2019 Review and EHT Black Hole Image

Introduction

Hello and welcome to our 2019 review. It was yet another interesting year. We'll see a comet from another solar system passing through ours. We'll take a close look at the Southern Crab Nebula. We'll identify Blue Straggler stars in a giant globular cluster in the Large Magellanic Cloud. We'll cover a unique Milky Way image created by the Pan-Starr Sky Survey. And we'll examine the space between two colliding galaxies. This past year, Hubble accidently discovered a new relatively nearby galaxy. We'll take a look. We'll see a galaxy that's losing all of its gas. And we'll see a rare Ring galaxy and cover how rings like it are created. We'll also cover one of the most powerful Gamma Ray Burst ever detected. And we'll see a distant galaxy that appears as an arc in a closer giant galaxy cluster.

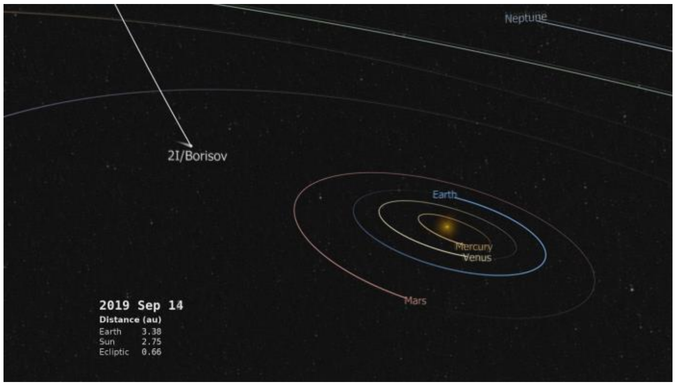
But the biggest news this past year was the release of a black hole image in the giant elliptical M87 galaxy produced by the Event Horizon Telescope team. We'll do a deep dive into both what they are showing, how they got it and some of the theoretical difficulties associated with interpreting radio wave data and the implications for Einstein's General Theory of Relativity.

In the credits, I'll show you the link to a wonderful new free online Astronomy textbook, and a link to the new How Far Way Is It Wiki where you can engage in discussions on the topics in this or any How Far Away Is It video. I trust you'll find it all interesting and informative.

Comet 2I/Borisov

On August 30 2019, amateur astronomer Gennady Borisov discovered a new comet – now named C2I/Borisov. We covered comets in our "How far away is it" segment on comets and the heliosphere where we pointed out that there are two sources for comets in our solar system: the Keiper Belt and the Oort Cloud. These two sources rotate in the solar system plane as do the comets they produce. But this comet has entered the inner solar system from a very steep angle.

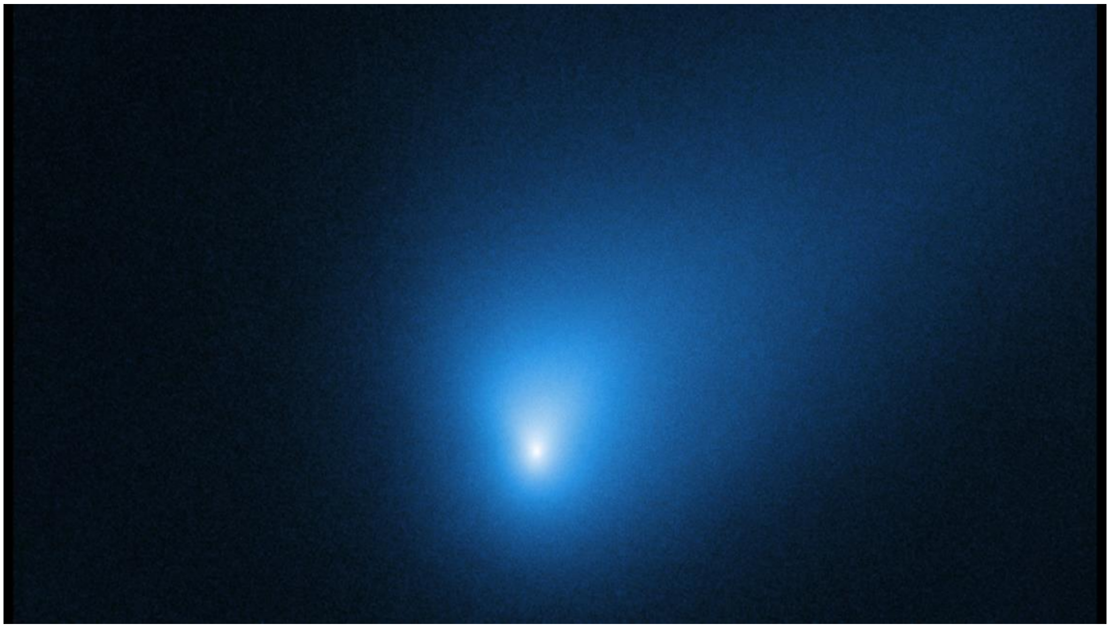
This has led astronomers to conclude that it is from another solar system. The comet made its closest approach to the Sun on December 7th. It's travelling at over 155,000 km/hr (that's over 96,000 miles/hr). It's following a hyperbolic path and by the middle of 2020, it will be on its way back into interstellar space.



Hubble photographed the comet in October at a distance of approximately 420 million kilometers from Earth (that's 260 million miles).

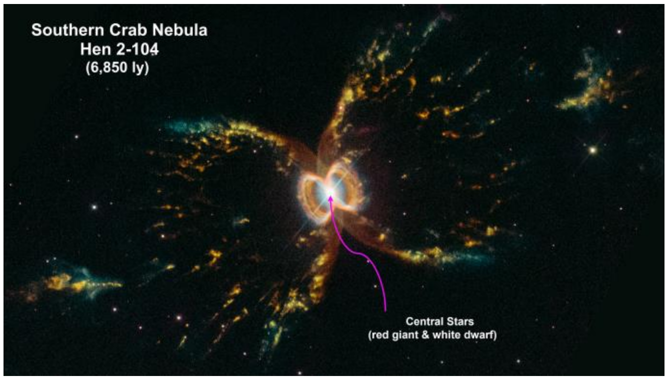
[This is only the second interstellar object ever discovered. We covered the asteroid Oumuamua - the first identified interstellar visitor in our 2017 Review. Unlike that asteroid, Borisov is quite active - more like our solar system's comets.]

Its tail marks it as cometary. Its nucleus has a radius of about 1 kilometer (or 6/10 of a mile), a common size for solar system comets. The nucleus is dominated by dust with traces of gas like our solar system comets. And the material it ejects travels at speeds similar to ejecta from solar system comets, suggesting a similar process. All in all, it appears remarkably similar to solar system comets even though it formed in a distant star system.

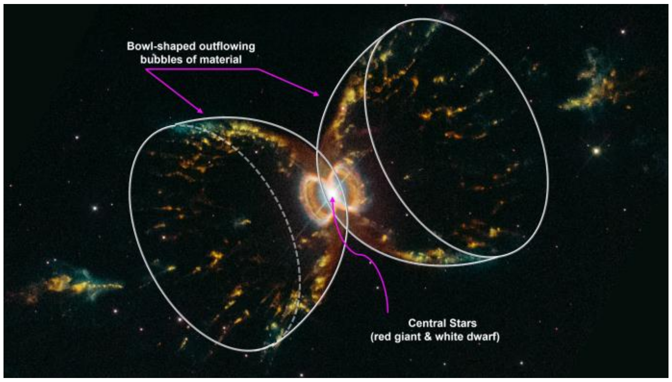


Southern Crab Nebula – 6,850 ly

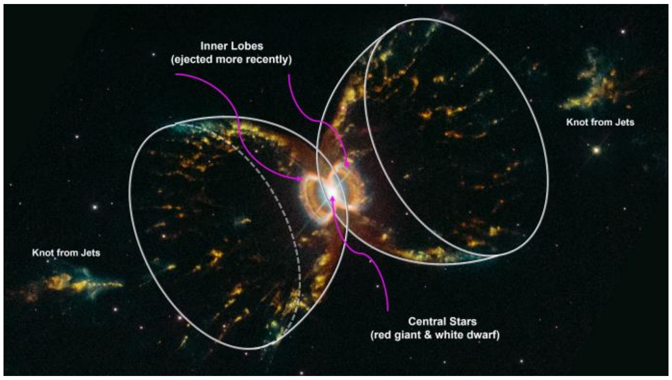
This nebula, nicknamed the Southern Crab, is located in the southern hemisphere seven thousand light-years from Earth. It has two stars at the center, an aging red giant star and a white dwarf. The red giant is shedding its outer layers. Some of this ejected material is attracted by the gravity of the companion white dwarf.



The result is that both stars are embedded in a flat disk of gas stretching between them. This belt of material constricts the outflow of gas so that it only speeds away above and below the disk. The result is an hourglass-shaped nebula. The bubbles of gas and dust appear brightest at the edges, giving the illusion of crab leg structures. These "legs" are likely to be the places where the outflow slams into surrounding interstellar gas and dust, or possibly material which was earlier lost by the red giant star.

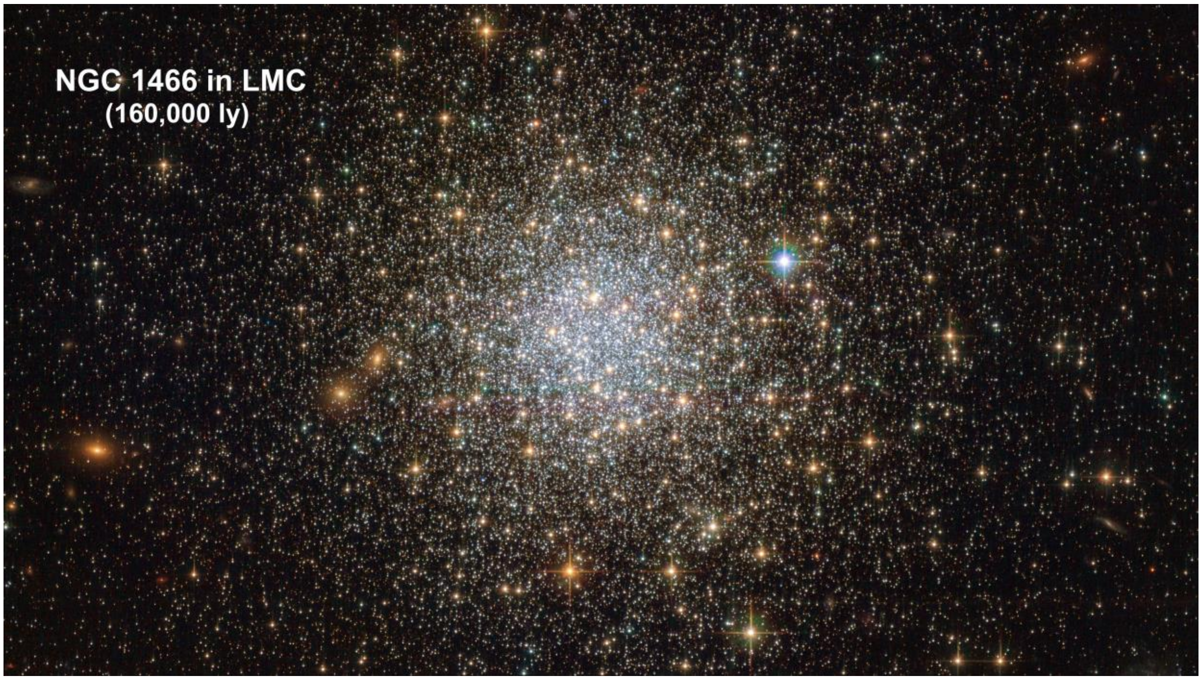


The outflow may only last a few thousand years, a tiny fraction of the lifetime of the system. This means that the outer structure may be just thousands of years old, but the inner hourglass must be a more recent outflow event. The red giant will ultimately collapse to become a white dwarf. After that, the surviving pair of white dwarfs will illuminate a shell of gas we know as a planetary nebula.



NGC 1466 - 160,000 ly

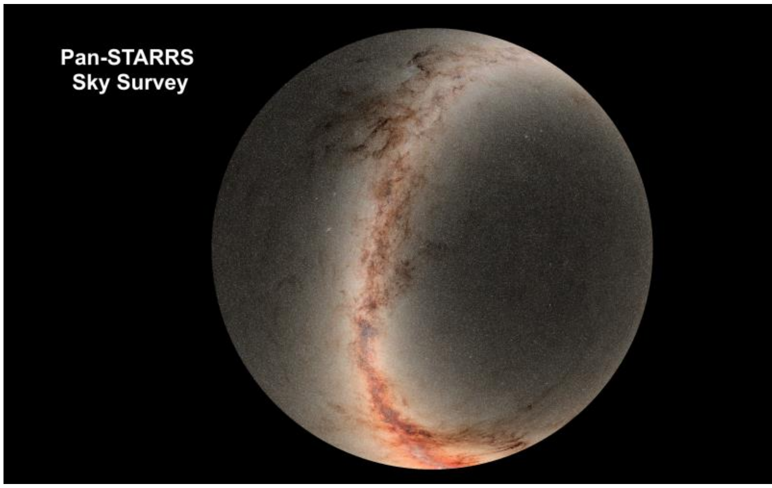
In 2019 I released the "How Old are Stars" video where we covered HR Diagram turnoff points to find the age of star clusters. Here's NGC 1466, a very old globular cluster in the Large Magellanic Cloud (LMC)160,000 ly away. It has a mass equivalent to roughly 140,000 Suns and a turnoff point that indicates its age as around 13.1 billion years - making it almost as old as the Universe itself.



All high mass blue stars would have moved into their Giant and Super Giant phases by now. But we do see blue stars in this and many other clusters of similar age.

These massive hot blue stars are a special type of re-invigorated stars called blue stragglers. Under certain circumstances, stars receive extra fuel that bulks them up and substantially brightens them. This can happen if one star pulls matter from a neighbor, or if two stars collide. Blue stragglers are so called because of their blue color, and the fact that their evolution lags behind that of the rest of the stars in the cluster.

Pan-STARRS Sky Survey

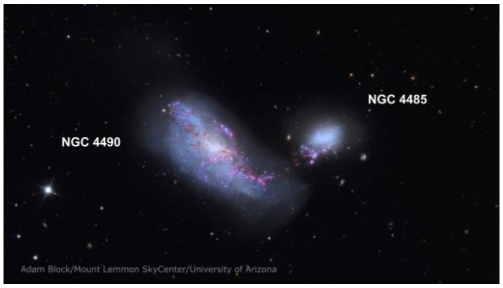


Here's an interesting image released in 2019. It's a mosaic of sky photographs taken by the Pan-STARRS Observatory, a 1.8-meter telescope located at the summit of Haleakalā, on Maui. The center of the circle is the north celestial pole, and the outer edge is a sky declination of -30 degrees, which is where the Pan-STARRS survey stopped (because it reached the southern horizon as seen in Hawaii). The bright band extending from top to bottom is our Milky Way galaxy. The center of the galaxy is near the bottom edge of the image where the galaxy is brightest. The Pan-STARRS data is being used to produce the best map of our galaxy's dust.

NGC 4485 – 25 mly

The irregular galaxy NGC 4485 shows all the signs of having been involved in a collision with another galaxy. The right side of the galaxy is ablaze with star formation, shown in the large number of young blue and pinkish star berth nebulas. The left side, however, looks intact. It contains hints of the galaxy's previous spiral structure, which, at one time, was undergoing normal galactic evolution.

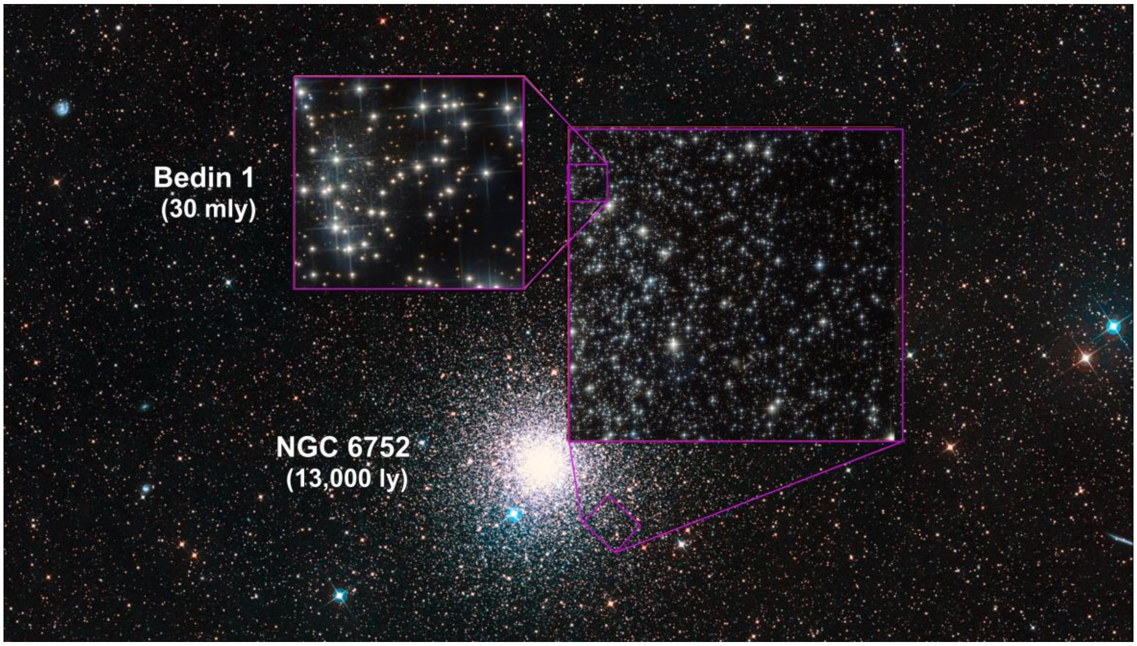
Here's the other colliding galaxy NGC 4490. The two galaxies sideswiped each other millions of years ago and are now 24,000 light-years apart. The gravitational tug-of-war between them created rippling patches of higher-density gas and dust within both galaxies.



Adam Block/Mount Lemmon SkyCenter/University of Arizona

Bedin 1 – 30 mly

An international team of astronomers recently used the Hubble Space Telescope to study white dwarf stars within the globular cluster NGC 6752. In the outer fringes of the observed area, they accidentally discovered a compact collection of stars that were much further away than any of the stars in the cluster. In fact, they were so far away that they could not be the Milky Way at all. Astronomers determined that they had found a new galaxy - a dwarf spheroidal galaxy 30 million light-years away they named Bedin 1.



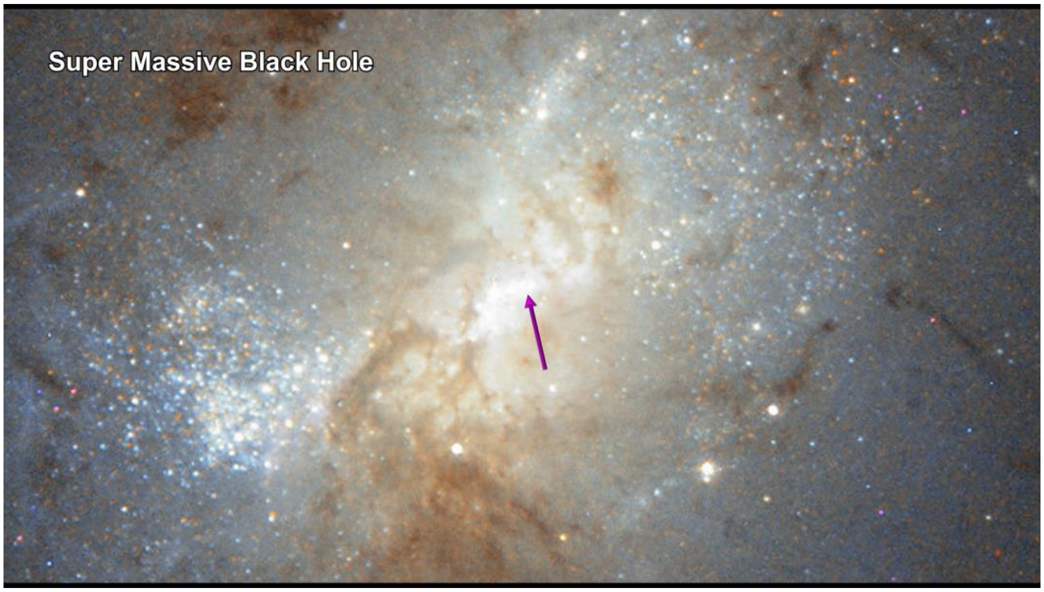
Henize 2-10 – 30 mly

Located about 30 million light-years away, ESO 495-21 (aka Henize 2-10) is a dwarf starburst galaxy around 3,000 light years in diameter containing just 3% the mass of the Milky Way.

In 2011, a radio wave source was pinpointed that corresponded to an earlier x-ray source at the same location. The balance of radiation levels in these different wavelengths pointed to the presence of a giant black hole accreting material from its surroundings. Based on these finding, the supermassive black hole is around one million solar masses – ¼ the mass of our supermassive black hole, Sagittarius A*.

The origin of the central supermassive black holes in galaxies is still a matter of debate. Do galaxies form first and then crush material at their centers into black holes? Or do pre-existing black holes gather galaxies around them? Or do they evolve together? Or could the answer be something else entirely?

With its small size, indistinct shape, and rapid starburst activity, astronomers think this galaxy may be an analogue for some of the first galaxies to have formed in the cosmos. Finding a black hole at this galaxy's center is a strong indication that black holes formed first, with galaxies developing later and evolving around them.

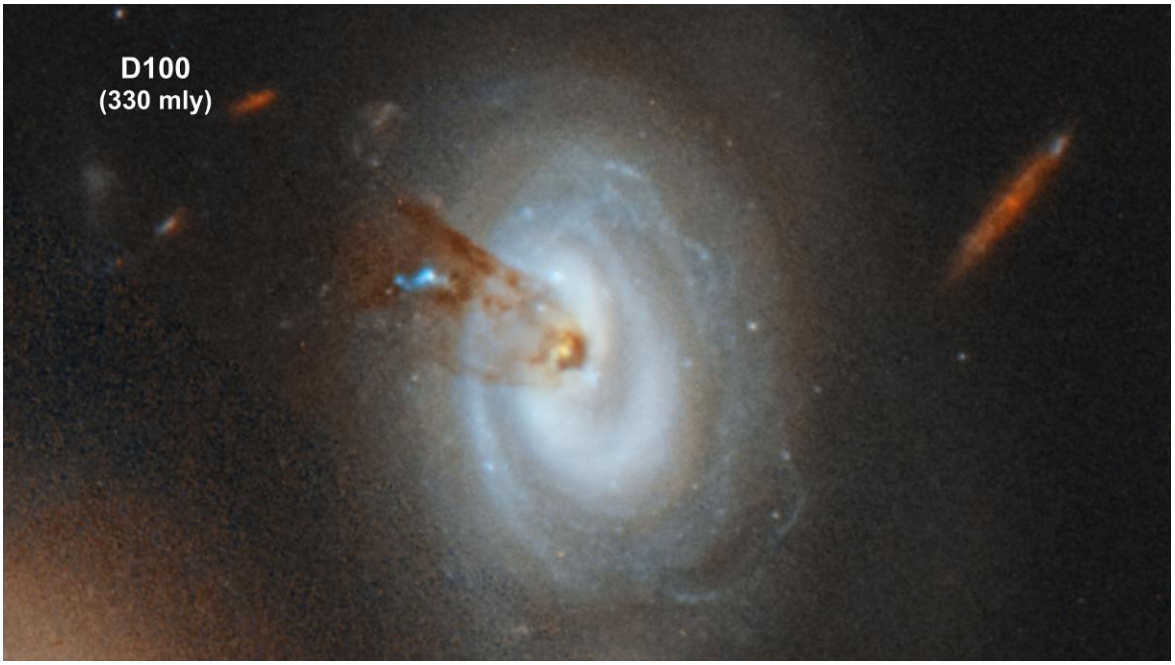


D100 Loosing Gas – 330 mly

New images from NASA's Hubble Space Telescope show D100 a spiral galaxy being stripped of its gas as it plunges toward the cluster's center. A long, thin streamer of gas and dust stretches from the galaxy's core and on into space. The tail, a mixture of dust and hydrogen gas, extends nearly 200,000 light-years. But the pencil-like structure is comparatively narrow, only 7,000 light-years wide.

Eventually, the galaxy will lose all of its gas. Without the material to create new stars, star formation in the galaxy will cease. The process is called "ram pressure stripping." It occurs when a galaxy, due to the pull of gravity, falls toward the dense center of a massive cluster of thousands of galaxies. During its plunge, the galaxy plows through intergalactic material. The material pushes gas and dust from the galaxy. It is estimated that the gas-stripping process in D100 began roughly 300 million years ago.

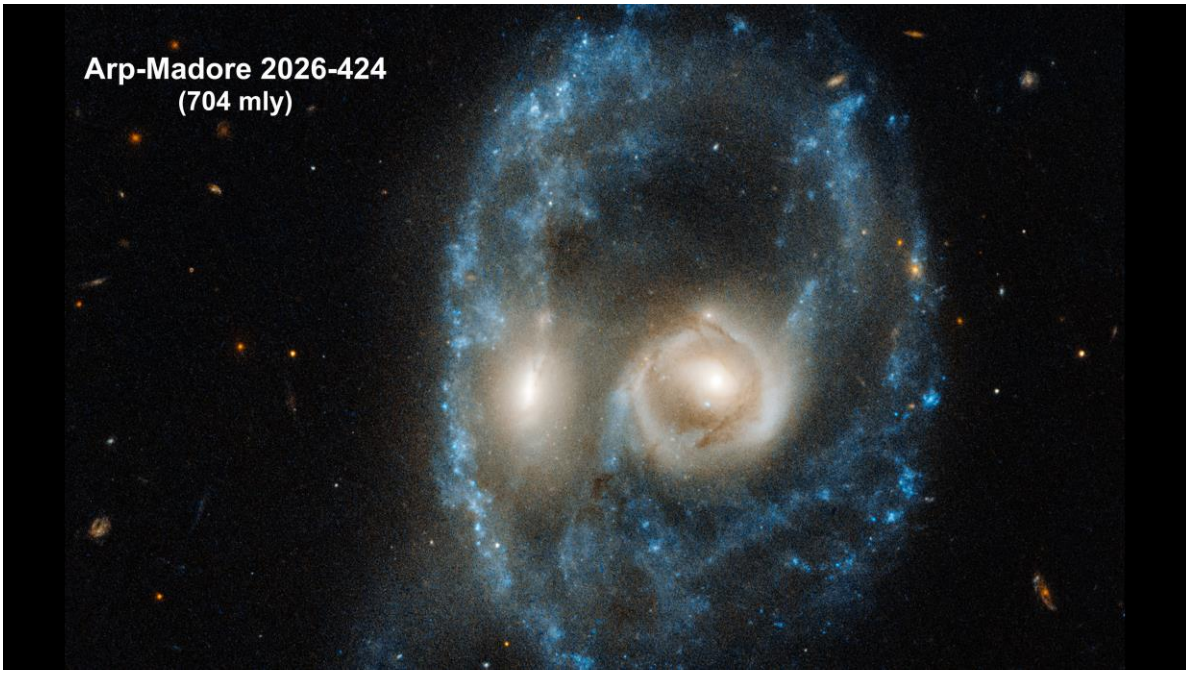
[The researchers' main goal was to study star formation along the tail. Hubble's sharp vision uncovered the blue glow of clumps of young stars. The brightest clump in the middle of the tail contains at least 200,000 stars, triggered by the ongoing gas loss from the galaxy. The Hubble data show that the gas-stripping process began on the outskirts of the galaxy and is moving in towards the center, which is typical in this type of mass loss. Based on the Hubble images, the gas has been cleared out all the way down to the central 6,400 light-years.]



Adding to this story is another galaxy in the image that foreshadows D100's fate. The object, named D99, began as a spiral galaxy similar in mass to D100. It underwent the same violent gas-loss process as D100 is now undergoing, and it can no longer form new stars.

Arp-Madore 2026-426 – 704 mly

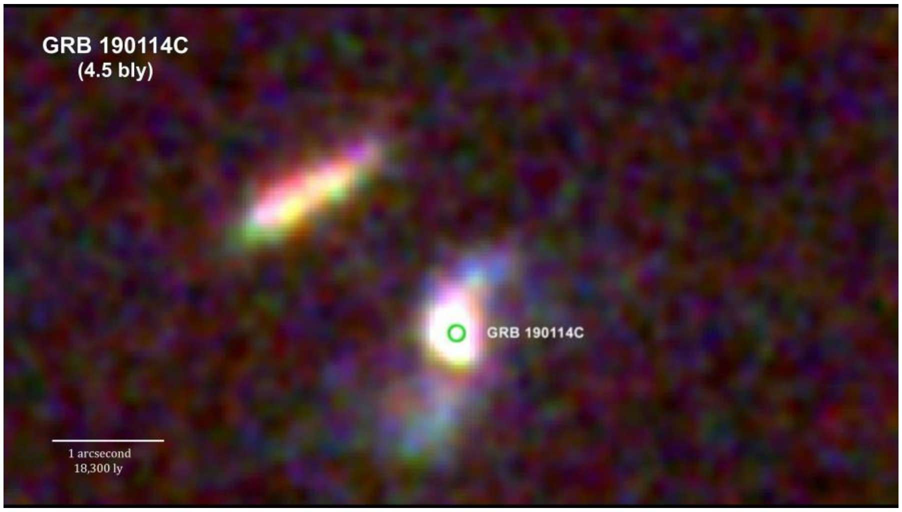
Here we are zooming into a rare Ring galaxy 704 mly away. Only a few hundred Ring galaxies reside in our local supercluster. These kinds of galaxies are formed when two galaxies of the same size collide at just the right orientation to pull and stretch their discs of gas, dust, and stars outward, to form the ring of intense star formation. The fact that the two central bulges are the same size tells us that the colliding galaxies where themselves the same size.



GRB 190114C – 4.5 bly

In January 2019, an extremely bright and long-duration Gamma Ray Burst named GRB 190114C was detected by a suite of telescopes. This Hubble image taken a few weeks later, caught the fading afterglow of the event in the center of the green circle. The short-lived after glow was located 4.5 billion light years away and about 800 light-years from the galaxy's core.

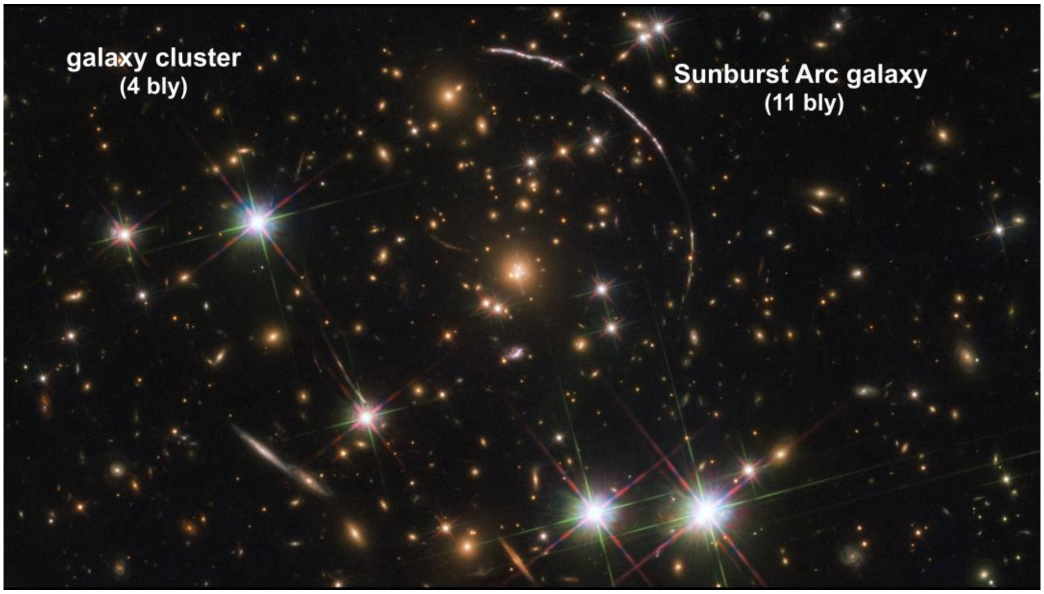
This GRB was one of the most powerful ever recorded. In just a few seconds, it emitted more energy than the Sun will produce over its entire 10-billion-year life.



Astrophysicists calculate that, to acquire this much energy, material has to be emitted from a collapsing star at 99.999% of the speed of light. Then, as the star's material is forced through the gas that surrounds the star, the shock creates the gamma-ray burst. This is an artist's depiction of what this might look like.

PSZ1 G311.65-18.48 Sunburst Arc galaxy – 11 bly

This Hubble image shows a massive galaxy cluster, about 4.6 billion light years away. Along its borders, four bright arcs are visible; these are copies of the same distant galaxy, nicknamed the Sunburst Arc. It's almost 11 billion light-years away. It's light is being lensed into multiple images by strong gravitational lensing. The Sunburst Arc is among the brightest lensed galaxies known and its image is visible at least 12 times within the four arcs. Here's a closer look at three of them. The lens makes various images from 10 and 30 times brighter. This allows Hubble to view structures as small as 520 light-years across — a rare detailed observation for an object that far away.



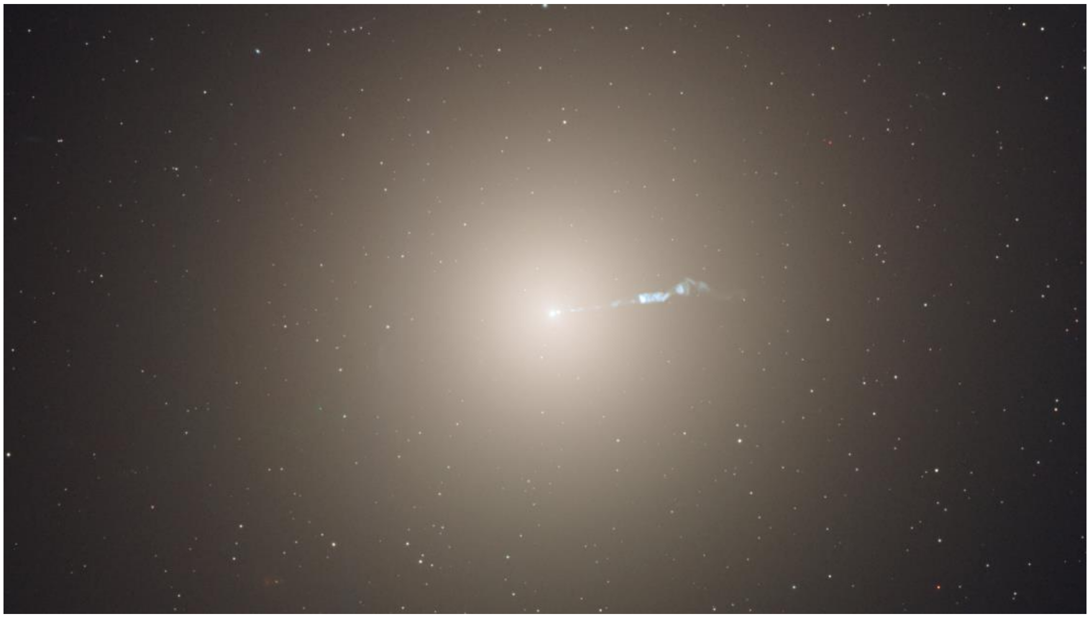
Hubble Legacy Field – 13 bly

Astronomers developed a mosaic of the distant Universe from nearly 7,500 individual exposures, called the Hubble Legacy Field. It documents 16 years of observations from the NASA/ESA Hubble Space Telescope. This image contains 200,000 galaxies that stretch back through 13.3 billion years of time to just 500 million years after the Big Bang. This was created.

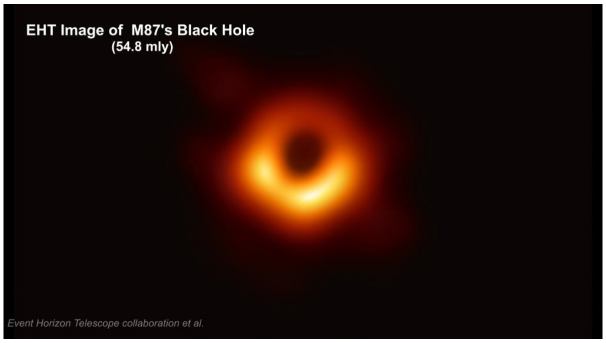
Event Horizon Telescope Black Hole Image

M87 Jets – 53.5 mly

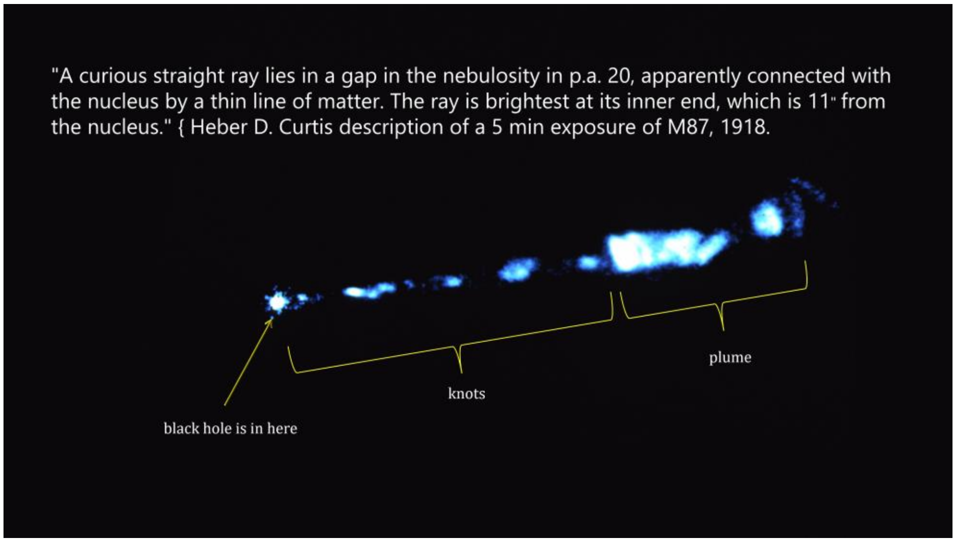
Here we are zooming into M87 - the dominant galaxy at the center of the Virgo Galaxy Cluster. It's a huge elliptical galaxy that contains several trillion stars. The steady increase in brightness of M87 towards its center is readily apparent in the image, showing that the stars in M87 are strongly concentrated towards its nucleus. Note the jet of material streaming out from the center. This indicates that the galaxy has an Active Galactic Nucleus (AGN for short). That is, it has a supermassive black hole at its center that is accumulating large amounts of matter from an accretion disk.



In 2019, The Event Horizon Telescope released an image of this black hole - the first ever image of a black hole. We'll cover this black hole and its image in a bit. But first we'll take a deeper look at this jet. It provides information on our line of sight orientation and explains some of the physics needed to fully understand the black hole's image.

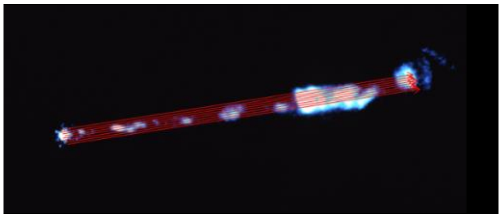


We’ve known about the jet of plasma shooting from the core of M87 since 1918, when astronomer Heber Curtis saw a ray of light connected to the galaxy center - five thousand light-years long and 2 light-years wide. Several things stand out about this jet: It’s blue, it’s very bright, it consists of chunks or knots, and it terminates in a plume. You may have also noted that there is no counter jet going out the other way like we’ve seen in other galaxies.

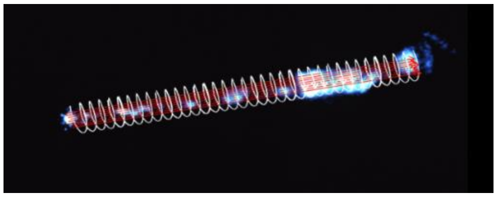


"A curious straight ray lies in a gap in the nebulosity in p.a. 20, apparently connected with the nucleus by a thin line of matter. The ray is brightest at its inner end, which is 11" from the nucleus." { Heber D. Curtis description of a 5 min exposure of M87, 1918.

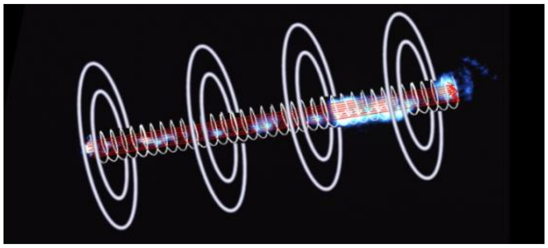
The jet is understood to have been formed in a strong magnetic field created by the interactions between the spinning black hole and the rotating accretion disk. Then, at the point where matter from the accretion disk is crossing the event horizon into the black hole, a small percentage of the charged particles are swept into this magnetic field and ejected into the jet at the black hole’s escape velocity, which is near the speed of light for objects as massive as a black hole.



These escaping particles are forced into circular orbits around the strong magnetic field. The European Space Agency’s Integral Gamma-ray Observatory has observed extremely hot matter just a few milliseconds before it would cross into a black hole. This study lends support for the theory. But just how this is accomplished is not yet understood.

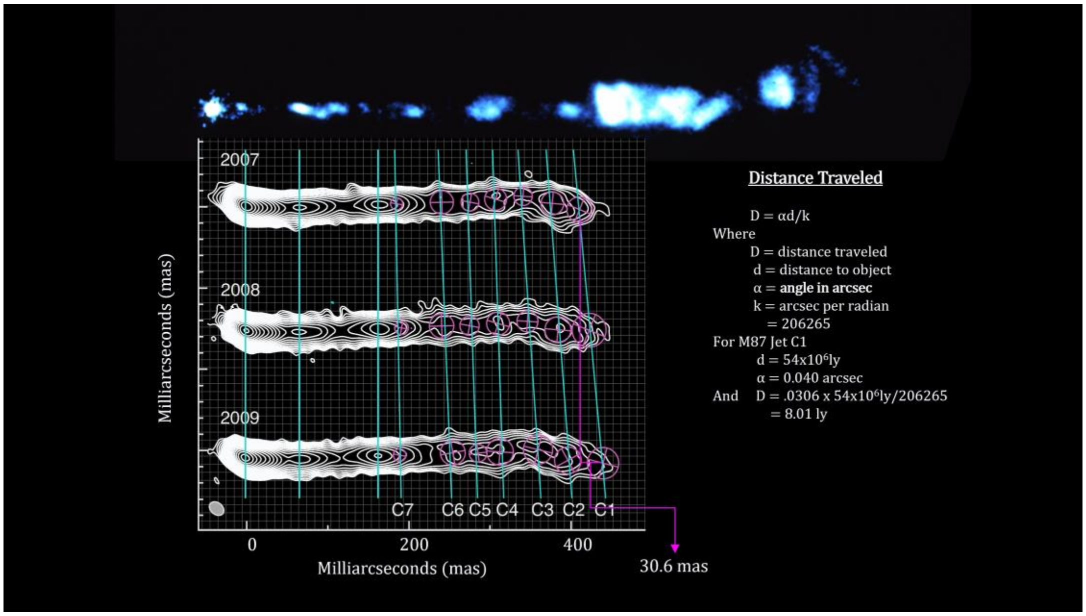


Theses circularly accelerating ions create electromagnetic radiation across a wide spectrum including radio, visible and x-ray light. This is what we are seeing with our radio, optical and x-ray telescopes. It's called synchrotron radiation and it's well understood because it's the same as the radiation from synchrotron particle accelerators we build here on Earth.



Superluminal motion

The two key jet features we observe directly are its apparent luminosity and its apparent motion across the sky. A study done by a team of astronomers using the European Very Long Baseline Interferometer Radio Telescope Network analyzed the motion of one of the knots near the jet's origin at the black hole. They found that one of the components moved 30 milliarcseconds over two years. That's a very tiny amount. But when we multiply it by the large distance to M87 we find that the distance traveled was 8 light years. To travel 8 light years in just 2 years means its velocity is 4 times the speed of light. We call apparent velocities greater than the speed of light 'Superluminal Motion'.



Distance Traveled

$D = \alpha d/k$

Where

D = distance traveled

d = distance to object

α = **angle in arcsec**

k = arcsec per radian

= 206265

For M87 Jet C1

$d = 54x10^6$ly

α = 0.040 arcsec

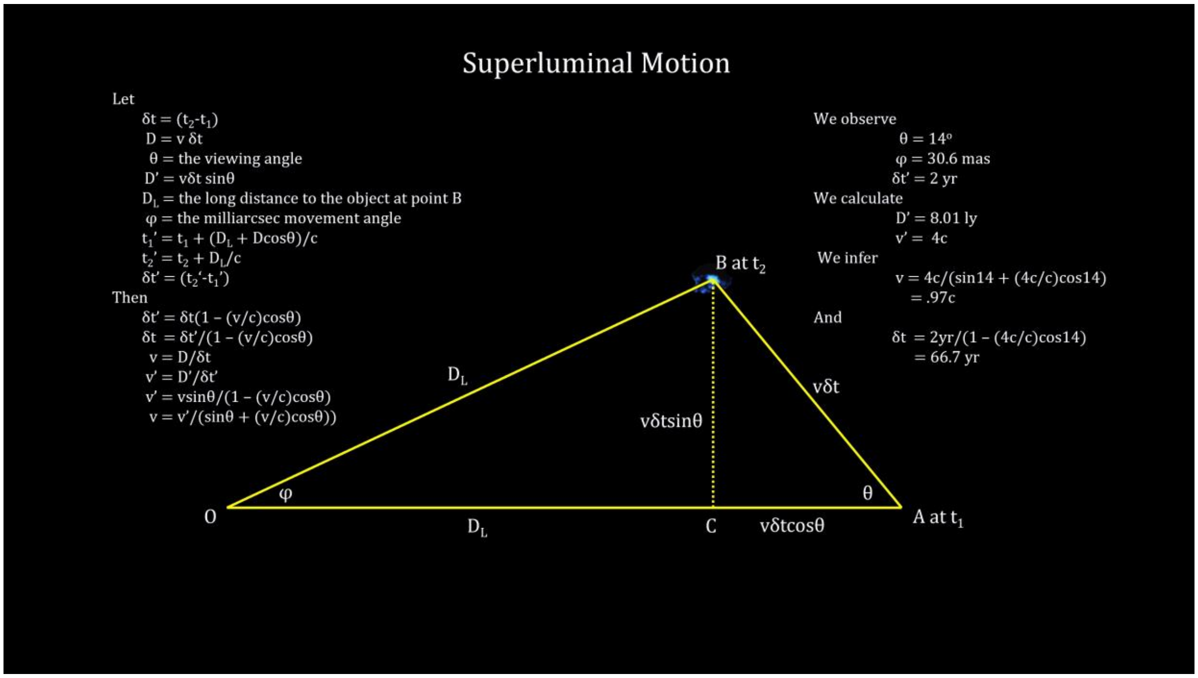
And $D = .0306 \text{ x } 54x10^6$ly/206265

= 8.01 ly

Here's how it works. Suppose we have an object at location A at time t_1 that moves to location B at time t_2 – the travel time being delta t. D is the distance traveled. It will equal the object's velocity times its travel time. We're observing this movement from a great distance at an angle θ from the object's line of motion.

We see only the proper or transverse motion across the sky, designated here as D prime. Our start time is the object's start time plus the time it takes the light to get from points A to O. Our end time is the object's end time plus the time it takes the light to get from points B to O. With that, we can calculate the observers view of the object's velocity in terms of the object's view, and vis-versa.

If we plug in the numbers we found for knot C of the M87 Jet, we find that the apparent velocity of 4 times the speed of light turns out to be .97c in the object's frame of reference, and the apparent elapsed time of 2 years movement turns out to have taken the object almost 67 years. It was not traveling faster than the speed of light. (Note that this only happens when the velocity of the object is near the speed of light and in addition, the viewing angle is small.)



Superluminal Motion

Let

$\delta t = (t_2 - t_1)$

$D = v\,\delta t$

θ = the viewing angle

$D' = v\delta t \sin\theta$

D_L = the long distance to the object at point B

φ = the milliarcsec movement angle

$t_1' = t_1 + (D_L + D\cos\theta)/c$

$t_2' = t_2 + D_L/c$

$\delta t' = (t_2' - t_1')$

Then

$\delta t' = \delta t(1 - (v/c)\cos\theta)$

$\delta t = \delta t'/(1 - (v/c)\cos\theta)$

$v = D/\delta t$

$v' = D'/\delta t'$

$v' = v\sin\theta/(1 - (v/c)\cos\theta)$

$v = v'/(\sin\theta + (v/c)\cos\theta))$

We observe

$\theta = 14^\circ$

$\varphi = 30.6$ mas

$\delta t' = 2$ yr

We calculate

$D' = 8.01$ ly

$v' = 4c$

We infer

$v = 4c/(\sin 14 + (4c/c)\cos 14)$

$= .97c$

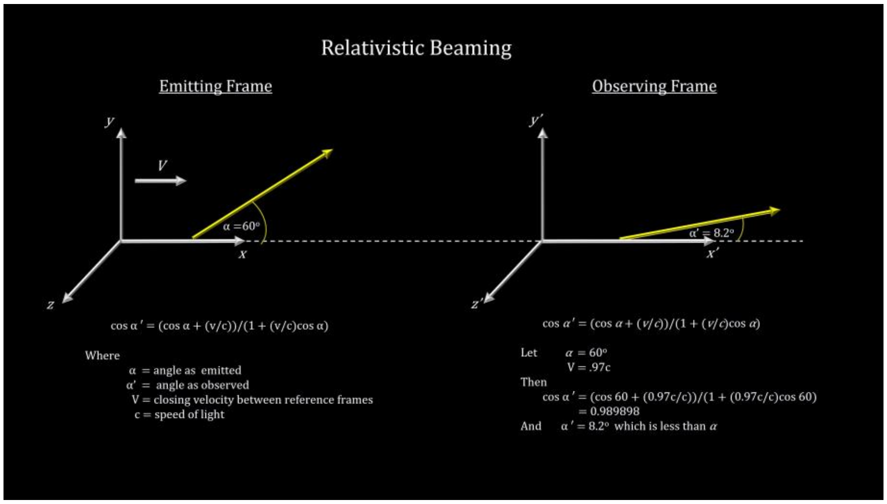
And

$\delta t = 2yr/(1 - (4c/c)\cos 14)$

$= 66.7$ yr

Relativistic Beaming

Another relativistic effect at play here is called Relativistic Beaming. To illustrate, consider an inertial reference frame moving to the right at relativistic speeds with respect to an aligned reference frame on the right. A particle emits a photon at an angle ∝ from the line of motion. The angle measured in the frame on the right can be computed using the Lorentz transformation. Using M87 C1's .97c as the velocity and 60 degrees as a sample angle, we see that the observed angle ∝' is considerably smaller at only 8.2 degrees.



Relativistic Beaming

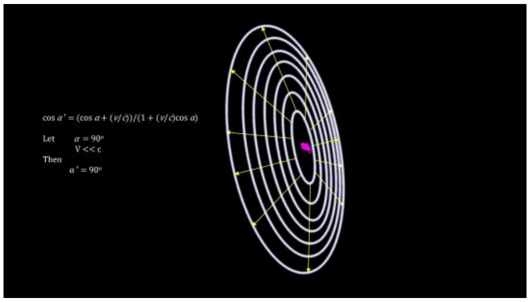
$\cos\alpha' = (\cos\alpha + (v/c))/(1 + (v/c)\cos\alpha)$

Where
α = angle as emitted
α' = angle as observed
V = closing velocity between reference frames
c = speed of light

$\cos\alpha' = (\cos\alpha + (v/c))/(1 + (v/c)\cos\alpha)$

Let $\alpha = 60°$
V = .97c
Then
$\cos\alpha' = (\cos 60 + (0.97c/c))/(1 + (0.97c/c)\cos 60)$
$= 0.989898$
And $\alpha' = 8.2°$ which is less than α

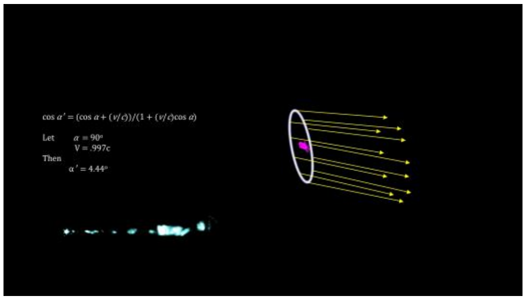
A synchrotron radiating electron moving at speeds far smaller than the speed of light will emit radiation in all directions. Distant observers would see just the portion of the light radiated in their direction. As the speed of the electron increases, these light rays shift in the direction the emitting object is moving.



$\cos\alpha' = (\cos\alpha + (v/c))/(1 + (v/c)\cos\alpha)$

Let $\alpha = 90°$
V << c
Then
$\alpha' = 90°$

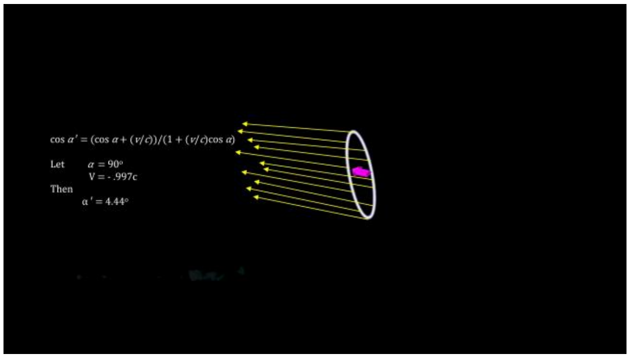
As the velocity of the emitting particle approaches the speed of light, the observed angle approaches zero. The light is beamed ahead of the emitter in the direction of the emitter's movement. This is the case, no matter what the emitted angle is in its own frame of reference.



$\cos\alpha' = (\cos\alpha + (v/c))/(1 + (v/c)\cos\alpha)$

Let $\alpha = 90°$
V = .997c
Then
$\alpha' = 4.44°$

For trillions of continually emitting particles, like the electrons in the M87 Jet, this beaming effect increases the photon density in the direction of movement causing the jet's luminosity to increase. This explains why the jet looks so bright. And, because jets moving in the opposite direction will have their photons beamed away from the observer, the jet becomes invisible. This explains why we see only one jet in M87.



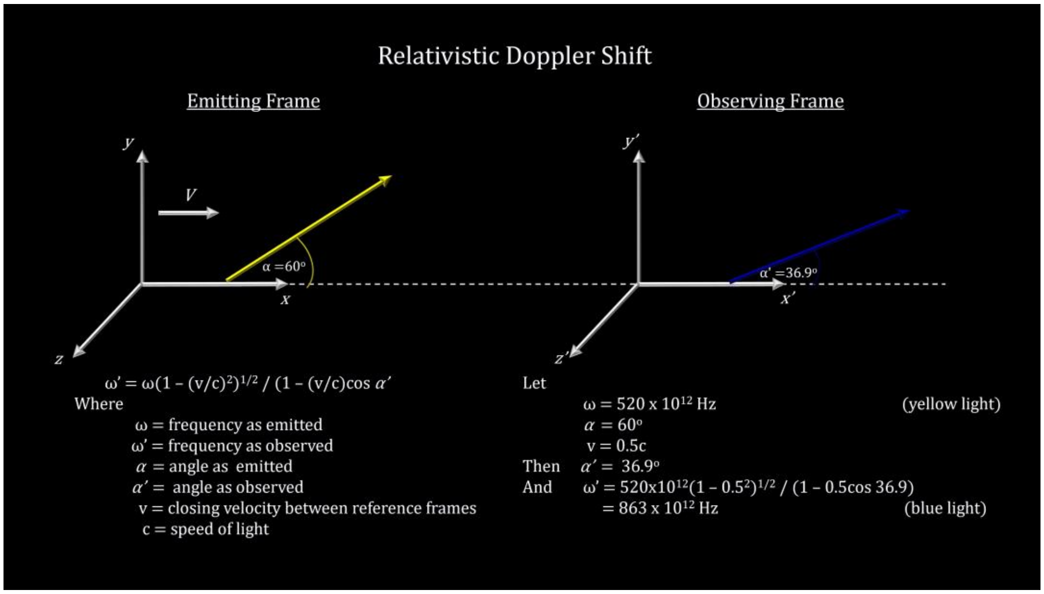
$\cos\alpha' = (\cos\alpha + (v/c))/(1 + (v/c)\cos\alpha)$

Let $\alpha = 90°$
$V = -.997c$

Then
$\alpha' = 4.44°$

Relativistic Doppler Shift

Our last relevant effect is called relativistic doppler shift. Due to space contraction, when we apply the Lorentz transformation against the frequency of a photon emitted in the same fashion as we just covered, we find that the frequency observed is greater than the frequency transmitted. This explains why the M87 jet is so blue.



Relativistic Doppler Shift

Emitting Frame

Observing Frame

$\omega' = \omega(1 - (v/c)^2)^{1/2} / (1 - (v/c)\cos\alpha'$

Where

ω = frequency as emitted
ω' = frequency as observed
α = angle as emitted
α' = angle as observed
v = closing velocity between reference frames
c = speed of light

Let

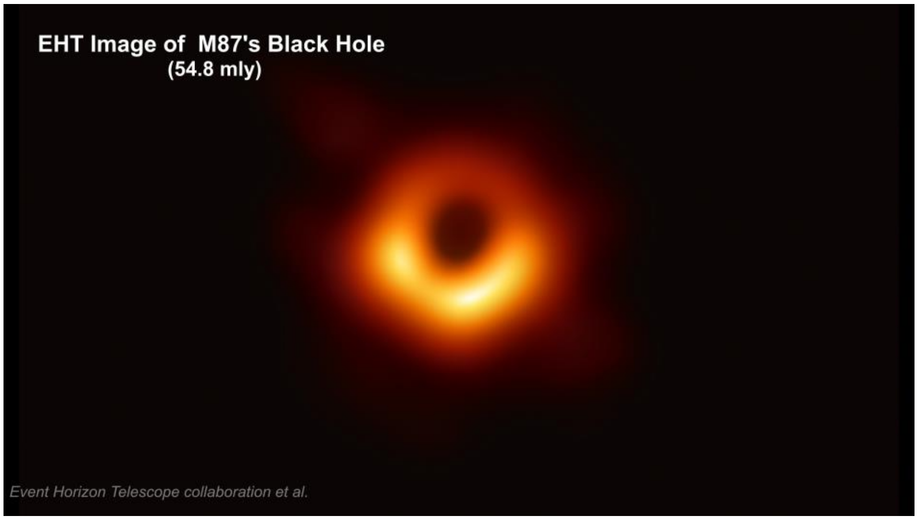
$\omega = 520 \times 10^{12}$ Hz (yellow light)
$\alpha = 60°$
$v = 0.5c$

Then $\alpha' = 36.9°$

And $\omega' = 520\times10^{12}(1 - 0.5^2)^{1/2} / (1 - 0.5\cos 36.9)$
$= 863 \times 10^{12}$ Hz (blue light)

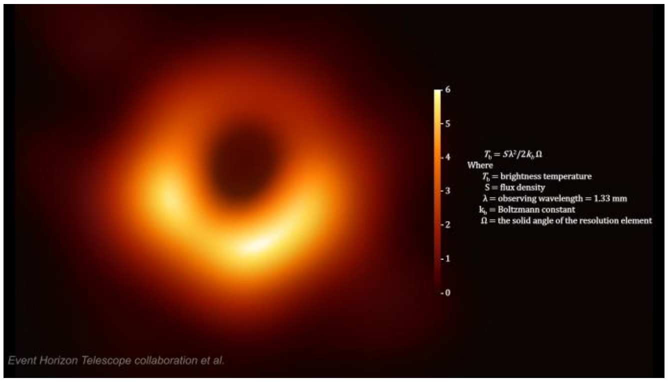
First Black Hole Image

In 2019, the Event Horizon Telescope (EHT for short) team released an image of the supermassive black hole at the center of M87 that created and powers the M87 Jets. This image represents the first direct visual evidence for a black hole. Basically, we're looking at an emission ring around a dark shadow. This is consistent with the idea that the ring is gravitationally lensed light produced by a hot, turbulent magnetized accretion disk orbiting close to the event horizon of a Kerr black hole and the darker center is the black hole's shadow. We covered Kerr black holes in our 2019 release of the 'How far away is it' chapter on the Milky Way as part of our close look at Sag A* the supermassive black hole at the center or our galaxy.



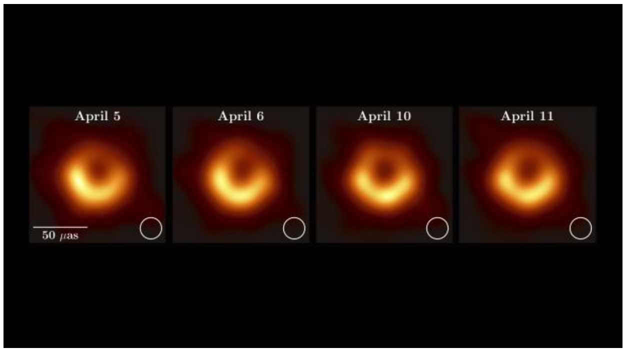
Event Horizon Telescope collaboration et al.

The light recorded was radio light (1.33 mm) which we cannot see with optical telescopes. To create this image, the EHT team chose to display the measured radio light intensity in units of brightness temperature with orange signifying low intensity radio light, yellow signifying more intense radio light and black signifying very little or no radio light.



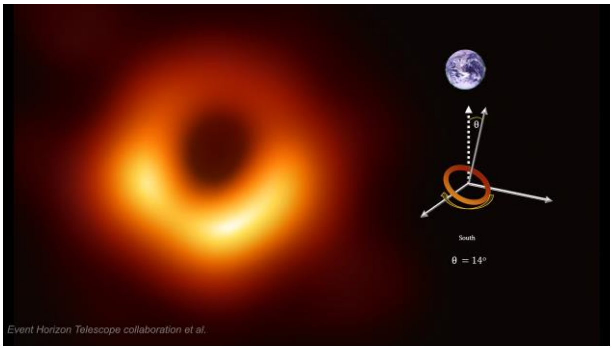
Event Horizon Telescope collaboration et al.

Four images were created from four different days in April 2017. They show movement with stability in the basic image structure. The movement indicates a clockwise rotation of the disk. But there is insufficient information to determine the disk's velocity.



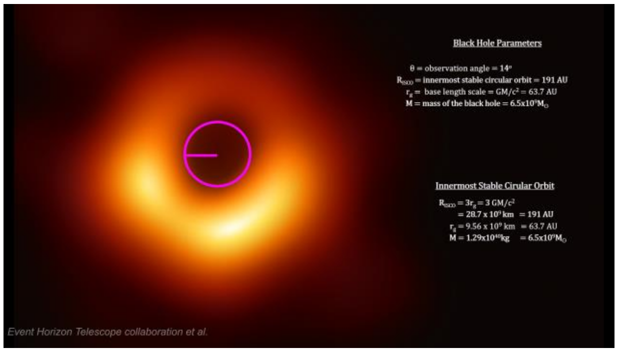
Note that the emission ring is brighter on the south side. If we were observing from directly above, the accretion disk would be moving perpendicular to our line of sight. No parts would be moving towards us or away from us. We would expect the luminosity to be the same across the entire disk.

But from our M87 Jet analysis we found that we are viewing from around a 14° angle to the west. This orients the ring in such a way that matter rotating in the southern half of the ring is moving closer to us and matter rotating in the northern half of the ring is moving further away from us. It is thought that the southern portion is brighter due to the Relativistic Beaming effect we covered earlier. This would in turn imply that the disk's plasma is rotating at speeds that are a significant percentage of the speed of light.



Event Horizon Telescope collaboration et al.

Here's the measured distance from the center of the black hole to the inner rim of the emission ring. This is the innermost stable circular orbit radius. It's also the photon sphere where photons can get trapped into an orbit around the black hole. With this radius, we can calculate the black hole's mass. Sag A* has the mass of 4 million suns. M87's black hole is 1600 time that mass with 6.5 billion suns. (This is in close agreement with star rotation studies that put the mass at 6.2 billion suns.)



Black Hole Parameters

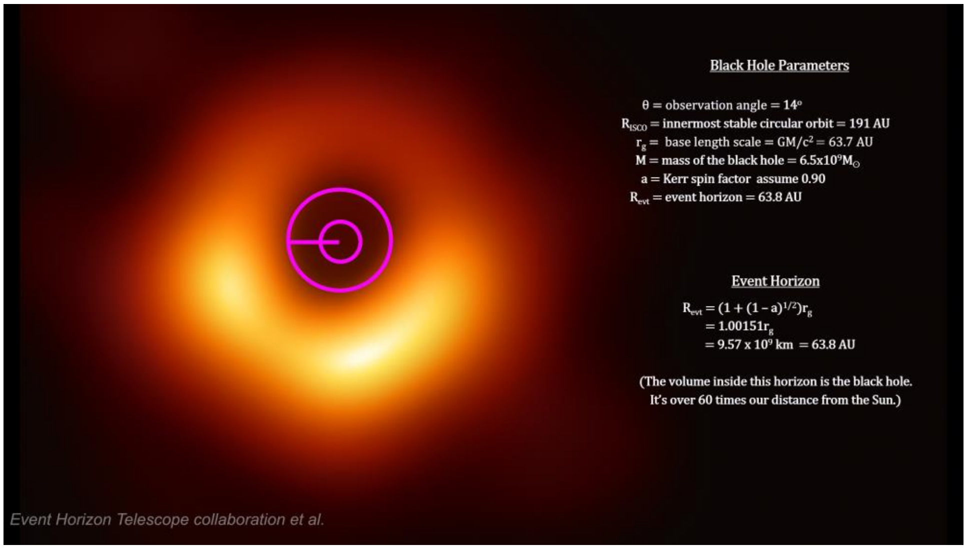
θ = observation angle = 14°
R_{ISCO} = innermost stable circular orbit = 191 AU
r_g = base length scale = GM/c^2 = 63.7 AU
M = mass of the black hole = $6.5 \times 10^9 M_\odot$

Innermost Stable Cirular Orbit

$R_{ISCO} = 3r_g = 3\,GM/c^2$
$= 28.7 \times 10^9$ km $= 191$ AU
$r_g = 9.56 \times 10^9$ km $= 63.7$ AU
$M = 1.29 \times 10^{40}$ kg $= 6.5 \times 10^9 M_\odot$

Event Horizon Telescope collaboration et al.

Modeling the disk as a rotating charged plasma in a strong and twisted magnetic field under general relativistic conditions, astrophysicists have determined that the spin of the black hole is aligned with this rotation. But again, there is not enough information to determine its spin. [I have seen estimates that range from 0.26 to .9 based on magnetic field twisting measurements, M87 Jet diameter shifts and on model-based behavior.] For our illustrative purposes we'll assume it's 0.9. With that we calculate the Event Horizon. It's over 63 times further away from its center than we are from the sun. The volume within this sphere is the black hole, and it is bigger than our entire solar system.



Black Hole Parameters

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R_{ISCO} = innermost stable circular orbit = 191 AU
r_g = base length scale = GM/c^2 = 63.7 AU
M = mass of the black hole = $6.5\times10^9 M_\odot$
a = Kerr spin factor assume 0.90
R_{evt} = event horizon = 63.8 AU

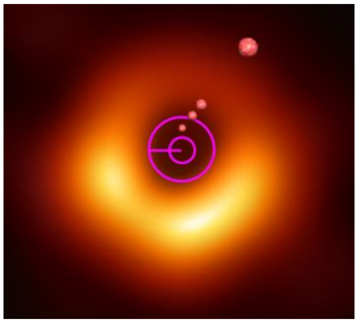
Event Horizon

$$R_{evt} = (1 + (1 - a)^{1/2})r_g$$
$$= 1.00151r_g$$
$$= 9.57 \times 10^9 \text{ km} = 63.8 \text{ AU}$$

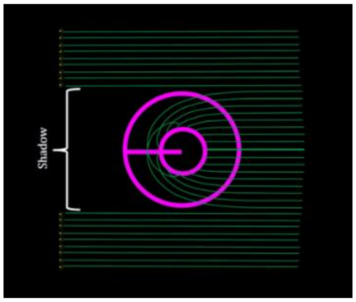
(The volume inside this horizon is the black hole.
It's over 60 times our distance from the Sun.)

Event Horizon Telescope collaboration et al.

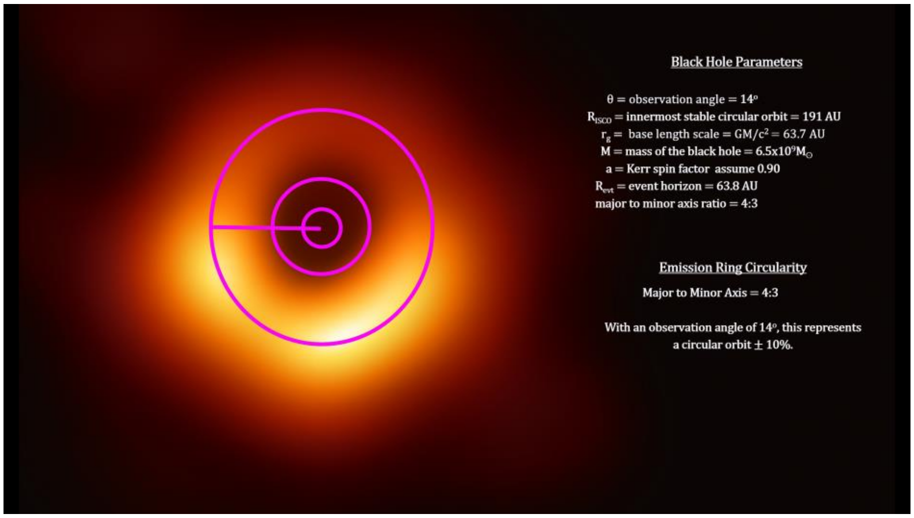
Unless it acquires additional energy, matter that crosses this innermost stable circular orbit threshold, will enter into a decaying orbit into the event horizon. But we know that the powerful magnetic field near the horizon is capable of accelerating charged particles to near the speed of light and ejecting them at escape velocity in jets perpendicular to the rotating accretion disk.



In addition, most photon trajectories into this region will also result in their eventually entering the black hole. This marks the extent of the black hole's shadow. Black hole shadows were expected to be significantly larger than the black hole itself. This one is triple the size of our entire solar system.



Here we have traced the peak of the emission in the ring in order to determine the shape of the image and obtain the ratio between major and minor axis of the ring. It's 4 to 3. With our 14° tilt, this corresponds to a true circle give or take 10%. This is what the general relativity theory predicts for co-rotating black holes.



Black Hole Parameters

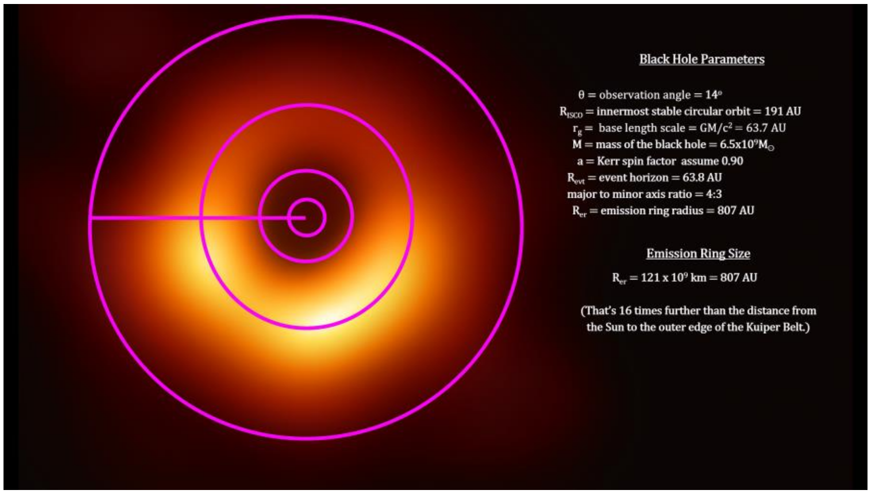
θ = observation angle = 14°
R_{ISCO} = innermost stable circular orbit = 191 AU
r_g = base length scale = GM/c^2 = 63.7 AU
M = mass of the black hole = $6.5\mathrm{x}10^9 M_\odot$
a = Kerr spin factor assume 0.90
R_{evt} = event horizon = 63.8 AU
major to minor axis ratio = 4:3

Emission Ring Circularity

Major to Minor Axis = 4:3

With an observation angle of 14°, this represents a circular orbit ± 10%.

And here we have the full size of the black hole and its emission ring. It's ten times further out than Voyager 1 has travelled since its launch in 1977. This may seem like a very large object. But due to the fact that it is 54.8 million light years away, it only spans 43 micro arcseconds across the sky. The smallest that optical telescopes can resolve, including the interferometer telescope used to study Sag A* is on the order of hundreds of micro arcseconds. To detect this object, we needed a much larger telescope.



Black Hole Parameters

θ = observation angle = 14°
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M = mass of the black hole = $6.5\mathrm{x}10^9 M_\odot$
a = Kerr spin factor assume 0.90
R_{evt} = event horizon = 63.8 AU
major to minor axis ratio = 4:3
R_{er} = emission ring radius = 807 AU

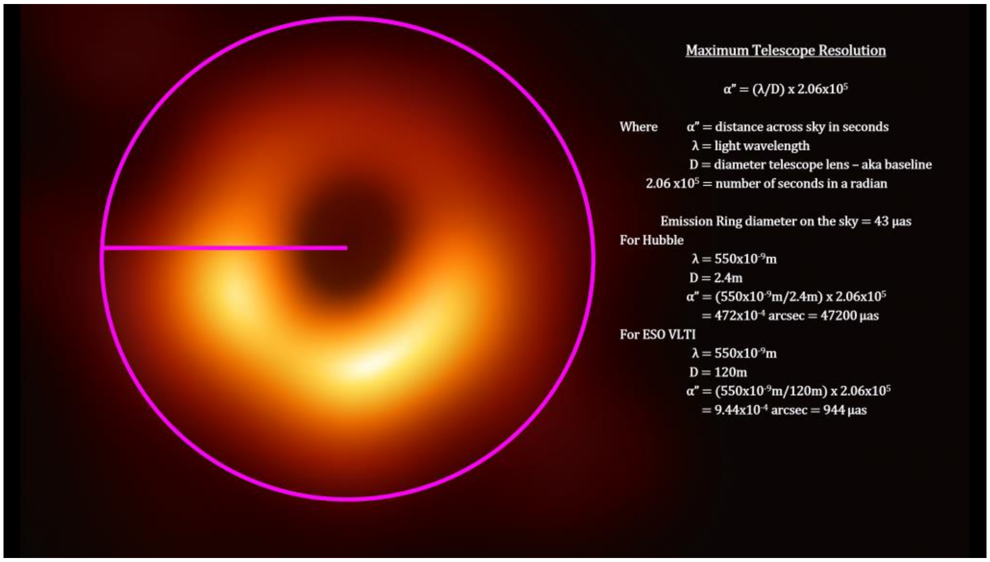
Emission Ring Size

$R_{er} = 121 \mathrm{x} 10^9$ km = 807 AU

(That's 16 times further than the distance from the Sun to the outer edge of the Kuiper Belt.)

The Event Horizon Telescope

The diameter of the M87 Black Hole emission ring 54.8 mly away is 43 millionths of an arc second. The resolving power of a telescope is the smallest angular distance between two objects that can be seen as separate objects. A telescope's resolving power is limited by its baseline - the diameter of its lens. The 2.4 meter Hubble Space Telescope has the resolving power to see down close to 50 mas. The M87 Black hole is over a thousand times too small for Hubble to see. The 120 m ESO VLTI used to study Sag A* has the resolving power to see down to 1 mas. The M87 Black hole is almost 22 times too small for ESO VLTI to see. To get down to the micro-arc second level, a much bigger telescope is needed.



Maximum Telescope Resolution

$\alpha'' = (\lambda/D) \times 2.06\times10^{5}$

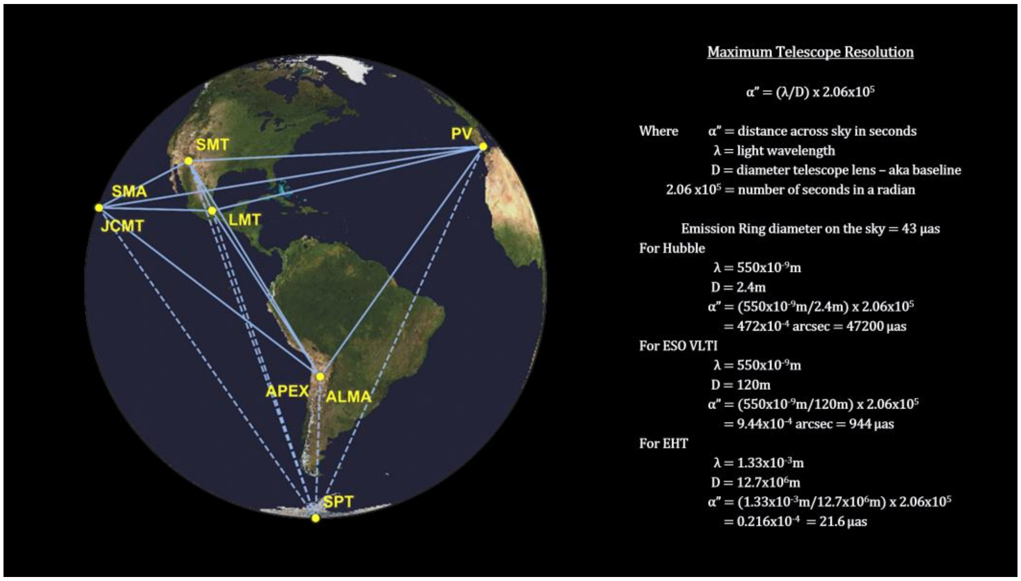
Where α'' = distance across sky in seconds
λ = light wavelength
D = diameter telescope lens – aka baseline
2.06×10^{5} = number of seconds in a radian

Emission Ring diameter on the sky = 43 µas

For Hubble
$\lambda = 550\times10^{-9}$m
$D = 2.4$m
$\alpha'' = (550\times10^{-9}\text{m}/2.4\text{m}) \times 2.06\times10^{5}$
$= 472\times10^{-4}$ arcsec = 47200 µas

For ESO VLTI
$\lambda = 550\times10^{-9}$m
$D = 120$m
$\alpha'' = (550\times10^{-9}\text{m}/120\text{m}) \times 2.06\times10^{5}$
$= 9.44\times10^{-4}$ arcsec = 944 µas

In order to get a telescope baseline large enough, the EHT team upgraded and connected a worldwide network of eight pre-existing radio telescopes deployed at a variety of high-altitude sites. These locations included volcanoes in Hawaii and Mexico, mountains in Arizona, Spain, and Chile and one in Antarctica. Baseline lengths between telescopes vary, but the resulting effective combined baseline is close to the diameter of the Earth. This results in an array with a resolution limit of around 21 µas. This is enough to see the M87 Black Hole's emission ring with its shadow. [In fact, it is enough to read a newspaper in New York from a sidewalk café in Paris.]



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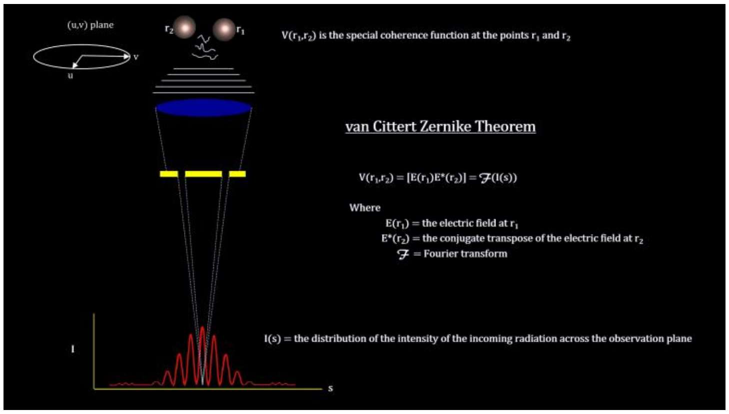
$\alpha'' = (550\times10^{-9}\text{m}/120\text{m}) \times 2.06\times10^{5}$
$= 9.44\times10^{-4}$ arcsec = 944 µas

For EHT
$\lambda = 1.33\times10^{-3}$m
$D = 12.7\times10^{6}$m
$\alpha'' = (1.33\times10^{-3}\text{m}/12.7\times10^{6}\text{m}) \times 2.06\times10^{5}$
$= 0.216\times10^{-4}$ = 21.6 µas

Although the telescopes are not physically connected, they are able to synchronize their recorded data with atomic clocks which precisely time their observations. Each telescope produced roughly 350 terabytes of data per day. This data was stored on high-performance hard drives, and flown to highly specialized supercomputers at the MIT Haystack Observatory and Max Planck Institute for Radio Astronomy where the data was combined.

In science, the "inverse problem" is the process of calculating from a set of observations back to the causal factors that produced them. [It is always a challenge to figure out what was actually happening at the source of the collected data.] For example, the ESO VLTI team reconstructed the motion of S2 around Sag A* in the (u,v) plane 26,000 light years away by applying interferometry techniques to images captured by the telescope in the observation plane here on Earth.



$V(r_1,r_2)$ is the special coherence function at the points r_1 and r_2

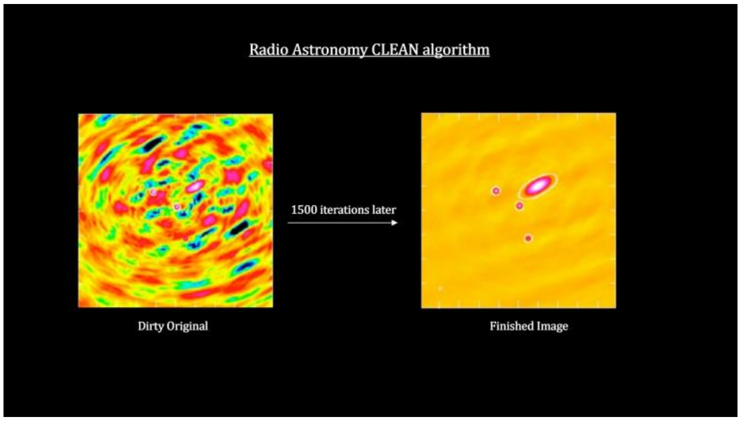
van Cittert Zernike Theorem

$V(r_1,r_2) = [E(r_1)E^*(r_2)] = \mathcal{F}(I(s))$

Where
$E(r_1)$ = the electric field at r_1
$E^*(r_2)$ = the conjugate transpose of the electric field at r_2
$\mathcal{F}$ = Fourier transform

$I(s)$ = the distribution of the intensity of the incoming radiation across the observation plane

The inverse problem is to calculate what caused this distribution and produce an image. Radio data is normally quite dirty. One of the primary radio astronomy interferometry techniques is a cleaning algorithm called CLEAN. It can this dirty image and do this.



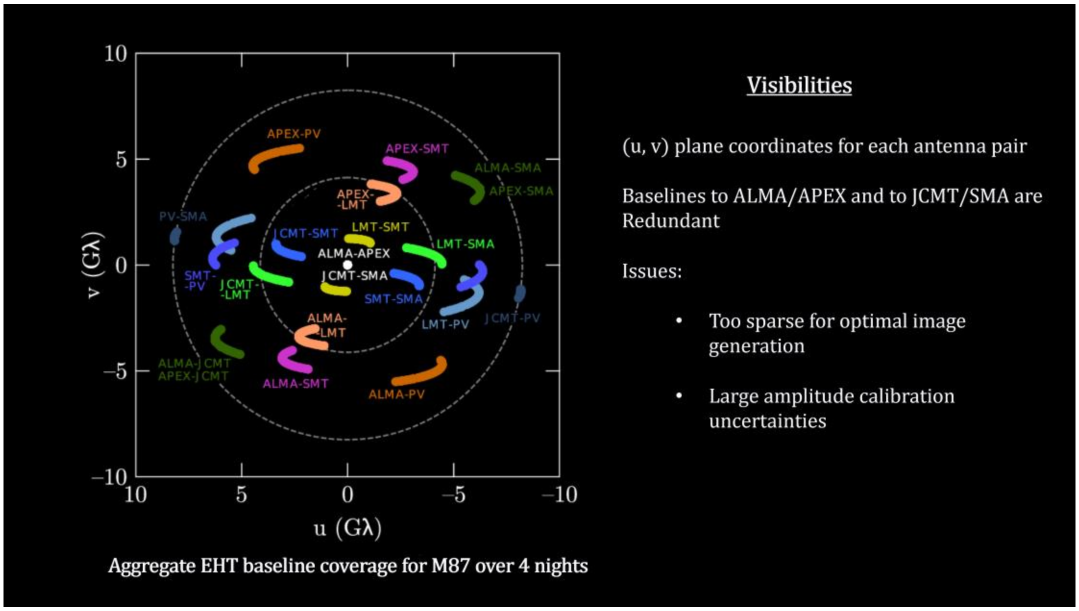
Radio Astronomy CLEAN algorithm

1500 iterations later

Dirty Original

Finished Image

However, there were two challenging issues with the EHT data. First, the samples were limited to only a few hours a day for 4 days. Because the source plane is only sparsely sampled, the inverse problem is under-constrained. That is, the number of potential causes that can lead to these visibilities expands dramatically. And second, the measured visibilities had large amplitude calibration uncertainties.



Aggregate EHT baseline coverage for M87 over 4 nights

Visibilities

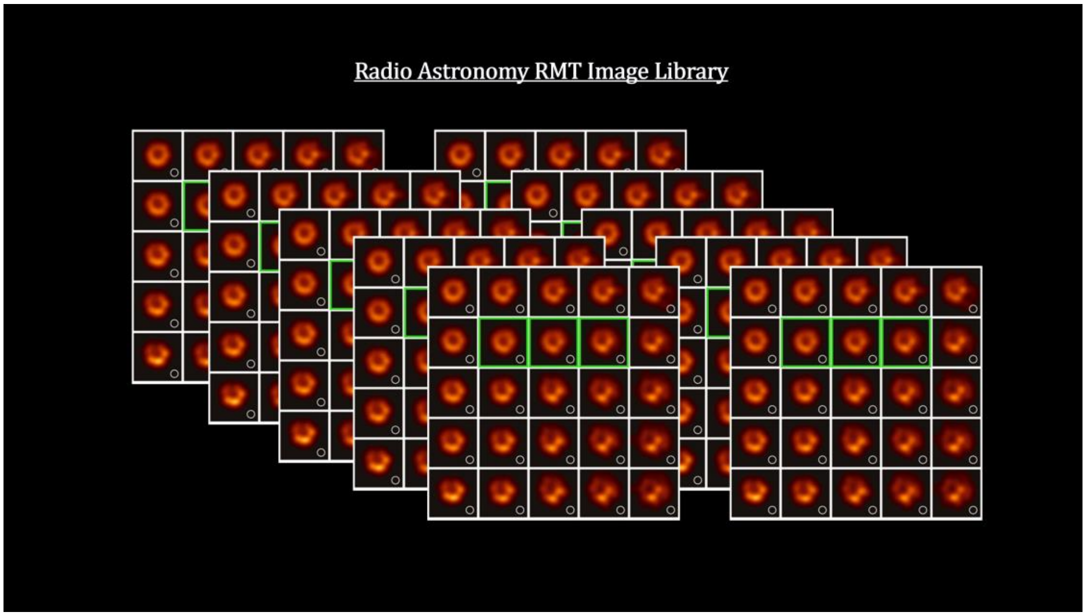
(u, v) plane coordinates for each antenna pair

Baselines to ALMA/APEX and to JCMT/SMA are Redundant

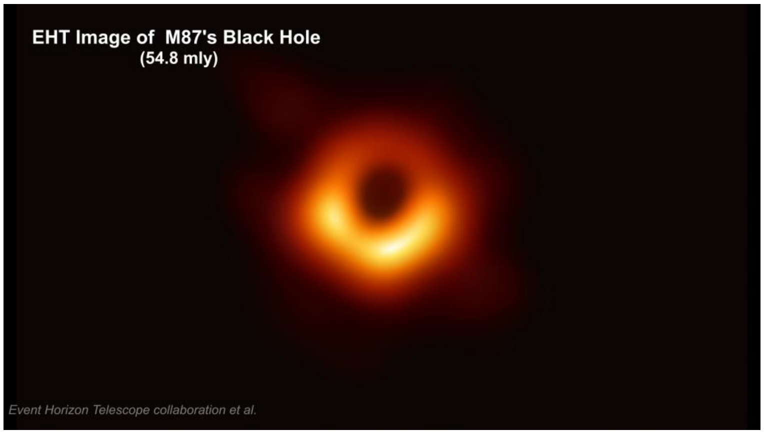
Issues:

- Too sparse for optimal image generation
- Large amplitude calibration uncertainties

To address these challenges, a new imaging algorithm was developed that incorporated additional assumptions and constraints designed to produce images that are physically plausible, while remaining consistent with the data. The algorithm is called regularized maximum likelihood (RML for short). It searches for an image that is not only consistent with the observed data but also favors specified image properties like smoothness and compactness. A library of tens of thousands of images was created with different parameter combinations associated with general relativistic magnetohydrodynamics.



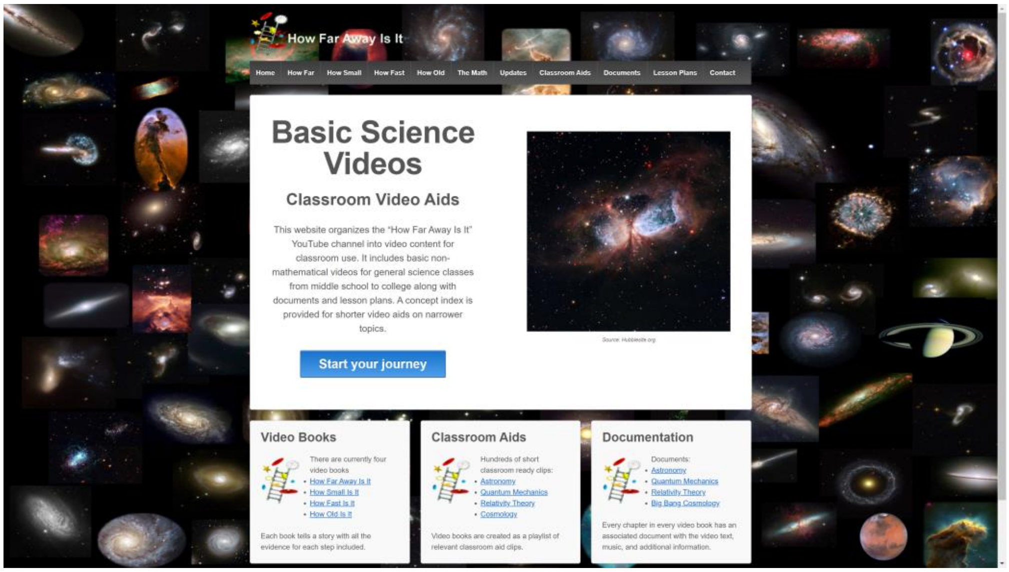
Using both CLEAN and RMT on the visibilities, this image was developed. It supports Einstein's General Theory of Relativity in part because it assumed general relativity in order to get the image. The visibilities could have been explained by some other theory, but without relativity, they just produced static.



Event Horizon Telescope collaboration et al.

Credits

Here are the links to Hubble sites, whitepapers and other locations where I found the information contained in this 2019 review. These are also the places where you can begin to do your own research.



Basic Science Videos

Classroom Video Aids

This website organizes the "How Far Away Is It" YouTube channel into video content for classroom use. It includes basic non-mathematical videos for general science classes from middle school to college along with documents and lesson plans. A concept index is provided for shorter video aids on narrower topics.

Source: Hubblesite.org

Video Books

There are currently four video books
- How Far Away Is It
- How Small Is It
- How Fast Is It
- How Old Is It

Each book tells a story with all the evidence for each step included.

Classroom Aids

Hundreds of short classroom ready clips:
- Astronomy
- Quantum Mechanics
- Relativity Theory
- Cosmology

Video books are created as a playlist of relevant classroom aid clips.

Documentation

Documents:
- Astronomy
- Quantum Mechanics
- Relativity Theory
- Big Bang Cosmology

Every chapter in every video book has an associated document with the video text, music, and additional information.

howfarawayisit.com

Also, thanks to Jonathan Onstead, there is a 'How Far Away Is It' wiki available for anyone who wants to engage in conversations about this or any channel video.

Home

Welcome to the Wiki

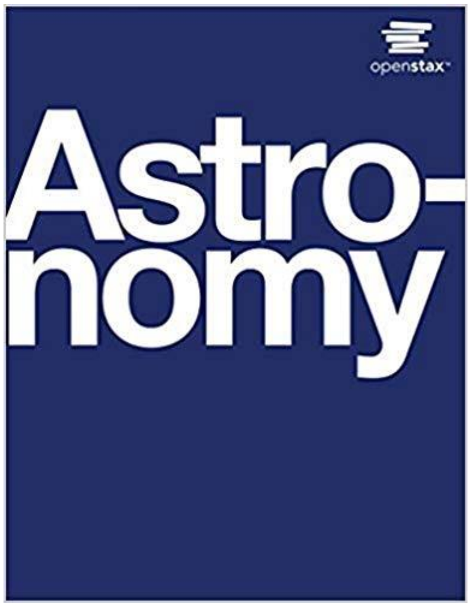
Welcome to the wiki. We're a collaborative community website about your topic that anyone, including you, can edit. Click the edit button at the top of any page to get started!

Welcome!

This is the official wiki for astronomy and physics information brought to you by David Butler and his youtube channel, Howfarawayisit

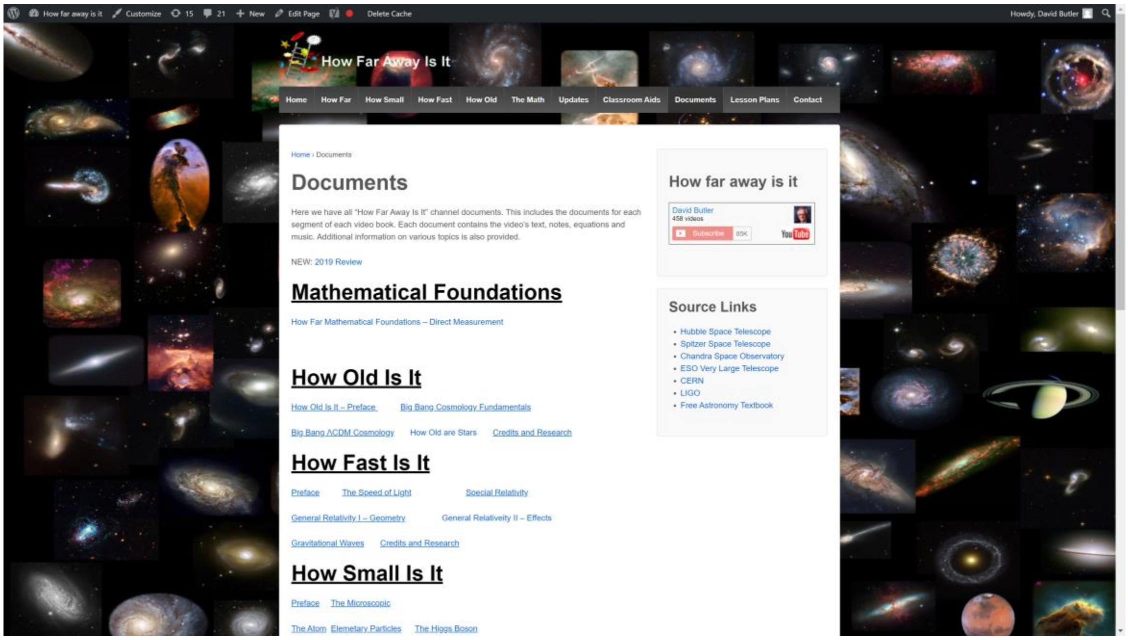
https://howfarawayisit.fandom.com/wiki/Encyclopedia_Howfarawayica

I want to call your attention to a new free online textbook called 'Astronomy" that anyone interested in astronomy can use. It is supported by OpenStax, a Rice University 501(C)(3) nonprofit charity. The book builds student understanding through the use of relevant analogies, clear and non-technical explanations, and rich illustrations. Take a look at Synchrotron radiation on page 972.



https://openstax.org/details/astronomy

And don't forget. Every video has a document on the howfarawayisit.com website containing all the text. Download and translate as needed. Thanks for watching.



Documents

Here we have all "How Far Away Is It" channel documents. This includes the documents for each segment of each video book. Each document contains the video's text, notes, equations and music. Additional information on various topics is also provided.

NEW: 2019 Review

Mathematical Foundations

How Far Mathematical Foundations – Direct Measurement

How Old Is It

How Old Is It – Preface   Big Bang Cosmology Fundamentals

Big Bang ΛCDM Cosmology   How Old are Stars   Credits and Research

How Fast Is It

Preface   The Speed of Light   Special Relativity

General Relativity I – Geometry   General Relativeity II – Effects

Gravitational Waves   Credits and Research

How Small Is It

Preface   The Microscopic

The Atom   Elemetary Particles   The Higgs Boson

How far away is it

Source Links

- Hubble Space Telescope
- Spitzer Space Telescope
- Chandra Space Observatory
- ESO Very Large Telescope
- CERN
- LIGO
- Free Astronomy Textbook

http://howfarawayisit.com/documents/

Comet 2I/Borisov
https://www.spacetelescope.org/news/heic1918/?lang
https://svs.gsfc.nasa.gov/4758

Southern Crab Nebula – 6,850 ly
https://www.spacetelescope.org/news/heic1907/?lang
http://hubblesite.org/image/4384/news_release/2019-15

NGC 1466 - 160,000 ly
https://www.spacetelescope.org/news/heic1915/?lang
https://iopscience.iop.org/article/10.1086/308066

Pan-STARRS Sky Survey
http://hubblesite.org/news_release/news/2019-12

NGC 4485 – 25 mly
http://hubblesite.org/image/4499/news_release/2019-30

Bedin 1 – 30 mly
https://www.spacetelescope.org/news/heic1903/

Henize 2-10 – 30 mly
https://www.spacetelescope.org/news/heic1911/?lang
https://www.scientificamerican.com/article/dwarf-galaxy-black-hole/https://chandra.harvard.edu/photo/2011/he210/

D100 Loosing Gas – 330 mly
http://hubblesite.org/news_release/news/2019-05

Arp-Madore 2026-426 – 704 mly
https://www.spacetelescope.org/news/heic1919/?lang

GRB 190114C – 4.5 bly
https://earthsky.org/space/jan-14-2019-gamma-ray-burst-brightest-so-far
https://hubblesite.org/contents/news-releases/2019/news-2019-56

PSZ1 G311.65-18.48 Sunburst Arc galaxy – 11 bly
https://www.spacetelescope.org/news/heic1920/?lang

Hubble Legacy Field – 13 bly
https://www.spacetelescope.org/images/heic1909a/

Event Horizon Telescope Black Hole Image

https://science.nrao.edu/facilities/alma/naasc-workshops/nrao-cd-uf17/InterfBasics_UFL.pdf
https://www.newscientist.com/article/2131889-weird-energy-beam-seems-to-travel-five-times-the-speed-of-light/#ixzz67O2Y2gIc
https://hubblesite.org/image/3228/news/49-elliptical-galaxies Hubble time laps
http://www.stsci.edu/ftp/science/m87/m87.html Hubble superluminal motion
https://en.wikipedia.org/wiki/Superluminal_motion superluminal formula
https://chandra.harvard.edu/photo/2001/0134/
https://chandra.harvard.edu/photo/2019/black_hole/
https://arxiv.org/pdf/1812.06025.pdf
https://home.strw.leidenuniv.nl/~algera/pages/RP1718/Lecture6.pdf
https://www.jpl.nasa.gov/edu/news/2019/4/19/how-scientists-captured-the-first-image-of-a-black-hole/
https://www.ashlarstem.com/post/relativistic-doppler-shift-vs-relativistic-beaming
https://ned.ipac.caltech.edu/level5/Biretta/Biretta2_3.html
https://arxiv.org/ftp/arxiv/papers/1210/1210.6132.pdf
https://ned.ipac.caltech.edu/level5/Biretta/Biretta3_3.html Jet Kinematics
https://en.wikipedia.org/wiki/Relativistic_beaming
https://physics.stackexchange.com/questions/71507/light-in-different-reference-frames
https://theoretical-physics-digest.fandom.com/wiki/Relativistic_Beaming
https://www.nsf.gov/news/news_images.jsp?cntn_id=298276&org=NSF
https://eventhorizontelescope.org/
https://eventhorizontelescope.org/science
https://www.youtube.com/watch?v=zUyH3XhpLTo Black Hole shadow
8213/ab0ec7/pdfhttps://eventhorizontelescope.org/infographics
https://achael.github.io/_pages/imaging/
https://blackholecam.org/research/bhshadow/vlbi/
https://science.nrao.edu/facilities/alma/naasc-workshops/almadata/indebetouw.pdf
https://fits.gsfc.nasa.gov/standard10/fits_standard10.pdf
https://arxiv.org/ftp/arxiv/papers/1906/1906.11240.pdf

Whitepapers

“Detection of proper motions in the M87 jet”
Biretta, J.A.; Zhou, F.; Owen, F.N.
Astrophys. J. **1995**, 447, 582–596.
https://ui.adsabs.harvard.edu/abs/1995ApJ...447..582B/abstract

“First M87 Event Horizon Telescope Results. I.
The Shadow of the Supermassive Black Hole”
The Event Horizon Telescope Collaboration
(See the end matter for the full list of authors.)
Received 2019 March 1; revised 2019 March 12; accepted 2019 March 12; published 2019 April 10
https://iopscience.iop.org/article/10.3847/2041-

“Measurement of the spin of the M87 black hole from its observed twisted light”
Fabrizio Tamburini, Bo Thidé, Massimo Della Valle
(Submitted on 16 Apr 2019 (v1), last revised 26 Nov 2019 (this version, v4))
https://arxiv.org/abs/1904.07923

Music

@02:17 Schubert, Franz: Impromptu in A-Flat; Evelyn Dubourg; from the album Meditation: Classical Relaxation 2010

@11:25 Giordani: Caro Mio Ben; from the album Meditation: Classical Relaxation 2010

@16:26 Tchaikovsky: Symphony No 5; from A Calendar Of Classics - A 12 CD Set Of Romantic Classics For Every Month Of The Year 2007

Greek letters:
- α β γ δ ε ζ η θ ι κ λ μ ν ξ ο π ρ σ τ υ φ χ ψ ω
- Α Β Γ Δ Ε Ζ Η Θ Ι Κ Λ Μ Ν Ξ Ο Π Ρ Σ Τ Υ Φ Χ Ψ Ω

⇒ → ± ⊙ ∞ ↛ ∃ ∄ ∈ ∉ ∬ ∫ ≅ ≥ ≤ ≈ ≠ ≡ √ ∛ ~ ∝ ħ ÷