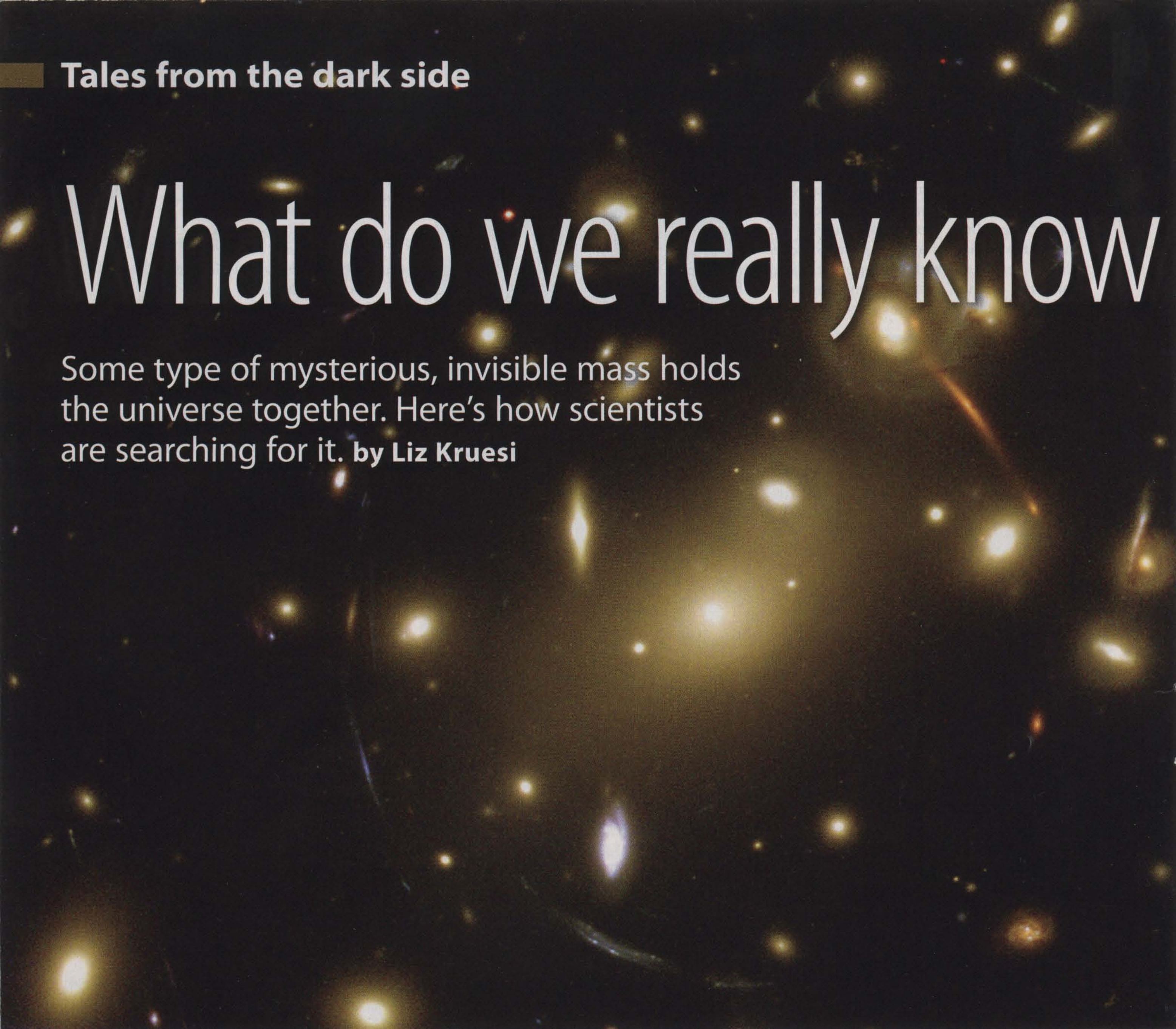


What do we really know

Some type of mysterious, invisible mass holds the universe together. Here's how scientists are searching for it. **by Liz Kruesi**

The universe doesn't abide by "what you see is what you get." In fact, the stuff we see in space — stars, gas, and dust — accounts for only 10 percent of the universe's mass. This visible stuff is ordinary matter, and it's made up of protons, neutrons, and electrons. Scientists call ordinary matter "baryonic matter" because protons and neutrons are subatomic particles called baryons. The other 90 percent of the mass is "dark matter," and it likely surrounds almost every galaxy in the universe.

Dark matter doesn't emit, absorb, or reflect any type of light (so, for example, it doesn't emit X-rays or absorb infrared radiation). This mysterious stuff is therefore invisible, yet astronomers learned it exists because dark matter interacts with ordinary matter through gravity.

Liz Kruesi *is an associate editor of* Astronomy.

Searching in the dark

Swiss astrophysicist Fritz Zwicky first proposed dark matter's existence in 1933. While studying the Coma cluster of galaxies, he found that the galaxies' collective gravity alone was much too small to hold the cluster together.

The next round of evidence came in the 1970s. Astronomers charted the velocities of stars at various distances from the center of a spiral galaxy and plotted the velocity versus the distance to create a "rotation curve." They expected the velocities to reach a maximum and then decrease farther from the center — but the data showed otherwise. The velocities reach a maximum and then plateau. With velocities so high at the outer edge of galaxies, the stars should fling out of their orbits. But they don't. Some sort of mass scientists can't detect must be holding these outer stars in orbit.

A very massive object — such as a galaxy cluster — can act as a gravitational lens. Some images of regions around galaxy clusters show numerous arcs. Those are background galaxies distorted and magnified by the cluster's gravity.

about **dark matter?**

Massive galaxy clusters like Abell 2218 have provided scientists with evidence for the existence of dark matter. By analyzing the arcs — warped images of a background galaxy — surrounding the cluster center, astronomers determined the cluster must have a lot more mass than meets the eye.
NASA/Andrew Fruchter/ERO Team [Sylvia Baggett (STScI), Richard Hook (ST-ECF), Zoltan Levay (STScI)] (STScI)

Astronomers study the sizes and shapes of those arcs to determine a cluster's mass. By comparing that calculated mass to the mass that comes from only luminous objects (the galaxies), astronomers can determine how much dark matter is in a cluster.

Other evidence has turned up in collisions of galaxy clusters, namely the Bullet cluster. This object is actually the aftermath of two galaxy clusters that collided. Astronomers used a multidetection approach to look at the galaxies, gas, and dark matter. When the clusters collided, the galaxies' stars passed through mostly unaffected because a lot of space exists between the stars. The clusters' hot gas makes up most of their baryonic mass. Ordinary matter interacts through electromagnetic forces. Thus, as matter collides it loses energy as radiation (in the form of X-rays, in this case). The hot gas slows during the collision.

Astronomers use gravitational lensing to indirectly map the dark matter distribution. It turns out that dark matter also passed through the collision unaffected. So images of the Bullet cluster show direct evidence of dark matter.

The evidence is piling up — with 3-D dark matter maps and other detections. Yet mapping the distribution is one thing; knowing the characteristics of this mysterious stuff is another story.

Unlike anything we've seen

For many years astronomers thought dark matter could consist of dead stars, black holes, and other known objects that emit little or no light. They used gravitational microlensing to look for these objects. This technique is similar to gravitational lensing except the foreground object is much less massive. Instead of light bending around the object, the body's gravity magnifies the light from behind it. While astronomers found some of these MAssive Compact Halo Objects (MACHOs), there weren't enough to account for all of the universe's missing mass.

So if dark matter isn't composed of normal objects, then it likely consists of

NASA/ESA/CXC/M. Bradac (University of California, Santa Barbara)/S. Allen (Stanford University)

Two massive galaxy clusters collided to form what's known as the Bullet cluster of galaxies. Ordinary matter — the hot gas, shown in pink — collided, lost energy, and slowed. The clusters' dark matter (shown in blue) interacted little and passed through the ordinary matter.

non-baryonic particles — meaning it's not made up of the same stuff as ordinary matter (protons and neutrons). Astronomers split non-baryonic dark matter into two categories: hot and cold. These titles have nothing to do with temperature. Hot means that early in the universe these particles traveled extremely fast — almost at the speed of light. Cold means that early in the universe the particles traveled more slowly.

How does particle speed relate to dark matter's composition? Slower particles will bunch up into small structures earlier in the universe. Those small structures will eventually collide and merge to form larger ones. Astronomers believe this is how structure develops and evolves in our universe: Smaller structures eventually merge into the massive superclusters we observe today. Astronomers simulate structure evolution with cold dark matter (CDM) and can create models that resemble today's universe.

What is CDM? Scientists aren't sure yet. They have a couple of options that branch from particle physics — but none contrived just to fit into dark matter theories. "Both [options] are generated by particle theories having nothing to do with dark matter," says Juan Collar of the University of Chicago. "However, these hypothetical particles turn out to have all of the properties (mass, abundance, lifetime, probability, and mode of interaction) required to be the dark matter, or at least a fraction of it."

For decades, physicists have worked to explain how the four fundamental physical forces fit together. (These forces are gravitation, electromagnetism, weak nuclear, and strong nuclear.) In the past 30 or so years, they've arrived at supersymmetry theory. This model predicts that each ordinary particle (such as an electron or quark) has a massive "superpartner" (a selectron or squark) that remains undetected.

The leading dark matter candidate is a class of particles that supersymmetry predicts. These particles have mass and interact through the weak nuclear force, but they don't interact through the electromagnetic force. Because these weakly interacting massive particles (WIMPs) interact via the weak force, they can collide with normal atomic nuclei and bounce off them without emitting light or absorbing radiation. The lightest WIMP — called the neutralino — is also the most popular dark matter possibility.

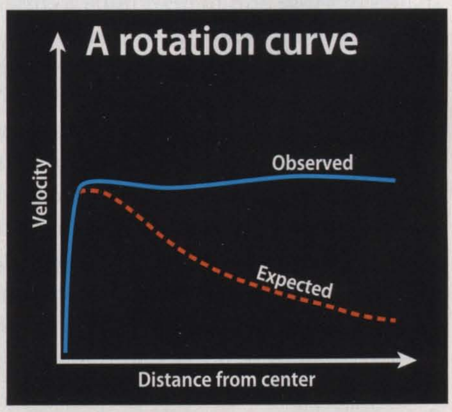
Another common CDM candidate is the axion. The axion is also a hypothetical particle, but it arises from a theory different from supersymmetry. This particle is not a "matter particle" but instead a force carrier, similar to the photon (which "carries" the electromagnetic force). It's much lighter than a WIMP — at least 1 billion times less massive — so the universe would need a whole lot more axions than WIMPs to make up all the invisible matter.

One would expect that with so many CDM particles, WIMPs or axions would be easy to find. But because they don't interact through the electromagnetic force, detecting them pushes scientists' experimental limits.

How to hunt CDM

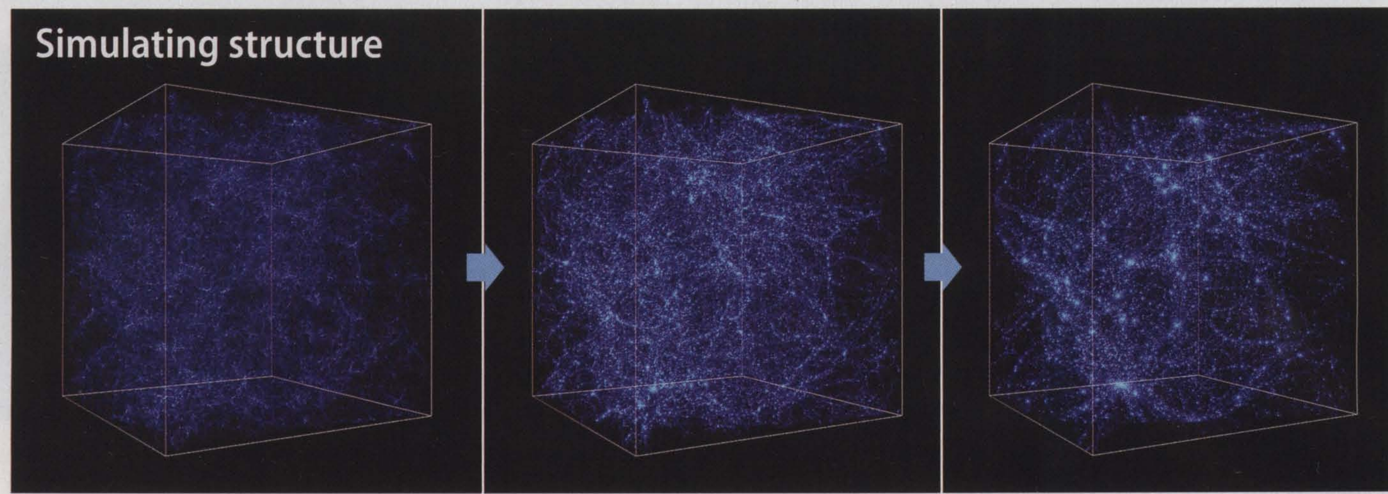
The method used to detect dark matter depends on what type of dark matter (WIMP or axion) scientists pursue. Scientists looking for WIMPs try to directly observe the interaction with ordinary

Astronomers were surprised to find that stars far from a galaxy's core travel at speeds similar to those close in. John Smith



A galaxy's rotation curve compares the disk stars' velocities with their distances from the galaxy's center. *Astronomy*: Roen Kelly

Simulating structure



Andrey Kravtsov (U. Chicago)/Anatoly Klypin (NMSU)

The universe's structure seems to evolve as smaller clumps bunch to form larger structures. Astronomers simulate structure evolution with cold dark matter and create models that resemble today's universe. This simulation shows dark matter distribution, where brighter areas represent more dense regions.

matter in a detector. A WIMP can collide with an atomic nucleus and move, or "scatter," the nucleus.

Another method is to indirectly detect dark matter. A WIMP's antiparticle is itself, so if two WIMPs interact, they annihilate each other and produce a shower of secondary particles. Astrophysicists can observe many of these secondary particles — such as electrons, positrons (the electron's antiparticle), gamma rays, and neutrinos.

Scientists' methods to locate axions are "totally different than the direct and indirect detection methods used to look for WIMPs," says Dan Hooper of Fermi National Accelerator Laboratory in Batavia, Illinois. When an axion traverses a detector that has a magnetic field, it will convert into a photon.

Instead of trying to detect CDM particles, some scientists aim to create the particles — WIMPs and axions — in the laboratory. To do this, they have to generate extremely high energies, similar to those shortly after the Big Bang. Only particle accelerators have this ability. After the Large Hadron Collider (the world's largest particle accelerator, located in Switzerland) comes back online late this year, scientists should be able to look for hypothetical particles that may make up dark matter.

NASA/ESA/C. Heymans (University of British Columbia, Vancouver)/M. Gray (University of Nottingham, U.K.)/M. Barden (Innsbruck)/the STAGES collaboration/C. Wolf (Oxford University, U.K.)/K. Meisenheimer (Max Planck Institute for Astronomy, Heidelberg)/the COMBO-17 collaboration

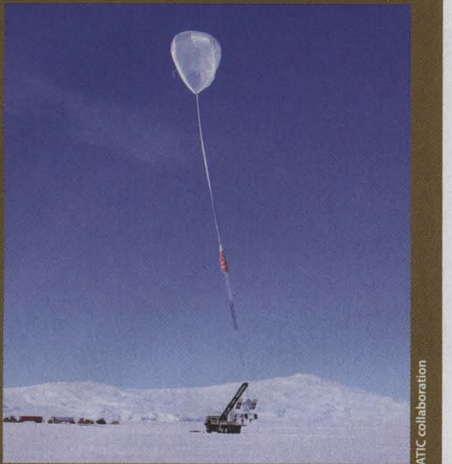
Supercluster Abell 901/902 contains hundreds of galaxies. Astronomers analyzed the distortion of some 60,000 background galaxies' shapes to determine the supercluster's distribution of dark matter. They then combined a visible-light image of the supercluster with the dark matter distribution map (shown as a magenta haze).

Bullying the WIMPs

Astronomers believe a spherical halo of CDM surrounds the luminous galactic disk of the Milky Way (and similar halos encase most other galaxies). As our solar system travels around the galaxy's center, it moves through this dark matter haze. These particles aren't the only things Earth collides with as it moves through the haze. Incoming high-energy ordinary particles called cosmic rays bombard Earth constantly. Radiation from the Sun and more distant sources do, too.

Scientists seek the WIMPs that may compose the CDM haze by placing most dark matter detectors underground and shielding them to block the detector material from cosmic rays. The key is to be able to block signals from "background noise" and detect when a dark matter particle interacts with the material. And if they can't block all of the noise, they must be able to tell the difference between noise and a WIMP.

Some scientists think about 600 million WIMPs pass through a square meter of Earth's surface every second. But remember that they interact weakly. So how do detectors "see" a WIMP? During a rare collision, the WIMP will transfer some of its energy to an atom's nucleus of the detector material, and, as a result, the nucleus scatters (think of pool balls). The amount the nucleus moves (or "recoils") is related to the WIMP's energy. Scientists detect this recoil a few different ways.



ATIC collaboration

The balloon-borne detector Advanced Thin Ionization Calorimeter (ATIC) found a nearby source of mysterious cosmic rays. The source could be a dark matter cloud.

Crumbs along the trail

A group using a balloon-borne detector last November disclosed a previously unknown source of high-energy electrons (cosmic rays). Cosmic-ray particles tend to lose much of their energy by the time they traverse the galaxy and Earth's atmosphere. So scientists typically detect low-energy cosmic rays near Earth's surface. The high-energy electrons that the Advanced Thin Ionization Calorimeter (ATIC) group found indicate the electrons are coming from a nearby source — within about 3,000 light-years.

By analyzing the electrons' detected energies, scientists can determine the energy the particles had before traversing the atmosphere. That energy matches what scientists expect from the products of a possible cold dark matter particle's annihilation. When two Kaluza-Klein (KK) particles meet, they annihilate each other and produce an electron and its antiparticle, the positron. (ATIC can't tell the difference between electrons and positrons, so its electron detection is a total number of electrons and positrons.) If the detected particles truly are products from KK annihilation, then our solar system may be passing through or near a large clump of KK dark matter.

However, these high-energy electrons could also arise from an undiscovered pulsar or other object. And more recent observations by the Fermi Gamma-ray Space Telescope cast doubt on the ATIC observations.

A group using a different detector — the Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) satellite — reported in 2008 that it saw a higher-than-expected number of positrons. PAMELA looks at energies lower than ATIC. Some scientists think that PAMELA may have observed positrons from another dark matter particle's annihilation. — *L. K.*

One type of detector uses crystals kept at frigid temperatures (only 0.01 degree above absolute zero). Crystals have a set structure, so when a WIMP collides with an atomic nucleus, the nucleus recoils and rams into surrounding structure. In these collisions, the scattered nucleus transfers some of its kinetic energy and slightly heats the material. The frigidity ensures that the detected vibrations have resulted from only incoming particle interactions. Of course, the scientists will likely detect particles other than just WIMPs. So most WIMP detectors use multiple methods to determine "on an event-by-event basis if what took place looked like a dark matter particle interaction or something more mundane," says Collar.

When a WIMP scatters the atomic nucleus and hits surrounding atoms, it could knock off electrons, therefore "ionizing" these atoms. Certain ionization detectors can measure these loose charges.

In some materials, such as liquid xenon, a light flash will indicate a WIMP. After the scattered nucleus rams into other atoms and frees electrons, the atom emits a light flash called scintillation. Usually if a detector looks for scintillation, it will also hunt for ionization.

Another approach to the direct search is using a bubble chamber — a glass jar filled with a specific type of liquid. When a WIMP hits an atomic nucleus, it will produce a tiny bubble. Scientists then watch the bubble grow. How it grows depends on whether the interacting particle was a WIMP or a background particle.

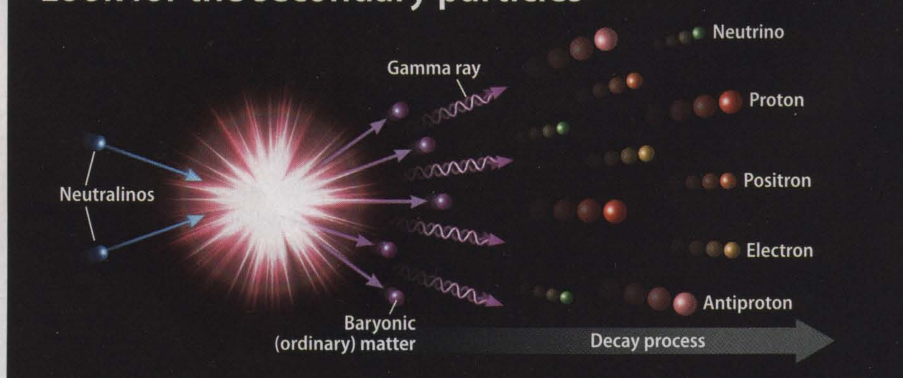
A reliable WIMP detection would be if the WIMP signal varied as a result of the time of year. This is because Earth revolves around the Sun. In June, Earth's movement is in the same direction as our solar system's path around the galaxy, so the detected signal should increase. In December, Earth moves in the opposite direction, and scientists should detect a signal some 5 to 10 percent smaller. This signal difference helps distinguish the WIMPs from the background noise because the noise remains the same while the WIMP signal modulates.

The team of scientists with the DArk MAtter (DAMA) experiment claimed some years ago (and again in 2008) that it found evidence for the existence of WIMPs by looking at this modulation. Unfortunately, DAMA used only one detection method and therefore may not have been able to discriminate between background noise and a WIMP signal. And no other scientific group has repeated DAMA's discovery. In science, if another group can't repeat a finding, then there's a distinct possibility that experimental error and not evidence is responsible.

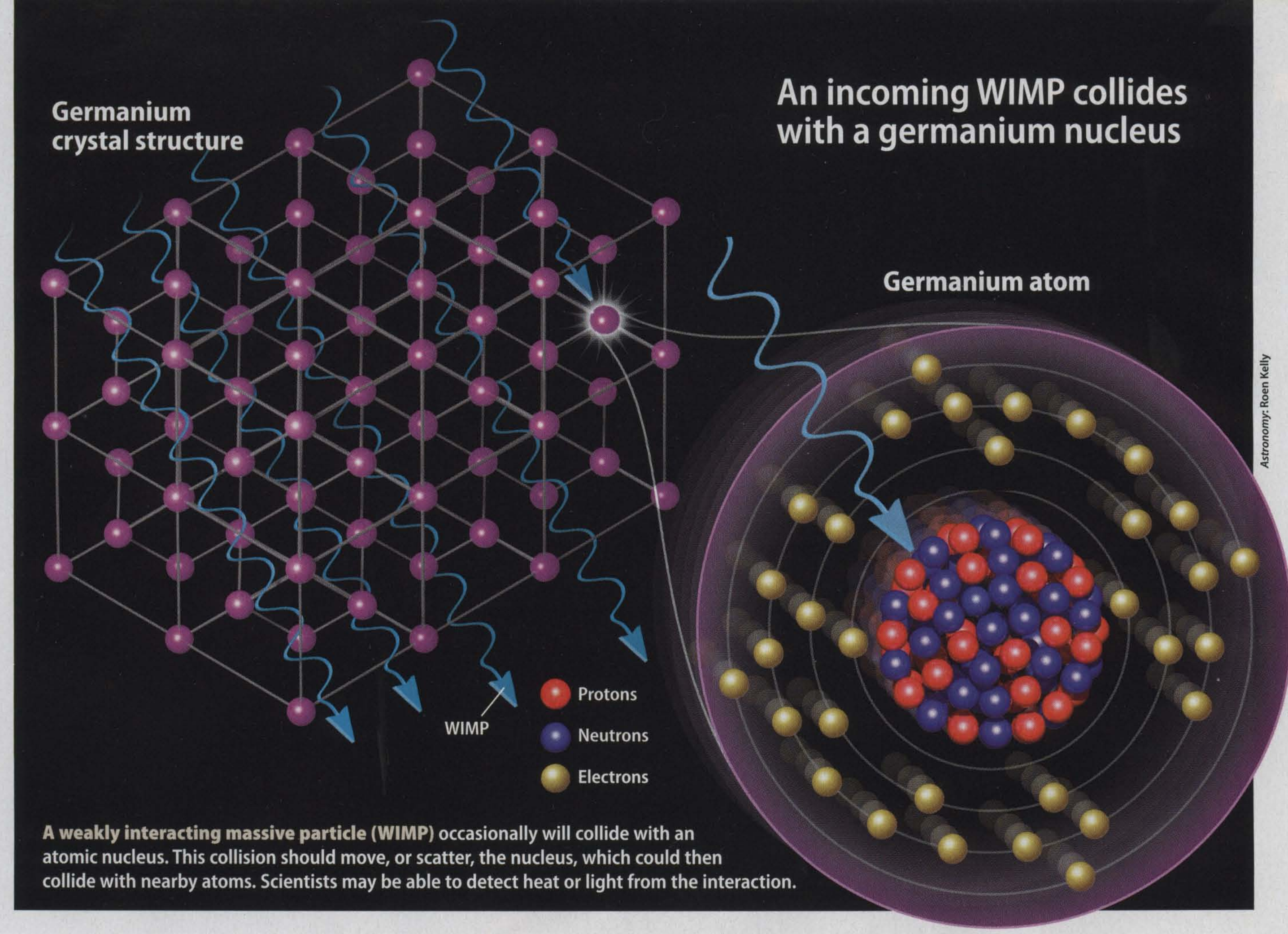
WIMPy signals

So far, direct searches haven't found WIMPs. Therefore scientists also look for the indirect signature of the dark matter candidates to complement direct searches. Neutralino annihilations should produce electrons, positrons, gamma rays, and neutrinos, along with other particles. Scientists can use certain detectors to look for each product.

Look for the secondary particles



The leading dark matter candidate is the theorized neutralino, the lightest weakly interacting massive particle. When two neutralinos collide, they annihilate each other and create a shower of secondary particles. Numerous detectors are looking for these secondary particles, which are therefore an indirect signature of dark matter. *Astronomy*: Roen Kelly



A weakly interacting massive particle (WIMP) occasionally will collide with an atomic nucleus. This collision should move, or scatter, the nucleus, which could then collide with nearby atoms. Scientists may be able to detect heat or light from the interaction.

The density of neutralinos (or other WIMPs) must be high in order for these particles to meet up and destroy each other. This typically happens within more massive objects.

A WIMP near the Sun or Earth could collide with an ordinary particle's nucleus. (This is similar to what happens within detector material.) The WIMP will lose energy, and its speed could decrease below the Sun or Earth's escape velocity. If that happens, the WIMP cannot escape the massive object's gravitational hold. The WIMP can collide with another nucleus and so on until it settles into the core of either the Sun or Earth.

At the core, the densities are so high that WIMPs collide and produce secondary particles and radiation. (As mentioned before, neutrinos and gamma rays are two such products.) Several experiments underground — such as Super-Kamiokande in Japan — detect neutrinos.

WIMP collisions aren't the only nearby events that release neutrinos — the Sun produces them. Neutrino detectors can decipher WIMP neutrinos from solar neutrinos because WIMP neutrinos have greater energies. And a larger detector should find more neutrinos (hopefully of the WIMP variety). The next-generation neutrino detector IceCube should help in this search. IceCube is currently being built at the South Pole, and will cover a very large area — a cubic kilometer.

Searches for gamma rays from WIMP annihilations also look promising. The gamma rays should have a specific energy spectrum that depends on how massive the WIMP is. The Fermi Gamma-ray Space Telescope may be able to detect that particular spectrum and offer an indirect observation of dark matter. Says Hooper, "If I had to wager a guess, I would say that the best prospects to detect WIMPs in the near future are with gamma-ray telescopes." A number of ground-based gamma-ray detectors are also on the lookout.

Where's the axion?

A WIMP may be the leading CDM candidate, but it isn't the only one. The axion is also a popular possibility.

An axion detector consists of two parts: a cavity with a magnetic field and an antenna with amplifier. According to theory, as an axion traverses the cavity, it will convert into a microwave photon. The photon's frequency will be proportional to the axion's mass. Scientists, however, aren't sure what the axion's mass is, which means they're unsure what frequency to search for. Using the antenna and amplifier, scientists will scan portions of the microwave region looking for a signal that stands out above the background noise.

Detector sensitivity is slowly getting to where it needs to be to pick out axions — and WIMPs — from background noise. It's not there yet, but scientists, with the help of elegant particle theories, are throwing everything they have at searching for (and hopefully detecting) dark matter.

"Very often in particle physics we have followed such 'natural' prescriptions, only to be surprised by nature," says Collar. With more advanced detectors coming in the next decade or so, cosmologists are sure to get a surprise — whether a hint that they're on the wrong path or a promising detection.