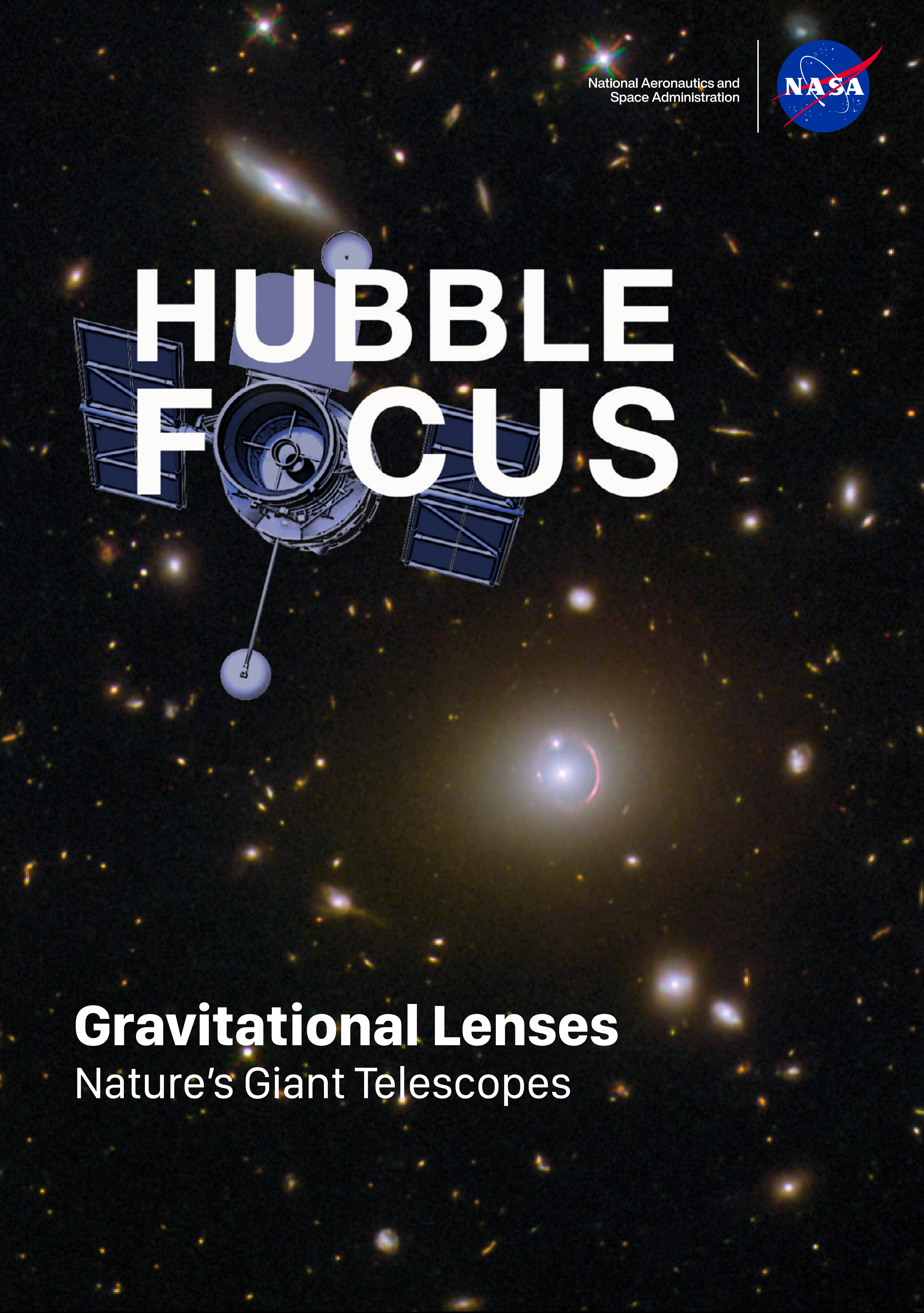
National Aeronautics and
Space Administration



HUBBLE FOCUS

Gravitational Lenses

Nature's Giant Telescopes

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About the Hubble Space Telescope

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

NASA

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 learned that galaxies evolve from smaller structures, found that supermassive black holes are common at the centers of galaxies, discovered 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.

The Hubble Space Telescope returns to orbit as an improved telescope after its second servicing mission in February 1997.

NASA

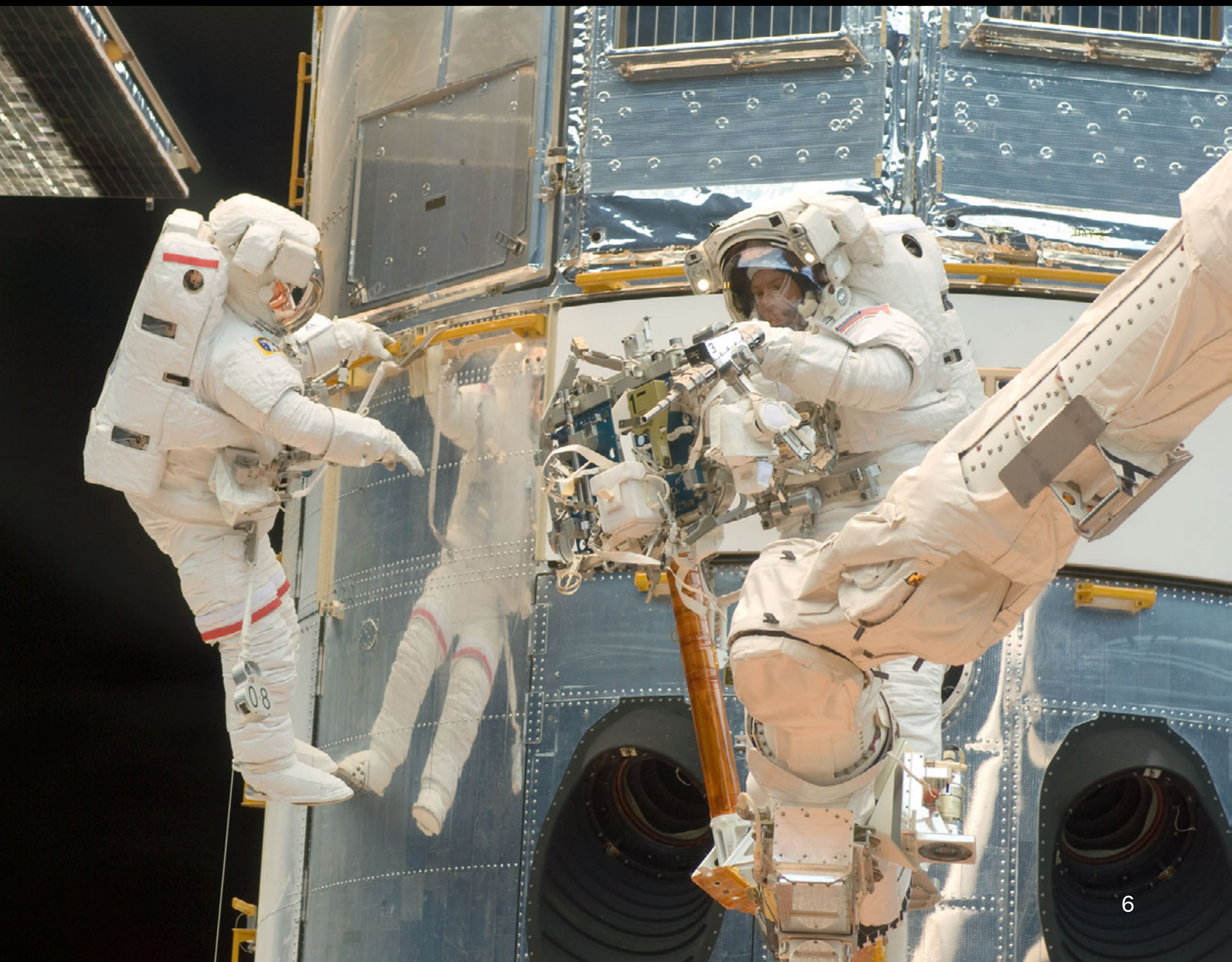
As NASA's first Great Observatory and the first major optical telescope in space, Hubble ushered in a new era of precision astronomy. The heart of the telescope is its 94.5-inch-diameter (2.4 meter) primary mirror. It is so smooth that if it were scaled up to the width of the United States, there would 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 10 to 20 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 13.8 billion years ago.

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.



Astronauts John Grunsfeld (left) and Andrew Feustel (right) perform work on the Hubble Space Telescope during the first of five spacewalks conducted on the last servicing mission in 2009.

NASA

Introduction

Hubble Frontier Fields
Image of Abell 2744.

NASA, ESA, and J. Lotz, M. Mountain, A. Koekemoer, and the HFF Team (STScI)

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.

Hubble Focus: Gravitational Lenses — Nature's Giant Telescopes highlights some of Hubble's recent discoveries about gravitational lenses, the universe's natural magnifying glasses.

Hubble's contributions are often in partnership with other observatories, and build on decades of discoveries that came before Hubble's launch. Its findings help us understand how our universe came to be the way it is today.

What Are Gravitational Lenses?

Imagine a telescope in space that dwarfs galaxies. Its power is so immense that it can reveal details of the light from a star almost 13 billion light-years away, born in the early universe. It can trace the presence of invisible dark matter and twist the light of distant galaxies into funhouse mirror arcs and rings.

Galaxy cluster ACO S 295 and a jostling crowd of background galaxies appear in this Hubble image. Galaxies of all shapes and sizes ranging from stately spirals to fuzzy ellipticals are visible in the cluster, whose tremendous mass has gravitationally lensed the background galaxies, distorting, smearing, and magnifying their shapes. One example is the squiggly line in the upper right corner, a lensed galaxy arc so bright it was seen by ground-based telescopes in the 1990s. The arc consists of three mirror images of the same galaxy strung together in a line.

ESA/Hubble & NASA, F. Pacaud, D. Coe

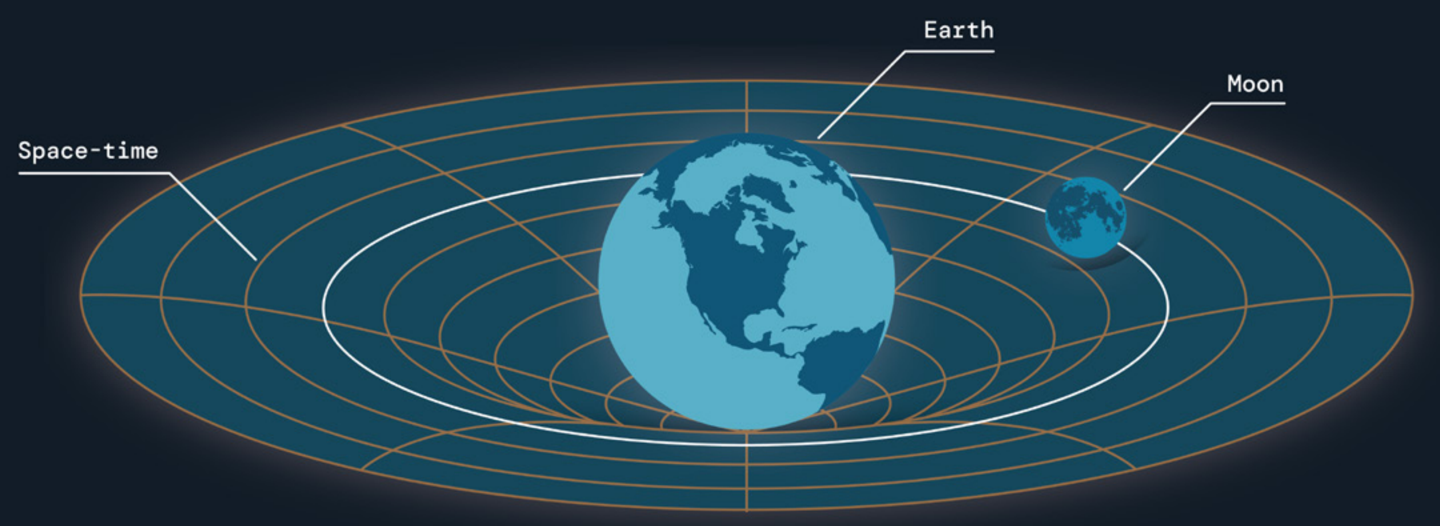
It sounds like science fiction — an immense, impossible project for a far-distant, imagined future. But these telescopes are real, a natural phenomenon called gravitational lensing. To understand how these cosmic lenses work, we look to theoretical physicist Albert Einstein and his theory of general relativity.

Bending Light

For many years, gravity was thought of only as a force that exists between objects with mass, a concept established by the scientist Isaac Newton. In 1915, Albert Einstein revised the concept of gravity to better explain certain observations — usually involving extremely massive objects and strong gravitational effects — that Newtonian gravity couldn't. He proposed that mass and energy warp space itself, curving space-time. This curvature affects anything that passes nearby, even light, and produces the effect we call gravity.

Gravitational Force

Gravity, the force that draws objects together, can be understood as bends and curves in the fabric of space-time. Anything with mass makes these dents.

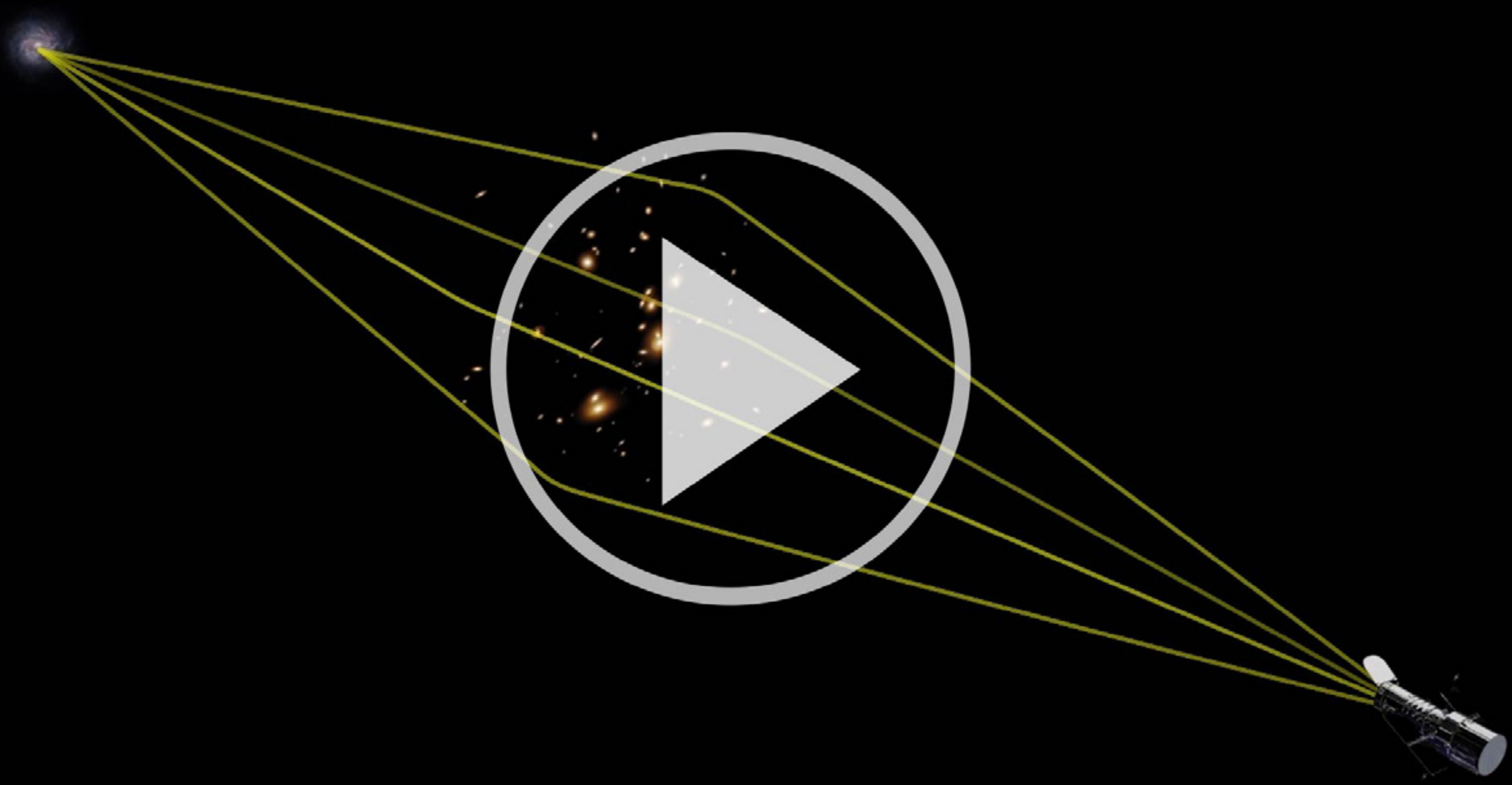


Mass creates bends and curves in the fabric of space-time, resulting in gravitational effects. Light follows these curves as it travels across the universe.

NASA

Gravitational lensing is a phenomenon that demonstrates how right Einstein was. When light travels past an immense mass — for example, a cluster of galaxies — it is bent, warped, and magnified as though by a giant cosmic lens. This enhancement allows us to see objects that would be too far away to glimpse otherwise, even though their images may be distorted or even duplicated by the passage of light through the lens. Since most of the mass in the universe consists of dark matter — the still-mysterious, invisible material that is the scaffolding upon which galaxies and galaxy clusters are built — gravitational lensing effects can help researchers map the presence and distribution of dark matter in galaxy clusters.

Hubble has used gravitational lensing to uncover incredibly distant stars and galaxies, study the early evolution of the universe, and even find planets around other stars.



This animation shows light taking a gravitationally lensed path around a massive star and through a galaxy cluster. As the light passes through the cluster, it is bent and magnified by the cluster's gravity before reaching Hubble.

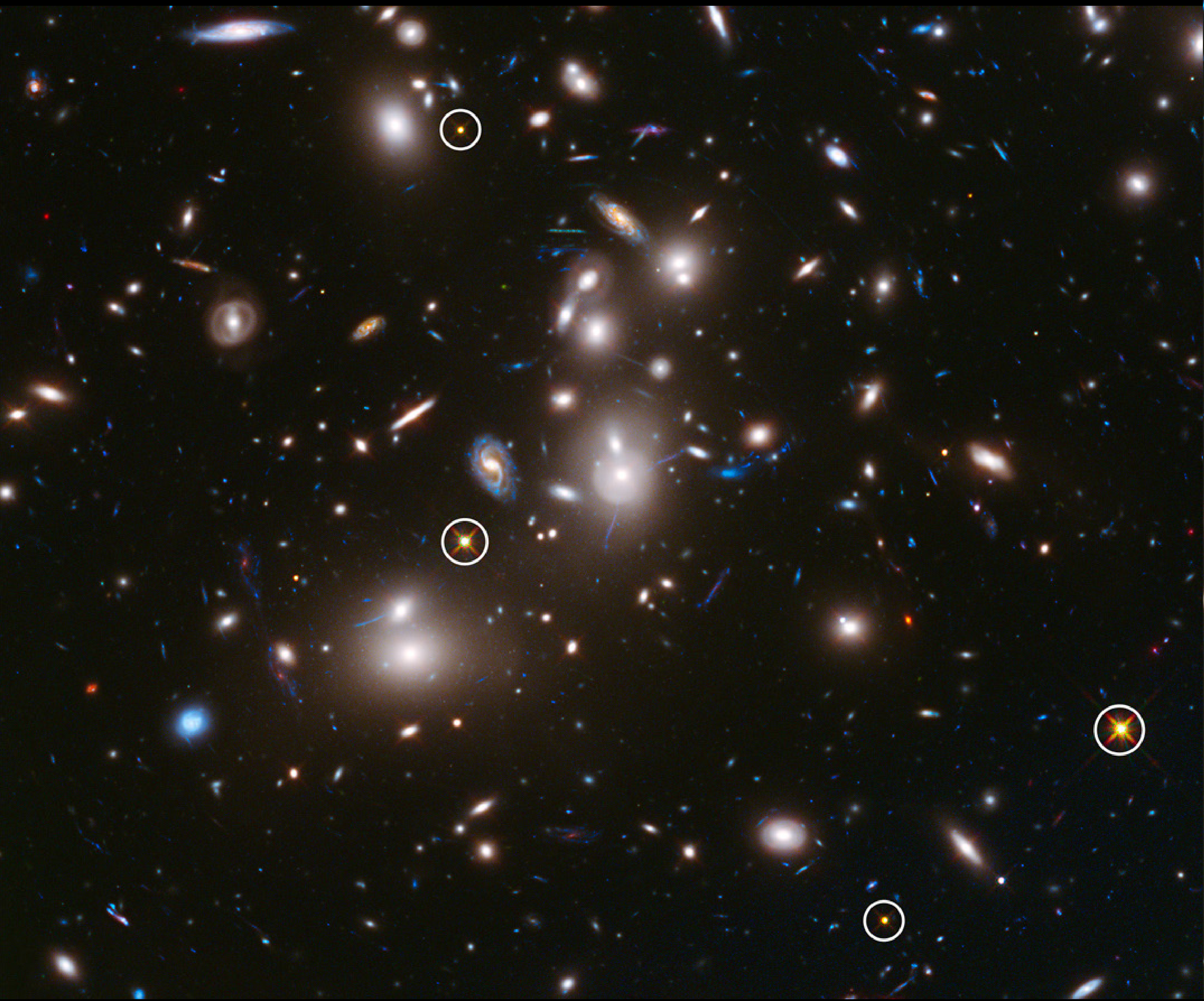
NASA, ESA, and Goddard Space Flight Center/K. Jackson

Hubble Science: Gravitational Lensing

Watch on YouTube: https://youtu.be/6yfvJfRLyGg?si=v5hqVZjA8IMEnj1a

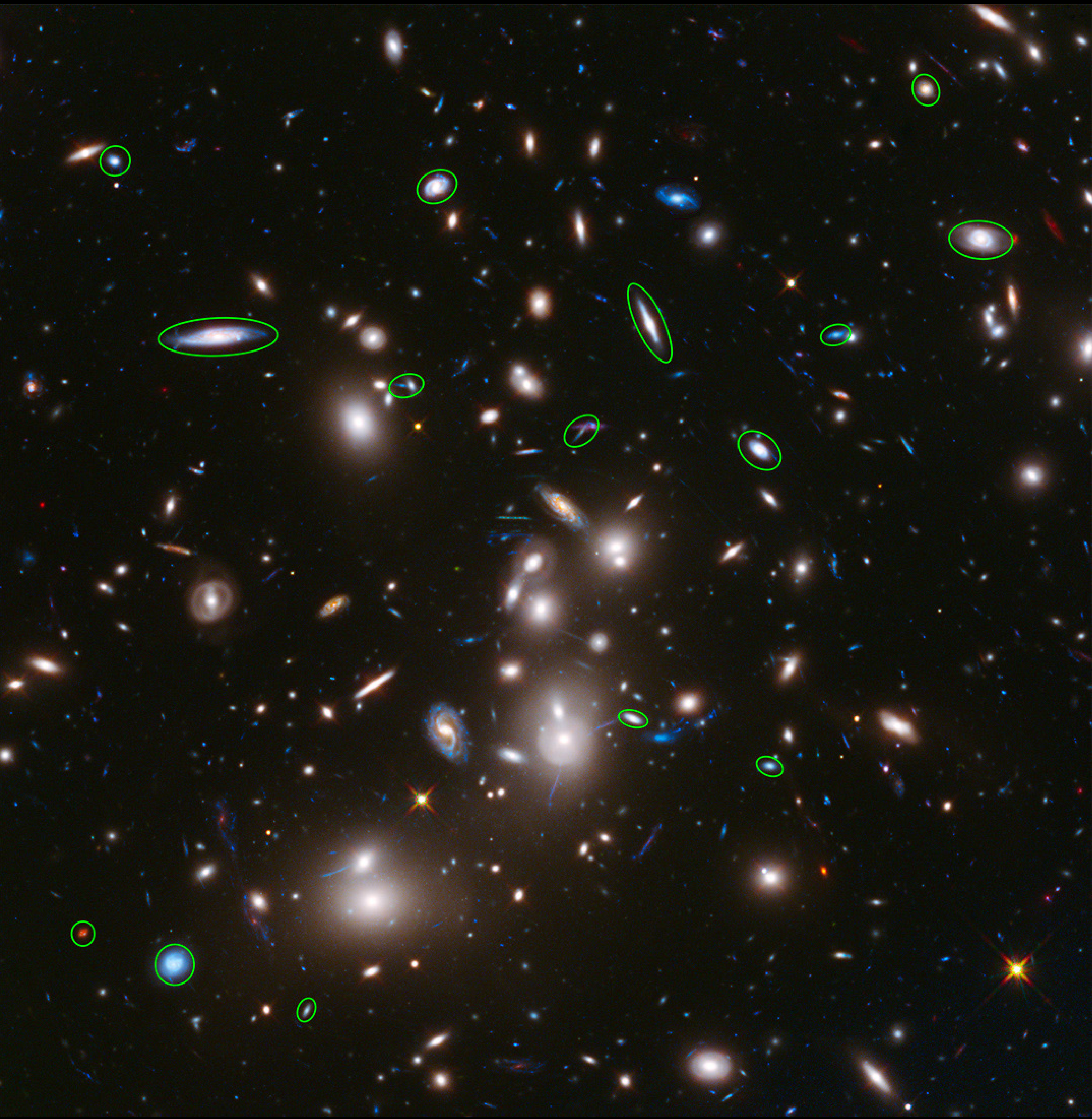
What's In a Gravitationally Lensed Image?

In this Hubble image of galaxy cluster Abell 2744, the strange arcs and streaks of magnified background galaxies scattered among glowing clusters of galaxies and bright foreground stars make for a visually arresting scene. But what are we really seeing when we look at one of Hubble's gravitationally lensed clusters?



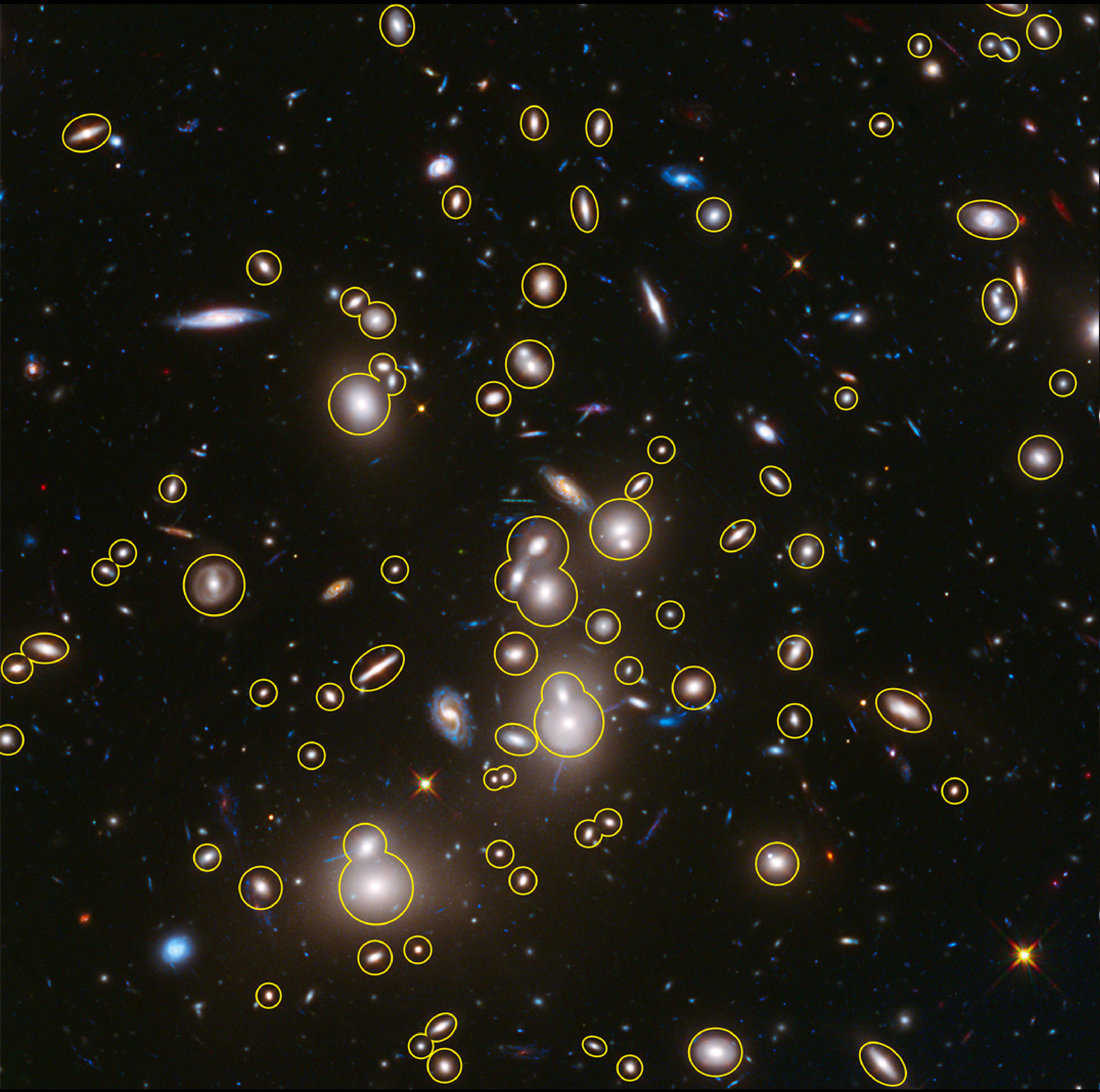
STARS

The white circles highlight stars in our own Milky Way galaxy. These foreground stars have a distinctive cross-shape created by light reflecting off the struts in the telescope. These "diffraction spikes" only occur with very bright, point-like objects.



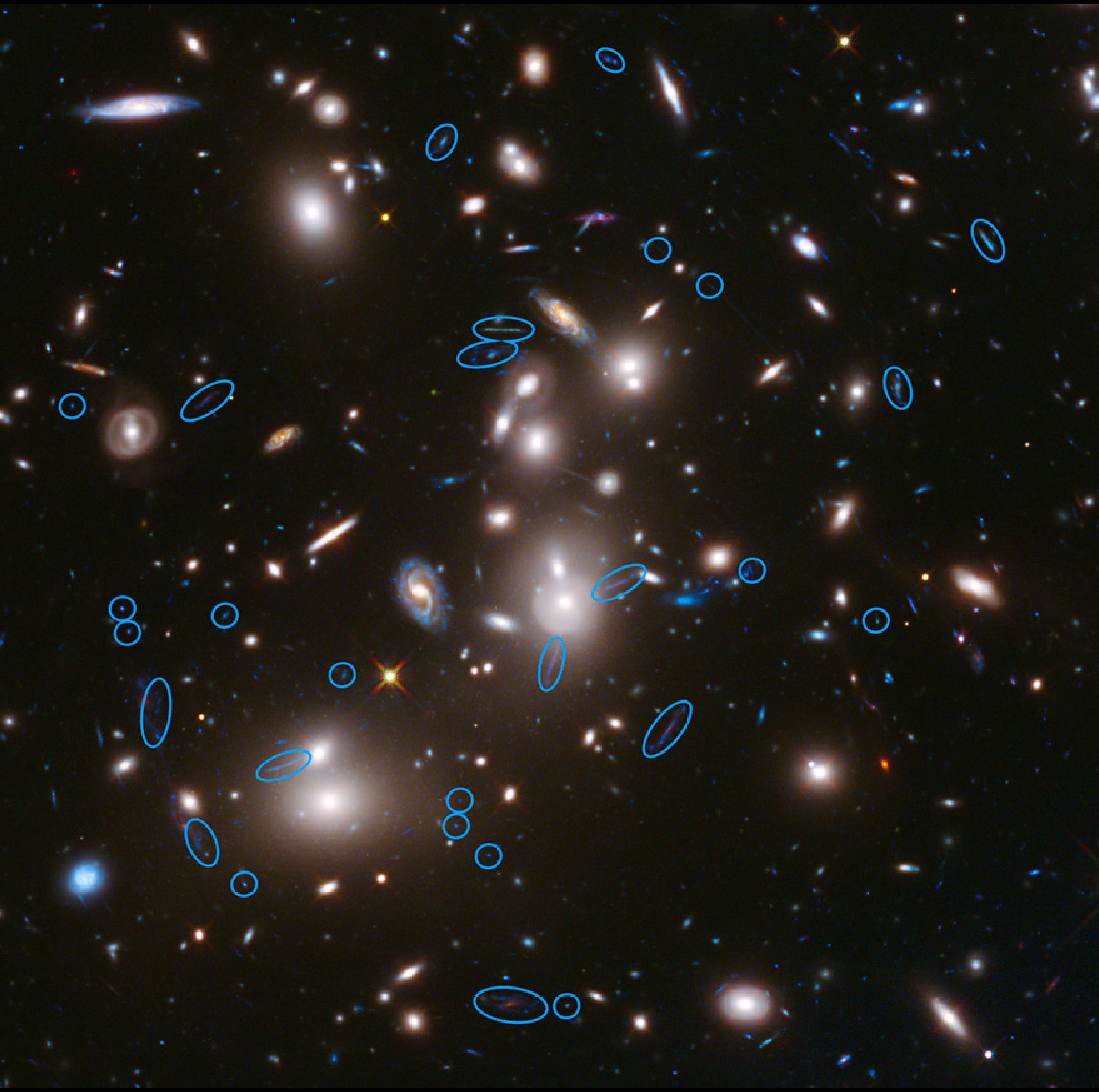
FOREGROUND GALAXIES

The green circles identify galaxies in the space between us and the Abell 2744 galaxy cluster. These foreground galaxies are not affected by the gravitational lens and their shapes are generally sharp, distinctive, and recognizable.



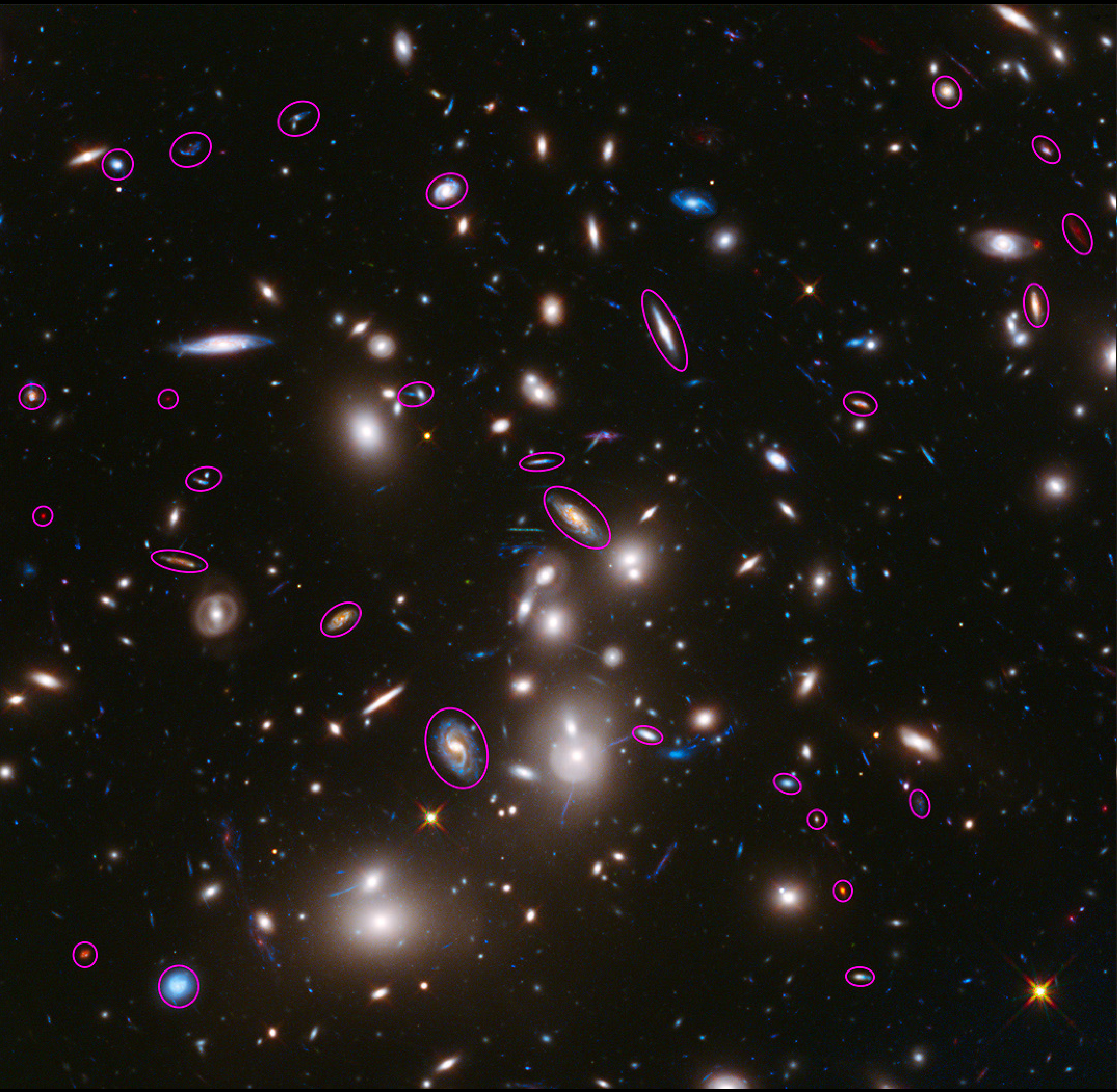
CLUSTER GALAXIES

The yellow circles indicate the cluster galaxies. These gravitationally bound galaxies vary in size from a thousandth of the mass of our Milky Way to up to 100 times more massive than the Milky Way. Some galaxies contain greater concentrations of mass than others, and thus have stronger gravitational effects, creating a stronger gravitational lens.



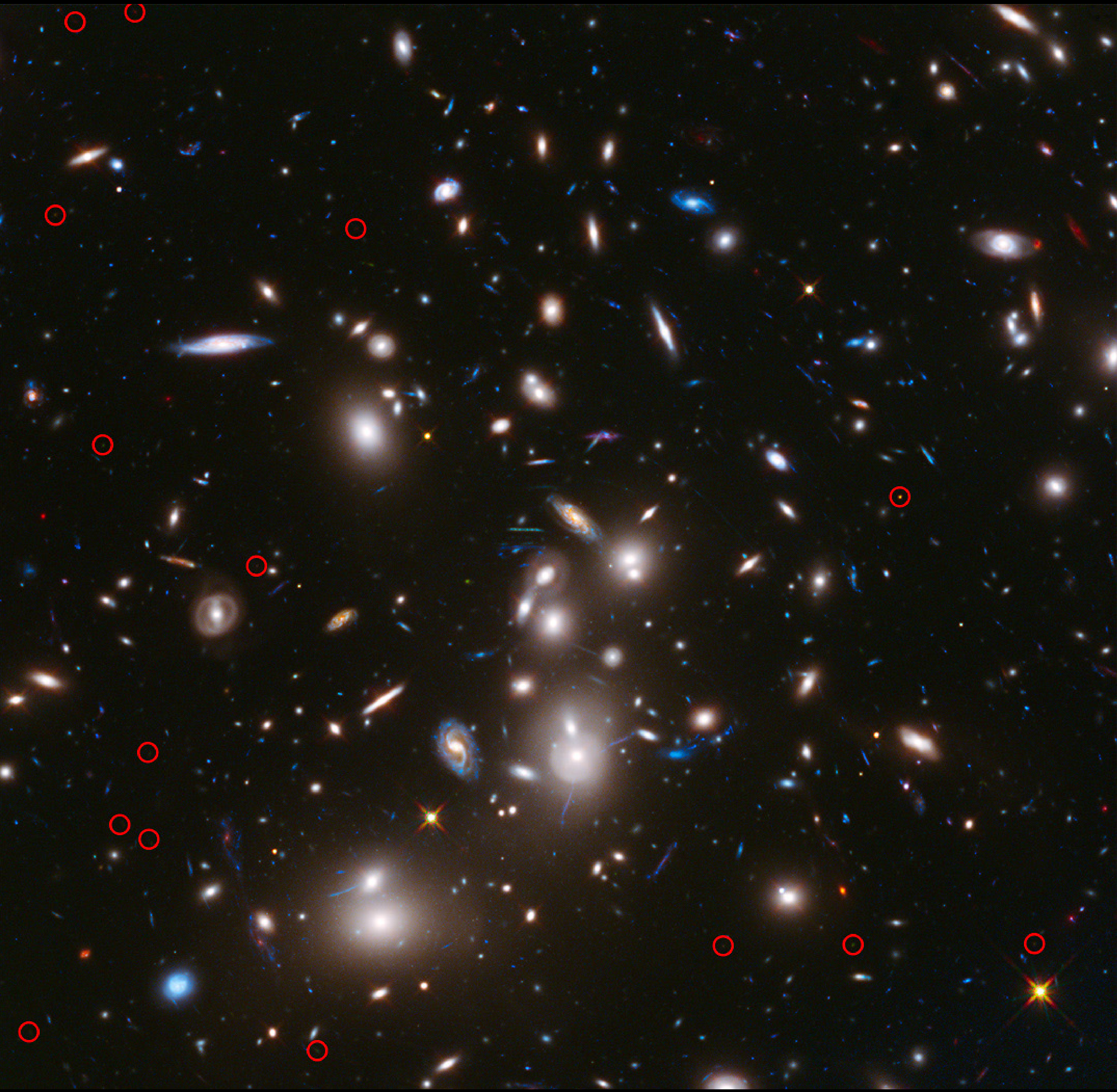
STRONGLY LENSED GALAXIES

These galaxies are seen through the cluster's gravitational lens. The light of these strongly lensed galaxies, circled in blue, shines through the cluster and is clearly distorted; many of these galaxies look like streaks and arcs. They're often concentrated along the same lines, and many of them have similar color schemes — blue with red patches.



WEAKLY LENSED GALAXIES

These magenta-circled objects are galaxies that are also behind the gravitational lens, but are not strongly distorted. Their light is still being magnified and brightened, but they fall in an area where the gravitational lens is relatively smooth. They are not as magnified as the strongly lensed galaxies.



Abell 2744 image credit: NASA, ESA, HFF Team, Jennifer Lotz (STScI), Matt Mountain (STScI), Anton Koekemoer (STScI)

DISTANT GALAXIES

The tiny red specks circled here are some of the farthest and faintest of the galaxies magnified by the gravitational lens. We see them as they appeared in the early universe – as far back as just millions of years after the Big Bang.

Hubble uses gravitational lensing to increase its own power, providing the deeper views into the universe.

NASA, James Leigh, and Origin Film

Hubble Science: Gravitational Lensing, Nature's Boost

Watch on YouTube: https://youtu.be/4e2plCS9Fn4?si=w4d2DAJm8AJRXhWU

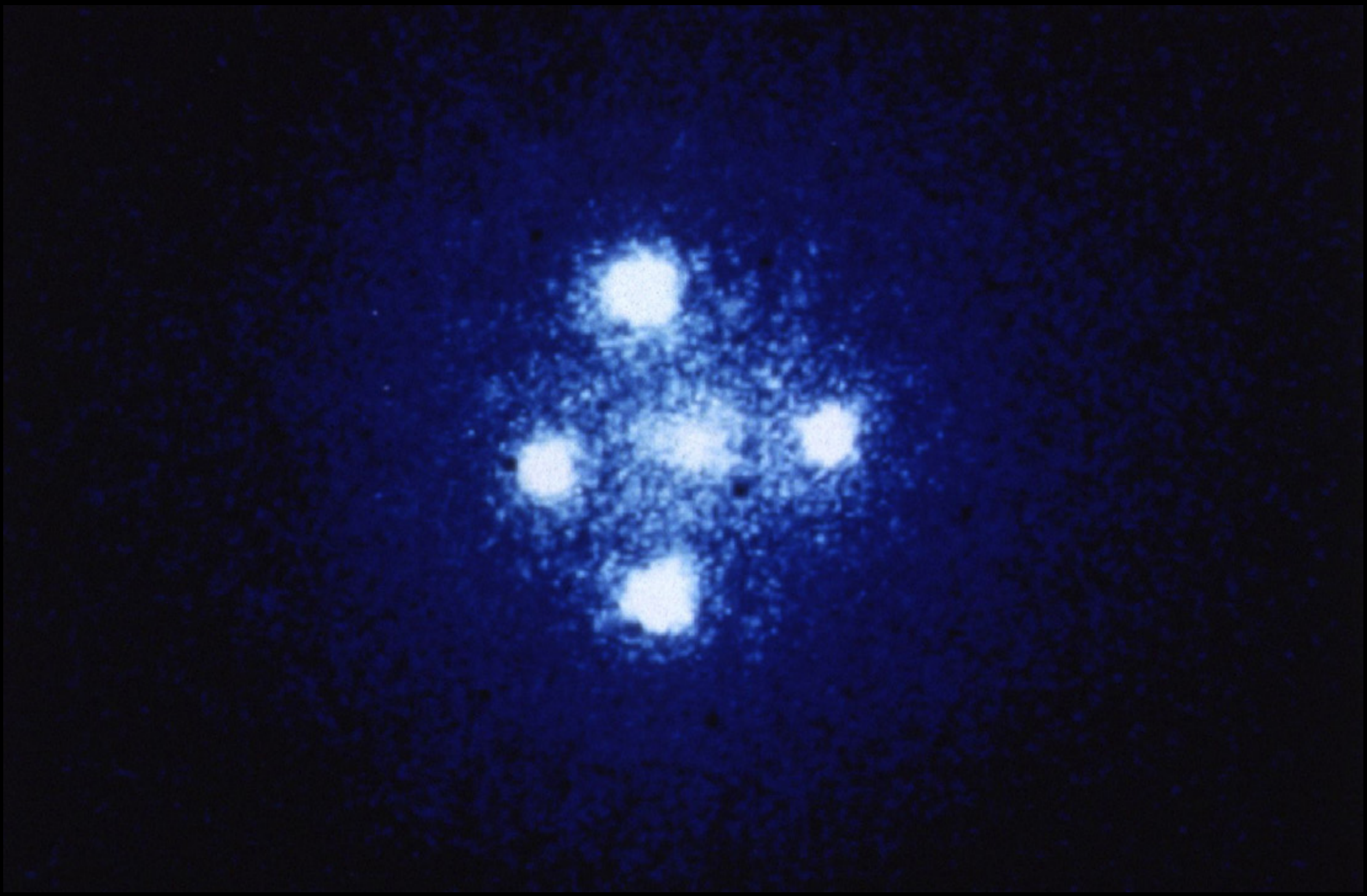
Chapter 1

History Repeats: Cosmic Objects Make Multiple Appearances

Several hundred galaxies are tied together by the gravity in galaxy cluster Abell 370. The arcs of blue light are distorted and magnified images of remote galaxies behind the cluster. Nearly a hundred distant galaxies have multiple images caused by the lensing effect.

NASA, ESA, and J. Lotz and the HFF Team (STScI)

Cosmic lenses are bumpy. The galaxies of a cluster, embedded in haloes of invisible dark matter, create lumps of mass. Light takes multiple paths around the galaxy cluster as it encounters these distortions in space-time. If you've ever seen multiple reflections of a candle in the bottom of a wineglass, you've seen this distorted lensing effect occur in everyday life. In fact, gravitational lensing is so similar to glass lensing that you could replicate the distortions of a gravitational lens by grinding a glass lens to the same proportions and bumps.

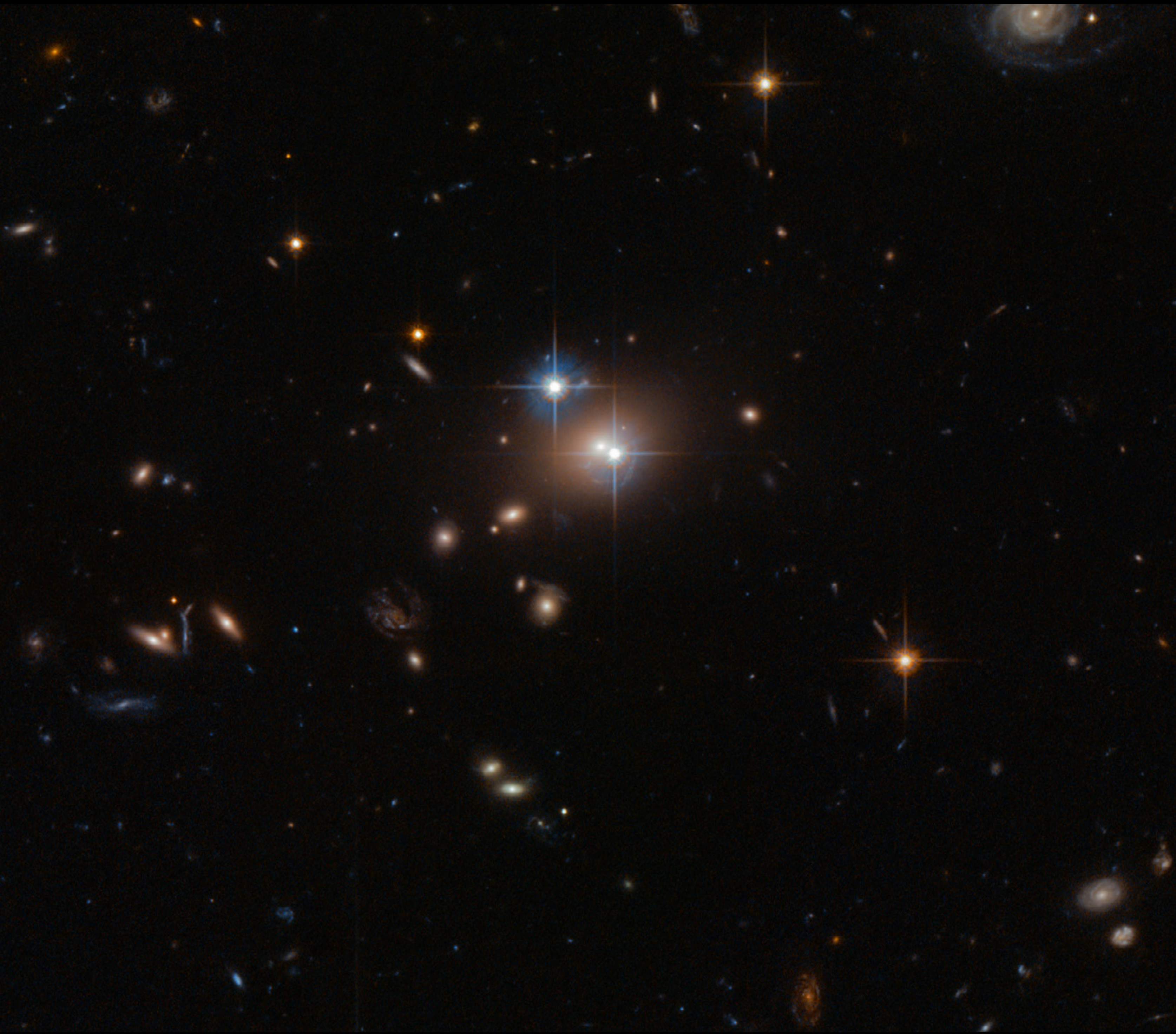


Hubble captured its first gravitationally lensed image in September 1990, shortly after launch. The photograph shows four images of a very distant quasar which has been multiple-imaged by lensing galaxy G2237 + 0305, in a configuration known as an Einstein Cross. The quasar is approximately 8 billion light-years away, while the galaxy (center object) is 400 million light-years away.

NASA, ESA, and STScI

The closer the light of more-distant galaxies passes to the lens, the stronger the deflection. If the light passes close enough to the lens, multiple images are likely to appear. The individual galaxies in the cluster also add small deflections, and occasionally help split the light into multiple paths.

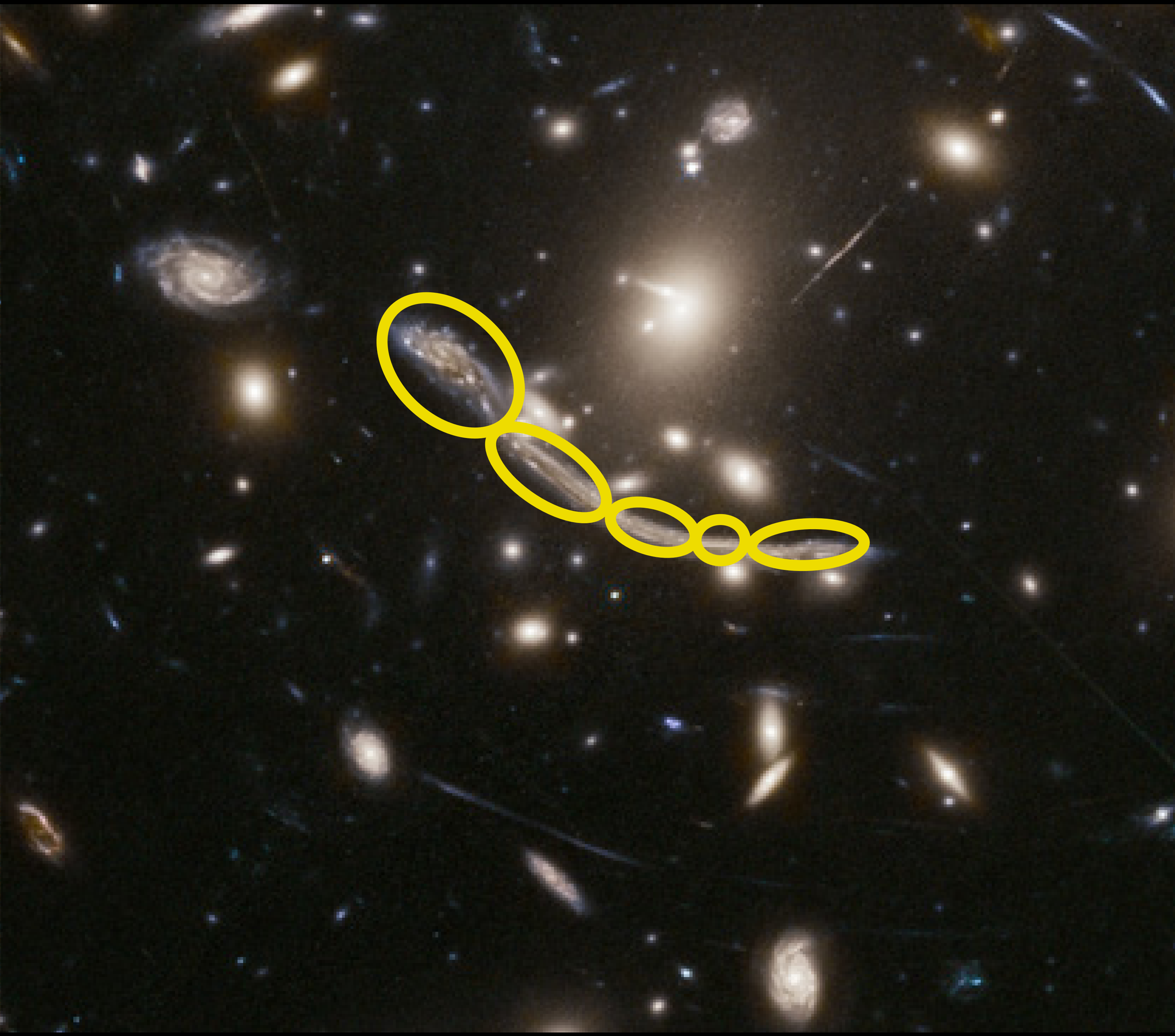
In 1937, Swiss-American astronomer Fritz Zwicky suggested that the bending and magnifying effect proposed by Einstein's theory of general relativity would let astronomers see lensed background galaxies behind galaxy clusters. One of the early displays of this type of galactic gravitational lensing, though unrealized at the time, was a long, odd arc in the galaxy cluster Abell 370 — first observed in 1973, and repeatedly dismissed as an imaging artifact. After being observed yet again in 1985 by the Canada-France-Hawaii telescope atop Hawaii's Mauna Kea volcano, astronomers began to theorize in earnest about what it might be.



The Twin Quasar appears as the two star-like objects with diffraction spikes (center image). Massive elliptical YGKOW G1, the first confirmed gravitational lens, exerts enough gravitational force alongside the other galaxies in its cluster to produce this double image of the background quasar.

ESA/Hubble and NASA

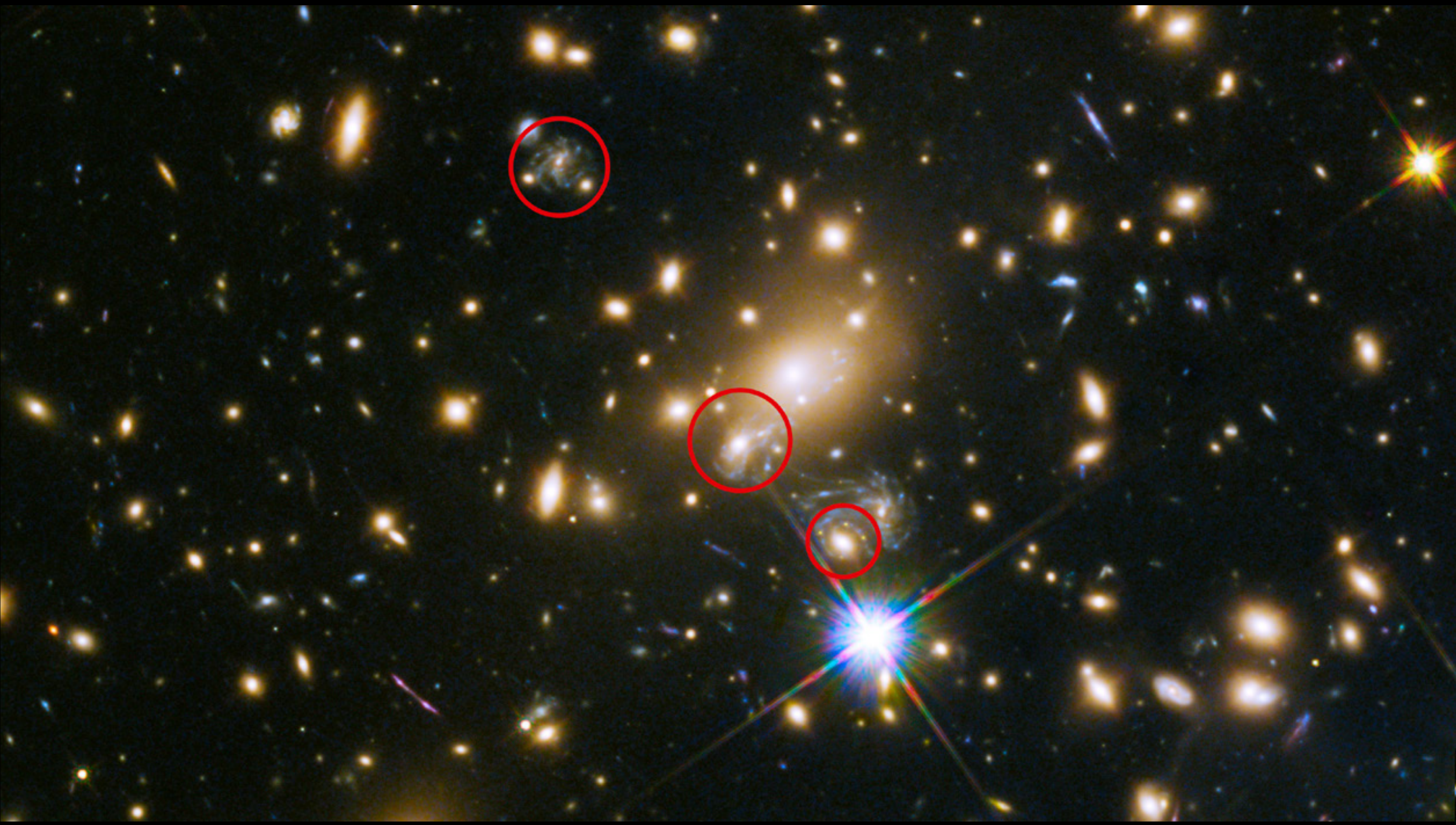
In 1979, astronomers had discovered the "Twin Quasar," QSO 0957+561, two identical objects that were found to be a single, gravitationally lensed center of a distant galaxy, but it wasn't until 1988 that they realized the distinctive curved line in Abell 370, nicknamed "The Dragon," was really the light of a single spiral galaxy repeated and stretched along a curve.



The Dragon is a series of repeated images of the same spiral galaxy. It was recorded in 1973, 1977, 1981, and 1985 before being identified as a lensed galaxy in 1988. The clearest image of the spiral is the "head" of the dragon.

NASA, ESA, and J. Lotz and the HFF Team (STScI)

Today, these multiple, repeated images of the same object are a well-known effect of gravitational lensing, and impart critical information about not only the cosmic background objects but the lensing galaxies themselves.



This image shows the appearances of supernova Refsdal in its host galaxy. The uppermost circle shows the host galaxy where the supernova could have been seen in 1998. The lowermost circle shows the galaxy that lensed the supernova four times — a discovery made in late 2014. The middle circle shows the host galaxy with the latest appearance of the reappearing supernova in 2015.

NASA, ESA, S. Rodney (John Hopkins University, USA) and the FrontierSN team; T. Treu (University of California Los Angeles, USA), P. Kelly (University of California Berkeley, USA) and the GLASS team; J. Lotz (STScI) and the Frontier Fields team; M. Postman (STScI) and the CLASH team; and Z. Levay (STScI)

Seeing Quadruple

In November 2014, scientists spotted four separate images of an exploding star, or supernova, around a galaxy within a cluster of galaxies called MACS J1149.5+2223. A massive galaxy within the cluster had warped and magnified the light from a much more distant supernova, forcing it into separate paths through the cluster and creating a configuration called an Einstein Cross, while the supernova's host galaxy appeared in at least three distinct images. (Calculations also indicated that the supernova had appeared once before in 1998 — an event not observed by any telescope.) The data provided a rare opportunity to determine where the next gravitationally lensed image of the supernova would appear as its light traveled yet another, longer path through the cluster.

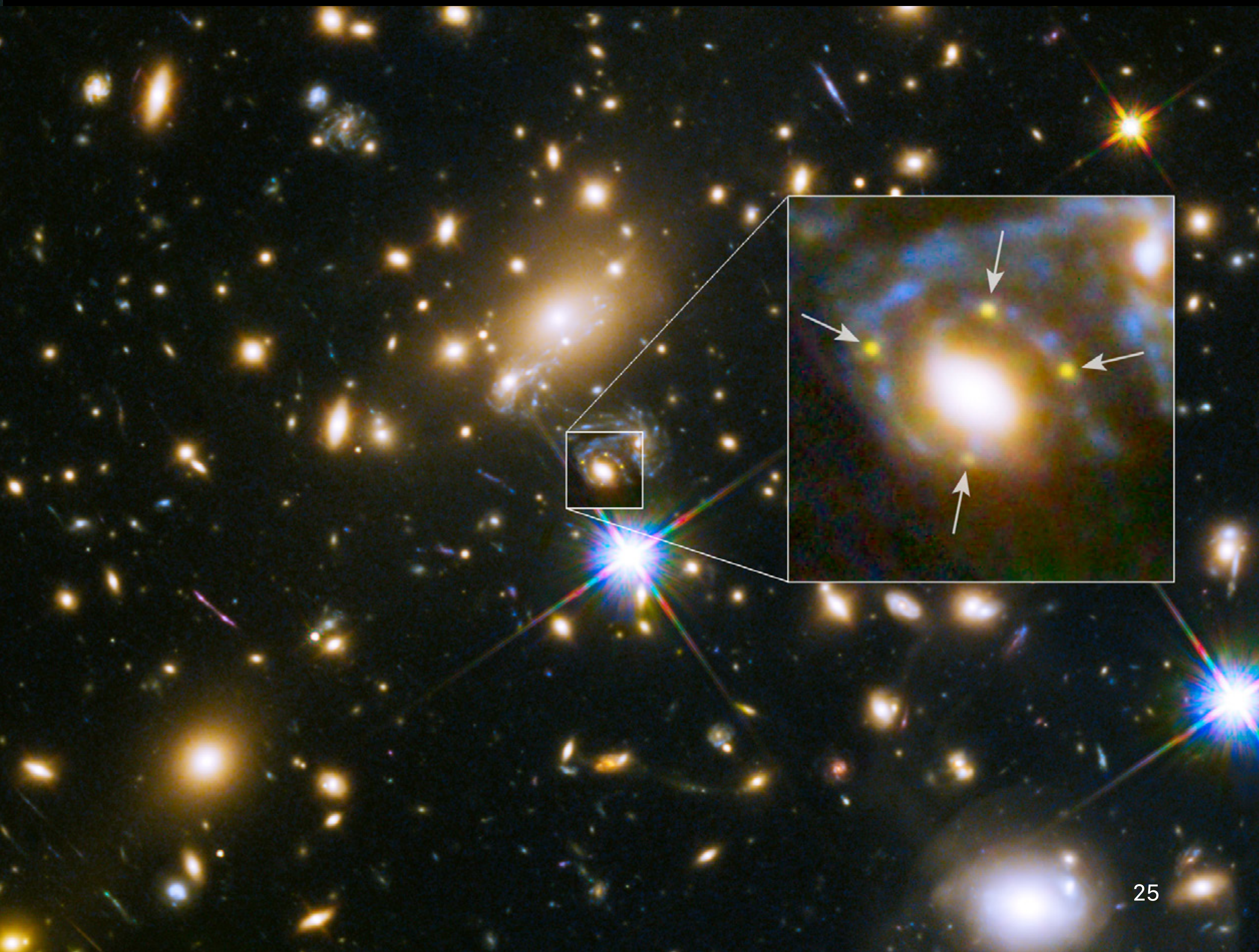
Using other lensed galaxies within the cluster and combining them with the discovery of the Einstein Cross event in 2014, astronomers applied sophisticated modeling techniques to precisely predict the reappearance of the supernova, nicknamed Refsdal.

Hubble started looking for the supernova to reappear in October 2015. On December 11, 2015, it flared into life in the cluster, not only when but where astronomers had predicted it would be. This was the first predicted observation of a supernova.

Refsdal's reappearance was more than a fascinating experiment. It helped astronomers determine the location of mass in the galaxy cluster, providing the opportunity to learn how matter — including invisible dark matter — was distributed throughout.

"We used seven different models of the cluster to calculate when and where the supernova was going to appear in the future … And remarkably all seven models predicted approximately the same time frame for when the new image of the exploding star would appear."

Tommaso Treu, University of California at Los Angeles



Four appearances of supernova Refsdal can be seen in this image of a spiral galaxy within galaxy cluster MACS J1149.6+2223, a configuration called an Einstein Cross.

NASA, ESA, Steve A. Rodney (JHU), Tommaso Treu (UCLA), Patrick Kelly (UC Berkeley), Jennifer Lotz (STScI), Marc Postman (STScI), Zolt G. Levay (STScI), FrontierSN Team, GLASS Team, HFF Team (STScI), CLASH Team

An astronomer explains the scientific significance of the images of reappearing, gravitationally lensed supernova Refsdal.

NASA, James Leigh, and Origin Films

Hubble's Inside the Image: Lensed Supernova Refsdal

Watch on YouTube: https://youtu.be/eae1xORzV30?si=UVGEraJ3LYw5t3JF

Learn more: https://science.nasa.gov/missions/hubble/hubble-captures-first-ever-predicted-exploding-star/

A Supernova Through Time

It's rare to glimpse a supernova in its short early stage, which can last anywhere from a few hours to a few days. But thanks to gravitational lensing, astronomers were able to see the first few days of a star that exploded more than 11 billion years ago, when the universe was less than a fifth of its current age.

In this case, the immense gravity of the galaxy cluster Abell 370 acted as a cosmic lens, bending and magnifying the light from the more distant supernova located behind the cluster. The magnified images took different routes through the cluster, resulting in differences in the length of the pathways the supernova light followed as it experienced the slowing of time and curvature of space due to gravity. Consequently, the warping produced three images of the same explosion at different times. All arrived at Earth simultaneously and were caught in one Hubble image, like a time-lapse photo spread.

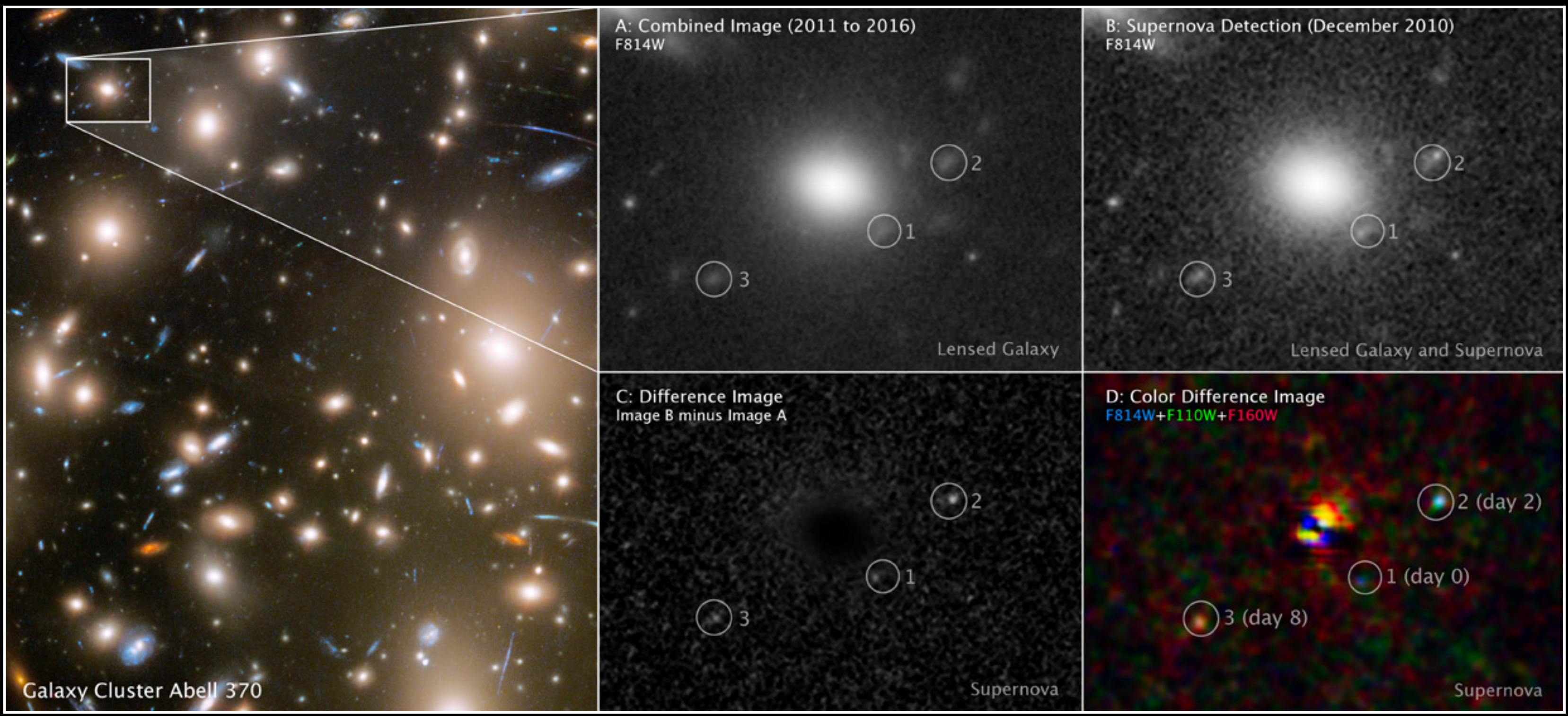
The Hubble image captured the fading supernova's rapid change of color, which indicates temperature change. The earliest phase captured is an intensely hot blue. As the supernova cooled, its light turned redder.

Based on the supernova's brightness and rate of cooling, both of which depend on the size of the progenitor star, astronomers were for the first time able to determine the size of a dying star in the early universe — about 500 times larger than our Sun.

> "You've got the massive star, the core collapses, it produces a shock, it heats up, and then you're seeing it cool over a week. I think that's probably one of the most amazing things I've ever seen."
>
> Patrick Kelly, University of Minnesota

Through gravitational lensing, three different moments in a far-off supernova explosion were captured in a single snapshot. The left panel shows the portion of Abell 370 where the multiple images of the supernova appeared. Panel A, a composite of Hubble observations from 2011 to 2016, shows the locations of the multiply imaged host galaxy after the supernova faded. Panel B, a Hubble picture from December 2010, shows the three images of the host galaxy and the supernova at different phases in its evolution. Panel C, which subtracts the image in Panel B from that in Panel A, shows three different faces of the evolving supernova. Using a similar image subtraction process for multiple filters of data, Panel D shows the different colors of the cooling supernova at three different stages in its evolution.

NASA, ESA, STScI, Hubble Frontier Fields, Wenlei Chen (UMN), Patrick Kelly (UMN)



The Hubble Space Telescope captured three different moments in the explosion of a very far-off supernova—all in one snapshot. They show the unfolding supernova over the course of a week.

NASA's Goddard Space Flight Center; Lead Producer: Paul Morris

Hubble Captures Three Faces of Evolving Supernova

Watch on YouTube: https://youtu.be/LUIl8bf9jgw?si=Sbhm3XP7d3PM6_uu

Learn more: https://science.nasa.gov/missions/hubble/hubble-captures-3-faces-of-evolving-supernova-in-early-universe/

Coming Soon: A Stellar Explosion

At some point near the year 2037, a telescope will turn its gaze onto a distant galaxy to witness an exploding star. The supernova's arrival will be something akin to a visit from an old friend — this will be the fourth known appearance of this particular explosion.

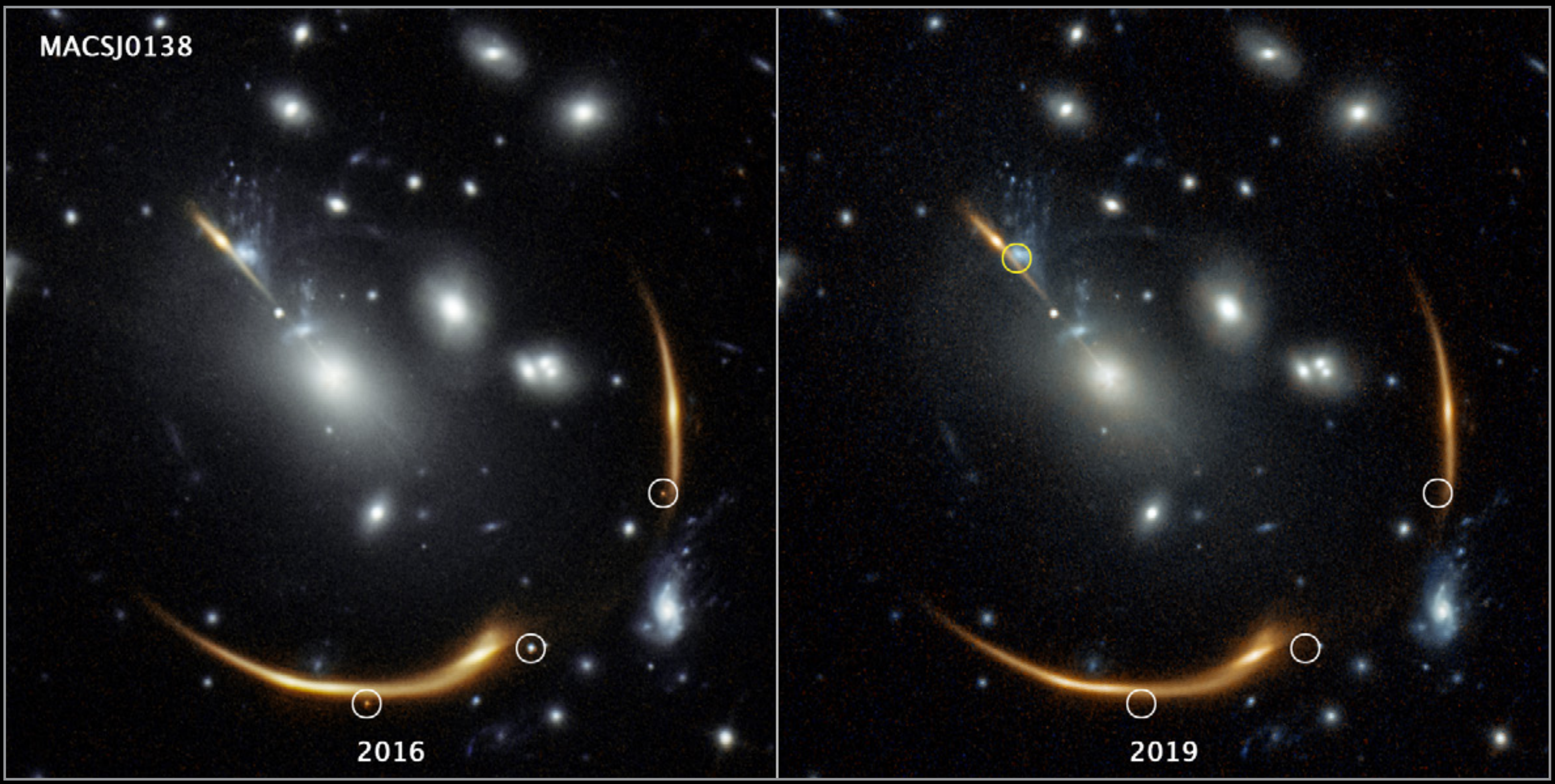
Supernova Requiem, as it's called, has been magnified, brightened, and split into separate images by the gravity of a massive foreground cluster of galaxies. Each image takes a different route through the galaxy cluster and arrives at Earth at a different time. Three images of the supernova were found in Hubble archival data taken in 2016. The fourth is still on the way, its light traveling directly through the middle of the cluster, where the densest amount of dark matter resides. The immense mass of the cluster bends the light, producing a longer time delay.

The light that Hubble captured from the galaxy cluster, MACS J0138.0-2155, took about 4 billion years to reach Earth. The light from Supernova Requiem needed an estimated 10 billion years for its journey, based on the distance of its host galaxy.

The supernova's return appearance is based on computer models of the cluster, which describe the various paths the supernova light is taking through the maze of clumpy dark matter in the galactic grouping. The supernova is predicted to appear a fifth time in 2042, but it will be so faint then that it's not likely to be visible.

Catching the rerun of the explosive event around 2037 will help astronomers measure the time delays between all four supernova images, which will offer clues to the type of warped-space terrain the exploded star's light had to cover. Armed with those measurements, researchers can fine-tune the models that map out the cluster's mass, including its invisible dark matter.

> "This is the last one to arrive because it's like the train that has to go deep down into a valley and climb back out again. That's the slowest kind of trip for light."
>
> Steve Rodney, University of South Carolina



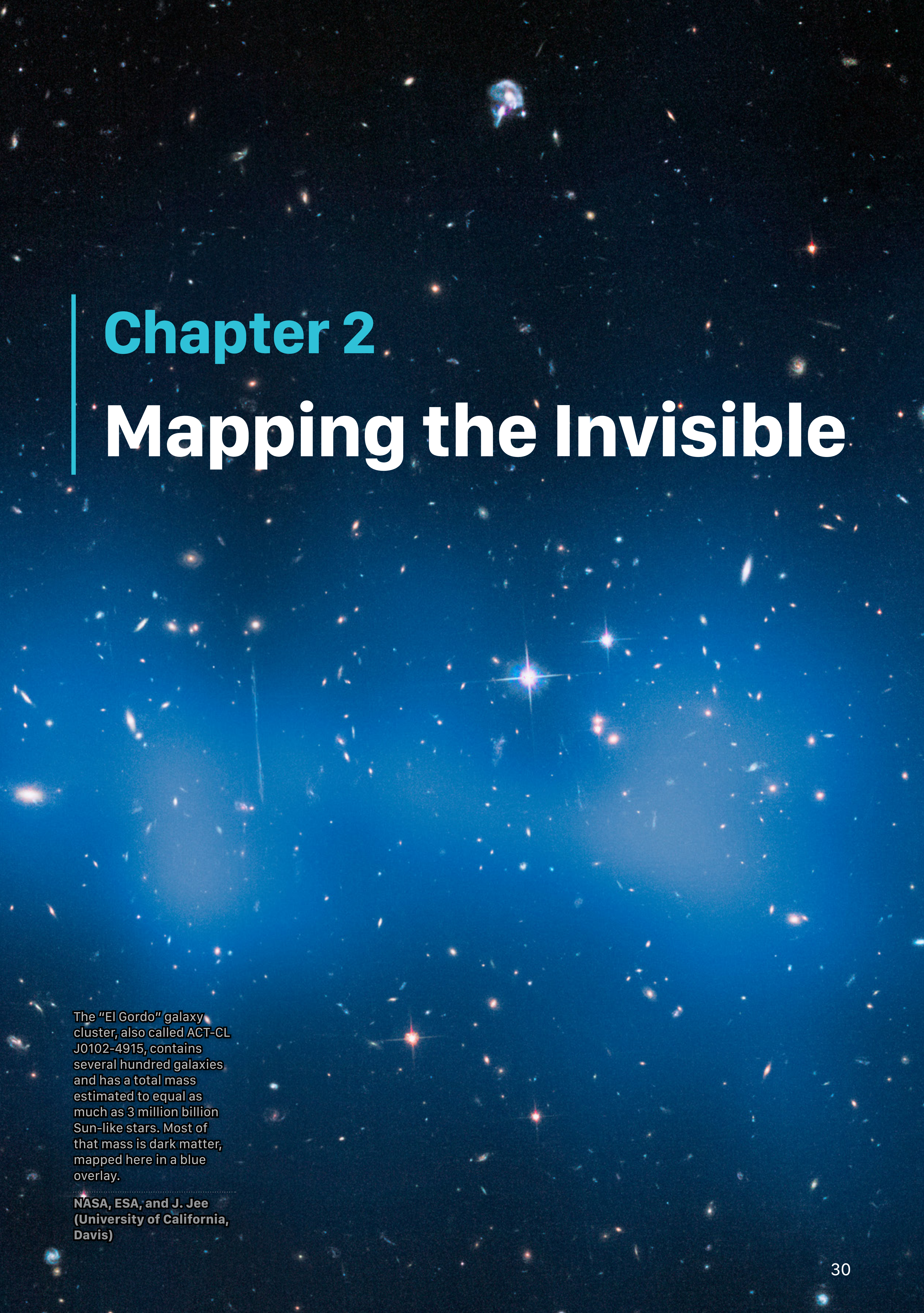
Three bright dots (circled) appear in the 2016 image on the left. By 2019 they're gone, having faded away over time. Researchers studying these images realized that they were seeing multiple images of a distant supernova, gravitationally lensed by the giant galaxy cluster MACS J0138. The yellow circle in the 2019 image indicates the predicted location of the supernova's reappearance in 2037. The bright supernova dots are surrounded by bright smears that are likely the supernova's host galaxy.

Steven Rodney (University of South Carolina), Gabriel Brammer (Cosmic Dawn Center/ Niels Bohr Institute/University of Copenhagen); Image Processing: Joseph DePasquale (STScI)

Learn more: https://science.nasa.gov/missions/hubble/rerun-of-supernova-blast-expected-to-appear-in-2037/

Chapter 2

Mapping the Invisible



The "El Gordo" galaxy cluster, also called ACT-CL J0102-4915, contains several hundred galaxies and has a total mass estimated to equal as much as 3 million billion Sun-like stars. Most of that mass is dark matter, mapped here in a blue overlay.

NASA, ESA, and J. Jee (University of California, Davis)

A dark matter ring, likely caused by the collision of two galaxy clusters, is evident in this Hubble map of the galaxy cluster CL0024+17. Astronomers map the distorted light of the gravitationally lensed galaxies to find the dark matter distribution. Dark matter here is represented in light blue.

NASA, ESA, M.J. Jee and H. Ford (Johns Hopkins University)

In the 1930s, astronomers began to realize that they had a significant problem with galaxies. Namely, galaxies just didn't have enough mass to produce the gravity needed to stick together. They should have been flying apart under the speed of their own motion.

In 1933, astronomer Fritz Zwicky found that galaxies in the Coma cluster were moving so quickly that gravity from visible matter should not be enough to keep them in a group. In the 1970s, American astronomers Vera Rubin and Kent Ford discovered a similar problem applied within individual spiral galaxies like Andromeda (M31). The stars toward the edge of the galaxy were moving too fast for the galaxy's visible matter to hold them in place.

The “El Gordo” galaxy cluster, also called ACT-CL J0102-4915, contains several hundred galaxies and has a total mass estimated to equal as much as 3 million billion Sun-like stars. Most of that mass is dark matter, mapped here in a blue overlay. Because dark matter doesn’t emit any radiation, researchers precisely measure how its gravity warps the images of background galaxies to determine its mass and location.

NASA, ESA, and J. Jee (University of California, Davis)

But clearly, galaxies and galaxy clusters weren’t flinging their contents into the cosmos like out-of-control carousels. Some other form of matter must exist to cement these galaxies and clusters together. We call this unseen substance dark matter, and today researchers are still trying to understand it — though it’s theorized to make up 85 percent of the universe’s total mass, or almost 30 percent of the universe’s combined mass-energy.

Dark matter doesn’t emit, absorb, or reflect light. Theories state that it consists of currently unknown particles that rarely interact with normal matter. To figure out what it is, we need to study it — and one of our best methods is through gravitational lensing, which allows researchers to map out the presence of dark matter in galaxies.

We can’t see dark matter, but thanks to gravitational lensing in galaxy clusters, we can tell where it is. As light from background galaxies travels through massive galaxy clusters, it follows the curving of space like a golf ball rolling along a putting green. Researchers analyze the way the light bends to pinpoint where the mass is in the cluster, using models to produce maps of the presence of unseen dark matter.

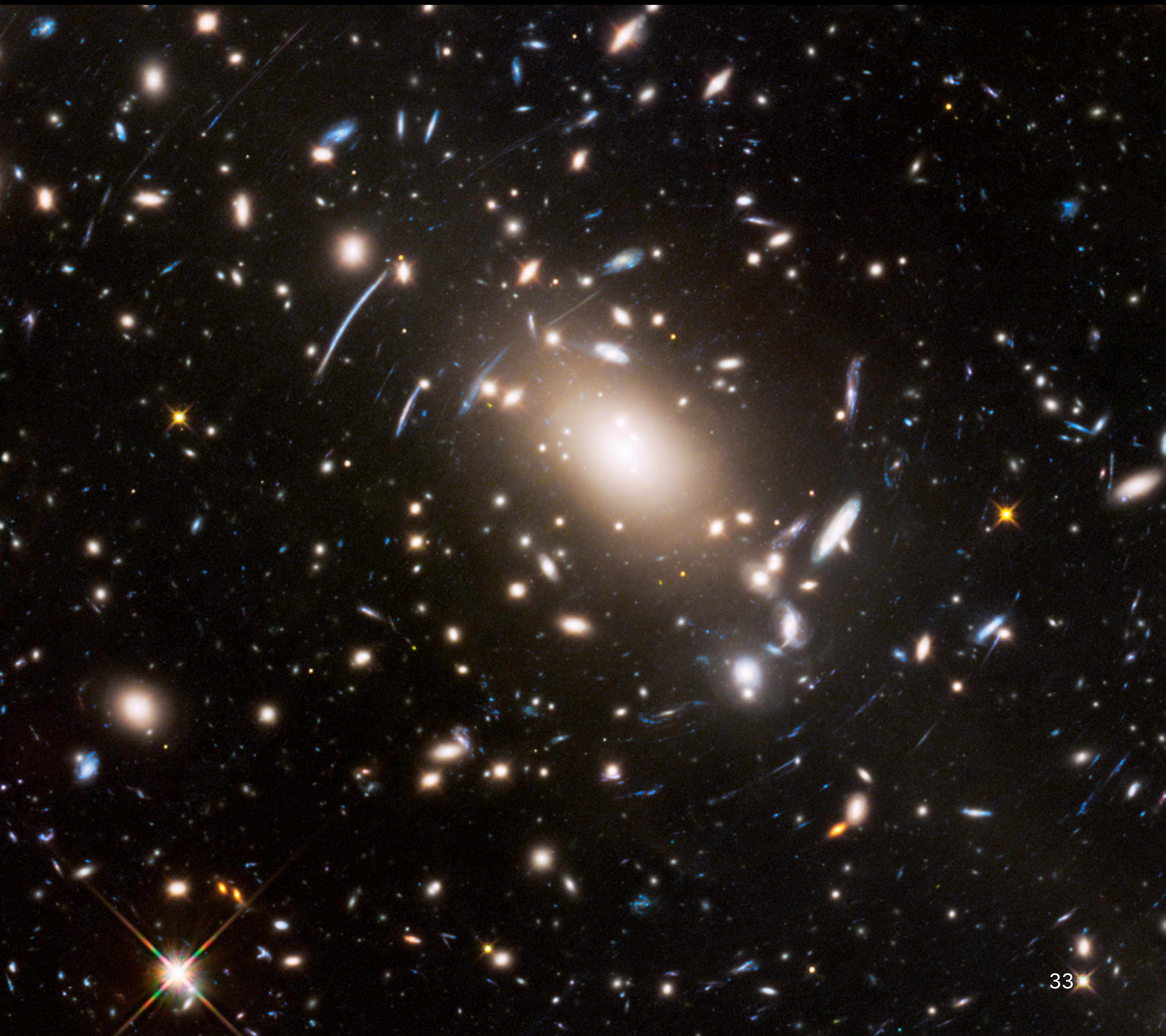
A Missing Ingredient in the Dark Matter Recipe?

Galaxy cluster Abell S1063, located 4 billion light-years away, is surrounded by bluish streaks that are magnified images of galaxies much farther away. The tremendous mass of the cluster — about 100 trillion solar masses, containing 51 confirmed galaxies and perhaps over 400 more — distorts and magnifies the light from galaxies that lie far behind the cluster.

NASA, ESA, and J. Lotz (STScI)

A little dark matter may go a long way. Observations of several massive galaxy clusters from the Hubble Space Telescope and the European Southern Observatory's Very Large Telescope (VLT) in Chile found that small-scale concentrations of dark matter in the clusters produce gravitational lensing effects 10 times stronger than expected.

Galaxy clusters, as the most massive structures in the universe, are the largest repositories of dark matter. The individual galaxies are full of dark matter, and the clusters themselves are held together by dark matter's gravity.



The distribution of dark matter in clusters is mapped by observing its gravitational lensing effect, or how light bends as it passes through the cluster. The higher the concentration of dark matter in a cluster, the more dramatic its light-bending effects.

Hubble's crisp images of three key galaxy clusters, MACS J1206.2-0847, MACS J0416.1-2403, and Abell S1063, coupled with spectra from the VLT, helped produce an accurate, high-fidelity dark-matter map with dozens of multiply imaged, lensed, background galaxies. The spectroscopic observations measured the velocity of the stars orbiting inside several of the cluster galaxies, which gave an estimate of each individual galaxy's mass, including dark matter.

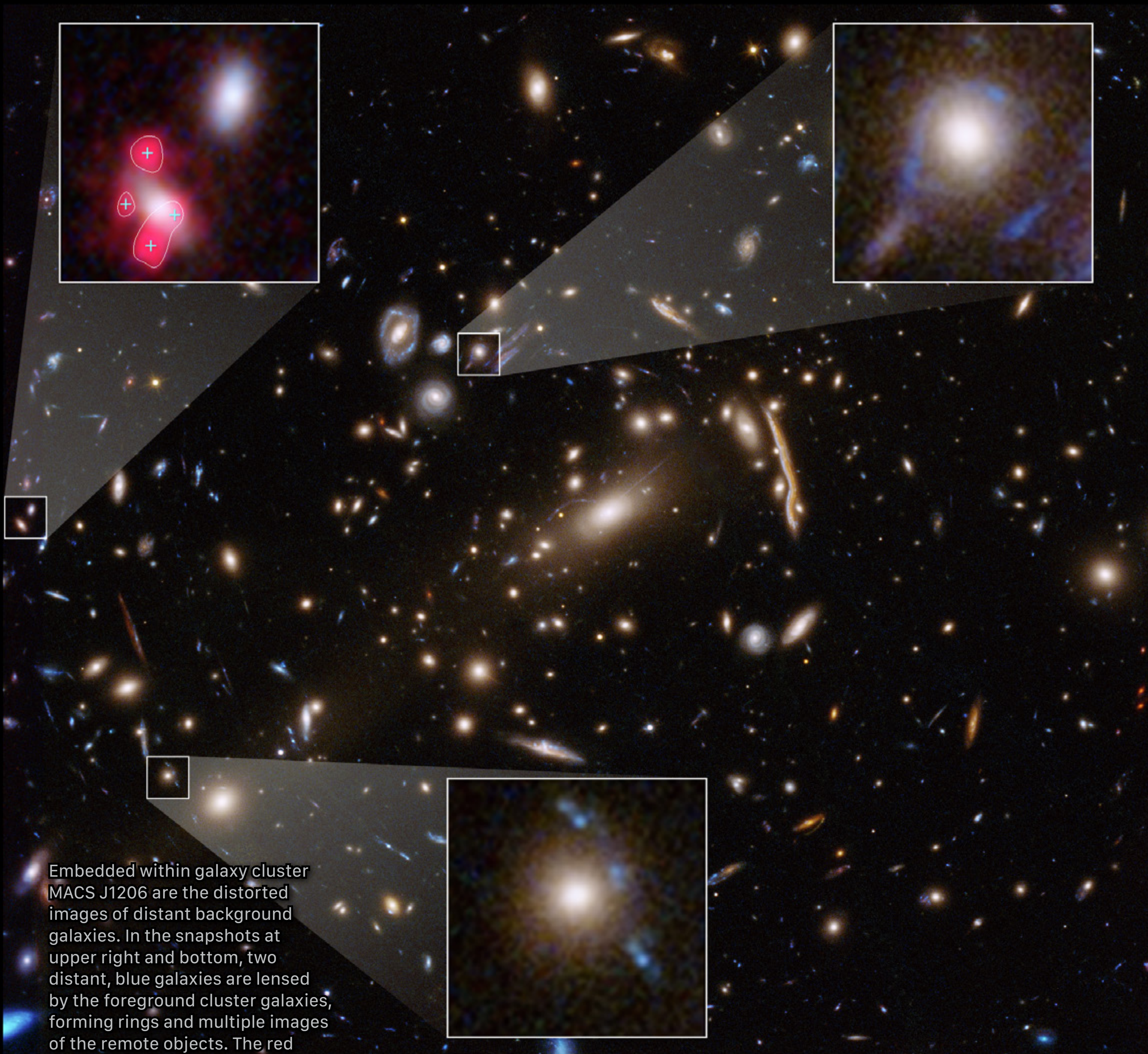
Surprisingly, the Hubble images also revealed smaller-scale arcs and distorted images nested within the larger-scale lens distortions in each cluster's core, where the most massive galaxies reside. The embedded lenses are likely produced by the gravity of dense concentrations of dark matter associated with individual cluster galaxies.

The team compared the dark-matter maps with samples of simulated galaxy clusters with similar masses, located at roughly the same distances as the observed clusters. The clusters in the computer simulations did not show the same level of dark-matter concentration on the smallest scales.

"Galaxy clusters are ideal laboratories to understand if computer simulations of the universe reliably reproduce what we can infer about dark matter and its interplay with luminous matter."

Massimo Meneghetti, National Institute for Astrophysics-Observatory of Astrophysics and Space Science of Bologna

This implies that the current theoretical models of the universe may be missing a key element. More research will need to be done to identify this potential gap in our understanding of dark matter and its properties.



Embedded within galaxy cluster MACS J1206 are the distorted images of distant background galaxies. In the snapshots at upper right and bottom, two distant, blue galaxies are lensed by the foreground cluster galaxies, forming rings and multiple images of the remote objects. The red blobs around the galaxy at upper left indicate emission from clouds of hydrogen in a single distant source, possibly a faint galaxy. The source is split into four images by gravitational lensing. These red blobs were detected by the Multi-Unit Spectroscopic Explorer (MUSE) at the European Southern Observatory's Very Large Telescope (VLT) in Chile and do not appear in the Hubble images.

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 Acknowledgment: NASA, ESA, M. Postman (STScI), and the CLASH team

"Galaxy clusters are ideal laboratories to understand if computer simulations of the universe reliably reproduce what we can infer about dark matter and its interplay with luminous matter."

Massimo Meneghetti, National Institute for Astrophysics-Observatory of Astrophysics and Space Science of Bologna

Learn more: https://science.nasa.gov/missions/hubble/hubble-observations-suggest-a-missing-ingredient-in-dark-matter-theories/

Tracing Light Through a Maze of Dark Matter

Knowing how fast the universe expands is the key to a host of other critical questions: How old is the universe? How big is it? What is its fate?

Astronomer Edwin Hubble, for whom the Hubble Space Telescope is named, discovered cosmic expansion in 1929, observing that the farther away a galaxy is from Earth, the faster it appears to be receding from us. The specific relationship between how far away an object is and how fast it recedes from us is called the Hubble Constant. Gravitational lensing has provided a new and precise method for determining that expansion rate by revealing the distance to galaxies.

The Hubble telescope viewed the light from six faraway quasars, brilliant objects whose brightness is generated by material orbiting around supermassive black holes at centers of galaxies. Light from each quasar was multiplied into four images by the gravity of a massive foreground galaxy. The galaxies studied are 3 billion to 6.5 billion light-years away. The quasars' average distance is 5.5 billion light-years from Earth.

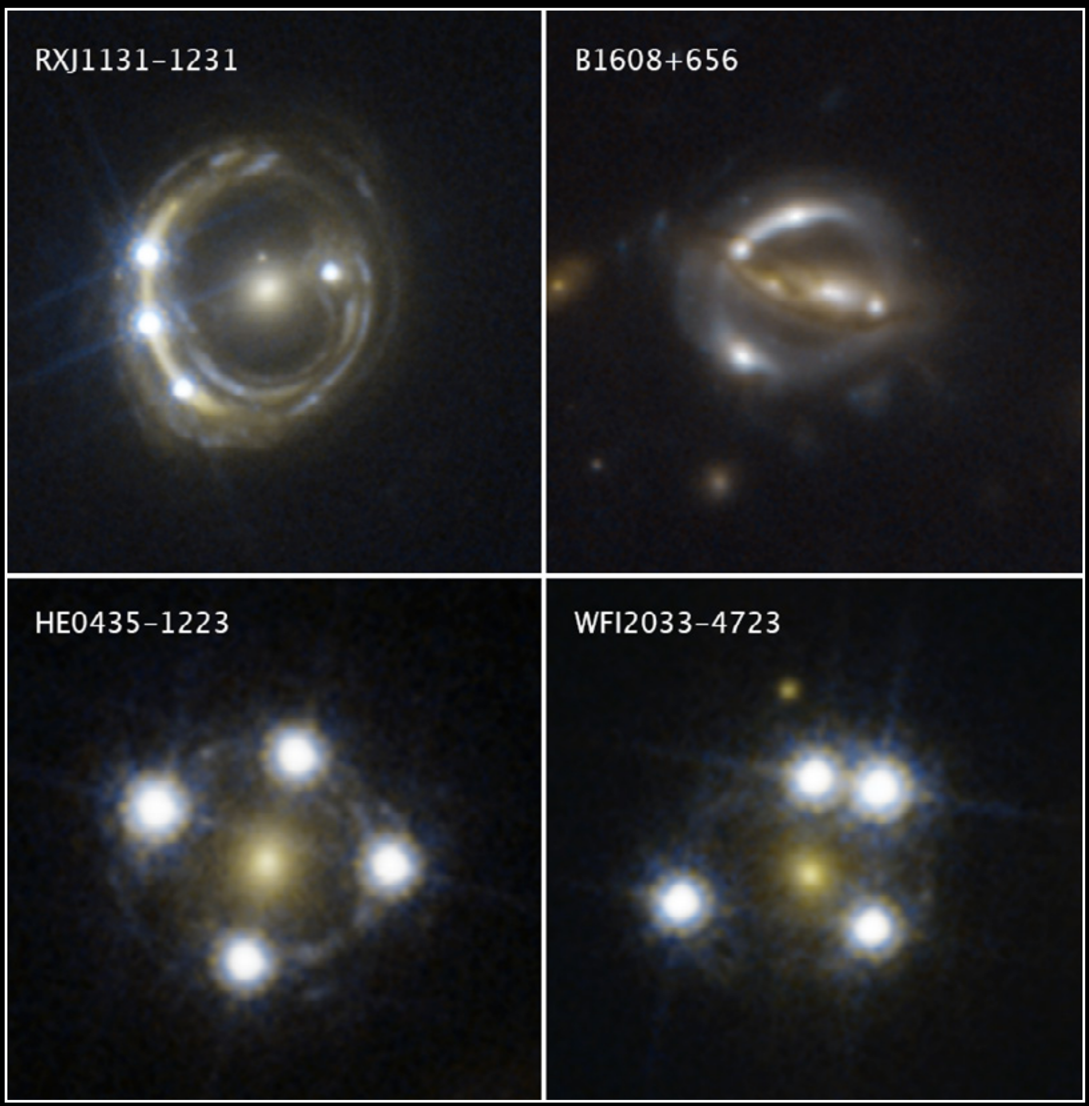
The light rays from each lensed quasar image take a slightly different path through space to reach Earth, due to the amount of matter — especially dark matter — that is distorting space along the line of sight to the quasar. To trace each pathway, the astronomers monitored the flickering of the quasar's light as its black hole devours material. When the light flickers, each lensed image brightens at a different time.

This flickering sequence allowed researchers to measure the time delays between each image as the lensed light travels along its path to Earth. To fully understand these delays, the team used Hubble to make accurate maps of the distribution of matter in each lensing galaxy. Astronomers could then deduce the distances from the galaxy to the quasar, and from Earth to the galaxy and to the background quasar. The researchers compared these distances to measure the universe's expansion rate.

The researchers calculated a Hubble constant of 73 kilometers per second per megaparsec (with 2.4 percent uncertainty). This means that for every additional 3.3 million light-years away a galaxy is from Earth, it appears to be moving 73 kilometers per second faster, because of the universe's expansion.

The result strengthens a mystifying discrepancy between the expansion rate calculated from measurements of the local universe and the rate as predicted by entirely separate measurements of the first radiation to travel through space. This radiation was released shortly after the Big Bang 13.8 billion years ago and is still detectable as a faint microwave radiation glow that fills the universe, and its measurement predicts an expansion rate of about 67-68 kilometers per second per megaparsec. It remains a mystery why these two measurements don't match up. This difference, called the Hubble Tension, is a major astronomical question that researchers continue to investigate.

> "It may be a hint that we do not yet fully understand how matter and energy evolved over time, particularly at early times."
>
> Sherry Suyu, Max Planck Institute for Astrophysics, the Technical University of Munich, and the Academia Sinica Institute of Astronomy and Astrophysics



Each of these Hubble images reveals four distorted images of a background quasar surrounding the central core of a foreground massive galaxy. The multiple quasar images were gravitationally lensed by the gravity of the foreground galaxy. The light rays from each lensed quasar image take a slightly different path through space to reach Earth, depending on how much matter is distorting space along the line of sight to the quasar. These time-delay measurements helped astronomers calculate how fast the universe is growing, a value called the Hubble constant.

NASA, ESA, S.H. Suyu (Max Planck Institute for Astrophysics, Technical University of Munich, and Academia Sinica Institute of Astronomy and Astrophysics), and K.C. Wong (University of Tokyo's Kavli Institute for the Physics and Mathematics of the Universe

Learn more: https://science.nasa.gov/missions/hubble/cosmic-magnifying-glasses-yield-independent-measure-of-universes-expansion/

Uncovering Some of the Smallest Clumps of Dark Matter

Astronomers using Hubble have found that dark matter forms much smaller clumps than previously known, confirming one of the fundamental predictions of the widely accepted "cold dark matter" theory.

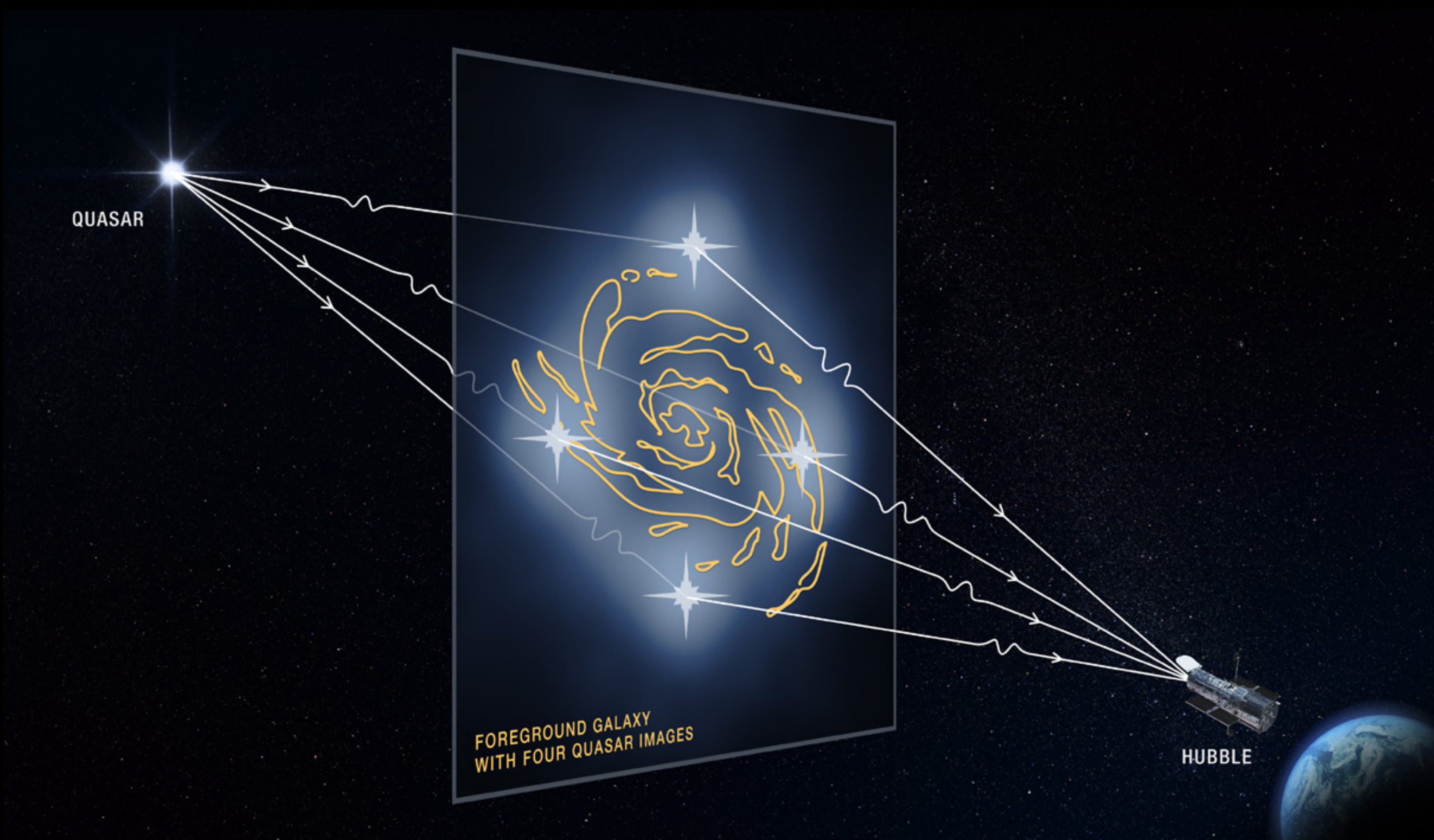
All galaxies, according to this theory, form and are embedded within clouds of dark matter. Dark matter itself consists of slow-moving (nicknamed "cold") particles that come together to form structures ranging from hundreds of thousands of times the mass of our Milky Way galaxy to clumps no more massive than a commercial airplane.

Although astronomers cannot see dark matter, they can detect its presence indirectly by measuring how its gravity affects stars and galaxies. But detecting the smallest dark matter formations by looking for embedded stars can be difficult or impossible, because they contain very few stars.

The Hubble research team targeted eight powerful and distant quasars, regions around active black holes that emit enormous amounts of light. The astronomers measured how the light emitted by oxygen and neon gas orbiting each of the quasars' black holes is warped by the gravity of a massive foreground galaxy.

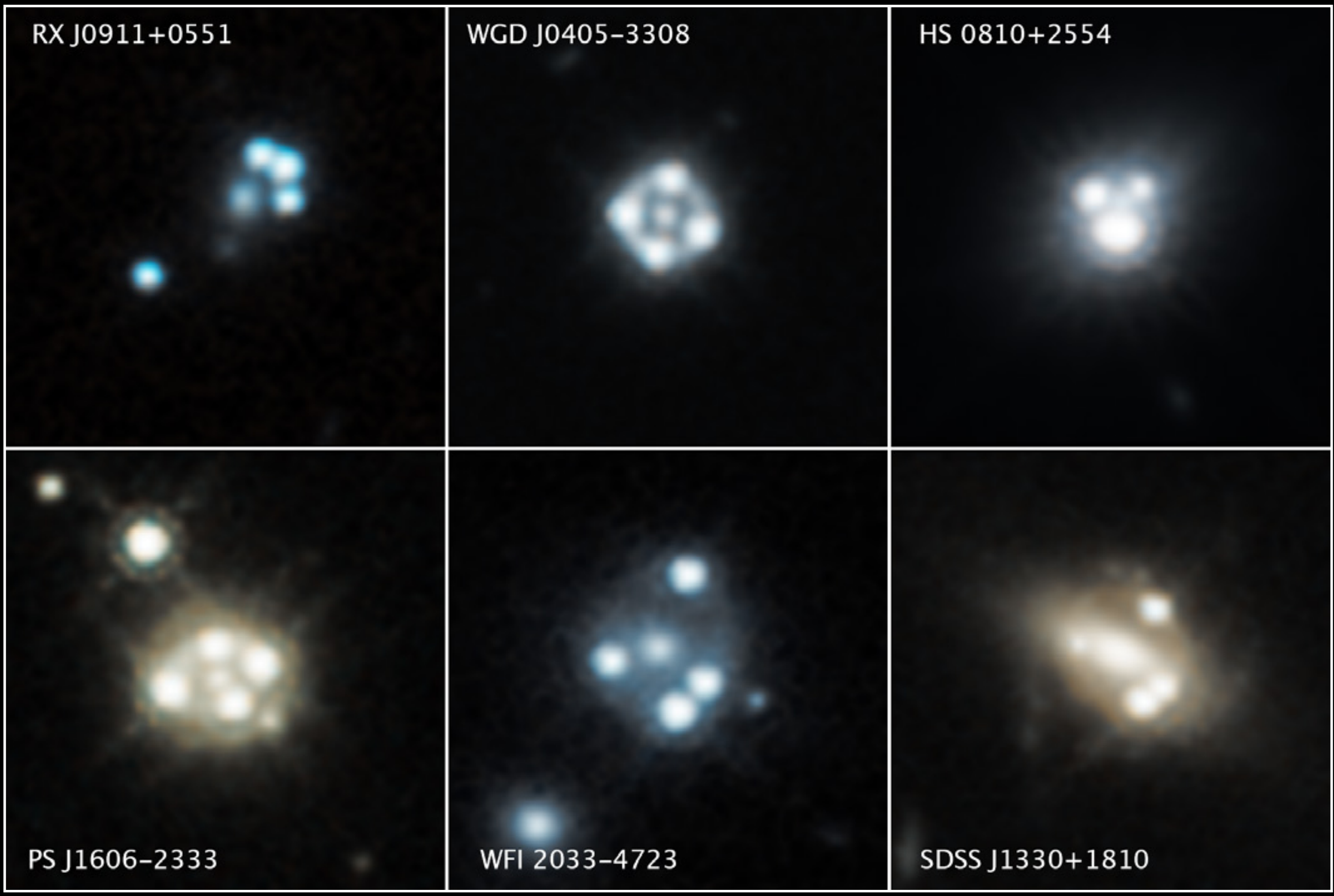
The presence of the dark matter clumps in and around the foreground galaxy alters the apparent brightness and position of each distorted quasar image by warping and slightly bending the light as it travels from the distant quasar to Earth (represented by the wiggly lines in the graphic). Astronomers compared these measurements with predictions of how the quasar images would look without the influence of the dark matter clumps. The researchers used these measurements to calculate the masses of the tiny dark matter concentrations.

NASA, ESA and D. Player (STScI)



Using this method, the team uncovered dark matter clumps along the telescope's line of sight to the quasars, as well as in and around the intervening lensing galaxies. The dark matter concentrations detected by Hubble are 1/10,000th to 1/100,000th times the mass of the Milky Way's dark matter halo. Many of these tiny groupings most likely do not contain even small galaxies, and would have been impossible to detect by looking for embedded stars.

> "Astronomers have carried out other observational tests of dark matter theories before, but ours provides the strongest evidence yet for the presence of small clumps of cold dark matter."
>
> Anna Nierenberg, Jet Propulsion Laboratory



Four gravitationally lensed images of a background quasar and its host galaxy surround the central core of a massive foreground galaxy in each of these Hubble images. Quasars are distant, extremely bright objects produced by active black holes. Such quadruple images of quasars are rare because of the nearly exact alignment needed between the foreground galaxy and background quasar.

NASA, ESA, A. Nierenberg (JPL) and T. Treu (UCLA)

Learn more: https://science.nasa.gov/missions/hubble/hubble-detects-smallest-known-dark-matter-clumps/

Interpreting a Cosmic Oddity

Three gravitationally lensed images of the odd-looking galaxy called Hamilton's Object appear in this Hubble image. Two of the magnified images, shown in the box at bottom right, are exact copies of each other. The background galaxy straddles a ripple in the fabric of space, an area of greatest magnification caused by the gravity of dense amounts of dark matter. As light from the faraway galaxy passes through the cluster along this ripple, these two mirror images are produced, along with a third image that can be seen off to the side.

The third image (top right box) most closely resembles the remote galaxy. By reconstructing this image, researchers determined that the distant galaxy appears to be an edge-on, barred spiral with ongoing, clumpy star formation.

NASA, ESA, Richard Griffiths (UH Hilo); Co-Author: Jenny Wagner (ZAH); Image Processing: Joseph DePasquale (STScI)

A mysterious pair of objects that stumped astronomers for years is actually a single, gravitationally lensed galaxy whose weird shape results from a "smooth" distribution of dark matter.

The oddball image consists of a pair of galaxy bulges (the central star-filled hub of a galaxy) and at least three nearly parallel split streaks. The distant galaxy was accidentally spotted by Hubble in 2013 while surveying quasars, the blazingly bright cores of active galaxies.

After a lot of head-scratching and eliminated theories, researchers announced in 2021 that the linear objects were the gravitationally lensed, stretched images of a galaxy located more than 11 billion light-years away. But at the time of their discovery, the mirrored images and parallel streaks were unlike anything the team members had seen before.

Further confusing things, there was no known lensing galaxy cluster in the region. Normally, astronomers who study galaxy clusters first see the foreground cluster that's causing the lensing, and then find the magnified images of distant galaxies within the cluster. A search of the Sloan Digital Sky Survey images revealed that a galaxy cluster resided in the same area as the magnified images. The fact that the strange images were at the center of a cluster made it clear that the cluster was producing the lensed images. The cluster resides more than 7 billion light-years away.

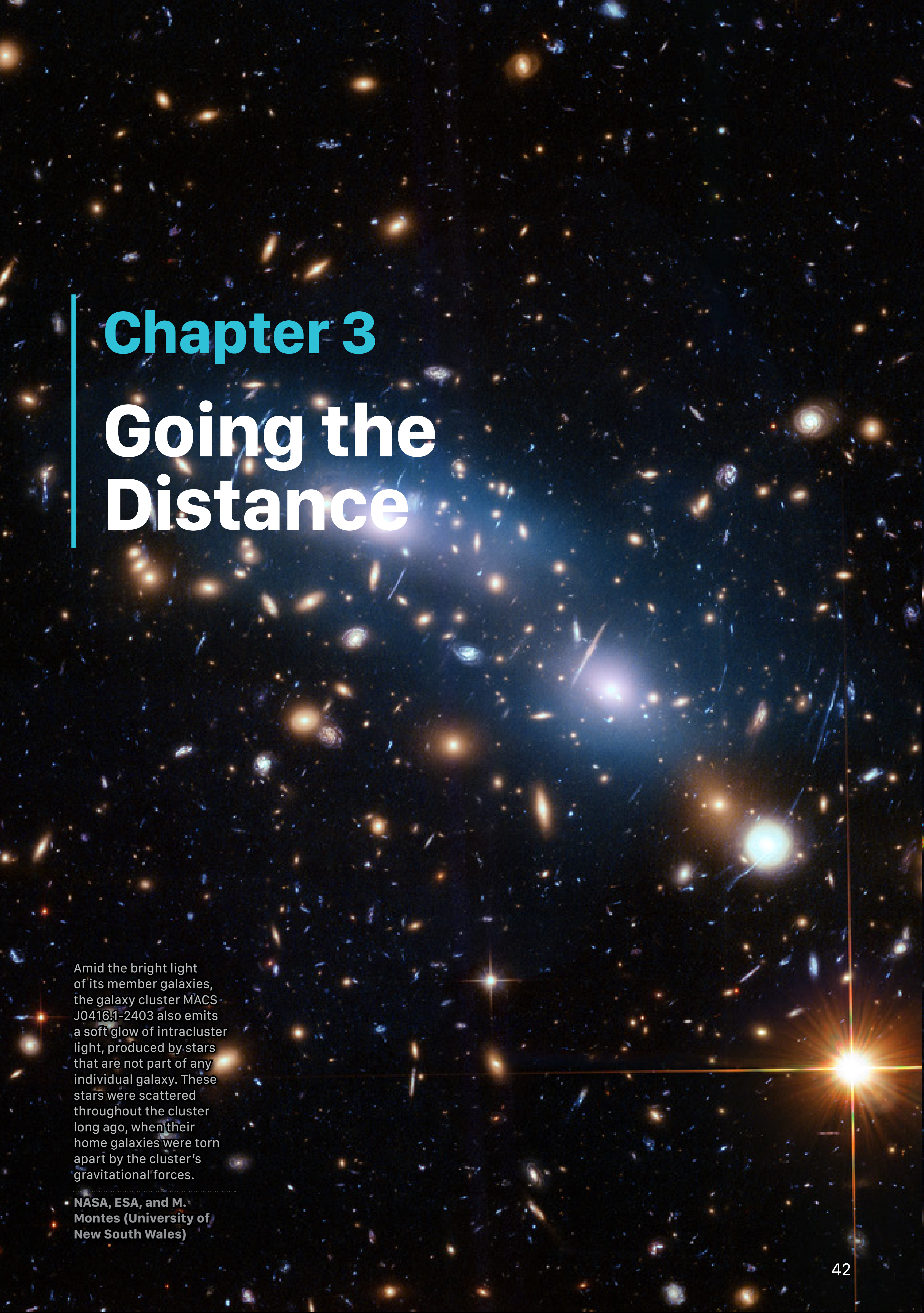
A precise alignment between the background galaxy and the foreground galaxy cluster produces twin magnified copies of the same image of the remote galaxy. This rare phenomenon occurs because the background galaxy straddles a ripple in the fabric of space. This "ripple" is an area of greatest magnification, caused by the gravity of a dense region of dark matter, the unseen glue that makes up most of the universe's mass.

As light from the faraway galaxy passes through the cluster along this ripple, two mirror images are produced, along with a third image that can be seen off to the side. Software developed to interpret unique gravitational lenses helped determine that the dark matter around the stretched images had to be "smoothly" distributed in space at small scales to produce this effect

This result is important because nearly a century after its discovery, astronomers still don't know what dark matter is. Information about dark matter clumping or smoothness gives clues to what kind of particle the mysterious substance may consist of, with smaller dark matter clumps hinting at more massive particles.

> "My first thought was that maybe they were interacting galaxies with tidally stretched-out arms. It didn't really fit well, but I didn't know what else to think."
>
> Timothy Hamilton, Shawnee State University

Learn more: https://science.nasa.gov/missions/hubble/double-galaxy-mystifies-hubble-astronomers/



Chapter 3

Going the Distance

Amid the bright light of its member galaxies, the galaxy cluster MACS J0416.1-2403 also emits a soft glow of intracluster light, produced by stars that are not part of any individual galaxy. These stars were scattered throughout the cluster long ago, when their home galaxies were torn apart by the cluster's gravitational forces.

NASA, ESA, and M. Montes (University of New South Wales)

Astronomers have many uses for gravitational lenses, but the most obvious is seeing things that are too far away to be imaged by any telescope. Hubble has used gravitational lenses to break distance records again and again. The James Webb Space Telescope, with infrared vision intended to see farther back in space than any other existing telescope, uses gravitational lenses as well for an added boost.

Among Hubble's long-distance triumphs were Tayna, a Large Magellanic Cloud-sized object that existed around 400 million years after the Big Bang (13.8 billion years ago), and two of the farthest individual stars ever seen.

Tanya, the red object highlighted in this image, is comparable in size to the Large Magellanic Cloud (LMC), a diminutive satellite galaxy of our Milky Way, but is making stars 10 times faster than the LMC. It may be the growing core of what would eventually become a full-sized galaxy.

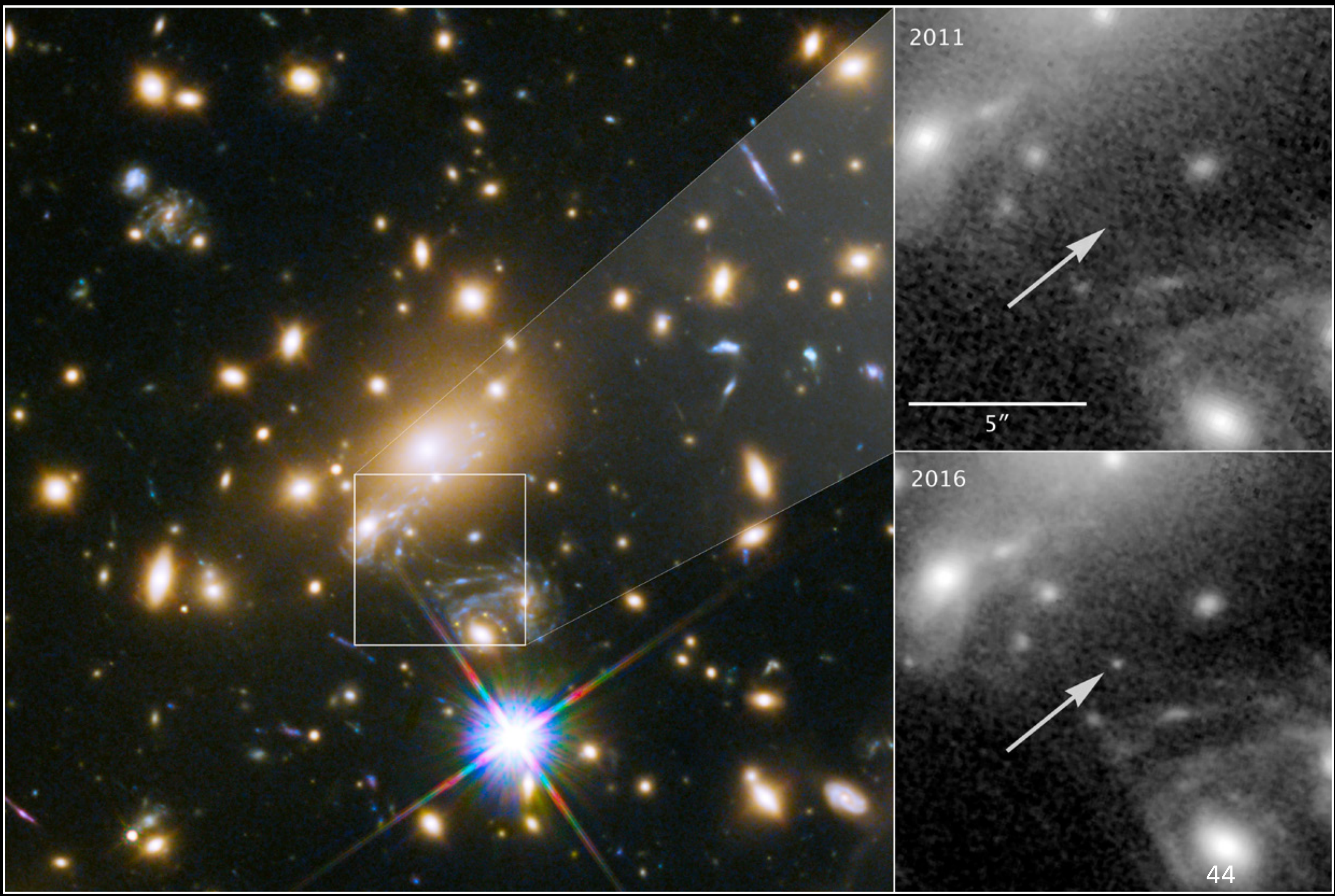
NASA, ESA, and L. Infante (Pontificia Universidad Católica de Chile)

The farther back in space and time that Hubble can see, the more information we can gather about the universe at its youthful stages. Because the light that reaches Earth from the farthest galaxies and stars began traveling toward us billions of years ago, we see those objects as they appeared in the early universe. The light from the farthest objects has been redshifted, or stretched into longer wavelengths of infrared light as it traveled through the expanding universe.

The more objects we view from that time period, the greater sample we have to compare and contrast — like studying snapshots of a few human beings versus compiling a photo album of humanity in all its diversity.

Spotting the Farthest Stars Ever Seen

In 2018, Hubble detected the farthest individual star ever seen. The gravitationally lensed star, Icarus, which existed when the universe was only 30 percent of its current age, was at least 100 times farther than the next individual star that could be studied. Its light had been traveling for 9 billion years.



Gravitationally lensed star Icarus was spotted by Hubble while monitoring a supernova. Researchers saw a point of light near the supernova that began to brighten. Analysis of the object's colors showed it was a blue supergiant star in the background galaxy whose magnification grew for several weeks due to the gravitational amplification of an intervening object, probably a star, in the galaxy cluster. The panels at the right show the view in 2011, without Icarus visible, compared with the star's brightening in 2016.

NASA, ESA, and P. Kelly (University of Minnesota)

The gravitationally lensed star Earendel (indicated with an arrow) stands out from its host galaxy, which appears as a red arc. The red dots on either side of Earendel are one star cluster that is mirrored on either side, a result of the gravitational lensing distortion. The entire galaxy, called the Sunrise Arc, appears three times, and knots along its length are more mirrored star clusters. Earendel's unique position right along the line of most extreme magnification allows it to be detected, even though it is not a cluster.

NASA, ESA, Brian Welch (JHU), Dan Coe (STScI); Image Processing: NASA, ESA, Alyssa Pagan (STScI)

And then in 2022, Hubble beat that record.

This time, the light from the star, named Earendel, had been traveling for 12.9 billion years, showing the star as it had appeared when the universe was an astounding 7 percent of its current age.

Typically at these distances, entire galaxies look like smudges, with the light of millions of stars blending together. But Earendel had a rare alignment with the magnifying galaxy cluster, appearing directly on, or extremely close to, a ripple in the fabric of space. This ripple provides maximum magnification and brightening and causes the star to pop out from the general glow of its home galaxy, magnifying it a thousandfold or more. Earendel's home galaxy, nicknamed the Sunrise Arc, is magnified and warped into a long crescent.

> "We almost didn't believe it at first, (Earendel) was so much farther than the previous most-distant, highest redshift star."
>
> Brian Welch, the Johns Hopkins University

Follow-up observations by the infrared James Webb Space Telescope revealed the star to be a massive B-type star more than twice as hot as our Sun, and about a million times more luminous. These hot, massive stars live short, intense lives, and Earendel would have perished 10 million to 100 million years after it was born. The light from this long-gone star is just reaching us, like a ghost from the past with a tale to tell.

Hubble detected the light of a star that existed within the first billion years after the universe's birth in the Big Bang—the farthest individual star ever seen to date.

NASA's Goddard Space Flight Center; Lead Producer: Paul Morris

Record Broken: Hubble Spots Farthest Star Ever Seen

Watch on YouTube: https://youtu.be/0YMRuh772IA?si=haXl1zYNyjI3gVbe

Learn more: https://science.nasa.gov/missions/hubble/record-broken-hubble-spots-farthest-star-ever-seen/

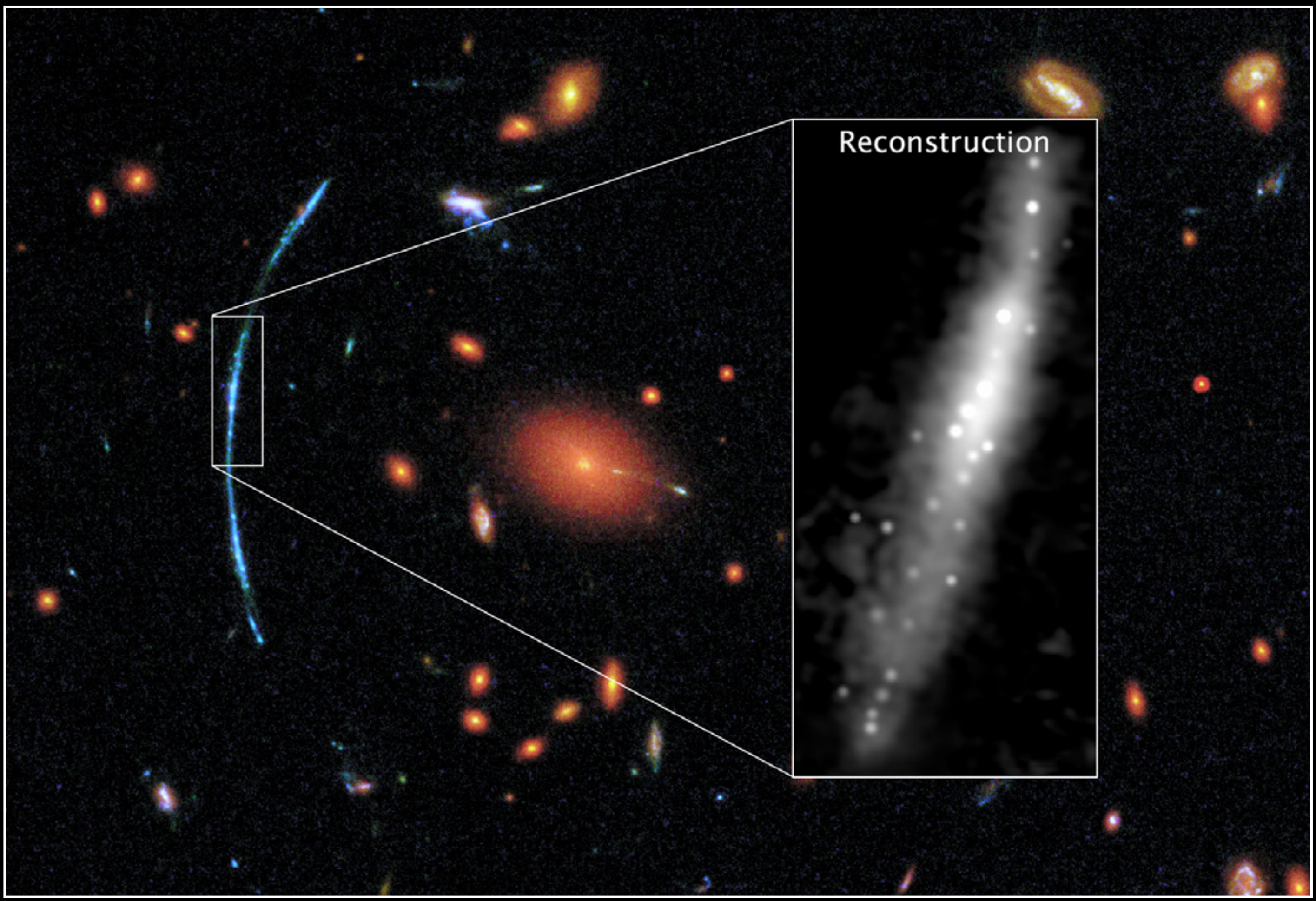
Reversing Gravitational Warping to Unveil Faraway Galaxies

By applying a new computational analysis to a galaxy magnified by a gravitational lens, astronomers have obtained images 10 times sharper than Hubble could achieve on its own. The results show an edge-on disk galaxy studded with brilliant patches of newly formed stars.

The galaxy in question is so far away that we see it as it appeared 11 billion years ago, only 2.7 billion years after the Big Bang. It has been magnified almost 30 times by the gravitational lensing effect of a foreground cluster of galaxies. Researchers developed special computer code to remove the distortions caused by the lens, and reveal the disk galaxy as it would normally appear.

The resulting reconstructed image uncovered two dozen clumps of newborn stars, each spanning about 200 to 300 light-years. This contradicted theories suggesting that star-forming regions in the distant, early universe were much larger, 3,000 light-years or more in size.

Without the magnification boost of the gravitational lens, the disk galaxy would appear perfectly smooth and unremarkable to Hubble, presenting a very different picture of where stars are forming.



The spotty blue arc that stands out against a background of red galaxies is actually three separate, gravitationally lensed images of the same background galaxy. Through sophisticated computer processing, researchers produced the reconstructed image at right that shows how the galaxy would look to Hubble without distortions.

NASA, ESA, and T. Johnson (University of Michigan)

"When we saw the reconstructed image we said, 'Wow, it looks like fireworks are going off everywhere.'"

Jane Rigby, NASA's Goddard Space Flight Center

Learn more: https://science.nasa.gov/missions/hubble/hubble-pushed-beyond-limits-to-spot-clumps-of-new-stars-in-distant-galaxy/

In these composite images from Hubble and ALMA, the pullouts show two of the six distant, massive galaxies where star formation stopped due to the depletion of cold hydrogen gas. Yellow shows starlight. The artificial purple color traces cold dust from ALMA observations.

Even with ALMA's sensitivity, scientists do not detect dust in most of the six galaxies sampled. One example is the lensed galaxy MRG-M1341, at upper right. In contrast, the purple blob to the left of the galaxy is a dust-and-gas-rich galaxy.

ALMA did detect cold dust in galaxy MRG-M2129 at bottom right. The galaxy only has dust and gas in the center. This suggests that star formation may have shut down from the outskirts inward.

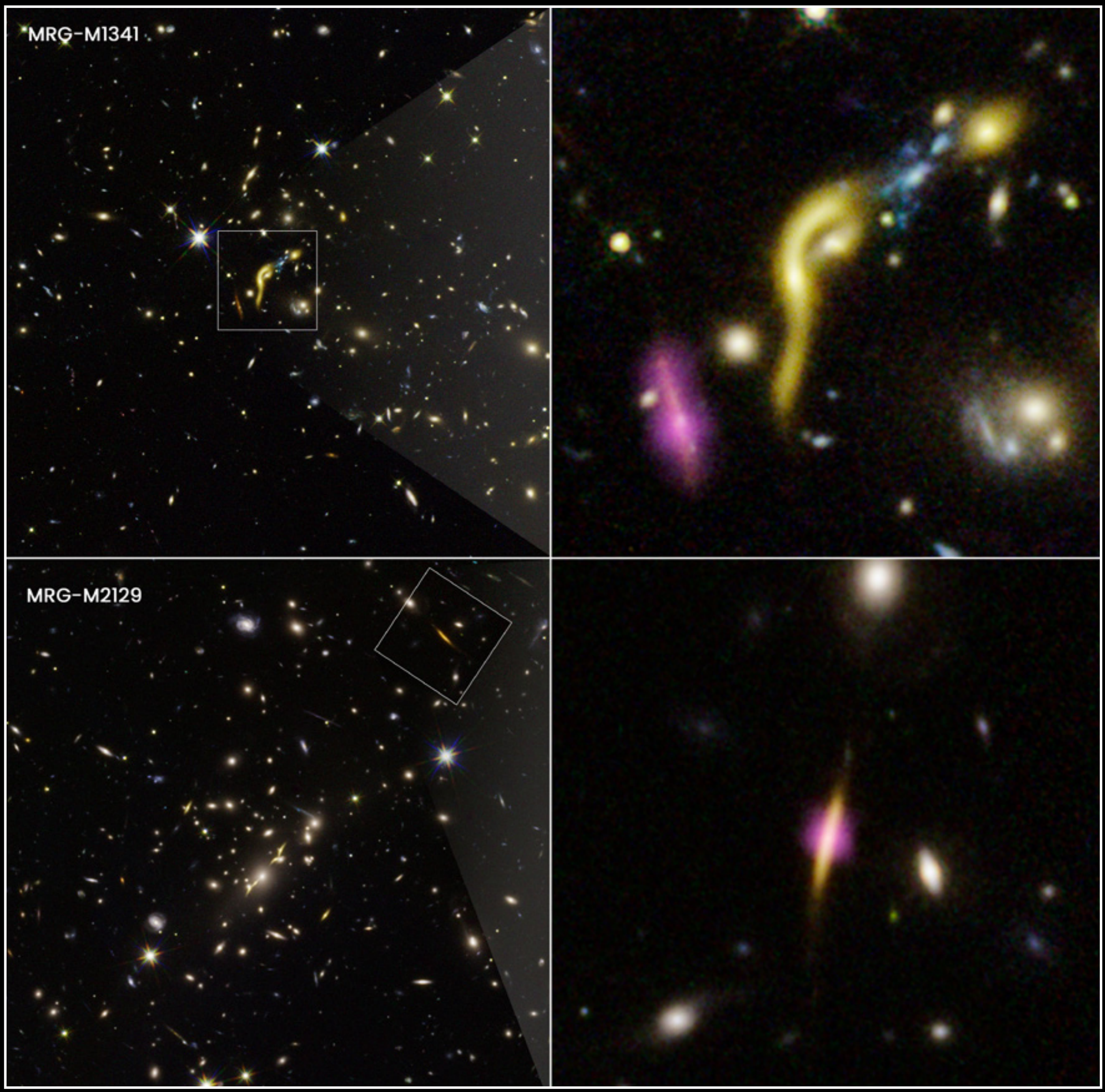
NASA, ESA, Katherine Whitaker (UMass); Image Processing: Joseph DePasquale (STScI)

Clues to a Cosmic Death Scene in the Distant Past

To solve the mystery of six dead galaxies, investigators turned to clues provided by gravitational lensing.

When the universe was about 3 billion years old, just 20 percent of its current age, it produced abundant amounts of stars — in fact, it was the most prolific period of star birth in history. But when Hubble and the Atacama Large Millimeter/submillimeter Array (ALMA) in northern Chile gazed toward cosmic objects in this period, they found something odd: six early, massive, "dead" galaxies that had run out of the cold hydrogen gas needed to make stars.

By combining the resolution of Hubble and ALMA with the strong gravitational lensing of massive foreground galaxy clusters, astronomers were able to scrutinize the formation of these six distant galaxies. Hubble pinpointed where in the galaxies the stars exist, showing where they formed in the past. By detecting the cold dust that



serves as a proxy for cold hydrogen gas, ALMA showed astronomers where stars could form in the future if enough fuel were present.

Researchers found that these dead galaxies don't appear to rejuvenate, even through later minor mergers and accretions of small, nearby galaxies and gas. They suspect that in the present-day universe, this type of compact galaxy is larger but still dead in terms of any new star formation.

> "By using strong gravitational lensing as a natural telescope, we can find the distant, most massive, and first galaxies to shut down their star formation."
>
> Kate Whitaker, University of Massachusetts, Amherst

Learn more: https://science.nasa.gov/missions/hubble/hubble-finds-early-massive-galaxies-running-on-empty/

IMAGE FEATURE

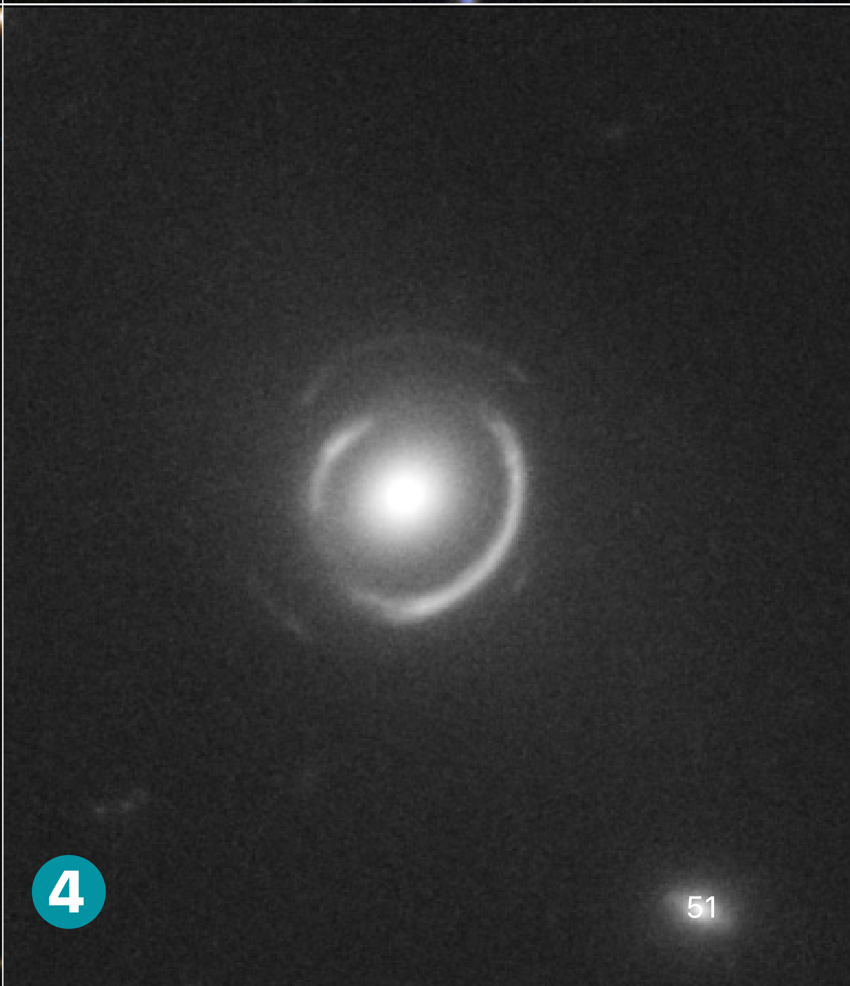
Einstein Rings

Galaxy cluster SDSS J1336-0331 warps and magnifies light from background galaxies.

ESA/Hubble & NASA

Einstein Rings

When a background galaxy lines up precisely with a gravitational lensing foreground galaxy, the warped and magnified light from the background galaxy can curve into a full or partial circle. This rare phenomenon is called an Einstein Ring. Hubble's observations have more than quadrupled the number of documented, visible Einstein Rings.



Some bright galaxies and an Einstein Ring form a cosmic smiley face in this Hubble image. The arcs are caused by the gravitational lensing galaxy cluster SDSS J1038+4849.

NASA/ESA; Acknowledgment: Judy Schmidt

Almost all the galaxies within this Hubble image are part of galaxy cluster SDSSJ0146-0929, but the graceful arcs forming an Einstein ring are a background galaxy whose light has been diverted and distorted around the mass of the cluster.

ESA/Hubble & NASA; Acknowledgment: Judy Schmidt

This "Molten Ring," as it is nicknamed, is one of the most complete and largest Einstein rings imaged. The background galaxy was found to be 9.4 billion light-years away, placing it at the peak epoch of star formation in cosmic evolution.

NASA, ESA, Anastasio Díaz-Sánchez (Universidad Politécnica de Cartagena), Saurabh Jha (Rutgers, The State University of New Jersey)

An even-rarer-than-normal double Einstein ring is created by the complex bending of light from two distant galaxies strung directly behind a foreground massive galaxy, like three beads on a string. The inner ring and outer ring are made up of multiple images of the two background galaxies at a distance of approximately 6 billion and 11 billion light-years. The odds of seeing such an alignment are estimated to be 1 in 10,000.

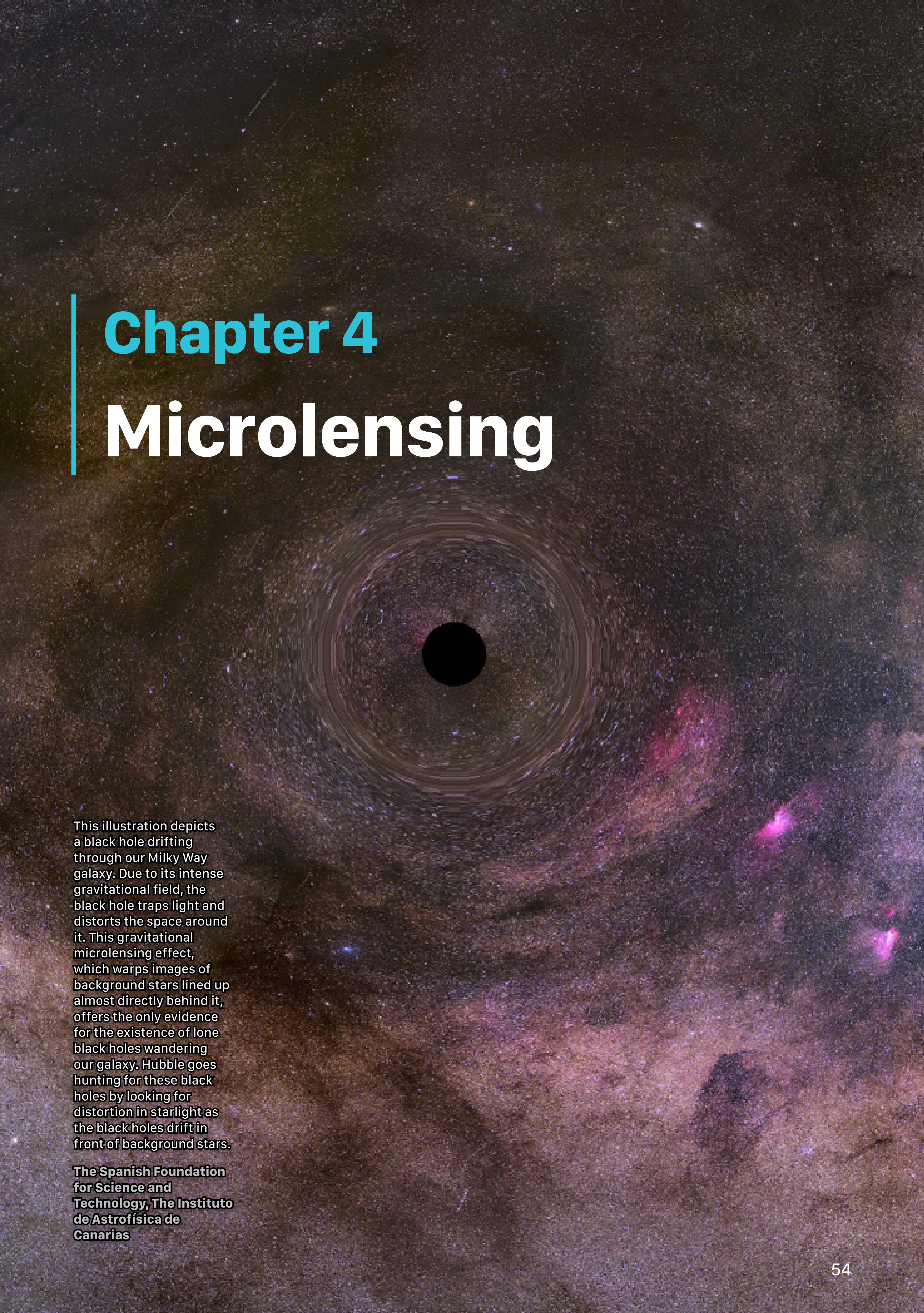
NASA, ESA, and R. Gavazzi and T. Treu (University of California, Santa Barbara)

The gravitational lensing effect was first theorized by Albert Einstein in 1912, and later worked into his theory of general relativity. In this video, astronomer Brian Welch explains Einstein Rings and why they are important.

NASA, James Leigh, and Origin Films

Einstein Rings: Optical Illusions

Watch on YouTube: https://youtu.be/jorMha-ZE4M?si=-E5wcr44xREfsEhG



Chapter 4

Microlensing

This illustration depicts a black hole drifting through our Milky Way galaxy. Due to its intense gravitational field, the black hole traps light and distorts the space around it. This gravitational microlensing effect, which warps images of background stars lined up almost directly behind it, offers the only evidence for the existence of lone black holes wandering our galaxy. Hubble goes hunting for these black holes by looking for distortion in starlight as the black holes drift in front of background stars.

The Spanish Foundation for Science and Technology, The Instituto de Astrofísica de Canarias

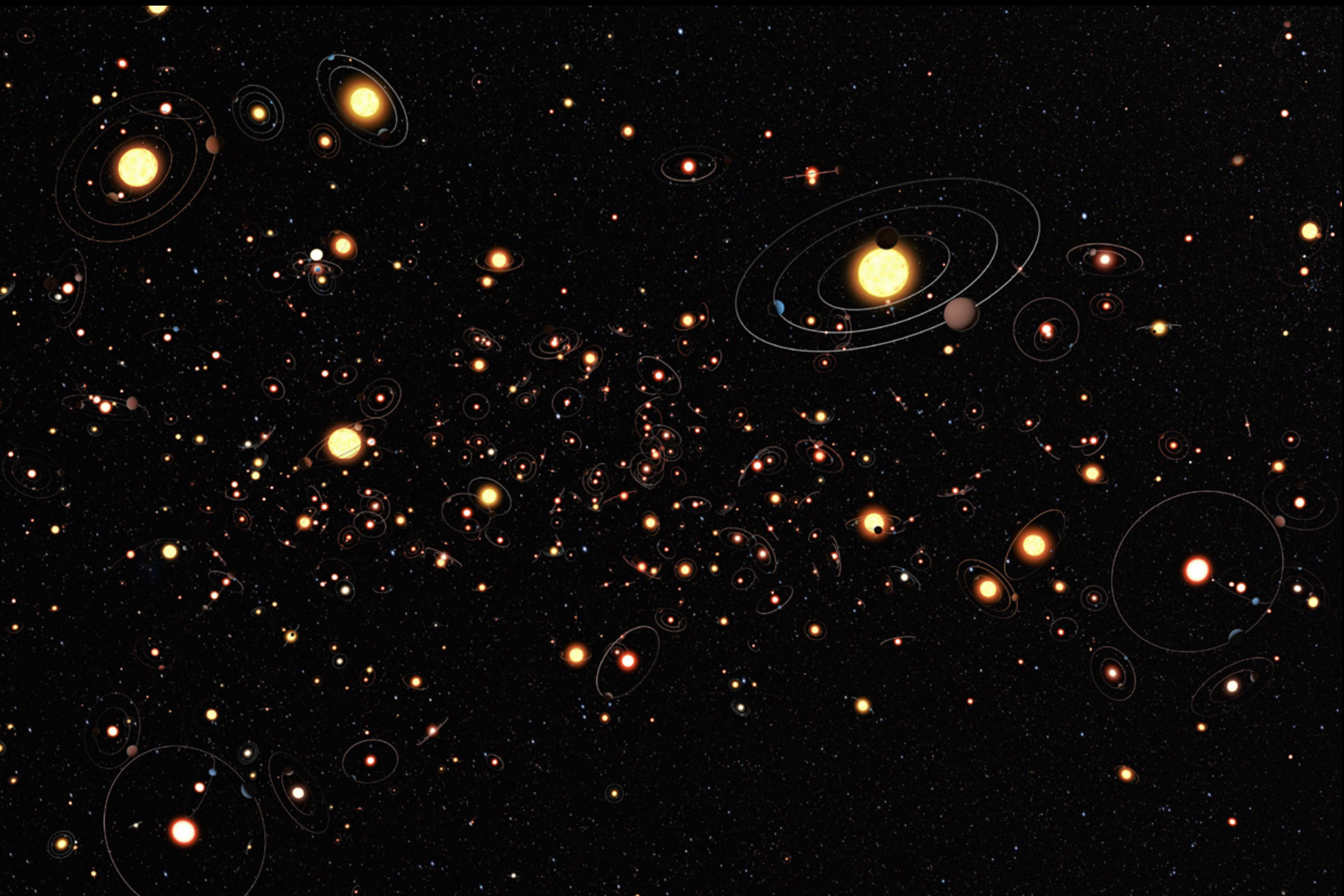
In 1919, British astronomer Arthur Eddington decided to test Einstein's theory of general relativity, designing an experiment to measure whether and by how much the Sun's gravity would deflect the path of starlight passing near the Sun. He accomplished this by photographing stars near the edge of the Sun during a total solar eclipse. It would be the first and best concrete observation of gravitational lensing for the next 60 years, until telescopes powerful enough to see lensed galaxies began to be built.

As Eddington demonstrated, not all gravitational lensing involves galaxy clusters. Gravitational microlensing occurs when a foreground object like a star or black hole magnifies the light of a background object that momentarily aligns with it. This phenomenon can be used to reveal clues about both the nature of the foreground object and the background object, which is typically another star.

Astronomers have used gravitational microlensing to gather information about the presence and nature of objects much too small and distant to ordinarily be seen by telescopes, such as individual stars and planets.

The Milky Way galaxy contains a minimum of 100 billion planets according to a detailed statistical study based on the detection of three extrasolar planets by microlensing. The survey concluded that planets around stars are the rule rather than the exception. This illustration gives an impression of how common planets are around the stars in the Milky Way. The planets, their orbits, and their host stars are all vastly magnified compared to their real separations.

NASA, ESA, and M. Kornmesser (ESO)



Uncovering an Isolated Exoplanet

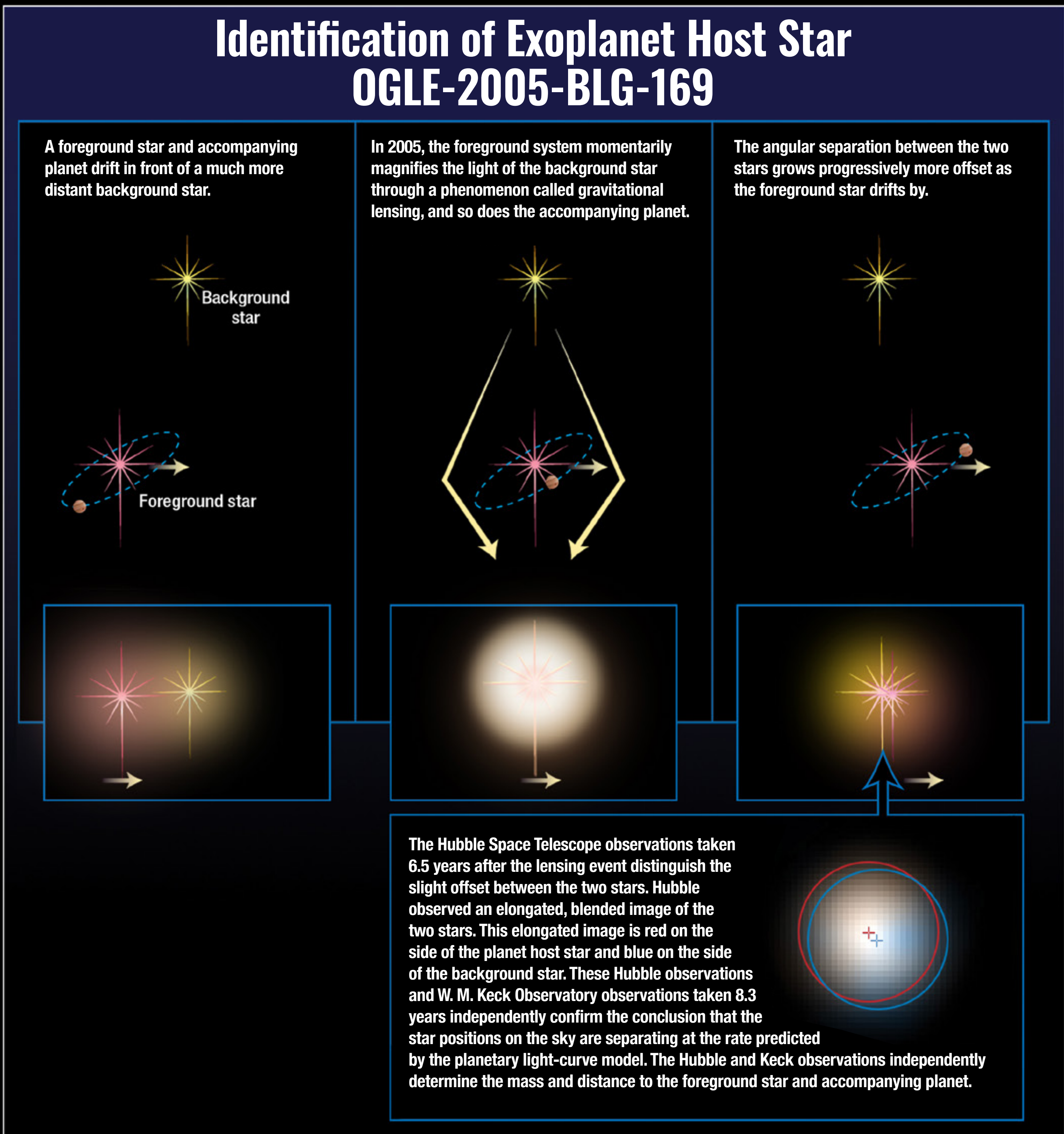
Hubble and the W. M. Keck Observatory in Hawaii have independently confirmed an exoplanet orbiting far from its central star. The gravitational microlensing technique used to find it opens the potential to uncover planets that are as far from their central stars as Jupiter and Saturn are from our Sun.

Most exoplanets that have been identified are very close to their host stars because that's what current planet-hunting techniques favor. But gravitational microlensing can find more distant and colder planets in long-period orbits.

Microlensing occurs when a foreground star amplifies the light of a background star when the two align. If the foreground star has planets, the planets may also amplify the light of the background star, but for a much shorter period of time than their host star. The exact timing and amount of light amplification can reveal clues to the nature of the foreground star and its accompanying planets.

Astronomers found that the system, named OGLE-2005-BLG-169, consists of a Uranus-sized planet orbiting about 370 million miles from its parent star, slightly less than the distance between Jupiter and the Sun. The host star is about 70 percent as massive as our Sun.

> "It's important to understand how these systems compare with our solar system. Gravitational microlensing is critical in helping astronomers gain insights into planetary formation theories."
>
> Jay Anderson, Space Telescope Science Institute



This graphic illustrates how a star can magnify and brighten the light of a background star when it passes in front of the distant star. If the foreground star has planets, then the planets may also magnify the light of the background star, but for a much shorter period of time than their host star. Astronomers use this method, called gravitational microlensing, to identify planets.

NASA, ESA, and A. Feild (STScI

Measuring a White Dwarf

Astronomers using Hubble directly measured the mass of a single, isolated white dwarf for the first time. The unique observation yields insights into theories of the structure and composition of white dwarfs.

The white dwarf — the surviving core of a burned-out Sun-like star — is 56 percent the mass of our Sun. This agrees with earlier theoretical predictions of the white dwarf's mass and corroborates current theories of how white dwarfs evolve from typical stars.

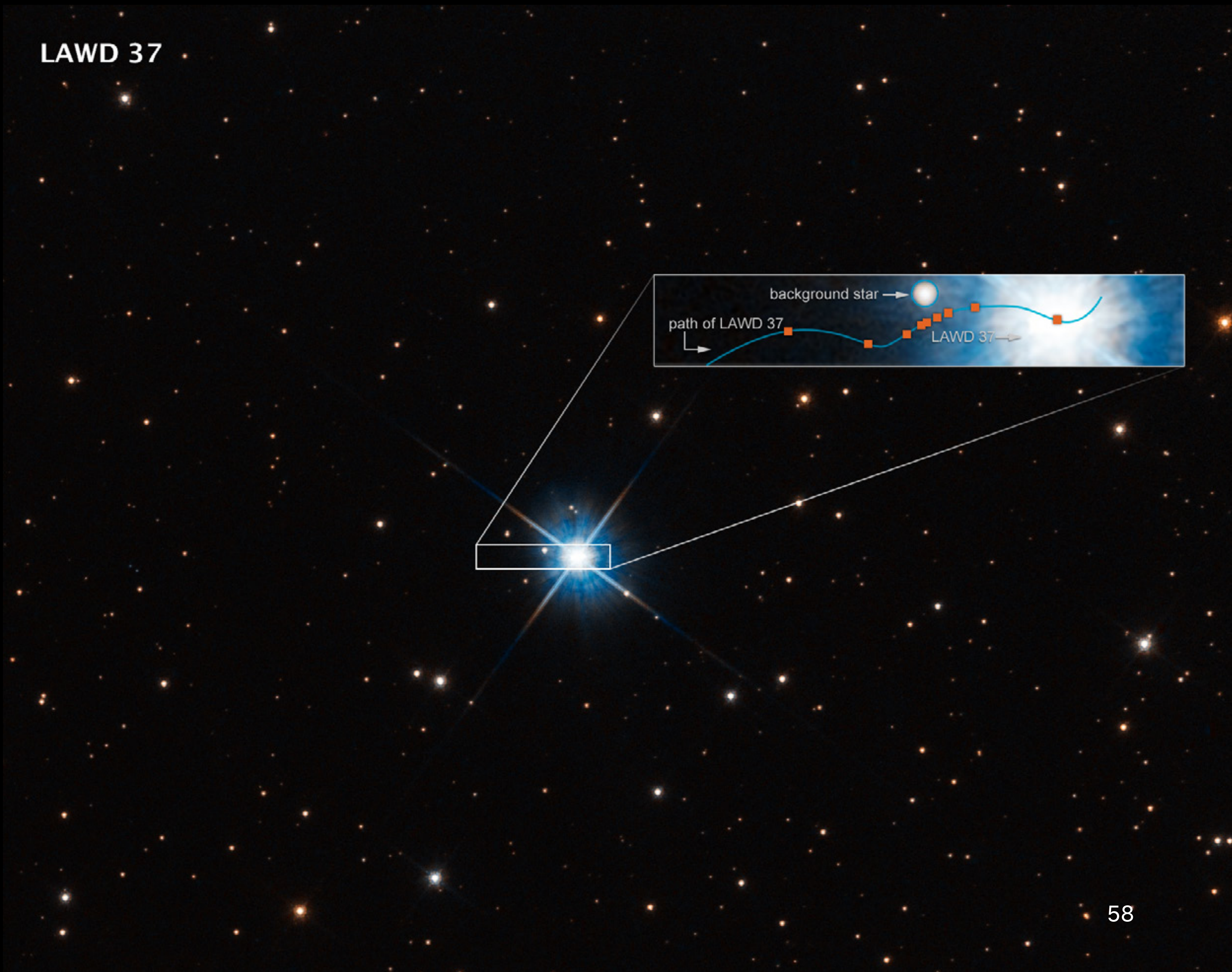
The box plots how the white dwarf LAWD 37 passed in front of a background star in 2019. The wavy blue line traces the dwarf's apparent motion across the sky as seen from Earth. Though the dwarf is following a straight trajectory, the motion of Earth orbiting the Sun imparts an apparent wave-like effect due to parallax. As the dwarf passed the fainter background star, its gravitational field warped space and this deflection was precisely measured by Hubble.

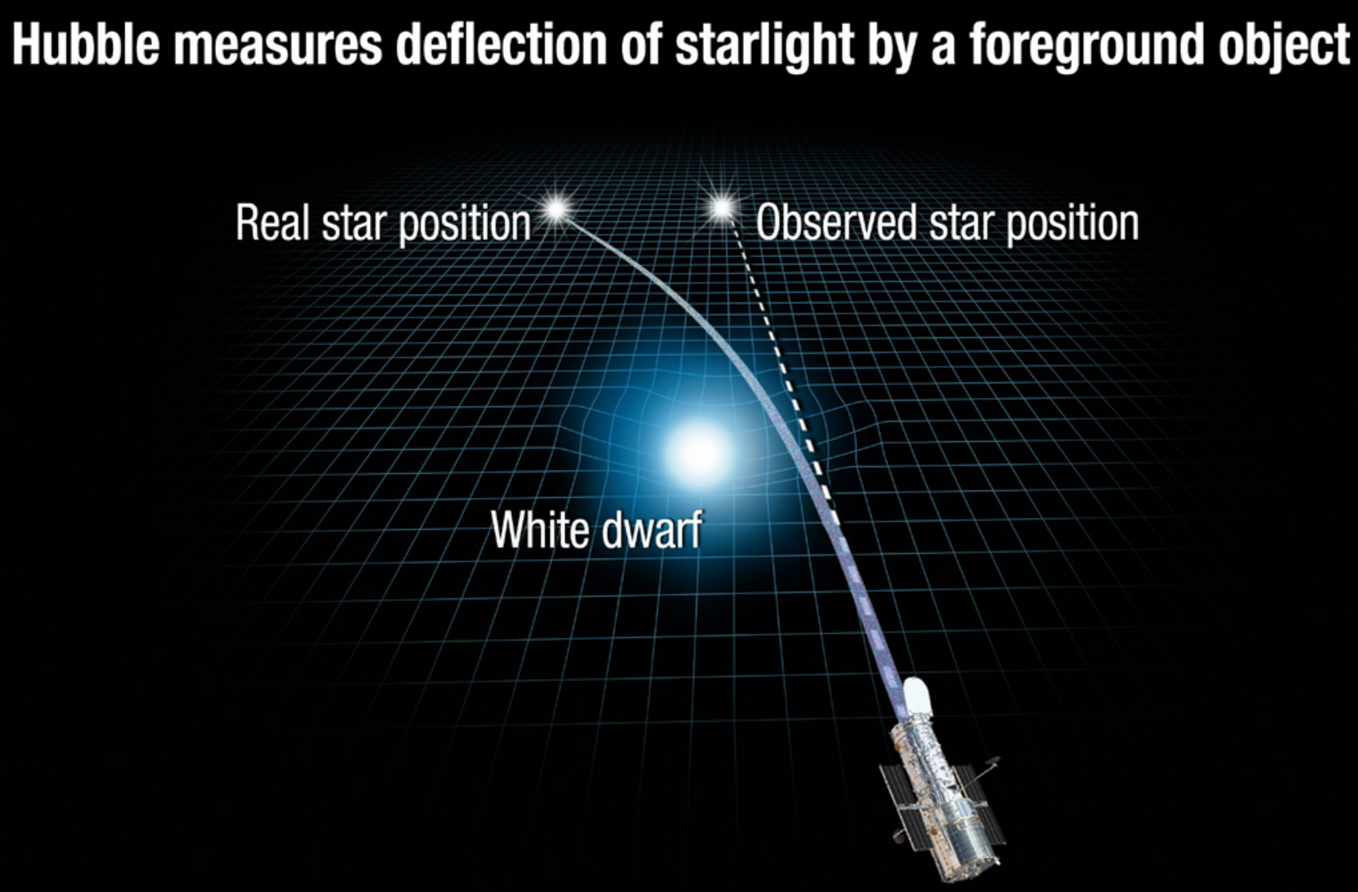
NASA, ESA, Ann Feild (STScI); NASA, ESA, Peter McGill (UC Santa Cruz, IoA), Kailash Sahu (STScI); Image Processing: Joseph DePasquale (STScI)

Most white dwarf mass measurements have been gleaned from observing white dwarfs in binary star systems. By watching the motion of two co-orbiting stars, straightforward Newtonian physics can be used to measure their masses. However, these measurements can be uncertain if the white dwarf's companion star is in a long-period orbit for hundreds or thousands of years. Telescopes can capture only a short period of the dwarf's orbital motion.

For this companion-less white dwarf, called LAWD 37, researchers used gravitational microlensing. The light from a background star was slightly deflected by the gravitational warping of space from the foreground dwarf star. As the white dwarf passed in front of the background star, microlensing caused the star to appear temporarily offset from its actual position on the sky. The measured offset is tiny, similar to measuring the length of a car on the Moon as seen from Earth.

Researchers found that the dwarf is 56 percent the mass of our Sun. LAWD 37 has been extensively studied because it is only 15 light-years away. Its star burned out around 1 billion years ago.





This illustration shows how the gravity of a foreground white dwarf star warps space and bends the light of a distant star behind it. The greater the temporary deflection of the background star's image, the more massive the foreground star is. (This deviation is so small that it is equivalent to observing an ant crawl across the surface of a quarter from 1,500 miles away.)

NASA, ESA, Ann Feild (STScI)

"Because this white dwarf is relatively close to us, we've got lots of data on it — we've got information about its spectrum of light, but the missing piece of the puzzle has been a measurement of its mass."

Peter McGill, University of Cambridge

Learn more: https://science.nasa.gov/missions/hubble/for-the-first-time-hubble-directly-measures-mass-of-a-lone-white-dwarf/

Microlensing to Find a Black Hole

Using a meticulous form of gravitational lensing called astrometric microlensing, Hubble may have found the first isolated stellar-mass black hole. It took six years of observations to identify the possible black hole, which would be up to about seven times the mass of the Sun and is roaming the galaxy.

Astronomers estimate the Milky Way contains some 100 million black holes, but these invisible, light-devouring objects are difficult to detect. Black holes like this occur when stars at least 20 times more massive than our Sun explode as supernovae, and the remnant core is crushed by gravity into a black hole. Because the self-detonation is not perfectly symmetrical, the black hole may get a kick that sends it sailing through our galaxy.

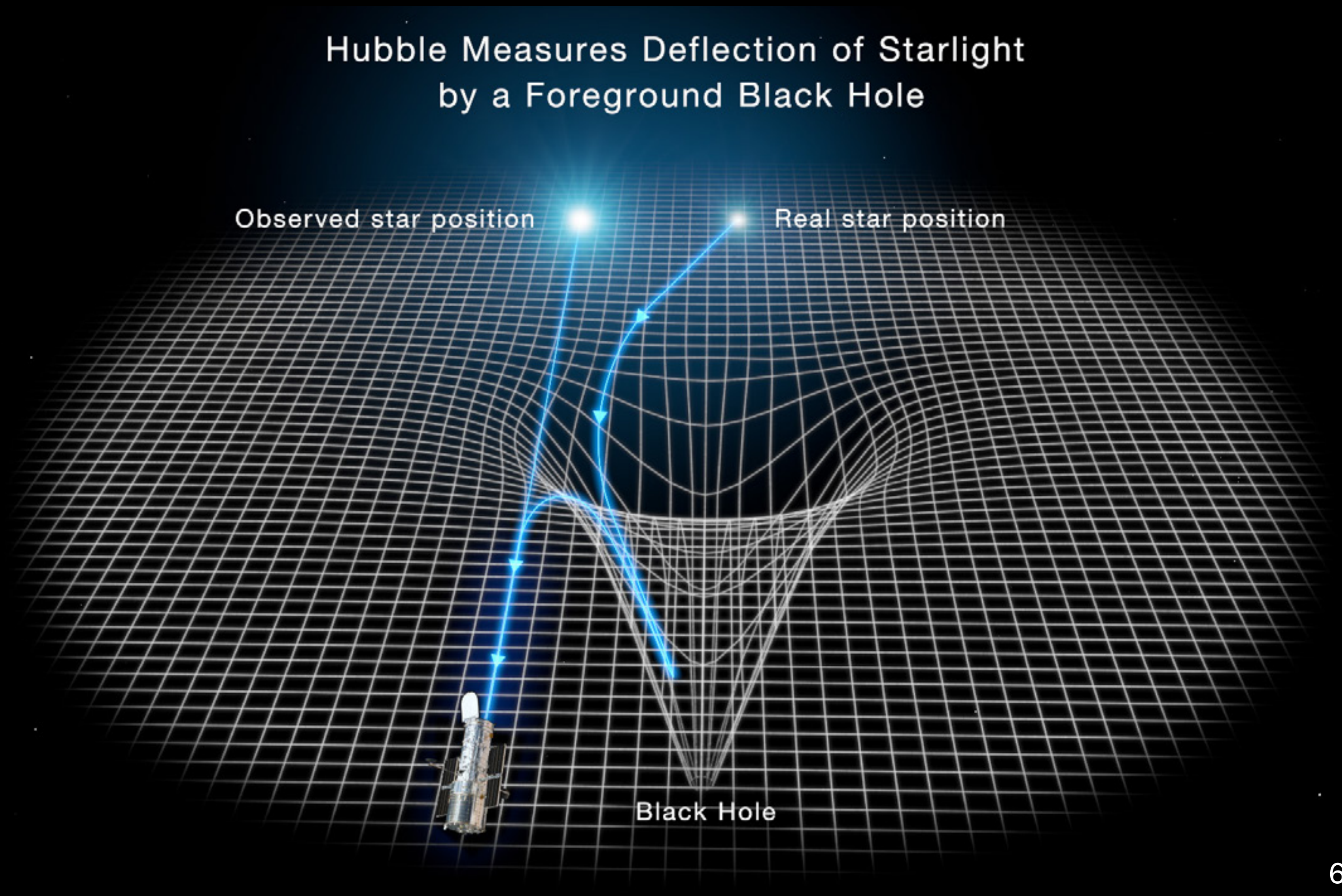
The gravity of a black hole is intense enough to gravitationally lens background starlight, brightening and bending it. Ground-based telescopes search for these brightening events to pinpoint potential black hole candidates. Using Hubble for its powerful resolution, researchers monitored the way light from a star far behind a compact object momentarily brightened and deflected.

The signature of a foreground black hole is unique among other microlensing events. The intense gravity of the black hole will stretch out the duration of the lensing event for over 200 days. Also, if the foreground object was a star rather than a black hole, it would cause a temporary color change in the starlight as measured, when the light from the foreground and background stars momentarily blend together. But no color change was seen during this event.

Next, Hubble was used to measure the amount of deflection of the background star's image by the possible black hole. The star's image was offset from where it normally would be by about a milliarcsecond, the equivalent of measuring the diameter of a 25-cent coin in Los Angeles as seen from New York City.

A black hole's intense gravity warps and deflects the light of stars lined up almost directly behind it. This diagram demonstrates how space becomes warped by the black hole, resulting in the shift of the star's light from its actual position to one slightly removed.

NASA, ESA, STScI, Joseph Olmsted



The lack of a change in the starlight's color, the duration of the lensing event, and the amount of light deflection suggested a black hole. Two teams of researchers measured the range of mass of the compact object, determining that it was either a black hole (if the mass is on the high end of the range) or a neutron star (on the low end). Only one in a few hundred microlensing events are predicted to be caused by isolated black holes.

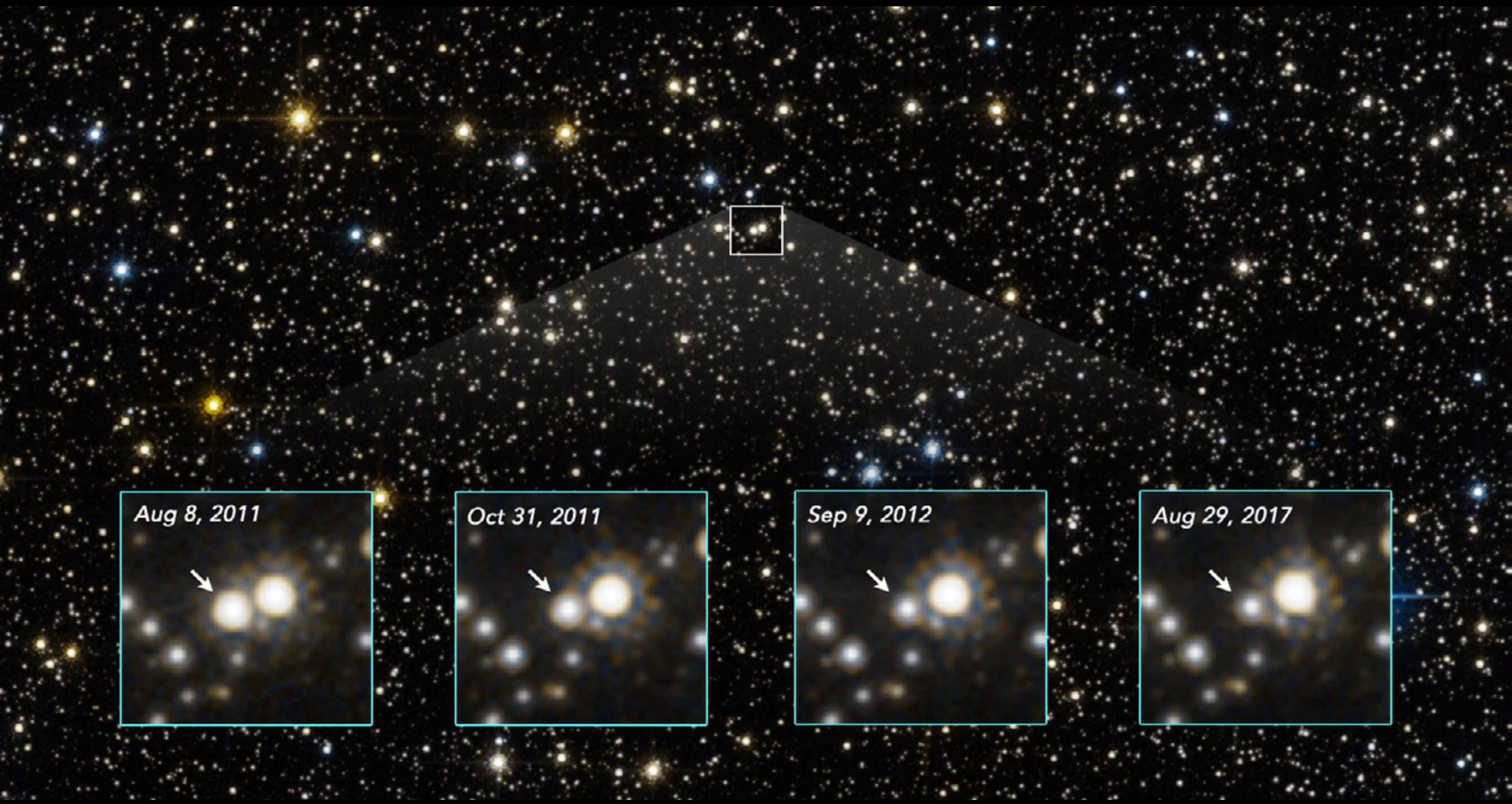
The isolated object is traveling across the galaxy at 100,000 miles per hour (160,000 km), fast enough to travel from Earth to the Moon in less than three hours. This potential black hole is 5,000 light-years away, but, statistically, its detection means that the nearest wandering black hole to Earth could be as close as 80 light-years away.

"Whatever it is, the object is the first dark stellar remnant discovered wandering through the galaxy, unaccompanied by another star."

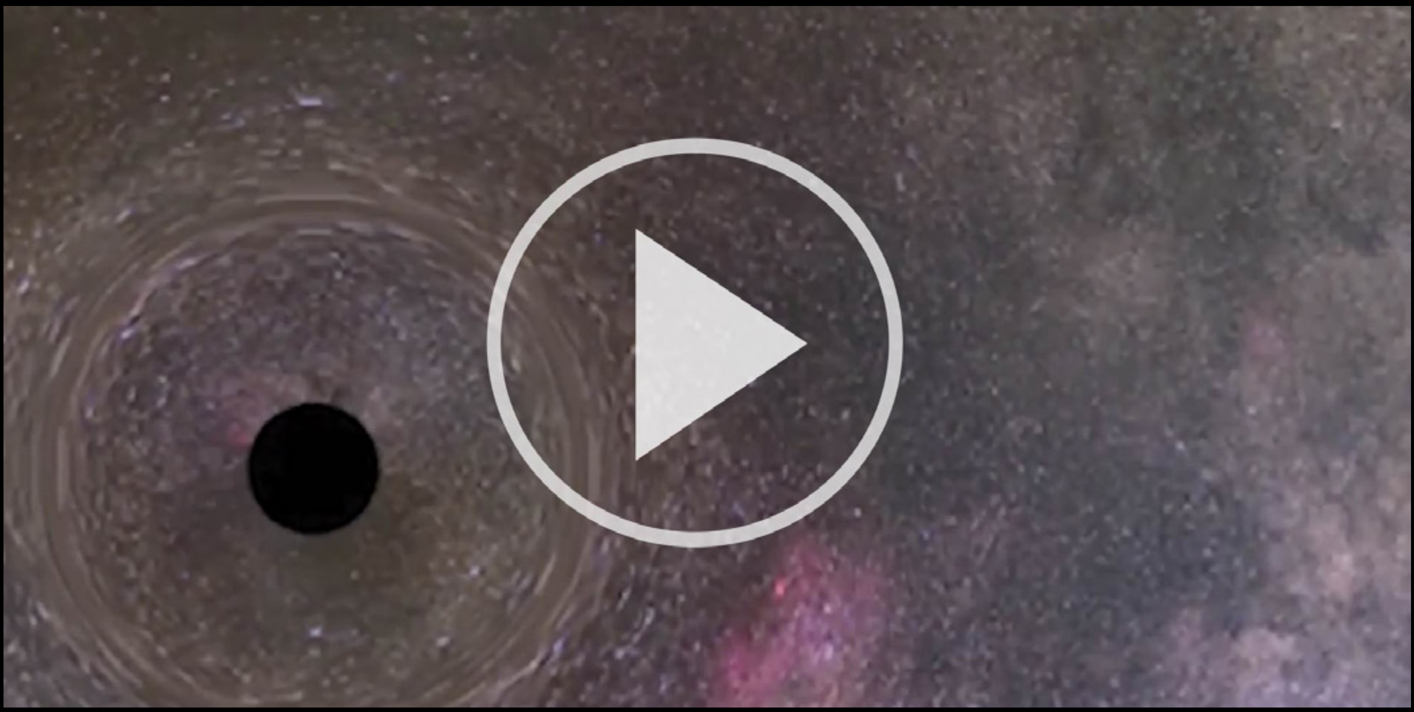
Casey Lam, University of California, Berkeley

This time-lapse of a set of four Hubble photos capture the gravitational microlensing effects of an invisible black hole drifting through our galaxy. As the black hole passed in front of the star, its gravitational field amplified the starlight, causing the background star to momentarily brighten, as first seen by Hubble in August 2011. The star then faded back to normal brightness.

NASA, ESA, Kailash Sahu (STScI); Image Processing: Joseph DePasquale (STScI)



Learn more: https://science.nasa.gov/missions/hubble/hubble-determines-mass-of-isolated-black-hole-roaming-our-milky-way-galaxy/



Like wandering ghosts, the presence of isolated black holes can only be deduced by seeing how they affect the environment around them.

NASA's Goddard Space Flight Center; Lead Producer: Paul Morris

Hubble Measures Potential Isolated Black Hole Roaming Galaxy

Watch on YouTube: https://youtu.be/eOSv-FhaDOA?si=2Q2SJOI6MRDSlQmD

Summary

A remote galaxy called the "Sunburst Arc" has been split into multiple images by gravitational lensing. The lensing produces at least 12 images of the background galaxy, distributed over four major arcs. The galaxy is almost 11 billion light-years from Earth and the foreground lensing cluster is 4.6 billion light-years away.

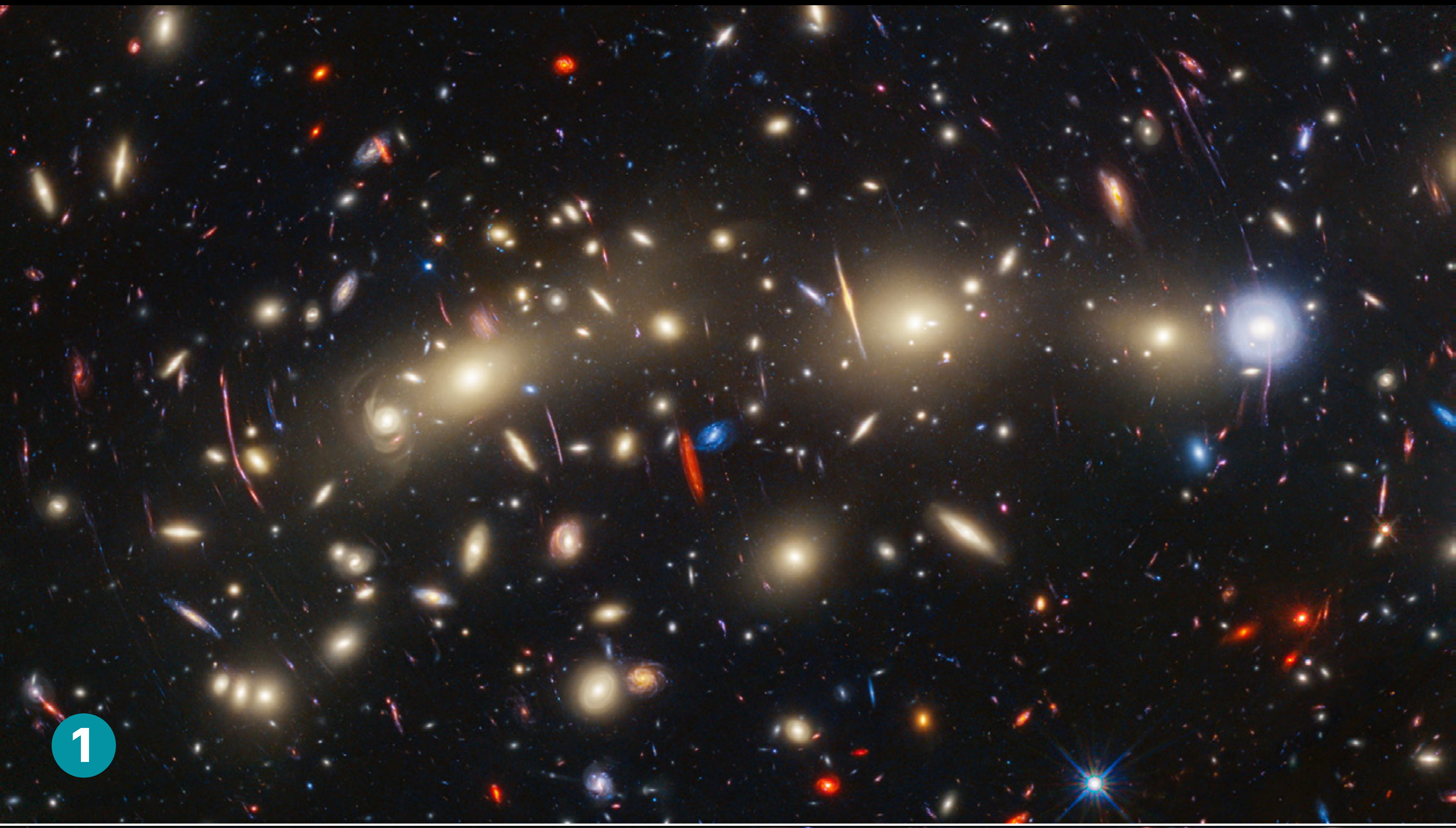
NASA, ESA, and E. Rivera-Thorsen (Institute of Theoretical Astrophysics Oslo, Norway)

This Hubble image shows a blue horseshoe-shaped Einstein ring around a massive galaxy. The foreground galaxy in this Hubble image, one of a group called Luminous Red Galaxies, has an unusually large mass, containing about 10 times the mass of the Milky Way. Its gravity has warped and magnified the light from a distant background galaxy into a nearly complete ring. The background galaxy appears as it did about 3 billion years after the Big Bang.

ESA/Hubble & NASA

When Albert Einstein first shared his thoughts on the phenomenon that would become known as gravitational lensing, he doubted astronomers would be able to witness its effects. "Some time ago, R.W. Mandl paid me a visit and asked me to publish the results of a little calculation, which I had made at his request," he began in a short piece in the academic journal "Science" describing the "Lens-like Action of a Star By the Deviation of Light in the Gravitational Field." He added, as a disclaimer, "Of course, there is no hope of observing this phenomenon directly."

Today, thanks to our advanced observatories, gravitational lensing is regularly used to push increasingly powerful telescopes past their limitations. Due to the magnifying power of gravitational lenses, we have witnessed tremendously distant objects — and gazed back in time to view these objects as they appeared in the early history of the cosmos. We have been able to map the presence of dark matter, and detect objects that would be difficult to impossible to find without the lensing effect. Hubble in particular has made significant use of gravitational lenses, since its sensitivity and exquisite resolution allow it to detect some of the fainter lensed images that would be beyond the reach of ground-based telescopes.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2
MOTHRA

1

MACS0416 is a galaxy cluster located about 4.3 billion light-years from Earth, meaning that light we see now left the cluster shortly after the formation of our solar system. The bluest galaxies in this image are relatively nearby and often show intense star formation, best detected by Hubble, while the redder galaxies tend to be more distant, or else contain copious amounts of dust, and are best detected by Webb. The image reveals a wealth of details that are only possible to capture by combining the power of both space telescopes.

NASA, ESA, CSA, STScI, J. Diego (Instituto de Física de Cantabria, Spain), J. D'Silva (U. Western Australia), A. Koekemoer (STScI), J. Summers & R. Windhorst (ASU), and H. Yan (U. Missouri)

2

The combined Hubble and Webb image found a gravitationally lensed background galaxy that existed about 3 billion years after the Big Bang. That galaxy contains a transient, or object that varies in observed brightness over time, that the science team nicknamed "Mothra." Mothra is a star or star system that is magnified by a factor of at least 4,000 times. The team believes that Mothra is magnified not only by the gravity of galaxy cluster MACS0416, but also by an unknown object called a "milli-lens" — possibly a globular star cluster too faint to see.

Image: NASA, ESA, CSA, STScI, Jose Diego (IFCA), Jordan D'Silva (UWA), Anton Koekemoer (STScI), Jake Summers (ASU), Rogier Windhorst (ASU), Haojing Yan (University of Missouri); Image Processing: Joseph DePasquale (STScI)

Hubble has also partnered with other telescopes to fully exploit the power of gravitational lenses. In 2023, Hubble and the James Webb Space Telescope combined observations to explore the immense galaxy cluster MACS0416. Hubble's visible-light view paired with Webb's infrared-only view to identify both lensed supernovae and even some individual stars — including one potential star that had been magnified around 4,000 times.

As telescope detectors continue to improve, gravitational lensing will enhance observations across observatories, capturing everything from magnified radio waves to gamma radiation — and even gravitational waves. Gravitationally lensed observations made in tandem with multiple observatories may open the door in the next five to 10 years to a vast treasure trove of discoveries about the nature of gravity, the expansion of the universe, the composition of dark matter, how objects like black holes form, and the evolution of immense explosions called kilonovae, among other cosmic riddles. Einstein's "little calculation" may end up helping to write the next chapters on some of the biggest astronomical questions of our time.

More Information

For more information about the Hubble Space Telescope mission and its discoveries, visit NASA's Hubble website at nasa.gov/hubble. Follow Hubble's exploration of gravitational lenses and other astronomical phenomena at the following social media sites.

Credits

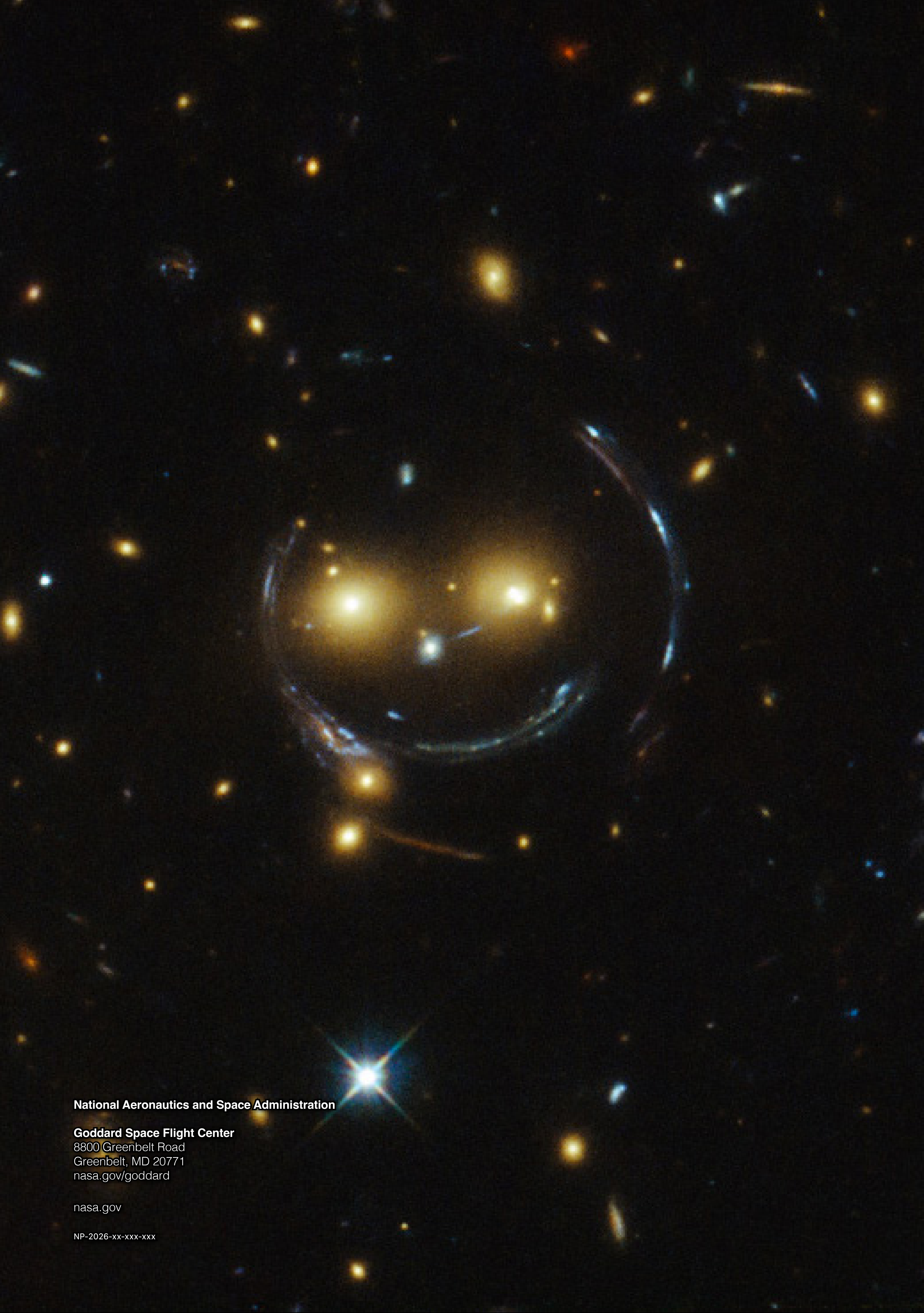
The Hubble Space Telescope is a cooperative project between the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA). The Hubble Space Telescope Operations Project at the NASA Goddard Space Flight Center (GSFC) manages the mission. The Space Telescope Science Institute (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.

Hubble Focus: Nature's Giant Telescopes was produced by the Hubble Space Telescope Project at GSFC. It was published in **Month and Year**.

This book was produced by NASA at the Goddard Space Flight Center. The production team included Tracy Vogel (writer) and Michelle Belleville (layout and epub designer), Ken Carpenter and Jennifer Wiseman (science advisors), Ray Villard/STScI, Kevin Hartnett, James Jeletic, and Andrea Gianopoulos (editors).

Cover image: An alignment of a trio of galaxies creates a gravitational lens effect called an Einstein ring. The trio consists of an elliptical galaxy whose core (center of the ring) is surrounded by a haze of stars, a second galaxy (intersecting the ring), and finally the distant, lensed galaxy -- which appears as a warped crescent of light.

ESA/Hubble & NASA, H. Nayyeri, L. Marchetti, J. Lowenthal



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