155 Lecture 16a (continues from 15b)

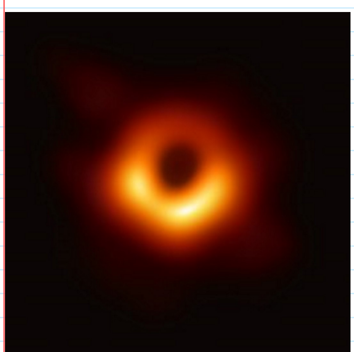
Monday, February 24, 2020 8:11 PM

NOTE: These lecture notes were used in my upper division General Relativity class. I offer them here for my first year seminar to be used mainly on an "impressionistic" basis. I am not expecting any technical aspects to be accessible to my FYS students.

I offer them for this class in lights of the announcement of the 2020 Nobel Prize in Physics. https://www.nobelprize.org/prizes/physics/

The Schwarzschild Metric

Introductory comments



From <https://en.wikipedia.org/wiki/Black_hole>

From <https://www.nasa.gov/audience/forstudents/k-4/stories/nasa-knows/what-is-a-black-hole-k4.html>

General relativity

See also: History of general relativity

Simulated view of a black hole in front of the Large Magellanic Cloud. Note the gravitational lensing effect, which produces two enlarged but highly distorted views of the Cloud. Across the top, the Milky Way disk appears distorted into an arc.

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.[24] 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.[25][26] 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 a non-physical coordinate singularity.[27] 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)."[28][29]

In 1931, Subrahmanyan Chandrasekhar calculated, using special relativity, that a non-rotating body of electron-degenerate matter above a certain limiting mass (now called the Chandrasekhar limit at 1.4 $M_\odot$) has no stable solutions.[30] 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.[31] They were partly correct: a white dwarf slightly more massive than the Chandrasekhar limit will collapse into a neutron star,[32] which is itself stable. But in 1939, Robert Oppenheimer and others predicted that neutron stars above another limit (the Tolman–Oppenheimer–Volkoff limit) would collapse further for the reasons presented by Chandrasekhar, and concluded that no law of physics was likely to intervene and stop at least some stars from collapsing to black holes.[33] Their original calculations, based on the Pauli exclusion principle, gave it as 0.7 $M_\odot$; subsequent consideration of strong force-mediated neutron-neutron repulsion raised the estimate to approximately 1.5 $M_\odot$ to 3.0 $M_\odot$.[34] Observations of the neutron star merger GW170817, which is thought to have generated a black hole shortly afterward, have refined the TOV limit estimate to ~2.17 $M_\odot$.[35][36][37][38][39]

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 to the Schwarzschild radius.[40]

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".[41] 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.[42]

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 by Jocelyn Bell Burnell in 1967,[43][44] which, by 1969, were shown to be rapidly rotating neutron stars.[45] 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.[*citation needed*]

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.[46] Through the work of Werner Israel,[47] Brandon Carter,[48][49] and David Robinson[50] 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.[51]

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[52] and Stephen Hawking used global techniques to prove that singularities appear generically.[53]

Work by James Bardeen, Jacob Bekenstein, Carter, and Hawking in the early 1970s led to the formulation of black hole thermodynamics.[54] These laws describe the behaviour of a black hole in close analogy to the laws of thermodynamics by relating mass to energy, area to entropy, and surface gravity to temperature. The analogy was completed when Hawking, in 1974, showed that quantum field theory implies that black holes should radiate like a black body with a temperature proportional to the surface gravity of the black hole, predicting the effect now known as Hawking radiation.[55]

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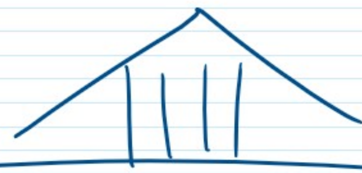
From <https://en.wikipedia.org/wiki/Black_hole>



Are BH's a real part of GR theory?

We had to wait until the 1960's to get some clarity

Do BH's exist in our observable Universe?

→ Answers were "yes" based on very indirect arguments when I was in college in the 70's. Some remained skeptical.

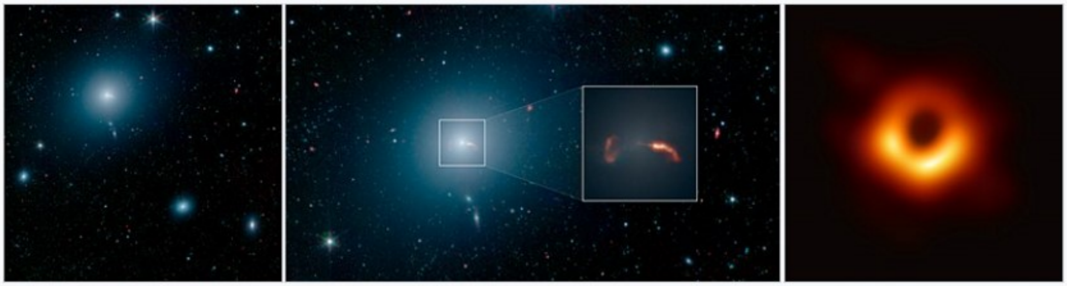
→ Today, much more evidence and little skepticism

→ a supermassive BH at the center

→ a supermassive BH at the center of every galaxy
→ More ~ $M_\odot$ mass BH than earlier estimates "swimming in BH's"

Observational evidence

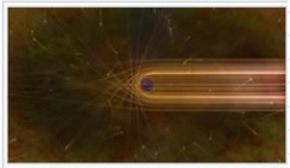
Messier 87 galaxy – home of the first imaged black hole



context | closeup | supermassive black hole

By nature, black holes do not themselves emit any electromagnetic radiation other than the hypothetical Hawking radiation, so astrophysicists searching for black holes must generally rely on indirect observations. For example, a black hole's existence can sometimes be inferred by observing its gravitational influence upon its surroundings.[140] 2019

On 10 April 2019 an image was released of a black hole, which is seen in magnified fashion because the light paths near the event horizon are highly bent. The dark shadow in the middle results from light paths absorbed by the black hole. The image is in false color, as the detected light halo in this image is not in the visible spectrum, but radio waves.



This artist's impression depicts the paths of photons in the vicinity of a black hole. The gravitational bending and capture of light by the event horizon is the cause of the shadow captured by the Event Horizon Telescope.

The Event Horizon Telescope (EHT), run by MIT's Haystack Observatory, is an active program that directly observes the immediate environment of the event horizon of black holes, such as the black hole at the centre of the Milky Way. In April 2017, EHT began observation of the black hole in the center of Messier 87.[141] "In all, eight radio observatories on six mountains and four continents observed the galaxy in Virgo on and off for 10 days in April 2017" to provide the data yielding the image two years later in April 2019.[142] After two years of data processing, EHT released the first direct image of a black hole, specifically the supermassive black hole that lies in the center of the aforementioned galaxy.[143][144] What is visible is not the black hole, which shows as black because of the loss of all light within this dark region, rather it is the gases at the edge of the event horizon, which are displayed as orange or red, that define the black hole.[145]

The brightening of this material in the 'bottom' half of the processed EHT image is thought to be caused by Doppler beaming, whereby material approaching the viewer at relativistic speeds is perceived as brighter than material moving away. In the case of a black hole this phenomenon implies that the visible material is rotating at relativistic speeds (>1,000 km/s), the only speeds at which it is possible to centrifugally balance the immense gravitational attraction of the singularity, and thereby remain in orbit above the event horizon. This configuration of bright material implies that the EHT observed M87* from a perspective catching the black hole's accretion disc nearly edge-on, as the whole system rotated clockwise.[146] However, the extreme gravitational lensing associated with black holes produces the illusion of a perspective that sees the accretion disc from above. In reality, most of the ring in the EHT image was created when the light emitted by the far side of the accretion disc bent around the black hole's gravity well and escaped such that most of the possible perspectives on M87* can see the entire disc, even that directly behind the "shadow".

Prior to this, in 2015, the EHT detected magnetic fields just outside the event horizon of Sagittarius A*, and even discerned some of their properties. The field lines that pass through the accretion disc were found to be a complex mixture of ordered and tangled. The existence of magnetic fields had been predicted by theoretical studies of black holes.[147][148]

Detection of gravitational waves from merging black holes

2015

Predicted appearance of non-rotating black hole with toroidal ring of ionised matter, such as has been proposed[149] as a model for Sagittarius A*. The asymmetry is due to the Doppler effect resulting from the enormous orbital speed needed for centrifugal balance of the very strong gravitational attraction of the hole.

On 14 September 2015 the LIGO gravitational wave observatory made the first-ever successful direct observation of gravitational waves.[14][150] 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.[14][151] This observation provides the most concrete evidence for the existence of black holes to date. For instance, the gravitational wave signal suggests that the separation of the two objects prior to the merger was just 350 km (or roughly four times the Schwarzschild radius corresponding to the inferred masses). The objects must therefore have been extremely compact, leaving black holes as the most plausible interpretation.[14]

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.[152] 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.[153] The frequency and decay time of the dominant mode observing a black hole.[152] 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.[153] 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.[152]

Doppler effect resulting from the enormous orbital speed needed for centrifugal balance of the very strong gravitational attraction of the hole.

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.[154]

On 15 June 2016, a second detection of a gravitational wave event from colliding black holes was announced,[155] and other gravitational wave events have since been observed.[16]

2016

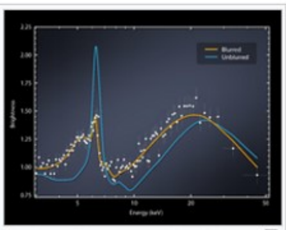
Proper motions of stars orbiting Sagittarius A*

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.[156] 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 $M_{\odot}$ object must be contained in a volume with a radius of 0.02 light-years to cause the motions of those stars.[157] Since then, one of the stars—called S2—has completed a full orbit. From the orbital data, astronomers were able to refine the calculations of the mass to 4.3 million $M_{\odot}$ and a radius of less than 0.002 light years for the object causing the orbital motion of those stars.[156] 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.[157] Additionally, there is some observational evidence that this object might possess an event horizon, a feature unique to black holes.[158]

Accretion of matter

See also: Accretion disk

Black hole with corona, X-ray source (artist's concept)[159]



Blurring of X-rays near black hole (NuSTAR; 12 August 2014)[159]

Due to conservation of angular momentum,[160] gas falling into the gravitational well created by a massive object will typically form a disk-like structure around the object. Artists' impressions such as the accompanying representation of a black hole with corona commonly depict the black hole as if it were a flat-space body hiding the part of the disk just behind it, but in reality gravitational lensing would greatly distort the image of the accretion disk.[161]

NASA simulated view from outside the horizon of a Schwarzschild black hole lit by a thin accretion disk.

Within such a disk, 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.[162]

When the accreting object is a neutron star or a black hole, the gas in the inner accretion disk orbits at very high speeds because of its proximity to the compact object. The resulting friction is so significant that it heats the inner disk to temperatures at which it emits vast amounts of electromagnetic radiation (mainly X-rays). These bright X-ray sources may be detected by telescopes. This process of accretion is one of the most efficient energy-producing processes known; up to 40% of the rest mass of the accreted material can be emitted as radiation.[162] (In nuclear fusion only about 0.7% of the rest mass will be emitted as energy.) In many cases, accretion disks are accompanied by relativistic jets that are emitted along the poles, which carry away much of the energy. The mechanism for the creation of these jets is currently not well understood, in part due to insufficient data.[163]

As such, many of the universe's more energetic phenomena have been attributed to the accretion of matter on black holes. In particular, active galactic nuclei and quasars are believed to be the accretion disks of supermassive black holes.[164] 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.[164] It has also been suggested that some ultraluminous X-ray sources may be the accretion disks of intermediate-mass black holes.[165]

In November 2011 the first direct observation of a quasar accretion disk around a supermassive black hole was reported.[166][167]

2011

Observations from O1 and O2/2015-2017 [edit]

List of binary merger events[7][8]

GW event and time (UTC)[n 2]	Date published	Location area[n 3] (deg^2)	Luminosity distance (Mpc)[n 4]	Energy radiated ($c^2M_\odot$) [n 5]	Chirp mass ($M_\odot$) [n 6]	Effective spin[n 7]	Primary Type	Primary Mass ($M_\odot$)	Secondary Type	Secondary Mass ($M_\odot$)	Remnant Type	Remnant Mass ($M_\odot$)	Remnant Spin[n 8]	Notes
GW150914 09:50:45	2016-02-11	179; mostly to the south	430^{+150}_{-170}	$3.1^{+0.4}_{-0.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	BH [n 9]	$35.6^{+4.8}_{-3.0}$	BH [n 10]	$30.6^{+3.0}_{-4.4}$	BH	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	First GW detection; first BH merger observed
GW151012 [fr] 09:54:43	2016-06-15	1555	1060^{+540}_{-480}	$1.5^{+0.5}_{-0.5}$	$15.2^{+2.0}_{-1.1}$	$0.04^{+0.28}_{-0.19}$	BH	$23.3^{+14.0}_{-5.5}$	BH	$13.6^{+4.1}_{-4.8}$	BH	$35.7^{+9.9}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	Formerly candidate LVT151012; accepted as astrophysical since February 2019
GW151226 03:38:53	2016-06-15	1033	440^{+180}_{-190}	$1.0^{+0.1}_{-0.2}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	BH	$13.7^{+8.8}_{-3.2}$	BH	$7.7^{+2.2}_{-2.6}$	BH	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	
GW170104 10:11:58	2017-06-01	924	960^{+430}_{-410}	$2.2^{+0.5}_{-0.5}$	$21.5^{+2.1}_{-1.7}$	$-0.04^{+0.17}_{-0.20}$	BH	$31.0^{+7.2}_{-5.6}$	BH	$20.1^{+4.9}_{-4.5}$	BH	$49.1^{+5.2}_{-3.5}$	$0.66^{+0.08}_{-0.10}$	
GW170608 02:01:16	2017-11-16	396; to the north	320^{+120}_{-110}	$0.9^{+0.0}_{-0.1}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	BH	$10.9^{+5.3}_{-1.7}$	BH	$7.6^{+1.3}_{-2.1}$	BH	$17.8^{+3.2}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	Smallest BH progenitor masses to date
GW170729 18:56:29	2018-11-30	1033	2750^{+1350}_{-1320}	$4.8^{+1.7}_{-1.7}$	$35.7^{+6.5}_{-4.7}$	$0.36^{+0.21}_{-0.25}$	BH	$50.6^{+16.6}_{-10.2}$	BH	$34.3^{+9.1}_{-10.1}$	BH	$80.3^{+14.6}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	Largest progenitor masses to date
GW170809 08:28:21	2018-11-30	340; towards Cetus	990^{+320}_{-380}	$2.7^{+0.6}_{-0.6}$	$25.0^{+2.1}_{-1.6}$	$0.07^{+0.16}_{-0.16}$	BH	$35.2^{+8.3}_{-6.0}$	BH	$23.8^{+5.2}_{-5.1}$	BH	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$	
GW170814 10:30:43	2017-09-27	87; towards Eridanus	580^{+160}_{-210}	$2.7^{+0.4}_{-0.3}$	$24.2^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.11}$	BH	$30.7^{+5.7}_{-3.0}$	BH	$25.3^{+2.9}_{-4.1}$	BH	$53.4^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	First announced detection by three observatories; first polarization measurement
GW170817 12:41:04	2017-10-16	16; NGC 4993	40 ± 10	≥ 0.04	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	NS	$1.46^{+0.12}_{-0.10}$	NS	$1.27^{+0.09}_{-0.09}$	NS [n 11]	≤ 2.8[n 12]	≤ 0.89	First NS merger observed in GW; first detection of EM counterpart (GRB 170817A; AT 2017gfo); nearest event to date
GW170818 02:25:09	2018-11-30	39; towards Pegasus	1020^{+430}_{-360}	$2.7^{+0.5}_{-0.5}$	$26.7^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	BH	$35.5^{+7.5}_{-4.7}$	BH	$26.8^{+4.3}_{-5.2}$	BH	$59.8^{+4.8}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	
GW170823 13:13:58	2018-11-30	1651	1850 ± 840	$3.3^{+0.9}_{-0.8}$	$29.3^{+4.2}_{-3.2}$	$0.08^{+0.20}_{-0.22}$	BH	$39.6^{+10.0}_{-6.6}$	BH	$29.4^{+6.3}_{-7.1}$	BH	$65.6^{+9.4}_{-6.6}$	$0.71^{+0.08}_{-0.10}$	

https://en.wikipedia.org/wiki/List_of_gravitational_wave_observations

AND Today, the quantum nature of BH's is one of the hottest topics in theoretical physics.

→ Does spacetime end (in some messy quantum "edge") at the horizon, or perhaps further inside the BH at a "firewall"?