# Black hole

A black hole is a region of spacetime exhibiting such strong gravitational effects that nothing ? including particles and electromagnetic radiation such as light ? can escape from inside it . The theory of general relativity predicts that a sufficiently compact mass can deform spacetime to form a black hole . The boundary of the region from which no escape is possible is called the event horizon . Although crossing the event horizon has enormous effect on the fate of the object crossing it , it appears to have no locally detectable features . In many ways a black hole acts like an ideal black body , as it reflects no light . Moreover , quantum field theory in curved spacetime predicts that event horizons emit Hawking radiation , with the same spectrum as a black body of a temperature inversely proportional to its mass . This temperature is on the order of billionths of a kelvin for black holes of stellar mass , making it essentially impossible to observe .

Objects whose gravitational fields are too strong for light to escape were first considered in the 18th century by John Michell and Pierre @-@ Simon Laplace . The first modern solution of general relativity that would characterize a black hole was found by Karl Schwarzschild in 1916 , although its interpretation as a region of space from which nothing can escape was first published by David Finkelstein in 1958 . Black holes were long considered a mathematical curiosity ; it was during the 1960s that theoretical work showed they were a generic prediction of general relativity . The discovery of neutron stars sparked interest in gravitationally collapsed compact objects as a possible astrophysical reality .

Black holes of stellar mass are expected to form when very massive stars collapse at the end of their life cycle . After a black hole has formed , it can continue to grow by absorbing mass from its surroundings . By absorbing other stars and merging with other black holes , supermassive black holes of millions of solar masses ( M ? ) may form . There is general consensus that supermassive black holes exist in the centers of most galaxies .

Despite its invisible interior , the presence of a black hole can be inferred through its interaction with other matter and with electromagnetic radiation such as visible light . Matter that falls onto a black hole can form an external accretion disk heated by friction , forming some of the brightest objects in the universe . If there are other stars orbiting a black hole , their orbits can be used to determine the black hole 's mass and location . Such observations can be used to exclude possible alternatives such as neutron stars . In this way , astronomers have identified numerous stellar black hole candidates in binary systems , and established that the radio source known as Sagittarius A * , at the core of our own Milky Way galaxy , contains a supermassive black hole of about 4 @.@ 3 million solar masses .

On 11 February 2016 , the LIGO collaboration announced the first observation of gravitational waves ; because these waves were generated from a black hole merger it was the first ever direct detection of a binary black hole merger . On 15 June 2016 , a second detection of a gravitational wave event from colliding black holes was announced .

## History

The idea of a body so massive that even light could not escape was first put forward by John Michell in a letter written in 1783 to Henry Cavendish of the Royal Society :

If the semi @-@ diameter of a sphere of the same density as the Sun were to exceed that of the Sun in the proportion of 500 to 1 , a body falling from an infinite height towards it would have acquired at its surface greater velocity than that of light , and consequently supposing light to be attracted by the same force in proportion to its vis inertiae , with other bodies , all light emitted from such a body would be made to return towards it by its own proper gravity .

In 1796 , mathematician Pierre @-@ Simon Laplace promoted the same idea in the first and second editions of his book Exposition du système du Monde ( it was removed from later editions ) . He justified his argument mathematically in 1799 .

Such " dark stars " were largely ignored in the nineteenth century , since it was not understood how a massless wave such as light could be influenced by gravity .

### General relativity

In 1915 , Albert Einstein developed his theory of general relativity , having earlier shown that gravity does influence light 's motion . Only a few months later , Karl Schwarzschild found a solution to the Einstein field equations , which describes the gravitational field of a point mass and a spherical mass . A few months after Schwarzschild , Johannes Droste , a student of Hendrik Lorentz , independently gave the same solution for the point mass and wrote more extensively about its properties . This solution had a peculiar behaviour at what is now called the Schwarzschild radius , where it became singular , meaning that some of the terms in the Einstein equations became infinite . The nature of this surface was not quite understood at the time . In 1924 , Arthur Eddington showed that the singularity disappeared after a change of coordinates ( see Eddington ? Finkelstein coordinates ) , although it took until 1933 for Georges Lemaître to realize that this meant the singularity at the Schwarzschild radius was an unphysical coordinate singularity . Arthur Eddington did however comment on the possibility of a star with mass compressed to the Schwarzschild radius in a 1926 book , noting that Einstein 's theory allows us to rule out overly large densities for visible stars like Betelgeuse because " a star of 250 million km radius could not possibly have so high a density as the sun . Firstly , the force of gravitation would be so great that light would be unable to escape from it , the rays falling back to the star like a stone to the earth . Secondly , the red shift of the spectral lines would be so great that the spectrum would be shifted out of existence . Thirdly , the mass would produce so much curvature of the space @-@ time metric that space would close up around the star , leaving us outside ( i.e. , nowhere ) . "

In 1931 , Subrahmanyan Chandrasekhar calculated , using special relativity , that a non @-@ rotating body of electron @-@ degenerate matter above a certain limiting mass ( now called the Chandrasekhar limit at 1 @.@ 4 M ? ) has no stable solutions . His arguments were opposed by many of his contemporaries like Eddington and Lev Landau , who argued that some yet unknown mechanism would stop the collapse . They were partly correct : a white dwarf slightly more massive than the Chandrasekhar limit will collapse into a neutron star , which is itself stable because of the Pauli exclusion principle . But in 1939 , Robert Oppenheimer and others predicted that neutron stars above approximately 3 M ? ( the Tolman ? Oppenheimer ? Volkoff limit ) would collapse into black holes for the reasons presented by Chandrasekhar , and concluded that no law of physics was likely to intervene and stop at least some stars from collapsing to black holes .

Oppenheimer and his co @-@ authors interpreted the singularity at the boundary of the Schwarzschild radius as indicating that this was the boundary of a bubble in which time stopped . This is a valid point of view for external observers , but not for infalling observers . Because of this property , the collapsed stars were called " frozen stars " , because an outside observer would see the surface of the star frozen in time at the instant where its collapse takes it inside the Schwarzschild radius .

### Golden age

In 1958 , David Finkelstein identified the Schwarzschild surface as an event horizon , " a perfect unidirectional membrane : causal influences can cross it in only one direction " . This did not strictly contradict Oppenheimer 's results , but extended them to include the point of view of infalling observers . Finkelstein 's solution extended the Schwarzschild solution for the future of observers falling into a black hole . A complete extension had already been found by Martin Kruskal , who was urged to publish it .

These results came at the beginning of the golden age of general relativity , which was marked by general relativity and black holes becoming mainstream subjects of research . This process was helped by the discovery of pulsars in 1967 , which , by 1969 , were shown to be rapidly rotating neutron stars . 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 .

In this period more general black hole solutions were found . In 1963 , Roy Kerr found the exact solution for a rotating black hole . Two years later , Ezra Newman found the axisymmetric solution for a black hole that is both rotating and electrically charged . Through the work of Werner Israel , Brandon Carter , and David Robinson the no @-@ hair theorem emerged , stating that a stationary black hole solution is completely described by the three parameters of the Kerr ? Newman metric : mass , angular momentum , and electric charge .

At first , it was suspected that the strange features of the black hole solutions were pathological artifacts from the symmetry conditions imposed , and that the singularities would not appear in generic situations . This view was held in particular by Vladimir Belinsky , Isaak Khalatnikov , and Evgeny Lifshitz , who tried to prove that no singularities appear in generic solutions . However , in the late 1960s Roger Penrose and Stephen Hawking used global techniques to prove that singularities appear generically .

Work by James Bardeen , Jacob Bekenstein , Carter , and Hawking in the early 1970s led to the formulation of black hole thermodynamics . These laws describe the behaviour of a black hole in close analogy to the laws of thermodynamics by relating mass to energy , area to entropy , and surface gravity to temperature . The analogy was completed when Hawking , in 1974 , showed that quantum field theory predicts that black holes should radiate like a black body with a temperature proportional to the surface gravity of the black hole .

The first use of the term " black hole " in print was by 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 . John Wheeler used the term " black hole " at a lecture in 1967 , leading some to credit him with coining the phrase . After Wheeler 's use of the term , it was quickly adopted in general use .

= = Properties and structure = =

The no @-@ hair theorem states that , once it achieves a stable condition after formation , a black hole has only three independent physical properties : mass , charge , and angular momentum . Any two black holes that share the same values for these properties , or parameters , are indistinguishable according to classical ( i.e. non @-@ quantum ) mechanics .

These properties are special because they are visible from outside a black hole . For example , a charged black hole repels other like charges just like any other charged object . Similarly , the total mass inside a sphere containing a black hole can be found by using the gravitational analog of Gauss 's law , the ADM mass , far away from the black hole . Likewise , the angular momentum can be measured from far away using frame dragging by the gravitomagnetic field .

When an object falls into a black hole , any information about the shape of the object or distribution of charge on it is evenly distributed along the horizon of the black hole , and is lost to outside observers . The behavior of the horizon in this situation is a dissipative system that is closely analogous to that of a conductive stretchy membrane with friction and electrical resistance ? the membrane paradigm . This is different from other field theories such as electromagnetism , which do not have any friction or resistivity at the microscopic level , because they are time @-@ reversible . Because a black hole eventually achieves a stable state with only three parameters , there is no way to avoid losing information about the initial conditions : the gravitational and electric fields of a black hole give very little information about what went in . The information that is lost includes every quantity that cannot be measured far away from the black hole horizon , including approximately conserved quantum numbers such as the total baryon number and lepton number . This behavior is so puzzling that it has been called the black hole information loss paradox .

= = = Physical properties = = =

The simplest static black holes have mass but neither electric charge nor angular momentum . These black holes are often referred to as Schwarzschild black holes after Karl Schwarzschild who discovered this solution in 1916 . According to Birkhoff 's theorem , it is the only vacuum solution

that is spherically symmetric . This means that there is no observable difference between the gravitational field of such a black hole and that of any other spherical object of the same mass . The popular notion of a black hole " sucking in everything " in its surroundings is therefore only correct near a black hole 's horizon ; far away , the external gravitational field is identical to that of any other body of the same mass .

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

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

<formula>

for a black hole of mass M. Black holes satisfying this inequality are called extremal . Solutions of Einstein 's equations that violate this inequality exist , but they do not possess an event horizon . These solutions have so @-@ called naked singularities that can be observed from the outside , and hence are deemed unphysical . The cosmic censorship hypothesis rules out the formation of such singularities , when they are created through the gravitational collapse of realistic matter . This is supported by numerical simulations .

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

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

<formula>

where rsh is the Schwarzschild radius and MSun is the mass of the Sun . This relation is exact only for black holes with zero charge and angular momentum ; for more general black holes it can differ up to a factor of 2 .

= = = Event horizon = = =

The defining feature of a black hole is the appearance of an event horizon ? a boundary in spacetime through which matter and light can only pass inward towards the mass of the black hole . Nothing , not even light , can escape from inside the event horizon . The event horizon is referred to as such because if an event occurs within the boundary , information from that event cannot reach an outside observer , making it impossible to determine if such an event occurred .

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

To a distant observer , clocks near a black hole appear to tick more slowly than those further away from the black hole . Due to this effect , known as gravitational time dilation , an object falling into a black hole appears to slow as it approaches the event horizon , taking an infinite time to reach it . At the same time , all processes on this object slow down , from the view point of a fixed outside observer , causing any light emitted by the object to appear redder and dimmer , an effect known as gravitational redshift . Eventually , the falling object becomes so dim that it can no longer be seen .

On the other hand , indestructible observers falling into a black hole do not notice any of these effects as they cross the event horizon . According to their own clocks , which appear to them to tick normally , they cross the event horizon after a finite time without noting any singular behaviour ; it is impossible to determine the location of the event horizon from local observations .

The shape of the event horizon of a black hole is always approximately spherical . For non @-@

rotating ( static ) black holes the geometry of the event horizon is precisely spherical , while for rotating black holes the sphere is oblate .

= = = Singularity = = =

At the center of a black hole , as described by general relativity , lies a gravitational singularity , a region where the spacetime curvature becomes infinite . For a non @-@ rotating black hole , this region takes the shape of a single point and for a rotating black hole , it is smeared out to form a ring singularity that lies in the plane of rotation . In both cases , the singular region has zero volume . It can also be shown that the singular region contains all the mass of the black hole solution . The singular region can thus be thought of as having infinite density .

Observers falling into a Schwarzschild black hole ( i.e. , non @-@ rotating and not charged ) cannot avoid being carried into the singularity , once they cross the event horizon . They can prolong the experience by accelerating away to slow their descent , but only up to a limit ; after attaining a certain ideal velocity , it is best to free fall the rest of the way . When they reach the singularity , they are crushed to infinite density and their mass is added to the total of the black hole . Before that happens , they will have been torn apart by the growing tidal forces in a process sometimes referred to as spaghettification or the " noodle effect " .

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

The appearance of singularities in general relativity is commonly perceived as signaling the breakdown of the theory . This breakdown , however , is expected ; it occurs in a situation where quantum effects should describe these actions , due to the extremely high density and therefore particle interactions . To date , it has not been possible to combine quantum and gravitational effects into a single theory , although there exist attempts to formulate such a theory of quantum gravity . It is generally expected that such a theory will not feature any singularities .

= = = Photon sphere = = =

The photon sphere is a spherical boundary of zero thickness in which photons that move on tangents to that sphere would be trapped in a circular orbit about the black hole . For non @-@ rotating black holes , the photon sphere has a radius 1 @.@ 5 times the Schwarzschild radius . Their orbits would be dynamically unstable , hence any small perturbation , such as a particle of infalling matter , would cause an instability that would grow over time , either setting the photon on an outward trajectory causing it to escape the black hole , or on an inward spiral where it would eventually cross the event horizon .

While light can still escape from the photon sphere , any light that crosses the photon sphere on an inbound trajectory will be captured by the black hole . Hence any light that reaches an outside observer from the photon sphere must have been emitted by objects between the photon sphere and the event horizon .

Other compact objects , such as neutron stars , can also have photon spheres . This follows from the fact that the gravitational field external to a spherically @-@ symmetric object is governed by the Schwarzschild metric , which depends only on the object 's mass rather than the radius of the object , hence any object whose radius shrinks to smaller than 1 @.@ 5 times the Schwarzschild radius will have a photon sphere .

= = = Ergosphere = = =

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

The ergosphere of a black hole is a volume whose inner boundary is the black hole 's event horizon and an outer boundary of an oblate spheroid , which coincides with the event horizon at the poles but noticeably wider around the equator . The outer boundary is sometimes called the ergosurface .

Objects and radiation can escape normally from the ergosphere . Through the Penrose process , objects can emerge from the ergosphere with more energy than they entered . This energy is taken from the rotational energy of the black hole causing the latter to slow .

= = = Innermost stable circular orbit ( ISCO ) = = =

In Newtonian gravity , test particles can stably orbit at arbitrary distances from a central object . In general relativity , however , there exists an innermost stable circular orbit ( often called the ISCO ) , inside of which , any infinitesimal perturbations to a circular orbit will lead to inspiral into the black hole . The location of the ISCO depends on the spin of the black hole , in the case of a Schwarzschild black hole ( spin zero ) is :
<formula>
and decreases with increasing spin .

= = Formation and evolution = =

Considering the exotic nature of black holes , it may be natural to question if such bizarre objects could exist in nature or to suggest that they are merely pathological solutions to Einstein 's equations . Einstein himself wrongly thought that black holes would not form , because he held that the angular momentum of collapsing particles would stabilize their motion at some radius . This led the general relativity community to dismiss all results to the contrary for many years . However , a minority of relativists continued to contend that black holes were physical objects , and by the end of the 1960s , they had persuaded the majority of researchers in the field that there is no obstacle to the formation of an event horizon .

Once an event horizon forms , Penrose proved , general relativity without quantum mechanics requires that a singularity will form within . Shortly afterwards , Hawking showed that many cosmological solutions that describe the Big Bang have singularities without scalar fields or other exotic matter ( see " Penrose ? Hawking singularity theorems " ) . The Kerr solution , the no @-@ hair theorem , and the laws of black hole thermodynamics showed that the physical properties of black holes were simple and comprehensible , making them respectable subjects for research . The primary formation process for black holes is expected to be the gravitational collapse of heavy objects such as stars , but there are also more exotic processes that can lead to the production of black holes .

= = = Gravitational collapse = = =

Gravitational collapse occurs when an object 's internal pressure is insufficient to resist the object 's own gravity . For stars this usually occurs either because a star has too little " fuel " left to maintain its temperature through stellar nucleosynthesis , or because a star that would have been stable receives extra matter in a way that does not raise its core temperature . In either case the star 's temperature is no longer high enough to prevent it from collapsing under its own weight . The collapse may be stopped by the degeneracy pressure of the star 's constituents , allowing the condensation of matter into an exotic denser state . The result is one of the various types of

compact star . The type of compact star formed depends on the mass of the remnant of the original star left after the outer layers have been blown away . Such explosions and pulsations lead to planetary nebula . This mass can be substantially less than the original star . Remnants exceeding 5 M ? are produced by stars that were over 20 M ? before the collapse .

 If the mass of the remnant exceeds about 3 ? 4 M ? ( the Tolman ? Oppenheimer ? Volkoff limit ) , either because the original star was very heavy or because the remnant collected additional mass through accretion of matter , even the degeneracy pressure of neutrons is insufficient to stop the collapse . No known mechanism ( except possibly quark degeneracy pressure , see quark star ) is powerful enough to stop the implosion and the object will inevitably collapse to form a black hole .

 The gravitational collapse of heavy stars is assumed to be responsible for the formation of stellar mass black holes . Star formation in the early universe may have resulted in very massive stars , which upon their collapse would have produced black holes of up to 103 M ? . These black holes could be the seeds of the supermassive black holes found in the centers of most galaxies . It has further been suggested that supermassive black holes with typical masses of ~ 105 M ? could have formed from the direct collapse of gas clouds in the young universe . Some candidates for such objects have been found in observations of the young universe .

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

= = = = Primordial black holes in the Big Bang = = = =

 Gravitational collapse requires great density . In the current epoch of the universe these high densities are only found in stars , but in the early universe shortly after the big bang densities were much greater , possibly allowing for the creation of black holes . The high density alone is not enough to allow the formation of black holes since a uniform mass distribution will not allow the mass to bunch up . In order for primordial black holes to form in such a dense medium , there must be initial density perturbations that can then grow under their own gravity . Different models for the early universe vary widely in their predictions of the size of these perturbations . Various models predict the creation of black holes , ranging from a Planck mass to hundreds of thousands of solar masses . Primordial black holes could thus account for the creation of any type of black hole .

= = = High @-@ energy collisions = = =

 Gravitational collapse is not the only process that could create black holes . In principle , black holes could be formed in high @-@ energy collisions that achieve sufficient density . As of 2002 , no such events have been detected , either directly or indirectly as a deficiency of the mass balance in particle accelerator experiments . This suggests that there must be a lower limit for the mass of black holes . Theoretically , this boundary is expected to lie around the Planck mass ( mP = ? ?c / G ? 1 @.@ 2 × 1019 GeV / c2 ? 2 @.@ 2 × 10 ? 8 kg ) , where quantum effects are expected to invalidate the predictions of general relativity . This would put the creation of black holes firmly out of reach of any high @-@ energy process occurring on or near the Earth . However , certain developments in quantum gravity suggest that the Planck mass could be much lower : some braneworld scenarios for example put the boundary as low as 1 TeV / c2 . This would make it conceivable for micro black holes to be created in the high @-@ energy collisions that occur when cosmic rays hit the Earth 's atmosphere , or possibly in the Large Hadron Collider at CERN . These theories are very speculative , and the creation of black holes in these processes is deemed unlikely by many specialists . Even if micro black holes could be formed , it is expected that they would

evaporate in about 10 ? 25 seconds , posing no threat to the Earth .

### = = = Growth = = =

Once a black hole has formed , it can continue to grow by absorbing additional matter . Any black hole will continually absorb gas and interstellar dust from its surroundings and omnipresent cosmic background radiation . This is the primary process through which supermassive black holes seem to have grown . A similar process has been suggested for the formation of intermediate @-@ mass black holes found in globular clusters .

Another possibility for black hole growth , is for a black hole to merge with other objects such as stars or even other black holes . Although not necessary for growth , this is thought to have been important , especially for the early development of supermassive black holes , which could have formed from the coagulation of many smaller objects . The process has also been proposed as the origin of some intermediate @-@ mass black holes .

### = = = Evaporation = = =

In 1974 , Hawking predicted that black holes are not entirely black but emit small amounts of thermal radiation ; this effect has become known as Hawking radiation . By applying quantum field theory to a static black hole background , he determined that a black hole should emit particles that display a perfect black body spectrum . Since Hawking 's publication , many others have verified the result through various approaches . 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 . The temperature of this thermal spectrum ( Hawking temperature ) is proportional to the surface gravity of the black hole , which , for a Schwarzschild black hole , is inversely proportional to the mass . Hence , large black holes emit less radiation than small black holes .

A stellar black hole of 1 M ? has a Hawking temperature of about 100 nanokelvins . 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 shrink . 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 millimeter .

If a black hole is very small , the radiation effects are expected to become very strong . Even a black hole that is heavy compared to a human would evaporate in an instant . A black hole with the mass of a car would have a diameter of about 10 ? 24 m and take a nanosecond to evaporate , during which time it would briefly have a luminosity of more than 200 times that of the Sun . Lower @-@ mass black holes are expected to evaporate even faster ; for example , a black hole of mass 1 TeV / c2 would take less than 10 ? 88 seconds to evaporate completely . For such a small black hole , quantum gravitation effects are expected to play an important role and could hypothetically make such a small black hole stable , although current developments in quantum gravity do not indicate so .

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

## = = Observational evidence = =

By their very nature , black holes do not directly emit any electromagnetic radiation other than the hypothetical Hawking radiation , so astrophysicists searching for black holes must generally rely on

indirect observations . For example , a black hole 's existence can sometimes be inferred by observing its gravitational interactions with its surroundings . However , the Event Horizon Telescope ( EHT ) , run by MIT 's Haystack Observatory , is an attempt to directly observe the immediate environment of the event horizon of Sagittarius A * , the black hole at the centre of the Milky Way . The first image of the event horizon may appear as early as 2018 . The existence of magnetic fields just outside the event horizon of Sagittarius A * , which were predicted by theoretical studies of black holes , was confirmed by the EHT in 2015 .

### Detection of gravitational waves from merging black holes

On 24 September 2015 the LIGO gravitational wave observatory made the first @-@ ever successful observation of gravitational waves . The signal was consistent with theoretical predictions for the gravitational waves produced by the merger of two black holes : one with about 36 solar masses , and the other around 29 solar masses . This observation provides the most concrete evidence for the existence of black holes to date . For instance , the gravitational wave signal suggests that the separation of the two object prior to merger was just 350 km ( or roughly 4 times the Schwarzschild radius corresponding to the inferred masses ) . The objects must therefore have been extremely compact , leaving black holes as the most plausible interpretation .
  More importantly , the signal observed by LIGO also included the start of the post @-@ merger ringdown , the signal produced as the newly formed compact object settles down to a stationary state . Arguably , the ringdown is the most direct way of observing a black hole . From the LIGO signal it is possible to extract the frequency and damping time of the dominant mode of the ringdown . From these it is possible to infer the mass and angular momentum of the final object , which match independent predictions from numerical simulations of the merger . The frequency and decay time of the dominant mode are determined by the geometry of the photon sphere . Hence , observation of this mode confirms the presence of a photon sphere , however it cannot exclude possible exotic alternatives to black holes that are compact enough to have a photon sphere .
  The observation also provides the first observational evidence for the existence of stellar @-@ mass black hole binaries . Furthermore , it is the first observational evidence of stellar @-@ mass black holes weighing 25 solar masses or more .

### Proper motions of stars orbiting Sagittarius A *

The proper motions of stars near the center of our own Milky Way provide strong observational evidence that these stars are orbiting a supermassive black hole . Since 1995 , astronomers have tracked the motions of 90 stars orbiting an invisible object coincident with the radio source Sagittarius A * . By fitting their motions to Keplerian orbits , the astronomers were able to infer , in 1998 , that a 2 @.@ 6 million M ? object must be contained in a volume with a radius of 0 @.@ 02 light @-@ years to cause the motions of those stars . Since then , one of the stars ? called S2 ? has completed a full orbit . From the orbital data , astronomers were able to make refine the calculations of the mass to 4 @.@ 3 million M ? and a radius of less than 0 @.@ 002 lightyears for the object causing the orbital motion of those stars . The upper limit on the object 's size is still too large to test whether it is smaller than its Schwarzschild radius ; nevertheless , these observations strongly suggest that the central object is a supermassive black hole as there are no other plausible scenarios for confining so much invisible mass into such a small volume . Additionally , there is some observational evidence that this object might possess an event horizon , a feature unique to black holes .

### Accretion of matter

Due to conservation of angular momentum , gas falling into the gravitational well created by a massive object will typically form a disc @-@ like structure around the object . Artists ' impressions such as the accompanying representation of a black hole with corona commonly depict the black

hole as if it were a flat @-@ space material body hiding the part of the disc just behind it , but detailed mathematical modelling shows that the image of the disc would actually be distorted by the bending of light that originated behind the black hole in such a way that the upper side of the disc would be entirely visible , while there would be a partially visible secondary image of the underside of the disk .

Within such a disc , friction would cause angular momentum to be transported outward , allowing matter to fall further inward , thus releasing potential energy and increasing the temperature of the gas .

When the accreting object is a neutron star or a black hole , the gas in the inner accretion disc orbits at very high speeds because of its proximity to the compact object . The resulting friction is so significant that it heats the inner disc to temperatures at which it emits vast amounts of electromagnetic radiation ( mainly X @-@ rays ) . These bright X @-@ ray sources may be detected by telescopes . This process of accretion is one of the most efficient energy @-@ producing processes known ; up to 40 % of the rest mass of the accreted material can be emitted as radiation . ( In nuclear fusion only about 0 @.@ 7 % of the rest mass will be emitted as energy . ) In many cases , accretion discs are accompanied by relativistic jets that are emitted along the poles , which carry away much of the energy . The mechanism for the creation of these jets is currently not well understood .

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

In November 2011 the first direct observation of a quasar accretion disk around a supermassive black hole was reported .

= = = X @-@ ray binaries = = =

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

If such a system emits signals that can be directly traced back to the compact object , it cannot be a black hole . The absence of such a signal does , however , not exclude the possibility that the compact object is a neutron star . By studying the companion star it is often possible to obtain the orbital parameters of the system and to obtain an estimate for the mass of the compact object . If this is much larger than the Tolman ? Oppenheimer ? Volkoff limit ( that is , the maximum mass a neutron star can have before it collapses ) then the object cannot be a neutron star and is generally expected to be a black hole .

The first strong candidate for a black hole , Cygnus X @-@ 1 , was discovered in this way by Charles Thomas Bolton , Louise Webster and Paul Murdin in 1972 . Some doubt , however , remained due to the uncertainties that result from the companion star being much heavier than the candidate black hole . Currently , better candidates for black holes are found in a class of X @-@ ray binaries called soft X @-@ ray transients . In this class of system , the companion star is of relatively low mass allowing for more accurate estimates of the black hole mass . Moreover , these systems are 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 disc is extremely faint allowing detailed observation of the companion star during this period . One of the best such candidates is V404 Cyg .

= = = = Quiescence and advection @-@ dominated accretion flow = = = =

The faintness of the accretion disc of an X @-@ ray binary during quiescence is suspected to be caused by the flow of mass entering a mode called an advection @-@ dominated accretion flow ( ADAF ) . In this mode , almost all the energy generated by friction in the disc is swept along with the flow instead of radiated away . If this model is correct , then it forms strong qualitative evidence for the presence of an event horizon , since if the object at the center of the disc had a solid surface , it would emit large amounts of radiation as the highly energetic gas hits the surface , an effect that is observed for neutron stars in a similar state .

= = = = Quasi @-@ periodic oscillations = = = =

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

= = = Galactic nuclei = = =

Astronomers use the term " active galaxy " to describe galaxies with unusual characteristics , such as unusual spectral line emission and very strong radio emission . Theoretical and observational studies have shown that the activity in these active galactic nuclei ( AGN ) may be explained by the presence of supermassive black holes , which can be millions of times more massive than stellar ones . The models of these AGN consist of a central black hole that may be millions or billions of times more massive than the Sun ; a disk of gas and dust called an accretion disk ; and two jets perpendicular to the accretion disk .
Although supermassive black holes are expected to be found in most AGN , only some galaxies ' nuclei have been more carefully studied in attempts to both identify and measure the actual masses of the central supermassive black hole candidates . Some of the most notable galaxies with supermassive black hole candidates include the Andromeda Galaxy , M32 , M87 , NGC 3115 , NGC 3377 , NGC 4258 , NGC 4889 , NGC 1277 , OJ 287 , APM 08279 + 5255 and the Sombrero Galaxy .
It is now widely accepted that the center of nearly every galaxy , not just active ones , contains a supermassive black hole . 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 the galaxy itself .

= = = Microlensing ( proposed ) = = =

Another way that the black hole nature of an object may be tested in the future is through observation of effects caused by a strong gravitational field in their vicinity . One such effect is gravitational lensing : The deformation of spacetime around a massive object causes light rays to be deflected much as light passing through an optic lens . Observations have been made of weak gravitational lensing , in which light rays are deflected by only a few arcseconds . However , it has never been directly observed for a black hole . One possibility for observing gravitational lensing by a black hole would be to observe stars in orbit around the black hole . There are several candidates for such an observation in orbit around Sagittarius A * .

= = = Alternatives = = =

The evidence for stellar black holes strongly relies on the existence of an upper limit for the mass of a neutron star . The size of this limit heavily depends on the assumptions made about the properties of dense matter . New exotic phases of matter could push up this bound . A phase of free quarks at

high density might allow the existence of dense quark stars , and some supersymmetric models predict the existence of Q stars . Some extensions of the standard model posit the existence of preons as fundamental building blocks of quarks and leptons , which could hypothetically form preon stars . These hypothetical models could potentially explain a number of observations of stellar black hole candidates . However , it can be shown from arguments in general relativity that any such object will have a maximum mass .

 Since the average density of a black hole inside its Schwarzschild radius is inversely proportional to the square of its mass , supermassive black holes are much less dense than stellar black holes ( the average density of a 108 M ? black hole is comparable to that of water ) . Consequently , the physics of matter forming a supermassive black hole is much better understood and the possible alternative explanations for supermassive black hole observations are much more mundane . For example , a supermassive black hole could be modelled by a large cluster of very dark objects . However , such alternatives are typically not stable enough to explain the supermassive black hole candidates .

 The evidence for the existence of stellar and supermassive black holes implies that in order for black holes to not form , general relativity must fail as a theory of gravity , perhaps due to the onset of quantum mechanical corrections . A much anticipated feature of a theory of quantum gravity is that it will not feature singularities or event horizons and thus black holes would not be real artifacts . In 2002 , much attention has been drawn by the fuzzball model in string theory . Based on calculations for specific situations in string theory , the proposal suggests that generically the individual states of a black hole solution do not have an event horizon or singularity , but that for a classical / semi @-@ classical observer the statistical average of such states appears just as an ordinary black hole as deduced from general relativity .

 = = Open questions = =


 = = = Entropy and thermodynamics = = =


 In 1971 , Hawking showed under general conditions that the total area of the event horizons of any collection of classical black holes can never decrease , even if they collide and merge . This result , now known as the second law of black hole mechanics , is remarkably similar to the second law of thermodynamics , which states that the total entropy of a system can never decrease . As with classical objects at absolute zero temperature , it was assumed that black holes had zero entropy . If this were the case , the second law of thermodynamics would be violated by entropy @-@ laden matter entering a black hole , resulting in a decrease of the total entropy of the universe . Therefore , Bekenstein proposed that a black hole should have an entropy , and that it should be proportional to its horizon area .

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

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

 Although general relativity can be used to perform a semi @-@ classical calculation of black hole

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

### Information loss paradox

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

The question whether information is truly lost in black holes ( the black hole information paradox ) has divided the theoretical physics community ( see Thorne ? Hawking ? Preskill bet ) . In quantum mechanics , loss of information corresponds to the violation of vital property called unitarity , which has to do with the conservation of probability . It has been argued that loss of unitarity would also imply violation of conservation of energy . Over recent years evidence has been building that indeed information and unitarity are preserved in a full quantum gravitational treatment of the problem .

### Popular reading

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### Review papers