SCIENCE DIGEST

MISSING:

97% OF THE UNIVERSE

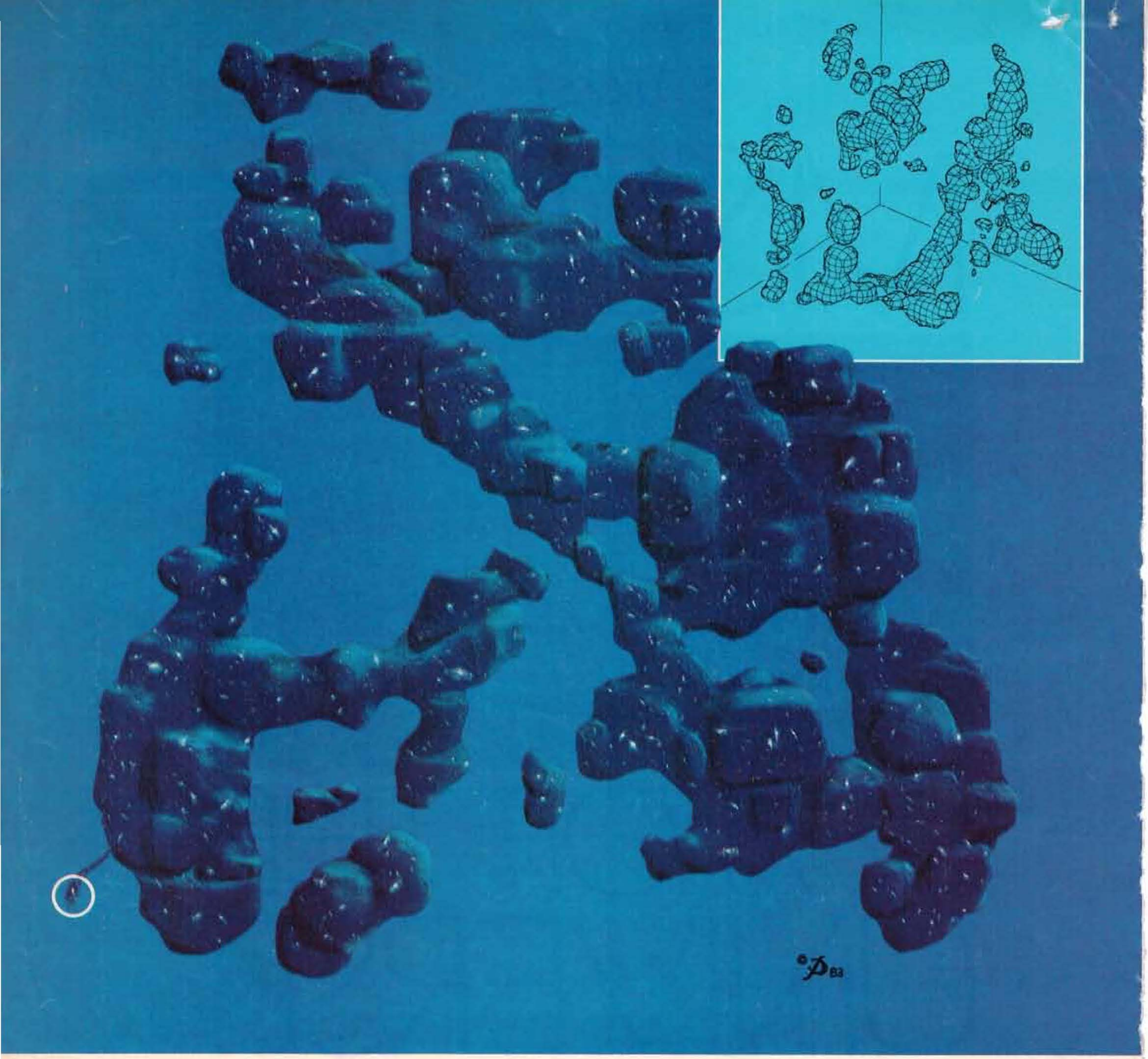
Its discovery will provide astronomers with the answer to the ultimate fate of the cosmos.

BY MARCIA BARTUSIAK The situation is mysterious, intriguing "and embarrassing," admits Princeton physicist P. James Peebles. Astronomer Joseph Silk, of the University of California, Berkeley, calls it cosmology's "dire secret": Most of the mass of the universe, perhaps as much as 97 percent, appears to be missing. Or maybe it is simply playing an awfully good game of hide-and-seek with all our Earthly detectors.

All over the globe, scientists are marshaling their efforts to

Are spiral galaxies immersed in invisible spherical halos of an enigmatic dark matter? That would explain their strange spins.

Photograph from Hale Observatory, Halton C. Arp Collection



ARE SWARMS OF BLACK HOLES THE SIZE OF BEACH BALLS HOARDING THE MISSING MASS? OR IS IT AN EXOTIC FORM OF MATTER? THE EXTENT OF OUR IGNORANCE CAN BE MEASURED BY THE AMAZING RANGE OF IDEAS.

identify this invisible material—called dark matter—pervading our cosmos. At stake is the ultimate fate of the universe. Will it expand forever or will it eventually collapse back to reform that primeval fireball? Explains Berkeley astronomer Marc Davis, "The mass that we can now see directly as galaxies is really only about one percent of the amount you need to make the universe close back up." Dark matter could turn the tide.

Astronomers are clearly baffled. Vera Rubin, of the Carnegie Institution of Washington, points out that the enormity of their ignorance can be measured by the astounding range of objects put forth as candidates for the missing mass—from a bevy of Jupiter-like planets to swarms of black holes the size of beach balls.

Marcia Bartusiak, with a master's degree in physics, writes frequently on astronomy for science magazines.

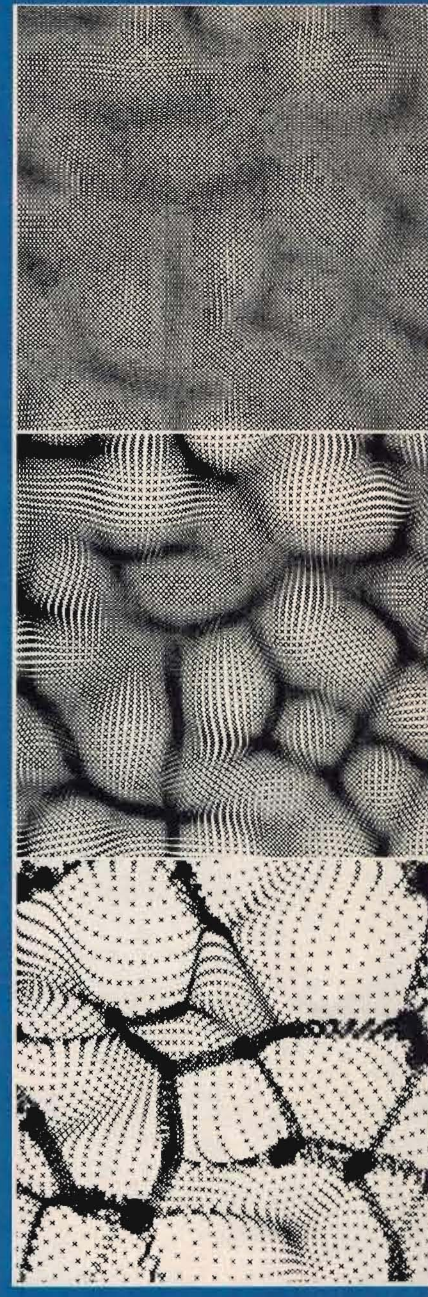
The dark haze may not even be composed of the protons and neutrons that make up the stuff of our everyday life. It may be made up of a more exotic species of matter, perhaps subatomic particles called neutrinos or yet-to-be-discovered gravitinos.

"The presence of this dark matter really extends the Copernican principle," notes theorist Douglas Lin of the University of California, Santa Cruz. "First, we found out that the Earth is not the center of the universe and later that the galaxy is not even the hub. Now, we're finding out that we might not even be made out of the most abundant material in the universe!"

The missing mass raises a question about the very endeavor of astronomy. Some are asking whether astronomers can really hope to understand the workings of the universe if the objects of their attention—exploding galaxies, spinning neutron stars and dusty molecular clouds—are

Illustration by Kim Poor from information provided by Carlos S. Frenk, Simon White and Marc Davis, University of California, Berkeley; inset computer simulation courtesy of Carlos S. Frenk

Could dark, Jupiter-size balls of gas, too small to ignite the nuclear burning that would allow them to blaze forth as stars, be hoarding the missing mass? Probably not, say most scientists; we have already accounted for most of the ordinary matter theory predicts was forged at the beginning of the universe.



Monstrous strands and clots of matter hover within vast empty spaces in this model of a typical region in our universe (left). Our galaxy is in the white circle at the lower left. A computer simulation (inset) shows how the universe would look if neutrinos, as some scientists suspect, have mass. The two versions turn out to be strikingly similar in basic structure.

only luminous flotsam floating in a much larger sea of invisible matter.

The first hint that something was amiss in the universe came 50 years ago. Astronomer Fritz Zwicky noticed some peculiar goings-on in a rich group of galaxies known as the Coma cluster, located 300 million light-years from Earth. The galaxies were moving about in the cluster much faster than expected. Zwicky added up all the light being emitted by the cluster and realized that there was not enough visible matter to bind the galaxies together, yet the cluster was obviously not flying apart. Where was this other mass that was providing the gravitational glue? It seemed to be missing—hence the tag, "missing mass." "It's not really missing," stresses Jeremiah Ostriker, a Princeton astrophysicist. "There's something there, you know it's there, but you just can't see it. It's missing light."

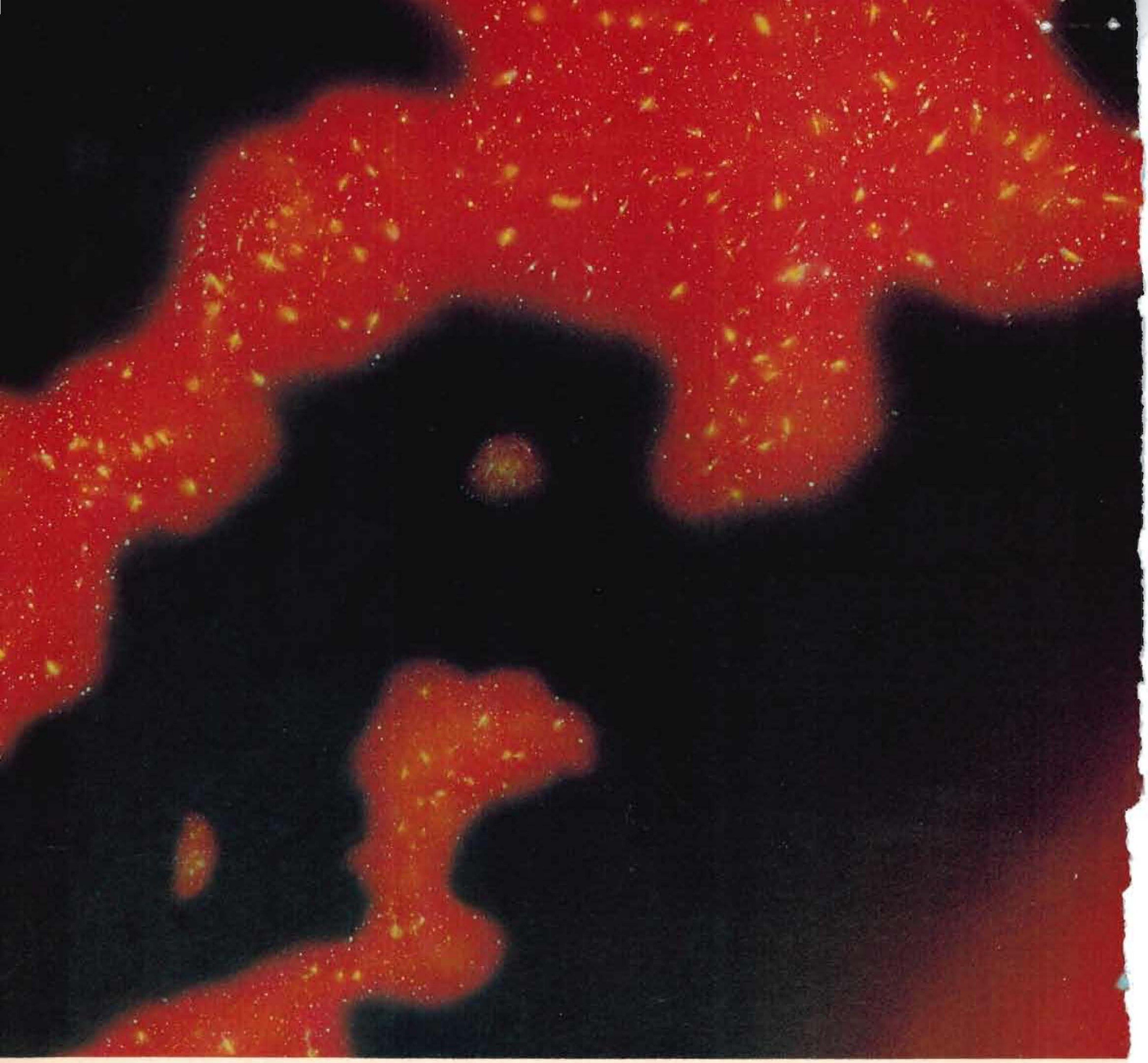
By the 1970s the problem moved closer to home. According to both theory and observation, dark matter was lurking about in our own galactic neighborhood. One physicist who realized this was David Schramm of the University of Chicago: "From all the light being emitted by the Milky Way, we can estimate that our galaxy contains the mass of about one hundred billion suns. But once we take this same object and see how it interacts with another galaxy, such as our neighbor Andromeda, we find that our galaxy is gravitating toward Andromeda as though it had a mass almost ten times greater."

It doesn't end there. The Milky Way is also falling toward a large collection of galaxies called the Virgo cluster at about 200 miles a second. From this gravitational tug-of-war, Berkeley's Davis estimates that the universe may have *40* times more mass than its output of light indicates. But where is this hidden mass located?

In 1973 Ostriker and Peebles came up with

ONE POSSIBLE HIDING PLACE: SPHERICAL HALOS. EVERY GLOWING GALACTIC DISK, THEY CONJECTURED, WAS IMMERSED

Amorphous clouds of hot, energetic particles such as massive neutrinos would have evolved as the mathematical model above shows. Based on a given distribution of particles, the model proceeds to calculate the gravitational force the particles exert on one another; the clumps and threads then form as the universe coalesces. The main problem with a neutrino universe is that the final stage—when superclusters become refined into individual galaxies—doesn't occur.



IF NEUTRINOS HAVE EVEN THE TINIEST MASS, THEY MAY BE ABLE TO BRING OUR EXPANDING UNIVERSE TO A GRINDING HALT AND RECOLLAPSE IT TOWARD THE BIG CRUNCH.

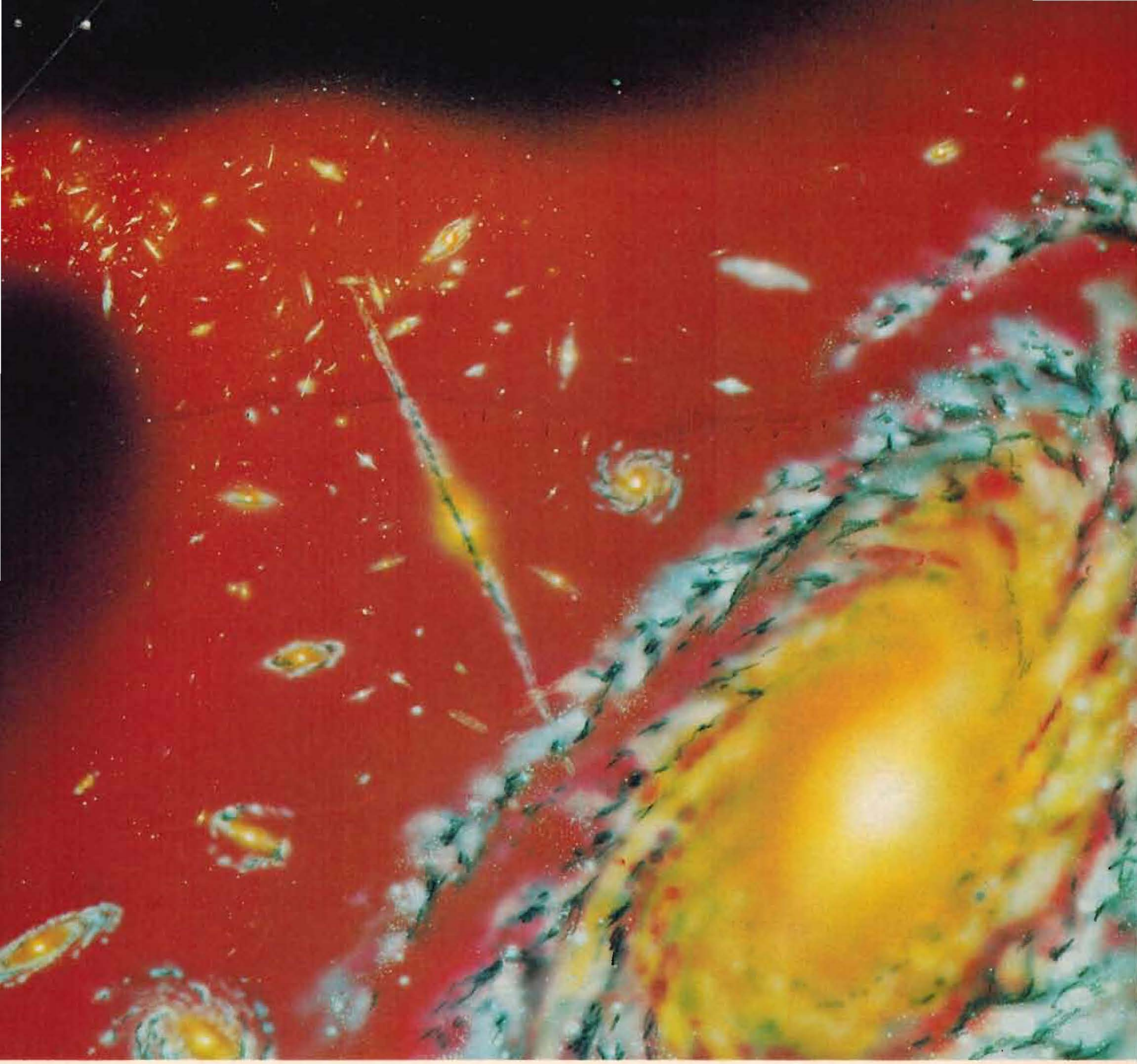
mersed in a sphere of dark material. "For me, that broke the logjam," recalls Santa Cruz astronomer Sandra Faber, an expert on the structure of galaxies. "For the first time, they gave us a physical picture, a conceptual hook to hang our hats on."

While the halo model circulated in the astronomical community, observational evidence was mounting to back it up. Both radio and optical telescopes were starting to reveal unexpected rotations in nearby galaxies. Vera Rubin, who has spent most of her 32-year career studying galactic rotations, explains: "In the solar system, the planets all orbit the sun with velocities that get smaller and smaller as they get farther from the sun, the system's center of mass. So the inner planets go fast, and the outer planets go slow. That's just a direct response to Newton's law, and it was always expected that the same thing would happen in galaxies, that the stars, gas and clouds in the outer edges would be orbiting slower."

But, to everyone's surprise, Rubin and others discovered that they did not. In galaxy after galaxy, the outer regions were moving just as fast as the inner galactic cores, sometimes even faster. "What our work has done is to show that dark matter is present in individual galaxies, as well as in clusters of galaxies [as Zwicky saw it]," says Rubin. "We just don't know, as yet, if this dark matter is the same on both levels."

At first, many blamed the missing-mass problem on bookkeeping errors: not counting all the very faint stars, cometary debris, dark planets and gas inhabiting the heavens. Indeed, improved detectors did uncover some additional mass. X-ray telescopes in space detected large amounts of X-ray-emitting gas in and around galactic clusters. More recently, Cornell University radio astronomers discovered that the vast

Illustration by Kim Poor



gulfs between galaxies may be harboring clouds of hydrogen—protogalaxies that failed to coalesce. And when University of Michigan researchers Dennis Hegyi and Garth Gerber used a sensitive photon-gathering device to look at a galaxy called NGC4565, they also upped the ante. "We found that NGC4565 was immersed in a faint halo of stars," states Hegyi. "Instead of the galaxy being a very thin disk, which is how it appears in standard photographs, it's actually puffed up, at least ten times thicker than people had ever noticed before."

The X-ray gas, faint stars and intergalactic clouds can account for only a small fraction of the missing mass. In fact, many suspect that the dark matter is not composed of the protons and neutrons that make up everything we see, from people to planets. To physicists these particles are collectively known as baryons. If it's a cold gas of baryons, points out Hegyi, the unenergetic atoms would have fallen into the centers of galaxies long ago. "And if it were a hot gas," he adds, "it would be giving off more X-rays than we now see." Aged stars, like tiny white dwarfs and neutron stars, are also bad candidates. "The death of a star is an operatic event, with most of its mass flung far out into space," notes Peebles. "If the dark matter is in the form of dead stars, we ought to see remnants. We don't."

This leaves "Jupiters" as the last baryonic hope—balls of gas too small to initiate nuclear burning deep in their cores. No one can imagine how so many near-stars are created in a halo, but Schramm is not anxious to nix the idea entirely. "We don't even know how to make stars yet," he exclaims. "Perhaps, once we learn how, we'll find out that you automatically make a bunch of little ones."

A more convincing argument for ruling out ordinary matter as the missing mass, say

Galaxies and clusters stretch out for millions and millions of light-years, like pathways amid the vacant wastes of the universe, in this artist's impression of its large-scale structure. Here, the dark matter that surrounds galaxies is shown glowing red.

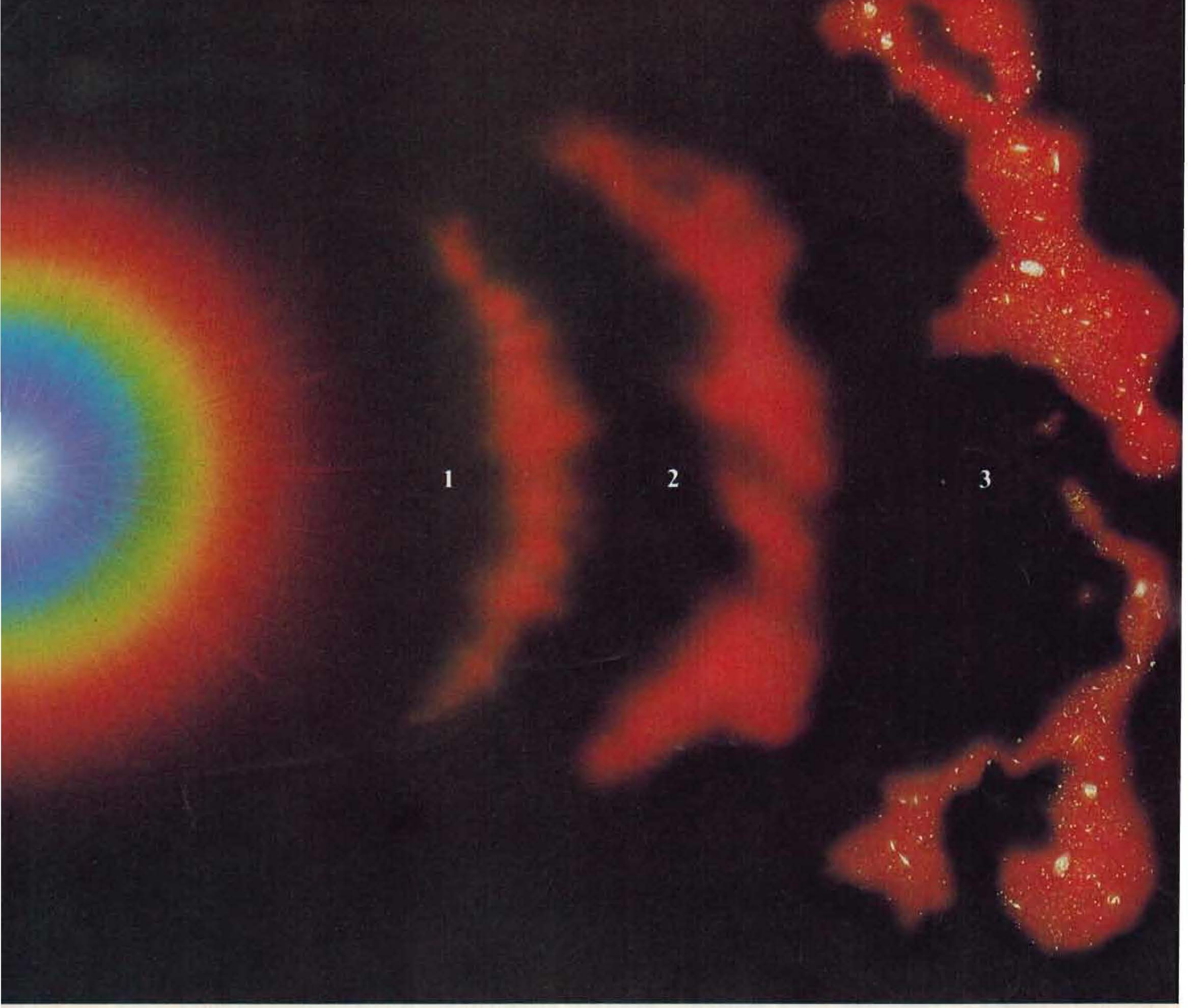
Bottom-Up theory: Not long after the Big Bang, particles of dark matter form relatively small clumps the size of galaxies (1). The normal matter that is drawn to the clumps forms glowing disks, each surrounded by a dark-matter halo (2). As gravity draws the galaxies into larger clusters, the individual halos begin to merge (3).

IF THE HEAVENS BEGAN AS A "LUMPY SOUP" OF BARYONS AND COLD PARTICLES LIKE AXIONS, THE RESULTING OBJECTS WOULD LOOK SUSPICIOUSLY LIKE GALAXIES.

Schramm and others, arises from man's current theories concerning the cataclysmic birth of our universe. If you count up all the luminous matter in the heavens, it just about matches the density of baryons estimated to have been forged after the Big Bang. It would upset the cosmic applecart to squeeze in 30 or 40 times as many.

This has convinced many physicists and astronomers that the missing mass must be a more bizarre material. Enthusiasm for this idea grew immensely three years ago when physicists in the United States and the Soviet Union independently announced that a strange elementary particle known as the neutrino had been found to have a small mass. Wolfgang Pauli first postulated the existence of neutrinos in 1930, but then they were considered bits of nothing, massless motes that carried away some energy during radioactive decay processes. They were nature's most indifferent particle, able to travel through

TOP-DOWN THEORY



Top-Down theory: Huge clouds of dark matter, each the size of a supercluster 100 million light-years across, form (1). Ordinary matter is drawn into this cloud, which spreads out (2) and forms clots and threads, fragmenting next into galaxies (3). Dark matter surrounds the cluster.

light-years of lead without interacting. Trillions are passing through you right now as you read this sentence.

Physicists calculate that hordes of these ghostly particles came spewing out of the Big Bang. They outnumber baryons, the particles of ordinary matter, by a billion to one. Hence, giving neutrinos even the tiniest mass would have enormous implications. They would not only account for the dark matter, but their combined mass might be enough to bring our expanding universe to a grinding halt and recollapse it toward the Big Crunch.

Recent experiments, however, have failed to confirm that neutrinos have mass. That hasn't stopped a number of research groups throughout the world from racing to their computers and asking, "If neutrinos do have mass, what would the universe look like?" Intriguingly, a cosmos filled with massive neutrinos closely resembles our own in many aspects.

The scenario begins tens of thousands of years after the Big Bang. "At this time, imagine the universe as a sea of particles," says Carlos Frenk, an astrophysicist at Berkeley. "But this sea is not perfectly smooth. It has ripples." These large ripples break the neutrinos into myriad clumps, each weighing about 1,000 trillion solar masses and stretching across 100 million light-years. That happens to be the exact size and mass of today's superclusters of galaxies.

Soon, these neutrino clumps shape themselves into a network of filaments—strands of matter separated by large voids, not unlike a three-dimensional cobweb. Interestingly enough, astronomers are now seeing that galaxies and clusters within our own universe appear to be strung out along lengthy linked chains separated by

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vast regions of nothingness. Schramm, who along with Gary Steigman of the Bartol Research Institute in Delaware was one of the first to consider a neutrino universe, remarks: "Suddenly, massive neutrinos could explain something which was previously a mystery—the supercluster-size filaments. It had the smell of truth about it."

According to the scenario, these giant clumps of neutrinos act as gravitational traps. Once ordinary matter settles out of that cosmic sea of particles, about a million years after the Big Bang, it is immediately drawn into these ready-made neutrino wells, like water into a whirlpool. This scheme greatly boosted the "top-down" theory of galactic formation, a model long championed by Soviet theorist Yakov Zeldovich. He and his colleagues have argued that cluster-size clouds of matter came first and then fragmented to form galaxies later.

But there's one problem: No one can figure out how to fragment these gigantic clouds of dust and gas into galaxies, and quickly. "You do have to wring your hands a bit to make galaxy-size objects when you start with a universe filled with superclusters," notes astrophysicist George Blumenthal of the University of California, Santa Cruz.

And if there are indeed halos of invisible matter around individual galaxies, rather than dark, massive clouds surrounding entire clusters, it's difficult to work with neutrinos; many physicists contend that these "hot," energetic particles won't settle down into a galaxy-size space. "Neutrinos do move around quite a bit," comments Peebles. "This makes them rather uncomfortable candidates for making galactic halos. It's a little hard to stuff them in. For that reason, I think the top-down theory is falling apart, and with it the neutrino game."

The Berkeley team of Carlos Frenk, Simon White and Marc Davis agrees. When they generated a neutrino universe on their computer, they came up with a nasty timing problem. "We get structures that are reminiscent of the chains and voids seen in our universe," explains Davis. "But the problem is, if you look at the structure and ask, 'When did it form?' you can see that this large-scale structure is forming *right now*. There's no time for galaxies to form."

But the problem is more fundamental than that, contends Peebles. "If the clusters formed first, then why aren't all galaxies stuck in clusters? Most galaxies are like ours—on the outskirts in loose groupings, just starting to fall in." Peebles is the leading supporter of the "bottom-up" model: Galaxies formed first, he says, then gathered into clusters and later into superclusters (clusters of clusters).

> The darlings of the missing-mass set were gravitinos and photinos until their Achilles' heels were found.

But if the dark matter is not made out of neutrinos or baryons, what else works? Particle physicists are providing some additional suspects. As they refine their theories about the subatomic world, new hypothetical particles pop out of their equations. Some predict that every particle we see today has a partner. For example, the photon has its photino, the W boson its Wino, and the graviton—the alleged mediator of the gravitational force—its gravitino. At the moment, all of these "inos" exist only on paper, but that hasn't deterred a number of physicists from musing on their cosmic effects.

PRIMORDIAL OCEAN

To George Blumenthal and Joel Primack at Santa Cruz and to Heinz Pagels at Rockefeller University in New York, gravitinos looked especially interesting. Just like massive neutrinos, they would condense out of that primordial ocean of particles very soon after the Big Bang and form clumps into which baryonic matter would later fall. Galaxy-size objects would be the natural outcome. If their mass and velocity are as predicted, gravitinos would tend to gather into clumps just about the size of a typical galaxy, a coincidence hard to ignore. Since a gravitino is not as "hot," or energetic, as a neutrino, it would confine itself to this smaller region. For this reason, physicists call it a "warm" particle.

With warm particles as the missing mass, the clustering of the universe proceeds in an entirely different sequence than it does with neutrinos. Now it grows from the small to the big. This is Peebles's bottom-up process.

For a while these warm particles, such as gravitinos and photinos, were the darlings of the missing-mass set. But physicists soon discovered the Achilles' heel of these exotic species. Galaxies that are surrounded by gravitino or photino halos cannot easily form those filamentary superclusters seen in our real universe. Where hot neutrinos fail on the small-scale job of generating galaxies, gravitinos and other such warm particles have trouble with the large-scale job of creating strings of superclusters. Supporters for each model were confident that these details of galactic evolution would be worked out in time, but a lonely vigil on top of Arizona's Mount Hopkins put a further monkey wrench in the works.

Over the past two years, astronomer Marc Aaronson, of the University of Arizona's Steward Observatory, has used the innovative Multiple Mirror Telescope to look closely into the Draco dwarf galaxy, one of seven such tiny neighbors of the Milky Way and located about 300,000 light-years away. He has painstakingly gathered the light from several carbon stars within Draco, giant red stars 100 times larger than our sun (an endeavor that led him to impishly entitle one of his papers "Carbon Stars and the Seven Dwarfs").

Aaronson's mission was simple: He wanted to know how fast these red beacons were moving within the dwarf. As with Zwicky's clusters and Rubin's spiral galaxies, the answer was a surprising one: The stars were much more agitated than expected. It implied that a dark halo must

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AN EXOTIC NEUTRINO?

Almost nothing can stop them. They shoot through the universe by the trillions, passing through matter with so little effect that a light-year's thickness of lead would hardly seem in the way. And now it appears that these mysterious wanderers—neutrinos—may even change their form in mid-flight. The process, called oscillation, is so bizarre that one physicist has compared it to a cat suddenly changing into a dog.

For over a decade, Raymond Davis and colleagues at Brookhaven National Laboratory have been tracking solar neutrinos; a 100,000-gallon tank of cleaning fluid deep in a South Dakota gold mine records their passage through the Earth. The scientists have consistently found only a fraction of the number expected.

Neutrino oscillation could provide an answer. If the ordinary electron neutrinos produced by the sun are changing into more exotic species—tau or muon neutrinos—before they reach Earth, they wouldn't be detected by Davis's apparatus. This would require a more sensitive sensor; some suggest that 50 tons of gallium, housed underground, might do the trick.

And for neutrinos to oscillate, they must have mass; this would mean a victory for scientists who believe neutrinos account for the universe's missing mass. *–Andrew Chaikin*

MISSING MASS

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be surrounding the dwarf to keep the stars in. Faber and Lin came to the same conclusion from a theoretical angle. How could the dwarf galaxies, they asked, survive the tidal forces of the much larger Milky Way? "One way," says Lin, "is fill them with lots of dark matter to keep them from being torn apart."

If Aaronson's very tentative finding is upheld, it places a severe constraint on what the dark matter can be. Some scientists have concluded that hot and warm particles cannot coalesce easily around objects as tiny as dwarf galaxies, systems 1,000 times less massive than the Milky Way. They reason that only a "cold," slower moving particle gets the job done. And again, the new physics has provided the perfect candidate—the axion, an almost stationary particle that is a trillion times lighter than an electron.

With the still-hypothetical axions as the dark matter, the universe evolves a little differently than it would in a cosmos inhabited by massive neutrinos or gravitinos. At first, the heavens look like a well-mixed soup of baryons and axions, "a sort of lumpy soup," notes Blumenthal. "But then," adds Sandra Faber, "when these clumps hit the magic temperature of ten thousand degrees, the baryons start to radiate away their energy. When they do this, they sink to the center of the clump." What results is a core of ordinary luminous matter surrounded by a halo of cold, dark axions—an object that looks suspiciously like a galaxy. There's an added bonus to this model: Plain, old thermodynamics limits the size of the clumps. They must weigh between 100 million and one trillion solar masses for the baryon sink to be triggered. Perhaps not coincidentally, that covers all the galaxy sizes we observe today, from dwarfs to giants. Many researchers are attracted by the beauty and simplicity of these particles working in concert.

COLD-PARTICLE CANDIDATES

Not every particle physicist believes that axions exist, but that doesn't really affect the scenario. A host of other cold-particle candidates will produce the same effect: heavier gravitinos and photinos, monopoles (weighty particles of magnetic "charge") or primordial black holes (Jupiter-size bodies squeezed down to the size of a beach ball during the first chaotic microsecond of the Big Bang).

Exotic cold matter recently got a boost. For a long time, many found it difficult to grow the filaments and voids out of it. "But that is no longer a problem," says Adrian Melott. The young University of Chicago astrophysicist, in collaboration with a team of Soviet scientists, was recently surprised to discover during his computer simulations that large filaments were naturally developing in his digital universe, which is composed of alien cold matter. "On my computer, as the little lumps formed, they also started lining up into long strings," he says. "In the end, this computer-generated picture seems to duplicate the universe as we see it today." The work of the Berkeley research team is showing similar promise.

Lastly, some think that a mixture of particles might work. Schramm and Steigman have already suggested that clouds of massive neutrinos might stretch over entire clusters, forging the large-scale structure in the universe, while some kind of baryonic material serves as the dark matter around individual galaxies. But no one else is ready to embrace this scheme.

When will this missing-mass mystery finally be solved? A bizarre cosmic particle shooting in from the far reaches of space might provide the answer tomorrow. But many observers believe it will take several years, perhaps even decades, to sort through this cosmic jigsaw puzzle. Faber believes that the new Space Telescope, scheduled for launch into Earth orbit in 1986, will provide some vital clues.

> In a wondrous marriage between astronomy and particle physics, the two ends of the cosmic scale are linking up.

"The keen eyes of the Space Telescope will give us a glimpse of the universe as it was when it was half its present age. That should tell us if the clusters or the galaxies came first."

Meanwhile, a sensitive infrared space observatory, such as the IRAS satellite now completing its mission, may find itself detecting the faint traces of heat radiation emitted by a halo of "Jupiters" around each galaxy. "My feeling is that the real hope of solving the missing-mass question will be with the new generation of particle accelerators, instruments that will be exploring much higher energies," suggests Schramm.

The search for the missing mass, in fact, has produced a strange and wondrous marriage between astronomy and particle physics. For the first time in the history of physics, the two ends of the universal scale are linking up. Blumenthal elaborates: "We're suddenly finding that the smallest objects in the universe, elementary atomic particles, may be determining the structure of the largest objects in the universe, the superclusters." Adds Faber, "It's such a beautiful concept, it might be right." ■

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