic Rare Event Search with Superconducting Thermometers) project run by Oxford's Cooper and her collaborators from Munich. Currently being nursed into action at Gran Sasso, the detector consists of four 262-gram sapphire crystals with a small rectangular patch of tungsten film stuck to each one. The very low temperature to which the detector is cooled lies just below the temperature at which tungsten undergoes a transition from a normal conductor into a superconductor. At this temperature, tungsten's electrical resistance is extremely sensitive to temperature, so the tiny temperature rise produced by an impacting WIMP will result in a detectable change in the film's resistance. The detector should be able to sense just 500 electron volts, the energy of a single soft x-ray photon. "We're specifically most sensitive to low-mass WIMPS," says Cooper, "complementing many other experiments."

A team of physicists from Paris and Saragossa, Spain, is building a smaller version of CRESST, dubbed ROSEBUD (Rare Object Searches with Bolometers Underground), in the Canfranc underground laboratory in the Spanish Pyrenees, with data taking expected to commence next year. But there are other ways of exploiting superconductivity to catch a WIMP. The Swiss ORPHEUS team is building a detector containing billions of tin granules, each just 30 micrometers in diameter. A total of more than a kilogram of the grains are cooled to the superconducting transition temperature for tin and swathed in a magnetic field, according to ORPHEUS leader Klaus Pretzl of the University of Bern. An incoming WIMP will strike a nucleus in a granule and warm it up. "When the granule is heated up, it then makes a transition from the superconducting phase to the normal conducting phase ... [creating a magnetic signal which] can be detected with a magnetometer," says Pretzl. The team expects to install the detector beneath the city of Bern at the end of the year.

One advantage of the magnetic "thermometer" strategy, says Tom Girard of the University of Lisbon, is its ability to reject spurious signals from natural radioactivity. A WIMP will strike only a single grain of tin, while radioactive background will cause transitions in a streak of grains, giving a larger blip in the magnetometer, he says. Girard and other researchers from Saragossa, Lisbon, and Paris are mounting a magnetic experiment resembling ORPHEUS, called SALOPARD, which will be installed in the Canfranc laboratory in a year or so. "We estimate the ability to reject 97% of the background contribution," says Girard.

Two other groups hope to eliminate spurious signals by exploiting different phase transitions at higher temperatures. Both teams, one in Canada and one a CERN-Lisbon-Paris collaboration, use liquid Freon droplets, a few tens of micrometers in diameter, entombed in a clear polymer gel. At room temperature, above Freon's boiling point, the droplets are confined in an unstable superheated state. If an impacting WIMP deposits enough energy in a Freon droplet, "there is a sudden phase transition during which the droplet is vaporized and expands into a bubble of Freon gas of about 1 millimeter in diameter, which is contained at its location in the polymer," says Viktor Zacek of the University of Montreal, spokesperson for the Canadian group. The result, says Juan Collar of CERN, a member of the competing team, "is a characteristic audible sound emission that can be picked up when this happens."

Such detectors "are totally insensitive to low-energy photons, the main source of background in dark-matter searches," Collar adds. Most background radiation does not deposit enough energy in a sufficiently short distance for the superheated bubbles to notice. "So life is much easier for the WIMP hunter," says Collar. Last month, the Canadian team started running a prototype system based on just a few grams of Freon droplets. Larger systems are in the pipeline, to be installed in the Creighton mine in Ontario. The European team, says Collar, plans to install its prototype in a shallow tunnel near Paris this year.

In spite of all the impressive technology being deployed, there remains the possibility that all these searches may draw a blank. WIMPs could simply be a fix conjured up by astronomers and cosmologists to get their theories to match what they see in the universe around them. But Sadoulet says the history of physics shows that what appears at the time to be a "fix" can later look like prescience. He points to the difficulties faced by Neils Bohr and his contemporaries in the early 1930s as they struggled to understand radioactive beta decay, in which some energy seemed to simply vanish. Bohr proposed dumping the principle of energy conservation, while Wolfgang Pauli proposed that the energy was fleeing in the form of a ghostly new particle, purely hypothetical at the time—the neutrino. The rest is history.

–Andrew Watson

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ASTRONOMY

Gamma-Ray Source in Distant Universe?

Discovering where a crime was committed isn't the same as solving it. But it's a good start, especially when one possible crime scene is just around the corner and the other is at unimaginably large distances. The crime, in this case, is a celestial act of violence called a gamma-ray burst—a bright flash of extremely energetic radiation from a mysterious source, at a random position in the sky. Just hours after astronomers had narrowed down the position of one burst, Jan van Paradijs of the University of Amsterdam and the University of Alabama, together with Paul Groot and Titus Galama of Amsterdam, pointed a telescope at the site and spotted what may be the source: a dim galaxy in the far reaches of the universe.


ISAAC NEWTON GROUP

Scoping out a burst. The William Herschel telescope.

"The key to [finding burst sources] is to observe the suspect region with a large optical telescope within 24 hours after the event," says van Paradijs. If he and his colleagues really have pinpointed a burst source, they will have taken a major step toward solving a decades-old mystery. Over the last 30 years, space-based detectors have picked up hundreds of these gamma-ray flashes, but astronomers disagree about what might be producing them and even where they come from. According to the "local" hypothesis, violent events on neutron stars—the dense relics of massive stars—in the neighborhood of our own galaxy are responsible. The competing "cosmological" hypothesis holds instead that gamma-ray bursts are even more violent events in distant galaxies.

Neither view could prevail because the poor directional resolution of gamma-ray detectors kept astronomers from linking the bursts to any identifiable objects. That may have changed, thanks to a series of observations beginning 28 February, when the Italian-Dutch satellite Beppo-SAX detected a burst and then spotted a source of x-rays at the burst position. The x-ray observation enabled astronomers to pinpoint the event to a patch of sky less than an arc minute across—about a thirtieth of the width of the full moon (*Science*, 14 March, p. 1560).

Only 21 hours after the burst, van Paradijs and his colleagues made an image of the stars and galaxies in this tiny patch of sky with the William Herschel and Isaac Newton telescopes at the Roque de los Muchachos Observatory on the Canary Islands. Eight days later, they made a second image—and found that one point of light in the field had faded. On 13 March, Griet van der Steene of the European Southern Observatory took a close look at the object, by then very faint, with ESO's 3.5-meter New Technology Telescope at La Silla, Chile, and discerned a small, dim galaxy.

Van Paradijs and his colleagues, who announced their discovery late last week in a circular of the International Astronomical Union, argue that "the position and rapid decline [of the galaxy] contemporaneous with that of the Beppo-SAX x-ray transient indicate that the two are related." Whether the x-ray source really corresponded to the original gamma-ray burst is a bit less certain, says van Paradijs, but the link "smells good." That would spell the death of the local hypothesis, he adds, noting that he himself has favored that view in the past. Cambridge University astronomer Martin Rees agrees that the Dutch observations "strongly tilt the balance in favor of the cosmological hypothesis," although he adds that it would take several more observations of the same kind to settle the question.

The burden would then be on theorists to explain what could produce a flash of gamma rays so powerful that it can be seen from the far reaches of the universe. Many believe that only the collision of two neutron stars could do the job. Neutron stars orbiting each other lose energy by emitting gravitational waves and gradually spiral together. This fatal attraction inevitably leads to the death of both, in a terrible *crime passionelle double*.

But as to how the energy of the cataclysm could be turned into gamma rays, "there are hardly any serious theories," says Frank Verbunt, an x-ray and high-energy astrophysicist at the University of Utrecht in the Netherlands. It will take more efforts like this one, combining gamma-ray, x-ray, and optical observations, to produce a full picture of the crime.

Such efforts may be hampered, however, by an ailing Beppo-SAX. Two of the six gyroscopes that stabilize the satellite have failed, one in December and one in January, and a third is faltering. Officials at the Italian Space Agency (ASI) are playing down the problem, insisting that they can control the satellite by other methods if more gyros fail. "It's no big deal. ... The mission could even continue without the gyroscope system," a senior ASI scientist told *Science*.

–Govert Schilling, with reporting by Susan Biggin

Schilling and Biggin are writers in the Netherlands and Italy, respectively.