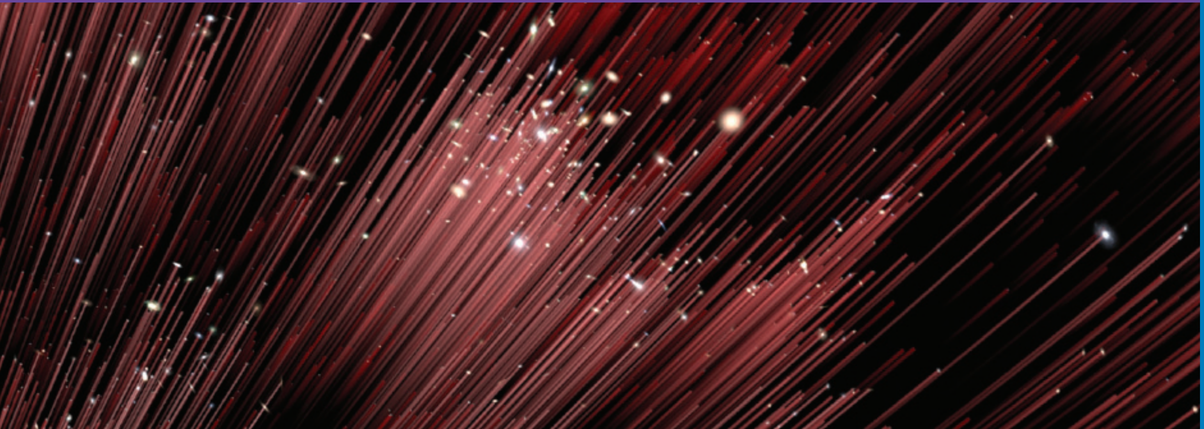
AMERICAN MUSEUM OF NATURAL HISTORY

EDUCATOR'S GUIDE

DARK UNIVERSE

amnh.org/darkuniverse/educators



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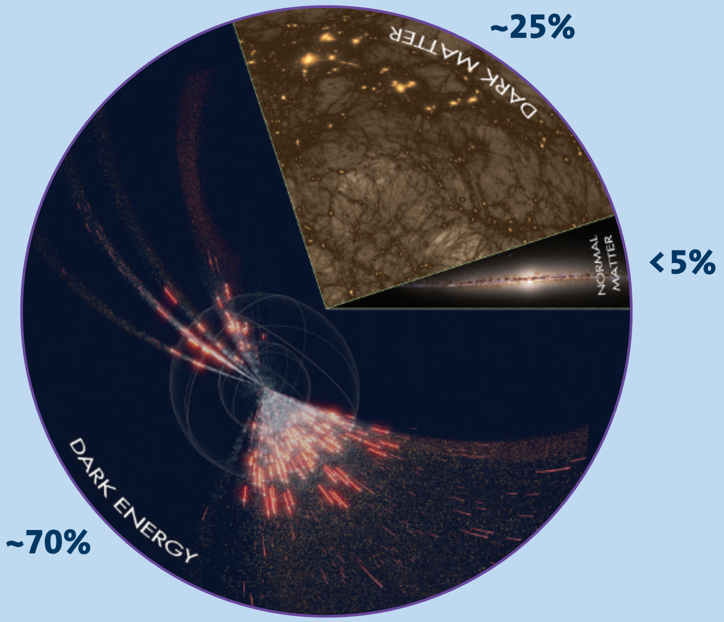
ESSENTIAL Questions

What does the universe contain?

The universe is made up of **matter** and energy. Visible, or **normal matter**, makes up everything we can touch and see, including ourselves, dogs, trees, planets, and stars. In the last 20 years we've discovered that this makes up less than 20% of the total mass of the universe. All the rest of the mass appears to be made of an invisible substance called **dark matter**. It emits and absorbs no light, but we can observe its gravitational effect on normal matter. Dark matter holds together the collections of stars called galaxies, and determines where galaxies gather together in clusters and filaments. A newer discovery is **dark energy**, a mysterious pressure that is actually overcoming gravity and causing the expansion of the universe to accelerate.

In his famous $E=mc^2$ equation, Einstein showed mass m and energy E to be equivalent, and related through the speed of light c. This means we can plot them together as **mass-energy**. The proportions in the pie chart explain the observed behavior of the universe.



How do scientists study the universe?

Almost all our information about the universe comes from light emitted, absorbed, or reflected by the objects in it. Since light takes time to travel, the farther out into space we look, the further back in time we see. When we flip a switch, the light from the light bulb reaches us in a few nanoseconds, but sunlight is 8 minutes old, light from nearby stars has taken years or centuries to reach us, and light from distant **galaxies** can be billions of years old. Telescopes on Earth, in orbit around Earth and the Sun, and traveling through space, can observe this light at many wavelengths. Space probes extend our reach by sending back data and samples from other parts of the solar system. Since scales of space and time are huge and conditions far too extreme to reproduce in a lab, scientists rely on mathematical modeling and computer simulations to understand our observations.

What do we know about the early universe?

13.8 billion years ago the entire observable universe was smaller than an atom, and almost infinitely hot and dense. This period is what scientists refer to as the **Big Bang**. Then the universe inflated to an astronomical size in just an instant. Its temperatures and density fell, but were still as hot and dense as the center of a star, so that heavy hydrogen (deuterium) and helium formed everywhere. No new deuterium has since been made, so measuring the amount the universe contains allows us to determine the extraordinary conditions that existed only fifteen minutes after the Big Bang. The universe was still so dense then that it was entirely opaque: the light was trapped with the matter. After some 380,000 years (less than 0.01% of the current age of the universe), as the universe continued to expand and cool, ionized hydrogen and helium combined with electrons to form neutral atoms, and the universe became transparent, allowing light to travel freely. This moment — when the universe became transparent — is captured in the **cosmic microwave background (CMB)**, the primordial **radiation** that still fills the cosmos and represents the limit of the observable universe.

How has the universe changed over time?

Ever since the Big Bang, the universe has been expanding. It contains the same amount of matter but is now a thousand times larger and cooler than it was at the moment recorded in the CMB. Over hundreds of millions of years, **gravity** acted on the small differences in the distribution of mass present at the time of the CMB. This formed clumps of matter that then collapsed inward to form the first stars and tiny galaxies, and then clusters and filaments of far larger galaxies. These clusters and all they contain are bound together by gravity; they do not expand. At the same time, cosmic space continues to stretch, carrying clusters of galaxies with it. Until 1998 the prevailing theory was that gravity should slow down the expansion of the universe. Instead, scientists discovered that gravity is being overcome by a mysterious pressure. Labeled dark energy, it has been accelerating this expansion for the last five billion years and is expected to continue to do so.

GLOSSARY

astrophysicist or **astronomer:** a scientist who studies the physical laws of the universe and the physical properties of celestial objects such as stars and galaxies

Big Bang: the moment some 13.8 billion years ago when the universe began to expand from an almost infinitely dense and hot state

cosmic microwave background (CMB): the microwave energy observed from all directions in the sky, at an equivalent temperature of 2.7 degrees above absolute zero, interpreted as the residual glow from the Big Bang

cosmology: the astrophysical study of the universe as a whole, including its origin, evolution, structure, and dynamics

dark matter: an invisible substance making up most of the mass in the universe that is detected by its gravitational influence. It has existed since the Big Bang.

dark energy: a mysterious pressure that is causing the universal expansion of the universe to accelerate

galaxy: a massive, gravitationally-bound assembly of stars, planets, interstellar clouds of gas and dust, and dark matter

gravity: the force of attraction between any two masses

mass: the amount of matter contained within a given object

mass-energy: the combined total of the mass m and energy E of an object or region, related through Einstein's equation $E = mc^2$, where c is the speed of light

matter: anything that exerts gravity and moves slower than the speed of light. Visible, or **normal matter** is made of protons, neutrons, electrons, and other subatomic particles.

nuclear fusion: the combination of light atoms such as hydrogen and helium into heavier ones, such as helium, carbon, and oxygen. This process can release energy. Hydrogen fusion powers the Sun and other normal stars.

radiation: energy that travels in the form of electromagnetic waves such as infrared, ultraviolet, or visible light, radio, X-rays, and gamma-rays, or in the form of subatomic particles moving near the speed of light

COME PREPARED CHECKLIST

- [ ] **Plan your visit.** For information about reservations, transportation, and lunchrooms, visit **amnh.org/plan-your-visit**.

- [ ] **Read the Essential Questions** in this guide to see how themes in the *Dark Universe* space show connect to your curriculum. Identify the key points that you'd like your students to learn.

- [ ] **Review the Synopsis** for an advance look at what you and your class will be watching.

- [ ] **Download activities and student worksheets** at **amnh.org/darkuniverse/educators**. Designed for use before, during, and after your visit, these activities focus on themes that correlate to the standards.

NOTE: Please plan to arrive at the space show boarding area, located on the 1st floor of the Rose Center, **15 minutes before the show starts**.

CORRELATIONS TO THE NEXT GENERATION SCIENCE STANDARDS

Scientific and Engineering Practices • Asking questions and defining problems • Developing and using models • Planning and carrying out investigations • Analyzing and interpreting data • Using mathematics and computational thinking • Constructing explanations and designing solutions • Engaging in argument from evidence • Obtaining, evaluating, and communicating information

Crosscutting Concepts • Patterns • Cause and effect: Mechanism and explanation • Scale, proportion, and quantity • Systems and system models • Energy and matter: Flows, cycles, and conservation • Structure and function • Stability and change

Disciplinary Core Ideas • PS1: Matter and Its Interactions • PS2: Motion and Stability: Forces and Interactions • PS3: Energy • PS4: Waves and Their Applications in Technologies for Information Transfer • ESS1: Earth's Place in the Universe • ESS1.A: The Universe and Its Stars • ESS1.B: Earth and the Solar System • ESS1.C: The History of Planet Earth

SYNOPSIS

We're finding our place in intergalactic space.

Our galaxy, the Milky Way

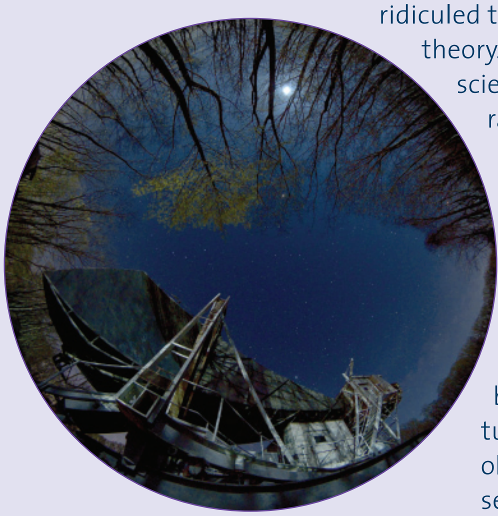
Out a hundred million light years from Earth, every point of light is an entire galaxy, each containing billions of stars. In the last hundred years, we've learned where these galaxies are, what they're made of, and how they got to be that way. We've learned that the universe was born in a fiery instant almost 14 billion years ago, and has been expanding and evolving ever since.

The Milky Way has lots of company.

Never before have humans known so much about nature on the grandest scales. We've also begun to glimpse how much we still don't know. This story begins in the 1920s at California's Mt. Wilson observatory, when astronomers discovered that the Andromeda nebula was actually a galaxy, like our own Milky Way, and that it's very far away. As they probed deeper, they saw other galaxies and were astonished to discover that the more distant ones were moving away from us at greater speeds. This implies that cosmic space is constantly stretching, carrying untold numbers of galaxies with it.

A crazy idea — the Big Bang — isn't crazy after all.

Since the universe cools as it expands, it must once have been far hotter — and denser — than it is today. Skeptics ridiculed this "Big Bang" theory. Then, in 1964, scientists testing a radio antenna at New Jersey's Bell Labs accidentally recorded low-level light coming from all directions: the cosmic microwave background. This turned out to be the oldest light ever seen: light emitted right after the hot Big Bang itself.

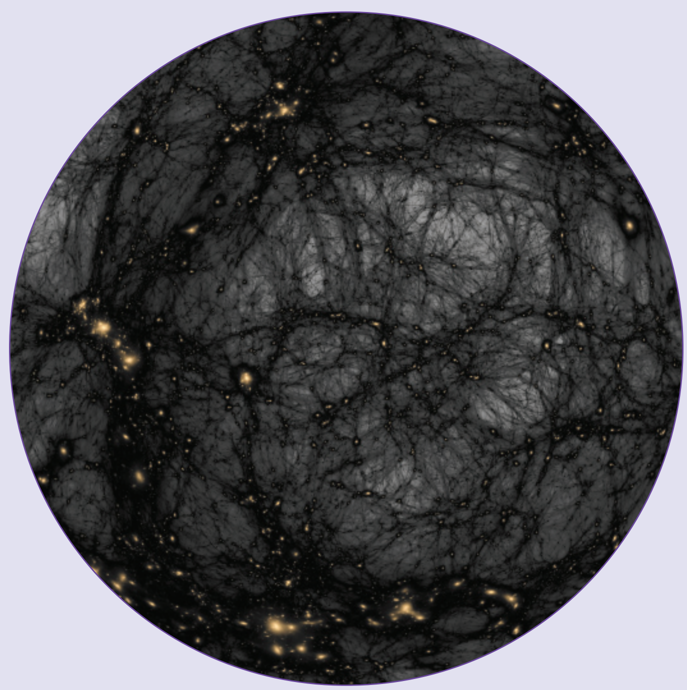


A radio antenna detected something astronomers couldn't explain.

Since then three extraordinary satellites have mapped this light in great detail, revealing the fundamental composition of the universe. More evidence for the Big Bang theory has come from measuring the abundance of hydrogen, deuterium, and helium. Scientists predicted that these light atoms formed by fusion during the initial extremely hot phase of the universe. In 1995 NASA's Galileo mission found that the amount of deuterium locked up in Jupiter's atmosphere confirmed this prediction.

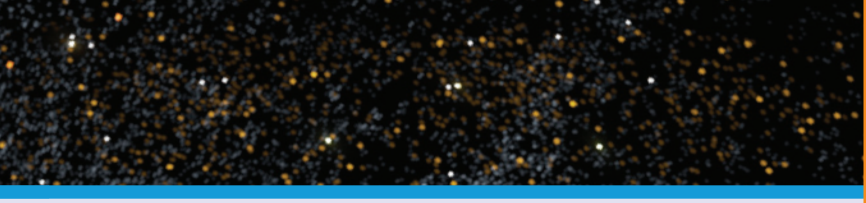
The universe turns out to be way darker than we thought.

While scientists were piecing together the history of atoms, evidence emerged that most of the universe isn't made of atoms at all. It now appears that all the glowing stars are the glittering froth on an invisible cosmic ocean made of what astronomers call dark matter and dark energy.



Dark matter neither emits nor absorbs light. But its gravitational influence on galaxies betrays its presence.

We can't see dark matter because it neither emits nor absorbs any sort of light. But its gravity interacts with the normal matter that we can see — like stars and galaxies — which is how astronomers know it exists. The gravity generated by dark matter is necessary for the large-scale web-like structure of today's universe to form. Scientists are using detectors deep beneath Earth's surface, at particle accelerators, and even on the International Space Station, to try to find out what it is.



The cosmos is expanding faster and faster.

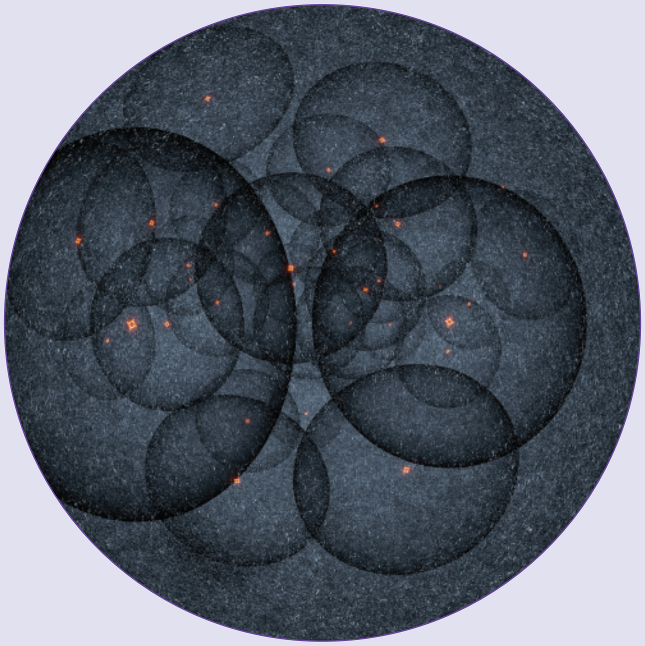
Another astonishing discovery occurred in 1998. Astronomers had predicted that the gravity exerted by all this matter would act like a brake, slowing the expansion of the universe. Instead, by measuring the distances and speeds of exploding stars called supernovas, they learned that the expansion of the universe is accelerating. The pressure causing the acceleration has been labeled dark energy.

We're in the dark (for now).

We don't understand the nature of dark energy yet, although it makes up nearly 70% of the total mass-energy of the universe. Dark matter accounts for almost all the rest. Visible matter — all that we are, all that we've ever seen or touched — amounts to less than 5% of the observable universe.

The universe extends far beyond what we can see.

We can only observe the part of the universe close enough for its light to have reached us over cosmic history. This sphere is our observable universe. Since every observer occupies the center of their own observable universe, the entire universe must be much larger than any observer can see, and could even be infinite. Peering into the dark, we stand on the threshold of many more discoveries.



Since every observer in the universe occupies the center of their *own* observable universe, the *entire* universe must be bigger than what we can observe.

BEHIND THE SCENES: MAKING THE SHOW

Space shows are a 21st-century example of a long-standing Museum tradition: scientists collaborating with artists and educators to bring accurate depictions of the natural world to the public.

The visualizations in *Dark Universe* are based on real data: millions of actual astronomical observations combined with physics-based numerical models. Powerful computers make complex calculations in order to simulate cosmic phenomena based on these models. The visualizations rely heavily on the Digital Universe, a three-dimensional atlas of all astronomical objects whose distance from Earth is known, which is maintained by Museum astrophysicists.

To make the show's visualization of the Milky Way, scientists used supercomputer models to simulate the galaxy and artists assigned colors and brightnesses to objects within it — like the pink areas that represent the youngest star-forming regions.

Leading scientists from around the world convened at the Museum to shape the broad story of *Dark Universe* and identify the best data to convey it. To bring the story to the dome, the production team worked directly from these datasets, consulting closely with scientists. Digital artists recreated space probes in minute detail in close consultation with engineers and scientists who worked on the missions. The visual experience is brought to life with a live-recorded original soundtrack, mixed with state-of-the-art, spatialized sound effects and narration.

ONLINE Resources

Cosmology
amnh.org/explore/science-topics/cosmology
All the Museum's resources related to the origin and development of the universe.

Astronomy OLogy
amnh.org/explore/ology/astronomy
Hands-on activities and articles for kids 7 and up, like How Did the Universe Begin? and Create Your Own Timeline of the Universe.

Science Bulletins: Astro
amnh.org/explore/science-bulletins/(category)/24937
Documentaries, visualizations, and breaking news in astrophysics, including stories about the Cosmic Microwave Background and dark energy (Our Expanding Universe).

Dark Energy, Dark Matter
science.nasa.gov/astrophysics/focus-areas/what-is-dark-energy
NASA's explanation of the evidence and search for dark matter and dark energy, with links to recent discoveries.

Planck Mission
esa.int/Our_Activities/Space_Science/Planck
Maintained by the European Space Agency, this site tells you all about Planck: the spacecraft, the team, the mission, the history, and findings so far.

Mount Wilson Observatory
www.mtwilson.edu
Videos, oral histories, virtual tours, and daily images explain the history of this important observatory and its ongoing role as a center for astronomical research.

Galileo Mission
solarsystem.nasa.gov/galileo
NASA's legacy site for the Galileo spacecraft, which changed the way we look at our solar system.

Did You Know?

Less than 100 years ago, many scientists thought that our Milky Way galaxy was the entire universe.

The Andromeda galaxy is the farthest object visible from Earth without a telescope. (It's over 2 million light years away!)

The radio astronomers at Bell Labs who detected the cosmic background radiation (evidence for the Big Bang theory) thought the faint signal might have been caused by pigeon poop on their telescope.

In the instant after the Big Bang, the universe expanded at least 10^{50} times in 10^{-24} seconds — or 100,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000 times in 0.000000000000000000000001 seconds!

The name "Big Bang" was coined by astronomer Fred Hoyle, who thought the theory was ridiculous. But the silly name stuck.

Dark matter and dark energy got their names independently. The darkness of dark matter is literal — it doesn't interact with light other than gravitationally. The darkness of dark energy is figurative — it describes our ignorance, because the only thing we know about it is how it works.

Dark Universe was created by the American Museum of Natural History, the Frederick Phineas and Sandra Priest Rose Center for Earth and Space, and the Hayden Planetarium

Made possible through the generous sponsorship of

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And proudly supported by

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The Museum also gratefully acknowledges major funding from the **Charles Hayden Foundation**.

Presented with special thanks to NASA and the National Science Foundation.

Dark Universe was developed by the American Museum of Natural History, New York (www.amnh.org), in collaboration with the California Academy of Sciences, San Francisco, and GOTO INC, Tokyo, Japan.

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Tools: Keck Observatory and Planck Satellite, © JPL/NASA; dark matter experiment, © Prof. Elena Aprile / XENON100 Collaboration; South Pole Telescope, © US Antarctic Program.
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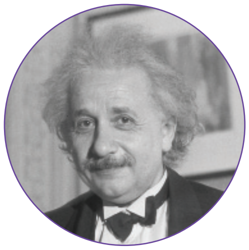
A Century of DISCOVERIES

Discoveries over the last century have transformed the science of cosmology, and with it, our grasp of our place in an expanding universe.



1905–16: Albert Einstein publishes his Theories of Special and General Relativity. These unify the previously separate concepts of space and time, providing a consistent explanation of the physical universe. Believing in a static universe, Einstein is shocked that his equations allow for one that expands.

1916–27: Dutch astronomer Willem de Sitter, Russian mathematician Alexander Friedmann and Belgian mathematician George Lemaître independently propose the idea of an expanding universe. This lays the groundwork for the Big Bang theory.

1918: Harlow Shapley determines that the Sun is located halfway between the center and the edge of our galaxy, the Milky Way — which at the time was thought to make up the entire universe.

1924–29: Edwin Hubble discovers that the more distant a galaxy, the faster it's moving away. This is the first actual observed evidence for the expansion of the universe.

1933–37: Fritz Zwicky observes the speed and directions of galaxies in clusters and suggests that clusters must be held together by vast amounts of invisible, unknown, "cold, dark material."

1948: George Gamow predicts the existence of cosmic background radiation as a relic of the hot, dense early universe.

1965: Arno Penzias and Robert Wilson accidentally discover that radiation: a diffuse microwave signal that emanates uniformly from all directions. This visual afterglow of the Big Bang is dubbed the Cosmic Microwave Background (CMB). The theory of an unchanging universe is definitively laid to rest.

1978: Vera Rubin's measurements of the orbits of stars in spiral galaxies confirm the gravitational grip of some sort of invisible dark matter (the material suggested by Zwicky four decades earlier). Rubin estimates that the vast majority of matter contained in galaxies is made of this substance.

1990: Sensitive, space-based measurements by the **Cosmic Background Explorer telescope** show that the CMB is not absolutely uniform. This is the first evidence of the earliest structures in the universe.

1998: Two independent teams of astronomers determine that the expansion of the universe is accelerating. This can only be explained by the existence of some previously undescribed energy or pressure — since named dark energy — that counteracts gravity.

2002: Measured by the Wilkinson Microwave Anisotropy Probe, characteristics of fluctuations in the CMB establish that ordinary matter accounts for under 5% of the mass and energy in the universe and dark matter only an additional 24%, with over 70% coming from dark energy.

2013: Data from the Planck satellite, launched by the European Space Agency in 2007, confirms the age and energy content of the universe in precise detail, and suggests that dark energy could be consistent with Einstein's original theory of general relativity.

TOOLS for Measuring the Universe

These four tools are being used by astronomers today to explore the history of the universe:

Keck Observatory

When: Keck I in operation since 1993, Keck II since 1996

Where: Mauna Kea volcano in Hawaii

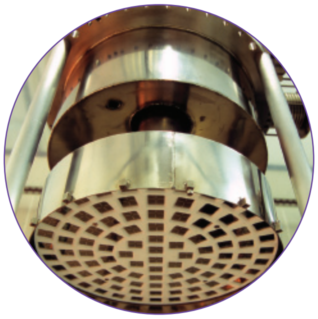
What: measures light in the infrared and visible bands

Why: to study the universe, including obtaining spectra of the most distant supernova explosions

Cool Fact: Giant air conditioners keep the domes at or below freezing and prevent temperature variations that could deform the telescope's steel and mirrors.

This observatory contains two of the largest optical and infrared telescopes on the planet. Each stands eight stories tall, with mirrors ten meters in diameter. Spectra they measure show that ancient supernovae exploded in a universe that was expanding more slowly than it does today. This indicates that the expansion of the universe has accelerated. Scientists attribute this acceleration to dark energy.

Experiments to Detect Dark Matter



When: since 2006

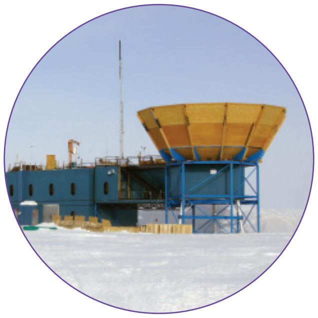
Where: half a dozen laboratories deep underground in North America and Europe

What & Why: to detect dark matter particles directly

Cool Fact: Ultra-sensitive detectors are buried up to a mile deep to shield them from cosmic radiation, which would otherwise drown out the faint signals.

The next important piece of evidence for the Big Bang model of cosmology is detecting dark matter directly, and the race is on. Results must be reproducible in order to be credible, so many experiments are being conducted simultaneously. One type observes interactions of dark matter with solids at extremely low temperatures, another observes interactions with liquified noble gases.

South Pole Telescope



When: in operation since 2007

Where: Amundsen-Scott South Pole Research Station

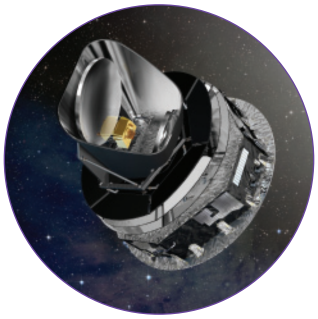
What: measures light in the microwave band

Why: to investigate the formation of large-scale structure across the universe and through time

Cool Fact: Ten meters in diameter, it's the largest telescope ever deployed at the South Pole, with no obstruction to distort and scatter incoming radio waves.

Without dark energy, many more massive galaxy clusters would have formed over 13 billion years than we see now. This radio telescope's novel design and strategic location make it a cluster-hunting machine. Following the history of cluster formation allows scientists to map the impact of dark energy over the universe's history.

Planck Satellite



When: launched in 2009

Where: orbiting the Sun near Earth at a point where Earth and the Sun's gravity balance each other exactly

What: measures light in the microwave band

Why: to fine-tune our knowledge of the age and content of the universe

Cool Fact: Each year Planck mapped the entire sky, observing some points thousands of times over.

On March 21, 2013, the Planck satellite team released the most sensitive and detailed all-sky map of the cosmic microwave background ever. Their measurements of minute fluctuations have helped establish when the first stars emerged, as well as other important cosmological parameters such as the age and expansion rate of the universe, and the relative contributions of normal matter, dark matter, and dark energy.