The Nobel prizes in physics for astrophysics and gravitation and the Nobel prize for black holes: Past, present, and future

José P. S. Lemos

Centro de Astrofísica e Gravitação - CENTRA,
Departamento de Física, Instituto Superior Técnico - IST,
Universidade de Lisboa - UL, Avenida Rovisco Pais 1, 1049-001,
Lisboa, Portugal, Electronic address: joselemos@tecnico.ulisboa.pt

We analyze the Nobel prizes in physics for astrophysics and gravitation since the establishment of the prize and highlight the 2020 Nobel prize for black holes. In addition, we comment on the names that could have received the prize in astrophysics and gravitation, and draw attention to the individuals who made outstanding contributions to black hole physics and astrophysics and should be mentioned as possible and deserved recipients of the prize. We speculate about the branches of research in astrophysics and gravitation, with an emphasis on the latter, that can be contemplated in the future with a Nobel prize.

I. INTRODUCTION

The Nobel prize in physics, awarded by the Royal Swedish Academy of Sciences to exceptional scientists and works, was inaugurated in 1901, having in that year been attributed to Röntgen, a German physicist, for the “the discovery of the remarkable rays subsequently named after him” by the Nobel electromagnetic radiation of high energy. The prize is conceded annually, and up to now several areas of physics had the privilege of being graced with this magnificent distinction.

The main criterion for the Nobel prizes in physics is that the scientific works and achievements to be considered for election have been time tested. In practice, this means that only established experimental works that led to the progress of physics and pioneering theoretical works that have been experimentally verified can aspire to the prize. Pure speculation by itself, for all the interest that it can have, does not adhere to this criterion and is simply not considered.
The process of selecting the candidates is judicious. It involves the Royal Swedish Academy of Sciences that elects the Nobel committee for physics, composed by five people, that in turn receives nomination proposals from previous Nobel prize in physics receivers and from other scientists. After selecting ten nomination proposals, the committee submits those to the Academy that, after the necessary meetings, votes in the prize winners of that year. At most there are three winners per year, a strict rule that the committee and the Academy adhere to.

This combination of confirmation of the work along a sufficient long time, of the hard-working and thorough laboring of the committee and the Academy, and of admitting at most three recipients, is very powerful and make the Nobel prize in physics, by farm the most important prize in physics. The Nobel prize in physics, beyond being a prize for exceptional physicists, is a prize for physics as a science, and the individual that receives it has that blessed felicity.

Within several areas of physics, we are interested in the areas of astrophysics and gravitation, which are two areas closely interlinked. An instance of this link is cosmology, the science of the Universe, that uses astrophysics to explain the physics of the relevant phenomena and works with gravitation to elucidate the global dynamics of the spacetime. Another instance of this interlink between the two areas is the black hole, an object with its existence established through astrophysical observations and also a product of pure speculation within gravitation, in particular within the general theory of relativity.

We will describe and analyze to whom and for which works the Nobel prize in astrophysics and gravitation was ascribed, including and highlighting the 2020 distinction to black holes. We will comment also on possible recipients, that for one reason or another were not honored with that consecrated prize of the Swedish Academy. In addition, we will speculate on possible branches of astrophysics and gravitation that can obtain in the future a Nobel prize.
II. THE NOBEL PRIZE IN PHYSICS FOR ASTROPHYSICS AND GRAVITATION FROM ITS CREATION TO 2019

A. The recipients

Astrophysics and gravitation are two vast branches of physics intimately connected since Newton discovered that gravitation is universal, linking conclusively the heavens and the Earth, and revealing a unified Universe with everything obeying the same laws of physics. The inaugural Nobel Prize attributed to Röngten for the discovery of X rays is certainly a prize neither to astrophysics nor to gravitation, although X rays have turned out to be an extremely important observational window in astrophysics. The Nobel prizes attributed directly to astrophysics and gravitation are several. We review them here, providing the date of attribution of the prize, the name of the recipient, and a summary of the text provided by the Nobel committee of the Royal Swedish Academy of Sciences, while weaving in some commentary on the corresponding and related accomplished works.

1921 Einstein - “For his services to theoretical physics, and especially for his discovery of the law of the photoelectric effect”. It is common practice to state that Einstein got the prize for the theoretical explanation of the photoelectric effect, but the announcement of the Nobel committee states much more than that, it explicitly refers to the services rendered to theoretical physics. Einstein’s services to theoretical physics are very many, and clearly we can include in those services the creation of the special and general relativity. General relativity is the theory of gravitation that succeeded Newton’s theory of gravitation and thus this prize is also a prize for gravitation.

1967 Bethe - “For his contributions to the theory of nuclear reactions, especially his discoveries concerning the energy production in stars”. Bethe was a German physicist that settled in the United States. A question raised by Eddington, a renowned English astrophysicist, was the need to solve the problem of energy generation in the center of a star, the Sun being an example. It was admitted that the energy should come from nuclear reactions, possibly from the transformation of four protons into a helium nucleus. The complicated details of those reactions that occur at the center of the stars were devised in 1939 by Bethe, he was by then in Cornell. This is a Nobel prize for both astrophysics and nuclear physics.

1974 Ryle; Hewish - “For their pioneering research in radio astrophysics. To Ryle for his
observations and inventions, in particular of the aperture synthesis technique, and to Hewish for his decisive role in the discovery of pulsars”. Ryle was an English astrophysicist based in Cambridge who developed a system of antennas to perform observations in radio waves. He showed around 1960 that distant galaxies, and thus younger galaxies, were different from nearby galaxies, and thus older galaxies, having this fact on one hand helped to corroborate the veracity of a universe in expansion and so in transformation, on the other hand, having been one of the first arguments of weight to demonstrate that the cosmological theory of a steady state universe, proposed by Bondi, Gold, and Hoyle, theoretical astrophysicists also based in Cambridge, was wrong, or putting it better, was a theory not compatible with our observed Universe. Hewish, an English astrophysicist also based in Cambridge, working also in radioastronomy, discovered in 1967 the first pulsar through the detection of fast wave pulses in radiofrequency coming from the sky. His PhD student Jocelyn Bell was in command of the instruments when the signal arrived, and reckoning, upon analyzing the registers, that was a new kind of signal and possibly an important one, immediately showed it to Hewish and the group. Soon after, it was shown by Gold, one of the Cambridge physicist of the steady state universe that was at the time in Cornell, and by other physicists, that pulsars were neutron stars in rapid rotation, neutron stars being stars of about one solar mass within a radius of 10 Km constituted essentially from neutrons. Neutron stars had been speculated to exist by Zwicky, a Swiss astrophysicist working at Caltech, in 1934, as stars that would remain in the center of a supernova explosion. This is a Nobel for astrophysics.

1978 Penzias and Wilson - “For their discovery of cosmic microwave background radiation”. Penzias, born in Germany and based in the USA, and Wilson, a Caltech-trained American physicist, had done their PhDs in microwave physics and radioastronomy and worked in the radio antennas of Bell Laboratories, in New Jersey. In 1965 they detected the cosmic microwave background radiation, which has a temperature of 2.7 K. This cosmic radiation had been predicted by Alpher and Herman, American physicists, disciples of Gamow, a Russian physicist who had settled in the United States of America. The detection by the fortunate Penzias and Wilson was by chance, they did not know the origin of the detected radiation. By coincidence, Dicke, an American physicist competent both in theoretical and experimental physics, and his group that included Peebles in Princeton, neighbors of the Bell Labs, were looking for that detection and interpreted immediately the detected radiation as being the cosmic microwave background radiation. Thus, this detection, that could have
been lost without any explanation, was clarified immediately and with that, the big bang as the standard model of the Universe was confirmed convincingly. One can argue that it is strange that Penzias and Wilson have received the prize for the discovery of a phenomenon that they did not yet understand, but the fact is that it is a discovery of first magnitude done by the two and it is within the criteria of the Nobel prize. The situation of the inaugural prize is identical. Röntgen had no idea what rays he had discovered, only later it was inferred that it was high energy electromagnetic radiation, and nobody, or almost nobody, knows who has made that inference. In any case, beginning in 2023, the 1978 Nobel prize archives will in principle be available to be consulted and we can then understand the arguments advanced for this recommendation. This is a Nobel prize for astrophysics and gravitation, more precisely to cosmology which is an instance of link between these two scientific areas. This discovery of Penzias an Wilson constituted half of the 1978 prize; the other half went to Kapitsa, an influential soviet physicist working in low temperature phenomena.

1983 Chandrasekhar; Fowler - To Chandrasekhar “for his theoretical studies of the physical processes of importance to the structure and evolution of the stars” and to Fowler ”for his theoretical and experimental studies of the nuclear reactions of importance in the formation of the chemical elements in the universe”. Chandrasekhar, was born in India, and went to Cambridge in his youth, where in the 1930s developed a remarkable work on the structure of white dwarfs, having discovered with precision what is the maximum mass of those stars, specifically, the mass above which gravitational collapse is inevitable. This mass is 1.4 solar masses. He had many other important works in astrophysics and gravitation. In one of them, in 1942, in collaboration with Mário Shenberg, a Brazilian physicist, when Shenberg was in Chicago where Chandrasekhar had installed himself, it was found a maximal mass to the central part in isothermal equilibrium of a red giant, called Schönberg-Chandrasekhar limit, above which the very center shrinks under its own weight, increasing its own temperature and beginning the burning of the existing helium. Fowler, an American physicist of Caltech, was a specialist in theoretical and experimental nuclear physics. In a paper in 1957 by the English couple Burbidge and Burbidge, Fowler, and Hoyle, known as the $B^2FH$, it was shown that all the chemical elements heavier than helium are generated in the center of the stars. This is a Nobel prize for astrophysics and gravitation from Chandrasekhar’s side and it is a Nobel prize for astrophysics and nuclear physics from Fowler’s side.

1993 Hulse and Taylor - “For the discovery of a new type of pulsar, a discovery that has
opened up new possibilities for the study of gravitation”. Taylor, an American astrophysicist from Princeton, and Hulse, American and PhD student at the time, discovered in 1974 a binary pulsar, constituted by a pulsar and a neutron star, in close proximity and in a conjoint orbit. This binary system of compact stars enabled the deduction of its own physical proprieties. In particular, the decrease of the orbital radius with time of the binary system is in accord with the general relativistic prediction taking into account the energy loss by gravitational radiation given by the theory. It is the first proof of the existence of gravitational waves, albeit indirect. This is a Nobel prize for gravitation through astrophysics.

2002 Davis, Koshiba; Giacconi – To Davis and Koshiba “for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos” and to Giacconi “for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources”. Davis, an American physicist, and Koshiba, a Japanese physicist, prepared sophisticated experiments in the 1960s in which neutrinos from the center of the Sun were detected for the first time, giving a crucial direct proof of the existence of nuclear reactions there. However, the flux of neutrinos received was a third of the calculated flux from the theory of stellar structure and the theory of elementary particles. This discrepancy opened a new line of research in neutrino physics and it gave rise to the experimental discovery that neutrinos have mass, although extremely small, and in flight they oscillate changing the identities in-between them, the original detectors being only apt to capture only one of the three neutrino identities. For the solution of this problem, Kajita, a Japanese physicist, and MacDonald, an American physicist, received the physics Nobel prize in 2015. Giacconi, an Italian physicist, that worked in several projects in Europe and in the United States of America, was one of the precursors in the construction of X ray detectors, or telescopes, the same X rays that had been discovered by Röntgen. These detectors have to be in orbit to avoid the Earth’s atmosphere which is opaque to X rays. An explorer satellite with an X ray detector on board, the Uhuru, was launched to space in 1970. One of the X ray sources, called Cygnus X1, that had been identified in the constellation Cygnus in 1964 by a predecessor satellite, was the target of special observations by the Uhuru satellite. The X ray intensity coming from the source suffered quick variations which, due to the finiteness of the speed of the light, indicated a very compact object. Additional studies showed that the source was composed of a binary system, with one of the stars being a blue giant of about 30 solar masses, and the other being a highly compact object of about 20 solar masses,
which could only be a black hole, the first stellar black hole candidate to be identified. The observed X rays are generated by the collision of the matter incoming from the blue giant against the matter of a disk revolving around the black hole. This is a Nobel prize for astrophysics and elementary particle physics from the side of Davis and Koshiba, and it is a Nobel for astrophysics, gravitation and other areas of physics from the side of Giacconi.

2006 Mather and Smoot – “For their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation”. Mather, an American physicist, specialist in instrumentation and cosmic microwave background radiation, and Smoot, an American physicist, specialist in instrumentation, particle physics and astrophysics, were in command of the science of the COBE satellite, acronym for Cosmic Background Explorer. After the spectacular detection in unexpected circumstances of the cosmic microwave background radiation in 1965, the next task was to understand the detailed physics of that radiation. In the primordial universe, radiation and matter were in thermal equilibrium, this radiation having a characteristic black body spectrum, until, due to the expansion of the Universe, the radiation decoupled from the matter and the corresponding spectrum having been congealed at this very time. For this reason, the detected radiation should have a blackbody spectrum, the signature of the initial thermal equilibrium. In addition, in the primordial universe there were matter density fluctuations and, due to the coupling between matter and radiation at that time, this implied that there were fluctuations in the temperature of the radiation. These fluctuations supposedly originated the galaxies. At the moment of decoupling, those fluctuations were imprinted in the temperature of the radiation, the temperature of a point in the sky should have a different temperature from a neighbor point in the sky. Mather, in charge of the form of the spectrum of the radiation obtained a perfect blackbody form for it, and Smoot, in charge for the measurements of the temperature fluctuations, obtained fluctuations of one part in \(10^5\), which was the expected value, and that many others before him tried to find but did not manage. This is a Nobel prize for astrophysics and gravitation, more precisely, to cosmology which is an instance of a link between these two scientific areas.

2011 Perlmutter, Schmidt and Riess – “For the discovery of the accelerating expansion of the Universe through observations of distant supernovae”. Perlmutter is an American physicist based in Berkeley, Schmidt is an American physicist based in Australia, and Riess is an American physicist based in the John Hopkins University. Since the discovery by Hubble in 1929 of the linear relation of galaxy redshifts as a function of their distance that one
was after to know whether this linearity would change with the distance into a nonlinear relation, and if it did, to which side of the line the law would change. If it changed to one side it would mean that the Universe was decelerating, and if it changed to the other side it would mean the Universe was accelerating. In the years 1990s, Perlmutter understood that the supernovas type IA, stars that explode just after they attain the Chandrasekhar limit by extracting matter from the companion star, if well used, would serve as standard candles, and because of that they would be excellent gauges for the far away distances since their brightness is extremely high. In 1988, after a great effort to obtain telescope time in all possible places of the planet, Perlmutter announced that the expansion of the Universe is accelerated. Schmidt and Riess, in a similar and parallel project, discovered concomitantly this accelerated expansion of the Universe. A physical explanation of this accelerated expansion requires a cosmological constant, or some other form of dark energy possibly associated to the vacuum energy, a subject that has stimulated an intense investigation in the areas of gravitation, quantum field theory, and elementary particle theory. This latter has been of enormous importance in cosmology, in the explanation of the physical phenomena of the primordial universe, after it was understood in 1973, from the works of the American physicists Politzer, Gross, and Wilczek, contemplated with the Nobel prize of 2004, that the strong interaction is asymptotically free, and so the three fundamental interactions, namely, the electromagnetic, the weak, and the strong interactions, can be united in a grand unified theory at a high energy scale, a little smaller than the Planck energy scale, the larger elementary energy scale possible. This is a Nobel prize for astrophysics and gravitation, more precisely, to cosmology which is an instance of a link between these two scientific areas.

2017 Weiss, Barish, and Thorne - “For decisive contributions to the LIGO detector and the observation of gravitational waves”. Weiss, born in Germany and settled in the United States of America, specifically at MIT, Barish, American particle physicist familiar with large science collaborations, and Thorne, an American physicist from Caltech and Wheeler’s student in Princeton, headed the LIGO project. LIGO is an acronym for Laser Interferometer Gravitational-Wave Observatory. Weiss in the 1960s realized that a laser interferometer would be the perfect apparatus to detect gravitational waves and constructed small prototypes in such a way to refine its functioning. Thorne, specialist in black holes and gravitational waves, developed the theory of gravitational waves in a systematic way and in a conjoint effort with Weiss created LIGO. At the end of the 1990s, Barish became the new
LIGO director, supervising the construction of the two interferometers, one in the state of Washington, the other in the state of Louisiana, separated by 3 thousand Kms. On September 14, 2015, the two laser interferometers vibrated in the same manner with an interval of approximately one hundredth of a second as a consequence of the passage of a gravitational wave through the Earth. The data gathered by the apparatuses showed that the wave had been generated by a collision, at cosmological distances, between two black holes of about 30 solar masses each. It was the first time humankind detected gravitational waves. Nowadays, one does astronomy and astrophysics with gravitational waves. This is a Nobel prize for gravitation.

2019 Peebles; Mayor and Queloz - “For contributions to our understanding of the evolution of the universe and Earth’s place in the cosmos with half of the prize going to James Peebles for theoretical discoveries in physical cosmology and the other half going to Michel Mayor and Didier Queloz for the discovery of an exoplanet orbiting a solar-type star”. Peebles, born in Canada and settled in Princeton, belonged to Dicke’s cosmology original group, being one of the authors of the 1965 paper that accompanies the paper by Penzias and Wilson. Peebles developed physical cosmology in a rigorous way. Among the several important contributions, he showed the physics that one could extract from the cosmic background radiation and the importance of the dark matter in galaxy formation. Mayor and Queloz, two Swiss astrophysicists based in Geneva, discovered for the first time a planet outside the solar system in a star of the Sun’s type. Nowadays about five thousand exoplanets are known and there are about the same amount of candidates waiting for validation. This is a Nobel for astrophysics and gravitation, more precisely to cosmology that is an example of the interlink between these two scientific areas from Peebles side and is a Nobel for astrophysics from Mayor and Queloz side.

B. The ones who could have won the prize

It is of interest to indicate and comment on those physicists that could have been honored with the Nobel prize in physics in astrophysics and gravitation, and for some reason the Nobel committee and the Royal Swedish Academy of Sciences did not place them in the maximum priority list.

Eddington, the great English astrophysicist from Cambridge, was the first to understand
around 1920 the interior of stars through a simple model that permits the calculation of the temperature and the density in the center of a star. He also recognized that the energy generated in the interior of a star had to be subatomic, i.e., it had to be nuclear energy, and this was confirmed when Bethe found the nuclear reactions at the center of star that did indeed generate the necessary energy, having received the Nobel prize for that work. Eddington gave many other contributions, namely, to galactic physics and galactic astronomy, to general relativity, notably to its confirmation through the test of light deviation in the eclipse of 1919 when he went to Principe Island, to cosmology, to fundamental physics, and to the general understanding of science. In the first two decades of the 20th century, works in astrophysics were hardly, or even never, considered for the Nobel prize, and for that reason one understands why Eddington never received it. It would have been a Nobel prize for astrophysics.

Hubble, an American astronomer, was head of the largest telescope in the world, located in California, the Mount Wilson telescope of 2.5 meters. Through precise observations he was able to produce a relation between the redshift and the distance of galaxies, and it allowed him to announce in 1929 the law that the velocity of a galaxy is proportional to its distance, known as the Hubble law. It was an extraordinary feat in astronomy. Note, nevertheless, that Hubble always stated that the relation did not mean for sure that the Universe was expanding. In this connection, it must be remembered that Lemaître, a Belgium physicist, disciple of Eddington, discovered between 1925 and 1927, with the observational data so far published and in possession of a solution of general relativity that gave an expansion universe that he himself had found, although Friedmann, a Russian physicist from St. Petersburg, had found the same solution three years before in 1922, the law that furnishes the proportional relation between the galaxy velocity and its distance, and for this reason is often called Lemaître-Hubble law. In addition, Lemaître was the first to propose a big bang scenario consistent with the Universe in expansion. It is hard to fathom why Hubble did not receive the physics Nobel prize. The discovery of the linear relation between the redshift and the distance of the galaxies, and the consequent inference that that means a Universe in expansion, is one of the greatest scientific discoveries of all times, done with a thorough, precise, and extremely difficult observational work. Perhaps, the Swedish Academy had doubts whether an observational work was eligible for a Nobel prize in physics, an error that was not repeated as the Nobel prizes for pulsars, cosmic
microwave background radiation, binary pulsars, solar neutrinos, X-ray observations, nature of the cosmic microwave background radiation, and acceleration of the Universe, testify. By inference, Lemaître could have received the Nobel prize with Hubble, although his work was more speculative and of difficult confirmation at the time. It would have been a Nobel prize for cosmology.

Gamow, born in Crimea in imperial Russia, obtained his PhD in St. Petersburg during the Soviet era, and later installed himself in the United States of America, first in Washington DC, and afterwards in Colorado. Gamow made decisive contributions to physics, astrophysics, and cosmology. In 1928, he discovered the tunneling effect in the decay of atomic nuclei, a generic effect and of enormous importance in quantum phenomena. From 1942 onwards he developed a big bang model in cosmology, in which the expanding Universe, in its first three minutes manufactured all the known elements starting with the hydrogen, from deuterium, to helium and to the transuranics. It was proved later that the light chemical elements, as deuterium, helium, and lithium, were manufactured in the primordial universe, whereas all other heavier elements were and are manufactured in the center of stars, according to the analysis of Hoyle and collaborators. Alpher and Herman, disciples of Gamow, proposed in 1948 the existence of a cosmic background radiation, a relic of that Gamow’s primordial universe. That radiation was detected 17 years later by Penzias and Wilson, and interpreted as being of cosmic origin by Dicke and his group. It is a fact that Dicke and his group in the respective inaugural papers on this subject, did not refer to the pioneering works of Gamow, Alpher, and Herman. It is also a fact that the radiation found was immediately interpreted correctly by Dicke. The Nobel committee came across many names in the theoretical side and since the Nobel is conceded only to three people at most, those who have detected that radiation, namely Penzias and Wilson, were preferred for the award, leaving out Gamow, Alpher, Herman, and Dicke. The Nobel prize to Peebles in 2019 has also a posthumous character of a prize to Dicke that was his supervisor and mentor at the time the cosmic background radiation was discovered. It would have been a Nobel prize for the theoretical side of cosmology.

Hoyle, an English astrophysicist at Cambridge, had a number of important and decisive ideas on how chemical elements in stellar interiors are generated. When Hoyle was in Caltech as a visitor in 1953, he understood that a resonance in the carbon nucleus had to occur, otherwise carbon would not be manufactured in the stars and we would not be here. Fowler
and his group at Caltech showed experimentally the existence of that resonance. Hoyle was also an important author of the 1957 B²FH paper in which the synthesis of all the elements in the stars is seminally proposed; additionally, he was the author of other papers with several collaborators in the 1960s, in which one concludes that the majority of the existing helium would have been primordial, and not manufactured in the stars. Together with Cambridge physicists Bondi and Gold, Hoyle proposed the imaginative steady state cosmology that did not flourish because of incompatibility with observations, despite Hoyle insisting on it to be correct up to the end. Hoyle also thought that the DNA molecule had originated outside the Earth, perhaps in some place within the solar system or even in some other location. He was harsh in dealing with adversaries and for that he gained many opponents. Even knowing the highly heterodox side of Hoyle within science, it is a mystery why the Royal Swedish Academy of Sciences decided to give the Nobel prize to Fowler without concomitantly awarding it to Hoyle. Neither Fowler understood nor was Hoyle happy. This would not have been a new Nobel prize to astrophysics, it would be within the 1983 Nobel prize.

Shapiro, an American physicist, is emeritus professor in Harvard, having also been a professor at MIT. In 1964, he discovered and proposed a fourth test of general relativity. General relativity had been proven correct in three tests, namely Mercury’s perihelion precession, the light deflection in the gravitational field of the Sun, and the redshift of light when climbing a gravitational field. These tests were proposed and verified around the 1920s and afterwards. It was in a totally unexpected manner that the fourth test appeared. This fourth test is the test of the delay in the radar echo from a planet, called Shapiro delay. When Venus is aligned with the Sun and the Earth and is situated in the opposite side on the Sun, the signal passes through the gravitational field of the Sun, and due to the curvature of space and spacetime the signal suffers a delay relatively to the propagation in a flat space, as it is the case in Newtonian gravitation. The test was performed and the result verified by Shapiro himself and collaborators in 1968. It is a brilliant and wonderful idea that confirmed once more the correctness of general relativity, during a time in which the theory had only passed three earlier tests, denominated classical tests. In addition, the Shapiro delay has proven useful in other astrophysical systems. One can understand that the Academy has not awarded a Nobel prize here; perhaps there are a number of ideas and tests of this level in other areas of physics, with the corresponding candidates expecting to
receive the Nobel prize. It would have been a Nobel prize to gravitation.

Jocelyn Bell, a British citizen born in Northern Ireland, is presently rector of the University of Dundee. In 1967, she was a PhD student in Cambridge with Hewish as supervisor. Bell was in charge of overseeing the data that arrived at the radiotelescope and one day in 1967 noted that there was a signal with a regular pulse with a period of about one second. Several identical regular pulse signals appeared soon afterward in other parts of the sky. These sources were denominated pulsars. Given the importance of the discovery, a paper accounting for the observation of the first pulsar was immediately published. This 1967 article which reports the discovery is signed by five authors, Hewish first, Bell second. Hewish was responsible for the development of the radiotelescope and was the head of the science to be done from the telescope. For the discovery of the first pulsar Hewish received the Nobel prize. Bell should also have received it conjointly, after all it was she that discovered the first pulsar, in analyzing the registers she identified without hesitation a nonusual radio source. The committee possibly considered that PhD students would not have status to receive the Nobel prize. It did not commit the same mistake again, attributing the prize to Hulse, Taylor’s student, in 1983. This would not have been a new Nobel prize to astrophysics, it would have been part of the 1974 prize.

III. THE NOBEL PRIZE IN PHYSICS 2020 FOR BLACK HOLES

A. The recipients

Given that the Nobel prize for the detection of gravitational waves was conceded in 2017 and these waves appeared from the collision of two black holes one could dream that the attribution of a Nobel prize for black holes would occur in the near future, and in such a case, one could speculate on the possible winners of the award. But dream and speculation is one thing, and reality is another. It was with great surprise that, on October 6, 2020, the announcement that the Nobel prize in physics was awarded for black holes was received. The statement of the committee for the Nobel prize in physics 2020 reads: “The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics 2020 to Roger Penrose, of University of Oxford, United Kingdom, to Reinhard Genzel, of Max Planck Institute for Extraterrestrial Physics, Garching, Germany and University of California at Berkeley, USA,
and to Andrea Ghez, University of California at Los Angeles, USA. One half goes to Roger Penrose for the discovery that black hole formation is a robust prediction of the general theory of relativity, and the other half goes jointly to Reinhard Genzel and Andrea Ghez for the discovery of a supermassive compact object at the centre of our galaxy”.

Who are these Nobel prize award-winners?

Penrose was born in 1931 in Colchester, England, obtained his PhD in Mathematics in Cambridge and is presently the Emeritus Rouse Ball Professor in Oxford University. He developed new mathematical techniques in topology and differential geometry and applied them to the study of the geometric properties of spacetimes in general and black holes in particular. He was the first to understand the essence of a black hole. He created in 1965 the concept of a trapped surface, a surface from which outgoing light rays converge, and that arises when the gravitational field interior to that surface is very intense. With that idea he managed to show that a singularity inside such a surface forms, presumably a singularity where the spacetime itself ends and the laws of physics as we know them disappear, putting an endpoint on the discussion of the inevitability of whether a black hole and a singularity forms in gravitational collapse. For many, his 1965 paper is considered the most important contribution to general relativity since the original formulation of the theory in 1915. But there are more celebrated contributions. Kerr, a New Zealander physicist working in Austin, Texas, in 1963, found an exact solution in general relativity that corresponded to a black hole in rotation, generalizing in an admirable fashion the solution found in 1916 by Schwarzschild, a German physicist, to a static spacetime. Penrose discovered in 1969 that it is possible to extract energy from a Kerr black hole through the decaying, near the event horizon, of

FIG. 1: Penrose.
a particle into two particles. One of the particles enters the black hole and the other is emitted with more energy to infinity at the expense of the black hole rotational energy. This work, of enormous importance, triggered an entirely new line of research into the physics of black holes that culminated with the discovery by Hawking that black holes radiate by quantum processes. Penrose promoted several other advances to physics and mathematics. For example, in cosmology he perceived that in the big bang, in the first instants, the entropy of the Universe was extremely low, as the gravitational degrees of freedom, holders of the largest part of the entropy, were practically frozen, although the matter degrees of freedom might have been highly excited. This fact requires very precise initial conditions that any cosmological theory must explain and to which the inflationary theories in vogue cannot answer presently, unless some form of anthropic principle in the context of a multiverse is invoked. It is certainly a honor for Penrose to win the Nobel prize, and it is also a privilege to the Swedish Academy to have Penrose amid the award-winning names and for this occasion the decision merits many congratulations.

Genzel was born in 1952 near Frankfurt, Germany. He obtained his PhD in 1978 from Bonn University and is now the director of the Max Planck Institute for Extraterrestrial Physics in Garching and professor in Berkeley. He leads the Gravity project associated to the European Southern Observatory - ESO, that he created in the 1990s and studies in maximum detail the stars in orbit around the very center of our galaxy. With his group he showed that those stars have very high velocities in their orbits, which is only compatible with the existence of a black hole of about 4 million solar masses in the center of our galaxy.

Ghez was born in 1965 in New York. She obtained her PhD in 1992 from Caltech, and is now professor in the University of California at Los Angeles. She leads a project in the Keck telescope in Hawaii, that started at the end of the 1990s, and that studies the kinematics of
the stars in orbit around the very center of our galaxy. Several new stars were observed and it was also shown that these have very high velocities only compatible with the existence of a black hole of about 4 mino acillion solar masses in the center of our galaxy. Genzel’s and Ghez’s projects, being totally independent, complete each other and minimize the errors that one of the two projects may present.

B. The ones who could have won the prize

There are several people who were associated with the concept of a black hole and its development and, due to the importance of their contributions, could have been awarded with a Nobel prize for black holes. We now mention these people with a description of their contributions.

Oppenheimer was born in 1904 in New York. He obtained his PhD in Göttingen, publishing important works with Born, a German physicist and a founder of quantum mechanics. He was professor in Berkeley and Caltech, and from 1942 to 1945, was director of the Manhattan project in Los Alamos that constructed the first two atomic bombs. Oppenheimer discovered black holes together with Snyder. In a 1939 paper, Oppenheimer and Volkoff, a PhD student in Berkeley, showed that a neutron star, a star that had been postulated by Zwicky and to some extent also by Landau, had a maximum mass of the order of the mass that Chandrasekhar had found for white dwarfs, above which the star would collapse. Intrigued by this collapse possibility of a neutron star, Oppenheimer recruited then another Berkeley PhD student, Snyder, with noted mathematical skills, to solve this problem together. They formulated an idealized model of a star collapsing under its own weight and
found that the ultimate state of such a collapse would be a black hole with an event horizon and a singularity. In this Oppenheimer and Snyder 1939 paper, all the ingredients that involve the black hole concept appear naturally, namely, the emergence of an event horizon, beyond which the spacetime is cut from the rest of the universe, and the description of the distinction between two totally different times, one time marked by the clocks of observers entering the black hole itself and running into the singularity, another time marked by clocks of stationary observers in the exterior that register an infinite time for the star's surface to reach the event horizon. With his move to Los Alamos, the political posterior incidents in the McCarthy era that marked his life, the directorship of the Institute of Advanced Studies in Princeton that occupied his daily routine, and the appearance of new interests, Oppenheimer did not work in collapsed stars and black holes ever again. Although he knew he discovered them, he never regarded his discovery of special worth, he seemingly considered it to be a minor discovery. Yet as was unravelled later, the black hole is the object par excellence of general relativity; it is pure and complex spacetime geometry. It would have been a Nobel prize for gravitation. Having died in 1967, he did not live to see the extraordinary later developments from the theory and observation of the object that he together with Snyder had created. In this initial stage, the requirements needed for black holes and their discoverers to be candidates to the Nobel prize in physics, let alone receive it, were not yet satisfied.

Wheeler was born in 1911 in Florida. He obtained his PhD at John Hopkins University and was professor in Princeton. He worked with Bohr in nuclear physics and invented the S-matrix formalism to explain the quantum scattering of particles. For that he was indicated for the Nobel prize, never having received one. In the 1950s, he developed the physics of
collapsed stars until he was convinced that the total collapse of a star into a black hole was inevitable, completing in a conclusive and decisive way the Oppenheimer-Snyder collapse result. With his vision, his PhD students created groundbreaking ideas and in certain cases extraordinary ones, namely his student Bekenstein, born in Mexico, answering a question of Wheeler himself correctly proposed that the entropy of a black hole is equal to its area in appropriate units. In 1968, Wheeler decided that the name black hole was the ideal and perfect name for completely gravitationally collapsed objects, and later invented the expression black holes have no hair to synthesize that a black hole in general relativity is characterized only by its mass, its angular momentum, and its electric charge, it only has three hairs. Clearly someone or something with three hairs is effectively bald. One can understand that the Academy has not given him the Nobel prize in this area. Wheeler died in 2008, seven years before the gravitational wave antennas confirmed beyond any doubt the existence of black holes. In addition, Wheeler’s contribution is spread along four decades in conjunction with many students, they themselves providing new and significant inputs. It would have been a Nobel prize for gravitation.

Lynden-Bell was born in 1935 in Dover, England. He did his PhD with Mestel, a British astrophysicist, in galactic dynamics, and was a professor in Cambridge. In 1969 he made the audacious proposal, accompanied with precise calculations to substantiate it, that all galaxies were dead quasars, i.e., all galaxies contained a supermassive black hole in their centers, although these galactic centers would have no activity for lack of gas and matter. Just after, with Rees, astrophysicist from Cambridge, they showed as a corollary of the original proposal, that our galaxy should contained a central supermassive black hole with 4
million solar masses. Towards the end of 1990 it was ratified that all, or almost all, galaxies have in fact a central supermassive black hole. The spectacular image of the black hole of the galaxy M87 done in 2018 by the EHT, acronym for Event Horizon Telescope, is but one example. For having foreseen that all galaxies contained a central black hole, Lynden-Bell was awarded the inaugural Kavli prize for astrophysics in 2008, together with Schmidt, an American astrophysicist of Dutch origin from Caltech, that had identified optically the first quasar in 1963. Clearly, by his daring proposal he could have been also considered as a candidate for the Nobel prize. The corollary of the idea that our galaxy contains a supermassive black hole has been proven by the observational work of Genzel and Ghez, that won the 2020 Nobel prize. Not having had the opportunity to celebrate this nomination, he died in 2018, it remains for us to think that he would have been exultant to see his ideas confirmed and cited in the announcement and in the official ceremonies of the Academy. Lynden-Bell worked and developed several and important topics in astrophysics and general relativity. It would have been a Nobel prize for astrophysics and gravitation.

Hawking was born in 1942 in Oxford. He obtained his PhD in 1966 in cosmology and was Lucasian Professor in Cambridge, the chair that had also been occupied by Newton and Dirac. From 1970 onwards he started his connection to the study of black holes to which he gave remarkable advances. He proved rigorously within general relativity that the area of a black hole never decreases, paving the way to the concept of black hole entropy, discovered immediately after by Bekenstein when he was doing his PhD in Princeton and developed by Bekenstein himself when he settled later in Israel. With Bardeen, an American physicist, and Carter, his colleague in Cambridge, Hawking showed that the mechanics of
black holes was ruled by laws that were identical in formal content to the laws of thermodynamics. Combining general relativity with quantum mechanics, two disciplines practically immiscible, he showed in 1974 that a black hole is not black, but irradiates at a temperature inversionally proportional to its mass. This temperature is called Hawking temperature and its expression involves the three fundamental constants of physics, namely, the universal gravitational constant, the velocity of light, and the Planck constant. This revolutionary discovery is probably the most important discovery in theoretical physics in the second half of the 20th century. With this calculation, it was definitively shown that black holes are not only mechanical objects but also thermodynamic objects. Now, thermodynamics is a convenient description of nature but not a fundamental one, giving rise to the open problem of knowing what are and where are the degrees of freedom of a black hole that give rise to its entropy. Although these are aspects that have been intensely studied since then and there are clues to understanding the black hole as a quantum object, there are no definite results. Hawking has also provided decisive contributions to cosmology, and made efforts, through the publication of books, to educate the general public in physics and science. He was a celebrity worldwide, comparable only to Einstein. Certainly he more than deserved the Nobel prize for all his revolutionary and groundbreaking work in black holes. He missed receiving it by a whisker, having died in 2018, facilitating the choice to the Academy that can only give to three people at most. It would have been a Nobel prize for gravitation.
IV. FROM THE DAWN OF SCIENCE TO THE NEXT NOBEL PRIZES IN ASTROPHYSICS AND GRAVITATION

A. From the dawn of science to black holes

Anaximander, Greek philosopher that lived around 550 BC, proposed that the “Earth is not sustained by anything, but remains motionless due to the fact that it is equidistant to all things. Its form is that of a drum. We walk in one of its flat surfaces, whereas the other surface is on the other side”. This is considered, notably by Popper, an Austrian science philosopher that settled in England, one of the most portentous ideas in the entire history of human thought. To think the Earth floating in equilibrium in the middle of space, staying still due to equidistance, is an extraordinary abstraction, one that anticipates Newton’s idea of an immaterial force of gravitation. Of course, the Earth is not a drum, i.e., a cylinder, the Earth is approximately spherical, but in a cosmological context, which is the context of Anaximander’s proposal, the manuscript incorrectness is irrelevant, in fact a cylinder and a sphere are topological equivalents in current language.

Today, 2500 years after, we have a science of astrophysics and gravitation that explains planets, stars, galaxies, large scale structure, the Universe itself, and black holes. In this endeavor of formidable discoveries all of physics is involved: general relativity and gravitation, astrophysics, condensed matter physics, and molecular, atomic, nuclear, and elementary particle quantum mechanics.

The appearance of the concept of a black hole as the object par excellence of general relativity and its observational confirmation as a naturally occurring object stands up between the great discoveries in physics. Decades of enthusiasm and commitment were necessary to better understand the essence of a black hole and with that obtain a more perfected vision of the world’s structure. This discovery has, finally and at the right time, been crowned with the 2020 Nobel prize by the Royal Swedish Academy of Sciences in the names of Penrose, Genzel, and Ghez.

Naturally, there are still many open problems in black hole theory and observation. In black hole theory, there is a fundamental problem of understanding the interior of a black hole, the region of spacetime that is inside the event horizon. General relativity predicts that inside the event horizon one finds a singularity where spacetime itself and the laws of
physics end. Related to this problem is cosmic censorship, a hypothesis suggested by Penrose in 1969, that all singularities are hidden inside the event horizon, i.e., there are no naked singularities. Still in black hole theory, there is no solution to the major problem raised by Bekenstein, namely, since the black hole has entropy, what are the basic constituents of that entropy, and yet another important conundrum introduced by Hawking, namely, to know if in the collapsing and evaporation process of a black hole, all the information that one has in the beginning is equal to the information one has in the end, or if not, whether the singularity has eliminated part of that information reducing the phase space drastically. Presumably, we will need a definitive quantum theory of gravity to solve and explain these phenomena. From the observational side regarding black holes, with the recent access to the gravitational wave astronomical window joining the detection in all the electromagnetic spectrum in all types of telescopes and detectors, one expects that many more black holes, stellar as well as galactic, isolated or in binary systems, distant one from the other or in collision, will be observed. Thus, we will have a better knowledge of the origin and evolution of such objects, of their physical properties, and of their populational distribution; the latter could even indicate whether black holes are important contributors to dark matter. The observations can even test the Kerr hypothesis, that states that astrophysical black holes are characterized by the Kerr solution, the only features they have being their mass and angular momentum, and also validate Hawking’s black hole area theorem, which implies that in a collision between two black holes, the area of the final black hole is greater than the sum of the areas of the initial black holes. In addition, there is also the unlikely possibility of observing very compact objects, with quasiblack holes or even wormholes being among those. For sure, other problems will come along.

B. The next Nobel prizes in astrophysics and gravitation

General relativity has changed our vision of the world. The fundamental equation of the theory is

\[ G_{ab} = \frac{8\pi G}{c^4} T_{ab}, \]  

where \( G_{ab} \) is the Einstein tensor and is related to geometry, \( T_{ab} \) is the energy-momentum tensor and is related to matter, \( G \) is the universal Newton constant of gravitation, and \( c \) is the velocity of light. In words, the Einstein equation says that geometry and matter
are coupled together. General relativity substitutes the field and gravitational force of Newtonian gravitation for the metric and spacetime geometry. In the wise words of Wheeler, space tells matter how to move and matter tells spacetime how to curve.

General relativity opened major and completely new branches in physics. They are: 1. Gravitational lenses, foreseen by Einstein in 1912 and that currently are an essential tool for probing the Universe; 2. Gravitational waves, worked out by Einstein in 1916 and 1918 and by Eddington in 1922, and followed up by many; 3. Cosmology, initiated by Einstein in 1917, continued by de Sitter, Lemaître, Gamow, and by many others up to the current model of extraordinary breadth; 4. Fundamental theories, an idea formulated by Weyl in 1918 to unify gravitation and electromagnetism and that survived until today in more complex forms. 5. Black holes, a concept originated by Oppenheimer and Snyder in 1939 and continued by Wheeler, Penrose, Hawking, and many others.

The second, third, and fifth branches already have Nobel prizes and certainly will have more. Gravitational waves generated in the primordial universe, possibly in an inflationary epoch, can also be detected in the future, which would be an admirable discovery that would merit a Nobel prize. Cosmological discoveries, for instance the nature of dark matter, are expected to happen sooner or later and certainly are of Nobel prize level. The discovery of new phenomena involving black holes, for example the collision of supermassive black holes, will also merit the prize. The first branch, gravitational lenses, and the fourth branch, unified theories, have not received the Nobel prize but are destined to get it in the future. In fact, gravitational lenses are a tool to probe the Universe and, specifically, to better understand the character of dark matter. The importance of this lensing comes from the fact that dark matter does not interact through the usual electromagnetic processes with baryonic matter of which we are made, but interacts gravitationally, so that in astronomical concentrations, incident light rays are bent to produce an effect of gravitational lens. A better understanding of dark matter through gravitational lensing could be revolutionary and thus such a discovery would also merit a Nobel prize. As theories of unification are concerned, in their current form, their importance lays in finding the gravitational theory that will supplant general relativity. General relativity is a remarkable theory that applies to scales larger than the Planck scale, where the Planck scale is defined as the scale where quantum effects of gravitation are important, Planck’s length is $10^{-33}$ cm. Theoretically there are indications that in scales near the Planck ones, general relativity suffers modifications,
new terms related to the spacetime curvature become important and new physical fields arise. It is thought that the big bang, and so the Universe as a whole, emerged from those Planck scales. This means that, since gravitation is modified at the Planck scale, that modification must also appear at the maximum scale, the scale of the Universe. Firm evidence that points to the correct, new, and elusive theory of gravitation can lead to a Nobel prize.

The criteria established by the Nobel committee and by the Royal Swedish Academy of Sciences to award a Nobel prize are very tight and appear extremely correct. This is evident from the incalculable prestige of the Nobel prize in physics. Let us examine two criteria. The criterion that the awarded work has to have experimental confirmation, is an appropriate criterion given that physics is a science of nature. Theoretical speculations are interesting and important, but they only become physics in a proper sense when they have confirmation. The other criterion, that the prize is given to at most three people, is very important. In this way it is guaranteed that the selection process is thorough, accurate, and robust, avoiding a devaluation of the prize because of dispersion. There are theses that the prize could also be given to big collaborations, but that would be inadequate. Imagine giving the prize to a scientific collaboration of 500 people. This means that each person of the collaboration has 1/500 of the prize, and clearly could not be considered effectively holder of a Nobel prize. One cannot mix an individual prize with a prize for an institution as it is the case of a collaboration. It would be propitious that some organization could create a special prize to big collaborations in science, encompassing physics, chemistry, biology, physiology, and possible other scientific disciplines, but the Nobel prize in physics as we know it is individual, or better, to three people at maximum, a fact that contributes to the great prestige that the prize has. Finally, when one awards a prize, in particular a Nobel prize, one has to make choices, and the choices always have a political side, science being no exception. For example, one needs to choose to which area of physics the prize will go in that year, or to ascertain if there is an outstanding discovery that supersedes the choice of the area. The detection of gravitational waves enters clearly in the latter case, they were detected in 2015 and the Nobel prize was awarded one year and a half later, in 2017. When one has to select three names out of several, there are those that stay outside. Nevertheless, the Nobel committee has been nearly flawless in their decisions. One can always argue that this or that name should have received the prize, in this context the name of Sommerfeld, a great German physicist that never received the prize, invariably comes up,
but as a whole, after more than one century of Nobel prizes in physics, the choices have been consistently correct. We can thus easily understand why the Nobel prize in physics has maximum prestige. Those who receive it have to be outstanding, clearly. But, in the midst of those outstanding afortunates, one has to distinguish those that yield prestige to the prize and those that receive prestige from the prize. Now, practically all the great names in physics have received the Nobel prize, and being they the great names of physics, confer in turn to the prize the enormous prestige that it has. The Nobel prize in physics is, by a great margin, the most important prize in physics, one can even say that it is the only prize of interest at a planetary scale. As it should have been made clear, the physics Nobel prize, beyond a prize for physicist, is a prize for physics as a science and a human endeavor.

We count with truly extraordinary new discoveries in astrophysics and gravitation, and in particular in gravitational waves and black holes, in a way as to merit, amidst the rigorous evaluations of the committee and the Academy, many more Nobel prizes. This would be motif of pride and glory, not properly by the prizes in themselves, but by what they represent and mean, notably, that our physical understanding of the Universe enlarges ever more.

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