## BLACK HOLES: FROM GALACTIC NUCLEI TO ELEMENTARY PARTICLES<sup>1</sup>

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#### Abstract

We present a broad review on black holes. We analyse some of the fundamental concepts in black hole theory, the observational and theoretical status of stellar and galactic black holes, and their appearance as quantum objects

#### 1. What is a black hole?

One of the basic ingredients of a physical theory is its set of fundamental constants. Thus, for instance, classical mechanics has no fundamental constants. The Newtonian theory of gravitation contains one constant alone, the universal constant of gravitation, G. The electromagnetism of Maxwell contains the velocity of light c, which in vacuum is a fundamental constant. Planck's constant h, which appeared directly from an experimental result (the black body spectrum), was immediately taken as the fundamental constant of quantum mechanics, developed among others by Bohr, Heisenberg and Schrödinger. Thermodynamics yields the Boltzmann constant  $k_B$  which arguably can be considered fundamental. These theories and their constants can then be combined to yield unified theories. If one tries to unite classical mechanics and electromagnetism one obtains the theory of special relativity which has  $c$  as a fundamental constant. The electric charge  $e$  is a constant of nature. If we join  $e$  and  $c$  one obtains classical electrodynamics of Thomson and Lorentz, which is of course related to special relativity. If one further joins  $h$  one obtains quantum electrodynamics due to Dirac and developed

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by others, afterwards. The unification of the electromagnetic and the weak forces by Weinberg and Salam as well as the inclusion of the strong force in the grand unified theories by Glashow and others also mix the fundamental constants of each separate theory. Finally, if one combines G and c one obtains the theory of general relativity of Einstein. On further joining Planck's constant h one should obtain quantum gravity, a theory which is still eluding the realm of physics, although there are some hints as to what it should be.

Black holes (BHs) are objects which belong to the theory of general relativity, and can be used to explain many powerful phenomena observed in the celestial sphere. On the other hand, their (quantum) effects and the singularities they hide yield an excellent framework to probe into the nature of quantum gravity.

A simple Newtonian argument can lead us to the concept of dark star, the Newtonian closest relative to the black hole (BH) of general relativity. The escape velocity  $v_e$  of an object ejected from the surface of a body, such as a star, of mass M and radius R, is given by  $\frac{1}{2}v_e^2 = \frac{GM}{R}$  $\frac{GM}{R}$ . The escape velocity on Earth is 11 km/s, on a white dwarf it is around 6000 Km/s. A dark star is defined as a star for which the escape velocity is greater or equal to the velocity of light, i.e., for which the following relation holds  $\frac{1}{2}c^2 \leq \frac{2GM}{R}$  $\frac{\dot{s}M}{R}$ . However, such a star is not a black hole for two reasons. First, the velocity of light is not a fundamental constant (i.e., it has no fundamental meaning) in Newtonian gravity, and thus other objects thrown with tachyonic velocities can escape and be detected at infinity. Second, the dark star is only dark for distant observers, near its surface the star is still bright since it emits light, although it cannot escape to infinity.

The correct theory to explain the BH phenomenon is general relativity. The BH is a "state of the gravitational field", different from the state of the gravitational field of a star. We can understand BHs most easily through thecollapse of a star (see e.g.  $\lceil 1 \rceil \lceil 2 \rceil \lceil 3 \rceil \lceil 4 \rceil \lceil 5 \rceil$ ). As the star collapses, its own radius shrinks. From Newtonian gravity we know that the force the star exerts on an object goes as  $r^{-2}$ . Thus, a contraction by a factor two increases the force by a factor four. In addition, if the star collapses to a point, the force becomes infinite at  $r = 0$ . General Relativity yields a different result, the gravitational force increases more rapidly than  $r^{-2}$ . The force is then infinite when the radius of the star is  $R = \frac{2GM}{c^2}$  $\frac{GM}{c^2}$ , the Schwarzschild radius. The spherical surface formed at this radius is called the event horizon. When a star of fixed mass M attains this radius, a BH is formed. The difference between Newtonian gravity and general relativity is of importance only when the star gets closer to its Schwarzschild radius, where the gravitational field is strong. Time near a strong gravitational field goes more slowly than time far away, and space is highly curved. BHs are holes in spacetime, caused by a strong space curvature and by drastic changes in the flow of time.

When the BH forms there are two regions connected to each other, the inside and the outside of the event horizon. As the matter of the star continues to collapse inside the event horizon it will form a singularity where curvatures and densities of infinite strength are formed. Inside the event horizon light is trapped. Light not only does not escape to infinity, it cannot escape to the outside of the BH. However, to an outside observer the story is different. As the BH is being formed, the luminosity of the original star decays exponentially,  $L = L_0 e^{-\frac{L}{\tau}}$  where the characteristic time is very short,  $\tau = 3\sqrt{3} \frac{GM}{c^3}$  $\frac{GM}{c^3} = 2.6 \times 10^{-5} \frac{\text{M}}{\text{M}_\odot}$ s. In a few millionths of a second the star turns totally black. Another important feature is that the collapse of the star results in a BH whose properties are characterized by three parameters only: mass, charge and angular momentum. One then says that BHs have no hair (in fact, they have three hairs). All the other properties, or "hair", of the matter of the star that formed the BH disappear. No observation can reveal the nature of the original star, whether it had a magnetic field, or possessed anti-matter, or was made of fermions, or bosons, or it had any other hairs.

### 2. Stellar black holes

BHs with stellar masses can form through the collapse of the iron cores of massive stars after they have reached the end of their thermonuclear evolution. The outer layers of the star explode in a supernova leaving at its center, depending on the core's mass, a neutron star or a BH. The maximum mass for a neutron star is still a matter of debate, since it depends strongly on the equation of state of the constitutive matter. Rhoades and Ruffini [[6](#page-13-0)] found amaximum mass of  $3.2M_{\odot}$ , while Hartle [[7\]](#page-13-0) can put an upper limit of  $5M_{\odot}$ , (see also[[8\]](#page-13-0)). However, Bachall et al. [\[9](#page-13-0)] argued that one can construct a  $100M_{\odot}$  star made of other types of matter at nuclear densities which they called Q-stars (related in some sense to Witten's strange stars [\[10\]](#page-13-0)). Thus the limit of the maximum mass 3.2 or  $5M_{\odot}$  is still uncertain, although probably correct. The sizes of a BH and a neutron star do not differ much. For a  $1M_{\odot}$ object, the neutron star has 10 Km of radius, whereas the BH has 3 Km.

An isolated stellar BH cannot be seen. A BH can only be observed if

it belongs to a binary system[[11\]](#page-13-0), and is detected through spectroscopic observations of the bright optical companion. The main problem is that the unseen body can also be a neutron star, and to distinguish between both possibilities one has to follow a complicated list of steps. A binary system can evolve in the following way: first, two massive stars, with masses of the order of  $20M_{\odot}$  form a binary system. Then, in a second stage, the more massive star evolves more rapidly and soon becomes a compact body with a few  $M_{\odot}$ after having exploded in a supernova. Finally, the other star also evolves to become a similar compact star. One thus has a binary system of two compact stars, of which the most famous example is the binary pulsar of Hulse and Taylor [\[12\]](#page-14-0). During the second stage, when the binary is composed of one compact and one giant star there is the production of spectacular phenomena visible in the X-ray band. The binary systems in this stage are called X-ray binaries.

X-ray binaries have a very short orbital period which by Kepler's third law implies the objects are very close. Since the Roche lobe of the binary system (the surface of gravitational neutrality) can be filled in part by the massive companion, the outer layers of the massive star are captured by the compact star. The captured gas then forms an accretion disk. The emission of X-rays can happen through several processes. If the compact star is a neutron star then the gas, through a magnetic field mechanism, hits the crust of the neutron star regularly with the consequent emission of X-rays. The neutron star is then called an X-ray pulsar, with luminosities of the order  $10^4L_\odot$ . If, instead of regular, the X-ray emission is sporadic, then the source is called a burster. Bursters are usually produced through an explosion of the surface of the neutron star, but can also appear by eruption of a very hot region of the accretion disk[[13\]](#page-14-0) [[14](#page-14-0)]. In this last case the matter from the luminous companion spirals towards the unseen compact object and emits X-rays with temperatures of  $10^8 - 10^9$ K. These temperatures are generated through dissipation by viscous processes of the gravitational energy of the infalling matter accelerated to high velocities.

BHs do not have a hard solid surface, the explosion happens in the disk. Is there any way to distinguish between BH and neutron stars bursts? One could think that variability would give some clues. If a source (disk, in the case) changes shape, the speed of change cannot exceed the speed of light. If one detects variability in a time  $\Delta t$ , the size of the source is at most  $l \stackrel{\leq}{\sim} c\Delta t$ .

If the source changes in  $\Delta t \sim 10^{-3}$ s, then its linear size is  $l \sim 300$  Km. For a stellar BH, its inner edge (defined as the last stable orbit, see e.g.[[15](#page-14-0)]), is of the order of 30 Km in radius say, so its circumference is around 200 Km. A rotating hot bubble emitting X-rays would have a varability in the milisecond range, as observed. This could be a signature for a BH. However, Circinus X-1 also shows fluctuation of this order, and it was shown that it also has periodic bursts which characterizes a neutron star[[16\]](#page-14-0). The identification of a black hole through radiation processes is not yet well developed, although it is a field advancing quickly. The best criterion to identify a BH is to find its mass through dynamical studies of the X-ray binaries. The weighing of stars in binaries is a technique fully understood nowadays.

Knowing the orbital period of the binary and the projected mean speed of the optical star, one can using Kepler's law to deduce the mass function defined by [\[17](#page-14-0)],  $f(M) \equiv \frac{(M_x \sin i)^3}{(M_x + M_c)^2}$  $\frac{(M_x \sin i)^3}{(M_x+M_c)^2} = \frac{P(V_c \sin i)^3}{2\pi G}$ , where  $M_x$  and  $M_c$  are the masses of the X-ray source and the companion respectively,  $i$  is the orbital inclination angle,  $P$  is the orbital period and  $V_c \sin i$  is the projected velocity semiamplitude of the optical companion. If one puts  $M_c = 0$  and  $i = 90^0$ one gets the mimimum possible value for  $M_x$  which in this case is equal to  $f(M)$ . What one would really like to obtain is an  $f(M)$  greater than  $5M_{\odot}$ . However, following the theory, a value close to  $3.2M_{\odot}$  yields already a good BH candidate.

There are three very strong candidates, two good candidates and a list of possible candidates. We start here giving some properties of the three verystrong candidates. (1a) Cygnus X-1 – It was discovered in 1971 [[18\]](#page-14-0) and it is a persistent source with  $L_x \sim 2 \times 10^{37} \text{erg/s}$ . It is a high mass X-ray binary. The orbital period is 5.6 days and  $V_c \sin i \simeq 76 \text{Km/s}$  which yields a low  $f(M) = 0.35 M_{\odot}$ . Now, one has to derive a reliable lower limit for the mass, which is a difficult task. The optical companion is a blue giant with mass  $M_c \sim 30 M_{\odot}$ . The inclination angle is supposed to be  $i \sim 30^0$ (there are no eclipses). This gives a mass of  $M_x \sim 16 M_{\odot}$  [[19\]](#page-14-0). The most conservative assumptions lead to  $M > 3M_{\odot}$ . (1b) LMC X-3 – It was discovered in 1983 [\[20\]](#page-14-0). It is a persistent source and a high mass X-ray binary with  $L_x \sim 3x10^{38} \text{erg/s}$ .  $P = 1.7 \text{ days}$  and  $V_c \sin i \simeq 235 \text{Km/s}$ . This gives  $f(M) = 2.3M_{\odot}$ . The mass of the companion is estimated to be  $M_c \sim 6M_{\odot}$ which then yields  $M_x \sim 6M_{\odot}$ . Since the distance to the Magellanic cloud is known one can use Paczyński method [\[21\]](#page-14-0) to infer  $M_x \stackrel{>}{\sim} 4M_{\odot}$ . (1c) 0620-00

– It was discovered in 1986[[22](#page-14-0)]. Contray to the other two, it is a transient source. It is a low mass X-ray binary with  $L_x \sim 1 \times 10^{38} \text{erg/s}$ .  $P = 0.32$ days and  $V_c \sin i \simeq 467$  Km/s yielding  $f(M) = 3.18 M_{\odot}$ . Based solely on the value of the mass function, the minimum mass is already equal to the BH threshold mass. It is considered the strongest of the very strong candidates.  $M_c \sim 0.7 M_{\odot}$  which is low, and yields the following lower limit  $M_x \sim 4 M_{\odot}$ .

There are two other candidates which have been weighed, although the uncertainties are greater than the sources mentioned above. (2a) CAL87 – One has  $L_x \sim 1 \times 10^{36} \text{erg/s}$ . It is an interesting system since it undergoes eclipses. If  $M_c > 0.4 M_{\odot}$  it was found that  $M_x \stackrel{>}{\sim} 4 M_{\odot}$  [[23\]](#page-14-0). (2b) LMC X-1  $-L_x \sim 2x10^{38} \text{erg/s}$ . The optical companion is still not identified conclusively. However, there are hints that  $M_x \stackrel{\text{&} 1}{\sim} 3M_{\odot}$ . There are a number of other candidates which have been selected because they show X-ray behavior similar to Cygnus X-1, of which the prime example is GX239-4, and others which show transient behavior similar to 0620-00, such as GS2000+25, GS2023+33, GS1124-68, 4U1543-47, 4U1630-47, H1705-250 [\[24](#page-14-0)]. Further dynamical studies are needed to obtain the masses of these sources . The spectacular source SS433 which shows emission of jets was recently discarded as a black hole, since its mass was shown to be  $M \sim 1.4 M_{\odot}$  [\[25](#page-14-0)].

What are then the features that allow us to identify a BH candidate? The classical steps are: 1) The luminosity of the X-ray source has to be high  $L_x > 10^{36} \text{erg/s}$  and of rapid variability < 1s. This implies that the binary system must contain an accreting compact object. 2) The optical companion is identified and allows to measure the orbital period and the projected orbital velocity, to yield  $f(M)$ . 3) The mass of the optical companion and the inclination of the orbit are inferred or limited, based on the distance, optical spectrum,  $L_c$ , and eclipes. Then using  $f(M)$  one deduces  $M_x$ . 4) If the mass of the object is  $M_x \stackrel{\textstyle >}{\sim} 3.2 M_{\odot}$  then it is considered a BH candidate. There are now three other criteria which can help in identifying a BH candidate: (i) the source has a spectrum with soft X-rays,  $\sim$  1Kev. (ii) Fe emission lines very near the compact object (will) allow one to measure the velocity of the rotating disk. This then implies a dynamical measure of  $M_x$  [[26\]](#page-14-0). (iii) Hard X-rays ∼ 100Kev are a signature of BHs, since neutron stars have a hard surface whose radiated photons cool the accretion disk through Compton cooling [\[27\]](#page-14-0). These last too criteria are very recent [\[28\]](#page-15-0), and it is expected the situation will improve with work on some other half-dozen sources.

One drawback is that all these criteria are indirect. One really wants to come close to the collapsed object. In the long run, one is after clear evidence for the existence of an event horizon [\[29\]](#page-15-0) [[30\]](#page-15-0). This might be possible after the gravitational antennas are fully operating, to detect unambiguously the formation of a BH. If the BH is in a binary one expects subsequent X-ray emission. How many BHs there are in the Galaxy? The last estimates give 1000-3000 BHs, of the same order as the number of neutron stars[[24](#page-14-0)].

#### 3. Black Holes in Galactic Nuclei

We have seen that in the complete gravitational collapse of a star a BH can form with mass in the range  $3 - 20M_{\odot}$ . Yet, the theory of gravitational collapse allows for the formation of BHs with much greater masses, masses that can be in the range  $10^3 - 10^9 M_{\odot}$ . These BHs may appear in the core of clusters of stars or in the center of galactic nuclei. If the mass of the original system is very large, there is no uncertainty in the equation of state of the collapsing matter when it crosses the event horizon. Indeed, at  $R = \frac{2GM}{c^2}$  $\frac{GM}{c^2}$ , the density of the matter is  $\rho = \frac{3c^6}{32\pi\epsilon}$  $\frac{3c^6}{32\pi G^3}\frac{1}{M}$ M  $\frac{2}{\omega} \simeq 1.3 \times 10^{16} (\frac{M_{\odot}}{M})$  $\frac{M_{\odot}}{M}$ <sup>2</sup>g/cm<sup>3</sup>. For a  $\sim 1 M_{\odot}$  BH the density is very high, above the nuclear density. However, for  $a \sim 10^8 M_{\odot}$  object one has  $\rho \sim 1 \text{gm/cm}^3$ . In this case one has  $\frac{R^3}{R_{\odot}^3} \sim 10^8$ . This roughly means that for a cluster composed of  $10<sup>8</sup>$  suns, the cluster crosses its own Schwarzschild radius when the suns, uniformly distributed over the volume, are touching each other. For a  $\sim 10^{10} M_{\odot}$  object one has  $\rho \sim 10^{-4}$ gm/cm<sup>3</sup>. In this case,  $\frac{R^2}{R_{\odot}^2} \sim 10^{10}$ , which roughly means that for a cluster made of  $10^{10}$  suns, it crosses its Schwarzschild radius when the suns, distributed uniformly over a spherical layer of thickness of one sun diameter, are touching each other. In all these latter cases the physics when the matter crosses the horizon is well known.

Theory and numerical simulations favor the appearance of a binary system in the center of globular clusters. The compact binary scatters any incoming star. There is, in principle no formation of a BH in the core of the cluster. This is supported by observation. However, central BHs are not totally excluded [\[13](#page-14-0)].

There is controversy about the existence of a central BH in our Galaxy since it was first proposed in 1971 [\[31\]](#page-15-0). The Galactic center has the following features: (1) a disk of gas with inner and outer radii given by  $5 - 30$  light years (ly); (2) a cavity interior to the disk with  $2x10^6$  stars; (3) a possible

BH with  $2x10^6$ Km ~  $2x10^{-7}$ ly accreting matter slowly. The evidence for a central compact source comes from the radio emission of a region as small as the orbit of saturn around the Sun[[32\]](#page-15-0). This source is called Sgr A<sup>∗</sup> and has  $L \sim 10^{34} \text{erg/s} \sim 10L_{\odot}$  (~  $10^{4}$  times the luminosity of a single radio pulsar). From the disk of gas, one can infer (if it is in a Keplerian orbit) a central mass of  $5 - 8x10^{6}M_{\odot}$ . Subtracting the mass in the red giants one obtains  $3-6x10^{6}M_{\odot}$ . The evidence favors the existence of a central BH, although it is not absolutely convincing [\[33\] \[34\]](#page-15-0). Evidence against the existence of a central BH has appeared after observations from the Sigma/GRANAT telescope led to the conclusion that, contrary to expectations, there is no X-ray source coincident with Sgr A<sup>∗</sup> [[35](#page-15-0)]. However, there are now models which can explain the phenomenon in a natural way in which the matter is swallowed before it has time to radiate [\[36](#page-15-0)].

There is also dynamical evidence that M31 (Andromeda) has a compact massive source at its center with  $M \sim 3x10^7 M_{\odot}$  which favors the existence of a BH [\[37\]](#page-15-0). M32 also harbors a central dark object of  $M \sim 5x10^6$ . There is evidence for very massive nuclei in other nearby galaxies, in NGC 4594 (the Sombrero galaxy)[[38](#page-15-0)] and in NGC 3115[[39](#page-15-0)].

The nuclei of most galaxies are inactive, in the sense that  $L \sim 10^{-4} L_{\text{galaxy}}$ . There are active galactic nuclei (AGN) which can shine more than the entire galaxy. Galaxies that have AGN are 1% of all the galaxies. Examples of AGN are the quasars (of which 3C273 has a luminosity equivalent to  $10^3$ galaxies), blazars, Seyferts, radio galaxies and other objects. In a spectrocospic classification these AGN are divided in AGN type 1 which show broad and narrow emission lines and AGN type 2 which show only narrow emission lines. They have some common features: (1) non-thermal radiation, (2) high concentration of mass in a small region, (3) variability in luminosity, (4) ejection of jets at great distances and (5) similarities with normal galaxies.

The idea is to explain generically all different objects and phenomena with one model. The most favored model invokes accretion onto central supermassive BHs as the ultimate power source for these luminous objects which radiate at the Eddingtom limit. Even, if one invokes other central objects, such as spinars (yielding their rotational energy) or a cluster of packed stars (supplying nuclear energy through supernova explosion), the emission of so much energy from such a small volume (which is measured through variability) leads inevitably to the collapse to a BH [\[40\]](#page-15-0). There is also the possibility that some galactic nuclei may contain two massive BHs in orbit around each other [\[41\]](#page-15-0). Further out from the central object, there is a dusty accretion torus which provides a mechanism to understand AGN 1 and $2 \vert 42 \vert$ . The jets, when they exist, point from the central region into two opposite directions aligned with the rotation axis of the torus. The blazars are thought to be quasars with one jet pointing towards us. The spectroscopic differences in AGN are also due to different orientations of the torus with respect to the Earth. If one can see the inner edge of the torus one observes both the broad lines emitted in the inner region by high speed clouds and the narrow lines emitted in the outer edge. If the torus is seen edge-on only the narrow lines are observable.

The evidence to detect the central mass, both in AGN and normal galaxies, is based in most cases on the increase of mass-to-light ratio in the central region. Only in two cases, M87 and NGC4258, is the value for the central mass based on gas dynamics rotating around the central mass. By using the Hubble Space Telescope it was possible to measure the Doppler shift of emission lines from doubly ionized oxygen around  $R \sim 60$ ly from the center ofM87 [[43](#page-15-0)]. This implies a rotation velocity of  $v \sim 550 \text{Km/s}$  for the gas in orbit which then gives  $M = \frac{v^2 R}{2G} \sim 2 - 3x 10^9 M_{\odot}$ . The mass is so great in such a small region that is difficult to think of any other explanation than a supermassive black hole inhabiting the center of the galaxy. If, for instance, the mass were contained in solar type stars in a dense cluster, they would be packed 100 thousand more times closely than in the solar neighborhood. However, this is discarded, since there is not enough light comimg from this region. In the case of NGC4258, recent work [\[44](#page-15-0)] [\[45\]](#page-16-0) has also pointed to the confirmation of two things: 1. Keplerian velocities of  $\sim 1000 \text{Km/s}$  in an inner orbit of very small radius,  $R \sim 0.4$ ly, around the central mass have been measured which imply a mass of  $M \sim 2x10^7 M_{\odot}$ . This work is considered to provide the strongest case for a supermassive BH in the center confirming the predictions of Lynden-Bell [\[46](#page-16-0)]. 2. The velocities are measured through water masers which are found to come from a torus-like region confirming theunifying model of Antonucci and Miller  $|42|$  $|42|$  $|42|$ . It has been suggested  $|47|$ that the best one can do for the black hole case is to refute the other models on physical grounds. For NGC4258 this has been undertaken[[48\]](#page-16-0).

One can thus have a model in which all galactic phenomena are unified, not only within AGN themselves, but also relating normal galaxies and AGN. In AGN, part of the potential energy is released when matter approaches the event horizon and the energy escapes as radiation providing the mechanism to power the emission. An accretion rate of a few tens of  $M_{\odot}$  per year, which can be supplied by surrounding gas and by stars tidally disrupted in the gravitational field, will provide a power greater than  $10^{47}$  erg/s which would explain even the highest quasar luminosities [\[49\]](#page-16-0). In normal galaxies there is no matter to be accreted. The real difference then between the nuclei of normal galaxies and AGN is, in this model, not the mass of the BH, but the phase of the cycle of accretion. The quiescent nuclei would be BHs starved of fuel, i.e., dead quasars.

#### 4. Quantum Black Holes and Elementary Particles

We have described in the previous sections stellar BHs with masses  $3 20M_{\odot}$  (and 10 – 60Km), and galactic BHs with  $10^6 - 10^9 M_{\odot}$ . But there also exists the possibility of having BHs with much smaller masses. For instance, if the Earth with mass  $\sim 10^{27}$ gm  $\sim 10^{-6} M_{\odot}$  was compressed to a radius of 1cm it would turn into a BH. There is the possibility that primordial BHs with mountain masses,  $10^{14}$ gm ~  $10^{-19}M_{\odot}$ , and a radius similar to theproton radius  $10^{-13}$ cm could be formed in the early universe [[50](#page-16-0)]. The smallest possible BH would have a mass of  $10^{-5}$ gm and a radius equal to 10<sup>−</sup><sup>33</sup>cm, the Planck radius, which is thought to be the minimum possible radius that occurs in nature. Smaller masses would have a Schwarzschild radius smaller than the Planck radius, and thus if compressed into a BH, these masses would be snatched by the Planck regime, (i.e., by the spactime foam[[51](#page-16-0)][[52](#page-16-0)]), before they had turned into a BH.

Of course, these BHs have a totally different interest from the macroscopic and giant BHs. Their physical effects are of a different kind. Let us take the mountain mass BH,  $M \sim 10^{-19} M_{\odot}$  and  $R \sim 10^{-13}$ cm. Its gravitational attraction at a distance of 10m would be relatively small ( $\sim 0.1 \text{m/s}^2$ ). Its tidal force on a 1cm tight object of 1gm would barely be felt at a distance of 10cm. Such a black hole could cause some damage on nearby objects, but not a lot. For a Planckian  $10^{-5}$ gm BH its gravitational atraction would give an acceleration of  $10^{-6}$ cm/s<sup>2</sup> at a distance of  $10^{-5}$ m, roughly the size of a living cell. On this basis, even if one of these BHs enters our body we would live without noticing it, the accretion onto it would be vanishingly small. However, there are other proceses that would made the BH noticeable, and these could cause damage in our body.

There was a great turn in BH theory after Hawking found in 1974 that BHs can radiate through quantum effects[[53](#page-16-0)]. There were already hints that BHs have a thermodynamic behavior. If one throws entropy S into the inside of the BH, this entropy disappears from our universe in direct violation of the second law of thermodynamics. Since there is a theorem[[54](#page-16-0)], within classical general relativity, that states that in any process the area A of a BH never decreases, Bekenstein proposed that  $S_{BH} \propto A$ , such that the second lawis not violated,  $S + S_{BH} \geq 0$  always [[55](#page-16-0)]. Since, to an entropy one can associate a temperature through the thermodynamic relation  $S = \frac{Q}{T}$  $\frac{Q}{T}$ , the BH must have a temperature. Indeed, by complicated calculations of quantum field theory in a BH background, Hawking was able to find that the BH emits blackbody radiation at a temperature  $T = \frac{\hbar c^3}{8\pi G k}$  $8\pi Gk_B$  $\frac{1}{M} \simeq 6 \times 10^{-8} (\frac{M_{\odot}}{M})$  $\frac{M_{\odot}}{M}$ ) $K$ . Since so many fundamental constants (section 1) enter this formula one can say that quantum mechanics, general relativity and thermodynamics must merge together in a unified theory. For  $M \sim 1 M_{\odot}$  one has  $T \sim 10^{-7}$ K. When  $M \sim 10^{-19} M_{\odot}$  implies  $T \sim 10^{12}$ K. For a Planckian BH,  $M \sim 10^{-5}$ gm, therefore,  $T \sim 10^{32}$ K. Making the translation  $E = k_B T$  one has that the energies involved in the evaporation of a Planckian size BH are  $\sim 10^{19}$ Gev  $\sim$ 100watt-hour. This could do some damage in our body. The mechanism for evaporation can be explained in several ways, the most popular uses the idea that the vacuum is full of virtual particles which are created and annihilated without violation of the uncertainty relation  $\Delta E \Delta t \stackrel{>}{\sim} \hbar$ . However near the event horizon it can happen that one particle enters the BH while the other escapes out to infinity. The net result is blackbody radiation at the Hawking temperature T. Now, the power emitted by a radiating BH is  $4\pi R^2 \sigma T^4 = \frac{\lambda}{M^2}$ , where  $\sigma$  is the Stefan-Boltzmann constant, and  $\lambda = \frac{\hbar c^6}{15360\pi G^2}$ , a value found through the equations given above. Then, one finds that the BH looses energy at a rate  $\frac{dMc^2}{dt} = -\frac{\lambda}{M^2}$  which can be integrated to give  $M = (M_0^3 - 3\frac{\lambda}{c^2})$  $(\frac{\lambda}{c^2}t)^{\frac{1}{3}}$ . For an initial mass of  $M_{\odot} \sim 1 M_{\odot}$  one gets that the BH evaporates in  $10^{67}$  years. If one puts  $M_0 \sim 10^{-19} M_{\odot}$  one finds  $t \sim 10^{10}$  years, which means if created in the primeval Universe these BHs should be evaporating by now. This could happen in a burst of final radiation after passing through the Planck scale. Some have speculated that the observed  $\gamma$ -ray bursts could come from these mini-BHs, but there are tight limits on their existence from gravitational lensing $|56|$  $|56|$  $|56|$ .

Thus, classically, BHs are stable, but quantum mechanically they are unstable, they slowly evaporate and shrink. One striking effect that arises immediately is the violation of baryon number. Baryon number conservation is a law in elementary particle physics. However, if, say, a totally isolated neutron star of  $10^{57}$  neutrons (baryons) collapses onto a BH, it will evaporate in a baryon-antibarion manner, actually most of the radiation will be in photons which carry zero baryon number anyway. Thus, gravity and quantum field theory produce violation of baryon number.

One problem that Hawking radiation gives rise to is called the information paradox. To describe a star completely, one must specify a large ammount of information, such as, total mass  $M$ , total charge  $Q$ , total angular momentum J, temperature, pressure, gravitational multipole moments, other chemical potentials, and so on, including the quantum states of the  $10^{57}$  protons and neutrons that constitute the star. When the star collapses to form a BH, the no-hair theorems say that the BH is described by only three parameters,  $M$ , Q and J. All the other information that was necessary to describe the original star is now hidden inside the event horizon. Hawking[[57\]](#page-16-0) found within his calculation, that the blackbody thermal spectrum of the emitted flux of particles would not carry the original information out to the exterior region. After the BH completely evaporates, the information that was trapped inside also vanishes with the BH. The information paradox for BHs is the problem of explaining what happens to the missing information. It is of great importance because, in usual quantum mechanics, the wavefunction  $\psi$  evolves in such a way that information contained in it is never lost. However, if the picture described here is correct, then gravitational collapse violates a fundamental principle of quantum mechanics.

Another important reason to study BH evaporation is that the final stages of the evaporation process involve physics near the Planck scale, where quantum gravity is expected to become important. Thus, BHs provide a theoretical laboratory where one can gain insight into the physics at this minimum scale.

All these issues are highly complicated in four spacetime dimensions. To understand better these problems one must resort to lower dimension theories. In two dimensions (one time plus one space dimension) general relativity is trivial, it has no dynamics. However, if one adds a dilaton scalar field the theory has many features similar to four dimensional general relativity (see, e.g. [\[58\]](#page-16-0)). There are many different theories in two dimensions with interesting dynamics  $[59][60][61]$  $[59][60][61]$  $[59][60][61]$  $[59][60][61]$ . One that has been extensively studied  $[62]$   $[63]$  $[63]$  $[63]$   $[64]$  $[64]$ is related to string theory (a consistent theory of quantum gravity, although it has problems in delivering the other three fundamental interactions). In three dimensions general relativity has dynamics, although not much (the theory has no local degrees of freedom). Surprisingly, it has been found that a three dimensional black hole in a space with constant curvature exists[[65\]](#page-17-0) [[66](#page-17-0)]. One can connect these three dimensional theories with four dimensional general relativity[[67\]](#page-17-0) [[68\]](#page-17-0) [[69](#page-17-0)][[70](#page-17-0)]. The results obtained using two, three and four dimensional theories to solve the information paradox are still controversial[[71](#page-17-0)]. However, theoretical experiments, involving annihilation of a pair of BH-antiBH, have shown that information can indeed disappear altogether, inside an event horizon [\[72\]](#page-17-0).

Extreme BHs also provide interesting results. A charged BH is called extreme when  $Q = M$  (in geometrical units where  $G = c = 1$ , otherwise we can write  $Q = \sqrt{GM}$ ). (If  $Q > M$  then there is no horizon, instead one has a naked singularity, which if it exists complicates the thermodynamic picture. That is one reason why cosmic censorship[[73\]](#page-17-0), which forbidds the existence of naked singularities, is widely accepted). For extreme BHs the Hawking temperature is zero, they do not radiate. Thus they can be considered stable particles, that do not decay. If one of these BHs absorbs an infalling neutral particle, the BH's mass will be increased, the charge-to-mass ratio is then lowered raising the Hawking temperature above zero. The BH then emits particles by the evaporation process, and returns to its ground state. This appears as a scattering process, an incoming initial state of one particle is scattered into other particles as a final state. There are other processes that resemble particle physics or are connected to other physical branches, e.g., BH-BH scatering, and the statistics a BH gas should obey (are BHs fermions, bosons or neither?[[74](#page-17-0)]).

Physicists believe that gravity becomes the dominant field at the quantum Planck scale 10<sup>−</sup><sup>33</sup>cm. It represents the minimum scale at which spacetime can be considered smooth. BHs are the objects to test this scale, through Hawking radiation, and related phenomena. Imagine the following futuristic experiment: two incoming particles in a huge accelerator are set to collide face-on, such that, a center of mass energy of  $\sim 10^{19}$ Gev is produced. Then, one might form a Planckian BH which will evaporate quickly in a burst, allowing us to study the physics at the Planck scale. One might think that by increasing the energy the study of sub-Planckian scales would follow. However, this is not the case. By increasing the energy one would produce a BH with larger mass, which would decay slowly, not allowing any test of Planckian physics.

### <span id="page-13-0"></span>4. Conclusions

BHs are used in many different phenomena, from high energy astrophysics to high energy elementary particle physics. The results brought from each area of study, either observational, theoretical or experimental, will serve to gain a better understanding of the physics of these beautiful objects. This review is a summary of some aspects of the nature of BHs.

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