The black hole symphony: probing new physics using gravitational waves

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The next decade will very likely see the birth of a new field of astronomy as we become able to directly detect gravitational waves (GWs) for the first time. The existence of GWs is one of the key predictions of Einstein’s theory of general relativity, but they have eluded direct detection for the last century. This will change thanks to a new generation of laser interferometers that are already in operation or which are planned for the near future. GW observations will allow us to probe some of the most exotic and energetic events in the Universe, the mergers of black holes. We will obtain information about the systems to a precision unprecedented in astronomy, and this will revolutionize our understanding of compact astrophysical systems. Moreover, if any of the assumptions of relativity theory are incorrect, this will lead to subtle, but potentially detectable, differences in the emitted GWs. Our observations will thus provide very precise verifications of the theory in an as yet untested regime. In this paper, I will discuss what GW observations could tell us about known and (potentially) unknown physics.

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1. Introduction

In Einstein’s theory of general relativity (GR), gravity arises as a result of the curvature of space–time. All massive objects warp space and time around them, and objects free falling in space–time follow these bends and warps, moving on the shortest (geodesic) path between points. A common analogy is to think of a taut rubber sheet. If a light object, e.g. a marble, is rolled across the sheet, it moves in a straight line. When a heavy object, e.g. a bowling ball, is placed on the sheet, the sheet bends around the ball. If another marble is now rolled across the sheet, it no longer moves in a straight line, but the path dips into and then out of the dent near the ball. In the theory of relativity, when a mass distribution undergoes a second-order change (an acceleration), it takes a while for information about that change to travel to distant observers. The gravitational ‘information’ is in the form of space–time curvature—when a system of masses is accelerated, this generates fluctuations in curvature, which propagate away from the system, carrying energy. These propagating curvature fluctuations are gravitational waves (GWs).

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GWs are very weakly interacting, which means that they can propagate over large distances without being scattered or absorbed, but this also makes them difficult to detect. The effect of a GW passing through a system is to periodically stretch and squeeze space in directions perpendicular to the direction of propagation of the wave, such that at any moment the effect is opposite in mutually perpendicular directions. This is illustrated in the inset of figure 1. The first attempts to directly detect GWs were made by Joseph Weber in the 1960s (Weber 1969) using a resonant bar. Resonant bars are large cylinders of metal that are seismically isolated, with sensors on the surface. An impinging GW with a frequency close to a resonant frequency of the cylinder will excite oscillations that can be sensed. Cryogenically cooled resonant bars are still being operated, but they have now been surpassed in sensitivity by laser-interferometric detectors. Laser interferometers exploit the fact that GWs stretch and squeeze space–time in opposite senses in perpendicular directions. The basic concept is to pass a laser through a beam splitter and send the two, initially in-phase, beams in perpendicular directions, reflect them off nominally equidistant, freely suspended mirrors and then recombine the beams.

This is illustrated in figure 1. In the presence of a GW, one arm of the interferometer is lengthened while the other is shortened, and so an interference pattern is observed. Over the past 15 years, several large-scale interferometers have been built—LIGO (three interferometers at two sites in the USA), GEO (in Germany), VIRGO (in Italy) and TAMA (in Japan). (Information about these projects can be found at http://www.ligo.caltech.edu/, http://geo600.aei.mpg.de/, http://www.virgo.infn.it/ and http://tamago.mtk.nao.ac.jp/.) LIGO has just finished collecting 1 year of data coincident between all three detectors, and is now being upgraded incrementally to provide first a factor of 2 and ultimately a factor of 10 improvement in sensitivity. Ground-based detectors are sensitive to
GWs in the 10–1000 Hz range, but their sensitivity is fundamentally limited at low frequency due to seismic noise, i.e. vibrations in the Earth’s crust, which arise from tectonic plate movements, ocean tides, cars, etc. A low-frequency (approx. 0.1–100 mHz) space-based detector, LISA (http://lisa.nasa.gov), is planned for launch in approximately 10 years. This will work on the same principle as the ground-based detectors, and will be composed of three satellites positioned at the corners of an equilateral triangle, with laser beams propagating in each direction along each arm of the constellation. To date, no confirmed detections of GWs have been reported by these new experiments, although we do have strong indirect evidence for the existence of GWs from observations of binary pulsars, such as PSR B1913+16 (Hulse & Taylor 1975).

GWs are generated when large quantities of mass are accelerated to velocities that are a significant fraction (approx. 10%) of the speed of light. This requires a system containing from one to many stellar masses of material ($\gtrsim 10^{30}$ kg), which is also very compact so that the material is accelerated to the necessary velocities. In a stellar system, e.g. a binary, the constituent stars must also be extremely compact so that they can get close enough to one another, without being disrupted, to reach velocities at which significant gravitational radiation is generated—they must be either white dwarfs, neutron stars or black holes. The frequency of the emitted GW scales as the inverse of the total mass of the system, which means that ground-based detectors will observe systems with mass from a few to a few hundred times the mass of the Sun, while LISA will observe supermassive black holes, with mass about a million times that of the Sun. Although a number of systems that are likely sources of GWs have been observed electromagnetically, GW observations will provide new and detailed information that will significantly improve our understanding. This will be briefly discussed in §2. Perhaps even more exciting is the fact that we will be detecting GWs that were generated in a regime of strong gravity in which GR has not been tested. GR has stood up robustly to many experimental tests since it was formulated, but these tests have been performed primarily in situations in which gravity is weak. GW observations will enable us to do precise tests of the predictions of GR in the strong-field, high-curvature regime in the vicinity of black holes. These observations might provide further confirmation of the theory, or indicate a breakdown that will stimulate the development of an improved theory. A discussion of how GW observations might be used to test the aspects of relativity theory is the main focus of this paper and can be found in §3.

2. Astrophysics with GWs

Ground-based detectors are searching for GWs from the inspiral and merger of compact stellar remnants (neutron stars or black holes), from rotating neutron stars, and from transient ‘burst’ events (e.g. stars collapsing in asymmetric supernova explosions or vibrating ‘cosmic strings’) and that are relic GWs that were produced at very early times in the Universe. Neutron stars and black holes are the endpoints of stellar evolution. Merger observations will tell us about the numbers and masses of such objects, which are important indicators of the distribution of masses of stars in the Universe, and of the details of stellar
evolution. Many of these systems are dark, i.e. they do not emit light, and so GWs will provide information that cannot be obtained by other means. GWs from rotating neutron stars and the signature of the disruption of a neutron star at the end of an inspiral could tell us about neutron star structure, while GW burst events will tell us about the asymmetries in supernova explosions. In both these situations, the physics is complicated and poorly understood at present, which means that any GW observations will provide unique new information. Finally, relic gravitational radiation left over from the early Universe is expected to be very weak in the 1 mHz–1 kHz frequency range and so it is unlikely to be detected by either ground-based interferometers or LISA. However, some non-standard scenarios that rely on new physical processes do predict an observable background (Hogan 2006), and so if we do see a signal it will dramatically change our understanding of that epoch. More information about sources for ground-based GW detectors can be found on the Web (see the websites of the various ground-based detectors as listed in §1) and in Thorne (1998).

Space-based detectors will search for GWs from merging supermassive black holes, from compact object (white dwarf or neutron star) binaries in our own Galaxy with periods less than a few hours and from the extreme-mass-ratio inspirals (EMRIs) of approximately stellar-mass compact objects (white dwarfs, neutron stars or black holes) into supermassive black holes in the centres of galaxies. Most galaxies are believed to contain supermassive black holes, and when galaxies merge these black holes will eventually also merge, producing a signal that LISA can see. LISA will be able to detect these events almost wherever they occur in the Universe and is expected to observe as many as a hundred such systems over the mission lifetime (Sesana et al. 2007). This will provide important information about galaxy evolution and the rate of galactic mergers. The LISA observations will be able to determine the masses and angular momenta of the merging black holes to a fraction of a per cent, which will revolutionize our understanding of astrophysical black holes (the most accurately known black hole masses have estimated errors of approx. 50%, and no angular momenta are known well). These systems could also serve as ‘standard candles’—LISA observations will determine the system parameters well enough that the intrinsic brightness of the source will be known. The observed apparent brightness then tells us the distance to the source very accurately, from which we can learn about the material (e.g. dark matter and dark energy) that makes up the Universe on large scales (e.g. Dalal et al. (2006) and references therein). EMRI observations will also measure the system parameters to accuracies of a fraction of a per cent, and LISA could see several hundreds of those sources (Gair et al. 2004). This will provide complementary information about black holes in the nearby Universe, plus information about the properties of stellar clusters in galactic cores, including the distribution of types and masses of compact objects. Finally, the LISA observations of hour-period compact binaries in the Milky Way will provide a detailed census of such binaries that will constrain models of stellar populations and evolution. Several LISA binaries are already known from optical observations (these are termed ‘verification’ binaries, as we can use them to verify that LISA is performing as expected), but LISA will increase the number of known systems by orders of magnitude.
3. Fundamental physics with GWs

It was realized in the 1970s that measurements of GWs would provide a powerful test of the nature of gravity (Eardley et al. 1973), since one of the fundamental properties of the GWs—the possible polarization states—could differ if GR was not correct. A practical means of making such a measurement for GWs generated by oscillations in the Sun, using a LISA-like detector, was suggested by Finn (1985). Since then, many other ways to test fundamental physics with GWs have been suggested. In this paper, I will focus on tests using EMRI observations, although I will also briefly mention tests that will use supermassive black hole inspiral and merger observations. An interested reader can find a comprehensive review of many different techniques for testing alternative theories of gravity in Will (2006).

(a) Holiodesy

As well as being useful for astrophysics, EMRIs are an ideal tool for probing black hole space–time structure. The extreme mass ratio ensures that the inspiralling body (IB) acts, on short time scales, like a test particle following geodesics of the background curvature caused by the central object (CO). We expect the orbits of EMRIs to be both eccentric and inclined to the equatorial plane of the CO, and over a LISA observation (typically, the last few years prior to plunge into the CO) the orbit will inspiral significantly, which means that the IB explores the full three-dimensional volume outside the CO. The motion of the body thus encodes a map of the structure of the space–time close to the CO, and this motion in turn is encoded in the GWs that are emitted. An EMRI orbit and gravitational waveform are depicted in figure 2. A simple way to understand how this mapping can work is to imagine a clock attached to the IB, emitting a signal at regular intervals. As the IB moves relative to the observer, the pulses take more or less time to arrive. The pulse timing thus approximately maps out the position and velocity of the particle, which maps out the orbit. In reality, this picture is too simplistic since the GWs do not really originate at the IB, but come from the whole region near the CO. Nonetheless, both the characteristic frequencies of the instantaneous geodesic orbit and how the orbit evolves as the inspiral proceeds are encoded in the emitted GWs. Using EMRI observations to map out space–time structure in this way is referred to as holiodesy by analogy with geodesy, in which satellite tracking is used to map out the (Newtonian) gravitational field of the Earth. If the CO is what we expect, i.e. a supermassive rotating black hole, this map provides us with the parameters of the system to the high precisions described in §2. If this expectation is wrong, then GW observations should be able to disprove it.

An observation of a system that is not what we expect will not necessarily provide proof that GR is incorrect, since our expectation is built on several assumptions: (i) the CO is a supermassive rotating black hole and hence has external structure given by the ‘Kerr metric’ of GR, (ii) the space–time external

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1 The term ‘holiodesy’ was coined by Marc Favata as an alternative to ‘bothrodesy’ proposed by Sterl Phinney. A history of this term can be found in Collins & Hughes (2004).
to the CO is vacuum, and (iii) GR is the correct theory of gravity. Interpretation of the observations will thus be quite challenging, but in the following sections I shall present some current ideas on what we might learn.

(i) Testing the ‘no-hair’ property

In Newtonian gravity, the potential $\phi$ due to a mass $m$ at a distance $r$ is simply $\phi \propto m/r$. The potential of a distribution of masses is obtained by adding up the potentials for each element in the distribution. At large distances, this net potential can be written as a sum of terms that fall off with radius $R$ at different
rates. The leading term is just $M/R$, where $M$ is the total mass of the system. The second term takes the form $Q/R^3$, where $Q$ is the mass quadrupole moment of the system (closely related to the moment of inertia) and so on. It is possible to do something analogous in GR: the asymptotic field in a vacuum, axisymmetric space–time can be decomposed as a sequence of mass multipoles, $M_l$, and current multipoles, $S_l$ (Geroch 1970; Hansen 1974). The current multipoles are associated with flows in the mass distribution and are absent in the Newtonian limit. Under certain assumptions (vacuum; axisymmetric; stationary, i.e. not changing with time; the presence of a horizon, i.e. an infinite-redshift surface from inside which information cannot propagate to an observer far from the system; and non-existence of closed time-like curves, i.e. no time travel), it has been proven that the Kerr metric is the unique solution of the GR field equations (Carter 1971). The cosmic censorship hypothesis (CCH) embodies the expectation that all singularities, i.e. points of infinite density, will be enclosed within a horizon (Penrose 1969), and hence that the Kerr metric will be the unique end state of gravitational collapse to a black hole. The Kerr metric is characterized by just two parameters—these are the two lowest multipole moments, the mass, $M_0$, and spin, $S_1$, of the black hole. The uniqueness of the Kerr solution as the end state of gravitational collapse is sometimes referred to as the ‘no-hair theorem’, since all higher multipole moments (‘hair’) of the Kerr metric are determined by these two lowest multipoles,

$$M_l + iS_l = M_0(iS_1/M_0)^l.$$  \hspace{1cm} (3.1)

Geodesic orbits in the Kerr space–time have three integrals of motion and are hence triperiodic. The three frequencies are the orbital frequency plus the frequencies of precession of the direction to periapsis (i.e. distance of the closest approach to the CO) and of the orbital plane. The observed GWs will also be triperiodic on short time scales, and the three frequencies will evolve as the inspiral proceeds. If the orbit is nearly circular and nearly equatorial, the two precession frequencies can be thought of as the frequencies of small (epicyclic) oscillations about the circular orbit in the radial and vertical directions, respectively. For such an orbit in an arbitrary space–time (in GR), the precession frequencies can be written as an expansion, $\Omega_p = a_0\Omega^{a_0} + a_1\Omega^{a_1} + \cdots$, in the orbital frequency, $\Omega$. The different multipole moments first enter the coefficients in this expansion, $a_i$, at different orders, $\alpha_i$ (Ryan 1995). In principle, such an expansion can be extracted from the frequencies measured by GW observations, allowing the multipole moments to be determined successively. If three moments are measured independently, consistency with equation (3.1) can be checked. A LISA observation should be able to simultaneously determine the first three multipoles with accuracies of a fraction of a per cent, allowing a strong (non-)confirmation of the Kerr nature of the object (Collins & Hughes 2004; Barack & Cutler 2007). The generalization of this idea to inclined and eccentric orbits introduces complications, since the additional orbital parameters (eccentricity and inclination) are not directly observable and must be simultaneously inferred from the observed frequencies (Gair et al. 2008). However, multipole moment extraction should still be possible (Barack & Cutler 2007).

The space–time structure is encoded not only in the precession frequencies, but also in the waveform structure and the rate at which energy is lost to GW emission. In some ways, these are ‘dirtier’ observables, as to use them requires
detailed modelling of GW emission in an arbitrary space–time. For some space–
times, geodesic motion is no longer guaranteed to be triperiodic. Observing
chaotic motion would be a clear ‘smoking gun’ for a deviation from the Kerr
metric, although I do not think that this is very likely to be seen in reality (Gair
et al. 2008). If we do identify a CO as being inconsistent with the Kerr metric, it
is important to realize that this does not contradict the no-hair theorem, which is
a mathematical theorem proven under certain assumptions. An observational
inconsistency indicates the failure of one or more assumptions: the space–time is
not vacuum or there is no horizon in the system (i.e. there is a ‘naked
singularity’, which would be a counter-example to the CCH) or GR is not the
correct theory of gravity.

(ii) Measuring properties of the CO

In principle, two different COs could have the same external space–time
structure. However, GW observations will also be able to probe the internal
structure of the CO. Whatever the nature of the CO, the IB will interact with it
tidally—the gravitational influence of the small IB creates a deformation of the
CO, in the same way that the Moon causes tides on the Earth. The tidal
interaction can be thought of in terms of energy being lost from the orbit and
absorbed by the CO (figure 3). The amount of energy carried away by GWs
propagating outwards to infinity depends primarily on the external space–time
structure and only weakly on the exact nature of the CO (Li & Lovelace 2008). If
the external space–time structure is determined from the precession rates, this
can therefore be predicted. The energy being lost from the orbit determines the
rate at which the IB’s orbit decays and hence can also be inferred by a remote
observer. The difference between the predicted and inferred rates of energy loss
measures the energy going into the tidal interaction and is therefore a direct
probe of the CO. Information about the CO also comes from the final stages of
the inspiral. A black hole has a horizon, and so the emission will cut off rapidly as
the IB reaches the last stable orbit and then plunges through the horizon into the
black hole. If the CO is something else, e.g. a boson star, the transition to plunge
will be different and emission may even persist for a period while the IB is passing
through the material of the CO (Kesden et al. 2005).

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(iii) Identifying the presence of external material

If material is present in the space–time external to the CO, this will produce an additional gravitational field that can perturb the orbit of the IB (figure 4). Observations of active galactic nuclei indicate that many supermassive black holes are accreting material from discs (e.g. articles in Barger 2004). A disc could leave a measurable imprint on the trajectory, but only if its density is implausibly high. Moreover, the effect can be partially mimicked by varying the mass and spin of the CO, i.e. we cannot distinguish a Kerr black hole with a disc from a slightly different Kerr black hole without a disc (Barausse et al. 2007). Material could also accrete onto the IB, creating a hydrodynamic drag. This is more likely to leave a small measurable imprint on the signal (Barausse & Rezzolla 2007). In either case, the effect of an external matter distribution is qualitatively different from the effect of an internal difference in the CO, and so we should be able to distinguish a failure of the no-hair property from the presence of matter in the system.

The multipole moment decomposition described above applies only to vacuum regions of the space–time and no generalization to non-vacuum situations is known at present. If these ideas can be generalized, and we observe a system in which the IB is passing through some external material, the space–time structure inferred from the observed GWs will tell us the energy and momentum distribution of that material. There are various energy conditions in relativity that we believe all physical material should satisfy, e.g. that the energy density is positive and that observers never see material exceeding the speed of light. It may be possible to use GW observations to test whether these conditions are obeyed or we are observing systems that contain a kind of exotic matter.

(iv) Testing alternative theories of gravity

An algorithm for analysing observations of EMRIs is illustrated in figure 5. The starting point is that the space–time is what we expect, i.e. a vacuum, axisymmetric space–time consistent with relativity. We can extract the
multipole moments from the observation and hence determine the space–time metric. Given the space–time structure, and the assumption that GR is the theory of gravity, we can then compute the expected gravitational waveform and rate of energy loss and compare with the observations. It is known that the Kerr metric is not unique to GR (e.g. Psaltis et al. 2008), but if the theory of gravity is different, its dynamical properties, i.e. the response of the space–time to a perturbation by the IB, will differ and so the emitted GWs will be different. If we find an inconsistency, we relax the first assumption that the space–time is vacuum. The analysis can then be repeated assuming that matter is present. If the observations are still inconsistent, we relax the assumption that GR is correct and consider alternative theories of gravity. If the observations are consistent, we can carry out the various tests outlined above—check the no-hair property of the multipoles; look for the existence of a horizon; compute the tidal interaction; or test the energy conditions.

Testing the observation for consistency with an alternative theory of gravity requires two things: (i) a viable alternative theory and (ii) computation of gravitational waveforms in the alternative theory. One possible alternative to GR is ‘scalar–tensor gravity’, in which the usual (tensor) gravitational field is coupled to an additional scalar field (which can be thought of as something similar to a temperature distribution pervading space). The simplest version of this, Brans–Dicke theory, depends on a single parameter, $\omega$, which measures the strength of the coupling between the scalar and tensor fields. Standard GR is

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Figure 5. A possible algorithm for testing relativity using EMRIs. Black arrows refer to the first iteration of tests, assuming a vacuum space–time, while red arrows refer to the second iteration, assuming non-vacuum. The question mark above the red arrow indicates that no method is presently known for extracting the metric from observations of inspirals in a non-vacuum space–time.

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recovered in the limit $\omega \to \infty$. A LISA–EMRI observation could put a constraint as high as $\omega > 10^5$ (i.e. if $\omega < 10^5$ there would be a detectable difference in the observed signal). This can be compared with the current constraint, based on observations of planetary motions in the Solar System, that $\omega > 4 \times 10^4$ (see Berti et al. (2005) and references therein). Although these numbers are comparable, the LISA observation will probe a vastly different scale of gravity, and will therefore be a powerful probe of the gravitational theory in a new curvature regime. A more general scalar–tensor theory is ‘$f(R)$ gravity’ (Barrow & Ottewill 1983), which has been invoked to explain the observed acceleration in the rate of expansion of the Universe. It should also be possible to constrain this theory in a new regime using GW observations, although such constraints have not yet been investigated.

(b) Mergers of supermassive black hole binaries

The preceding discussion has focused on probing physics using observations of EMRIs. The merger of two black holes also produces a characteristic signal that might be used as a probe of GR. The merger at the end of an EMRI is too weak to be individually detected, but LISA should also detect GWs from mergers between pairs of comparable-mass supermassive black holes (each component with mass about a million times that of the Sun). During the merger alone, such systems emit energy in GWs at a rate that exceeds the combined electromagnetic radiation emitted by all the stars in the observable Universe. LISA will detect these mergers very clearly. GR is a highly nonlinear theory—mass/energy generates curvature, which in turn modifies the energy density and thus affects the curvature—and the merger radiation depends on all the complex nonlinearities in the theory. Recent breakthroughs (beginning with Pretorius 2005) have allowed accurate numerical simulations of mergers to be computed for the first time. It should thus be possible to compare these detailed predictions with what we observe with LISA, and look for any deviations that might indicate a failure in the theory.

In addition, observations of supermassive black hole inspirals and mergers can be used as standard candles to test our models of the large-scale structure of the Universe, as described in §2. These observations can also be used to test Hawking’s ‘area theorem’ (Hawking 1971) and to look for ‘parity’ violations. The area theorem states that, during a merger, the surface area of a black hole event horizon should increase and, therefore, the surface area of the black hole remnant after the merger should exceed the sum of the surface areas of the two pre-merger black holes. GW observations will determine the parameters of all three black holes with sufficient accuracy that a test of this theorem can be carried out. Regarding parity, a GW can be decomposed into a combination of a ‘left’ and a ‘right’ circular polarization state. Referring to the ring of test particles in the inset of figure 1, the deformation of the ring would appear to rotate under the influence of a circularly polarized wave. The direction of this rotation is different for left and right modes. In GR, these two modes propagate exactly in the same way. However, in some alternative theories, inspired by string theory, this parity is broken and the two modes propagate in different ways, leading to a net amplification of one polarization relative to the other. Over the distances to the furthest merger sources that LISA could
see, this effect can accumulate sufficiently to leave an observable signature, allowing a test for the presence of such a ‘Chern–Simons’ correction to gravity (Alexander et al. 2007). A further test of GR can be carried out by observing ‘ringdown’ radiation emitted by the remnant black hole after a merger, as it settles back down to an equilibrium state. Ringdown GWs can be used to test the no-hair property of the remnant black hole if at least two different modes are observed from the same system (Berti et al. 2006). Observations of supermassive black hole inspiral, merger and ringdown radiations will thus provide further stringent tests of relativity theory, which will complement the tests from EMRI observations.

4. Prospects for the future

The first direct detections of GWs should be made within 10 years by the enhanced LIGO or Advanced LIGO/Virgo+ interferometers (due online in ca 2009 and ca 2014, respectively). These initial observations will provide direct verification of the existence of GWs. Within 15 years, GW observations should be routine, both in ground-based detectors and in the first generation of space-based detectors (LISA). On a longer time scale (approx. 20–30 years), there will be a third generation of ground-based detectors and probably a future space mission. These detectors will be capable of carrying out a census of all compact object binaries out to very great distances and of detecting relic GWs generated in the first second of the existence of the Universe. Moreover, the ground-based detectors will be measuring such small displacements of the test masses that quantum-mechanical effects will be important, and these instruments will provide a first means to probe quantum mechanics in macroscopic systems. The first scientific pay-offs of GW observations will be astrophysical—counting the number of events that occur, estimating the system parameters and using these to constrain models of astrophysical processes occurring in the Universe. Beyond that we will begin to use these observations to do detailed tests of GR, as outlined in this paper. This will either provide further confirmation of the theory in a new and untested regime, or indicate when and how the theory breaks down. Either result will be a vital ingredient in one of the central goals of modern physics, namely unifying the force of gravity with quantum mechanics.

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