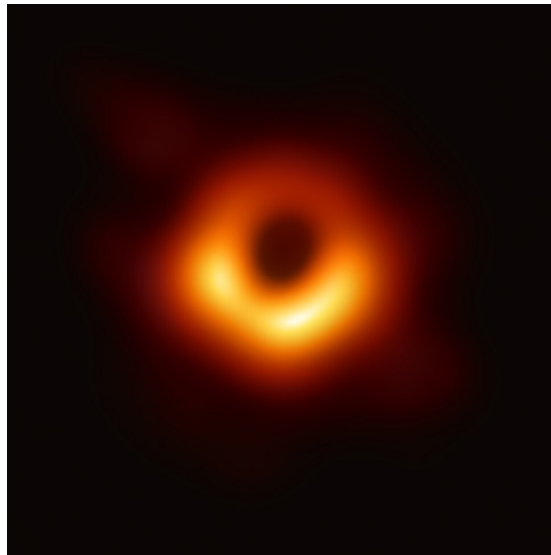
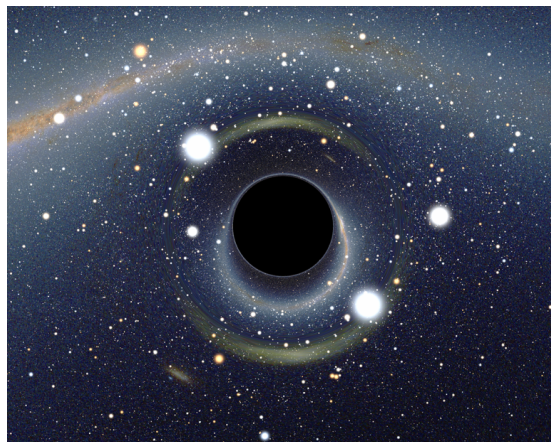


Black hole

A **black hole** is a massive, compact astronomical object so dense that its gravity prevents anything from escaping, even light. Albert Einstein's theory of general relativity predicts that a sufficiently compact mass will form a black hole.^[4] The boundary of no escape is called the event horizon. A black hole has a great effect on the fate and circumstances of an object crossing it, but has no locally detectable features according to general relativity.^[5] In many ways, a black hole acts like an ideal black body, as it reflects no light.^{[6][7]} Quantum field theory in curved spacetime predicts that event horizons emit Hawking radiation, with the same spectrum as a black body of a temperature inversely proportional to its mass. This temperature is of the order of billionths of a kelvin for stellar black holes, making it essentially impossible to observe directly.



An image of the core region of Messier 87, a supermassive black hole, processed from a sparse array of radio telescopes known as the EHT with colors indicating brightness temperature.^{[1][2]}



Simulated view of a Schwarzschild black hole in front of the Large Magellanic Cloud. Note the gravitational lensing

effect, which produces two enlarged but highly distorted views of the Cloud. Across the top, the Milky Way disk appears distorted into an arc.^[3]

Objects whose gravitational fields are too strong for light to escape were first considered in the 18th century by John Michell and Pierre-Simon Laplace. In 1916, Karl Schwarzschild found the first modern solution of general relativity that would characterise a black hole. Due to his influential research, the Schwarzschild metric is named after him. David Finkelstein, in 1958, first published the interpretation of "black hole" as a region of space from which nothing can escape. Black holes were long considered a mathematical curiosity; it was not until the 1960s that theoretical work showed they were a generic prediction of general relativity. The first black hole known was Cygnus X-1, identified by several researchers independently in 1971.^{[8][9]}

Black holes typically form when massive stars collapse at the end of their life cycle. After a black hole has formed, it can grow by absorbing mass from its surroundings. Supermassive black holes of millions of solar masses may form by absorbing other stars and merging with other black holes, or via direct collapse of gas clouds. There is consensus that supermassive black holes exist in the centres of most galaxies.

The presence of a black hole can be inferred through its interaction

with other matter and with electromagnetic radiation such as visible light. Matter falling toward a black hole can form an accretion disk of infalling plasma, heated by friction and emitting light. In extreme cases, this creates a quasar, some of the brightest objects in the universe. Stars passing too close to a supermassive black hole can be shredded into streamers that shine very brightly before being "swallowed."^[10] If other stars are orbiting a black hole, their orbits can be used to determine the black hole's mass and location. Such observations can be used to exclude possible alternatives such as neutron stars. In this way, astronomers have identified numerous stellar black hole candidates in binary systems and established that the radio source known as Sagittarius A*, at the core of the Milky Way galaxy, contains a supermassive black hole of about 4.3 million solar masses.

History

The idea of a body so big that even light could not escape was briefly proposed by English astronomical pioneer and clergyman John Michell and independently by French scientist Pierre-Simon Laplace. Both scholars proposed very large stars rather than the modern model of stars with extraordinary density.^[11]

Michell's idea, in a short part of a letter published in 1784, calculated

that a star with the same density but 500 times the radius of the sun would not let any emitted light escape; the surface escape velocity would exceed the speed of light. Michell correctly noted that such supermassive but non-radiating bodies might be detectable through their gravitational effects on nearby visible bodies.^{[11][12][13]}

In 1796, Laplace mentioned that a star could be invisible if it were sufficiently large while speculating on the origin of the Solar System in his book *Exposition du Système du Monde*. Franz Xaver von Zach asked Laplace for a mathematical analysis, which Laplace provided and published in journal edited by von Zach.^[11]

Scholars of the time were initially excited by the proposal that giant but invisible 'dark stars' might be hiding in plain view, but enthusiasm dampened when the wavelike nature of light became apparent in the early nineteenth century,^[14] since light was understood as a wave rather than a particle, it was unclear what, if any, influence gravity would have on escaping light waves.^{[11][13]}

General relativity

In 1915, Albert Einstein developed his theory of general relativity, having earlier shown that gravity does influence light's motion. Only a

few months later, Karl Schwarzschild found a solution to the Einstein field equations that describes the gravitational field of a point mass and a spherical mass.^{[15][16]} A few months after Schwarzschild, Johannes Droste, a student of Hendrik Lorentz, independently gave the same solution for the point mass and wrote more extensively about its properties.^{[17][18]} This solution had a peculiar behaviour at what is now called the Schwarzschild radius, where it became singular, meaning that some of the terms in the Einstein equations became infinite. The nature of this surface was not quite understood at the time.

In 1924, Arthur Eddington showed that the singularity disappeared after a change of coordinates. In 1933, Georges Lemaître realised that this meant the singularity at the Schwarzschild radius was a non-physical coordinate singularity.^[19] Arthur Eddington commented on the possibility of a star with mass compressed to the Schwarzschild radius in a 1926 book, noting that Einstein's theory allows us to rule out overly large densities for visible stars like Betelgeuse because "a star of 250 million km radius could not possibly have so high a density as the Sun. Firstly, the force of gravitation would be so great that light would be unable to escape from it, the rays falling back to the star like a stone to the earth. Secondly, the red shift of the spectral lines would be so great that the spectrum would be shifted out of existence. Thirdly, the mass would produce so much curvature of the spacetime metric that space would close up around the star, leaving us outside (i.e., nowhere)."^{[20][21]}

In 1931, Subrahmanyan Chandrasekhar calculated, using special relativity, that a non-rotating body of electron-degenerate matter above a certain limiting mass (now called the Chandrasekhar limit at $1.4 M_{\odot}$) has no stable solutions.^[22] His arguments were opposed by many of his contemporaries like Eddington and Lev Landau, who argued that some yet unknown mechanism would stop the collapse.^[23] They were partly correct: a white dwarf slightly more massive than the Chandrasekhar limit will collapse into a neutron star,^[24] which is itself stable.

In 1939, Robert Oppenheimer and George Volkoff predicted that neutron stars above another limit, the Tolman–Oppenheimer–Volkoff limit, would collapse further for the reasons presented by Chandrasekhar, and concluded that no law of physics was likely to intervene and stop at least some stars from collapsing to black holes.^[25] Their original calculations, based on the Pauli exclusion principle, gave it as $0.7 M_{\odot}$. Subsequent consideration of neutron-neutron repulsion mediated by the strong force raised the estimate to approximately $1.5 M_{\odot}$ to $3.0 M_{\odot}$.^[26] Observations of the neutron star merger GW170817, which is thought to have generated a black hole shortly afterward, have refined the TOV limit estimate to $\sim 2.17 M_{\odot}$.^[27]
^[28]^[29]^[30]^[31]

Oppenheimer and his co-authors interpreted the singularity at the boundary of the Schwarzschild radius as indicating that this was the boundary of a bubble in which time stopped. This is a valid point of

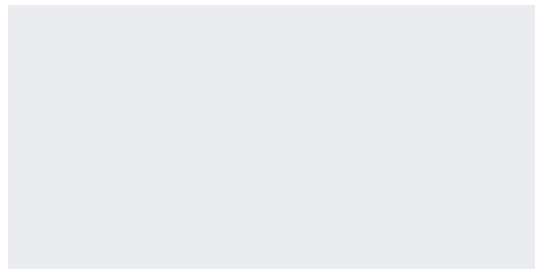
view for external observers, but not for infalling observers. The hypothetical collapsed stars were called "frozen stars", because an outside observer would see the surface of the star frozen in time at the instant where its collapse takes it to the Schwarzschild radius.^[32]

Also in 1939, Einstein attempted to prove that black holes were impossible in his publication "On a Stationary System with Spherical Symmetry Consisting of Many Gravitating Masses", using his theory of general relativity to defend his argument.^[33] Months later, Oppenheimer and his student Hartland Snyder provided the Oppenheimer–Snyder model in their paper "On Continued Gravitational Contraction",^[34] which predicted the existence of black holes. In the paper, which made no reference to Einstein's recent publication, Oppenheimer and Snyder used Einstein's own theory of general relativity to show the conditions on how a black hole could develop, for the first time in contemporary physics.^[33]

In 1958, David Finkelstein identified the Schwarzschild surface as an event horizon, "a perfect unidirectional membrane: causal influences can cross it in only one direction".^[35] Finkelstein created a new reference frame to include the point of view of infalling observers.^{[36]:103} Finkelstein's solution extended the Schwarzschild solution for the future of observers falling into a black hole. A similar concept had already been found by Martin Kruskal but Wheeler had not understood its significance.^{[36]:103} Eventually the Kruskal–Szekeres coordinates helped physics understand black holes from multiple

perspectives.^{[32][37]}

Golden age



The first simulated image of a black hole, created by Jean-Pierre Luminet in 1978 and featuring the characteristic shadow, photon sphere, and lensed accretion disk. The disk is brighter on one side due to the Doppler effect and the Einstein effect.^{[38][39]}

The era from the mid-1960s to the mid-1970s was the "golden age of black hole research", when general relativity and black holes became mainstream subjects of research.^{[40][41]:258}

In this period more general black hole solutions were found. In 1963, Roy Kerr found the exact solution for a rotating black hole. Two years later, Ezra Newman found the axisymmetric solution for a black hole that is both rotating and electrically charged.^[42] Through the work of

Werner Israel,^[43] Brandon Carter,^{[44][45]} and David Robinson^[46] the no-hair theorem emerged, stating that a stationary black hole solution is completely described by the three parameters of the Kerr–Newman metric: mass, angular momentum, and electric charge.^[47]

At first, it was suspected that the strange features of the black hole solutions were pathological artefacts from the symmetry conditions imposed, and that the singularities would not appear in generic situations. This view was held in particular by Vladimir Belinsky, Isaak Khalatnikov, and Evgeny Lifshitz, who tried to prove that no singularities appear in generic solutions. However, in the late 1960s Roger Penrose^[48] and Stephen Hawking used global techniques to prove that singularities appear generically.^[49] For this work, Penrose received half of the 2020 Nobel Prize in Physics, Hawking having died in 2018.^[50]

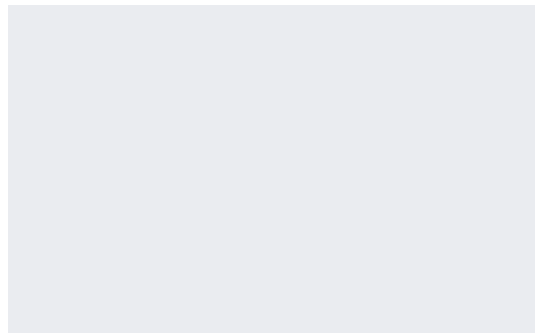
Astronomical observations also made great strides during this era. In 1967 Antony Hewish and Jocelyn Bell Burnell discovered pulsars^[51]^[52] and by 1969, these were shown to be rapidly rotating neutron stars.^[53] Until that time, neutron stars, like black holes, were regarded as just theoretical curiosities; but the discovery of pulsars showed their physical relevance and spurred a further interest in all types of compact objects that might be formed by gravitational collapse.^[54] Based on observations in Greenwich and Toronto in the early 1970s, Cygnus X-1, a galactic X-ray source discovered in 1964, became the first astronomical object commonly accepted to be a black hole.^[55]

[56]

Work by James Bardeen, Jacob Bekenstein, Carter, and Hawking in the early 1970s led to the formulation of black hole thermodynamics.

[57] These laws describe the behaviour of a black hole in close analogy to the laws of thermodynamics by relating mass to energy, area to entropy, and surface gravity to temperature. The analogy was completed when Hawking, in 1974, showed that quantum field theory implies that black holes should radiate like a black body with a temperature proportional to the surface gravity of the black hole, predicting the effect now known as Hawking radiation. [58]

Observation



An infographic explaining in detail the appearance of a black hole.

On 11 February 2016, the LIGO Scientific Collaboration and the Virgo collaboration announced the first direct detection of gravitational waves, representing the first observation of a black hole merger.^[59]

On 10 April 2019, the first direct image of a black hole and its vicinity was published, following observations made by the Event Horizon Telescope (EHT) in 2017 of the supermassive black hole in Messier 87's galactic centre.^{[60][61][62]} Gaia mission observations have found evidence of a Sun-like star orbiting a black hole named Gaia BH1 around 1,560 light-years (480 parsecs) away;^[63] evidence suggests a brown dwarf star orbits Gaia BH2.^[64] Though only a couple dozen black holes have been found so far in the Milky Way, there are thought to be hundreds of millions, most of which are solitary and do not cause emission of radiation.^[65] Therefore, they would only be detectable by gravitational lensing.

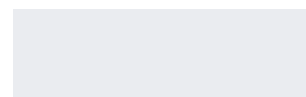
Etymology

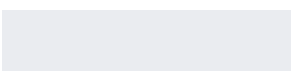
In December 1967, a student reportedly suggested the phrase "black hole" at a lecture by John Wheeler; Wheeler adopted the term for its brevity and "advertising value", and Wheeler's stature in the field ensured it quickly caught on.^{[36][66]} leading some to credit Wheeler with coining the phrase.^[67] However the term was used by others

around that time. Science writer Marcia Bartusiak traces the term "black hole" to physicist Robert H. Dicke, who in the early 1960s reportedly compared the phenomenon to the Black Hole of Calcutta, notorious as a prison where people entered but never left alive. The term "black hole" was used in print by Life and Science News magazines in 1963, and by science journalist Ann Ewing in her article "'Black Holes' in Space", dated 18 January 1964, which was a report on a meeting of the American Association for the Advancement of Science held in Cleveland, Ohio.^[36]

Properties and structure

The escape velocity from a black hole exceeds the speed of light. The formula for escape velocity is

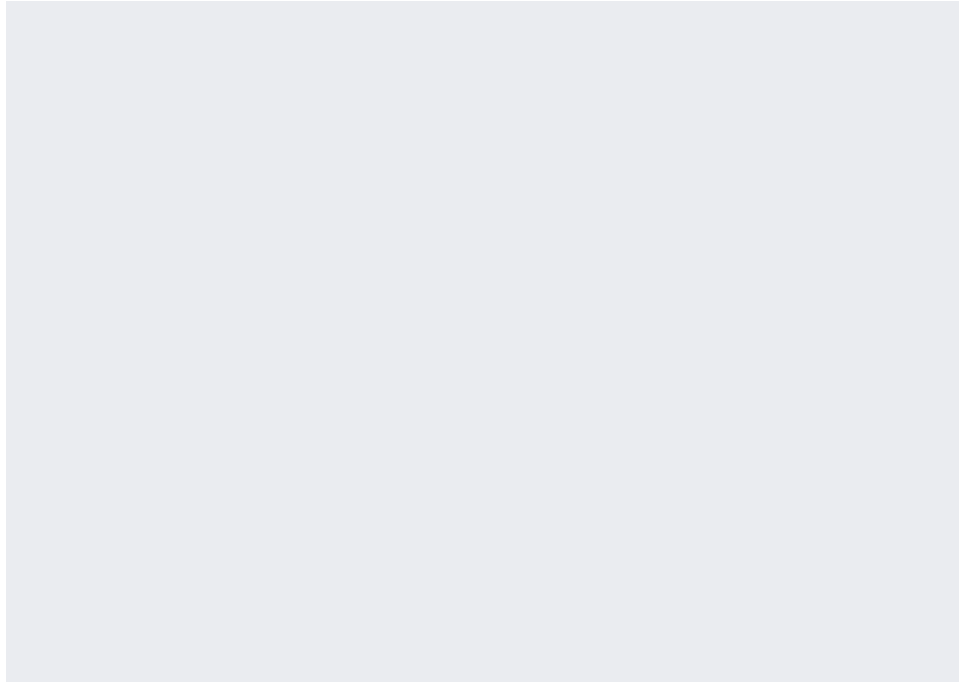


for an object at radius R from a spherical mass M , with G being the gravitational constant. When the velocity is the speed of light, c , the radius,  is called the Schwarzschild radius.^{[68]:27} A

technical definition of a black hole is any object whose mass is contained in a radius smaller than its Schwarzschild radius, a limit derived from one solution to the equations of general relativity.^{[69]:410}

The no-hair theorem postulates that, once it achieves a stable condition after formation, a black hole has only three independent physical properties: mass, electric charge, and angular momentum; the black hole is otherwise featureless. If the conjecture is true, any two black holes that share the same values for these properties, or parameters, are indistinguishable from one another. The degree to which the conjecture is true for real black holes under the laws of modern physics is currently an unsolved problem.^[47]

These properties are special because they are visible from outside a black hole. For example, a charged black hole repels other like charges just like any other charged object. Similarly, the total mass inside a sphere containing a black hole can be found by using the gravitational analogue of Gauss's law (through the ADM mass), far away from the black hole.^[70] Likewise, the angular momentum (or spin) can be measured from far away using frame dragging by the gravitomagnetic field, through for example the Lense–Thirring effect.^[71]



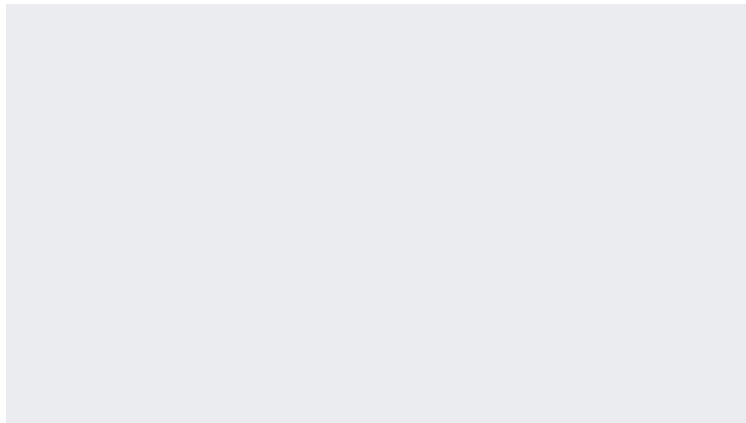
An artistic depiction of a black hole and its features

When an object falls into a black hole, any information about the shape of the object or distribution of charge on it is evenly distributed along the horizon of the black hole, and is lost to outside observers. The behaviour of the horizon in this situation is a dissipative system that is closely analogous to that of a conductive stretchy membrane with friction and electrical resistance—the membrane paradigm.^[72] This is different from other field theories such as electromagnetism, which do not have any friction or resistivity at the microscopic level, because they are time-reversible.^{[73][74]}

Because a black hole eventually achieves a stable state with only three parameters, there is no way to avoid losing information about the initial conditions: the gravitational and electric fields of a black

hole give very little information about what went in. The information that is lost includes every quantity that cannot be measured far away from the black hole horizon, including approximately conserved quantum numbers such as the total baryon number and lepton number. This behaviour is so puzzling that it has been called the black hole information loss paradox.^{[73][74]}

Physical properties



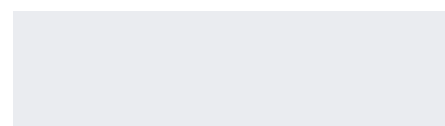
Radii for shadow and photon sphere relative to event horizon.

The simplest static black holes have mass but neither electric charge nor angular momentum. These black holes are often referred to as Schwarzschild black holes after Karl Schwarzschild who discovered

this solution in 1916.^[16] According to Birkhoff's theorem, it is the only vacuum solution that is spherically symmetric.^[75] This means there is no observable difference at a distance between the gravitational field of such a black hole and that of any other spherical object of the same mass. The popular notion of a black hole "sucking in everything" in its surroundings is therefore correct only near a black hole's horizon; far away, the external gravitational field is identical to that of any other body of the same mass.^[76]

Solutions describing more general black holes also exist. Non-rotating charged black holes are described by the Reissner–Nordström metric, while the Kerr metric describes a non-charged rotating black hole. The most general stationary black hole solution known is the Kerr–Newman metric, which describes a black hole with both charge and angular momentum.^[77]

While the mass of a black hole can take any positive value, the charge and angular momentum are constrained by the mass. The total electric charge Q and the total angular momentum J are expected to satisfy the inequality



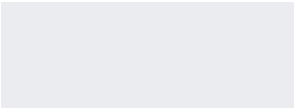
for a black hole of mass M . Black holes with the minimum possible mass satisfying this inequality are called extremal. Solutions of Einstein's equations that violate this inequality exist, but they do not

possess an event horizon. These solutions have so-called naked singularities that can be observed from the outside, and hence are deemed *unphysical*. The cosmic censorship hypothesis rules out the formation of such singularities, when they are created through the gravitational collapse of realistic matter.^[78] This is supported by numerical simulations.^[79]

Due to the relatively large strength of the electromagnetic force, black holes forming from the collapse of stars are expected to retain the nearly neutral charge of the star. Rotation, however, is expected to be a universal feature of compact astrophysical objects. The black-hole candidate binary X-ray source GRS 1915+105^[80] appears to have an angular momentum near the maximum allowed value. That uncharged limit is^[81]



allowing definition of a dimensionless spin parameter such that^[81]



^[81] ^[Note 1]

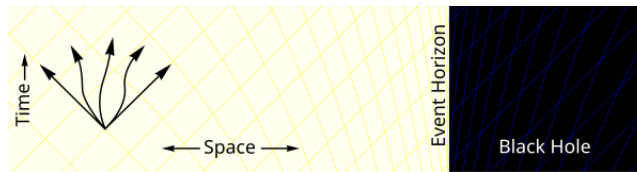
Black holes are commonly classified according to their mass, independent of angular momentum, J . The size of a black hole, as determined by the radius of the event horizon, or Schwarzschild radius, is proportional to the mass, M , through

Black hole classifications

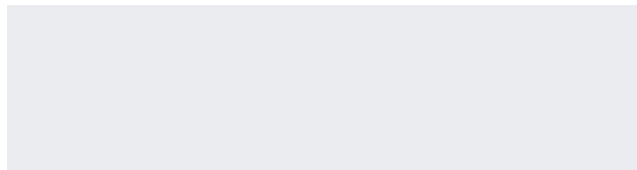
Class	Approx. mass	Approx. radius
<u>Ultramassive black hole</u>	$10^9\text{--}10^{11} M_{\odot}$	$>1,000 \text{ AU}$
<u>Supermassive black hole</u>	$10^6\text{--}10^9 M_{\odot}$	$0.001\text{--}400 \text{ AU}$
<u>Intermediate-mass black hole</u>	$10^2\text{--}10^5 M_{\odot}$	$10^3 \text{ km} \approx R_{\text{Earth}}$
<u>Stellar black hole</u>	$2\text{--}150 M_{\odot}$	30 km
<u>Micro black hole</u>	up to M_{Moon}	up to 0.1 mm

where r_s is the Schwarzschild radius and M_{\odot} is the mass of the Sun.
[83] For a black hole with nonzero spin or electric charge, the radius is smaller, [Note 2] until an extremal black hole could have an event horizon close to [84]

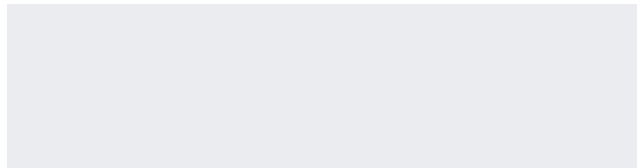
Event horizon



Far away from the black hole, a particle can move in any direction, as illustrated by the set of arrows. It is restricted only by the speed of light.



Closer to the black hole, spacetime starts to deform. There are more paths going towards the black hole than paths moving away. [\[Note 3\]](#)



Inside of the event horizon, all paths bring the particle closer to the centre of the black hole. It is no longer possible for the particle to escape.

The defining feature of a black hole is the appearance of an event horizon—a boundary in spacetime through which matter and light can pass only inward towards the mass of the black hole. Nothing, not

even light, can escape from inside the event horizon.^{[86][87]} The event horizon is referred to as such because if an event occurs within the boundary, information from that event cannot reach an outside observer, making it impossible to determine whether such an event occurred.^[88]

As predicted by general relativity, the presence of a mass deforms spacetime in such a way that the paths taken by particles bend towards the mass.^[89] At the event horizon of a black hole, this deformation becomes so strong that there are no paths that lead away from the black hole.^[90]

In a thought experiment, a distant observer can imagine clocks near a black hole which would appear to tick more slowly than those farther away from the black hole.^[91] This effect, known as gravitational time dilation, would also cause an object falling into a black hole to appear to slow as it approaches the event horizon, taking an infinite amount of time to reach it.^[92] All processes on this object would appear to slow down, from the viewpoint of a fixed outside observer, and any light emitted by the object to appear redder and dimmer, an effect known as gravitational redshift.^[93] Eventually, the falling object fades away until it can no longer be seen. Typically this process happens very rapidly with an object disappearing from view within less than a second.^[94]

On the other hand, imaginary, indestructible observers falling into a black hole would not notice any of these effects as they cross the

event horizon. Their own clocks appear to them to tick normally, they cross the event horizon after a finite time without noting any singular behaviour. In general relativity, it is impossible to determine the location of the event horizon from local observations, due to Einstein's equivalence principle.^{[95][96]}

The topology of the event horizon of a black hole at equilibrium is always spherical.^{[Note 4][99]} For non-rotating (static) black holes the geometry of the event horizon is precisely spherical, while for rotating black holes the event horizon is oblate.^{[100][101][102]}

Singularity

At the centre of the unrealistically simple Schwarzschild model of a black hole is a gravitational singularity, a region where the spacetime curvature becomes infinite.^[103] For a non-rotating black hole, this region takes the shape of a single point; for a rotating black hole it is smeared out to form a ring singularity that lies in the plane of rotation.^[104] In both cases, the singular region has zero volume. It can also be shown that the singular region contains all the mass of the black hole solution.^[105] The singular region can thus be thought of as having infinite density.^[106]

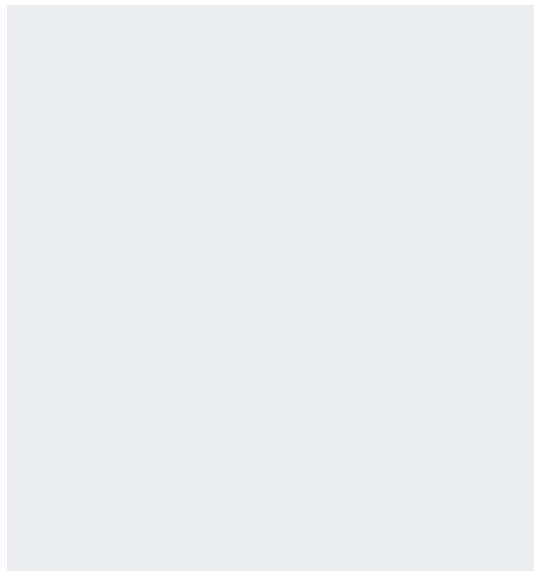
Even though the Schwarzschild model is not valid at the singularity,^[103] observers falling into a Schwarzschild black hole (i.e., non-rotating and not charged) cannot avoid being carried into the singularity once they cross the event horizon. They can prolong the experience by accelerating away to slow their descent, but only up to a limit.^[107] When they reach the singularity, they are crushed to infinite density and their mass is added to the total of the black hole. Before that happens, they will have been torn apart by the growing tidal forces in a process sometimes referred to as spaghettification or the "noodle effect".^[108]

In the case of a charged (Reissner–Nordström) or rotating (Kerr) black hole, it is possible to avoid the singularity. Extending these solutions as far as possible reveals the hypothetical possibility of exiting the black hole into a different spacetime with the black hole acting as a wormhole.^[109] The possibility of travelling to another universe is, however, only theoretical since any perturbation would destroy this possibility.^[110] It also appears to be possible to follow closed timelike curves (returning to one's own past) around the Kerr singularity, which leads to problems with causality like the grandfather paradox.^[111] It is expected that none of these peculiar effects would survive in a proper quantum treatment of rotating and charged black holes.^[112]

The appearance of singularities in general relativity signals the breakdown of the theory.^[113] This breakdown occurs where quantum effects should describe these actions, due to the extremely high

density and therefore particle interactions. To date, it has not been possible to combine quantum and gravitational effects into a single theory, although there exist attempts to formulate such a theory of quantum gravity. It is generally expected that such a theory will not feature singularities.^{[114][115]}

Photon sphere



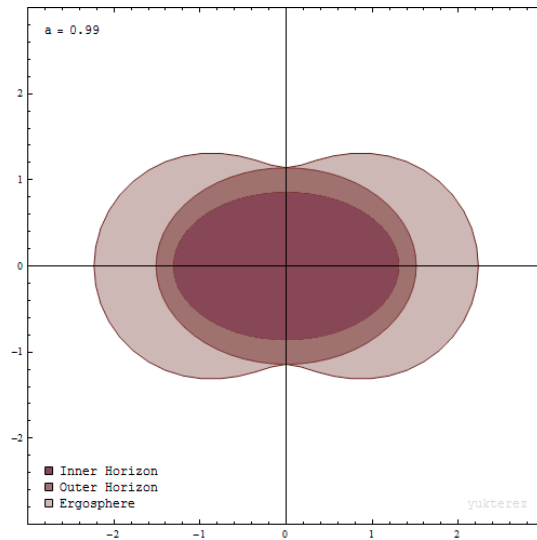
Orbits of four photons around a Schwarzschild black hole.

The photon sphere is a spherical boundary where photons that move on tangents to that sphere would be trapped in a non-stable but

circular orbit around the black hole.^[116] For non-rotating black holes, the photon sphere has a radius 1.5 times the Schwarzschild radius. Their orbits would be dynamically unstable, hence any small perturbation, such as a particle of infalling matter, would cause an instability that would grow over time, either setting the photon on an outward trajectory causing it to escape the black hole, or on an inward spiral where it would eventually cross the event horizon.^[117]

While light can still escape from the photon sphere, any light that crosses the photon sphere on an inbound trajectory will be captured by the black hole. Hence any light that reaches an outside observer from the photon sphere must have been emitted by objects between the photon sphere and the event horizon.^[117] For a Kerr black hole the radius of the photon sphere depends on the spin parameter and on the details of the photon orbit, which can be prograde (the photon rotates in the same sense of the black hole spin) or retrograde.^[118]
^[119]

Ergosphere



The ergosphere is a region outside of the event horizon, where objects cannot remain in place.^[120]

Rotating black holes are surrounded by a region of spacetime in which it is impossible to stand still, called the ergosphere. This is the result of a process known as frame-dragging; general relativity predicts that any rotating mass will tend to slightly "drag" along the spacetime immediately surrounding it. Any object near the rotating mass will tend to start moving in the direction of rotation. For a rotating black hole, this effect is so strong near the event horizon that an object would have to move faster than the speed of light in the opposite direction to just stand still.^[121]

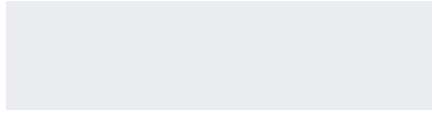
The ergosphere of a black hole is a volume bounded by the black hole's event horizon and the *ergosurface*, which coincides with the event horizon at the poles but is at a much greater distance around the equator.^[120]

Objects and radiation can escape normally from the ergosphere. Through the Penrose process, objects can emerge from the ergosphere with more energy than they entered with. The extra energy is taken from the rotational energy of the black hole. Thereby the rotation of the black hole slows down.^[122] A variation of the Penrose process in the presence of strong magnetic fields, the Blandford–Znajek process is considered a likely mechanism for the enormous luminosity and relativistic jets of quasars and other active galactic nuclei.

Innermost stable circular orbit (ISCO)

In Newtonian gravity, test particles can stably orbit at arbitrary distances from a central object. In general relativity, however, there exists an innermost stable circular orbit (often called the ISCO), for which any infinitesimal inward perturbations to a circular orbit will lead to spiraling into the black hole, and any outward perturbations will, depending on the energy, result in spiraling in, stably orbiting between apastron and periastron, or escaping to infinity.^[123] The location of the ISCO depends on the spin of the black hole, in the case of a

Schwarzschild black hole (spin zero) is:



and decreases with increasing black hole spin for particles orbiting in the same direction as the spin.^[118]

Plunging region

The final observable region of spacetime around a black hole is called the plunging region. In this area it is no longer possible for matter to follow circular orbits or to stop a final descent into the black hole. Instead it will rapidly plunge toward the black hole close to the speed of light.^{[124][125]}

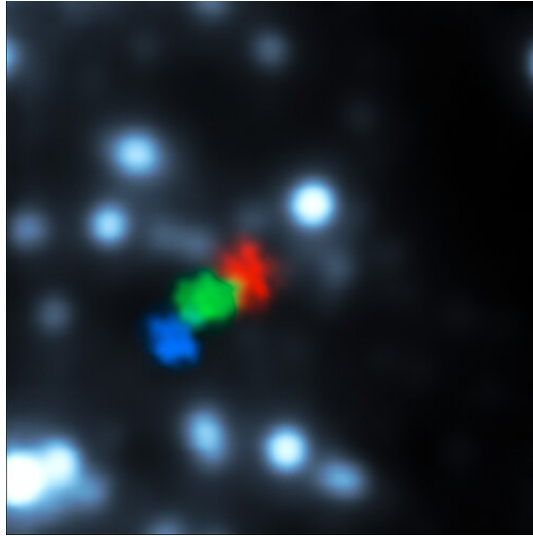
Formation and evolution

Given the bizarre character of black holes, it was long questioned whether such objects could actually exist in nature or whether they were merely pathological solutions to Einstein's equations. Einstein

himself wrongly thought black holes would not form, because he held that the angular momentum of collapsing particles would stabilise their motion at some radius.^[126] This led the general relativity community to dismiss all results to the contrary for many years. However, a minority of relativists continued to contend that black holes were physical objects,^[127] and by the end of the 1960s, they had persuaded the majority of researchers in the field that there is no obstacle to the formation of an event horizon.^[128]

Penrose demonstrated that once an event horizon forms, general relativity without quantum mechanics requires that a singularity will form within.^[48] Shortly afterwards, Hawking showed that many cosmological solutions that describe the Big Bang have singularities without scalar fields or other exotic matter. The Kerr solution, the no-hair theorem, and the laws of black hole thermodynamics showed that the physical properties of black holes were simple and comprehensible, making them respectable subjects for research.^[129] Conventional black holes are formed by gravitational collapse of heavy objects such as stars, but they can also in theory be formed by other processes.^{[130][131]}

Gravitational collapse



Gas cloud being ripped apart by black hole at the centre of the Milky Way (observations from 2006, 2010 and 2013 are shown in blue, green and red, respectively).^[132]

Gravitational collapse occurs when an object's internal pressure is insufficient to resist the object's own gravity. For stars this usually occurs either because a star has too little "fuel" left to maintain its temperature through stellar nucleosynthesis, or because a star that would have been stable receives extra matter in a way that does not raise its core temperature. In either case the star's temperature is no longer high enough to prevent it from collapsing under its own weight.^[133]

The collapse may be stopped by the degeneracy pressure of the star's constituents, allowing the condensation of matter into an exotic denser state. The result is one of the various types of compact star.

Which type forms depends on the mass of the remnant of the original star left if the outer layers have been blown away (for example, in a Type II supernova). The mass of the remnant, the collapsed object that survives the explosion, can be substantially less than that of the original star. Remnants exceeding $5 M_{\odot}$ are produced by stars that were over $20 M_{\odot}$ before the collapse.^[133]

If the mass of the remnant exceeds about $3\text{--}4 M_{\odot}$ (the Tolman–Oppenheimer–Volkoff limit^[25]), either because the original star was very heavy or because the remnant collected additional mass through accretion of matter, even the degeneracy pressure of neutrons is insufficient to stop the collapse. No known mechanism (except possibly quark degeneracy pressure) is powerful enough to stop the implosion and the object will inevitably collapse to form a black hole.^[133]

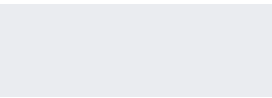
The gravitational collapse of heavy stars is assumed to be responsible for the formation of stellar mass black holes. Star formation in the early universe may have resulted in very massive stars, which upon their collapse would have produced black holes of up to $10^3 M_{\odot}$. These black holes could be the seeds of the supermassive black holes found in the centres of most galaxies.^[134] It has further been suggested that massive black holes with typical masses of $\sim 10^5 M_{\odot}$ could have formed from the direct collapse of gas clouds in the young universe.^[130] These massive objects have been proposed as the seeds that eventually formed the earliest quasars observed already at

redshift .^[135] Some candidates for such objects have been found in observations of the young universe.^[130]

While most of the energy released during gravitational collapse is emitted very quickly, an outside observer does not actually see the end of this process. Even though the collapse takes a finite amount of time from the reference frame of infalling matter, a distant observer would see the infalling material slow and halt just above the event horizon, due to gravitational time dilation. Light from the collapsing material takes longer and longer to reach the observer, with the light emitted just before the event horizon forms delayed an infinite amount of time. Thus the external observer never sees the formation of the event horizon; instead, the collapsing material seems to become dimmer and increasingly red-shifted, eventually fading away.^[136]

Primordial black holes and the Big Bang

Gravitational collapse requires great density. In the current epoch of the universe these high densities are found only in stars, but in the early universe shortly after the Big Bang densities were much greater, possibly allowing for the creation of black holes. High density alone is not enough to allow black hole formation since a uniform mass distribution will not allow the mass to bunch up. In order for primordial

black holes to have formed in such a dense medium, there must have been initial density perturbations that could then grow under their own gravity. Different models for the early universe vary widely in their predictions of the scale of these fluctuations. Various models predict the creation of primordial black holes ranging in size from a Planck mass ( $\approx 1.2 \times 10^{19} \text{ GeV}/c^2 \approx 2.2 \times 10^{-8} \text{ kg}$) to

hundreds of thousands of solar masses.^[131]

Despite the early universe being extremely dense, it did not re-collapse into a black hole during the Big Bang, since the expansion rate was greater than the attraction. Following inflation theory, general relativity predicts that the gravitational field slows the expansion of the universe. The negative pressure overcomes the positive energy density to produce a net repulsive gravitational field.^[137]

Models for the gravitational collapse of objects of relatively constant size, such as stars, do not necessarily apply in the same way to rapidly expanding space such as the Big Bang.^[138]

High-energy collisions

Gravitational collapse is not the only process that could create black

holes. In principle, black holes could be formed in high-energy collisions that achieve sufficient density. As of 2002, no such events have been detected, either directly or indirectly as a deficiency of the mass balance in particle accelerator experiments.^[139] This suggests that there must be a lower limit for the mass of black holes. Theoretically, this boundary is expected to lie around the Planck mass, where quantum effects are expected to invalidate the predictions of general relativity.^[140]

This would put the creation of black holes firmly out of reach of any high-energy process occurring on or near the Earth. However, certain developments in quantum gravity suggest that the minimum black hole mass could be much lower: some braneworld scenarios for example put the boundary as low as $1 \text{ TeV}/c^2$.^[141] This would make it conceivable for micro black holes to be created in the high-energy collisions that occur when cosmic rays hit the Earth's atmosphere, or possibly in the Large Hadron Collider at CERN. These theories are very speculative, and the creation of black holes in these processes is deemed unlikely by many specialists.^[142] Even if micro black holes could be formed, it is expected that they would evaporate in about 10^{-25} seconds, posing no threat to the Earth.^[143]

Growth



Simulation of two black holes colliding

Once a black hole has formed, it can continue to grow by absorbing additional matter. Any black hole will continually absorb gas and interstellar dust from its surroundings. This growth process is one possible way through which some supermassive black holes may have been formed, although the formation of supermassive black holes is still an open field of research.^[134] A similar process has been suggested for the formation of intermediate-mass black holes found in globular clusters.^[144] Black holes can also merge with other objects such as stars or even other black holes. This is thought to have been important, especially in the early growth of supermassive black holes, which could have formed from the aggregation of many smaller objects.^[134] The process has also been proposed as the origin of some intermediate-mass black holes.^{[145][146]}

Evaporation

In 1974, Hawking predicted that black holes are not entirely black but emit small amounts of thermal radiation at a temperature $\hbar c^3 / (8\pi G M k_B)$; ^[58] this effect has become known as Hawking radiation. By applying quantum field theory to a static black hole background, he determined that a black hole should emit particles that display a perfect black body spectrum. Since Hawking's publication, many others have verified the result through various approaches. ^[147] If Hawking's theory of black hole radiation is correct, then black holes are expected to shrink and evaporate over time as they lose mass by the emission of photons and other particles. ^[58] The temperature of this thermal spectrum (Hawking temperature) is proportional to the surface gravity of the black hole, which, for a Schwarzschild black hole, is inversely proportional to the mass. Hence, large black holes emit less radiation than small black holes. ^[148]

A stellar black hole of $1 M_{\odot}$ has a Hawking temperature of 62 nanokelvins. ^[149] This is far less than the 2.7 K temperature of the cosmic microwave background radiation. Stellar-mass or larger black holes receive more mass from the cosmic microwave background than they emit through Hawking radiation and thus will grow instead of shrinking. ^[150] To have a Hawking temperature larger than 2.7 K

(and be able to evaporate), a black hole would need a mass less than the Moon. Such a black hole would have a diameter of less than a tenth of a millimetre.^[151]

If a black hole is very small, the radiation effects are expected to become very strong. A black hole with the mass of a car would have a diameter of about 10^{-24} m and take a nanosecond to evaporate, during which time it would briefly have a luminosity of more than 200 times that of the Sun. Lower-mass black holes are expected to evaporate even faster; for example, a black hole of mass $1 \text{ TeV}/c^2$ would take less than 10^{-88} seconds to evaporate completely. For such a small black hole, quantum gravity effects are expected to play an important role and could hypothetically make such a small black hole stable, although current developments in quantum gravity do not indicate this is the case.^{[152][153]}

The Hawking radiation for an astrophysical black hole is predicted to be very weak and would thus be exceedingly difficult to detect from Earth. A possible exception, however, is the burst of gamma rays emitted in the last stage of the evaporation of primordial black holes. Searches for such flashes have proven unsuccessful and provide stringent limits on the possibility of existence of low mass primordial black holes.^[154] NASA's Fermi Gamma-ray Space Telescope launched in 2008 will continue the search for these flashes.^[155]

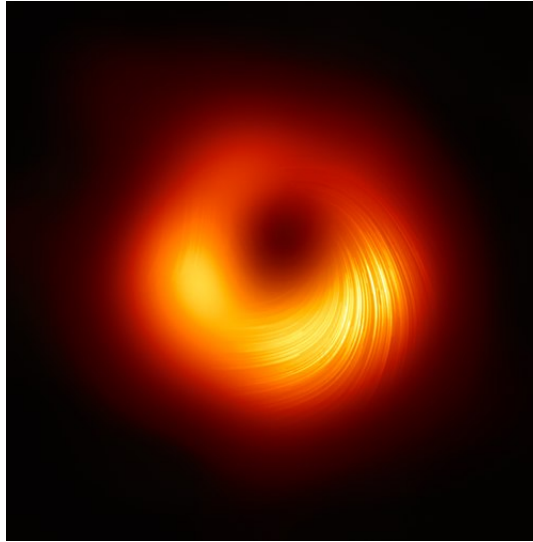
If black holes evaporate via Hawking radiation, a solar mass black hole will evaporate (beginning once the temperature of the cosmic

microwave background drops below that of the black hole) over a period of 10^{64} years.^[156] A supermassive black hole with a mass of $10^{11} M_{\odot}$ will evaporate in around 2×10^{100} years.^[157] During the collapse of a supercluster of galaxies, supermassive black holes are predicted to grow to perhaps $10^{14} M_{\odot}$. Even these would evaporate over a timescale of up to 10^{106} years.^[156]

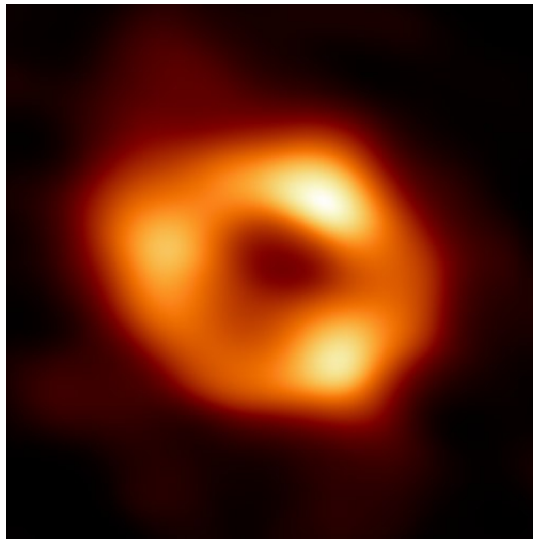
Observational evidence

By nature, black holes do not themselves emit any electromagnetic radiation other than the hypothetical Hawking radiation, so astrophysicists searching for black holes must generally rely on indirect observations. For example, a black hole's existence can sometimes be inferred by observing its gravitational influence on its surroundings.^[158]

Direct interferometry



A view of supermassive black hole M87* in polarised light



Sagittarius A*, the supermassive black hole in the center of the Milky Way

The Event Horizon Telescope (EHT) is an active program that directly observes the immediate environment of black holes' event horizons, such as the black hole at the centre of the Milky Way. In April 2017,

EHT began observing the black hole at the centre of Messier 87.^[159]
^[160] "In all, eight radio observatories on six mountains and four continents observed the galaxy in Virgo on and off for 10 days in April 2017" to provide the data yielding the image in April 2019.^[161]

After two years of data processing, EHT released its first image of a black hole, at the center of the Messier 87 galaxy.^{[162][163]} What is visible is not the black hole—which shows as black because of the loss of all light within this dark region. Instead, it is the gases at the edge of the event horizon, displayed as orange or red, that define the black hole.^[164]

On 12 May 2022, the EHT released the first image of Sagittarius A*, the supermassive black hole at the centre of the Milky Way galaxy. The published image displayed the same ring-like structure and "shadow" seen in the M87* black hole. The boundary of the shadow or area of less brightness matches the predicted gravitationally lensed photon orbits.^[165] The image was created using the same techniques as for the M87 black hole. The imaging process for Sagittarius A*, which is more than a thousand times smaller and less massive than M87*, was significantly more complex because of the instability of its surroundings.^[166] The image of Sagittarius A* was partially blurred by turbulent plasma on the way to the galactic centre, an effect which prevents resolution of the image at longer wavelengths.^[167]

The brightening of this material in the 'bottom' half of the processed EHT image is thought to be caused by Doppler beaming, whereby

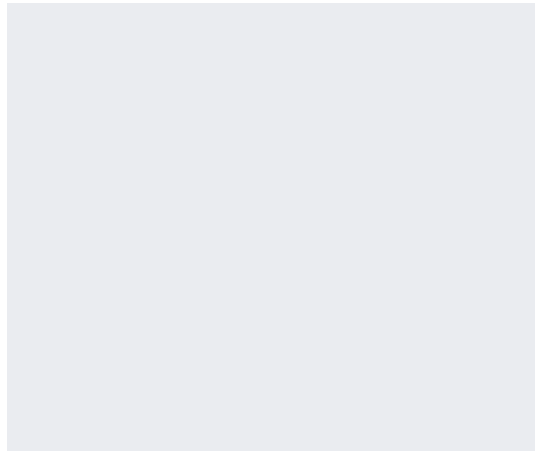
material approaching the viewer at relativistic speeds is perceived as brighter than material moving away. In the case of a black hole, this phenomenon implies that the visible material is rotating at relativistic speeds ($>1,000$ km/s [$2,200,000$ mph]), the only speeds at which it is possible to centrifugally balance the immense gravitational attraction of the singularity, and thereby remain in orbit above the event horizon. This configuration of bright material implies that the EHT observed M87* from a perspective catching the black hole's accretion disc nearly edge-on, as the whole system rotated clockwise.^{[168][164]}

The extreme gravitational lensing associated with black holes produces the illusion of a perspective that sees the accretion disc from above. In reality, most of the ring in the EHT image was created when the light emitted by the far side of the accretion disc bent around the black hole's gravity well and escaped, meaning that most of the possible perspectives on M87* can see the entire disc, even that directly behind the "shadow".

In 2015, the EHT detected magnetic fields just outside the event horizon of Sagittarius A* and even discerned some of their properties. The field lines that pass through the accretion disc were a complex mixture of ordered and tangled. Theoretical studies of black holes had predicted the existence of magnetic fields.^{[169][170]}

In April 2023, an image of the shadow of the Messier 87 black hole and the related high-energy jet, viewed together for the first time, was presented.^{[171][172]}

Detection of gravitational waves from merging black holes



LIGO measurement of the gravitational waves at the Livingston (right) and Hanford (left) detectors, compared with the theoretical predicted values

On 14 September 2015, the LIGO gravitational wave observatory made the first-ever successful direct observation of gravitational waves.^{[59][173]} The signal was consistent with theoretical predictions for the gravitational waves produced by the merger of two black

holes: one with about 36 solar masses, and the other around 29 solar masses.^{[59][174]} This observation provides the most concrete evidence for the existence of black holes to date. For instance, the gravitational wave signal suggests that the separation of the two objects before the merger was just 350 km, or roughly four times the Schwarzschild radius corresponding to the inferred masses. The objects must therefore have been extremely compact, leaving black holes as the most plausible interpretation.^[59]

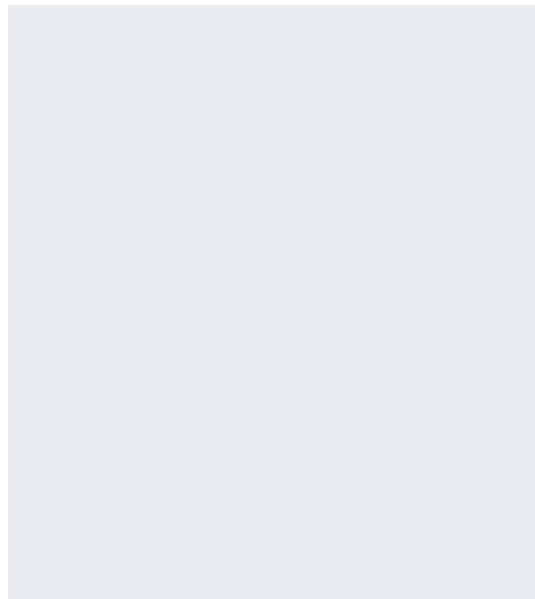
More importantly, the signal observed by LIGO also included the start of the post-merger ringdown, the signal produced as the newly formed compact object settles down to a stationary state. Arguably, the ringdown is the most direct way of observing a black hole.^[175] From the LIGO signal, it is possible to extract the frequency and damping time of the dominant mode of the ringdown. From these, it is possible to infer the mass and angular momentum of the final object, which match independent predictions from numerical simulations of the merger.^[176] The frequency and decay time of the dominant mode are determined by the geometry of the photon sphere. Hence, observation of this mode confirms the presence of a photon sphere; however, it cannot exclude possible exotic alternatives to black holes that are compact enough to have a photon sphere.^{[175][177]}

The observation also provides the first observational evidence for the existence of stellar-mass black hole binaries. Furthermore, it is the first observational evidence of stellar-mass black holes weighing 25

solar masses or more.^[178]

Since then, many more gravitational wave events have been observed.^[179]

Stars orbiting Sagittarius A*



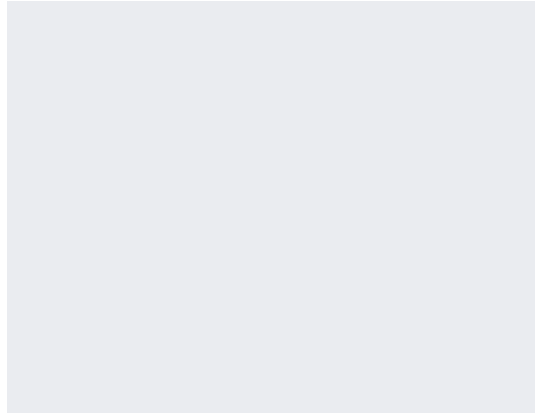
Stars moving around Sagittarius A* as seen in 2021

The proper motions of stars near the centre of our own Milky Way provide strong observational evidence that these stars are orbiting a supermassive black hole.^[180] Since 1995, astronomers have tracked

the motions of 90 stars orbiting an invisible object coincident with the radio source Sagittarius A*. By fitting their motions to Keplerian orbits, the astronomers were able to infer, in 1998, that a $2.6 \times 10^6 M_{\odot}$ object must be contained in a volume with a radius of 0.02 light-years to cause the motions of those stars.^[181]

Since then, one of the stars—called S2—has completed a full orbit. From the orbital data, astronomers were able to refine the calculations of the mass to $4.3 \times 10^6 M_{\odot}$ and a radius of less than 0.002 light-years for the object causing the orbital motion of those stars.^[180] The upper limit on the object's size is still too large to test whether it is smaller than its Schwarzschild radius. Nevertheless, these observations strongly suggest that the central object is a supermassive black hole as there are no other plausible scenarios for confining so much invisible mass into such a small volume.^[181] Additionally, there is some observational evidence that this object might possess an event horizon, a feature unique to black holes.^[182]

Accretion of matter



Blurring of X-rays near black hole
(NuSTAR; 12 August 2014)^[183]

Due to conservation of angular momentum,^[184] gas falling into the gravitational well created by a massive object will typically form a disk-like structure around the object. Artists' impressions such as the accompanying representation of a black hole with corona commonly depict the black hole as if it were a flat-space body hiding the part of the disk just behind it, but in reality gravitational lensing would greatly distort the image of the accretion disk.^[185]

Within such a disk, friction would cause angular momentum to be transported outward, allowing matter to fall farther inward, thus releasing potential energy and increasing the temperature of the gas.^[186]

When the accreting object is a neutron star or a black hole, the gas in the inner accretion disk orbits at very high speeds because of its proximity to the compact object. The resulting friction is so significant that it heats the inner disk to temperatures at which it emits vast

amounts of electromagnetic radiation (mainly X-rays). These bright X-ray sources may be detected by telescopes. This process of accretion is one of the most efficient energy-producing processes known. Up to 40% of the rest mass of the accreted material can be emitted as radiation.^[186] In nuclear fusion only about 0.7% of the rest mass will be emitted as energy. In many cases, accretion disks are accompanied by relativistic jets that are emitted along the poles, which carry away much of the energy. The mechanism for the creation of these jets is currently not well understood, in part due to insufficient data.^[187]

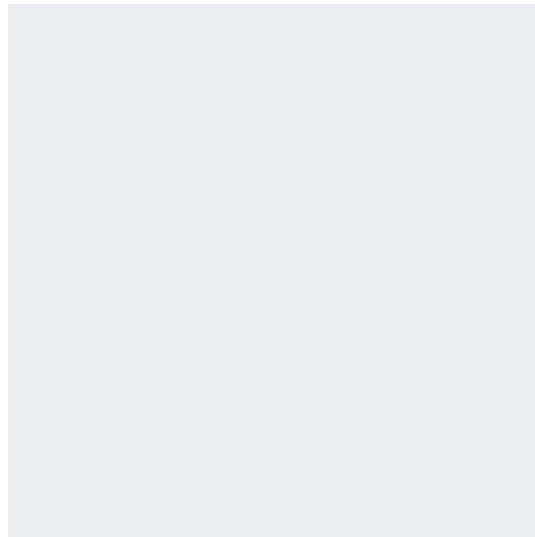
As such, many of the universe's more energetic phenomena have been attributed to the accretion of matter on black holes. In particular, active galactic nuclei and quasars are believed to be the accretion disks of supermassive black holes.^[188] Similarly, X-ray binaries are generally accepted to be binary star systems in which one of the two stars is a compact object accreting matter from its companion.^[188] It has also been suggested that some ultraluminous X-ray sources may be the accretion disks of intermediate-mass black holes.^[189]

Stars have been observed to get torn apart by tidal forces in the immediate vicinity of supermassive black holes in galaxy nuclei, in what is known as a tidal disruption event (TDE). Some of the material from the disrupted star forms an accretion disk around the black hole, which emits observable electromagnetic radiation.

In November 2011 the first direct observation of a quasar accretion

disk around a supermassive black hole was reported.^[190]^[191]

X-ray binaries



A Chandra X-Ray Observatory image of Cygnus X-1, which was the first strong black hole candidate discovered

X-ray binaries are binary star systems that emit a majority of their radiation in the X-ray part of the spectrum. These X-ray emissions are generally thought to result when one of the stars (compact object) accretes matter from another (regular) star. The presence of an ordinary star in such a system provides an opportunity for studying the central object and to determine if it might be a black hole.^[188]

If such a system emits signals that can be directly traced back to the

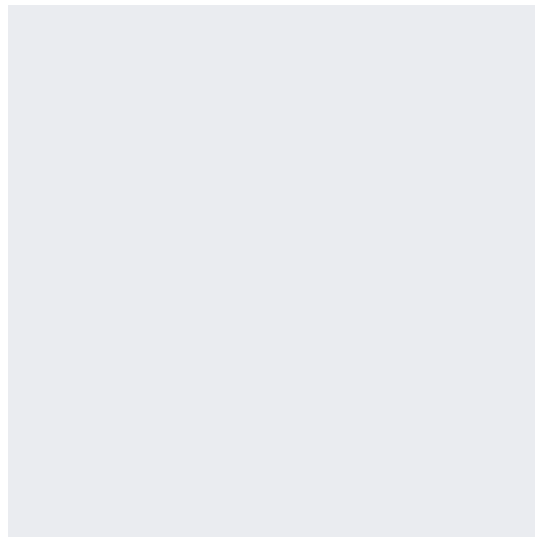
compact object, it cannot be a black hole. The absence of such a signal does, however, not exclude the possibility that the compact object is a neutron star. By studying the companion star it is often possible to obtain the orbital parameters of the system and to obtain an estimate for the mass of the compact object. If this is much larger than the Tolman–Oppenheimer–Volkoff limit (the maximum mass a star can have without collapsing) then the object cannot be a neutron star and is generally expected to be a black hole.^[188]

The first strong candidate for a black hole, Cygnus X-1, was discovered in this way by Charles Thomas Bolton,^[9] Louise Webster, and Paul Murdin^[8] in 1972.^{[192][56]} Some doubt remained, due to the uncertainties that result from the companion star being much heavier than the candidate black hole. Currently, better candidates for black holes are found in a class of X-ray binaries called soft X-ray transients. In this class of system, the companion star is of relatively low mass allowing for more accurate estimates of the black hole mass. These systems actively emit X-rays for only several months once every 10–50 years. During the period of low X-ray emission, called quiescence, the accretion disk is extremely faint, allowing detailed observation of the companion star during this period. One of the best such candidates is V404 Cygni.^[188]

Quasi-periodic oscillations

The X-ray emissions from accretion disks sometimes flicker at certain frequencies. These signals are called quasi-periodic oscillations and are thought to be caused by material moving along the inner edge of the accretion disk (the innermost stable circular orbit). As such their frequency is linked to the mass of the compact object. They can thus be used as an alternative way to determine the mass of candidate black holes.^[193]

Galactic nuclei



Detection of unusually bright X-ray flare from Sagittarius A*, a black hole in the centre of the Milky Way galaxy on 5 January 2015.^[194]

Astronomers use the term "active galaxy" to describe galaxies with

unusual characteristics, such as unusual spectral line emission and very strong radio emission. Theoretical and observational studies have shown that the activity in these active galactic nuclei (AGN) may be explained by the presence of supermassive black holes, which can be millions of times more massive than stellar ones. The models of these AGN consist of a central black hole that may be millions or billions of times more massive than the Sun; a disk of interstellar gas and dust called an accretion disk; and two jets perpendicular to the accretion disk.^{[195][196]}

Although supermassive black holes are expected to be found in most AGN, only some galaxies' nuclei have been more carefully studied in attempts to both identify and measure the actual masses of the central supermassive black hole candidates. Some of the most notable galaxies with supermassive black hole candidates include the Andromeda Galaxy, M32, M87, NGC 3115, NGC 3377, NGC 4258, NGC 4889, NGC 1277, OJ 287, APM 08279+5255 and the Sombrero Galaxy.^[197]

It is now widely accepted that the centre of nearly every galaxy, not just active ones, contains a supermassive black hole.^[198] The close observational correlation between the mass of this hole and the velocity dispersion of the host galaxy's bulge, known as the M–sigma relation, strongly suggests a connection between the formation of the black hole and that of the galaxy itself.^[199]

Microlensing

Another way the black hole nature of an object may be tested is through observation of effects caused by a strong gravitational field in their vicinity. One such effect is gravitational lensing: The deformation of spacetime around a massive object causes light rays to be deflected, such as light passing through an optic lens. Observations have been made of weak gravitational lensing, in which light rays are deflected by only a few arcseconds. Microlensing occurs when the sources are unresolved and the observer sees a small brightening. The turn of the millennium saw the first 3 candidate detections of black holes in this way,^{[200][201]} and in January 2022, astronomers reported the first confirmed detection of a microlensing event from an isolated black hole.^[202]

Another possibility for observing gravitational lensing by a black hole would be to observe stars orbiting the black hole. There are several candidates for such an observation in orbit around Sagittarius A*.^[203]

Alternatives

The evidence for stellar black holes strongly relies on the existence of

an upper limit for the mass of a neutron star. The size of this limit heavily depends on the assumptions made about the properties of dense matter. New exotic phases of matter could push up this bound.^[188] A phase of free quarks at high density might allow the existence of dense quark stars,^[204] and some supersymmetric models predict the existence of Q stars.^[205] Some extensions of the standard model posit the existence of preons as fundamental building blocks of quarks and leptons, which could hypothetically form preon stars.^[206] These hypothetical models could potentially explain a number of observations of stellar black hole candidates. However, it can be shown from arguments in general relativity that any such object will have a maximum mass.^[188]

Since the average density of a black hole inside its Schwarzschild radius is inversely proportional to the square of its mass, supermassive black holes are much less dense than stellar black holes. The average density of a $10^8 M_{\odot}$ black hole is comparable to that of water.^[188] Consequently, the physics of matter forming a supermassive black hole is much better understood and the possible alternative explanations for supermassive black hole observations are much more mundane. For example, a supermassive black hole could be modelled by a large cluster of very dark objects. However, such alternatives are typically not stable enough to explain the supermassive black hole candidates.^[188]

The evidence for the existence of stellar and supermassive black

holes implies that in order for black holes not to form, general relativity must fail as a theory of gravity, perhaps due to the onset of quantum mechanical corrections. A much anticipated feature of a theory of quantum gravity is that it will not feature singularities or event horizons and thus black holes would not be real artefacts.^[207] For example, in the fuzzball model^[208] based on string theory, the individual states of a black hole solution do not generally have an event horizon or singularity, but for a classical/semiclassical observer the statistical average of such states appears just as an ordinary black hole as deduced from general relativity.^[209]

A few theoretical objects have been conjectured to match observations of astronomical black hole candidates identically or near-identically,^[177] but which function via a different mechanism. These include the gravastar,^[210] the black star,^[211] related nestar^[212] and the dark-energy star.^[213]

Open questions

Entropy and thermodynamics

$$S = \frac{1}{4} \frac{c^3 k}{G \hbar}$$

The formula for the Bekenstein–Hawking entropy (S) of a black hole, which depends on the area of the black hole (A). The constants are the speed of light (c), the Boltzmann constant (k), Newton's constant (G), and the reduced Planck constant (\hbar). In Planck units, this reduces to $S = \frac{A}{4}$.

In 1971, Hawking showed under general conditions^[Note 5] that the total area of the event horizons of any collection of classical black holes can never decrease, even if they collide and merge.^[214] This result, now known as the second law of black hole mechanics, is remarkably similar to the second law of thermodynamics, which states that the total entropy of an isolated system can never decrease. As with classical objects at absolute zero temperature, it was assumed

that black holes had zero entropy. If this were the case, the second law of thermodynamics would be violated by entropy-laden matter entering a black hole, resulting in a decrease in the total entropy of the universe. Therefore, Bekenstein proposed that a black hole should have an entropy, and that it should be proportional to its horizon area. [215]

The link with the laws of thermodynamics was further strengthened by Hawking's discovery in 1974 that quantum field theory predicts that a black hole radiates blackbody radiation at a constant temperature. This seemingly causes a violation of the second law of black hole mechanics, since the radiation will carry away energy from the black hole causing it to shrink. The radiation also carries away entropy, and it can be proven under general assumptions that the sum of the entropy of the matter surrounding a black hole and one quarter of the area of the horizon as measured in Planck units is in fact always increasing. This allows the formulation of the first law of black hole mechanics as an analogue of the first law of thermodynamics, with the mass acting as energy, the surface gravity as temperature and the area as entropy. [215]

One puzzling feature is that the entropy of a black hole scales with its area rather than with its volume, since entropy is normally an extensive quantity that scales linearly with the volume of the system. This odd property led Gerard 't Hooft and Leonard Susskind to propose the holographic principle, which suggests that anything that

happens in a volume of spacetime can be described by data on the boundary of that volume.^[216]

Although general relativity can be used to perform a semiclassical calculation of black hole entropy, this situation is theoretically unsatisfying. In statistical mechanics, entropy is understood as counting the number of microscopic configurations of a system that have the same macroscopic qualities, such as mass, charge, pressure, etc. Without a satisfactory theory of quantum gravity, one cannot perform such a computation for black holes. Some progress has been made in various approaches to quantum gravity. In 1995, Andrew Strominger and Cumrun Vafa showed that counting the microstates of a specific supersymmetric black hole in string theory reproduced the Bekenstein–Hawking entropy.^[217] Since then, similar results have been reported for different black holes both in string theory and in other approaches to quantum gravity like loop quantum gravity.^[218]

Information loss paradox

Unsolved problem in

physics

? *Is physical information
lost in black holes?*

More unsolved problems in
physics

Because a black hole has only a few internal parameters, most of the information about the matter that went into forming the black hole is lost. Regardless of the type of matter which goes into a black hole, it appears that only information concerning the total mass, charge, and angular momentum are conserved. As long as black holes were thought to persist forever this information loss is not that problematic, as the information can be thought of as existing inside the black hole, inaccessible from the outside, but represented on the event horizon in accordance with the holographic principle. However, black holes slowly evaporate by emitting Hawking radiation. This radiation does not appear to carry any additional information about the matter that formed the black hole, meaning that this information appears to be gone forever.^[219]

The question whether information is truly lost in black holes (the black hole information paradox) has divided the theoretical physics community. In quantum mechanics, loss of information corresponds to the violation of a property called unitarity, and it has been argued that loss of unitarity would also imply violation of conservation of energy,^[220] though this has also been disputed.^[221] Over recent years evidence has been building that indeed information and unitarity are preserved in a full quantum gravitational treatment of the problem.^[222]

One attempt to resolve the black hole information paradox is known as black hole complementarity. In 2012, the "firewall paradox" was introduced with the goal of demonstrating that black hole complementarity fails to solve the information paradox. According to quantum field theory in curved spacetime, a single emission of Hawking radiation involves two mutually entangled particles. The outgoing particle escapes and is emitted as a quantum of Hawking radiation; the infalling particle is swallowed by the black hole. Assume a black hole formed a finite time in the past and will fully evaporate away in some finite time in the future. Then, it will emit only a finite amount of information encoded within its Hawking radiation. According to research by physicists like Don Page^{[223][224]} and Leonard Susskind, there will eventually be a time by which an outgoing particle must be entangled with all the Hawking radiation the black hole has previously emitted.

This seemingly creates a paradox: a principle called "monogamy of entanglement" requires that, like any quantum system, the outgoing particle cannot be fully entangled with two other systems at the same time; yet here the outgoing particle appears to be entangled both with the infalling particle and, independently, with past Hawking radiation.^[225] In order to resolve this contradiction, physicists may eventually be forced to give up one of three time-tested principles: Einstein's equivalence principle, unitarity, or local quantum field theory. One possible solution, which violates the equivalence principle, is that a "firewall" destroys incoming particles at the event horizon.^[226] In general, which—if any—of these assumptions should be abandoned remains a topic of debate.^[221]

In science fiction

Christopher Nolan's 2014 science fiction epic *Interstellar* features a black hole known as Gargantua, which is the central object of a planetary system in a distant galaxy. Humanity accessed this system via a wormhole in the outer solar system, near Saturn.

See also

***Astronomy
portal***

***History of
science
portal***

***Mathematics
portal***

***Physics
portal***

Stars portal

- Black brane or Black string
- Black Hole Initiative
- Black hole starship
- Black holes in fiction

- Blanet
- BTZ black hole
- Dark star (dark matter)
- Golden binary
- Hypothetical black hole (disambiguation)
- Kugelblitz (astrophysics)
- List of black holes
- List of nearest black holes
- Outline of black holes
- Planck star

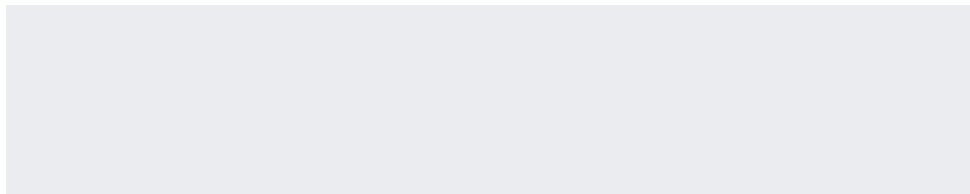
- Sonic black hole
- Susskind-Hawking battle
- Timeline of black hole physics
- Virtual black hole
- White hole

Notes

1. *The value of cJ/GM^2 can exceed 1 for objects other than black holes. The largest value known for a neutron*

star is ≤ 0.4 , and commonly used equations of state would limit that value to < 0.7 .^[82]

2. *The (outer) event horizon radius scales as:*



3. *The set of possible paths, or more accurately the future light cone containing all*

possible world lines (in this diagram the light cone is represented by the V-shaped region bounded by arrows representing light ray world lines), is tilted in this way in Eddington–Finkelstein coordinates (the diagram is a "cartoon" version of an Eddington–Finkelstein coordinate diagram), but in other coordinates the light

cones are not tilted in this way, for example in Schwarzschild coordinates they narrow without tilting as one approaches the event horizon, and in Kruskal–Szekeres coordinates the light cones do not change shape or orientation at all.^[85]

4. *This is true only for four-dimensional spacetimes. In higher dimensions more*

*complicated horizon
topologies like a black ring
are possible.*^{[97][98]}

5. *In particular, he assumed
that all matter satisfies the
weak energy condition.*

References

1. *The Event Horizon
Telescope Collaboration;
Akiyama, Kazunori; Alberdi,
Antonio; Alfaro, Walter; Anzole*

*Anixoni; Aiei, Walter; Asada,
Keiichi; Azulay, Rebecca;
Baczko, Anne-Kathrin; Ball,
David; Baloković, Mislav;
Barrett, John; Bintley, Dan;
Blackburn, Lindy; Boland,
Wilfred; Bouman, Katherine
L.; Bower, Geoffrey C. (10
April 2019). "First M87
Event Horizon Telescope
Results. IV. Imaging the
Central Supermassive Black
Hole" (<https://doi.org/10.38>*

47%2F2041-8213%2Fab0e85) . *The Astrophysical Journal Letters*. **875** (1): L4. *arXiv:1906.11241* (<https://arxiv.org/abs/1906.11241>)[ⓘ]. *Bibcode:2019ApJ...875L...4E* (<https://ui.adsabs.harvard.edu/abs/2019ApJ...875L...4E>) . *doi:10.3847/2041-8213/ab0e85* (<https://doi.org/10.3847%2F2041-8213%2Fab0e85>)[ⓘ]. ISSN 2041-

8205 (<https://search.worldcat.org/issn/2041-8205>) .

2. *"Astronomers capture first image of a black hole"* (<https://new.nsf.gov/news/astronomers-capture-first-image-black-hole#image-caption-credit-block>) . *new.nsf.gov*. 10 April 2019. Retrieved 28 January 2025.

3. *Riazuelo, Alain (2019). "Seeing relativity -- I. Ray*

*tracing in a Schwarzschild metric to explore the maximal analytic extension of the metric and making a proper rendering of the stars". International Journal of Modern Physics D. **28** (2): 1950042.*

arXiv:1511.06025 (<https://arxiv.org/abs/1511.06025>)^g.

Bibcode:2019IJMPD..2850042R (<https://ui.adsabs.harv>

*ard.edu/abs/2019IJMPD..28
50042R) .*

*doi:10.1142/S02182718195
00421 ([https://doi.org/10.11
42%2FS021827181950042
1](https://doi.org/10.1142%2FS0218271819500421)) . S2CID 54548877 ([http
s://api.semanticscholar.org/
CorpusID:54548877](http://api.semanticscholar.org/CorpusID:54548877)) .*

4. Overbye, Dennis (8 June 2015). "Black Hole Hunters" (<https://www.nytimes.com/2015/06/09/science/black-h>

.

ole-event-horizon-telescope.html) . NASA. Archived (<https://web.archive.org/web/20150609023631/http://www.nytimes.com/2015/06/09/science/black-hole-event-horizon-telescope.html>) from the original on 9 June 2015. Retrieved 8 June 2015.

5. *Hamilton, A. "Journey into a Schwarzschild black hole" (<http://jila.colorado.edu/~ajsh/insidebh/achv.html>)*

insidebh/schw.html) .
jila.colorado.edu. Archived (
<https://web.archive.org/web/20190903235853/https://jila.colorado.edu/~ajsh/insidebh/schw.html>) *from the*
original on 3 September
2019. Retrieved 28 June
2020.

6. Schutz, Bernard F. (2003).
Gravity from the ground up (
<https://books.google.com/books?id=DT0xyhDrcsIC>

ons: id=P_T0xxhDcs/C) .

Cambridge University Press.

p. 110. ISBN 978-0-521-

45506-0. Archived ([https://](https://web.archive.org/web/20161202222711/https://books.google.com/books?id=P_T0xxhDcs/C)

[web.archive.org/web/20161](https://web.archive.org/web/20161202222711/https://books.google.com/books?id=P_T0xxhDcs/C)

[202222711/https://books.go](https://web.archive.org/web/20161202222711/https://books.google.com/books?id=P_T0xxhDcs/C)

[ogle.com/books?id=P_T0xxh](https://web.archive.org/web/20161202222711/https://books.google.com/books?id=P_T0xxhDcs/C)

Dcs/C) from the original on

2 December 2016.

7. *Davies, P. C. W. (1978).*

"Thermodynamics of Black

Holes" ([https://web.archive.](https://web.archive.org/web/20130510184530/)

[ora/web/20130510184530/](https://web.archive.org/web/20130510184530/)

...g, ... , ... , ... , ... , ... ,
<http://cosmos.asu.edu/publications/papers/ThermodynamicTheoryofBlackHoles%2034.pdf>) (PDF). *Reports on Progress in Physics*. **41** (8): 1313–1355.

Bibcode:1978RPPh...41.1313 D (<https://ui.adsabs.harvard.edu/abs/1978RPPh...41.1313D>) . doi:10.1088/0034-4885/41/8/004 (<https://doi.org/10.1088%2F0034-488>

5%2F41%2F8%2F004) .

S2CID 250916407 (<https://api.semanticscholar.org/CorpusID:250916407>) .

Archived from the original (<http://cosmos.asu.edu/publications/papers/ThermodynamicTheoryofBlackHoles%2034.pdf>) (PDF) on 10 May 2013.

8. *Webster, B. Louise; Murdin, Paul (1972), "Cygnus X-1—a*

*Spectroscopic Binary with a Heavy Companion?", Nature, **235** (5332): 37–38, Bibcode:1972Natur.235...37W (<https://ui.adsabs.harvard.edu/abs/1972Natur.235...37W>) , doi:10.1038/235037a0 (<https://doi.org/10.1038%2F235037a0>) , S2CID 4195462 (<https://api.semanticscholar.org/CorpusID:4195462>)*

9. *Bolton, C. T. (1972),
"Identification of Cygnus X-1
with HDE 226868", Nature,
235 (5336): 271–273,
Bibcode:1972Natur.235..27
1B ([https://ui.adsabs.harvar
d.edu/abs/1972Natur.235..2
71B](https://ui.adsabs.harvard.edu/abs/1972Natur.235..271B)) ,
doi:10.1038/235271b0 ([http
s://doi.org/10.1038%2F235
271b0](http://doi.org/10.1038%2F235271b0)) , S2CID 4222070 ([h
ttps://api.semanticscholar.or
g/CorpusID:4222070](https://api.semanticscholar.org/CorpusID:4222070))*

g/corpusID.4222070)

10. Clery D (2020). "Black holes caught in the act of swallowing stars". *Science*. **367** (6477): 495.

Bibcode:2020Sci...367..495

C (<https://ui.adsabs.harvard.edu/abs/2020Sci...367..495C>) .

doi:10.1126/science.367.647

7.495 (<https://doi.org/10.1126/science.367.6477.495>)

PMID 32001633 (<https://pubmed.ncbi.nlm.nih.gov/32001633/>)

51 *PMID 32001633* (<https://pubmed.ncbi.nlm.nih.gov/32001633/>)

5, 11112-12001000 (<https://pubmed.ncbi.nlm.nih.gov/32001633>) .

S2CID 210984462 (<https://api.semanticscholar.org/CorpusID:210984462>) .

11. *Montgomery, Colin; Orchiston, Wayne; Whittingham, Ian (2009). "Michell, Laplace and the origin of the black hole concept" ([\[https://en.m.wikipedia.org/wiki/Black_hole\]\(https://en.m.wikipedia.org/wiki/Black_hole\)](https://researchonline.icu.edu.au/9892/1/Micr</i></div><div data-bbox=)*

Microsoft Word - Paper__Black
_Hole_Concept_Final_.pdf)

(PDF). *Journal of*

Astronomical History and

Heritage. **12** (2): 90–96.

Bibcode:2009JAHH...12...9

0M ([https://ui.adsabs.harvard.edu/abs/2009JAHH...12...](https://ui.adsabs.harvard.edu/abs/2009JAHH...12...90M)

[d.edu/abs/2009JAHH...12...](https://ui.adsabs.harvard.edu/abs/2009JAHH...12...90M)

[90M](https://ui.adsabs.harvard.edu/abs/2009JAHH...12...90M)) .

doi:10.3724/SP.J.1440-

2807.2009.02.01 ([https://do](https://doi.org/10.3724%2FSP.J.1440-2807.2009.02.01)

[i.org/10.3724%2FSP.J.1440](https://doi.org/10.3724%2FSP.J.1440-2807.2009.02.01)

-2807.2009.02.01) .

S2CID 55890996 (<https://api.semanticscholar.org/CorpusID:55890996>) .

12. *Michell, J. (1784). "On the Means of Discovering the Distance, Magnitude, &c. of the Fixed Stars, in Consequence of the Diminution of the Velocity of Their Light, in Case Such a Diminution Should be Found*

*to Take Place in any of
Them, and Such Other Data
Should be Procured from
Observations, as Would be
Farther Necessary for That
Purpose" (<https://doi.org/10.1098%2Frstl.1784.0008>) .
*Philosophical Transactions
of the Royal Society. 74: 35–
57.**

*Bibcode:1784RSPT...74...35
M (<https://ui.adsabs.harvard.>
<https://ui.adsabs.harvard.org/abs/1784RSPT...74...35M>*

*edu/abs/1784RSP1.../4...35
M)* .

doi:10.1098/rstl.1784.0008 (
https://doi.org/10.1098%2Fr
*stl.1784.0008)*³.

JSTOR 106576 (https://ww
w.jstor.org/stable/106576) .

13. *Thorne 1994, pp. 123–124*

14. *Slayter, Elizabeth M.; Slayter,*
Henry S. (1992). Light and
Electron Microscopy (http
s://books.google.com/book
s?id=...

s?id=LlePVS9oq/MC) .

Cambridge University Press.

ISBN 978-0-521-33948-3.

Archived ([https://web.archive.org/web/2017113015104](https://web.archive.org/web/20171130151044/https://books.google.com/books?id=LlePVS9oq7MC)

e.org/web/2017113015104

4/[https://books.google.com/](https://books.google.com/books?id=LlePVS9oq7MC)

books?id=LlePVS9oq7MC)

from the original on 30

November 2017.

15. *Levy, Adam (11 January 2021). "How black holes morphed from theory to*

reality" (<https://www.bbc.com/news/science-environment-56812345>

really (<https://knowablemagazine.org/article/physical-world/2021/how-black-holes-morphed-theory-reality>)⁶.

Knowable Magazine.

doi:10.1146/knowable-010921-1 (<https://doi.org/10.1146%2Fknowable-010921-1>)⁶. Retrieved 25 March 2022.

16. Schwarzschild, K. (1916).
"Über das Gravitationsfeld
eines Massenpunktes nach

eines massenpunktes nach
der Einsteinschen Theorie" (
<https://archive.org/stream/sitzungsberichte1916deutsch#page/188/mode/2up>) .
Sitzungsberichte der
Königlich Preussischen
Akademie der
Wissenschaften. **7**: 189–
196.

Bibcode:1916SPAW.....189
S (<https://ui.adsabs.harvard.edu/abs/1916SPAW.....189>

S) .

- *Translation: Antoci, S.; Loinger, A. (1999). "On the gravitational field of a mass point according to Einstein's theory". arXiv:physics/9905030 (https://arxiv.org/abs/physics/9905030)[Ⓜ]. and Schwarzschild, K.*

*(1916). "Über das
Gravitationsfeld einer
Kugel aus
inkompressibler
Flüssigkeit nach der
Einsteinschen
Theorie" (<https://archive.org/stream/sitzungsberichte1916deutsch#page/424/mode/2up>) .*

Sitzungsberichte der

*Königlich
Preussischen
Akademie der
Wissenschaften. 18:
424–434.*

*Bibcode:1916skpa.co
nf..424S ([https://ui.ad
sabs.harvard.edu/ab
s/1916skpa.conf..424
S](https://ui.adsabs.harvard.edu/abs/1916skpa.conf..424S)) .*

- *Translation: Antoci, S.
(1999). "On the
gravitational field of a*

*gravitational field of a
sphere of
incompressible fluid
according to
Einstein's theory".*

arXiv:physics/99120

*33 ([https://arxiv.org/a](https://arxiv.org/abs/physics/9912033)
[bs/physics/991203](https://arxiv.org/abs/physics/9912033)*

3)³.

17. *Droste, J. (1917). "On the
field of a single centre in
Einstein's theory of*

.. .. ,

*gravitation, and the motion of a particle in that field" (<https://web.archive.org/web/20130518034708/http://www.dwc.knaw.nl/DL/publications/PU00012325.pdf>) (PDF). Proceedings Royal Academy Amsterdam. **19** (1): 197–215. Archived from the original (<http://www.dwc.knaw.nl/DL/publications/PU00012325.pdf>) (PDF) on 18 May 2013. Retrieved*

16 September 2012.

18. Kox, A. J. (1992). "General Relativity in the Netherlands: 1915–1920" (https://books.google.com/books?id=vDHCF_3vIhUC&pg=PA41) . In Eisenstaedt, Jean; Kox, A. J. (eds.). *Studies in the history of general relativity*. Birkhäuser. p. 41. ISBN 978-0-8176-3479-7. Archived (<https://web.archive.org/web/2>

0160810215219/https://books.google.com/books?id=vDHCF_3vIhUC&pg=PA41)
from the original on 10
August 2016. Retrieved
23 February 2016.

19. 't Hooft, G. (2009).
"Introduction to the Theory
of Black Holes" (<https://web.archive.org/web/20090521082736/http://www.phys.uu.nl/~thooft/lectures/blackh>

oles/BH_lecturenotes.pdf)
(PDF). Institute for
Theoretical Physics /
Spinoza Institute. pp. 47–48.
Archived from the original (h
ttp://www.phys.uu.nl/~thoof
t/lectures/blackholes/BH_lec
turenotes.pdf) (PDF) on 21
May 2009. Retrieved
24 June 2010.

20. *Eddington, Arthur (1926).*
The Internal Constitution of

the Stars (<https://books.google.com/books?id=RjC9DpnWFbkC&pg=PA6>) . *Science*. Vol. 52. Cambridge University Press. pp. 233–40.

Bibcode:1920Sci....52..233E (<https://ui.adsabs.harvard.edu/abs/1920Sci....52..233E>) . *doi:10.1126/science.52.1341.233* (<https://doi.org/10.1126/science.52.1341.233>) .

*ISBN 978-0-521-33708-3.
PMID 17747682 (<https://pubmed.ncbi.nlm.nih.gov/17747682>) . Archived (<https://web.archive.org/web/20160811034409/https://books.google.com/books?id=RjC9DpnWFbkC&lpg=PP1&pg=PA6>)
from the original on 11 August 2016.*

21. *Thorne, Kip S.; Hawking, Stephen (1994). Agrawal, Milan (ed.). Black Holes and*

Millan (ed.). Black Holes and Time Warps: Einstein's Outrageous Legacy (<https://archive.org/details/blackholestimewa0000thor>) (1st ed.). W. W. Norton & Company. pp. 134 (<https://archive.org/details/blackholestimewa0000thor/page/134>) –135. ISBN 978-0-393-31276-8. Retrieved 12 April 2019.

"The first conclusion was the Newtonian version of light

... not escaping; the second was a semi-accurate, relativistic description; and the third was typical Eddingtonian hyperbole ... when a star is as small as the critical circumference, the curvature is strong but not infinite, and space is definitely not wrapped around the star. Eddington may have known this, but his

description made a good story, and it captured in a whimsical way the spirit of Schwarzschild's spacetime curvature."

22. Venkataraman, G. (1992). *Chandrasekhar and his limit* (<https://books.google.com/books?id=HNSdDFOJ4wkC&pg=PA89>) . Universities Press. p. 89. ISBN 978-81-7371-035-3. Archived (<http>

s://web.archive.org/web/20160811035848/https://books.google.com/books?id=HNSdDFOJ4wkC&pg=PA89) from the original on 11 August 2016.

23. *Detweiler, S. (1981).*

*"Resource letter BH-1: Black holes". American Journal of Physics. **49** (5): 394–400. Bibcode:1981AmJPh..49..394D (<https://ui.adsabs.harvar>*

d.edu/abs/1981AmJPh..49..
394D) . doi:10.1119/1.12686
([https://doi.org/10.1119%2F
1.12686](https://doi.org/10.1119%2F1.12686)) .

24. Harpaz, A. (1994). *Stellar evolution* (<https://books.google.com/books?id=kd4VEZv8oo0C&pg=PA105>) . A K Peters. p. 105. ISBN 978-1-56881-012-6. Archived ([https://web.archive.org/web/20160811025449/https://bo](https://web.archive.org/web/20160811025449/https://books.google.com/books?id=kd4VEZv8oo0C&pg=PA105)

oks.google.com/books?id=k
d4VEZv8oo0C&pg=PA105)
from the original on 11
August 2016.

25. Oppenheimer, J. R.; Volkoff,
G. M. (1939). "On Massive
Neutron Cores". *Physical
Review*. **55** (4): 374–381.
Bibcode:1939PhRv...55..374
O ([https://ui.adsabs.harvard.
edu/abs/1939PhRv...55..374
O](https://ui.adsabs.harvard.edu/abs/1939PhRv...55..374O)) .
doi:10.1103/PhysRev.55.374

doi:10.1103/PhysRev.55.374
(<https://doi.org/10.1103%2FPhysRev.55.374>) .

26. Bombaci, I. (1996). "The Maximum Mass of a Neutron Star". *Astronomy and Astrophysics*. **305**: 871–877. Bibcode:1996A&A...305..871B (<https://ui.adsabs.harvard.edu/abs/1996A&A...305..871B>) .

27. Cho, A. (16 February 2018).
"A"

*"A weight limit emerges for neutron stars". Science. **359** (6377): 724–725.*

Bibcode:2018Sci...359..724 C (<https://ui.adsabs.harvard.edu/abs/2018Sci...359..724C>) .

doi:10.1126/science.359.6377.724 (<https://doi.org/10.1126/science.359.6377.724>) . PMID 29449468 (<https://pubmed.ncbi.nlm.nih.gov/29449468/>) .

., —

28. *Margalit, B.; Metzger, B. D.*
(1 December 2017).

*"Constraining the Maximum
Mass of Neutron Stars from
Multi-messenger
Observations of GW170817"*
([https://doi.org/10.3847/2F](https://doi.org/10.3847/2F2041-8213/2Faa991c)
2041-8213/2Faa991c) .
The Astrophysical Journal.
850 (2): L19.
arXiv:1710.05938 ([https://ar](https://arxiv.org/abs/1710.05938)
[xiv.org/abs/1710.05938](https://arxiv.org/abs/1710.05938))⁶.

*Bibcode:2017ApJ...850L..19
M (https://ui.adsabs.harvard.
edu/abs/2017ApJ...850L..19
M) . doi:10.3847/2041-
8213/aa991c (https://doi.or
g/10.3847%2F2041-8213%
2Faa991c)*⁶.

*S2CID 119342447 (https://a
pi.semanticscholar.org/Corp
usID:119342447) .*

29. *Shibata, M.; Fujibayashi, S.;
Hotokezaka, K.; Kiuchi, K.;*

*Kyutoku, K.; Sekiguchi, Y.;
Tanaka, M. (22 December
2017). "Modeling
GW170817 based on
numerical relativity and its
implications". Physical
Review D. **96** (12): 123012.
arXiv:1710.07579 (<https://arxiv.org/abs/1710.07579>)[ⓘ].
Bibcode:2017PhRvD..96l30
12S (<https://ui.adsabs.harvard.edu/abs/2017PhRvD..96l3012S>*

012S) .

doi:10.1103/PhysRevD.96.12

3012 ([https://doi.org/10.110](https://doi.org/10.1103/PhysRevD.96.123012)

3%2FPhysRevD.96.123012)

. S2CID 119206732 ([https://](https://api.semanticscholar.org/CorpusID:119206732)

api.semanticscholar.org/Cor

pusID:119206732) .

30. *Ruiz, M.; Shapiro, S. L.;*

Tsokaros, A. (11 January

2018). "GW170817, general

relativistic

magnetohydrodynamic

*simulations, and the neutron star maximum mass" (<https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6036631>) .
Physical Review D. **97** (2):
021501. *arXiv:1711.00473* (<https://arxiv.org/abs/1711.00473>)³.*

Bibcode:2018PhRvD..97b1501R (<https://ui.adsabs.harvard.edu/abs/2018PhRvD..97b1501R>) .

doi:10.1103/PhysRevD.97.02

doi:10.1103/PhysRevD.97.021501 (https://doi.org/10.1103/PhysRevD.97.021501) . PMC 6036631 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6036631)⁶. PMID 30003183 (https://pubmed.ncbi.nlm.nih.gov/30003183) .

31. *Rezzolla, L.; Most, E. R.; Weih, L. R. (9 January 2018). "Using Gravitational-wave Observations and*

.....
*Quasi-universal Relations to
Constrain the Maximum
Mass of Neutron Stars"* (<https://doi.org/10.3847%2F2041-8213%2Faaa401>) .

Astrophysical Journal. **852**
(2): L25. *arXiv:1711.00314* (<https://arxiv.org/abs/1711.00314>)⁶.

Bibcode:2018ApJ...852L..25R (<https://ui.adsabs.harvard.edu/abs/2018ApJ...852L..>

25R) . doi:10.3847/2041-8213/aaa401 (<https://doi.org/10.3847%2F2041-8213%2Faaa401>)³.

S2CID 119359694 (<https://api.semanticscholar.org/CorpusID:119359694>) .

32. *Ruffini, R.; Wheeler, J. A. (1971). "Introducing the black hole" (<https://web.archive.org/web/20110725133758/http://authors.library.calt>*

ech.edu/14972/1/Ruffini2009p1645Phys_Today.pdf)
(PDF). *Physics Today*. **24**
(1): 30–41.

Bibcode:1971PhT....24a..30
R (<https://ui.adsabs.harvard.edu/abs/1971PhT....24a..30R>) . doi:10.1063/1.3022513
(<https://doi.org/10.1063%2F1.3022513>) . Archived from
the original (http://authors.library.caltech.edu/14972/1/Ruffini2009p1645Phys_Today.pdf)
on 2009-10-15. Retrieved 2016-05-11.

*uttini2009p1645Phys_Ioda
y.pdf) (PDF) on 25 July
2011. Retrieved 5 December
2009.*

33. *Bernstein, Jeremy (2007).
"The Reluctant Father of
Black Holes" ([https://www.scientificamerican.com/article/
the-reluctant-father-of-blac
k-holes-2007-04/](https://www.scientificamerican.com/article/the-reluctant-father-of-black-holes-2007-04/))⁸.
Scientific American. **17**: 4–
11.
[doi:10.1038/scientificameric](https://doi.org/10.1038/scientificameric)*

doi:10.1038/scientificamerican0407-4sp (https://doi.org/10.1038/scientificamerican0407-4sp) . Retrieved 3 August 2023.

34. Oppenheimer, J.R.; Snyder, H. (1939). "On Continued Gravitational Contraction" (<https://doi.org/10.1103/PhysRev.56.455>) . *Physical Review*. **56** (5): 455–459. *Bibcode:1939PhRv...56..455O (https://ui.adsabs.harvar*

CC (<https://ui.adsabs.harvard.edu/abs/1939PhRv...56..455O>) .

doi:10.1103/PhysRev.56.455
(<https://doi.org/10.1103%2FPhysRev.56.455>)⁶.

35. *Finkelstein, D. (1958). "Past-Future Asymmetry of the Gravitational Field of a Point Particle". Physical Review. **110** (4): 965–967. Bibcode:1958PhRv..110..965F (<https://ui.adsabs.harvard.edu/abs/1958PhRv..110..965F>)*

d.edu/abs/1958PhRv..110..965F) .

doi:10.1103/PhysRev.110.965 (https://doi.org/10.1103%2FPhysRev.110.965) .

36. *Bartusiak, Marcia (2015). Black Hole: How an Idea Abandoned by Newtonians, Hated by Einstein, and Gambled On by Hawking Became Loved. New Haven, CT: Yale University Press.*

ISBN 978-0-300-21363-8.

37. *Kruskal, M. (1960). "Maximal Extension of Schwarzschild Metric". Physical Review. **119** (5): 1743.*

Bibcode:1960PhRv..119.1743K (<https://ui.adsabs.harvard.edu/abs/1960PhRv..119.1743K>) .

doi:10.1103/PhysRev.119.1743 (<https://doi.org/10.1103%2FPhysRev.119.1743>) .

38. *Luminet, J.-P. (May 1979).
"Image of a spherical black
hole with thin accretion disk"
(<https://ui.adsabs.harvard.edu/abs/1979A&A....75..228L/abstract>) . Astronomy and
Astrophysics. **75**: 228–235.
Bibcode:1979A&A....75..228
L (<https://ui.adsabs.harvard.edu/abs/1979A&A....75..228L>) . ISSN 0004-6361 (<https://search.worldcat.org/issn/>*

0004-6361) .

39. *French National Centre for Scientific Research (10 April 2019). "First ever image of a black hole: a CNRS researcher had simulated it as early as 1979" (<https://www.cnrs.fr/en/press/first-ever-image-black-hole-cnrs-researcher-had-simulated-it-early-1979>) . CNRS. Retrieved 18 June 2025.*

40. *Thorne, Kip (2003).*
"Warping spacetime". The
future of theoretical physics
and cosmology: celebrating
Stephen Hawking's 60th
birthday (<https://books.google.com/books?id=yLy4b61rfPwC>) . Cambridge
University Press. p. 74.
ISBN 0-521-82081-2.
Extract of page 74 ([https://b](https://books.google.com/books?id=)
ooks.google.com/books?id=

yLy4b61rfPwC&pg=PA74)

41. *Thorne, Kip (1995). Black Holes and Time Warps: Einstein's Outrageous Legacy (Commonwealth Fund Book Program). Commonwealth Fund Book Program Series (1 ed.). Erscheinungsort nicht ermittelbar: W. W. Norton & Company, Incorporated. ISBN 978-0-393-31276-8.*

42. *Newman, E. T.; et al. (1965). "Metric of a Rotating, Charged Mass". Journal of Mathematical Physics. 6 (6): 918.*

Bibcode:1965JMP....6..918 N (https://ui.adsabs.harvard.edu/abs/1965JMP....6..918 N) . doi:10.1063/1.1704351 (https://doi.org/10.1063%2F1.1704351) .

43. *Israel, W. (1967). "Event*
... ..

*Horizons in Static Vacuum Space-Times". Physical Review. **164** (5): 1776.*

Bibcode:1967PhRv..164.1776l (<https://ui.adsabs.harvard.edu/abs/1967PhRv..164.1776l>) .

doi:10.1103/PhysRev.164.1776 (<https://doi.org/10.1103%2FPhysRev.164.1776>) .

44. Carter, B. (1971).

"Axisymmetric Black Hole Has Only Two Degrees of

*Has Only Two Degrees of Freedom". Physical Review Letters. **26** (6): 331.*

Bibcode:1971PhRvL..26..331C (<https://ui.adsabs.harvard.edu/abs/1971PhRvL..26..331C>) .

doi:10.1103/PhysRevLett.26.331 (<https://doi.org/10.1103/PhysRevLett.26.331>) .

45. Carter, B. (1977). "The vacuum black hole uniqueness theorem and its

*uniqueness theorem and its conceivable generalisations".
Proceedings of the 1st
Marcel Grossmann meeting
on general relativity.
pp. 243–254.*

46. *Robinson, D. (1975).
"Uniqueness of the Kerr
Black Hole". Physical Review
Letters. **34** (14): 905.
Bibcode:1975PhRvL..34..90
5R (<https://ui.adsabs.harvard.edu/abs/1975PhRvL..34..905R>)*

05R) .

doi:10.1103/PhysRevLett.34.
905 (<https://doi.org/10.1103/PhysRevLett.34.905>) .

47. Heusler, M. (2012).

*"Stationary Black Holes:
Uniqueness and Beyond"* ([https://www.ncbi.nlm.nih.gov/
pmc/articles/PMC525589](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5255892)

2) . *Living Reviews in
Relativity*. **15** (7): 7.

arXiv:1205.6112 (<https://arxiv.org/abs/1205.6112>)

v.org/abs/1205.6112)³.

Bibcode:2012LRR....15....7C

(<https://ui.adsabs.harvard.edu/abs/2012LRR....15....7C>) .

doi:10.12942/lrr-2012-7 (<https://doi.org/10.12942%2Flrr-2012-7>)³. PMC 5255892 (

[https://www.ncbi.nlm.nih.gov/pmc/articles/PMC525589](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5255892)

2)³. PMID 28179837 (<http>

[s://pubmed.ncbi.nlm.nih.gov/28179837](https://pubmed.ncbi.nlm.nih.gov/28179837)) .

48. *Penrose, R. (1965).*

*"Gravitational Collapse and Space-Time Singularities" (<https://web.archive.org/web/20201011221750/http://pdfs.semanticscholar.org/faad/1f4358fddf70df2e00c0a290b7e4501c27de.pdf>) (PDF). *Physical Review Letters*. **14** (3): 57.*

Bibcode:1965PhRvL..14...57 P (<https://ui.adsabs.harvard>.

*edu/abs/1965PhRvL..14...57
P) .*

*doi:10.1103/PhysRevLett.14.
57 ([https://doi.org/10.1103%
2FPhysRevLett.14.57](https://doi.org/10.1103%2FPhysRevLett.14.57)) .*

*S2CID 116755736 ([https://a
pi.semanticscholar.org/Corp
usID:116755736](https://api.semanticscholar.org/CorpusID:116755736)) . Archived
from the original ([http://pdfs.
semanticscholar.org/faad/1f
4358fddf70df2e00c0a290
b7e4501c27de.pdf](http://pdfs.semanticscholar.org/faad/1f4358fddf70df2e00c0a290b7e4501c27de.pdf)) (PDF)
on 11 October 2020*

on 11 October 2020.

49. Ford, L. H. (2003). "The Classical Singularity Theorems and Their Quantum Loopholes". *International Journal of Theoretical Physics*. **42** (6): 1219–1227. arXiv:gr-qc/0301045 (<https://arxiv.org/abs/gr-qc/0301045>)[ⓘ]. Bibcode:2003gr.qc....1045F (<https://ui.adsabs.harvard.edu/abs/2003gr.qc....1045F>)

[edu/abs/2009i.46.....1040](#)

F) .

doi:10.1023/A:10257545151

97 ([https://doi.org/10.102](https://doi.org/10.1023%2FA%3A1025754515197)

3%2FA%3A102575451519

7) . S2CID 14404560 ([http](http://api.semanticscholar.org/CorpusID:14404560)

s://api.semanticscholar.org/

CorpusID:14404560) .

50. *"The Nobel Prize in Physics 2020" (<https://www.nobelprize.org/prizes/physics/2020/summary/>) . NobelPrize.org. Archived (<https://web.archive.org/web/20201025111010/https://www.nobelprize.org/prizes/physics/2020/summary/>)*

... https://www.nobelprize.org/web/20210424115309/https://www.nobelprize.org/prizes/physics/2020/summary/) from the original on 24 April 2021. Retrieved 8 October 2020.

51. *Hewish, A.; et al. (1968). "Observation of a Rapidly Pulsating Radio Source". **Nature**. **217** (5130): 709–713. Bibcode:1968Natur.217..70*

9H (<https://ui.adsabs.harvard.edu/abs/1968Natur.217..709H>) .

doi:10.1038/217709a0 (<https://doi.org/10.1038%2F217709a0>) . S2CID 4277613 (<https://api.semanticscholar.org/CorpusID:4277613>) .

52. *Pilkington, J. D. H.; et al. (1968). "Observations of some further Pulsed Radio Sources". Nature. **218***

(5137): 126–129.

Bibcode:1968Natur.218..126

P (<https://ui.adsabs.harvard.edu/abs/1968Natur.218..126>

P) . doi:10.1038/218126a0 (<https://doi.org/10.1038%2F218126a0>) .

S2CID 4253103 (<https://api.semanticscholar.org/CorpusID:4253103>) .

53. *Hewish, A. (1970). "Pulsars".
Annual Review of Astronomy*

*and Astrophysics. 8 (1):
265–296.*

*Bibcode:1970ARA&A...8..26
5H ([https://ui.adsabs.harvard.edu/abs/1970ARA&A...8..
265H](https://ui.adsabs.harvard.edu/abs/1970ARA&A...8..265H)) .*

*doi:10.1146/annurev.aa.08.0
90170.001405 ([https://doi.o
rg/10.1146%2Fannurev.aa.0
8.090170.001405](https://doi.org/10.1146%2Fannurev.aa.08.090170.001405)) .*

54. *Boissoneault, Lorraine (28
February 2018). "Fifty Years*

*Ago, a Grad Student's
Discovery Changed the
Course of Astrophysics" (<https://www.smithsonianmag.com/science-nature/Fifty-years-ago-grad-students-discovery-changed-course-astrophysics-180968288/>) .
Smithsonian Magazine.
Retrieved 22 December
2023.*

55. *Rolston, Bruce (10*

November 1997), The First Black Hole (https://web.archive.org/web/20080307181205/http://www.news.utoronto.ca/bin/bulletin/nov10_97/art4.htm) , University of Toronto, archived from the original (http://news.utoronto.ca/bin/bulletin/nov10_97/art4.htm) on 7 March 2008, retrieved 11 March 2008

56. Shipman, H. L.; Yu, Z; Du, X. (2005) "The"

*Y.W (1975), "The implausible history of triple star models for Cygnus X-1 Evidence for a black hole", Astrophysical Letters, **16** (1): 9–12, Bibcode:1975ApL....16....9S (<https://ui.adsabs.harvard.edu/abs/1975ApL....16....9S>) , doi:10.1016/S0304-8853(99)00384-4 (<https://doi.org/10.1016%2FS0304-8853%2899%2900384-4>)*

57 *Bardner, J. M. ; Carter, D. .*

31. Bardeen, J. M., Carter, B.,
 Hawking, S. W. (1973). "The
 four laws of black hole
 mechanics" (<http://projecteuclid.org/euclid.cmp/1103858>
 973) . *Communications in
 Mathematical Physics*. **31**
 (2): 161–170.
Bibcode:1973CMaPh..31..16
1B ([https://ui.adsabs.harvard.edu/abs/1973CMaPh..31..1](https://ui.adsabs.harvard.edu/abs/1973CMaPh..31..161B)
61B) .
doi:10.1007/BF01645742 (h

*https://doi.org/10.1007%2FB
F01645742) . MR 0334798
(https://mathscinet.ams.org/
mathscinet-getitem?mr=033
4798) . S2CID 54690354 (
https://api.semanticscholar.o
rg/CorpusID:54690354) .
Zbl 1125.83309 (https://zb
math.org/?format=complet
e&q=an:1125.83309) .
Archived (https://web.archiv
e.org/web/2020051621160*

4/<https://projecteuclid.org/euclid.cmp/1103858973>)
from the original on 16 May
2020. Retrieved 4 June
2021.

58. Hawking, S. W. (1974).
"Black hole explosions?".
Nature. **248** (5443): 30–31.
Bibcode:1974Natur.248...30
H (<https://ui.adsabs.harvard.edu/abs/1974Natur.248...30H>) . doi:10.1038/248030a0

(<https://doi.org/10.1038%2F248030a0>) .

S2CID 4290107 (<https://api.semanticscholar.org/CorpusID:4290107>) .

59. *Abbott, B.P.; et al. (2016).*

*"Observation of Gravitational Waves from a Binary Black Hole Merger". Phys. Rev. Lett. **116** (6): 061102.*

arXiv:1602.03837 (<https://arxiv.org/abs/1602.03837>)[ⓐ].

Bibcode:2016PhRvL.116f1102A (<https://ui.adsabs.harvard.edu/abs/2016PhRvL.116f1102A>) .

doi:10.1103/PhysRevLett.116.061102 (<https://doi.org/10.1103/PhysRevLett.116.061102>) . PMID 26918975 (<https://pubmed.ncbi.nlm.nih.gov/26918975>) .

S2CID 124959784 (<https://api.semanticscholar.org/CorpusID:124959784>)

arXiv:124333704) .

60. *Event Horizon Telescope, The (2019). "First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole" (<https://doi.org/10.3847/2F2041-8213%2Fab0ec7>) . The Astrophysical Journal. **875** (1): L1. arXiv:1906.11238 (<https://arxiv.org/abs/1906.11238>)⁶. Bibcode:2019ApJ...875L...1*

E (<https://ui.adsabs.harvard.edu/abs/2019ApJ...875L...1E>) . doi:10.3847/2041-8213/ab0ec7 (<https://doi.org/10.3847%2F2041-8213%2Fab0ec7>)⁶.

S2CID 145906806 (<https://api.semanticscholar.org/CorpusID:145906806>) .

61. *Bouman, Katherine L.; Johnson, Michael D.; Zoran, Daniel; Fish, Vincent L.;*

Doeleman, Sheperd S.;
Freeman, William T. (2016).
"Computational Imaging for
VLBI Image Reconstruction".
2016 IEEE Conference on
Computer Vision and Pattern
Recognition (CVPR).
pp. 913–922.
arXiv:1512.01413 (<https://arxiv.org/abs/1512.01413>)³.
doi:10.1109/CVPR.2016.105
(<https://doi.org/10.1109%2F>

CVPR.2016.105) .

hdl:1721.1/103077 (<https://hdl.handle.net/1721.1%2F103077>) . ISBN 978-1-4673-8851-1. S2CID 9085016 (<https://api.semanticscholar.org/CorpusID:9085016>) .

62. *Gardiner, Aidan (12 April 2018). "When a Black Hole Finally Reveals Itself, It Helps to Have Our Very Own Cosmic Reporter –*

Astronomers announced Wednesday that they had captured the first image of a black hole. The Times's Dennis Overbye answers readers' questions" (<https://ghostarchive.org/archive/20220101/https://www.nytimes.com/2019/04/12/reader-center/black-holes-dennis-overbye.html>) . The New York Times. Archived from the original ([\[https://en.m.wikipedia.org/wiki/Black_hole\]\(https://en.m.wikipedia.org/wiki/Black_hole\)](https://www.nytime</i></p></div><div data-bbox=)

original (<https://www.nytimes.com/2019/04/12/reader-center/black-holes-dennis-overbye.html>)⁶ on 1 January 2022. Retrieved 15 April 2019.

63. *El-Badry, Kareem; Rix, Hans-Walter; Quataert, Eliot; Howard, Andrew W.; Isaacson, Howard; Fuller, Jim; Hawkins, Keith; Breivik, Katelyn; Wong, Kaze W. K.; Rodriguez, Antonio C.*

*Rodríguez, Antonio C.;
Conroy, Charlie; Shahaf,
Sahar; Mazeh, Tsevi;
Arenou, Frédéric; Burdge,
Kevin B.; Bashi, Dolev;
Faigler, Simchon; Weisz,
Daniel R.; Seeburger, Rhys;
Monter, Silvia Almada;
Wojno, Jennifer (2023). "A
Sun-like star orbiting a black
hole" (<https://doi.org/10.1093%2Fmnras%2Fstac3140>) .
Monthly Notices of the Royal*

*Astronomical Society. 518:
1057–1085.*

arXiv:2209.06833 (<https://arxiv.org/abs/2209.06833>)³.

doi:10.1093/mnras/stac3140 (<https://doi.org/10.1093/mnras/stac3140>)³.

64. *Marchant, Pablo;
Bodensteiner, Julia
(September 2024). "The
Evolution of Massive Binary
Stars" (<https://doi.org/10.114>*

6%2Fannurev-astro-052722-105936) . *Annual Review of Astronomy and Astrophysics*. **62** (1): 21–61. *arXiv:2311.01865* (<https://arxiv.org/abs/2311.01865>)⁶. *Bibcode:2024ARA&A..62...21M* (<https://ui.adsabs.harvard.edu/abs/2024ARA&A..62...21M>) . *doi:10.1146/annurev-astro-052722-105936* (<https://doi.org/10.1146/annurev-astro-052722-105936>)

*i.org/10.1146%2Fannurev-astro-052722-105936)*⁶.

ISSN 0066-4146 (https://search.worldcat.org/issn/0066-4146) .

65. *"ESO Instrument Finds Closest Black Hole to Earth" (https://www.eso.org/public/news/eso2007/) . European Southern Observatory. 6 May 2020. Archived (https://web.archive.org/web/20000500000455" . . . "*

200506232455/https://www.eso.org/public/news/eso2007/) from the original on 6 May 2020. Retrieved 2 April 2021.

66. "Pioneering Physicist John Wheeler Dies at 96" (<https://www.scientificamerican.com/article/pioneering-physicist-john-wheeler-dies/>) . Scientific American. Archived (<https://web.archive.org/web/2016112905075>

e.org/web/20101128030739/https://www.scientificamerican.com/article/pioneering-physicist-john-wheeler-dies/) from the original on 28 November 2016. Retrieved 27 November 2016.

67. Overbye, Dennis (14 April 2008). "John A. Wheeler, Physicist Who Coined the Term 'Black Hole,' Is Dead at 96" (<https://www.nytimes.com/2008/04/14/science/14w>

http://2008/04/14/science/14wheeler.html) . The New York Times. Archived (<https://web.archive.org/web/20161122210005/http://www.nytimes.com/2008/04/14/science/14wheeler.html>) from the original on 22 November 2016. Retrieved 27 November 2016.

68. *Susskind, Leonard (2008). The black hole war: my battle with Stephen Hawking*

to make the world safe for quantum mechanics
(1st ed.). New York: Little, Brown. ISBN 978-0-316-01640-7. OCLC 181603165 (<https://search.worldcat.org/oclc/181603165>) .

69. Zee, Anthony (2013). *Einstein Gravity in a Nutshell. In a Nutshell Series* (1st ed.). Princeton: Princeton University Press. ISBN 978-

0-691-14558-7.

70. *Carroll 2004, p. 253*

71. *Reynolds, Christopher S.*
(January 2019). "Observing
black holes spin" (<https://www.nature.com/articles/s41550-018-0665-z>) . Nature
Astronomy. 3 (1): 41–47.
arXiv:1903.11704 (<https://arxiv.org/abs/1903.11704>)⁶.
Bibcode:2019NatAs...3...41
R (<https://ui.adsabs.harvard>.

*edu/abs/2019NatAs...3...41
R) . doi:10.1038/s41550-
018-0665-z ([https://doi.or
g/10.1038/s41550-018-
0665-z](https://doi.org/10.1038/s41550-018-0665-z)) . ISSN 2397-3366
([https://search.worldcat.org/
issn/2397-3366](https://search.worldcat.org/issn/2397-3366)) .
S2CID 85543351 ([https://a
pi.semanticscholar.org/Corp
usID:85543351](https://api.semanticscholar.org/CorpusID:85543351)) . Archived (
[https://web.archive.org/web/
20201118092121/https://w](https://web.archive.org/web/20201118092121/https://w)*

www.nature.com/articles/s41550-018-0665-z) from the original on 18 November 2020. Retrieved 21 August 2020.

72. *Thorne, K. S.; Price, R. H. (1986). Black holes: the membrane paradigm. Yale University Press. ISBN 978-0-300-03770-8.*

73. *Anderson, Warren G. (1996). "The Black Hole*

Information Loss Problem" (https://web.archive.org/web/20090122223839/http://math.ucr.edu/home/baez/physics/Relativity/BlackHoles/info_loss.html) . Usenet Physics FAQ. Archived from the original (http://math.ucr.edu/home/baez/physics/Relativity/BlackHoles/info_loss.html) on 22 January 2009. Retrieved 24 March 2009.

74. *Preskill, J. (21 October 1994). Black holes and information: A crisis in quantum physics (<https://web.archive.org/web/20080518054438/http://www.theory.caltech.edu/~preskill/talks/blackholes.pdf>) (PDF). Caltech Theory Seminar. Archived from the original (<http://www.theory.caltech.edu/~preskill/talks/blackholes.>*

*pdf) (PDF) on 18 May
2008. Retrieved 17 May
2009.*

75. *Hawking & Ellis 1973,
Appendix B*

76. *Seeds, Michael A.; Backman,
Dana E. (2007).*

Perspectives on Astronomy (
[https://books.google.com/bo](https://books.google.com/books?id=CXom04KGIL8C&pg=PA167)
[oks?id=CXom04KGIL8C&pg](https://books.google.com/books?id=CXom04KGIL8C&pg=PA167)
=PA167) . Cengage

Learning. p. 167. ISBN 978-
0-07-16050-0 .

0-495-11352-2. Archived (<https://web.archive.org/web/20160810211808/https://books.google.com/books?id=CXom04KGIL8C&pg=PA167>) from the original on 10 August 2016.

77. Shapiro, S. L.; Teukolsky, S. A. (1983). *Black holes, white dwarfs, and neutron stars: the physics of compact objects*. John Wiley and Sons. ISBN 0-471-07000-0.

sons. p. 357. ISBN 978-0-471-87316-7.

78. Wald, R. M. (1997).

"Gravitational Collapse and Cosmic Censorship". In Iyer, B. R.; Bhawal, B. (eds.).

Black Holes, Gravitational Radiation and the Universe.

Dordrecht: Springer. pp. 69–

86. arXiv:gr-qc/9710068 (ht

tps://arxiv.org/abs/gr-qc/97

10068)[Ⓜ]. doi:10.1007/978-

01-017-0931-7 (https://doi

94-017-0934-7 (<https://doi.org/10.1007%2F978-94-017-0934-7>) . ISBN 978-94-017-0934-7.

79. *Berger, B. K. (2002). "Numerical Approaches to Spacetime Singularities" (<https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5256073>) . Living Reviews in Relativity. **5** (1): 2002–1. arXiv:gr-qc/0201056 (<https://arxiv.org/abs/gr-qc/0201056>)[ⓘ].*

g/abs/9. 49/220.000, .
Bibcode:2002LRR.....5....1B
(<https://ui.adsabs.harvard.edu/abs/2002LRR.....5....1B>) .
doi:10.12942/lrr-2002-1 (<https://doi.org/10.12942%2Flrr-2002-1>)[Ⓜ]. PMC 5256073 (<https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5256073>)[Ⓜ]. PMID 28179859 (<https://pubmed.ncbi.nlm.nih.gov/28179859>) .

80. *McClintock, J. E.; Shafee, R.;*

*Narayan, R.; Remillard, R. A.;
Davis, S. W.; Li, L.-X.*

*(2006). "The Spin of the
Near-Extreme Kerr Black
Hole GRS 1915+105".*

*Astrophysical Journal. **652***

*(1): 518–539. arXiv:astro-
ph/0606076 ([https://arxiv.o
rg/abs/astro-ph/0606076](https://arxiv.org/abs/astro-ph/0606076))[ⓘ].*

*Bibcode:2006ApJ...652..51
8M ([https://ui.adsabs.harvar
d.edu/abs/2006ApJ...652..5](https://ui.adsabs.harvard.edu/abs/2006ApJ...652..5)*

18M) . doi:10.1086/508457
(<https://doi.org/10.1086%2F508457>) . S2CID 1762307 (<https://api.semanticscholar.org/CorpusID:1762307>) .

81. *Abbott, B. P.; et al. (LIGO Scientific Collaboration and Virgo Collaboration) (1 June 2017). "GW170104: Observation of a 50-Solar-Mass Binary Black Hole Coalescence at Redshift*

0.2". *Physical Review Letters*. **118** (22): 221101.
arXiv:1706.01812 (<https://arxiv.org/abs/1706.01812>)^a.
Bibcode:2017PhRvL.118v1101A (<https://ui.adsabs.harvard.edu/abs/2017PhRvL.118v1101A>) .
doi:10.1103/PhysRevLett.118.221101 (<https://doi.org/10.1103/PhysRevLett.118.221101>) . *PMID 28621973* (<http://pubmed.ncbi.nlm.nih.gov/28621973/>)

ps://pubmed.ncbi.nlm.nih.gov/28621973) .

S2CID 206291714 (https://api.semanticscholar.org/CorpusID:206291714) .

82. *Abbott, B. P.; et al. (LIGO Scientific Collaboration & Virgo Collaboration) (16 October 2017). "GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral". **Physical Review Letters** **119***

Physical Review Letters. **119**
(16): 161101.

arXiv:1710.05832 (<https://arxiv.org/abs/1710.05832>)^a.

Bibcode:2017PhRvL.119p1101A (<https://ui.adsabs.harvard.edu/abs/2017PhRvL.119p1101A>) .

doi:10.1103/PhysRevLett.119.161101 (<https://doi.org/10.1103/PhysRevLett.119.161101>) . *PMID 29099225* (<https://pubmed.ncbi.nlm.nih.gov>

v/29099225) .

S2CID 217163611 (<https://api.semanticscholar.org/CorpusID:217163611>) .

83. *Wald 1984, pp. 124–125*

84. *Saa, Alberto; Santarelli, Raphael (18 July 2011).*

"Destroying a near-extremal Kerr–Newman black hole".

Physical Review D. **84** (2):

027501. *arXiv:1105.3950* (<https://arxiv.org/abs/1105.39>

50)³.

Bibcode:2011PhRvD..84b7501S (<https://ui.adsabs.harvard.edu/abs/2011PhRvD..84b7501S>) .

doi:10.1103/PhysRevD.84.027501 (<https://doi.org/10.1103/PhysRevD.84.027501>) . S2CID 118487989 (<https://api.semanticscholar.org/CorpusID:118487989>) .

85. *Misner, Thorne & Wheeler*

1973, p. 848

86. *Davies, Paul (1992). The New Physics (<https://books.google.com/books?id=akb2FpZSGnMC>) (illustrated ed.). Cambridge University Press. p. 26. ISBN 978-0-521-43831-5. Archived (<https://web.archive.org/web/20210817161727/https://books.google.com/books?id=akb2FpZSGnMC>)*

*from the original on 17
August 2021. Retrieved
25 September 2020. Extract
of page 26 (<https://books.google.com/books?id=akb2FpZSGnMC&pg=PA26>)
Archived (<https://web.archive.org/web/20210815222341/https://books.google.com/books?id=akb2FpZSGnMC&pg=PA26>) 15 August 2021
at the Wayback Machine*

87. *Fleisch, Daniel; Kregenow, Julia (2013). A Student's Guide to the Mathematics of Astronomy (<https://books.google.com/books?id=x4gaBQAAQBAJ>) (illustrated ed.). Cambridge University Press. p. 168. ISBN 978-1-107-03494-5. Archived (<https://web.archive.org/web/20210817045139/https://books.google.com/books?id=x4gaBQAAQBAJ>) from the original*

*QAAQBAJ) from the original
on 17 August 2021.*

*Retrieved 25 September
2020. Extract of page 168 (
<https://books.google.com/books?id=x4gaBQAAQBAJ&pg=PA168>) Archived (<https://web.archive.org/web/20210817113029/https://books.google.be/books?id=x4gaBQAAQBAJ&pg=PA168>) 17
August 2021 at the Wayback
Machine*

-
88. *Wheeler 2007, p. 179*
89. *Carroll 2004, Ch. 5.4 and 7.3*
90. *"Singularities and Black Holes > Lightcones and Causal Structure" (<https://plato.stanford.edu/entries/spacetime-singularities/lightcone.html>) . plato.stanford.edu. Stanford Encyclopedia of Philosophy. Archived (<http://web.archive.org/web/201>*

s://web.archive.org/web/20190517122738/https://plato.stanford.edu/entries/spacetime-singularities/lightcone.html) from the original on 17 May 2019. Retrieved 11 March 2018.

91. *Carroll 2004, p. 217*

92. *Carroll 2004, p. 218*

93. *"Inside a black hole" (https://web.archive.org/web/20090423053437/http://nrumian*

*o.free.fr/Estars/int_bh.html) .
Knowing the universe and its
secrets. Archived from the
original (http://nrumiano.free.fr/Estars/int_bh.html) on
23 April 2009. Retrieved
26 March 2009.*

94. *"What happens to you if you
fall into a black hole" ([http://
math.ucr.edu/home/baez/ph
ysics/Relativity/BlackHoles/f
all_in.html](http://math.ucr.edu/home/baez/physics/Relativity/BlackHoles/fall_in.html)) . math.ucr.edu.*

... ..

John Baez. Archived (http://web.archive.org/web/20190213124648/http://math.ucr.edu/home/baez/physics/Relativity/BlackHoles/fall_in.html) from the original on 13 February 2019. Retrieved 11 March 2018.

95. *Carroll 2004, p. 222*

96. *"Watch: Three Ways an Astronaut Could Fall Into a Black Hole" (<https://web.arc>*

hive.org/web/20190415101947/https://news.nationalgeographic.com/news/2014/01/140130-black-holes-stephen-hawking-work-space-astronomy/) . 1 February 2014. Archived from the original (https://news.nationalgeographic.com/news/2014/01/140130-black-holes-stephen-hawking-work-space-astronomy/) on 15 April 2019. Retrieved 13 March 2018

RETRIEVED 10 MARCH 2010.

97. *Emparan, R.; Reall, H. S.*
(2008). "Black Holes in
Higher Dimensions" ([https://
www.ncbi.nlm.nih.gov/pmc/a
rticles/PMC5253845](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5253845)) .
Living Reviews in Relativity.
11 (6): 6. *arXiv:0801.3471* ([h
ttps://arxiv.org/abs/0801.34
71](https://arxiv.org/abs/0801.3471))³.
Bibcode:2008LRR....11....6E
([https://ui.adsabs.harvard.ed
u/abs/2008LRR....11....6E](https://ui.adsabs.harvard.edu/abs/2008LRR....11....6E)) .

doi:10.12942/lrr-2008-6 (<https://doi.org/10.12942%2Flrr-2008-6>)[Ⓜ]. *PMC 5253845* (<https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5253845>)[Ⓜ]. *PMID 28163607* (<https://pubmed.ncbi.nlm.nih.gov/28163607>) .

98. *Obers, N. A. (2009). Papantonopoulos, Eleftherios (ed.). Physics of Black Holes* (<https://cds.cern>

n.ch/record/1164174/files/978-3-540-88460-6_BookT
OC.pdf) (PDF). Lecture
Notes in Physics. Vol. 769.
Berlin: Springer. pp. 211–
258. arXiv:0802.0519 (<http://arxiv.org/abs/0802.0519>)³.

Bibcode:2009LNP...769....P
(<https://ui.adsabs.harvard.edu/abs/2009LNP...769....P>) .
doi:10.1007/978-3-540-

88460-6 (<https://doi.org/10.1007%2F978-3-540-88460-6>) . ISBN 978-3-540-88459-0. Archived (https://web.archive.org/web/20180726103141/https://cds.cern.ch/record/1164174/files/978-3-540-88460-6_BookTOC.pdf) (PDF) from the original on 26 July 2018. Retrieved 27 July 2018.

99. *Hawking & Ellis 1973, Ch.*

9.3

100. *Smarr, L. (1973). "Surface Geometry of Charged Rotating Black Holes". Physical Review D. 7 (2): 289–295.*
- Bibcode:1973PhRvD...7..289 S* (<https://ui.adsabs.harvard.edu/abs/1973PhRvD...7..289S>) .
- doi:10.1103/PhysRevD.7.289* (<https://doi.org/10.1103%2F>

— — — — —

PhysRevD.7.289) .

101. Visser, M. (22 January 2009). "The Kerr spacetime: A brief introduction". In Wiltshire, D.L.; Visser, M.; Scott, S.M. (eds.). *The Kerr Spacetime: Rotating Black Holes in General Relativity* (https://books.google.com/books?id=wymJBq_80Q0C) . Cambridge University Press. *arXiv:0706.0622* (<https://arxiv.org/abs/0706.0622>) .

iv.org/aps/U/U6.U6ZZ)ö.

ISBN 978-0-521-88512-6.

Archived (https://web.archive.org/web/20200520134643/https://books.google.com/books?id=wymJBq_80Q0C) from the original on 20 May 2020. Retrieved 12 January 2020.

102. *Delgado, J.F. M.; Herdeiro, C.A. R.; Radu, E. (2018). "Horizon geometry for Kerr black holes with*

black holes with

*synchronized hair". Physical
Review D. **97** (12): 124012.*

arXiv:1804.04910 (<https://arxiv.org/abs/1804.04910>)^g.

*Bibcode:2018PhRvD..97I40
12D (<https://ui.adsabs.harvard.edu/abs/2018PhRvD..97I4012D>) .*

*doi:10.1103/PhysRevD.97.12
4012 (<https://doi.org/10.1103/PhysRevD.97.124012>)
. hdl:10773/24121 (<https://h>*

dl.handle.net/10773%2F24121) . S2CID 55732213 (<http://api.semanticscholar.org/CorpusID:55732213>) .

103. *Carroll 2004, p. 205*

104. *Carroll 2004, pp. 264–265*

105. *Carroll 2004, p. 252*

106. *"Sizes of Black Holes? How Big is a Black Hole?" (<https://www.skyandtelescope.com/astronomy-resources/how-big>*

g-is-a-black-hole/) . Sky & Telescope. 22 July 2014. Archived (<https://web.archive.org/web/20190403035741/https://www.skyandtelescope.com/astronomy-resources/how-big-is-a-black-hole/>) from the original on 3 April 2019. Retrieved 9 October 2018.

107. Lewis, G. F.; Kwan, J. (2007). "No Way Back: Maximizing Survival Time

*maximizing survival time
Below the Schwarzschild
Event Horizon". Publications
of the Astronomical Society
of Australia. **24** (2): 46–52.
arXiv:0705.1029 (<https://arxiv.org/abs/0705.1029>)^o.
Bibcode:2007PASA...24...4
6L ([https://ui.adsabs.harvard.edu/abs/2007PASA...24...
46L](https://ui.adsabs.harvard.edu/abs/2007PASA...24...46L)) . doi:10.1071/AS07012
([https://doi.org/10.1071%2F
AS07012](https://doi.org/10.1071%2FAS07012)) .*

S2CID 17261076 (<https://api.semanticscholar.org/CorpusID:17261076>) .

108. *Wheeler 2007, p. 182*

109. *Carroll 2004, pp. 257–259
and 265–266*

110. *Droz, S.; Israel, W.; Morsink,
S. M. (1996). "Black holes:
the inside story". *Physics
World*. **9** (1): 34–37.*

*Bibcode:1996PhyW....9...34
D (<https://ui.adsabs.harvard>*

D (<https://ui.adsabs.harvard.edu/abs/1996PhyW....9...34D>) . doi:10.1088/2058-7058/9/1/26 (<https://doi.org/10.1088%2F2058-7058%2F9%2F1%2F26>) .

111. Carroll 2004, p. 266

112. Poisson, E.; Israel, W. (1990). "Internal structure of black holes". *Physical Review D*. **41** (6): 1796–1809. Bibcode:1990PhRvD..41.1796P (<https://ui.adsabs.harvard.edu/abs/1990PhRvD..41.1796P>) . doi:10.1088/0147-5202/41/6/001

OF (<https://ui.adsabs.harvard.edu/abs/1990PhRvD..41.1796P>) .

doi:10.1103/PhysRevD.41.1796 (<https://doi.org/10.1103/2FPhysRevD.41.1796>) .

PMID 10012548 (<https://pubmed.ncbi.nlm.nih.gov/10012548>) .

113. *Wald 1984, p. 212*

114. *Hamade, R. (1996). "Black Holes and Quantum Gravity"*
(<https://arxiv.org/abs/hep-th/9601034>)

(https://web.archive.org/web/20090407043337/http://www.damtp.cam.ac.uk/user/gr/public/bh_hawk.html) . Cambridge Relativity and Cosmology. University of Cambridge. Archived from the original (http://www.damtp.cam.ac.uk/user/gr/public/bh_hawk.html) on 7 April 2009. Retrieved 26 March 2009.

115 *Delmer D "Ask an*

113. *Fallick, D. Ask an*

Astrophysicist: Quantum Gravity and Black Holes" (https://web.archive.org/web/20090328064842/http://imagine.gsfc.nasa.gov/docs/ask_astro/answers/980420b.html) . NASA. Archived from the original (https://imagine.gsfc.nasa.gov/docs/ask_astro/answers/980420b.html) on 28 March 2009. Retrieved 26 March 2009.

116. *Cramer, Claes R. (1997).*

*"Using the Uncharged Kerr
Black Hole as a Gravitational
Mirror". General Relativity
and Gravitation. **29** (4):
445–454. arXiv:gr-
qc/9510053 ([https://arxiv.or
g/abs/gr-qc/9510053](https://arxiv.org/abs/gr-qc/9510053))^g.
Bibcode:1997GReGr..29..44
5C ([https://ui.adsabs.harvar
d.edu/abs/1997GReGr..29..4
45C](https://ui.adsabs.harvard.edu/abs/1997GReGr..29..445C)) .*

doi:10.1023/A:1018878515046 (https://doi.org/10.1023%2FA%3A1018878515046) . S2CID 9517046 (https://api.semanticscholar.org/CorpusID:9517046) .

117. *Nitta, Daisuke; Chiba, Takeshi; Sugiyama, Naoshi (September 2011). "Shadows of colliding black holes". Physical Review D. **84** (6): 063008.*

arXiv:1106.2425 (<https://arxiv.org/abs/1106.2425>)⁶.

Bibcode:2011PhRvD..84f3008N (<https://ui.adsabs.harvard.edu/abs/2011PhRvD..84f3008N>) .

doi:10.1103/PhysRevD.84.063008 (<https://doi.org/10.1103/PhysRevD.84.063008>) . S2CID 119264596 (<https://api.semanticscholar.org/CorpusID:119264596>) .

118. *Bardeen, James M.; Press, William H.; Teukolsky, Saul A. (1 December 1972). "Rotating Black Holes: Locally Nonrotating Frames, Energy Extraction, and Scalar Synchrotron Radiation". The Astrophysical Journal. **178**: 347–370. Bibcode:1972ApJ...178..347B (<https://ui.adsabs.harvard.edu/abs/1972ApJ...178..347B>)*

*edu/aps/1972ApJ...178..347
B) . doi:10.1086/151796 (http://doi.org/10.1086%2F151796) .*

119. *"Black Hole Calculator" (http://www.fabiopacucci.com/resources/black-hole-calculator/) . Fabio Pacucci.
Archived (https://web.archive.org/web/20201021154805/https://www.fabiopacucci.com/resources/black-hole-calculator/) from the original*

*calculator)) from the original
on 21 October 2020.*

*Retrieved 29 September
2020.*

120. *Visser, Matt (2007). "The
Kerr spacetime: A brief
introduction". page 35, Fig.
3. arXiv:0706.0622 ([https://
arxiv.org/abs/0706.0622](https://arxiv.org/abs/0706.0622))[ⓘ]
[gr-qc ([https://arxiv.org/arch
ive/gr-qc](https://arxiv.org/archive/gr-qc))].*

121. *Carroll 2004, Ch. 6.6*

122. "Black hole" [Wikipedia](#).

122. *Carroll 2004, Ch. 6.7*
123. *Misner, Thorne & Wheeler 1973, Box 25.6*
124. *"First proof of black hole 'plunging regions' " (<https://www.physics.ox.ac.uk/news/first-proof-black-hole-plunging-regions>) . Department of Physics. University of Oxford. 16 May 2024.*
125. *Mummery, Andrew; Ingram, Adam; Davis, Shane; Fabian,*

Andrew (June 2024).

*"Continuum emission from within the plunging region of black hole discs" (<https://doi.org/10.1093/mnras/stae1160>) . Monthly Notices of the Royal Astronomical Society. **531** (1): 366–386. [arXiv:2405.09175](https://arxiv.org/abs/2405.09175) (<https://arxiv.org/abs/2405.09175>)^g. [doi:10.1093/mnras/stae1160](https://doi.org/10.1093/mnras/stae1160) (<https://doi.org/10.1093/mnras/stae1160>)*

*mnras%2Fstae116U)*³.

126. *Einstein, A. (1939). "On A Stationary System With Spherical Symmetry Consisting of Many Gravitating Masses" (<https://web.archive.org/web/20190228153449/http://pdfs.semanticscholar.org/8dd0/dfafef0c53c428fdc3b58f8099aafcf7d089.pdf>) (PDF).*

Annals of Mathematics. **40**

1915. 022 026

(4). 922-930.

Bibcode:1939AnMat..40..922E (<https://ui.adsabs.harvard.edu/abs/1939AnMat..40..922E>) .

doi:10.2307/1968902 (<https://doi.org/10.2307/1968902>) . *JSTOR 1968902* (<https://www.jstor.org/stable/1968902>) .

S2CID 55495712 (<https://api.semanticscholar.org/CorpusID:55495712>) . *Archived*

from the original (<http://pdfs.semanticscholar.org/8dd0/dfafef0c53c428fdc3b58f8099aafcf7d089.pdf>) (PDF) on 28 February 2019.

127. *Kerr, R. P. (2009). "The Kerr and Kerr-Schild metrics". In Wiltshire, D. L.; Visser, M.; Scott, S. M. (eds.). The Kerr Spacetime. Cambridge University Press.*
- arXiv:0706.1109 (<https://arxiv.org/abs/0706.1109>)*

v.org/abs/0706.1109)³.

Bibcode:2007arXiv0706.1109K (https://ui.adsabs.harvard.edu/abs/2007arXiv0706.1109K) . ISBN 978-0-521-88512-6.

128. *Findley, Kate (27 December 2019). "The Discovery of Black Holes: From Theory to Actuality" (https://web.archive.org/web/20220925103539/https://www.wondriumdail*

y.com/the-discovery-of-black-holes-from-theory-to-actuality/) . *Wondrium Daily*.

Archived from the original (<https://www.wondriumdaily.com/the-discovery-of-black-holes-from-theory-to-actuality/>) on 25 September 2022. Retrieved 29 June 2022.

129. *Hawking, S. W.; Penrose, R. (January 1970). "The Singularities of Gravitational*

Collapse and Cosmology" (<https://doi.org/10.1098/rspa.1970.0021>) .

*Proceedings of the Royal Society A. **314** (1519): 529–548.*

Bibcode:1970RSPSA.314..529H (<https://ui.adsabs.harvard.edu/abs/1970RSPSA.314..529H>) .

doi:10.1098/rspa.1970.0021 (<https://doi.org/10.1098/rspa.1970.0021>) .

rspa.1970.0021)³.

JSTOR 2416467 (<https://www.jstor.org/stable/2416467>)

.

130. *Pacucci, F.; Ferrara, A.; Grazian, A.; Fiore, F.; Giallongo, E. (2016). "First Identification of Direct Collapse Black Hole Candidates in the Early Universe in CANDELS/GOODS-S" (<http://doi.org/10.1093/mnras/stw250>*

[s://doi.org/10.1093/mnras/stw725](https://doi.org/10.1093/mnras/stw725)) . *Mon. Not. R. Astron. Soc.* **459** (2): 1432.
arXiv:1603.08522 (<https://arxiv.org/abs/1603.08522>)⁶.
Bibcode:2016MNRAS.459.1432P (<https://ui.adsabs.harvard.edu/abs/2016MNRAS.459.1432P>) .
doi:10.1093/mnras/stw725 (<https://doi.org/10.1093/mnras/stw725>)⁶.
S2CID 118578313 (<https://a>

pi.semanticscholar.org/CorpusID:118578313) .

131. *Carr, B. J. (2005).*

"Primordial Black Holes: Do They Exist and Are They Useful?". In Suzuki, H.; Yokoyama, J.; Suto, Y.; Sato, K. (eds.). Inflating Horizon of Particle Astrophysics and Cosmology. Universal Academy Press. pp. astro-ph/0511743. arXiv:astro-

ph/0511743 (<https://arxiv.org/abs/astro-ph/0511743>)³.

Bibcode:2005astro.ph.11743C (<https://ui.adsabs.harvard.edu/abs/2005astro.ph.11743C>) . ISBN 978-4-946443-94-7.

132. *"Ripped Apart by a Black Hole" (<https://web.archive.org/web/20130721014626/http://www.eso.org/public/news/eso1332/>) . ESO Press*

Release. Archived from the original (<http://www.eso.org/public/news/eso1332/>) on 21 July 2013. Retrieved 19 July 2013.

133. *Carroll 2004, Section 5.8*

134. *Rees, M. J.; Volonteri, M. (2007). "Massive black holes: Formation and evolution". In Karas, V.; Matt, G. (eds.). Black Holes from Stars to Galaxies – Across*

the Range of Masses.

Proceedings of the

International Astronomical

Union. pp. 51–58.

arXiv:astro-ph/0701512 (<https://arxiv.org/abs/astro-ph/0701512>)^a.

Bibcode:2007IAUS..238...51

R ([https://ui.adsabs.harvard.](https://ui.adsabs.harvard.edu/abs/2007IAUS..238...51R)

edu/abs/2007IAUS..238...51

R) .

doi:10.1017/S17439213070

04681 (<https://doi.org/10.1017%2FS1743921307004681>)³. ISBN 978-0-521-86347-6. S2CID 14844338 (<https://api.semanticscholar.org/CorpusID:14844338>) .

135. *Bañados, Eduardo; Venemans, Bram P.; Mazzucchelli, Chiara; Farina, Emanuele P.; Walter, Fabian; Wang, Feige; Decarli, Roberto; Stern, Daniel; Fan, Xiangdong et al.*

*Xiaohui; Davies, Frederick B.; Hennawi, Joseph F. (1 January 2018). "An 800-million-solar-mass black hole in a significantly neutral Universe at a redshift of 7.5". **Nature**. **553** (7689): 473–476. arXiv:1712.01860 (<https://arxiv.org/abs/1712.01860>)^a.*

Bibcode:2018Natur.553..473B (<https://ui.adsabs.harvard.edu/abs/2018Natur.553..473B>)

doi:10.1038/nature25180 (https://doi.org/10.1038/nature25180) .

PMID 29211709 (https://pubmed.ncbi.nlm.nih.gov/29211709) . S2CID 205263326 (https://api.semanticscholar.org/CorpusID:205263326) .

136. Penrose, R. (2002). "Gravitational Collapse: The Role of General Relativity" (https://arxiv.org/abs/2002.03907v1 [gr-qc]) .

136. Penrose, R. (2002).

"Gravitational Collapse: The Role of General Relativity" (https://arxiv.org/abs/2002.03907v1 [gr-qc]) .

https://web.archive.org/web/20130526224126/http://www.imamu.edu.sa/Scientific_selections/abstracts/Physics/Gravitational%20Collapse%20The%20Role%20of%20General.pdf (PDF). *General Relativity and Gravitation*. **34** (7): 1141.

Bibcode:2002GReGr..34.1141P (<https://ui.adsabs.harvard.edu/abs/2002GReGr..34.1>

141P) .

doi:10.1023/A:1016578408204 (<https://doi.org/10.1023%2FA%3A1016578408204>) . S2CID 117459073 (<http://api.semanticscholar.org/CorpusID:117459073>) .

Archived from the original (http://www.imamu.edu.sa/Scientific_selections/abstracts/Physics/Gravitational%20Collapse%20The%20Role%20

www.imamu.edu.sa/Scientific_selections/abstracts/Physics/Gravitational%20Collapse%20The%20Role%20

*of%20General.pdf) (PDF)
on 26 May 2013.*

137. *Guth, Alan (1997). "Was Cosmic Inflation the 'Bang' of the Big Bang? - A. Guth" (<https://ned.ipac.caltech.edu/level5/Guth/Guth3.html>) . NASA/IPAC Extragalactic Database (NED). Retrieved 2 July 2025.*

138. *Philip Gibbs. "Is the Big Bang a black hole?" (<http://m>*

ath.ucr.edu/home/baez/physics/Relativity/BlackHoles/universe.html) . John Baez.

Archived (<https://web.archive.org/web/20181231021714/http://math.ucr.edu/home/baez/physics/Relativity/BlackHoles/universe.html>) from the original on 31 December 2018. Retrieved 16 March 2018.

139. *Giddings, S. B.; Thomas, S.*

(2002). *"High energy colliders as black hole factories: The end of short distance physics"*. *Physical Review D*. **65** (5): 056010. *arXiv:hep-ph/0106219* (<https://arxiv.org/abs/hep-ph/0106219>)^g.

Bibcode:2002PhRvD..65e6010G (<https://ui.adsabs.harvard.edu/abs/2002PhRvD..65e6010G>) .

doi:10.1103/PhysRevD.65.05

6010 (<https://doi.org/10.1103/PhysRevD.65.056010>) . S2CID 1203487 (<https://api.semanticscholar.org/CorpusID:1203487>) .

140. *Harada, T. (2006). "Is there a black hole minimum mass?". Physical Review D. **74** (8): 084004. arXiv:gr-qc/0609055 (<https://arxiv.org/abs/gr-qc/0609055>)[ⓘ]. Bibcode:2006PhRvD..74h4*

004H (<https://ui.adsabs.harvard.edu/abs/2006PhRvD..74h4004H>) .

doi:10.1103/PhysRevD.74.084004 (<https://doi.org/10.1103/PhysRevD.74.084004>) . S2CID 119375284 (<https://api.semanticscholar.org/CorpusID:119375284>) .

141. *Arkani-Hamed, N.; Dimopoulos, S.; Dvali, G. (1998). "The hierarchy*

problem and new dimensions at a millimeter".
Physics Letters B. **429** (3–4): 263–272. *arXiv:hep-ph/9803315* (<https://arxiv.org/abs/hep-ph/9803315>)⁶.
Bibcode:1998PhLB..429..263A (<https://ui.adsabs.harvard.edu/abs/1998PhLB..429..263A>) . *doi:10.1016/S0370-2693(98)00466-3* (<https://doi.org/10.1016%2FS0370->

2693%2898%2900466-3) . S2CID 15903444 (<http://api.semanticscholar.org/CorpusID:15903444>) .

142. *LHC Safety Assessment Group (2008). "Review of the Safety of LHC Collisions" (<http://lsag.web.cern.ch/lsag/LSAG-Report.pdf>) (PDF). Journal of Physics G: Nuclear Physics. **35** (11): 115004. arXiv:0806.3414 (h*

<https://arxiv.org/abs/0806.3414>)⁶.

Bibcode:2008JPhG...35k5004E (<https://ui.adsabs.harvard.edu/abs/2008JPhG...35k5004E>) .

doi:10.1088/0954-3899/35/11/115004 (<https://doi.org/10.1088/0954-3899/35/11/115004>) . S2CID 53370175 (<https://api.semanticscholar.org/CorpusID:53370175>)

g/corpusID:33373173/ .

Archived (<https://web.archive.org/web/20100414160742/http://lsag.web.cern.ch/lsag/LSAG-Report.pdf>) (PDF) from the original on 14 April 2010.

143. *Cavaglià, M. (2010).*

"Particle accelerators as black hole factories?" (<http://web.archive.org/web/20130508085759/http://www.einstein-online.info/spotlight>

s/accelerators_bh) .

Einstein-Online. 4: 1010.

Archived from the original (http://www.einstein-online.info/spotlights/accelerators_bh/) on 8 May 2013.

Retrieved 8 May 2013.

144. *Vesperini, E.; McMillan, S. L. W.; d'Ercole, A.; et al. (2010). "Intermediate-Mass Black Holes in Early Globular Clusters". The Astrophysical*

*Journal Letters. **713** (1):
L41 – L44. arXiv:1003.3470
(<https://arxiv.org/abs/1003.3470>)^a.*

*Bibcode:2010ApJ...713L..41
V (<https://ui.adsabs.harvard.edu/abs/2010ApJ...713L..41V>) . doi:10.1088/2041-
8205/713/1/L41 (<https://doi.org/10.1088%2F2041-8205%2F713%2F1%2FL41>) .
S2CID 119120429 (<https://a>*

pi.semanticscholar.org/CorpusID:119120429) .

145. *Zwart, S. F. P.; Baumgardt, H.; Hut, P.; et al. (2004). "Formation of massive black holes through runaway collisions in dense young star clusters". Nature. **428** (6984): 724–726. arXiv:astro-ph/0402622 (<https://arxiv.org/abs/astro-ph/0402622>)^g.*

Bibcode:2004Natur.428..724P (<https://ui.adsabs.harvard.edu/abs/2004Natur.428..724P>) .

doi:10.1038/nature02448 (<https://doi.org/10.1038%2Fnature02448>) .

PMID 15085124 (<https://pubmed.ncbi.nlm.nih.gov/15085124>) . S2CID 4408378 (<https://api.semanticscholar.org/CorpusID:4408378>) .

146. O'Leary, R. M.; Rasio, F. A.; Fregeau, J. M.; et al. (2006). "Binary Mergers and Growth of Black Holes in Dense Star Clusters". *The Astrophysical Journal*. **637** (2): 937–951. [arXiv:astro-ph/0508224](https://arxiv.org/abs/astro-ph/0508224) (<https://arxiv.org/abs/astro-ph/0508224>)[ⓘ].
Bibcode:2006ApJ...637..937O (<https://ui.adsabs.harvard.edu/abs/2006ApJ...637..937O>) doi:10.1086/498446

07/07/2016 10:10:00/400440
(<https://doi.org/10.1086%2F498446>) . S2CID 1509957
(<https://api.semanticscholar.org/CorpusID:1509957>) .

147. *Page, D. N. (2005).*

*"Hawking radiation and
black hole thermodynamics".*

New Journal of Physics. 7

(1): 203. arXiv:hep-

th/0409024 (<https://arxiv.org/abs/hep-th/0409024>)⁶.

Bibcode:2005NJPh....7..203

P (<https://ui.adsabs.harvard.edu/abs/2005NJPh....7..203P>) . doi:10.1088/1367-2630/7/1/203 (<https://doi.org/10.1088%2F1367-2630%2F7%2F1%2F203>) .
S2CID 119047329 (<https://api.semanticscholar.org/CorpusID:119047329>) .

148. *Carroll 2004, Ch. 9.6*

149. *Siegel, Ethan (2017). "Ask Ethan: Do Black Holes Grow*

Ethan: Do Black Holes Grow

Faster Than They

Evaporate?" (<https://www.forbes.com/sites/startswithabang/2017/08/19/ask-ethan-do-black-holes-grow-faster-than-they-evaporate/>) .

Forbes ("Starts With A

Bang" blog). Archived ([http](http://web.archive.org/web/20181122031830/https://www.forbes.com/sites/startswithabang/2017/08/19/ask-ethan-)

s://web.archive.org/web/201

81122031830/https://www.f

orbes.com/sites/startswithab

ang/2017/08/19/ask-ethan-

do-black-holes-grow-faster-than-they-evaporate/) from the original on 22 November 2018. Retrieved 17 March 2018.

150. Sivaram, C. (2001). "Black hole Hawking radiation may never be observed!". *General Relativity and Gravitation*. **33** (2): 175–181.

Bibcode:2001GReGr..33..175S (<https://ui.adsabs.harvar>

d.edu/abs/2001GReGr..33..175S) .

doi:10.1023/A:1002753400430 (https://doi.org/10.1023%2FA%3A1002753400430) . S2CID 118913634 (https://api.semanticscholar.org/CorpusID:118913634) .

151. *"Evaporating black holes?" (https://web.archive.org/web/20110722055345/http://www.einstein-online.info/elem*

*entary/quantum/evaporating
_bh/?set_language=en) .
Einstein online. Max Planck
Institute for Gravitational
Physics. 2010. Archived
from the original ([http://www.einstein-online.info/elementary/quantum/evaporating_
bh/?set_language=en](http://www.einstein-online.info/elementary/quantum/evaporating_bh/?set_language=en)) on
22 July 2011. Retrieved
12 December 2010.*

152. *Giddings, S. B.; Mangano,*

*M. L. (2008). "Astrophysical implications of hypothetical stable TeV-scale black holes". Physical Review D. **78** (3): 035009.*

arXiv:0806.3381 (<https://arxiv.org/abs/0806.3381>)^g.

Bibcode:2008PhRvD..78c5009G (<https://ui.adsabs.harvard.edu/abs/2008PhRvD..78c5009G>) .

doi:10.1103/PhysRevD.78.035009 (<https://doi.org/10.1103/PhysRevD.78.035009>)

0000 (<https://doi.org/10.1103/PhysRevD.78.035009>) . S2CID 17240525 (<http://api.semanticscholar.org/CorpusID:17240525>) .

153. *Peskin, M. E. (2008). "The end of the world at the Large Hadron Collider?" (<https://doi.org/10.1103/Physics.1.14>) . Physics. 1: 14. Bibcode:2008PhyOJ...1...14P (<https://ui.adsabs.harvard.edu/abs/2008PhvOJ...1...14>*

P) . doi:10.1103/Physics.1.14
([https://doi.org/10.1103%2F
Physics.1.14](https://doi.org/10.1103%2FPhysics.1.14))⁸.

154. *Fichtel, C. E.; Bertsch, D. L.;
Dingus, B. L.; et al. (1994).
"Search of the energetic
gamma-ray experiment
telescope (EGRET) data for
high-energy gamma-ray
microsecond bursts".
Astrophysical Journal. **434**
(2): 557–559.*

Bibcode:1994ApJ...434..557F (https://ui.adsabs.harvard.edu/abs/1994ApJ...434..557F) . doi:10.1086/174758 (https://doi.org/10.1086%2F174758) .

155. *Naeye, R. "Testing Fundamental Physics" (https://www.nasa.gov/mission_pages/GLAST/science/testing_fundamental_physics.html) . NASA. Archived (https://*

web.archive.org/web/20080831045232/http://www.nasa.gov/mission_pages/GLAST/science/testing_fundamental_physics.html) from the original on 31 August 2008. Retrieved 16 September 2008.

156. *Frautschi, S. (1982). "Entropy in an Expanding Universe". Science. **217** (4560): 593–599.*

Bibcode:1982Sci...217..593F
(<https://ui.adsabs.harvard.edu/abs/1982Sci...217..593F>) .
doi:10.1126/science.217.456
0.593 (<https://doi.org/10.1126/science.217.4560.593>) .
PMID 17817517 (<https://pubmed.ncbi.nlm.nih.gov/17817517>) .
S2CID 27717447 (<https://api.semanticscholar.org/CorpusID:27717447>) .
See page 596: table 1 and

*section "black hole decay"
and previous sentence on
that page.*

157. *Page, Don N. (1976).*

*"Particle emission rates from
a black hole: Massless
particles from an uncharged,
nonrotating hole". Physical
Review D. **13** (2): 198–206.
Bibcode:1976PhRvD..13..19
8P (<https://ui.adsabs.harvard.edu/abs/1976PhRvD..13..198P>)*

98P) .

doi:10.1103/PhysRevD.13.198 (https://doi.org/10.1103%2FPhysRevD.13.198) .. See in particular equation (27).

158. *"Black Holes | Science Mission Directorate" (https://science.nasa.gov/astrophysics/focus-areas/black-holes) . NASA. Archived (https://web.archive.org/web/20171117232123/https://science.nasa.gov/astrophysics/focus-ar*

sa.gov/astrophysics/focus-areas/black-holes) from the original on 17 November 2017. Retrieved 17 March 2018.

159. *"April 2017 Observations" (<https://eventhorizontelescope.org/galleries/2017-observations>) . Event Horizon Telescope. Archived (<https://web.archive.org/web/20190410223148/https://eventhorizontelescope.org/galleries/2017-observations>)*

.2017-observations) from the original on 10 April 2019. Retrieved 11 April 2019.

160. Overbye, Dennis (24 January 2024). "That Famous Black Hole Gets a Second Look - Repeated studies of the supermassive black hole in the galaxy Messier 87 confirm that it continues to act as Einstein's theory predicted it would" (h

https://www.nytimes.com/2024/01/24/science/space/black-holes-photography-m87.html) . The New York Times. Archived (https://archive.today/20240124200523/https://www.nytimes.com/2024/01/24/science/space/black-holes-photography-m87.html) from the original on 24 January 2024. Retrieved 25 January 2024.

161. Overbye, Dennis (10 April 2019). "Darkness Visible, Finally: Astronomers Capture First Ever Image of a Black Hole" (<https://www.nytimes.com/2019/04/10/science/black-hole-picture.html>) . The New York Times. Archived (<https://web.archive.org/web/20190521020231/https://www.nytimes.com/2019/04/10/science/black-hole-picture.h>

tml) from the original on 21 May 2019. Retrieved 11 April 2019.

162. *AP (10 April 2019).*

"Astronomers Reveal the First Picture of a Black Hole" (<https://www.nytimes.com/video/science/space/100000006453594/first-image-black-hole.html>) . The New York Times (video). Archived (<https://web.archive.org/we>

b/20190522052307/https://www.nytimes.com/video/science/space/1000000006453594/first-image-black-hole.html) from the original on 22 May 2019. Retrieved 11 April 2019.

163. *Doeleman, Shep (4 April 2016). "The Event Horizon Telescope: Imaging and Time-Resolving a Black Hole" (https://www.youtube.*

com/watch?v=_yGSgUUYYDQ8&t=46m50s) . Physics @ Berkeley. Event occurs at 46:50. Archived (https://web.archive.org/web/20161201115303/https://www.youtube.com/watch?v=_yGSgUUYYDQ8&t=46m50s) from the original on 1 December 2016. Retrieved 8 July 2016.

164. Grossman, Lisa; Conover, Emily (10 April 2010). "The

Emily (10 April 2019). "The first picture of a black hole opens a new era of astrophysics" (<https://www.sciencenews.org/article/black-hole-first-picture-event-horizon-telescope>) . Science News. Archived (<https://web.archive.org/web/20190427192956/https://www.sciencenews.org/article/black-hole-first-picture-event-horizon-telescope>) from the original


*on 27 April 2019. Retrieved
11 April 2019.*

165. *Event Horizon Telescope
Collaboration; Akiyama,
Kazunori; Alberdi, Antxon;
Alef, Walter; Algaba, Juan
Carlos; Anantua, Richard;
Asada, Keiichi; Azulay,
Rebecca; Bach, Uwe;
Baczko, Anne-Kathrin; Ball,
David; Baloković, Mislav;
Barrett, John; Bauböck,*

*Michi; Benson, Bradford A.
(1 May 2022). "First
Sagittarius A* Event Horizon
Telescope Results. I. The
Shadow of the
Supermassive Black Hole in
the Center of the Milky Way"
([https://doi.org/10.3847%2F2041-8213%2Fac6674](https://doi.org/10.3847/2F2041-8213/2Fac6674)) .
The Astrophysical Journal
Letters. **930** (2): L12.
arXiv:2311.08680 (<https://ar>*

*xiv.org/abs/2311.08680)*⁶.
Bibcode:2022ApJ...930L..1
2E (https://ui.adsabs.harvar
d.edu/abs/2022ApJ...930L..
12E) . doi:10.3847/2041-
8213/ac6674 (https://doi.or
g/10.3847%2F2041-8213%
*2Fac6674)*⁶. ISSN 2041-
8205 (*https://search.worldc*
at.org/issn/2041-8205) .
"The ring usually lies near
the gravitationally lensed
photon orbits that define the

photon orbits that define the boundary of what we hereafter refer to as the black hole "shadow." "

166.  *This article incorporates text available under the CC BY 4.0 license. "Astronomers Reveal First Image of the Black Hole at the Heart of Our Galaxy" (<https://eventhorizontelescope.org/blog/astronomers-reveal-first-image-black-hole-heart>*

*first image black hole near
t-our-galaxy) .*

eventhorizontelescope.org.

*12 May 2022. Retrieved
22 June 2022.*

167. C. Bower, Geoffrey (May 2022). "Focus on First Sgr A* Results from the Event Horizon Telescope" (https://iopscience.iop.org/journal/2041-8205/page/Focus_on_First_Sgr_A_Results) . *The Astrophysical Journal Letters*

(2041–8205).

168. *Event Horizon Telescope Collaboration (2021). "First M87 Event Horizon Telescope Results. VII. Polarization of the Ring" (<https://doi.org/10.3847/2041-8213/2Fabe71d>) . The Astrophysical Journal. **910** (1): L12. [arXiv:2105.01169](https://arxiv.org/abs/2105.01169) (<https://arxiv.org/abs/2105.01169>)⁶.*

*Bibcode:2021ApJ...910L..12
E (https://ui.adsabs.harvard.
edu/abs/2021ApJ...910L..12
E) . doi:10.3847/2041-
8213/abe71d (https://doi.or
g/10.3847%2F2041-8213%
2Fabe71d)*⁶.

*S2CID 233851995 (https://
api.semanticscholar.org/Cor
pusID:233851995) .*

169. *Johnson, M. D.; Fish, V. L.;
Doeleman, S. S.; Marrone, D.*

P.; Plambeck, R. L.; Wardle, J. F. C.; Akiyama, K.; Asada, K.; Beaudoin, C. (4 December 2015). "Resolved magnetic-field structure and variability near the event horizon of Sagittarius A". Science. **350** (6265): 1242–1245. arXiv:1512.01220 (<https://arxiv.org/abs/1512.01220>)^o.*

Bibcode:2015Sci...350.1242

J (<https://ui.adsabs.harvard.edu/abs/2015Sci...350.1242J>) .

doi:10.1126/science.aac7087 (<https://doi.org/10.1126%2Fscience.aac7087>) .

PMID 26785487 (<https://pubmed.ncbi.nlm.nih.gov/26785487>) . *S2CID 21730194* (<https://api.semanticscholar.org/CorpusID:21730194>) .

170. *"Event Horizon Telescope*

— — — — —

Reveals Magnetic Fields at Milky Way's Central Black Hole" (<https://www.cfa.harvard.edu/news/2015-28>) .

cfa.harvard.edu. 3

December 2015. Archived (<https://web.archive.org/web/20151231211408/https://www.cfa.harvard.edu/news/2015-28>) from the original on 31 December 2015.

Retrieved 12 January 2016.

171 *Overbye, Dennis (20 April*

1 / 1. Overbye, Dennis (26 April 2023). "A Fresh View of an Increasingly Familiar Black Hole - Radio astronomers have captured a wide-angle image of one of the most violent locales in the cosmos" (<https://www.nytimes.com/2023/04/26/science/astronomy-black-hole-m87.html>) . The New York Times. Archived (<https://archive.today/2023042621293>

2/<https://www.nytimes.com/2023/04/26/science/astronomy-black-hole-m87.html>) from the original on 26 April 2023. Retrieved 26 April 2023.

172. Lu, Ru-Sen; et al. (26 April 2023). "A ring-like accretion structure in M87 connecting its black hole and jet" (<https://www.ncbi.nlm.nih.gov/pmc/articles/PMC10132962>)

. *Nature*. **616** (7958): 686–690. *arXiv:2304.13252* (<https://arxiv.org/abs/2304.13252>)^a.

Bibcode:2023Natur.616..686L (<https://ui.adsabs.harvard.edu/abs/2023Natur.616..686L>) . *doi:10.1038/s41586-023-05843-w* (<https://doi.org/10.1038/s41586-023-05843-w>) .

PMC 10132962 (<https://www>

*w.ncbi.nlm.nih.gov/pmc/articles/PMC10132962)*³.

PMID 37100940 (https://pubmed.ncbi.nlm.nih.gov/37100940) .

173. Overbye, Dennis (11 February 2016). "Physicists Detect Gravitational Waves, Proving Einstein Right" (<https://www.nytimes.com/2016/02/12/science/ligo-gravitational-waves-black-holes-einst>

ein.html) . *The New York Times*. Archived (<https://web.archive.org/web/20160211165128/http://www.nytimes.com/2016/02/12/science/ligo-gravitational-waves-black-holes-einstein.html>) from the original on 11 February 2016. Retrieved 11 February 2016.

174. *Abbott, Benjamin P.; et al. (LIGO Scientific*

Collaboration) "Observation of Gravitational Waves from a Binary Black Hole Merger"

*Collaboration & Virgo
Collaboration) (11 February
2016). "Properties of the
binary black hole merger
GW150914". *Physical
Review Letters*. **116** (24):
241102. *arXiv:1602.03840* (
<https://arxiv.org/abs/1602.03840>)[ⓘ].*

*Bibcode:2016PhRvL.116x11
02A* (<https://ui.adsabs.harvard.edu/abs/2016PhRvL.116x1102A>)

Phys Rev Lett .

doi:10.1103/PhysRevLett.116.241102 (<https://doi.org/10.1103/PhysRevLett.116.241102>) . PMID 27367378 (<https://pubmed.ncbi.nlm.nih.gov/27367378/>) .

S2CID 217406416 (<https://api.semanticscholar.org/CorpusID:217406416>) .

175. Cardoso, V.; Franzin, E.; Pani, P. (2016). "*Is the gravitational-wave ringdown*

~ ~

*a probe of the event horizon?". Physical Review Letters. **116** (17): 171101. arXiv:1602.07309 (<https://arxiv.org/abs/1602.07309>)⁶. Bibcode:2016PhRvL.116q1101C (<https://ui.adsabs.harvard.edu/abs/2016PhRvL.116q1101C>) . doi:10.1103/PhysRevLett.116.171101 (<https://doi.org/10.1103/PhysRevLett.116.171101>)*

01) . PMID 27176511 (<http://pubmed.ncbi.nlm.nih.gov/27176511>) .

S2CID 206273829 (<https://api.semanticscholar.org/CorpusID:206273829>) .

176. *Abbott, Benjamin P.; et al. (LIGO Scientific Collaboration & Virgo Collaboration) (11 February 2016). "Tests of general relativity with GW150914" (h*

<https://web.archive.org/web/20160215165039/https://dcc.ligo.org/P1500213/public>) . *Physical Review Letters*. **116** (22): 221101.

arXiv:1602.03841 (<https://arxiv.org/abs/1602.03841>)^g.

Bibcode:2016PhRvL.116v1101A (<https://ui.adsabs.harvard.edu/abs/2016PhRvL.116v1101A>) .

doi:10.1103/PhysRevLett.116
221101 (<https://doi.org/10.1103/PhysRevLett.116.221101>)

.221101 (<https://doi.org/10.1103%2FPhysRevLett.116.221101>) . PMID 27314708 (<https://pubmed.ncbi.nlm.nih.gov/27314708>) .

S2CID 217275338 (<https://api.semanticscholar.org/CorpusID:217275338>) . Archived from the original (<https://dcc.ligo.org/P1500213/public>) on 15 February 2016.

Retrieved 12 February 2016.

177 *Murk Sebastian (2023)*

177. MURK, Sebastian (2023).

*"Nomen non est omen: Why it is too soon to identify ultra-compact objects as black holes". International Journal of Modern Physics D. **32** (14): 2342012–2342235. arXiv:2210.03750 (<https://arxiv.org/abs/2210.03750>)³.*

Bibcode:2023IJMPD..3242012M (<https://ui.adsabs.harvard.edu/abs/2023IJMPD..3242012M>)

42012M) .

doi:10.1142/S02182718234

20129 (<https://doi.org/10.11>

42%2FS021827182342012

9) . S2CID 252781040 (<http>

s://api.semanticscholar.org/

CorpusID:252781040) .

178. *Abbott, B. P.; et al. (LIGO Scientific Collaboration & Virgo Collaboration) (2016). "Astrophysical Implications of the Binary Black Hole*

*Merger GW150914" ([https://
dcc.ligo.org/P1500262/public](https://dcc.ligo.org/P1500262/public)) . *Astrophys. J. Lett.* **818**
(2): L22. *arXiv:1602.03846*
(<https://arxiv.org/abs/1602.03846>)³.*

Bibcode:2016ApJ...818L..22
A ([https://ui.adsabs.harvard.
edu/abs/2016ApJ...818L..22](https://ui.adsabs.harvard.edu/abs/2016ApJ...818L..22A)
A) . *doi:10.3847/2041-*
8205/818/2/L22 ([https://do
i.org/10.3847%2F2041-820](https://doi.org/10.3847/2041-8205/818/2/L22)

5%2F818%2F2%2FL22)³.
 hdl:1826/11732 ([https://hdl.
 handle.net/1826%2F11732](https://hdl.handle.net/1826%2F11732))
 . S2CID 209315965 ([http
 s://api.semanticscholar.org/
 CorpusID:209315965](http://api.semanticscholar.org/CorpusID:209315965)) .
 Archived ([https://web.archiv
 e.org/web/2016031605393
 8/https://dcc.ligo.org/P1500
 262/public](https://web.archive.org/web/20160316053938/https://dcc.ligo.org/P1500262/public)) from the
 original on 16 March 2016.

179. "Detection of gravitational

" " " " " "

waves" (<https://www.ligo.org/detections.php>) . LIGO. Archived (<https://web.archive.org/web/20200520134427/https://www.ligo.org/detections.php>) from the original on 20 May 2020. Retrieved 9 April 2018.

180. *Gillessen, S.; Eisenhauer, F.; Trippe, S.; et al. (2009). "Monitoring Stellar Orbits around the Massive Black Hole in the Galactic Center"*

Hole in the Galactic Center .

The Astrophysical Journal.

692 (2): 1075–1109.

arXiv:0810.4674 (<https://arxiv.org/abs/0810.4674>)³.

Bibcode:2009ApJ...692.107

5G ([https://ui.adsabs.harvard.edu/abs/2009ApJ...692.1](https://ui.adsabs.harvard.edu/abs/2009ApJ...692.1075G)

075G) . doi:10.1088/0004-

637X/692/2/1075 ([https://d](https://doi.org/10.1088%2F0004-637X%2F692%2F2%2F1075)

oi.org/10.1088%2F0004-63

7X%2F692%2F2%2F1075)

. S2CID 1431308 (<https://ap>

i.semanticscholar.org/CorpusID:1431308) .

181. *Ghez, A. M.; Klein, B. L.; Morris, M.; et al. (1998). "High Proper-Motion Stars in the Vicinity of Sagittarius A*: Evidence for a Supermassive Black Hole at the Center of Our Galaxy". The Astrophysical Journal. 509 (2): 678–686. arXiv:astro-ph/9807210 (htt*

ps://arxiv.org/abs/astro-ph/9807210)^a.

Bibcode:1998ApJ...509..678G (https://ui.adsabs.harvard.edu/abs/1998ApJ...509..678G) . doi:10.1086/306528 (https://doi.org/10.1086%2F306528) .

S2CID 18243528 (https://api.semanticscholar.org/CorpusID:18243528) .

182. *Broderick, Avery; Loeb,*

*Abraham; Narayan, Ramesh
(August 2009). "The Event
Horizon of Sagittarius A*".*

The Astrophysical Journal.

701 (2): 1357–1366.

arXiv:0903.1105 (<https://arxiv.org/abs/0903.1105>)⁶.

*Bibcode:2009ApJ...701.135
7B* (<https://ui.adsabs.harvard.edu/abs/2009ApJ...701.1357B>) . doi:10.1088/0004-
637X/701/2/1357 (<https://doi.org/10.1088/0004-637X/701/2/1357>)

oi.org/10.1088%2F0004-637X%2F701%2F2%2F1357) .
S2CID 12991878 (<https://api.semanticscholar.org/CorpusID:12991878>) .

183. *"NASA's NuSTAR Sees Rare Blurring of Black Hole Light"* (<https://web.archive.org/web/20140813072002/http://www.jpl.nasa.gov/news/news.php?release=2014-273>) .
NASA. 12 August 2014.

.....

*Archived from the original (<https://www.jpl.nasa.gov/news/news.php?release=2014-273>) on 13 August 2014.
Retrieved 12 August 2014.*

184. *"Researchers clarify dynamics of black hole rotational energy" (<https://phys.org/news/2018-02-dynamics-black-hole-rotational-energy.html>) . Archived (<https://web.archive.org/web/20180217105220/https://phys.org/news/2018-02-dynamics-black-hole-rotational-energy.html>)*

80917/105550/https://phys.org/news/2018-02-dynamics-black-hole-rotational-energy.html) from the original on 17 September 2018.
Retrieved 17 September 2018.

185. Marck, Jean-Alain (1 March 1996). "Short-cut method of solution of geodesic equations for Schwarzschild black hole". *Classical and Quantum Gravity* **13** (3).

Quantum Gravity. 13 (3).
393–402. arXiv:gr-
qc/9505010 (<https://arxiv.org/abs/gr-qc/9505010>)³.
Bibcode:1996CQGra..13..39
3M (<https://ui.adsabs.harvard.edu/abs/1996CQGra..13..393M>) . doi:10.1088/0264-
9381/13/3/007 (<https://doi.org/10.1088%2F0264-9381%2F13%2F3%2F007>) .
ISSN 0264-9381 ([https://se
arch.worldcat.org/issn/0264](https://search.worldcat.org/issn/0264)

-9381) . S2CID 119508131 (
<https://api.semanticscholar.org/CorpusID:119508131>) .

186. *McClintock, J. E.; Remillard, R. A. (2006). "Black Hole Binaries". In Lewin, W.; van der Klis, M. (eds.). Compact Stellar X-ray Sources. p. 157. arXiv:astro-ph/0306213 (<https://arxiv.org/abs/astro-ph/0306213>)^a.*

Bibcode:2006csxs.book..15

7M (<https://ui.adsabs.harvard.edu/abs/2006csxs.book..157M>) . ISBN 978-0-521-82659-4. section 4.1.5.

187. *"What powers a black hole's mighty jets?"* (<https://www.science.org/content/article/what-powers-black-holes-mighty-jets>) . Science | AAAS. 19 November 2014.

Archived (<https://web.archive.org/web/2019050517121>

7/https://www.sciencemag.org/news/2014/11/what-powers-black-holes-mighty-jets) from the original on 5 May 2019. Retrieved 19 March 2018.

188. Celotti, A.; Miller, J. C.; Sciama, D. W. (1999). "Astrophysical evidence for the existence of black holes" (<https://cds.cern.ch/record/411555/files/9912186.pdf>)

(PDF). Classical and
Quantum Gravity. **16** (12A):
A3 – A21. arXiv:astro-
ph/9912186 (<https://arxiv.org/abs/astro-ph/9912186>)^g.
Bibcode:1999CQGra..16A...
3C (<https://ui.adsabs.harvard.edu/abs/1999CQGra..16A...3C>) . doi:10.1088/0264-9381/16/12A/301 (<https://doi.org/10.1088%2F0264-9381%2F16%2F12A%2F301>) .
C2CID 17677759 (<https://or>

Corpus ID: 17677758 (<https://api.semanticscholar.org/CorpusID:17677758>) . Archived (<https://web.archive.org/web/20180727052939/https://cds.cern.ch/record/411555/files/9912186.pdf>) (PDF) from the original on 27 July 2018. Retrieved 27 July 2018.

189. Winter, L. M.; Mushotzky, R. F.; Reynolds, C. S. (2006). "XMM-Newton Archival Study of the Ultraluminous

*Study of the Circumnuclear
X-Ray Population in Nearby
Galaxies". The Astrophysical
Journal. **649** (2): 730–752.
arXiv:astro-ph/0512480 (<https://arxiv.org/abs/astro-ph/0512480>)⁶.*

Bibcode:2006ApJ...649..730W (<https://ui.adsabs.harvard.edu/abs/2006ApJ...649..730W>) . doi:10.1086/506579 (<https://doi.org/10.1086%2F506579>) .

S2CID 118445260 (<https://api.semanticscholar.org/CorpusID:118445260>) .

190. *information@eso.org.*

*"Hubble directly observes
the disk around a black hole"
(<https://www.spacetelescope.org/news/heic1116/>) .*

www.spacetelescope.org.

Archived (<https://web.archive.org/web/20160308001224/http://spacetelescope.org/>

news/heic1116/) from the original on 8 March 2016. Retrieved 7 March 2016.

191. *Muñoz, José A.; Mediavilla, Evencio; Kochanek, Christopher S.; Falco, Emilio; Mosquera, Ana María (1 December 2011). "A Study of Gravitational Lens Chromaticity with the Hubble Space Telescope". The Astrophysical Journal.*

742 (2): 67. *arXiv:1107.5932*
(<https://arxiv.org/abs/1107.5932>)⁶.

Bibcode:2011ApJ...742...67
M (<https://ui.adsabs.harvard.edu/abs/2011ApJ...742...67M>) . doi:10.1088/0004-637X/742/2/67 (<https://doi.org/10.1088%2F0004-637X%2F742%2F2%2F67>) .

S2CID 119119359 (<https://api.semanticscholar.org/CorpusID:119119359>)

USID:119119359) .

192. *Rolston, B. (10 November 1997). "The First Black Hole" (https://web.archive.org/web/20080502230214/http://news.utoronto.ca/bin/bulletin/nov10_97/art4.htm) . The bulletin. University of Toronto. Archived from the original (http://news.utoronto.ca/bin/bulletin/nov10_97/art4.htm) on 2 May 2008. Retrieved 11 March 2008*

RETRIEVED 11 MARCH 2008.

193. *"NASA scientists identify smallest known black hole" (https://web.archive.org/web/20081227195554/http://www.eurekalert.org/pub_releases/2008-04/nsfc-nsi040108.php) (Press release). Goddard Space Flight Center. 1 April 2008. Archived from the original (http://www.eurekalert.org/pub_releases/2008-04/nsfc-nsi*

*.../2008/01/15/040108.php) on 27
December 2008. Retrieved
14 March 2009.*

194. *Chou, Felicia; Anderson, Janet; Watzke, Megan (5 January 2015). "RELEASE 15-001 – NASA's Chandra Detects Record-Breaking Outburst from Milky Way's Black Hole" (<https://www.nasa.gov/press/2015/january/nasa-s-chandra-detects-reco>*

rd-breaking-outburst-from-milky-way-s-black-hole/) .
NASA. Archived (*<https://web.archive.org/web/20150106100532/http://www.nasa.gov/press/2015/january/nasa-s-chandra-detects-record-breaking-outburst-from-milky-way-s-black-hole/>*) from the original on 6 January 2015. Retrieved 6 January 2015.

195. *Krolik, J. H. (1999). Active Galactic Nuclei (<https://books.google.com/books?id=oRK8otMiWlgC&q=Active+Galactic+Nuclei>) . Princeton University Press. Ch. 1.2. ISBN 978-0-691-01151-6. Archived (<https://web.archive.org/web/20210814220336/https://books.google.com/books?id=oRK8otMiWlgC&q=Active+Galactic+Nuclei>)*

*from the original on 14
August 2021. Retrieved
16 October 2020.*

196. *Sparke, L. S.; Gallagher, J. S. (2000). Galaxies in the Universe: An Introduction (<https://books.google.com/books?id=N8Hngab5liQC&q=Galaxies+in+the+Universe:+An+Introduction>) . Cambridge University Press. Ch. 9.1. ISBN 978-0-521-59740-1.*

Archived (<https://web.archive.org/web/20220322141933/https://books.google.com/books?id=N8Hngab5liQC&q=Galaxies+in+the+Universe%3A+An+Introduction>) from the original on 22 March 2022. Retrieved 16 October 2020.

197. *Kormendy, J.; Richstone, D. (1995). "Inward Bound – The Search For Supermassive*

*Black Holes In Galactic Nuclei". Annual Review of Astronomy and Astrophysics. **33** (1): 581–624.*

Bibcode:1995ARA&A..33..581K (<https://ui.adsabs.harvard.edu/abs/1995ARA&A..33..581K>) .

doi:10.1146/annurev.aa.33.090195.003053 (<https://doi.org/10.1146%2Fannurev.aa.33.090195.003053>) .

....., .

198. *King, A. (2003). "Black Holes, Galaxy Formation, and the MBH- σ Relation". The Astrophysical Journal Letters. **596** (1): 27–29. [arXiv:astro-ph/0308342](https://arxiv.org/abs/astro-ph/0308342) (<https://arxiv.org/abs/astro-ph/0308342>)^a.
Bibcode:2003ApJ...596L..27K (<https://ui.adsabs.harvard.edu/abs/2003ApJ...596L..27K>) . *doi:10.1086/379143* (*

<https://doi.org/10.1086%2F379143>) . S2CID 9507887 (<https://api.semanticscholar.org/CorpusID:9507887>) .

199. *Ferrarese, L.; Merritt, D. (2000). "A Fundamental Relation Between Supermassive Black Holes and their Host Galaxies". The Astrophysical Journal Letters. **539** (1): 9–12. arXiv:astro-ph/0006053 (ht*

tps://arxiv.org/abs/astro-ph/0006053)³.

Bibcode:2000ApJ...539L...9 F (https://ui.adsabs.harvard.edu/abs/2000ApJ...539L...9 F) . doi:10.1086/312838 (https://doi.org/10.1086%2F312838) . S2CID 6508110 (https://api.semanticscholar.org/CorpusID:6508110) .

200. *Bennett, D. P.; Becker, A. C.; Quinn, J. L.; Tomaney, A. B.;*

*Alcock, C.; Allsman, R. A.;
Alves, D. R.; Axelrod, T. S.;
Calitz, J. J.; Cook, K. H.;
Drake, A. J.; Fragile, P. C.;
Freeman, K. C.; Geha, M.;
Griest, K. (1 November
2002). "Gravitational
Microlensing Events Due to
Stellar-Mass Black Holes" ([https://ui.adsabs.harvard.edu/
abs/2002ApJ...579..639B/a
bstract](https://ui.adsabs.harvard.edu/abs/2002ApJ...579..639B/abstract)) . *The Astrophysical**

Journal. **579** (2): 639–659.
arXiv:astro-ph/0109467 (<https://arxiv.org/abs/astro-ph/0109467>)^g.

Bibcode:2002ApJ...579..639B (<https://ui.adsabs.harvard.edu/abs/2002ApJ...579..639B>) . *doi:10.1086/342225* (<https://doi.org/10.1086%2F342225>) . *ISSN 0004-637X* (<https://search.worldcat.org/issn/0004-637X>) .

2014 *Massachusetts Institute of Technology*

2011. Mao, Snude; Smith, Martin C.; Woźniak, P.; Udalski, A.; Szymański, M.; Kubiak, M.; Pietrzyński, G.; Soszyński, I.; Żebruń, K. (1 January 2002). "Optical Gravitational Lensing Experiment OGLE-1999-BUL-32: the longest ever microlensing event - evidence for a stellar mass black hole?" (<https://doi.org/10.1046%2Fj.1365-8711.2002.04986.x>) . Monthlv

*Notices of the Royal
Astronomical Society.* **329**
(2): 349–354. *arXiv:astro-
ph/0108312* (<https://arxiv.org/abs/astro-ph/0108312>)^a.
Bibcode:2002MNRAS.329..
349M ([https://ui.adsabs.harvard.edu/abs/2002MNRAS.](https://ui.adsabs.harvard.edu/abs/2002MNRAS.329..349M)
329..349M) .
doi:10.1046/j.1365-
8711.2002.04986.x ([https://](https://doi.org/10.1046%2Fj.1365-8)
doi.org/10.1046%2Fj.1365-8

711.2002.04986.x)³.

ISSN 0035-8711 (<https://search.worldcat.org/issn/0035-8711>) .

202. Sahu, K. C. (2022). "An Isolated Stellar-Mass Black Hole Detected Through Astrometric Microlensing" (<https://doi.org/10.3847/1538-4357/2F1538-4357/2Fac739e>) . *Astrophysical Journal*. **933** (1): 83. *arXiv:2201.13296* (<https://arxiv.org/abs/2201.13296>)

<https://arxiv.org/abs/2201.13296>)⁶.

Bibcode:2022ApJ...933...83S (<https://ui.adsabs.harvard.edu/abs/2022ApJ...933...83S>) . *doi:10.3847/1538-4357/ac739e* (<https://doi.org/10.3847%2F1538-4357%2Fac739e>)⁶.

S2CID 246430448 (<https://api.semanticscholar.org/CorpusID:246430448>) .

203. *Bozza, V. (2010).*

*"Gravitational Lensing by
Black Holes". General
Relativity and Gravitation. **42**
(9): 2269–2300.*

arXiv:0911.2187 (<https://arxiv.org/abs/0911.2187>)^o.

*Bibcode:2010GReGr..42.22
69B ([https://ui.adsabs.harvard.edu/abs/2010GReGr..42.
2269B](https://ui.adsabs.harvard.edu/abs/2010GReGr..42.2269B)) .*

*doi:10.1007/s10714-010-
0000-2 ([https://doi.org/10.1](https://doi.org/10.1007/s10714-010-0000-2)*

0900-2 (<https://doi.org/10.1007%2Fs10714-010-0988-2>) . S2CID 118635353 (<http://api.semanticscholar.org/CorpusID:118635353>) .

204. Kovacs, Z.; Cheng, K. S.; Harko, T. (2009). "Can stellar mass black holes be quark stars?" (<https://doi.org/10.1111%2Fj.1365-2966.2009.15571.x>) . *Monthly Notices of the Royal Astronomical Society* **400**

Astronomical Society. 400

(3): 1632–1642.

arXiv:0908.2672 (<https://arxiv.org/abs/0908.2672>)[ⓘ].

Bibcode:2009MNRAS.400.1632K (<https://ui.adsabs.harvard.edu/abs/2009MNRAS.400.1632K>) .

doi:10.1111/j.1365-2966.2009.15571.x (<https://doi.org/10.1111%2Fj.1365-2966.2009.15571.x>)[ⓘ].

S2CID 18263809 (<https://a>

pi.semanticscholar.org/CorpusID:18263809 .

205. *Kusenko, A. (2006).*

"Properties and signatures of supersymmetric Q-balls". arXiv:hep-ph/0612159 (<http://arxiv.org/abs/hep-ph/0612159>)⁶.

206. *Hansson, J.; Sandin, F.*

(2005). "Preon stars: a new class of cosmic compact objects". Physics Letters B.

616 (1–2): 1–7. *arXiv:astro-ph/0410417* (<https://arxiv.org/abs/astro-ph/0410417>)³.

Bibcode:2005PhLB..616....1H (<https://ui.adsabs.harvard.edu/abs/2005PhLB..616....1H>) .

doi:10.1016/j.physletb.2005.04.034 (<https://doi.org/10.1016%2Fj.physletb.2005.04.034>) . S2CID 119063004 (<https://api.semanticscholar.org>

g/CorpusID:119063004) .

207. *Kiefer, C. (2006). "Quantum gravity: general introduction and recent developments". Annalen der Physik. **15** (1–2): 129–148. arXiv:gr-qc/0508120 (<https://arxiv.org/abs/gr-qc/0508120>)^g. Bibcode:2006AnP...518..129 K (<https://ui.adsabs.harvard.edu/abs/2006AnP...518..129K>)* .

doi:10.1002/andp.200510175 (<https://doi.org/10.1002%2Fandp.200510175>) .

S2CID 12984346 (<https://api.semanticscholar.org/CorpusID:12984346>) .

208. *Mathur, Samir D. (2005).*

*"The fuzzball proposal for black holes: an elementary review". Fortschritte der Physik. **53** (7–8): 793.*

arXiv:hep-th/0502050 ([http](http://arxiv.org/abs/hep-th/0502050)

s://arxiv.org/abs/hep-th/0502050)⁶.

Bibcode:2005ForPh..53..793M (https://ui.adsabs.harvard.edu/abs/2005ForPh..53..793M) .

doi:10.1002/prop.200410203 (https://doi.org/10.1002/2Fprop.200410203) .

S2CID 15083147 (https://api.semanticscholar.org/CorpusID:15083147) .

200 Alexander K. Taylor M

209. Skenderis, K.; Taylor, M.
 (2008). "The fuzzball
 proposal for black holes".
Physics Reports. **467** (4–5):
 117. arXiv:0804.0552 (<http://arxiv.org/abs/0804.0552>)^a.
Bibcode:2008PhR...467..117
S (<https://ui.adsabs.harvard.edu/abs/2008PhR...467..117S>) .
doi:10.1016/j.physrep.2008.08.001 (<https://doi.org/10.1016/j.physrep.2008.08.001>)

16%2Fj.physrep.2008.08.001) . S2CID 118403957 (<https://api.semanticscholar.org/CorpusID:118403957>) .

210. Mazur, Pawel O.; Mottola, Emil (2004). "Gravitational vacuum condensate stars" (<https://www.ncbi.nlm.nih.gov/pmc/articles/PMC470711>) . *Proceedings of the National Academy of Sciences of the United*

*States of America. **101** (26):
9545–9550. arXiv:gr-
qc/0407075 (<https://arxiv.org/abs/gr-qc/0407075>)[ⓐ].*

*Bibcode:2004PNAS..101.95
45M ([https://ui.adsabs.harv
ard.edu/abs/2004PNAS..10
1.9545M](https://ui.adsabs.harvard.edu/abs/2004PNAS..101.9545M)) .*

*doi:10.1073/pnas.04027171
01 ([https://doi.org/10.1073%
2Fpnas.0402717101](https://doi.org/10.1073%2Fpnas.0402717101))[ⓐ].*

PMC 470711 (<https://www.n>

*cbi.nlm.nih.gov/pmc/articles/PMC470711)*⁶.

PMID 15210982 (https://pubmed.ncbi.nlm.nih.gov/15210982) . S2CID 2607263 (https://api.semanticscholar.org/CorpusID:2607263) .

211. *Choi, Charles Q. (2018). "Black Hole Pretenders Could Really Be Bizarre Quantum Stars" (https://www.scientificamerican.com/art*

icle/black-hole-pretenders-could-really-be-bizarre-quantum-stars/) . Scientific American. Archived (<https://web.archive.org/web/20190617164631/https://www.scientificamerican.com/article/black-hole-pretenders-could-really-be-bizarre-quantum-stars/>) from the original on 17 June 2019. Retrieved 17 March 2018.

240 11 2019 10:51

212. *McRae, Mike (20 February 2024). "Bubble-Like 'Stars Within Stars' Could Explain Black Hole Weirdness" (<https://www.sciencealert.com/bubble-like-stars-within-stars-could-explain-black-hole-weirdness>) . ScienceAlert. Archived (<https://archive.today/20240220150012/https://www.sciencealert.com/bubble-like-stars-within-stars-could-explain-black-hole-w>*

*could explain black hole weirdness) from the original on 20 February 2024.
Retrieved 20 February 2024.*

213. *Ball, Philip (31 March 2005). "Black holes 'do not exist' ". Nature.
doi:10.1038/news050328-8
(<https://doi.org/10.1038%2Fnews050328-8>) .*

214. *Hawking, S. W. (1971). "Gravitational Radiation from*

*Gravitational Radiation from
Colliding Black Holes".*

*Physical Review Letters. 26
(21): 1344–1346.*

Bibcode:1971PhRvL..26.1344H (<https://ui.adsabs.harvard.edu/abs/1971PhRvL..26.1344H>) .

doi:10.1103/PhysRevLett.26.1344 (<https://doi.org/10.1103/PhysRevLett.26.1344>)

.

215. *Wald. R. M. (2001). "The*

Thermodynamics of Black Holes" (<https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5253844>) . *Living Reviews in Relativity*. **4** (1): 6.

arXiv:gr-qc/9912119 (<https://arxiv.org/abs/gr-qc/9912119>)[ⓘ].

Bibcode:2001LRR.....4....6W
(<https://ui.adsabs.harvard.edu/abs/2001LRR.....4....6W>) .
doi:10.12942/lrr-2001-6 (<http://www.lrr-2001-6.org>)

ps://doi.org/10.12942%2Flrr-2001-6)[Ⓐ]. *PMC 5253844 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5253844)*[Ⓐ]. *PMID 28163633 (https://pubmed.ncbi.nlm.nih.gov/28163633)* .

216. *'t Hooft, G. (2001). "The Holographic Principle". In Zichichi, A. (ed.). Basics and Highlights in Fundamental Physics. Subnuclear series.*

005) . ISBN 978-981-02-4536-8. S2CID 119383028 (<https://api.semanticscholar.org/CorpusID:119383028>) .

217. Strominger, A.; Vafa, C. (1996). "Microscopic origin of the Bekenstein-Hawking entropy". *Physics Letters B*. **379** (1–4): 99–104. *arXiv:hep-th/9601029* (<http://arxiv.org/abs/hep-th/9601029>)^o.

Physics Letters B 379 (1996) 99–104

DISCUSS. 1996PHLB..379...99S (https://ui.adsabs.harvard.edu/abs/1996PhLB..379...99S) . doi:10.1016/0370-2693(96)00345-0 (https://doi.org/10.1016%2F0370-2693%2896%2900345-0) . S2CID 1041890 (https://api.semanticscholar.org/CorpusID:1041890) .

218. *Carlip, S. (2009). "Black Hole Thermodynamics and Statistical Mechanics"*

Statistical Mechanics .

Physics of Black Holes.

Lecture Notes in Physics.

Vol. 769. Berlin: Springer.

pp. 89–123.

arXiv:0807.4520 (<https://arxiv.org/abs/0807.4520>)⁶.

Bibcode:2009LNP...769...89C (<https://ui.adsabs.harvard.edu/abs/2009LNP...769...89C>) . doi:10.1007/978-3-540-88460-6_3 (<https://doi.org/10.1007%2F978-3-54>

0-88460-6_3) . ISBN 978-3-540-88459-0.

S2CID 15877702 (<https://api.semanticscholar.org/CorpusID:15877702>) .

219. *Hawking, S. W. "Does God Play Dice?"* (<https://web.archive.org/web/20120111012413/http://www.hawking.org.uk/does-god-play-dice.html>) . www.hawking.org.uk.
Archived from the original (h

ttp://www.hawking.org.uk/does-god-play-dice.html) on 11 January 2012. Retrieved 14 March 2009.

220. *Giddings, S. B. (1995). "The black hole information paradox". Particles, Strings and Cosmology. Johns Hopkins Workshop on Current Problems in Particle Theory 19 and the PASCOS Interdisciplinary Symposium*

5. *arXiv:hep-th/9508151* (<https://arxiv.org/abs/hep-th/9508151>)³.

Bibcode:1995hep.th....8151 G (<https://ui.adsabs.harvard.edu/abs/1995hep.th....8151G>) .

221. *Unruh, William G.; Wald, Robert M. (2017).*

*"Information loss". Reports on Progress in Physics. **80** (9): 092002.*

arXiv:1703.02140 (<https://arxiv.org/abs/1703.02140>)⁶.

Bibcode:2017RPPh...80i2002U (<https://ui.adsabs.harvard.edu/abs/2017RPPh...80i2002U>) . doi:10.1088/1361-6633/aa778e (<https://doi.org/10.1088%2F1361-6633%2Faa778e>) .

PMID 28585922 (<https://pubmed.ncbi.nlm.nih.gov/28585922>) . S2CID 39957660 (<https://orcid.org/0000-0001-9146-0001>)

<https://api.semanticscholar.org/CorpusID:39957660> .

222. *Mathur, S. D. (2011). The information paradox: conflicts and resolutions. XXV International Symposium on Lepton Photon Interactions at High Energies. Pramana. Vol. 79, no. 5. pp. 1059–1073. arXiv:1201.2079 (https://arxiv.org/abs/1201.2079)⁶. Bibcode:2012Prama 79105*

9M (<https://ui.adsabs.harvard.edu/abs/2012Prama..79.1059M>) .

doi:10.1007/s12043-012-0417-z (<https://doi.org/10.1007/s12043-012-0417-z>) .

223. *Page, Don N. (1993).*

*"Information in black hole radiation". Phys. Rev. Lett. **71** (23): 3743–3746. arXiv:hep-th/9306083 (<https://arxiv.org>*

g/abs/hep-th/9306083)^g.

Bibcode:1993PhRvL..71.374

3P (https://ui.adsabs.harvard.edu/abs/1993PhRvL..71.3743P) .

CiteSeerX 10.1.1.267.174 (https://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.267.174)^g.

doi:10.1103/PhysRevLett.71.3743 (https://doi.org/10.1103/PhysRevLett.71.3743)

. PMID 10055062 (<https://pubmed.ncbi.nlm.nih.gov/10055062>) . S2CID 9363821 (<https://api.semanticscholar.org/CorpusID:9363821>) .

224. *Page, Don N. (1993). "Average entropy of a subsystem". Phys. Rev. Lett. **71** (9): 1291–1294. arXiv:gr-qc/9305007 (<https://arxiv.org/abs/gr-qc/9305007>)⁶. Bibcode:1993PhRvL..71.129*

1P (<https://ui.adsabs.harvard.edu/abs/1993PhRvL..71.1291P>) .

CiteSeerX 10.1.1.339.7694 (<https://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.339.7694>)^a.

doi:10.1103/PhysRevLett.71.1291 (<https://doi.org/10.1103/PhysRevLett.71.1291>) .

PMID 10055503 (<https://pubmed.ncbi.nlm.nih.gov/10055503/>) .

5503) . SZCID 17058654 (<https://api.semanticscholar.org/CorpusID:17058654>) .

225. Merali, Zeeya (3 April 2013). "Astrophysics: Fire in the hole!" (<https://doi.org/10.1038%2F496020a>) . *Nature*. **496** (7443): 20–23. Bibcode:2013Natur.496...20M (<https://ui.adsabs.harvard.edu/abs/2013Natur.496...20M>) . doi:10.1038/496020a (<https://doi.org/10.1038/496020a>)

[doi:10.1038/496020a](https://doi.org/10.1038/496020a) (<https://doi.org/10.1038/496020a>)³. PMID 23552926 (<https://pubmed.ncbi.nlm.nih.gov/23552926>) .

226. *Amheiri, Ahmed; Marolf, Donald; Polchinski, Joseph; Sully, James (2013). "Black holes: Complementarity or Firewalls?". Journal of High Energy Physics. **2013** (2): 62. arXiv:1207.3123 (<https://arxiv.org/abs/1207.3123>)³.*

<https://ui.adsabs.harvard.edu/abs/2013JHEP...02..062A> .

Bibcode:2013JHEP...02..06

2A ([https://ui.adsabs.harvar](https://ui.adsabs.harvard.edu/abs/2013JHEP...02..062A)

[d.edu/abs/2013JHEP...02..0](https://ui.adsabs.harvard.edu/abs/2013JHEP...02..062A)

[62A](https://ui.adsabs.harvard.edu/abs/2013JHEP...02..062A)) .

doi:10.1007/JHEP02(2013)

062 ([https://doi.org/10.100](https://doi.org/10.1007/JHEP02(2013)062)


[7%2FJHEP02%282013%29](https://doi.org/10.1007/JHEP02(2013)062)

[062](https://doi.org/10.1007/JHEP02(2013)062)) . S2CID 55581818 ([htt](https://api.semanticscholar.org/CorpusID:55581818)

[ps://api.semanticscholar.or](https://api.semanticscholar.org/CorpusID:55581818)

[g/CorpusID:55581818](https://api.semanticscholar.org/CorpusID:55581818)) .

Sources

- Carroll, Sean M. (2004).
Spacetime and Geometry.
Addison Wesley. ISBN 978-0-
8053-8732-2., the lecture
notes on which the book was
based are available for free from
Sean Carroll's website ([https://w
ww.preposterousuniverse.com/s
pacetimeandgeometry/](https://www.preposterousuniverse.com/spacetimeandgeometry/)).

Archived (<https://web.archive.org/web/20170323013522/http://www.preposterousuniverse.com/spacetimeandgeometry/>).²³
March 2017 at the Wayback Machine

- Hawking, S. W.; Ellis, G. F. R.
(1973). *Large Scale Structure of space time* (https://books.google.com/books?id=QagG_KI7LI8C).²⁴ Cambridge University Press.
ISBN 978-0-521-09906-6.

Archived (https://web.archive.org/web/20200721064932/http://books.google.com/books?id=QagG_KI7LI8C)[🔗] from the original on 21 July 2020.

Retrieved 16 May 2020.

- Misner, Charles; Thorne, Kip S.; Wheeler, John (1973).

Gravitation. W. H. Freeman and Company. ISBN 978-0-7167-0344-0.


- Thorne, Kip S. (1994). *Black Holes and Time Warps*. Norton, W. W. & Company, Inc.
ISBN 978-0-393-31276-8.
- Wald, Robert M. (1984). *General Relativity* (<https://books.google.com/books?id=9S-hzg6-moYC>). University of Chicago Press.
ISBN 978-0-226-87033-5.
Archived (<https://web.archive.org/web/20160811035125/http://books.google.com/books?id=9S-hzg6-moYC>).

=9S-hzg6-moYC). from the
original on 11 August 2016.
Retrieved 23 February 2016.


- Wheeler, J. Craig (2007).
Cosmic Catastrophes (2nd ed.).
Cambridge University Press.
ISBN 978-0-521-85714-7.

Further reading

Popular reading

- Begelman, Mitchell C.; Rees, Martin J. (2021). *Gravity's fatal attraction: black holes in the universe* (<https://books.google.com/books?id=ZPwAEAAAQBAJ>)  (3rd ed.). Cambridge, United Kingdom ; New York, NY: Cambridge University Press. ISBN 978-1-108-87112-9.
- Ferguson, Kitty (1991). *Black Holes in Space-Time*. Watts Franklin. ISBN 978-0-531-

12524-3.

- Hawking, Stephen (1988). A Brief History of Time. Bantam Books, Inc. ISBN 978-0-553-38016-3.
- Hawking, Stephen; Penrose, Roger (1996). The Nature of Space and Time (<https://books.google.com/books?id=LstaQTXP65cC>).  Princeton University Press. ISBN 978-0-691-

03791-2. Archived (<https://web.archive.org/web/20211018031528/https://books.google.com/books?id=LstaQTXP65cC>).[🔗] from the original on 18 October 2021. Retrieved 16 May 2020.

- Levin, Janna (2020). *Black hole survival guide* (<https://books.google.com/books?id=9rITEAAQBAJ>).[🔗] New York: Alfred A. Knopf. ISBN 978-0-525-65822-1. Archived (<https://web.archive.org/web/20211018031528/https://books.google.com/books?id=9rITEAAQBAJ>).[🔗]

[archive.org/web/20220322141933/https://www.google.com/books/edition/Black_Hole_Survival_Guide/9rITEAAQBAJ?hl=en&gbpv=1&dq=janna+levin&printsec=frontcover\)](https://archive.org/web/20220322141933/https://www.google.com/books/edition/Black_Hole_Survival_Guide/9rITEAAQBAJ?hl=en&gbpv=1&dq=janna+levin&printsec=frontcover) from the original on 22 March 2022.

Retrieved 6 November 2021.

- [Melia, Fulvio](https://archive.org/details/blackholeatcente0000meli) (2003). *[The Black Hole at the Center of Our Galaxy](https://archive.org/details/blackholeatcente0000meli)* (<https://archive.org/details/blackholeatcente0000meli>).[ⓘ].

Princeton U Press. ISBN 978-0-691-09505-9.

- Melia, Fulvio (2003). *The Edge of Infinity. Supermassive Black Holes in the Universe* (https://archive.org/details/edgeofinfinitys_u00meli). Cambridge U Press. ISBN 978-0-521-81405-8.
- Pickover, Clifford (1998). *Black Holes: A Traveler's Guide*. Wiley, John & Sons, Inc. ISBN 978-0-

471-19704-1.

- Susskind, Leonard (2008). *The black hole war: my battle with Stephen Hawking to make the world safe for quantum mechanics* (1st ed.). New York: Little, Brown. ISBN 978-0-316-01640-7. OCLC 181603165 (<https://search.worldcat.org/oclc/181603165>)[🔗].

University textbooks and monographs

- Carter, B. (1973). "Black hole equilibrium states". In DeWitt-Morette, Cécile; DeWitt, Bryce S. (eds.). *Black holes*. New York: Gordon and Breach. ISBN 978-0-677-15610-1.
- Chandrasekhar, Subrahmanyan (1999). *Mathematical Theory of Black Holes*. Oxford University

Press. ISBN 978-0-19-850370-5.

- Frolov, Valeri P.; Novikov, Igor D. (1998). *Black Hole Physics*.

Fundamental Theories of Physics. Vol. 96.

doi:10.1007/978-94-011-5139-9 (<https://doi.org/10.1007/978-94-011-5139-9>)[🔗].

ISBN 978-0-7923-5146-7.

- Frolov, Valeri P.; Zelnikov, Andrei

(2011). *Introduction to Black Hole Physics* (https://books.google.com/books?id=r_l5AK9DdXsC&pg=PA34).[🔗] Oxford: Oxford University Press. ISBN 978-0-19-969229-3. Zbl 1234.83001 (<https://zbmath.org/?format=complete&q=an:1234.83001>).[🔗] Archived (https://web.archive.org/web/20220322142008/http://books.google.com/books?id=r_l5AK9DdXsC&pg=PA34).[🔗]

from the original on 22 March 2022. Retrieved 2 January 2022.

- Melia, Fulvio (2007). *The Galactic Supermassive Black Hole*. Princeton U Press. ISBN 978-0-691-13129-0.
- Taylor, Edwin F.; Wheeler, John Archibald (2000). *Exploring Black Holes*. Addison Wesley Longman. ISBN 978-0-201-

38423-9.

- Wald, Robert M. (1992). *Space, Time, and Gravity: The Theory of the Big Bang and Black Holes*. University of Chicago Press. ISBN 978-0-226-87029-8.
- Price, Richard; Creighton, Teviet (2008). "Black holes" (<https://doi.org/10.4249%2Fscholarpedia.4277>). [🔗] *Scholarpedia*. **3** (1):

4277.

Bibcode:2008SchpJ...3.4277C

(<https://ui.adsabs.harvard.edu/abs/2008SchpJ...3.4277C>).[🔗]

doi:10.4249/scholarpedia.4277

(<https://doi.org/10.4249%2Fscholarpedia.4277>).[🌐]

Review papers

- Hughes, Scott A. (2005). "Trust but verify: The case for astrophysical black holes".

[arXiv:hep-ph/0511217](https://arxiv.org/abs/hep-ph/0511217) (<https://arxiv.org/abs/hep-ph/0511217>).³.

Lecture notes from 2005 SLAC
Summer Institute.

- Gallo, Elena; Marolf, Donald
(2009). "Resource Letter BH-2:
Black Holes". *American Journal
of Physics*. **77** (4): 294–307.

[arXiv:0806.2316](https://arxiv.org/abs/0806.2316) (<https://arxiv.org/abs/0806.2316>).³.

[Bibcode:2009AmJPh..77..294G](https://ui.adsabs.harvard.edu/abs/2009AmJPh..77..294G)
(<https://ui.adsabs.harvard.edu/abs/2009AmJPh..77..294G>

[bs/2009AmJPh..77..294G](#)[.doi:10.1119/1.3056569](#) (<https://doi.org/10.1119%2F1.3056569>). [S2CID 118494056](#) (<https://api.semanticscholar.org/CorpusID:118494056>)[.](#)

- Cardoso, Vitor; Pani, Paolo (2019). "Testing the nature of dark compact objects: a status report". *Living Reviews in Relativity*. **22** (1): 4. [arXiv:1904.05363](#) (<https://arxiv>.

[org/abs/1904.05363](#)^g.

Bibcode:2019LRR....22....4C (<https://ui.adsabs.harvard.edu/abs/2019LRR....22....4C>)^h.

doi:10.1007/s41114-019-0020-4 (<https://doi.org/10.1007%2Fs41114-019-0020-4>)^h.

S2CID 256465740 (<https://api.semanticscholar.org/CorpusID:256465740>)^h.

- Mann, Robert B.; Murk, Sebastian; Terno, Daniel R.

(2022). "Black holes and their horizons in semiclassical and modified theories of gravity". *International Journal of Modern Physics D*. **31** (9): 2230015–2230276. [arXiv:2112.06515](https://arxiv.org/abs/2112.06515) (<https://arxiv.org/abs/2112.06515>).^g

.


[Bibcode:2022IJMPD..3130015 M](https://ui.adsabs.harvard.edu/abs/2022IJMPD..3130015M) (<https://ui.adsabs.harvard.edu/abs/2022IJMPD..3130015M>).^u

.

[doi:10.1142/S0218271822300154](https://doi.org/10.1142/S0218271822300154) (<https://doi.org/10.1142%2FS0218271822300154>).[↗]

[S2CID 245123647](https://api.semanticscholar.org/CorpusID:245123647) (<https://api.semanticscholar.org/CorpusID:245123647>).[↗]

External links

 Scholia has a profile for **[black hole \(Q589\)](#)**.

- [Black Holes](https://www.bbc.c) (<https://www.bbc.c>

[o.uk/programmes/p00547f4](https://www.bbc.com/programmes/p00547f4)).[↗]

on *In Our Time* at the BBC


- *Stanford Encyclopedia of Philosophy*: "Singularities and Black Holes (<https://plato.stanford.edu/entries/spacetime-singularities/>).[↗]" by Erik Curiel and Peter Bokulich.
- Black Holes: Gravity's Relentless Pull (<https://hubblesite.org/contents/articles/black-ho>

les.html).[☞] – Interactive multimedia Web site about the physics and astronomy of black holes from the Space Telescope Science Institute (HubbleSite)


- ESA's Black Hole Visualization (<https://www.esa.int/gsp/ACT/phy/Projects/Blackholes/WebGL.html>).[☞] Archived (<https://web.archive.org/web/20190503070935/https://www.esa.int/gsp/ACT/phy/Projects/Blackholes/WebGL.html>)

ml).[🔗] 3 May 2019 at the
Wayback Machine

- Frequently Asked Questions (FAQs) on Black Holes (https://apod.nasa.gov/htmltest/gifcity/bh_pub_faq.html).[🔗]
- Schwarzschild Geometry (<http://web.archive.org/web/19980118051503/http://casa.colorado.edu/~ajsh/schwp.html>).[🔗]
- Black holes - basic (NYT; April

2021) (<https://www.nytimes.com/2021/04/22/science/black-holes-astrophysics-names.html>).

Videos



- 16-year-long study tracks stars orbiting Sagittarius A* (<https://www.eso.org/public/videos/eso0846b/>).
- Movie of Black Hole Candidate from Max Planck Institute (<https://web.archive.org/web/20040>

925044354/http://www.mpe.mpg.de/ir/GC/index.php).⁴

- Cowen, Ron (20 April 2015).
"3D simulations of colliding black holes hailed as most realistic yet" (<https://doi.org/10.1038%2Fnature.2015.17360>).⁴

Nature.

[doi:10.1038/nature.2015.17360](https://doi.org/10.1038/nature.2015.17360)
(<https://doi.org/10.1038%2Fnature.2015.17360>).⁶

- Computer visualisation of the signal detected by LIGO (<https://www.bbc.com/news/science-environment-35524440>).
- Two Black Holes Merge into One (based upon the signal GW150914) (https://www.youtube.com/watch?v=I_88S8DWbcU).


Retrieved from

"https://en.wikipedia.org/w/index.php?title=Black_hole&oldid=1298392513"

WIKIPEDIA



This page was last edited on 2 July 2025, at 06:23 (UTC). •

Content is available under [CC BY-SA 4.0](#)  unless otherwise noted.