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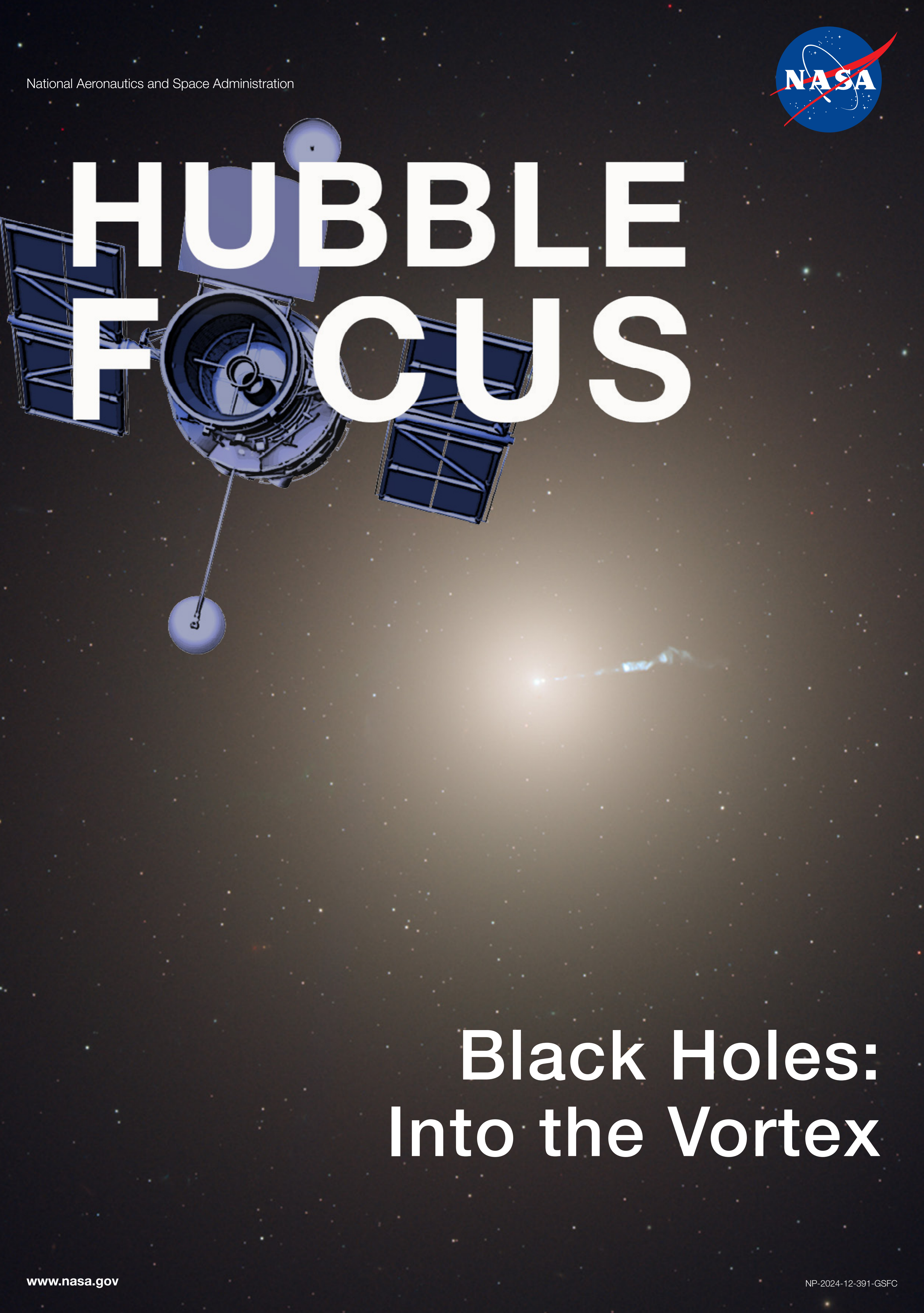

HUBBLE FOCUS

Black Holes: Into the Vortex

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Cover image: A black hole-powered jet of electrons and other particles traveling at nearly the speed of light blasts from the core of elliptical galaxy M87. The jet originates in the disk of superheated gas swirling around the galaxy's supermassive black hole. *Hubble's* observations of M87 led to the first confirmation of a black hole at the center of a galaxy.

Credit: NASA and The Hubble Heritage Team (STScI/AURA)

About the *Hubble Space Telescope*

Since its launch in 1990, NASA's *Hubble Space Telescope* has made more than one million observations, amassed a huge archive of scientific findings, and had a profound effect on all areas of observational astronomy. *Hubble* has addressed fundamental cosmic questions and explored far beyond the most ambitious plans of its builders. It has captured views farther out in space and further back in time than nearly any other observatory to date. *Hubble* has 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.

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 (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 ten to twenty times better than typically possible with large ground-based telescopes. It also can observe those objects across a range of the electromagnetic spectrum, from ultraviolet light through visible and to near-infrared wavelengths.

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

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

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

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

INTRODUCTION

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

Hubble Focus: Black Holes: Into the Vortex, highlights some of *Hubble's* recent discoveries about one of the most mysterious and mind-bending phenomena in the universe: black holes.

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.

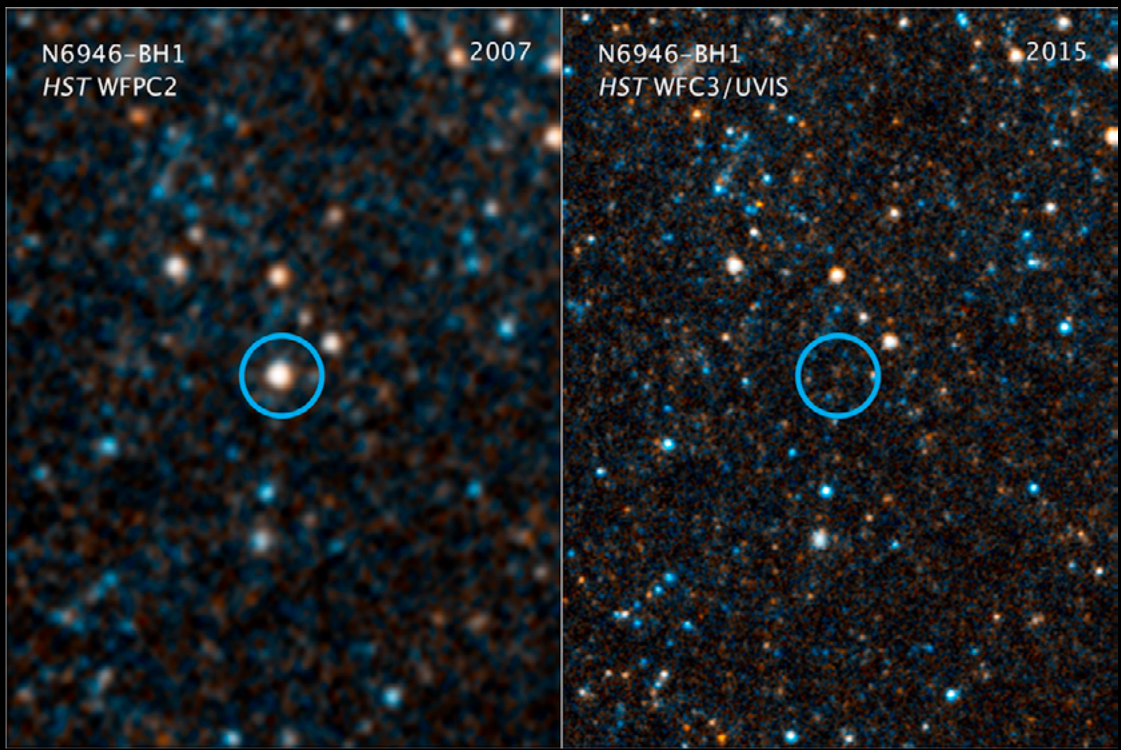
What Are Black Holes?

Black holes aren't holes.

And despite their ominous reputation, they aren't cosmic vacuum cleaners that suck up anything in their region of the universe.

But black holes are still some of the most strange, fascinating, and violent phenomena in the universe: invisible objects of immense density whose gravity is so overpowering that not even light can escape them, born when a vast amount of matter collapses down to a point that shatters the laws of physics as we know them.

Stellar-mass black holes, which range from five to 10 times the mass of our Sun, are either born in the deaths of massive stars – forming in seconds from the star's collapse – or from the addition of mass to incredibly dense neutron stars. Stars strike a balance between the inward pull of gravity and the outward push of photons created by fusion reactions in the star's core. When a massive star runs out of fuel, that balance is upset and the star's core collapses under its own gravity, triggering a shock wave that flings the star's outer layers into space. In many cases, this leaves behind a small, dense object with tightly packed neutrons – a neutron star. But if the collapsing core is massive enough, gravity compresses everything even further, into a black hole.

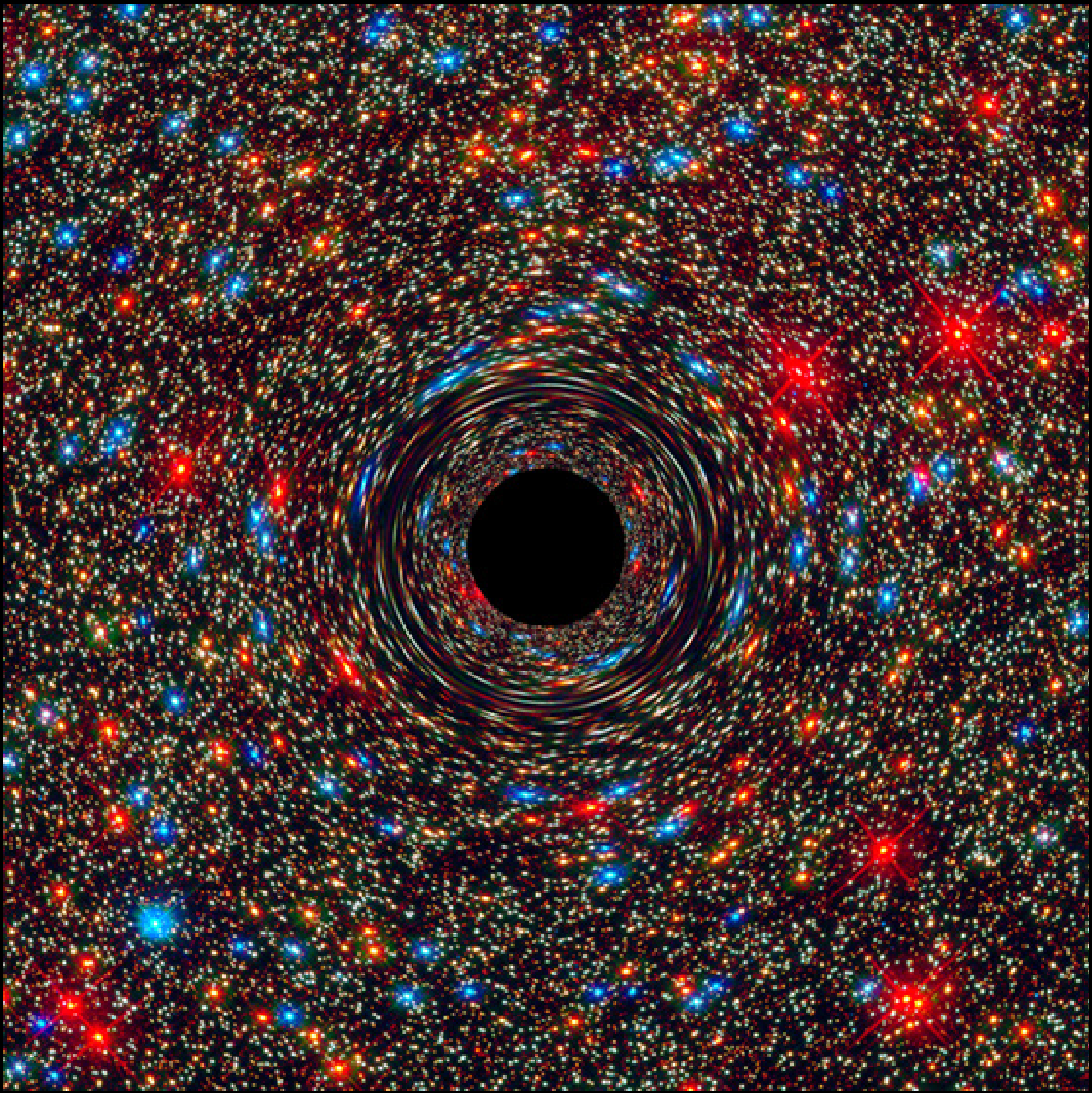


These *Hubble* images may capture the birth of a black hole. In 2007, *Hubble* observed a star 25 times the mass of the Sun in galaxy NGC 6946. In 2009, it began to brighten. The star was expected to perish in a bright supernova explosion. Instead, by 2015, it had vanished. Astronomers used *Hubble* and NASA's *Spitzer Space Telescope* were used to look for the star, in case it had just dimmed or been hidden by a cloud of dust, but the star was gone. Astronomers concluded that the star had probably become a black hole. Some small amount of infrared radiation was detected where the star once was, probably emanating from debris falling onto the black hole.

Credit: NASA, ESA, and C. Kochanek (OSU)

Hubble observations revealed that stellar-mass black holes' much-bigger brothers, supermassive black holes, lurk in the hearts of most galaxies and can be hundreds of thousands to billions of times the mass of our Sun. The processes that create them are still being investigated.

Black holes are made up of a singularity, a point so dense and so small that our understanding of the laws of physics no longer apply; and the event horizon, the point of no return where the velocity needed to escape becomes equal to the speed of light – ensuring that nothing that passes beyond this boundary escapes. To be consumed by a black hole, an object must cross this event horizon. Otherwise, objects can orbit a black hole the way they would any other gravitational source. If the Sun were somehow magically replaced by a black hole of the same mass, the planets would continue to orbit as they normally do.



This computer-simulated image shows a supermassive black hole at the core of a galaxy. The black region in the center represents the black hole's event horizon, where no light can escape the massive object's gravitational grip. The black hole's powerful gravity distorts space around it like a funhouse mirror. Light from background stars is stretched and smeared as it skims by the black hole.

Credit: NASA, ESA, and D. Coe, J. Anderson, and R. van der Marel (STScI)

Black Holes, From Myth to Reality

Hubble played a key role in taking supermassive black holes from theory to reality.

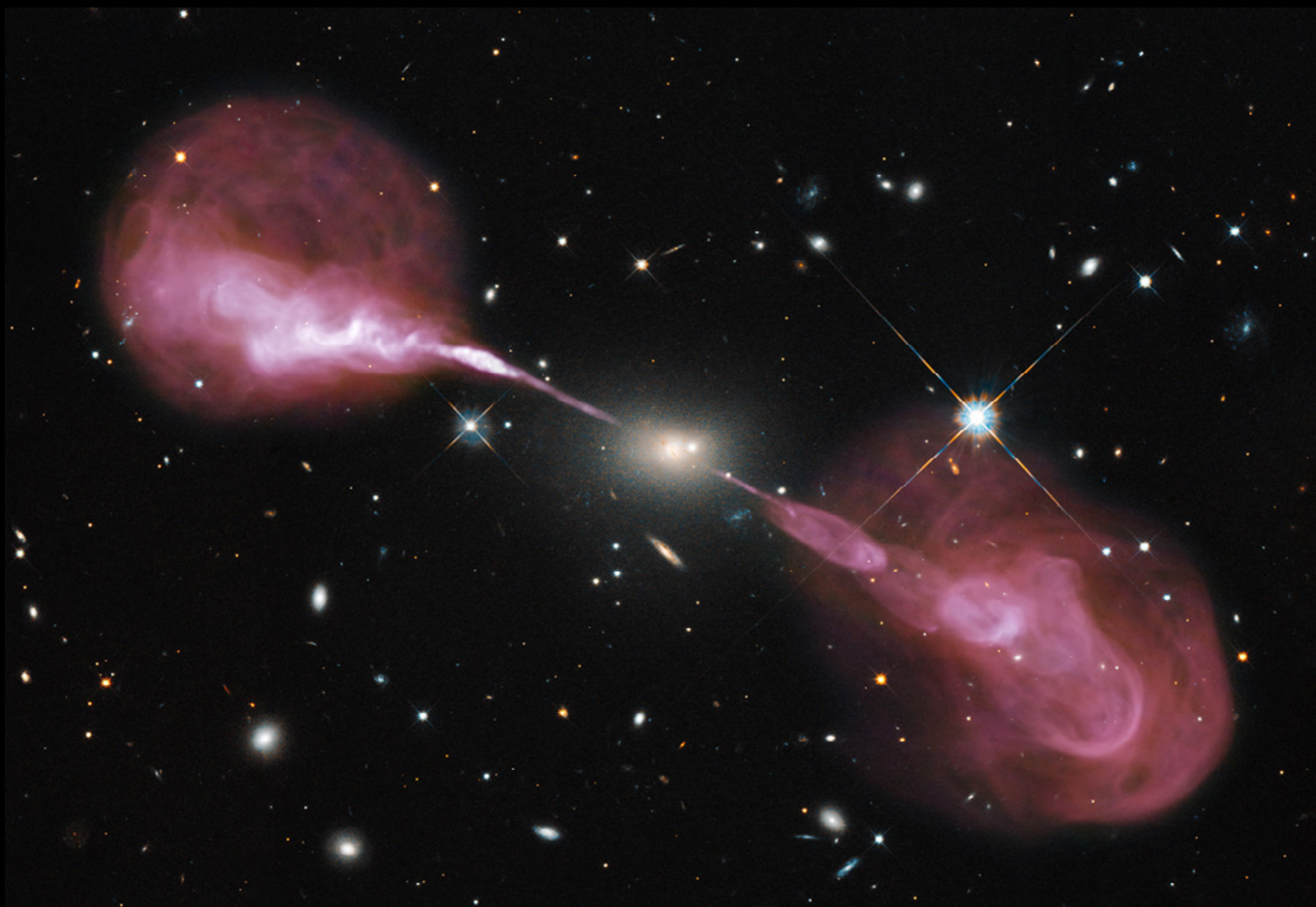
Credit: NASA, James Leigh, and Origin Films

Chapter 1: Hunting Elusive Black Holes

Black holes capture the imagination with extremes.

They pack immense amounts of mass into tiny areas, creating gravity so intense that nothing can escape it. To enter the “event horizon” of a black hole, that region from which escape becomes impossible, is to become subject to an entirely different perception of time and space, while the gravity of the black hole compresses matter horizontally and stretches it vertically, a phenomenon evocatively termed “spaghettification.” General relativity predicts that the very center of a black hole contains a point where matter is crushed to infinite density.

The accretion disks of material whirling around supermassive black holes burrowed into the centers of galaxies can unleash jets of particles that travel hundreds of thousands of light-years into space at close to the speed of light.



A 2.5-billion-solar-mass black hole at the center of elliptical galaxy Hercules A (3C 348) powers immense jets that, at one-and-a-half million light-years wide, dwarf the visible galaxy from which they emerge. The galaxy itself, at the center of the image, is only about 250,000 light-years across. The jets, visible in radio wavelengths, consist of very-high-energy plasma beams, subatomic particles, and magnetic fields shot at nearly the speed of light from the vicinity of the supermassive black hole. *Hubble's* visible light data was combined with radio observations from the Karl G. Jansky Very Large Array (VLA) radio telescope in New Mexico to produce this image.

Credit: NASA, ESA, S. Baum and C. O'Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team (STScI/AURA)

And yet, despite all this violent activity, black holes are difficult to observe. Because they trap light, they're invisible. Scientists find and study black holes by observing the behavior of matter around them – the X-ray glow of an accretion disk, the telltale beam of a jet, the orbits of stars. The most elusive of black holes are the intermediate-mass black holes, the middle ground between stellar-mass black holes and supermassive black holes.

Intermediate-mass black holes (IMBH) should theoretically exist. Black holes grow in mass by colliding and merging with each other or by consuming stars. Over time, collisions between stellar-mass black holes should have created some intermediate-mass black holes, ranging from around 100 to 100,000 times the Sun's mass. However, examples of these mid-sized black holes have been difficult to confirm, despite scientists actively searching for them.

The best place to look for intermediate-mass black holes is globular clusters: compact, gravitationally bound clusters of tens of thousands to millions of stars. These densely packed environments provide plenty of opportunities for collisions between cosmic objects, providing a fertile breeding ground for intermediate-mass black holes. *Hubble's* keen resolution allows it to distinguish individual stars in the Milky Way's globular clusters, while its more than three decades in space has enabled it to build a history of observations of these clusters, making it a key tool in the hunt for intermediate-mass black holes.

The Omega Centauri globular cluster is made up of some 10 million gravitationally bound stars – almost the size of a small galaxy. It's visible to the unaided eye in the night sky from Earth. *Hubble's* view recently revealed new evidence of a possible intermediate-mass black hole in its center, with a mass at least 8,200 times that of our Sun. This *Hubble* image captures the central region of Omega Centauri, where the IMBH is located.

Credit: ESA/Hubble, NASA, Maximilian Häberle (MPIA)

Finding Intermediate-Mass Black Holes Close to Home

The first black hole ever discovered was found in 1971: Cygnus X-1, a stellar-mass black hole 21 times the mass of the Sun. In the 1960s-70s, scientists theorized a different type of black hole, the supermassive black holes millions to billions of times the mass of the Sun, stationed in the centers of galaxies. *Hubble* found that these indeed existed within most galaxies.

Today scientists continue to search for the missing link between the two: intermediate-mass black holes 100 to 100,000 times the Sun's mass. Intermediate-mass black holes may be in the process of evolving into supermassive black holes.

Hubble has given astronomers some of their best evidence yet for this rare type of black hole by observing the motions of stars in the hearts of globular clusters: spherical, tightly bound clusters of stars that are known to contain some of the oldest stars in the galaxy.

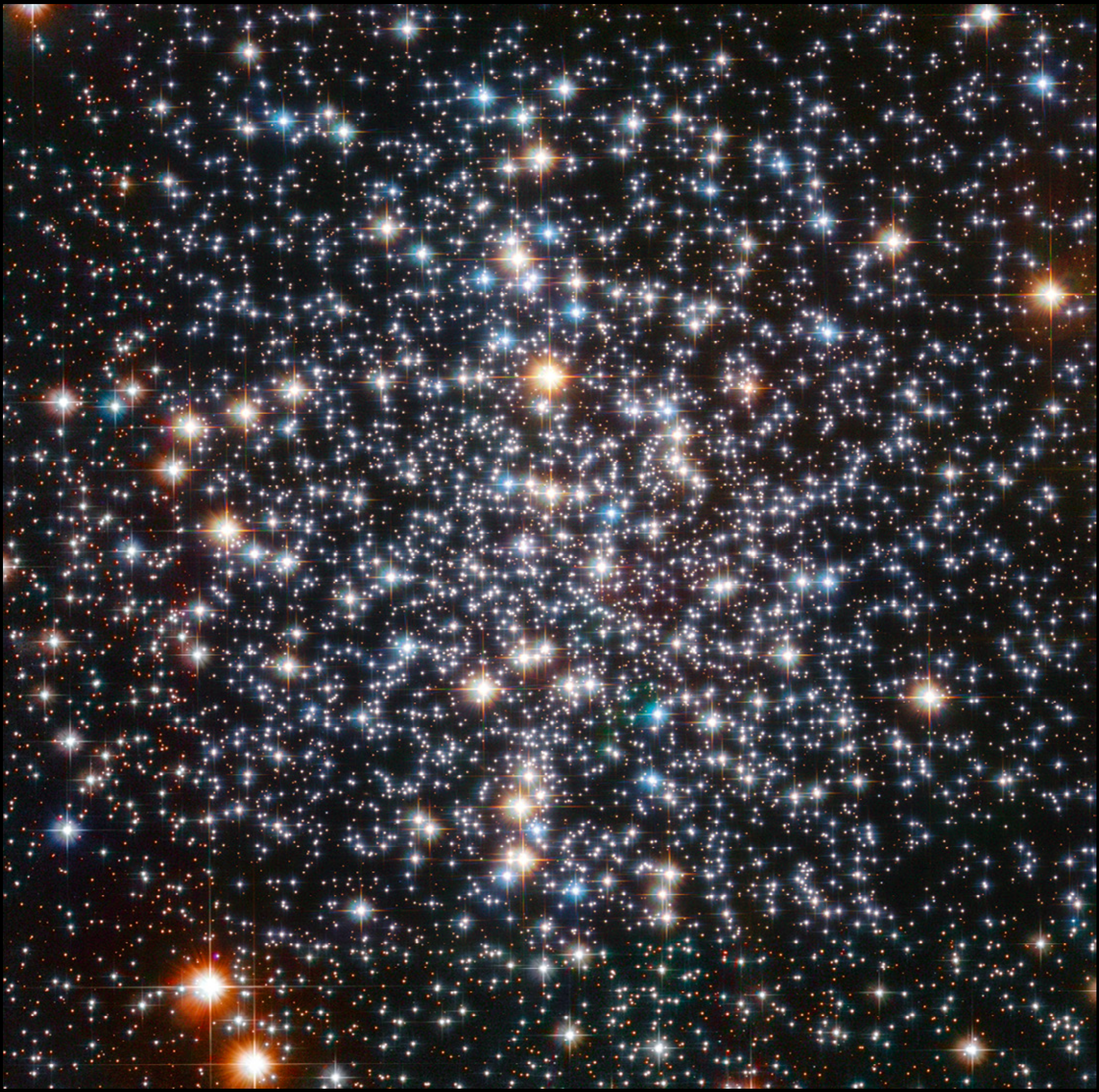
"If the closest globular cluster to our Sun could have an intermediate-mass black hole, it tells us that this black hole class might not be that rare after all."

Eduardo Vitral, Space Telescope Science Institute (STScI) and Paris Institute of Astrophysics

One suspected black hole was uncovered in the closest globular star cluster to Earth, Messier 4 (M4), located 6,000 light-years away. The object can't be seen, but its mass was calculated by studying the motion of stars caught in its gravitational field, like bees swarming around a hive.

Measuring their motion takes the time and precision that only *Hubble* can provide. Astronomers looked at 12 years' worth of M4 observations from *Hubble* and resolved pinpoint stars, identifying a potential 800-solar-mass black hole in the center of the cluster. *Hubble's* data tend to rule out alternative theories for this object, such as a compact central cluster of unresolved stellar remnants like neutron stars, or smaller black holes swirling around each other. The observations point toward either a black hole or a stellar mechanism currently unknown in physics.

The motion of seven fast-moving stars in the innermost region of the roughly 10 million-star globular cluster Omega Centauri provided evidence for another intermediate-mass black hole. The seven stars are moving so fast that they should be able to escape the cluster and never return. A probable explanation is that a very massive object is gravitationally pulling on these stars and keeping them close to the cluster's center – specifically, a black hole with a mass at least 8,200 times that of our Sun. Alternatively, some studies propose that the mass pinning the stars in place could be contributed by a group of stellar-mass black holes.



Astronomers suspect that an elusive intermediate-mass black hole – weighing as much as 800 times the mass of our Sun – lurks unseen at the core of globular star cluster Messier 4, a dense collection of several hundred thousand stars. *Hubble* observations over 12 years show stars in the cluster swarming in the gravitational field of a possible black hole.

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

Learn more: NASA's *Hubble* Hunts for Intermediate-Sized Black Hole Close to Home

NASA's *Hubble* Finds Strong Evidence for Intermediate-Mass Black Hole in Omega Centauri

Hubble Hunts for Intermediate-Sized Black Hole Close to Home

Virtually all black holes seem to come in two sizes: small and humongous. A long-sought missing link is an intermediate-mass black hole, weighing in somewhere between 100 and 10,000 solar masses. How would they form, where would they hang out, and why do they seem to be so rare?

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

Revealing a Secretive Black Hole

An intermediate-mass black hole may have betrayed its existence by tearing apart a star that passed too close.

In 2006, a powerful flare of X-rays detected by NASA's *Chandra X-ray Observatory* and the European Space Agency's X-ray Multi-Mirror Mission (XMM-Newton) alerted scientists to the possibility of a star being shredded by close contact with a gravitationally powerful compact object, like a black hole.

IMBHs have been difficult to find because they are smaller and less active than supermassive black holes; they do not have readily available sources of fuel, nor as strong a gravitational pull to draw stars and other cosmic material that would produce telltale X-ray glows. Astronomers essentially have to catch an IMBH red-handed in the act of devouring a star.

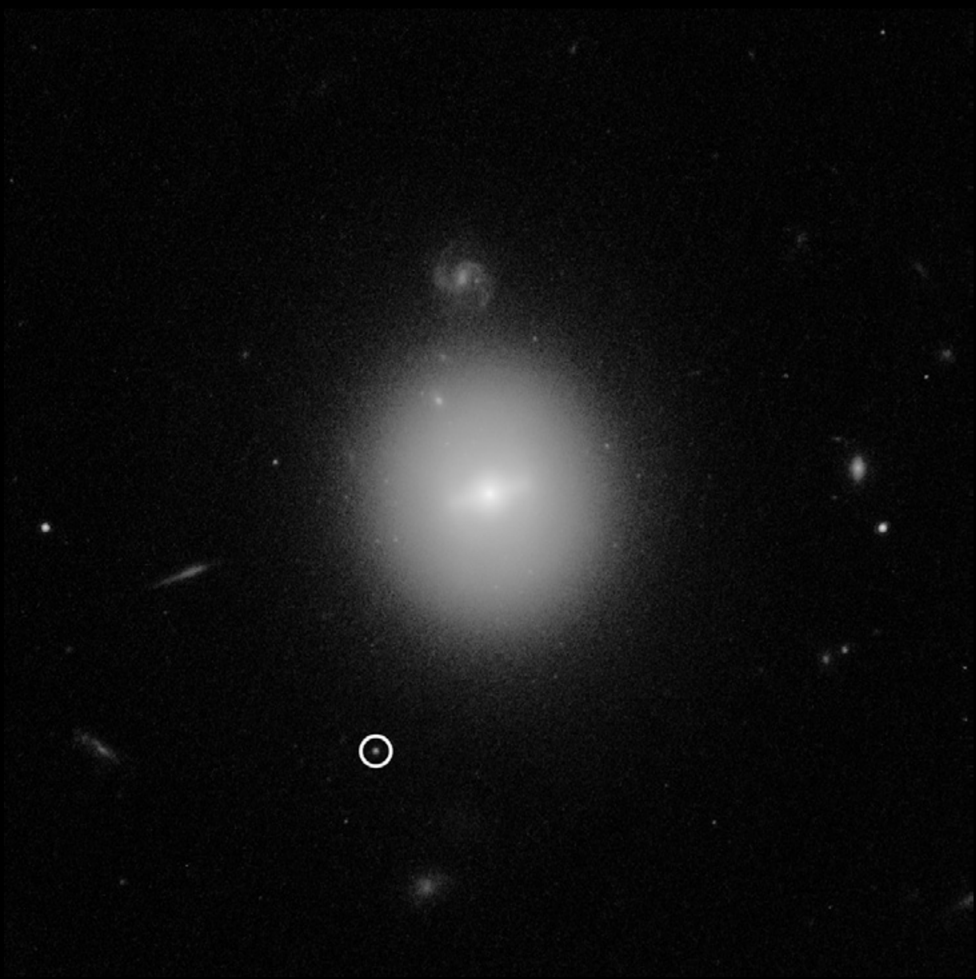
"Intermediate-mass black holes are very elusive objects, and so it is critical to carefully consider and rule out alternative explanations for each candidate. That is what Hubble has allowed us to do for our candidate."

Dacheng Lin, University of New Hampshire

The X-ray source – named 3XMM J215022.4−055108 – was not located in the center of a galaxy where massive black holes would normally reside, raising the possibility that an IMBH was the culprit. But another suspect had to be ruled out first: the burst of X-rays could also have been produced by a closer object, a neutron star in our own Milky Way galaxy.

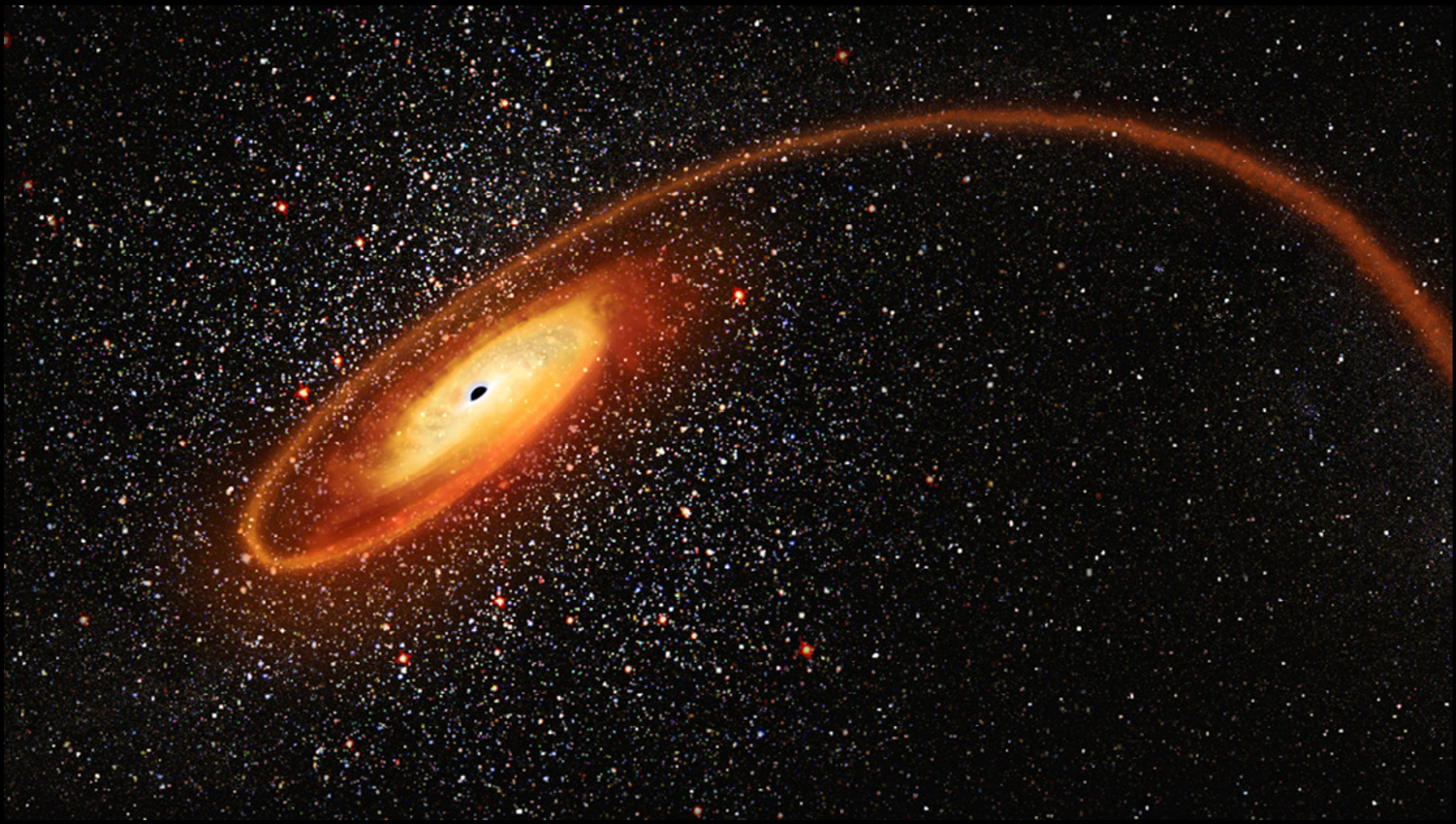
Scientists turned to *Hubble's* deep, high-resolution imaging to find out whether the X-rays came from within our galaxy or beyond. *Hubble* found that the X-rays emanated from a distant, dense star cluster on the outskirts of another galaxy — just the type of place astronomers expected to find an IMBH.

The glow from the shredded star allowed astronomers to estimate the black hole's mass of 50,000 solar masses, based on both X-ray luminosity and spectroscopic data. Finding this IMBH opens the door to the possibility of many more lurking undetected in the dark, waiting to be given away by a passing star.



A white circle shows the location of an intermediate-mass black hole identified in this *Hubble Space Telescope* image. The black hole weighs over 50,000 times the mass of our Sun (making it much smaller than supermassive black holes found in the centers of galaxies). The star cluster is in the vicinity of the galaxy at the center of the image.

Credit: NASA, ESA, and D. Lin (University of New Hampshire)



This artist's concept depicts a star being ripped apart by the intense gravitational pull of an intermediate-mass black hole. The stellar remains are forming an accretion disk around the black hole. Flares of X-ray light from the super-heated gas disk alerted astronomers to the black hole's location.

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

Hubble Finds Evidence of Mid-Sized Black Hole

Astronomers using *Hubble* have found the best evidence for a black hole of an elusive class known as “intermediate-mass,” which betrayed its existence by tearing apart a wayward star that passed too close.

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

Learn More: [*Hubble* Finds Best Evidence for Elusive Mid-Sized Black Hole]

Identifying a Swarm of Black Holes

Not all intermediate-mass black hole candidates pan out, but a *Hubble* investigation into one suspected IMBH uncovered an unexpected and intriguing phenomenon – a bevy of black holes concentrated in the center of a globular cluster.

The globular cluster at the focus of this study, NGC 6397, is almost as old as the universe itself. This cluster resides 7,800 light-years away, making it one of the closest globular clusters to Earth. Scientists studied the motion of stars inside the cluster, which would be affected by the black hole's gravitational pull. They used the velocities of stars in the cluster to determine the distribution of its total mass. The more mass at a location, the faster stars travel around it.

"Our discovery of extended dark mass in this cluster and another is an important step in understanding whether collections of black holes hide in the cores of globular clusters."

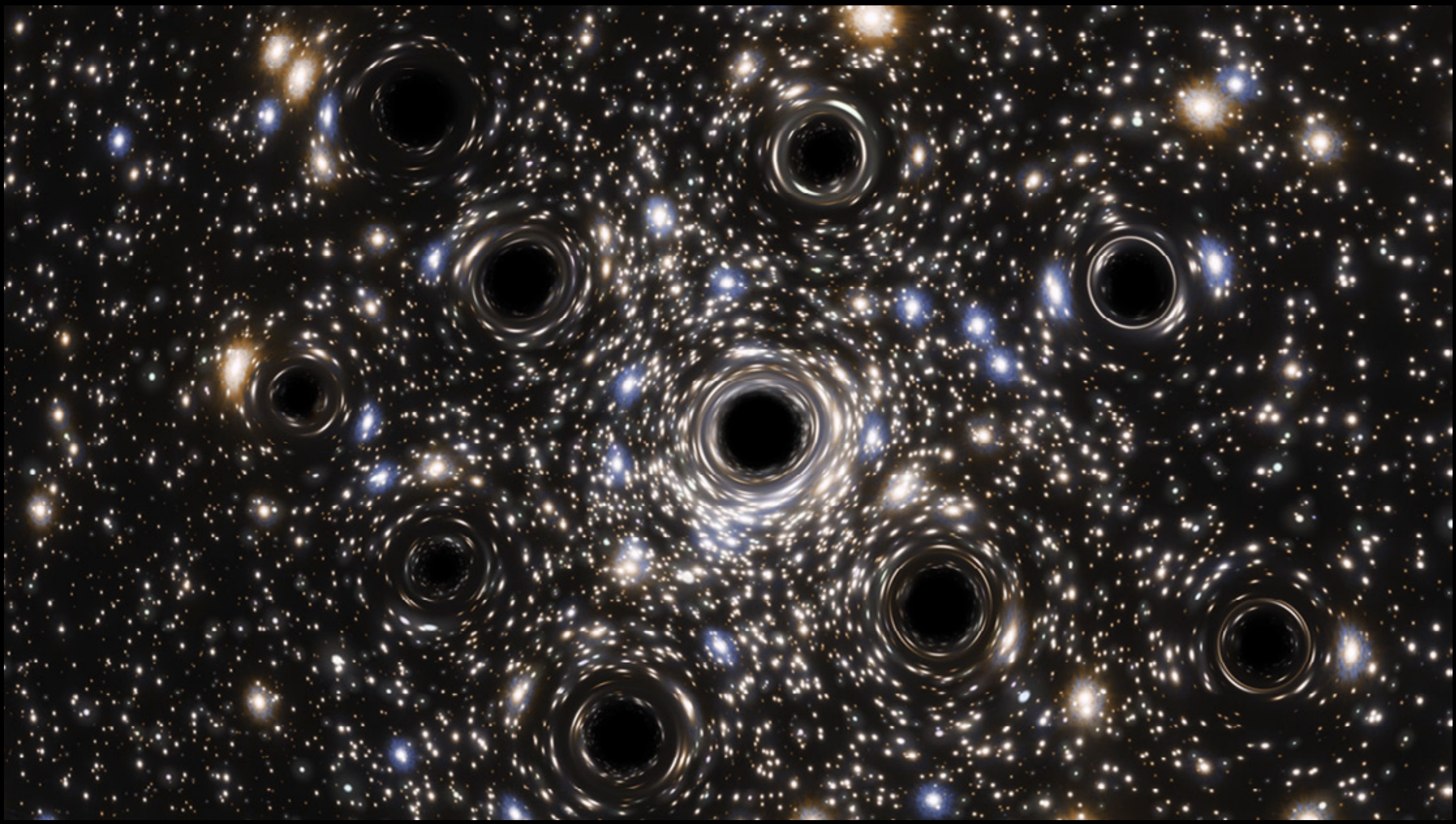
Gary Mamon, Paris Institute of Astrophysics

The researchers used previous estimates of the stars' apparent motions on the sky to determine their true velocities within the cluster. These precise measurements for stars in the cluster's core could only be made with *Hubble* over several years of observation. The *Hubble* data were added to apparent motion measurements provided by the European Space Agency's Gaia space observatory, which are less precise than *Hubble's* observations in the core.

The results showed that the cluster holds not just one hefty black hole, but as many as 20 smaller black holes. They congregate in the core due to a gravitational pinball game in which massive objects sink to the center of the cluster by exchanging momentum with smaller stars, which migrate in turn to the cluster's outskirts. The central black holes may eventually merge, sending ripples across space as gravitational waves.

Ancient globular cluster NGC 6397 contains hundreds of thousands of stars. *Hubble* gauged the cluster's distance at 7,800 light-years away, making it one of the closest globular clusters to Earth. The amplitudes and shapes of stellar orbits in the cluster led to the conclusion that it contains a swarm of black holes at the core.

Credit: NASA, ESA, Eduardo Vitral (IAP), Gary A. Mamon (IAP); Image Processing: NASA, ESA, Tom M. Brown (STScI), Stefano Casertano (STScI), Jay Anderson (STScI)



This artist's interpretation of globular cluster NGC 6397 depicts the concentration of black holes at the center of NGC 6397. In reality, the small black holes here are far too small for the direct observing capacities of any existing or planned future telescope, including *Hubble*, and the size and effect of the black holes on the light we see is exaggerated for clarity. It is predicted that this core-collapsed globular cluster could be host to more than 20 black holes.

Credit: ESA/Hubble, N. Bartmann

Hubble Uncovers Concentration of Small Black Holes

Astronomers on the hunt for an intermediate-mass black hole at the heart of the globular cluster NGC 6397 found something they weren't expecting: a flock of smaller black holes.

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

Learn more: [*Hubble* Uncovers Concentration of Small Black Holes]

Chapter 2: Black Holes: Agents of Change

Spiral galaxy NGC 4951, located roughly 50 million light-years away from Earth, is classified as a Seyfert galaxy, an extremely energetic type of galaxy with an active galactic nucleus (AGN). AGNs are powered by supermassive black holes at their centers. As matter whirls into the black hole, it generates radiation across the entire electromagnetic spectrum, making the AGN shine brightly. Seyfert galaxies are unique among AGNs because their galaxies are visible – typically for other AGNs, the nuclei are so bright that they drown out their host galaxies.

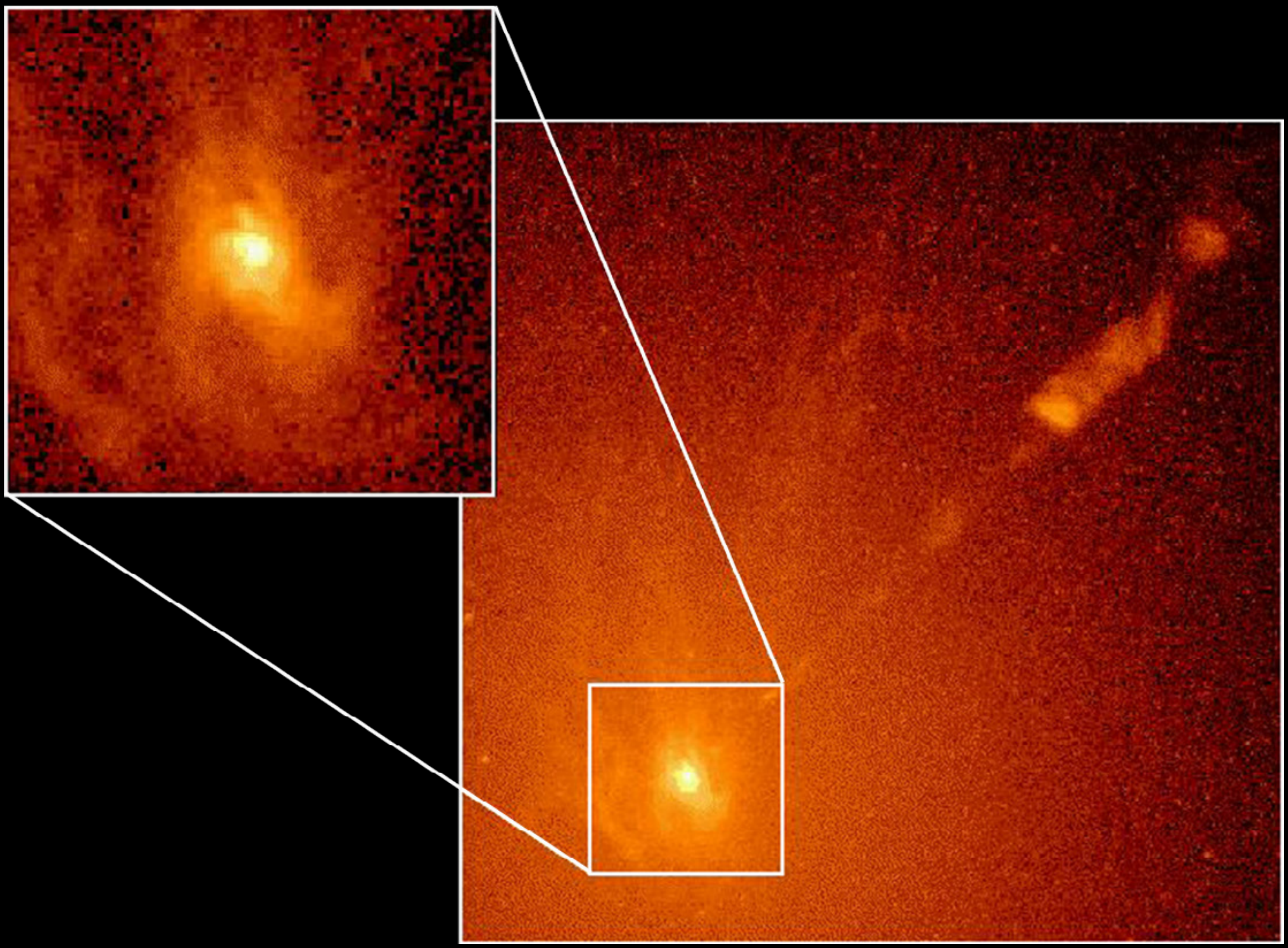
Credit: NASA, ESA, and D. Thilker (The Johns Hopkins University); Image Processing: Gladys Kober (NASA/Catholic University of America)

Black holes are more than threatening cosmic oddballs. They play a vital, yet still mysterious, role in the most intricate workings of the universe. They reside at the heart of most Milky Way-sized galaxies, evolving and shaping their structure. *Hubble* observations have led to the discovery that a supermassive black hole's mass is linked to the mass of a galaxy's central bulge of stars – the more massive the bulge, the more massive the black hole, suggesting that the growth of a galaxy and its central black hole are tied together.

Supermassive black holes were still fairly new to the world of astronomy when *Hubble* launched in 1990. In the 1960s and 1970s, astronomers began building the case for supermassive black holes and finding candidates in galaxies, including Sagittarius A* at the center of the Milky Way. *Hubble's* observations opened the door to a universe full of black holes, pinpointing dazzling bright black hole-powered galactic nuclei called "quasars" at the centers of galaxies and making the first-ever confirmation of the presence of a suspected black hole at the center of a galaxy. *Hubble's* further investigations showed that black holes were at the hearts of most galaxies, and integral to their development.

Today, astronomers think the Milky Way alone may also have as many as 100 million smaller black holes with the mass of stars. Though black holes are famed for consuming mass, they are also "messy eaters" whose violent, turbulent surroundings fling jets of matter and outflows of gas into space, spreading material throughout their galaxies and influencing the development of new stars. These outflows and jets can blast apart stars in their path or stir up material to trigger the formation of new stars.

This shows that despite their destructive powers, black holes are also a powerful catalyst for change, and *Hubble* has caught black holes in acts of transformation and even creation.



In 1994, *Hubble* measured the velocity of gas circling around a suspected black hole at the core of elliptical galaxy M87. Astronomers found that the hot, ionized gas was orbiting at tremendous speeds around a central object that is extremely massive but extraordinarily compact: a black hole. This discovery was the first confirmation of a supermassive black hole at the center of a galaxy.

Credit: Holland Ford, Space Telescope Science Institute/Johns Hopkins University; Richard Harms, Applied Research Corp.; Zlatan Tsvetanov, Arthur Davidsen, and Gerard Kriss at Johns Hopkins; Ralph Bohlin and George Hartig at Space Telescope Science Institute; Linda Dressel and Ajay K. Kochhar at Applied Research Corp. in Landover, Md.; and Bruce Margon from the University of Washington in Seattle; NASA

Connecting Young Galaxies and Supermassive Black Holes

Poring over *Hubble* archival data, researchers discovered a rapidly growing black hole in the early universe that is considered a crucial "missing link" between young star-forming galaxies and the first supermassive black holes.

"GNz7q … provides a new avenue toward understanding the rapid growth of supermassive black holes in the early days of the universe."

Seiji Fujimoto, Niels Bohr Institute of the University of Copenhagen

The object, nicknamed GNz7q, had been hiding unnoticed in one of the best-studied areas of the night sky, the Great Observatories Origins Deep Survey-North (GOODS-North) field.

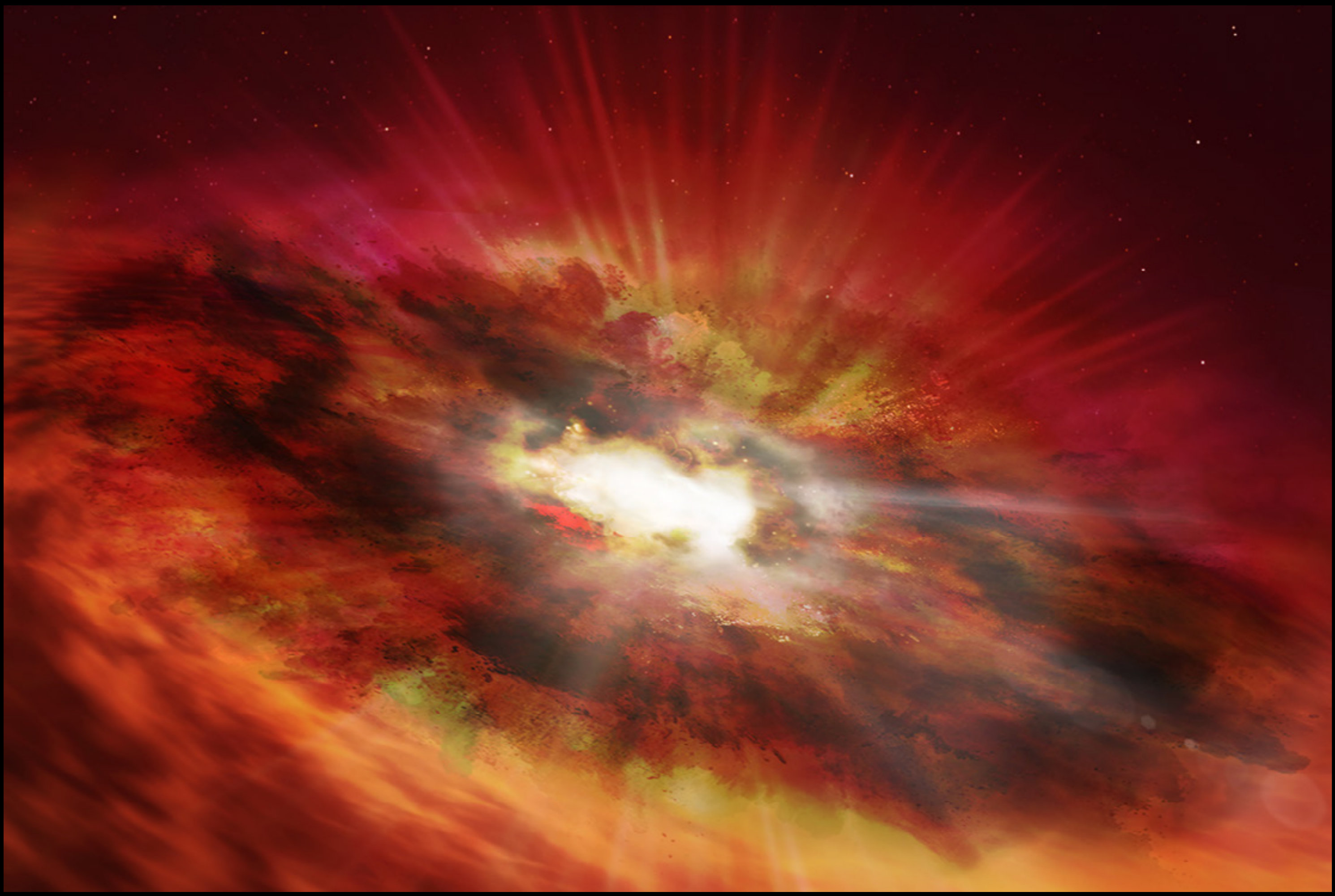
GNz7q is a compact source of ultraviolet (UV) and infrared light, consistent with the radiation expected from materials falling into a black hole. It existed just 750 million years after the Big Bang.

This portion of a deep-sky *Hubble Space Telescope* survey called the GOODS (Great Observatories Origins Deep Survey) North was viewed using *Hubble's* ultraviolet vision. The field features approximately 15,000 galaxies.

Credit: NASA, ESA, P. Oesch (University of Geneva), and M. Montes (University of New South Wales)

An outstanding astronomical mystery is how the supermassive black holes that reside in galactic cores, weighing millions to billions of times the mass of the Sun, grew to such tremendous mass so quickly. Current theories propose that they began their lives in the dust-shrouded cores of vigorously star-forming "starburst" galaxies before expelling the surrounding gas and dust and emerging as extremely luminous quasars. While extremely rare, both these dusty starburst galaxies and luminous quasars have been detected in the early universe. But rapidly growing black holes in dusty, early star-forming galaxies had not been observed until now.

The accretion disk of a massive black hole should be very bright in both UV and X-ray light. Although *Hubble* detected UV light in GNz7q, other observatories were unable to find X-ray light. This suggests that the core of the accretion disk, where X-rays originate, is still obscured; while the outer part of the accretion disk, where UV light originates, is becoming revealed. This interpretation matches with a rapidly growing black hole still obscured by the dusty core of its star-forming host galaxy.



This artist's illustration depicts GNz7q, a supermassive black hole inside the dust-shrouded core of a vigorously star-forming "starburst" galaxy. It will eventually become an extremely bright quasar, an intensely luminous type of active galactic nucleus, once the dust is gone.

Credit: NASA, ESA, N. Bartmann

Learn more: *Hubble* Sheds Light on Origins of Supermassive Black Holes

Surveilling an Upcoming Black Hole Collision

Peering through thick walls of gas and dust surrounding the cores of merging galaxies, astronomers discovered a rare view of close pairs of supermassive black holes plunging toward collision.

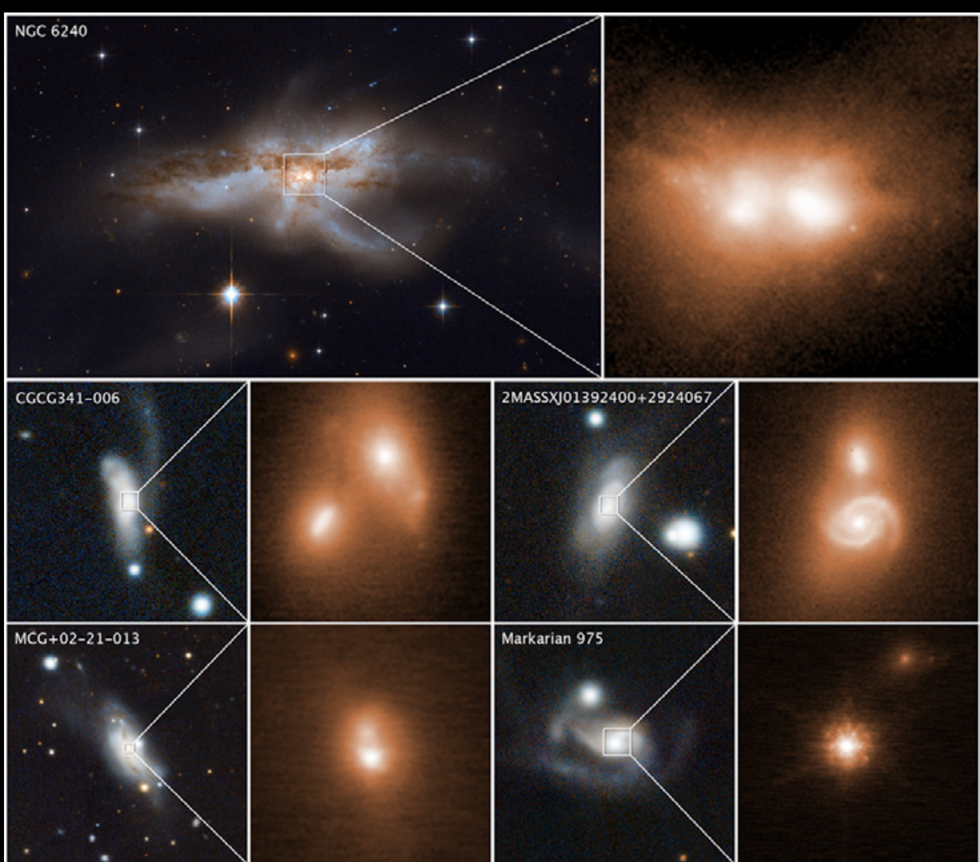
Pairing 20 years' worth of *Hubble* observations with near-infrared data from the W. M. Keck Observatory in Hawaii, researchers surveyed cores of nearby galaxies in near-infrared light. The observations support computer simulations showing that black holes grow fastest during the final stages of mergers, near the time when they interact. This helps explain how supermassive black holes grow so quickly to enormous mass.

> "Seeing the pairs of merging galaxy nuclei associated with these huge black holes so close together was pretty amazing,"
>
> Michael Koss, Eureka Scientific Inc.

A galaxy merger is a slow process lasting more than a billion years. Galaxies are drawn together by gravity, widely flinging their gas and dust in the process. The ejected material often forms a thick curtain around the centers of the coalescing galaxies, shielding them from view in visible light.

Some of the material also falls onto the black holes at the cores of the merging galaxies. The black holes grow rapidly as they devour, causing the infalling gas to blaze brightly. This speedy growth occurs during the last 10 million to 20 million years of the union. The *Hubble* and Keck Observatory images captured close-up views of this final stage, when the bulked-up black holes are only about 3,000 light-years apart — a near-embrace in cosmic terms. Because the thick dust and gas make the locations of merging nuclei difficult to observe, most prior observations of colliding galaxies caught the coalescing black holes at earlier stages, when they were about 10 times farther apart.

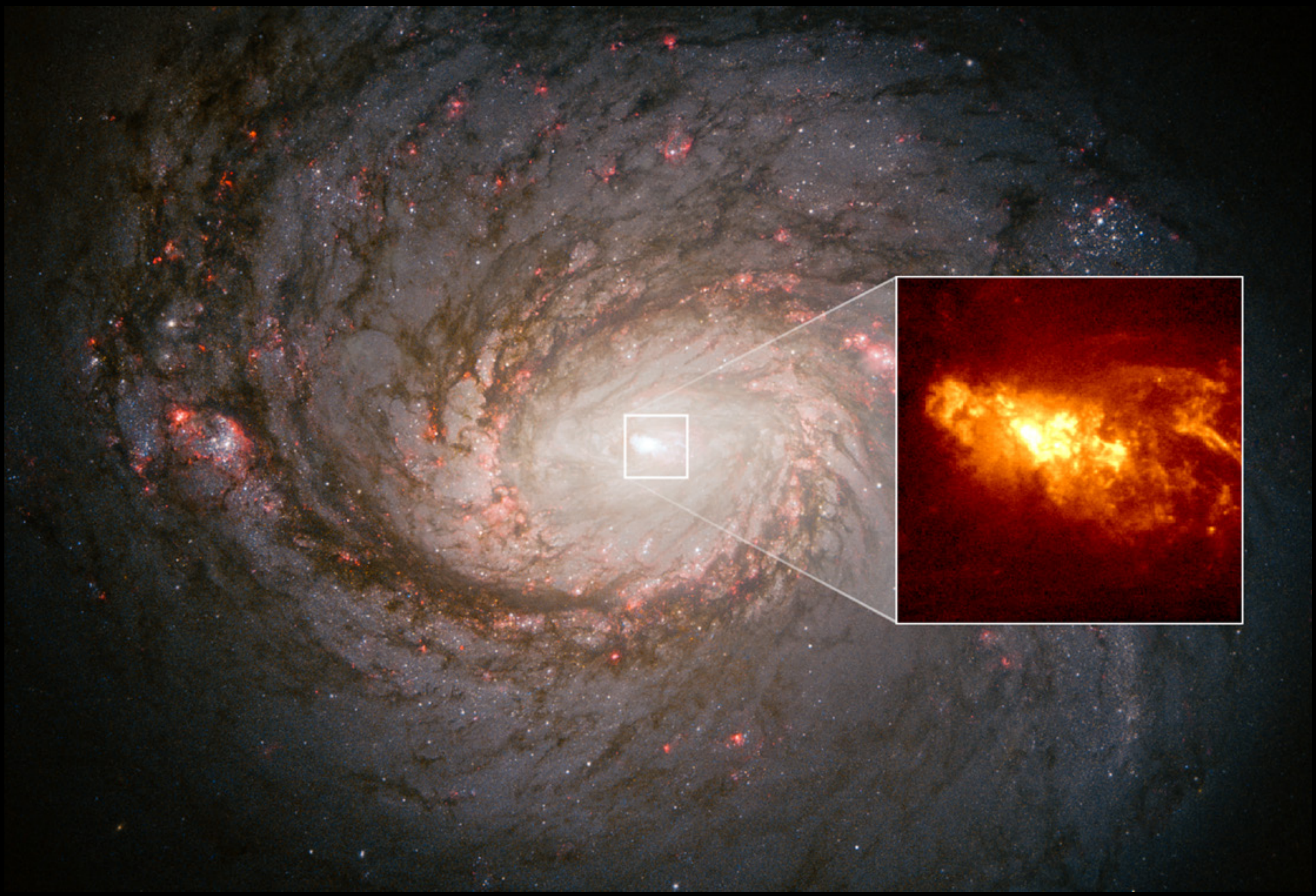
The images provide a close-up preview of a phenomenon that must have been more common in the early universe, when galaxy mergers were more frequent, and previews the upcoming collision of our Milky Way with the neighboring Andromeda galaxy in several billion years.



These images reveal the final stage of a union between pairs of galactic nuclei in the cores of colliding galaxies. The image at top left, taken by *Hubble's* Wide Field Camera 3, shows the merging galaxy NGC 6240 in visible and ultraviolet light. A close-up of the two brilliant cores of this galactic merger is shown at top right. This view, taken by *Hubble* in infrared light, pierces the dense cloud of dust and gas encasing the two colliding galaxies and uncovers the active cores. Images of four other colliding galaxies, along with close-up views of their coalescing nuclei in the bright cores, are shown beneath the snapshots of NGC 6240. The reddish images of the bright cores were taken in near-infrared light by the W. M. Keck Observatory in Hawaii, using adaptive optics to sharpen the view (right). The reference images (left) of the merging galaxies were taken by the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS). These observations are part of the largest-ever survey of the cores of nearby galaxies using high-resolution images in near-infrared light taken by the *Hubble* and Keck observatories.

Credit: NASA, ESA, and M. Koss (Eureka Scientific, Inc.); Hubble image: NASA, ESA, and M. Koss (Eureka Scientific, Inc.); Keck images: W. M. Keck Observatory and M. Koss (Eureka Scientific, Inc.); Pan-STARRS images: Panoramic Survey Telescope and Rapid Response System and M. Koss (Eureka Scientific, Inc.)

Learn more: Astronomers Unveil Growing Black Holes in Colliding Galaxies



Because we live inside the Milky Way, much of our view of the galaxy's center and its supermassive black hole is blocked by clouds of gas and dust. But *Hubble's* view of barred spiral galaxy NGC 1068, 45 million light-years away, gives us a good look at a comparative galaxy and its black hole outbursts. The inset *Hubble* image resolves hydrogen clouds as small as 10 light-years across within 150 light-years of the core. The clouds are glowing because they are caught in radiation beamed from the material that swirls around the galaxy's black hole before being consumed. The black hole in NGC 1068 is larger and more active than the black hole in the heart of our galaxy.

Credit: NASA, ESA, Alex Filippenko (UC Berkeley), William Sparks (STScI), Luis C. Ho (KIAA-PKU), Matthew A Malkan (UCLA), Alessandro Capetti (STScI); Image Processing: Alyssa Pagan (STScI)

Detecting Black Hole-Driven Star Formation

Data from *Hubble*, the *Chandra X-ray Observatory*, and the Karl Jansky Very Large Array, building on previous observations, have identified a long-sought phenomenon: a galaxy cluster where stars are forming at a furious rate, apparently linked to a weakened central black hole and its jets.

The black hole is in the center of a galaxy cluster called the Phoenix Cluster, located about 5.8 billion light-years from Earth. The large galaxy hosting the black hole is surrounded by hot gas with temperatures of millions of degrees and a mass several times greater than the combined mass of all the galaxies in the cluster.

This hot gas loses energy as it glows in X-rays, which should cause it to cool until it can form large numbers of stars. However, in all other observed galaxy clusters, bursts of energy driven by such a black hole keep most of the hot gas from cooling, preventing widespread star birth. Here, the black hole's less energetic jets fail to raise the gas' temperature enough to prevent star formation.

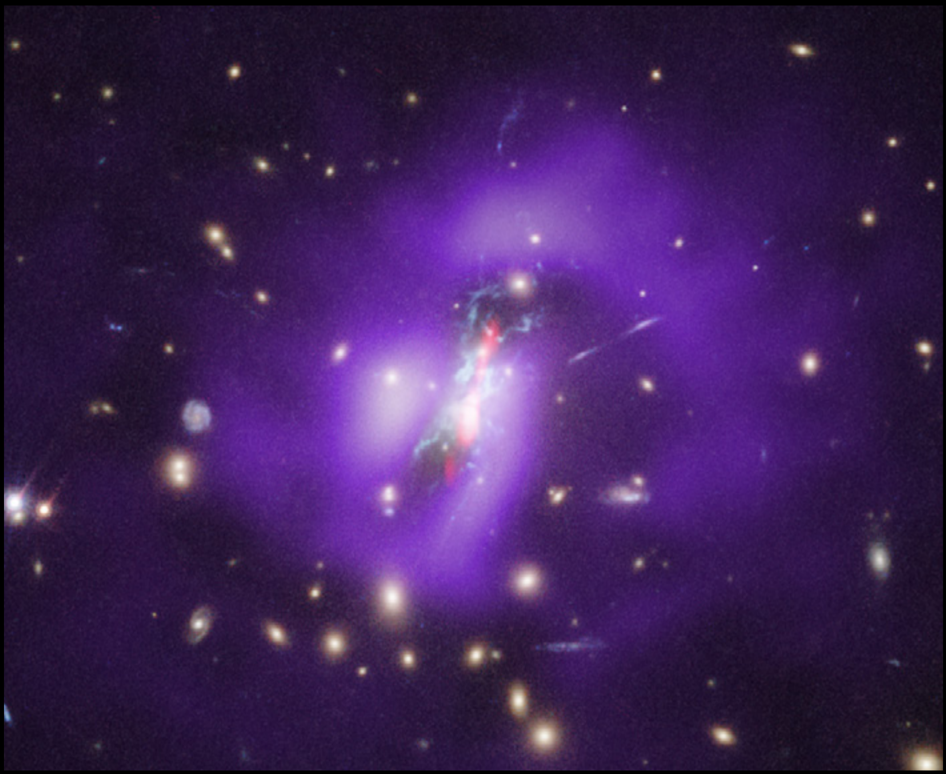
"This is a phenomenon that astronomers had been trying to find for a long time. This cluster demonstrates that, in some instances, the energetic output from a black hole can actually enhance cooling, leading to dramatic consequences."

Michael McDonald, Massachusetts Institute of Technology

Hubble data show that about 10 billion solar masses of cool gas are located along filaments leading towards the black hole, and young stars are forming from this cool gas at a rate of about 500 solar masses per year. By comparison, stars form in the Milky Way galaxy at a rate of about one solar mass per year.

This black hole may have been undersized compared to the mass of its host galaxy, which would allow rapid cooling to go unchecked. Outbursts from the black hole can also carry gas away from the center of the cluster and the heating influence of the black hole, with the gas cooling faster than it can fall back towards the center of the cluster.

As the black hole strengthens it will likely have the same effect as in other clusters, stifling star birth as it heats the environment. This will continue until the outburst ceases and the build-up of cool gas begins again. The whole cycle may then repeat.



The Phoenix galaxy cluster contains the first confirmed supermassive black hole that is unable to prevent large numbers of stars from forming in the core of the galaxy cluster where it resides. Data from NASA's Chandra X-ray Observatory show that the coolest gas it can detect is located near the center of the cluster. In the absence of significant sources of heat, astronomers expect cooling and related star formation to occur at the highest rates in a cluster's center, where the densest gas is located. Hubble visible light observations provide evidence for further cooling of gas near the center of the Phoenix Cluster. Ten billion solar masses of cooler gas are located along filaments to the north and south of the supermassive black hole located in the center of the image. Outbursts from the black hole generated jets seen in radio waves by the Very Large Array (VLA) radio telescope. As the jets push outward, they inflate cavities, or bubbles, in the hot gas that pervades the cluster. Chandra's X-ray vision detected these cavities.

Credit: NASA, ESA, and NRAO

Learn more: A Weakened Black Hole Allows Its Galaxy to Awaken

Catching a Dwarf Galaxy's Black Hole Nurturing Stars

A black hole at the heart of the dwarf galaxy Henize 2-10, 30 million light-years away, is creating stars rather than devouring them.

An outflow of gas, launched from the energetic region around the black hole, stretches across space from the black hole to a bright stellar nursery. The region was already home to a dense cocoon of gas when the outflow arrived. *Hubble* spectroscopy shows the outflow is moving about 1 million miles per hour, slamming into the dense gas like water from a garden hose hitting a pile of dirt and spreading out. Newborn star clusters dot the path of the outflow's spread, their ages also calculated by *Hubble*.

"Dwarf galaxies may retain some memory of the black hole seeding scenario that has otherwise been lost to time and space."

Amy Reines, eXtreme Gravity Institute, Montana State University

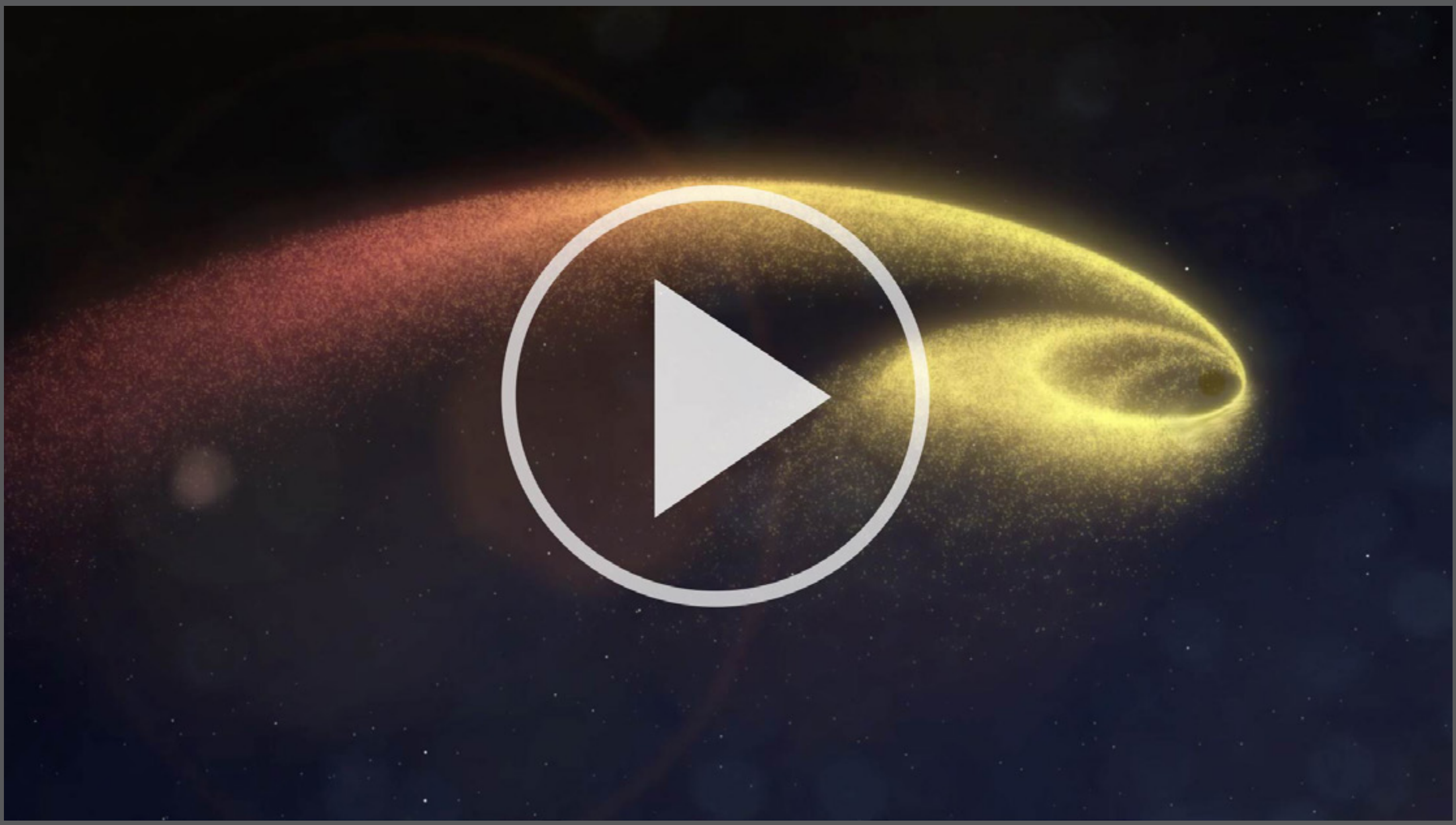
This is the opposite effect of what's seen in larger galaxies, where material falling toward the black hole is whisked away by surrounding magnetic fields, forming jets of plasma moving at close to the speed of light. Gas clouds caught in the jets' path would become too hot to cool back down and form stars. But with the less-massive black hole in Henize 2-10, and its gentler outflow, gas was compressed just enough to trigger new star formation.

Henize 2-10 contains only one-tenth the number of stars found in our Milky Way and is poised to play a big part in solving the mystery of where supermassive black holes came from in the first place. Because dwarf galaxies have remained small over cosmic time, astronomers think their black holes could serve as an analog for black holes in the early universe, when they were just beginning to form and grow.

Dwarf starburst galaxy Henize 2-10 glitters with young stars in this *Hubble* visible-light image. The bright region at the center, surrounded by pink clouds and dark dust lanes, indicates the location of the galaxy's massive black hole and active stellar nurseries.

Credit: NASA, ESA, Zachary Schutte (XGI), Amy Reines (XGI); Image Processing: Alyssa Pagan (STScI)

Hubble Finds a Black Hole Igniting Star Formation in a Dwarf Galaxy



Black holes are often described as the monsters of the universe—tearing apart stars, consuming anything that comes too close, and holding light captive. Detailed evidence from *Hubble*, however, shows a black hole in a new light: fostering, rather than suppressing, star formation.

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

Learn more: [Hubble Finds a Black Hole Igniting Star Formation in a Dwarf Galaxy]

Black Hole Beam Causes Stellar Explosions

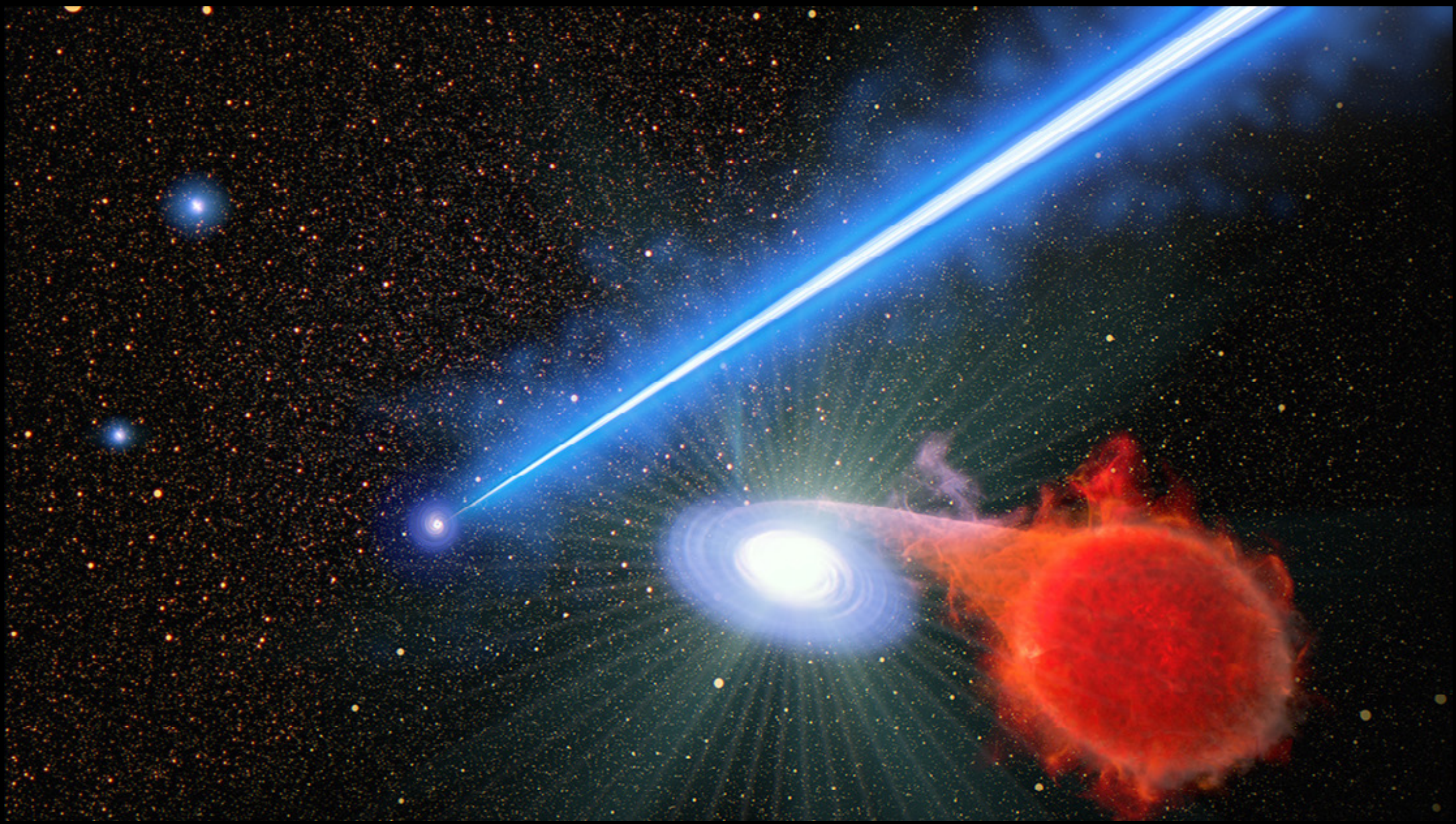
Surprised astronomers discovered that the blowtorch-like jet from a supermassive black hole at the core of galaxy M87 seems to cause stars to erupt along its trajectory. The stars, called novae, are not caught inside the jet, but apparently in a dangerous region nearby.

A nova occurs in a double-star system where an aging, swelled-up, normal star spills hydrogen onto a burned-out white dwarf companion star. When the dwarf collects a mile-deep (1.6 km) surface layer of hydrogen, that layer explodes like a giant nuclear bomb. The white dwarf isn't destroyed by the nova eruption. It ejects its surface layer and then goes back to siphoning fuel from its companion, and the nova-outburst cycle starts over again.

"This means there's something missing from our understanding of how black hole jets interact with their surroundings."

Alec Lessing, Stanford University

Hubble found twice as many novae going off near the black hole jet as elsewhere in the galaxy during the surveyed time period. The jet is launched by a 6.5-billion-solar-mass central black hole surrounded by a disk of swirling matter. Emanating from that superheated disk, the 3,000-light-year-long jet of plasma blazes through space at nearly the speed of light. Anything caught in the energetic beam would be sizzled. But these stars are only nearby. Perhaps the jet somehow snowplows hydrogen fuel onto the white dwarfs, causing them to erupt more frequently, or the jet could be heating the dwarf's companion star, causing it to overflow further and dump more hydrogen onto the dwarf. Astronomers are still searching for an explanation for these *Hubble* findings.



In this artist's concept, a supermassive black hole ejects a 3,000-light-year-long jet of plasma. In the foreground is a binary star system, far from the black hole but in the vicinity of the jet. A swelled-up, normal star spills hydrogen onto a white dwarf companion star, which will erupt when it accumulates enough hydrogen.

Credit: NASA, ESA, Joseph Olmsted (STScI)

Learn More: NASA's *Hubble* Finds that a Black Hole Beam Promotes Stellar Eruptions

Chapter 3: Black Holes Behaving Oddly

The spiral galaxy visible in the center of the image, RX J1140.1+0307, presents an enigma. Its central supermassive black hole has one of the lowest masses known in any luminous galactic core. What puzzles scientists about this particular galaxy is that the calculations don't add up. With such a relatively low mass for the central black hole, models for the emission from the object cannot explain the observed spectrum. There must be other mechanisms at play in the interactions between the inner and outer parts of the accretion disk surrounding the black hole.

Credit: ESA/Hubble & NASA; Acknowledgement: Judy Schmidt

Black holes shape the universe around them in strange, unexpected, and sometimes bewildering ways. The black hole phenomenon is rife with mysteries, and our observations of these objects often surprise us.

Hubble has found that supermassive black holes can be both slightly offset from the centers of their galaxies and knocked quite far away from their cores. It has studied rare and bizarre cosmic explosions that may be caused by black holes devouring stars or even colliding. It was the first to observe that black hole disks could be warped or twisted, meaning the environment around black holes was more varied than originally thought.

It sometimes seems that the more we study black holes, the more difficult it is to make what we know about them add up. But with the help of *Hubble*, researchers are uncovering more and more details about the inner workings of black holes and the role they play in their cosmic surroundings.

On the Trail of a Runaway Black Hole

A streak first thought to be an illusion, specifically a mark caused by a stray cosmic ray striking a *Hubble* detector, turned out to be a 200,000-light-year-long trail of newborn stars – twice the diameter of our Milky Way galaxy – spawned by a runaway black hole.

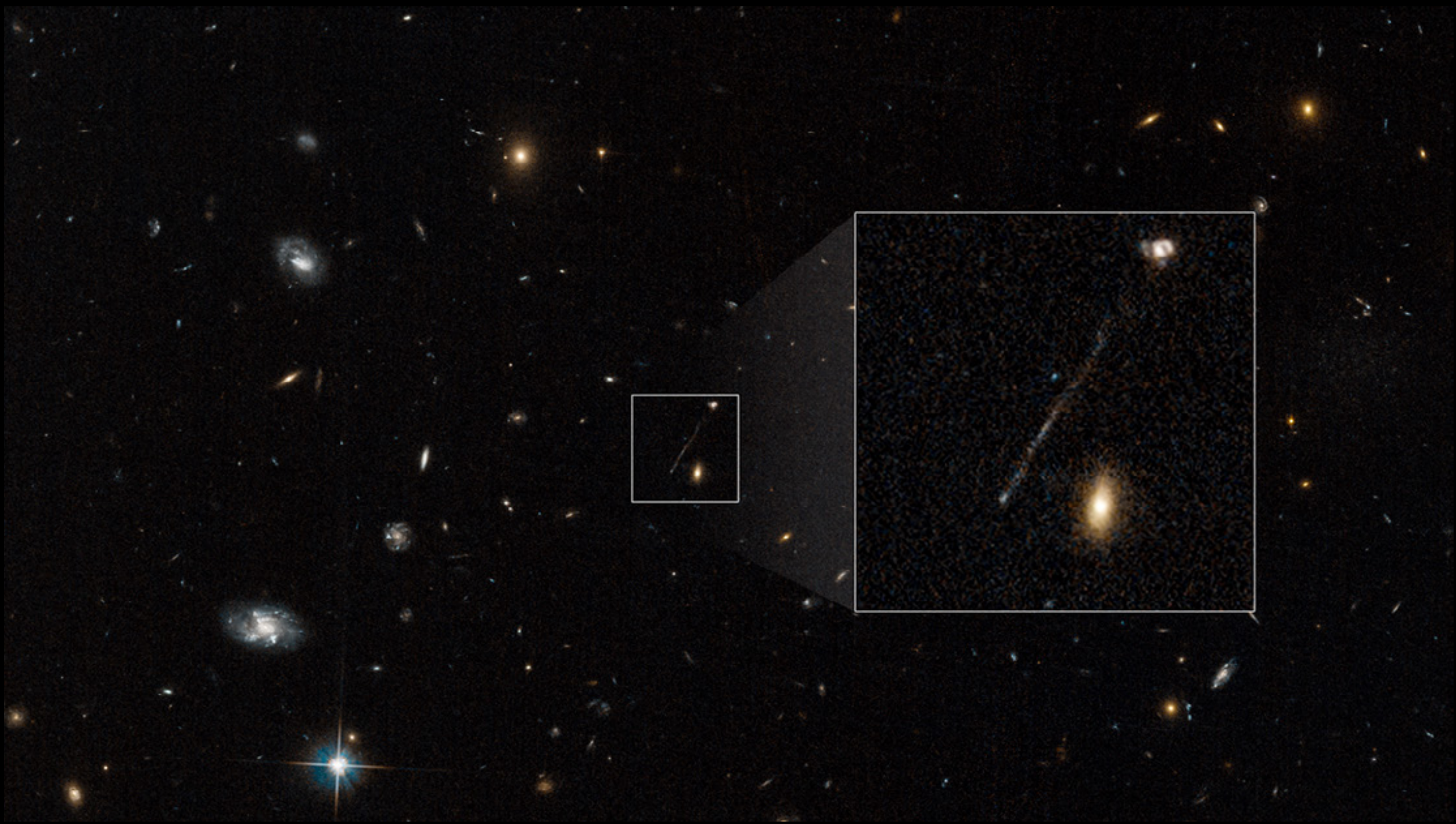
“When we eliminated cosmic rays we realized it was still there. It didn’t look like anything we’ve seen before.”

Pieter van Dokkum, Yale University

Nothing like the trail has ever been seen before. *Hubble* captured it by sheer chance in an observation of a dwarf galaxy.

A supermassive black hole, weighing as much as 20 million Suns, was likely kicked out of its galaxy by gravitational interactions between galaxies. One pair of galaxies would have merged perhaps 50 million years ago, creating a binary black hole with two supermassive black holes orbiting each other. A third galaxy arrived later, carrying its own supermassive black hole. The configuration of the three black holes became unstable and tossed one of the black holes out of its host galaxy. As that single black hole took off in one direction, the binary black holes shot off in the opposite direction. A feature visible on the opposite side of the host galaxy might be the binary black holes.

As the ejected black hole plowed into the gas in front of it, it triggered new star formation along a narrow corridor, leaving a wake of cooling gas and forming stars as it passed. The black hole now lies at one end of the column, which stretches back to its parent galaxy. A bright knot of ionized oxygen at the outermost tip of the column is probably gas being shocked and heated from the motion of the black hole, or radiation from an accretion disk around the black hole.



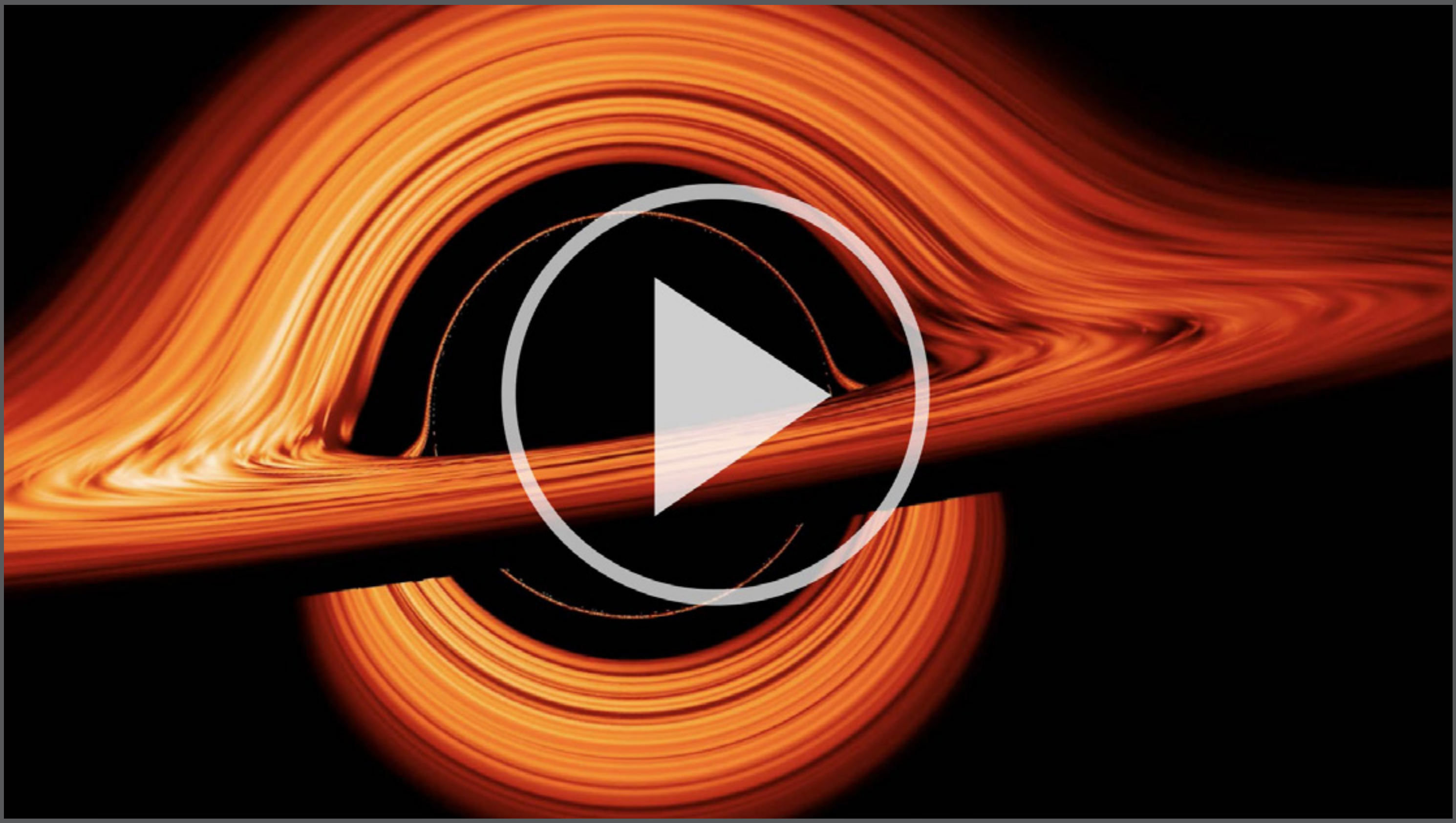
This *Hubble* archival photo captures a curious linear feature that is so unusual it was first dismissed as an imaging artifact from *Hubble’s* cameras. But follow-up spectroscopic observations reveal it is a 200,000-light-year-long chain of young blue stars. A supermassive black hole lies at the tip of the bridge at lower left. The black hole was ejected from the galaxy at upper right. It compressed gas in its wake to leave a long trail of young blue stars. Nothing like this has ever been seen before in the universe. This unusual event happened when the universe was approximately half its current age.

Credit: NASA, ESA, Pieter van Dokkum (Yale); Image Processing: Joseph DePasquale (STScI)

This artist's impression depicts a runaway supermassive black hole that was ejected from its host galaxy as a result of a tussle between it and two other black holes. As the black hole plows through intergalactic space it compresses gas in front of it, birthing hot blue stars.

Credit: NASA, ESA, Leah Hustak (STScI)

Hubble Catches Possible Runaway Black Hole



A potential supermassive black hole, weighing as much as 20 million Suns, has left behind a never-before-seen 200,000 light-year-long trail of newborn stars – twice the diameter of our Milky Way galaxy. It's likely the result of a rare, bizarre game of galactic billiards among three massive black holes.

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

Learn more: [*Hubble* Sees Possible Runaway Black Hole Creating a Trail of Stars]

Watching a Black Hole Twist a Star Into a Donut

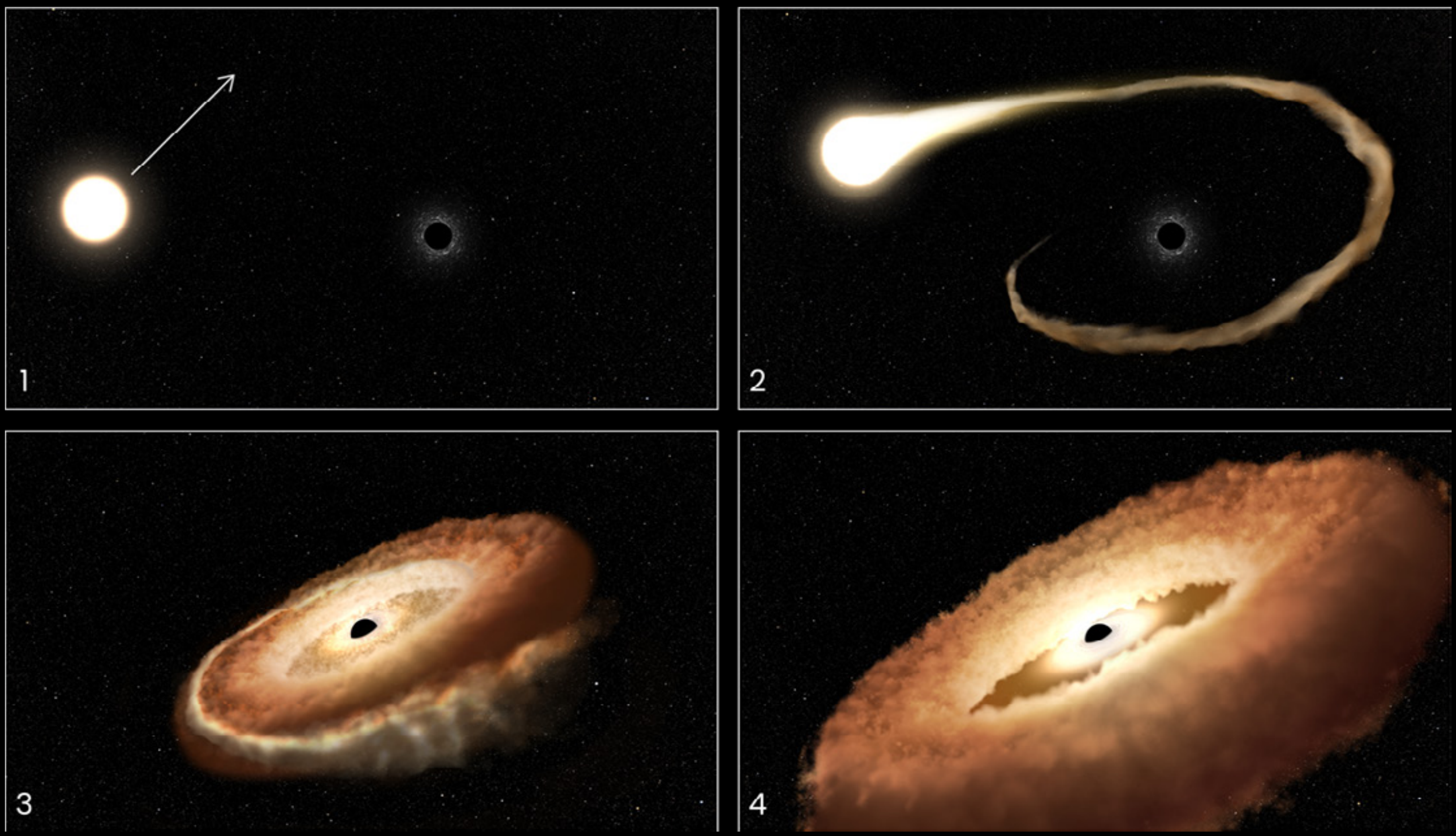
Hubble has recorded a star's demise as it was swallowed by a black hole, analyzing its light to paint a picture of a stellar shredding.

Alerted by the All-Sky Automated Survey for Supernovae to a flash of high-energy radiation from the core of a galaxy 300 million light-years away, scientists trained *Hubble* on the region to glean clues about what's called a "tidal disruption event," when a star is pulled into a black hole. Astronomers used *Hubble's* powerful ultraviolet sensitivity to study the light from the shredded star.

> "This is an exciting place for scientists to be: right at the interface of the known and the unknown."
>
> Peter Maksym, Center for Astrophysics | Harvard & Smithsonian (CfA)

The *Hubble* spectroscopic data are interpreted as coming from a very bright, hot, donut-shaped area of gas that was once the star. This area, known as a torus, is the size of the solar system and is swirling around a black hole in the middle. Astronomers think the star was torn apart and pulled toward the black hole like a piece of stretched taffy, forming the donut-shaped ring of stellar material and superheated gas. A stellar wind sweeps away from the black hole at speeds of 20 million miles per hour (three percent of the speed of light).

For any given galaxy with a dormant or "quiescent" supermassive black hole at the center, it's estimated that this stellar shredding happens only a few times every 100,000 years. Changes in the doomed star's condition take place on the order of months or even days, making *Hubble's* ringside seat for the event critical for understanding what happens to matter as it swirls into a black hole.

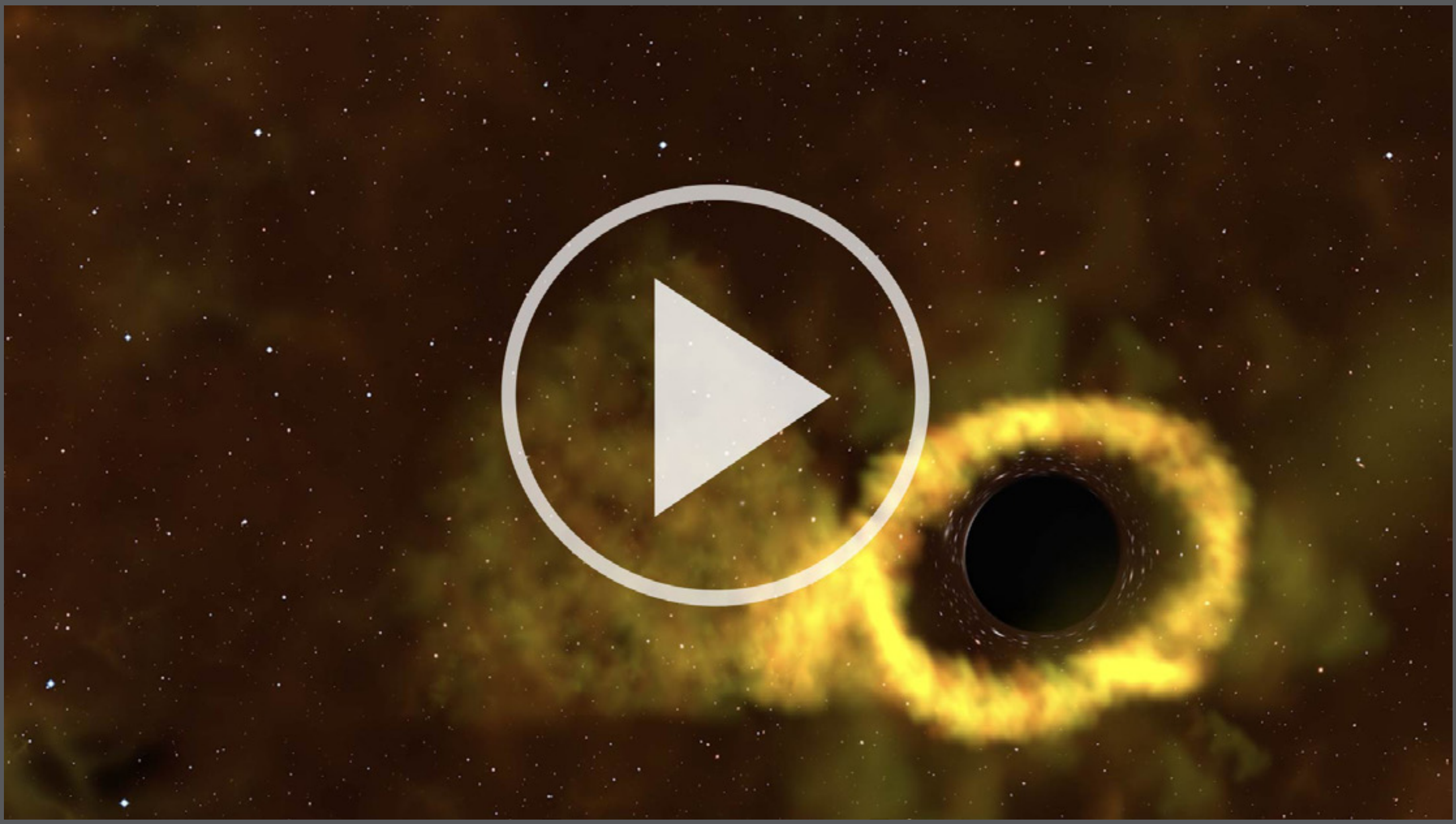


This sequence of artist's illustrations shows how a black hole can devour a bypassing star. In panel 1, a normal star passes near a supermassive black hole in the center of a galaxy. In panel 2, the star's outer gasses are pulled into the black hole's gravitational field. Panel 3 shows the star being shredded as tidal forces pull it apart. Finally, in panel 4, the stellar remnants are pulled into a donut-shaped ring around the black hole, and will eventually fall into the black hole, unleashing a tremendous amount of light and high-energy radiation.

Credit: NASA, ESA, Leah Hustak (STScI)

Learn more: *Hubble* Finds Hungry Black Hole Twisting Captured Star Into Donut Shape

Hubble Finds Hungry Black Hole Twisting Captured Star Into Donut Shape



Black holes lie in wait until a hapless star wanders by. When the star gets close enough, the black hole's gravitational grasp rips it apart and devours its gases while spewing intense radiation. Astronomers using *Hubble* have recorded a star's final moments in detail as it gets gobbled up by a black hole.

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

Investigating a Black Hole Puzzle

Astronomers have found a mystery: a thin disk of material furiously whirling around a supermassive black hole at the heart of the magnificent spiral galaxy NGC 3147.

The disk shouldn't be there, based on current astronomical theories, and calls into question the understanding of gas dynamics in very faint, active galaxies.

"We've never seen the effects of both general and special relativity in visible light with this much clarity."

Marco Chiaberge, European Space Agency, the Space Telescope Science Institute, and Johns Hopkins University.

NGC 3147, located 130 million light-years away, is an example of a galaxy with a malnourished central black hole. These types of galaxies don't contain enough gravitationally captured material to feed their black holes regularly. The thin haze of infalling material typically puffs up like a donut rather than flattening out in a pancake-shaped disk. So it's puzzling why NGC 3147 has a thin disk that resembles the much more powerful disks found in extremely active galaxies with monster black holes.

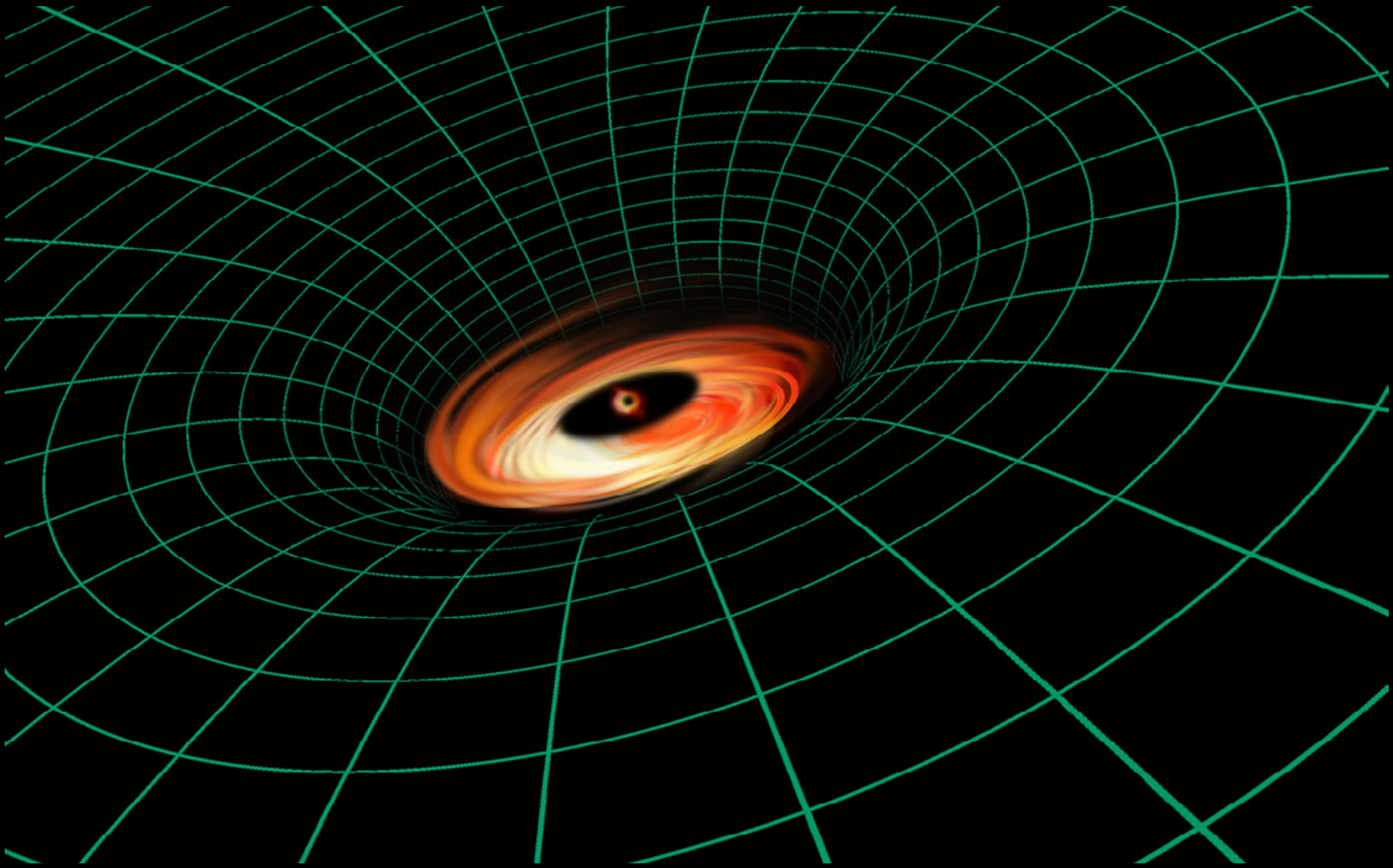
NGC 3147's black hole weighs 250 million times the mass of our Sun. The disk is so deeply embedded in the black hole's intense gravitational field that its light is being stretched and intensified by the black hole's powerful grasp, providing a unique, real-world demonstration of Einstein's laws of relativity.

By capturing spectroscopic data, *Hubble* clocked material moving around the black hole at more than 10% of the speed of light. At those extreme velocities, the gas appears to brighten as it travels toward Earth on one side, and dims as it speeds away from our planet on the other side (an effect called "relativistic beaming"). *Hubble's* observations also show that the gas is so entrenched in the gravitational well the light is struggling to climb out, and therefore appears stretched to redder wavelengths.

Since the galaxy's stars outshine and overpower any light from its nucleus, only *Hubble* had the resolution to isolate the faint light from the black hole region and block out nearby starlight. Researchers plan to use *Hubble* to hunt for other very compact disks around low-wattage black holes in similar active galaxies.

At the center of spiral galaxy NGC 3147 is a malnourished black hole surrounded by a thin, compact disk of stars, gas, and dust that have been caught up in a gravitational maelstrom. The black hole's gravity is so intense that anything that ventures near it gets swept up in the disk.

Credit: NASA, ESA, S. Bianchi (Università degli Studi Roma Tre University), A. Laor (Technion-Israel Institute of Technology), and M. Chiaberge (ESA, STScI, and JHU)



An illustration shows the supermassive black hole residing at the core of spiral galaxy NGC 3147. The reddish-yellow features swirling around the center are the glow of light from gas trapped by the black hole's powerful gravity. The black hole is embedded deep within its gravitational field, shown by the green grid that illustrates warped space. The gravitational field is so strong that light struggles to climb out. Material also is whipping so fast around the black hole that it brightens as it approaches Earth on one side of the disk and gets fainter as it moves away. This effect, called relativistic beaming, was predicted by Einstein's theory of special relativity.

Credit: NASA, ESA, and A. Feild and L. Hustak (STScI)

Learn more: *Hubble* Uncovers Black Hole Disk that Shouldn't Exist

Beholding a Belching Black Hole

Embedded in the hearts of galaxies, supermassive black holes can lie dormant for long periods of time until their next meal comes along. A flickering supermassive black hole in galaxy SDSS J1354+1327 (aka J1354), located about 800 million light-years away, seems to have enjoyed two recent meals.

Astronomers using observations from *Hubble*, the *Chandra X-ray Observatory*, the W.M. Keck Observatory in Mauna Kea, Hawaii, and the Apache Point Observatory near Sunspot, New Mexico, zeroed in on a black hole that appears to have consumed large amounts of gas while intermittently blasting off outflows of high-energy particles.

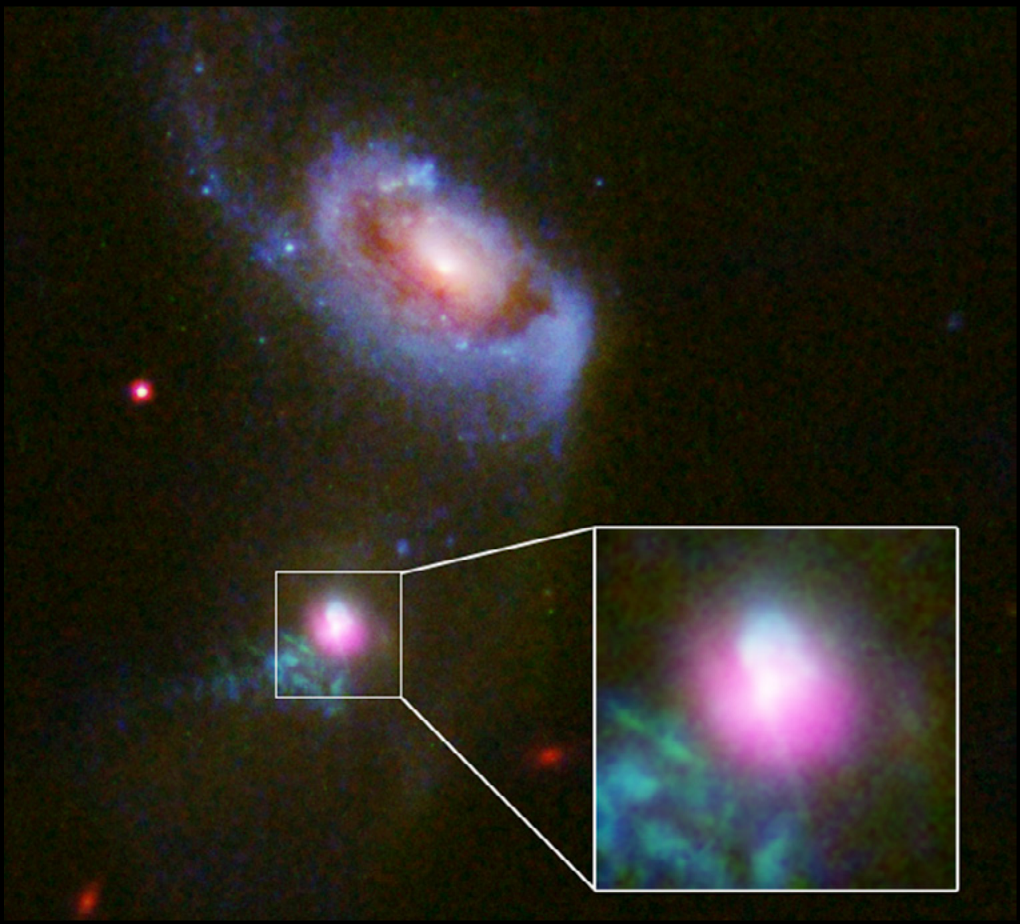
"We are seeing this object feast, burp, and nap, and then feast and burp once again, which theory had predicted."

Julie Comerford, University of Colorado (CU) Boulder

The two-course meal for the black hole comes from a companion galaxy that collided with J1354 in the past. This collision produced a stream of stars and gas that links J1354 and the other galaxy. The separate outbursts from the black hole are caused by different clumps from this stream being consumed by the supermassive black hole. Some of this gas will fall into the black hole, while a portion will be expelled in a powerful outflow of high-energy particles. The researchers determined these two outflows of particles, or "burps," happened about 100,000 years apart.

Evidence of electrons being stripped from atoms in a cone of gas extending some 30,000 light years south from the galaxy's center points to a burst of radiation from the vicinity of the black hole, indicating that the first of the two feasting events had occurred. Researchers also found evidence for a shock wave, similar to a sonic boom, located about 3,000 light-years north from the black hole. This suggests that a burp occurred after a different clump of gas had been consumed roughly 100,000 years later.

The observations provide strong evidence that accreting black holes can switch their power output off and on again over timescales that are short compared to the 13.8-billion-year age of the universe.



This is an image of galaxy SDSS J1354+1327 (lower center) and its companion galaxy SDSS J1354+1328 (upper right). The inset panel to the right is a four-color image that combines *Hubble* red, green, and blue filtered exposures with Chandra X-ray observations, colored purple. The *Hubble* image shows the northern bubble of hot ionized gas in the vicinity of a supermassive black hole. The black hole appears to have blasted out jets of bright light from gas it's accreting from the companion galaxy. This happened twice in the past 100,000 years. While astronomers have predicted such objects can flicker on and off as a result of gas-feeding events, this is the first time one has convincingly been caught in the act. The galaxy pair is 800 million light-years from Earth.

Credit: NASA, ESA, and J. Comerford (University of Colorado-Boulder)

Learn more: Researchers Catch Supermassive Black Hole Burping – Twice

Casting Light on a Black Hole's Shadow

Hubble has glimpsed a unique phenomenon – light blazing out of the brilliant center of an active galaxy and being split by the dusty ring of matter swirling around its black hole, like rays of light and shadow peeking through clouds at sunset.

A supermassive black hole pulls stars and gas into a dust disk that swirls around it until it's consumed. The feeding generates a prodigious amount of energy, producing a powerful outpouring of light from superheated infalling gas. These disks are so far away that it's nearly impossible to discern any detail about them.

"We know this phenomenon should happen, but in this case, we can see the effects throughout the galaxy."

Peter Maksym, Center for Astrophysics | Harvard & Smithsonian (CfA)

But in this case, a collection of narrow, cone-shaped bright rays and dark shadows beaming out of the center of galaxy IC 5063 and sweeping at least 36,000 light-years across space may give clues to the structure of the disk around the black hole.

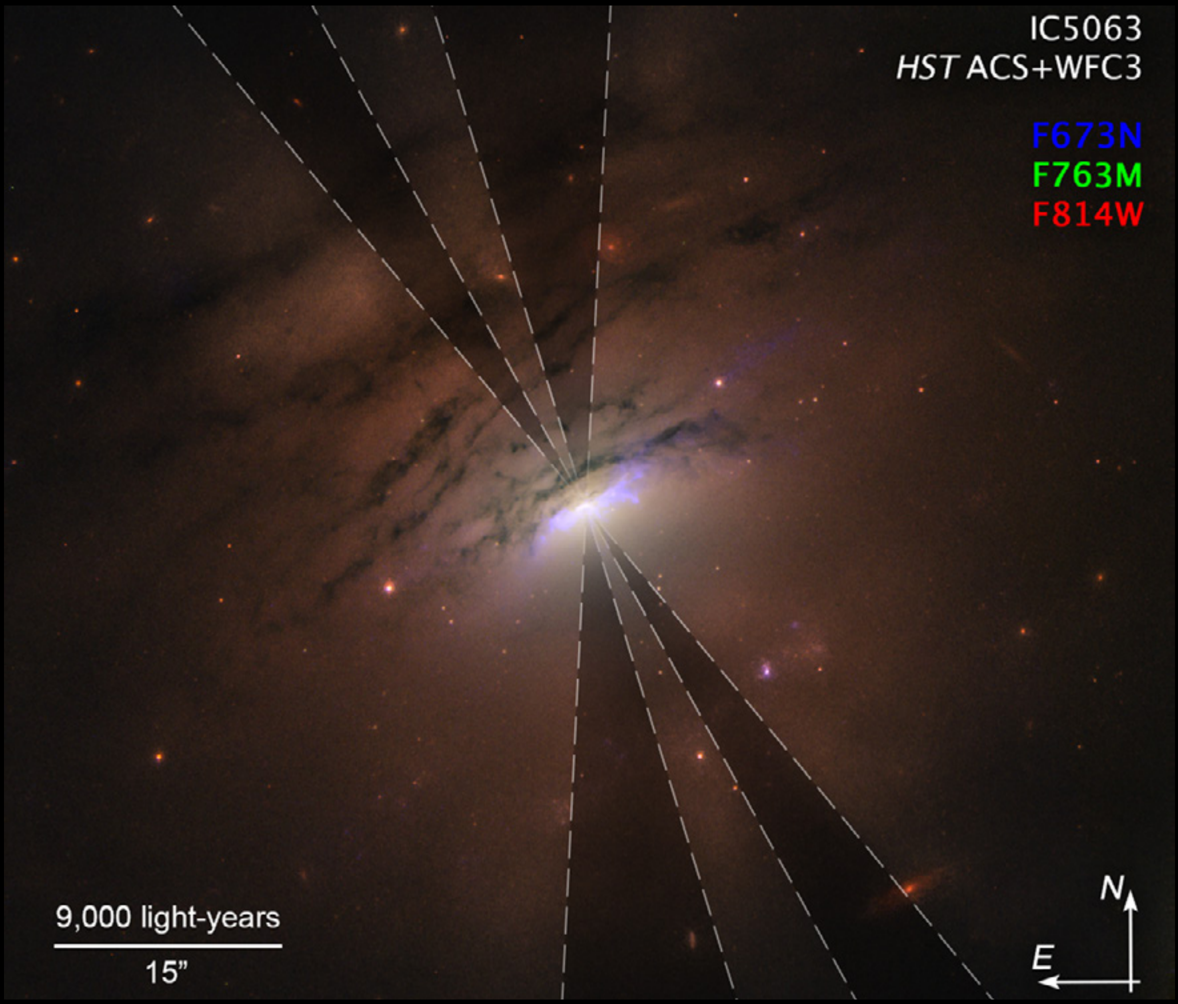
One plausible theory for the striking lightshow is that an inner-tube-shaped ring, or torus, of dusty material surrounding the black hole is casting its shadow into space. Some light penetrates gaps in the dust ring, creating bright rays. Some of the light hits dense patches in the ring, casting dark, finger-like shapes. The disk in IC 5063 could be very thin, which explains why light is leaking out all around the structure.

IC 5063 is relatively nearby, only 156 million light-years from Earth. The discovery of the rays was possible due to *Hubble's* sharp resolution, which allows it to see very faint objects, and its field of view, which encompassed the entire galaxy. An amateur astronomer uncovered the interplay of light and shadows streaming across space while reprocessing *Hubble* exposures of the galaxy.

Knowing more about the geometry of the torus will have implications for anyone trying to understand the behavior of supermassive black holes and their environments, as well as how galaxies are shaped by their black holes.

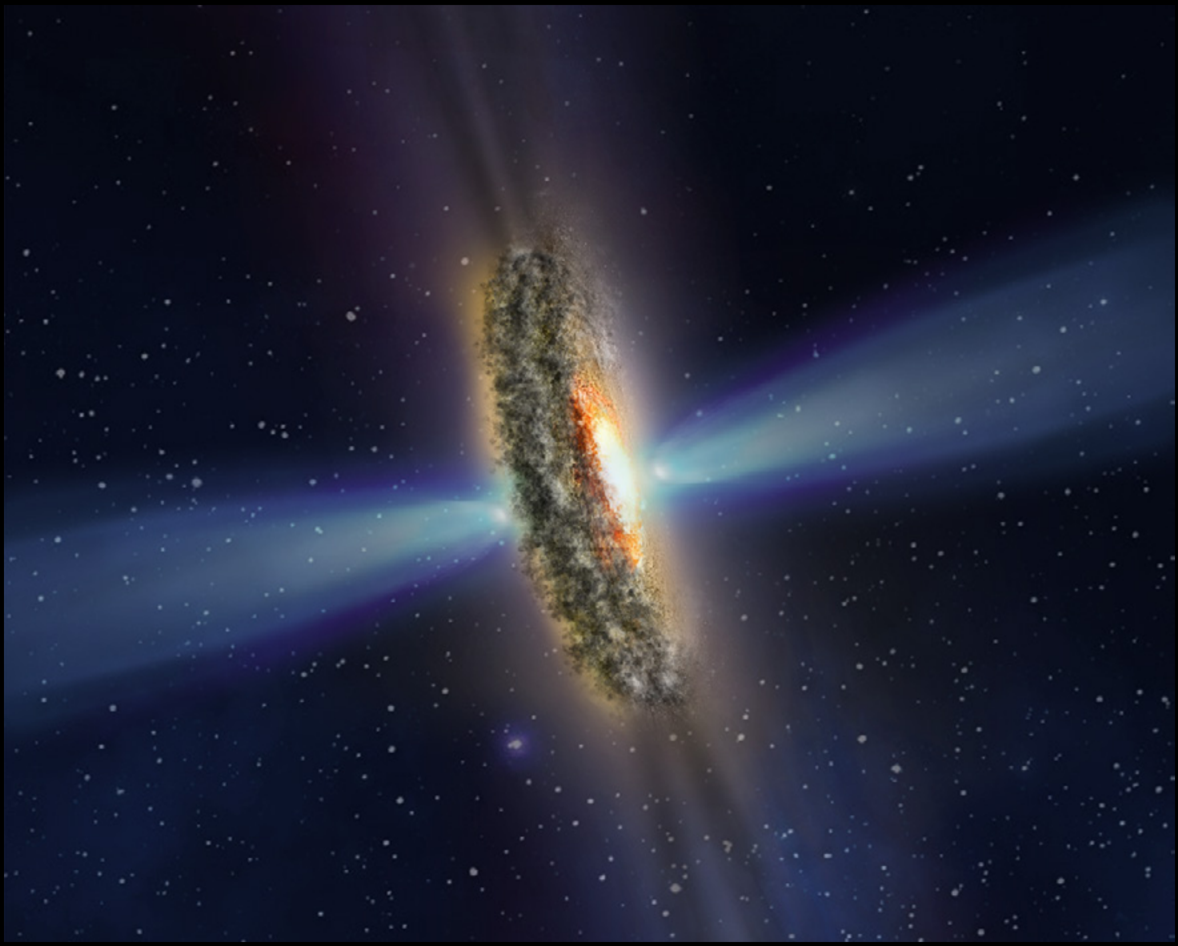
This *Hubble* image of the heart of nearby active galaxy IC 5063 reveals a mixture of bright rays and dark shadows coming from its core, home of a supermassive black hole. A ring of dusty material surrounding the black hole may be casting its shadow into space.

Credit: NASA, ESA, STScI and W.P. Maksym (CfA)



This annotated *Hubble* image highlights the shadows emanating from the direction of the black hole.

Credit: NASA, ESA, STScI and W.P. Maksym (CfA)



This illustration depicts one possible explanation for the mysterious bright rays and dark shadows observed emanating from the center of nearby active galaxy IC 5063. The dusty disk surrounding the supermassive black hole casts its shadow into space, while bright rays leak through gaps in the disk. Shadows and rays extend from both sides of the disk, seen edge-on in this view. High-speed jets of plasma shoot out of the black hole without smashing into the disk.

Credit: NASA, ESA, and Z. Levy (STScI)

Learn more: [Hubble Catches 'Shadow Play' of the Disk Around a Black Hole]

Chapter 4: Black Hole Neighbors

Roughly one out of every thousand stars that form is massive enough to become a black hole, which means our own Milky Way galaxy is packed with around 100 million of these invisible cosmic devourers. Our galaxy provides our closest and most detailed view of these violent and fascinating objects, helping us to interpret their many mysteries.

Hubble's constant eye in space for over 30 years has allowed it to build up a vast archive of observations that can be used to track down black holes and refine our understanding of what they are, where they are, and how they work. *Hubble's* ability to see ultraviolet light is particularly helpful when studying black holes, since the disks of gas and matter swirling around them can unleash a torrent of ultraviolet light as material approaches the black hole. Meanwhile, *Hubble's* visible light capabilities allow it to study everything from the motion of stars orbiting near black holes to starlight being warped and brightened by the black hole's intense gravity.

As *Hubble* captures snapshots of our galaxy, it inevitably witnesses the effects of black holes, from lingering traces of our central supermassive black hole's outbursts to the orbits of stars captured by black holes' gravitational pull. And working hand-in-hand with other observatories, it continues to zero in on known and potential black holes, gathering details that will slowly solve the puzzles of the universe's most bewildering objects.

Hubble observations have helped build a history of Eta Carinae, an unstable, supermassive star system 7,500 light-years away in our own Milky Way galaxy, which is likely to become a black hole after its eventual death as a supernova. Eta Carinae is prone to violent outbursts, including an episode in the 1840s that ejected material to form the bipolar bubbles seen here.

Credit: NASA, ESA, N. Smith (University of Arizona), and J. Morse (BoldlyGo Institute)

Uncovering the Distant History of Our Galaxy

About 3.5 million years ago, a glowing spot appeared along the arc of the star-studded Milky Way, evidence of a tremendous explosion around a black hole that rocked the center of our galaxy.

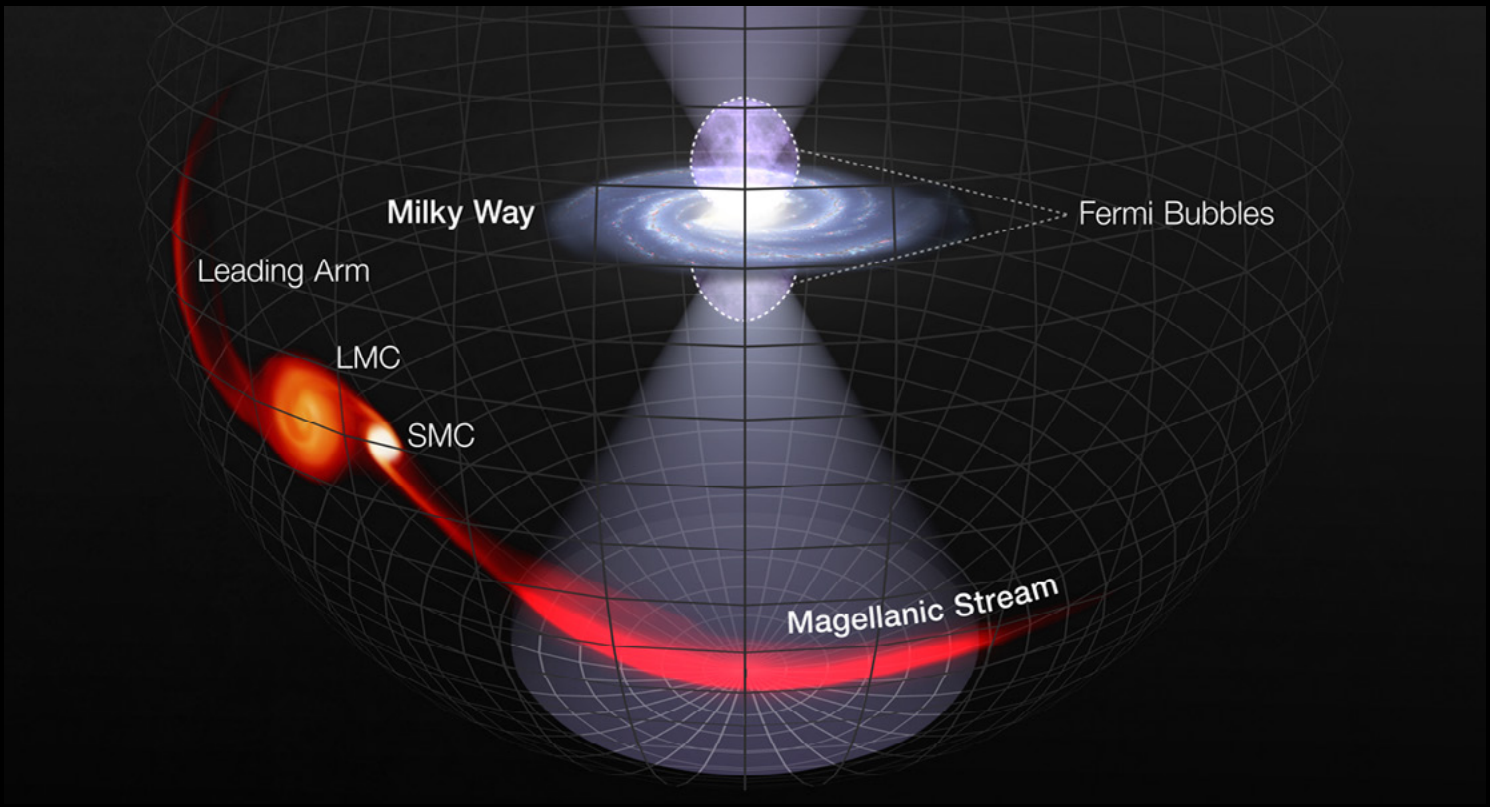
The outburst was probably caused by a hydrogen cloud up to 100,000 times the Sun's mass falling onto the disk of material swirling near the Milky Way's supermassive black hole. The resulting outburst sent cones of intense ultraviolet radiation above and below the plane of the galaxy and deep into space.

The radiation cone that blasted out of the Milky Way's south pole lit up a ribbon-like gas structure called the Magellanic Stream that lies about 200,000 light-years beyond our galaxy. The flash lit up a portion of the stream, ionizing its hydrogen (enough to make 100 million Suns) by stripping atoms of their electrons.

> "This shows us that different regions of the galaxy are linked—what happens in the galactic center makes a difference to what happens out in the Magellanic Stream."
>
> Andrew Fox, Space Telescope Science Institute (STScI)

Researchers used *Hubble's* ultraviolet capabilities to probe the stream by using background quasars—the bright cores of distant, active galaxies—as light sources. *Hubble's* Cosmic Origins Spectrograph can see the fingerprints of ionized atoms in the ultraviolet light from the quasars. As the light from the quasar passes through the gas, specific wavelengths get absorbed by atoms in the cloud, revealing information about the nature of the gas.

The same event that caused the radiation flare also "burped" hot plasma that now towers about 30,000 light-years above and below the plane of our galaxy. These invisible bubbles, weighing the equivalent of millions of Suns, are called the Fermi Bubbles. Their energetic gamma-ray glow was discovered in 2010 by NASA's Fermi Gamma-ray Space Telescope. *Hubble's* ultraviolet spectroscopy was used to measure the expansion velocity and composition of the ballooning lobes.



This illustration shows cones of radiation blasting from above and below the plane of the Milky Way. The southern cone lights up the Magellanic Stream, a vast train of gas that trails the Milky Way's two prominent satellite galaxies: the Large Magellanic Cloud (LMC), and its companion, the Small Magellanic Cloud (SMC). The astronomers studied sightlines to quasars far behind the Magellanic Stream and behind another feature called the Leading Arm, a tattered and shredded gaseous "arm" that precedes the LMC and SMC in their orbit around the Milky Way. Unlike the Magellanic Stream, the Leading Arm did not show evidence of being lit up by the flare. This makes sense since it was not in the path of the cone. The same black hole outburst that caused the radiation flare also produced a prominent feature of the Milky Way, the hot plasma Fermi Bubbles.

Credit: NASA, ESA, and L. Hustak (STScI)

Researchers thought that the Fermi Bubbles and Magellanic Stream were unrelated, but *Hubble's* observations show that that powerful flash from the Milky Way's central black hole played a major role in both phenomena.

Our ancient hominid ancestors would have seen a mysterious glowing spot along the arc of the star-studded Milky Way, evidence of a tremendous outburst from the vicinity of our galaxy's supermassive black hole. It may have shone for a million years.

Credit: NASA, ESA, G. Cecil (UNC, Chapel Hill), and J. DePasquale (STScI); Acknowledgment: P. Horálek/ESO

Learn more: Intense Flash From Milky Way's Black Hole Illuminated Gas Far Outside of Our Galaxy

Unwrapping a Black Hole Snack

Our Milky Way's central black hole is fairly peaceful but rouses when a significant snack of a star or gas cloud falls into it, blasting out jets of high-energy particles. Researchers using *Hubble* found signs of one such blowtorch-like jet dating back several thousand years. *Hubble* didn't photograph the phantom jet but helped find evidence that it is still pushing feebly into a huge hydrogen cloud and then splattering, like the narrow stream from a hose aimed into a pile of sand.

In 2013, evidence for a stubby southern jet near the black hole came from X-rays detected by the Chandra X-ray Observatory and radio waves detected by the Jansky Very Large Array telescope in New Mexico. This jet appears to be plowing into gas near the black hole.

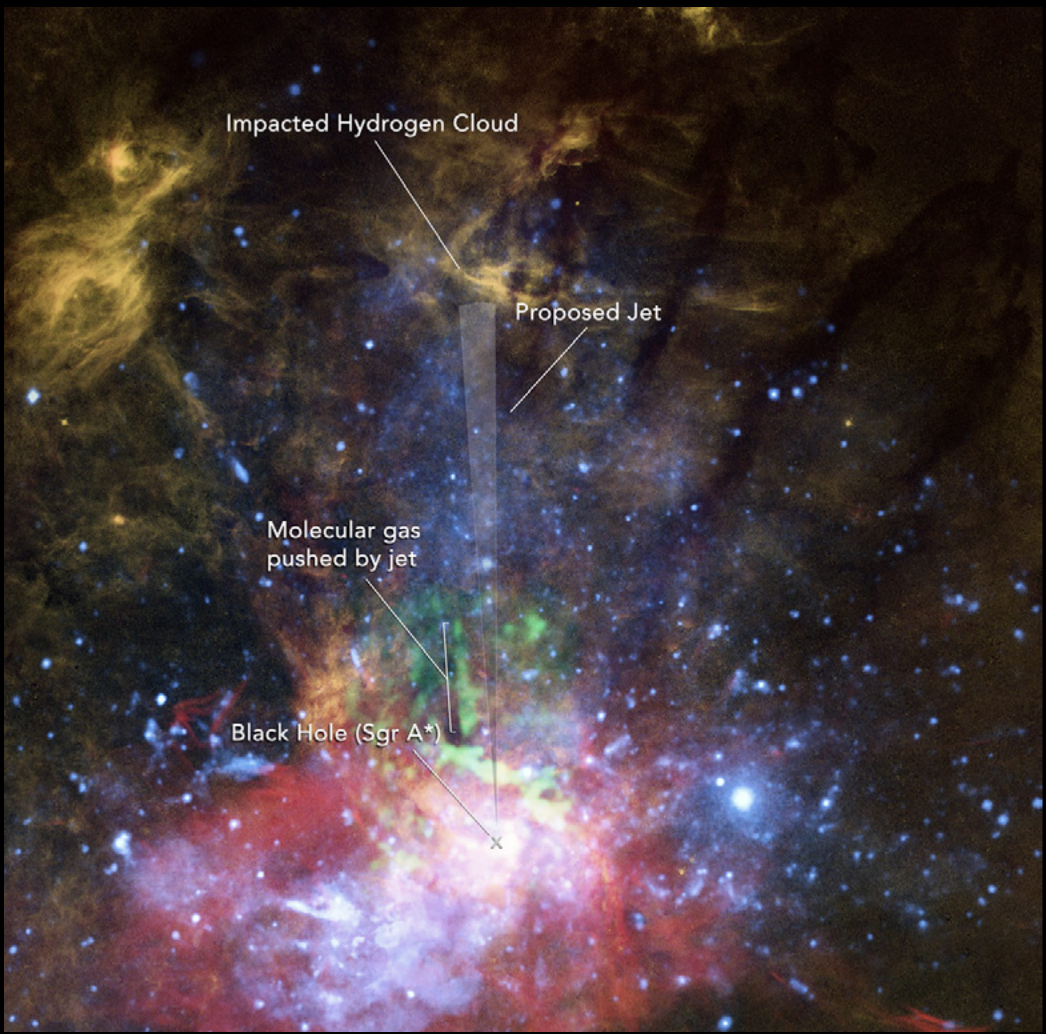
"The Milky Way's currently faint central black hole flashed a million-fold brighter many millennia ago to form bubbles and connecting channels in surrounding gas that still glow today."

Gerald Cecil, University of North Carolina in Chapel Hill

Researchers began looking for evidence of a corresponding northern jet. Spectral evidence from the Atacama Large Millimeter/submillimeter Array Observatory in Chile revealed an expanding, narrow, linear feature in molecular gas that can be traced for 15 light-years back towards the black hole.

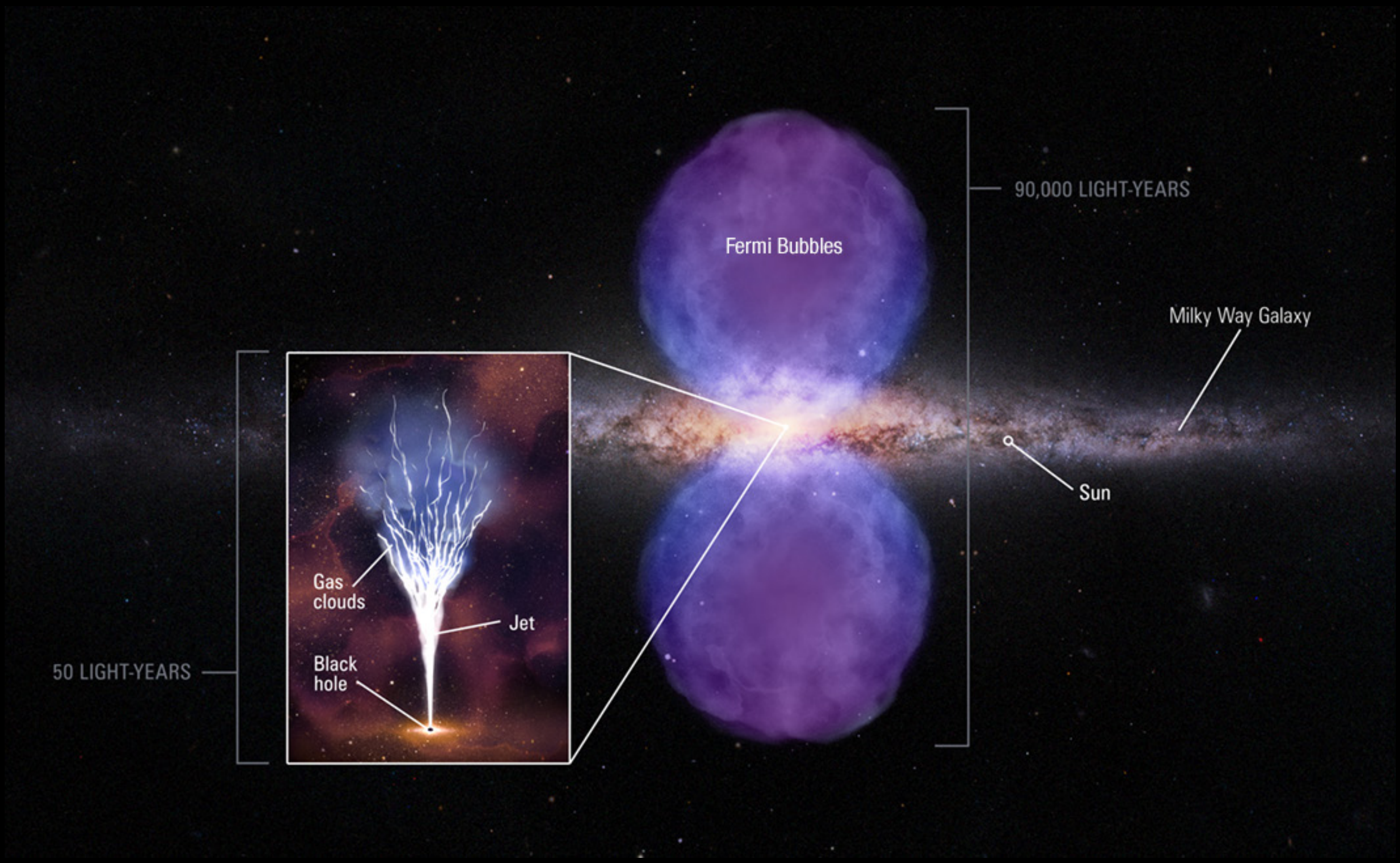
Researchers turned to *Hubble* infrared images to find a glowing, inflating bubble of hot gas that aligns to the jet at a distance of at least 35 light-years from the black hole. This suggests that the black hole jet plowed into the gas, inflating the bubble.

As it blows through the gas, the jet hits material and bends along multiple streams, transforming from a pencil stream into something more akin to the tendrils of an octopus. This creates a series of expanding bubbles that extend out to at least 500 light-years.



This annotated image points out the location of the Milky Way jet and its associated features, including the Milky Way's central supermassive black hole, Sagittarius A*, glowing hydrogen gas in orange, and superheated blue and green molecular gas.

Credit: NASA, ESA, Gerald Cecil (UNC-Chapel Hill); Image Processing: Joseph DePasquale (STScI)



This illustration shows the Fermi Bubbles extending outward from the Milky Way and, in the inset, the jet and tendrils of gas interacting with a glowing cloud of hydrogen near the black hole.

Credit: NASA, ESA, Gerald Cecil (UNC-Chapel Hill), Dani Player (STScI)

Learn More: Mini-Jet Found Near Milky Way's Supermassive Black Hole

Tracking Down a Roaming Black Hole

Hubble may have found an isolated stellar-mass black hole, the first time such an object has been discovered. It took six years of meticulous observations to identify the possible black hole, which would be about seven times the mass of the Sun.

Astronomers estimate that 100 million black holes roam among the stars in our Milky Way galaxy, but these light-devouring objects are difficult to detect. Previously, black holes of this mass had only been found through their effects on other objects, as in binary systems where the black hole was gravitationally bound to a star.

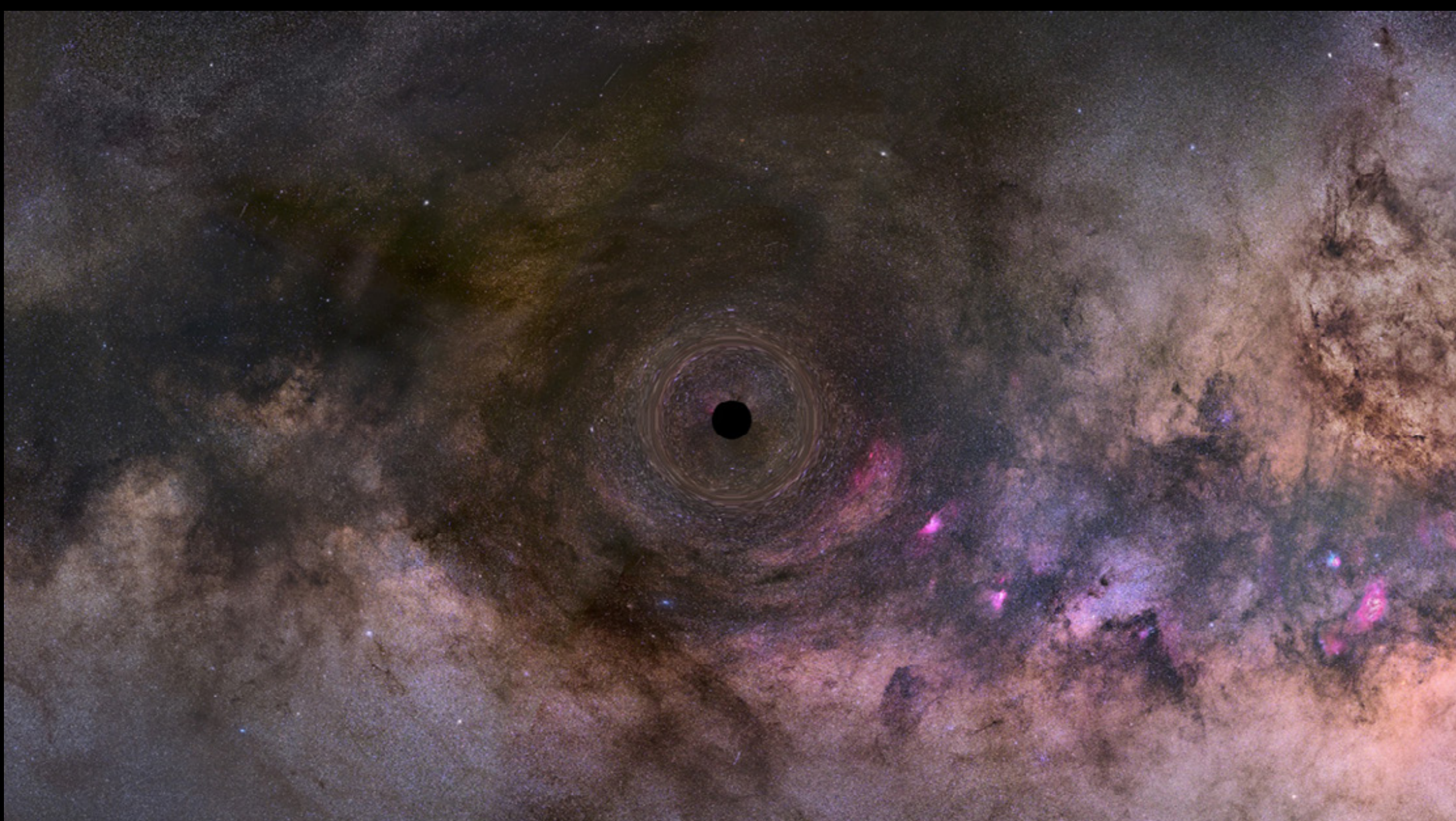
"Detections of isolated black holes will provide new insights into the population of these objects in our Milky Way."

Kailash Sahu, Space Telescope Science Institute

These black holes occur when stars at least 20 times more massive than our Sun (less than one-thousandth of the galaxy's stellar population) explode as supernovae, and the remnant core is crushed by gravity into a black hole. But because the self-detonation is not perfectly symmetrical, the black hole may get a kick and go careening through our galaxy.

The gravity of a black hole is so intense it can brighten and bend background starlight, an effect known as gravitational microlensing. Ground-based telescopes search for these brightening events to pinpoint potential black hole candidates. Using *Hubble's* exquisite resolution, researchers monitored the way light from a star far behind a compact object was momentarily brightened and deflected. The lack of a change in the starlight's color and the duration of the lensing event suggested a black hole, as did the amount of light deflection. (The star's image was offset from where it normally would be by about a milliarcsecond – the equivalent to measuring the diameter of a 25-cent coin in Los Angeles from a vantage point in New York City.)

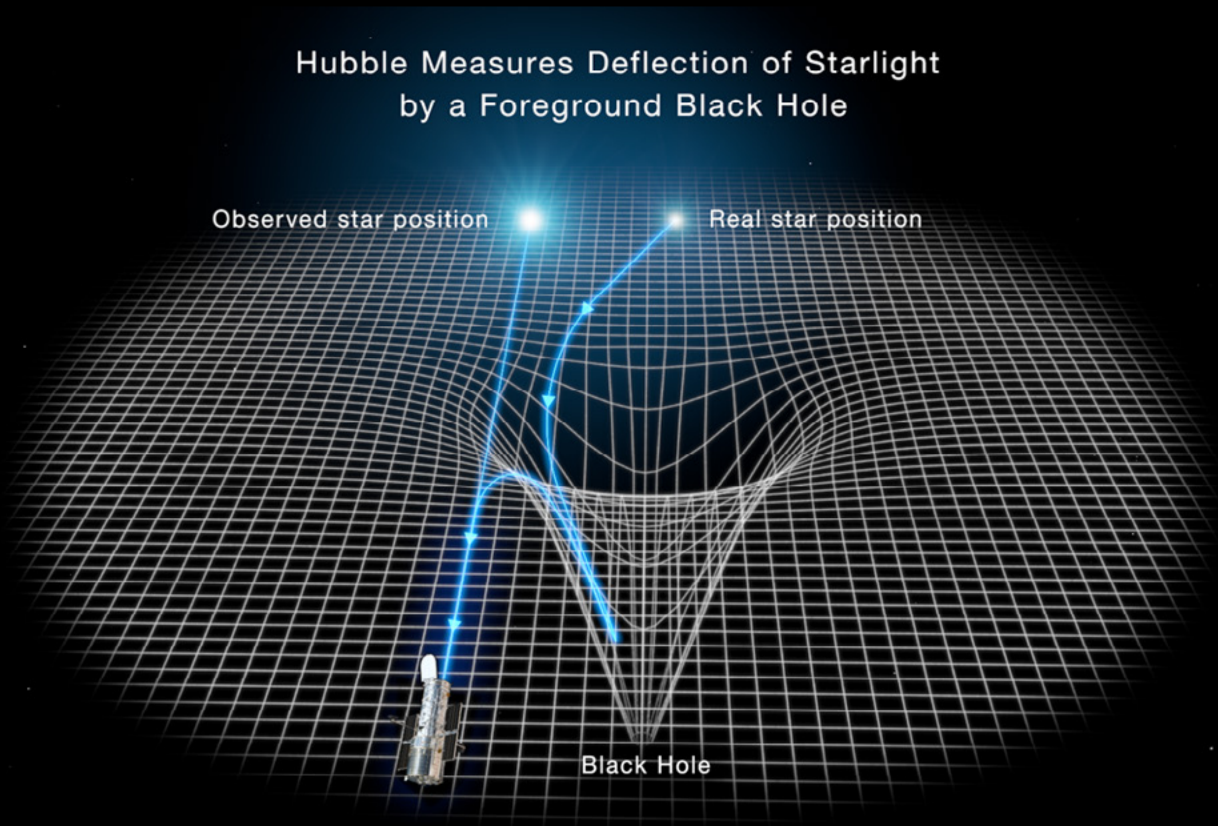
Two teams of researchers measured the mass of the compact object, determining that it was either a black hole (if the mass is on the high end of the range) or a neutron star (on the low end).



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 lensing effect, which warps images of background stars lined up almost directly behind it, offers the only telltale evidence for the existence of lone black holes wandering our galaxy.

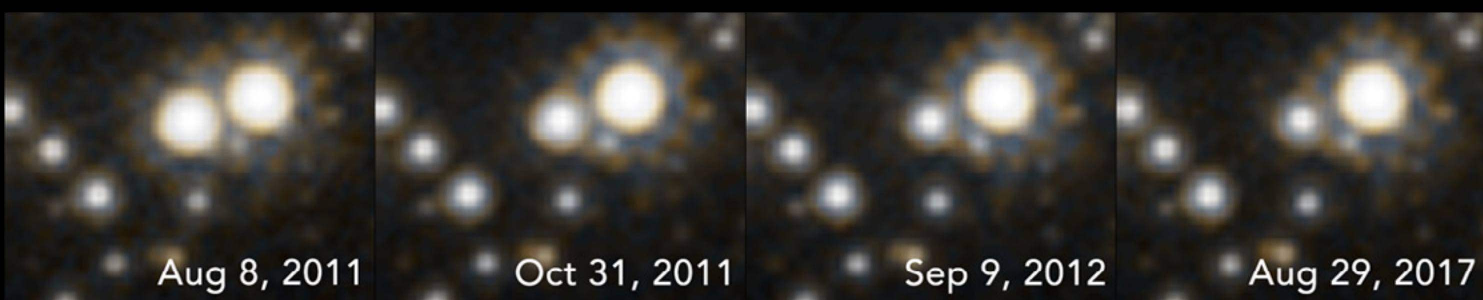
Credit: FECYT, IAC

The isolated black hole 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 black hole is 5,000 light-years away. But, statistically, its detection means that the nearest wandering black hole to Earth could be no more than 80 light-years away.



A black hole's gravity is so intense that it distorts the space around it, which 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.

Credit: NASA, ESA, STScI, Joseph Olmsted



This time-lapse of a set of four *Hubble* photos capture the gravitational 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.

Credit: NASA, ESA, Kailash Sahu (STScI); Animation: Joseph DePasquale (STScI)

Learn More: *Hubble* Determines Mass of Isolated Black Hole Roaming Our Milky Way Galaxy

Hubble Measures Potential Isolated Black Hole Roaming Galaxy

The space between the stars is plied by the dead, burned-out, and crushed remnants of once glorious stars. These black holes cannot be directly seen because their intense gravity swallows light. Like wandering ghosts, their presence can only be deduced by seeing how they affect the environment around them.

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

Summary

The Sombrero Galaxy contains one of the heftiest black holes in the neighboring universe. It is as massive as a billion Suns.

Credit: NASA and The Hubble Heritage Team (STScI/AURA)

The science of black holes has grown in leaps and bounds since the work of Albert Einstein and astronomer Karl Schwarzschild established their theoretical existence early in the 20th century. We now know of at least three different types of black holes: stellar, intermediate, and supermassive. We've watched them swallow stars, blast vast jets across space, and edge toward collision. We've seen them in the far-distant reaches of the early universe and in our own cosmic backyard.

We know so much more than we did, but black holes remain a vast mystery. Scientists are still working to understand how supermassive black holes form and grow within galaxies, the dynamics of accretion disks around black holes, whether primordial black holes from the early universe still exist, and if information devoured by a black hole is truly lost forever.

That last question points to one of the biggest enigmas around black holes. Black holes are where our understanding of general relativity – which describes how gravity works on the immense scale of planets, stars, and galaxies – meets our understanding of quantum physics, or the physics of the incredibly small. Black holes are where those two fields collide, and science has yet to reconcile them. To truly understand black holes, we will need one theory that can explain both.

As astronomers gather more and more information about black holes – capturing the first-ever picture of a supermassive black hole in 2019 and physically detecting the undulations in spacetime caused by gravitational waves from colliding black holes for the first time in 2015 – *Hubble* continues to play a critical role by providing the kind of resolution and wavelength coverage that makes it possible to seek out the telltale effects of black holes on their environments. With *Hubble's* ringside seat to the cosmos, our understanding of black holes and their role in the universe will continue to expand until perhaps, someday, "black hole" will no longer be synonymous with incomprehensible mystery.

Using the Event Horizon Telescope, scientists obtained the first-ever image of a black hole, specifically the supermassive black hole at the center of galaxy M87. The black hole is outlined by emission from hot gas swirling around it under the influence of strong gravity near its event horizon.

Credit: Event Horizon Telescope collaboration et al.

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 black holes at the following social media sites.

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

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

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

Galaxies like NGC 1961 are thought to have supermassive black holes at their cores churning out bright jets and winds that shape their evolution.

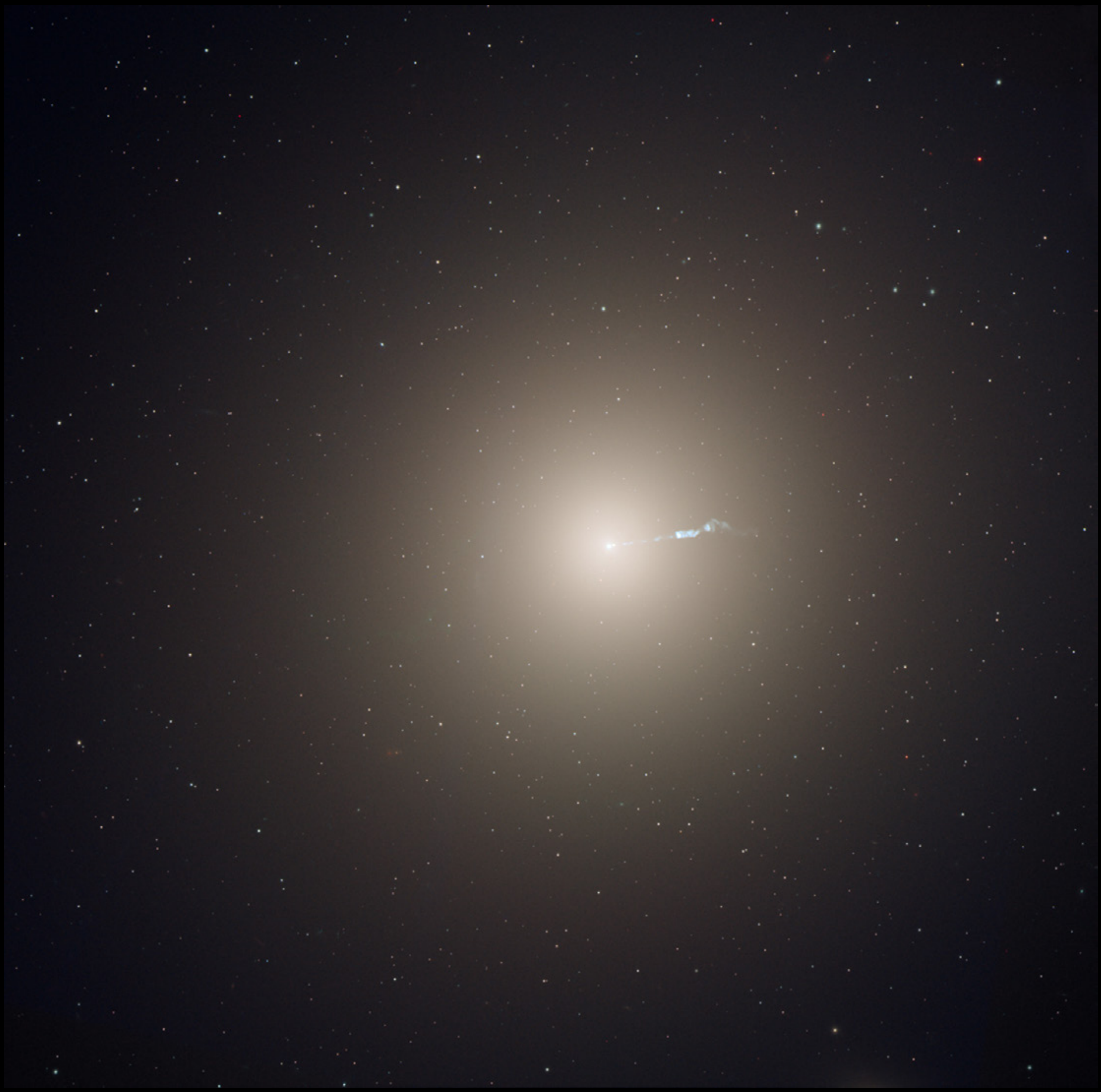
Credit: NASA, ESA, J. Dalcanton (University of Washington), R. Foley (University of California - Santa Cruz); Image Processing: Gladys Kober (NASA Goddard/Catholic University of America)

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: Black Holes: Into the Vortex was produced by the *Hubble Space Telescope* Project at GSFC. It was published in May 2025.

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



Cover image: A black hole-powered jet of electrons and other particles traveling at nearly the speed of light blasts from the core of elliptical galaxy M87. The jet originates in the disk of superheated gas swirling around the galaxy's supermassive black hole. *Hubble's* observations of M87 led to the first confirmation of a black hole at the center of a galaxy.

Credit: NASA and The Hubble Heritage Team (STScI/AURA)