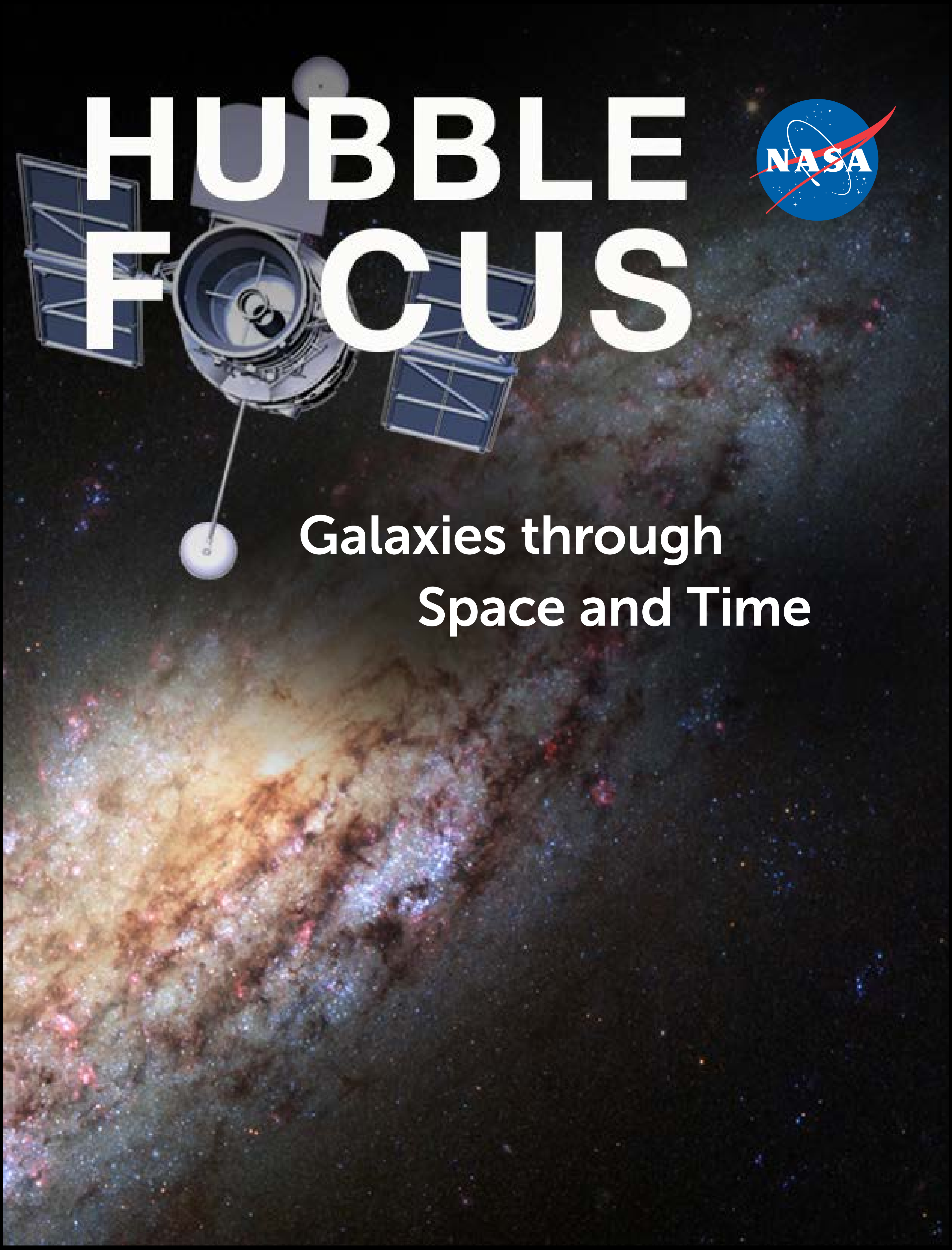
HUBBLE FOCUS

Galaxies through Space and Time



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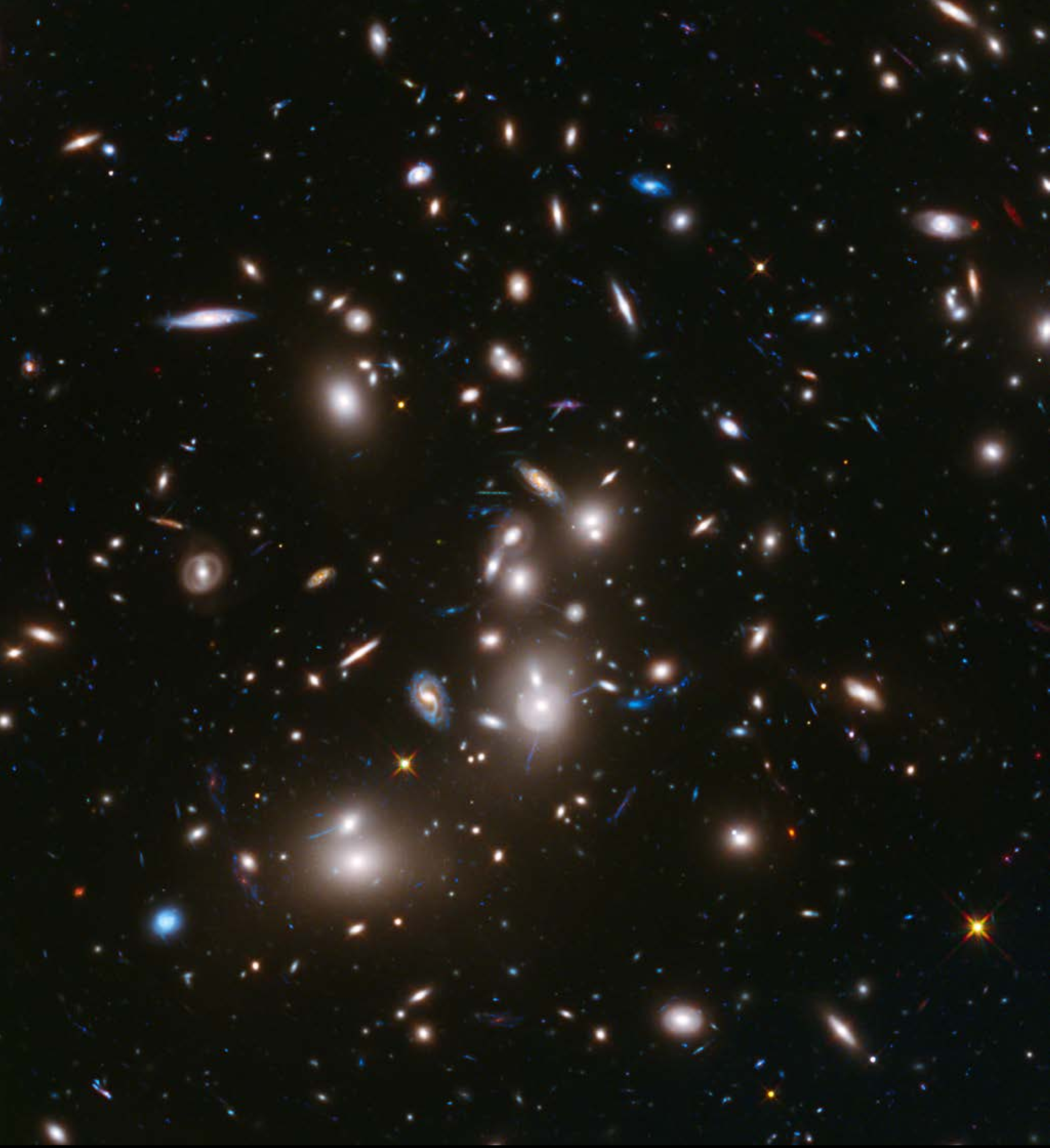


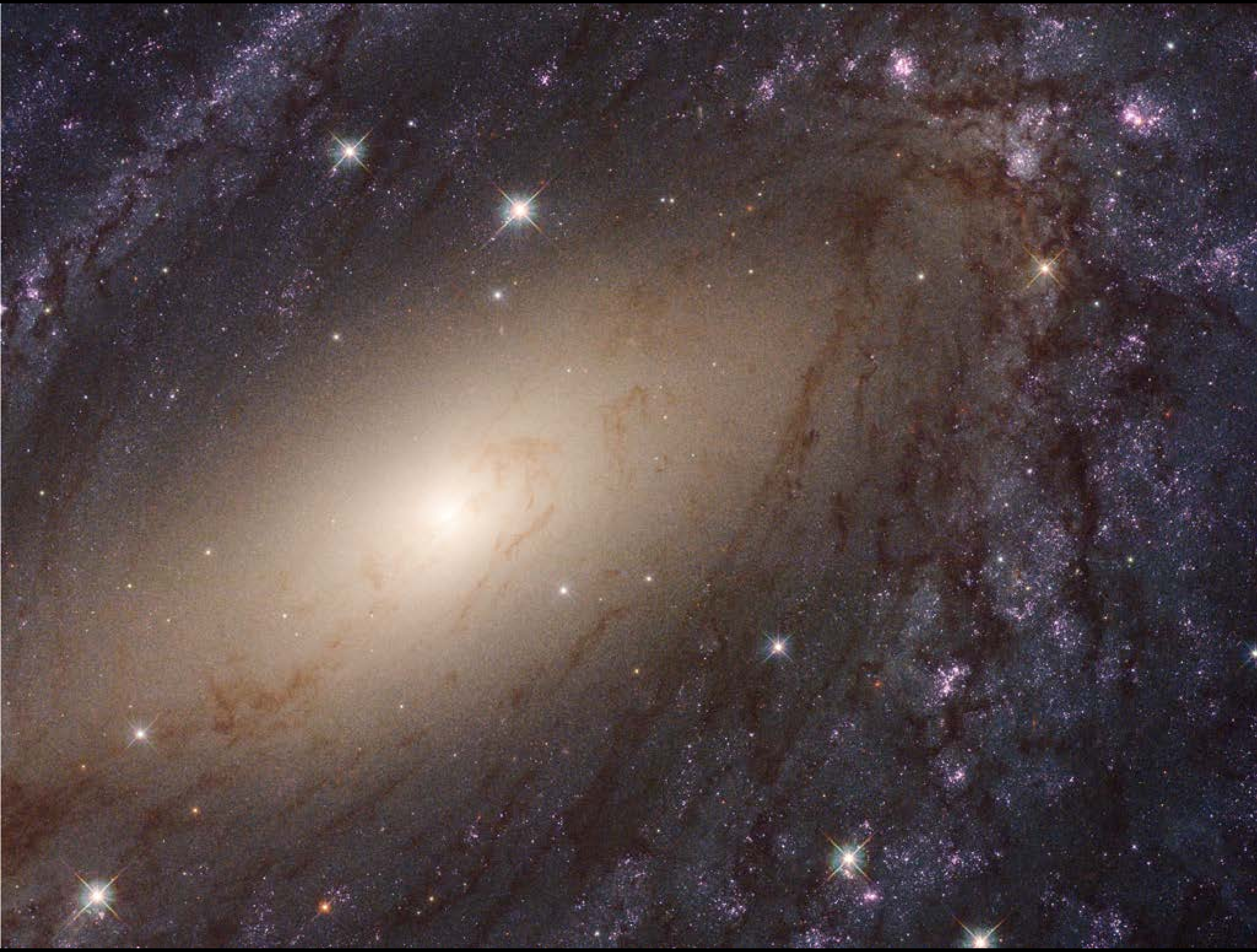
This deep *Hubble* image captures many of the hundreds of galaxies that belong to the massive galaxy cluster Abell 2744, located 3.5 billion light-years from Earth. In the background are small, faint galaxies that lie even farther in the distance, some more than 12 billion light-years away.

Credit: NASA, ESA, and J. Lotz, M. Mountain, A. Koekemoer, and the *Hubble* Frontier Fields Team (STScI)

INTRODUCTION

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

This book, *Hubble Focus: Galaxies through Space and Time*, highlights some of *Hubble*'s recent discoveries about the homes of stars, nebulas, and planets: galaxies—from our very own galaxy, the Milky Way, to the most distant galaxies anyone has ever seen. *Hubble*'s recent contributions are often in partnership with other space telescopes as well as those on the ground, and build on decades of discoveries that came before *Hubble*'s launch. Its findings are helping us understand how our universe has come to be the way it is today.



Sparkling with new star formation, spiral galaxy NGC 6744 is similar in shape to our Milky Way galaxy but is more than double the size.

Credit: NASA, ESA, and the Legacy ExtraGalactic UV Survey (LEGUS) team

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 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 nebulas, 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 the smoothest optical mirror ever polished, with no deviations greater than one-millionth of an inch.

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 well beyond 2020.

Astronauts John Grunsfeld and Andrew Feustel replace a Fine Guidance Sensor on *Hubble* during the last servicing mission in May 2009.

Credit: NASA

Our Understanding of Galaxies: A Timeline

Galaxies are cosmic islands of stars, planets, nebulas, gas, dust, and dark matter that are separated from one another in space but collectively help to tell the story of the universe. With the *Hubble Space Telescope*, we have begun to understand galaxies as time capsules that chronicle how the universe evolved, from the birth of stars within them to the buildup of immense galaxy clusters. However, this modern realization of the cosmic role and significance of galaxies, including our own, took centuries to emerge.

1610

Italian scientist Galileo Galilei uses a newly invented instrument—the telescope—to resolve the band of light running across the night sky, known as the Milky Way, into myriad stars that he presumes must be at a great distance.

1750

English astronomer Thomas Wright speculates that some fuzzy patches in the night sky called nebulae (or nebulas) are external galaxies like the Milky Way, far beyond our own.

1771

French comet-hunter Charles Messier publishes the first version of his catalog of non-stellar objects, which eventually includes over three dozen galaxies even though he has no idea of their nature or great distances.

1845

William Parsons, Ireland's third Earl of Rosse, uses the world's largest telescope of the time to resolve spiral nebulae such as M51 (known today as the Whirlpool galaxy). Astronomers largely assume it is a nearby whirlpool of gas because no stars can be resolved.

1920

At the Great Debate, held before a public audience in Washington, DC, astronomers Harlow Shapley and Heber Curtis argue whether spiral nebulae are part of our galaxy or outside of it.

1924

American astronomer Edwin Hubble publishes a paper demonstrating that M31, known then as the Andromeda Nebula, lies far outside our own galaxy. He later develops an evolutionary sequence of galaxy types in an attempt to organize his observations. *Hubble* also uses galaxies as "markers of space" to measure the expansion rate, and hence the age, of the universe.

1932

Studies of galaxy motion (building on earlier studies of stellar motion) provide evidence that an invisible form of matter, later dubbed dark matter, dominates the universe. Galaxies contain only a small fraction of the mass in the universe.

1964

The discovery of the cosmic microwave background provides observational evidence for the Big Bang hypothesis. This means that galaxies must have evolved from a hot and dense fireball.

1970s

Astronomers Vera Rubin and Kent Ford confirm the existence and dominance of dark matter in galaxies by measuring the motions of stars within.

1990

NASA's Cosmic Background Explorer (COBE) reveals minor temperature fluctuations in the early universe that led to the amalgamation of matter and the formation of early galaxies.

1994

Hubble confirms the existence of a supermassive black hole in the core of galaxy M87. Subsequent *Hubble* surveys find that such black holes are common to galaxies and that a black hole's mass correlates with the mass of its parent galaxy.

1995

The *Hubble* Deep Field finds thousands of galaxies, including many very distant ones, in a comparatively blank-looking patch of sky.

1996

High-resolution imaging from *Hubble* definitively shows that brilliant objects known as quasars are located at the cores of faint, distant galaxies. Many quasar host galaxies interact with neighboring galaxies, which fuels activity near supermassive black holes at galactic cores.

1998

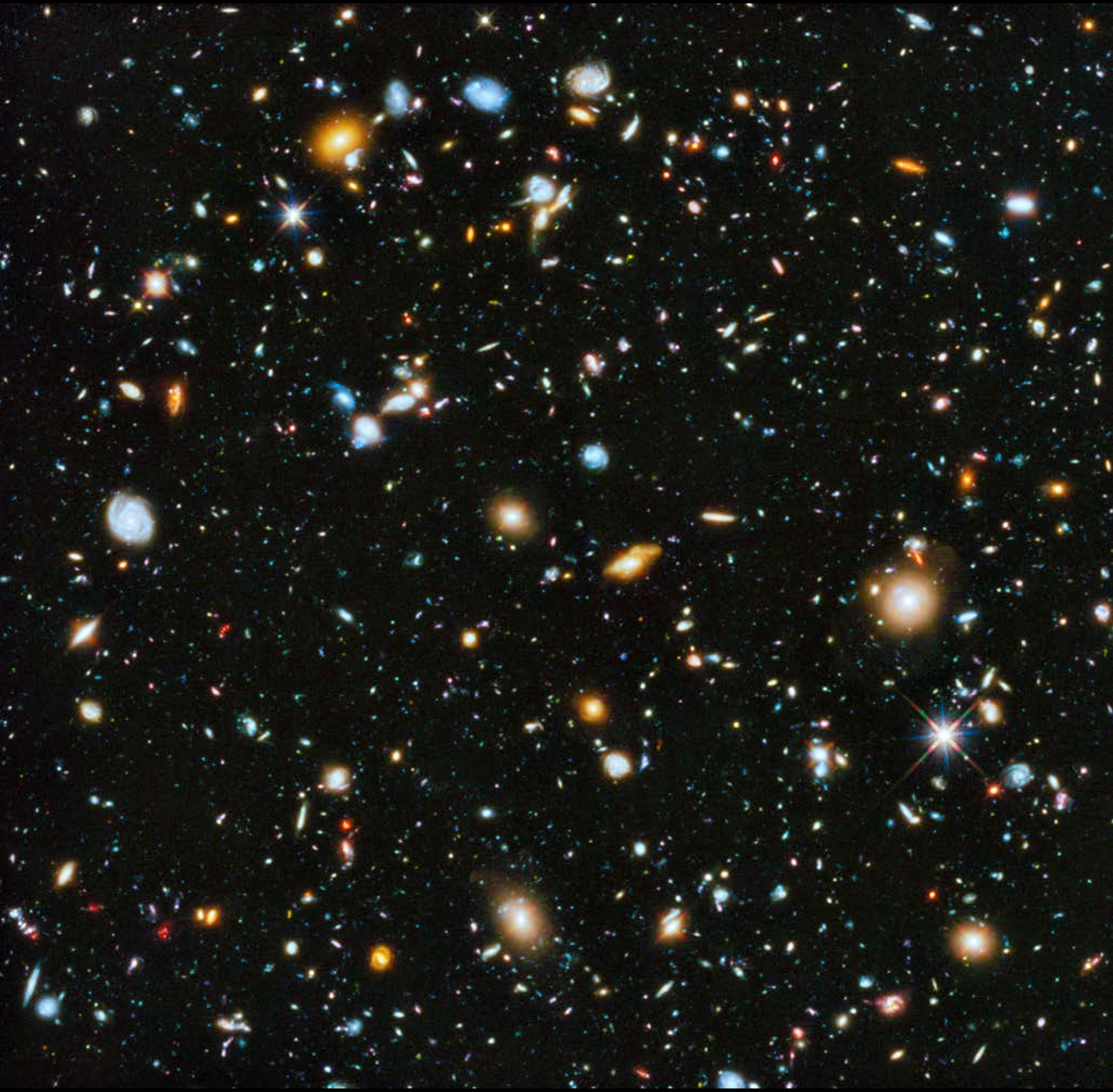
Observations of supernovas in distant galaxies show that the expanding universe is accelerating. Astrophysicists hypothesize that this is caused by an unknown form of energy, labeled "dark energy," that permeates all of space, pushing the galaxies farther apart at an ever-increasing rate.

2003

NASA's Wilkinson Microwave Anisotropy Probe (WMAP) produces an even higher-quality map of the cosmic microwave background showing fine structure in the early universe, which led to the distribution of mass and galaxies observed in the universe today.

2014

A ten-year compilation of observations allows astronomers to assemble the most comprehensive picture of the evolving universe, spanning ultraviolet to near-infrared wavelengths, in a small patch of sky known as the *Hubble* Ultra Deep Field.



This image of the *Hubble* Ultra Deep Field, released in 2014, is a colorful and comprehensive view of the evolving universe, capturing approximately 10,000 galaxies seen across space and time. The image combines *Hubble* observations taken in visible, infrared, and ultraviolet light between 2002 and 2012.

Credit: NASA, ESA, H. Teplitz and M. Rafelski (IPAC/Caltech), A. Koekemoer (STScI), R. Windhorst (Arizona State University), and Z. Levay (STScI)

CHAPTER 1: Our Galactic Neighborhood

A mere century ago, most astronomers believed that everything we could see in the night sky belonged to one galaxy, our own Milky Way. Yet, there were doubts. Some suspected that fuzzy patches of light known as nebulas were actually distant "islands of stars" far beyond our galaxy. Still, no one knew for sure until 1923, when Edwin Hubble used the world's largest telescope, perched atop Mount Wilson in California, to measure the distance to the Great Andromeda Nebula, proving that it was much too far away to belong to our galaxy.

The Andromeda galaxy, as we know it today, is the Milky Way's biggest galactic neighbor. The Milky Way and Andromeda are actually the largest members of the Local Group, a collection of nearby galaxies bound together by gravity. These two companions are spiral galaxies, each sporting star-filled arms that wrap around a bright, dense core of older stars. And each is surrounded by a number of small, oddly shaped satellite galaxies known as irregular dwarf galaxies. Observations made with *Hubble* and other telescopes suggest that spiral galaxies such as the Milky Way and Andromeda grew as dwarf galaxies merged, and that they continue to grow larger even now by pulling in and absorbing these smaller galactic satellites.

In fact, the Milky Way and Andromeda galaxies are on a collision course of their own, fated to crash into each other and unite into an even larger galaxy billions of years in the future. Computer simulations fed by *Hubble* observations of Andromeda's motion show that the dramatic encounter, predicted to begin four billion years from now, will be a head-on impact, flinging our Sun and its planets into a different part of the galaxy, and taking about two billion years to eventually settle into the much larger, oval-shaped, elliptical galaxy.

More than 7,000 *Hubble* exposures were combined to create this grand mosaic of a portion of the Andromeda galaxy. Even though the galaxy is 2.5 million light-years away, *Hubble*'s view resolves individual stars in the galaxy's disk—more than 100 million of which are captured here.

Credit: NASA, ESA, J. Dalcanton, B.F. Williams, and L.C. Johnson (University of Washington), the PHAT team, and R. Gendler

These two spiral galaxies are similar to the Milky Way and Andromeda, but they look quite different from each other. That's because the galaxy on the left (called NGC 4302) is turned to the side so we see it edge-on, while the one on the right (NGC 4298) appears face-on so we get a full view of its spiral shape.

Credit: NASA, ESA, and M. Mutchler (STScI)

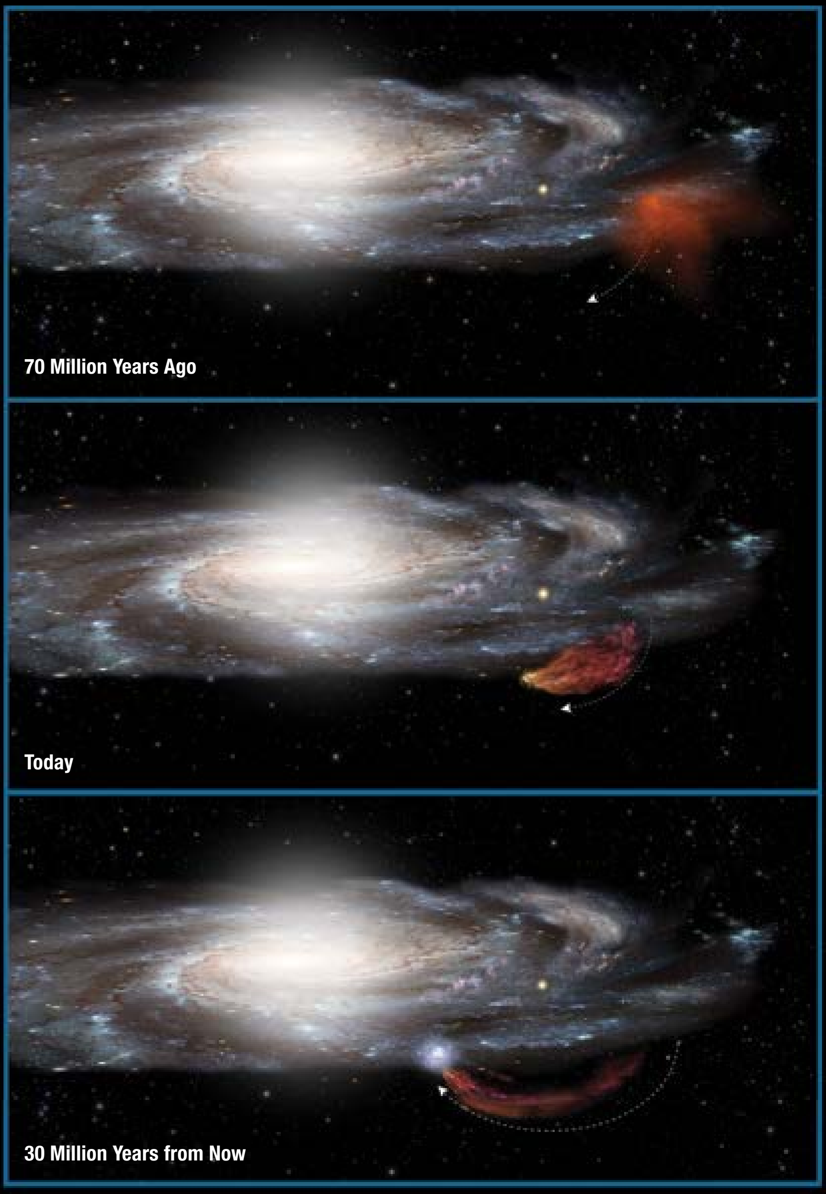
Seeking the Source of Falling Gas

An invisible but immense cloud of gas is plummeting toward our galaxy at nearly 700,000 miles per hour, but until recently, astronomers did not know where it was coming from. Named the Smith Cloud after astronomy student Gail Smith, who discovered it in the 1960s, the comet-shaped clump of gas is an estimated 11,000 light-years long and 2,500 light-years across. Astronomers suspected it might be a failed, starless galaxy, or gas falling into the Milky Way from intergalactic space. However, when they called upon *Hubble* to study its composition, they found that it was not likely to be either one of those things.

By using *Hubble* to examine the light from distant galaxies that filtered through the Smith Cloud, astronomers found out that the cloud has just as much sulfur as the outer part of the Milky Way's disk. This was surprising, because that much sulfur can only be supplied by previous generations of stars, which would not have existed in a cloud of pristine hydrogen from outside our galaxy or in the remnant of a failed galaxy lacking stars. The likeliest explanation is that the gas was ejected from the Milky Way itself about 70 million years ago and is now on a return collision course. Astronomers expect the gas cloud to plow into the Milky Way's disk in about 30 million years. When it does, it will likely ignite a spectacular burst of star formation, perhaps providing enough gas to forge 2 million suns. *Hubble*'s observations are helping astronomers understand how our galaxy is recycling material and continuing to evolve.

"The Milky Way is a bubbling, very active place where gas can be thrown out of one part of the disk and then return back down into another."

Andrew Fox, Space Telescope Science Institute



These panels illustrate the trajectory of the Smith Cloud, from when it left the Milky Way's disk, through today, and to when it will return to the disk in the future.

Illustration credit: NASA, ESA, and A. Feild (STScI)

Learn more:
https://hubblesite.org/contents/news-releases/2016/news-2016-04.html

PIERCING THE MILKY WAY'S HEART

Using its infrared vision, *Hubble* pierced the dust-enshrouded heart of our Milky Way galaxy to reveal more than half a million stars at its core, some 27,000 light-years away. By using *Hubble* to study the motions of some of these stars over four years, astronomers were able to calculate the mass and structure of the stars packed into this central region. The incredibly dense area is so full of stars it would be like having a million suns crammed into the space between our Sun and its closest neighbor, Alpha Centauri, 4.3 light-years away. These stars surround a supermassive black hole, 4 million times as massive as our Sun, at the center of our galaxy. This movie zooms into *Hubble*'s view starting from a ground-based image of the Milky Way.

Credit: NASA, ESA, and G. Bacon (STScI)

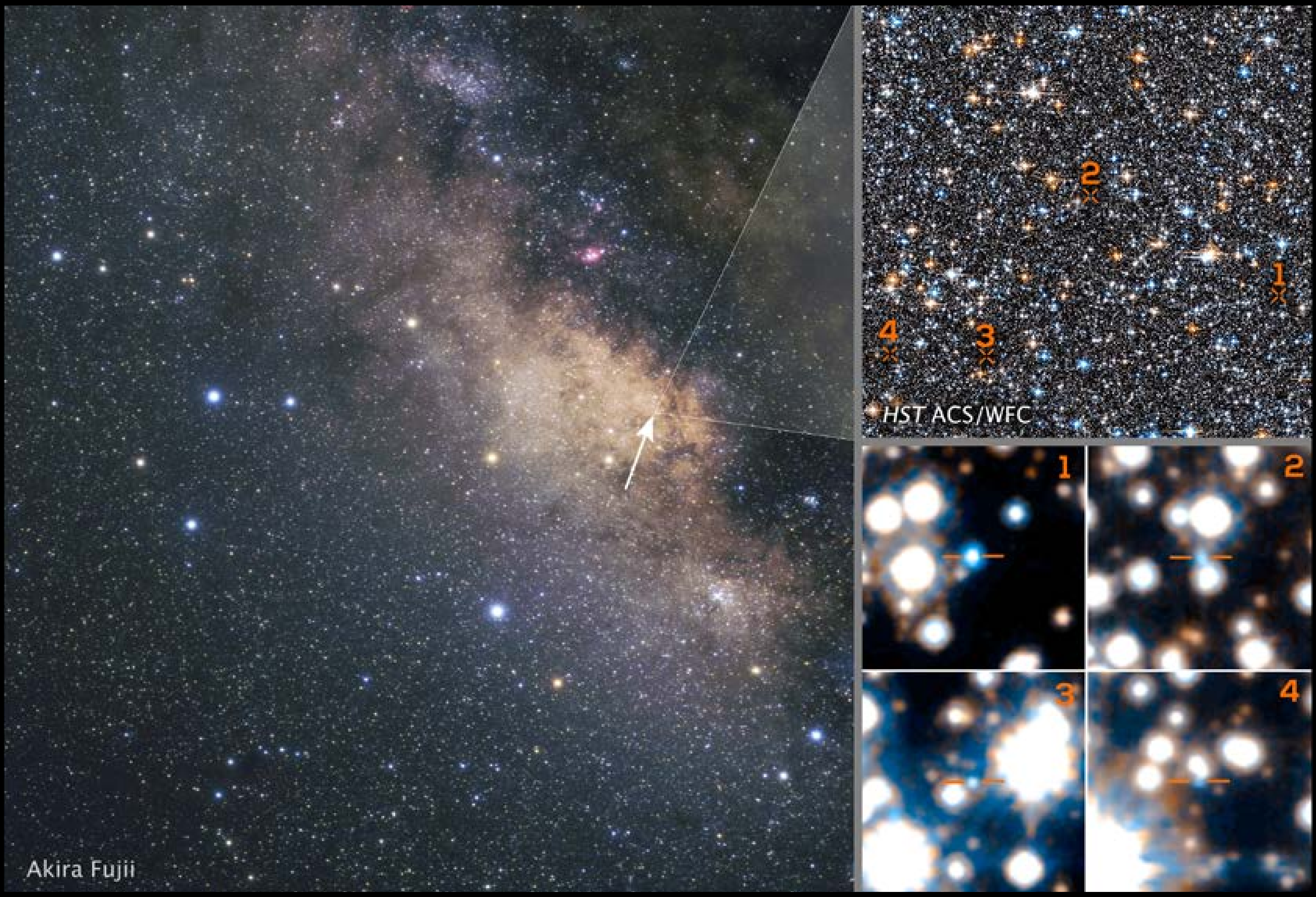
Studying Ancient Stars in the Milky Way

Conducting a "cosmic archaeological dig" at the center of our Milky Way galaxy, astronomers used *Hubble* to uncover a population of ancient white dwarfs—smoldering remnants of once-vibrant stars that inhabited the core. The observations are the deepest, most detailed study of the galaxy's foundational structure—its vast central bulge, which lies in the middle of a pancake-shaped disk of stars (where our solar system dwells). Finding these relics can yield clues to how our galaxy was built, long before our Earth and Sun formed.

Hubble's observations support the idea that the Milky Way's bulge formed before its disk did, and that the bulge's stellar inhabitants were born in a relatively quick 2 billion years or less. The rest of the galaxy's sprawling disk of second- and third-generation stars grew more slowly in the suburbs, encircling the central bulge. The *Hubble* survey also found slightly more low-mass stars in the bulge, compared to those in the galaxy's disk, suggesting that the star-birth environment in the bulge was different than it was in the disk.

"The environment in the bulge may have been different than the one in the disk, resulting in a different star-formation mechanism."

Annalisa Calamida, Space Telescope Science Institute

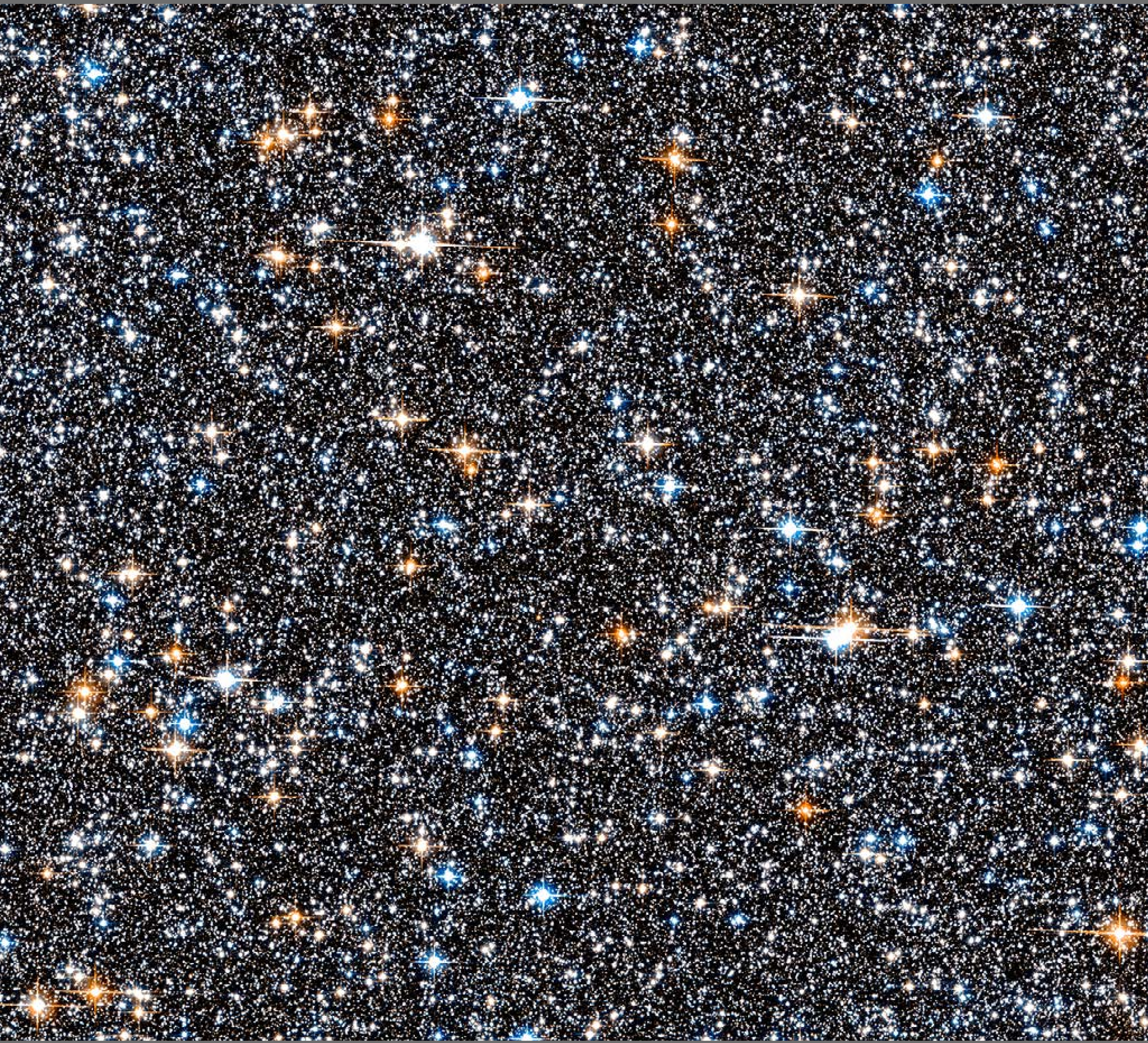


At left, a ground-based image of our Milky Way shows where *Hubble* peered in its search for white dwarfs at the center of the galaxy. *Hubble*'s image in the upper right is marked with the locations of four of the brightest white dwarfs the telescope found (shown in the lower right).

Credit: NASA, ESA, A. Calamida and K. Sahu (STScI), and the Sagittarius Window Eclipsing Extrasolar Planet Search (SWEEPS) Science Team (*Hubble* images); A. Fujii (ground-based Image)

Learn more: https://hubblesite.org/contents/news-releases/2015/news-2015-38.html

SWEEPING FOR WHITE DWARFS



Within this sparkling field of stars, astronomers identified 16 white dwarfs in the bulge of our galaxy, the Milky Way. Located 26,000 light-years away, these ancient stellar relics hold clues to how our galaxy grew and developed in its early years. This image, taken by *Hubble*'s Advanced Camera for Surveys, shows a small section of the Sagittarius Window Eclipsing Extrasolar Planet Search (SWEEPS) field. Astronomers managed to pick out the white dwarfs among all of these stars by painstakingly analyzing the motion, brightness, and color of individual stars.

Credit: NASA, ESA, A. Calamida and K. Sahu (STScI), and the SWEEPS Science Team

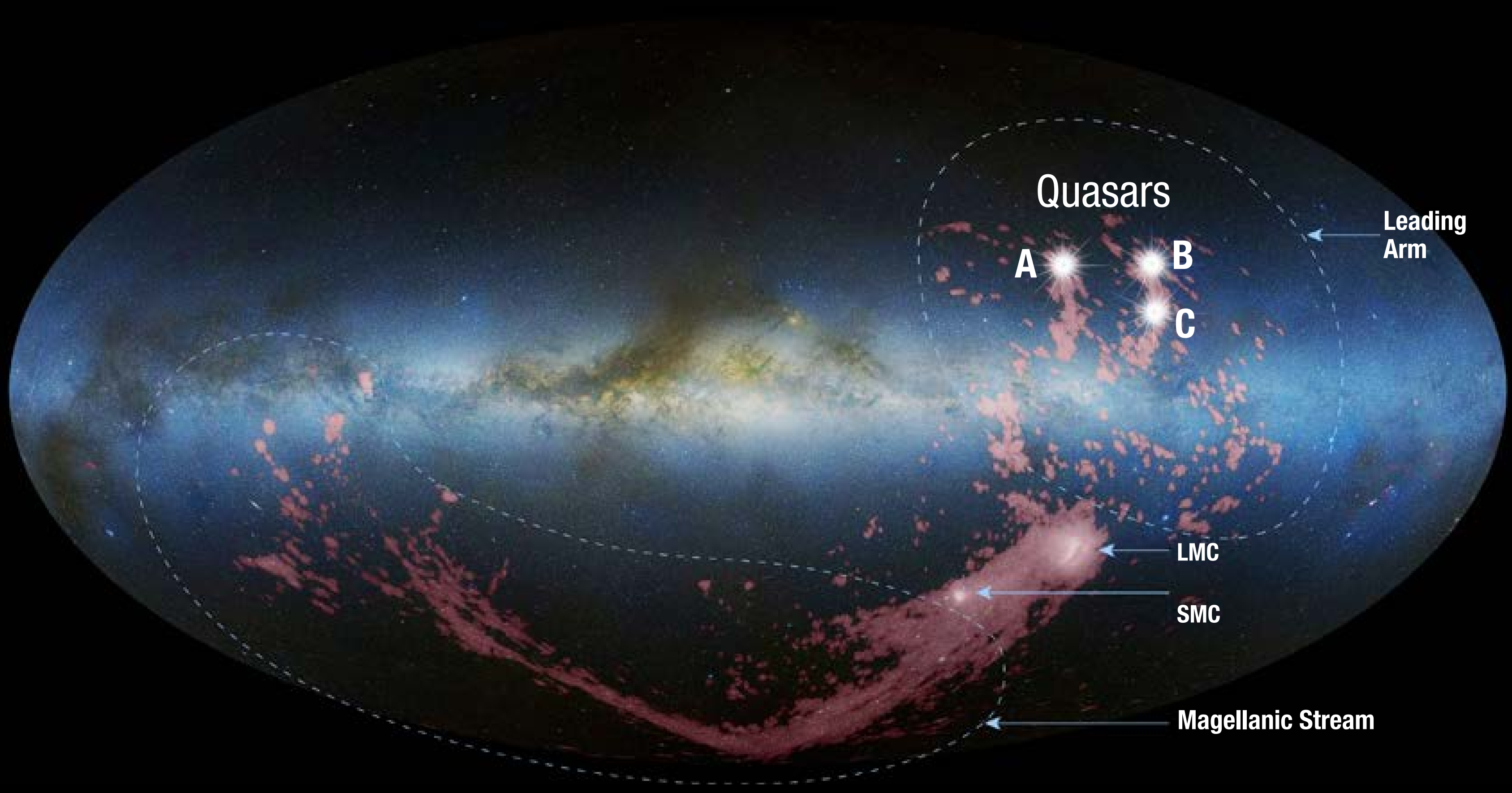
Tracing the Origin of an Intergalactic Cloud

Just beyond the edges of our galaxy, two nearby dwarf galaxies are engaged in a cosmic tug-of-war. These galaxies, the Large Magellanic Cloud and Small Magellanic Cloud, orbit our Milky Way and gravitationally pull on one another as they do. Over the past billion years or two, one of the galaxies has torn a huge cloud of gas out of the other—a structure that stretches half the length of our galaxy and connects the Magellanic Clouds to the Milky Way. This cloud is supplying fresh material to our galaxy, which feeds new star formation. Astronomers call it the Leading Arm because it extends out ahead of the Magellanic Clouds in the direction of their motion. However, until recently, they did not know which of the two dwarf galaxies was responsible for pulling this gas from the other and from which galaxy the gas was coming.

Astronomers used *Hubble* to study what the Leading Arm is made of to see whether it was more like the Small Magellanic Cloud or the Large Magellanic Cloud. They analyzed the light from seven quasars (the bright cores of active galaxies) billions of light-years behind the Leading Arm. *Hubble*'s Cosmic Origins Spectrograph measured how much light was absorbed by different elements in the Leading Arm's gas. These measurements, combined with observations from the Green Bank Telescope radio observatory, suggested the gas in the Leading Arm came from the Small Magellanic Cloud, and that it was the Large Magellanic Cloud winning that gravitational tug-of-war.

"We can measure the composition and velocity of the gas to determine which dwarf galaxy is the culprit."

Kat Barger, Texas Christian University



Radio images, colored in pink, overlaid on a visible-light image of our Milky Way, show the locations of the Leading Arm (upper right), the Large and Small Magellanic Clouds (lower right), and the Magellanic Stream (bottom). Astronomers studied the light from quasars behind the Leading Arm to determine its composition and origin.

Illustration credit: D. Nidever et al., NRAO/AUI/NSF and A. Mellinger, Leiden-Argentine-Bonn (LAB) Survey, Parkes Observatory, Westerbork Observatory, Arecibo Observatory, and A. Feild (STScI)

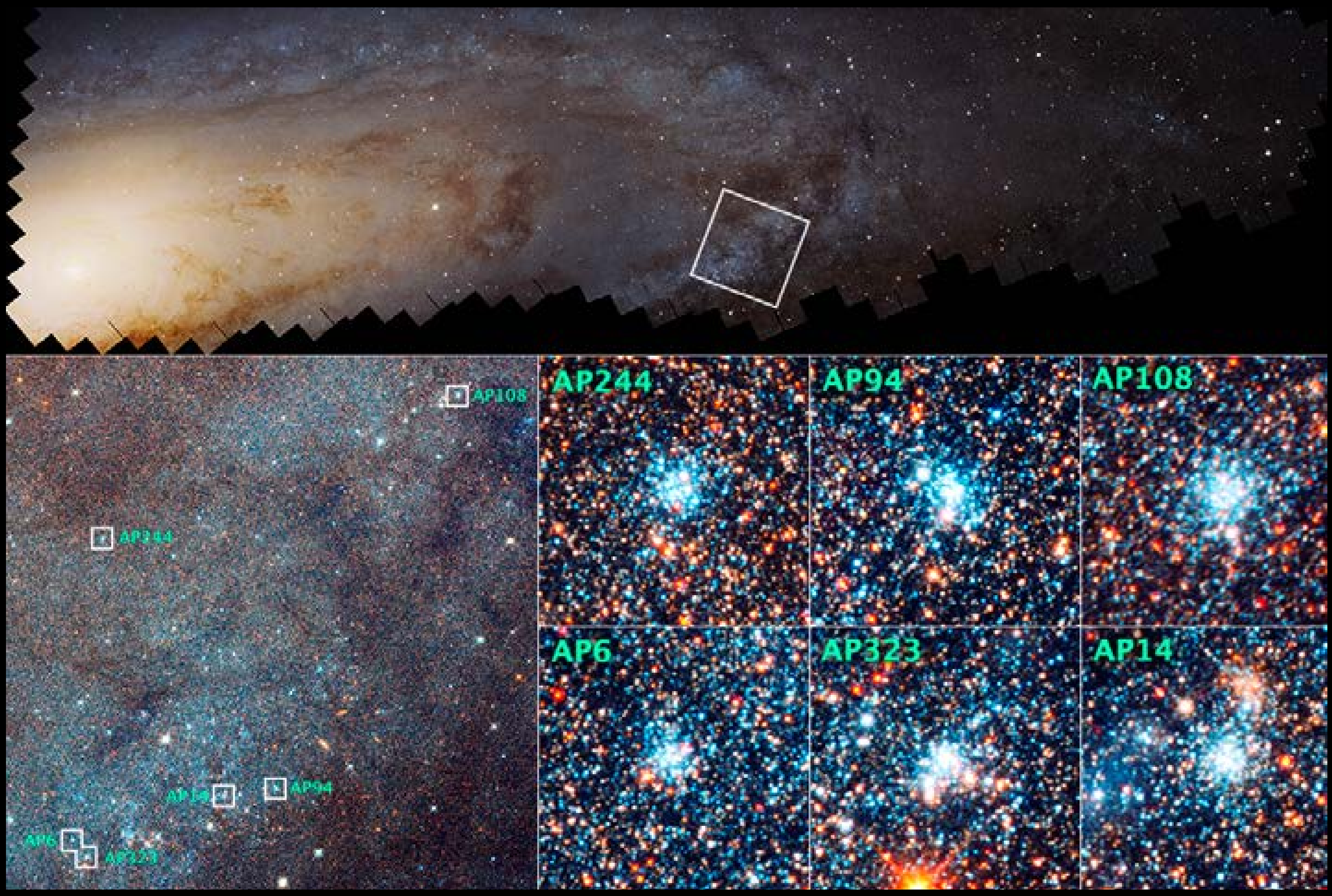
Learn more: https://hubblesite.org/contents/news-releases/2018/news-2018-15.html

Surveying Star Clusters in the Andromeda Galaxy

A detailed *Hubble* survey of our largest galactic neighbor, the Andromeda galaxy, allowed astronomers to make a surprising discovery: the percentages of massive stars and low-mass stars in Andromeda's star clusters are similar to what's found in our Milky Way. This suggests that the universe follows a formula when creating new stars, producing a consistent distribution of stellar types, from massive blue supergiants to small red dwarfs, every time. Astronomers did not expect this stellar-mass ratio to be so similar in both galaxies, given the complex physics involved in star formation. This insight will help them better interpret the light from distant galaxies and understand how stars formed throughout the universe's history.

The Panchromatic *Hubble* Andromeda Treasury (PHAT) program captured nearly 8,000 images of 117 million stars and 2,753 young, blue star clusters in the Andromeda galaxy. Astronomers recruited the help of 30,000 "citizen scientist" volunteers, who sifted through the thousands of *Hubble* images to search for these star clusters, which range in age from 4 million to 24 million years old. One specific finding from the analysis was that the most massive stars in the clusters are 25 percent less abundant than previously predicted. This implies that astronomers were underestimating the number of smaller stars forming alongside the massive stars and thus underestimating the masses of distant star clusters and galaxies. The results also indicate that the early universe did not have as many heavy elements for making planets, because there were fewer supernovas from massive stars to produce those elements.

> "Given the sheer volume of *Hubble* images, our study … would not have been possible without the help of citizen scientists."
>
> **Daniel Weisz, University of Washington**



The sweeping panorama of the nearby Andromeda galaxy at top spans more than 61,000 light-years of our galaxy's large neighbor. A box shows a small region of the galaxy where six star clusters are highlighted in the lower left. Close-up views of those star clusters appear in the lower right.

Credit: NASA, ESA, J. Dalcanton, B.F. Williams, and L.C. Johnson (University of Washington), the PHAT team, and R. Gendler

Learn more: https://hubblesite.org/contents/news-releases/2015/news-2015-18.html

ZOOMING IN TO A MASSIVE MOSAIC

More than 7,000 *Hubble* exposures were combined to create a grand mosaic of a portion of the Andromeda galaxy. Even though the galaxy is 2.5 million light-years away, *Hubble*'s view resolves more than 100 million individual stars in the galaxy's disk. This movie begins with a wide view of the sky and zooms in to reveal some of the individual stars *Hubble* saw within the galaxy.

Credit: NASA, ESA, and G. Bacon (STScI); Acknowledgment: A. Mellinger, Digitized Sky Survey (STScI/AURA, Palomar/Caltech, and UKSTU/AAO), J. Dalcanton (University of Washington), the PHAT team, and R. Gendler

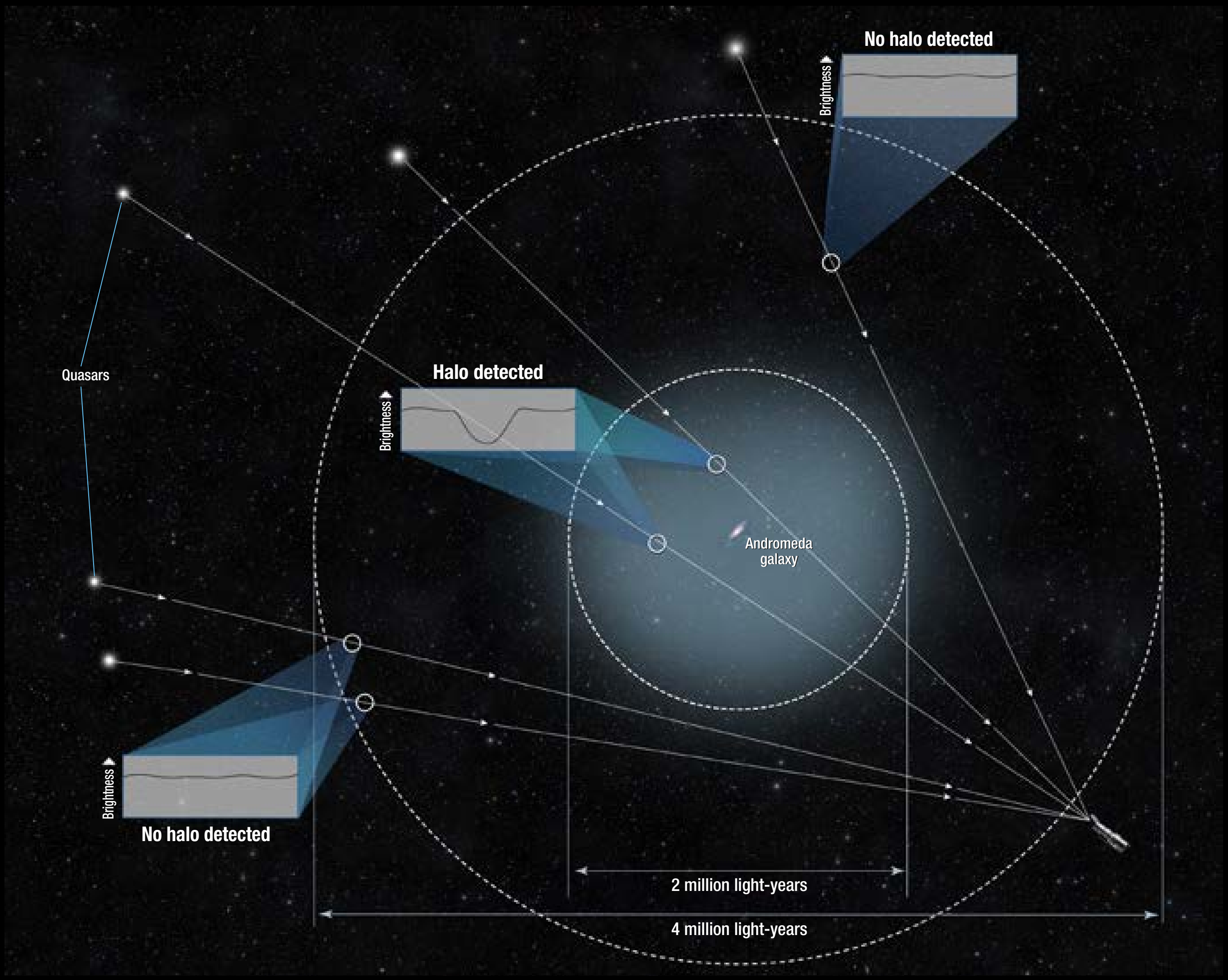
Measuring a Giant Halo around the Andromeda Galaxy

Analyzing five years' worth of archived *Hubble* observations, astronomers discovered that the immense halo of gas enveloping the Andromeda galaxy is about six times larger and a thousand times more massive than previously thought. The dark, nearly invisible halo stretches about a million light-years from its host galaxy, halfway to our own Milky Way galaxy. There is so much hot gas in this immense halo that its mass is half that of all the stars in the galaxy itself. If it could be viewed with the naked eye, the halo would be 100 times the diameter of the full Moon in our sky.

However, the gas in Andromeda's halo is dark. So astronomers used *Hubble* to study quasars—the bright cores of distant galaxies—located behind Andromeda to see how the quasar light was affected as it passed through the gas. By measuring how much a quasar's light is dimmed at certain wavelengths, astronomers could determine how much gas is in Andromeda's halo between us and the quasar. In addition to determining the size and mass of the halo, astronomers also determined that it is enriched in elements much heavier than hydrogen and helium, which only come from exploding stars called supernovas. These findings offer more insight about the evolution and structure of giant spiral galaxies, one of the most common types of galaxies in the universe.

"The properties of these gaseous halos control the rate at which stars form in galaxies."

Nicolas Lehner, University of Notre Dame



This diagram illustrates how astronomers determined the size of the halo around the Andromeda galaxy. When light from a distant quasar passed through the halo, *Hubble* saw that some of the light was absorbed. When light did not pass through the halo, there was no absorption.

Illustration credit: NASA, ESA, and A. Feild (STScI)

Learn more: https://hubblesite.org/contents/news-releases/2015/news-2015-15.html

CHAPTER 2:
Intriguing Galaxies across the Universe

Hubble's exceptional views of the cosmos have allowed astronomers to examine galaxies better than they ever could before, resolving features that would otherwise elude detection. Its observations continually reveal intriguing galaxies with surprising features, both near and far, showing how different they can be from one another, but also how they relate.

Hubble, like all telescopes, is a time machine that astronomers can use to see into the past. Because light from the universe does not reach us instantly but takes time to travel vast cosmic distances, *Hubble* reveals galaxies not as they are today, but as they appeared when their light left those galaxies millions or billions of years ago. The farther the galaxy *Hubble* studies, the farther back in time it sees. Faraway galaxies are earlier versions of those seen nearby. By observing galaxies at a range of distances, *Hubble* helps astronomers piece together the story of how galaxies have evolved over time.

In addition, each galaxy has a story to tell about its own history and ongoing evolution. Some galaxies observed by *Hubble* divulge secrets about the role supermassive black holes play at the hearts of their galactic hosts. Others tell a tale of how stars there were born, lived, and died, and how intergalactic encounters can spark new episodes of stellar birth. Some exhibit different stages of collisions, as they merge to form new, even larger galaxies. Still other galaxies show how they can assemble into gigantic clusters, creating the largest objects in the universe bound together by gravity.

UGC 12591 is a kind of galactic hybrid, a cross between two types of galaxies. It features a large, diffuse bulge of stars like a so-called lenticular galaxy, but has dark dust lanes that wrap around like spiral arms. Dozens of galaxies lie in the background, farther in the distance.

Credit: ESA/*Hubble* & NASA

The spiral galaxy NGC 3344, located about 20 million light-years away, tells a colorful, ongoing story of star formation in this *Hubble* portrait. Pockets of pink-colored gas are the crucibles where stars are being born. Patches of blue shine with the light of hot, young stars that burst to life in the not-too-distant cosmic past. The yellowish heart is home to the galaxy's oldest stars.

Credit: ESA/*Hubble*, NASA

Excavating a Prehistoric Galaxy in Our Cosmic Backyard

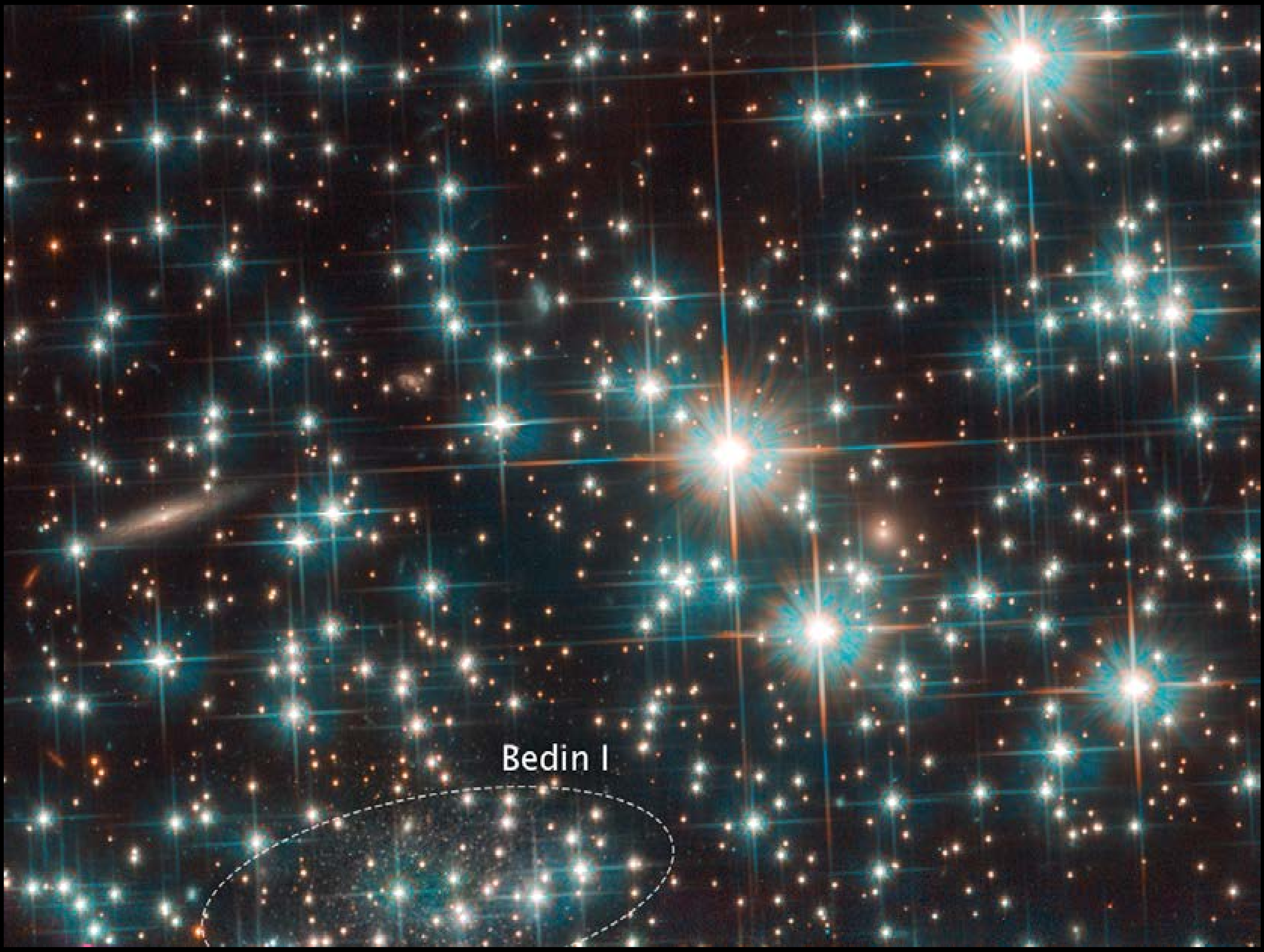
While using *Hubble* to study stars within one of our own galaxy's star clusters, astronomers stumbled across something they did not expect to find: a faint dwarf galaxy hidden behind the cluster's bright stars. Along its lengthiest dimension, the dwarf galaxy spans only 3,000 light-years, which is 30 times smaller than our Milky Way galaxy. It is also about a thousand times fainter than the Milky Way.

Nicknamed Bedin I (after the leader of the discovery team), the galaxy resides a mere 30 million light-years away, which is not very far beyond our Local Group of galaxies.

Bedin I appears to be relatively isolated, at least 2 million light-years from the nearest large galaxy. Its stellar population suggests the dwarf galaxy is also very old—about 13 billion years of age, or nearly as old as the universe itself. It likely experienced a burst of star formation when it formed, but has remained quiet ever since. These qualities make Bedin I a fascinating galactic fossil from the universe's early days.

"Had the galaxy been ten times farther away, it would have been much harder to detect, even with *Hubble*."

Luigi Bedin, Astronomical Observatory of Padua



A dashed oval shows the location of the faint dwarf galaxy Bedin I, nearly concealed behind the much brighter stars of the globular cluster NGC 6752.

Credit: NASA, ESA, and L. Bedin (Astronomical Observatory of Padua, Italy)

Learn more: https://hubblesite.org/contents/news-releases/2019/news-2019-09.html

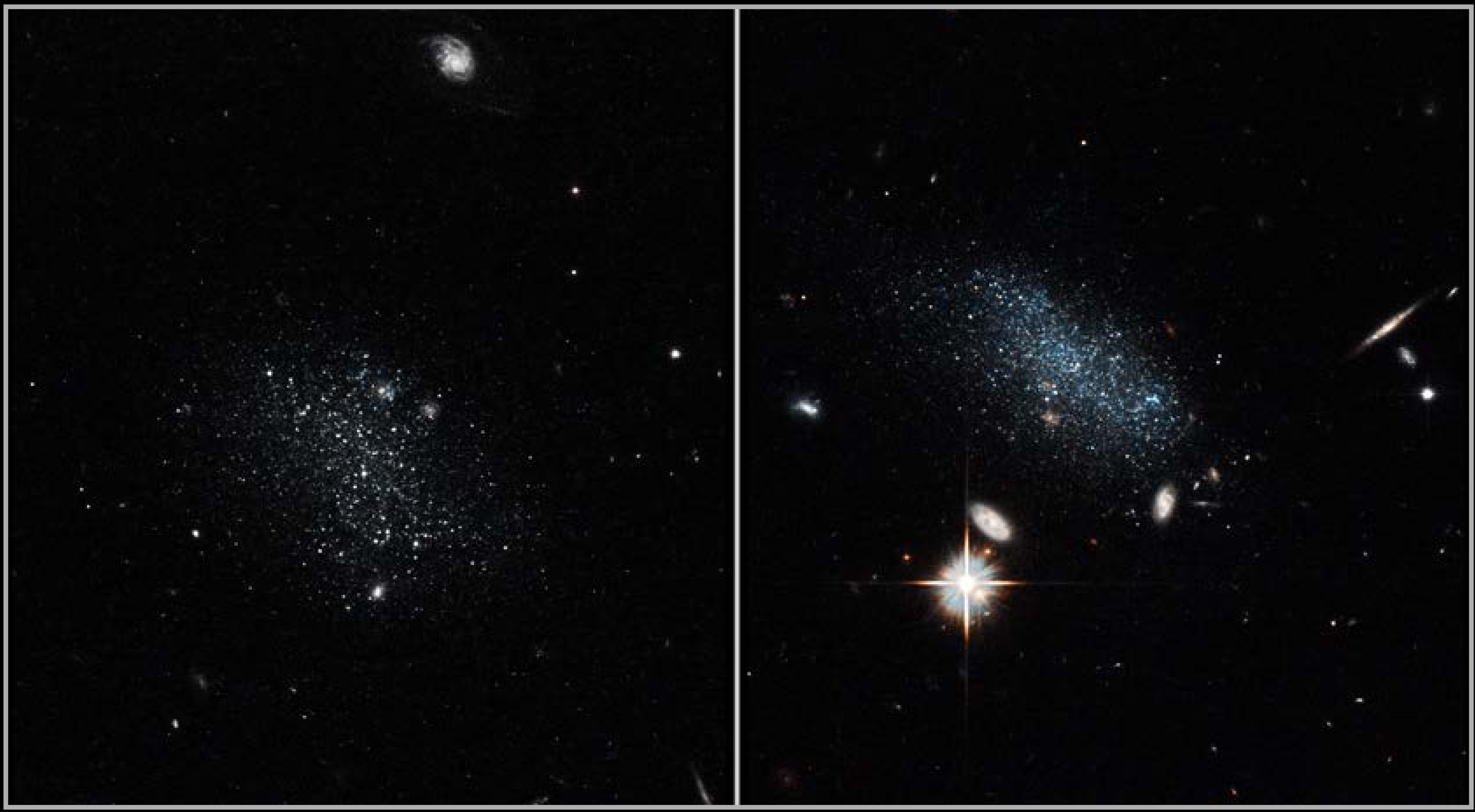
Witnessing a Rash of Star Formation in Long-Quiet Dwarf Galaxies

For billions of years, two tiny dwarf galaxies lived quiet lives out on their own in a relatively empty part of space, far from other galaxies that were growing from mergers and igniting a rush of new star formation. But less than 100 million years ago, these tranquil galaxies joined in on the action and suddenly started turning out new stars at twice their previous rate.

Called Pisces A and Pisces B, the galaxies were first detected by ground-based radio telescopes as small blobs of dense hydrogen gas. *Hubble*'s observations confirmed that they were dwarf galaxies located roughly 19 million and 30 million light-years away that only recently began forming stars in earnest. Because hydrogen is the fuel needed to make stars, the high concentrations of hydrogen in Pisces A and B provided a clue that these galaxies hadn't yet used up their hydrogen in the star formation process as more developed galaxies have. Stars often form in earnest when their host galaxy encounters a cloud of gas outside the galaxy. The lack of prior active star formation in Pisces A and B suggests they lingered in the Local Void, a region with very few galaxies and very little gas to trigger new star birth. They are now entering a more gas-rich environment and appear to be located near the edge of a filament of dense gas, which is likely interacting with the galaxies to spark their late swell of star birth.

"These galaxies may have spent most of their history in the void."

Erik Tollerud, Space Telescope Science Institute



These *Hubble* images show the dwarf galaxies Pisces A (on the left) and Pisces B (on the right), which remained dormant for much of their lives and only began forming stars in earnest less than 100 million years ago.

Credit: NASA, ESA, and E. Tollerud (STScI)

Learn more: https://hubblesite.org/contents/news-releases/2016/news-2016-29.html

STARS ARISE IN A DIMINUTIVE GALAXY

Stars are forming throughout the irregularly shaped dwarf galaxy UGC 5340. However, a region of especially intense and recent star birth appears at one end of the galaxy, in the lower right of this *Hubble* image. UGC 5340 is one of 50 nearby galaxies *Hubble* studied as part of the Legacy ExtraGalactic UV Survey (LEGUS), the sharpest, most comprehensive ultraviolet-light survey of star-forming galaxies in the nearby universe.

Credit: NASA, ESA, and the LEGUS team

Investigating New Star Birth in a Tiny 'Tadpole' Galaxy

A firestorm of star birth is lighting up one end of the dwarf galaxy Kiso 5639, located 82 million light-years away. Shaped like a flattened pancake, the galaxy is a rare nearby example of elongated galaxies that are much more common in the distant universe. *Hubble*'s Ultra Deep Field and other observations of the early universe reveal that about 10 percent of all galaxies have these elongated shapes. However, astronomers have found only a few of these tadpole-shaped galaxies in the local universe. Kiso 5639 offers a close-up look at what those earlier galaxies, which merged and grew into modern-day galaxies, were like.

Hubble provided a detailed view of the frenzy of star formation in the galaxy's head, which extends over 2,700 light-years. The telescope uncovered several dozen star clusters there that average less than a million years old and have masses three to six times greater than other clusters in the galaxy. Elsewhere in the galaxy, star formation happens at a much smaller scale, and star clusters are older, between several million and a few billion years old. Astronomers think that, less than a million years ago, Kiso 5639's leading edge encountered a filament of gas, which deposited a large clump of new material into the galaxy and sparked the vigorous star birth.

"I think Kiso 5639 is a beautiful, up-close example of what must have been common long ago."

Debra Elmegreen, Vassar College

The head of the "tadpole" galaxy Kiso 5639 blazes with the bright pink glow of hydrogen gas, where swarms of new stars are forming. Astronomers think this rash of star formation erupted when the galaxy ran into a cloud of intergalactic gas.

Credit: NASA, ESA, and D. Elmegreen (Vassar College) et al.

Learn more: https://hubblesite.org/contents/news-releases/2016/news-2016-23.html

AN ELLIPTICAL GALAXY'S ETHEREAL GLOW

The pale-white glow of stars in the enormous elliptical galaxy M86 fills most of the field of this *Hubble* image. White dots scattered throughout the scene are giant star clusters that orbit the galaxy's brilliant core. An edge-on spiral galaxy, much farther in the distance, appears as a thin, blue figure in the lower left.

Credit: NASA, ESA, STScI, and S. Faber (University of California, Santa Cruz) and P. Côté (Dominion Astrophysical Observatory)

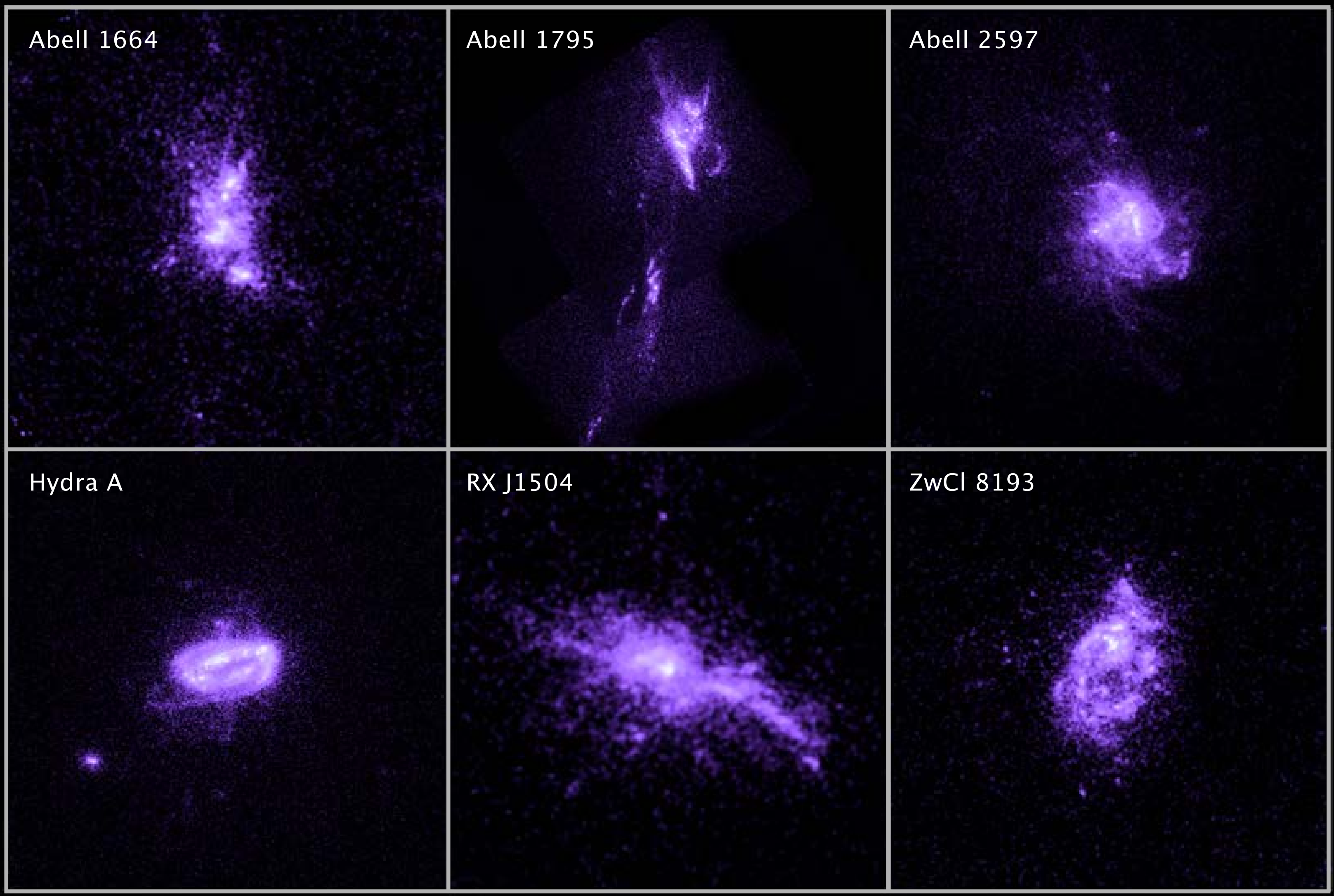
Seeing Star Formation in Elliptical Galaxies

Hubble's high resolution and ultraviolet vision have revealed brilliant knots of hot, blue stars forming along the jets of active black holes at the centers of giant elliptical galaxies. The observations help explain how the universe's largest galaxies continue making stars long after their peak star-forming years, and why they aren't forming more stars than they do.

Combining *Hubble*'s observations with those from other telescopes, astronomers found that the black hole, jets, and newborn stars in these elliptical galaxies are all parts of a self-regulating cycle. Cool gas is necessary to form stars. However, high-energy jets shooting from each galaxy's central black hole heat up a halo of surrounding gas, moderating the rate at which the gas cools and falls into the galaxy to form stars. While some outwardly flowing gas will cool, the black hole's activity heats the rest of the gas around a galaxy, which prevents the whole gaseous envelope from cooling more quickly. If the jets add too much heat, less gas cools and falls into the galaxy. Because the jets are powered by gas around the black hole, this also reduces their fuel supply and eventually weakens the jets. On the other hand, if too much cooling happens, their supply increases, the jets become more powerful, and they add more heat. This feedback system regulates the star-forming process.

"What we are seeing is a process like a thunderstorm. Some of that gas cools and precipitates into cold clumps that fall back toward the galaxy's center like raindrops."

Megan Donahue, Michigan State University

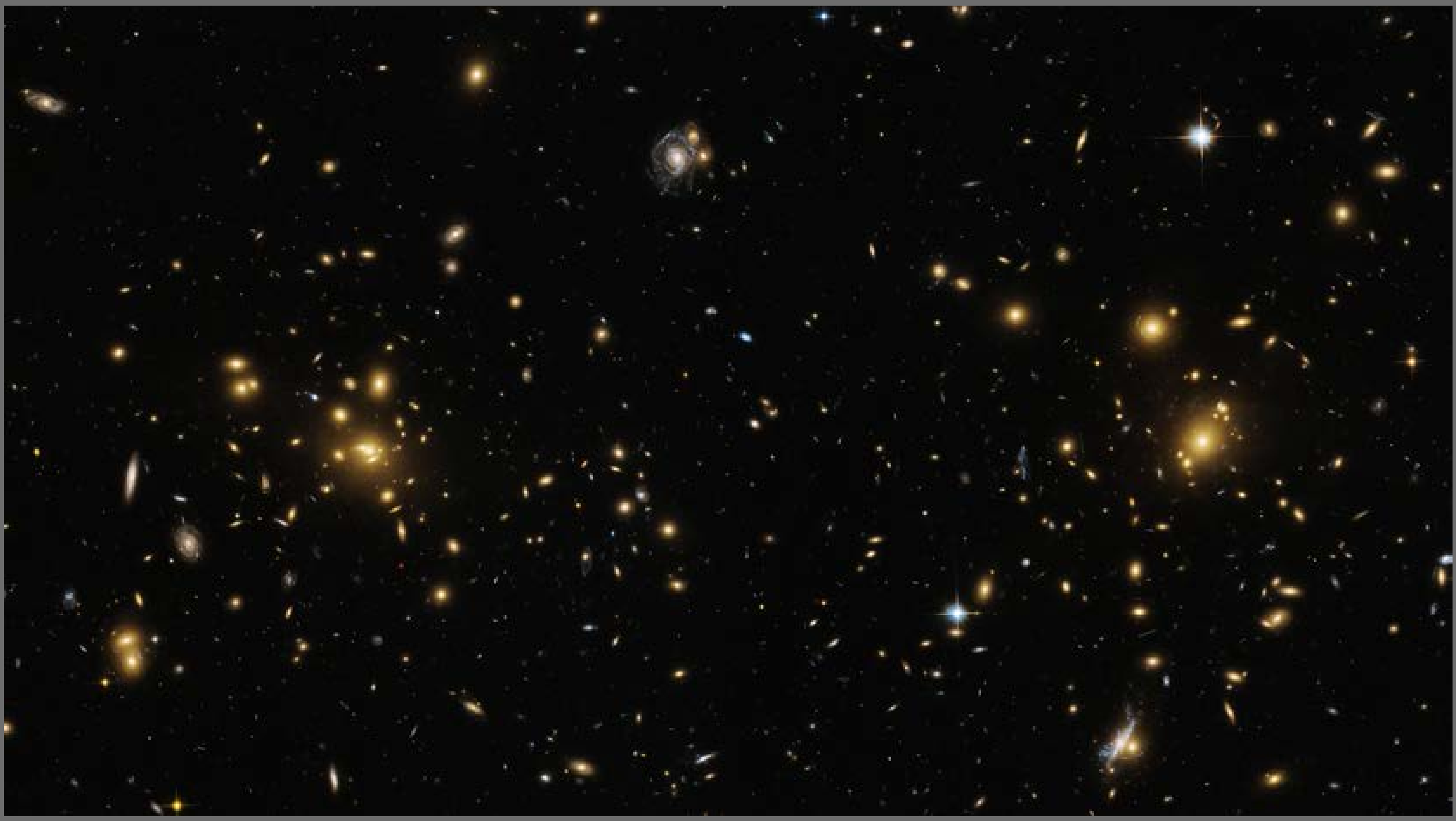


These ultraviolet *Hubble* images show chains of star formation in six elliptical galaxies.

Credit: NASA, ESA, G. Tremblay (Yale University), and R. Mittal (Rochester Institute of Technology, and Max Planck Institute for Gravitational Physics)

Learn more: https://hubblesite.org/contents/news-releases/2015/news-2015-26.html

CLUSTERS WITHIN CLUSTERS



These glowing galaxies belong to a large cluster of galaxies called Abell 1758, located 3.2 billion light-years from Earth. This *Hubble* image shows just the northern part of the cluster, known as A1758N. However, it also shows that this part of the cluster is actually made up of two sub-sections with separate concentrations on the left and right sides of the image. Disturbances seen within these sub-sections provide evidence that they have been built up by smaller galaxy clusters colliding and merging. It is likely these two sub-sections will eventually merge together as well. Investigating how clusters come together helps astronomers understand the way large cosmic structures develop.

Credit: NASA, ESA

Finding a Relic Galaxy Close to Home

Hubble turned up a nearby galaxy that has remained virtually unchanged for the past 10 billion years—providing a glimpse of what galaxies were like in the very early universe. In its early days, galaxy NGC 1277 was churning out new stars a thousand times faster than our Milky Way does today. Yet for some reason, that flurry of activity came to an early end, causing the galaxy's stars to grow older and redder. *Hubble* has seen such "red and dead" galaxies, appearing as faint crimson dots, in the distant universe, but never one so close—just 240 million light-years away. NGC 1277 gives astronomers a chance to examine one up close and better understand what galaxies might have been like billions of years ago.

Astronomers used *Hubble* to study large, spherical groupings of stars known as globular clusters on the outskirts of NGC 1277. While most massive galaxies have both metal-rich clusters (which appear red) and metal-poor clusters (which appear blue), *Hubble* found that all of the globular clusters in NGC 1277 are red and metal-rich. Astronomers believe the red clusters form with the galaxy, while the blue clusters are acquired later as the galaxy swallows up smaller, satellite galaxies. The lack of blue, metal-poor clusters suggests that NGC 1277 never kept growing by gobbling up surrounding galaxies—unlike our own Milky Way, which continues to cannibalize galaxies that come too close. In addition, the galaxy likely halted its stellar production because it was starved of fresh, outside material needed to make new stars.

"We can explore such original galaxies in full detail and probe the conditions of the early universe."

Ignacio Trujillo, Instituto de Astrofísica de Canarias at the University of La Laguna

Hubble studied a relic galaxy in the Perseus cluster 240 million light-years away that is an example of a "red and dead" galaxy that are usually seen much, much farther away. This video zooms into the galaxy, called NGC 1277.

Credit: NASA, ESA, M. Beasley (Instituto de Astrofísica de Canarias), and P. Kehusmaa

Learn more: https://hubblesite.org/contents/news-releases/2018/news-2018-17.html

AFTERMATH OF A COLLISION

This distorted galaxy, named NGC 3256, is the product of a collision that occurred roughly 500 million years ago between two spiral galaxies. The heart of the galaxy is aglow with countless newborn stars that burst to life during the merger. Starry tails that extend away from the galaxy contain young, blue stars that were born out of the colossal impact of gas and dust.

Credit: ESA/*Hubble*, NASA

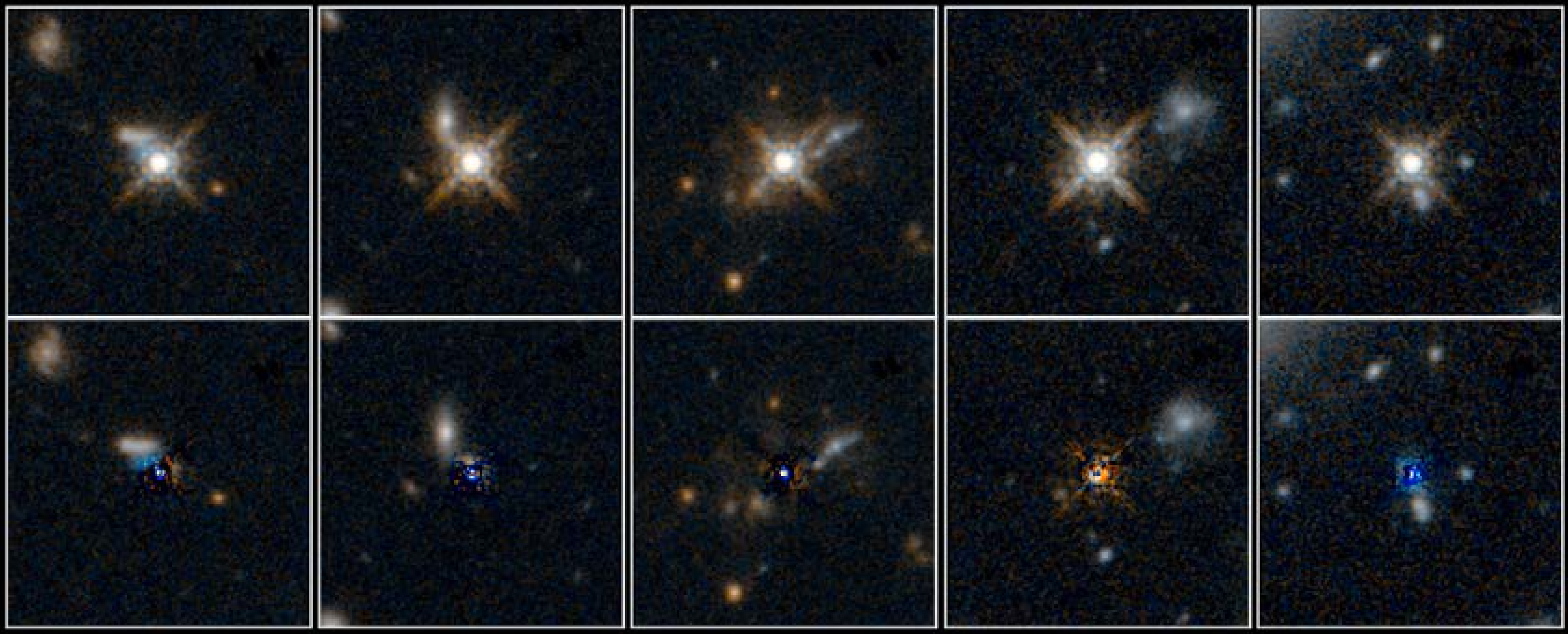
Identifying the Spark that Ignites Quasars

As the brightest beacons of the universe, quasars can shine with the light of a trillion suns and are powered by over-fed supermassive black holes at the cores of distant galaxies. Yet how are these cosmic blazes ignited? Astronomers had theorized that mergers between two galaxies could spark these cosmic flares, but the overwhelming glow of a quasar drowns out the light of its accompanying galaxy, making the signs of mergers quite difficult to see.

Using *Hubble*'s infrared camera, astronomers examined quasars that are dimmed by dust to get a better look at the quasars' surroundings. *Hubble*'s detailed views revealed that chaotic galaxy collisions are indeed giving birth to these quasars by fueling their supermassive black holes. The quasars light up because the gravitational forces of the mergers disrupt the gas in the individual galaxies and send the gas falling directly toward the supermassive black hole. The accretion zone around the black hole is so overwhelmed with new fuel it converts this bounty into a fountain of radiation that blazes across the universe.

"The brightest quasars in the universe really do live in merging galaxies."

Kevin Schawinski, Swiss Federal Institute of Technology



Five ultra-bright quasars, billions of light-years from Earth, shine brilliantly in the *Hubble* images in the top row. In the bottom row, the glaring quasar light has been subtracted, allowing astronomers to see signs of the galaxy collisions that gave birth to these quasars.

Credit: NASA, ESA, and E. Glikman (Middlebury College, Vermont)

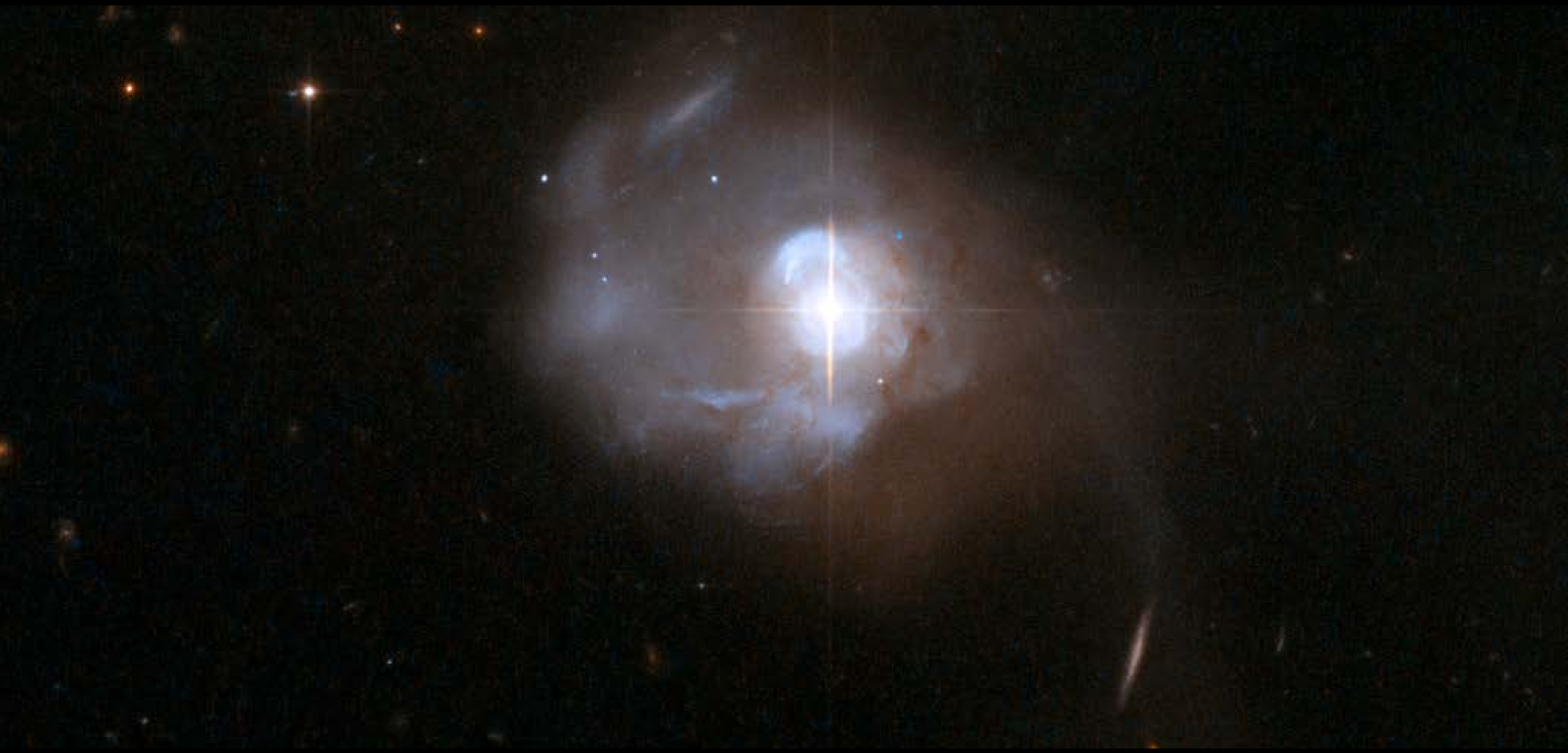
Learn more: https://hubblesite.org/contents/news-releases/2015/news-2015-20.html

Detecting a Double Black Hole

Hubble uncovered evidence that the closest quasar to Earth is powered by two supermassive black holes whirling around each other at the center of the galaxy Markarian 231. Quasars are the brilliant cores of active galaxies that blaze with the light of billions of stars compressed into a region not much larger than our solar system. Supermassive black holes, millions or billions of times more massive than our Sun, are the only imaginable powerhouse that could generate such energy. However, when *Hubble* examined the ultraviolet glow from a disk of material falling into the center of Markarian 231, it revealed what astronomers call "extreme and surprising properties."

> "Binary black holes are natural consequences of these mergers of galaxies."
>
> **Xinyu Dai, University of Oklahoma**

If only one black hole were present in the center of the galaxy, the whole accretion disk would glow in ultraviolet rays. Instead, the ultraviolet glow of the dusty disk abruptly drops off toward the center. This suggests that the disk has a big donut hole encircling the central black hole. The best explanation for the observational data, based on dynamical models, is that the center of the disk is carved out by the action of two black holes orbiting each other. The second black hole must have come from a smaller galaxy that merged with Markarian 231 to ignite the quasar about one million years ago. The finding suggests that quasars might commonly include two central supermassive black holes that fall into orbit about one another after two galaxies merge.



A brilliant, starlike glow at the center of the galaxy Markarian 231 is the nearest quasar to Earth at 581 million light-years away, and is likely powered by two supermassive black holes orbiting one another.

Credit: NASA, ESA, the *Hubble* Heritage Team (STScI/AURA)-ESA/*Hubble* Collaboration, and A. Evans (University of Virginia, Charlottesville/NRAO/Stony Brook University)

Learn more: https://hubblesite.org/contents/news-releases/2015/news-2015-31.html

A FLIGHT THROUGH THE UNIVERSE

This visualization flies through a field of galaxies captured by *Hubble* for the CANDELS (Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey) program. The sequence begins with a cluster of galaxies about 6 billion light-years away and continues on to show galaxies more than twice that distance.

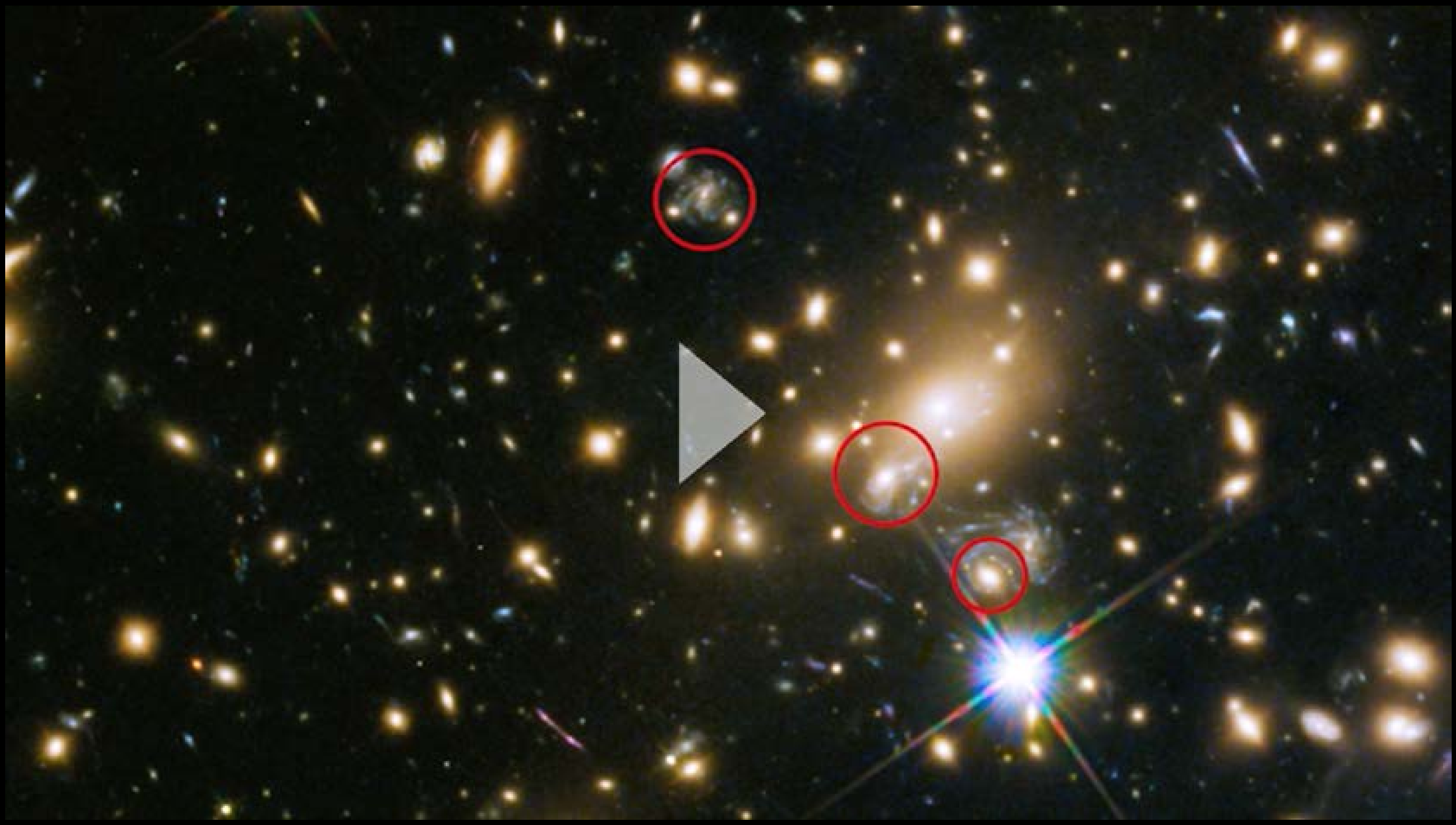
Credit: NASA, ESA, F. Summers, J. DePasquale, G. Bacon, and Z. Levay (STScI)

CHAPTER 3: The Farthest Galaxies

Our perception of the far universe was much different and quite limited before *Hubble* was launched. Astronomers at best could only detect galaxies halfway across the universe, out to about 7 billion light-years. The brilliant beacons known as quasars could be seen as far as roughly 10 billion light-years, but it was largely a mystery as to what these objects were.

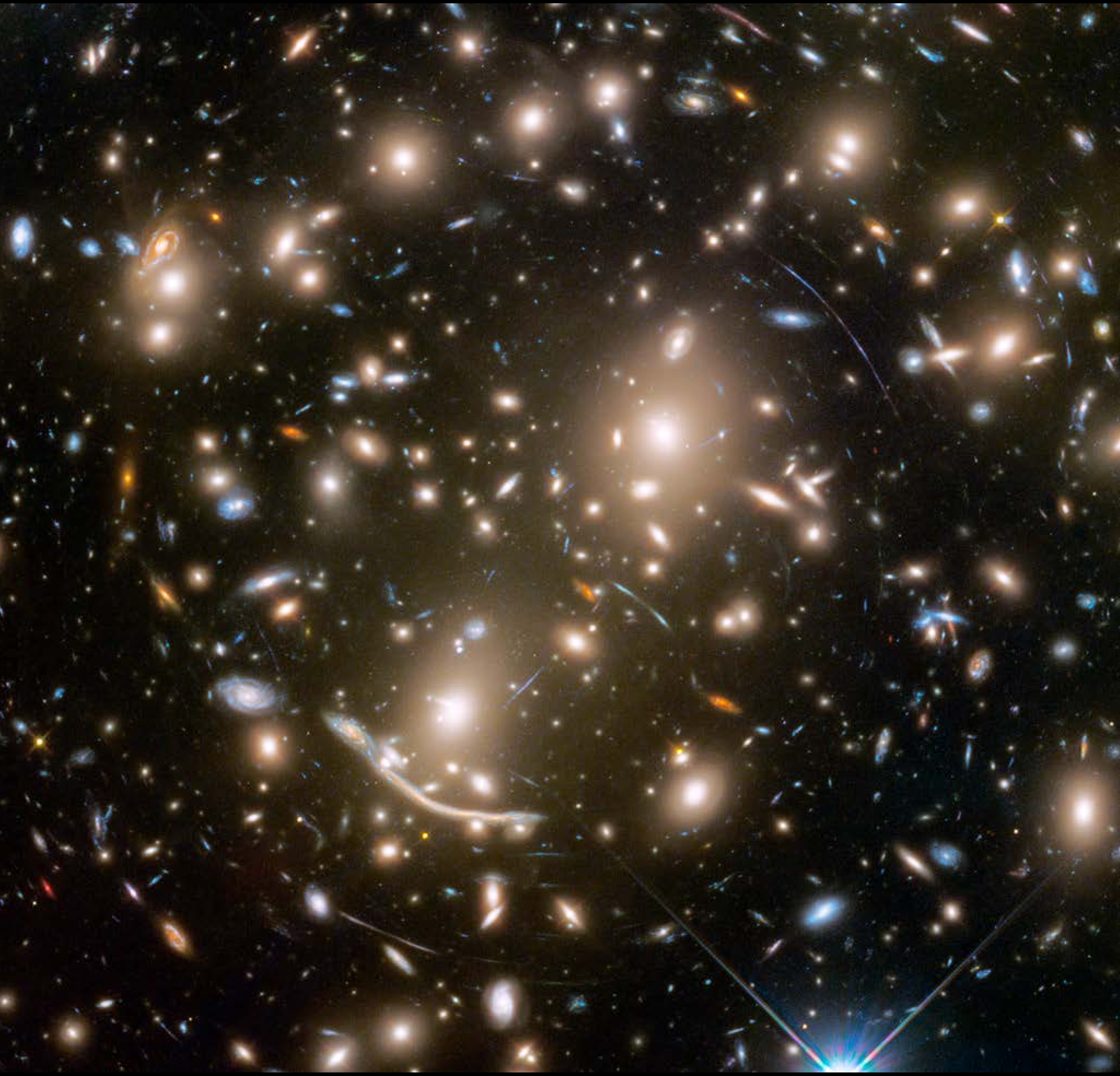
With its ability to stare deep into the sky with clarity and precision, *Hubble* has extended our vision, revealing galaxies more than 13.4 billion light-years away—closer to the dawn of time than any other telescope can see today. One of the ways *Hubble* has uncovered these far-distant galaxies is with the help of natural zoom lenses in space. In a phenomenon known as gravitational lensing, the gravitational fields of massive galaxy clusters bend and magnify the light of much more distant galaxies that reside behind the clusters, allowing *Hubble* to see farther than it could otherwise on its own.

Hubble has targeted dozens of galaxy clusters to search for these nascent, far-off relics of the primordial universe. Sometimes these remote galaxies appear as faint, red dots, or sometimes as arcs of light bending around the brightest galaxies of the intervening cluster. Using *Hubble* to study these early galactic specimens, astronomers have begun to discover how the universe's first galaxies arose, what was going on inside of them, and how they eventually evolved into the modern, mature galaxies that reside around us, within our cosmic neighborhood.



This animation illustrates how a galaxy cluster acts like a lens to bend the light of a more distant object.

Illustration credit: NASA, ESA, and Z. Levay (STScI)



Streaking arcs of light scattered among the members of galaxy cluster Abell 370 tell of mighty gravitational forces warping the very fabric of space and time. The bright arcs are the distorted forms of even more distant galaxies whose light has been bent and magnified by the cluster's gravity as it passed through the cluster on its way to Earth. Without this effect, called gravitational lensing, *Hubble* would not be able to detect these far-off galaxies on its own.

Credit: NASA, ESA, and J. Lotz and the *Hubble* Frontier Fields Team (STScI)

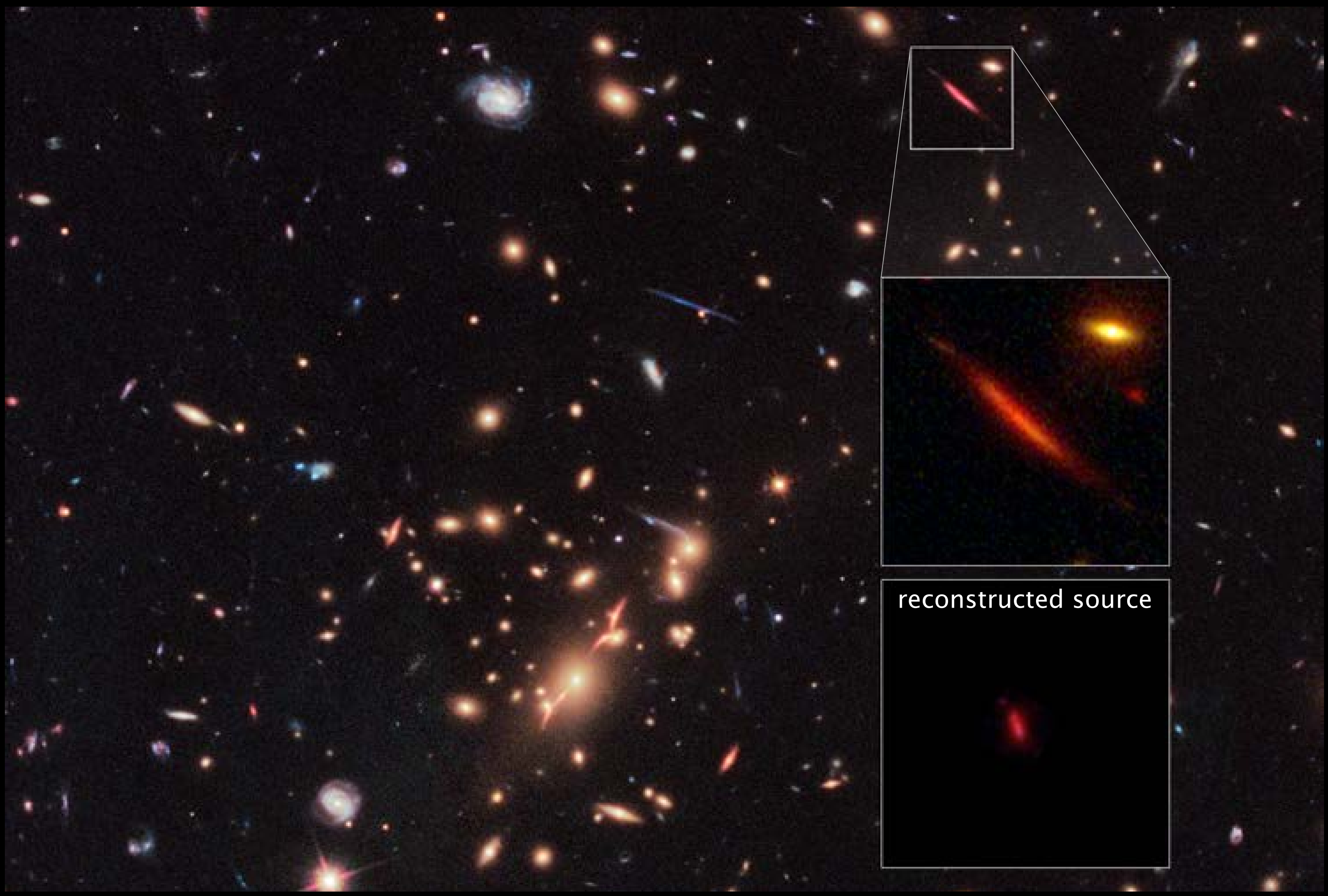
Discovering a Distant 'Dead' Disk Galaxy

Hubble surprised astronomers by revealing a "dead" disk-shaped galaxy—one that's no longer forming any new stars—that existed at a time when the universe was still quite young, just a few billion years old. Astronomers had seen other galaxies that gave up star formation long ago, but had assumed those galaxies resembled the rounded, elliptical galaxies we see in the present-day universe. They had thought star formation in the universe's earliest galaxies was sparked by mergers between young galaxies, which would produce larger galaxies that are round or oval-shaped. However, *Hubble*'s observations show that in this particular galaxy (named MACS 2129-1), stars formed in a disk instead. Finding such a galaxy so early in the history of the universe forces astronomers to rethink how massive galaxies formed and evolved.

Hubble imaged the intriguing galaxy with the help of a natural gravitational lens, an intervening cluster of galaxies whose powerful gravity magnified the light from the distant disk galaxy. Analyzing this and additional archived observations from *Hubble*, astronomers determined that the faraway galaxy is three times as massive as the Milky Way but only half the size. Measurements from the European Southern Observatory's Very Large Telescope (VLT) showed that the disk galaxy is spinning more than twice as fast as the Milky Way. However, astronomers are still unsure why this galaxy stopped forming stars.

"Perhaps we have been blind to the fact that early 'dead' galaxies could in fact be disks."

Sune Toft, Niels Bohr Institute, University of Copenhagen



The gravity of the extremely massive galaxy cluster MACS J2129-0741 has magnified, brightened, and stretched out a much more distant galaxy, shown in the top inset. The bottom box is a reconstructed image showing what the galaxy would look like without the distortion produced by gravitational lensing.

Credit: NASA, ESA, and S. Toft (University of Copenhagen)

Learn more: https://hubblesite.org/contents/news-releases/2017/news-2017-26.html

Detailing the Universe's Brightest Infrared Galaxies

Assisted by gravitational lensing, *Hubble* captured detailed images of the brightest infrared galaxies in the universe—rare, distant galaxies that give off 10,000 times more infrared light than our Milky Way does. *Hubble* sees these galaxies as they existed 8 billion to 11.5 billion years ago, during the height of the universe's star-producing days. Using the same amount of star-forming gas as exists in the Milky Way, these remote galaxies are creating 5,000 to 10,000 times more stars than our galaxy does today. Enshrouded in dust, the galaxies are too faint to detect in visible light. However, these galaxies glow fiercely in dust-penetrating infrared light, shining with the brilliance of 10 trillion to 100 trillion suns.

Astronomers estimate that only a few dozen of these distant, ultra-bright infrared galaxies exist. Still, these faraway beacons have much to tell us about how stars were born and how galaxies grew long ago. They might be distant relatives of the ultra-luminous infrared galaxies that exist more locally, in which galaxy collisions fuel star birth. However, astronomers do not yet know what fueled the more distant galaxies—whether collisions between galaxies or possibly foreign gas raining down on the galaxies. Other observatories were the first to detect these galaxies, but *Hubble*'s high resolution could help astronomers solve the mystery of the galaxies' extraordinary luminescence. Gravitational lensing magnifies the galaxies, allowing astronomers to see more detail with *Hubble* than they could have possibly seen otherwise.

"We want to understand what's powering these monsters, and gravitational lensing allows us to study them in greater detail."

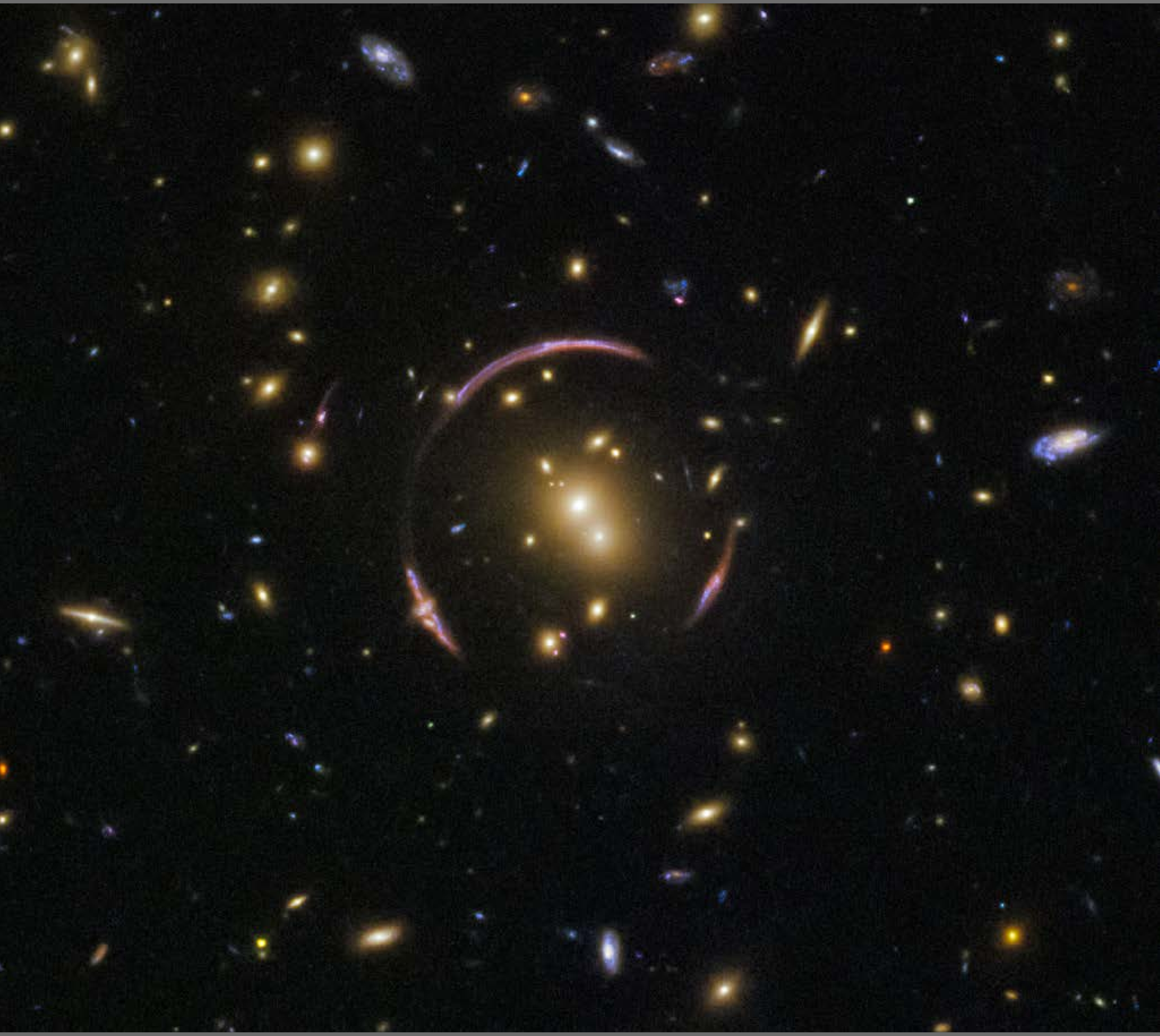
James Lowenthal, Smith College

These six *Hubble* images show galaxies surrounded by strange patterns of arcs, streaks, and smeared rings. These odd features are the stretched-out shapes of the universe's brightest infrared galaxies, which have been magnified by gravitational lensing.

Credit: NASA, ESA, and J. Lowenthal (Smith College)

Learn more: https://hubblesite.org/contents/news-releases/2017/news-2017-24.html

A RING AROUND THE GALAXIES



In this *Hubble* image, the light from a far-distant galaxy is being forced by gravity to bend around the center of a galaxy cluster to form what's known as an Einstein ring. The light of the background galaxy is diverted along multiple paths around the cluster SDSS J0146-0929 on its way to Earth, making it appear as if the galaxy is in several places at once. This gravitational lensing effect was predicted by Albert Einstein's general theory of relativity, which stated that massive cosmic objects would warp space-time.

Credit: ESA/*Hubble* & NASA; Acknowledgment: Judy Schmidt

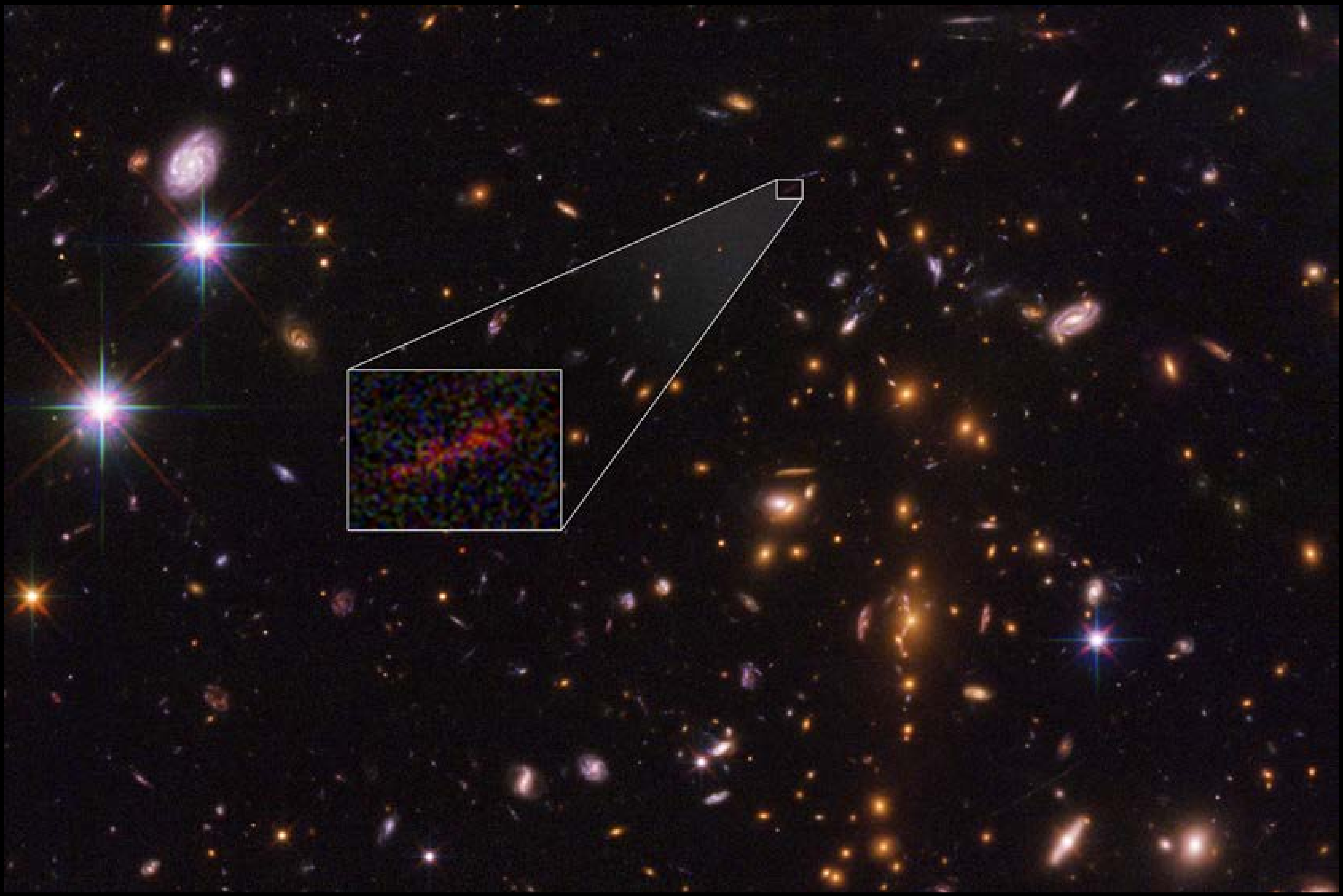
Uncovering a Stretched-Out Galaxy from the Very Early Universe

Hubble received a little help from gravitational lensing to spot a galaxy so far away that it existed when the universe was only 500 million years old. The feeble light from this embryonic galaxy, named SPT0615-JD, was magnified and stretched out by the intense gravity of a much closer group of galaxies. *Hubble* has spotted a few other primitive galaxies from this early era of the universe, but most appear as small, red dots. This is the farthest galaxy yet discovered to be gravitationally lensed and stretched into an extended arc, which provides more information about its size and shape.

By combining observations from *Hubble* and NASA's *Spitzer Space Telescope*, astronomers determined that the remote galaxy lies 13.3 billion light-years away. Early analysis suggests the galaxy contains no more than 3 billion times the mass of the Sun, or only about 1/100th the mass of our Milky Way galaxy. It is also less than 2,500 light-years across, making it only half the size of the Small Magellanic Cloud, a dwarf galaxy orbiting the much larger Milky Way. The galaxy is likely representative of young galaxies from its time, thus giving us a glimpse of what some of the universe's first galaxies were like.

"This galaxy… offers the unique opportunity for resolving stellar populations in the very early universe."

Brett Salmon, Space Telescope Science Institute



A tiny red streak (magnified in the inset) in this *Hubble* image is a galaxy seen at a time when the universe was just 500 million years old. Its light has been magnified and stretched out by the gravitational lensing of a closer galaxy cluster.

Credit: NASA, ESA, and B. Salmon (STScI)

Learn more: https://hubblesite.org/contents/news-releases/2018/news-2018-02.html

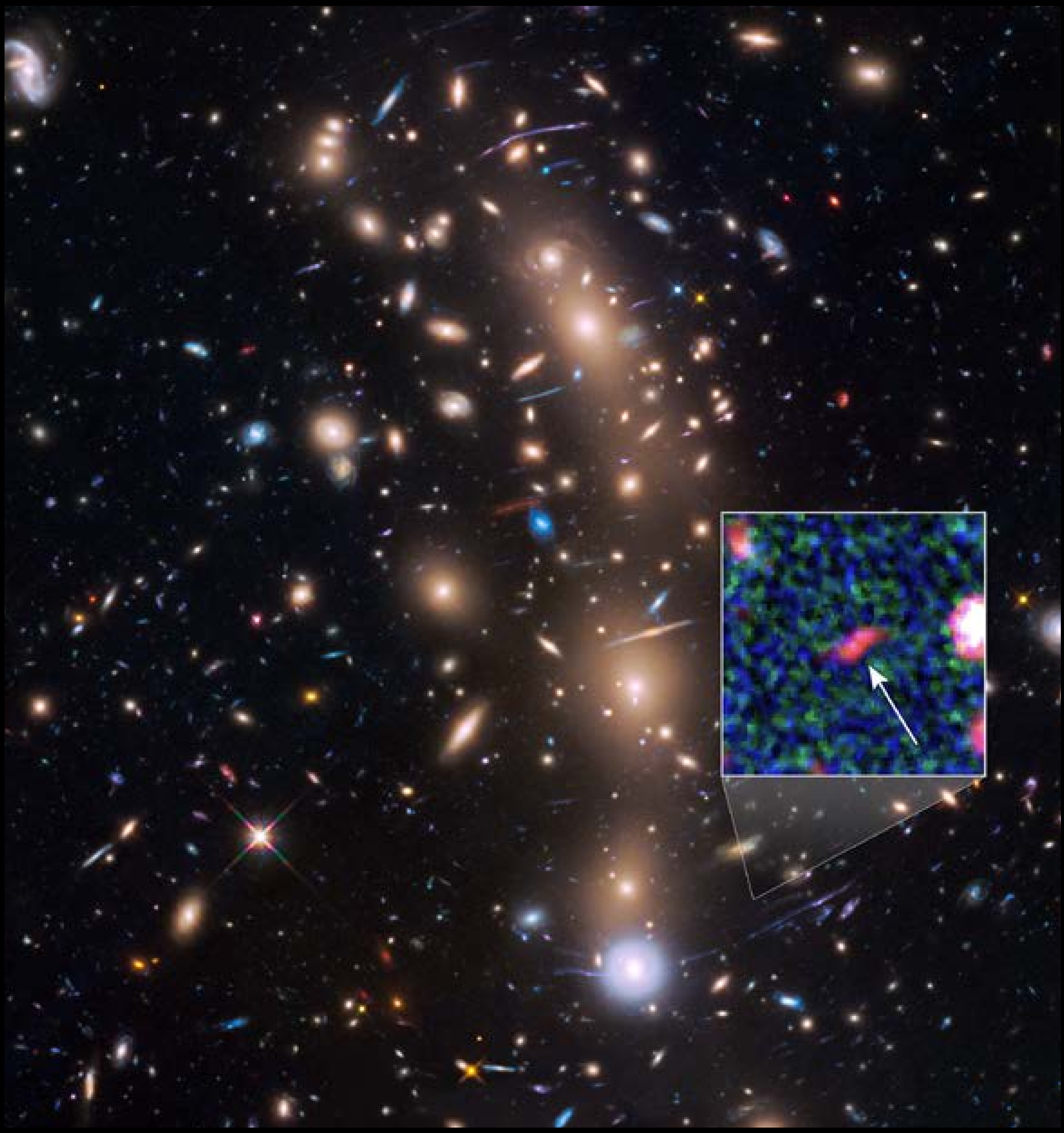
Spotting the Faintest Galaxy Yet Seen in the Distant Universe

Taking advantage of a natural zoom lens in space, *Hubble* spotted the faintest galaxy yet found in the very early universe. Existing about 400 million years after the Big Bang, the dim, remote galaxy was made to look 20 times brighter than normal by the gravitational lensing of a massive cluster of galaxies called MACS J0416.1-2403. The galaxy is comparable in size to the Large Magellanic Cloud (LMC), but it is rapidly making stars at a rate ten times faster than the LMC. The object might be the growing core of what will likely evolve into a full-sized galaxy.

Although astronomers have located other, brighter galaxies that are slightly farther away, this object represents a smaller, fainter class of newly forming galaxies that must have been common in the early universe but have largely evaded detection. These very dim objects may be more representative of the early universe, and offer new insight on the formation and evolution of the universe's first galaxies.

"The team has been able to study for the first time the properties of extremely faint objects formed not long after the Big Bang."

Leopoldo Infante, Pontifical Catholic University of Chile



Within this cluster of galaxies, called MACS J0416.1-2403, *Hubble* identified an extremely faint and distant galaxy (inset image) that existed just 400 million years after the Big Bang.

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

Learn more: https://hubblesite.org/contents/news-releases/2015/news-2015-45.html

GAZING ACROSS THE FRONTIER

With an assist from gravitational lensing, galaxy cluster Abell S1063 helped *Hubble* peer deeper into space than it could otherwise to view galaxies far across the universe. The blue arcs of light that curve around the massive central galaxy form when the light of galaxies located behind Abell S1063 gets bent and magnified by the cluster's powerful gravitational field. Abell S1063 is one of six galaxy clusters astronomers observed with *Hubble* as part of the Frontier Fields program. This cluster's magnifying capability allowed *Hubble* to find a galaxy that appears as it did when the universe was a mere one billion years old.

Credit: NASA, ESA, and J. Lotz (STScI)

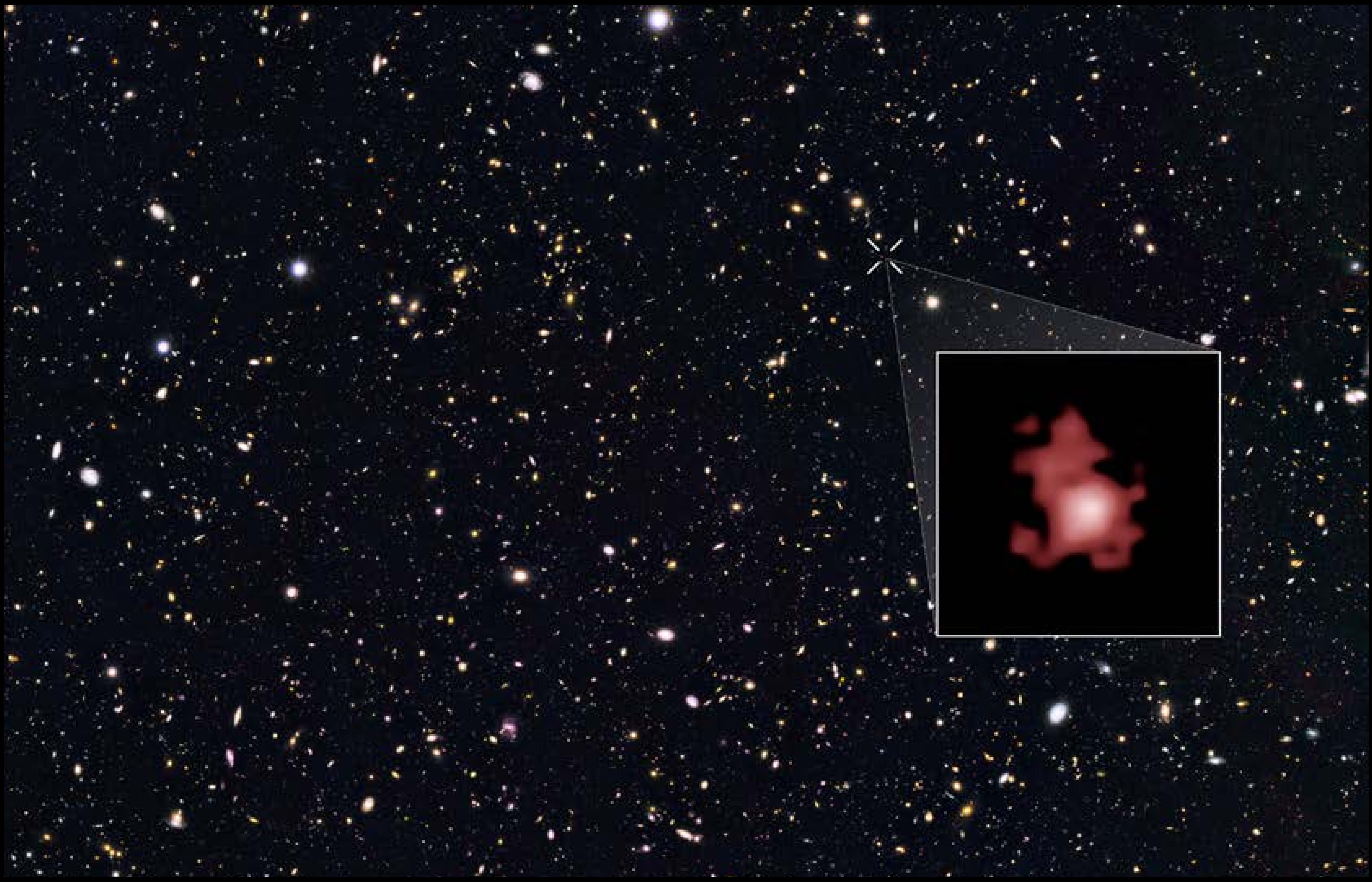
Pushing the Limits of Our Cosmic View

Using *Hubble*, astronomers found what could be the farthest galaxy ever seen to date. Dubbed GN-z11, the infant galaxy appears as it was about 13.4 billion years in the past, when the universe was only about three percent of its current age. GN-z11 is 25 times smaller than the Milky Way and possesses just one percent of our galaxy's mass in stars. However, the fledgling galaxy is growing fast, forming stars about 20 times faster than our galaxy does today. Up close, the galaxy would appear to be ablaze with bright, young, blue stars, but it looks red because its light has been stretched to longer (redder) wavelengths by the expansion of the universe.

Astronomers had previously estimated GN-z11's distance based on its color in images from *Hubble* and NASA's *Spitzer Space Telescope*. Follow-up spectroscopic observations with *Hubble*, however, provided a more precise measurement for the distance and revealed that the galaxy was even farther away than originally thought. It is the first time astronomers have made such a measurement for a galaxy so far away. GN-z11 is at the limit of what *Hubble* can observe, and its discoverers think the galaxy is likely to hold on to the distance record until NASA's *James Webb Space Telescope* launches and begins to use its infrared cameras to peer even deeper into the universe.

"We've taken a major step back in time, beyond what we'd ever expected to be able to do with *Hubble*."

Pascal Oesch, Yale University



The most distant galaxy ever observed, GN-z11 (inset), was found in the northern field of the Great Observatories Origins Deep Survey (GOODS), located in the constellation Ursa Major.

Credit: NASA, ESA, P. Oesch (Yale University), G. Brammer (STScI), P. van Dokkum (Yale University), and G. Illingworth (University of California, Santa Cruz)

Learn more: https://hubblesite.org/contents/news-releases/2016/news-2016-07.html

SUMMARY

Like a mother's photo collection showing her child growing from birth to adulthood, *Hubble*'s rich photographic anthology captures scenes of galaxies developing throughout cosmic history. In *Hubble*'s images, we find some of the universe's youngest galaxies in the far distant reaches of space, throngs of unruly adolescent galaxies still coming of age several billion light-years away, as well as mature, adult ones residing in our own cosmic neighborhood.

By revealing galaxies more remote than any telescope had seen before, *Hubble* has shown that the earliest galaxies were smaller and more irregularly shaped than their modern-day brethren. It has gathered a bounty of evidence that galaxies collide and merge to form bigger galaxies, and that our own Milky Way galaxy continues to grow from dwarf galaxies that venture too close. It has revealed new details about the inevitable collision between the Milky Way and the neighboring Andromeda galaxy. It has resolved previously unseen features of galaxies, and identified different ways explosions of star birth can erupt in galaxies of various types and sizes. And it has shown that the composition of galaxies changes over time as generations of stars come and go, enriching their environment with new material.

Partnering *Hubble* with other space telescopes that view additional wavelengths of light—such as the *Chandra X-ray Observatory*, and the infrared-detecting *Spitzer Space Telescope* and upcoming *James Webb Space Telescope*—astronomers can and will continue to learn even more about how galaxies and the universe itself came to be the way we see them today.

The Pinwheel galaxy (M101), a spiral galaxy comparable in size to our Milky Way, takes on a much different appearance when viewed in visible light (from *Hubble*), infrared light (from the *Spitzer Space Telescope*), and in X-rays (from the *Chandra X-ray Observatory*).

Video credit: NASA, ESA, and G. Bacon (STScI); image credits: NASA, ESA, K. Kuntz (JHU), F. Bresolin (University of Hawaii), J. Trauger (Jet Propulsion Lab), J. Mould (NOAO), Y.-H. Chu (University of Illinois, Urbana), and STScI

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 galaxies at the following social media sites.

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https://www.instagram.com/NASAHubble

YouTube
https://www.youtube.com/playlist?list=PL3E861DC9F9A8F2E9

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

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

Hubble shows the large spiral galaxy NGC 1512 and the diminutive dwarf galaxy NGC 1510 in the very early stages of a merger that is already producing visible changes in both galaxies.

Credit: NASA, ESA

CREDITS

The *Hubble Space Telescope* is a cooperative project between the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA). 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 contract NAS5-26555.

Hubble Focus: Galaxies through Space and Time was produced by NASA's Goddard Space Flight Center (GSFC) with support from STScI. It was published in July 2019.

The production team for this book included Vanessa Thomas (chief writer and editor), Ken Carpenter and Jennifer Wiseman (science advisors), Pat Crouse, Kevin Hartnett, and James Jeletic (editors) at GSFC, as well as Pam Jeffries (designer) and Ray Villard (writer/editor) at STScI.

The twisted form of NGC 2623 shows what happens after two galaxies collide. The crash sent trails of stars streaming out in opposite directions and triggered even more stars to form as clouds of gas and dust from the two galaxies slammed together.

Credit: ESA/*Hubble* & NASA