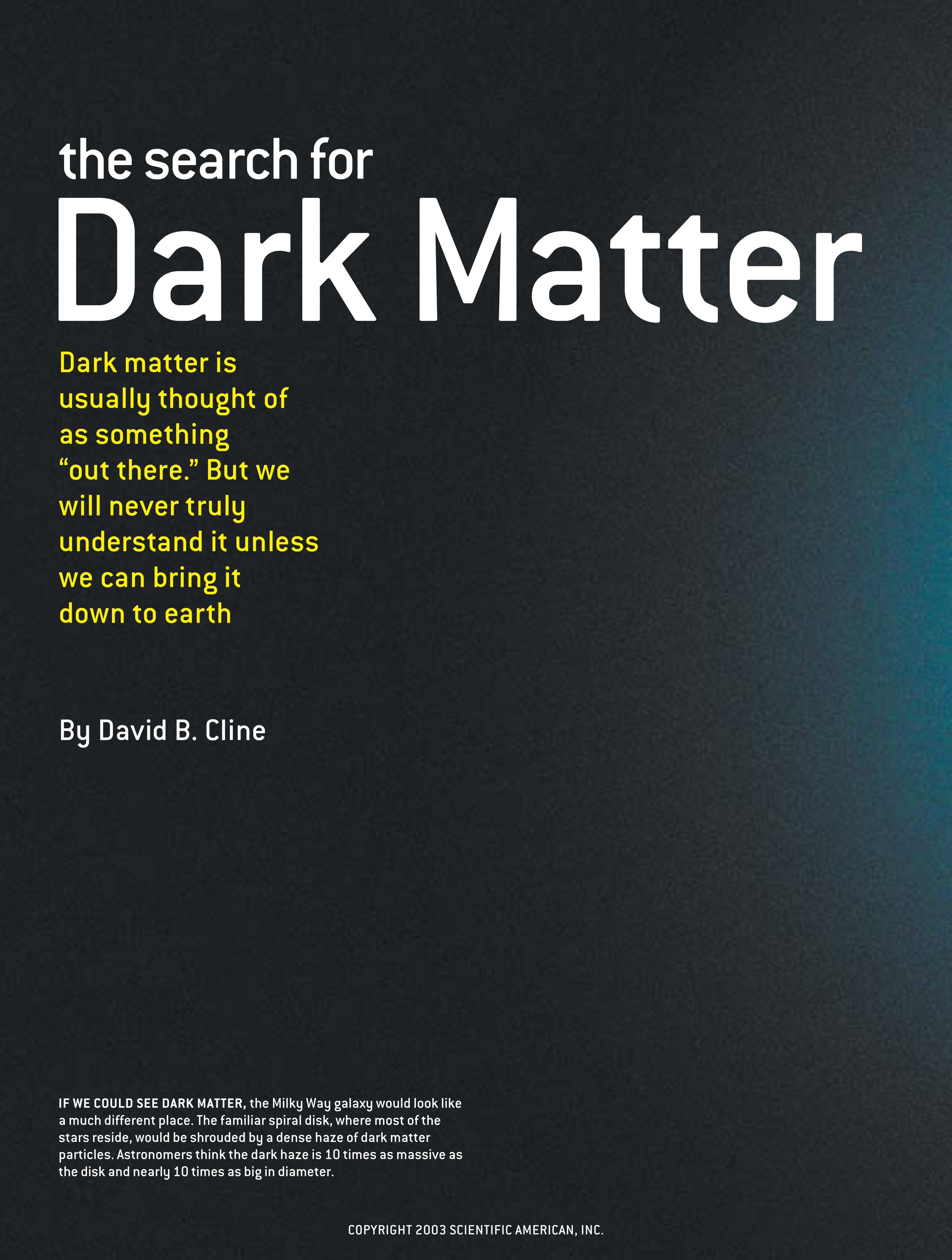
the search for
Dark Matter

Dark matter is usually thought of as something "out there." But we will never truly understand it unless we can bring it down to earth

By David B. Cline



IF WE COULD SEE DARK MATTER, the Milky Way galaxy would look like a much different place. The familiar spiral disk, where most of the stars reside, would be shrouded by a dense haze of dark matter particles. Astronomers think the dark haze is 10 times as massive as the disk and nearly 10 times as big in diameter.

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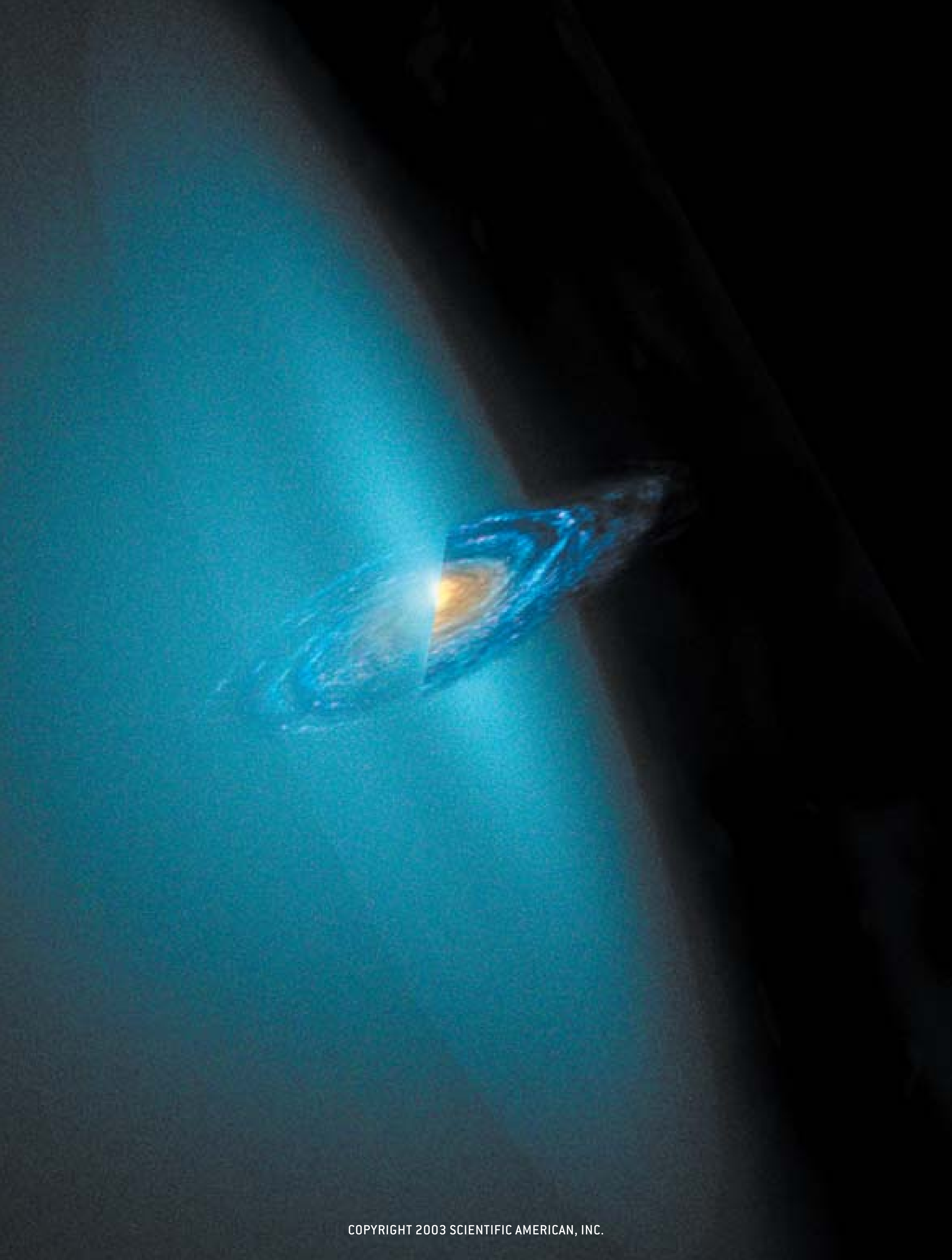

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The universe around us is not what it appears to be. The stars make up less than 1 percent of its mass; all the loose gas and other forms of ordinary matter, less than 5 percent. The motions of this visible material reveal that it is mere flotsam on an unseen sea of unknown material. We know little about that sea. The terms we use to describe its components, "dark matter" and "dark energy," serve mainly as expressions of our ignorance.

For 70 years, astronomers have steadily gathered circumstantial evidence for the existence of dark matter, and nearly everyone accepts that it is real. But circumstantial evidence is unsatisfying. It cannot conclusively rule out alternatives, such as modified laws of physics [see "Does Dark Matter Really Exist?" by Mordehai Milgrom; Scientific American, August 2002]. Nor does it reveal much about the properties of the supposed material. Essentially, all we know is that dark matter clumps together, providing a gravitational anchor for galaxies and larger structures such as galaxy clusters. It almost certainly consists of a hitherto undiscovered type of elementary particle. Dark energy, despite its confusingly similar name, is a separate substance that entered the picture only in 1998. It is spread uniformly through space, exerts a negative pressure and causes the expansion of the universe to accelerate.

Ultimately the details of these dark components will have to be filled in not by astronomy but by particle physics. Over the past eight years the two disciplines have pooled their resources, coming together at meetings such as the Symposia on Sources and Detection of Dark Matter and Dark Energy in the Universe. The next symposium will be held in February 2004 in Marina del Rey, Calif. The goal has been to find ways to detect and study dark matter using the same techniques that have been so successful for analyzing particles such as positrons and neutrinos. Rather than inferring its presence by looking at distant objects, scientists would seek the dark matter here on Earth.

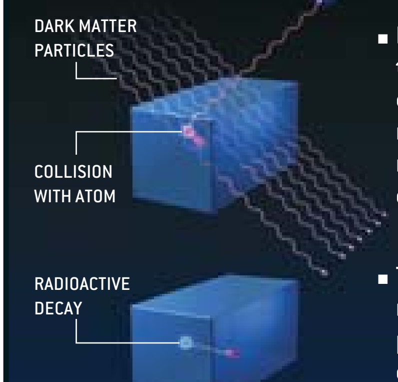
The search for dark matter particles is among the most difficult experiments ever attempted in physics. (The search for particles of dark energy is even less tractable and has been put aside, at least for the time being.) At the first symposium, in February 1994, participants expressed a nearly total lack of confidence that a particle detector in an Earth-based lab could ever register dark matter. The sensitivity of even the best instruments was a factor of 1,000 too low to pick up hypothesized types of dark particles. But since then, detector sensitivity has improved 1,000-fold, and instrument builders expect soon to wring out another factor of 1,000. More than 15 years of research and development on detector methods are finally bearing fruit. We may soon know what the universe is really like. Either dark matter will prove to be real, or else the theories that underlie modern physics will have to fall on their swords.

Through the Looking Glass

WHAT KIND OF particle could dark matter be made of? Astronomical observation and theory provide some general clues. It cannot be protons, neutrons, or anything that was once made of protons or neutrons, such as massive stars that became black holes. According to calculations of particle synthesis during the big bang, such particles are simply too few in number to make up the dark mat-

Overview/*Dark Matter Detectors*

Most astronomers think the heavens are filled with dark matter, but their observations are too imprecise to provide unequivocal proof, let alone measure the detailed properties of the supposed material. Particle physicists are trying to take up the slack by building detectors to look for the dark matter as it streams through Earth.



- Particles of dark matter, though reluctant to interact with ordinary atoms, should still do so occasionally. When such a particle ricochets off an atomic nucleus, the nucleus recoils, hits surrounding atoms and releases energy in the form of heat or light.
- The real trick is to distinguish this energy release from the effects of more prosaic processes, such as radioactive decay. Such effects may account for the only reported detection of dark matter to date.

DON DIXON (*preceding pages*); SLIM FILMS (*this page*)

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COMPOSITION OF THE UNIVERSE

MATERIAL	REPRESENTATIVE PARTICLES	TYPICAL PARTICLE MASS OR ENERGY (ELECTRON VOLTS)	NUMBER OF PARTICLES IN OBSERVED UNIVERSE	PROBABLE CONTRIBUTION TO MASS OF UNIVERSE	SAMPLE EVIDENCE
Ordinary (“baryonic”) matter	Protons, electrons	10^6 to 10^9	10^{78}	5%	Direct observation, inference from element abundances
Radiation	Cosmic microwave background photons	10^{-4}	10^{87}	0.005%	Microwave telescope observations
Hot dark matter	Neutrinos	≤ 1	10^{87}	0.3%	Neutrino measurements, inference from cosmic structure
Cold dark matter	Supersymmetric particles?	10^{11}	10^{77}	25%	Inference from galaxy dynamics
Dark energy	“Scalar” particles?	10^{-33} (assuming dark energy comprises particles)	10^{118}	70%	Supernova observations of accelerated cosmic expansion

ter. Those calculations have been corroborated by measurements of primordial hydrogen, helium and lithium in the universe.

Nor can more than a small fraction of the dark matter be neutrinos, a lightweight breed of particle that zips through space and is unattached to any atom. Neutrinos were once a prominent possibility for dark matter, and their role remains a matter of discussion, but experiments have found that they are probably too lightweight [see “Detecting Massive Neutrinos,” by Edward Kearns, Takaaki Kajita and Yoji Totsuka; Scientific American, August 1999]. Moreover, they are “hot”—that is, in the early universe they were moving at a velocity comparable to the velocity of light. Hot particles were too fleet-footed to settle into observed cosmic structures.

The best fit to the astronomical observations involves “cold” dark matter, a term that refers to some undiscovered particle that, when it formed, moved sluggishly. Although cold dark matter has its own problems in explaining cosmic structures [see “The Life Cycle of Galaxies,” by Guinevere Kauffmann and Frank van den Bosch; Scientific American, June 2002], most cosmologists consider these problems minor compared with the difficulties faced by alternative hypotheses. The current Standard Model of elementary particles contains no examples of particles that could serve as cold dark matter, but extensions of the Standard Model—developed for reasons quite separate from the needs of astronomy—offer many plausible candidates.

By far the most studied extension of this kind is supersymmetry, so I will concentrate on this theory. Supersymmetry is an attractive explanation for dark matter because it postulates a whole new family of particles—one “superpartner” for every known elementary particle. These new particles are all heavier (hence more sluggish) than known particles. Several are natural candidates for cold dark matter. The one that gets the most attention is the neutralino, which is an amalgam of the superpartners of the photon (which transmits the electromagnetic force), the *Z* boson (which transmits the so-called weak nuclear force) and perhaps other particle types. The name is somewhat unfortunate: “neutralino” sounds much like “neutrino,” and the two particles indeed share various properties, but they are otherwise quite distinct.

Although the neutralino is heavy by normal standards, it is generally thought to be the lightest supersymmetric particle. If so, it has to be stable: if a superparticle is unstable, it must decay into two lighter superparticles, and the neutralino is already the lightest. As the name implies, the neutralino has zero charge, so it is unaffected by electromagnetic forces (such as those involving light). The hypothesized mass, stability and neutrality of the neutralino satisfy all the requirements of cold dark matter.

The big bang theory gives an estimate of the number of neutralinos that were created within the hot primordial plasma of the cosmos. The plasma was a chaotic soup of all types of particles. No individual particle survived for long. It would quickly collide with another particle, annihilating both but producing new particles in the process; those new particles soon collided with others, in a cycle of destruction and creation. But as the universe cooled down and thinned out, the collisions became less violent, and the process

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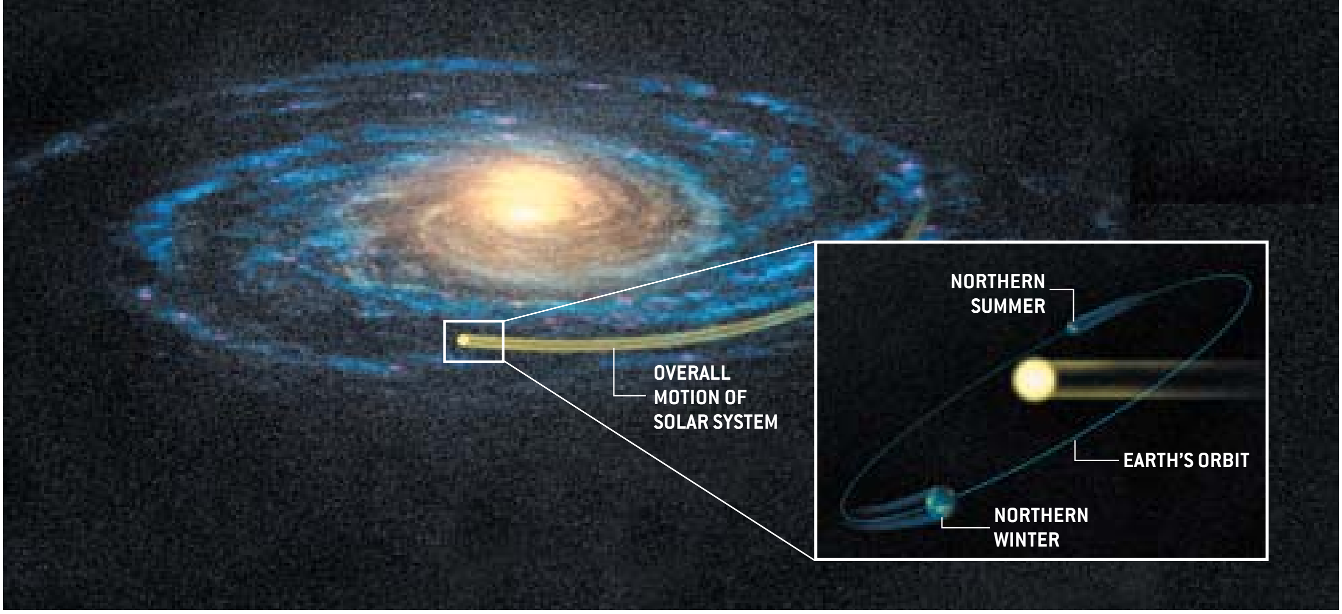
THE DARK WIND

LIKE MOTORCYCLISTS FEELING the wind in their face, we on planet Earth are being blasted by a head wind of dark matter. The dark matter is essentially a stagnant gas—particles move randomly but have no organized motion—and our solar system roars through this material at 220 kilometers a second. Within the solar system, Earth orbits at 30 kilometers a second. When the tilt of the orbit is taken into account, the head wind has a net velocity of 235 kilometers a second in the northern summer and 205 kilometers a second in winter. This variation distinguishes dark matter from noise, which does not change with the seasons.



DON DIXON

ground to a halt. Particles condensed out one by one, beginning with those that tended to collide less often and proceeding to more collision-prone types.

Shy but No Hermit

THE NEUTRALINO is a particularly collision-shy particle, so it froze out early on. At the time, the density of the universe was still very high, so a huge number of neutralinos were produced. In fact, based on the expected neutralino mass and its low tendency to collide, the total mass in neutralinos almost exactly matches the inferred mass of dark matter in the universe. This correspondence is a strong sign that neutralinos are indeed dark matter.

To detect dark matter, scientists need to know how it interacts with normal matter. Astronomers assume that it interacts only by means of gravitation, the weakest of all the known forces of nature. If that is really the case, physicists have no hope of ever detecting it. But the astronomers' assumption is probably just a convenient approximation—something that lets them describe cosmic structures without worrying about the detailed properties of the particles.

Theories of supersymmetry predict that the neutralino will interact by a force stronger than gravitation: the weak nuclear force. This is similar to the interaction that betrays neutrinos [see "The Search for Intermediate Vector Bosons," by David B. Cline, Carlo Rubbia and Simon van der Meer; Scientific American, March 1982]. The vast majority of neutralinos will slip through a slab of matter without interacting, but the occasional neutralino will hit an atomic nucleus. The unlucky particle will transfer a small amount of its energy to the nucleus.

The improbability and feebleness of the interaction are offset by the sheer number of particles. After all, dark matter is thought to dominate the galaxy. Being dark, it was never able to lose energy by emitting radiation, so it never could agglomerate into subgalactic clumps such as stars and planets. Instead it continues to suffuse interstellar space like a gas. Our solar system is orbiting around the center of the galaxy at 220 kilometers a second, so we are pushing through this gas at quite a clip [*see illustration above*]. Researchers estimate that a billion dark matter particles flow through every square meter every second.

Leszek Roszkowski and his team at the University of Lancaster in England recently carried out a complete calculation of the rates of neutralino interactions with normal matter. The rates are usually expressed as the number of events that would occur in a day in a sin-

THE AUTHOR

DAVID B. CLINE has now written seven articles for *Scientific American,* a new record for a researcher. Cline is professor of physics and astrophysics at the University of California, Los Angeles. His research has addressed the most important topics in particle physics: high-energy neutrinos, proton decay and the *W* and *Z* bosons, carriers of the weak nuclear force. More recently, his interests have turned to the search for dark matter. He works with the CMS detector at CERN near Geneva, which could one day produce dark matter.

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gle kilogram of normal matter. Depending on the theoretical details, the figures vary from 0.0001 to 0.1 event per kilogram a day. Current experiments are able to detect event rates in the high end of this range.

The main difficulty is no longer detector sensitivity but detector impurity. All materials on Earth, including the metal out of which the detectors are built, contain a trace amount of radioactive material such as uranium and thorium. The decay of this material produces particles that register much as dark matter would. Terrestrial radioactivity typically outpowers the putative neutralino signal by a factor of 10^6. If the detectors are located aboveground, cosmic rays worsen the situation by an equal factor. To identify dark matter particles with any confidence, researchers must reduce both these unwanted backgrounds a millionfold.

Turning the Other Cheek

PHYSICISTS THUS FACE two challenges: to detect the inherently weak interaction of dark matter with ordinary matter and to screen out confounding noise. To take the first challenge first, several properties of matter can be used to record the recoil of a nucleus that has been struck by a neutralino. Perhaps the simplest of all possible methods is just to look for the heating that will occur when the recoiling nucleus plows into the surrounding matter and gives up its kinetic energy, thereby raising the temperature of the material slightly. To detect this heating, the material must be at a very low temperature to start with. This is the principle of a cryogenic detector.

Cryogenic detectors such as those used by two leading search programs, the Cryogenic Dark Matter Search (CDMS) and Edelweiss, are designed to measure individual phonons, or quanta of heat, in a material. They operate at a temperature of about 25 millikelvins and use thermistors to record the temperature rise in the various parts of the apparatus. Individual detectors have a mass of a few hundred grams, and researchers can stack a large number of detectors to reach a total mass of a few kilograms or more, thereby boosting the signal. The latest incarnation of CDMS, located inside the Soudan Mine in Minnesota, is scheduled to start taking data later this year.

A second method watches for another effect of the recoiling nucleus: ionization. The nucleus knocks some electrons off surrounding atoms, resulting in excited ions known as excimers. Those ions eventually recapture an electron and return to normal. In some materials, mainly noble gas liquids such as xenon, the process triggers the emission of light, called scintillation light. This is how excimer lasers—those used in eye surgery—work. For liquid xenon, the light is very intense and lasts about 10 nanoseconds. A photomultiplier can amplify the signal to detectable levels.

In the early 1990s the ZEPLIN project—led by HanGuo Wang and me at U.C.L.A. and Pio Picchi of the University of Turin in Italy—developed two-phase liquid-xenon detectors. These instruments amplify the light by introducing a layer of gas threaded by an electric field; the field accelerates the electrons that get kicked off by recoiling nuclei, thereby turning a handful of particles into an avalanche. Eventually it should be possible

LEADING SEARCHES FOR DARK MATTER

PROJECT	LOCATION	START DATE	PRIMARY DETECTOR TYPE	PRIMARY DETECTOR MATERIAL	PRIMARY DETECTOR MASS (kg)	DISCRIMINATION DETECTOR TYPE(S)
UKDMC	Boulby, U.K.	1997	Scintillation	Sodium iodide	5	None
DAMA	Gran Sasso, Italy	1998	Scintillation	Sodium iodide	100	None
ROSEBUD	Canfranc, Spain	1999	Cryogenic	Aluminum oxide	0.05	Thermal
PICASSO	Sudbury, Canada	2000	Liquid droplets	Freon	0.001	None
SIMPLE	Rustrel, France	2001	Liquid droplets	Freon	0.001	None
DRIFT	Boulby, U.K.	2001	Ionization	Carbon disulfide gas	0.16	Directional
Edelweiss	Frejus, France	2001	Cryogenic	Germanium	1.3	Ionization, thermal
ZEPLIN I	Boulby, U.K.	2001	Scintillation	Liquid xenon	4	Timing
CDMS II	Soudan, Minn., U.S.	2003	Cryogenic	Silicon, germanium	7	Ionization, thermal
ZEPLIN II	Boulby, U.K.	2003	Scintillation	Liquid xenon	30	Ionization, scintillation
CRESST II	Gran Sasso, Italy	2004	Cryogenic	Calcium tungsten oxide	10	Scintillation, thermal

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to construct a 10-metric-ton liquid-xenon detector, which should be sensitive to the neutralinos even if their interactivity is very low.

The xenon need not be in liquid form. Some detectors use it in gaseous form. Although the gas has a lower density than the liquid does, gas more readily reveals the trail left by the recoiling nucleus. The trail points back to the direction of the incoming dark matter, allowing a further check that a galactic neutralino is responsible. Detectors of this type are being developed for the Boulby underground laboratories in England.

Xenon is convenient because it has no natural long-lived radioactive isotopes (thus reducing the background noise) and is readily available in the atmosphere (after purification to remove radioactive krypton left over from nuclear bomb tests). But it is not the only material that scintillates. DAMA, an experiment being conducted at the Gran Sasso Laboratory near Rome, uses sodium iodide. With a mass of 100 kilograms, DAMA is the largest detector in the world.

Telling the Difference

THREE STEPS are generally taken to cope with the other great challenge, overcoming the background noise from natural radioactivity and cosmic rays. First, researchers screen out cosmic rays by placing detectors deep underground and enclosing them in special shields. Second, they purify the detector material to reduce radioactive contamination. Third, they build special instruments to look for the telltale signs that distinguish dark matter from other particles.

Even when the first two steps are taken, they are not enough. Therefore, new dark matter detectors all take the third step, employing some form of event discrimination. The first line of defense is to look for an annual variation of the signal. The flux of dark matter should be higher

TWO TYPES OF DARK MATTER DETECTORS

SCINTILLATION DETECTOR

ZEPLIN II project (*also below*)

Principle:
Looks for slight pulses of light triggered by dark matter passing through, in this case, liquid xenon

Advantages:

- Measurement of shape of pulse, potentially distinguishing dark matter from ordinary matter
- Measurement of multiple particle properties

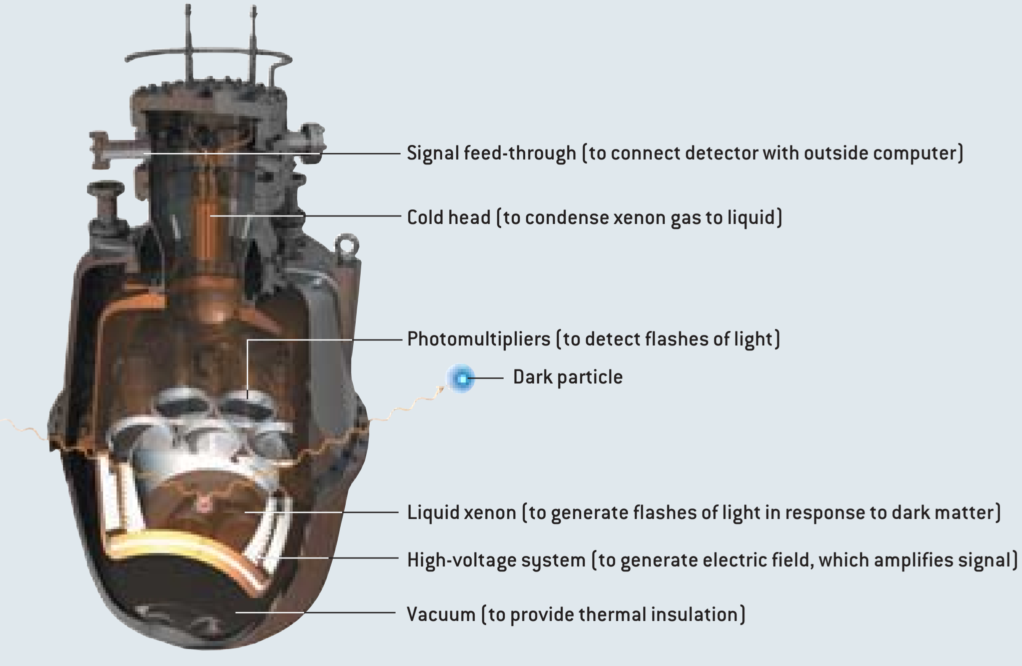
CRYOGENIC DETECTOR

CDMS II project

Principle:
Looks for slight pulses of heat generated by dark matter passing through a supercooled crystal

Advantages:

- Simplicity
- High sensitivity to low-energy particles
- Precise measurement of particle energy



COURTESY OF DAVID B. CLINE; ROY PREECE *Dark Matter Group, Rutherford Appleton Laboratory (cutaway illustration)*

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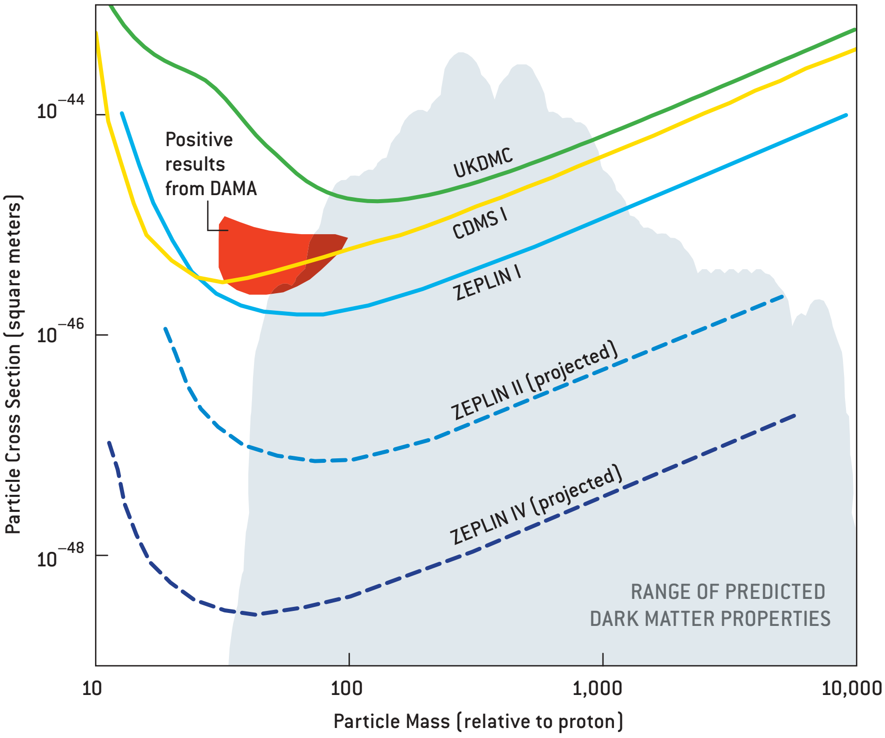
in the northern summer, when Earth's orbital motion adds to the overall motion of the solar system through the galaxy, than in the northern winter, when Earth's motion subtracts from that of the solar system [*see illustration on page 54*]. The signal variation could be as high as a few percent.

The most advanced projects add a secondary detector, built using a different technology from that of the primary. The two detectors will respond to different types of particles in slightly different ways. For example, background particles tend to produce more ionization than a nucleus recoiling from a neutralino collision. By combining two detectors, this difference can be caught.

Using one or more of the above techniques, searches for dark matter signals started in earnest in the late 1980s. All but one have been null to date, which is not surprising, because they have only recently achieved the requisite sensitivity and noise tolerance. The lone exception is DAMA. Four years ago this project reported an observation of annual variation, which created excitement and skepticism in equal measure [see "Revenge of the WIMPs," by George Musser; News & Analysis, SCIENTIFIC AMERICAN, March 1999]. The problem was that DAMA does not use multiple detectors to discriminate between signal and noise. Three other experiments that do use multiple detectors have since cast doubt on DAMA's claims. Edelweiss, ZEPLIN I and CDMS I observed nothing in much of the range of parameters that DAMA had probed. The CDMS I team claimed a confidence level of 98 percent for the null result. If independent projects continue to come up empty-handed, the DAMA researchers will have to attribute their signal to radioactive processes or other noise.

The new generation of detectors should be able to rule neutralinos conclusively in or out. If they do not find anything, then supersymmetry must not be the solution that nature has chosen for the dark matter problem. Theorists would have to turn to other ideas, however distasteful that may now seem. But if the detectors do register and verify a signal, it would go down as one of the great accomplishments of the 21st century. The discovery of 25 percent of the universe (leaving only the dark energy unexplained) would obviously be the most spectacular implication. Other valuable information would follow. If detectors can spot particles of dark matter, particle accelerators such as CERN's Large Hadron Collider near Geneva might be able to re-create them and conduct controlled experiments. The confirmation of supersymmetry would imply a vast number of new particles waiting to be discovered and would lend support to string theory, in which supersymmetry plays an integral role. The greatest mystery in modern astrophysics may soon be solved.



DARK MATTER PROPERTIES are predicted by theory to fall somewhere within a certain range (*gray area*). The two properties shown here are the mass and the effective cross-sectional area, which is a measure of how likely it is that the dark matter particles will interact with ordinary matter. Detectors (*colored curves*) already probe a substantial part of this predicted range; the colored curves indicate the limit of their sensitivity. Most have found nothing, but one, known as DAMA, has seen hints of dark matter with a narrow band of possible properties (*red area*). Future detectors should be able to probe most of the predicted range, either proving the existence of dark matter or ruling it out.

JOHNNY JOHNSON; SOURCE: RICK GAITSKELL AND VUK MANDIC *University of California, Berkeley (dendera.berkeley.edu/plotter/entryform.html)*

MORE TO EXPLORE

Through a Universe Darkly: A Cosmic Tale of Ancient Ethers, Dark Matter, and the Fate of the Universe. Marcia Bartusiak. HarperCollins, 1993.

Supersymmetric Dark Matter. Gerard Jungman, Marc Kamionkowski and Kim Griest in *Physics Reports,* Vol. 267, pages 195–373; March 1996. Available at **arXiv.org/abs/hep-ph/9506380**

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Quintessence: The Mystery of the Missing Mass. Lawrence M. Krauss. Basic Books, 2001.

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WIMP Direct Detection Overview. Yorck Ramachers. Invited review at Neutrino 2002 conference, Munich, Germany, May 25–30, 2002. **arXiv.org/abs/astro-ph/0211500**

Some Web sites on specific programs:
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cdms.berkeley.edu
www.lngs.infn.it/lngs/htexts/dama
hepwww.rl.ac.uk/ukdmc/ukdmc.html
avmp01.mppmu.mpg.de/cresst

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