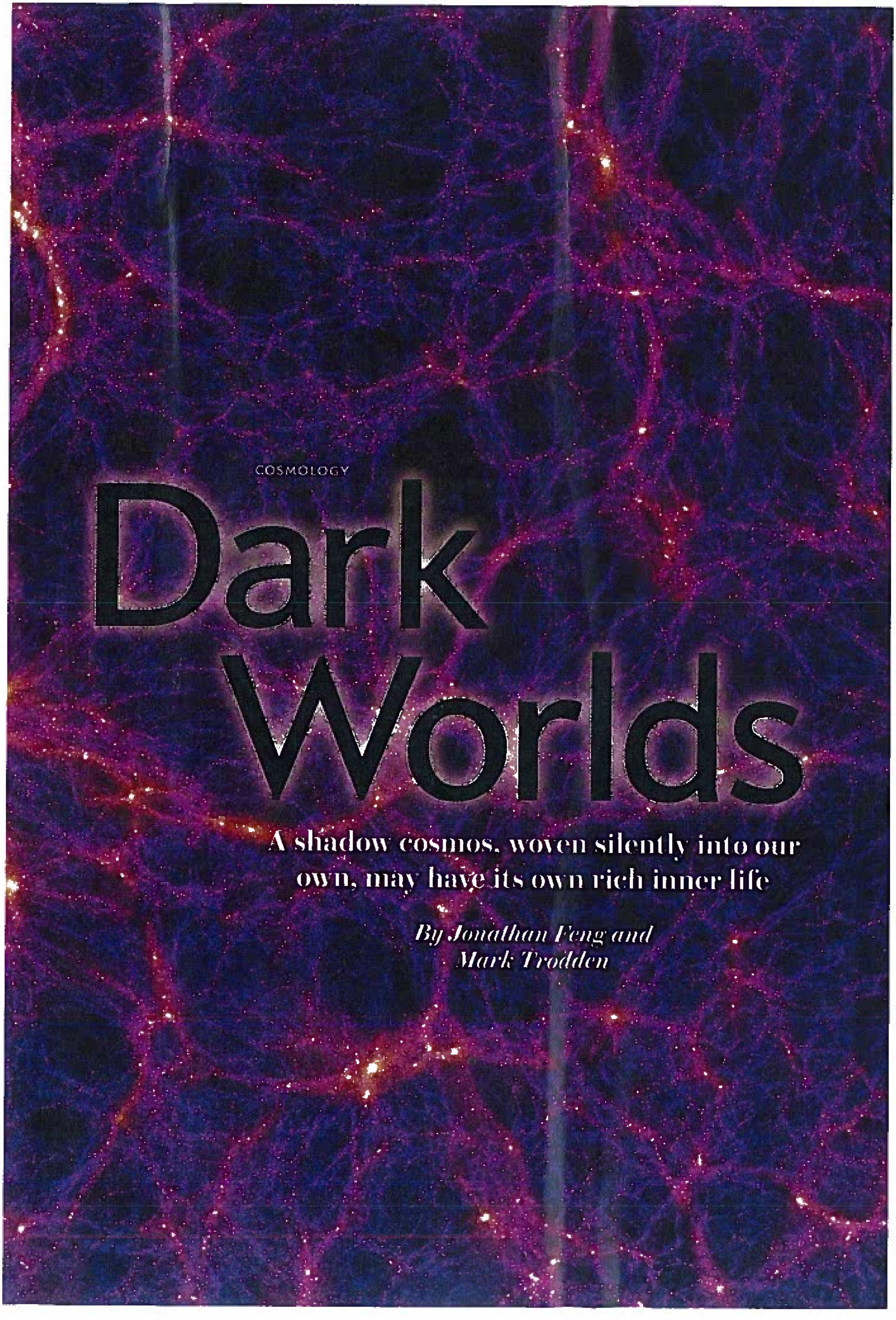


COSMOLOGY

Dark Worlds

A shadow cosmos, woven silently into our own, may have its own rich inner life

By Jonathan Feng and Mark Trodden

Jonathan Feng is a theoretical physicist working at the intersection of particle physics and cosmology, with a focus on dark matter. Currently a professor of physics and astronomy at the University of California, Irvine, he played the trumpet in a former life.

Mark Trodden studies particle physics and cosmology. He is co-director of the Center for Particle Cosmology at the University of Pennsylvania and an author of Cosmic Variance, a leading physics blog. When not pondering the cosmos, he can often be found sipping wine in a busy kitchen.

ON SEPTEMBER 23, 1846, JOHANN GOTTFRIED Galle, director of the Berlin Observatory, received a letter that would change the course of astronomical history. It came from a Frenchman, Urbain Le Verrier, who had been studying the motion of Uranus and concluded that its path could not be explained by the known gravitational forces acting on it. Le Verrier suggested the existence of a hitherto unobserved object whose gravitational pull was perturbing Uranus's orbit in precisely the way required to account for the anomalous observations. Following Le Verrier's directions, Galle went to his telescope that night and discovered the planet Neptune.

A similar drama—in which astronomers observe anomalous cosmic motions, deduce the presence of new matter and go out to hunt for it—is playing out again today in modern cosmology. In the role of Uranus, we see stars and galaxies moving in ways they should not; in the role of Neptune, we deduce the existence of hitherto unobserved substances, provisionally called dark matter and dark energy. From the types of anomalies we see, we can glean a few basic facts about them. Dark matter seems to be a sea of invisible particles that fills space unevenly; dark energy is spread out uniformly and acts as if it is woven into the fabric of space itself. Scientists have yet to repeat Galle's accomplishment of pointing an instrument at the sky and glimpsing the unseen players definitively, but tantalizing inklings, such as blips in particle detectors, continue to accumulate.

From its discovery as a shadowy force on Uranus, Neptune proved to be a fascinating world in its own right. Might the same be true of dark matter and dark energy? Scientists are increasingly considering the possibility that dark matter, in particular, is not just a contrivance to account for the motion of visible matter but a hidden side of the universe with a rich inner life. It may consist of a veritable zoo of particles interacting through novel forces of nature—an entire universe interwoven silently with our own.

THE DARK SIDE

THESE IDEAS ARE A SHIFT from the long-held assumption that dark matter and dark energy are the most antisocial substances in the cosmos. Since astronomers first inferred the existence of dark matter in the 1930s, they have considered inertness its defining property. Observations suggest it outweighs ordinary matter by a factor of 6 to 1. Galaxies and galaxy clusters are embedded in giant balls, or "halos," of dark matter. For such a mass of material to elude direct detection, astronomers reason that it has to consist of particles that scarcely interact with ordinary matter or, indeed, with one another. All they do is provide the gravitational scaffolding for luminous matter.

Astronomers think the halos formed early on in cosmic history and then drew in ordinary matter, which, being capable of a rich range of behaviors, developed into intricate structures, while dark matter, being inert, remained in its primitive state. As for dark energy, its only role appears to be to accelerate cosmic expansion, and the available evidence indicates it has remained completely unchanged over the life of the cosmos.

The prospect that dark matter might be rather more interesting is driven not so much by the field of astronomy but by detailed investigations of the inner workings of atoms and the world of subatomic particles. Particle physicists have a tradition of seeing glimmers of unknown forms of matter in the behavior of known matter, and their evidence is completely independent of cosmic motions.

In the case of dark matter, the train of thought began with the discovery of radioactive beta decay in the early 1900s. Italian theorist Enrico Fermi sought to explain the phenomenon

IN BRIEF

Scientists have two independent reasons for thinking that the cosmos is filled with some unknown form of matter, dark matter. Not only do stars, galaxies and gas clouds move as if they are being tugged by the gravity of hidden material, but processes such as radioactivity present puzzles that can be solved by the existence of hitherto unknown particles.

Dark matter is usually assumed to consist of WIMPs, a kind of particle that scarcely interacts with the visible world. Boringness is its sine qua non.

Or at least that is the usual assumption. Might dark matter in fact have a rich inner life? Particle physicists striving to understand what makes up dark matter think it could interact through a full range of forces, including a form of light to which our eyes are totally blind.

What Lurks in the Shadows

Modern scientific instruments have revealed the existence of unseen mass and energy in the universe but have barely scratched the surface of the types of stuff that might make it up.

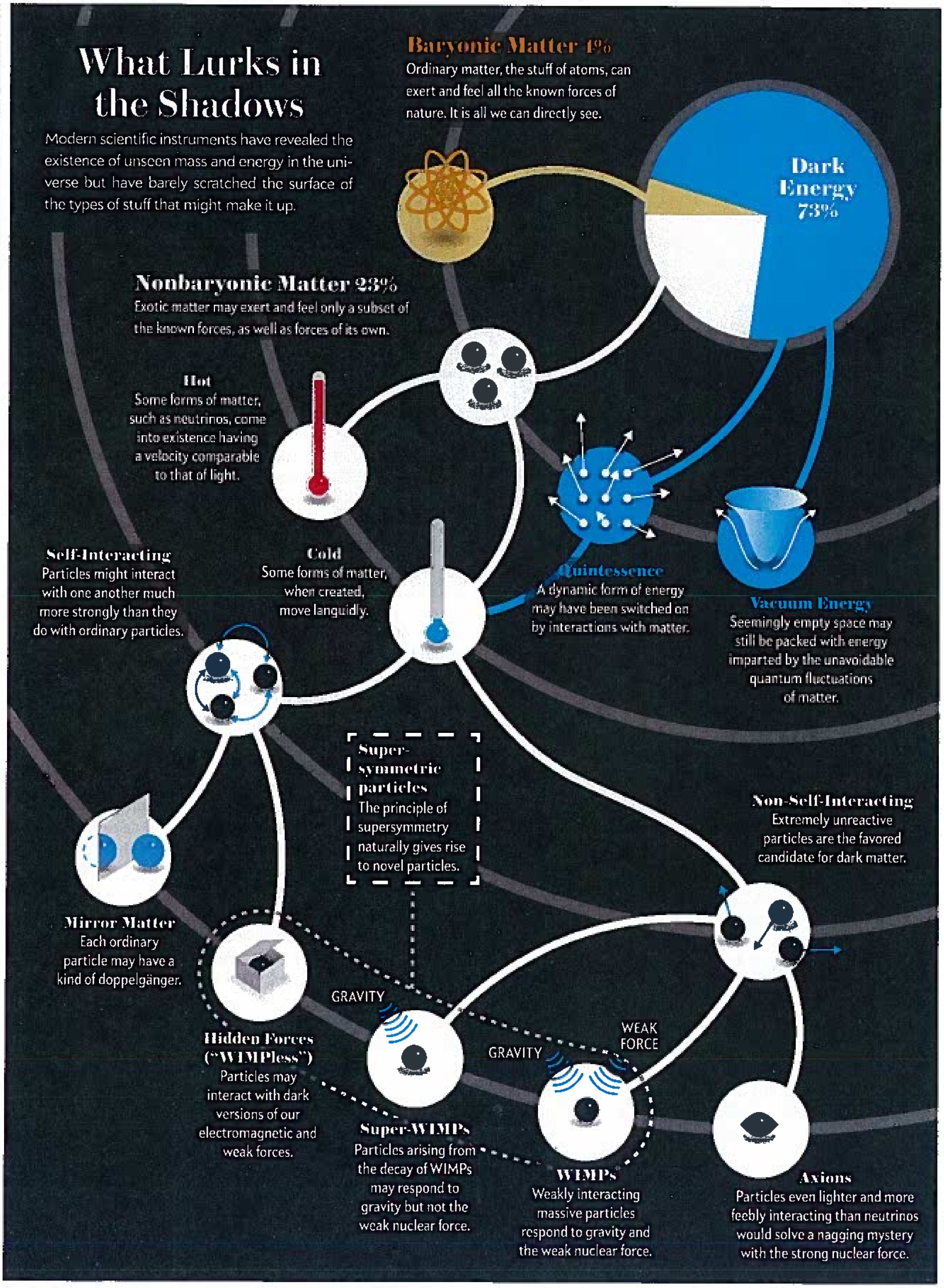
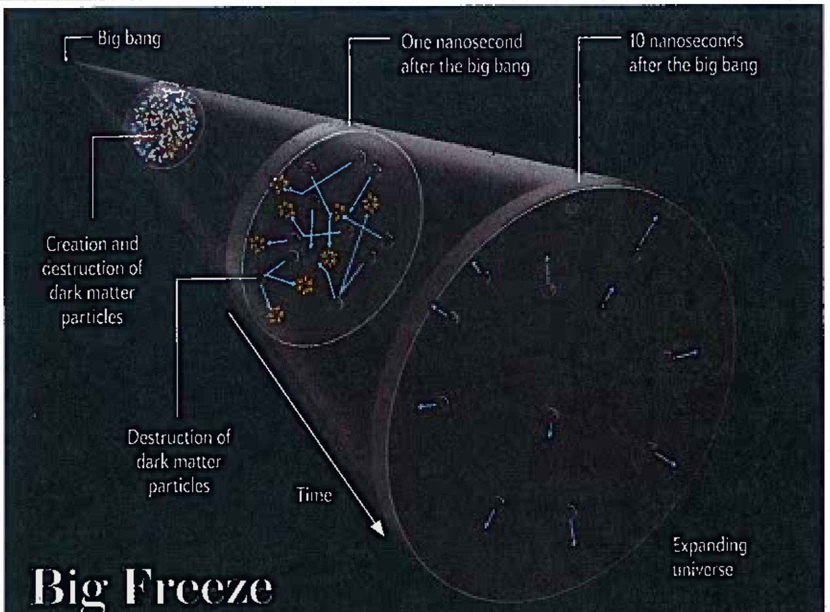


Illustration by Bryan Christie

WHERE DARK MATTER CAME FROM



Big Freeze

In the hot, dense early universe, dark matter particles such as WIMPs were created and destroyed in a dynamic equilibrium. As the cosmos expanded, it cooled and eventually was no longer able to create new particles. Those left over became so spread out that they ceased colliding and getting destroyed. For WIMPs, theory makes a firm prediction for the amount of material that survived, which is consistent with observations.

by postulating a new force of nature and new force-carrying particles that caused atomic nuclei to decay. This new force was similar to electromagnetism and the new particles to photons, the particles of light—but with a key twist. Unlike photons, which are massless and therefore highly mobile, Fermi argued that the new particles had to be heavy. Their mass would limit their range and account for why the force causes nuclei to fall apart but otherwise goes unnoticed. To reproduce the observed half-life of radioactive isotopes, they had to be quite heavy—around 100 times that of the proton, or about 100 giga-electron-volts, in the standard units of particle physics.

The new force is now known as the weak nuclear force and the hypothesized force-carrying particles are the *W* and *Z* particles, which were discovered in the 1980s. They are not dark matter themselves, but their properties hint at dark matter. A priori, they should not be so heavy. Their high mass suggests that something is acting on them—novel particles that cause them to take on mass like a friend who encourages you to give into temptation and eat another slice of cake. One goal of the Large Hadron Collider is to look for those particles, which should have masses comparable to those of the *W* and *Z*. Indeed, physicists think dozens of types of particles may be waiting to be discovered—one for each of the known particles, paired off in an arrangement known as supersymmetry.

These hypothetical particles include some collectively known as weakly interacting massive particles, or WIMPs. The name arises because the particles interact only by means of the weak nuclear force. Being immune to the electric and magnetic forces that dominate the everyday world, they are totally invisible and have scarcely any direct effect on normal particles. Therefore, they make the perfect candidate for cosmic dark matter.

Whether they can truly explain dark matter, though, depends on how many of them there are. Here is where the particle physics argument really gains traction. Like any other breed of particle, WIMPs would have been produced in the fury of the big bang. High-energy particle collisions back then both created and destroyed WIMPs, allowing a certain number of them to exist at any given moment. This number varied with time depending on two competing effects driven by the expansion of the universe. The first was the cooling of the primordial soup, which reduced the amount of energy available to create WIMPs, so that their number diminished. The second effect was the dilution of particles, which reduced the frequency of collisions until they effectively ceased to occur. At that point, about 10 nanoseconds after the big bang, the number of WIMPs became frozen in. The universe no longer had either the energy needed to create WIMPs or the dense concentrations of mass needed to destroy them.

Given the expected mass of WIMPs and the strength of their interactions, which govern how often they annihilate one another, physicists can easily calculate how many WIMPs should be left over. Rather amazingly, the number matches the number required to account for cosmic dark matter today, within the precision of the mass and interaction-strength estimates. This remarkable agreement is known as the WIMP coincidence. Thus, particles motivated by a century-old puzzle in particle physics beautifully explain cosmological observations.

This line of evidence, too, indicates that WIMPs are inert. A quick calculation predicts that nearly one billion of these particles have passed through your body since you started reading this article, and unless you are extraordinarily lucky, none has had any discernible effect. Over the course of a year you might expect just one of the WIMPs to scatter off the atomic nuclei in your cells and deposit some meager amount of energy. To have any hope of detecting such events, physicists set their particle detectors to monitor large volumes of liquid or other material for long periods. Astronomers also look for bursts of radiation in the galaxy that mark the rare collision and annihilation of orbiting WIMPs. A third way to find WIMPs is to try to synthesize them in terrestrial experiments [*see box on page 44*].

OUT-WIMPING THE WIMPS

THE EXTRAORDINARY EFFORT now being devoted to WIMP searches might leave the impression that these particles are the only theoretically plausible dark matter candidate. Are they? In fact, recent developments in particle physics have uncovered other possibilities. This work hints that the WIMP is just the tip of the iceberg. Lurking under the surface could be hidden worlds, complete with their own matter particles and forces.

One such development is the concept of particles even more wimpy than WIMPs. Theory suggests that WIMPs formed in the first nanosecond of cosmic history might have been unstable. Seconds to days later they could have decayed to particles that have a comparable mass but do not interact by the weak nuclear force; gravity is their only connection to the rest of the natural world. Physicists, tongue in cheek, call them super-WIMPs.

The idea is that these particles, rather than WIMPs, constitute the dark matter of today's universe. Super-WIMPs would elude direct observational searches but might be inferred from the telltale imprint they would leave on the shapes of galaxies. When created, super-WIMPs would have been moving at a significant fraction of the speed of light. They would have taken time to come to rest, and galaxies could not have begun forming until they did. This delay would have left less time for matter to accrete onto the centers of galaxies before cosmic expansion diluted it. The density at the center of dark matter halos should therefore reveal whether they are made of WIMPs or super-WIMPs; astronomers are now checking. In addition, the decay from WIMP to super-WIMP should have produced photons or electrons as a by-product, and these particles can smash into light nuclei and break them apart. There is some evidence that the universe has less lithium than expected, and the super-WIMP hypothesis is one way to explain the discrepancy.

The super-WIMP scenario also inspires fresh possibilities for what experimental physicists might observe. For instance, the original WIMP need not have been either dark or wimpy; it could have had an electric charge. Any charge it had would not have affected the evolution of the cosmos, because the particle decayed so quickly. It would, however, mean that WIMPs would be extremely conspicuous if experimentalists were able to re-create them. Particle detectors would register them as electrons on steroids; having the same charge as an electron but 100,000 times more mass, such a particle would barrel through the detectors, leaving spectacular tracks in its path.

DARK FORCES, HIDDEN WORLDS

THE MAIN LESSON of super-WIMP models is that there is no reason, either theoretically or observationally, that dark matter should be as boring as astronomers tend to presume. Once one admits the possibility of hidden particles with properties that go beyond the standard WIMP scenario, it is natural to consider the full range of possibilities. Could there be a whole sector of hidden particles? Could there be a hidden world that is an exact copy of ours, containing hidden versions of electrons and protons, which combine to form hidden atoms and molecules, which combine to form hidden planets, hidden stars and even hidden people?

The possibility that a hidden world could be identical to ours has been explored at length, beginning in 1956 with an offhand comment in a Nobel Prize–winning paper by Tsung-Dao Lee and Chen Ning Yang and more recently by many others, including Robert Foot and Raymond Volkas of the University of Melbourne in Australia. The idea is truly tantalizing. Could it be that what we see as dark matter is really evidence for a hidden world that mirrors ours? And are hidden physicists and astronomers even now peering through their telescopes and wondering what their dark matter is, when in fact their dark matter is us?

Unfortunately, basic observations indicate that hidden worlds cannot be an exact copy of our visible world. For one, dark matter is six times more abundant than normal matter. For another, if dark matter behaved like ordinary matter, halos would have flattened out to form disks like that of the Milky Way—with dramatic

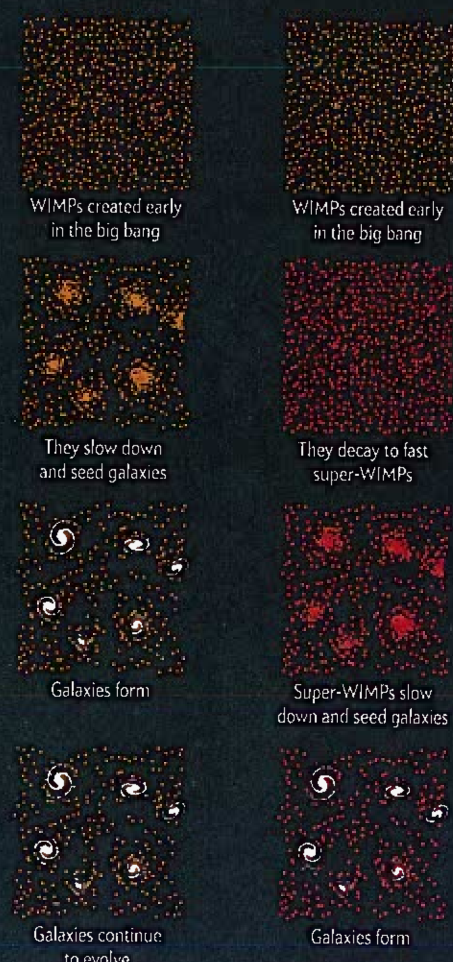
A NEW TYPE OF DARK MATTER

Varieties of Weaklings

Super-WIMPs were the first proposed type of particle that enriches the standard WIMP scenario for dark matter. The term is intentionally ironic: these particles are "super" not because they are mightier than WIMPs but because they are wimpier: they interact with ordinary matter only through the force of gravity.

	Baryonic	WIMP	Super-WIMP
Gravity	✓	✓	✓
Electromagnetic force	✓		
Weak nuclear force	✓	✓	
Strong nuclear force	✓		
Possible dark forces		✓	✓

In the WIMP scenario (*left column*), WIMPs seed galaxy formation directly. In the super-WIMP scenario (*right column*), they decay to super-WIMPs, which do the seeding—with a delay relative to the WIMP scenario.



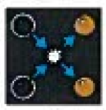
gravitational consequences that have not been seen. Last, the existence of hidden particles identical to ours would have affected cosmic expansion, altering the synthesis of hydrogen and helium in the early universe; compositional measurements rule that out. These considerations argue strongly against hidden people.

That said, the dark world might indeed be a complicated web of particles and forces. In one line of research, several investigators, including one of us (Feng) and Jason Kumar of the University of Hawaii at Manoa, have found that the same supersymmetric framework that leads to WIMPs allows for alternative scenarios that lack WIMPs but have multiple other types of particles. What is more, in many of these WIMP-less theories, these particles interact with one another through newly postulated dark forces. We found that such forces would alter the rate of particle

PHYSICS OBSERVATIONS

How to See the Unseeable

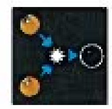
So far everything astronomers know about dark matter comes from its gravitational effects on visible matter. But they need to detect it directly if they are to find out what it is. That will not be easy: dark matter is elusive by definition. Nevertheless, motivated by the promise of discovering what a quarter of the universe is, thousands of researchers are looking. Most of their efforts have focused on WIMPs, and the three common search strategies are to look for the particles' annihilation, scattering and production.



ANNIHILATION When two WIMPs meet, they obliterate each other and leave behind a clutch of other particles such as electrons, antielectrons (known as positrons) and neutrinos. Such annihilation cannot be very common, or else no WIMPs would be left by now. Fortunately, current experiments are sensitive enough to notice if even a tiny fraction of WIMPs are being annihilated.

Detectors on high-altitude balloons and satellites have sought electrons and positrons. In the coming year the space shuttle is scheduled to transport the Alpha Magnetic Spectrometer to the International Space Station, where it will sit docked, looking for positrons. Other observatories such as the Super-Kamiokande experiment in Japan and IceCube in Antarctica are watching for neutrinos.

DIRECT DETECTION Dark matter should be streaming through our planet as it travels through the galaxy. On rare occasions, a WIMP will bump into an atomic nucleus and cause it to recoil, just as a pool ball does when struck by the cue ball. The predicted recoil energies are almost imperceptible but may be within the range of sensitive detectors. Cryogenic technology slows the natural vibrations of atoms and makes it easier to notice any recoil. The energy deposited in the detector holds the key to pinning down the fundamental properties of dark matter. Two experiments, DAMA and CoGeNT, have claimed to detect a signal (*below*), but others, such as XENON and CDMS, have found nothing. These and other new experiments are improving their sensitivities rapidly, promising an exciting near future for this field.



PRODUCTION Dark matter might be created at particle colliders, such as the Large Hadron Collider at CERN near Geneva, a mammoth experiment that collides protons together at extremely high energies. Dark matter production is dark matter annihilation played backward: if dark matter can annihilate into normal particles, it can also be produced by the collisions of normal particles. The signature of dark matter production would be the observation of collisions in which energy and momentum seem to go missing, indicating that some unreactive particles have been produced and then escaped the detector without registering. These giant experiments, designed to tease out the secrets of the subatomic world, may wind up discovering the dominant form of matter in the universe.

Experiments That Claim to Have Detected Dark Matter Particles

EXPERIMENT	CDMS	DAMA	CoGeNT	PAMELA
What it stands for	Cryogenic Dark Matter Search	DArk MAtter	Coherent Germanium Neutrino Technology	Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics
Where it is	Soudan mine in Minnesota	Gran Sasso underground lab in Italy	Soudan mine	Attached to Russian satellite
What it has seen	Two recoil events	Annual variation in the number of recoil events	Recoil events	Excess of positrons
Why the signal might be real	Direct, expected signal of dark matter	Statistically significant	Sensitive to ultralow energy recoils	Direct, expected signal of dark matter annihilation
Why it might not be	Not statistically significant	Apparently excluded by other results	Normal nuclear events might be responsible	Could be explained by astrophysical sources
Which experiments will follow up	SuperCDMS, XENON	XENON, MAJORANA Demonstrator	XENON, MAJORANA Demonstrator	Alpha Magnetic Spectrometer

tion and annihilation in the early universe, but again the bers work out so that the right number of particles are left to account for dark matter. These models predict that dark er may be accompanied by a hidden weak force or, even e remarkably, a hidden version of electromagnetism, imply- hat dark matter may emit and reflect hidden light.

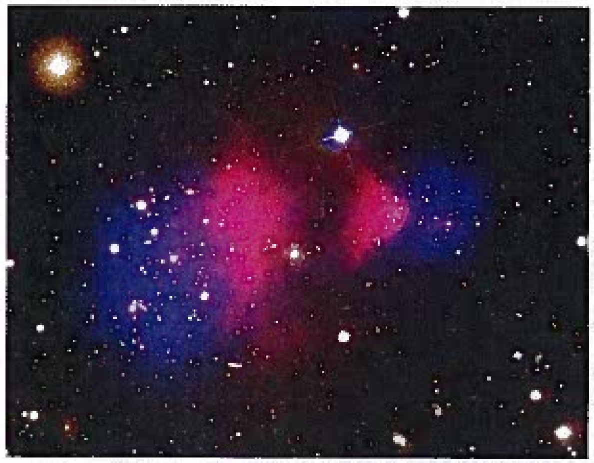
'his "light" is, of course, invisible to us, and so the dark mat- emains dark to our eyes. Still, new forces could have very ificant effects. For example, they could cause clouds of dark icles to become distorted as they pass through one another. onomers have searched for this effect in the famous Bullet ter, which consists of two clusters of galaxies that have ed through each other. Observations show that the brief ingling of clusters left the dark matter largely unper- ed, indicating that any dark forces could not be very strong. archers are continuing to look in other systems.

uch forces would also allow dark particles to exchange en- and momentum with one another, a process that would to homogenize them and cause initially lopsided halos to me spherical. This homogenizing process should be most ounced for small galaxies, also known as dwarf galaxies, re the dark matter is slow-moving, particles linger near one her and small effects have time to build up. The observa- that small galaxies are systematically rounder than their r cousins would be a telltale sign of dark matter interact- hrough new forces. Astronomers are only just beginning to rtake the requisite studies.

ASTRONOMICAL OBSERVATIONS

Silver Bullet

The famous Bullet Cluster is among astronomers' most persuasive evidence for dark matter. It is actually a pair of galaxy clusters that collided. The collision did not affect the galaxies' stars (*visible image*), because they present small targets on these scales, but interstellar gas clouds rammed into one another and emitted x-rays (*pink*). Dark matter (*blue*) betrayed its presence because its gravity distorted the light of background objects. It remained aligned with the stars—indicating that whatever particles make it up are highly unreactive.



FROM ONE DARK THING TO ANOTHER

QUALLY INTRIGUING POSSIBILITY is that dark matter interacts dark energy. Most existing theories treat the two as dis- iected, but there is no real reason they must be, and physi- are now considering how dark matter and dark energy it affect each other. One hope is that couplings between the might mitigate some cosmological problems, such as the cidence problem—the question of why the two have com- ble densities. Dark energy is roughly three times as dense rk matter, but the ratio might have been 1,000 or a million. coincidence would make sense if dark matter somehow ered the emergence of dark energy.

ouplings with dark energy might also allow dark matter cles to interact with one another in ways that ordinary cles do not. Recent models allow and sometimes even date dark energy to exert a different force on dark matter it does on ordinary matter. Under the influence of this , dark matter would tend to pull apart from any ordinary er it had been interlaced with. In 2006 Marc Kamionkow- f the California Institute of Technology and Michael Kes- then at the Canadian Institute for Theoretical Astrophys- Toronto, suggested looking for this effect in dwarf galax- hat are being torn apart by their larger neighbors. The tarius dwarf galaxy, for example, is being dismembered by Ailky Way, and astronomers think its dark matter and ordi- matter are spilling into our galaxy. Kamionkowski and en calculate that if the forces acting on dark matter are at 4 percent stronger or weaker than the forces acting on the ary matter, then the two components should drift apart observable amount. At present, however, the data show ing of the sort.

nother idea is that a connection between dark matter and dark energy would alter the growth of cosmic structures, which depends delicately on the composition of the universe, including its dark side. A number of researchers, including one of us (Trodden) with collaborators Rachel Bean, Éanna Flanagan and Istvan Laszlo of Cornell University, have recently used this powerful constraint to rule out a large class of models.

Despite these null results, the theoretical case for a complex dark world is now so compelling that many researchers would find it more surprising if dark matter turned out to be nothing more than an undifferentiated swarm of WIMPs. After all, visible matter comprises a rich spectrum of particles with multiple interactions determined by beautiful underlying symmetry principles, and nothing suggests that dark matter and dark energy should be any different. We may not encounter dark stars, planets or people, but just as we could hardly imagine the solar system without Neptune, Pluto and the swarm of objects that lie even farther out, one day we might not be able to conceive of a universe without an intricate and fascinating dark world. ■

MORE TO EXPLORE

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