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Review

Gravitational Waves, Event Horizons and Black Hole Observation: A New Frontier in Fundamental Physics

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Abstract: The observation of supermassive black holes by the Event Horizon Telescope Collaboration and the detection of gravitational waves emitted during the merging phase of compact binary objects to stellar-mass black holes by the LIGO–Virgo–KAGRA collaboration constitute major achievements of modern science. Gravitational wave signals emitted by stellar-mass black holes are being used to test general relativity in an unprecedented way in the regime of strong gravitational fields, as well as to address other physics questions such as the formation of heavy elements or the Hawking Area Theorem. These discoveries require further research in order to answer critical questions about the population density and the formation processes of binary systems. The detection of supermassive black holes considerably extends the range of scientific investigation by making it possible to probe the structure of spacetime around the horizon of the central mass of our galaxy as well as other galaxies. The huge amount of information collected by the VLBI worldwide network will be used to investigate general relativity in a further range of physical conditions. These investigations hold the potential to pave the way for the detection of quantum-mechanical effects such as a possible graviton mass. In this paper we will review, in a cursory way, some of the results of both the LIGO–Virgo–KAGRA and the EHT collaborations.

Keywords: black holes; gravitational waves; event horizon

Citation: Giammarchi, M.; Ricci, F. Gravitational Waves, Event Horizons and Black Hole Observation: A New Frontier in Fundamental Physics. *Symmetry* **2022**, *14*, 2276. https://doi.org/10.3390/sym14112276

Academic Editor: Kazuharu Bamba

Received: 7 October 2022
Accepted: 25 October 2022
Published: 30 October 2022

1. General Relativity and Black Holes

General relativity (GR) is the modern theory of gravitation, a geometric theory proposed by A. Einstein in 1915 [1], based on the equivalence principle that has been, as of time at writing, verified at the level of 10^{-15} [2]. Among the most important predictions of the theory was the existence of gravitational waves (GW) [3] and of black holes (BH) [4]. Black holes are vacuum solutions of general relativity (GR) that, at equilibrium, are fully characterized by their mass M, charge Q and spin J (*No hair theorem*). When a BH results from the collapse of an isolated massive star with zero charge and zero angular momentum, the resulting BH is the simplest classical body, defined only by its mass M. It is a pure static geometrical object and the spacetime around it has spherical symmetry and is asymptotically flat: it is the GR solution of the gravitational field generated by a static mass derived by Karl Schwarzschild in 1916 [4]. In addition, according to the Birkhoff theorem [5,6] this is the only possible solution for this physical scenario. The mass of the Schwarzschild BH defines the event horizon, the spherical surface of radius R_S

$$R_S = 2\,G\,M/c^2 \tag{1}$$

where G is the gravitational constant and c the speed of light. Following the classical vision of GR, the horizon allows the entrance but not the escape of matter and radiation from its interior and hides a singularity inside it: this surface is the barrier beyond which any information is lost. The hypothesis that BHs could exist lacked observational evidence for a long time, so that the possibility of their observation was considered unlikely. Theoretical indications in favor of their existence had become more robust already at the end of the 30s' of the past *siècle*, but the physics community was still reluctant to accept this GR prediction. We had to wait at least thirty more years for the prevailing atmosphere of skepticism to be reversed. At the end of the 60s' J. A. Wheeler actually invented the term "black hole" for the physical state of this GR solution. Then, the first very strong black hole candidate was discovered: Cygnus X-1, located within the Milky Way in the constellation of Cygnus, the Swan. The astronomers detected X rays emitted from a bright blue star orbiting a strange dark object. In 1971 it was suggested that the detected X-rays were a result of stellar material being stripped away from the bright star and "swallowed" by a dark spot, the black hole. While indirect, this evidence was considered rather convincing [7].

Other evidence of the existence of BHs followed: in the case of potential supermassive black holes (SMBH) located at the center of some nearby galaxies, evidence was obtained by carefully tracing the motion of stars near the BHs or thanks to the very energetic emission of accretion disks. The disks consist of gas molecules swirling around the BH so fast as to emit electromagnetic radiation that is detected on Earth.

In parallel, theoretical studies progressed and, in 1963, the GR solution for the rotating BH, the Kerr solution, was found [8]. Rotating black holes (actually, the vast majority if not the totality) were called Kerr black holes or (if charged) Kerr–Newman. They feature an exterior region, outside the event horizon, in which any reference frame rotates alongside it at the speed of light, the so-called frame-dragging effect. This region, named the *ergosphere* has, as an inner border the event horizon, while the outer is an approximate spheroid having an oblateness proportional to the BH angular momentum.

2. Black Hole Formation

Mass and spin distributions of stellar mass BHs are important sources of information on the formation mechanism and the evolution of galaxies. The birth of a stellar-mass BH, ranging in the interval ~5–150 $M_\odot$, is due to the spectacular phase of a massive star's core collapse, an event involving the emission of multi-messenger signals such as neutrinos, GW's and electromagnetic radiation in several bands.

For main sequence stars, the collapse proceeds in a rather complicated way: once the nuclear pressure is unable to sustain the overall stellar equilibrium, the core becomes unstable and gravitationally collapses inward upon itself. With the onset of contraction, increasing density and electron chemical potential, electron captures by nuclei speed up and accelerates the implosion. Then, the collapse stops abruptly when nuclear densities ($>2.7 \times 10^{14}$ g cm^{-3}) are reached; the overshooting inner core rebounds and the following shock wave leads to the disruption of the star in the supernova explosion. However, the process seems to be much more complex: simulations indicate that the shock wave generated after the bounce can stall because of the opacity of matter surrounding the core. In order to produce the supernova explosion, a mechanism is therefore needed to revive the shock. The most efficient way for this to happen seems to be neutrino re-heating, which should determine, some hundreds of milliseconds later, the mantle ejection. The neutrino heating is a consequence of the contraction of the collapsing core of the star associated with the compactification of its surroundings during the post-bounce accretion phase. This contraction leads to the increase of the neutrino temperatures and therefore the increase of the average energy of the radiated neutrinos.

This hypothetic scenario is still uncertain; a significant effort both in three-dimensional simulations and theoretical modeling is needed to have a complete understanding of the collapse, a process giving rise to neutron stars, pulsars, magnetars and stellar-mass black holes, such as those detected by LIGO and Virgo.

Core-collapse supernova is not the only mechanism that can end the life of a massive star. When the helium core of a star grows to ≥ 60 $M_\odot$ and the central temperature reaches $\sim 10^9$ K, electron and positron pairs are produced at an efficient rate. The star then undergoes electron–positron pair instability, where oxygen, neon, and silicon are burned explosively and the entire star is disrupted. This leaves no remnant, unless the star's helium core is $\geq$130 $M_\odot$.

The combination of all the predictions concerning the core-collapse mechanisms come together to define the BH mass spectrum. In particular, the electron–positron pair instability should determine a gap in the mass interval between ~50(−10, +20) $M_\odot$ and 100–130 $M_\odot$. The uncertainty around this mass gap is mainly connected with poorly known nuclear reaction rates in the collapse of the residual hydrogen envelope and with the role of stellar rotation.

The gravitational wave signals detected by LIGO and Virgo are generated by binary systems with short orbital separation so that the GW emission can guarantee the coalescence in a time lower than Hubble time (the initial separation of the two masses should be less than a few tens of solar radii). Thus, we also face the challenge of clarifying the formation mechanism of a binary black hole (BBH) system. In the present literature two main scenarios are confronted: (a) the isolated binary evolution scenario, (b) the formation of the binary BH starting in a star cluster, the densest place of the universe in terms of stars (>10^3 stars pc^{-3}), where the star orbits are constantly perturbed by the dynamic interaction with other objects in the cluster.

A binary black hole system (BBH) formation in isolation (first scenario) is complicated by several different processes occurring during the evolution of the system, primarily the mass transfer and the role of the gas surrounding both binary stars, usually called in astronomy the *common envelope.* This gigantic cloud can be formed when one of the stars expands rapidly and does not rotate generally with the binary system, leading to a drag effect which tends to reduce the orbital separation between a BH and the massive companion star. Then, if the common envelope is ejected and the core of the companion star collapses in a BH *without receiving a strong kick*, then a BBH is formed. For massive BHs the most likely spin configuration of the BBH system features spins well aligned to the orbital angular momentum and nearly zero orbital eccentricity.

The dynamical formation of BBHs in dense stellar environments (second scenario) is based on the hypothesis that an original binary system interacts with a third body, which replaces one of the binary components. The process tends to reduce the major axis of the orbit by absorbing momentum thereby assisting the formation of the couple. The relevant dynamical exchange involved in this process is compatible with a random distribution of the spin directions.

3. Black Holes and Quantum Mechanics

In 1974, S. Hawking and J. Bekenstein theorized that black holes were more than simple geometrical objects. Indeed, in pure general relativity, black holes do not emit any radiation, so they should be regarded as bodies at absolute zero temperature. If we include quantum mechanics (QM) in the BH description, the compact object then acquires some temperature. Hawking evaluated the particle creation effects for a body that collapses into a black hole and discovered that a distant observer would see a thermal distribution of particles emitted at finite temperature (*Hawking radiation* [9]). From this perspective, BHs are macroscopic thermodynamic objects with an entropy S given by the Bekenstein–Hawking Formula [10–12]:

$$S\,(M, \chi) = k_B\, A/(4\, l_P{}^2) = 2\, \pi\, k_B\, (M/m_P)^2\, [1 + (1 - \chi)^{1/2}] \tag{2}$$

where k_B is the Boltzmann constant. S is proportional to the area A of the BH horizon and depends on $\chi = [c\, J/(G\, M^2)]$, the dimensionless spin parameter of a rotating black hole of mass M. In Equation (2) the quantities $l_P = (h\, G/2\, \pi\, c^3)^{1/2}$ and $m_P = (h\, c/2\, \pi\, G)^{1/2}$ are the Planck length and mass, respectively. According to this formula, a black hole has a huge entropy, much larger than that of a star of the same mass, which seems reasonable since a BH is the final possible stage of gravitational evolution.

Entropy and internal energy of the BH concur to define its temperature (often known as *Hawking temperature*) which we recall here in the case of a Schwarzschild BH:

$$T = (h\, c^3)/(16\, \pi^3\, k_B\, G\, M) \tag{3}$$

leading to the conclusion that BHs are probably the coldest objects in the whole universe (and of course especially the supermassive ones).

Thus, the search within BH physics is interlaced with one of the most intriguing problems of modern physics: how to harmonize general relativity and quantum mechanics. Following the Boltzmann approach the laws of thermodynamics should emerge as a macroscopic description of an ensemble of many microscopic states corresponding to the different possible ways of forming the same macroscopic situation. Enumerating these microstates leads to the entropy S as indeed—using statistical mechanics—we can derive the laws of thermodynamics from the kinetic theory of gases. Similarly, the laws of black hole thermodynamics are properties of gravity: BH entropy and temperature, while intrinsically quantum in nature, must be related to macroscopic quantities such as horizon area and surface gravity (as provided by GR). Therefore, it should be possible to derive black hole thermodynamics starting from a fundamental theory of quantum gravity and taking some appropriate average limit.

For a given quantum system described through its density matrix ρ the *fine-grain* Von-Neumann entropy:

$$S = \mathrm{Tr}\, |\, \rho \log \rho\, | \tag{4}$$

is the variable quantifying our ignorance about the precise quantum state of the system (if it is equal to zero, as in the case of a pure state, it certifies our full knowledge of the quantum state). The classical concept of entropy is more related to the semi-classical notion of *coarse-grained entropy*, i.e., for a given density matrix we measure just few observables of the system, which in ordinary thermodynamics, for example, can be energy and volume. Numerous different theoretical approaches have been proposed. However, up to now, we can conclude that Equation (2) is robust when it is challenged following the statistical approach, i.e., to derive the entropy starting from the computation of the microstates of the microcanonical ensemble behaving as the BH: $N \sim e^{S\,(M,\,\chi)}$.

Nowadays, after the first GW detection of 2015 and the more recent Event Horizon Telescope (EHT) observations, a new phase is opening where the theoretical effort to challenge the GR picture of a black hole can be supported by experimental observations. In the following sections, we will shortly review the first attempts to use the GW signals emitted by a collapsing black hole to provide tests of the microcanonical ensemble of the Bekenstein–Hawking entropy (the *coarse-grained* entropy). More generally, the study of GW signals and of the event horizon of supermassive black holes will provide decisive physical insight at the edge between quantum mechanics and general relativity.

4. The Long Path toward the Direct Detection of Gravitational Waves

The era of experimentation with gravitational waves was opened by the seminal work of J. Weber in the 60's: he built an aluminum resonant bar at the University of Maryland [13], the first device aimed at the detection of GWs. At the beginning of the 70's W. Fairbank, at Stanford University, B. Hamilton at Louisiana State University, as well as E. Amaldi and G. Pizzella of the Rome University *Sapienza*, built cryogenic antennas which took data in coincidence in 1989. This is still considered the pioneering example of an international network for the detection of gravitational waves [14]. The cryogenic detectors, while never actually detecting gravitational waves, were able to reach a sensitivity in the change of a ~1 m bar equivalent length of 10^{-19} m, a value already sensitive to the quantum nature of the macroscopic detector. To push further the detector sensitivity new measurement strategies were developed, and among these we would like to mention the "*Quantum Non-Demolition*" systems conceived to circumvent the limit imposed by the Heisenberg principle in the process of monitoring the change in the dynamic state of a massive Weber bar. The debate around this topic even transcended the GW search spreading over to other fields of science [15].

Since the beginning of the 70s, an alternative approach to Weber's bars has been emerging: using light (and interferometry) to monitor the relative movement of mirrors in free fall. The idea, pioneered by R. Weiss [16], consisted in realizing a wideband interferometric detector, capable of detecting not only impulsive signals, such as supernovae, but also being sensitive to periodic or quasi-periodic sources, such as in the coalescence of compact binaries. R. Weiss, R. Drever and K. Thorne (and later B. Barish) played a crucial role in the definition of the detection strategy and in the realization of actual LIGO interferometric detectors of gravitational waves. At the same time, in the 80s, A. Giazotto emphasized the importance of developing detectors in the low frequency (10–100 Hz) range, where the spectral contribution of coalescence signals of black hole binary systems with stellar mass is greater. In the 80s Giazotto and A. Brillet proposed the construction of Virgo, the 3 km interferometer located in Cascina (Pisa).

In the first decade of the 2000s' LIGO and Virgo did not actually detect gravitational waves and in 2007, the two collaborations agreed to collaborate by sharing data and analysis processes, thereby acting as a single worldwide collaborating group. In this way the network of the three long arm interferometers could increase the statistical confidence of detected events, as well as improve the coverage of the sky and the location of the source emitting a transient signal.

In April 2008 the US National Science Foundation approved the Advanced LIGO project [17] and almost two years later, in December 2009. Advanced Virgo was approved by the Istituto Nazionale di Fisica Nucleare in Italy and the Conseil National de Recherche in France [18]. The *advanced* projects aimed to improve the sensitivity of first-generation interferometers by a factor of ten and, consequently, allow the exploration of a volume of the Universe 1000-times greater than previously possible, since the volume observed increases with the cube of the radius. The two LIGO interferometers, in the advanced configuration, returned to operation in September 2015 and finally, on 14 September 2015 at 09:50:45 UTC, the first gravitational wave signal was detected with a very high statistical significance [19]. This GW signal, due to the collapse of a binary system of black holes, was followed by several others, detected by the LIGO–Virgo collaboration. To date the most recent catalog of GW events is named Gravitational Waves Transient Catalog (GWTC-3) and includes 90 events [20], all of which are due to the merger of two compact stellar mass objects. The LIGO–Virgo network of detectors has recently (in 2020) been enlarged by the addition of the Japanese KAGRA interferometer, featuring 3 km long arms and located in the Kamioka mine, near the city of Hida. As a technical novelty, KAGRA is the first GW detector operating underground and at cryogenic temperatures [21].

5. Black Hole Coalescence and Gravitational Wave Signals

As we anticipated in the previous section, at present the catalog of GW signals includes tens of events; the majority of these events are *Binary BH* (BBH) mergers with masses ranging from two to 150 solar masses. The GWTC-3 catalog contains candidate GW's arising from the so-called compact binary coalescences (CBCs), merging binaries consisting of black holes and neutron stars. The naming of these GW candidates follows the format GWYYMMDD hhmmss, encoding the date and coordinated universal time (UTC) of the signal. Once a candidate signal is identified, the properties of the emitting source are inferred by coherently analyzing the data from the GW detector network. Information about the source parameters is encoded within the amplitude and phase of the GW signal recorded by each detector in the network. To extract this information, the analysis procedure is based on the matched filtering technique where model waveform templates are matched to the observed data, to calculate the posterior probability of a given set of parameters. The templates include effects such as spin precession and higher-order multipole gravitational moments of post-Newtonian expansion.

Masses set the time evolution of the GW signal both in frequency and amplitude, so that they are typically the best constrained parameters. The detectors on Earth directly measure the redshifted masses (1 + z) M_i, where z is the source redshift. The source masses are calculated by combining the redshifted mass and luminosity distance. We should note that the chirp mass, a combination of the masses of the binary compact objects,

$$M_{chirp} = (M_1\ M_2)^{3/5}/(M_1 + M_2)^{1/5} = (c^3/G)\ [(5/96)\ \pi^{-8/3}\ f^{-11/3}\ (df/dt)]^{3/5} \quad (5)$$

is measured with an accuracy higher than the two component masses thanks to its dependence on the instantaneous values of the GW signal frequency f and its derivative df/dt. However, the individual masses will indicate the nature of the source, and whether the compact object is a BH or a neutron star (NS).

As an example, we refer to the interesting event GW191219_163120 with a source chirp mass M_{chirp} = 4.32 (+0.12, −0.17) $M_\odot$ and a source total mass M = 32.3 (+2.2,−2.7) $M_\odot$ which correspond to mass components M_1 = 31.1(+2.2, −2.8) $M_\odot$ and M_2 = 1.17 (+0.07, −0.06) $M_\odot$, respectively. The great interest of this event is the extreme mass ratio of the two components, such that the M_2 object is identified as NS, assessing the existence of such a "*hybrid*" binary system.

Another example of primary interest was the event GW170817, characterized by the presence of at least one neutron star with a mass in the 1–3 $M_\odot$ range and located in the somewhat nearby (140 million light years away) NGC4993 galaxy [22]. Also alerted by prompt information from the Fermi satellite, the three-interferometer system of LIGO and Virgo was able to confine the event in the sky in an area that could be quickly scanned by 1 m size telescopes located along the Andes mountains. Another key factor was the distance information provided by the GW interferometer themselves—a feature that is unique among astronomical detectors. That distance estimate gave reasonable hope of optical detection, which was quickly made and allowed subsequent follow up of the emission source for months. This remarkable event marked the so-called beginning of *Multimessenger astronomy* and is being used by the astrophysical community to enlighten the details of so-called kilonova stellar explosions.

The spins of the compact objects are more difficult to infer than their masses and are analyzed by the time evolution of the signal. When the binary system is significantly unbalanced in the values of the two masses, it may also be possible to better constrain the primary spin χ.

In a more general case, when the spins of the black holes are misaligned to the orbital angular momentum, the orbital plane and the individual spins precess about the total angular momentum. Thus, the signals depend on the mass-weighted combinations of the spins χ_1 and χ_2 of the two components. However, as two BHs merge, the morphology of the resulting gravitational waveform and the spin dependence of the waveform can be parametrised using two phenomenological quantities, the effective inspiral spin χ_{eff} and the effective precession spin χ_p:

$$\chi_{eff} = [\chi_1 \cos\vartheta_1 + \chi_2 \cos\vartheta_2\ ]/(1 + M_2/M_1) \quad (6)$$

where ϑ_i (with i = 1,2) are the misalignment angles between the component spins and the orbital angular momentum.

$$\chi_p = \max\ \{\chi_1 \sin\vartheta_1 + [q(4q + 3)/(4 + 3q)]\ \chi_2 \sin\vartheta_2\} \quad (7)$$

where $q = M_2/M_1$ is the mass ratio between the two components. χ_p is a measure of the *mass-weighted in-plane spin component*: the value $\chi_p = 0$ implies no precession, while for $\chi_p = 1$ the precession is maximal. High values of χ_p are associated with significant amplitude modulation of the gravitational waveform. We recall here that the first unambiguous measurements of BH spin were in the case of GW151226, with $\chi_{eff} > 0$ at 99% credibility, finding that at least one of the component black holes had a spin greater than 0.2 and spin misalignment angles were consistent with $\vartheta_1 = \vartheta_2 = 0$.

6. Black Hole Observation and Future Perspectives

As we discussed in Section 2, the mass distribution of black holes can tell us more about the BH formation mechanism. The events already collected by the LIGO–Virgo-KAGRA collaboration challenge the proposed mechanism of the formation scenario.

The first determination of the mass distribution for merging binary BH's was established, under some assumptions, in 2021. We refer to the study carried out using the O3a catalog, which includes two binary neutron star (BNS) events, 44 confident BBH events, and one neutron star–black hole (NSBH) candidate that may be a BBH defined as a system where both masses are above 3 $M_\odot$.

As we anticipated in the previous section a key question to be addressed is *Are there BH systems with masses higher that 45* $M_\odot$? As we mentioned in Section 2, the sharp cut-off around this mass value in the density function of the mass distribution is the lower edge of the pair–instability mass gap. The noticeable BBH merger events GW190521, GW190602_175927, and GW190519_153544 imply a nonzero rate of BH beyond this mass limit. The GW observation of BH mergers permits the setting of a limit for the rate at 0.70 (+0.65, −0.35) $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ for systems with primary masses in the 45–100 $M_\odot$ interval. The consequence for the star formation modeling is that we have to consider a multiple formation scenario to be compliant with these observations and the models on the population synthesis have to become more and more complex.

To date, the total BBH rate, estimated using the GW data of the O3a catalog, is of 23 (+14.3, −8.6) $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ assuming a uniform distribution in the comoving volume. In the hypothetical case of a rate which evolves with redshift, at the redshift z = 0 the local merger rate is estimated to be 19(+57.3, −15.9) $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ while it changes slightly as $\sim(1+z)^{2.7}$.

The majority of the GW observations are consistent with equal-mass binaries, with mass ratios $q = M_2/M_1 \sim 1$. However, the new catalog includes the two events: GW190412 with a mass ratio $q = M_2/M_1 = 0.28$ (+0.12, 0.06), and GW190814 with a mass ratio q = 0.112 (+0.008, −0.009), with strong asymmetric components. This second event has a secondary mass $M_2 = 2.59$ (+0.08, 0.09) $M_\odot$, making it either the lightest BH or the heaviest NS ever observed in a double compact-object system. This event is intriguing because in both cases (of BH or NS companion), the consolidated astrophysical scenario of star formation needs some retuning. In fact: (a) a BH mass below 3 $M_\odot$ is much lower than those exhibited by the galactic X-ray binary population; (b) if the secondary mass of GW190814 is an NS, it should have a significantly high spin to satisfy constraints on the maximum NS mass. The asymmetry in the masses of GW190814 means that the spin of the more massive object dominates contributions to χ_{eff} and χ_p. As both χ_{eff} and χ_p are tightly constrained, we are able to set the strongest constraint on the primary spin $\chi_1 \leq 0.07$ for any gravitational wave event collected until now.

We have outlined above that, using the information hidden in the GW signal, some parameters can be extracted with good precision, while others are correlated, and that they can be estimated with less accuracy, these include parameters such as the mass ratio and black hole spins. Nonetheless, estimated parameters from several observations can be combined to obtain both distributions of black hole masses and spins. In fact, the GW waveform of a coalescent BBH is well described using post-Newtonian expansion, where the dominant term depends on the chirp mass [5]. The second term depends both on the effective spin χ_{eff} and the mass ratio q. For lower mass systems, whose observed signal is mainly due to the inspiral phase, the two parameters result in a degeneration. For higher mass binaries, the degeneracy is less significant because the last few orbits of the binary system contribute less to the signal while the merger and ringdown parts of the waveform, which depend primarily on the total mass of the system, are more important. Thus, the spin distribution can be obtained by marginalizing over the joint estimate of the mass and spin distribution $p\,(M_1, M_2, \chi_1, \chi_2)$.

In addition, the inference of the spin population is affected by a selection bias: a spin–orbit coupling causes binaries with a positive χ_{eff} to undergo a greater number of orbits prior to merger and emit larger amplitude gravitational waves, compared to those with a zero or negative χ_{eff}. It follows that BBHs with high, aligned spins can be observed at greater distances. However, the observational distance depends also on the mass, which implies that the selection effects will also depend on the assumed mass distribution. To account for these effects a combined analysis of masses and spins is undertaken assuming a Bayesian point of view with priors that maximize the overall probability of observing all the gravitational wave signals.

The spin distribution has been therefore analyzed assuming different models. Without entering into the analysis details [20], the main conclusion based on the O3a catalog is that, although the data are consistent with tilt angle distributions that favor alignment, distributions that are highly peaked at $\cos\vartheta_{1,2} = 1$ are ruled out. Using a gaussian spin model for the distribution we end up with a mean value slightly different from zero ($\mu_{\chi eff} \approx 0.2$) with a tail of the distribution spread even at negative values of χ_{eff}, i.e., BBH systems with at least one component spin tilted by $\vartheta > 90^{\circ}$ relative to the orbital angular momenta.

The existence of BBH systems with $\chi_{eff} < 0$ has an impact on the BBH formation scenario: the binary system formed from isolated stellar progenitors should contain spins nearly aligned with their orbital angular momenta, although sufficiently strong supernova kicks might produce modest misalignments. Thus, at present we should conclude that even the spin distribution advocates for a multiple formation scenario. In the future, with more data and a more accurate characterization of the effects of in-plane spins on detection efficiency, the knowledge of the $\cos\vartheta$ and χ_p distributions will be largely improved.

Another area that is being addressed by the observation of GW's is black hole description and their characteristics. Assuming the point of view of classical thermodynamics, the merger of two black holes can in fact be modeled as an adiabatic irreversible process. This implies that the entropy difference between the final and the initial state of the system must be positive according to the second law of thermodynamics. The Bekenstein–Hawking entropy of a black hole depends on the BH area (*The Area Theorem* [9,10]), so after the merger we expect that the total horizon areas should always increase. The area is in turn a function of BH mass and spin and, using the values given by the Oa3 catalog, it is rather straightforward to test the entropy increase for all coalescent events [20].

However, a fundamental objection has been raised as to the validity of this approach: these quantities are extracted by fitting the GW data with numerical relativity formulas, which assume the validity of general relativity, together with the increase of the Bekenstein–Hawking entropy (as a consequence of the GR description). In order to circumvent this objection, a method to test the entropy increase on gravitational wave signals from BBH coalescences has been proposed [23] that ignores the information from the merger phase and ensures that the initial and final masses are measured without assuming GR during the merger process. The idea is to use just the information associated with the two asymptotic states of the thermodynamical transformation. The masses of the initial black holes are then computed using only the part of the GW signal corresponding to the time when the two black holes were clearly separated, while the final black hole mass is obtained by looking just to the ringdown phase.

This separation of the inspiral part of the GW signal from the ringdown part is, however, not trivial, since it implies to assume a specific time to begin and stop the estimation process. In addition, complications come from the uncertainty of the sky location of the event, which affects the arrival time of the signals in the detectors of the network.

According to Formula (2), the Bekenstein–Hawking entropy is smaller in the case of larger spins (for a given fixed mass M). The statistical mechanical interpretation of this consequence of Formula (2) implies that there are fewer microstates with large spin than with small spin. The probability of finding a spin χ in a fixed microcanonical ensemble of mass M is

$$P_M(\chi) = \chi^2 \, e^{S\,(\chi,M)}/N \tag{8}$$

where N is the normalization factor counting for the microstates of all the spins and masses. The identification of the microstate nature and their counting depends on the quantum gravity approach as the explicit expression of the probability function [8]. The indication of the Bekenstein–Hawking formula is that (for solar mass black holes) there is a high probability for coalescent systems to have $\chi_{eff} \approx 0$. Once the event statistics increase with new GW observations, it will be possible to compare the data with the models predicting the BH population according to the microcanonical ensemble. This would provide the first observational evidence for the statistical mechanics of BHs and their entropy [24,25].

7. Primordial Black Holes and Gravitational Waves

The most robust hypothesis on the formation of primordial black holes (PBH's) is dated from 1971. At that time S. Hawking proposed that overdense regions of inhomogeneities in the primordial universe could directly undergo gravitational collapse that would also produce small BHs, as light with a Planck mass of ~10^{-8} kg and a very short lifetime. This is computed on the base of the energy emitted in the form of Hawking radiation, an effect that is insignificant for black holes formed by stellar collapses. In fact, the predicted lifetime is proportional to the cubic power of the BH mass

$$\tau = [(10{,}240\, \pi^2\, G^2)/(h\, c^4)]M^3 \approx 2.1 \times 10^{67}\, (M/M_\odot)^3 \text{ yr} \tag{9}$$

and for $(M/M_\odot) > 1$ (the solar mass $M_\odot \approx 2 \times 10^{30}$ kg), τ and results in a length of time much longer than the age of the universe, e. g., assuming the age of the universe 1.4×10^{10} yr as BH lifetime, we could conclude that it is today only possible to detect BHs that are heavier than ~$2 \times 10^{-19}\, M_\odot$. In modern cosmology the formation of PBHs has been studied even in connection with the inflation phase, when vacuum quantum fluctuations were amplified and stretched to astrophysical distances by the rapid expansion process.

PBH's are a possible constituent of dark matter and this makes their search particularly interesting; if one assumes that PBHs have formed in the radiation-dominated era (universal time less than ~50,000 years), the nucleosynthesis constraint that baryons can have at most 5% of the critical density does not hold anymore. PHBs should therefore be classed as non-baryonic and from a dynamical perspective they behave like any other form of cold dark matter. Evidence has been found from gravitational microlensing surveys of the Large Magellanic Cloud that almost 20% of the galactic halo is composed of massive compact halo objects (MACHOs) with masses in the interval 0.15–0.9 $M_\odot$ [26]. However, the nature of the majority of observed lenses was controversial and the debate on how to constrain PBHs was partially solved by taking advantage of the gravitational microlensing effect, a more robust method that does not require that the lensing objects be directly visible. Taking into account other astrophysical constraints [27], the conclusion is that MACHOs could comprise only 20% of dark matter and, in general, that it is difficult (but still possible) to consider all dark matter as PBHs if the BH mass function is a broad function, as expected in several models.

Before concluding, we should also note that some fraction of PBHs may exist in binaries which are coalescing today, so that we can detect PBHs via GWs emitted during the coalescent phase [28]. If such low mass PBHs are not detected in this way, an alternative direct gravitational wave probe would be the detection of a very high redshift merger (z ~ 40), which would be a signature from such early times that stellar objects would not yet have had time to collapse into compact objects.

A less direct, but still promising, approach to demonstrate the existence of PBHs would be via the detection of their contribution to the GW stochastic background at high redshift. For instance, the Pulsar Time Array collaborations can search this signal in the very low frequency range (10^{-8} Hz) and possibly get some evidence of this contribution.

In the detection case we will have the possibility to use, in a synergistic way, the result with the corresponding BH mass distribution obtained by the LIGO–Virgo–KAGRA network.

8. Supermassive Black Holes

Supermassive black holes (SMBHs) are classically defined as black holes having a mass greater than 10^5 $M_\odot$; they are generally associated with galactic nuclei, especially active galactic nuclei (AGN) and often related with exceptionally energetic systems, such as quasars or very active galaxies. Accretion of interstellar matter and gas is the chief mechanism invoked to explain the power generation in such systems. Various classes of AGNs are also considered responsible for the production and generation of the highest-energy cosmic rays in the universe, arriving at Earth with energies of up to 10^{20} eV (seven orders of magnitude higher than a proton circulating in the Large Hadron Collider [29].

The story of the discovery of SMBHs is closely connected to the identification of quasars, starting from the '60s: those deeply cosmological objects seemed capable of releasing an exceptionally large amount of energy. E. Salpeter and Y. Zeldovich suggested the possibility that such an amount of energy could be explained by mass falling onto a super-massive compact object. This mechanism could also explain the phenomenon of relativistic jets of particles being emitted from these sources.

The first evidence of the existence of SMBHs is therefore linked to their extraordinary energetics and the consequent powerful emission of particles and radiation. Galactic nuclei were considered as natural places to host these amazing astronomical objects and in the course of the 70's it was hypothesized that an SMBH be at the center of our own galaxy—called Sagittarius A*. Evidence mounted that showed the factual existence of Sagittarius A* in the form of a radio source emitting synchrotron radiation.

Besides their huge mass, SMBHs have different properties than their stellar counterparts: for instance, near their horizons, tidal forces can be surprisingly small. As small as the gravity force felt on the Earth. This type of black hole is of course stable against evaporation by means of Hawking radiation, having a predicted lifetime many orders of magnitude bigger than the Hubble time (Equation (3)): for instance, in the case of a 100 billion $M_\odot$, the predicted evaporation lifetime is of the order of 10^{100} years!

Another important piece of evidence in favor of the existence of SMBHs was strictly gravitational in character: because of its huge mass, the SMBH at the center of our own galaxy was expected to influence the motion of the innermost stars. The careful study of the inferred orbits of six stars around the center of our galaxy led in fact to an estimate of 4.1 million $M_\odot$ for the Sagittarius A* supermassive black hole [30].

The same kind of dynamical evidence of a central SMBH has been obtained for a number of other galaxies belonging to the local group. The technique consists in the study of star velocities in the vicinity of the center, to confirm that the laws of motion are consistent with an almost point-like central mass. These studies in fact excluded with good confidence level the existence of more complex (and more extended) configurations of gravitational sources, such as clusters of neutron stars or clusters of several black holes.

In addition to the study of the energies and the trajectories of central stars, another technique has emerged to increase the evidence for the existence of SMBHs at the center of galaxies, the study of the so-called M-σ correlation plot. An M- σ plot relates the mass of the supermassive black hole to the velocity dispersion of the stars in the central parsec of the nearby galaxies [31]. The very small dispersion of such a correlation plot is proof of the presence of SMBHs at the center of galaxies in general, possibly with the reasonable exception of low-mass, small dwarf galaxies. The M-σ relation has also contributed to the solution of previous discrepancies about the mass estimates of black holes and is currently used to estimate central black hole masses for thousands of galaxies. After its discovery it became widely accepted that SMBHs are a fundamental constitutive element of most galaxies in our universe.

There are several hypotheses to explain the formation mechanism of SMBHs. The early progenitor can be a stellar-mass black hole growing by accretion of matter or of other

BHs. In this scenario, SMBH formation is explained as a consequence of the death of the first stars of the universe. However, alternative mechanisms have been proposed in which large amount of gas directly collapse to a huge black hole at the time of the formation of the first stars. Dark matter halos have been invoked to facilitate such a possible scenario. In general, all the scenarios have to solve the problem of explaining the formation of a very small and dense volume of matter having a small amount of angular momentum.

Since the quasars were much more common when the universe was younger, it is generally believed that most of the formation of SMBHs took place when the universe was perhaps a billion years of age.

9. VLBI Radioastronomy and the Observation of Supermassive Black Holes

Supermassive black holes cannot be observed using the currently existing GW interferometers on Earth. Their detection bandwidth permits the study of cosmic events on a characteristic time scale shorter than a second, i.e., to study the phenomena associated with highly compact stellar objects moving at very high velocity. While in principle interferometers in space with arms of millions of kilometers could in the future have an important role, the current best technique to study black holes of masses in the range 10^6–10^{10} $M_\odot$ is very long baseline interferometry (VLBI) in the radio domain.

Radioastronomy has made giant steps from the time of the foundational work undertaken by K. Jansky and Grote Reber in the 30's who opened a new astronomical window of observations. This technique has played a leading role in the discovery (and the subsequent study) of astrophysical relevant objects such as pulsars, quasars and the nuclei of galaxies. During the 60's and 70's M. Ryle and H. Hewish significantly improved the possibilities of radioastronomy by pioneering radio-interferometry, allowing the combination of signals coming from different radio telescopes.

In this technique, a signal is collected at multiple sites on Earth and the different observations are combined, so that the whole system acts as a radio telescope of planetary size. For the technique to be effective, it is necessary to cross-correlate the output signals of radio-telescope antennas located hundreds of kilometers apart. An exact and synchronized timekeeping at the single stations is required: this is achieved by linking a clock that timestamps the observational data to a super stable oscillator, such as an H maser and, more recently, to a GPS network, for long-term stability. Many well localized astrophysical sources emitting in the radio band have been observed in this way; this method is nowadays extended to a network of several antennas, where the *phase closure technique* can be applied.

In oversimplified terms, the sum of the signal phase differences from one antenna to the next must be equal to the total phase difference between the first and the last:

$$\Delta\varphi_{1,2} + \Delta\varphi_{2,3} + \cdots + \Delta\varphi_{n-1,n} - \Delta\varphi_{1,n} = 0, \tag{10}$$

By applying this method, the overall phase noise contribution of each observing station cancels out. The accuracy of these measurements increases with the baseline. In the VLBI technique, the antennas are thousands of kilometers distant and the measurement is carried out in the solar barycentric system (SBS) reference frame; therefore, the timing must take into account both the rotation and the revolution of the Earth.

The Event Horizon Telescope (EHT) VLBI array [32] is based on radio antennas distributed in Europe, America and the South Pole: it observes at a wavelength of 1.3 mm, with a typical angular resolution of about 35 micro arc-sec. To give a flavor of the experimental difficulties in detecting the signals, we note that on the Earth in the radio band of interest to the EHT, the power density is about 3×10^{-26} W m^{-2} Hz^{-1}. Given that the typical antenna aperture of the EHT network is ~10 m, the detected power amounts to about 1×10^{-16} W in 8 GHz bandwidth. The signals are amplified before the correlator, so that signal and the noise are added in to the amplification. The signal-to-noise ratio improves as $n^{1/2}$, where n is the number of independent measurements, and equals to $2\,B\,\tau$, where B is the bandwidth (8 GHz for EHT case) and τ is the integration time. The latter parameter is limited by the coherence time set by atmospheric fluctuations, so the way to improve sensitivity is to increase the bandwidth of the receiving system's electronics.

The most celebrated results of the Event Horizon Telescope collaboration are the images of the supermassive black holes in the center of M87 [33] and of the Milky Way (Sgr A*) [34]: the images feature an impressive *central brightness depression* related to the underlying SMBH shadow. The detection of such photon-trapping regions near to the two SMBHs, required enough resolving power, also called angular resolution, to match the small angular size of these systems. The supermassive BH in M87 (~6.7×10^9 $M_\odot$) is about 1500-times more massive than Sgr A* (~4.3×10^6 $M_\odot$); on the other hand, M87 is 2000-times more distant than the center of our Milky Way. Given the size of the two SMBHs and galaxy distances, it is straightforward to conclude that EHT has to resolve the M87 event horizon of about 22 micro-arc-sec to be compared with the 53 micro-arc-sec of Sgr A*. The observation of the space-time structure just around a supermassive black hole, with angular resolution comparable to the event horizon, can lead to images of strong gravity effects that enlighten the dynamics of photons and matter orbiting in a black hole's proximity. As in the case of the GW signals from a BBH coalescences, these observations help verify the existence of event horizons, help study the accretion and outflow processes of radiation and matter at the edge of a black hole, can be used to test general relativity in the strong field regime and can help look for new fundamental physics.

10. Fundamental Physics Tests with the EHT

The observation of both M87* and SgrA* profited from these objects being optically thin and geometrically thick, due to the modest efficiency of the radiative part of the accretion flow. This fact has another important advantage: the size of the bright ring can be used as a good indicator of the shadow size r_{sh} of the SMBH—determined to be 2.6-times the Schwarzschild radius R_s—assuming little or no dependence on the accretion flow.

In addition to r_{sh}, other important parameters are the deviation from circularity ΔC (oblateness of the shadow), the photon ring and the azimuthal angle lapse. These can be studied both from the point of view of the testing of classical GR as well as from the point of view of the observation of manifestations of possible quantum effects. In general, modifications to general relativity, the presence of additional fields or possible modifications of other fundamental physical laws can in fact leave some signature on the SMBH shadow or the photon ring.

Among the possible "classical" tests, in a vast class of theories, deviations from GR are postulated by substituting the GR black hole with some other compact object whose properties approach those of an ordinary GR black hole sufficiently far from the event horizon [35]. These possible alternatives are interesting because, by construction, they well reproduce the expected "black hole" physics for accretion disks and the trajectory of nearby stars. In addition, these possibilities can be parametrized by an effective perturbative theory by means of an *l/r* expansion—*l* being a length scale over which deviations from GR are important, while *r* is a measure of the distance from the event horizon. These classes of searches can also be sensitive to quantum effects, provided the GR derivation is analyzed in the same perturbative way.

Deviations from circularity of the M87 are already being studied in relation to the rotational structure [36] and by keeping in mind the possibility of the emergence of new physical phenomena: the oblateness of the shadow can in fact be related to possible deviations from the quadrupole moment predicted by the Kerr metric.

From the quantum mechanical viewpoint, during the last century it was generally believed that, due to the smallness of the curvature near the event horizon of a SMBH, the relevant physical regime was the one of GR. This view started to change because of the new studies on the evolution of BHs, namely through the Hawking effect [37]. This motivates the need to modify the description of BHs to take into account quantum effects. In addition, general quantum considerations suggest the need to address the following problem: since BHs absorb information and will then evaporate away (because of Hawking radiation), the information would then be destroyed contradicting the principle of quantum unitarity. Therefore, in order to harmonize GR and quantum mechanics, it appears that some information should be released from an SMBH during its very evolution in time; in other words, this implies a search of a local quantum field theory evolution on a classical BH geometry [38].

From the observational viewpoint, these quantum effects will generate fluctuations and may introduce a time dependence of the shape and size of the shadow. The underlying idea is that, as a "*minimal effect*", the quantum information from the black-hole state is transferred to the outgoing radiation, which will recover the unitarity of the quantum-mechanical evolution. In addition, the information-transferring couplings can produce a flux of gravitons from the black hole in addition to that from the Hawking radiation: in these conditions, the BH thermal equilibrium is not characterized by the entropy S and temperature T given by Formulas (2) and (3). The *fine*-grained entropy could resultantly be higher than the *coarse* one. To preserve an approximation of the standard thermodynamic description and equilibrium conditions, the main hypothesis is that there exists a universal coupling to all the fields (including gravitation) that can radiate from the black hole, and that these should closely match the Hawking radiation. As already stated, the observational effect could be linked to the stability (or variation!) of the shadow of the SMBH event horizon during time. Another potential effect of quantum fluctuation is a perturbation of the trajectories of the photons that would have crossed the horizon to escape and vice versa. Radial quantum fluctuations can cause the shrinking and divergence of the light rays with different impact parameters, modifying the brightness amplification introduced by gravitational lensing and leading to bright structures in the images.

Finally, we would like to mention another possible scenario, one that emerges by applying quantum field theory considerations to curved spacetime: this approach begins by observing that loop corrections involving ordinary matter fields induce new gravitational interactions beyond GR [39]. These terms involve the square of the spacetime curvature tensor ("*quadratic gravity*") and are suppressed by the Planck mass scale. According to this proposal, gravity can be viewed as an effective field theory where GR provides the leading terms. Among other interesting aspects of quadratic gravity, *naked singularity* and *wormholes* are admitted as possible physical solutions.

In summary, the study of observables related to the SMBH shadow, of the light ring and of the horizon oblateness can open scenarios beyond GR and possibly include quantum mechanical effect. Given the paramount interest and the proliferation of predictions (as well as the inevitable scarcity of data), in case a deviation from standard GR is found, the problem of degeneracy between various non-orthodox models will need to be properly addressed. Another challenge for the future!

11. A Selection of EHT Preliminary Studies

In terms of the experimental observations from the EHT, after the image of M87* and SgrA* one can say that for the case of M87* (which is more favorable from the observation viewpoint) both r_{sh} and ΔC are becoming accessible, while only r_{sh} is available for SgrA* up to now.

In the case of M87*, the relative stability of the object (which does not vary too quickly), its huge mass (6.7 billion of solar masses!) and the presence of a 5000 light years jet make it the ideal place to look for magnetic effects. This was achieved by the EHT group by first looking at the polarization of the radiation [40]. It was possible to actually build polarization intensity maps around the M87* shadow, demonstrating a small level of polarization, thereby confirming the view of a hot ionized plasma: as expected, the polarization pattern has a prevailing azimuthal structure. The magnetic structure around the horizon could then be studied [41]. It has been estimated that about a Jupiter mass is being swallowed by the SMBH per year.

The study of the polarization of the accreting material around M87* has also been used to look for new physics, namely axions, the postulated particles that solve the strong interactions CP problem. If existing, the axions would naturally get lumped into highly massive objects, such as black holes. The observation by the EHT collaboration concentrated on the study of the linear polarization of the radiation emitted in the surrounding of the SMBH shadow [42]. The study of polarization in different days is in fact sensitive to the presence of axion clouds spinning around the SMBH.

One of the most spectacular consequences of GR in the vicinity of a black hole surrounded by an accretion disk is the possible manifestation of a photon closed orbit, a *light ring*—which are actually caused by photons following a closed orbit and interacting with surrounding matter. This structure was observed by the EHT collaboration [43] around M87*. A discussion, however, started because it seems that the structure is more intense than actually expected [44]: this unexpected brightness could occur because some of the light from the main glow gets lumped in with the photon ring. If so, the ring's apparent brightness could not depend only on the light coming from the ring itself.

12. Conclusions

During the last decades, and especially during the last seven years, black holes have emerged from the realm of GR calculations, indirect evidence and speculation to enter the area of experimental testing and detailed comparison with existing theories and their extensions.

This offers an enormous variety of new possibilities for physical explorations, involving gravitation in the strong regime, both in study of stellar-mass BHs and in the case of SMBHs. Unluckily, we do not have, yet, a system where both the GWs and the Event Horizon Telescope can both contribute to the study.

Black holes, both stellar and supermassive, still hold a special place in physics: if one defines the universe as "everything which can be observed", they technically lie "outside", while clearly physical interactions claim that they belong to the system! This challenge, extending beyond the level of physics (to epistemology) will soon be faced for the case of entropy and information—as it was already for the mass and spin of black holes.

Author Contributions: All authors (M.G. and F.R.) have contributed equally to all the aspect of the paper preparation and they both agreed to the published version of the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Einstein, A. *Die Feldgleichungen der Gravitation*; Sitzungsbericht; Königlich Preussische Akademie der Wissenschaften: Berlin, Germay, 1915; pp. 844–847.
2. Touboul, P.; Métris, G.; Rodrigues, M.; André, Y.; Baghi, Q.; Bergé, J.; Boulanger, D.; Bremer, S.; Chhun, R.; Christophe, B.; et al. The MICROSCOPE mission: First results of a space test of the equivalence principle. *Phys. Rev. Lett.* **2017**, *119*, 231101. [CrossRef] [PubMed]
3. Einstein, A. *Gravitationswellen (On Gravitational Waves)*; Erster Halbband; Königlich Preussische Akademie der Wissenschaften: Berlin, Germany, 1918; pp. 154–167.
4. Schwarzschild, K. Über das Gravitationsfeld einer Kugel aus inkompressibler Flüssigkeit; Reimer, Berlin 1916, S. 424-434 (Sitzungsberichte der Königlich-Preussischen Akademie der Wissenschaften; 1916)—On the Gravitational Field of a Sphere of Incompressible Liquid, According to Einstein's Theory. *Abraham Zelmanov J.* **2008**, *1*, 20–32.
5. Israel, W. Event Horizons in Static Vacuum Space-Times. *Phys. Rev.* **1967**, *164*, 1776. [CrossRef]
6. Jebsen, J.T. Uber Die Allgemeinen Kugelsymmetrschen Losungen Der Einstei'Schen GavitationsgleiChungen Im Vakuum. *Ark. Mat. Astron. Fys.* **1921**, *15*, 1.
7. Shipman, H.L. The implausible history of triple star models for Cygnus X-1 Evidence for a black hole. *Astrophys. Lett.* **1975**, *16*, 9.
8. Kerr, R.P. Gravitational Field of a Spinning Mass as an Example of Algebraically Special Metrics. *Phys. Rev. Lett.* **1963**, *11*, 237. [CrossRef]
9. Visser, M. Hawking Radiation without Black Hole Entropy. *Phys. Rev. Lett.* **1998**, *80*, 3436. [CrossRef]
10. Hawking, S.W. Black holes and thermodynamics. *Phys. Rev.* **1976**, *D13*, 191. [CrossRef]

11. Bekenstein, J.B. Black Holes and the Second Law. *Lett. Nuovo Cim.* **1972**, *4*, 737–740. [CrossRef]
12. Bekenstein, J.B. Black Holes and Entropy. *Phys. Rev. D* **1973**, *7*, 2333. [CrossRef]
13. Weber, J. Gravitational Radiation. *Phys. Rev. Lett.* **1967**, *18*, 498. [CrossRef]
14. Amaldi, E.; Aguiar, O.; Bassan, M.; Bonifazi, P.; Carelli, P.; Castellano, M.G.; Cavallari, G.; Coccia, E.; Cosmelli, C.; Fairbank, W.M.; et al. First Gravity Wave Coincidence Experiment Between Three Cryogenic Resonant-Mass Detectors: Lousiana-Rome-Stanford. *Astron. Astrophys.* **1989**, *216*, 325.
15. Bocko, M.; Onofrio, R. On the measurement of a weak classical force coupled to a harmonic oscillator: Experimental progress. *Rev. Mod. Phys.* **1996**, *68*, 755. [CrossRef]
16. Weiss, R. *Electromagnetically Coupled Broadband Gravitational Antenna*; Quaternary Progress Report; MIT: Cambridge, MA, USA, 1972.
17. Aasi, J.; Abbott, B.P.; Abbott, R.; Abbott, T.; Abernathy, M.R.; Ackley, K.; Adams, C.; Adams, T.; Addesso, P.; Adhikari, R.X.; et al. Advanced LIGO. *Class. Quantum Gravity* **2015**, *32*, 115012. [CrossRef]
18. Acernese, F.; Agathos, M.; Agatsuma, K.; Aisa, D.; Allemandou, N.; Allocca, A.; Amarni, J.; Astone, P.; Belestri, G.; Ballardin, G.; et al. Advanced Virgo: A Second-Generation of Interferometric Gravitational Wave Detector. *Class. Quantum Gravity* **2015**, *32*, 024001. [CrossRef]
19. Abbott, B.P.; Abbott, R.; Abbott, T.D.; Abernathy, M.R.; Acernese, F.; Ackley, K.; Adams, C.; Adams, T.; Addesso, P.; Adhikari, R.X.; et al. Observation of Gravitational Waves from a Binary Black Hole merger. *Phys. Rev. Lett.* **2016**, *116*, 061102. [CrossRef]
20. Abbott, B.P.; Abott, D.T.; Acernese, F.; Ackley, K.; Adams, C.; Adhikari, N.; Adhikari, R.X.; Adya, V.B.; Affeldt, C.; Agarwal, D.; et al. GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run. *arXiv* **2021**, arXiv:2111.03606.
21. Akutsu, A.; Ando, M.; Arai, K.; Arai, Y.; Araki, S.; Araya, A.; Aritomi, N.; Aso, Y.; Bae, S.-W.; Bae, Y.-B.; et al. Overview of KAGRA: Detector design and construction history. *Prog. Theor. Exp. Phys.* **2021**, *2021*, 05A101. [CrossRef]
22. Abbott, B.P.; Abbott, R.; Abbott, T.D.; Acernese, F.; Ackley, K.; Adams, C.; Adams, T.; Addesso, P.; Adhikari, R.X.; Adya, V.B.; et al. GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral. *Phys. Rev. Lett.* **2017**, *119*, 161101. [CrossRef] [PubMed]
23. Cabero, M.; Collin, M.; Capano, D.; Fischer-Birnholtz, O.; Krishnan, B.; Nielsen, A.B.; Nitz, A.H.; Biwer, C.M. Observational tests of the black hole area increase law. *Phys. Rev. D* **2018**, *97*, 124069. [CrossRef]
24. Bianchi, E.; Gupta, A.; Haggard, H.M.; Sathyaprakash, B.S. Small Spins of Primordial Black Holes from Random Geometries: Bekenstein-Hawking Entropy and Gravitational Wave Observations. *arXiv* **2018**, arXiv:1812.05127v2.
25. Salerno, V. Il segnale di onde gravitazionali GW150914 e la variazione di entropia associata. Bachelor's Thesis, University of Rome, Rome, Italy, 2022.
26. Alcock, C.; Allsman, R.A.; Alves, D.; Axelrod, T.S.; Becker, A.C.; Bennett, D.P.; Cook, K.H.; Freeman, K.C.; Griest, K.; Guern, J.; et al. The MACHO Project Large Magellanic Cloud Microlensing Results from the First Two Years and the Nature of the Galactic Dark Halo. *Astrophys. J.* **1997**, *486*, 697. [CrossRef]
27. Tisserand, P.; Guillou, C.; Afonso, J.N.; Albert, J.; Andersen, R.; Ansari, E.; Aubourg, P.; Bareyre, J.P.; Beaulieu, X.; Charlot, C.; et al. Limits on the Macho content of the Galactic Halo from the EROS-2 Survey of the Magellanic Clouds. *Astron. Astrophys.* **2007**, *469*, 387. [CrossRef]
28. Magee, R.; Deutsch, A.S.; McClincy, P.; Hanna, C.; Horst, C.; Meacher, D.; Messick, C.; Shandera, S.; Wade, M. Methods for the detection of gravitational waves from subsolar mass ultracompact binaries. *Phys. Rev. D* **2018**, *98*, 103024. [CrossRef]
29. Aab, A.; Abreu, P.; Aglietta, M.; Albury, J.M.; Allekotte, I.; Almela, A.; Alvarez Castillo, J.; Alvarez-Muñiz, J.; Alves Batista, R.; Anastasi, G.A.; et al. Features of the Energy Spectrum of Cosmic Rays above 2.5×10^{18} eV Using the Pierre Auger Observatory. *Phys. Rev. Lett.* **2020**, *125*, 121106. [CrossRef] [PubMed]
30. Eisenhower, F.; Genzel, R.; Alexander, T.; Abuter, R.; Paumard, T.; Ott, T.; Gilbert, A.; Gillessen, S.; Horrobin, M.; Trippe, S.; et al. Young Stars and Infrared Flares in the Central Light-Month. *Astrophys. J.* **2005**, *628*, 246. [CrossRef]
31. Merritt, D.; Ferrarese, L. The M-σ Relation for Supermassive Black Holes. *Astrophys. J.* **2000**, *539*, L9–L12.
32. Doeleman, S.; Agol, E.; Backer, D.; Baganoff, F.; Bower, G.C.; Broderick, A.; Fabian, A.; Fish, V.; Gammie, C.; Ho, P.; et al. Astro2010: The Astronomy and Astrophysics Decadal Survey, Science White Papers. *arXiv* **2010**, arXiv:0906.3899.
33. Akiyama, K.; Alberdi, A.; Alef, W.; Asada, K.; Azulay, R.; Baczko, A.-K.; Ball, D.; Balokovic, M.; Barrett, J. First M87 Event Horizon Telescope Results. VI. The Shadow and Mass of the Central Black Hole. *Astroph. J. Lett.* **2019**, *875*, L6.
34. Johnson, M.D.; Narayan, R.; Psaltis, D.; Blackburn, L.; Kovalev, Y.Y.; Gwinn, C.R.; Zhao, G.-Y.; Bower, G.C.; Moran, J.M.; Kino, M.; et al. The Scattering and Intrinsic Structure of Sagittarius A* at Radio Wavelengths. *Astroph. J.* **2018**, *865*, 104. [CrossRef]
35. Rummel, M.; Burgess, C.P. Constraining fundamental physics with the event horizon telescope. *JCAP* **2020**, *05*, 051. [CrossRef]
36. Bambi, C.; Freese, K.; Vagnozzi, S.; Visinelli, L. Testing the rotational nature of the supermassive object M87* from the circularity and size of its first image. *Phys. Rev. D* **2019**, *100*, 044057. [CrossRef]
37. Hawking, S.W. Particle creation by black holes. *Commun. Math. Phys.* **1975**, *43*, 199. [CrossRef]
38. Giddings, S.B. Searching for Quantum Black Hole Structure with the Event Horizon Telescope. *Universe* **2019**, *5*, 201. [CrossRef]
39. Daas, J.; Kuijpers, K.; Saueressig, F.; Wondrak, M.F.; Falcke, H. Probing Quadratic Gravity with the Event Horizon Telescope. *arXiv* **2022**, arXiv:2204.08480v1.

40. Akiyama, K.; Algaba, J.C.; Alberdi, A.; Alef, W.; Anantua, R.; Asada, K.; Azulay, R.; Baczko, A.-K.; Ball, D.; Baloković, M.; et al. First M87 Event Horizon Telescope Results. VII. Polarization of the Ring. *Astroph. J. Lett.* **2021**, *910*, L12. [CrossRef]
41. Akiyama, K.; Algaba, J.C.; Alberdi, A.; Alef, W.; Anantua, R.; Asada, K.; Azulay, R.; Baczko, A.-K.; Ball, D.; Baloković, M.; et al. First M87 Event Horizon Telescope Results. VIII. Magnetic Field Structure near The Event Horizon. *Astroph. J. Lett.* **2021**, *910*, L13. [CrossRef]
42. Chen, Y.; Liu, Y.; Lu, R.S.; Mizuno, Y.; Shu, J.; Xue, X.; Yuan, Q.; Zhao, Y. Stringent axion constraints with Event Horizon Telescope polarimetric measurements of M87. *Nat. Astron.* **2022**, *6*, 592. [CrossRef]
43. Broderick, A.E.; Pesce, D.W.; Gold, R.; Tiede, P.; Pu, H.-Y.; Anantua, R.; Britzen, S.; Ceccobello, C.; Chatterjee, K.; Chen, Y.; et al. The Photon Ring in M87. *Astroph. J.* **2022**, *935*, 61. [CrossRef]
44. Lockhart, W.; Gralla, S.E. How narrow is the M87* ring? II. A new geometric model. *Mon. Not. R. Astron. Soc.* **2022**, *517*, 2462–2470. [CrossRef]