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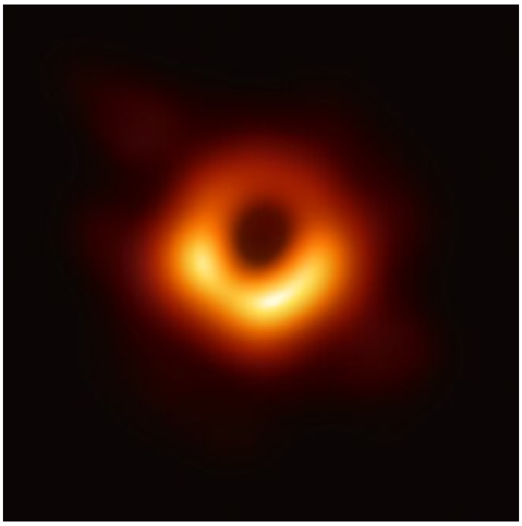
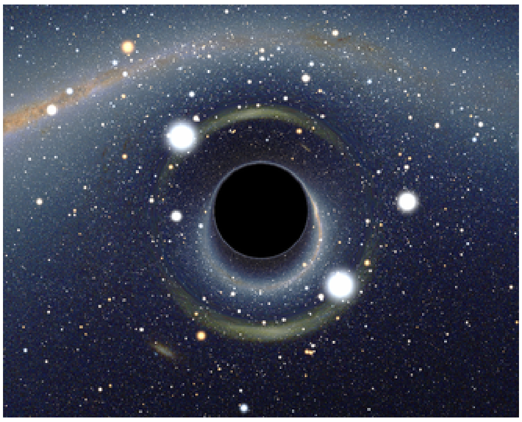
Black hole

A **black hole** is an astronomical body so compact that its gravity prevents anything, including light, from escaping. Albert Einstein's theory of general relativity, which describes gravitation as the curvature of spacetime, predicts that any sufficiently compact mass will form a black hole.[4] The boundary of no escape is called the event horizon. In general relativity, crossing a black hole's event horizon traps an object inside but produces no locally detectable change. General relativity also predicts that every black hole should have a central singularity, where the curvature of spacetime is infinite.



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 colours indicating brightness temperature[1][2]



Simulated view of a nonspinning, uncharged black hole in front of the Large Magellanic Cloud. The gravitational lensing effect produces two enlarged but 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. In 1916, the first solution of general relativity that would characterise a black hole was found. By the late 1950s, this solution began to be interpreted physically 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 widely-accepted black hole was Cygnus X-1, identified by several researchers independently in 1971.[5][6]

Black holes typically form when very 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 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.

Quantum field theory in curved spacetime predicts that event horizons emit Hawking radiation, with its rate of emission being inversely proportional to its mass. This causes the black hole to very slowly lose mass, provided it is not accreting matter. However, even the smallest class of black holes observed, stellar black holes, are gaining mass from the cosmic microwave background faster than they are losing mass via Hawking radiation.

The presence of a black hole can be inferred through its interaction with matter and 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. Merging black holes can be detected by the gravitational waves they emit. If stars are orbiting a black hole, their motions can be used to determine the black hole's mass and location. 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 massive that even light could not escape was first proposed in the late 18th century by English astronomer and clergyman John Michell and independently by French scientist Pierre-Simon Laplace. Both scholars proposed very large stars in contrast to the modern concept of an extremely dense object.[7]

Michell's idea, in a short part of a letter published in 1784,[8] 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.[9]:122 Michell correctly hypothesized that such non-radiating bodies might be detectable through their gravitational effects on nearby visible bodies.[7] In 1796, while speculating on the origin of the Solar System in his book *Exposition du Système du Monde*, Laplace made a qualitative suggestion that a star could be invisible if it were sufficiently large. Franz Xaver von Zach asked Laplace for a mathematical analysis, which Laplace provided and published in von Zach's journal *Allgemeine Geographische Ephemeriden*.[7]

General relativity

In 1905, Albert Einstein showed that the laws of electromagnetism are identical for observers travelling at different velocities relative to each other. The laws of mechanics had already been shown to be invariant in this way. However, the theory of gravitation was yet to be included.[10]:19

In 1907, Einstein published a paper proposing his equivalence principle, the hypothesis that inertial mass and gravitational mass have a common cause. Using the principle, Einstein predicted the redshift and the lensing effect of gravity on light; his prediction of gravitational lensing was one-half of the value that the full theory of general relativity would predict.[10]:19 By 1915, Einstein refined these ideas into his general theory of relativity, which explained how matter affects spacetime, which in turn affects the motion of other matter.[11][12] This formed the basis for black hole physics.[13]

Singular solutions in general relativity

Only a few months after Einstein published the field equations describing general relativity, astrophysicist Karl Schwarzschild set out to apply the idea to stars. He assumed spherical symmetry with no spin and found a solution to Einstein's equations.[9]:124[14] A few months after Schwarzschild, Johannes Droste, a student of Hendrik Lorentz, independently gave the same solution.[15][16] At a certain radius from the center of the mass, the Schwarzschild solution became singular, meaning that some of the terms in the Einstein equations became infinite. The nature of this radius, which later became known as the Schwarzschild radius, was not understood at the time.[17]

Many physicists of the early 20th century were sceptical of the existence of black holes. In a 1926 popular science book, Arthur Eddington critiqued the idea of a star with mass compressed to its Schwarzschild radius as a flaw in the then-poorly-understood theory of general relativity.[18][9]:134 In 1939, Einstein used his theory of general relativity in an attempt to prove that black holes were impossible.[19][20] His work relied on increasing pressure or increasing centrifugal force balancing the force of gravity so that the object would not collapse beyond its Schwarzschild radius. He missed the possibility that implosion would drive the system below this critical value.[9]:135

Gravity vs degeneracy pressure

By the 1920s, astronomers had classified a number of white dwarf stars as too cool and dense to be explained by the gradual cooling of ordinary stars. In 1926, Ralph Fowler showed that these stars are not like main-sequence stars, where thermal pressure balances gravity. Instead, a type of quantum-mechanical pressure balances gravity at these temperatures and densities.[9]:145 In 1931, Subrahmanyan Chandrasekhar studied the new state of matter that results from this balance, called electron-degenerate matter, discovering that it is stable below a certain limiting mass. By 1934 he showed that this explained the catalogue of white dwarf stars.[9]:151 When Chandrasekhar announced his results, Eddington pointed out that stars above this limit would radiate until they were sufficiently dense to prevent light from exiting, a conclusion he considered absurd. Eddington and, later, Lev Landau argued that some yet unknown mechanism would stop the collapse.[21]

In the 1930s, Fritz Zwicky and Walter Baade studied stellar novae, focusing on exceptionally bright ones they called supernovae. Zwicky promoted the idea that supernovae produced stars with the density of atomic nuclei—neutron stars—but this idea was largely ignored at the time.[9]:171 In 1939, based on Chandrasekhar's reasoning, J. Robert Oppenheimer and George Volkoff predicted that neutron stars below a certain mass limit, later called the Tolman–Oppenheimer–Volkoff limit, would be stable due to neutron degeneracy pressure. Above that limit, they reasoned that either their model would not apply or that gravitational contraction would not stop.[22]:380

John Archibald Wheeler and two of his students resolved questions about the model behind the Tolman–Oppenheimer–Volkoff (TOV) limit. In 1965, Harrison and Wheeler developed the equations of state relating density to pressure for cold matter all the way through electron degeneracy and neutron degeneracy. Masami Wakano and Wheeler then used the equations to compute the equilibrium curve for stars, relating mass to circumference. They found no additional features that would invalidate the TOV limit. This meant that the only thing that could prevent black holes from forming was a dynamic process ejecting sufficient mass from a star as it cooled.[9]:205

Birth of modern model

The modern concept of black holes was formulated by Robert Oppenheimer and his student Hartland Snyder in 1939.[19][23]:80 In the paper,[24] Oppenheimer and Snyder solved Einstein's equations of general relativity for an idealised imploding star, in a model later called the Oppenheimer–Snyder model, then described the results from far outside the star. The implosion starts as one might expect: the star material rapidly collapses inward. However, as the density of the star increases, gravitational time dilation increases and the collapse, viewed from afar, seems to slow down further and further until the star reaches its Schwarzschild radius, where it appears frozen in time.[9]:217

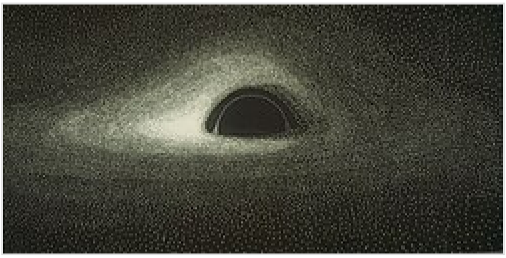
In 1958, David Finkelstein identified the Schwarzschild surface as an event horizon, calling it "a perfect unidirectional membrane: causal influences can cross it in only one direction". This means that events that occur inside the black hole cannot affect events that occur outside the black hole.[25] Finkelstein created a new reference frame to include the point of view of infalling observers.[23]:103 Finkelstein's new frame of reference allowed events at the surface of an imploding star to be related to events far away. By 1962 the two points of view were reconciled, convincing many sceptics that implosion into a black hole made physical sense.[9]:226

Golden age

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.[28][9]:258

In this period, solutions to the equations of general relativity under various different physical constraints were discovered. In 1963, Roy Kerr found the exact solution for a rotating black hole.[29] Two years later, Ezra Newman found the cylindrically symmetric solution for a black hole that is both rotating and electrically charged.[30]

In 1967, Werner Israel found that the Schwarzschild solution was the only possible solution for a nonspinning, uncharged black hole, meaning that a Schwarzschild black hole would be defined by its mass alone.[31] Similar identities were later found for Reissner-Nordstrom and Kerr black holes, defined only by their mass and their charge or spin respectively.[32][33] Together, these findings became known as the no-hair theorem, which states that a stationary black hole is completely described by the three parameters of the Kerr–Newman metric: mass, angular momentum, and electric charge.[34]



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 Doppler beaming.[26][27]

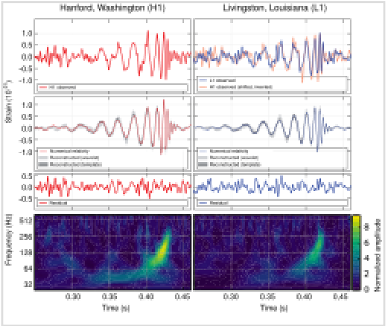
At first, it was suspected that the strange mathematical singularities found in each of the black hole solutions only appeared due to the assumption that a black hole would be perfectly spherically symmetric, and therefore the singularities would not appear in generic situations where black holes would not necessarily be symmetric. This view was held in particular by Vladimir Belinski, Isaak Khalatnikov, and Evgeny Lifshitz, who tried to prove that no singularities appear in generic solutions, although they would later reverse their positions.[35] However, in 1965, Roger Penrose proved that general relativity predicts that singularities appear in all black holes,[36] although this may not still hold when quantum mechanics is taken into account.[37]

Astronomical observations also made great strides during this era. In 1967, Antony Hewish and Jocelyn Bell Burnell discovered pulsars[38][39] and by 1969, these were shown to be rapidly rotating neutron stars.[40] 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.[41] 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.[42][43]

Work by James Bardeen, Jacob Bekenstein, Carter, and Hawking in the early 1970s led to the formulation of black hole thermodynamics.[44] These laws describe the behaviour of a black hole in a manner analogous to the laws of thermodynamics. Under this analogy, the properties of mass, surface area, and surface gravity for a black hole are related to the thermodynamical concepts of energy, entropy, and temperature respectively. The analogy was completed[9]:442 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.[45]

Modern research and observation

While Cygnus X-1, a stellar-mass black hole, was generally accepted by the scientific community as a black hole by the end of 1973,[42] it would be decades before a supermassive black hole would gain the same broad recognition. Although, as early as the 1960s, physicists such as Donald Lynden-Bell and Martin Rees had suggested that powerful quasars in the center of galaxies were powered by accreting supermassive black holes, little observational proof existed at the time.[46][47] However, the Hubble Space Telescope, launched in the 1990s, found that supermassive black holes were not only present in these active galactic nuclei, but that supermassive black holes in the center of galaxies were ubiquitous: almost every galaxy had a supermassive black hole at its center. The black holes in quiescent galaxies accrete matter more slowly or radiate less efficiently.[48][49]



The first detection of gravitational waves, imaged by LIGO observatories in Hanford Site, Washington and Livingston, Louisiana

In 1999, David Merritt proposed the M–sigma relation, which related the dispersion of the velocity of matter in the center bulge of a galaxy to the mass of the supermassive black hole at its core.[50] Subsequent studies confirmed this correlation.[51] Around the same time, based on telescope observations of the velocities of stars at the center of the Milky Way galaxy, independent work groups led by Andrea Ghez and Reinhard Genzel concluded that the compact radio source in the center of the galaxy, Sagittarius A*, was likely a supermassive black hole.[52][53]

In late 2015, the LIGO Scientific Collaboration and Virgo Collaboration made the first direct detection of gravitational waves, named GW150914, representing the first observation of a black hole merger.[54] At the time of the merger, the black holes were approximately 1.4 billion light-years away from Earth and had masses roughly 30 and 35 times that of the Sun.[55]:6 In 2017, Rainer Weiss, Kip Thorne, and Barry Barish, who had spearheaded the project, were awarded the Nobel Prize in Physics for their work.[56] Since the initial discovery in 2015, hundreds more gravitational waves have been observed.[57]

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.[58] In 2022, the Event Horizon Telescope collaboration released an image of the black hole in the center of the Milky Way galaxy, Sagittarius A*; The data had been collected in 2017.[59]

In 2020, the Nobel Prize in Physics was awarded for work on black holes. Andrea Ghez and Reinhard Genzel shared one-half for their discovery that Sagittarius A* is a supermassive black hole.[60] Penrose received the other half for his work showing that the mathematics of general relativity requires the formation of black holes.[61] Cosmologists lamented that Hawking's extensive theoretical work on black holes would not be honoured since he had died in 2018.[62]

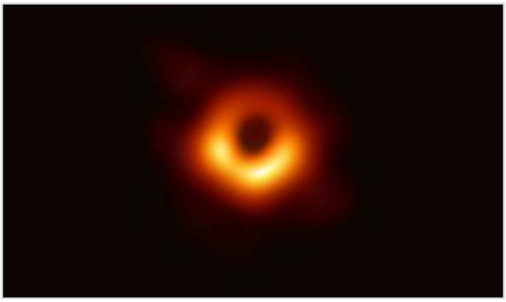


Image by the Event Horizon Telescope of the supermassive black hole in the center of Messier 87

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,[23][63] leading some to credit Wheeler with coining the phrase.[64] 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 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.[23]

Definition

A black hole is generally defined as a region of spacetime from which no information-carrying signals or objects can escape.[65] However, verifying an object as a black hole by this definition would require waiting for an infinite time and at an infinite distance from the black hole to verify that indeed, nothing has escaped, and thus cannot be used to identify a physical black hole.[66] There are several other definitions that can be used to describe or identify a black hole, although they are not universally agreed upon by physicists. Among astrophysicists, a black hole is a compact object with a mass larger than four solar masses.[67] A black hole may also be defined as a reservoir of information[68]:142 or a region where space is falling inwards faster than the speed of light.[69][70]

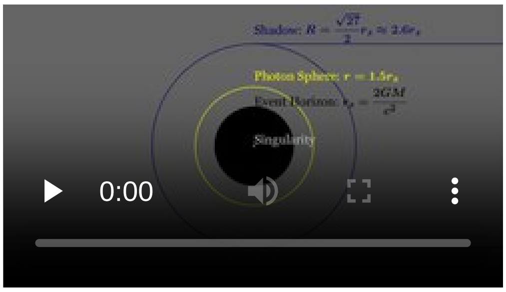
Properties

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 is currently an unsolved problem.[34][71]

The simplest static black holes, called *Schwarzschild black holes*, have mass but neither electric charge nor angular momentum. 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.[72]

Mass

The simplest static black holes have mass but neither electric charge nor angular momentum. Contrary to the popular notion of a black hole "sucking in everything" in its surroundings, from far away, the external gravitational field of a black hole is identical to that of any other body of the same mass.[73]



Radii for shadow and photon sphere relative to the event horizon

While a black hole can theoretically have any positive mass, its charge and angular momentum are limited by its mass, with this limit being greater for more massive black holes. The net electric charge Q and the total angular momentum J satisfy the inequality

$$\frac{Q^2}{4\pi\epsilon_0} + \frac{c^2 J^2}{GM^2} \leq GM^2$$

for a black hole of mass M, where ϵ_0 is the vacuum permittivity constant, c is the speed of light and G is the gravitational constant. Black holes with the maximum possible combination of charge and spin satisfying this inequality are called extremal black holes. Solutions of Einstein's equations that violate this inequality exist, but they do not possess an event horizon. These are so-called naked singularities that can be observed from the outside.[74] Because these singularities make the universe inherently unpredictable, many physicists believe they could not exist.[75] The weak cosmic censorship hypothesis, proposed by Penrose, rules out the formation of such singularities, when they are created through the gravitational collapse of realistic matter. However, this theory has not yet been proven, and some physicists believe that naked singularities could exist.[76] It is also unknown whether black holes could even become extremal, forming naked singularities, since natural processes counteract increasing spin and charge when a black hole becomes near-extremal.[77]

The total mass of a black hole can be estimated by analysing the motion of objects near the black hole, such as stars or gas.[49]

Spin and angular momentum

All black holes spin, often fast—One supermassive black hole, GRS 1915+105, has been estimated to spin at over 1,000 revolutions per second.[78][79] The Milky Way's central black hole Sagittarius A* rotates at about 90% of the maximum possible rate.[80][81]

The spin rate can be inferred from measurements of atomic spectral lines in the X-ray range. As gas near the black hole plunges inward, high energy X-ray emission from electron-positron pairs illuminates the gas further out, appearing red-shifted due to relativistic effects. Depending on the spin of the black hole, this plunge happens at different radii from the hole, with different degrees of redshift. Astronomers can use the gap between the x-ray emission of the outer disk and the redshifted emission from plunging material to determine the spin of the black hole.[82]

A newer way to estimate spin is based on the temperature of gasses accreting onto the black hole. The method requires an independent measurement of the black hole mass and inclination angle of the accretion disk followed by computer modelling. Gravitational waves from coalescing binary black holes can also provide the spin of both progenitor black holes and the merged hole, but such events are rare.[82]

A spinning black hole has angular momentum. The supermassive black hole in the center of the Messier 87 (M87) galaxy appears to have an angular momentum very close to the maximum theoretical value.[83][84] By setting Q equal to 0, the maximum spin of an uncharged black hole can be simplified to[85]

$$J \leq \frac{GM^2}{c},$$

allowing definition of a dimensionless spin magnitude such that[85][86]

$$0 \leq \frac{cJ}{GM^2} \leq 1.$$

Charge

Most black holes are believed to have an approximately neutral charge. For example, Michal Zajaček, Arman Tursunov, Andreas Eckart, and Silke Britzen found the electric charge of Sagittarius A* to be at least ten orders of magnitude below the theoretical maximum.[87] A charged black hole repels other like charges just like any other charged object.[88] If a black hole were to become charged, particles with an opposite sign of charge would be pulled in by the extra electromagnetic force, while particles with the same sign of charge would be repelled, neutralising the black hole. This effect may not be as strong if the black hole is also spinning.[89] The presence of charge can reduce the diameter of the black hole by up to 38%.[87][90]

The charge Q for a nonspinning black hole is bounded by

$$Q \leq \sqrt{G}M,$$

where G is the gravitational constant and M is the black hole's mass.[91]

Classification

Black holes are classified by the theory of their formation and by their mass (expressed in terms of $M_\odot$, the mass of the Sun), but these criteria are intertwined. Stellar black holes are formed by stellar collapse. The minimum mass of a black hole formed by stellar gravitational collapse is governed by the maximum mass of a neutron star and is believed to be 2-4 $M_\odot$.[93] Hypothetical primordial black holes, believed to have formed soon after the Big Bang, could be far smaller, with masses as little as 10^{-5} grams at formation.[94] These very small black holes are sometimes called micro black holes.[95][96]

Stellar black holes can have a wide range of masses. Estimates of their maximum mass at formation vary, but generally range from 10-100 $M_\odot$, with higher estimates for black holes progenated by low-metallicity stars.[97] Stellar black holes can gain mass via accretion of nearby matter, often from a companion object such as a star[98][99] or by merger with another black hole.[54]

Black hole classifications

Class	Approx. mass	Approx. radius
Ultramassive black hole	10^9–10^{11} $M_\odot$	>1,000 AU
Supermassive black hole	10^6–10^9 $M_\odot$	0.001–400 AU
Intermediate-mass black hole[92]	10^2–10^5 $M_\odot$	10^3 km ≈ R_{Earth}
Stellar black hole	2–150 $M_\odot$	30 km
Micro black hole	up to M_{Moon}	up to 0.1 mm

Black holes that are larger than stellar black holes but smaller than supermassive black holes are called intermediate-mass black holes, with approximately 10^2-10^5 $M_\odot$. These black holes seem to be rarer than their stellar and supermassive counterparts, with only a small number of candidates observed so far.[92] Physicists have speculated that such black holes may form from collisions in globular and star clusters or at the center of low-mass galaxies.[100] They may also form as the result of mergers of smaller black holes, with several LIGO observations finding merged black holes within 110–350 $M_\odot$.[101][102]

The black holes with the largest masses are called supermassive black holes, with masses more than 10^6 $M_\odot$.[103] These black holes are believed to exist at the centers of almost every large galaxy, including the Milky Way.[48][49] Some scientists have proposed a subcategory of even larger black holes, called ultramassive black holes, with masses greater than 10^9-10^{10} $M_\odot$.[104][105] Theoretical models predict that the accretion disc that feeds black holes will be unstable once a black hole reaches 50×10^9–100×10^9 $M_\odot$, setting a rough upper limit to black hole mass.[106][107]

Structure

While black holes are conceptually invisible sinks of all matter and light, in astronomical settings, their enormous gravity alters the motion of surrounding objects and pulls nearby gas inwards at near-light speed, making the area around black holes the brightest objects in the universe.[108]

External geometry

Relativistic jets

Some black holes have relativistic jets—thin streams of plasma travelling away from the black hole at more than one-tenth of the speed of light.[109] A small fraction of the matter falling towards the black hole gets accelerated away along the hole rotation axis.[110] These jets can extend as far as millions of light-years from the black hole itself.[111]

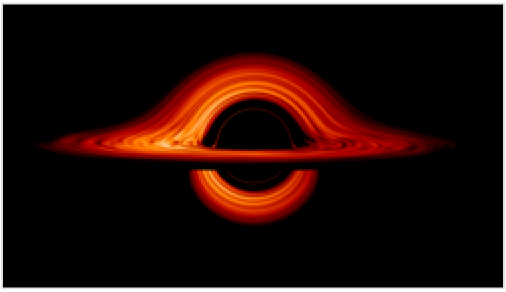
Black holes of any mass can have jets.[112] However, they are typically observed around spinning black holes with strongly-magnetized accretion disks.[113][114] Relativistic jets were more common in the early universe, when galaxies and their corresponding supermassive black holes were rapidly gaining mass.[113][115] All black holes with jets also have an accretion disk, but the jets are usually brighter than the disk.[109][116] *Quasars*, typically found in other galaxies, are believed to be supermassive black holes with jets; *microquasars* are believed to be stellar-mass objects with jets, typically observed in the Milky Way.[117]

The mechanism of formation of jets is not yet known,[112] but several options have been proposed. One method proposed to fuel these jets is the Blandford-Znajek process, which suggests that the dragging of magnetic field lines by a black hole's rotation could launch jets of matter into space.[118][119] The Penrose process, which involves extraction of a black hole's rotational energy, has also been proposed as a potential mechanism of jet propulsion.[120][121]

Relativistic jets from the supermassive black hole in Centaurus A extend perpendicularly from the galaxy.

Accretion disk

Due to conservation of angular momentum, gas falling into the gravitational well created by a massive object will typically form a disk-like structure around the object.[124]:242 As the disk's angular momentum is transferred outward due to internal processes, its matter falls farther inward, converting its gravitational energy into heat and releasing a large amount of x-rays.[125][126] The temperature of these disks can range from thousands to millions of kelvins, and temperatures differ throughout a single accretion disk.[127][128] Accretion disks can also emit in other parts of the electromagnetic spectrum, depending on the disk's turbulence and magnetisation and the black hole's mass and angular momentum.[129]



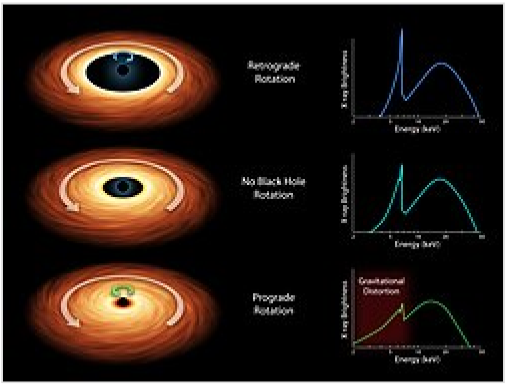
Visualization of a black hole with an orange accretion disk. The parts of the disk circling over and under the hole are actually gravitationally lensed from the back side of the black hole.[122][123]

Accretion disks can be defined as geometrically thin or geometrically thick. Geometrically thin disks are mostly confined to the black hole's equatorial plane and have a well-defined edge at the innermost stable circular orbit (ISCO), while geometrically thick disks are supported by internal pressure and temperature and can extend inside the ISCO. Disks with high rates of electron scattering and absorption, appearing bright and opaque, are called *optically thick*; *optically thin* disks are more translucent and produce fainter images when viewed from afar.[130] Accretion disks of black holes accreting beyond the Eddington limit are often referred to as *polish donuts* due to their thick, toroidal shape that resembles that of a donut.[131][132]

Quasar accretion disks are expected to usually appear blue in colour.[133] The disk for a stellar black hole, on the other hand, would likely look orange, yellow, or red, with its inner regions being the brightest.[134] Theoretical research suggests that the hotter a disk is, the bluer it should be, although this is not always supported by observations of real astronomical objects.[135] Accretion disk colours may also be altered by the Doppler effect, with the part of the disk travelling towards an observer appearing bluer and brighter and the part of the disk travelling away from the observer appearing redder and dimmer.[136][137]

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 a smallest possible radius for which a massive particle can orbit stably. Any infinitesimal inward perturbations to this orbit will lead to the particle spiraling into the black hole, and any outward perturbations will, depending on the energy, cause the particle to spiral in, move to a stable orbit further from the black hole, or escape to infinity. This orbit is called the **innermost stable circular orbit**, or ISCO.[139][140] The location of the ISCO depends on the spin of the black hole and the spin of the particle itself. In the case of a Schwarzschild black hole (spin zero) and a particle without spin, the location of the ISCO is:



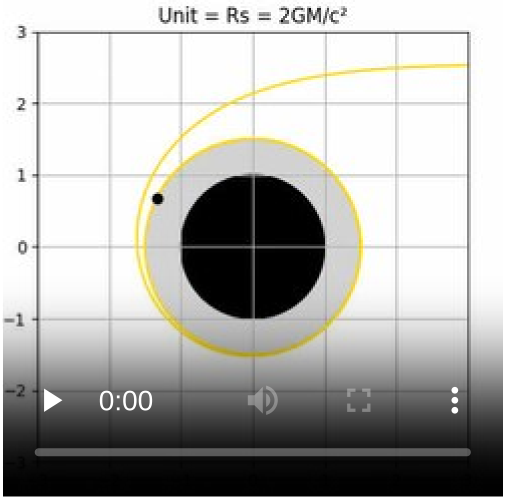
Since particles in a black hole's accretion disk must orbit at or outside the ISCO, astronomers can observe the properties of accretion disks to determine black hole spins.[138]

$$r_{\text{ISCO}} = 3\,r_{\text{s}} = \frac{6\,GM}{c^2},$$

where r_{ISCO} is the radius of the ISCO, r_{s} is the Schwarzschild radius of the black hole, G is the gravitational constant, and c is the speed of light.[141] The radius of this orbit changes slightly based on particle spin.[142][143] For charged black holes, the ISCO moves inwards.[142] For spinning black holes, the ISCO is moved inwards for particles orbiting in the same direction that the black hole is spinning (prograde) and outwards for particles orbiting in the opposite direction (retrograde).[140] For example, the ISCO for a particle orbiting retrograde can be as far out as about $9r_{\text{s}}$, while the ISCO for a particle orbiting prograde can be as close as at the event horizon itself.[140][144]

Photon sphere and shadow

The photon sphere is a spherical boundary for which photons moving on tangents to that sphere are bent completely around the black hole, possibly orbiting multiple times.[145] Light rays with impact parameters less than the radius of the photon sphere enter the black hole.[146] For Schwarzschild black holes, the photon sphere has a radius 1.5 times the Schwarzschild radius; the radius for non-Schwarzschild black holes is at least 1.5 times the radius of the event horizon.[147][148] When viewed from a great distance, the photon sphere creates an observable **black hole shadow**.[147] Since no light emerges from within the black hole, this shadow is the limit for possible observations.[149]:152 The shadow of colliding black holes should have characteristic warped shapes, allowing scientists to detect black holes that are about to merge.[150]

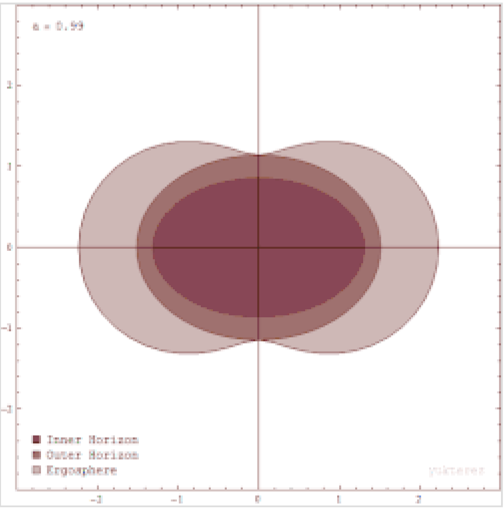


Video of a photon being captured by a Schwarzschild black hole

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. Therefore, 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.[150] Light emitted towards the photon sphere may also curve around the black hole and return to the emitter.[151]

For a rotating, uncharged black hole, the radius of the photon sphere depends on the spin parameter and whether the photon is orbiting prograde or retrograde.[141] For a photon orbiting prograde, the photon sphere will be 1-3 Schwarzschild radii from the center of the black hole, while for a photon orbiting retrograde, the photon sphere will be between 3-5 Schwarzschild radii from the center of the black hole. The exact locations of the photon spheres depend on the magnitude of the black hole's rotation.[152] For a charged, nonrotating black hole, there will only be one photon sphere, and the radius of the photon sphere will decrease for increasing black hole charge.[153] For non-extremal, charged, rotating black holes, there will always be two photon spheres, with the exact radii depending on the parameters of the black hole.[154]

Ergosphere



The ergosphere is a region outside of the event horizon, where objects cannot remain in place.[155]

Near a rotating black hole, spacetime rotates similar to a vortex. The rotating spacetime will drag any matter and light into rotation around the spinning black hole. This effect of general relativity, called frame dragging, gets stronger closer to the spinning mass. The region of spacetime in which it is impossible to stay still is called the ergosphere.[156]

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 bulges out from it around the equator.[155]

Matter and radiation can escape 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, slowing down the rotation of the black hole.[157]:268 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.[118][158]

Plunging region

The observable region of spacetime around a black hole closest to its event horizon is called the plunging region. In this area it is no longer possible for free falling matter to follow circular orbits or stop a final descent into the black hole. Instead, it will rapidly plunge toward the black hole at close to the speed of light, growing increasingly hot and producing a characteristic, detectable thermal emission.[159][160] However, light and radiation emitted from this region can still escape from the black hole's gravitational pull.[161]

Radius

For a nonspinning, uncharged black hole, the radius of the event horizon, or Schwarzschild radius, is proportional to the mass, M, through

$$r_\mathrm{s} = \frac{2GM}{c^2} \approx 2.95\,\frac{M}{M_\odot}~\mathrm{km},$$

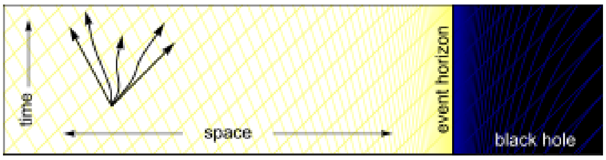
where r_s is the Schwarzschild radius, G is the gravitational constant, c is the speed of light, and $M_\odot$ is the mass of the Sun.[162]:124 For a black hole of the same mass with nonzero spin or electric charge, the radius is smaller.[Note 1] As a black hole's charge and spin approach the maximum allowed value, the radius of the event horizon nears

$$r_+ = \frac{GM}{c^2},$$

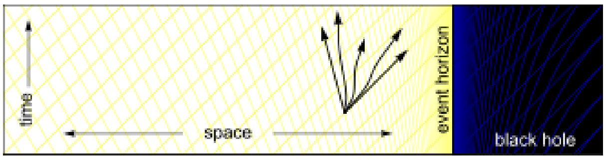
half the radius of a nonspinning, uncharged black hole of the same mass.[163]

Since the volume within the Schwarzschild radius increases with the cube of the radius, 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.[164][165]

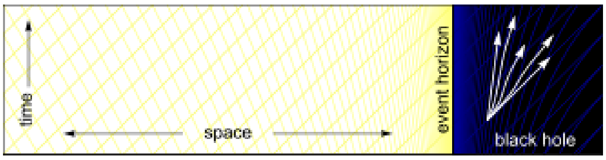
Event horizon



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 2]



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 existence of an event horizon, a boundary in spacetime through which matter and light can pass only inward towards the center of the black hole. Nothing, not even light, can escape from inside the event horizon.[166][167] The event horizon is referred to as such because if an event occurs within the boundary, information from that event cannot reach or affect an outside observer, making it impossible to determine whether such an event occurred.[168]:179 For non-rotating black holes, the geometry of the event horizon is precisely spherical, while for rotating black holes, the event horizon is oblate.[169][170]

To a distant observer, a clock near a black hole would appear to tick more slowly than one further from the black hole.[171]:217[172] This effect, known as gravitational time dilation, would also cause an object falling into a black hole to appear to slow as it approached the event horizon, never quite reaching the horizon from the perspective of an outside observer.[171]:218 All processes on this object would appear to slow down, and any light emitted by the object to appear redder and dimmer, an effect known as gravitational redshift.[173] An object falling from half of a Schwarzschild radius above the event horizon would fade away until it could no longer be seen, disappearing from view within one hundredth of a second.[174] It would also appear to flatten onto the black hole, joining all other material that had ever fallen into the hole.[175]

On the other hand, an observer 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, and 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.[171]:222[176]

Internal geometry

Cauchy horizon

Black holes that are rotating and/or charged have an inner horizon, often called the Cauchy horizon, inside of the black hole.[177] The inner horizon is divided up into two segments: an ingoing section and an outgoing section.[178]

At the ingoing section of the Cauchy horizon, radiation and matter that fall into the black hole would build up at the horizon, causing the curvature of spacetime to go to infinity. This would cause an observer falling in to experience tidal forces.[177][178] This phenomenon is often called mass inflation, since it is associated with a parameter dictating the black hole's internal mass growing exponentially,[177][179] and the buildup of tidal forces is called the mass-inflation singularity[180][178] or Cauchy horizon singularity.[181][182] Some physicists have argued that in realistic black holes, accretion and Hawking radiation would stop mass inflation from occurring.[183][184]

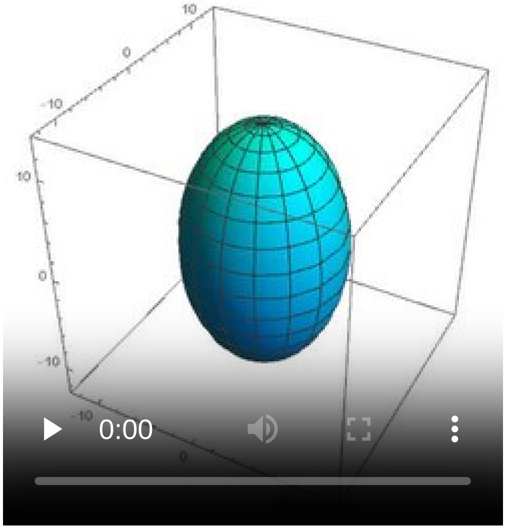
At the outgoing section of the inner horizon, infalling radiation would backscatter off of the black hole's spacetime curvature and travel outward, building up at the outgoing Cauchy horizon. This would cause an infalling observer to experience a gravitational shock wave and tidal forces as the spacetime curvature at the horizon grew to infinity. This buildup of tidal forces is called the shock singularity.[179][178]

Both of these singularities are weak, meaning that an object crossing them would only be deformed a finite amount by tidal forces, even though the spacetime curvature would still be infinite at the singularity. This is as opposed to a strong singularity, where an object hitting the singularity would be stretched and squeezed by an infinite amount.[180][179] They are also null singularities, meaning that a photon could travel parallel to them without ever being intercepted.[178]

Singularity

Ignoring quantum effects, every black hole has a singularity inside, points where the curvature of spacetime becomes infinite, and geodesics terminate within a finite proper time.[171]:205[185] 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.[171]:264 In both cases, the singular region has zero volume. All of the mass of the black hole ends up in the singularity.[171]:252 Since the singularity has nonzero mass in an infinitely small space, it can be thought of as having infinite density.[186]

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.[187][188] As they fall further into the black hole, they will be torn apart by the growing tidal forces in a process sometimes referred to as spaghettification or the *noodle effect*. Eventually, they will reach the singularity and be crushed into an infinitely small point.[168]:182 However, any perturbations, such as those caused by matter or radiation falling in, would cause space to oscillate chaotically near the singularity. Any matter falling in would experience intense tidal forces rapidly changing in direction, all while being compressed into an increasingly small volume.[189][172]:231



Chaotic oscillations of spacetime experienced by an object approaching a gravitational singularity

Alternative forms of general relativity, including addition of some quantum effects, can lead to *regular*, or *nonsingular*, black holes without singularities.[190][191] For example, the fuzzball model, based on string theory, states that black holes are actually made up of quantum microstates and need not have a singularity or an event horizon.[192][193] The theory of loop quantum gravity proposes that the curvature and density at the center of a black hole is large, but not infinite.[194]

Formation

Black holes are formed by gravitational collapse of massive stars, either by direct collapse or during a supernova explosion in a process called *fallback*.[195] Black holes can result from the merger of two neutron stars or a neutron star and a black hole.[196] Other more speculative mechanisms include primordial black holes created from density fluctuations in the early universe, the collapse of dark stars, a hypothetical object powered by annihilation of dark matter, or from hypothetical self-interacting dark matter.[197]

Supernova

Gravitational collapse occurs when an object's internal pressure is insufficient to resist the object's own gravity. At the end of a star's life, it will run out of hydrogen to fuse, and will start fusing more and more massive elements, until it gets to iron. Since the fusion of elements heavier than iron would require more energy than it would release, nuclear fusion ceases. If the iron core of the star is too massive, the star will no longer be able to support itself and will undergo gravitational collapse.[198][199]

The mass of a black hole formed via a supernova has a lower bound: if the progenitor star is too small, the collapse may be stopped by the degeneracy pressure of the star's constituents, allowing the condensation of matter into an exotic denser state. Degeneracy pressure occurs from the Pauli exclusion principle: particles will resist being in the same place as each other. Progenitor stars with masses less than about 8 $M_\odot$ will become white dwarfs, where the degeneracy pressure of electrons balances gravity. For more massive progenitor stars, the force of gravity overcomes electron degeneracy pressure and the star compresses until neutron degeneracy pressure resists gravity, forming a neutron star. If the star is even more massive, neutron degeneracy pressure will not be able to resist the force of gravity and the star will collapse into a black hole.[200][171]:5.8

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 delay growing to infinity as the emitting material reaches the event horizon. 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.[201]

Other mechanisms

Observations of quasars from less than a billion years after the Big Bang[202][203] has led to investigations of other ways to form black holes. The accretion process to build supermassive black holes has a limiting rate of mass accumulation and a billion years is not enough time to reach quasar status. One suggestion is direct collapse of nearly pure hydrogen gas (low metalicity) clouds characteristic of the young universe, forming a supermassive star which collapses into a black hole. It has been suggested that seed black holes with typical masses of ~10^5 $M_\odot$ could have formed in this way which then could grow to ~10^9 $M_\odot$. However, the very large amount of gas required for direct collapse is not typically stable against fragmentation which would form multiple stars. Thus another approach suggests massive star formation followed by collisions that seed massive black holes which ultimately merge to create a quasar.[204]:85

A neutron star in a common envelope with a regular star can accrete sufficient material to collapse to a black hole or two neutron stars can merge. These avenues for the formation of black holes are considered relatively rare.[205]

Primordial black holes and the Big Bang

In the current epoch of the universe, conditions needed to form black holes are rare and are mostly only found in stars. However, in the early universe, conditions may have allowed for black hole formations via other means. Fluctuations of spacetime soon after the Big Bang may have formed areas that were denser than their surroundings. Initially, these regions would not have been compact enough to form a black hole, but eventually, the curvature of spacetime in the regions become large enough to cause them to collapse into a black hole.[206][207] 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 from a Planck mass (~2.2×10^{-8} kg) to hundreds of thousands of solar masses.[208][209] Primordial black holes with masses less than 10^{12} kg would have evaporated by now due to Hawking radiation.[94]

Despite the early universe being extremely dense, it did not re-collapse into a black hole during the Big Bang, since the universe was expanding rapidly and did not have the gravitational differential necessary for black hole formation. 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.[210]

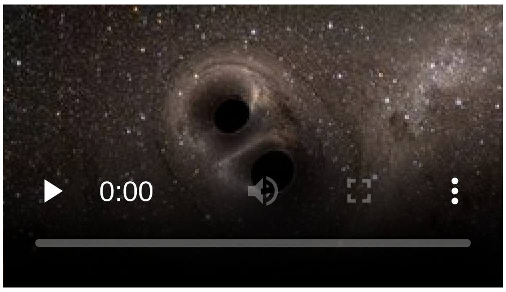
High-energy collisions

In principle, black holes could be formed in high-energy particle collisions that achieve sufficient density, although no such events have been detected.[211][212] These hypothetical micro black holes, which could form from the collision of cosmic rays and Earth's atmosphere or in particle accelerators like the Large Hadron Collider, would not be able to aggregate additional mass.[213] Instead, they would evaporate in about 10^{-25} seconds, posing no threat to the Earth.[214]

Evolution

After a black hole forms, it may change through phenomena such as mergers, accretion of matter, and evaporation via Hawking radiation.

Merger



Simulation of two black holes colliding

Black holes can merge with other objects such as stars or 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.[215] The process has also been proposed as the origin of some intermediate-mass black holes.[216][217] Mergers of supermassive black holes may take a long time: As a binary of supermassive black holes approach each other, most nearby stars are slingshotted away, leaving little for the black holes to gravitationally interact with that would allow them to get closer to each other. This phenomenon has been called the final parsec problem, as the distance at which this happens is usually around one parsec.[218][219]

Accretion of matter

The active galactic nucleus of galaxy Centaurus A in X-ray light, believed to be powered by a supermassive black hole (centre) and surrounded by x-ray binaries (blue dots)

When a black hole accretes matter, the gas in the inner accretion disk orbits at very high speeds because of its proximity to the black hole. The resulting friction heats the inner disk to temperatures at which it emits vast amounts of electromagnetic radiation (mainly X-rays) detectable by telescopes. By the time the matter of the disk reaches the ISCO, between 5.7% and 42% of its mass will have been converted to energy, depending on the black hole's spin. About 90% of this energy is released within 20 black hole radii.[220] In many cases, accretion disks are accompanied by relativistic jets that are emitted along the black hole's poles, which carry away much of the energy.[221]

Many of the universe's most energetic phenomena have been attributed to the accretion of matter on black holes. Active galactic nuclei and quasars are powered by accretion onto supermassive black holes.[222][223] X-ray binaries are generally accepted to be binary systems in which one of the two objects is a compact object accreting matter from its companion.[164] Ultraluminous X-ray sources may be the accretion disks of intermediate-mass black holes.[224]

At a certain rate of accretion, the outward radiation pressure will become as strong as the inward gravitational force, and the black hole should, in theory, be unable to accrete any faster. This limit is called the Eddington limit. Realistically, many black holes accrete beyond this rate due to their non-spherical geometry or instabilities in the accretion disk. Accretion beyond the limit is called super-Eddington accretion and may have been commonplace in the early universe.[225][226]

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.[227][228]

Interaction with galaxies

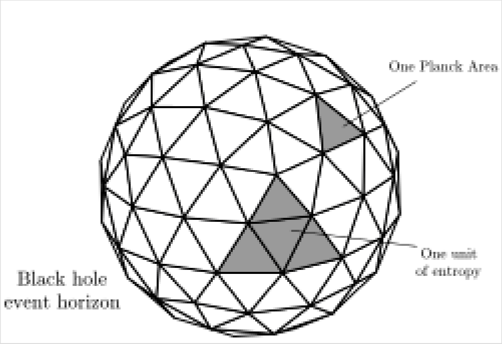
The correlation between the masses of supermassive black holes in the centres of galaxies with the velocity dispersion and mass of stars in their host bulges suggests that the formation of galaxies and the formation of their central black holes are related. Black hole winds from rapid accretion, particularly when the galaxy itself is still accreting matter, can compress gas nearby, accelerating star formation. However, if the winds become too strong, the black hole may blow nearly all of the gas out of the galaxy, quenching star formation. Black hole jets may also energise nearby cavities of plasma and eject low-entropy gas from out of the galactic core, causing gas in galactic centers to be hotter than expected.[229]

Evaporation

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.[45] The temperature of this thermal spectrum (Hawking temperature) is proportional to the surface gravity of the black hole, which is inversely proportional to the mass. Hence, large black holes emit less radiation than small black holes.[171]:Ch. 9.6[230] A stellar black hole of 1 $M_\odot$ has a Hawking temperature of 62 nanokelvins.[231] 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.[232] 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.[233]

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 is the microsecond-long 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, with modern research predicting that primordial black holes must make up less than a fraction of 10^{-7} of the universe's total mass.[234][94] NASA's Fermi Gamma-ray Space Telescope, launched in 2008, has searched for these flashes, but has not yet found any.[235][236]

Laws of mechanics and thermodynamics



A black hole's entropy scales with the surface area of its event horizon.

When based in general relativity, the constraints on a black hole's properties are called the laws of black hole mechanics. For a black hole that is not still forming or accreting matter, the zeroth law of black hole mechanics states the black hole's surface gravity is constant across the event horizon. The first law relates changes in the black hole's surface area, angular momentum, and charge to changes in its energy. The second law says the surface area of a black hole never decreases on its own. Finally, the third law says that the surface gravity of a black hole is never zero. These laws are mathematical analogues of the laws of thermodynamics. They are not equivalent, however, because, according to general relativity without quantum mechanics, a black hole can never emit radiation, and thus its temperature must always be zero.[237]:11[238]

Quantum mechanics predicts that a black hole will continuously emit thermal Hawking radiation, and therefore must always have a nonzero temperature. It also predicts that all black holes have entropy which scales with their surface area. When quantum mechanics is accounted for, the laws of black hole mechanics become equivalent to the classical laws of thermodynamics.[237][239] However, these conclusions are derived without a complete theory of quantum gravity, although many potential theories do predict black holes having entropy and temperature. Thus, the true quantum nature of black hole thermodynamics continues to be debated.[237]:29[238]

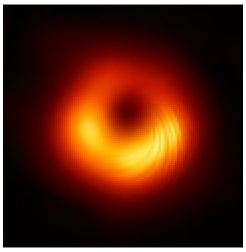
Observational evidence

Millions of black holes derived from stellar collapse are expected to exist in the Milky Way. Even a dwarf galaxy like Draco should have hundreds.[240] Only a few of these have been detected. By nature, black holes do not themselves emit any electromagnetic radiation other than the hypothetical, typically extremely weak Hawking radiation, so astrophysicists searching for black holes must rely on indirect observations. The defining characteristic of a black hole is its event horizon. The horizon itself cannot be imaged,[241] so all other possible explanations for these indirect observations must be considered and eliminated before concluding that a black hole has been observed.[242]:11

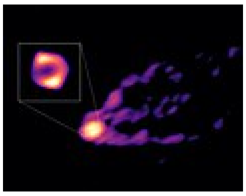
Direct interferometry

The Event Horizon Telescope (EHT) is a global system of radio telescopes capable of directly observing a black hole shadow.[58] The angular resolution of a telescope is based on its aperture and the wavelengths it is observing. Because the angular diameters of Sagittarius A* and Messier 87* in the sky are very small, a single telescope would need to be about the size of the Earth to clearly distinguish their horizons using radio wavelengths. By combining data from several different radio telescopes around the world, the Event Horizon Telescope creates an effective aperture the diameter size of the Earth. The EHT team used imaging algorithms to compute the most probable image from the data in its observations of Sagittarius A* and M87*.[243][1]

Gravitational waves



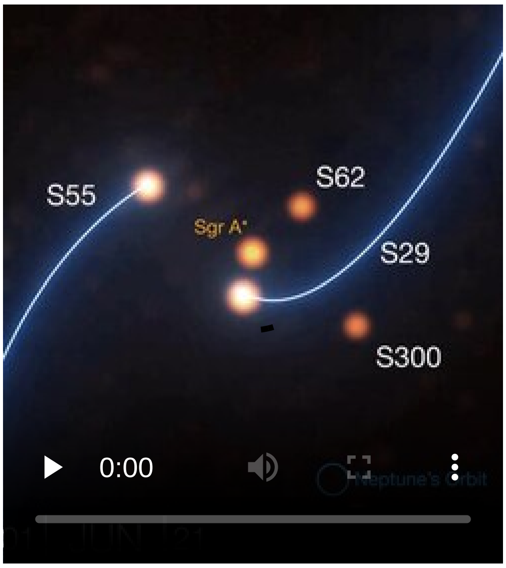
An M87* image with superimposed lines representing the magnitude and direction of polarisation



The M87* relativistic jet; inset is the black hole shadow

Gravitational-wave interferometry can be used to detect merging black holes and other compact objects. In this method, a laser beam is split, sent down two long arms of a tunnel, then reflected at the far end of the tunnels to reconverge at the intersection of the arms, precisely cancelling each other. However, when a gravitational wave passes, it warps spacetime, changing the relative lengths of the arms themselves. Since each laser beam is now travelling a slightly different distance, they do not cancel out and produce a recognisable signal. Analysis of the signal can give scientists information about what caused the gravitational waves. Since gravitational waves are very weak, gravitational-wave observatories such as LIGO must have arms several kilometres long and carefully control for noise from Earth to be able to detect these gravitational waves.[244] Since the first measurements in 2016, multiple gravitational waves from black holes have been detected and analysed.[108]

Stars orbiting Sagittarius A*

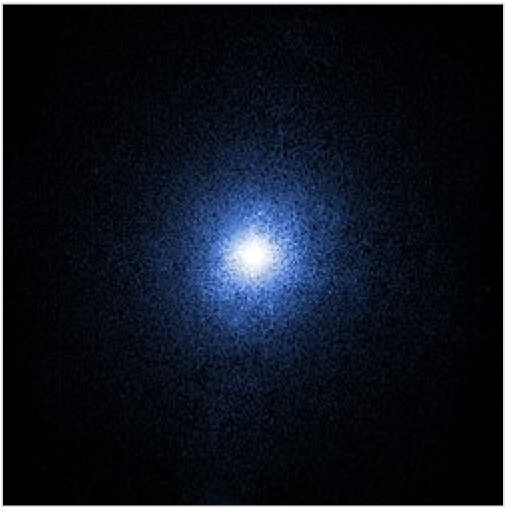


Stars moving around Sagittarius A*, as seen in 2021

The proper motions of stars near the centre of the Milky Way provide strong observational evidence that these stars are orbiting a supermassive black hole.[245] Astronomers have tracked the motions of 90 stars orbiting an invisible object coincident with the radio source Sagittarius A*. One of the stars—called S2—completed a full orbit. By fitting the motions of stars to Keplerian orbits, the astronomers were able to infer that the invisible object assumed to be Sagittarius A* must have a mass of $4.3 \times 10^6\ M_\odot$, with a radius of less than 0.002 light-years.[245] This upper limit radius is larger than the Schwarzschild radius for the estimated mass, so the combination does not prove Sagittarius A* is a black hole. 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.[53] Additionally, luminosity data from this object implies it must possess an event horizon, a defining feature of black holes.[246] The Event Horizon Telescope image of Sagittarius A*, released in 2022, provided further confirmation that it is indeed a black hole.[59]

Binaries

X-ray binaries are binary systems that emit a majority of their radiation in the X-ray part of the electromagnetic spectrum. These X-ray emissions result when a compact object accretes matter from an ordinary star.[247] 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. By measuring the orbital period of the binary, the distance to the binary from Earth, and the mass of the companion star, scientists can estimate the mass of the compact object.[248] The Tolman-Oppenheimer-Volkoff limit (TOV limit) dictates the largest mass a nonrotating neutron star can be, and is estimated to be about two solar masses. While a rotating neutron star can be slightly more massive, if the compact object is much more massive than the TOV limit, it cannot be a neutron star and is generally expected to be a black hole.[164][249]


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

The first strong candidate for a black hole, Cygnus X-1, was discovered in this way by Charles Thomas Bolton,[6] Louise Webster, and Paul Murdin[5] in 1972.[250][43] Observations of rotation broadening of the optical star reported in 1986 lead to a compact object mass estimate of 16 solar masses, with 7 solar masses as the lower bound.[164] In 2011, this estimate was updated to $14.1 \pm 1.0\ M_\odot$ for the black hole and $19.2 \pm 1.9\ M_\odot$ for the optical stellar companion.[251]

X-ray binaries can be categorised as either *low-mass* or *high-mass*; This classification is based on the mass of the companion star, not the compact object itself.[98] In a class of X-ray binaries called soft X-ray transients, 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.[164] Numerous black hole candidates have been measured by this method.[252] Black holes are also sometimes found in binaries with other compact objects, such as white dwarfs,[98] neutron stars,[253][254] and other black holes.[255][256]

Galactic nuclei

The centre of nearly every galaxy contains a supermassive black hole.[257] 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.[258][259]

Active galactic nucleus

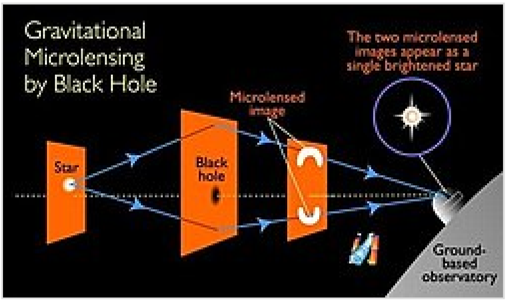
Astronomers use the term *active galaxy* to describe galaxies with unusual characteristics, such as unusual spectral line emission and very strong radio emission. Theoretical and observational studies have shown that the high levels of activity in the centers of these galaxies, regions called active galactic nuclei (AGN), may be explained by accretion onto supermassive black holes. 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.[261]

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, Messier 32, Messier 87, the Sombrero Galaxy, and the Milky Way itself.[262][263]

Microlensing

Another way black holes can be detected is through observation of effects caused by their strong gravitational field. One such effect is gravitational lensing: the deformation of spacetime around a massive object causes light rays to be deflected, making objects behind them appear distorted.[264] When the lensing object is a black hole, this effect can be strong enough to create multiple images of a star or other luminous source.[265] However, the distance between the lensed images may be too small for contemporary telescopes to resolve—this phenomenon is called microlensing.[266] Instead of seeing two images of a lensed star, astronomers see the star brighten slightly as the black hole moves towards the line of sight between the star and Earth and then return to its normal luminosity as the black hole moves away.[267] The first three candidate black holes detected in this way were found around the turn of the millennium.[268][269] In January 2022, astronomers reported the first confirmed detection of an *isolated* stellar black hole—a black hole with no binary partner—and its mass; The black hole was found via detection of microlensing by the Hubble Space Telescope.[270][271]

Detection of an unusually bright X-ray flare from Sagittarius A*, a black hole in the centre of the Milky Way galaxy on 5 January 2015[260]



The intense gravitational field of a foreground black hole acts like a powerful lens, distorting and brightening the image of a background star.

Areas of investigation

Information loss paradox

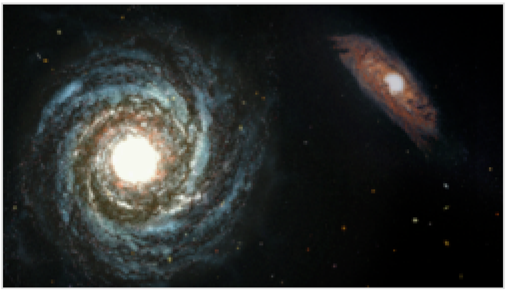
Unsolved problem in physics

? *Is physical information lost in black holes?*

More unsolved problems in physics

According to the no-hair theorem, a black hole is defined by only three parameters: its mass, charge, and angular momentum. This seems to mean that all other information about the matter that went into forming the black hole is lost, as there is no way to determine anything about the black hole from outside other than those three parameters. When black holes were thought to persist forever, this information loss was not problematic, as the information can be thought of as existing inside the black hole. 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 is seemingly gone forever. This is called the black hole information paradox.[272][273][274] Theoretical studies analysing the paradox have led to both further paradoxes and new ideas about the intersection of quantum mechanics and general relativity. While there is no consensus on the resolution of the paradox, work on the problem is expected to be important for a theory of quantum gravity.[275]:126

Supermassive black holes in the early universe


Two galaxies from the first billion years after the Big Bang. The galaxy on the left hosts a luminous quasar at its center.

Observations of faraway galaxies have found that ultraluminous quasars, powered by supermassive black holes, existed in the early universe as far as redshift $z \geq 7$.[276] These black holes have been assumed to be the products of the gravitational collapse of large population III stars.[277][278] However, these stellar remnants were not massive enough to produce the quasars observed at early times without accreting beyond the Eddington limit, the theoretical maximum rate of black hole accretion.[279][280]

Physicists have suggested a variety of different mechanisms by which these supermassive black holes may have formed. It has been proposed that smaller black holes may have also undergone mergers to produce the observed supermassive black holes.[281][282] It is also possible that they were seeded by direct-collapse black holes, in which a large cloud of hot gas avoids fragmentation that would lead to multiple stars, due to low angular momentum or heating from a nearby galaxy. Given the right circumstances, a single supermassive star forms and collapses directly into a black hole without undergoing typical stellar evolution.[283][284] Additionally, these supermassive black holes in the early universe may be high-mass primordial black holes, which could have accreted further matter in the centers of galaxies.[285] Finally, certain mechanisms allow black holes to grow faster than the theoretical Eddington limit, such as dense gas in the accretion disk limiting outward radiation pressure that prevents the black hole from accreting.[279][286] However, the formation of bipolar jets prevent super-Eddington rates.[226]

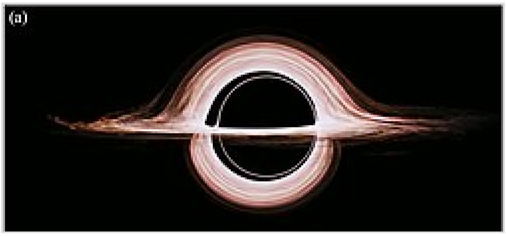
Alternatives to black holes

While there is a strong case for supermassive black holes,[287][288] the dividing line between lighter black holes and neutron stars relies on theories of extremely dense matter. Direct observational tests are not available: objects observed to have mass higher than the predictions for neutron stars are assumed to be black holes. Recent evidence from gravitational wave events suggests modifications of these theories may be needed.[97] New exotic phases of matter could allow other kinds of massive objects.[164] Quark stars would be made up of quark matter and supported by quark degeneracy pressure, a form of degeneracy pressure even stronger than neutron degeneracy pressure. This would halt gravitational collapse at a higher mass than for a neutron star.[289][290] Even stronger stars called electroweak stars would convert quarks in their cores into leptons, providing additional pressure to stop the star from collapsing.[291][292] If, as some extensions of the Standard Model posit, quarks and leptons are made up of the even-smaller fundamental particles called preons, a very compact star could be supported by preon degeneracy pressure.[293] While none of these hypothetical models can explain all of the observations of stellar black hole candidates, a Q star is the only alternative which could significantly exceed the mass limit for neutron stars and thus provide an alternative for supermassive black holes.[164]:12

A few theoretical objects have been conjectured to match observations of astronomical black hole candidates identically or near-identically, but which function via a different mechanism.[294] A dark energy star would convert infalling matter into vacuum energy; This vacuum energy would be much larger than the vacuum energy of outside space, exerting outwards pressure and preventing a singularity from forming.[295][296] A black star would be gravitationally collapsing slowly enough that quantum effects would keep it just on the cusp of fully collapsing into a black hole.[297] A gravastar would consist of a very thin shell and a dark-energy interior providing outward pressure to stop the collapse into a black hole or formation of a singularity; It could even have another gravastar inside, called a 'nestar'.[298]

In fiction

Black holes have been portrayed in science fiction in a variety of ways. Even before the advent of the term itself, objects with characteristics of black holes appeared in stories such as the 1928 novel The Skylark of Space with its "black Sun" and the "hole in space" in the 1935 short story *Starship Invincible*.[299] As black holes grew to public recognition in the 1960s and 1970s, they began to be featured in films as well as novels, such as Disney's *The Black Hole*. Black holes have also been used in works of the 21st century, such as Christopher Nolan's science fiction epic *Interstellar*.[300][301]



The black hole and accretion disk used in the movie Interstellar, without lens flare

Authors and screenwriters have exploited the relativistic effects of black holes, particularly gravitational time dilation.[302] For example, *Interstellar* features a black hole planet with a time dilation factor of over 60,000:1,[172]:163 while the 1977 novel *Gateway* depicts a spaceship approaching but never crossing the event horizon of a black hole from the perspective of an outside observer due to time dilation effects.[303] Black holes have also been appropriated as wormholes or other methods of faster-than-light travel, such as in the 1974 novel *The Forever War*, where a network of black holes is used for interstellar travel.[302][304] Additionally, black holes can feature as hazards to spacefarers and planets: A black hole threatens a deep-space outpost in 1978 short story *The Black Hole Passes*, and a binary black hole dangerously alters the orbit of a planet in the 2018 Netflix reboot of *Lost in Space*.[301][304]

Notes

1. The (outer) event horizon radius scales as: $M+\sqrt{M^{2}-(J/M)^{2}-Q^{2}}$.
2. 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.[139]:848

References

1. The Event Horizon Telescope Collaboration; et al. (10 April 2019). "First M87 Event Horizon Telescope Results. IV. Imaging the Central Supermassive Black Hole" (https://doi.org/10.3847%2F2041-8213%2Fab0e85). *The Astrophysical Journal Letters*. **875** (1): L4. arXiv:1906.11241 (https://arxiv.org/abs/1906.11241). Bibcode:2019ApJ...875L...4E (https://u

i.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). Bibcode:2019IJMPD..2850042R (https://ui.adsabs.harvard.edu/abs/2019IJMPD..2850042R). doi:10.1142/S0218271819500421 (https://doi.org/10.1142%2FS0218271819500421). S2CID 54548877 (https://api.semanticscholar.org/CorpusID:54548877).
4. Overbye, Dennis (8 June 2015). "Black Hole Hunters" (https://www.nytimes.com/2015/06/09/science/black-hole-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. Webster, B. Louise; Murdin, Paul (1972), "Cygnus X-1—a Spectroscopic Binary with a Heavy Companion?", *Nature* (Letter), **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)
6. Bolton, C. T. (1972), "Identification of Cygnus X-1 with HDE 226868", *Nature* (Letter), **235** (5336): 271–273, Bibcode:1972Natur.235..271B (https://ui.adsabs.harvard.edu/abs/1972Natur.235..271B), doi:10.1038/235271b0 (https://doi.org/10.1038%2F235271b0), S2CID 4222070 (https://api.semanticscholar.org/CorpusID:4222070)
7. Montgomery, Colin; Orchiston, Wayne; Whittingham, Ian (2009) [Available online 18 April 2023]. "Michell, Laplace and the Origin of the Black Hole Concept" (https://researchonline.jcu.edu.au/9892/1/Microsoft_Word_-_Paper__Black_Hole_Concept_Final_.pdf) (PDF). *Journal of Astronomical History and Heritage* (Research article). **12** (2): 90–96. Bibcode:2009JAHH...12...90M (https://ui.adsabs.harvard.edu/abs/2009JAHH...12...90M). doi:10.3724/SP.J.1440-2807.2009.02.01 (https://doi.org/10.3724%2FSP.J.1440-2807.2009.02.01). S2CID 55890996 (https://api.semanticscholar.org/CorpusID:55890996).
8. 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...35M (https://ui.adsabs.harvard.edu/abs/1784RSPT...74...35M). doi:10.1098/rstl.1784.0008 (https://doi.org/10.1098%2Frstl.1784.0008). JSTOR 106576 (https://www.jstor.org/stable/106576).
9. Thorne, Kip S.; Hawking, Stephen (1994). Agrawal, Milan (ed.). *Black Holes and Time Warps: Einstein's Outrageous Legacy* (https://archive.org/details/blackholestimewa0000thor) (1st ed.). W. W. Norton & Company. ISBN 978-0-393-31276-8. Retrieved 12 April 2019.
10. Weinberg, Steven (1972). *Gravitation and Cosmology* (https://archive.org/details/gravitationcosmo00stev_0). John Wiley & Sons. ISBN 978-0-471-92567-5.
11. Einstein, Albert (1915). "Feldgleichungen der Gravitation" [Field Equations of Gravitation]. *Preussische Akademie der Wissenschaften, Sitzungsberichte*: 844–847.
12. Janssen, Michel; Renn, Jürgen (2015). "Arch and Scaffold: How Einstein Found His Field Equations" (https://doi.org/10.1063%2FPT.3.2979). *Physics Today* (Feature article). **68** (11): 30–36. Bibcode:2015PhT....68k..30J (https://ui.adsabs.harvard.edu/abs/2015PhT....68k..30J). doi:10.1063/PT.3.2979 (https://doi.org/10.1063%2FPT.3.2979). hdl:11858/00-001M-0000-002A-8ED7-1 (https://hdl.handle.net/11858%2F00-001M-0000-002A-8ED7-1).

13. Fraknoi, Andrew; Morrison, David; Wolff, Sidney C. (2022). "24.5 Black Holes". *Astronomy 2e* (https://assets.openstax.org/oscms-prodcms/media/documents/Astronomy2e-WEB.pdf) (PDF) (2e ed.). OpenStax. pp. 839–846. ISBN 978-1-951693-50-3. OCLC 1322188620 (https://search.worldcat.org/oclc/1322188620).
14. Schwarzschild, K. (1916). "Über das Gravitationsfeld eines Massenpunktes nach der Einsteinschen Theorie" (https://archive.org/stream/sitzungsberichte1916deutsch#page/188/mode/2up) [On the gravitational field of a mass point according to Einstein's theory]. *Sitzungsberichte der Königlich Preussischen Akademie der Wissenschaften*. **7**: 189–196. Bibcode:1916SPAW.......189S (https://ui.adsabs.harvard.edu/abs/1916SPAW.......189S) – via Internet Archive.
    - Translation: Antoci, S.; Loinger, A. (12 May 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.conf..424S (https://ui.adsabs.harvard.edu/abs/1916skpa.conf..424S).
    - Translation: Antoci, S. (1999). "On the Gravitational Field of a Sphere of Incompressible Fluid According to Einstein's Theory". arXiv:physics/9912033 (https://arxiv.org/abs/physics/9912033).
15. Droste, J. (1917). "The Field of a Single Centre in Einstein's Theory of Gravitation, And the Motion of a Particle in That Field" (http://www.dwc.knaw.nl/DL/publications/PU00012325.pdf) (PDF). Physics. *Proceedings of the Section of Sciences*. **19** (1). Koninklijke Akademie van Wetenschappen: 197–215. Bibcode:1917KNAB...19..197D (https://ui.adsabs.harvard.edu/abs/1917KNAB...19..197D). Archived (https://web.archive.org/web/20130518034708/http://www.dwc.knaw.nl/DL/publications/PU00012325.pdf) (PDF) from the original on 18 May 2013. Retrieved 16 September 2012.
16. 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/20160810215219/https://books.google.com/books?id=vDHCF_3vIhUC&pg=PA41) from the original on 10 August 2016. Retrieved 23 February 2016.
17. 't Hooft, G. (2009). "Introduction to the Theory of Black Holes" (http://www.phys.uu.nl/~thooft/lectures/blackholes/BH_lecturenotes.pdf) (PDF). Institute for Theoretical Physics / Spinoza Institute. pp. 47–48. Archived (https://web.archive.org/web/20090521082736/http://www.phys.uu.nl/~thooft/lectures/blackholes/BH_lecturenotes.pdf) (PDF) from the original on 21 May 2009. Retrieved 24 June 2010.
18. 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%2Fscience.52.1341.233). 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. ISBN 978-0-521-33708-3
19. Bernstein, Jeremy (2007). "The Reluctant Father of Black Holes" (https://www.scientificamerican.com/article/the-reluctant-father-of-black-holes-2007-04/). *Scientific American*. Vol. 17. pp. 4–11. doi:10.1038/scientificamerican0407-4sp (https://doi.org/10.1038%2Fscientificamerican0407-4sp). Retrieved 3 August 2023.
20. Einstein, Albert (10 May 1939). "On a Stationary System With Spherical Symmetry Consisting of Many Gravitating Masses". *Annals of Mathematics*. **40** (4): 922–936. doi:10.2307/1968902 (https://doi.org/10.2307%2F1968902). JSTOR 1968902 (https://www.jstor.org/stable/1968902).

21. Detweiler, S. (1981). "Resource Letter BH-1: Black Holes". *American Journal of Physics* (Paper). **49** (5): 394–400. Bibcode:1981AmJPh..49..394D (https://ui.adsabs.harvard.edu/abs/1981AmJPh..49..394D). doi:10.1119/1.12686 (https://doi.org/10.1119%2F1.12686).
22. Oppenheimer, J. R.; Volkoff, G. M. (1939). "On Massive Neutron Cores". *Physical Review*. **55** (4): 374–381. Bibcode:1939PhRv...55..374O (https://ui.adsabs.harvard.edu/abs/1939PhRv...55..374O). doi:10.1103/PhysRev.55.374 (https://doi.org/10.1103%2FPhysRev.55.374).
23. Bartusiak, Marcia (2015). *Black Hole: How an Idea Abandoned by Newtonians, Hated by Einstein, And Gambled On by Hawking Became Loved*. Yale University Press. ISBN 978-0-300-21363-8.
24. Oppenheimer, J.R.; Snyder, H. (1939). "On Continued Gravitational Contraction" (https://doi.org/10.1103%2FPhysRev.56.455). *Physical Review* (Highlighted article). **56** (5): 455–459. Bibcode:1939PhRv...56..455O (https://ui.adsabs.harvard.edu/abs/1939PhRv...56..455O). doi:10.1103/PhysRev.56.455 (https://doi.org/10.1103%2FPhysRev.56.455).
25. Finkelstein, D. (1958). "Past-Future Asymmetry of the Gravitational Field of a Point Particle". *Physical Review* (Article). **110** (4): 965–967. Bibcode:1958PhRv..110..965F (https://ui.adsabs.harvard.edu/abs/1958PhRv..110..965F). doi:10.1103/PhysRev.110.965 (https://doi.org/10.1103%2FPhysRev.110.965).
26. 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..228L (https://ui.adsabs.harvard.edu/abs/1979A&A....75..228L). ISSN 0004-6361 (https://search.worldcat.org/issn/0004-6361).
27. 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.
28. Thorne K (2003). "5. Warping spacetime". In Shellard ES, Gibbons GW, Rankin SJ (eds.). *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.
29. Kerr, R. P. (2009). "Discovering 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). Bibcode:2007arXiv0706.1109K (https://ui.adsabs.harvard.edu/abs/2007arXiv0706.1109K). ISBN 978-0-521-88512-6.
30. Newman ET, Couch E, et al. (1965). "Metric of a Rotating, Charged Mass". *Journal of Mathematical Physics* (Research article). **6** (6): 918. Bibcode:1965JMP.....6..918N (https://ui.adsabs.harvard.edu/abs/1965JMP.....6..918N). doi:10.1063/1.1704351 (https://doi.org/10.1063%2F1.1704351).
31. Israel, W. (1967). "Event Horizons in Static Vacuum Space-Times". *Physical Review* (Article). **164** (5): 1776. Bibcode:1967PhRv..164.1776I (https://ui.adsabs.harvard.edu/abs/1967PhRv..164.1776I). doi:10.1103/PhysRev.164.1776 (https://doi.org/10.1103%2FPhysRev.164.1776).
32. Carter, B. (1971). "Axisymmetric Black Hole Has Only Two Degrees of Freedom". Elementary Particles and Fields. *Physical Review Letters* (Letter). **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%2FPhysRevLett.26.331).
33. Carter, B. (1977). "The vacuum black hole uniqueness theorem and its conceivable generalisations". *Proceedings of the 1st Marcel Grossmann Meeting on General Relativity*. pp. 243–254.

34. Chruściel PT, Costa JL, Heusler M (2012). "Stationary Black Holes: Uniqueness and Beyond" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5255892). *Living Reviews in Relativity* (Article). **15** (7) 7. arXiv:1205.6112 (https://arxiv.org/abs/1205.6112). 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). PMC 5255892 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5255892). PMID 28179837 (https://pubmed.ncbi.nlm.nih.gov/28179837).
35. Penrose, Roger (1996). "Chandrasekhar, Black Holes, And Singularities". *Journal of Astrophysics and Astronomy* (Article). **17** (3–4): 213–231. Bibcode:1996JApA...17..213P (https://ui.adsabs.harvard.edu/abs/1996JApA...17..213P). doi:10.1007/BF02702305 (https://doi.org/10.1007%2FBF02702305).
36. Penrose, R. (1965). "Gravitational Collapse and Space-Time Singularities". *Physical Review Letters*. **14** (3): 57. Bibcode:1965PhRvL..14...57P (https://ui.adsabs.harvard.edu/abs/1965PhRvL..14...57P). doi:10.1103/PhysRevLett.14.57 (https://doi.org/10.1103%2FPhysRevLett.14.57). S2CID 116755736 (https://api.semanticscholar.org/CorpusID:116755736).
37. 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). doi:10.1023/A:1025754515197 (https://doi.org/10.1023%2FA%3A1025754515197). S2CID 14404560 (https://api.semanticscholar.org/CorpusID:14404560).
38. Hewish, A.; Bell, S. J.; et al. (1968). "Observation of a Rapidly Pulsating Radio Source". *Nature*. **217** (5130): 709–713. Bibcode:1968Natur.217..709H (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).
39. Pilkington, J. D. H.; Hewish, A.; et al. (1968). "Observations of Some Further Pulsed Radio Sources". *Nature*. **218** (5137): 126–129. Bibcode:1968Natur.218..126P (https://ui.adsabs.harvard.edu/abs/1968Natur.218..126P). doi:10.1038/218126a0 (https://doi.org/10.1038%2F218126a0). S2CID 4253103 (https://api.semanticscholar.org/CorpusID:4253103).
40. Hewish, A. (1970). "Pulsars". *Annual Review of Astronomy and Astrophysics*. **8** (1): 265–296. Bibcode:1970ARA&A...8..265H (https://ui.adsabs.harvard.edu/abs/1970ARA&A...8..265H). doi:10.1146/annurev.aa.08.090170.001405 (https://doi.org/10.1146%2Fannurev.aa.08.090170.001405).
41. 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.
42. 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.
43. Shipman, H. L.; Yu, Z; Du, 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)

44. Bardeen, J. M.; Carter, B.; Hawking, S. W. (1973). "The Four Laws of Black Hole Mechanics" (http://projecteuclid.org/euclid.cmp/1103858973). *Communications in Mathematical Physics*. **31** (2): 161–170. Bibcode:1973CMaPh..31..161B (https://ui.adsabs.harvard.edu/abs/1973CMaPh..31..161B). doi:10.1007/BF01645742 (https://doi.org/10.1007%2FBF01645742). MR 0334798 (https://mathscinet.ams.org/mathscinet-getitem?mr=0334798). S2CID 54690354 (https://api.semanticscholar.org/CorpusID:54690354). Zbl 1125.83309 (https://zbmath.org/?format=complete&q=an:1125.83309). Archived (https://web.archive.org/web/20200516211604/https://projecteuclid.org/euclid.cmp/1103858973) from the original on 16 May 2020. Retrieved 4 June 2021.
45. Hawking, S. W. (1974). "Black Hole Explosions?". *Nature*. **248** (5443): 30–31. Bibcode:1974Natur.248...30H (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).
46. Lynden-Bell, D. (1969). "Galactic Nuclei as Collapsed Old Quasars". *Nature*. **223** (5207): 690–694. Bibcode:1969Natur.223..690L (https://ui.adsabs.harvard.edu/abs/1969Natur.223..690L). doi:10.1038/223690a0 (https://doi.org/10.1038%2F223690a0).
47. Rees, Martin J. (1984). "Black Hole Models for Active Galactic Nuclei". *Annual Review of Astronomy and Astrophysics*. **22**: 471–506. Bibcode:1984ARA&A..22..471R (https://ui.adsabs.harvard.edu/abs/1984ARA&A..22..471R). doi:10.1146/annurev.aa.22.090184.002351 (https://doi.org/10.1146%2Fannurev.aa.22.090184.002351).
48. Ferrarese, Laura; Ford, Holland (2005). "Supermassive Black Holes in Galactic Nuclei: Past, Present and Future Research". *Space Science Reviews*. **116** (3–4): 523–624. arXiv:astro-ph/0411247 (https://arxiv.org/abs/astro-ph/0411247). Bibcode:2005SSRv..116..523F (https://ui.adsabs.harvard.edu/abs/2005SSRv..116..523F). doi:10.1007/s11214-005-3947-6 (https://doi.org/10.1007%2Fs11214-005-3947-6).
49. Peterson, Bradley M. (2014). "Measuring the Masses of Supermassive Black Holes". *Space Science Reviews*. **183** (1–4): 253–275. Bibcode:2014SSRv..183..253P (https://ui.adsabs.harvard.edu/abs/2014SSRv..183..253P). doi:10.1007/s11214-013-9987-4 (https://doi.org/10.1007%2Fs11214-013-9987-4).
50. Merritt, David (1999). "Black holes and galaxy evolution" (https://archive.org/details/xvthiapmeetingdy0197iapm/page/221). In Combes, F.; Mamon, G. A.; Charmandaris, V. (eds.). *Dynamics of Galaxies: from the Early Universe to the Present*. Vol. 197. Astronomical Society of the Pacific. pp. 221–232 (https://archive.org/details/xvthiapmeetingdy0197iapm/page/221). arXiv:astro-ph/9910546 (https://arxiv.org/abs/astro-ph/9910546). Bibcode:2000ASPC..197..221M (https://ui.adsabs.harvard.edu/abs/2000ASPC..197..221M). ISBN 978-1-58381-024-8.
51. Tremaine, Scott; Gebhardt, Karl; et al. (2002). "The Slope of the Black Hole Mass Versus Velocity Dispersion Correlation". *The Astrophysical Journal*. **574** (2): 740–753. arXiv:astro-ph/0203468 (https://arxiv.org/abs/astro-ph/0203468). Bibcode:2002ApJ...574..740T (https://ui.adsabs.harvard.edu/abs/2002ApJ...574..740T). doi:10.1086/341002 (https://doi.org/10.1086%2F341002).

    Ferrarese, Laura; Merritt, David (2000). "A Fundamental Relation Between Supermassive Black Holes and Their Host Galaxies". *The Astrophysical Journal*. **539** (1): L9–L12. arXiv:astro-ph/0006053 (https://arxiv.org/abs/astro-ph/0006053). Bibcode:2000ApJ...539L...9F (https://ui.adsabs.harvard.edu/abs/2000ApJ...539L...9F). doi:10.1086/312838 (https://doi.org/10.1086%2F312838).

    Nelson, Charles H.; Green, Richard F.; et al. (2004). "The Relationship Between Black Hole Mass and Velocity Dispersion in Seyfert 1 Galaxies". *The Astrophysical Journal*. **615** (2): 652–661. arXiv:astro-ph/0407383 (https://arxiv.org/abs/astro-ph/0407383). Bibcode:2004ApJ...615..652N (https://ui.adsabs.harvard.edu/abs/2004ApJ...615..652N). doi:10.1086/424657 (https://doi.org/10.1086%2F424657).

52. Genzel, R.; Eckart, A.; et al. (1997). "On the Nature of the Dark Mass in the Centre of the Milky Way" (https://doi.org/10.1093%2Fmnras%2F291.1.219). *Monthly Notices of the Royal Astronomical Society*. **291**: 219–234. doi:10.1093/mnras/291.1.219 (https://doi.org/10.1093%2Fmnras%2F291.1.219).
53. Ghez, A. M.; Klein, B. L.; 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 (https://arxiv.org/abs/astro-ph/9807210). 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).
54. 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%2FPhysRevLett.116.061102). PMID 26918975 (https://pubmed.ncbi.nlm.nih.gov/26918975). S2CID 124959784 (https://api.semanticscholar.org/CorpusID:124959784).
55. The LIGO Scientific Collaboration and The Virgo Collaboration (2016). "An Improved Analysis of GW150914 Using a Fully Spin-Precessing Waveform Model". *Physical Review X*. **6** (4) 041014. arXiv:1606.01210 (https://arxiv.org/abs/1606.01210). Bibcode:2016PhRvX...6d1014A (https://ui.adsabs.harvard.edu/abs/2016PhRvX...6d1014A). doi:10.1103/PhysRevX.6.041014 (https://doi.org/10.1103%2FPhysRevX.6.041014). S2CID 18217435 (https://api.semanticscholar.org/CorpusID:18217435).
56. "The Nobel Prize in Physics 2017" (https://www.nobelprize.org/nobel_prizes/physics/laureates/2017/press.html). Nobel Foundation.
57. Burtnyk, Kimberly (20 March 2025). "LIGO-Virgo-KAGRA Announce the 200th Gravitational Wave Detection of O4!" (https://www.ligo.caltech.edu/news/ligo20250320). *LIGO Caltech*. Retrieved 22 October 2025.
58. 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). Bibcode:2019ApJ...875L...1E (https://ui.adsabs.harvard.edu/abs/2019ApJ...875L...1E). doi:10.3847/2041-8213/ab0ec7 (https://doi.org/10.3847%2F2041-8213%2Fab0ec7). S2CID 145906806 (https://api.semanticscholar.org/CorpusID:145906806).
59. "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-our-galaxy). *Event Horizon Telescope*. 12 May 2022. Archived (https://web.archive.org/web/20250926081853/https://eventhorizontelescope.org/blog/astronomers-reveal-first-image-black-hole-heart-our-galaxy) from the original on 26 September 2025. Retrieved 2 December 2025.
60. Poffenberger, Leah. "2020 Nobel Prize in Physics" (https://www.aps.org/archives/publications/apsnews/202011/nobel-physics.cfm). *American Physical Society*. Retrieved 20 October 2025.
61. "The Nobel Prize in Physics 2020" (https://www.nobelprize.org/prizes/physics/2020/summary/). *NobelPrize.org*. Archived (https://web.archive.org/web/20210424115309/https://www.nobelprize.org/prizes/physics/2020/summary/) from the original on 24 April 2021. Retrieved 8 October 2020.
62. Overbye, Dennis; Taylor, Derrick Bryson (6 October 2020). "Nobel Prize in Physics Awarded to 3 Scientists for Work on Black Holes" (https://www.nytimes.com/2020/10/06/science/nobel-prize-physics.html). *The New York Times*. Retrieved 6 October 2020.
63. "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/20161128050759/https://www.scientificamerican.com/article/pioneering-physicist-john-wheeler-dies/) from the original on 28 November 2016. Retrieved 27 November 2016.

64. 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/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.
65. Frolov, Valeri P.; Zelnikov, Andrei (1 December 2011). *Introduction to Black Hole Physics* (1st ed.). Oxford University Press. p. 1. ISBN 978-0-19-969229-3.
66. Booth, Ivan (2005). "Black-hole boundaries". *Canadian Journal of Physics*. **83** (11): 1073–1099. arXiv:gr-qc/0508107 (https://arxiv.org/abs/gr-qc/0508107). Bibcode:2005CaJPh..83.1073B (https://ui.adsabs.harvard.edu/abs/2005CaJPh..83.1073B). doi:10.1139/p05-063 (https://doi.org/10.1139%2Fp05-063).
67. Curiel, Erik (2019). "The many definitions of a black hole". *Nature Astronomy*. **3**: 27–34. arXiv:1808.01507 (https://arxiv.org/abs/1808.01507). Bibcode:2019NatAs...3...27C (https://ui.adsabs.harvard.edu/abs/2019NatAs...3...27C). doi:10.1038/s41550-018-0602-1 (https://doi.org/10.1038%2Fs41550-018-0602-1).
68. Susskind, Leonard (2008). *The black hole war: my battle with Stephen Hawking to make the world safe for quantum mechanics* (1st ed.). Little, Brown. ISBN 978-0-316-01640-7. OCLC 181603165 (https://search.worldcat.org/oclc/181603165).
69. Hamilton, Andrew J. S.; Lisle, Jason P. (1 June 2008). "The river model of black holes" (https://pubs.aip.org/ajp/article/76/6/519/237222/The-river-model-of-black-holes). *American Journal of Physics*. **76** (6): 519–532. arXiv:gr-qc/0411060 (https://arxiv.org/abs/gr-qc/0411060). Bibcode:2008AmJPh..76..519H (https://ui.adsabs.harvard.edu/abs/2008AmJPh..76..519H). doi:10.1119/1.2830526 (https://doi.org/10.1119%2F1.2830526). ISSN 0002-9505 (https://search.worldcat.org/issn/0002-9505).
70. Hamilton, Andrew. "A Black Hole is a Waterfall of Space" (https://jila.colorado.edu/~ajsh/insidebh/waterfall.html). *Inside Black Holes*. Archived (https://web.archive.org/web/20250820063124/https://jila.colorado.edu/%7Eajsh/insidebh/waterfall.html) from the original on 20 August 2025. Retrieved 24 October 2025.
71. Yang, Xilong; Tang, Meirong; Xu, Zhaoyi (2024). "Exploring the Possibility of Testing the No-Hair Theorem with Minkowski-Deformed Regular Hairy Black Holes via Photon Rings" (https://doi.org/10.1140%2Fepjc%2Fs10052-024-13343-y). *The European Physical Journal C*. **84** (9) 977. doi:10.1140/epjc/s10052-024-13343-y (https://doi.org/10.1140%2Fepjc%2Fs10052-024-13343-y).
72. Shapiro, S. L.; Teukolsky, S. A. (1983). *Black Holes, White Dwarfs, And Neutron Stars: The Physics of Compact Objects*. John Wiley and Sons. p. 357. ISBN 978-0-471-87316-7.
73. Seeds, Michael A.; Backman, Dana E. (2007). *Perspectives on Astronomy* (https://books.google.com/books?id=CXom04KGIL8C&pg=PA167). Cengage Learning. p. 167. ISBN 978-0-495-11352-2. Archived (https://web.archive.org/web/20160810211808/https://books.google.com/books?id=CXom04KGIL8C&pg=PA167) from the original on 10 August 2016.
74. Wald, R. M. (1997). "Gravitational Collapse and Cosmic Censorship". In Iyer, B. R.; Bhawal, B. (eds.). *Black Holes, Gravitational Radiation and the Universe*. Springer. pp. 69–86. arXiv:gr-qc/9710068 (https://arxiv.org/abs/gr-qc/9710068). doi:10.1007/978-94-017-0934-7 (https://doi.org/10.1007%2F978-94-017-0934-7). ISBN 978-94-017-0934-7.
75. Berger, B. K. (2002). "Numerical Approaches to Spacetime Singularities" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5256073). *Living Reviews in Relativity*. **5** (1) 1: 2002–1. arXiv:gr-qc/0201056 (https://arxiv.org/abs/gr-qc/0201056). 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).
76. Joshi, Pankaj S. (1 February 2009). "Naked Singularities". *Scientific American*. Vol. 300, no. 2. pp. 36–43. JSTOR 26001219 (https://www.jstor.org/stable/26001219).

77. Ghosh, Rajes; Mishra, Akash K.; Sarkar, Sudipta (2021). "Overcharging Extremal Black Holes". *Physical Review D*. **104** (10) 104043. arXiv:2106.10667 (https://arxiv.org/abs/2106.10667). Bibcode:2021PhRvD.104j4043G (https://ui.adsabs.harvard.edu/abs/2021PhRvD.104j4043G). doi:10.1103/PhysRevD.104.104043 (https://doi.org/10.1103%2FPhysRevD.104.104043).
78. "Black Hole Basics" (https://science.nasa.gov/universe/black-holes/). *NASA.gov*. 13 March 2024. Retrieved 25 October 2025.
79. Eilon, Ehud; Ori, Amos (2016). "Numerical Study of the Gravitational Shock Wave Inside a Spherical Charged Black Hole". *Physical Review D*. **94** (10) 104060. arXiv:1610.04355 (https://arxiv.org/abs/1610.04355). Bibcode:2016PhRvD..94j4060E (https://ui.adsabs.harvard.edu/abs/2016PhRvD..94j4060E). doi:10.1103/PhysRevD.94.104060 (https://doi.org/10.1103%2FPhysRevD.94.104060).
80. Daly, Ruth A. (2019). "Black Hole Spin and Accretion Disk Magnetic Field Strength Estimates for More Than 750 Active Galactic Nuclei and Multiple Galactic Black Holes" (https://doi.org/10.3847%2F1538-4357%2Fab35e6). *The Astrophysical Journal*. **886** (1): 37. arXiv:1905.11319 (https://arxiv.org/abs/1905.11319). Bibcode:2019ApJ...886...37D (https://ui.adsabs.harvard.edu/abs/2019ApJ...886...37D). doi:10.3847/1538-4357/ab35e6 (https://doi.org/10.3847%2F1538-4357%2Fab35e6).
81. Daly, Ruth A.; Donahue, Megan; et al. (2024). "New Black Hole Spin Values for Sagittarius A* Obtained with the Outflow Method" (https://doi.org/10.1093%2Fmnras%2Fstad3228). *Monthly Notices of the Royal Astronomical Society*. **527**: 428–436. doi:10.1093/mnras/stad3228 (https://doi.org/10.1093%2Fmnras%2Fstad3228).
82. 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). Bibcode:2019NatAs...3...41R (https://ui.adsabs.harvard.edu/abs/2019NatAs...3...41R). doi:10.1038/s41550-018-0665-z (https://doi.org/10.1038%2Fs41550-018-0665-z). ISSN 2397-3366 (https://search.worldcat.org/issn/2397-3366). S2CID 85543351 (https://api.semanticscholar.org/CorpusID:85543351). Archived (https://web.archive.org/web/20201118092121/https://www.nature.com/articles/s41550-018-0665-z) from the original on 18 November 2020. Retrieved 21 August 2020.
83. Tamburini, Fabrizio; Thidé, Bo; Della Valle, Massimo (2020). "Measurement of the Spin of the M87 Black Hole from Its Observed Twisted Light" (https://doi.org/10.1093%2Fmnrasl%2Fslz176). *Monthly Notices of the Royal Astronomical Society: Letters*. **492**: L22–L27. arXiv:1904.07923 (https://arxiv.org/abs/1904.07923). doi:10.1093/mnrasl/slz176 (https://doi.org/10.1093%2Fmnrasl%2Fslz176).
84. Bambi, Cosimo; Freese, Katherine; et al. (2019). "Testing the Rotational Nature of the Supermassive Object M87* from the Circularity and Size of Its First Image". *Physical Review D*. **100** (4) 044057. arXiv:1904.12983 (https://arxiv.org/abs/1904.12983). Bibcode:2019PhRvD.100d4057B (https://ui.adsabs.harvard.edu/abs/2019PhRvD.100d4057B). doi:10.1103/PhysRevD.100.044057 (https://doi.org/10.1103%2FPhysRevD.100.044057).
85. 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). Bibcode:2017PhRvL.118v1101A (https://ui.adsabs.harvard.edu/abs/2017PhRvL.118v1101A). doi:10.1103/PhysRevLett.118.221101 (https://doi.org/10.1103%2FPhysRevLett.118.221101). PMID 28621973 (https://pubmed.ncbi.nlm.nih.gov/28621973). S2CID 206291714 (https://api.semanticscholar.org/CorpusID:206291714).
86. Horbatsch, M.W; Burgess, C.P (2012). "Cosmic Black-Hole Hair Growth and Quasar OJ287". *Journal of Cosmology and Astroparticle Physics* (5): 010. arXiv:1111.4009 (https://arxiv.org/abs/1111.4009). Bibcode:2012JCAP...05..010H (https://ui.adsabs.harvard.edu/abs/2012JCAP...05..010H). doi:10.1088/1475-7516/2012/05/010 (https://doi.org/10.1088%2F1475-7516%2F2012%2F05%2F010).

87. Zajaček, Michal; Tursunov, Arman; et al. (2018). "On the Charge of the Galactic Centre Black Hole" (https://doi.org/10.1093%2Fmnras%2Fsty2182). *Monthly Notices of the Royal Astronomical Society*. **480** (4): 4408–4423. arXiv:1808.07327 (https://arxiv.org/abs/1808.07327). doi:10.1093/mnras/sty2182 (https://doi.org/10.1093%2Fmnras%2Fsty2182).
88. Xu, Hao; Ong, Yen Chin; Yung, Man-Hong (2020). "Cosmic Censorship and the Evolution of d-Dimensional Charged Evaporating Black Holes". *Physical Review D*. **101** (6) 064015. arXiv:1911.11990 (https://arxiv.org/abs/1911.11990). Bibcode:2020PhRvD.101f4015X (https://ui.adsabs.harvard.edu/abs/2020PhRvD.101f4015X). doi:10.1103/PhysRevD.101.064015 (https://doi.org/10.1103%2FPhysRevD.101.064015).
89. Gong, Yi; Cao, Zhoujian; et al. (2019). "On Neutralization of Charged Black Holes" (https://doi.org/10.1093%2Fmnras%2Fstz1904). *Monthly Notices of the Royal Astronomical Society*. **488** (2): 2722–2731. arXiv:1907.05239 (https://arxiv.org/abs/1907.05239). doi:10.1093/mnras/stz1904 (https://doi.org/10.1093%2Fmnras%2Fstz1904).
90. Zakharov, A. F.; De Paolis, F.; et al. (2005). "Direct Measurements of Black Hole Charge with Future Astrometrical Missions". *Astronomy & Astrophysics*. **442** (3): 795–799. arXiv:astro-ph/0505286 (https://arxiv.org/abs/astro-ph/0505286). Bibcode:2005A&A...442..795Z (https://ui.adsabs.harvard.edu/abs/2005A&A...442..795Z). doi:10.1051/0004-6361:20053432 (https://doi.org/10.1051%2F0004-6361%3A20053432).
91. Turimov, Bobur; Boboqambarova, Madina; et al. (2022). "Distinguishable Feature of Electric and Magnetic Charged Black Hole". *The European Physical Journal Plus*. **137** (2) 222. doi:10.1140/epjp/s13360-022-02390-7 (https://doi.org/10.1140%2Fepjp%2Fs13360-022-02390-7).
92. Coleman Miller, M.; Colbert, E. J. M. (2004). "Intermediate-Mass Black Holes". *International Journal of Modern Physics D*. **13** (1): 1–64. arXiv:astro-ph/0308402 (https://arxiv.org/abs/astro-ph/0308402). Bibcode:2004IJMPD..13....1M (https://ui.adsabs.harvard.edu/abs/2004IJMPD..13....1M). doi:10.1142/S0218271804004426 (https://doi.org/10.1142%2FS0218271804004426).
93. Cromartie, H. T.; Fonseca, E.; et al. (2019). "Relativistic Shapiro Delay Measurements of an Extremely Massive Millisecond Pulsar". *Nature Astronomy*. **4**: 72–76. arXiv:1904.06759 (https://arxiv.org/abs/1904.06759). doi:10.1038/s41550-019-0880-2 (https://doi.org/10.1038%2Fs41550-019-0880-2).

    Drischler, Christian; Han, Sophia; et al. (2021). "Limiting Masses and Radii of Neutron Stars and Their Implications". *Physical Review C*. **103** (4) 045808. arXiv:2009.06441 (https://arxiv.org/abs/2009.06441). Bibcode:2021PhRvC.103d5808D (https://ui.adsabs.harvard.edu/abs/2021PhRvC.103d5808D). doi:10.1103/PhysRevC.103.045808 (https://doi.org/10.1103%2FPhysRevC.103.045808).

    Farr, Will M.; Sravan, Niharika; et al. (2011). "The Mass Distribution of Stellar-Mass Black Holes". *The Astrophysical Journal*. **741** (2): 103. arXiv:1011.1459 (https://arxiv.org/abs/1011.1459). Bibcode:2011ApJ...741..103F (https://ui.adsabs.harvard.edu/abs/2011ApJ...741..103F). doi:10.1088/0004-637X/741/2/103 (https://doi.org/10.1088%2F0004-637X%2F741%2F2%2F103).

94. Carr, Bernard; Kohri, Kazunori; et al. (2021). "Constraints on Primordial Black Holes". *Reports on Progress in Physics*. **84** (11). arXiv:2002.12778 (https://arxiv.org/abs/2002.12778). Bibcode:2021RPPh...84k6902C (https://ui.adsabs.harvard.edu/abs/2021RPPh...84k6902C). doi:10.1088/1361-6633/ac1e31 (https://doi.org/10.1088%2F1361-6633%2Fac1e31). PMID 34874316 (https://pubmed.ncbi.nlm.nih.gov/34874316).
95. Nakama, Tomohiro; Yokoyama, Jun'Ichi (2019). "Micro Black Holes Formed in the Early Universe and Their Cosmological Implications". *Physical Review D*. **99** (6) 061303. arXiv:1811.05049 (https://arxiv.org/abs/1811.05049). Bibcode:2019PhRvD..99f1303N (https://ui.adsabs.harvard.edu/abs/2019PhRvD..99f1303N). doi:10.1103/PhysRevD.99.061303 (https://doi.org/10.1103%2FPhysRevD.99.061303).

96. Scardigli, Fabio (2000). "Gravity Coupling from Micro-Black Holes". *Nuclear Physics B – Proceedings Supplements*. **88** (1–3): 291–294. arXiv:hep-th/9907150 (https://arxiv.org/abs/hep-th/9907150). Bibcode:2000NuPhS..88..291S (https://ui.adsabs.harvard.edu/abs/2000NuPhS..88..291S). doi:10.1016/S0920-5632(00)00788-X (https://doi.org/10.1016%2FS0920-5632%2800%2900788-X).
97. Vink, Jorick S.; Higgins, Erin R.; et al. (2021). "Maximum Black Hole Mass Across Cosmic Time" (https://doi.org/10.1093%2Fmnras%2Fstab842). *Monthly Notices of the Royal Astronomical Society*. **504**: 146–154. arXiv:2010.11730 (https://arxiv.org/abs/2010.11730). doi:10.1093/mnras/stab842 (https://doi.org/10.1093%2Fmnras%2Fstab842).
98. Dunn, R. J. H.; Fender, R. P.; et al. (2010). "A Global Spectral Study of Black Hole X-Ray Binaries" (https://doi.org/10.1111%2Fj.1365-2966.2010.16114.x). *Monthly Notices of the Royal Astronomical Society*. **403** (1): 61–82. arXiv:0912.0142 (https://arxiv.org/abs/0912.0142). Bibcode:2010MNRAS.403...61D (https://ui.adsabs.harvard.edu/abs/2010MNRAS.403...61D). doi:10.1111/j.1365-2966.2010.16114.x (https://doi.org/10.1111%2Fj.1365-2966.2010.16114.x).
99. Shao, Yong; Li, Xiang-Dong (2020). "Population Synthesis of Black Hole X-Ray Binaries" (https://doi.org/10.3847%2F1538-4357%2Faba118). *The Astrophysical Journal*. **898** (2): 143. arXiv:2006.15961 (https://arxiv.org/abs/2006.15961). Bibcode:2020ApJ...898..143S (https://ui.adsabs.harvard.edu/abs/2020ApJ...898..143S). doi:10.3847/1538-4357/aba118 (https://doi.org/10.3847%2F1538-4357%2Faba118).
100. Coleman Miller, M.; Hamilton, Douglas P. (2002). "Production of Intermediate-Mass Black Holes in Globular Clusters" (https://doi.org/10.1046%2Fj.1365-8711.2002.05112.x). *Monthly Notices of the Royal Astronomical Society*. **330** (1): 232–240. arXiv:astro-ph/0106188 (https://arxiv.org/abs/astro-ph/0106188). Bibcode:2002MNRAS.330..232C (https://ui.adsabs.harvard.edu/abs/2002MNRAS.330..232C). doi:10.1046/j.1365-8711.2002.05112.x (https://doi.org/10.1046%2Fj.1365-8711.2002.05112.x).

    Rizzuto, Francesco Paolo; Naab, Thorsten; et al. (2021). "Intermediate Mass Black Hole Formation in Compact Young Massive Star Clusters" (https://doi.org/10.1093%2Fmnras%2Fstaa3634). *Monthly Notices of the Royal Astronomical Society*. **501** (4): 5257–5273. arXiv:2008.09571 (https://arxiv.org/abs/2008.09571). doi:10.1093/mnras/staa3634 (https://doi.org/10.1093%2Fmnras%2Fstaa3634).

    Barai, Paramita; De Gouveia Dal Pino, Elisabete M. (2019). "Intermediate-Mass Black Hole Growth and Feedback in Dwarf Galaxies at High Redshifts" (https://doi.org/10.1093%2Fmnras%2Fstz1616). *Monthly Notices of the Royal Astronomical Society*. **487** (4): 5549–5563. arXiv:1807.04768 (https://arxiv.org/abs/1807.04768). doi:10.1093/mnras/stz1616 (https://doi.org/10.1093%2Fmnras%2Fstz1616).

101. Ruiz-Rocha, Krystal; Yelikar, Anjali B.; et al. (2025). "Properties of "Lite" Intermediate-Mass Black Hole Candidates in LIGO-Virgo's Third Observing Run" (https://doi.org/10.3847%2F2041-8213%2Fadc5f8). *The Astrophysical Journal Letters*. **985** (2): L37. arXiv:2502.17681 (https://arxiv.org/abs/2502.17681). Bibcode:2025ApJ...985L..37R (https://ui.adsabs.harvard.edu/abs/2025ApJ...985L..37R). doi:10.3847/2041-8213/adc5f8 (https://doi.org/10.3847%2F2041-8213%2Fadc5f8).
102. Abbott, R.; Abbott, T. D.; et al. (2022). "Search for Intermediate-Mass Black Hole Binaries in the Third Observing Run of Advanced LIGO and Advanced Virgo". *Astronomy & Astrophysics*. **659**: A84. arXiv:2105.15120 (https://arxiv.org/abs/2105.15120). Bibcode:2022A&A...659A..84A (https://ui.adsabs.harvard.edu/abs/2022A&A...659A..84A). doi:10.1051/0004-6361/202141452 (https://doi.org/10.1051%2F0004-6361%2F202141452).
103. Mezcua, Mar (2021). "Black Holes". *Encyclopedia of Astrobiology*. pp. 1–8. arXiv:2110.08629 (https://arxiv.org/abs/2110.08629). doi:10.1007/978-3-642-27833-4_5510-1 (https://doi.org/10.1007%2F978-3-642-27833-4_5510-1). ISBN 978-3-642-27833-4.

104. Natarajan, Priyamvada; Treister, Ezequiel (2009). "Is There an Upper Limit to Black Hole Masses?" (https://doi.org/10.1111%2Fj.1365-2966.2008.13864.x). *Monthly Notices of the Royal Astronomical Society*. **393** (3): 838–845. arXiv:0808.2813 (https://arxiv.org/abs/0808.2813). Bibcode:2009MNRAS.393..838N (https://ui.adsabs.harvard.edu/abs/2009MNRAS.393..838N). doi:10.1111/j.1365-2966.2008.13864.x (https://doi.org/10.1111%2Fj.1365-2966.2008.13864.x).
105. Dullo, Bililign T.; Gil De Paz, Armando; Knapen, Johan H. (2021). "Ultramassive Black Holes in the Most Massive Galaxies: M $_{BH}$–σ Versus M $_{BH}$–R $_{b}$" (https://doi.org/10.3847%2F1538-4357%2Fabceae). *The Astrophysical Journal*. **908** (2): 134. arXiv:2012.04471 (https://arxiv.org/abs/2012.04471). Bibcode:2021ApJ...908..134D (https://ui.adsabs.harvard.edu/abs/2021ApJ...908..134D). doi:10.3847/1538-4357/abceae (https://doi.org/10.3847%2F1538-4357%2Fabceae).
106. King, Andrew (February 2016). "How big can a black hole grow?" (https://doi.org/10.1093%2Fmnrasl%2Fslv186). *Monthly Notices of the Royal Astronomical Society: Letters*. **456** (1): L109–L112. arXiv:1511.08502 (https://arxiv.org/abs/1511.08502). Bibcode:2016MNRAS.456L.109K (https://ui.adsabs.harvard.edu/abs/2016MNRAS.456L.109K). doi:10.1093/mnrasl/slv186 (https://doi.org/10.1093%2Fmnrasl%2Fslv186). S2CID 40147275 (https://api.semanticscholar.org/CorpusID:40147275).
107. Clery, Daniel (21 December 2015). "Limit to how big black holes can grow is astonishing" (https://www.science.org/content/article/limit-how-big-black-holes-can-grow-astonishing). *sciencemag.org*. Retrieved 27 November 2018.
108. Reynolds, Christopher S. (8 September 2021). "Observational Constraints on Black Hole Spin" (https://www.annualreviews.org/doi/10.1146/annurev-astro-112420-035022). *Annual Review of Astronomy and Astrophysics*. **59** (1): 117–154. arXiv:2011.08948 (https://arxiv.org/abs/2011.08948). Bibcode:2021ARA&A..59..117R (https://ui.adsabs.harvard.edu/abs/2021ARA&A..59..117R). doi:10.1146/annurev-astro-112420-035022 (https://doi.org/10.1146%2Fannurev-astro-112420-035022). ISSN 0066-4146 (https://search.worldcat.org/issn/0066-4146).
109. Mirabel, I. F.; Rodríguez, L. F. (1999). "Sources of Relativistic Jets in the Galaxy". *Annual Review of Astronomy and Astrophysics*. **37**: 409–443. arXiv:astro-ph/9902062 (https://arxiv.org/abs/astro-ph/9902062). Bibcode:1999ARA&A..37..409M (https://ui.adsabs.harvard.edu/abs/1999ARA&A..37..409M). doi:10.1146/annurev.astro.37.1.409 (https://doi.org/10.1146%2Fannurev.astro.37.1.409).
110. "Relativistic Jets" (https://nustar.caltech.edu/page/relativistic-jets). *NuSTAR*. Retrieved 9 November 2025.
111. Bagchi, Joydeep; Vivek, M.; et al. (2014). "Megaparsec Relativistic Jets Launched from an Accreting Supermassive Black Hole in an Extreme Spiral Galaxy". *The Astrophysical Journal*. **788** (2): 174. arXiv:1404.6889 (https://arxiv.org/abs/1404.6889). Bibcode:2014ApJ...788..174B (https://ui.adsabs.harvard.edu/abs/2014ApJ...788..174B). doi:10.1088/0004-637X/788/2/174 (https://doi.org/10.1088%2F0004-637X%2F788%2F2%2F174).
112. Nemmen, R. S.; Georganopoulos, M.; et al. (2012). "A Universal Scaling for the Energetics of Relativistic Jets from Black Hole Systems". *Science*. **338** (6113): 1445–1448. arXiv:1212.3343 (https://arxiv.org/abs/1212.3343). Bibcode:2012Sci...338.1445N (https://ui.adsabs.harvard.edu/abs/2012Sci...338.1445N). doi:10.1126/science.1227416 (https://doi.org/10.1126%2Fscience.1227416). PMID 23239730 (https://pubmed.ncbi.nlm.nih.gov/23239730).
113. Blandford, Roger; Meier, David; Readhead, Anthony (2019). "Relativistic Jets from Active Galactic Nuclei". *Annual Review of Astronomy and Astrophysics*. **57**: 467–509. arXiv:1812.06025 (https://arxiv.org/abs/1812.06025). Bibcode:2019ARA&A..57..467B (https://ui.adsabs.harvard.edu/abs/2019ARA&A..57..467B). doi:10.1146/annurev-astro-081817-051948 (https://doi.org/10.1146%2Fannurev-astro-081817-051948).

114. Chen 陈, Yongyun 永云; Gu 顾, Qiusheng 秋生; et al. (2021). "The Powers of Relativistic Jets Depend on the Spin of Accreting Supermassive Black Holes" (https://doi.org/10.3847%2F1538-4357%2Fabf4ff). *The Astrophysical Journal*. **913** (2): 93. arXiv:2104.04242 (https://arxiv.org/abs/2104.04242). Bibcode:2021ApJ...913...93C (https://ui.adsabs.harvard.edu/abs/2021ApJ...913...93C). doi:10.3847/1538-4357/abf4ff (https://doi.org/10.3847%2F1538-4357%2Fabf4ff).
115. Ghisellini, G.; Haardt, F.; et al. (2013). "The Role of Relativistic Jets in the Heaviest and Most Active Supermassive Black Holes at High Redshift" (https://doi.org/10.1093%2Fmnras%2Fstt637). *Monthly Notices of the Royal Astronomical Society*. **432** (4): 2818–2823. doi:10.1093/mnras/stt637 (https://doi.org/10.1093%2Fmnras%2Fstt637).
116. Ghisellini, G.; Tavecchio, F.; et al. (2014). "The Power of Relativistic Jets Is Larger Than the Luminosity of Their Accretion Disks". *Nature*. **515** (7527): 376–378. arXiv:1411.5368 (https://arxiv.org/abs/1411.5368). Bibcode:2014Natur.515..376G (https://ui.adsabs.harvard.edu/abs/2014Natur.515..376G). doi:10.1038/nature13856 (https://doi.org/10.1038%2Fnature13856). PMID 25409827 (https://pubmed.ncbi.nlm.nih.gov/25409827).
117. Mirabel, I. F.; Rodríguez, L. F. (April 1998). "Microquasars in Our Galaxy" (https://www.nature.com/articles/33603). *Nature*. **392** (6677): 673–676. Bibcode:1998Natur.392..673M (https://ui.adsabs.harvard.edu/abs/1998Natur.392..673M). doi:10.1038/33603 (https://doi.org/10.1038%2F33603). ISSN 0028-0836 (https://search.worldcat.org/issn/0028-0836).
118. Lee, Hyun Kyu; Wijers, R.A.M.J.; Brown, G.E. (2000). "The Blandford–Znajek Process as a Central Engine for a Gamma-Ray Burst". *Physics Reports*. **325** (3): 83–114. arXiv:astro-ph/9906213 (https://arxiv.org/abs/astro-ph/9906213). Bibcode:2000PhR...325...83L (https://ui.adsabs.harvard.edu/abs/2000PhR...325...83L). doi:10.1016/S0370-1573(99)00084-8 (https://doi.org/10.1016%2FS0370-1573%2899%2900084-8).
119. Blandford, R. D.; Znajek, R. L. (1977). "Electromagnetic Extraction of Energy from Kerr Black Holes" (https://doi.org/10.1093%2Fmnras%2F179.3.433). *Monthly Notices of the Royal Astronomical Society*. **179** (3): 433. arXiv:astro-ph/0506302 (https://arxiv.org/abs/astro-ph/0506302). Bibcode:1977MNRAS.179..433B (https://ui.adsabs.harvard.edu/abs/1977MNRAS.179..433B). doi:10.1093/mnras/179.3.433 (https://doi.org/10.1093%2Fmnras%2F179.3.433).
120. Penrose, R. (1969). "Gravitational Collapse: The Role of General Relativity". *Rivista del Nuovo Cimento*. **1**: 252–276. Bibcode:1969NCimR...1..252P (https://ui.adsabs.harvard.edu/abs/1969NCimR...1..252P).
121. Narayan, Ramesh; McClintock, Jeffrey E.; Tchekhovskoy, Alexander (2014). "Energy Extraction from Spinning Black Holes Via Relativistic Jets". *General Relativity, Cosmology and Astrophysics*. pp. 523–535. arXiv:1303.3004 (https://arxiv.org/abs/1303.3004). doi:10.1007/978-3-319-06349-2_25 (https://doi.org/10.1007%2F978-3-319-06349-2_25). ISBN 978-3-319-06348-5.
122. "Black Hole Anatomy" (https://web.archive.org/web/20250424044622/https://science.nasa.gov/universe/black-holes/anatomy/). *NASA Science*. 2 August 2022. Archived from the original (https://science.nasa.gov/universe/black-holes/anatomy/) on 24 April 2025. Retrieved 13 October 2025.
123. Cunha, Pedro; Eiró, Nelson; Herdeiro, Carlos; Lemos, José (16 March 2020). "Lensing and Shadow of a Black Hole Surrounded by a Heavy Accretion Disk" (https://iopscience.iop.org/article/10.1088/1475-7516/2020/03/035). *Journal of Cosmology and Astroparticle Physics*. **2020** (3): 035. arXiv:1912.08833 (https://arxiv.org/abs/1912.08833). Bibcode:2020JCAP...03..035C (https://ui.adsabs.harvard.edu/abs/2020JCAP...03..035C). doi:10.1088/1475-7516/2020/03/035 (https://doi.org/10.1088%2F1475-7516%2F2020%2F03%2F035) – via IOPscience.
124. Demtröder, Wolfgang (2024). "Astrophysics" (https://link.springer.com/book/10.1007/978-3-031-22135-4). *Undergraduate Lecture Notes in Physics*. doi:10.1007/978-3-031-22135-4 (https://doi.org/10.1007%2F978-3-031-22135-4). ISBN 978-3-031-22133-0. ISSN 2192-4791 (https://search.worldcat.org/issn/2192-4791).

125. Blaes, Omer (2014). "General Overview of Black Hole Accretion Theory". *Space Science Reviews*. **183** (1–4): 21–41. arXiv:1304.4879 (https://arxiv.org/abs/1304.4879). Bibcode:2014SSRv..183...21B (https://ui.adsabs.harvard.edu/abs/2014SSRv..183...21B). doi:10.1007/s11214-013-9985-6 (https://doi.org/10.1007%2Fs11214-013-9985-6).
126. Page, Don N.; Thorne, Kip S. (1974). "Disk-Accretion Onto a Black Hole. Time-Averaged Structure of Accretion Disk". *The Astrophysical Journal*. **191**: 499. Bibcode:1974ApJ...191..499P (https://ui.adsabs.harvard.edu/abs/1974ApJ...191..499P). doi:10.1086/152990 (https://doi.org/10.1086%2F152990).
127. Lasota, Jean-Pierre (2016). "Black Hole Accretion Discs". *Astrophysics of Black Holes*. Astrophysics and Space Science Library. Vol. 440. pp. 1–60. arXiv:1505.02172 (https://arxiv.org/abs/1505.02172). doi:10.1007/978-3-662-52859-4_1 (https://doi.org/10.1007%2F978-3-662-52859-4_1). ISBN 978-3-662-52857-0.
128. Beloborodov, A. M. (1998). "Super-Eddington Accretion Discs Around Kerr Black Holes" (https://doi.org/10.1046%2Fj.1365-8711.1998.01530.x). *Monthly Notices of the Royal Astronomical Society*. **297** (3): 739–746. arXiv:astro-ph/9802129 (https://arxiv.org/abs/astro-ph/9802129). Bibcode:1998MNRAS.297..739B (https://ui.adsabs.harvard.edu/abs/1998MNRAS.297..739B). doi:10.1046/j.1365-8711.1998.01530.x (https://doi.org/10.1046%2Fj.1365-8711.1998.01530.x).
129. Page, Don N.; Thorne, Kip S. (1974). "Disk-Accretion Onto a Black Hole. Time-Averaged Structure of Accretion Disk". *The Astrophysical Journal*. **191**: 499. Bibcode:1974ApJ...191..499P (https://ui.adsabs.harvard.edu/abs/1974ApJ...191..499P). doi:10.1086/152990 (https://doi.org/10.1086%2F152990).

    Bisnovatyi-Kogan, Gennady (2019). "Accretion into Black Hole, And Formation of Magnetically Arrested Accretion Disks" (https://doi.org/10.3390%2Funiverse5060146). *Universe*. **5** (6): 146. arXiv:1905.13731 (https://arxiv.org/abs/1905.13731). Bibcode:2019Univ....5..146B (https://ui.adsabs.harvard.edu/abs/2019Univ....5..146B). doi:10.3390/universe5060146 (https://doi.org/10.3390%2Funiverse5060146).

    Zakharov, A. F.; Repin, S. V. (2002). "Model Radiation Spectrum for an Accretion Disk Near a Rotating Black Hole". *Astronomy Reports*. **46** (5): 360–365. Bibcode:2002ARep...46..360Z (https://ui.adsabs.harvard.edu/abs/2002ARep...46..360Z). doi:10.1134/1.1479423 (https://doi.org/10.1134%2F1.1479423).

130. Wang, Zi-Liang (2025). "Exploring the Role of Accretion Disk Geometry in Shaping Black Hole Shadows". *Physical Review D*. **112** (6) 064052. arXiv:2506.21148 (https://arxiv.org/abs/2506.21148). Bibcode:2025PhRvD.112f4052W (https://ui.adsabs.harvard.edu/abs/2025PhRvD.112f4052W). doi:10.1103/fhqj-wgcm (https://doi.org/10.1103%2Ffhqj-wgcm).
131. Gimeno-Soler, Sergio; Font, José A. (2017). "Magnetised Polish Doughnuts Revisited". *Astronomy & Astrophysics*. **607**: A68. arXiv:1707.03867 (https://arxiv.org/abs/1707.03867). Bibcode:2017A&A...607A..68G (https://ui.adsabs.harvard.edu/abs/2017A&A...607A..68G). doi:10.1051/0004-6361/201730935 (https://doi.org/10.1051%2F0004-6361%2F201730935).
132. Abramowicz, M.A. (2005). "Super-Eddington Black Hole Accretion". *Growing Black Holes: Accretion in a Cosmological Context*. ESO Astrophysics Symposia. pp. 257–273. doi:10.1007/11403913_49 (https://doi.org/10.1007%2F11403913_49). ISBN 978-3-540-25275-7.
133. Kishimoto, Makoto; Antonucci, Robert; et al. (2008). "The Characteristic Blue Spectra of Accretion Disks in Quasars as Uncovered in the Infrared". *Nature*. **454** (7203): 492–494. arXiv:0807.3703 (https://arxiv.org/abs/0807.3703). Bibcode:2008Natur.454..492K (https://ui.adsabs.harvard.edu/abs/2008Natur.454..492K). doi:10.1038/nature07114 (https://doi.org/10.1038%2Fnature07114). PMID 18650919 (https://pubmed.ncbi.nlm.nih.gov/18650919).
134. Fukue, Jun; Yokoyama, Takushi (1988). "Color Photographs of an Accretion Disk Around a Black Hole". *Publications of the Astronomical Society of Japan*. **40**: 15–24. doi:10.1093/pasj/40.1.15 (https://doi.org/10.1093%2Fpasj%2F40.1.15).

135. Bonning, E. W.; Cheng, L.; et al. (2007). "Accretion Disk Temperatures and Continuum Colors in QSOs". *The Astrophysical Journal*. **659** (1): 211–217. arXiv:astro-ph/0611263 (https://arxiv.org/abs/astro-ph/0611263). Bibcode:2007ApJ...659..211B (https://ui.adsabs.harvard.edu/abs/2007ApJ...659..211B). doi:10.1086/510712 (https://doi.org/10.1086%2F510712).
136. James, Oliver; Tunzelmann, Eugénie von; et al. (2015). "Gravitational Lensing by Spinning Black Holes in Astrophysics, And in the Movie *Interstellar*". *Classical and Quantum Gravity*. **32** (6). arXiv:1502.03808 (https://arxiv.org/abs/1502.03808). Bibcode:2015CQGra..32f5001J (https://ui.adsabs.harvard.edu/abs/2015CQGra..32f5001J). doi:10.1088/0264-9381/32/6/065001 (https://doi.org/10.1088%2F0264-9381%2F32%2F6%2F065001).
137. Guo, Sen; Huang, Yu-Xiang; et al. (2023). "Unveiling the Unconventional Optical Signatures of Regular Black Holes Within Accretion Disk" (https://doi.org/10.1140%2Fepjc%2Fs10052-023-12208-0). *The European Physical Journal C*. **83** (11) 1059. arXiv:2310.20523 (https://arxiv.org/abs/2310.20523). Bibcode:2023EPJC...83.1059G (https://ui.adsabs.harvard.edu/abs/2023EPJC...83.1059G). doi:10.1140/epjc/s10052-023-12208-0 (https://doi.org/10.1140%2Fepjc%2Fs10052-023-12208-0).
138. McClintock, Jeffrey E.; Narayan, Ramesh; et al. (2011). "Measuring the Spins of Accreting Black Holes". *Classical and Quantum Gravity*. **28** (11). arXiv:1101.0811 (https://arxiv.org/abs/1101.0811). Bibcode:2011CQGra..28k4009M (https://ui.adsabs.harvard.edu/abs/2011CQGra..28k4009M). doi:10.1088/0264-9381/28/11/114009 (https://doi.org/10.1088%2F0264-9381%2F28%2F11%2F114009).
139. Misner, Charles; Thorne, Kip S.; Wheeler, John (1973). *Gravitation*. W. H. Freeman and Company. ISBN 978-0-7167-0344-0.
140. Jefremov, Paul I.; Tsupko, Oleg Yu.; Bisnovatyi-Kogan, Gennady S. (2015). "Innermost Stable Circular Orbits of Spinning Test Particles in Schwarzschild and Kerr Space-Times". *Physical Review D*. **91** (12) 124030. arXiv:1503.07060 (https://arxiv.org/abs/1503.07060). Bibcode:2015PhRvD..91l4030J (https://ui.adsabs.harvard.edu/abs/2015PhRvD..91l4030J). doi:10.1103/PhysRevD.91.124030 (https://doi.org/10.1103%2FPhysRevD.91.124030).
141. 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). doi:10.1086/151796 (https://doi.org/10.1086%2F151796).
142. Zhang, Yu-Peng; Wei, Shao-Wen; et al. (2018). "Innermost Stable Circular Orbit of Spinning Particle in Charged Spinning Black Hole Background". *Physical Review D*. **97** (8) 084056. arXiv:1711.09361 (https://arxiv.org/abs/1711.09361). Bibcode:2018PhRvD..97h4056Z (https://ui.adsabs.harvard.edu/abs/2018PhRvD..97h4056Z). doi:10.1103/PhysRevD.97.084056 (https://doi.org/10.1103%2FPhysRevD.97.084056).
143. Tsupko, O. Yu.; Bisnovatyi-Kogan, G. S.; Jefremov, P. I. (2016). "Parameters of Innermost Stable Circular Orbits of Spinning Test Particles: Numerical and Analytical Calculations". *Gravitation and Cosmology*. **22** (2): 138–147. arXiv:1605.04189 (https://arxiv.org/abs/1605.04189). Bibcode:2016GrCo...22..138T (https://ui.adsabs.harvard.edu/abs/2016GrCo...22..138T). doi:10.1134/S0202289316020158 (https://doi.org/10.1134%2FS0202289316020158).
144. Jefremov, Paul I.; Tsupko, Oleg Yu.; Bisnovatyi-Kogan, Gennady S. (2017). "Spin-induced changes in the parameters of ISCO in Kerr spacetime". *The Fourteenth Marcel Grossmann Meeting*. pp. 3715–3721. doi:10.1142/9789813226609_0486 (https://doi.org/10.1142%2F9789813226609_0486). ISBN 978-981-322-659-3.
145. Vázquez, S.E.; Esteban, E.P. (7 December 2004). "Strong-Field Gravitational Lensing by a Kerr Black Hole" (https://doi.org/10.1393/ncb/i2004-10121-y). *Il Nuovo Cimento B*. **119** (5): 489–519. arXiv:gr-qc/0308023 (https://arxiv.org/abs/gr-qc/0308023). Bibcode:2004NCimB.119..489V (https://ui.adsabs.harvard.edu/abs/2004NCimB.119..489V). doi:10.1393/ncb/i2004-10121-y (https://doi.org/10.1393%2Fncb%2Fi2004-10121-y).

146. 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.org/abs/gr-qc/9510053). Bibcode:1997GReGr..29..445C (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).
147. Lü, H.; Lyu, Hong-Da (2020). "Schwarzschild Black Holes Have the Largest Size". *Physical Review D*. **101** (4) 044059. arXiv:1911.02019 (https://arxiv.org/abs/1911.02019). Bibcode:2020PhRvD.101d4059L (https://ui.adsabs.harvard.edu/abs/2020PhRvD.101d4059L). doi:10.1103/PhysRevD.101.044059 (https://doi.org/10.1103%2FPhysRevD.101.044059).
148. Qiao, Chen-Kai (2022). "Curvatures, Photon Spheres, And Black Hole Shadows". *Physical Review D*. **106** (8) 084060. arXiv:2208.01771 (https://arxiv.org/abs/2208.01771). Bibcode:2022PhRvD.106h4060Q (https://ui.adsabs.harvard.edu/abs/2022PhRvD.106h4060Q). doi:10.1103/PhysRevD.106.084060 (https://doi.org/10.1103%2FPhysRevD.106.084060).
149. Horvath, Jorge Ernesto (2022). "High-Energy Astrophysics" (https://link.springer.com/book/10.1007/978-3-030-92159-0). *Undergraduate Lecture Notes in Physics*. doi:10.1007/978-3-030-92159-0 (https://doi.org/10.1007%2F978-3-030-92159-0). ISBN 978-3-030-92158-3. ISSN 2192-4791 (https://search.worldcat.org/issn/2192-4791).
150. 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). Bibcode:2011PhRvD..84f3008N (https://ui.adsabs.harvard.edu/abs/2011PhRvD..84f3008N). doi:10.1103/PhysRevD.84.063008 (https://doi.org/10.1103%2FPhysRevD.84.063008). S2CID 119264596 (https://api.semanticscholar.org/CorpusID:119264596).
151. Cramer, Claes R. (April 1997). "Using the Uncharged Kerr Black Hole as a Gravitational Mirror" (https://link.springer.com/10.1023/A:1018878515046). *General Relativity and Gravitation*. **29** (4): 445–454. arXiv:gr-qc/9510053 (https://arxiv.org/abs/gr-qc/9510053). Bibcode:1997GReGr..29..445C (https://ui.adsabs.harvard.edu/abs/1997GReGr..29..445C). doi:10.1023/A:1018878515046 (https://doi.org/10.1023%2FA%3A1018878515046). ISSN 0001-7701 (https://search.worldcat.org/issn/0001-7701).
152. Teo, Edward (2003). "Spherical Photon Orbits Around a Kerr Black Hole" (http://scholarbank.nus.edu.sg/handle/10635/97985). *General Relativity and Gravitation*. **35** (11): 1909–1926. Bibcode:2003GReGr..35.1909T (https://ui.adsabs.harvard.edu/abs/2003GReGr..35.1909T). doi:10.1023/A:1026286607562 (https://doi.org/10.1023%2FA%3A1026286607562).
153. Heydarzade, Yaghoub; Vertogradov, Vitalii (2024). "Dynamical Photon Spheres in Charged Black Holes and Naked Singularities" (https://doi.org/10.1140%2Fepjc%2Fs10052-024-12945-w). *The European Physical Journal C*. **84** (6) 582. arXiv:2311.08930 (https://arxiv.org/abs/2311.08930). Bibcode:2024EPJC...84..582H (https://ui.adsabs.harvard.edu/abs/2024EPJC...84..582H). doi:10.1140/epjc/s10052-024-12945-w (https://doi.org/10.1140%2Fepjc%2Fs10052-024-12945-w).
154. Chen, Ying-Xuan; Huang, Jia-Hui; Jiang, Haoxiang (2023). "Radii of Spherical Photon Orbits Around Kerr-Newman Black Holes". *Physical Review D*. **107** (4) 044066. arXiv:2210.08509 (https://arxiv.org/abs/2210.08509). Bibcode:2023PhRvD.107d4066C (https://ui.adsabs.harvard.edu/abs/2023PhRvD.107d4066C). doi:10.1103/PhysRevD.107.044066 (https://doi.org/10.1103%2FPhysRevD.107.044066).
155. Visser, Matt (2007). "The Kerr Spacetime: A Brief Introduction". page 35, Fig. 3. arXiv:0706.0622 (https://arxiv.org/abs/0706.0622) [gr-qc (https://arxiv.org/archive/gr-qc)].
156. Reynolds, Christopher S. (2019). "Observing Black Holes Spin". *Nature Astronomy*. **3**: 41–47. arXiv:1903.11704 (https://arxiv.org/abs/1903.11704). Bibcode:2019NatAs...3...41R (https://ui.adsabs.harvard.edu/abs/2019NatAs...3...41R). doi:10.1038/s41550-018-0665-z (https://doi.org/10.1038%2Fs41550-018-0665-z).

157. Carroll, Sean M. (8 August 2019). *Spacetime and Geometry: An Introduction to General Relativity* (https://www.cambridge.org/core/product/identifier/9781108770385/type/book) (1 ed.). Cambridge University Press. doi:10.1017/9781108770385 (https://doi.org/10.1017%2F9781108770385). ISBN 978-1-108-48839-6.
158. "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/20180917105330/https://phys.org/news/2018-02-dynamics-black-hole-rotational-energy.html) from the original on 17 September 2018. Retrieved 17 September 2018.
159. Mummery, Andrew; Ingram, Adam; et al. (June 2024). "Continuum Emission from Within the Plunging Region of Black Hole Discs" (https://doi.org/10.1093%2Fmnras%2Fstae1160). *Monthly Notices of the Royal Astronomical Society*. **531** (1): 366–386. arXiv:2405.09175 (https://arxiv.org/abs/2405.09175). doi:10.1093/mnras/stae1160 (https://doi.org/10.1093%2Fmnras%2Fstae1160).
160. Machida, Mami; Matsumoto, Ryoji (2003). "Global Three-Dimensional Magnetohydrodynamic Simulations of Black Hole Accretion Disks: X-Ray Flares in the Plunging Region". *The Astrophysical Journal*. **585** (1): 429–442. arXiv:astro-ph/0211240 (https://arxiv.org/abs/astro-ph/0211240). Bibcode:2003ApJ...585..429M (https://ui.adsabs.harvard.edu/abs/2003ApJ...585..429M). doi:10.1086/346070 (https://doi.org/10.1086%2F346070).
161. Prisco, Jacopo (17 May 2024). "Study Proves Black Holes Have a 'Plunging Region,' Just as Einstein Predicted" (https://www.cnn.com/2024/05/17/world/black-holes-einstein-plunging-region-scn). *CNN*.
162. 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/https://books.google.com/books?id=9S-hzg6-moYC) from the original on 11 August 2016. Retrieved 23 February 2016.
163. 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/1105.3950). Bibcode:2011PhRvD..84b7501S (https://ui.adsabs.harvard.edu/abs/2011PhRvD..84b7501S). doi:10.1103/PhysRevD.84.027501 (https://doi.org/10.1103%2FPhysRevD.84.027501). S2CID 118487989 (https://api.semanticscholar.org/CorpusID:118487989).
164. Celotti, A.; Miller, J. C.; Sciama, D. W. (1999). "Astrophysical Evidence for the Existence of Black Holes" (https://web.archive.org/web/20180727052939/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). 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). S2CID 17677758 (https://api.semanticscholar.org/CorpusID:17677758). Archived from the original (https://cds.cern.ch/record/411555/files/9912186.pdf) (PDF) on 27 July 2018.
165. Reid, M. J.; Brunthaler, A. (2020). "The Proper Motion of Sagittarius A*. III. The Case for a Supermassive Black Hole" (https://doi.org/10.3847%2F1538-4357%2Fab76cd). *The Astrophysical Journal*. **892** (1): 39. arXiv:2001.04386 (https://arxiv.org/abs/2001.04386). Bibcode:2020ApJ...892...39R (https://ui.adsabs.harvard.edu/abs/2020ApJ...892...39R). doi:10.3847/1538-4357/ab76cd (https://doi.org/10.3847%2F1538-4357%2Fab76cd).
166. 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

167. 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 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
168. Wheeler, J. Craig (2007). *Cosmic Catastrophes* (2nd ed.). Cambridge University Press. ISBN 978-0-521-85714-7.
169. Smarr, L. (1973). "Surface Geometry of Charged Rotating Black Holes". *Physical Review D*. **7** (2): 289–295. Bibcode:1973PhRvD...7..289S (https://ui.adsabs.harvard.edu/abs/1973PhRvD...7..289S). doi:10.1103/PhysRevD.7.289 (https://doi.org/10.1103%2FPhysRevD.7.289).
170. Visser, M. (22 January 2009). "The Kerr spacetime: A brief introduction". In Wiltshire, D.L.; Visser, M.; Scott, S.M. (eds.). *Horizon Geometry for Kerr Black Holes with Synchronized Hair* (https://books.google.com/books?id=wymJBq_80Q0C). Vol. 97. Cambridge University Press. arXiv:0706.0622 (https://arxiv.org/abs/0706.0622). Bibcode:2018PhRvD..97l4012D (https://ui.adsabs.harvard.edu/abs/2018PhRvD..97l4012D). doi:10.1103/PhysRevD.97.124012 (https://doi.org/10.1103%2FPhysRevD.97.124012). 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.
171. Carroll, Sean M. (2003). *Spacetime and Geometry: An Introduction to General Relativity*. 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://www.preposterousuniverse.com/spacetimeandgeometry/) Archived (https://web.archive.org/web/20170323013522/http://www.preposterousuniverse.com/spacetimeandgeometry/) 23 March 2017 at the Wayback Machine
172. Thorne, Kip (7 November 2014). *The Science of Interstellar*. W. W. Norton & Company. ISBN 978-0-393-35137-8.
173. "Inside a Black Hole" (https://web.archive.org/web/20090423053437/http://nrumiano.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.
174. "What Happens to You If You Fall into a Black Hole" (http://math.ucr.edu/home/baez/physics/Relativity/BlackHoles/fall_in.html). *math.ucr.edu*. John Baez. Archived (https://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.
175. Susskind, Leonard (1 April 1997). "Black Holes and the Information Paradox" (https://www.jstor.org/stable/24993702?seq=1). *Scientific American*. No. April 1997. p. 52-57. JSTOR 24993702 (https://www.jstor.org/stable/24993702). Retrieved 9 December 2025.
176. Hamilton, A. "Journey into a Schwarzschild black hole" (http://jila.colorado.edu/~ajsh/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.
177. Poisson, Eric; Israel, Werner (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:10.1103/PhysRevD.41.1796 (https://doi.org/10.1103%2FPhysRevD.41.1796). PMID 10012548 (https://pubmed.ncbi.nlm.nih.gov/10012548).
178. Scheel, M. A.; Thorne, K. S. (2014). "Geometrodynamics: The Nonlinear Dynamics of Curved Spacetime". *Physics-Uspekhi*. **57** (4): 342–351. arXiv:1706.09078 (https://arxiv.org/abs/1706.09078). Bibcode:2014PhyU...57..342S (https://ui.adsabs.harvard.edu/abs/2014PhyU...57..342S). doi:10.3367/UFNe.0184.201404b.0367 (https://doi.org/10.3367%2FUFNe.0184.201404b.0367).

179. Marolf, Donald; Ori, Amos (2012). "Outgoing Gravitational Shock Wave at the Inner Horizon: The Late-Time Limit of Black Hole Interiors". *Physical Review D*. **86** (12) 124026. arXiv:1109.5139 (https://arxiv.org/abs/1109.5139). Bibcode:2012PhRvD..86l4026M (https://ui.adsabs.harvard.edu/abs/2012PhRvD..86l4026M). doi:10.1103/PhysRevD.86.124026 (https://doi.org/10.1103%2FPhysRevD.86.124026).
180. Ori, Amos (1991). "Inner Structure of a Charged Black Hole: An Exact Mass-Inflation Solution". *Physical Review Letters*. **67** (7): 789–792. Bibcode:1991PhRvL..67..789O (https://ui.adsabs.harvard.edu/abs/1991PhRvL..67..789O). doi:10.1103/PhysRevLett.67.789 (https://doi.org/10.1103%2FPhysRevLett.67.789). PMID 10044989 (https://pubmed.ncbi.nlm.nih.gov/10044989).
181. Burko, Lior M. (1997). "Structure of the Black Hole's Cauchy-Horizon Singularity". *Physical Review Letters*. **79** (25): 4958–4961. arXiv:gr-qc/9710112 (https://arxiv.org/abs/gr-qc/9710112). Bibcode:1997PhRvL..79.4958B (https://ui.adsabs.harvard.edu/abs/1997PhRvL..79.4958B). doi:10.1103/PhysRevLett.79.4958 (https://doi.org/10.1103%2FPhysRevLett.79.4958).
182. Burko, Lior M.; Khanna, Gaurav; Zenginoğlu, Anıl (2016). "Cauchy-Horizon Singularity Inside Perturbed Kerr Black Holes". *Physical Review D*. **93** (4) 041501. arXiv:1601.05120 (https://arxiv.org/abs/1601.05120). Bibcode:2016PhRvD..93d1501B (https://ui.adsabs.harvard.edu/abs/2016PhRvD..93d1501B). doi:10.1103/PhysRevD.93.041501 (https://doi.org/10.1103%2FPhysRevD.93.041501).
183. Hamilton, Andrew J. S. (2017). "Mass Inflation Followed by Belinskii-Khalatnikov-Lifshitz Collapse Inside Accreting, Rotating Black Holes". *Physical Review D*. **96** (8) 084041. arXiv:1703.01921 (https://arxiv.org/abs/1703.01921). Bibcode:2017PhRvD..96h4041H (https://ui.adsabs.harvard.edu/abs/2017PhRvD..96h4041H). doi:10.1103/PhysRevD.96.084041 (https://doi.org/10.1103%2FPhysRevD.96.084041).
184. Barceló, Carlos; Boyanov, Valentin; et al. (2022). "Classical Mass Inflation Versus Semiclassical Inner Horizon Inflation". *Physical Review D*. **106** (12) 124006. arXiv:2203.13539 (https://arxiv.org/abs/2203.13539). Bibcode:2022PhRvD.106l4006B (https://ui.adsabs.harvard.edu/abs/2022PhRvD.106l4006B). doi:10.1103/PhysRevD.106.124006 (https://doi.org/10.1103%2FPhysRevD.106.124006).
185. Hawking, S. W.; Penrose, R. (1970). "The Singularities of Gravitational Collapse and Cosmology". *Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences*. **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%2Frspa.1970.0021).
186. "Sizes of Black Holes? How Big Is a Black Hole?" (https://www.skyandtelescope.com/astronomy-resources/how-big-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.
187. Lewis, G. F.; Kwan, J. (2007). "No Way Back: Maximizing Survival Time Below the Schwarzschild Event Horizon" (https://www.cambridge.org/core/journals/publications-of-the-astronomical-society-of-australia/article/no-way-back-maximizing-survival-time-below-the-schwarzschild-event-horizon/2A1CCF5CB13E7BEFA6441B3038C635A3). *Publications of the Astronomical Society of Australia*. **24** (2): 46–52. arXiv:0705.1029 (https://arxiv.org/abs/0705.1029). Bibcode:2007PASA...24...46L (https://ui.adsabs.harvard.edu/abs/2007PASA...24...46L). doi:10.1071/AS07012 (https://doi.org/10.1071%2FAS07012). S2CID 17261076 (https://api.semanticscholar.org/CorpusID:17261076).
188. Toporensky, Alexei; Popov, Sergei (2023). "How to Delay Death and Look Further into the Future If You Fall into a Black Hole" (https://link.springer.com/article/10.1007/s12045-023-1602-8). *Resonance*. **28** (5): 737–749. doi:10.1007/s12045-023-1602-8 (https://doi.org/10.1007%2Fs12045-023-1602-8).

189. Belinskii, V.A.; Lifshitz, E.M.; Khalatnikov, I.M.; Agyei, A.K. (1992). "The oscillatory mode of approach to a singularity in homogeneous cosmological models with rotating axes". *Perspectives in Theoretical Physics*. pp. 677–689. doi:10.1016/B978-0-08-036364-6.50048-X (https://doi.org/10.1016%2FB978-0-08-036364-6.50048-X). ISBN 978-0-08-036364-6.
190. Lan, Chen; Yang, Hao; et al. (2023). "Regular Black Holes: A Short Topic Review". *International Journal of Theoretical Physics*. **62** (9) 202. arXiv:2303.11696 (https://arxiv.org/abs/2303.11696). Bibcode:2023IJTP...62..202L (https://ui.adsabs.harvard.edu/abs/2023IJTP...62..202L). doi:10.1007/s10773-023-05454-1 (https://doi.org/10.1007%2Fs10773-023-05454-1).
191. Olmo, Gonzalo; Rubiera-Garcia, Diego (2015). "Nonsingular Black Holes in ƒ (R) Theories" (https://doi.org/10.3390%2Funiverse1020173). *Universe*. **1** (2): 173–185. arXiv:1509.02430 (https://arxiv.org/abs/1509.02430). Bibcode:2015Univ....1..173O (https://ui.adsabs.harvard.edu/abs/2015Univ....1..173O). doi:10.3390/universe1020173 (https://doi.org/10.3390%2Funiverse1020173).
192. Mathur, Samir D. (2005). "The Fuzzball Proposal for Black Holes: An Elementary Review". *Fortschritte der Physik*. **53** (7–8): 793. arXiv:hep-th/0502050 (https://arxiv.org/abs/hep-th/0502050). 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).
193. Avery, Steven G.; Chowdhury, Borun D.; Puhm, Andrea (2013). "Unitarity and Fuzzball Complementarity: "Alice Fuzzes but May Not Even Know It!" ". *Journal of High Energy Physics* (9) 12. arXiv:1210.6996 (https://arxiv.org/abs/1210.6996). Bibcode:2013JHEP...09..012A (https://ui.adsabs.harvard.edu/abs/2013JHEP...09..012A). doi:10.1007/JHEP09(2013)012 (https://doi.org/10.1007%2FJHEP09%282013%29012).
194. Bojowald, Martin (2020). "Black-Hole Models in Loop Quantum Gravity" (https://doi.org/10.3390%2Funiverse6080125). *Universe*. **6** (8): 125. arXiv:2009.13565 (https://arxiv.org/abs/2009.13565). Bibcode:2020Univ....6..125B (https://ui.adsabs.harvard.edu/abs/2020Univ....6..125B). doi:10.3390/universe6080125 (https://doi.org/10.3390%2Funiverse6080125).
195. Woosley, S. E.; Heger, A.; Weaver, T. A. (7 November 2002). "The Evolution and Explosion of Massive Stars" (https://link.aps.org/doi/10.1103/RevModPhys.74.1015). *Reviews of Modern Physics*. **74** (4): 1015–1071. Bibcode:2002RvMP...74.1015W (https://ui.adsabs.harvard.edu/abs/2002RvMP...74.1015W). doi:10.1103/RevModPhys.74.1015 (https://doi.org/10.1103%2FRevModPhys.74.1015). ISSN 0034-6861 (https://search.worldcat.org/issn/0034-6861).
196. Zappa, Francesco; Bernuzzi, Sebastiano; et al. (25 July 2019). "Black-Hole Remnants from Black-Hole–Neutron-Star Mergers" (https://link.aps.org/doi/10.1103/PhysRevLett.123.041102). *Physical Review Letters*. **123** (4) 041102. arXiv:1903.11622 (https://arxiv.org/abs/1903.11622). Bibcode:2019PhRvL.123d1102Z (https://ui.adsabs.harvard.edu/abs/2019PhRvL.123d1102Z). doi:10.1103/PhysRevLett.123.041102 (https://doi.org/10.1103%2FPhysRevLett.123.041102). ISSN 0031-9007 (https://search.worldcat.org/issn/0031-9007). PMID 31491270 (https://pubmed.ncbi.nlm.nih.gov/31491270).
197. Inayoshi, Kohei; Visbal, Eli; Haiman, Zoltán (18 August 2020). "The Assembly of the First Massive Black Holes" (https://www.annualreviews.org/content/journals/10.1146/annurev-astro-120419-014455). *Annual Review of Astronomy and Astrophysics*. **58**: 27–97. arXiv:1911.05791 (https://arxiv.org/abs/1911.05791). Bibcode:2020ARA&A..58...27I (https://ui.adsabs.harvard.edu/abs/2020ARA&A..58...27I). doi:10.1146/annurev-astro-120419-014455 (https://doi.org/10.1146%2Fannurev-astro-120419-014455). ISSN 0066-4146 (https://search.worldcat.org/issn/0066-4146).
198. Janka, H.; Langanke, K.; et al. (2007). "Theory of Core-Collapse Supernovae". *Physics Reports*. **442** (1–6): 38–74. arXiv:astro-ph/0612072 (https://arxiv.org/abs/astro-ph/0612072). Bibcode:2007PhR...442...38J (https://ui.adsabs.harvard.edu/abs/2007PhR...442...38J). doi:10.1016/j.physrep.2007.02.002 (https://doi.org/10.1016%2Fj.physrep.2007.02.002).

199. Fryer, Chris L.; Holz, Daniel E.; Hughes, Scott A. (2002). "Gravitational Wave Emission from Core Collapse of Massive Stars". *The Astrophysical Journal*. **565** (1): 430–446. arXiv:astro-ph/0106113 (https://arxiv.org/abs/astro-ph/0106113). Bibcode:2002ApJ...565..430F (https://ui.adsabs.harvard.edu/abs/2002ApJ...565..430F). doi:10.1086/324034 (https://doi.org/10.1086%2F324034).
200. Bennett, Jeffrey (2025). "Degeneracy Pressure in Stars and Stellar Corpses". *The Physics Teacher*. **63** (3): 212–213. Bibcode:2025PhTea..63c.212B (https://ui.adsabs.harvard.edu/abs/2025PhTea..63c.212B). doi:10.1119/5.0260882 (https://doi.org/10.1119%2F5.0260882).
201. Penrose, R. (2002). "Gravitational Collapse: The Role of General Relativity" (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..34.1141P). doi:10.1023/A:1016578408204 (https://doi.org/10.1023%2FA%3A1016578408204). S2CID 117459073 (https://api.semanticscholar.org/CorpusID:117459073). Archived from the original (http://www.imamu.edu.sa/Scientific_selections/abstracts/Physics/Gravitational%20Collapse%20The%20Role%20of%20General.pdf) (PDF) on 26 May 2013.
202. Bañados, Eduardo; Venemans, Bram P.; et al. (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). Bibcode:2018Natur.553..473B (https://ui.adsabs.harvard.edu/abs/2018Natur.553..473B). doi:10.1038/nature25180 (https://doi.org/10.1038%2Fnature25180). PMID 29211709 (https://pubmed.ncbi.nlm.nih.gov/29211709). S2CID 205263326 (https://api.semanticscholar.org/CorpusID:205263326).
203. Boylan-Kolchin, Michael; Weisz, Daniel R. (2021). "Uncertain Times: The Redshift–Time Relation from Cosmology and Stars" (https://doi.org/10.1093%2Fmnras%2Fstab1521). *Monthly Notices of the Royal Astronomical Society*. **505** (2): 2764–2783. doi:10.1093/mnras/stab1521 (https://doi.org/10.1093%2Fmnras%2Fstab1521).
204. Klessen, Ralf S.; Glover, Simon C. O. (18 August 2023). "The First Stars: Formation, Properties, And Impact" (https://www.annualreviews.org/content/journals/10.1146/annurev-astro-071221-053453). *Annual Review of Astronomy and Astrophysics*. **61**: 65–130. arXiv:2303.12500 (https://arxiv.org/abs/2303.12500). Bibcode:2023ARA&A..61...65K (https://ui.adsabs.harvard.edu/abs/2023ARA&A..61...65K). doi:10.1146/annurev-astro-071221-053453 (https://doi.org/10.1146%2Fannurev-astro-071221-053453). ISSN 0066-4146 (https://search.worldcat.org/issn/0066-4146).
205. Fryer, Chris L.; Kalogera, Vassiliki (10 June 2001). "Theoretical Black Hole Mass Distributions" (https://iopscience.iop.org/article/10.1086/321359). *The Astrophysical Journal*. **554** (1): 548–560. Bibcode:2001ApJ...554..548F (https://ui.adsabs.harvard.edu/abs/2001ApJ...554..548F). doi:10.1086/321359 (https://doi.org/10.1086%2F321359). ISSN 0004-637X (https://search.worldcat.org/issn/0004-637X).
206. Yoo, Chul-Moon (2022). "The Basics of Primordial Black Hole Formation and Abundance Estimation" (https://doi.org/10.3390%2Fgalaxies10060112). *Galaxies*. **10** (6): 112. arXiv:2211.13512 (https://arxiv.org/abs/2211.13512). Bibcode:2022Galax..10..112Y (https://ui.adsabs.harvard.edu/abs/2022Galax..10..112Y). doi:10.3390/galaxies10060112 (https://doi.org/10.3390%2Fgalaxies10060112).
207. Balzer, Ashley (7 May 2024). "Primordial Black Holes" (https://svs.gsfc.nasa.gov/14524/). *NASA SVS*. Archived (https://web.archive.org/web/20250827012141/https://svs.gsfc.nasa.gov/14524/) from the original on 27 August 2025. Retrieved 23 November 2025.
208. Carr, Bernard (26 November 2025). *Primordial Black Holes: Do They Exist and Are They Useful?*. 59th Yamada Conference on Inflating Horizon of Particle Astrophysics and Cosmology. arXiv:astro-ph/0511743 (https://arxiv.org/abs/astro-ph/0511743).

209. Pacucci, Fabio; Ferrara, Andrea; et al. (2005). "First Identification of Direct Collapse Black Hole Candidates in the Early Universe in CANDELS/GOODS-S" (https://doi.org/10.1093%2Fmnras%2Fstw725). *Monthly Notices of the Royal Astronomical Society*. **459** (2). Universal Academy Press: astro–ph/0511743. arXiv:astro-ph/0511743 (https://arxiv.org/abs/astro-ph/0511743). Bibcode:2005astro.ph.11743C (https://ui.adsabs.harvard.edu/abs/2005astro.ph.11743C). doi:10.1093/mnras/stw725 (https://doi.org/10.1093%2Fmnras%2Fstw725). ISBN 978-4-946443-94-7.
210. Philip Gibbs. "Is the Big Bang a Black Hole?" (http://math.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.

    Sutter, Paul (21 June 2023). "Why Didn't the Infant Universe Collapse into a Black Hole?" (https://www.space.com/why-infant-universe-not-collapse-black-hole). *Space.com*. Archived (https://web.archive.org/web/20250325152015/https://www.space.com/why-infant-universe-not-collapse-black-hole) from the original on 25 March 2025. Retrieved 24 November 2025.

    Musser, George (22 September 2003). "According to the Big Bang Theory, All the Matter in the Universe Erupted from a Singularity. Why Didn't All This Matter—Cheek by Jowl as It Was—Immediately Collapse into a Black Hole?" (https://www.scientificamerican.com/article/according-to-the-big-bang/). *Scientific American*. Archived (https://web.archive.org/web/20250426033551/https://www.scientificamerican.com/article/according-to-the-big-bang/) from the original on 26 April 2025. Retrieved 24 November 2025.

211. Kaloper, Nemanja; Terning, John (2007). "How Black Holes Form in High Energy Collisions". *General Relativity and Gravitation*. **39** (10): 1525–1532. arXiv:0705.0408 (https://arxiv.org/abs/0705.0408). Bibcode:2007GReGr..39.1525K (https://ui.adsabs.harvard.edu/abs/2007GReGr..39.1525K). doi:10.1007/s10714-007-0468-5 (https://doi.org/10.1007%2Fs10714-007-0468-5).
212. 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). Bibcode:2002PhRvD..65e6010G (https://ui.adsabs.harvard.edu/abs/2002PhRvD..65e6010G). doi:10.1103/PhysRevD.65.056010 (https://doi.org/10.1103%2FPhysRevD.65.056010). S2CID 1203487 (https://api.semanticscholar.org/CorpusID:1203487).
213. 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 (https://arxiv.org/abs/0806.3414). Bibcode:2008JPhG...35k5004E (https://ui.adsabs.harvard.edu/abs/2008JPhG...35k5004E). doi:10.1088/0954-3899/35/11/115004 (https://doi.org/10.1088%2F0954-3899%2F35%2F11%2F115004). S2CID 53370175 (https://api.semanticscholar.org/CorpusID:53370175). Archived (https://web.archive.org/web/20100414160742/http://lsag.web.cern.ch/lsag/LSAG-Report.pdf) (PDF) from the original on 14 April 2010.
214. Peskin, M. E. (2008). "The End of the World at the Large Hadron Collider?" (https://doi.org/10.1103%2FPhysics.1.14). *Physics*. **1** 14. Bibcode:2008PhyOJ...1...14P (https://ui.adsabs.harvard.edu/abs/2008PhyOJ...1...14P). doi:10.1103/Physics.1.14 (https://doi.org/10.1103%2FPhysics.1.14).
215. 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). Bibcode:2007IAUS..238...51R (https://ui.adsabs.harvard.edu/abs/2007IAUS..238...51R). doi:10.1017/S1743921307004681 (https://doi.org/10.1017%2FS1743921307004681). ISBN 978-0-521-86347-6. S2CID 14844338 (https://api.semanticscholar.org/CorpusID:14844338).

216. Zwart, S. F. P.; Baumgardt, H.; 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). 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).
217. O'Leary, R. M.; Rasio, F. A.; 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). Bibcode:2006ApJ...637..937O (https://ui.adsabs.harvard.edu/abs/2006ApJ...637..937O). doi:10.1086/498446 (https://doi.org/10.1086%2F498446). S2CID 1509957 (https://api.semanticscholar.org/CorpusID:1509957).
218. Ryu, Taeho; Perna, Rosalba; et al. (2018). "Interactions Between Multiple Supermassive Black Holes in Galactic Nuclei: A Solution to the Final Parsec Problem" (https://doi.org/10.1093%2Fmnras%2Fstx2524). *Monthly Notices of the Royal Astronomical Society*. **473** (3): 3410–3433. doi:10.1093/mnras/stx2524 (https://doi.org/10.1093%2Fmnras%2Fstx2524).
219. Vasiliev, Eugene; Antonini, Fabio; Merritt, David (2014). "The Final-Parsec Problem in Nonspherical Galaxies Revisited". *The Astrophysical Journal*. **785** (2): 163. arXiv:1311.1167 (https://arxiv.org/abs/1311.1167). Bibcode:2014ApJ...785..163V (https://ui.adsabs.harvard.edu/abs/2014ApJ...785..163V). doi:10.1088/0004-637X/785/2/163 (https://doi.org/10.1088%2F0004-637X%2F785%2F2%2F163).
220. 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). Bibcode:2006csxs.book..157M (https://ui.adsabs.harvard.edu/abs/2006csxs.book..157M). ISBN 978-0-521-82659-4. section 4.1.5.
221. Kuroda, Takami; Shibata, Masaru (2024). "Numerical Relativity Simulations of Black Hole and Relativistic Jet Formation" (https://doi.org/10.1093%2Fmnrasl%2Fslae069). *Monthly Notices of the Royal Astronomical Society: Letters*. **533**: L107–L112. doi:10.1093/mnrasl/slae069 (https://doi.org/10.1093%2Fmnrasl%2Fslae069).
222. Saikia, D. J. (2022). "Jets in Radio Galaxies and Quasars: An Observational Perspective". *Journal of Astrophysics and Astronomy*. **43** (2) 97. arXiv:2206.05803 (https://arxiv.org/abs/2206.05803). doi:10.1007/s12036-022-09863-2 (https://doi.org/10.1007%2Fs12036-022-09863-2).
223. Czerny, Bożena; Cao, Shulei; et al. (2023). "Accretion Disks, Quasars and Cosmology: Meandering Towards Understanding". *Astrophysics and Space Science*. **368** (2) 8. doi:10.1007/s10509-023-04165-7 (https://doi.org/10.1007%2Fs10509-023-04165-7).
224. Winter, L. M.; Mushotzky, R. F.; et al. (2006). "XMM-Newton Archival Study of the Ultraluminous X-Ray Population in Nearby Galaxies". *The Astrophysical Journal*. **649** (2): 730–752. arXiv:astro-ph/0512480 (https://arxiv.org/abs/astro-ph/0512480). 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).
225. Brightman, M.; Bachetti, M.; et al. (2019). "Breaking the Limit: Super-Eddington Accretion Onto Black Holes and Neutron Stars". *Bulletin of the American Astronomical Society*. **51** (3): 352. arXiv:1903.06844 (https://arxiv.org/abs/1903.06844). Bibcode:2019BAAS...51c.352B (https://ui.adsabs.harvard.edu/abs/2019BAAS...51c.352B).
226. Regan, John A.; Downes, Turlough P.; et al. (2019). "Super-Eddington Accretion and Feedback from the First Massive Seed Black Holes" (https://doi.org/10.1093%2Fmnras%2Fstz1045). *Monthly Notices of the Royal Astronomical Society*. **486** (3): 3892–3906. doi:10.1093/mnras/stz1045 (https://doi.org/10.1093%2Fmnras%2Fstz1045).

227. Evans, Charles R.; Kochanek, Christopher S. (1989). "The Tidal Disruption of a Star by a Massive Black Hole". *The Astrophysical Journal*. **346**: L13. Bibcode:1989ApJ...346L..13E (https://ui.adsabs.harvard.edu/abs/1989ApJ...346L..13E). doi:10.1086/185567 (https://doi.org/10.1086%2F185567).
228. Komossa, S. (2015). "Tidal Disruption of Stars by Supermassive Black Holes: Status of Observations". *Journal of High Energy Astrophysics*. **7**: 148–157. arXiv:1505.01093 (https://arxiv.org/abs/1505.01093). Bibcode:2015JHEAp...7..148K (https://ui.adsabs.harvard.edu/abs/2015JHEAp...7..148K). doi:10.1016/j.jheap.2015.04.006 (https://doi.org/10.1016%2Fj.jheap.2015.04.006).
229. Cattaneo, A.; Faber, S. M.; et al. (2009). "The Role of Black Holes in Galaxy Formation and Evolution". *Nature*. **460** (7252): 213–219. arXiv:0907.1608 (https://arxiv.org/abs/0907.1608). doi:10.1038/nature08135 (https://doi.org/10.1038%2Fnature08135). PMID 19587763 (https://pubmed.ncbi.nlm.nih.gov/19587763).
230. Ruiz, O.; Molina, U.; Viloria, P. (2019). "Thermodynamic Analysis of Kerr-Newman Black Holes". *Journal of Physics: Conference Series*. **1219** (1) 012016. Bibcode:2019JPhCS1219a2016R (https://ui.adsabs.harvard.edu/abs/2019JPhCS1219a2016R). doi:10.1088/1742-6596/1219/1/012016 (https://doi.org/10.1088%2F1742-6596%2F1219%2F1%2F012016). "From this, an expression is established for the Hawking temperature of a Kerr-Newman black hole as a function of its mass M, angular moment J and load Q. As the black hole loses mass, its temperature increases inversely proportional."
231. Siegel, Ethan (2017). "Ask 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 (https://web.archive.org/web/20181122031830/https://www.forbes.com/sites/startswithabang/2017/08/19/ask-ethan-do-black-holes-grow-faster-than-they-evaporate/) from the original on 22 November 2018. Retrieved 17 March 2018.
232. 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.harvard.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).
233. "Evaporating Black Holes?" (https://web.archive.org/web/20110722055345/http://www.einstein-online.info/elementary/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) on 22 July 2011. Retrieved 12 December 2010.
234. Fichtel, C. E.; Bertsch, D. 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).
235. 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.
236. Federico, Kevin; Profumo, Stefano (2025). "Black Hole Explosions as Probes of New Physics". *Physical Review D*. **111** (6) 063006. doi:10.1103/PhysRevD.111.063006 (https://doi.org/10.1103%2FPhysRevD.111.063006).

237. Wald, Robert 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 (https://doi.org/10.12942%2Flrr-2001-6). ISSN 1433-8351 (https://search.worldcat.org/issn/1433-8351). PMC 5253844 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5253844). PMID 28163633 (https://pubmed.ncbi.nlm.nih.gov/28163633).

238. Carlip, S. (2014). "Black Hole Thermodynamics". *International Journal of Modern Physics D*. **23** (11). arXiv:1410.1486 (https://arxiv.org/abs/1410.1486). doi:10.1142/S0218271814300237 (https://doi.org/10.1142%2FS0218271814300237).

239. Witten, Edward (2025). "Introduction to Black Hole Thermodynamics". *The European Physical Journal Plus*. **140** (5) 430. doi:10.1140/epjp/s13360-025-06288-y (https://doi.org/10.1140%2Fepjp%2Fs13360-025-06288-y).

240. Elbert, Oliver D.; Bullock, James S.; Kaplinghat, Manoj (1 January 2018). "Counting Black Holes: The Cosmic Stellar Remnant Population and Implications for LIGO" (https://academic.oup.com/mnras/article/473/1/1186/4060726). *Monthly Notices of the Royal Astronomical Society*. **473** (1): 1186–1194. arXiv:1703.02551 (https://arxiv.org/abs/1703.02551). doi:10.1093/mnras/stx1959 (https://doi.org/10.1093%2Fmnras%2Fstx1959). ISSN 0035-8711 (https://search.worldcat.org/issn/0035-8711).

241. Abramowicz, M. A.; Kluźniak, W.; Lasota, J.-P. (December 2002). "No Observational Proof of the Black-Hole Event-Horizon" (http://www.aanda.org/10.1051/0004-6361:20021645). *Astronomy & Astrophysics*. **396** (3): L31–L34. arXiv:astro-ph/0207270 (https://arxiv.org/abs/astro-ph/0207270). Bibcode:2002A&A...396L..31A (https://ui.adsabs.harvard.edu/abs/2002A&A...396L..31A). doi:10.1051/0004-6361:20021645 (https://doi.org/10.1051%2F0004-6361%3A20021645). ISSN 0004-6361 (https://search.worldcat.org/issn/0004-6361).

242. Event Horizon Telescope Collaboration; et al. (May 2022). "First Sagittarius A* Event Horizon Telescope Results. VI. Testing the Black Hole Metric" (https://doi.org/10.3847%2F2041-8213%2Fac6756). *The Astrophysical Journal Letters*. **930** (2): L17. Bibcode:2022ApJ...930L..17E (https://ui.adsabs.harvard.edu/abs/2022ApJ...930L..17E). doi:10.3847/2041-8213/ac6756 (https://doi.org/10.3847%2F2041-8213%2Fac6756). ISSN 2041-8205 (https://search.worldcat.org/issn/2041-8205).

243. Akiyama, Kazunori; Alberdi, Antxon; et al. (2019). "First M87 Event Horizon Telescope Results. II. Array and Instrumentation" (https://doi.org/10.3847%2F2041-8213%2Fab0c96). *The Astrophysical Journal Letters*. **875**: L2. doi:10.3847/2041-8213/ab0c96 (https://doi.org/10.3847%2F2041-8213%2Fab0c96).

244. "FAQ" (https://www.ligo.caltech.edu/page/faq). *LIGO Lab*. Archived (https://web.archive.org/web/20260113010624/https://www.ligo.caltech.edu/page/faq) from the original on 13 January 2026. Retrieved 5 February 2026.

245. Gillessen, S.; Eisenhauer, F.; et al. (2009). "Monitoring Stellar Orbits Around the Massive Black Hole in the Galactic Center". *The Astrophysical Journal*. **692** (2): 1075–1109. arXiv:0810.4674 (https://arxiv.org/abs/0810.4674). Bibcode:2009ApJ...692.1075G (https://ui.adsabs.harvard.edu/abs/2009ApJ...692.1075G). doi:10.1088/0004-637X/692/2/1075 (https://doi.org/10.1088%2F0004-637X%2F692%2F2%2F1075). S2CID 1431308 (https://api.semanticscholar.org/CorpusID:1431308).

246. 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). Bibcode:2009ApJ...701.1357B (https://ui.adsabs.harvard.edu/abs/2009ApJ...701.1357B). doi:10.1088/0004-637X/701/2/1357 (https://doi.org/10.1088%2F0004-637X%2F701%2F2%2F1357). S2CID 12991878 (https://api.semanticscholar.org/CorpusID:12991878).

247. Schatz, H.; Rehm, K.E. (2006). "X-Ray Binaries". *Nuclear Physics A*. **777**: 601–622. arXiv:astro-ph/0607624 (https://arxiv.org/abs/astro-ph/0607624). Bibcode:2006NuPhA.777..601S (https://ui.adsabs.harvard.edu/abs/2006NuPhA.777..601S). doi:10.1016/j.nuclphysa.2005.05.200 (https://doi.org/10.1016%2Fj.nuclphysa.2005.05.200).
248. Quirrenbach, Andreas; Frink, Sabine; Tomsick, John (1 December 2004). "Masses and Luminosities of X-Ray Binaries" (https://ntrs.nasa.gov/api/citations/20050186757/downloads/20050186757.pdf) (PDF). *SIM PlanetQuest: Science with the Space Interferometry Mission*. National Aeronautics and Space Administration. Bibcode:2002swsi.conf...33Q (https://ui.adsabs.harvard.edu/abs/2002swsi.conf...33Q).
249. Cho, Adrian (2018). "A Weight Limit Emerges for Neutron Stars". *Science*. **359** (6377): 724–725. Bibcode:2018Sci...359..724C (https://ui.adsabs.harvard.edu/abs/2018Sci...359..724C). doi:10.1126/science.359.6377.724 (https://doi.org/10.1126%2Fscience.359.6377.724). PMID 29449468 (https://pubmed.ncbi.nlm.nih.gov/29449468).
250. 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.
251. Orosz, Jerome A.; McClintock, Jeffrey E.; et al. (9 November 2011). "The Mass of the Black Hole in Cygnus X-1". *The Astrophysical Journal*. **742** (2): 84. arXiv:1106.3689 (https://arxiv.org/abs/1106.3689). Bibcode:2011ApJ...742...84O (https://ui.adsabs.harvard.edu/abs/2011ApJ...742...84O). doi:10.1088/0004-637x/742/2/84 (https://doi.org/10.1088%2F0004-637x%2F742%2F2%2F84). ISSN 0004-637X (https://search.worldcat.org/issn/0004-637X).
252. Corral-Santana, J. M.; Casares, J.; et al. (1 March 2016). "BlackCAT: A Catalogue of Stellar-Mass Black Holes in X-Ray Transients" (https://www.aanda.org/articles/aa/abs/2016/03/aa27130-15/aa27130-15.html). *Astronomy & Astrophysics*. **587**: A61. arXiv:1510.08869 (https://arxiv.org/abs/1510.08869). Bibcode:2016A&A...587A..61C (https://ui.adsabs.harvard.edu/abs/2016A&A...587A..61C). doi:10.1051/0004-6361/201527130 (https://doi.org/10.1051%2F0004-6361%2F201527130). ISSN 0004-6361 (https://search.worldcat.org/issn/0004-6361).
253. Broekgaarden, Floor S.; Berger, Edo (2021). "Formation of the First Two Black Hole–Neutron Star Mergers (GW200115 and GW200105) from Isolated Binary Evolution" (https://doi.org/10.3847%2F2041-8213%2Fac2832). *The Astrophysical Journal Letters*. **920** (1): L13. arXiv:2108.05763 (https://arxiv.org/abs/2108.05763). Bibcode:2021ApJ...920L..13B (https://ui.adsabs.harvard.edu/abs/2021ApJ...920L..13B). doi:10.3847/2041-8213/ac2832 (https://doi.org/10.3847%2F2041-8213%2Fac2832).
254. Chattopadhyay, Debatri; Stevenson, Simon; et al. (2022). "Modelling the Formation of the First Two Neutron Star–Black Hole Mergers, GW200105 and GW200115: Metallicity, Chirp Masses, And Merger Remnant Spins" (https://doi.org/10.1093%2Fmnras%2Fstac1283). *Monthly Notices of the Royal Astronomical Society*. **513** (4): 5780–5789. doi:10.1093/mnras/stac1283 (https://doi.org/10.1093%2Fmnras%2Fstac1283).
255. Ziosi, B. M.; Mapelli, M.; et al. (2014). "Dynamics of Stellar Black Holes in Young Star Clusters with Different Metallicities – II. Black Hole-Black Hole Binaries" (https://doi.org/10.1093%2Fmnras%2Fstu824). *Monthly Notices of the Royal Astronomical Society*. **441** (4): 3703–3717. arXiv:1404.7147 (https://arxiv.org/abs/1404.7147). doi:10.1093/mnras/stu824 (https://doi.org/10.1093%2Fmnras%2Fstu824).
256. "Sources and Types of Gravitational Waves" (https://www.ligo.caltech.edu/page/gw-sources). *LIGO Caltech*. Retrieved 26 October 2025.
257. Cattaneo, A.; Faber, S. M.; et al. (July 2009). "The Role of Black Holes in Galaxy Formation and Evolution" (https://www.nature.com/articles/nature08135). *Nature*. **460** (7252): 213–219. arXiv:0907.1608 (https://arxiv.org/abs/0907.1608). Bibcode:2009Natur.460..213C (https://ui.adsabs.harvard.edu/abs/2009Natur.460..213C). doi:10.1038/nature08135 (https://doi.org/10.1038%2Fnature08135). ISSN 0028-0836 (https://search.worldcat.org/issn/0028-0836). PMID 19587763 (https://pubmed.ncbi.nlm.nih.gov/19587763).

258. 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). 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).
259. 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 (https://arxiv.org/abs/astro-ph/0006053). Bibcode:2000ApJ...539L...9F (https://ui.adsabs.harvard.edu/abs/2000ApJ...539L...9F). doi:10.1086/312838 (https://doi.org/10.1086%2F312838). S2CID 6508110 (https://api.semanticscholar.org/CorpusID:6508110).
260. 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-record-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.
261. Krolik, J. H. (1999). *Active Galactic Nuclei* (https://books.google.com/books?id=oRK8otMiWIgC&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=oRK8otMiWIgC&q=Active+Galactic+Nuclei) from the original on 14 August 2021. Retrieved 16 October 2020.

    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.

    Marconi, A.; Risaliti, G.; et al. (2004). "Local Supermassive Black Holes, Relics of Active Galactic Nuclei and the X-Ray Background" (https://doi.org/10.1111%2Fj.1365-2966.2004.07765.x). *Monthly Notices of the Royal Astronomical Society*. **351** (1): 169–185. arXiv:astro-ph/0311619 (https://arxiv.org/abs/astro-ph/0311619). Bibcode:2004MNRAS.351..169M (https://ui.adsabs.harvard.edu/abs/2004MNRAS.351..169M). doi:10.1111/j.1365-2966.2004.07765.x (https://doi.org/10.1111%2Fj.1365-2966.2004.07765.x).

262. 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).
263. Melia, Fulvio; Falcke, Heino (2001). "The Supermassive Black Hole at the Galactic Center". *Annual Review of Astronomy and Astrophysics*. **39**: 309–352. arXiv:astro-ph/0106162 (https://arxiv.org/abs/astro-ph/0106162). Bibcode:2001ARA&A..39..309M (https://ui.adsabs.harvard.edu/abs/2001ARA&A..39..309M). doi:10.1146/annurev.astro.39.1.309 (https://doi.org/10.1146%2Fannurev.astro.39.1.309).
264. Wambsganss, Joachim (1998). "Gravitational Lensing in Astronomy" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5567250). *Living Reviews in Relativity*. **1** (1) 12. arXiv:astro-ph/9812021 (https://arxiv.org/abs/astro-ph/9812021). Bibcode:1998LRR.....1...12W (https://ui.adsabs.harvard.edu/abs/1998LRR.....1...12W). doi:10.12942/lrr-1998-12 (https://doi.org/10.12942%2Flrr-1998-12). PMC 5567250 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5567250). PMID 28937183 (https://pubmed.ncbi.nlm.nih.gov/28937183).

265. Bozza, V.; Mancini, L. (2005). "Gravitational Lensing of Stars in the Central Arcsecond of Our Galaxy". *The Astrophysical Journal*. **627** (2): 790–802. arXiv:astro-ph/0503664 (https://arxiv.org/abs/astro-ph/0503664). Bibcode:2005ApJ...627..790B (https://ui.adsabs.harvard.edu/abs/2005ApJ...627..790B). doi:10.1086/430664 (https://doi.org/10.1086%2F430664).
266. Wambsganss, J. (2006). "Gravitational Microlensing". *Gravitational Lensing: Strong, Weak and Micro*. Saas-Fee Advanced Courses. Vol. 33. pp. 453–540. arXiv:astro-ph/0604278 (https://arxiv.org/abs/astro-ph/0604278). doi:10.1007/978-3-540-30310-7_4 (https://doi.org/10.1007%2F978-3-540-30310-7_4). ISBN 978-3-540-30309-1.
267. Mao, Shude (2012). "Astrophysical Applications of Gravitational Microlensing". *Research in Astronomy and Astrophysics*. **12** (8): 947–972. arXiv:1207.3720 (https://arxiv.org/abs/1207.3720). Bibcode:2012RAA....12..947M (https://ui.adsabs.harvard.edu/abs/2012RAA....12..947M). doi:10.1088/1674-4527/12/8/005 (https://doi.org/10.1088%2F1674-4527%2F12%2F8%2F005).
268. Bennett, D. P.; Becker, A. C.; et al. (1 November 2002). "Gravitational Microlensing Events Due to Stellar-Mass Black Holes" (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). 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).
269. Mao, Shude; Smith, Martin C.; et al. (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). *Monthly Notices of the Royal Astronomical Society*. **329** (2): 349–354. arXiv:astro-ph/0108312 (https://arxiv.org/abs/astro-ph/0108312). Bibcode:2002MNRAS.329..349M (https://ui.adsabs.harvard.edu/abs/2002MNRAS.329..349M). doi:10.1046/j.1365-8711.2002.04986.x (https://doi.org/10.1046%2Fj.1365-8711.2002.04986.x). ISSN 0035-8711 (https://search.worldcat.org/issn/0035-8711).
270. Sahu, K. C. (2022). "An Isolated Stellar-Mass Black Hole Detected Through Astrometric Microlensing" (https://doi.org/10.3847%2F1538-4357%2Fac739e). *Astrophysical Journal*. **933** (1): 83. arXiv:2201.13296 (https://arxiv.org/abs/2201.13296). 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). S2CID 246430448 (https://api.semanticscholar.org/CorpusID:246430448).
271. Lam, Casey Y.; Lu, Jessica R. (1 October 2023). "A Reanalysis of the Isolated Black Hole Candidate OGLE-2011-BLG-0462/MOA-2011-BLG-191" (https://doi.org/10.3847%2F1538-4357%2Faced4a). *The Astrophysical Journal*. **955** (2): 116. arXiv:2308.03302 (https://arxiv.org/abs/2308.03302). Bibcode:2023ApJ...955..116L (https://ui.adsabs.harvard.edu/abs/2023ApJ...955..116L). doi:10.3847/1538-4357/aced4a (https://doi.org/10.3847%2F1538-4357%2Faced4a). ISSN 0004-637X (https://search.worldcat.org/issn/0004-637X).
272. 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 (http://www.hawking.org.uk/does-god-play-dice.html) on 11 January 2012. Retrieved 14 March 2009.
273. 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.
274. 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.

275. Raju, Suvrat (January 2022). "Lessons from the Information Paradox" (https://linkinghub.elsevier.com/retrieve/pii/S0370157321003720). *Physics Reports*. **943**: 1–80. arXiv:2012.05770 (https://arxiv.org/abs/2012.05770). Bibcode:2022PhR...943....1R (https://ui.adsabs.harvard.edu/abs/2022PhR...943....1R). doi:10.1016/j.physrep.2021.10.001 (https://doi.org/10.1016%2Fj.physrep.2021.10.001).
276. Wang, Feige; Yang, Jinyi; et al. (2021). "A Luminous Quasar at Redshift 7.642" (https://doi.org/10.3847%2F2041-8213%2Fabd8c6). *The Astrophysical Journal Letters*. **907** (1): L1. arXiv:2101.03179 (https://arxiv.org/abs/2101.03179). Bibcode:2021ApJ...907L...1W (https://ui.adsabs.harvard.edu/abs/2021ApJ...907L...1W). doi:10.3847/2041-8213/abd8c6 (https://doi.org/10.3847%2F2041-8213%2Fabd8c6).
277. Trenti, M.; Stiavelli, M. (2007). "Distribution of the Very First Population III Stars and Their Relation to Bright $z \approx 6$ Quasars". *The Astrophysical Journal*. **667** (1): 38–48. arXiv:0705.3843 (https://arxiv.org/abs/0705.3843). Bibcode:2007ApJ...667...38T (https://ui.adsabs.harvard.edu/abs/2007ApJ...667...38T). doi:10.1086/520502 (https://doi.org/10.1086%2F520502).
278. Singh, Jasbir; Monaco, Pierluigi; Tan, Jonathan C. (2023). "The Formation of Supermassive Black Holes from Population III.1 Seeds. II. Evolution to the Local Universe" (https://doi.org/10.1093%2Fmnras%2Fstad2346). *Monthly Notices of the Royal Astronomical Society*. **525**: 969–982. doi:10.1093/mnras/stad2346 (https://doi.org/10.1093%2Fmnras%2Fstad2346).
279. Smith, Aaron; Bromm, Volker (2019). "Supermassive Black Holes in the Early Universe". *Contemporary Physics*. **60** (2): 111–126. arXiv:1904.12890 (https://arxiv.org/abs/1904.12890). Bibcode:2019ConPh..60..111S (https://ui.adsabs.harvard.edu/abs/2019ConPh..60..111S). doi:10.1080/00107514.2019.1615715 (https://doi.org/10.1080%2F00107514.2019.1615715).
280. Jeon, Myoungwon; Pawlik, Andreas H.; et al. (2014). "Radiative Feedback from High-Mass X-Ray Binaries on the Formation of the First Galaxies and Early Reionization" (https://doi.org/10.1093%2Fmnras%2Fstu444). *Monthly Notices of the Royal Astronomical Society*. **440** (4): 3778–3796. doi:10.1093/mnras/stu444 (https://doi.org/10.1093%2Fmnras%2Fstu444).
281. Miralda-Escudé, Jaiyul Yoo Jordi; Miralda-Escudé, Jordi (2004). "Formation of the Black Holes in the Highest Redshift Quasars". *The Astrophysical Journal*. **614** (1): L25–L28. arXiv:astro-ph/0406217 (https://arxiv.org/abs/astro-ph/0406217). Bibcode:2004ApJ...614L..25Y (https://ui.adsabs.harvard.edu/abs/2004ApJ...614L..25Y). doi:10.1086/425416 (https://doi.org/10.1086%2F425416).
282. Trakhtenbrot, Benny (2019). "What Do Observations Tell Us About the Highest-Redshift Supermassive Black Holes?". *Proceedings of the International Astronomical Union*. **15**: 261–275. arXiv:2002.00972 (https://arxiv.org/abs/2002.00972). doi:10.1017/S1743921320003087 (https://doi.org/10.1017%2FS1743921320003087).
283. Mayer, Lucio; Bonoli, Silvia (2019). "The Route to Massive Black Hole Formation via Merger-Driven Direct Collapse: A Review". *Reports on Progress in Physics*. **82** (1): 016901. arXiv:1803.06391 (https://arxiv.org/abs/1803.06391). Bibcode:2019RPPh...82a6901M (https://ui.adsabs.harvard.edu/abs/2019RPPh...82a6901M). doi:10.1088/1361-6633/aad6a5 (https://doi.org/10.1088%2F1361-6633%2Faad6a5). PMID 30057369 (https://pubmed.ncbi.nlm.nih.gov/30057369).
284. Agarwal, Bhaskar; Dalla Vecchia, Claudio; et al. (2014). "The First Billion Years Project: Birthplaces of Direct Collapse Black Holes" (https://doi.org/10.1093%2Fmnras%2Fstu1112). *Monthly Notices of the Royal Astronomical Society*. **443**: 648–657. doi:10.1093/mnras/stu1112 (https://doi.org/10.1093%2Fmnras%2Fstu1112).
285. Shinohara, Takumi; He, Wanqiu; et al. (2023). "Supermassive Primordial Black Holes: A View from Clustering of Quasars at $z \sim 6$". *Physical Review D*. **108** (6) 063510. doi:10.1103/PhysRevD.108.063510 (https://doi.org/10.1103%2FPhysRevD.108.063510).

286. Mayer, Lucio (2019). "Super-Eddington accretion; flow regimes and conditions in high-z galaxies". *Formation of the First Black Holes*. pp. 195–222. arXiv:1807.06243 (https://arxiv.org/abs/1807.06243). doi:10.1142/9789813227958_0011 (https://doi.org/10.1142%2F9789813227958_0011). ISBN 978-981-322-794-1.
287. Maoz, Eyal (1998). "Dynamical Constraints on Alternatives to Supermassive Black Holes in Galactic Nuclei". *The Astrophysical Journal*. **494** (2): L181–L184. arXiv:astro-ph/9710309 (https://arxiv.org/abs/astro-ph/9710309). Bibcode:1998ApJ...494L.181M (https://ui.adsabs.harvard.edu/abs/1998ApJ...494L.181M). doi:10.1086/311194 (https://doi.org/10.1086%2F311194).
288. Miller, M. Coleman (2006). "Constraints on Alternatives to Supermassive Black Holes" (https://doi.org/10.1111%2Fj.1745-3933.2006.00135.x). *Monthly Notices of the Royal Astronomical Society: Letters*. **367** (1): L32–L36. arXiv:astro-ph/0512194 (https://arxiv.org/abs/astro-ph/0512194). Bibcode:2006MNRAS.367L..32M (https://ui.adsabs.harvard.edu/abs/2006MNRAS.367L..32M). doi:10.1111/j.1745-3933.2006.00135.x (https://doi.org/10.1111%2Fj.1745-3933.2006.00135.x).
289. 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** (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://api.semanticscholar.org/CorpusID:18263809).
290. Sotani, Hajime; Kohri, Kazunori; Harada, Tomohiro (2004). "Restricting Quark Matter Models by Gravitational Wave Observation". *Physical Review D*. **69** (8) 084008. arXiv:gr-qc/0310079 (https://arxiv.org/abs/gr-qc/0310079). Bibcode:2004PhRvD..69h4008S (https://ui.adsabs.harvard.edu/abs/2004PhRvD..69h4008S). doi:10.1103/PhysRevD.69.084008 (https://doi.org/10.1103%2FPhysRevD.69.084008).
291. Bonkowsky, Charles (5 January 2025). "Between Neutron Stars and Black Holes" (https://www.thecolumbiasciencereview.com/online-articles/between-neutron-stars-and-black-holes). *Columbia Science Review*. Retrieved 6 December 2025.
292. Dai, De-Chang; Lue, Arthur; et al. (2010). "Electroweak Stars: How Nature May Capitalize on the Standard Model's Ultimate Fuel". *Journal of Cosmology and Astroparticle Physics* (12): 004. arXiv:0912.0520 (https://arxiv.org/abs/0912.0520). Bibcode:2010JCAP...12..004D (https://ui.adsabs.harvard.edu/abs/2010JCAP...12..004D). doi:10.1088/1475-7516/2010/12/004 (https://doi.org/10.1088%2F1475-7516%2F2010%2F12%2F004).
293. 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). 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/CorpusID:119063004).
294. 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: 2342012–2342235. arXiv:2210.03750 (https://arxiv.org/abs/2210.03750). Bibcode:2023IJMPD..3242012M (https://ui.adsabs.harvard.edu/abs/2023IJMPD..3242012M). doi:10.1142/S0218271823420129 (https://doi.org/10.1142%2FS0218271823420129). S2CID 252781040 (https://api.semanticscholar.org/CorpusID:252781040).
295. Bagheri Tudeshki, A.; Bordbar, G.H.; Eslam Panah, B. (2022). "Dark Energy Star in Gravity's Rainbow". *Physics Letters B*. **835** 137523. arXiv:2208.07063 (https://arxiv.org/abs/2208.07063). Bibcode:2022PhLB..83537523B (https://ui.adsabs.harvard.edu/abs/2022PhLB..83537523B). doi:10.1016/j.physletb.2022.137523 (https://doi.org/10.1016%2Fj.physletb.2022.137523).
296. Ball, Philip (31 March 2005). "Black Holes 'Do Not Exist' ". *Nature*. doi:10.1038/news050328-8 (https://doi.org/10.1038%2Fnews050328-8).

297. Barceló, Carlos; Liberati, Stefano; et al. (2008). "Fate of Gravitational Collapse in Semiclassical Gravity". *Physical Review D*. **77** (4) 044032. arXiv:0712.1130 (https://arxiv.org/abs/0712.1130). Bibcode:2008PhRvD..77d4032B (https://ui.adsabs.harvard.edu/abs/2008PhRvD..77d4032B). doi:10.1103/PhysRevD.77.044032 (https://doi.org/10.1103%2FPhysRevD.77.044032).
298. Jampolski, Daniel; Rezzolla, Luciano (2024). "Nested Solutions of Gravitational Condensate Stars". *Classical and Quantum Gravity*. **41** (6). arXiv:2310.13946 (https://arxiv.org/abs/2310.13946). Bibcode:2024CQGra..41f5014J (https://ui.adsabs.harvard.edu/abs/2024CQGra..41f5014J). doi:10.1088/1361-6382/ad2317 (https://doi.org/10.1088%2F1361-6382%2Fad2317).
299. Westfahl, Gary (2021). "Black Holes" (https://books.google.com/books?id=WETPEAAAQBAJ&pg=PA159). *Science Fiction Literature Through History: An Encyclopedia*. ABC-CLIO. pp. 159–162. ISBN 978-1-4408-6617-3.
300. Johnson, David Kyle (19 June 2019). "Understanding Black Holes Through Science Fiction" (https://www.sciphijournal.org/index.php/2019/06/19/understanding-black-holes-through-science-fiction/). *Sci Phi Journal*. Retrieved 20 December 2025.
301. Rodriguez, Mario. " "Blame It on the Black Star": Black Holes in Culture" (https://www.researchgate.net/publication/376983839). *IAFOR Journal of Cultural Studies*. **8** (2) – via ResearchGate.
302. Stableford, Brian (2006). "Black Hole" (https://books.google.com/books?id=uefwmdROKTAC&pg=PA65). *Science Fact and Science Fiction: An Encyclopedia*. Taylor & Francis. pp. 65–67. ISBN 978-0-415-97460-8.
303. Langford, David (2005). "Black Holes" (https://archive.org/details/greenwoodencyclo0000unse_k2b9/page/89/mode/2up). In Westfahl, Gary (ed.). *The Greenwood Encyclopedia of Science Fiction and Fantasy: Themes, Works, And Wonders*. Greenwood Publishing Group. pp. 89–91. ISBN 978-0-313-32951-7.
304. Fraknoi, Andrew (January 2024). "Science Fiction Stories with Good Astronomy & Physics: A Topical Index" (https://astrosociety.org/file_download/inline/7b5edc23-7a89-46c1-a6b3-33a30ed4c876) (PDF). *Astronomical Society of the Pacific* (7.3 ed.). pp. 3–4. Archived (https://web.archive.org/web/20240210011957/https://astrosociety.org/file_download/inline/7b5edc23-7a89-46c1-a6b3-33a30ed4c876) (PDF) from the original on 10 February 2024. Retrieved 21 June 2024.

External links

- *Stanford Encyclopedia of Philosophy*: "Singularities and Black Holes (https://plato.stanford.edu/entries/spacetime-singularities/)" by Erik Curiel and Peter Bokulich.
- ESA's Black Hole Visualization (https://www.esa.int/gsp/ACT/phy/Projects/Blackholes/WebGL/) Archived (https://web.archive.org/web/20190503070935/https://www.esa.int/gsp/ACT/phy/Projects/Blackholes/WebGL.html) 3 May 2019 at the Wayback Machine
- Fall Into A Black Hole (https://web.archive.org/web/19980118023013/http://casa.colorado.edu/~ajsh/schw.shtml) on Andrew Hamilton's website
- Black Hole Parameters (https://space.geometrian.com/calcs/black-hole-params.php) Calculator
- Black Hole News (https://science.nasa.gov/astrophysics/focus-areas/black-holes/stories/) from NASA

Videos

- *Black Hole Apocalypse* (https://www.pbs.org/video/black-hole-apocalypse-yj34qi/) – documentary on NOVA
- Black Holes Playlist (https://www.youtube.com/playlist?list=PLsPUh22kYmNBl4h0i4mI5zDflExXJMo_x) on YouTube from *PBS Space Time*
- Computer Visualisation of a Signal Detected by LIGO (https://www.bbc.com/news/science-environment-35524440) – artistic visualization of gravitational waves from merging black holes
- Two Black Holes Merge Into One (Based Upon the Signal GW150914) (https://www.youtube.com/watch?v=I_88S8DWbcU) – realistic simulation of merging black holes
- Plunge Into A Black Hole (https://www.youtube.com/watch?v=crXGmeWFb9o) – 360° NASA simulation and explanation (https://www.youtube.com/watch?v=chhcwk4-esM)