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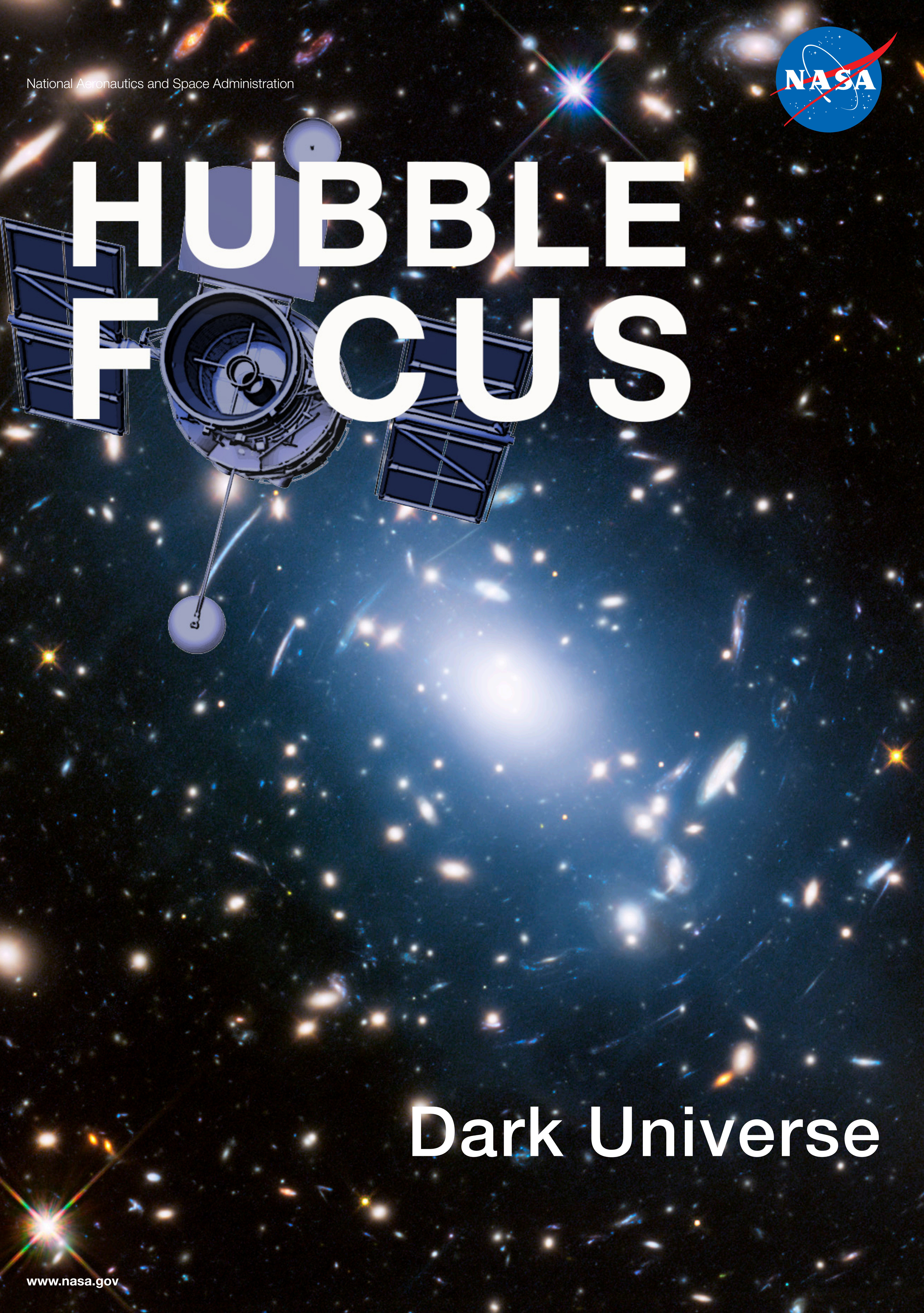

HUBBLE FOCUS

Dark Universe

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About the *Hubble Space Telescope*

Since its launch in 1990, NASA's *Hubble Space Telescope* has made more than one million observations, amassed a huge archive of scientific findings, and had a profound effect on all areas of observational astronomy. *Hubble* has addressed fundamental cosmic questions and explored far beyond the most ambitious plans of its builders. It has captured views farther out in space and further back in time than nearly any other observatory to date. *Hubble* has discovered that galaxies evolve from smaller structures, found that supermassive black holes are common at the centers of galaxies, verified that the universe's expansion is accelerating, probed the birthplaces of stars inside colorful nebulae, analyzed the atmospheres of extrasolar planets, and supported interplanetary missions. The rate of discovery with *Hubble* is simply unparalleled for any telescope in the history of astronomy.

Hubble observes the universe from Earth orbit, just outside our planet's atmosphere.

Credit: NASA

As NASA's first Great Observatory and the first major optical telescope in space, *Hubble* ushered in a new era of precision astronomy. The heart of the telescope is its 94.5-inch-diameter primary mirror. It is so smooth that if it were scaled up to the width of the United States, there would be no bumps taller than six inches.

Operating above Earth, free from the blurring and filtering effects of our planet's atmosphere, *Hubble* can resolve astronomical objects ten to twenty times better than typically possible with large ground-based telescopes. It also can observe those objects across a range of the electromagnetic spectrum, from ultraviolet light through visible and to near-infrared wavelengths.

Hubble can detect objects as faint as 31st magnitude, which is about 10 billion times fainter than the human eye can see. The telescope can see faint objects near bright objects—an important requirement for studying the regions around stars and close to the glowing nuclei of active galaxies. Astronomers have used *Hubble*'s sharp vision to probe the limits of the visible universe, uncovering never-before-seen objects that existed not long after the birth of the universe in the big bang.

Hubble's view is optically stable, meaning the quality of its observing conditions never changes from day to day or even orbit to orbit. *Hubble* can revisit celestial targets with the same acuity and image quality over and over again. This is crucial for precision observations in which astronomers try to detect small changes in the light, motion, or other behavior of a celestial object.

Hubble is more technologically advanced now than it was when launched, thanks to the maintenance and upgrades provided by five space shuttle servicing missions between 1993 and 2009. *Hubble* is expected to continue operating for years to come.

Astronaut John Grunsfeld performs work on the *Hubble Space Telescope* during the first of five spacewalks conducted on the last servicing mission in 2009.
Credit: NASA

INTRODUCTION

This e-book is part of a series called *Hubble Focus*. Each book presents some of *Hubble*'s more recent and important observations within a particular topic. The subjects span from our nearby solar system out to the limit of *Hubble*'s view.

This book, *Hubble Focus: The Dark Universe*, highlights some of *Hubble*'s recent discoveries about dark matter and dark energy—two mysterious, invisible components of the universe. *Hubble*'s contributions are often in partnership with other observatories, and build on decades of discoveries that came before *Hubble*'s launch. Its findings are helping us understand how our universe came to be the way it is today.

This *Hubble* image features an unusually close-knit collection of five galaxies, called The Hickson Compact Group 40. Though such cozy groupings can be found in the heart of huge galaxy clusters, these galaxies are notably isolated in their own small patch of the universe. One possible explanation is that there's a lot of dark matter holding these galaxies together. *Hubble*'s sensitivity, resolution, and wavelength range help astronomers probe the fundamental nature of the universe, including its most mysterious components.

Credit: Science: NASA, ESA, STScI; Image processing: Alyssa Pagan (STScI)

Chapter 1: A Cosmic Accelerant Propels the Universe

The search for the universe's expansion rate was the great Holy Grail of 20th century cosmology. In 1908, astronomer Henrietta Leavitt published a discovery that helped kick off this quest. Cepheid variable stars brighten and dim periodically, and Leavitt noticed a relationship between the time the star took to fluctuate and its average intrinsic brightness. That made distance calculations possible because astronomers could compare the actual brightness of the star to how bright it appears from Earth using a simple mathematical formula.

Using this information, astronomer Edwin Hubble determined the distance to several smudgy spots in the night sky that, in telescopes of the time, appeared to be nebulae—great clouds of gas and dust found between stars. His distance measurements of Cepheid stars within these "nebulae" showed that some were far beyond the edge of our galaxy, proving they were actually entire galaxies of their own.

Hubble shared this discovery in 1924, followed by an equally shocking announcement in 1929—with very few exceptions, galaxies are racing away from each other. These discoveries meant the universe was far from static—it was ballooning outward. Astronomers then toiled to pin down how fast the universe is expanding, which would help determine its age. They began by using ground-based telescopes to measure the apparent brightness of supernova explosions in relatively nearby galaxies as another way to gauge their distance, relating this to their apparent outward velocity. By the time the *Hubble Space Telescope* launched in 1990, the universe's expansion rate was still so uncertain that its age might only be 8 billion years or as great as 20 billion years. *Hubble*'s early observations greatly reduced this uncertainty, determining the age of the universe must be 9-14 billion years; subsequent studies have continued to greatly refine the concluded age.

New shock waves of surprise rippled through the scientific community in 1998, when *Hubble* observations of supernovae in more distant galaxies were paired with ground-based observations. The result led to the Nobel prize winning discovery that the universe actually expanded more slowly in the past than it does today. The expansion of the universe was not slowing down due to gravity, as many thought it should—it was speeding up.

In 1998, *Hubble* helped open up one of the greatest mysteries in cosmology–dark energy. Now, the observatory continues to serve as a vital instrument to probe this strange phenomenon.

Credit: NASA's Goddard Space Flight Center

Today, we still don’t know the exact cause of this mysterious acceleration, but theoretical cosmologists coined the term “dark energy” to describe it. Dark energy is so weak that gravity overpowers it on the scale of humans, planets, and even within the galaxy, which is why it was unobserved for so long. Dark energy is present in the room with you as you read, even within your body, but gravity is much stronger at smaller scales, which is why you don’t fly out of your seat. It is only on an intergalactic scale that dark energy becomes noticeable, acting like a weak opposition to gravity.

While trying to solve the dark energy puzzle, astronomers stumbled across yet another conundrum. The universe’s current expansion rate is different than expected based on our cosmological model and measurements of the early universe. Scientists hope that pairing continued *Hubble* observations with data from new and upcoming telescopes will help unravel the mysteries surrounding dark energy. Learning more about this puzzling energy component that accounts for nearly 70 percent of the makeup of the cosmos will surely shine a light on many other cosmic mysteries as well.

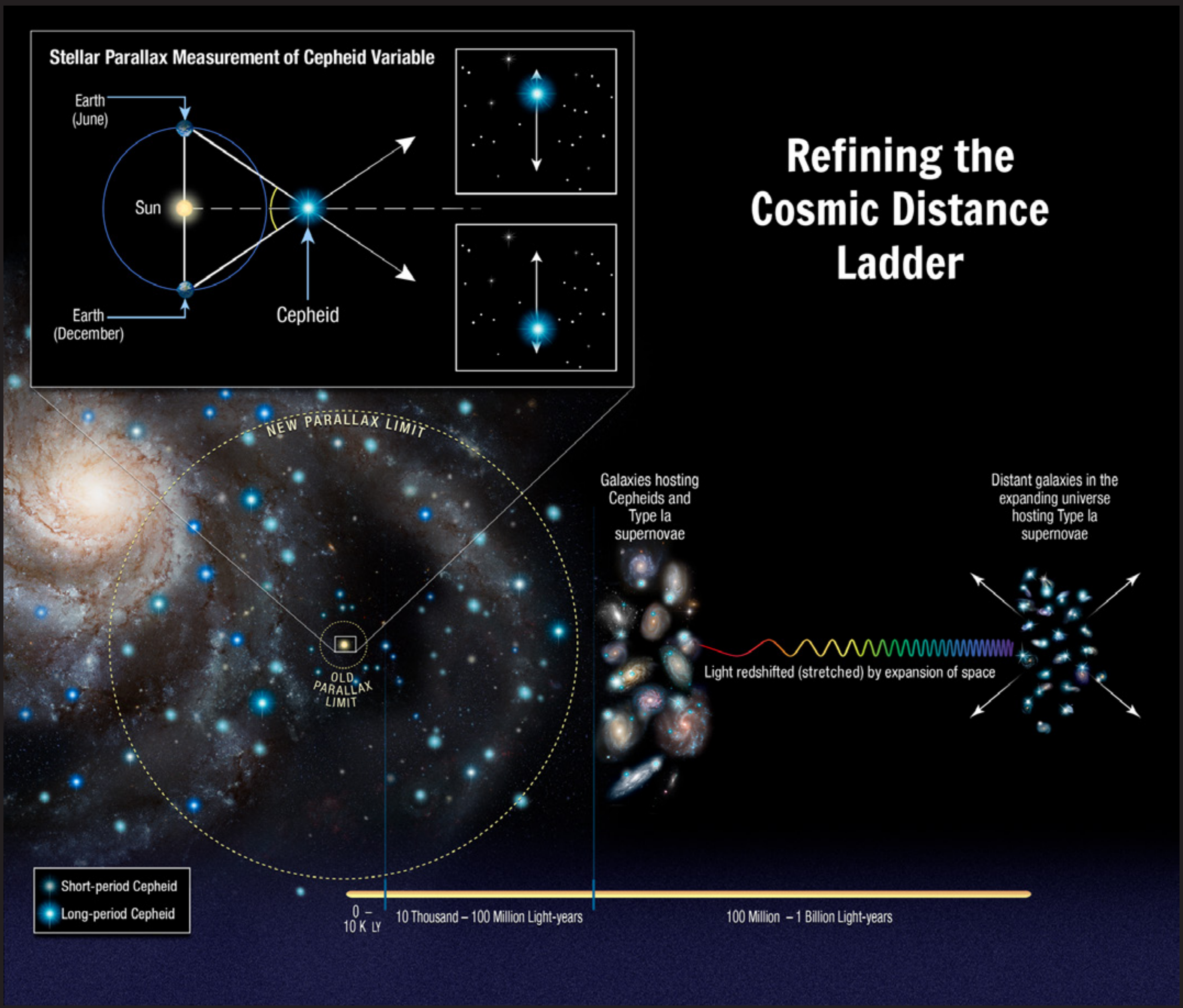
Discovering Fresh Evidence for New Physics in the Universe

In 2018, astronomers using *Hubble* announced the most precise measurement of the universe's expansion rate to date. The results, which hinted at something unknown about the makeup of the universe, were a bit unsettling.

> "It is increasingly likely that this is not a bug but a feature of the universe."
>
> Adam Riess, Space Telescope Science Institute (STScI) and Johns Hopkins University

Scientists previously used the European Space Agency's *Planck* satellite to gather data from when the universe was very young. By plugging this data into the standard model of cosmology, astronomers found that the universe should currently expand at about 67 kilometers per second for every megaparsec of distance (a megaparsec is about 3.3 million light-years).

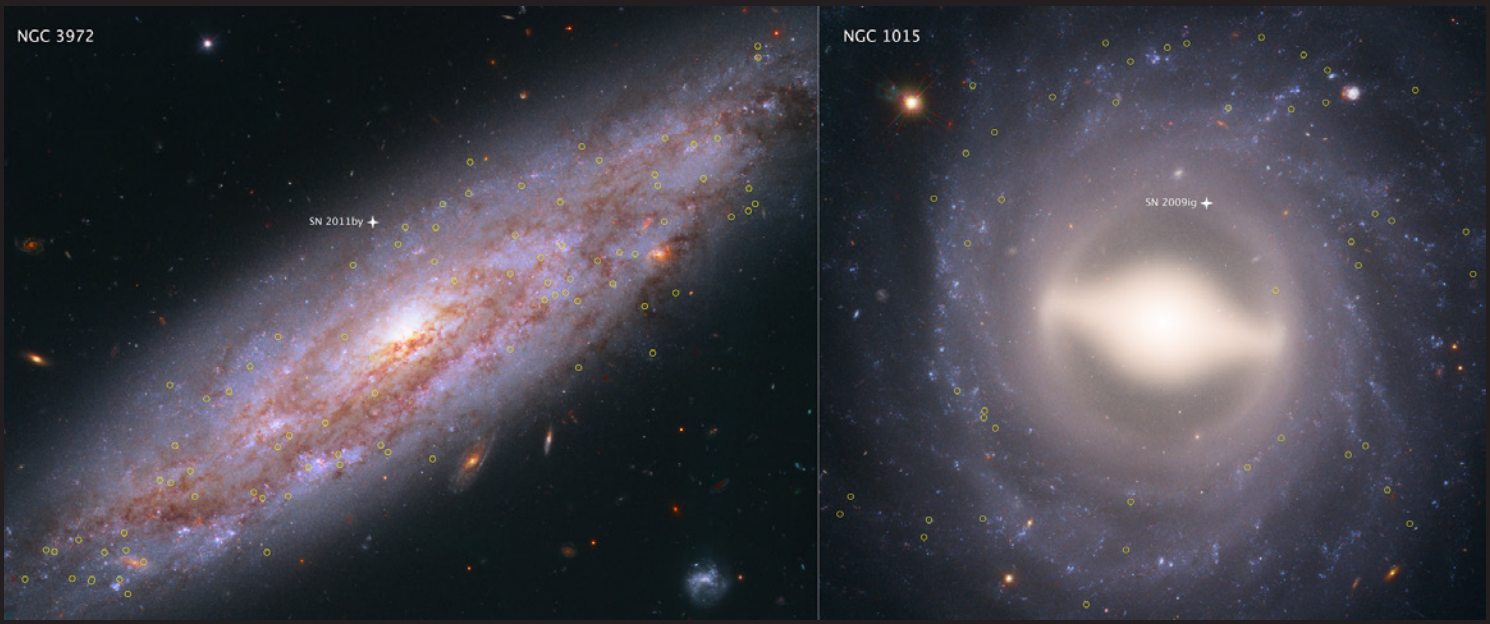
But the *Hubble* results indicate that the universe is expanding at a rate of about 73 kilometers per second per megaparsec—significantly faster than early universe data predicts. To make sure the distance calibrators for these measurements were as accurate as possible, astronomers extended the number of analyzed Cepheid stars to distances up to 10 times farther across our galaxy than previous *Hubble* results. The team harnessed a new technique to measure the stars' distances and intrinsic brightness more precisely than ever before. Then the distances to other



This illustration shows how astronomers used *Hubble* to improve the cosmic distance ladder, which helps determine how far away cosmic objects are. The box at the upper left illustrates how *Hubble* measured the parallax of pulsating stars called Cepheid variables to gauge their distances. Parallax is the apparent shift of an object's position due to a change in the observer's point of view. As depicted at the lower left, *Hubble* was able to expand its parallax measurements to Cepheids that are much farther away than any studied before. The lower right explains how astronomers used Cepheids to calibrate the distance to supernovae and the galaxies that host them. First, they looked at galaxies that host both types of objects to calibrate their distance measurements to the exploding stars, which are visible from much farther away. Then they used that information to measure how far away even more distant galaxies are, in which we can only see supernovae. Combining these measured distances with how fast the far-flung galaxies appear to be moving away helped astronomers estimate the Hubble constant, or the universe's current expansion rate.
Credit: NASA, ESA, A. Feild (STScI), and A. Riess (STScI/JHU)

galaxies harboring Cepheids and other brightness calibrators could be more precisely measured and correlated with their apparent outward velocities, yielding the expansion rate of the universe with fewer systematic errors.

The newly refined rate underscores a nagging discrepancy showing the universe is expanding faster now than was expected from its trajectory seen shortly after the big bang, even with a cosmological model that includes accelerated expansion. The team later conducted a follow-up study to refine the measurements even further.



These *Hubble* images showcase two of the 19 galaxies analyzed in a project to improve the precision of the universe's expansion rate, a value known as the Hubble constant. The galaxy known as NGC 3972 (left) is located 65 million light-years from Earth, while NGC 1015 (right) is 118 million light-years distant. The yellow circles in each galaxy represent the locations of pulsating stars called Cepheid variables. These stars blink at a rate matched closely by their intrinsic brightness, making them ideal cosmic lighthouses for measuring accurate distances to relatively nearby galaxies.
Credit: NASA, ESA, A. Riess (STScI/JHU)

Learn more: Improved Hubble Yardstick Gives Fresh Evidence for New Physics in the Universe

Fueling a Cosmic Conundrum

Predictions of how fast the cosmos should be expanding based on early universe data remain at odds with measurements of how fast it is actually expanding. To investigate this mystery, astronomers used *Hubble* and the European Space Agency's *Gaia* space observatory to measure the universe's expansion rate with unprecedented precision. Some may have hoped the findings would help clear up the strange discrepancy, but instead the study underscored it.

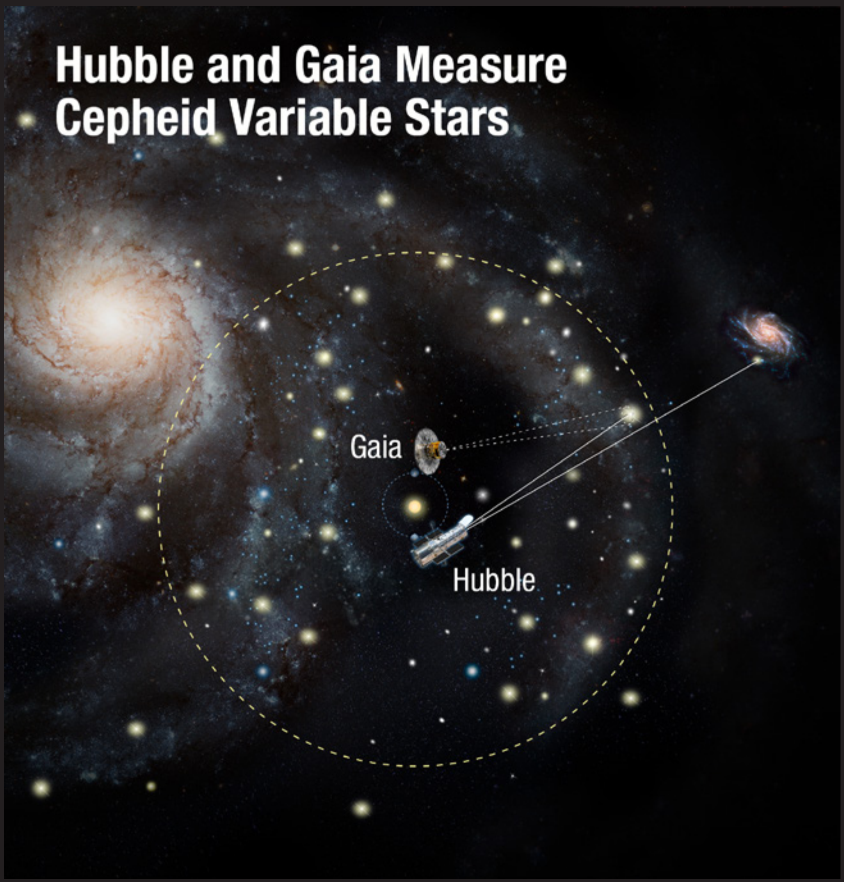
"The tension seems to have grown into a full-blown incompatibility between our views of the early and late time universe."

Adam Riess, Space Telescope Science Institute (STScI) and Johns Hopkins University

The team began by using *Hubble* to refine the relationship between a Cepheid star's intrinsic brightness and its pulsation rate. They compared the stars' actual brightnesses, calculated from their fluctuation rates, with how bright they appear. Then *Gaia* cross-checked these results by measuring the Cepheids' distances geometrically. By calibrating Cepheids in our own galaxy, the team was able to use the same kind of star in other galaxies as milepost markers to determine their distances more accurately.

They then compared the galaxies' distances to how fast they are receding, and found that the universe is expanding at a rate of 73.5 kilometers per second per megaparsec. But based on early universe data and our understanding of cosmology, the universe should only be expanding at 67 kilometers per second per megaparsec. The small uncertainties in these numbers do not overlap, affirming the discrepancy.

Astronomers are still trying to figure out why the expansion rate is so much higher than predicted. It could signal new, unknown physics underlying the foundations of the universe. Possible explanations include the interaction strength of dark matter, dark energy being even more exotic than previously thought, or an unknown particle in the tapestry of space. Astronomers plan to continue refining expansion rate measurements to help solve the mystery.



Astronomers used *Hubble* and the European Space Agency's *Gaia* to gauge the distances to nearby galaxies using Cepheid variable stars as cosmic yardsticks. By using the two telescopes and independent methods to measure how far away the Cepheids are, astronomers were able to more precisely calibrate the distances to Cepheids in other galaxies.
Credit: NASA, ESA, and A. Feild (STScI)

Learn more: Hubble and Gaia Team Up to Fuel Cosmic Conundrum

Zooming in on Tell-Tale Stars

This ancient stellar jewel box, a globular cluster called NGC 6397, glitters with the light from hundreds of thousands of stars. Astronomers used *Hubble* to gauge the distance to this brilliant stellar grouping, obtaining the first precise measurement to an ancient globular cluster. The same type of measurement, which relied on Cepheid variable stars and geometric measurements, offers astronomers a distance marker to calculate the universe's expansion rate.
Credit: NASA, ESA, and G. Bacon (STScI)

Gathering Clues from Ancient Stars

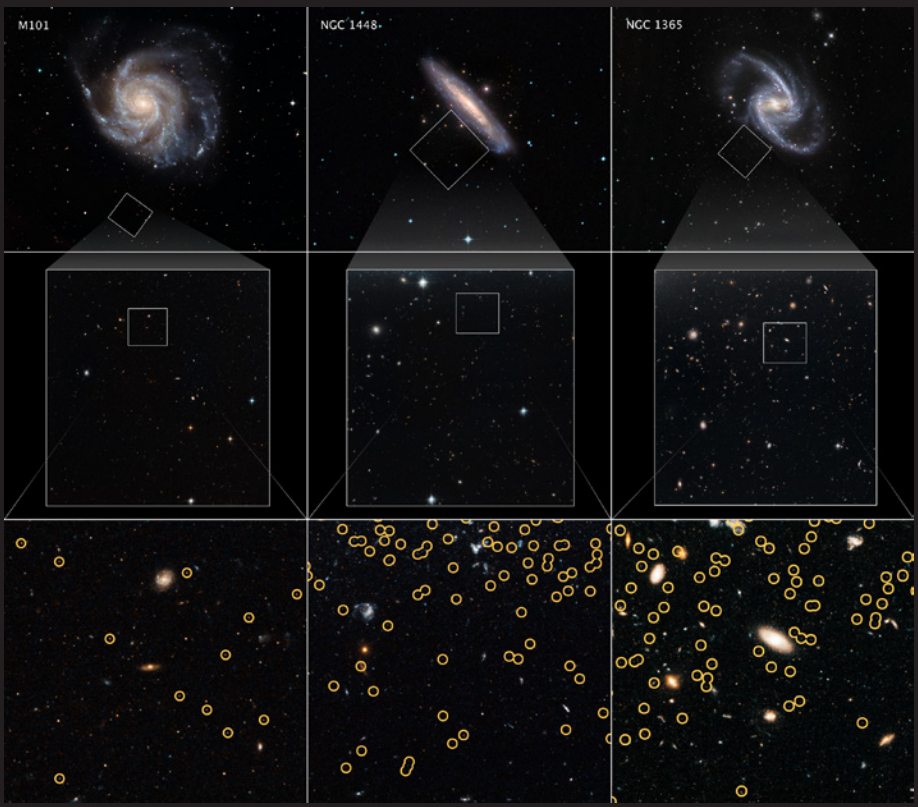
One possible solution to the mismatch between predictions and modern measurements of the universe's expansion rate involves flaws in the measurements of distances. Astronomers can test out that solution by using another method and comparing the results. Instead of using Cepheid variable stars, a team used *Hubble* to analyze distances using ancient red giant stars in nearby galaxies.

"Our measurements give us a means of testing our entire cosmological model, with dark matter and dark energy, from 400,000 years after the big bang to the present day."

Wendy Freedman, University of Chicago

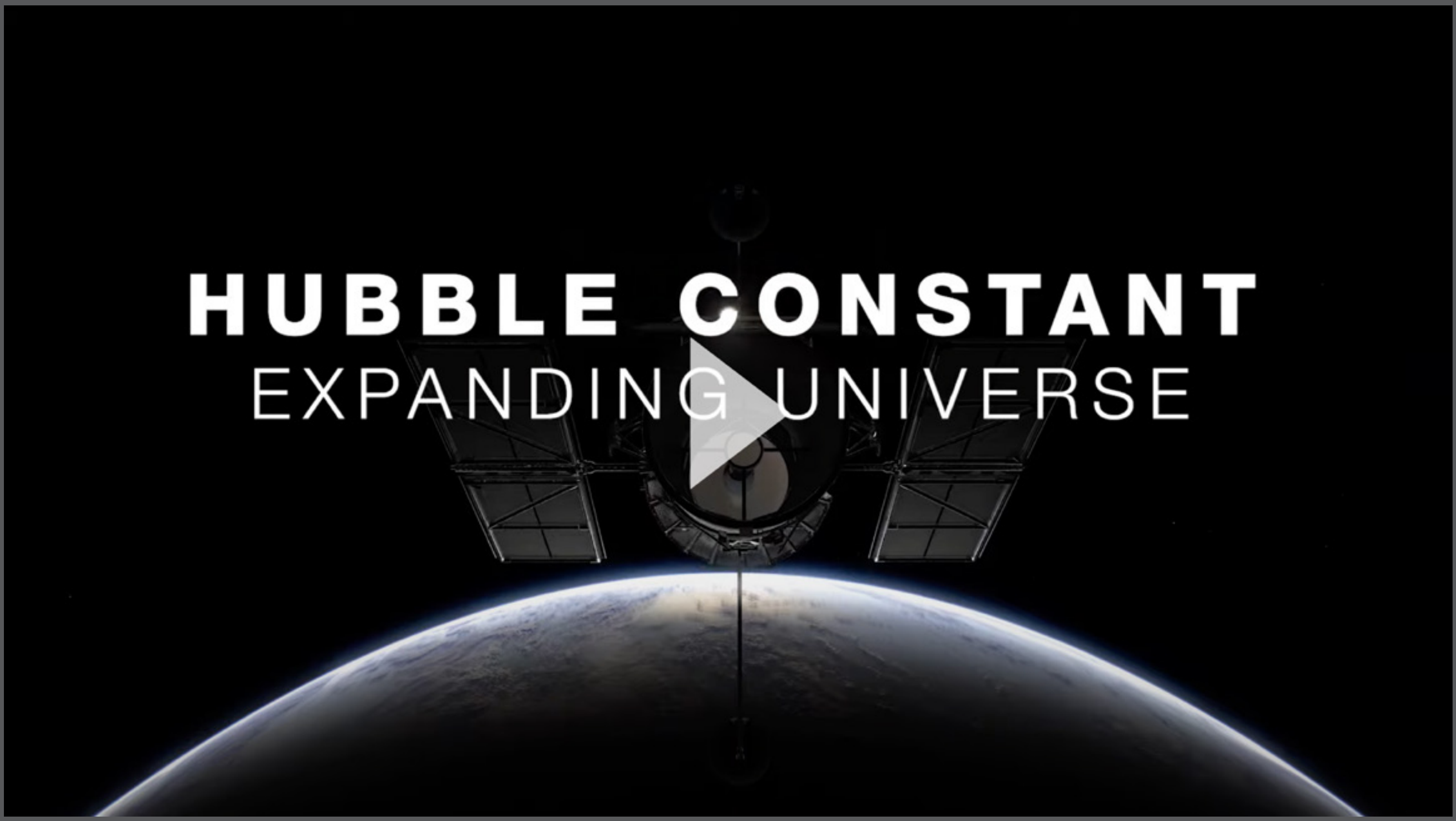
Low- to medium-mass stars like the Sun swell to become red giants after they exhaust their nuclear fuel. Astronomers use them as milepost markers because they reach the same peak brightness at a critical stage of their late evolution, in addition to being bright enough to see from far away. Equipped with this knowledge, astronomers can use them to measure distances and calculate the universe's expansion rate. A team using *Hubble* did just that and once again found a nagging discrepancy between the universe's modern expansion rate and predictions based on early universe data. The result supports other studies that suggest there may be something fundamentally flawed in our current model of the universe.

Yet there is an additional layer of discrepancy in the measurement, since it doesn't quite match the value found using Cepheid stars to calculate cosmic distances. Scientists are working to figure out where all of the discord is stemming from, whether there's something missing from our model of the universe or we don't fully understand the stars we're using to calculate the expansion rate. One thing isn't in question—learning more about this hotly debated topic could lead to a new interpretation of the universe's fundamental properties.



This set of images shows three galaxies (top row) that *Hubble* targeted as part of a program to measure the universe's expansion rate. The insets in the middle row zoom in on an area of each galaxy's halo, which is a nearly spherical volume of thinly scattered stars, globular clusters, and tenuous gas surrounding the galaxy. Astronomers compared the apparent brightness of red giant stars in these regions with nearby red giants, whose distances were measured with other methods, to determine how far away each of the host galaxies are. The bottom row zooms in even tighter to identify the red giants analyzed in each galaxy, circled in yellow.
Credit: NASA, ESA, W. Freedman (University of Chicago), ESO, and the Digitized Sky Survey

Learn more: New Hubble Constant Measurement Adds to Mystery of Universe's Expansion Rate



Observations of the early universe suggest that the cosmos should currently be expanding at about 67 kilometers per second for every megaparsec of distance (a megaparsec is about 3.3 million light-years). But astronomers have measured the expansion rate to be significantly higher. To make things more complicated, different telescopes and measurement methods don't quite agree on just how fast the universe is now expanding. Combining *Hubble* data with the *James Webb Space Telescope*'s sharper and deeper observations will help measure the expansion rate even more precisely, which will help astronomers learn more about what is causing the acceleration.

Credit: NASA's Goddard Space Flight Center

Widening the Mystery of the Universe's Expansion Rate

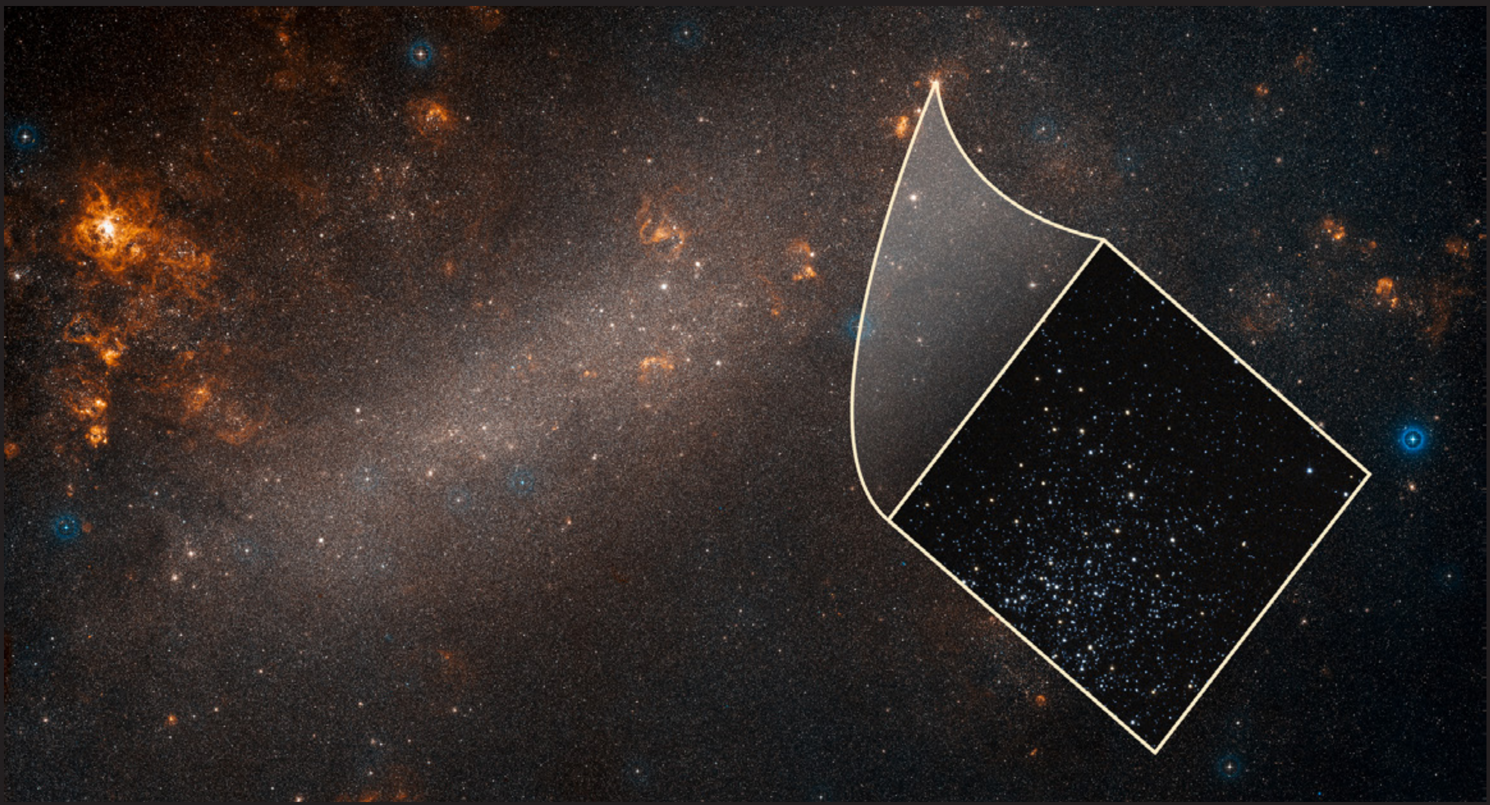
Many astronomers thought the discrepancies in the universe's expansion rate might be the result of an instrumental or observational error. However, a *Hubble* study reduced the chances that the mismatch is a mistake from 1 in 3,000 to 1 in 100,000. Since expansion rate values predicted from observations of the early universe remain at odds with measurements of the modern universe, it's increasingly likely that something may be missing in the cosmological model that connects the two eras.

"As the quality of our measurements improves, the discrepancy with cosmological results grows more significant."

Stefano Casertano, Space Telescope Science Institute (STScI) and Johns Hopkins University

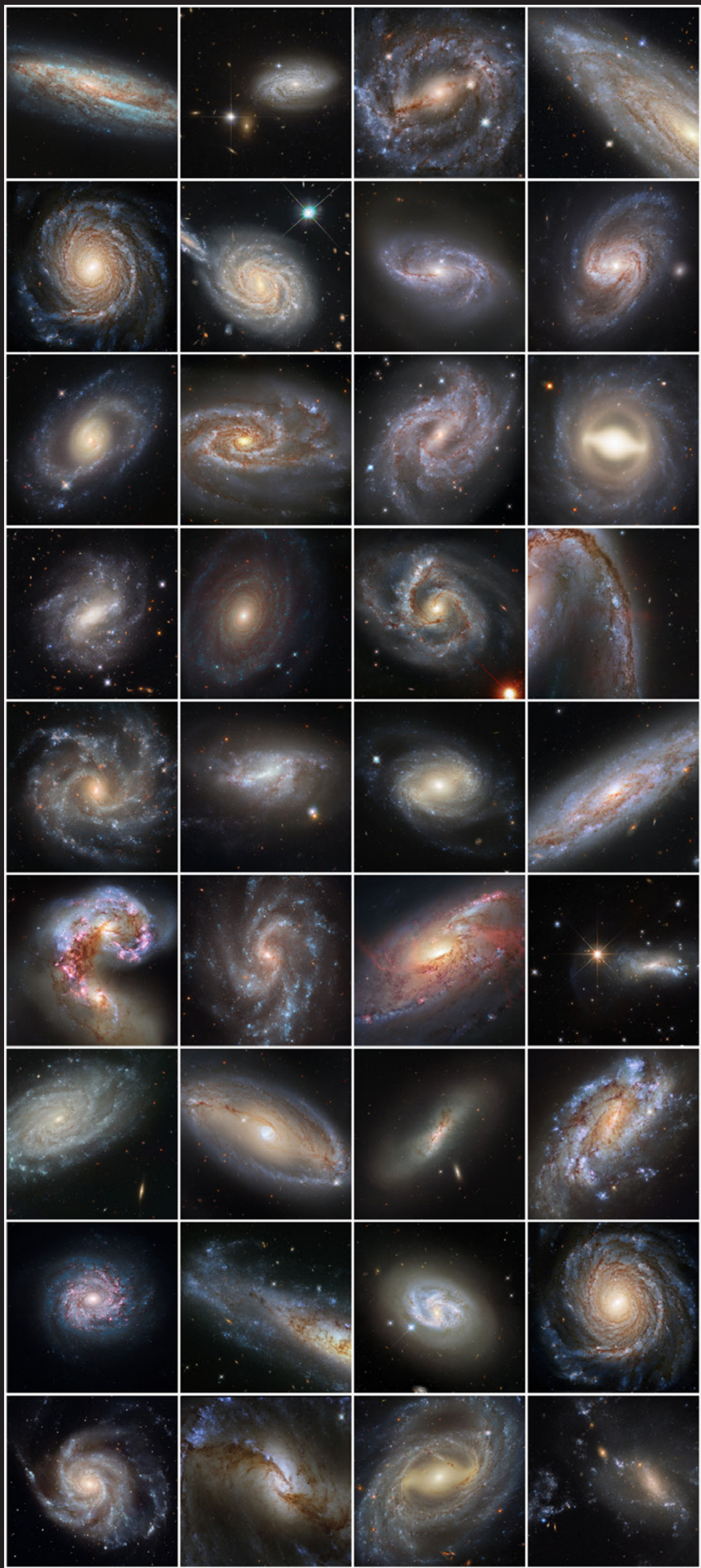
Astronomers used *Hubble* to observe 70 pulsating Cepheid stars in the Large Magellanic Cloud—a dwarf galaxy that orbits our Milky Way galaxy. Measuring so many Cepheids would usually be impractical due to how long it would take, but the team used a clever new method to make it possible. Instead of observing a single Cepheid during one of *Hubble*'s 95-minute orbits around Earth, the team targeted groups of Cepheids bunched closely enough together that the telescope could observe a dozen per orbit. Combining their results with another set of observations made by the Araucaria Project—a collaboration between astronomers from institutions in Chile, the U.S., and Europe—helped refine calculations of the Cepheids' true brightness.

With this more accurate result, astronomers have better refined the tools used to make cosmic distance measurements. However, instead of leading to an expansion rate that more closely matches predictions, the new result widens the gap. While a previous study measured that the universe is expanding at a rate of 73.5 kilometers per second per megaparsec, the new results indicate it's even higher—74 kilometers per second per megaparsec, which is 9% faster than the predicted rate. Theorists are searching for an explanation for the disparity that could reshape our understanding of the very underpinnings of the universe.



This ground-based image from the Digitized Sky Survey (DSS) shows the Large Magellanic Cloud–a smaller satellite galaxy of our Milky Way. The inset image, taken by *Hubble*, reveals one of the dwarf galaxy's star clusters. Cepheid variable stars are sprinkled relatively close to each other among the cluster's other stars. Because of their proximity, *Hubble* could observe as many as a dozen within the same 45-minute observing period by utilizing slight nudges to the telescope. This helped astronomers measure the universe's expansion rate more accurately.
Credit: NASA, ESA, A. Riess (STScI/JHU), and Palomar Digitized Sky Survey

Learn more: [Mystery of the Universe's Expansion Rate Widens With New Hubble Data]



This collection of 36 *Hubble* images features galaxies that host both Cepheid variable stars and supernovae. These two celestial phenomena are both crucial tools used by astronomers to determine cosmic distances and refine our measurement of the universe's expansion rate.
Credit: NASA, ESA, Adam G. Riess (STScI, JHU)

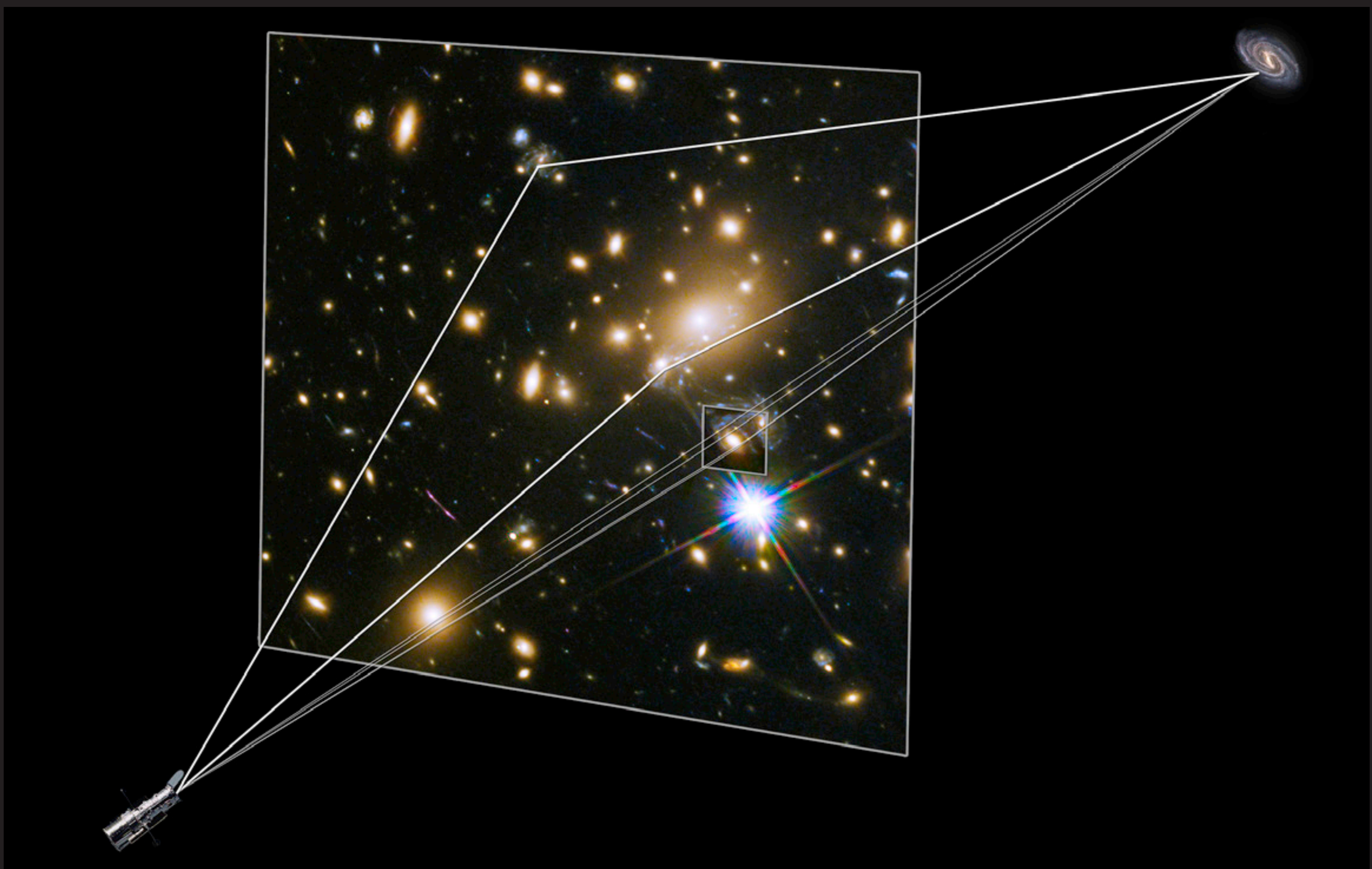
Chapter 2: Wrinkles in Space-time Reveal Ghostly Matter

Dark matter is a phantom in the machinery of the universe. Though it makes up the vast majority of the universe's bulk, dark matter would evade even the best "ghost hunters" because it is invisible, detectable only through its effects on normal matter. Its gravitational pull is the muscle of the cosmos, holding together both individual galaxies and galaxy clusters. Although scientists have long suspected its existence, dark matter's true nature remains one of the biggest mysteries in modern physics.

More than 80 years ago, Swiss-American astronomer Fritz Zwicky observed that galaxies in the Coma cluster were moving so quickly that gravity from visible matter was not enough to hold them—yet they remained gravitationally bound to the cluster. Then in the 1970s, American astronomer Vera Rubin discovered the same type of phenomenon in individual spiral galaxies. Stars toward the edge of the galaxy move too fast for the galaxy's luminous matter to keep them, hinting that there must be much more matter than we can see in these galaxies to hold the stars in orbit.

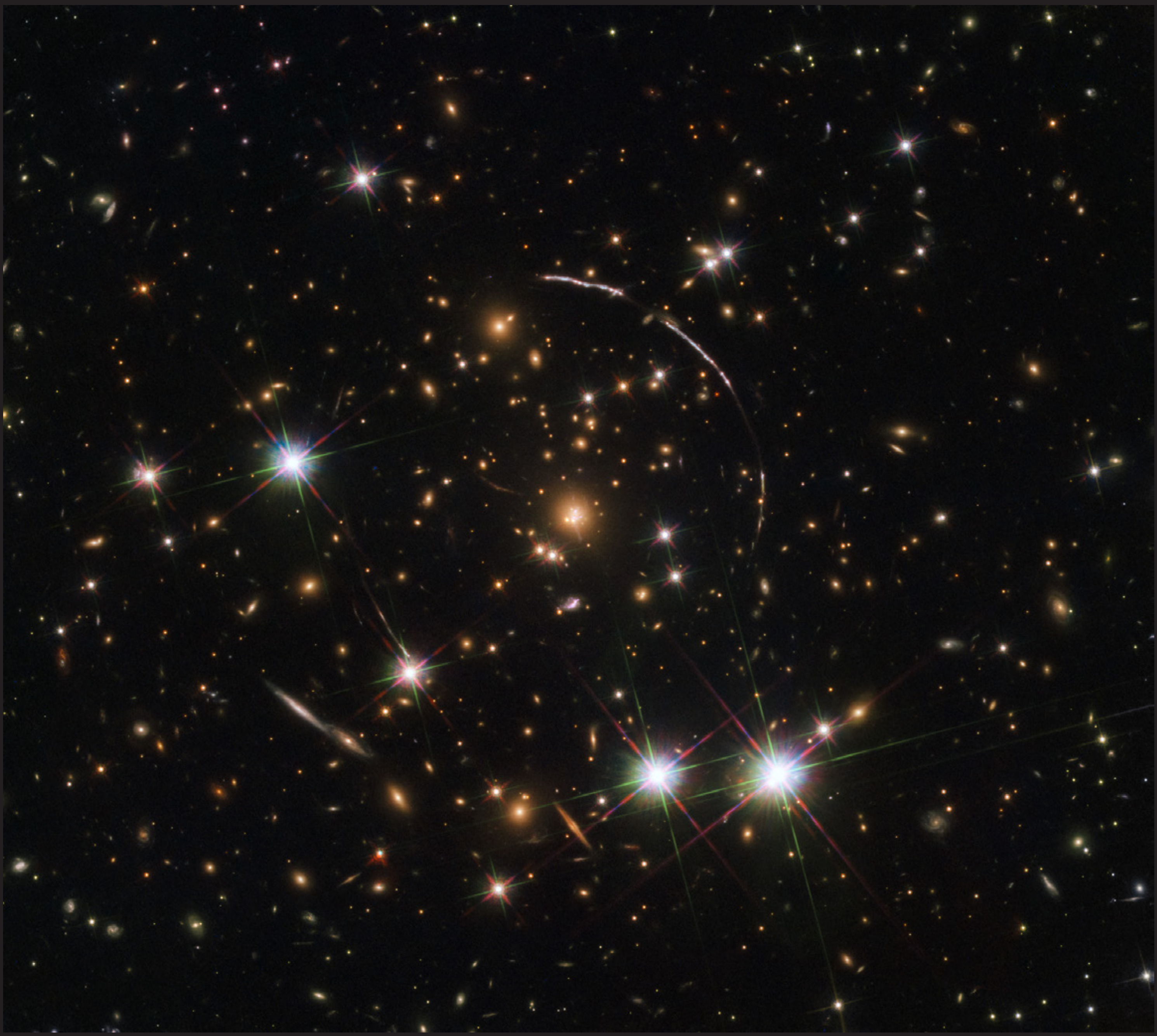
Modern astronomers have detected vast filaments of dark matter stretching between galaxies, like connective tissue in a body. We know that it is not composed of electrons, protons, and neutrons like normal matter—the stuff that makes up everything we can see, from people to planets—but its true nature remains shrouded in mystery.

Hubble's cosmic detective work offers clues by exploring the way matter is structured and distributed throughout space. It does so using a quirk of light called gravitational lensing. Concentrations of mass curve the fabric of the universe, or space-time. When light passes an object in space, the object's gravity (or curved space-time) bends the light's path. Light from a background source like a star or galaxy that passes near a galaxy cluster curves around it, producing intensified—and sometimes multiple—images of the background source. This process transforms large galaxies or galaxy clusters—behemoths brimming with unseen dark matter—into natural telescopes that give us a glimpse of distant cosmic objects that would normally be too faint to see.



This artist's concept illustrates how light from distant objects can be gravitationally lensed by intervening mass.
Credit: NASA, ESA

Using this light-bending phenomenon, *Hubble* has tested different theories about the type of particle that could make up dark matter. Some of these theories hinge on dark matter's temperature, meaning how energetic and fast-moving its particles are. If it's "warm," it will be harder for the particles to stick together; if it's "cold," the particles will be sluggish and clump together even in small concentrations. By discovering such small clumps of dark matter, *Hubble* has offered support to the latter theory. But sometimes studying warped space-time has made dark matter even more mysterious. *Hubble*'s observations haven't always matched predictions, hinting that our theoretical models still have several missing pieces. Astronomers will continue using *Hubble*, in tandem with other telescopes, to trace the distribution of dark matter in ways that tell us about its composition. Uncovering the true nature of dark matter will help scientists predict its effect on the evolution of galaxies, galaxy clusters, and the universe at large.



This cosmic kaleidoscope is a *Hubble* photo of a gravitationally lensed remote galaxy. A foreground galaxy cluster's gravity distorts the fabric of space-time, magnifying and smearing the light from the more distant galaxy behind it into an arc. The lensing effect stretches and creates multiple images of the background galaxy.
Credit: NASA, ESA, and E. Rivera-Thorsen (Institute of Theoretical Astrophysics Oslo, Norway)

Using a Cosmic Quirk to Test a Dark Matter Theory

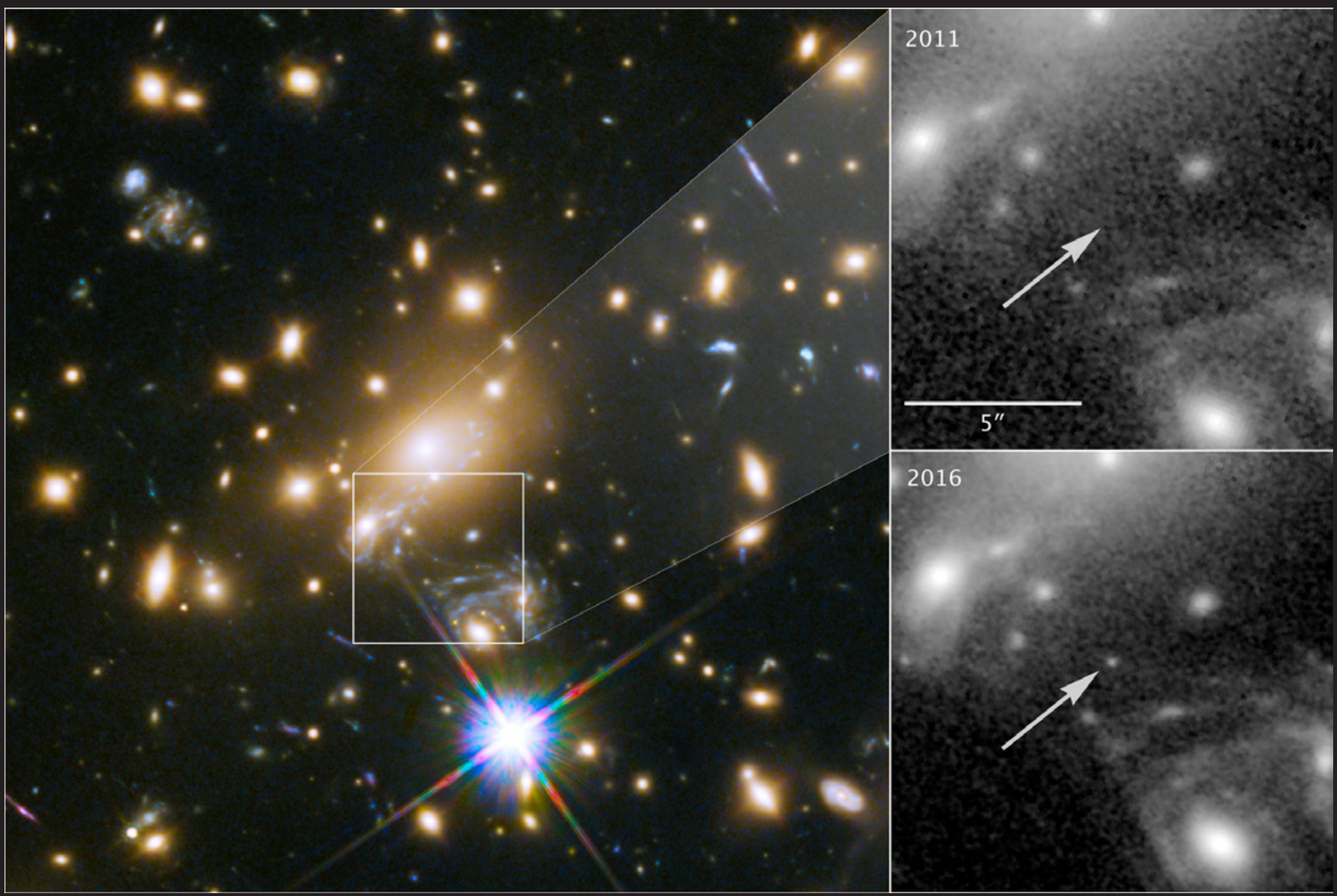
Astronomers regularly use the light-bending phenomenon known as gravitational lensing to bring distant galaxies into view. A team combined this effect with *Hubble*'s powerful view to spot one of the farthest individual stars ever seen. The gravity of a foreground galaxy cluster (located 5 billion light-years away) magnified light from a more distant spiral galaxy (about 9 billion light-years away). The team noticed an individual star that was especially magnified, which provided an opportunity to test a theory of dark matter.

"For this type of research, nature has provided us with a larger telescope than we can possibly build!"

Alex Filippenko, University of California, Berkeley

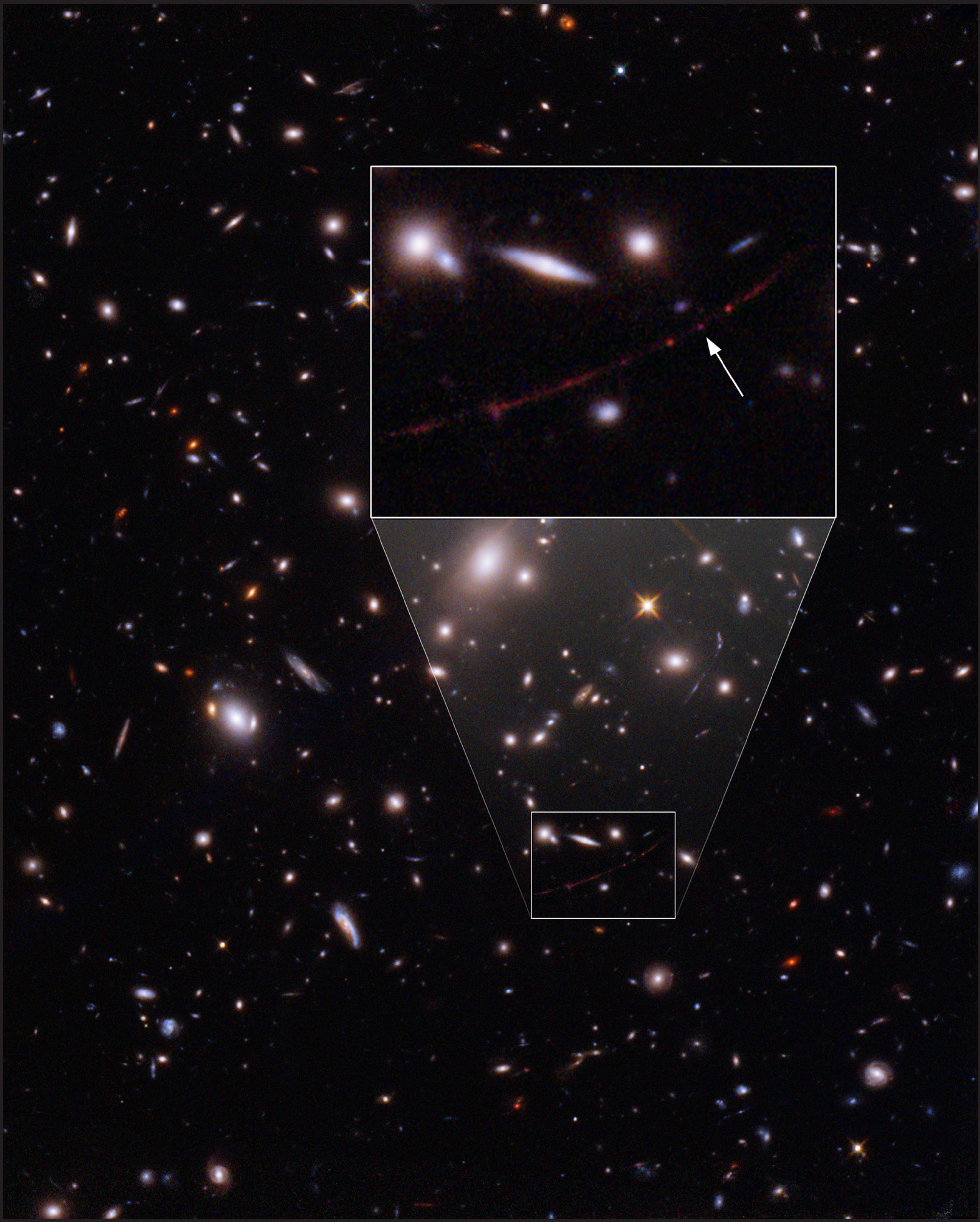
Researchers were monitoring a supernova in the distant galaxy when they spotted the brightened star, which they nicknamed "Icarus" after the character in Greek mythology. The lensing effect was so strong that Icarus briefly skyrocketed over several weeks to appear 2,000 times its true brightness before returning to its original luster. This provided the opportunity to learn more about the foreground cluster's composition.

Scientists found evidence against a theory which proposes that dark matter might be explained by a large number of primordial black holes that formed shortly after the big bang. The results of this unique test suggest that explanation is incorrect because light fluctuations from Icarus, which *Hubble* monitored for 13 years, would have looked different if there were a swarm of intervening black holes. The *James Webb Space Telescope*'s extraordinary sensitivity will allow astronomers to find additional stars like Icarus and learn even more.



Hubble used a cosmic quirk to set a new record for the farthest individual star ever seen. The galaxy cluster (left) sits between Earth and the star, which is nicknamed Icarus. Gravity from the cluster amplified light from the more distant star, which is nestled in a faraway spiral galaxy. Since it is 9 billion light-years away, Icarus would normally be much too faint for even *Hubble* to observe. Thanks to gravitational lensing, astronomers were able to probe the galaxy cluster's dark matter content by analyzing how its gravity affected the distant star's light.
Credit: NASA, ESA, and P. Kelly (University of Minnesota)

Learn more: [Hubble Uncovers the Farthest Star Ever Seen]



The combination of an intervening galaxy cluster's dark-matter-dominant heft and a farther star's lucky alignment made for a record-smashing *Hubble* observation. *Hubble* previously set a record for the most distant individual star ever seen by spotting Icarus. Its light traveled about 9 billion light-years to reach *Hubble*'s "eyes." Discovering the star indicated by the white arrow in this *Hubble* image beat that record by a long shot. Nicknamed Earendel, which means "morning star" in Old English, this star's light had to travel across about 13 billion light-years of intervening space to reach *Hubble*. Since light travels at a finite speed, we see these distant stars as they were when the light was emitted–when the universe was about 4 billion years old for Icarus, and less than 1 billion years old for Earendel. The ultra-faraway star was visible because of its alignment on or very near a ripple in the fabric of space created by the intervening galaxy cluster's mass, which magnified the star's light enough to be detected by *Hubble*. A nearby star cluster, seen as a red streak on either side of Earendel, was also lensed. The *James Webb Space Telescope* followed up on *Hubble*'s observation to study the star in even more detail, more accurately determining its temperature and luminosity.
Credit: Science: NASA, ESA, Brian Welch (JHU), Dan Coe (STScI); Image Processing: NASA, ESA, Alyssa Pagan (STScI)

Detecting the Smallest Known Dark Matter Clumps

Most known dark matter concentrations are hefty. Astronomers spot them indirectly by measuring how their gravity influences stars and galaxies. But one theory predicts that dark matter particles are sluggish, making it easier for them to clump together in small concentrations. Detecting tiny clumps is a challenge because they may not contain any stars to signal their presence. Using *Hubble*'s powerful view coupled with a new observing technique, a team discovered dark matter clumps that are smaller than any scientists had previously detected.

"We made a very compelling observational test for the cold dark matter model and it passes with flying colors."

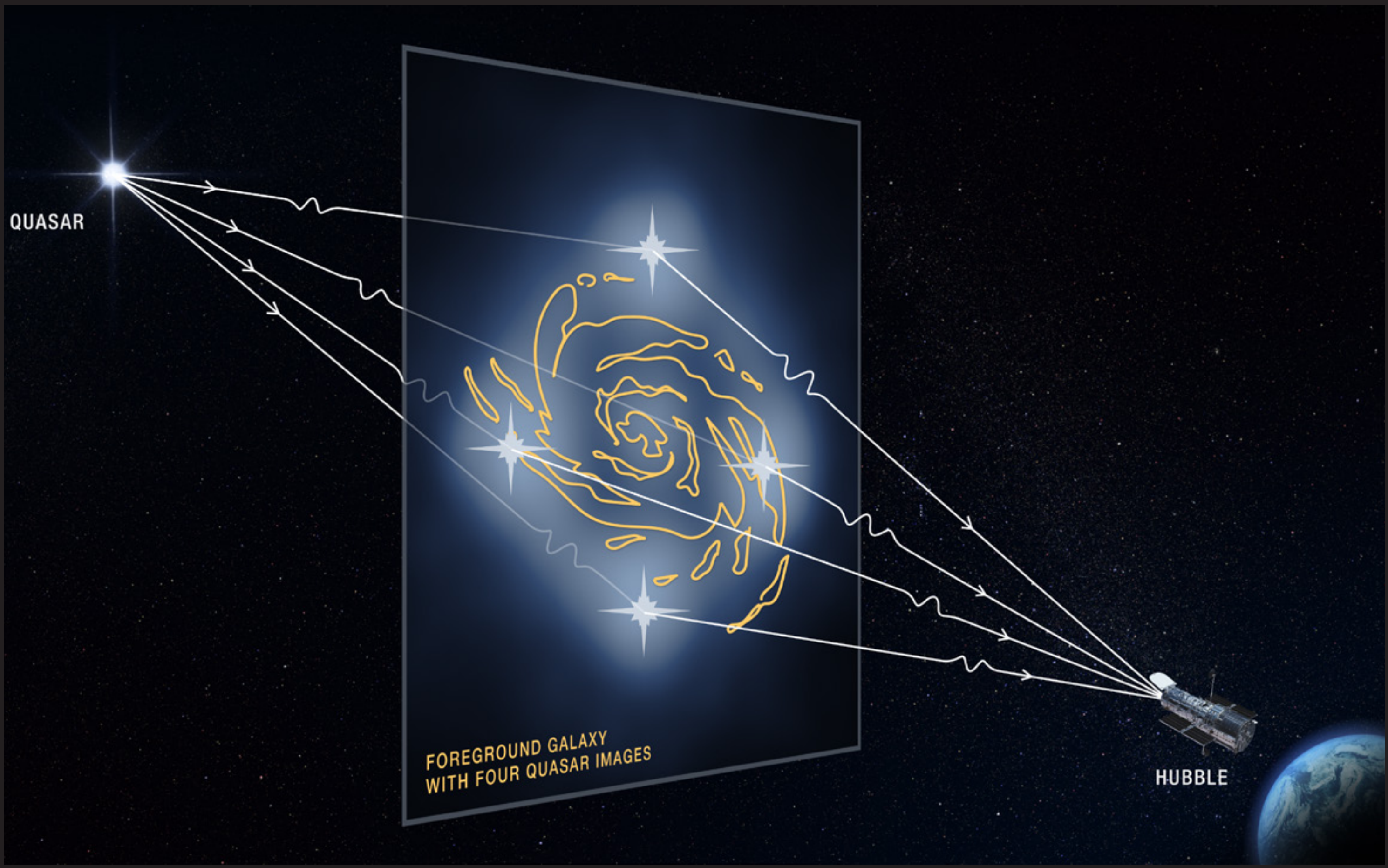
Tommaso Treu, University of California, Los Angeles (UCLA)

Instead of relying on stars, researchers sifted through ground-based observations by the Sloan Digital Sky Survey and Dark Energy Survey to identify powerful gravitational lenses. Then they used *Hubble* to target eight foreground galaxies that were each warping the light of a separate, more distant quasar—the region around an active black hole that emits an enormous amount of light. The presence of dark matter clumps, found both in the foreground galaxies and elsewhere along the line of sight to each quasar, alters the brightness and position of each lensed quasar image. Astronomers used these observations to calculate the mass of dark matter concentrations. Detecting such lightweight clumps confirmed a fundamental prediction of the cold dark matter theory.

Hubble's observations improve our understanding of dark matter. Now, observatories such as the *James Webb* and upcoming *Nancy Grace Roman* space telescopes will be able to hone the search for dark matter even further.

Each of these *Hubble* images contains a massive foreground galaxy located about 2 billion light-years from Earth. Each galaxy is flanked by four distorted images of a more distant quasar, located roughly 10 billion light-years from Earth. Gravity from the foreground galaxies acts as giant cosmic lenses, magnifying and warping the quasars' light and producing multiple images of the quasars. The presence of dark matter clumps in the foreground galaxy alters the brightness and position of each lensed quasar image. Astronomers used these observations to detect the smallest clumps of dark matter ever found.
Credit: NASA, ESA, A. Nierenberg (JPL) and T. Treu (UCLA)

Learn more: [Hubble Detects Smallest Known Dark Matter Clumps]



This graphic illustrates how a massive foreground galaxy and tiny dark matter clumps alter a faraway quasar's light path. The galaxy's powerful gravity warps and magnifies the quasar's light, producing four distorted images of the single quasar. *Hubble* observed eight of these galaxy-quasar pairs to study dark matter, which makes up the bulk of the universe's mass and forms the scaffolding upon which galaxies are built.

Credit: NASA, ESA, and D. Player (STScI)

Spotting a Possible Flaw in Theoretical Models

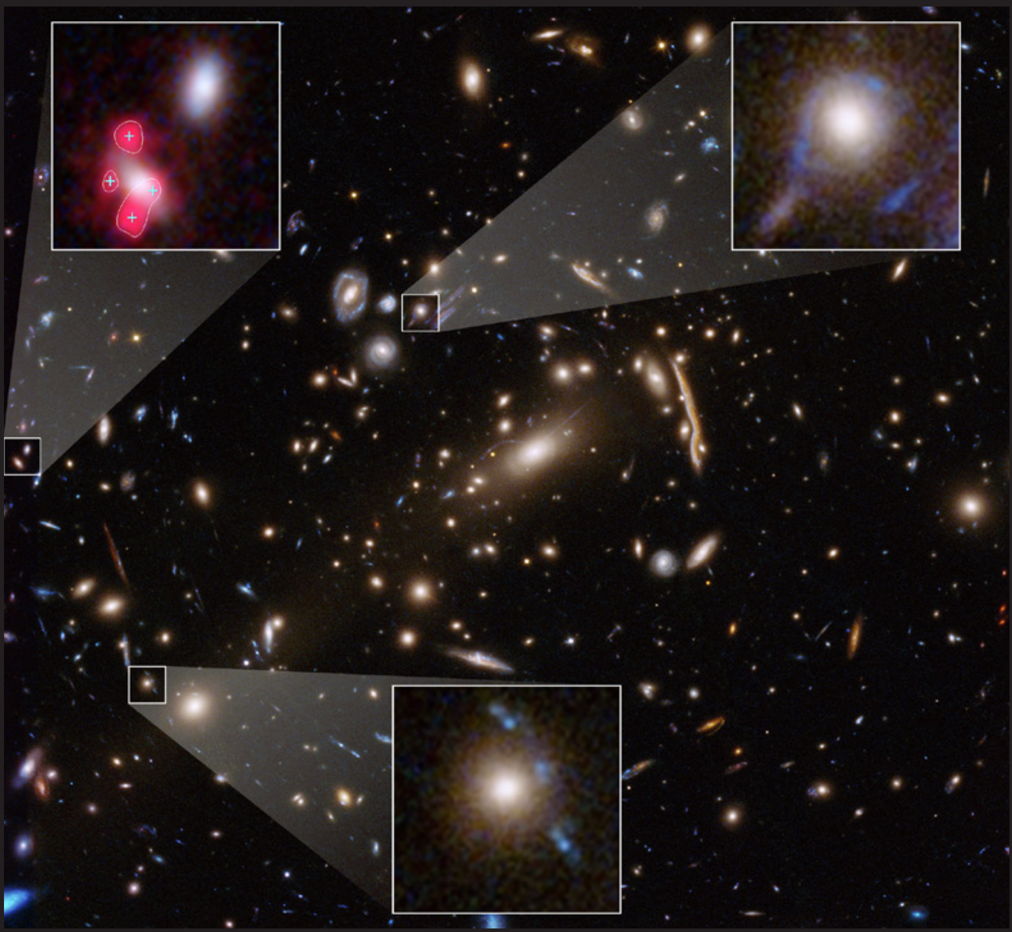
Matter warps the fabric of space-time in ways astronomers can detect because it alters, or lenses, the path of light from more distant sources. Using *Hubble* and the European Southern Observatory's Very Large Telescope in Chile, a team found that some small clumps of dark matter are so concentrated that the lensing effects they produce are 10 times stronger than expected. However, theoretical models of dark matter's distribution in galaxy clusters appear to be at odds with these observations.

"This could signal a gap in our current understanding of the nature of dark matter and its properties."

Priyamvada Natarajan, Yale University

Researchers studied 11 hefty galaxy clusters in unprecedented detail by combining *Hubble*'s crisp images with spectra from the Very Large Telescope. They identified dozens of warped background galaxies in the images. By measuring the lensing distortions, astronomers were able to map the distribution and amount of dark matter. To the team's surprise, the *Hubble* images revealed small-scale distortions nested within larger ones in each cluster's core, where the most massive galaxies reside. The embedded lenses are likely the result of gravity from dense concentrations of dark matter found in individual galaxies.

Follow-up spectroscopy helped astronomers measure the velocity of the stars orbiting inside several of the cluster galaxies. These measurements allowed the team to estimate the distances to the galaxies as well as their individual masses, which included the amount of dark matter they contain. But the observations don't match up with simulations based on theoretical dark matter models, suggesting astronomers may be missing some key physics. The future *Nancy Grace Roman Space Telescope* could detect even more remote galaxies via gravitational lensing, allowing scientists to further test dark matter models and possibly pin down the missing ingredient in our cosmic recipe of the nature of dark matter.



This *Hubble* image shows the massive galaxy cluster MACS J1206. The streaks of light around the center are distorted images of distant background galaxies, warped by the foreground galaxy cluster's gravity. The three insets highlight galaxies with less obvious distortions. In the snapshots at upper-right and bottom, two distant, blue galaxies are lensed by nearer ones that are part of the foreground cluster. The four pink blobs overlaid on the upper-left image are from distant clouds of glowing hydrogen lensed by intervening dark matter, detected by the European Southern Observatory's Very Large Telescope. Astronomers analyzed all these effects to produce a detailed map of the cluster's dark matter distribution.

Credit: NASA, ESA, P. Natarajan (Yale University), G. Caminha (University of Groningen), M. Meneghetti (INAF-Observatory of Astrophysics and Space Science of Bologna), and the CLASH-VLT/Zooming teams; Acknowledgement: NASA, ESA, M. Postman (STScI), and the CLASH team

Learn more: [Hubble Observations Suggest a Missing Ingredient in Dark Matter Theories]

This *Hubble* image spotlights Abell 370–a cluster of several hundred galaxies located about 4 billion light-years from Earth. The picture includes much of the area surrounding the cluster as well, which contains thousands more galaxies strewn across space and time. The observation is from a program called Beyond Ultra-deep Frontier Fields And Legacy Observations (BUFFALO), which is built around the six massive galaxy clusters that *Hubble* first observed under its Frontier Fields program. By surveying the areas around galaxy clusters, astronomers hope to learn more about when the most massive and luminous galaxies formed and how they are linked to dark matter.

Credit: NASA, ESA, A. Koekemoer (STScI), M. Jauzac (Durham University), C. Steinhardt (Niels Bohr Institute), and the BUFFALO team

Illuminating Ghostly Matter via the Faint Glow from Orphaned Stars

By viewing decade-old data in a new way, one team demonstrated a different method to trace the distribution of dark matter using intracluster light, seen by *Hubble* in near-infrared wavelengths. This type of light emanates from stars orphaned during galaxy cluster mergers. The dynamics of the merger freed these stars from the gravitational grip of their home galaxy, and they eventually fell into orbits dictated by the newly-formed galaxy cluster's gravity. Their new location happens to be where the vast majority of dark matter also resides. Observing intracluster light with *Hubble* helped researchers trace the location of dark matter.

"This method puts us in the position to characterize the ultimate nature of dark matter."

Mireia Montes, University of New South Wales, Australia

The team used *Hubble*'s past observations of six massive galaxy clusters in the Frontier Fields Program. They measured the similarities between the contours of intracluster light and the contours of different mass maps of the clusters. This analysis showed that the intracluster light matched the mass distribution of the six galaxy clusters better than X-ray emission, as derived from the *Chandra X-ray Observatory*'s archived observations. X-ray light indicates where groups of galaxies are colliding, but not the underlying structure of the cluster. Intracluster light offers an additional layer of detail, making it a more precise tracer of dark matter than existing methods that observe X-ray light. It is also more efficient because it relies only on deep imaging rather than spectroscopy, which is more complex and time-intensive.

A more recent *Hubble* study found that the stars that produce intracluster light have been orphans for billions of years. That means they're not a product of more recent dynamical activity inside a galaxy cluster. They must have been cast out of their home galaxies in the early stages of the cluster's formation. Learning more about these wayward stars' origins using both *Hubble* and observatories like the *James Webb* and future *Nancy Grace Roman* space telescopes will help scientists use intracluster light to better trace the dark matter that envelopes galaxy clusters.

Learn more: Faint Glow Within Galaxy Clusters Illuminates Dark Matter
Hubble Finds That Ghost Light Among Galaxies Stretches Far Back In Time

A soft blue haze, called intracluster light, casts an otherworldly glow in this *Hubble* image of the Abell S1063 galaxy cluster. The stars producing this glow were thrown free of their home galaxies. These stars now live solitary lives, no longer part of a galaxy but aligning themselves with the gravity of the overall cluster. Astronomers found that tracing intracluster light offers a good indicator of how invisible dark matter is distributed in the cluster.
Credit: NASA, ESA, and M. Montes (University of New South Wales)

Mapping Invisible Matter Using Diffuse Starlight

This animation switches between an original *Hubble* image of the galaxy cluster MACS J0416.1–2403 and a version that highlights the soft, blue glow of intracluster light. Stars scattered throughout the cluster when their home galaxies merged produce this glow. The homeless stars eventually aligned themselves with the gravity of the overall cluster. *Hubble*'s unique sensitivity and resolution captured their faint light and used it to trace the location of invisible dark matter, which dominates the cluster's gravitational field.

Credit: ESA/Hubble, NASA, HST Frontier Fields team (STScI), and M. Montes & I. Trujillo

Finding Dark Matter Hints via a 'Double' Galaxy

Astronomers typically identify the objects they see relatively quickly, but when one team of scientists used *Hubble* to analyze quasars—the blazing cores of active galaxies—they accidentally stumbled upon something so oddly shaped it took several years to figure out what it was. Their findings ultimately offered important clues to dark matter's makeup.

"We only need two mirror images in order to get the scale of how clumpy dark matter can be at these positions."

Jenny Wagner, University of Heidelberg, Germany

The researchers spotted two bright, linear objects that appeared to be mirror images of each other. With the help of two gravitational lensing experts and spectroscopic measurements from the Gemini and W. M. Keck observatories, the team eventually determined that the objects are distorted images of a previously undiscovered galaxy, located more than 11 billion light-years away. The galaxy's warped appearance is the result of the immense gravity of an uncatalogued intervening galaxy cluster. *Hubble* had observed instances of gravitational lensing before, however at the time of the initial discovery no lenses like this had yet been seen. Spotting exact copies of a lensed galaxy is rare because it requires a precise alignment between the faraway galaxy and foreground cluster.

With the help of computer software designed to interpret unique gravitational lenses, researchers learned how the lensed images were produced. Their findings suggest the smooth distribution of dark matter at small scales around the stretched images. This result offers clues about the dark matter particles, because particles that are more massive will lead to smaller dark matter clumps.

The galaxy cluster in this *Hubble* image contains three strange, distorted objects. The two mirrored images in the lower-right inset, called "Hamilton's Object" for their discoverer, drew scientists' attention because such an object had never been observed before. Researchers eventually identified it as duplicate images of a galaxy whose appearance is warped by the intervening cluster's gravity. A third image of the lensed galaxy appears in the top-right inset. By reconstructing this image, the team discovered that it is an edge-on barred spiral galaxy experiencing ongoing, clumpy star formation. Using computer software, the team also found clues about dark matter located around the stretched images. Their results offer hints about the composition of dark matter particles.
Credit: NASA, ESA, Richard E. Griffiths (UH Hilo), Jenny Wagner (ZAH); Image processing: Joseph DePasquale (STScI)

Learn more: 'Double' Galaxy Mystifies Hubble Astronomers

Uncovering Dark Matter Details from a Rare Repeating Supernova

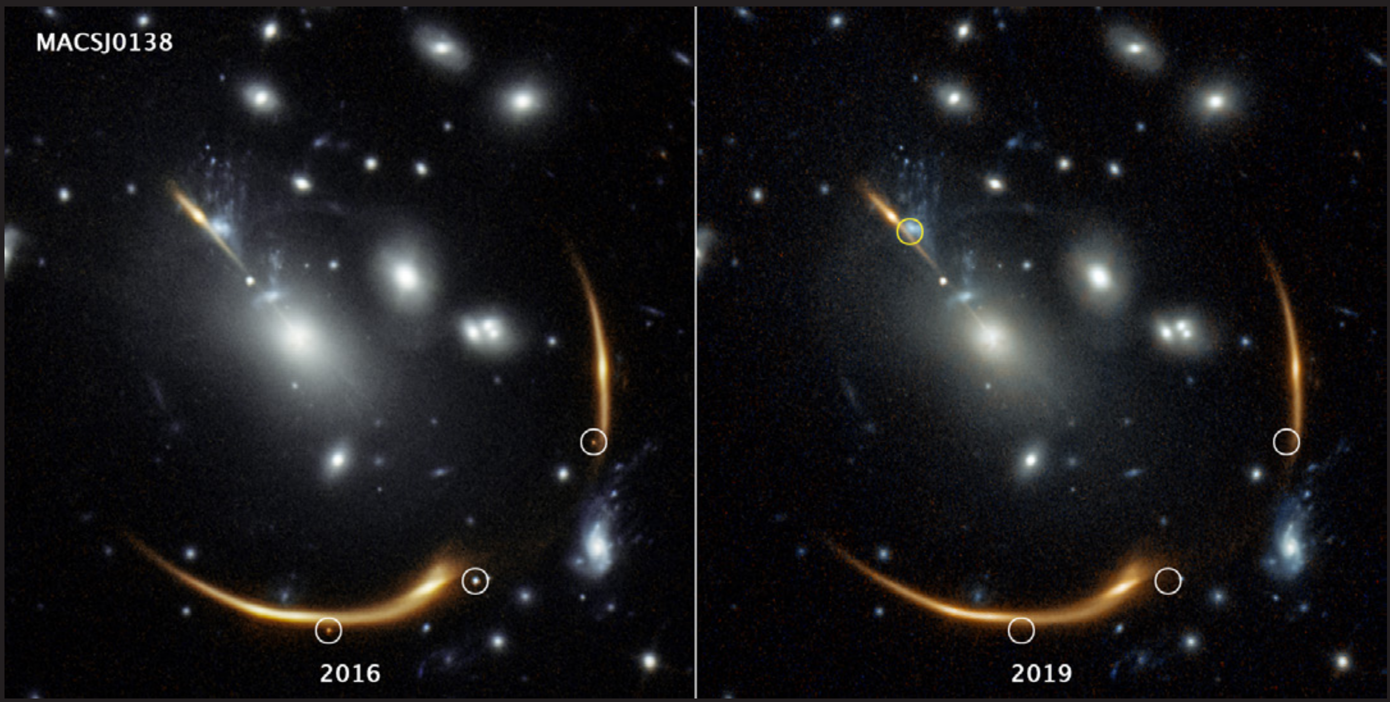
Supernova explosions usually flare up and fizzle out over the course of a few weeks or months, never to be seen again. But in rare cases, thanks to gravitational lensing, astronomers can witness an encore. Using *Hubble*, a team of scientists predicted one such repeat, due in roughly the year 2037.

> "The multiply-imaged supernova in this beautiful gravitational lens has constraining power for both cosmology and dark matter substructure."
>
> Justin Pierel, Space Telescope Science Institute (STScI)

Multiple apparitions of one supernova explosion in a distant galaxy are made possible by an intervening galaxy cluster. The cluster's enormous gravity warps space, splitting and bending the light's path as it travels toward us. Scientists discovered three magnified copies of the same supernova explosion embedded within a distorted distant galaxy in *Hubble* images of the foreground galaxy cluster. Because the cluster split the supernova's light, it took multiple paths navigating the cluster's maze of clumpy dark matter. Since the length of each route varies, the light arrives at Earth at different times.

The team made a map of the cluster's dark matter based on the lensing they observed. Based on computer models, they predict that an additional light path through the foreground cluster will yield another sighting of the supernova sometime in 2037. Catching the rerun of the explosive event will help astronomers measure the time delays between all four supernova images. This will offer new information about both the cluster's dark matter and the dark energy that is stretching the space between the supernova and us.

Hubble's sharp view and ability to spot dim objects made this rare observation, only the third of its kind, possible. Future telescopes that have even larger fields of view, including the *Nancy Grace Roman Space Telescope* and ground-based Vera C. Rubin Observatory in Chile, should spot hundreds more of these lensed, repeating supernovae. Studying them will help astronomers fine-tune dark matter maps and investigate the nature of dark energy.

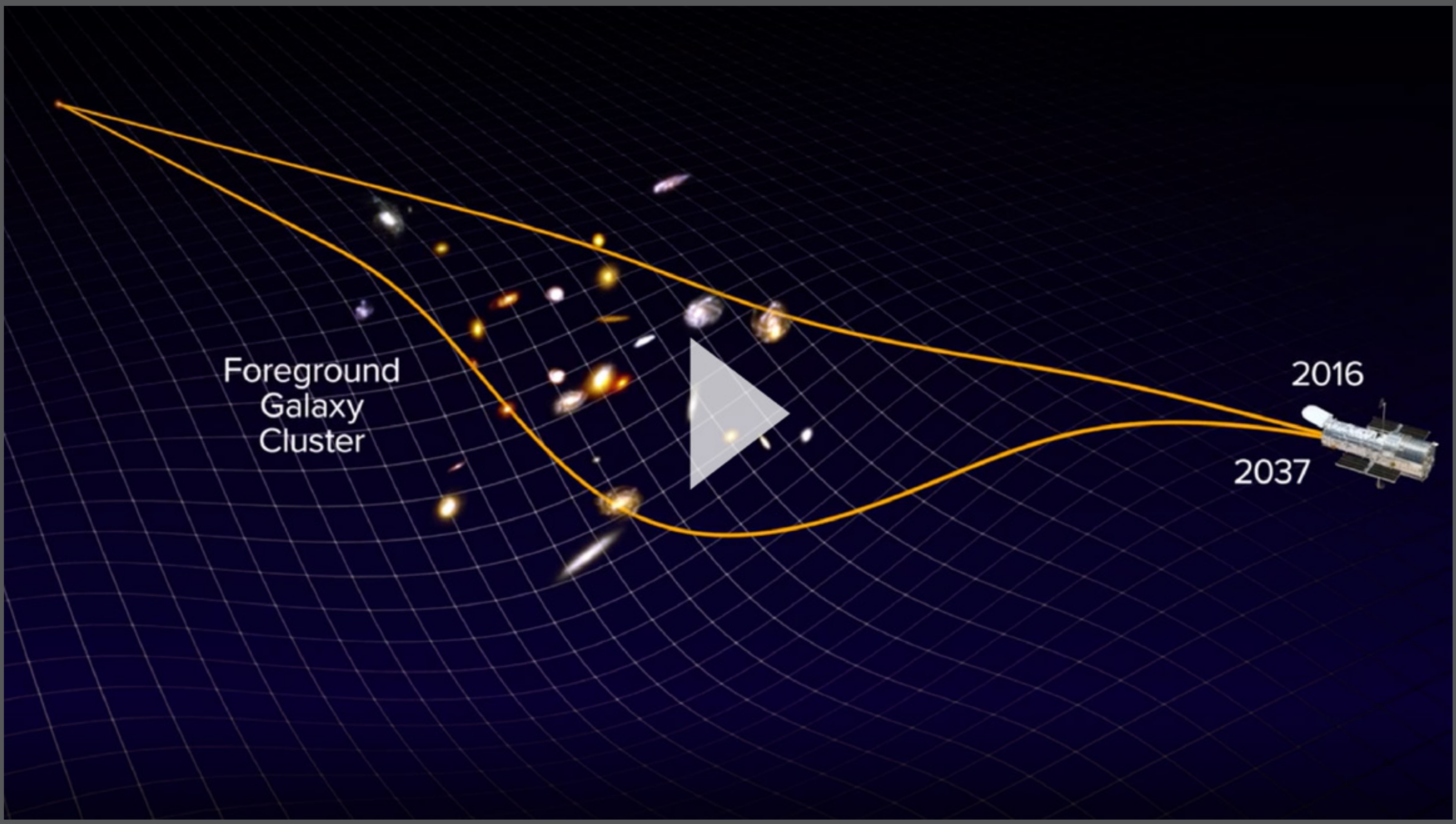


These *Hubble* images showcase a distant galaxy, seen as orange streaks, that was magnified and distorted by a foreground galaxy cluster's gravity. By comparing observations from 2016 and 2019, astronomers discovered a supernova within the far-flung galaxy. It appears as three points of light circled in the 2016 image, which disappeared by 2019. Each image of the lensed supernova is a snapshot of the light from different times after the explosive event. Astronomers expect to see a fourth copy of the exploded star in 2037–a prediction based on computer models that describe the paths the supernova light is taking through the maze of clumpy dark matter in the galaxy cluster.

Credit: Steve A. Rodney (University of South Carolina), Gabriel Brammer (Cosmic Dawn Center/Niels Bohr Institute/University of Copenhagen); Image processing: Joseph DePasquale (STScI)

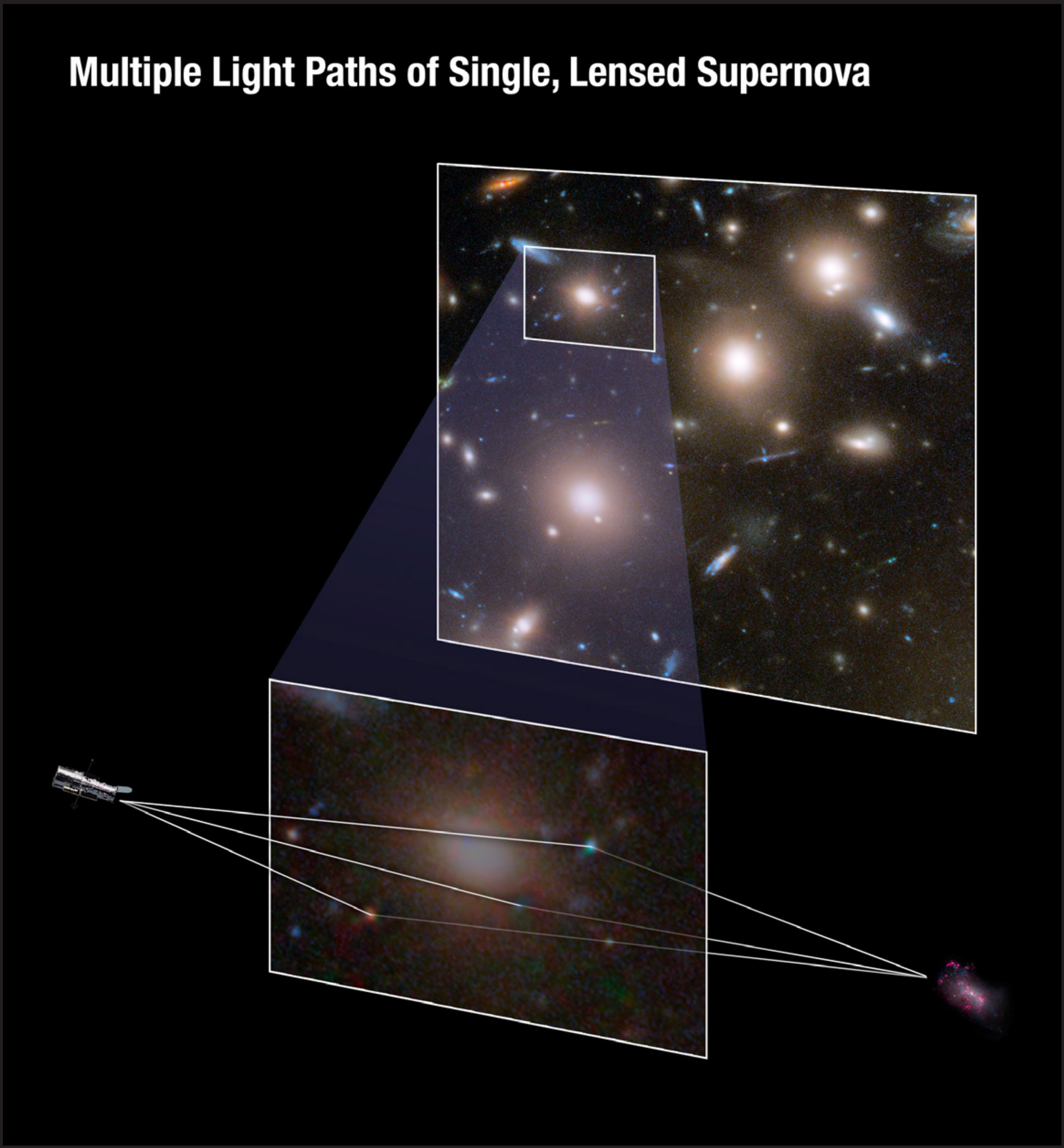
Learn more: Rerun of Supernova Blast Expected to Appear in 2037

Tracing the Path of a Supernova’s Light Through Dark Matter



This animation illustrates how light from a supernova travels through a galaxy cluster on its way toward Earth. Scientists used *Hubble* images to identify the supernova embedded within a distant galaxy. The intervening galaxy cluster’s gravity, which warps the fabric of space-time, magnified and duplicated the supernova’s light. Light from each copy of the supernova follows a different path through the cluster’s field of dark matter and arrives at Earth at a different time. The team predicts that the supernova will reappear in 2037, offering astronomers another opportunity to fine-tune maps of the cluster’s dark matter.

Credit: NASA, ESTEC, STScI, Greg T. Bacon (STScI)



Hubble saw another case of a repeating supernova thanks to gravitational lensing. The observation, shown in this *Hubble* image, captured the explosion in three different stages. The top box shows a portion of the galaxy cluster Abell 370, which lensed the farther supernova's light. The smaller box within it marks the area where the supernova was multiply lensed. The bottom image zooms in on that area and illustrates the way the supernova's light passed from its home galaxy (bottom right), through the dark-matter-rich cluster, and on to *Hubble*. The light was split as it passed through the cluster. Each path it traveled is a different length, so it took the light a different amount of time to navigate each one. That's how the warping produced three images of the explosion from different time periods that all arrived at *Hubble* simultaneously.
Credit: NASA, ESA, Alyssa Pagan (STScI)

Chapter 3: Invisible Matter Mystifies Closer to Home

Galaxies and galaxy clusters are arranged in clumps along invisible threads in a tapestry the size of the universe. This tapestry reveals the large-scale structure of the universe to be web-like, made up of tendrils of gas that are hundreds of millions of light-years long. Dark matter provides the unseen scaffolding to which the gas and galaxies cling, with the latter primarily found at intersections of the filaments. Observing the filaments themselves is all but impossible unless astronomers know just where to look, since the gas they're made of is so faint and the dark matter is invisible. Pairing clever algorithms, informed by one of the smallest inhabitants of the cosmos, with *Hubble*'s sharp view has helped make it possible.

Learning more about the backbone upon which galaxies are built offers clues about our universe, which is dominated by dark matter both on cosmic scales and within individual galaxies. Astronomers have explored many galaxies whose dark matter contributes to gravitational lensing, where gravity bends space itself and magnifies images of more distant galaxies. But though this method helps astronomers map dark matter far out in space, its effects are often too small to reveal dark matter closer to Earth.

For that, astronomers sometimes study the motions of globular clusters—huge, spherical clouds of ancient stars bound to each other by their mutual gravity—to learn about their host galaxy's gravitational field. *Hubble* did just that to tally up how much dark matter is in our own galaxy, and calculated a value that aligned pretty closely with what they expected. But when *Hubble* took a close look at one of the Milky Way's galactic neighbors, astronomers discovered a huge surprise—a rare galaxy that appears to have little to no dark matter. Current galaxy formation theories all involve dark matter as a main component, however it seems there must be another way to build a galaxy.

Astronomers will continue hunting down dark matter using both *Hubble* and other telescopes. Teaming up with other observatories will allow us to put together far more pieces of the puzzle than each could assemble on its own by offering detailed, complementary observations that span much more of the electromagnetic spectrum. Perhaps one day soon we will understand dark matter's role in the evolution of our universe or be able to detect it directly for the first time.

This *Hubble* image showcases the majestic spiral galaxy UGC 2885, located 232 million light-years from Earth. The galaxy is 2.5 times wider than our Milky Way and contains 10 times as many stars–about 1 trillion–embedded inside a vast halo of invisible dark matter. The image is dappled with several foreground stars that reside in our Milky Way, identified by their diffraction spikes. This galaxy has been nicknamed "Rubin's galaxy," after astronomer Vera Rubin, who studied the galaxy's rotation rate in search of dark matter.

Credit: NASA, ESA, and B. Holwerda (University of Louisville)

Exposing a Galaxy's Missing Dark Matter

Sometimes the most curious cosmic discoveries involve what we don't find. Astronomers trained *Hubble* on a bizarre, see-through galaxy and noticed a dearth of dark matter. They targeted the relatively nearby galaxy, called NGC 1052-DF2, because it is so faint and diffuse. Though it's as big as our Milky Way galaxy, it only has 1/200th as many stars. Such large, faint galaxies are surprisingly common, but NGC 1052-DF2 stands out from the rest. While dark matter is typically a galaxy's most dominant component, researchers found that this one contains at most 1/400th the amount they expected. This opens the question of how the galaxy formed in the first place, since current theories hold that dark matter provides the scaffolding on which galaxies form.

"This result suggests that there may be more than one way to form a galaxy."

Pieter van Dokkum, Yale University

Researchers originally found the galaxy using the Dragonfly Telephoto Array, a custom-built telescope in New Mexico they designed to find these ghostly galaxies. Then they used the W. M. Keck Observatory in Hawaii to measure the motions of 10 giant groupings of stars called globular clusters in the galaxy, which allowed them to calculate the galaxy's mass. Adding up the mass from the galaxy's stars leaves little, if any, room for dark matter to be present. Using the Gemini Observatory in Hawaii, the team found that the galaxy does not show signs of an interaction with another galaxy. *Hubble* helped the researchers better identify the globular clusters and measure the galaxy's distance.

Scientists later used more *Hubble* observations to better nail down the galaxy's distance. If the galaxy were closer than astronomers thought, the dark matter mystery would dissolve because it would imply a lower number of stars are giving the galaxy its observed brightness. With fewer stars in the mix, more dark matter would account for the total mass driving the motion of globular clusters. However, they found that the galaxy is actually slightly farther away than first measured, confirming that dark matter really is missing in the galactic oddball. Now it's up to theorists to figure out why.

Distant galaxies speckle the background in this *Hubble* image of NGC 1052-DF2, which is such a sparse galaxy we can see right through it. Astronomers used *Hubble* to refine its distance after discovering its lack of dark matter. They observed about 5,400 aging red giant stars, which serve as reliable cosmic yardsticks since they reach the same peak brightness. Thanks to these observations, astronomers learned the galaxy resides about 72 million light-years from Earth.
Credit: Science: NASA, ESA, STScI, Zili Shen (Yale), Pieter van Dokkum (Yale), Shany Danieli (IAS); Image Processing: Alyssa Pagan (STScI)

Learn more: [Dark Matter Goes Missing in Oddball Galaxy]
[Mystery of Galaxy's Missing Dark Matter Deepens]

Probing New Realms of Physics

Scientists first suspected dark matter's existence in the 1930s after observing members of the Coma cluster—a giant group of more than a thousand galaxies. The galaxies were moving so quickly they should have been flung away into space, yet they remained gravitationally bound to the cluster by unseen matter. Fast forward to the present and *Hubble* is helping astronomers trace the same cluster's dark matter distribution, this time using some of its most diminutive members.

> "With a patchwork of *Hubble* observations, we obtained the largest and most detailed study of globular clusters in Coma ever made."
>
> Juan Madrid, Australian Telescope National Facility

Hubble peered into the heart of the Coma cluster and captured a whopping 22,426 globular star clusters—glittering snowball-shaped islands of myriad stars crowded together—scattered throughout the galaxies. Researchers assembled a mosaic of the central region of the cluster from numerous archived *Hubble* images. The team developed an algorithm to identify globular clusters using their color (dominated by the glow of aging red stars) and spherical shape to eliminate extraneous objects.

The star clusters likely broke away from their home galaxies due to interactions with other galaxies in the traffic-jammed Coma cluster. They trace the gravitational field in the cluster, which in turn traces the distribution of the cluster's dark matter. Since globular clusters are much smaller and more abundant than entire galaxies, they provide a more detailed way to explore how the fabric of space is distorted by the Coma cluster's gravity. The study also paves the way for the *Nancy Grace Roman Space Telescope* to do similar work with its much larger field of view, which could capture an entire galaxy cluster in a single image.

More than 20,000 globular star clusters are very faintly dusted throughout this *Hubble* image of the Coma galaxy cluster, located 321 million light-years from Earth. Astronomers used the globular clusters to map how dark matter is distributed throughout the galaxies.
Credit: NASA, ESA, J. Mack (STScI), and J. Madrid (Australian Telescope National Facility)

Learn more: [Hubble Uncovers Thousands of Globular Star Clusters Scattered Among Galaxies]

This video zooms into and then pans across a *Hubble* mosaic of the immense Coma cluster of over 1,000 galaxies, revealing thousands of globular star clusters (circled in green). The star groupings trace the distribution of dark matter and allow astronomers to map the galaxy cluster's gravity.
Credit: NASA, ESA, and J. DePasquale and G. Bacon (STScI)

Measuring the Milky Way's Mass

> "Globular star clusters are some of the best tracers astronomers have to measure the mass of the vast envelope of dark matter surrounding our galaxy."
>
> Tony Sohn, Space Telescope Science Institute (STScI)

Our Milky Way galaxy may contain as many as 200 billion stars, but they account for only a small amount of the galaxy's total mass. Scientists know that dark matter makes up most of the rest, but it's been difficult to know just how much of it there is. Previous estimates of the Milky Way's total mass have varied widely, ranging from 500 billion to 3 trillion times the mass of the Sun. Astronomers came up with a clever way to more precisely "weigh" the galaxy using *Hubble* and the European Space Agency's *Gaia* satellite.

Globular star clusters orbit our galaxy like bees buzz around a hive. By studying their motions, astronomers can estimate the Milky Way's mass; the faster the clusters move under the pull of gravity, the more massive the galaxy must be to keep them from flying away. Earlier measurements were along the line of sight to globular clusters, telling astronomers how fast they move toward or away from Earth. Researchers used *Hubble* and *Gaia* to gauge the clusters' sideways motion, from which a more reliable speed (and therefore gravitational acceleration) can be calculated. *Gaia* measured 34 globular clusters out to 65,000 light-years, and then *Hubble* measured an additional 12 clusters out to 130,000 light-years.

The researchers concluded that our galaxy weighs 1.5 trillion solar masses, with most of it locked up in dark matter. The new estimate puts our galaxy on the beefier side, compared to other galaxies in the universe. The lightest galaxies are around a billion solar masses, while the heaviest are 30 trillion, or 30,000 times more massive. The Milky Way's mass is fairly normal for a galaxy of its brightness. This measurement allows astronomers to better understand how the myriad galaxies throughout the universe form and evolve.

This illustration shows the fundamental architecture of our island city of stars, the Milky Way galaxy: a spiral disk extending outward from a central bulge, all of which is encased by a diffuse halo of stars and globular star clusters. Not shown is the vast halo of dark matter surrounding our galaxy. A comprehensive survey that combined the observing prowess of both *Hubble* and the European Space Agency's *Gaia* satellite measured the combined mass of the Milky Way's seen and unseen matter to be 1.5 trillion solar masses. Having a more refined mass measurement for our galaxy helps astronomers address many cosmological questions.
Credit: NASA, ESA, and A. Feild (STScI)

Learn more: [What Does the Milky Way Weigh? Hubble and Gaia Investigate]

Unraveling the Cosmic Web Using Slime Mold

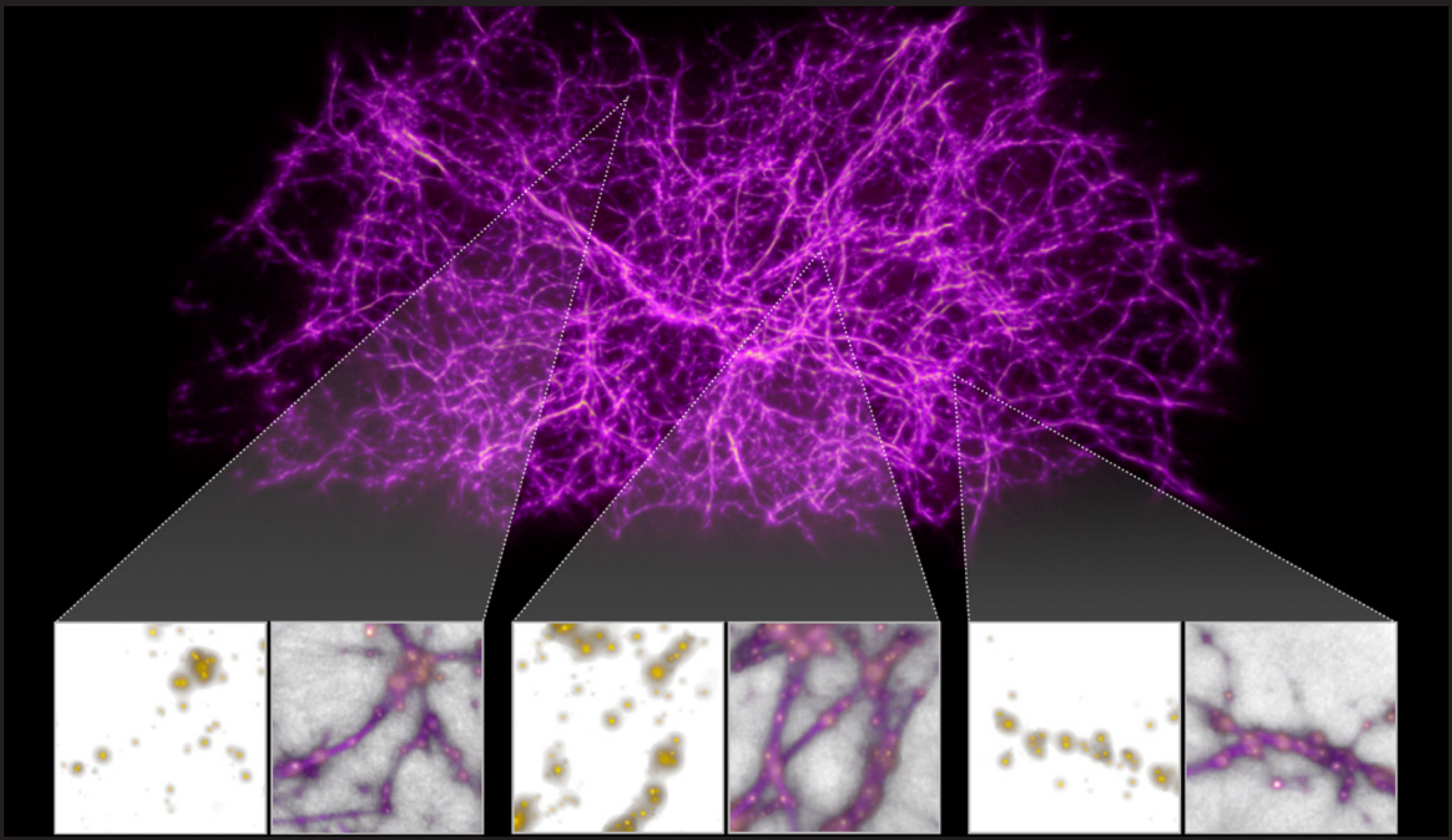
Astronomers routinely observe some of the largest structures in the universe, but even the tiniest members of the cosmos can offer clues about space. A team of scientists studied the behavior of a simple single-cell organism called slime mold to help them trace the "cosmic web." Built by gravity, this vast network of filaments ties galaxies and clusters of galaxies together along faint bridges of dark matter and gas that are hundreds of millions of light-years long. But astronomers have had a difficult time finding these elusive strands, because the gas is so dim (the dark matter, of course, is invisible).

"One of the simplest forms of life actually enables insight into the very largest-scale structures in the universe."

Joseph Burchett, University of California, Santa Cruz

Researchers noted a striking similarity between how slime mold builds complex filaments to capture new food, and how gravity, in shaping the universe, constructs the cosmic web strands between galaxies and galaxy clusters. Though they lack brains, the tiny organisms have an uncanny ability to find near-optimal pathways to reach the dead plant material they feed on.

The team designed an algorithm informed by slime-mold behavior and seeded it with the charted positions of 37,000 galaxies mapped by the Sloan Digital Sky Survey to generate a filamentary map. That told them where to look in archived *Hubble* observations to detect and study the faint gas permeating the web. By pairing the slime-mold simulation with *Hubble* data, the team was able to measure gas on the outskirts of the invisible filaments. The study allowed astronomers to learn more about the backbone upon which galaxies are built.



The simulation shown here illustrates how scientists detected gas in strands of the cosmic web. Researchers used an algorithm to produce a 3D map of the cosmic web's underlying network of filaments (the purple structure in the image). The left box in each inset contains some of the individual galaxies (yellow dots) that were "fed" to the algorithm. The boxes at the right in each inset show the deduced strands in the cosmic web (purple) connecting the galaxies. The simulation helped researchers know where to look to detect those strands.
Credit: NASA, ESA, and J. Burchett and O. Elek (UC Santa Cruz)

Learn more: [Slime Mold Simulations Used to Map Dark Matter Holding Universe together]

Summary

The trillions of stars, planets, galaxies, and other visible objects strewn throughout the cosmos represent just four percent of what's truly out there. Visible matter is like the tip of an iceberg, or the foam on top of a latte. All the rest of the universe—dark matter and dark energy—is mired in mystery.

Decades after they each were discovered, the nature of both these invisible substances remains elusive. Yet they have played major roles in cosmic evolution, with dark matter drawing galaxies into alignment on the cosmic web and dark energy stretching the space between galaxy clusters. They continue to drive the universe and will influence its ultimate fate.

Pinning down these puzzling cosmic components is astronomy's greatest ghost hunt. They indicate that for all we've learned about the universe, we still don't know much about its underpinnings. But instead of frustrating astronomers, these mysteries open the door to discovering exciting new physics.

Hubble continues to be a vital tool to address questions about the underlying workings of the universe. Scientists will pair its wide wavelength coverage with *James Webb Space Telescope*'s powerful vision, the upcoming *Nancy Grace Roman Space Telescope*'s panoramic view, and a fleet of additional space- and ground-based telescopes to explore the cosmos as never before. We have far more left to learn among the stars.

The stars in galaxy NGC 1052-DF2, pictured in this *Hubble* image, are so sparse that the galaxy looks like a mere foggy blob. It appears to be missing some of the usual main components of galaxies, including dark matter. No theories predict such a galaxy, making this one an alluring mystery.
Credit: NASA, ESA, and P. van Dokkum (Yale University)

More Information

For more information about the *Hubble Space Telescope* mission and its discoveries, visit NASA's *Hubble* website at nasa.gov/hubble. For additional details and resources, visit HubbleSite.org.

Follow *Hubble*'s exploration of Dark Matter and Dark Energy at the following social media sites.

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Flickr
https://www.flickr.com/photos/nasahubble

Pinterest
https://www.pinterest.com/nasa/hubble-space-telescope/

This is an artist's impression of how the very early universe may have looked, when so-called starburst galaxies were still forming new stars at a furious pace. Scientists think these nascent galaxies formed under the influence of dark matter, which drew luminous matter together.
Credit: A. Schaller (STScI)

Credits

The *Hubble Space Telescope* is a cooperative project between the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA). The *Hubble Space Telescope* Operations Project at the NASA Goddard Space Flight Center (GSFC) manages the mission. The Space Telescope Science Institute (STScI), operated by the Association of Universities for Research in Astronomy (AURA), conducts the science operations for the *Hubble Space Telescope* under a contract with NASA. Lockheed Martin conducts the mission operations for *Hubble* under a contract with NASA.

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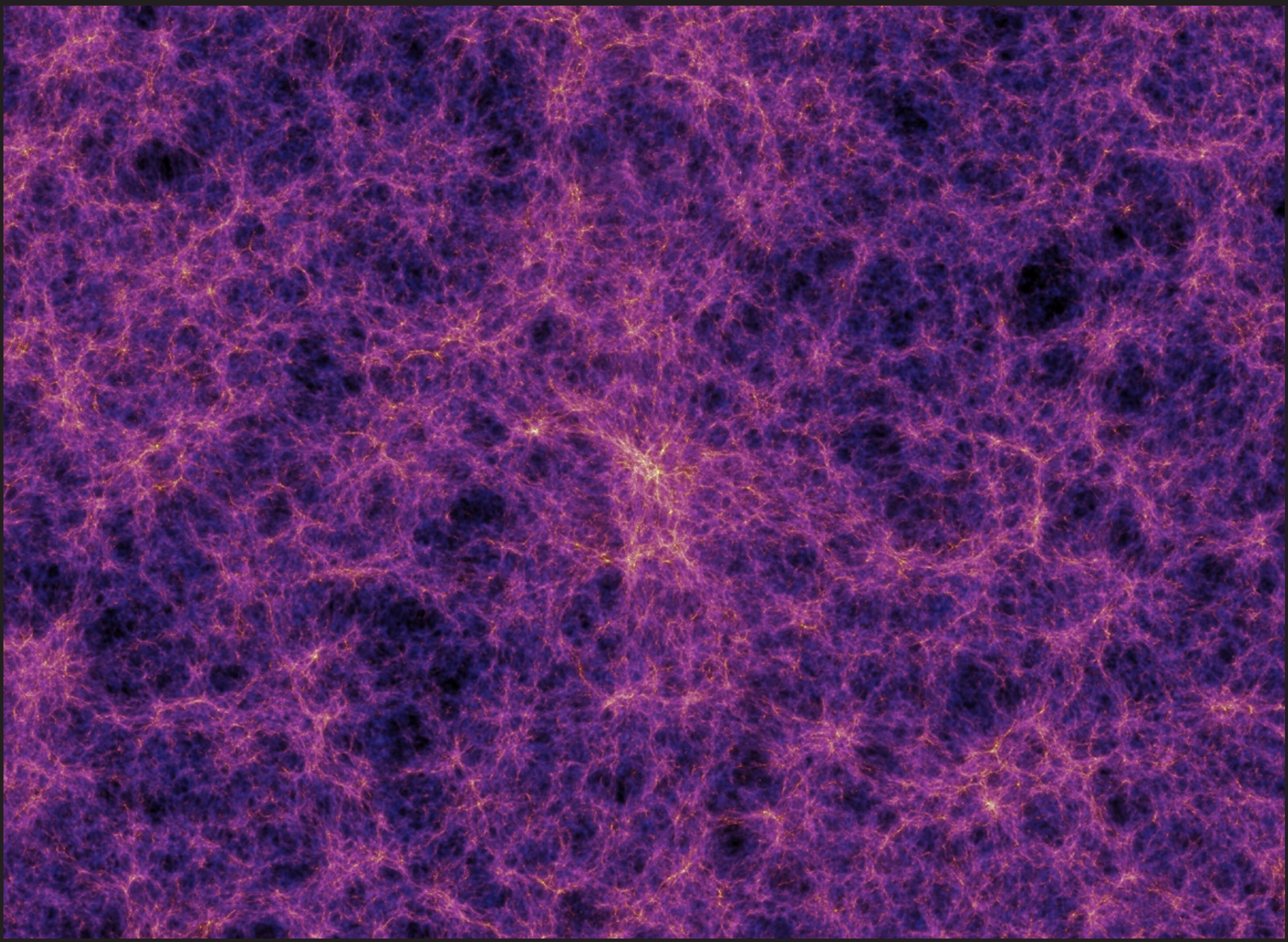
The production team for this book included Ashley Balzer (writer); Mike Marosy and Ed Henderson (designers); Ken Carpenter and Jennifer Wiseman (science advisors); Andrea Gianopoulos, Kevin Hartnett, and James Jeletic (editors); Ray Villard (STScI) (content consultant).



An artist's impression of the cosmic web. Gravity builds a vast cobweb-like structure of filaments tying galaxies and galaxy clusters together along invisible bridges hundreds of millions of light-years long. *Hubble* studies the cosmic web to help us better understand the invisible forces that have shaped our universe into this structure.
Credit: Volker Springel (Max Planck Institute for Astrophysics) et al.

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