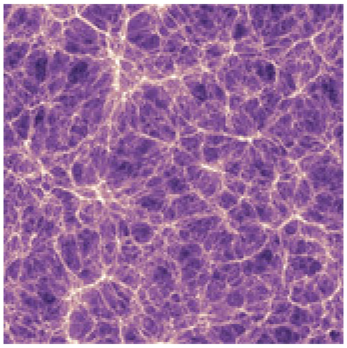
Unit 10: Dark Matter



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Unit Overview

Most of the mass in galaxies like our own Milky Way does not reside in the stars and gas that can be directly observed with telescopes. Rather, around 90 percent of the mass in a typical galaxy is "dark matter," a substance that has so far evaded direct detection. How can scientists make this astonishing claim? Because, although we have yet to detect dark matter, we can infer its existence from the gravitational pull it exerts on the luminous material we *can* see. Another facet of the dark matter problem comes at larger scales, where the total amount of mass in the universe exceeds the inventory of atoms we think were made in the Big Bang. A third indication of something missing comes from the evolution of the large-scale structure in the Universe, where fluctuations in the dark matter density are needed to seed the formation of the tendrils and filaments of galaxies we see in observations. So what is dark matter, and how might we find out? Determining the nature and distribution of dark matter is one of the most pressing (and most interesting!) open questions in modern science—it resides at the interface of particle physics, astrophysics, and gravity. Many candidates for dark matter have been suggested, from the ghostly axion (particles with a tiny amount of mass) to Weakly Interacting Massive Particles (WIMPs) that weigh in at 100 times the proton's mass. In this unit, we shall review the observational and theoretical evidence for dark matter, and describe the attempts that are under way to find it.

Content for This Unit

Sections:

Section 1: Introduction

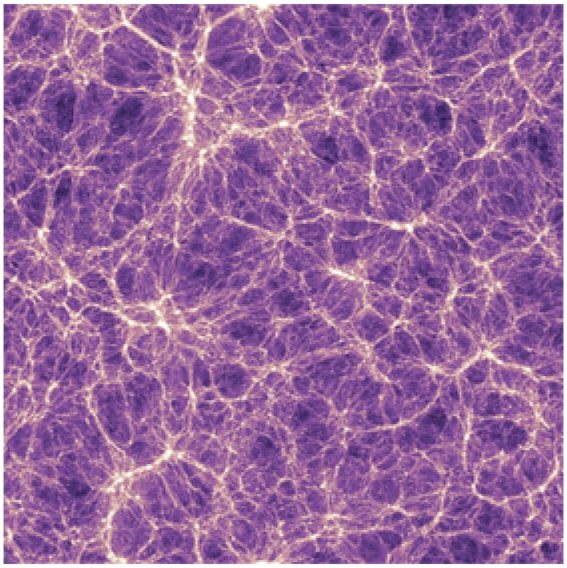

Figure 1: Distribution of dark matter in the universe.
Source: © Raul Angulo, Max Planck Institute for Astrophysics.

Dark matter is something beyond the stuff we encounter here on Earth. We all consist of neutrons, protons, and electrons, and our particle physics experiments with cosmic rays and accelerators tell us that a whole set of particles interact with each other to make up the world we see. As we learned in Units 1 and 2, the Standard Model describes these known particles and their interactions. But careful astronomical measurements, computer-based simulations, and nuclear theory calculations have all led us to believe that the particles described by the Standard Model account for only 4 percent of the mass of the universe. What makes up the missing 96 percent? Physicists believe, based on cosmological measurements described in this unit and Unit 11, that 23 percent is dark matter and 73 percent is dark energy. Dark energy and dark matter are very different. We shall learn about dark energy in Unit 11. Here, we focus on dark matter.

The first evidence of dark matter appeared in the 1930s, when astronomer Fritz Zwicky noticed that the motion of galaxies bound together by gravity was not consistent with the laws of gravity we learned about in Unit 3 unless there was a lot more matter in the galaxy cluster than he could see with his telescope. Development of more powerful and more precise theoretical and experimental tools in subsequent decades strengthened the case for dark matter. By the 1990s, dark matter was required to explain not just the motion of galaxies, but also how those galaxies and other large structures in the universe form, and the detailed pattern of temperature fluctuations in the cosmic microwave background radiation left over from the early universe.

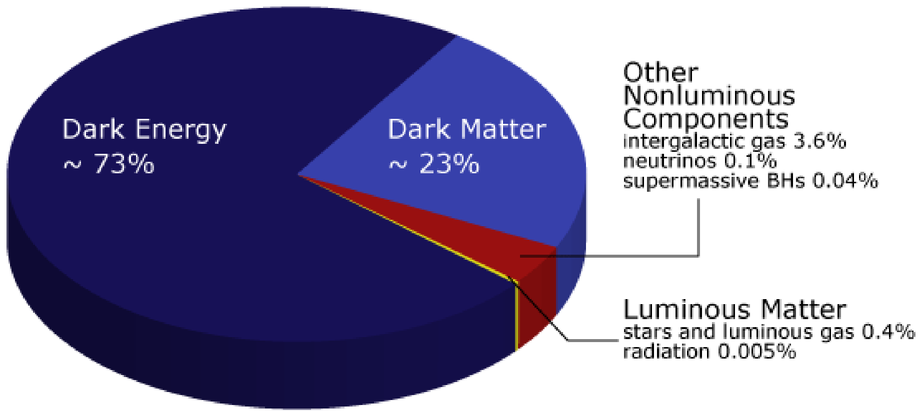

Figure 2: The composition of the universe, with 96 percent invisible and unfamiliar.
Source:

With these distinct reasons to believe that dark matter is a real part of our universe, scientists struggled to understand what comprises dark matter. Could it consist of familiar objects like brown dwarfs and large planets—made of the stuff of the Standard Model, but not emitting light and therefore invisible to astronomers? Both theory and experiment eventually pointed away from this simple explanation, strongly suggesting that dark matter is something entirely new and different. A generation of experiments was developed to look for new types of particles—beyond the Standard Model—that could account for some or all of dark matter. In parallel, theorists have developed creative visions of what new physics could explain about the motion of galaxies, large scale structure, and variations in the cosmic microwave background in one fell swoop.

The process of discovery has not run smoothly. It has survived successive periods of disinterest, progressing as new technologies developed, scientists made fresh observations in disparate fields, and general scientific interest in the topic increased. In this unit, we describe why we think dark matter exists, its role in determining the structure of galaxies and clusters of galaxies, and how it connects with particle physics. Finally, we discuss the ongoing quest to determine what dark matter is made of in both theory and experiment.

Dark matter and gravity

The connection between dark matter and gravity bears special mention because it is the one thing about dark matter of which physicists are certain. Everything we know about dark matter so far comes from astronomy. The astronomical measurements deal exclusively with the way in which dark matter interacts gravitationally. We have two ways of studying the effects of gravity on astronomical bodies: We can either see how a group of astronomical objects moves under the influence of gravity or measure how gravitation changes the way in which light travels. Experimentally, we have no reason to believe that dark matter interacts with normal matter or with itself in any way other than via gravitation, although there is a great deal of theoretical speculation to the contrary.

Figure 3: Clusters of galaxies contain significantly more dark matter than visible matter.
Source: © ESO.

The effects of dark matter did not become apparent until astronomers began to study the motion of galaxies and clusters of galaxies. Since a galaxy that measures 150,000 light-years across contains 2 to 10 times as much dark matter as normal matter, the gravity from the dark matter plays a large role in its movements. However, the normal matter is clumped in solar systems (stars and planets), while the dark matter is spread out. Typical solar systems are about 10 light-hours across and are separated from each other by about 2 light-years. So, in conventional terms, the galaxy consists of mostly empty space interspersed with very dense clumps of normal matter.

Since a solar system contains far more normal matter than dark matter (2×10^{30} kilograms vs. 9×10^{9} kilograms), dark matter plays an insignificant role in shaping our solar system. At the next level of size, observations indicate that normal and dark matter play roughly similar roles in determining the dynamics of galaxies. And at the largest-size scales, dark matter dominates the dynamics of galaxy clusters and superclusters—clusters of clusters. To study dark matter, we need to investigate objects the size of a galaxy or larger.

Section 2: Initial Evidence of Dark Matter

Fritz Zwicky, an astronomer at the California Institute of Technology, stumbled across the gravitational effects of dark matter in the early 1930s while studying how galaxies move within the Coma Cluster. The Coma Cluster consists of approximately 1,000 galaxies spread over about two degrees on the sky —roughly the size of your thumb held at arm's length, and four times the size of the Sun and the Moon seen from Earth. Gravity binds the galaxies together into a cluster, known as a galaxy cluster. Unlike the gravitationally bound planets in our solar system, however, the galaxies do not orbit a central heavy object like the Sun and thus execute more complicated orbits.

The Father of Dark Matter—and More

Fritz Zwicky.
Source: © AIP Emilio Segrè Visual Archives, Physics Today Collection.

Bulgarian born and Swiss naturalized, Fritz Zwicky found his scientific home at the California Institute of Technology. From his perch on Caltech's Mount Wilson Observatory, Zwicky discovered more of the exploding stars known as "supernovae" than all his predecessors combined. But astrophysicists today admire him mostly for his theoretical insights into such phenomena as neutron stars, gravitational lenses, and—perhaps most important of all—dark matter.

Zwicky's observations of supernovae in distant galaxies laid the foundation of his theoretical work. As he detected supernovae in ever-more distant galaxies, he realized that most galaxies combined in clusters. Careful measurements of the light from clusters led him to suggest the existence of dark matter. That may represent his greatest legacy, but he made other key contributions to astrophysics. He predicted that galaxies could act as gravitational lenses, an effect first observed in 1979, five years after his death. And he and his colleague Walter Baade predicted the transition of ordinary stars into neutron stars, first observed in 1967.

To carry out his observations, Zwicky persuaded Caltech to build an 18-inch Schmidt telescope that could capture large numbers of galaxies in a single wide-angle photograph. He used the instrument to make a survey of all the galaxies in the cluster and used measurements of the Doppler shift of their spectra to determine their velocities. He then applied the virial theorem. A straightforward application of classical mechanics, the virial theorem relates the velocity of orbiting objects to the amount of gravitational force acting on them. Isaac Newton's theory tells us that gravitational force is proportional to the masses of the objects involved, so Zwicky was able to calculate the total mass of the Coma Cluster from his measured galactic velocities. See the math

Figure 4: The Coma Cluster, which provided the first evidence for dark matter.
Source: © NASA, JPL-Caltech, SDSS, Leigh Jenkins, Ann Hornschemeier (Goddard Space Flight Center) et al.

Zwicky also measured the total light output of all the cluster's galaxies, which contain about a trillion stars altogether. When he compared the ratio of the total light output to the mass of the Coma Cluster with a similar ratio for the nearby Kapteyn stellar system, he found the light output per unit mass for the cluster fell short of that from a single Kapteyn star by a factor of over 100. He reasoned that the Coma Cluster must contain a large amount of matter not accounted for by the light of the stars. He called it "dark matter."

Zwicky's measurements took place just after astronomers had realized that galaxies are very large groups of stars. It took some time for dark matter to become the subject of active research it is today. When Zwicky first observed the Coma Cluster, tests of Einstein's theory were just starting, the first cosmological measurements were taking place, and nuclear physicists were only beginning to develop the theories that would explain the Big Bang and supernovae. Since galaxies are complex, distant objects, it is not surprising that astronomers did not immediately begin to worry about "the dark matter problem."

By the early 1970s, technology, astronomy, and particle physics had advanced enough that the dark matter problem seemed more tractable. General relativity and nuclear physics had come together in the Big Bang theory of the early universe, and the detection of microwave photons from the time when the first atoms formed from free electrons and protons had put the theory on a solid footing. Larger telescopes and more precise and more sensitive light detectors made astronomical measurements quicker and better. Just as important, the emergence of affordable mini-computers allowed physics and astronomy departments to purchase their own high-performance computers for dedicated astronomical calculations. Every advance set the scene for a comprehensive study of dark matter, and two very important studies of dark matter soon appeared.

Dark matter appears in galactic simulations

Figure 5: James Peebles (left) and Jeremiah Ostriker (right) found evidence for dark matter in their computer simulations.
Source: © AIP, Physics Today Collection and Tenn Collection.

In 1973, Princeton University astronomers Jeremiah Ostriker and James Peebles used numerical simulation to study how galaxies evolve. Applying a technique called N-body simulation, they programmed 300 mass points into their computer to represent groups of stars in a galaxy rotating about a central point. Their simulated galaxy had more mass points, or stars, toward the center and fewer toward the edge. The simulation started by computing the gravitational force between each pair of mass points from Newton's law and working out how the mass points would move in a small interval of time. By repeating this calculation many times, Ostriker and Peebles were able to track the motion of all the mass points in the galaxy over a long period of time.

For a galaxy the size of the Milky Way (4×10^{20} meters), a mass point about halfway out the edge moves at about 200 kilometers per second and orbits the center in about 50 million years. Ostriker and Peebles found that in a time less than an orbital period, most of the mass points would collapse to a bar-shaped, dense concentration close to the center of the galaxy with only a few mass points at larger radii. This looked nothing like the elegant spiral or elliptical shapes we are used to seeing. However, if they added a static, uniform distribution of mass three to 10 times the size of the total mass of the mass points, they found a more recognizable structure would emerge. Ostriker and Peebles had solid numerical evidence that dark matter was necessary to form the types of galaxies we observe in our universe.

Fresh evidence from the Andromeda galaxy

At about the same time, astronomers Kent Ford and Vera Cooper Rubin at the Carnegie Institution of Washington began a detailed study of the motion of stars in the nearby galaxy of Andromeda. Galaxies are so large that even stars traveling at 200 kilometers per second appear stationary; astronomers must measure their Doppler shifts to obtain their velocities. However, early measurements of stellar velocities in different portions of Andromeda proved very difficult. Since the spectrometers used to measure the shift in frequency took a long time to accumulate enough light, observations of a given portion of Andromeda required several hours or even several nights of observing. Combining images from several observations was difficult and introduced errors into the measurement. However, new and more sensitive photon detectors developed in the early 1970s allowed much shorter measurement times and enabled measurements further out from the center of the galaxy.

From Controversy to Credibility

Vera Cooper Rubin at the Lowell Observatory. Kent Ford has his back to us.
Source: © Bob Rubin.

Vera Cooper Rubin faced several obstacles on her way to a career in astronomy. A high school physics teacher tried to steer her away from science. A college admissions officer suggested that she avoid majoring in astronomy. Princeton University did not grant her request for a graduate catalogue in 1948, because its graduate astronomy program did not accept women until 27 years later. Senior astronomers took a scornful view of her first paper, presented in 1950, on galactic motions independent of the classic expansion of the universe. And when she and collaborator Kent Ford expanded that research in the 1970s, they met so much dissent that they shifted to another field.

The shift proved providential. Rubin and Ford measured the rotational velocities of interstellar matter in orbit around the center of the nearby Andromeda galaxy. Their readings, confirmed by observations on other galaxies, led them to infer that the galaxies must contain dark matter. Confirmation of that fact sealed Rubin's reputation as an astronomer.

Rubin and Ford measured the velocity of hydrogen gas clouds in and near the Andromeda galaxy using the new detectors. These hydrogen clouds orbit the galaxy much as stars orbit within the galaxy. Rubin and Ford expected to find that the hydrogen gas outside the visible edge of the galaxy would be moving slower than gas at the edge of the galaxy. This is what the virial theorem predicts if the mass in the galaxy is concentrated where the galaxy emits light. Instead, they found the opposite: the orbital velocity of the hydrogen clouds remained constant outside the visible edge of the galaxy. If the virial theorem is to be believed, there must be additional *dark* matter outside the visible edge of the galaxy. If Andromeda obeyed Newton's laws, Rubin reasoned, the galaxy must contain dark matter, in quantities that increased with increasing distance from the galactic center.

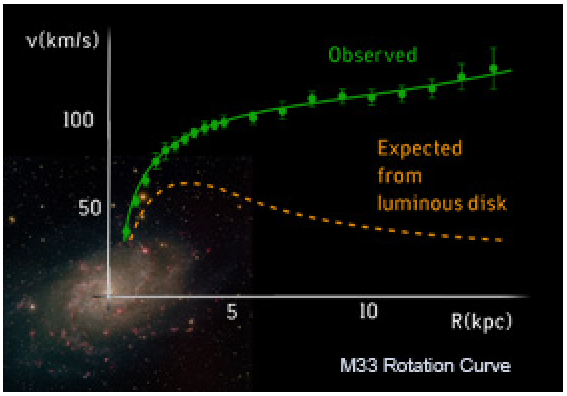

Figure 6: Observed and predicted rotation curves for the galaxy M33, also known as the "Triangulum Galaxy."
Source: © M33 Image: NOAO, AURA, NSF, T. A. Rector.

Alternative explanations of the Andromeda observations soon emerged. Theories of Modified Newtonian Dynamics (MOND), for example, aimed to explain the findings by modifying the gravitational interaction over galactic and larger distances. At very low accelerations, which correspond to galactic distances, the theories posit that the gravitational force varies inversely with the distance alone rather than the square of the distance. However, MOND would overturn Einstein's theory in an incredible way: General relativity is based on the simple idea of the equivalence principle. This states that there is no difference between gravitational mass (the mass that causes the gravitational force) and inertial mass (the mass that resists acceleration). There is no fundamental reason to expect these two masses to be the same, nor is there any reason to expect them to be different. But their equivalence forms the cornerstone of Einstein's general theory. MOND theories break that equivalence because they modify either gravity or inertia. If MOND were correct, a fundamental assumption underlying all of modern physics would be false.

Section 3: Dark Matter in the Early Universe

By the end of the 1970s, two compelling lines of evidence for dark matter had appeared. The motion of galaxies within clusters and the motion of gas clouds around individual galaxies strongly suggested that either our understanding of gravity is fundamentally wrong, or that there is far more matter in the galaxies and clusters than meets the eye. Further, simulations of galaxy formation showed that the spiral and elliptical galaxies we observe in the night sky cannot form without large amounts of dark matter in addition to the luminous stars. A third line of evidence developed in the 1990s, as radio telescopes above the atmosphere mapped the cosmic microwave background (CMB).

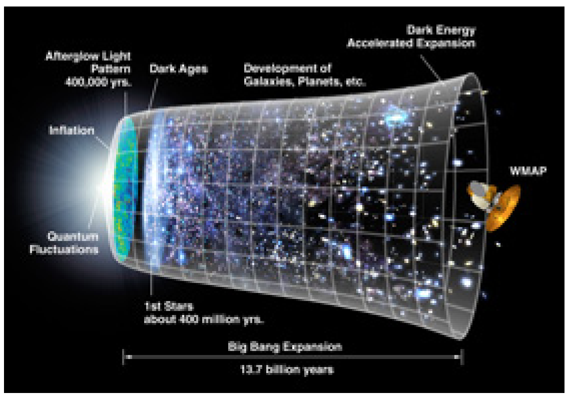

Figure 7: The history of the universe according to our standard model of cosmology.
Source: © NASA, WMAP Science Team.

This new evidence for dark matter has its origin in the early universe. About one second after the Big Bang, astrophysicists believe, a very dense mixture of protons, neutrons, photons, electrons, and other subatomic particles filled the universe. The temperature was so high that the electrons could not bind with the protons to form atoms. Instead, all the particles scattered off of each other at high rates, keeping all the different species at the same temperature—that is, in thermal equilibrium—with each other. The photons also scattered off of the electrically charged protons and electrons so much that they could not travel very far.

As the universe expanded, the temperature dropped to about one billion degrees Kelvin (K). At that point, the protons and neutrons began to bind together to form atomic nuclei. At roughly 390,000 years after the Big Bang, continued expansion and cooling had dropped the temperature of the universe to about 3000 K. By that point, all the electrons and protons had bound to form electrically neutral hydrogen atoms, and all the other charged particles had decayed. After the primordial hydrogen formed, the universe became so transparent to photons that they have been traveling throughout it for the entire 13.7 billion years since then. These relic photons from the early universe have a microwave wavelength, and are known as the cosmic microwave background, or CMB.

Density fluctuations and dark matter

Before the neutral hydrogen formed, the matter was distributed almost uniformly in space—although small variations occurred in the density of both normal and dark matter owing to quantum mechanical fluctuations. Gravity pulled the normal and dark matter in toward the center of each fluctuation. While the dark matter continued to move inward, the normal matter fell in only until the pressure of photons pushed it back, causing it to flow outward until the gravitational pressure overcame the photon pressure and the matter began to fall in once more. Each fluctuation "rang" in this way with a frequency that depended on its size. The yo-yoing influenced the temperature of the normal matter. It heated up when it fell in and cooled off when it flowed out. The dark matter, which does not interact with photons, remained unaffected by this ringing effect.

When the neutral hydrogen formed, areas into which the matter had fallen were hotter than the surroundings. Areas from which matter had streamed out, by contrast, were cooler. The temperature of the matter in different regions of the sky—and the photons in thermal equilibrium with it—reflected the distribution of dark matter in the initial density fluctuations and the ringing normal matter. This pattern of temperature variations was frozen into the cosmic microwave background when the electrons and protons formed neutral hydrogen. So a map of the temperature variations in the CMB traces out the location and amount of different types of matter 390,000 years after the Big Bang.

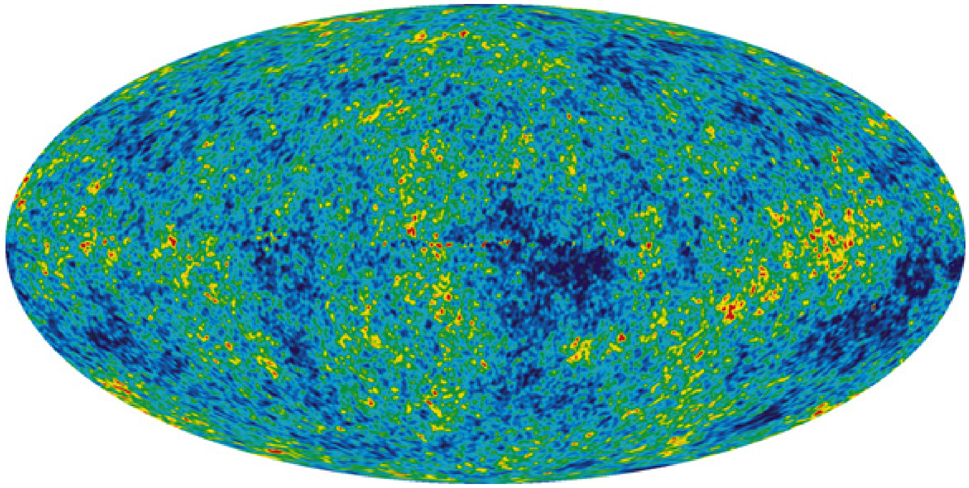

Figure 8: Map of the temperature variations in the cosmic microwave background measured by the WMAP satellite.
Source: © NASA, WMAP Science Team.

American physicists Ralph Alpher, Robert Herman, and George Gamow predicted the existence of the CMB in 1948. Seventeen years later, Bell Labs scientists Arno Penzias and Robert Wilson detected them. Initial measurements showed the intensity of the relic photons to be constant across the sky to a fraction of 1 percent. In the early 1990s, however, NASA's Cosmic Background Explorer (COBE) spacecraft used a pair of radio telescopes to measure differences among relic photons to one part per million between two points in the sky. A subsequent spacecraft, the Wilkinson Microwave Anisotropy Probe (WMAP), made an even more precise map. This revealed hot and cold spots about 1.8 degrees in size across the sky that vary in intensity by a few parts per million.

The angular size and the extent of variation indicate that the universe contained about five times as much dark matter as normal matter when the neutral hydrogen formed. Combined with measurements of supernovae and the clustering of galaxies, this indicates that dark energy comprises 73 percent of the universe, dark matter 23 percent, and normal matter just 4 percent.

Section 4: Dark Matter Bends Light

With three independent reasons to believe that dark matter existed—motion of galaxies, structure simulations, and temperature fluctuations in the cosmic microwave background—increasing numbers of physicists and astronomers turned their attention to trying to understand just what the dark matter is made of, and how it is distributed throughout the universe. Gravitational lensing proved a useful tool with which to probe the dark matter.

Quasars, lensing, and dark matter

Images of quasars gravitationally lensed by galaxies provide insight into the distribution of dark matter inside the lensing galaxies. Quasars are distant objects that emit huge amounts of light and other radiation. Since many quasars are visible behind galaxies, their light must pass through those intervening galaxies on the way to us. We know from general relativity theory that the matter in any galaxy—both normal and dark matter—bends space time. That bending distorts the image of any quasar whose light passes through a galaxy.

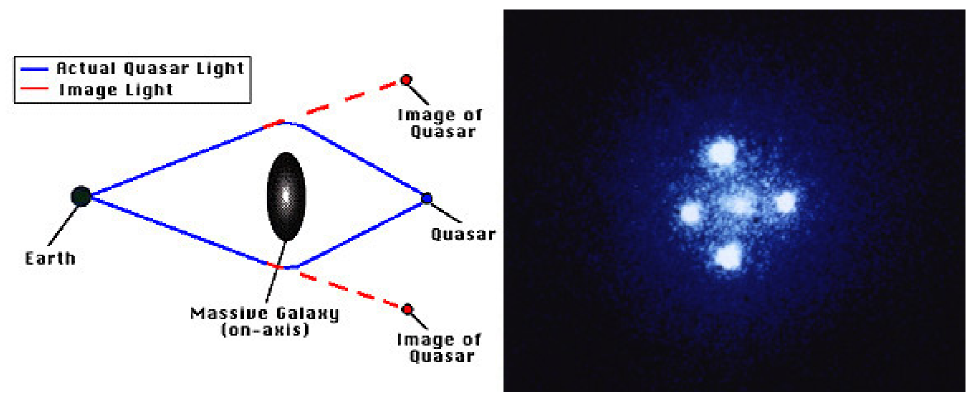

Figure 9: Gravitational lensing produces more than one image of distant quasars, as seen in this shot from the Hubble Space Telescope.
Source: © NASA/ESA Hubble Space Telescope, NASA/Goddard Space Flight Center.

In many cases, this lensing causes several images of the same quasar to appear in our telescopes. Careful measurements of the brightness of the different images of the quasar give hints about the distribution of the matter in the galaxy. Since the matter in each part of the galaxy determines the amount of bending of space time in that part of the galaxy, the brightness of the images tells us how matter, both normal and dark, is distributed. Optical measurements inform astronomers where the normal matter is. They can then use the brightness of the multiple quasar images to trace out the dark matter.

So far, astronomers have identified about 10 such lenses like this. Careful observations have shown that any clumps of dark matter in the galaxies must be smaller than about 3,000 light-years. More sensitive telescopes will find more lenses and will improve our understanding of how dark matter is distributed in galaxies.

Evidence from colliding clusters

Observing colliding galaxy clusters provides another useful way of understanding the nature of dark matter. When two clusters collide, the dark matter in one passes through the other unaffected; dark matter doesn't interact much with either itself or normal matter. But the normal matter in one cluster does interact with the dark matter and the normal matter in the other cluster, as well as with the dark matter in its own cluster. During the collision, the normal matter is dragged forward by the dark matter in its own cluster and dragged back by both the dark matter and normal matter in the other cluster. The net effect of the collision, therefore, is to cause the normal matter in each cluster to fall behind the dark matter in the same cluster.

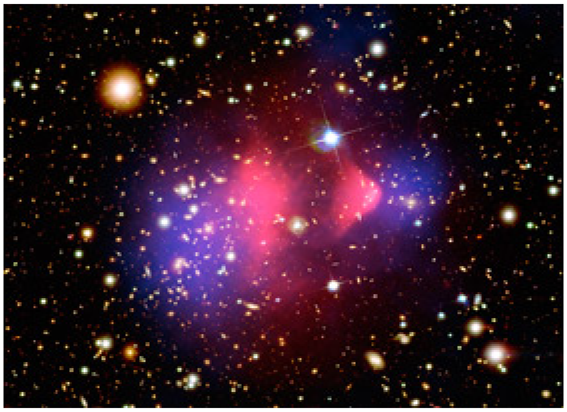

Figure 10: X-ray and visible light images of the Bullet Cluster reveal strong evidence for the existence of dark matter.
Source: © X-ray: NASA, CXC, CfA, M. Markevitch et al.; Optical: NASA, STScI; Magellan, U. Arizona, D. Clowe et al.; Lensing Map: NASA, STScI; ESO WFI; Magellan, U. Arizona, D.Clowe et al.

Astronomers gained solid evidence of that scenario when they imaged a pair of colliding galaxy clusters named the Bullet Cluster in two ways: through its emission of visible light and x-rays. The collision between the normal matter in each subcluster heats up the normal matter, causing the colliding subclusters to emit x-rays. In 2004, NASA's orbiting Chandra x-ray observatory captured an x-ray image of the Bullet Cluster that gives the locations of the normal matter in the two subclusters. At the same time, the entire Bullet Cluster distorts the images of galaxies behind it through the gravitational lensing effect that we reviewed above in the context of quasars. By carefully measuring the shape of the distorted background galaxies, astronomers could determine the average position and mass of each of the subclusters. Since galaxy clusters contain a few times as much dark matter as normal matter, the lensing measurement gives the location of the dark matter, while the x-rays locate the normal matter. The image that combines both measurements shows that the dark matter has run ahead of the normal matter in both subclusters, confirming expectation.

The measurements of the Bullet Cluster were a blow to the MOND theories that we encountered earlier in this unit. Those theories predict no difference between the x-ray and lensing images. Some theorists have tried to modify the MOND approach in such a way that it accommodates the evidence from the Bullet Cluster and other observations, but the clear consensus of astronomers is that dark matter is a reality.

Dark matter in our galaxy

With gravitational lensing successfully being used to "weigh" entire galaxy clusters, the question arose whether it could be brought to bear more locally, to search for dark matter objects in the outer regions of our own Milky Way galaxy. The answer is a resounding yes. A clever gravitational lensing survey to search for clumps of dark matter in the halo of our galaxy began in 1992. The survey was designed to find MACHOs, or massive compact halo objects, which is a fancy term for "chunks of dark matter." It was initially thought that MACHOs would be failed stars or large, drifting planets—familiar objects that don't emit light—but the MACHO project was designed to be sensitive to any lump of dark matter with a mass between the Earth's mass and 10 times the Sun's mass.

Figure 11: This Australian telescope unsuccessfully sought evidence for the existence of MACHOs based on their putative effect on starlight.
Source: © The Australian National University.

The MACHO project used a telescope to monitor the light from stars just outside the Milky Way in a very small satellite galaxy called the "Large Magellanic Cloud." If a MACHO passes in front of one of these stars, the gravitational lensing effect predicted by Einstein's general theory of relativity and confirmed in 1979 will increase the measured flux of the starlight by a tiny amount. The Anglo-American-Australian MACHO Project used an automated telescope at Australia's Mount Stromlo Observatory to observe transits. None showed anywhere near enough change in the starlight to account for dark matter as consisting of faint stars or large planets.

A similar project, named "EROS" and run by the European Organisation for Astronomical Research in the Southern Hemisphere at Chile's La Silla Observatory, has had the same negative result. For example, a study of 7 million stars revealed only one possible MACHO transit; in theory, MACHOs would have produced 42 events. But physicists refused to give up the hunt. The SuperMACHO survey, a successor to the MACHO Project, used the 4-meter Victor M. Blanco telescope in Chile's Cerro Tololo Inter-American Observatory to monitor tens of millions of stars in the Large Magellanic Cloud in search of evidence that

MACHOS exist. SuperMACHO also found that MACHOs cannot account for the vast amount of dark matter in the galaxy.

The astronomical evidence we have for dark matter ranges from within our galaxy to the farmost regions of space and time that we are able to probe. We now understand that dark matter dominates at the scale of galaxy clusters, normal matter dominates at the subgalactic scale, and they duke it out on the galactic scale. We know that dark matter gravitationally interacts with itself and normal matter, but we still do not know what the dark matter is.

Section 5: From Astronomy to Particle Physics

The abundance of astronomical evidence for dark matter in the early 1970s intrigued physicists working in other fields. Cosmologists and nuclear physicists were developing our current model of cosmology, trying to understand how the universe we live in—dark matter and all—formed. Concurrently, others wondered how the dark matter fit, if at all, into the Standard Model we learned about in Unit 1.

By the late 1970s, the Standard Model of particle interactions had gained a firm experimental footing. At the same time, physicists were refining their standard model of cosmology in which the universe began its existence when a singularity, a point of infinite density and infinite temperature, exploded in the Big Bang and began a process of expansion that continues today. Application of the Standard Model and nuclear theory to the Big Bang model allowed physicists to quantify nucleosynthesis, the process responsible for creating elements out of the protons, neutrons, electrons, and energy that suffused the infant universe.

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Figure 12: This series of reactions created the lightest elements in the infant universe.
Source: © Wikimedia Commons, Public Domain, Author: Lokal_Profil, 5 August 2008.

This model of Big Bang nucleosynthesis, supported by careful astronomical observations of the abundance of light elements in the universe, makes a particularly significant prediction about the density of baryons in the first few minutes: The Big Bang could not have created enough normal matter at the start of the universe to account for dark matter. Astrophysicists concluded that dark matter must be some new form of matter not yet observed, possibly even a new type of particle.

New dark matter particles

One of the first attempts to explain dark matter with new particles arose in a surprising place: the Homestake Gold Mine in South Dakota that we first encountered in Unit 1. The Homestake neutrino detector was monitoring neutrinos thought to come from the Sun. In 1976, it became apparent that this experiment only counted about half the predicted number. One explanation was that some new form of heavy particles that did not interact much would collect in the center of the Sun, cooling it off very slightly. This new heavy particle would have the same properties required by dark matter: very weak interaction with other particles, copious in our solar system, and left over from the Big Bang.

We now know that the deficit of neutrinos is due to their oscillation; but at the time, it was an intriguing hint that dark matter could be made up of a new type of particle, possibly not included in the Standard Model. Heavy neutrinos were once considered a candidate for particle dark matter, but large-scale structure simulations of neutrino dark matter have ruled them out. The remainder of this unit will focus on particle dark matter in both theory and experiment. In section 8, we will explore the two leading non-Standard Model candidates for particle dark matter and experimental efforts to detect them. We also will examine how the constant theoretical effort to explain dark matter often generates new possibilities for particle dark matter. The table below summarizes all the possibilities for dark matter that appear in this unit.

Table 1. Possible candidates for Dark Matter

Candidate	Mass range	Pros	Cons
Astronomical objects (failed stars, black holes, MACHOs...)	10^{50}-10^{63} eV	Rather conservative scenario; lensing searches effective	Amount of ordinary matter made in Big Bang falls short of total dark matter we need; not detected via lensing searches
Neutrinos	< 2 eV	Known to exist, and have mass so a natural candidate	Tiny neutrino mass inhibits clumping on small scales needed to hold galaxies together
Axions	10^{-6} eV	Postulated to solve a different problem altogether; dark matter aspect comes for free	Tough to detect
Weakly Interacting Massive Particles (WIMPs)	10^{10} eV	Plausible class of new elementary particles that emerge from multiple theories beyond the Standard Model	Have evaded detection in accelerators to date
Alternative Gravity Scenarios	N/A	No mysterious new matter needed, but rather a modification of gravity	Hard to reconcile with Bullet Cluster observations; theories seen as "inelegant"
Dark Sector Interactions	N/A	Two new pieces of physics: exotic dark matter particles plus new interactions between them; might help reconcile experiments	Added complexity; wider range of phenomenology; tougher to rule out

Section 6: The Search for Particle Dark Matter

Starting in the late 1980s with the idea that dark matter could be a new kind of particle, nuclear and particle physicists began experiments to detect dark matter in the event that it interacts directly with normal matter. There are two main ideas about what these particles could be. One views the dark matter as a very light particle known as the axion. Hypothesized to explain a confusing property of the strong force that binds quarks together (see Unit 2), an axion would weigh about one-trillionth as much as a proton. The other idea comes from a very broad class of theories that predicts an electrically neutral particle weighing between 100 and 1,000 times as much as a proton. The general name of this kind of particle is a "weakly interacting massive particle" or WIMP. Physicists first introduced this concept to explain the problem of solar neutrinos that we met in Section 5.

Figure 13: If dark matter consists of axions, the Axion Dark Matter Experiment shown here could detect them in the next decade.
Source: © ADMX.

So far, physicists have found no evidence that axions or WIMPs actually exist; both particles remain in the realm of hypothesis. However, the physics community found the theoretical reasoning that led to the hypotheses were compelling enough to mount experimental searches for them. Some of their experiments have provided fascinating hints of the presence of these peculiar particles.

The types of experiments differ considerably, based on which particle they aim to detect. In each case, they rely on the specific physical properties of the two proposed particles. Because axions are hypothesized to have no electric charge or spin, extremely small masses, and minimal interaction with ordinary matter, experimenters must use indirect methods to detect them. In contrast, theorists see WIMPs as not only possessing large masses but also interacting—although infrequently—with ordinary matter. Thus, it may be possible to detect them directly as well as indirectly.

The quest for axions

The concept of the axion emerged as a solution to the so-called strong-CP problem. We first encountered CP, the product of charge conjugation and parity, in Unit 1. There we discovered that CP violation occurs in weak interactions, but does not appear to occur in strong interactions. In 1977, theorists Roberto Peccei and Helen Quinn suggested that this difference between the strong and the weak force was due to a broken symmetry. In Unit 2, we learned that symmetry breaking is accompanied by a new particle called a "Nambu-Goldstone boson." The new particle associated with the broken Peccei-Quinn symmetry would interact with ordinary matter so weakly as to be virtually undetectable. MIT theorist Frank Wilczek named it the axion after a laundry detergent because, he said, it cleaned up the strong-CP problem. Later, the weakness of its interactions made it a strong candidate for dark matter.

Figure 14: Axion hunters: two Fermilab physicists with their experiment designed to detect axions.
Source: © Fermilab.

Experimentalists who want to detect the particle can choose either to make their own axions or to search for those that already exist. Many of these experiments attempt to detect axions as they interact with photons. The basic idea is that when an axion collides with a photon, two photons are produced in the collision that have an energy proportional to the axion mass. Dark matter axions do not move very fast and are very light. Therefore, the photons produced would be low energy, with a wavelength roughly corresponding to radio waves. Axions are expected to interact with photons very weakly—much more weakly than electrons or protons—so the trick to detecting axions is to build a very sensitive radio antenna.

Trapping radio waves to identify axions

The process starts with a magnetic field about 200,000 times more powerful than Earth's field. When an axion interacts with the magnetic field, radio waves are generated. To capture the radio waves, experimentalists use a hollow superconducting cylinder called a "resonant cavity." The size and shape of the cavity are carefully selected to amplify radio waves of a particular frequency.

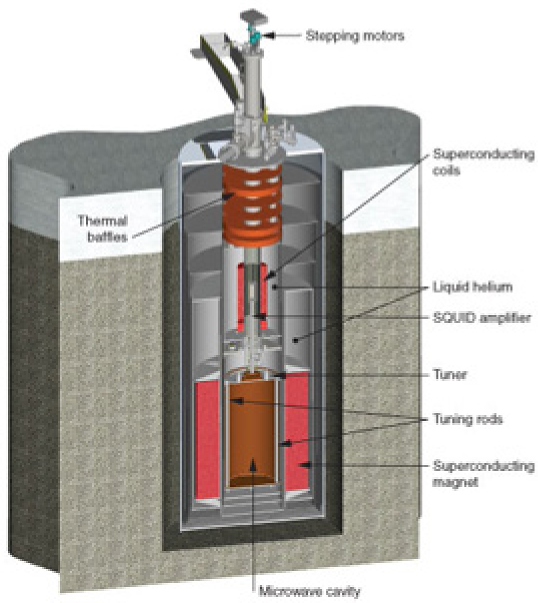

Figure 15: SQUID technology boosts the ability of the Axion Dark Matter Experiment to detect the faint signals that would indicate the presence of axions.
Source: © Lawrence Livermore National Laboratory.

For a typical mass of 2μeV, roughly 10^{30} axions would stream through the detector each second. Over time, the trapped radio waves would build up to a detectable amount. The radio waves built up in the resonant cavity are measured using a tool called a SQUID, for superconducting quantum interference device, which greatly improves the experiment's ability to detect faint signals. Since physicists do not know the mass of the hypothetical axion, they would have to adjust the radio frequency of the cavity in small steps, like tuning a radio, to scan for a signal from dark matter axions.

The best-known experiment of this type, the Axion Dark Matter Experiment (ADMX), has operated since 1995 without detecting a signal. Physicists at Lawrence Livermore National Laboratory and collaborating institutions improved ADMX in 2008 by adding sensitive amplifiers to the apparatus. Further enhancements include adding a cooling system that will improve the system's sensitivity. The team will add more improvements and will continue to operate the experiment for many years before exhausting all its potential to hunt for axions.

Other searches for axions have started in recent years. A Japanese project, the Cosmic Axion Research with Rydberg Atoms in a Resonant Cavity (CARRAC) experiment, seeks axions in a range of masses similar to that sought by ADMX. An Italian group's PVLAS (for Polarizzazione del Vuoto con LASer) experiment looks for minute changes in the polarization of light that might stem from axions. And in contrast to those earthbound methods, the European Nuclear Research Center's Axion Solar Telescope (CAST) searches for axions produced in the Sun.

Seeking the elusive WIMPs

As theorized, WIMPs interact with normal matter in the simplest way, by colliding with it. They don't do that very often; they easily penetrate the Earth or Sun without interacting at all. But very occasionally a WIMP will hit an atomic nucleus and cause it to recoil. Theorists believe that 5 million dark matter particles will pass through a 2 kilogram piece of normal matter, containing roughly 10^{25} atoms, every second. In rough numbers, just one of the WIMPs will hit a nucleus in an entire year. The nucleus will recoil and deposit its energy in the surrounding matter in the form of ionization electrons, which can attach to ions to create neutral atoms, or heat. The amount of energy deposited in this way resembles that of an x-ray photon. Physicists searching for dark matter face the twin challenge of collecting this deposited energy and ensuring that the energy they collect came from a dark matter interaction and not from a conventional physics process.

Distinguishing between dark matter interactions and conventional interactions proves to be very difficult. At sea level, 100 cosmic rays pass through each square meter of the Earth's surface each second, along with 28 neutrons from cosmic ray interactions in the atmosphere and 10,000 x-rays from low-level contamination in normal materials. In addition, everything contains trace amounts of uranium and thorium, both of which give rise to sequential radioactive decays. All these processes can mimic the scattering of dark matter off a nucleus.

Underground searches for WIMPs

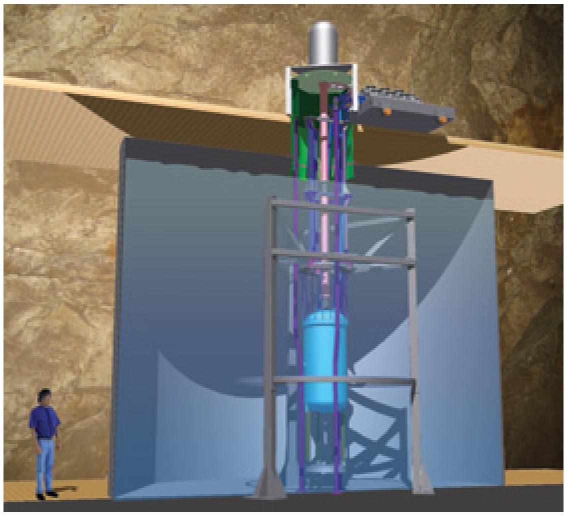

Figure 16: The Large Underground Xenon detector will have 100 times more sensitivity to WIMPs than previous detection methods.
Source: © The LUX Experiment.

Dark matter recoil experiments address these problems in several ways. Since few cosmic rays penetrate deep underground, experiments placed in tunnels and mines under a kilometer of rock remove that source of interference. The Large Underground Xenon (LUX) detector, which will operate 1,463 meters deep in the familiar Homestake Gold Mine in South Dakota, exemplifies this approach. As its detector, LUX will use a cylinder containing 350 kilograms of liquid and gaseous xenon, which scintillates and becomes ionized when struck by particles, including WIMPs. Several precautions will minimize the number of non-WIMP particles likely to impact the detector. Up to a meter of high-purity lead or copper shielding will absorb x-rays and gamma rays emitted by the walls of the mine. In future experiments, a meter or so of water will absorb neutrons from both cosmic rays and the cavern's walls. Finally, experimenters will use only tested, low-radioactivity materials to build the detector.

Other groups are also undertaking the underground route to detecting WIMPs. The international Xenon Dark Matter Project uses a xenon detector in a laboratory under Italy's Gran Sasso Mountain. The second Cryogenic Dark Matter Search (CDMSII) project relies on cryogenic germanium and silicon detectors in Minnesota's Soudan Mine, another location well used by scientists; the original experiment had taken place in a tunnel under the Stanford University campus. And, the Italian-American WIMP Argon Program (WARP) uses argon in place of the more expensive xenon in its detector.

To clarify their results, the dark matter detectors measure the energy of the recoiling nucleus in two different ways. A neutron or dark matter interaction will divide its energy between heat and ionization electrons, while other radioactive decays will put virtually all their energy into ionization electrons. In the late 1980s, the first dark matter experiments were able to exclude neutrinos as dark matter by measuring the energy only one way. The two energy measurement techniques developed since then have led to an improvement of 10 million in sensitivity to dark matter interactions. Future detectors will have even greater sensitivity.

Monitoring the direction of dark matter

If dark matter WIMPs exist, we could learn more about them by measuring the direction from which they come toward Earth from space. A directional measurement would use gas molecules at about one-twentieth of an atmosphere pressure as targets for the dark matter particles to hit. Each nucleus struck by a WIMP would travel about 1 millimeter. That's a long enough distance for physicists to measure by collecting the ionization electrons created by the collisions directly or by converting them to scintillation light and using a charge-coupled device (CCD) camera to create an image. Since each struck nucleus will generally travel in the same direction as that in which the dark matter particle traveled before it hit the nucleus, measuring the direction of the recoiling nuclei will give experimenters critical details about dark matter in our galaxy.

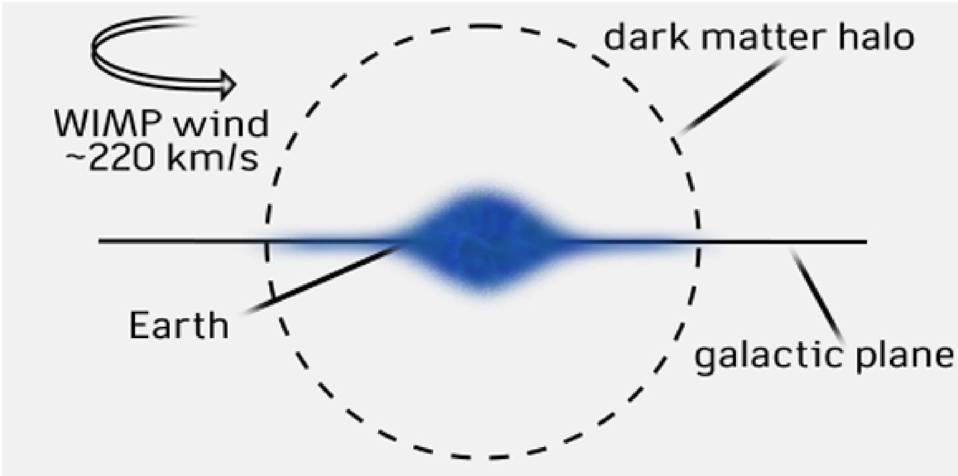

Figure 17: If they exist, WIMPs could stream toward Earth in a specific direction in a "WIMP wind" that might be experimentally detectable.
Source:

In the simplest picture, the normal matter in our Milky Way galaxy rotates through a stationary halo of dark matter. If we could easily detect dark matter on Earth, we would see a "wind" of dark matter coming from the direction in which our solar system is moving through the Milky Way. Since the constellation Cygnus orbits around the galactic center ahead of our solar system, the dark matter would appear to be streaming at us from Cygnus. Thus, a directional experiment would see nuclei recoiling away from Cygnus. Measuring direction in this way not only would yield information about dark matter, but it also would make the experiment more sensitive, since no background source of radiation would follow the trajectory of Cygnus. In addition, a detector able to measure direction would begin to explore the velocity distribution of dark matter in the Milky Way much more directly than ever before. A directional detector would work, in effect, as a dark matter telescope.

Collider and satellite searches for dark matter

If WIMPs comprise dark matter, high-energy collisions may also shed light on their nature. Both the Tevatron and the Large Hadron Collider (LHC) may be able to produce WIMPs by colliding protons and antiprotons or protons and protons at energies high enough to fuse the quarks inside those particles into WIMPs. Teams at both the Tevatron and LHC will continue sifting through vast amounts of data, hoping to find evidence of WIMPs in their detectors.

Figure 18: NASA's Fermi Gamma-ray Space Telescope has spotted an excess of normal matter particles that may have arisen when WIMPs annihilated each other.
Source: © NASA/Fermi Gamma-ray Space Telescope.

Finally, it may be that WIMP dark matter particles annihilate each other in the galaxy to produce extra amounts of normal matter (such as protons, electrons, antiprotons, positrons, neutrinos, or gamma rays), which could be detected from Earth or in space-borne experiments. Separating these extra normal particles from cosmic rays is difficult. But in the last year, two satellite experiments may have observed some hints of dark matter. NASA's Fermi Gamma-ray Space Telescope, launched in 2008, discovered evidence of more high-energy electrons and their antimatter positrons than anticipated. The excess could stem from WIMP annihilations. About the same time, the European Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) satellite, launched in 2006, detected more positrons than expected. However, it is much too early to tell whether either satellite has actually seen dark matter.

Section 7: Dark Forces

WIMPs and axions are compelling candidates for dark matter particles, but neither one has been detected experimentally. While ever-more sensitive laboratory experiments are conducted, theorists constantly develop new models, sometimes inventing new possibilities for dark matter. A plausible third candidate for dark matter has recently emerged, called dark forces. The dark forces theory is really an extension of the supersymmetry theory we first reviewed in Unit 2. In addition to the heavy WIMP particles, the latest version of supersymmetry theory posits the existence of light particles called φ, the Greek letter *phi*. If the φ exists, it is predicted to be more massive than two electrons, but less massive than 200 electrons. It would interact with other particles just like a photon, but with an interaction strength at least 1,000 times weaker.

The idea for dark forces arose when an Italian cosmic ray experiment called "DAMA/LIBRA" (DArk MAtter/Large sodium Iodide Bulk for RAre processes) observed energetic electrons and positrons unaccompanied by antiprotons. Ordinary WIMPs cannot explain this DAMA/LIBRA result, but in the dark forces version of supersymmetry, heavy WIMP particles would annihilate with one another and produce high-energy φ particles. The φ particles would then decay into energetic electron-positron pairs.

Figure 19: A technician works on detectors for the DAMA/LIBRA project, which stimulated the theory of dark forces.
Source: © DAMA/LIBRA.

The emergence of the dark forces theory has led to a series of new ideas for current and new experiments. If the theory is correct, WIMPs produced in high-energy collisions at the Tevatron and Large Hadron Collider would decay to several φ particles. Those particles would then decay to a large number of electrons, positrons, or muons, giving a clear experimental signature. At low-energy colliders, the φ would manifest itself in rare decays of known particles. In lower-energy electron-proton collisions, extra electrons and positrons in the decay products would indicate that the collision produced φ particles. Physicists would need to gather a huge amount of data to test dark forces. Because the φ interacts with one-thousandth the strength of a photon, only one event in a million might contain a φ.

Although the dark forces theory arose to explain cosmic ray experiments and the DAMA/LIBRA results, it would still be viable even if the experimental basis were shown to be a fluctuation or result of a known process. Like axions and supersymmetry, the dark forces theory as yet has no solid experimental basis. However, it is a perfectly reasonable description of dark matter in every respect and should be experimentally pursued.

Supersymmetry theory has suggested other possible sources of dark matter. They include the gravitino, the supersymmetry partner of the graviton, and the electrically neutral neutralino, a particle with very small mass. Like other dark matter candidates, they have so far defied experimental efforts to detect them.

Section 8: The Search Continues

Dark matter remains an active area of research, with the results of current and planned experiments eagerly anticipated by the entire physics community. In coming years, large-scale studies of galaxies like the continuing Sloan Digital Sky Survey and the Anglo-Australian 2dF Galaxy Redshift Survey, supported by numerical simulations, will continue to develop our picture of the way in which dark matter is distributed over galactic and larger distances. Better cosmological measurements of supernovae and the cosmic microwave background will sharpen our knowledge of cosmological parameters, in particular the total amount of normal and dark matter. Detailed measurements of galaxies using gravitational lensing will tell us more about the distribution of dark matter within a galaxy. New space probes, nuclear recoil, and axion experiments will continue to hunt for evidence that dark matter interacts with normal matter in ways other than gravity. In addition, colliding beam accelerators, particularly the LHC, will try to make dark matter particles in the laboratory.

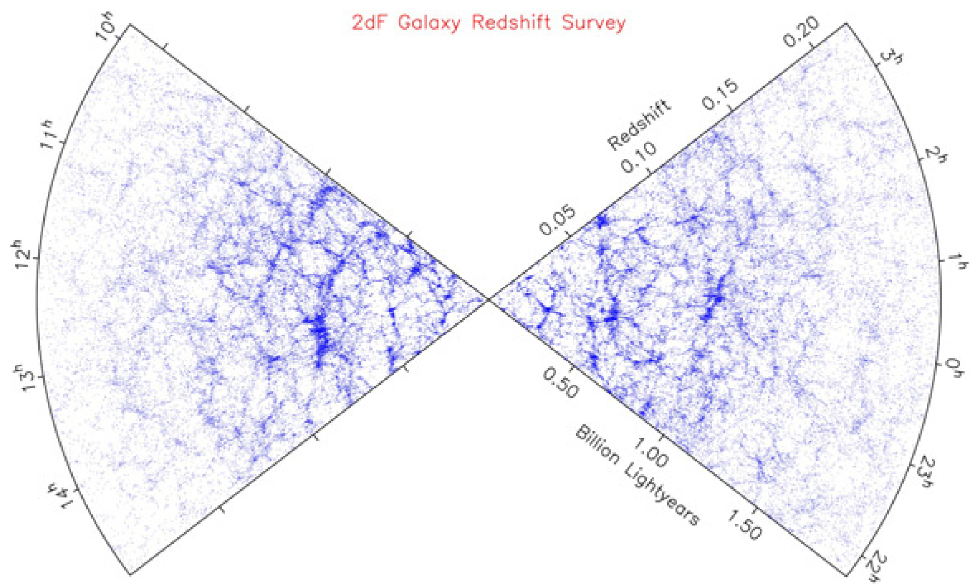

Figure 20: Galactic studies such as the "2dF Galaxy Redshift Survey" will improve our understanding of the distribution of dark and normal matter.
Source: © The 2dF Galaxy Redshift Team, 30 June 2003. Reproduced by permission of Commonwealth of Australia.

If some or all of the dark matter consists of WIMPs, the final picture will not emerge from any single endeavor. Rather, physicists will combine evidence produced by many different measurements to understand just what these new particles are. Even though the sensitivity of searches for dark matter on Earth has improved by about a factor of ten every few years over the past two decades, it might still take some time before the first convincing laboratory evidence for dark matter appears. Following first indications, further measurements using different targets will sharpen the picture. But conclusive evidence will require a directional signal as well as consistency with cosmic ray experiments, astronomical observations, and exploration of the Terascale from collider experiments.

What if dark matter consists of axions? In that case, ADMX may make an observation in the next 10 years—if dark matter conforms to theory.

Of course, dark matter may be something completely new and unexpected. It may be a different manifestation of dark energy or it may be that we never find out. Dark matter raises the question of what it means to discover something. We already know what dark matter *does*: how it regulates the structure of galaxies and clusters of galaxies. This knowledge will certainly improve steadily as we make more astronomical observations. Learning what dark matter actually *is*, however, will take a big jump—one that we may never make. What does it mean for science if we find that we can't make this jump? Most likely, we will never have to answer that question. Physicists will continue to probe the universe in expectation of eventually unearthing its deepest secrets.

Section 9: Further Reading

- W. Goldstein, et al., "Neutrinos, Dark Matter and Nuclear Detection," *NATO Science for Peace and Security Series*, Part 2, 2007, p.117.
- Wayne Hu and Martin White, "The Cosmic Symphony," *Scientific American*, Feb. 2004, p. 44.
- Gordon Kane, "Supersymmetry: Unveiling the Ultimate Laws of Nature," *Basic Books*, 2001.
- Stacy McGaugh, "MOND over Matter," *Astronomy Now*, Nov./Jan. 2002, p. 63.
- Mordehai Milgrom, "Does Dark Matter Really Exist?," *Scientific American*, August 2002, p. 43.

Glossary

axion: The axion is a hypothetical particle that naturally arises in the solution to the strong-CP problem proposed by Peccei and Quinn in 1977. Axions are electrically neutral, and experiments have shown that their mass must be less than 1 eV. While they are relatively light particles, slow-moving axions could be produced in copious amounts in the early universe, and thus could be a significant component of the dark matter.

cosmic microwave background: The cosmic microwave background (CMB) radiation is electromagnetic radiation left over from when atoms first formed in the early universe, according to our standard model of cosmology. Prior to that time, photons and the fundamental building blocks of matter formed a hot, dense soup, constantly interacting with one another. As the universe expanded and cooled, protons and neutrons formed atomic nuclei, which then combined with electrons to form neutral atoms. At this point, the photons effectively stopped interacting with them. These photons, which have stretched as the universe expanded, form the CMB. First observed by Penzias and Wilson in 1965, the CMB remains the focus of increasingly precise observations intended to provide insight into the composition and evolution of the universe.

CP violation: The CP operation is a combination of charge conjugation (C) and parity (P). In most interactions, CP is conserved, which means that the interaction proceeds exactly the same way if the CP operation is performed on the interacting particles. If CP is conserved, particles with opposite charge and parity will interact in the same way as the original particles. CP violation occurs when an interaction proceeds differently when the CP operation is performed—particles with opposite charge and parity interact differently than the original particles. CP violation was first observed in neutral kaon systems.

dark forces: Dark forces arise in a 2009 theory to explain various experimental results in high-energy astrophysics. The theory proposes that dark matter WIMPs can decay into force-carrying particles, denoted by the Greek letter *phi* (φ). The φ particles would be associated with a new force of nature, distinct from the strong force, weak force, electromagnetism, and gravity.

Doppler shift (Doppler effect): The Doppler shift is a shift in the wavelength of light or sound that depends on the relative motion of the source and the observer. A familiar example of a Doppler shift is the apparent change in pitch of an ambulance siren as it passes a stationary observer. When the ambulance is moving toward the observer, the observer hears a higher pitch because the wavelength of the sound waves is shortened. As the ambulance moves away from the observer, the wavelength is lengthened and the observer hears a lower pitch. Likewise, the wavelength of light emitted by an object moving toward an observer is shortened, and the observer will see a shift to blue. If the light-emitting object is moving away from the observer, the light will have a longer wavelength and the observer will see a shift to red. By observing this shift to red or blue, astronomers can determine the velocity of distant stars and galaxies relative to the Earth. Atoms moving relative to a laser also experience a Doppler shift, which must be taken into account in atomic physics experiments that make use of laser cooling and trapping.

equivalence principle: The equivalence principle is a basic premise that is essential to every experimentally verified physical theory, including General Relativity and the Standard Model. It states that an object's inertial mass is equivalent to its gravitational mass. The inertial mass of an object appears in Newton's second law: the force applied to the object is equal to its mass times its acceleration. The gravitational mass of an object is the gravitational equivalent of electric charge: the physical property of an object that causes it to interact with other objects through the gravitational force. There is no a priori reason to assume that these two types of "mass" are the same, but experiments have verified that the equivalence principle holds to a part in 10^{13}.

galaxy cluster: A galaxy cluster is a group of galaxies bound together by the force of gravity. Like the planets in our solar system, galaxies in a cluster orbit a common center of mass. However, galaxies execute more complicated orbits than the planets because there is no massive central body in the cluster playing the role of the Sun in our solar system. Galaxy clusters typically contain a few hundred galaxies, and are several megaparsecs (ten million light-years) in size. The orbital velocities of galaxies in clusters provide strong evidence for dark matter.

gravitational lensing: Gravitational lensing occurs when light travels past a very massive object. According to Einstein's theory of general relativity, mass shapes spacetime and space is curved by massive objects. Light traveling past a massive object follows a "straight" path in the curved space, and is deflected as if it had passed through a lens. Strong gravitational lensing can cause stars to appear as rings as their light travels in a curved path past a massive object along the line of sight. We observe microlensing when an object such as a MACHO moves between the Earth and a star. The gravitational lens associated with the MACHO focuses the star' light, so we observe the star grow brighter then dimmer as the MACHO moves across our line of sight to the star.

gravitino: The gravitino is the superpartner of the graviton. See: superpartner, supersymmetry.

graviton: The graviton is the postulated force carrier of the gravitational force in quantum theories of gravity that are analogous to the Standard Model. Gravitons have never been detected, nor is there a viable theory of quantum gravity, so gravitons are not on the same experimental or theoretical footing as the other force carrier particles.

ionization electron: An ionization electron is a free electron moving at high speed that knocks an electron off a neutral atom, turning the atom into an ion.

ion: An ion is an atom with nonzero electrical charge. A neutral atom becomes an ion when one or more electrons are removed, or if one or more extra electrons become bound to the atom's nucleus.

light-year: A light-year is the distance that light, which moves at a constant speed, travels in one year. One light-year is equivalent to 9.46×10^{15} meters, or 5,878 billion miles.

MACHO: A MACHO, or massive compact halo object, is a localized mass that has a gravitational influence on the matter around it but does not emit any light. Black holes and brown dwarf stars are examples of MACHOs. MACHOs were once thought to make a significant contribution to dark matter; however, gravitational lensing surveys have demonstrated that most of the dark matter must be something else.

mini-computer: The mini-computer was a precursor to the personal computers that are ubiquitous today. Prior to the development of the mini-computer, scientists doing computer-intensive calculations shared mainframe computers that were expensive multi-user facilities the size of small houses. Mini-computers cost ten times less than mainframe computers, fit into a single room, and had sufficient computing power to solve numerical problems in physics and astronomy when fully dedicated to that purpose. When mini-computers first became available, many areas of scientific research blossomed, including the study of how structure formed in the universe.

MOND: MOND, or Modified Newtonian Dynamics, is a theory that attempts to explain the evidence for dark matter as a modification to Newtonian gravity. There are many versions of the theory, all based on the premise that Newton's laws are slightly different at very small accelerations. A ball dropped above the surface of the Earth would not deviate noticeably from the path predicted by Newtonian physics, but the stars at the very edges of our galaxy would clearly demonstrate modified dynamics if MOND were correct.

N-body simulation: An N-body simulation is a computer simulation that involves a large number of particles interacting according to basic physical laws. N-body simulations are used to study how the structures in our universe may have evolved. Typically, many millions of particles are configured in an initial density distribution and allowed to interact according to the laws of gravity. The computer calculates how the particles will move under the influence of gravity in a small time step, and uses the resulting distribution of particles as the starting point for a new calculation. By calculating many time steps, the simulation can track the growth of structures in the model system. Depending on the initial density distribution and cosmological parameters selected, different structures appear at different stages of evolution. N-body simulations have provided strong support to the idea that our universe consists primarily of dark energy and dark matter. These simulations are resource intensive because the number of interactions the computer must calculate at each time step is proportional to the number of particles squared. A sophisticated N-body simulation can require tens of thousands of supercomputer hours.

neutralino: The neutralino is the superpartner of the neutrino. See: neutrino, superpartner, supersymmetry.

neutrinos: Neutrinos are fundamental particles in the lepton family of the Standard Model. Each generation of the lepton family includes a neutrino (see Unit 1, Fig. 18). Neutrinos are electrically neutral and nearly massless. When neutrinos are classified according to their lepton family generation, the three different types of neutrinos (electron, muon, and tau) are referred to as "neutrino flavors." While neutrinos are created as a well-defined flavor, the three different flavors mix together as the neutrinos travel through space, a phenomenon referred to as "flavor oscillation." Determining the exact neutrino masses and oscillation parameters is still an active area of research.

nucleosynthesis: The term "nucleosynthesis" refers either to the process of forming atomic nuclei from pre-existing protons and neutrons or to the process of adding nucleons to an existing atomic nucleus to form a heavier element. Nucleosynthesis occurs naturally inside stars and when stars explode as supernovae. In our standard model of cosmology, the first atomic nuclei formed minutes after the Big Bang, in the process termed "Big Bang nucleosynthesis."

parity: Parity is an operation that turns a particle or system of particles into its mirror image, reversing their direction of travel and physical positions.

singularity: Singularity is a mathematical term that refers to a point at which a mathematical object is undefined, either because it is infinite or degenerate. A simple example is the function 1/x. This function has a singularity at x = 0 because the fraction 1/0 is undefined. Another example is the center of a black hole, which has infinite density. In our standard model of cosmology, the universe we live in began as a spacetime singularity with infinite temperature and density.

Sloan Digital Sky Survey: The Sloan Digital Sky Survey (SDSS) is one of the most extensive and ambitious astronomical surveys undertaken by modern astronomers. In its first two stages, lasting from 2000 to 2008, SDSS mapped almost 30 percent of the northern sky using a dedicated 2.5 meter telescope at the Apache Point Observatory in New Mexico. The survey used a 120-megapixel camera to image over 350 million objects, and collected the spectra of hundreds of thousands of galaxies, quasars, and stars. Notable SDSS discoveries include some of the oldest known quasars and stars moving fast enough to escape from our galaxy. SDSS data has also been used to map the distribution of dark matter around galaxies through observations of weak gravitational lensing and to study the evolution of structure in the universe through observations of how both galaxies and quasars are distributed at different redshifts. The third phase of the survey is scheduled to end in 2014, and is expected to yield many exciting scientific discoveries.

SQUID: A superconducting quantum interference device, or SQUID, is a tool used in laboratories to measure extremely small magnetic fields. It consists of two half-circles of a superconducting material separated by a small gap. The quantum mechanical properties of the superconductor make this arrangement exquisitely sensitive to tiny changes in the local magnetic field. A typical SQUID is sensitive to magnetic fields hundreds of trillions of times weaker than that of a simple refrigerator magnet.

strong-CP problem: The strong-CP problem is a particular inconsistency between experimental observations of strong interactions and the theory that describes them. Unlike in weak interactions, CP violation has never been observed in strong interactions. However, the theory that describes strong interactions allows CP violation to occur. So why is it not observed? That is the strong-CP problem. Various attempts to resolve the strong-CP problem have been proposed, but none have been experimentally verified. See: axion, charge, CP violation, parity.

supersymmetry: Supersymmetry, or SUSY, is a proposed extension to the Standard Model that arose in the context of the search for a viable theory of quantum gravity. SUSY requires that every particle have a corresponding superpartner with a spin that differs by 1/2. While no superpartner particles have yet been detected, SUSY is favored by many theorists because it is required by string theory and addresses other outstanding problems in physics. For example, the lightest superpartner particle could comprise a significant portion of the dark matter.

WIMP: The WIMP, or weakly interacting massive particle, is a candidate for what may comprise the dark matter. WIMPs interact with other forms of matter through gravity and the weak nuclear force, but not through the electromagnetic force or the strong nuclear force. The lack of electromagnetic interactions means that WIMPs are nonluminous and therefore dark. They are assumed to be much heavier than the known Standard Model particles, with a mass greater than a few GeV. WIMP is a general term that can be applied to any particle fitting the above criteria. The neutralino, the supersymmetric partner of the neutrino, is an example of a WIMP candidate.