Gravitational-Wave Astronomy with the Next-Generation Earth-Based Observatories

Exploring the Universe from Planck to Hubble Scales

GWIC, GWIC-3G, GWIC-3G-SCT-Consortium
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Gravity, Spacetime and Gravitational Waves

The nature of space and time has fascinated the human intellect for millennia. In the 17th century Newton laid out the first concrete notions in his *Principia Mathematica* by asserting that space and time are immutable and not amenable to change due to external influence:

*Absolute, true, and mathematical time, of itself, and from its own nature, flows equally without relation to anything external.*  

*Absolute space, in its own nature, without relation to anything external, remains always similar and immovable.*

A cornerstone of Newtonian physics is the *principle of relativity* according to which the laws of physics are the same for all observers in relative motion. Specifically, spatial separations and time intervals between physical events are identical for all observers. This meant that the speed of light was different for observers depending on their relative motion. These notions were the guiding principles of physics for over two centuries and formed the basis for building the theory of gravitation.

At the beginning of the 20th century Einstein formulated the special theory of relativity in which the speed of light was the same for all observers as required by the decisive precision experiment of Michelson and Morley a few years before. The idea of absolute space and time was incompatible with special relativity in which spatial separations and time intervals depended on an observer’s motion. Furthermore, he soon realized that matter must alter the geometry of space and the flow of time. This eventually led him to a new theory of gravity, the general theory of relativity, according to which matter and energy warp spacetime\(^1\) and accelerated masses can create ripples in that distortion, called *gravitational waves*, that travel outward from their sources at the speed of light.

Large amplitude gravitational waves emanate from regions of strong gravity with masses moving at relativistic speeds, making them ideal for studying dynamical spacetimes. They interact weakly with matter and are hardly dispersed as they propagate from their sources to Earth; so the waves carry uncorrupted signature of their sources. A passing gravitational wave causes the rate at which clocks tick and physical distance between test masses to vary—the basic principle behind gravitational wave detectors. Gravitational waves were deemed responsible for the measured decrease in the orbital period of a pair of neutron stars discovered by Hulse and Taylor in 1976.

**Observation of Gravitational Waves from Binary Black Holes**

In 2015, National Science Foundation’s Laser Interferometer Gravitational-Wave Observatory (LIGO) made the first observation of gravitational waves. The waves were observed for 200 ms and came from the final stages of the inspiral and merger of a pair of black holes at a distance of 1.3 billion light years.

\(^1\) The warping of spacetime is evident in the operation of the GPS satellites whose clocks run slower because of their motion and faster because they experience weaker gravity relative to Earth’s clocks. If relativistic effects are uncorrected GPS satellites would fail to work properly within minutes.
Since that first discovery LIGO and the European Virgo detector have announced nine other confirmed detections of binary black hole mergers and a large number of candidates. These detections have led to multiple levels of investigation including new tests of Einstein’s theory of gravity and whether these black holes formed in the primordial universe and account for the elusive dark matter.

**Discovery of Binary Neutron Star Merger**

In August 2017 LIGO and Virgo made another monumental discovery, this time gravitational waves from the inspiral and coalescence of a pair of neutron stars. Fermi Gamma-ray Space Telescope and the International Gamma-Ray Astrophysics Laboratory, both observed short gamma ray bursts 1.7 s after the gravitational-wave signal, thus confirming the long-held conjecture that merging binary neutron stars are progenitors of short gamma ray bursts. The LIGO–Virgo alert triggered an observational campaign by some 70 telescopes all over the world, leading to the identification of the host galaxy, followed by detection of the source in X-rays, UV, optical, infra-red, and radio in the following hours and weeks. These observations are already providing clues to some of the long-standing problems in relativistic astrophysics, while raising new ones that require louder signals and a larger sample.

**Beyond Advanced Detectors**

In 2008-2011, the design study of a third generation (3G) gravitational-wave observatory in Europe named Einstein Telescope (ET) developed the concept of a triangular interferometer with sensitivity a factor of \( \sim 20 \) better than Virgo and low-frequency sensitivity down to 1-3 Hz. A similar effort is currently underway in the US to study the science case for and the feasibility of a 3G network including a 40 km arm length interferometer called Cosmic Explorer (CE) with strain sensitivity similar to ET. Figure 1, left plot, shows the planned strain sensitivity of ET and CE compared to the sensitivity of Advanced LIGO\(^2\). For the current study we assume that the 3G network consists of one Einstein Telescope at the location of Virgo \((\lambda = +43.6^\circ, \phi = +10.5^\circ, \theta_{XE} + 71^\circ)\), one CE each in the United States \((\lambda = +40.3^\circ, \phi = -113.7^\circ, \theta_{XE} + 25^\circ)\), and Australia \((\lambda = -31.5^\circ, \phi = +118.0^\circ, \theta_{XE} + 32^\circ)\), where \(\lambda\) and \(\phi\) are the latitude and longitude and \(\theta_{XE}\) is the counterclockwise angle from local east to the base of the triangle in the case of ET and x-arm of the interferometer in the case of CE.

### Science Targets for the Next Generation of Gravitational Wave Detectors

Until LIGO’s discovery electromagnetic waves were the only wave phenomena that was used to explore the Universe. Gravitational wave astronomy provides a complementary window that could reveal a whole new world. With a new generation of gravitational-wave detectors we will be able to:

- **explore** new physics in gravity and in the fundamental properties of compact objects,
- **determine** the properties of the hottest and densest matter in the Universe,
- **reveal** the merging black hole population throughout the Universe and search for massive black hole seeds,
- **understand** the physical processes and mechanisms that underlie the most powerful astrophysical phenomena,
- **investigate** the particle physics of the primeval Universe and probe its dark sectors.

The immense science potential of such a network is apparent in the distance at which it can observe compact merging binaries. In Figure 1 the right plot shows the distance from which the 3G network can observe gravitational waves from binary coalescences, it goes well beyond redshifts at which electromagnetic telescopes are able to observe individual sources. Consequently, the next generation of detectors offer

a unique window to earliest moments of the formation of structure in the Universe. In the next several paragraphs we summarize the science targets of the 3G network.

**Extreme Gravity and Fundamental Physics.**

Gravitational waves emanate from regions of strong gravity and large curvature, carrying uncorrupted information from their sources. Imprint in the signal is the nature of the gravitational field, characteristics of the sources and the physical environment in which they reside. Their observation in 3G detectors can put general relativity to the most stringent tests, help explore violations of the theory in strong fields such as the dynamics of black hole horizons, and discover properties of dark matter.

The 3G network offers numerous opportunities to discover failure of general relativity that could be seen, for example, in the form of new particles and fields that violate the strong equivalence principle, Lorentz invariance violations or variation in Newton’s constant imprint in the propagation of gravitational waves, presence of scalar fields around compact objects, and extra polarizations in addition to the two that occur in general relativity. One might also see the signature of quantum gravity, e.g., pseudo-scalar configurations that violate parity, whose signature would be seen in the dynamics of binary black holes, or birefringence of the waves propagating over great distances. Ultra-light Bosonic fields proposed in certain extensions of the Standard Model could be detected via their effect on the orbital dynamics of black hole binaries and spin properties of black holes.

Black holes are the most compelling explanation for the companion stars in binary coalescences discovered by LIGO and Virgo detectors. The tell tale signature of its presence would be seen in the quasi-normal mode spectrum of the merger remnant, whose frequencies and damping times should depend only on two parameters: the remnant’s mass and spin. Signature of additional degrees of freedom would be seen as inconsistency in the remnant’s parameters determined by the different modes. Certain alternatives to black holes could mimic the quasi-normal mode spectra, but they could emit additional signals in the form of echoes of the ingoing radiation reflected from their surface, which could be observable in the 3G network.

Big bang cosmology is largely consistent with general relativity but the accelerated expansion of the Universe in its recent history cannot be explained by the theory, indicating either its failure or the presence of exotic form of matter-energy density, of which we know very little. Observations on galactic to cosmological scale provide unequivocal indirect evidence for the presence of weakly interacting dark matter, but none has been directly detected in spite of concerted efforts over the past six decades. The 3G network might detect
various forms of dark matter including axionic and other dark matter fields around black holes and neutron stars, primordial black holes, etc.

**Extreme Matter, Extreme Environ**

Neutron stars are the densest objects in the Universe and sites of stupendously large magnetic fields, in some cases billions of Tesla. Six decades after their initial discovery we still lack a clear understanding of the equation of state of their deep cores and the origin of their strong magnetic fields. Neutron stars in a binary are subject to the tidal fields of their companions. Due to their exceptionally small size, the tides raised are extremely small but the extent of tidal deformation depends on the state of matter in neutron star cores. The net effect is to accelerate the rate of inspiral and coalescence of these systems and thereby modify the phase evolution of the observed gravitational waves. Moreover, the merger remnant could be a short-lived hypermassive neutron star that could reveal unknown physics in the state of ultra-high density matter, e.g. phase transition from nucleons to quark-gluon plasma.

The origin of heavy elements in the Universe has been a long-standing problem. Electromagnetic observation of GW170817 provided irrefutable evidence that binary neutron star mergers are sites of production of lanthanides and other heavy elements. 3G observatories will provide the unique opportunity to electromagnetically follow-up thousands of mergers, a number that is required to confirm if solar and stellar abundance of heavy elements can be explained by mergers alone or if other production channels are necessary.

3G observatories will detect binary neutron stars from an epoch when the rate of star formation in the Universe was greatest. Millions of mergers expected to be detected by the 3G network, the properties of the detected sources and the environments in which they occur will provide key data to test astrophysical models of the formation and evolution of double neutron star and black hole-neutron star binaries.

GW170817 resolved that binary neutron star mergers are progenitors of short, hard gamma-ray bursts. Nevertheless key questions about central engines that produce gamma rays still remain. For example, we do not have a clear picture of the jet properties nor how those properties depend on the progenitor characteristics. As before, what is required here is the electromagnetic follow-up of a large population of mergers to better understand the physics of gamma-ray jets, the opening angle of the jet and its distribution. There is also the question of the fate of the merger remnant in the case of binary neutron stars: is it a transient hypermassive neutron star, how long does it last, what properties of the progenitor binary determines the fate of the remnant? These are some of the pressing questions in astrophysics that could be clearly addressed the 3G network by directly observing gravitational waves from the remnant.

**Observing Stellar-mass Black Holes Throughout the Universe.**

The 3G network of ET and CE will have sensitivity to sources nearly all over the sky. They can detect binary black holes at redshifts of $z \sim 20$ over the total mass range $10–100 \, M_\odot$, and mergers of even higher-mass systems at $z \sim 0.3–20$ (see Figs. 1 and 2). This immense reach makes it possible to obtain a complete census of stellar mass black holes, starting from an epoch when the Universe was still assembling its first stars.

The merger rate of binary black holes inferred from Advanced LIGO and Virgo imply that the 3G network will detect millions of mergers each year. This large population will help us study the merger rate and the underlying star formation rate as a function of redshift up to the beginning of the epoch of reionization. It will also help us explore how these rates are correlated with metallicity and galaxy evolution.
GW150914 was not only the first discovery of gravitational waves, it was the first ever discovery of heavy black holes with masses in excess of 20 solar mass. It was widely believed that irrespective of how massive a star is the black hole that results from it would be less than about 20 solar mass. The larger companion in GW150914 was at least 32 solar mass. Understanding how heavy and massive black holes (in excess of millions of solar mass) form and evolve is an outstanding problem which can be squarely addressed by the 3G network.

There are many competing models of compact binary formation and evolution. Black holes that form in isolation in globular clusters might sink into the dense cluster cores, where they dynamically interact with other holes to form coalescing binaries. Alternatively, binaries of massive stars formed in active star formation sites could directly evolve into binary black holes that merge within the Hubble time. It is also possible that heavy black holes that formed in the primeval Universe as a result of large density fluctuations now reside in galactic halos and occasionally form merging binaries when they randomly find each other in the halo. This last scenario is particularly attractive as primordial black holes have long been thought to be a candidate for dark matter. The 3G network will pin down mass and spin demographics of black holes, determine principal formation channels and resolve fundamental questions about their origin.

Sources at the Frontier of Observations

The physics of supernovae, stellar glitches and quakes is an open problem in astrophysics. Many of these systems will generate gravitational waves that will be observable with 3G detectors at distances of several million light years for supernovae and within the galaxy for quakes in pulsars and glitches in magnetars. Multimessenger observations of these systems with the 3G network, enhanced by EM and neutrino observatories, will allow us to probe extreme astrophysics and address key questions that have hindered progress in our understanding of the mechanism behind stellar explosions.

From the observed spectrum of gravitational waves it will be possible to determine the physics of core collapse supernova, the different phases of the collapse and explosion that dominate production of gravitational waves, and the asymmetry of the collapse and what triggers that asymmetry. Information about the rotation rate of the progenitor star is also encoded in the observed signal and it should be possible to understand how the initial state of the progenitor star determines the final state of the collapse, a black hole or a neutron star. Such observations will be greatly aided by all sky optical and infrared surveys of the stellar population in nearby galaxies, as well as cosmic rays and neutrinos.

Isolated neutron stars could emit gravitational waves if they are not spherical and don’t rotate about their symmetry axis. Indeed, they are persistent sources with the emission lasting for millions of years. Advanced detectors are not likely to detect continuous waves from known pulsars, although all-sky blind searches may reveal hitherto unexpected sources. The 3G network could observe neutron stars whose polar and equatorial radii differ by no more than 10 to 100 microns. This will provide invaluable information about their crustal strengths and the equation of state of high density nucleons in their outer cores.

Accreting neutron stars, such as those in low-mass x-ray binaries, could acquire deformations from the infalling matter that could lead to a perpetual source of gravitational radiation. Indeed, the 3G network will help resolve if the accretion torque balanced by gravitational-wave back reaction is responsible for the observed limiting spin frequencies of neutron stars in low-mass x-ray binaries. The 3G network will also
probe the role of magnetic fields in transient radio emission from magnetars and if the mechanism is caused by crustal quakes resulting in the emission of gravitational waves. This could further constrain the equation of state of ultra dense matter.

**Cosmology and Early History of the Universe.**

The geometry and expansion rate of the Universe can be inferred by measuring distances and redshifts to sources at cosmological distances of several billion light years. Gravitational waves from the inspiral and merger of compact binaries can be used to infer the luminosity distance to their sources without the need to calibrate them with standard candles. This is because the orbital dynamics of binary black holes and neutron stars is largely determined by Einstein’s theory of gravity.

A handful of parameters, e.g. masses and spins of the companion stars, precisely control the pattern of the emitted gravitational waves. The amplitude of that pattern is fixed by the distance to the source, sky position and orientation of the source relative to a detector, which can be inferred with a network of three or more non-collocated detectors. This contrasts with the dynamics of other astrophysical systems, such as supernovae, that require detailed modelling of their composition and environment, making it extremely hard to predict the emitted gravitational wave signal with any precision. Consequently, with a population of compact binary mergers observed with 3G detectors, and their redshifts obtained by follow up electromagnetic observations, it will be possible to accurately measure cosmological parameters such as the Hubble parameter, dark matter and dark energy densities and the equation of state of dark energy, giving a completely independent and complementary measurement of the dynamics of the Universe.

Cosmological population of point sources create a stochastic background of gravitational waves. Indeed, advanced interferometers are expected to detect the confusion background created by binary black holes and neutron stars by cross correlating data from two or more detectors. It will be possible to learn about the history of the formation and evolution of these sources and the underlying stellar population. 3G detectors can identify every binary black hole merger and most binary neutron star mergers in the Universe, giving us a treasure trove of data to study the large scale distribution of galaxies and their clusters.

Stochastic gravitational waves are expected to be produced in the early Universe. As the Universe cools from its primeval hot and dense phase it undergoes several phase transitions that are expected to generate a gravitational-wave background. Detection of such a background would dramatically transform our state of knowledge of the underlying particle theory at energy scales that will never be accessible in terrestrial accelerators. Defects, such as cosmic strings, associated with symmetry breaking and phase transitions could also be source of stochastic or deterministic sources. The landscape of cosmic sources of gravitational waves while uncertain is a high-risk high-reward endeavor to pursue in the era of 3G detectors.

**Summary**

LIGO and Virgo detections have ushered in the new era of multi-messenger physics and astronomy. Gravitational-wave observations can be used for understanding not just the sky but also to test general relativity in dynamical spacetimes, to gain insights into the nature of matter under extreme physical conditions of gravity, density, and pressure, to discover the nature of dark matter, dark energy and other exotic objects, to explore the nature of most violent processes in the Universe, to study the formation and evolution of stellar mass black holes throughout the Universe and to probe the physics of the early history and evolution of the Universe. The science case for building a new generation of gravitational wave detectors that can probe deep into the cosmos and observe a verity of different processes is immensely rich and massively rewarding.
# Acronyms & abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>3G</td>
<td>Third-generation, the next generation of ground-based gravitational-wave observatories consisting of 1 ET in Europe, 1 CE each in the US and Australia</td>
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<tr>
<td>BAO</td>
<td>Baryon Acoustic Oscillations</td>
</tr>
<tr>
<td>BBH</td>
<td>Binary Black Hole, a binary system of two black holes</td>
</tr>
<tr>
<td>BH</td>
<td>Black Hole</td>
</tr>
<tr>
<td>BNS</td>
<td>Binary Neutron Star, a binary system of two black holes</td>
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<tr>
<td>CE</td>
<td>Cosmic Explorer, concept for a US third generation interferometer with 40 km arms</td>
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<td>CMB</td>
<td>Cosmic Microwave Background</td>
</tr>
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<td>ECO</td>
<td>Exotic Compact Object, an alternative to a neutron star or a black hole</td>
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<tr>
<td>EM</td>
<td>Electromagnetic</td>
</tr>
<tr>
<td>ET</td>
<td>Einstein Telescope, concept for a European triangular shaped interferometer with 30 km arms</td>
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<tr>
<td>GR</td>
<td>General relativity</td>
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<tr>
<td>GSF</td>
<td>Gravitational Self-Force</td>
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<td>GW</td>
<td>Gravitational Wave</td>
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<tr>
<td>GW150914</td>
<td>Binary black hole merger event detected on 14 September 2015</td>
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<td>GW151226</td>
<td>Binary black hole merger event detected on 26 October 2015</td>
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<td>GW170104</td>
<td>Binary black hole merger event detected on 4 January 2017</td>
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<td>GW170814</td>
<td>Binary black hole merger event detected on 14 August 2017</td>
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<td>GW170817</td>
<td>Binary neutron star merger event detected on 17 August 2017</td>
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<tr>
<td>INTEGRAL</td>
<td>International Gamma-Ray Astrophysics Laboratory</td>
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<td>LIGO</td>
<td>Laser Interferometer Gravitational-Wave Observatory, 4 km arm length interferometers in the US at Hanford WA and Livingston LA</td>
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<tr>
<td>LIGO-India</td>
<td>LIGO interferometer being built in India</td>
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<td>LISA</td>
<td>Laser Interferometer Space Antenna</td>
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<td>NR</td>
<td>Numerical Relativity</td>
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<td>NS</td>
<td>Neutron Star</td>
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<tr>
<td>NSBH</td>
<td>Neutron Star–Black Hole, a binary system of one neutron star and one black hole</td>
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<td>PM</td>
<td>Post-Minkowskian</td>
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<td>PN</td>
<td>Post-Newtonian</td>
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<tr>
<td>QCD</td>
<td>Quantum Chromodynamics</td>
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<tr>
<td>SASI</td>
<td>Standing Accretion Shock Instability</td>
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<tr>
<td>SM</td>
<td>Standard Model of particle physics</td>
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<tr>
<td>SN</td>
<td>Supernova</td>
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<tr>
<td>SNR</td>
<td>Signal-to-noise ratio</td>
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<tr>
<td>Virgo</td>
<td>3 km arm length interferometer located in Cascina, Italy</td>
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1. Extreme Gravity and Fundamental Physics

**Science Target**

*Explore new physics in gravity and in the fundamental properties of compact objects*

In general relativity (GR), gravitational waves (GWs) are non-stationary solutions of Einstein’s equations arising as a result of time-varying quadrupole and higher-order multipole moments that translate into freely propagating oscillations in the fabric of spacetime [1]. They emanate from regions of strong gravity and relativistic motion, yet the waves carry uncorrupted physical signatures of their sources. They interact very weakly with matter and are hardly dispersed as they propagate from their sources to Earth, making them ideal for studying the dynamics of spacetime geometry [2, 3].

On September 14, 2015 the twin LIGO instruments at Hanford and Livingston made the first observation of GWs [4]. Dubbed GW150914, the waves were observed for \( \approx 200 \text{ ms} \) and came from the final stages of the inspiral and merger of a binary black hole (BBH) system at a distance of \( \approx 450 \text{ Mpc} \). To date the LIGO detectors in the USA and Virgo in Italy have detected ten BBH mergers [5] that have probed strong-field gravity for the first time at unprecedented precision [6].

On August 17, 2017 LIGO and Virgo made another monumental discovery, this time the inspiral and coalescence of a pair of neutron stars (NSs) [7]. The *Fermi Gamma-ray Space Telescope* and the *International Gamma-Ray Astrophysics Laboratory (INTEGRAL)*, both observed short gamma ray bursts 1.7 s after the GW signal [8], thus confirming the long-held conjecture that merging binary neutron stars (BNSs) are progenitors of short gamma-ray bursts.

**Key Science Goals**

Future gravitational-wave observations will enable unprecedented and unique science in *extreme gravity and fundamental physics*, that form the core topics of the Thematic Area 7 of Astro-2020 decadal survey.

- **The nature of gravity:** Can we prove Einstein wrong? What building-block principles and symmetries in nature invoked in the description of gravity can be challenged?
- **The nature of dark matter:** Is dark matter composed of particles, dark objects or modifications of gravitational interactions?
- **The nature of compact objects:** Are black holes (BHs) and NSs the only astrophysical extreme compact objects in the Universe? What is the equation of state of densest matter?

These detections have ushered in a new era of fundamental physics. GW observations can be used for uniquely testing general relativity in dynamical spacetimes [9–12] and in providing insights into the nature of matter under extreme physical conditions of gravity, density and pressure [13–16]. Advanced LIGO and Virgo will only be first steps in this new endeavor that is guaranteed to change our perception of the Universe in the coming decades. Indeed, the 3G network of GW observatories consisting of the Einstein Telescope and...
Cosmic Explorer, will witness merging BHs and NSs when the Universe was still in its infancy, assembling its first stars and BHs. At such sensitivity levels we can expect to measure extremely loud events that could reveal subtle signatures of new physics. 3G observatories promise to deliver data that could transform the landscape of physics, addressing some of the most pressing problems in fundamental physics and strong gravitational fields.

1.1 Nature of Gravity.

Probing the nature of gravity and its possible implications on fundamental physics is a high-reward, even if uncertain, prospect of GW observations. To our knowledge, astrophysical BHs and relativistic stars exhibit the largest curvature of spacetime accessible to us. They are, therefore, ideal systems to observe the behavior of spacetimes under the most extreme gravitational conditions.

New physics indicative of departures from the basic tenants of GR could reveal itself in high fidelity waveforms expected to be observed in the next generation of detectors. Such signals would provide a unique access to extremely warped spacetimes and gain invaluable insights on GR or what might replace it as the theory of gravity governing such systems.

Figure 1.1 provides a perspective of the reach of different missions/facilities and their target regime with respect to characteristic spacetime curvature \( R \) and gravitational potential \( \Phi \) (which for binary systems can be equated with \( v^2/c^2 \), where \( v \) is the binary’s characteristic velocity and \( c \) the speed of light). To this end, beyond having access to the sensitivity and frequency windows of 3G detectors, guidance from theory, together with further refinements in data analysis, will be of utmost importance to harness this potentially revolutionary opportunity.

On the theoretical front [17, 18], a major challenge in extracting new physics with GWs is that, in principle, one needs to model the characteristics of the emitted signal for the desired physical scenarios beyond the framework of GR and then confront it with the data. The powerful perspective of effective field theory (e.g., Refs. [19–22]) allows one to build extensions to GR with higher-order corrections, and enables the search for unknown new physics, even before a new fundamental theory and its low-energy phenomenology is fully developed (see, e.g., Refs. [23–25]). Among possible departures under scrutiny are:

**New fields, particles and polarizations:** Lovelock’s uniqueness theorem in 4-dimensions [26] implies that departures from GR that preserve locality necessarily require the presence of extra degrees of freedom, which generically also arise from theories of quantum gravity in the low-energy limit. This often leads to violations of the strong equivalence principle through the fields’ nonminimal coupling with matter. Among possible theories, those with an additional scalar field are relatively simple [27, 28] yet could give rise to exciting new strong-field phenomenology [29, 30]. Together with examples of strong-field GW signatures in more complicated scenarios inspired by the low-energy limit of quantum gravity theories [31, 32] they also serve as
1.1 Nature of Gravity.

excellent proxies of the type of new physics we can hope to detect. In addition, if a binary’s constituents can become dressed with a scalar configuration [33–36], the system emits scalar waves in addition to tensorial ones, with the dominant component being dipolar emission [17], although this may be suppressed for massive fields [37, 38]. Extra polarizations can be detected directly [11], and indirectly inferred from their effects on the system’s dynamics and consequent impact on GWs [17].

**Graviton mass:** Recently, the possibility that gravitons could have a mass has resurfaced in theoretical physics within extensions of GR [39, 40]. The current best bound on the graviton mass from GWs through modified dispersion relations is $m_g < 5.0 \times 10^{-23} \text{eV}/c^2$ [6] and improvements of two orders of magnitude would be possible with the 3G network with detected sources $\sim 100$ times further away.

**Lorentz violations:** Lorentz symmetry is regarded as a fundamental property of the Standard Model of particle physics, tested to spectacular accuracy in particle experiments [41]. In the gravitational sector, constraints are far less refined. Theories with Lorentz invariance violation (e.g., Hofava–Lifschitz [42] and Einstein-æther [43]) give rise to significant effects on BHs [44, 45], additional polarizations [46], and the propagation of GWs (e.g., through dispersion and birefringence [47, 48]) which can be greatly constrained by 3G detectors that will observe sources at high redshifts of $z \sim 10–20$ [49].

**Parity violations:** Parity violations in gravity arise naturally within some flavors of string theory [50], loop quantum gravity [51] and inflationary models [21]. The associated phenomenologies are, to some degree, understood from effective theories [52]. For instance, they give rise to BHs with nontrivial pseudo-scalar configurations that violate spatial parity [53]. The resulting scalar dipole leads to a correction to the GWs produced in a binary inspiral and merger signal [54, 55, 31]. Additionally, parity violating theories can exhibit birefringence, thus impacting the characteristics of GWs tied to their handedness [49].

**Time variability of gravitational constant:** Gravitational theories have been presented that manifest a time-varying gravitational constant $G$, as well as breaking local position invariance. 3G detectors and their ability to capture signals from systems at redshifts as high as $z \sim 15$ would enable constraints on such variability that are 8 orders of magnitude beyond those that can be obtained with advanced LIGO and Virgo [9, 56]. It will also be possible to constrain $\frac{\dot{G}}{G}$ at the same level as globular clusters, pulsars, lunar ranging and Big Bang nucleosynthesis by calibrating supernova luminosities with compact binary mergers [57].

**Ultra-light Bosonic Clouds:** Ultralight bosons have been proposed in various extensions of the Standard Model [58]. When the Compton wavelength of such light bosons (masses of $10^{-21}$-$10^{-11}$ eV) is comparable to the horizon size of a spinning stellar-mass or supermassive black hole, superradiance can cause the spin to decay, populating bound Bohr orbits around the BH, with an exponentially large number of particles [59–61]. Such bound states, in effect gravitational atoms, have bosonic clouds with masses up to $\sim 10\%$ of the BH mass [62–64]. Once formed, the clouds annihilate over a longer timescale through the emission of coherent, nearly-monochromatic, GWs [62, 65].

Presence of such clouds could be detected via blind searches in the Milky Way [65–69] or directed searches aimed at a candidate BH, such as that formed in a merger event [65, 66, 70, 67, 71], or observations of a stochastic background from an unresolved population [68, 69]. Annihilation of such clouds can also impact a binary’s dynamics and thus the GWs produced during the inspiral [72].

Such a modified GW signal is a promising target for 3G detectors with a few to hundreds of events per year expected for bosons in the $\sim 10^{-13}$–$10^{-12}$ eV range [66]. Measuring the spin and mass distribution of merging BBHs can provide evidence for characteristic BH spindown from superradiance [66, 67], which would allow exploration of new parameter space for ultralight bosons [73]. In addition, the presence of such clouds can be probed through the imprint of finite-size effects on the compact objects in a binary system [72]. Some dark-matter candidates alternative to weakly interacting massive particles (e.g., fuzzy dark matter [74], axion-like particles, and other ultralight bosons [58]) predict exotic compact objects (ECOs; see below) either in the form of boson stars or in the form of condensates that form spontaneously due to BH superradiant instabilities.

**Large, non-local, quantum effects:** Semi-classical arguments have been put forward to support the pos-
sibility of exotic states of matter or dressed compact objects with further structure stemming from quantum gravitational origin. Examples of electromagnetically dark but horizonless compact objects include fuzzballs [75, 76], gravastars [77], dark stars [78, 79], and others [80, 81]. Additionally, new non-local physics at the horizon scale has been suggested by firewall arguments [82] as well as other quantum effects [83–86].

Various scenarios described above can generically give rise to signatures that can potentially be detected. GWs provide a unique window to these arguably speculative ideas, with far reaching consequences if observed. The following section describes key phenomenology that can arise and the extent to which they can be uniquely probed by 3G detectors.

### 1.2 Nature of Compact Objects.

Observational evidence so far suggests that compact massive objects in the Universe exist in the form of BHs and NSs.

Binary systems composed of such objects provide ideal scenarios to unravel both astrophysical and fundamental physics puzzles such as elucidating the connections of strong gravity with the most energetic phenomena in our Universe, exploring the final state conjecture [87] (namely, the end point of gravitational collapse is a Kerr BH), and probing the existence of horizons.

**Nature of black holes:** Black holes in isolation are the simplest macroscopic objects in the Universe. Astrophysical black holes are electrically neutral and are described by just two parameters—their mass and spin angular momentum.

A perturbed BH returns to its quiescent state by oscillating with its characteristic quasi-normal modes, whose frequency and decay time are uniquely determined by the two parameters. By detecting several quasi-normal modes 3G detectors can facilitate multiple null-hypothesis tests of the Kerr metric [88–95]. As shown in Fig. 1.2, 3G detectors largely improve the precision of those tests with respect to advanced LIGO and Virgo for a single event. The precision can be further increased combining multiple events.

**Beyond black holes:** From a phenomenological standpoint, BHs and NSs are just two species of a larger family of compact objects. More exotic species are theoretically predicted in extensions to GR, but also in particular scenarios within GR [86, 96]. For instance, ECOs arise from beyond-standard model fundamental fields minimally coupled to gravity (e.g., boson stars [97]), in Grand Unified Theories in the early Universe (e.g., cosmic strings [98]), from exotic states of matter, as dressed compact objects with further structure stemming from quantum gravitational origin [83, 85] or new physics at the horizon scale (e.g., firewalls [82]), or as horizonless compact objects in a variety of scenarios, for example, fuzzballs, gravastars, and dark stars [75, 77–81].

GW observations provide a unique discovery opportunity in this context, since exotic matter might not

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**Figure 1.2: Test of black hole nature:** Projections of the 95% confidence intervals for 2 QNM (complex) frequencies, notably \((f_{22}, \tau_{22}, f_{33})\), as function of the mass \((M)\) and dimensionless spin \((j \equiv J/M^2)\) of the final compact object for a single GW150914-like event with advanced detectors at design sensitivity (HLV, dashed curves) and 3G detectors (continuous curves). The yellow star corresponds to the true value of mass and spin used in the simulation.
1.3 Nature of Dark Matter.

The exquisite ability of 3G detectors to probe the population and dynamics of electromagnetically dark objects throughout the Universe and harness deep insights on gravity can help reveal the nature of dark matter and answer key questions about its origin.

**Black holes as dark matter candidates:** LIGO and Virgo discoveries have revived interest in the possibility that dark matter could be composed, in part, of BHs of masses $\sim 0.1$–$100 M_\odot$ [101–103]. Such BHs might have been produced from the collapse of large primordial density fluctuations in the very early Universe or during inflation [104, 105]. The exact distribution of masses depends on the model of inflation, and might be further affected by processes in the early Universe such as the quantum-chromodynamic phase transition [106].
The detection of GWs from binary systems composed of objects much lighter than stellar-mass BHs, or with a mass distribution demonstrating an excess within a certain range, could point towards the existence of primordial BHs [107]. The detection of very high redshift sources would be another hint towards this formation channel [108].

With a sensitivity to observe stellar mass BHs at redshifts of \( \sim 10–20 \), 3G detectors will be uniquely positioned to determine their mass and spatial distribution, which will be crucial to test this hypothesis [109]. Figure 1.4 summarizes current bounds and shows the discovery potential of 3G detectors.

![Figure 1.4: Primordial black holes as dark matter: Upper limits from different observations of microlensing of stars [110, 111], microlensing of supernovae (SNe) [112], caustic disruption [113–115], Planck [116, 117], stability of Eridanus II [118, 119]. Gravitational-wave constraints correspond to LIGO searches for sub-solar compact objects [107] and high-mass estimates [120]. The shaded regions correspond to the mass function imprinted by the quantum chromodynamics (QCD) phase transition, for different primordial BH abundances and a primordial scale invariant spectrum [106]. 3G detectors can improve the current bounds by many orders of magnitude.]

**Detection of dark matter with compact objects:** Beyond probing whether dark matter can be partially made up of BHs, GWs can also scrutinize models where dark matter consists of particles beyond the standard model (e.g., weakly interacting massive particles [121], fuzzy dark matter [74] or axion-like particles [58]). Indeed, BBHs evolving in a dark-matter rich environment will not only accrete the surrounding material, but also exert a gravitational drag on the dark matter medium, which affects the inspiral dynamics [122–124]. Even though their magnitude is small, drag and accretion could have a cumulative effect over a large number of orbits that could be detected by a combination of observatories in space and 3G detectors [96].

Additionally, dark matter that interacts with standard model particles can scatter, lose energy, and be captured in astrophysical objects [125–128]. The dark-matter material eventually thermalizes with the star, and accumulates inside a finite-size core. The presence of this core might imprint a GW signature on the matter effects during the inspiral and merger of such objects in a binary system [129]. In certain models, asymmetric dark matter can accumulate and collapse to a BH in the dense interiors of NSs. The core can grow by accumulating the remaining NS material, in effect turning NSs into light BHs in regions of high dark-matter density such as galactic centers [130, 131]. This provides a mechanism for creating light BHs that could be observed by 3G detectors. However, BHs that result from implosion of dark matter accreting NSs will always be heavier than \( \sim 1M_\odot \), any BH candidates of mass \( \lesssim 1M_\odot \) could only be of primordial origin.

In summary, Einstein’s description of gravity led to a revolution in our thinking of the very nature of spacetime itself. Gravity is the manifestation of the curvature of spacetime caused by matter and energy density. General theory of relativity has so far passed every test to which it has been subject to, yet some of its predictions are deeply troubling. The physical singularity at the birth of the Universe, loss of information when matter and energy fall into a black hole are but examples of predicaments faced by the theory for which no satisfactory resolutions exist. Moreover, all observations are hinting that our knowledge of the constituents of the Universe is underwhelmingly poor and breakthroughs in the detection of new particles and fields is keenly awaited. Gravitational-wave observations by the 3G network could provide answers to some of the most fundamental questions about the structure of spacetime and dark matter.
2. Extreme Matter, Extreme Environs

**Science Target**

Determine the properties of the hottest and densest matter in the Universe

The discovery of GW170817 [7] was a watershed moment in astronomy and astrophysics. GW and EM observations of this event provided incontrovertible evidence that BNS mergers are connected to short gamma-ray bursts [132, 133] and the precise optical localization [134] unveiled that these are prolific sites of heavy element nucleosynthesis [135–137]. Furthermore, they showed that to an outstanding accuracy the speed of GWs is identical to the speed of light. These multimessenger observations have allowed the first measurement of the Hubble constant using GW standard sirens [138, 139], ushering in a new era in cosmology, and first measurement of the tidal deformability of NSs [132, 16] that is already constraining the properties of dense nuclear matter [15, 140, 13, 16, 14]. Circumstantial evidence for the formation of a black hole on a timescale of tens of milliseconds have provided model dependent constraints on the maximum mass of NSs and a lower limit on the NS radius [141–143]. However, a number of questions were left unanswered (see Sec. 2.1); observations with detectors of significantly greater sensitivity will be key to shedding light on extreme matter in extreme environments.

**Key Science Goals**

Future GW detector networks and EM observatories will provide a unique opportunity to observe the most luminous events in the Universe involving matter in extreme environs. The observations will address some of the key questions in physics and astronomy:

- **Structure of Neutron Stars.** What can GW observations reveal about fundamental properties of hot and dense nuclear matter? Do NSs undergo a phase transition to de-confined quarks at their cores?
- **Formation and Evolution of Compact Binaries.** How do BNS and NSBH binaries form and evolve; what are their demographics, merger rates, and mass and spin distributions as a function of redshift?
- **Sites of Formation of Heavy Elements.** What is the role of BNS mergers in the production of heavy elements in the Universe? Are they able to explain abundances in the Solar System and stars?
- **Jet physics.** What is the physics of central engines in mergers, and how do they relate to short gamma-ray bursts? How do the jet properties vary with progenitor binary parameters?

**Capabilities of Next Generation Detector Networks:** The next generation of GW detectors (see Table 2.1) will compile surveys of the Universe for close binary coalescence events in which one of the companions is a NS and the other is either a stellar mass black hole or also a NS. The Table shows the capability of 3G observatories compared to the current network of advanced detectors at their design sensitivity. For this simulation, source redshifts were sampled from a merger redshift distribution of BNSs, assuming the Madau–Dickinson star formation rate, with an exponential time delay between formation and merger with e-fold time of 100 Myr (see [144]) and a local co-moving BNS merger rate of 1000 Gpc$^{-3}$ yr$^{-1}$. It is clear that the 3G network will provide ample opportunities for EM follow-up of BNS mergers.
Key science questions addressed by the detected population in the 3G era is very rich and diverse. GW observations of the pre- and post-merger signal will help measure the masses and radii of NSs and determine the equation of state of dense matter, observing the EM counterpart will allow characterization of matter in extreme environments, the redshift of the host galaxy enables cosmological applications, whilst the sub-arcsecond localization of the kilonova provides information about the nucleosynthesis, environment of the event, jet physics and formation scenarios.

## 2.1 Nature of Matter at Highest Densities and Temperatures

Neutron stars are precious laboratories for physics under extreme conditions. The phases and properties of dense matter encountered inside NSs is of fundamental interest to nuclear physics and their role in shaping multimessenger observation of BNS mergers and core-collapse SNe is of broad interest to nuclear and particle astrophysics. Our current understanding of the NS interior is captured in Fig. 2.1.

Theories of dense matter up to densities encountered inside terrestrial nuclei ($\rho_0 \simeq 2.5 \times 10^{14}$ g/cm$^3$) are fairly advanced and provide a description of matter in the NS crust and outer core. The equation of state of the outer core, where the density $\rho \approx \rho_0 - 2\rho_0$, has a significant impact on the radii of low-mass NSs with masses $M \lesssim 1.3\, M_{\odot}$, and an accurate determination of the NS radius can constrain the nuclear Hamiltonian and validate quantum many-body theories of dense nuclear matter [145]. However, in heavier NSs a large fraction of the core is at higher densities and a description in terms of nucleons may not be adequate. The quark sub-structure of hadrons becomes relevant when the density $\gtrsim 2\rho_0 - 3\rho_0$ (for a recent review, see Ref. [146]). With increasing density, a phase transition to matter containing de-confined quarks is expected. The nature of this transition, which could be complex, directly affects NS structure and its dynamics. Properties of matter in this region determines the NS maximum mass.

### Detection Capability of 3G Network

<table>
<thead>
<tr>
<th>Network</th>
<th>$N_1$</th>
<th>$N_{10}$</th>
<th>$N_{100}$</th>
<th>$M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HLV</td>
<td>48</td>
<td>0</td>
<td>48</td>
<td>19</td>
</tr>
<tr>
<td>HLVKI</td>
<td>48</td>
<td>0</td>
<td>48</td>
<td>7</td>
</tr>
<tr>
<td>1ET+2CE</td>
<td>990k</td>
<td>14k</td>
<td>410k</td>
<td>970k</td>
</tr>
</tbody>
</table>

### Table 2.1: Expected BNS detections per year $N$; number detected with a resolution of $<1$, $<10$ and $<100$ sq. deg. $N_1$, $N_{10}$ and $N_{100}$, respectively, and median localization error $M$ in sq. deg., in a network consisting of LIGO-Hanford, LIGO-Livingston and Virgo (HLV), HLV, KAGRA and LIGO-India (HLVKI) and 1 Einstein Telescope and 2 Cosmic Explorer detectors (1ET+2CE).

These considerations have motivated significant observational [147, 148] and theoretical [149, 145] efforts to use multimessenger observations of to constrain their EOS, by identifying strategies to measure their masses and radii. Radio observations of pulsars have yielded accurate mass measurements of a handful of NSs [150]. The discovery of a massive NS J0348+0432 with $M \simeq 2\, M_{\odot}$ [151] has had far-reaching
implications for the equation of state of dense matter, ruling out strong first-order phase transitions in the NS core [152]. However, accurate measurements of the NS radius and/or its compactness ($GM/c^2R$) has been more challenging since it relies on our ability to model X-ray emission from the surface.

Efforts to model and interpret X-ray data from accreting NSs during bursts, and in quiescence, suggest that NS radii are in the range 9–13 km [150, 153], albeit with untested model assumptions.

GW emission from BNS and NSBH systems during the late inspiral and post-merger phases are sensitive to the structure of NSs and the properties of dense matter encountered in their cores. Signature of matter in GWs from a merging binary result from a number of effects: rotational deformations [154], various kinds of tidal interactions including the excitation of internal oscillation modes [155–159], spin-tidal couplings [160, 161], and the presence of a hard surface [162–164]. The most striking matter imprints in the waveform occur during the tidal disruption in a NSBH binary [165, 166], or the merger and post-merger epochs in BNS collisions [167]. Fig. 2.2 shows a projection of the precision with which 3G detectors will allow us to measure the NS mass and radius.

The remnant of a BNS merger depends primarily on the companion masses and the NS equation of state [168–171]. It could promptly collapse to a black hole above a critical total mass of the binary. For a wide range of smaller masses, a significant amount of gravitational radiation could be emitted by hypermassive NS [172–191]. Signals from these regimes have frequencies in the range 1–5 kHz and last over a timescale of $\sim 100$ ms.

Due to their high frequencies, they are very difficult to measure with advanced detectors. However, the 3G network will be sensitive to properties of matter encountered in hypermassive NSs that form during the post-merger phase when density and temperature are most extreme, arguably the largest in the universe. This is depicted in the QCD phase diagram in Fig. 2.3, showing various phases of strongly interacting matter.

At lower temperatures and densities $< 2\rho_0$ the composition of matter is well understood. With increasing density and temperature other hadrons, including pions and heavier mesons and baryons containing strangeness become relevant. A transition region in which hadrons dissolve to produce de-confined quark matter is also shown.

The nature of this transition is unknown, expected to be complex because QCD matter is strongly correlated in this region. Since matter encountered during BNS and NSBH mergers explores a large swath of the QCD phase diagram, whose approximate extent is shown as light-green shaded region, there is great potential to constrain its properties through multimessenger observations of BNS mergers. The 3G network will improve current measurements of tidal deformability by a factor of $\sim 10$ and thus determine the cold equation of state significantly better, and enable unprecedented measurements of the new physics encountered during the coalescence and post-merger epochs.
Chapter 2. Extreme Matter, Extreme Environs

Gravitational-wave observations by the 3G network could shed light on many critical questions about the nature of NSs: Does matter encountered in NSs and BNS mergers contain novel phases not realized inside nuclei and heavy-ion collisions? How do nuclear reactions and neutrinos shape NS merger dynamics and nucleosynthesis? How do the properties of nuclei that are far from stability impact the EM emission from material ejected during NS mergers? Do large scale (magneto)hydrodynamic instabilities play a role in merging BNS systems? Can we combine GW and EM signatures to validate multi-physics simulations of BNS and NSBH mergers to predict ejecta, nucleosynthesis, and the gamma-ray burst mechanism?

2.2 Demographics of Compact Binary Mergers

A key question about compact binary mergers is their demographics, as this could reveal their formation mechanism. Localization of merger events to less than galactic scales (∼ 30 kpc) is essential to unambiguously infer associations of mergers with their host galaxies. Without an EM counterpart the vast majority of events will have error boxes that greatly exceed the typical radii of potential host galaxies. The merger fraction split between early type and star-formation galaxies will provide a fascinating insight into the fraction of mergers that are created with short gravitational fuses [192] that are comparable to the evolutionary timescales of massive stars and those that extend out to a Hubble time. Their locations [193, 194] within the hosts will give insights into the kick velocities imparted to the binaries during their SN explosions.

EM follow-up of BNS mergers will be critical in pinning down host galaxies. BBH mergers, not believed to produce any EM counterparts, will not be resolved well enough to unambiguously identify their hosts. The situation is more optimistic for NSBH mergers. Theoretical predictions suggest that when the mass ratio is not too extreme depending on the black hole spin, conditions could be favorable for the creation of an accretion disk around that might rival the absolute visual magnitude of the GW170817 kilonova, and, therefore, be detectable out to $z = 0.5$ in the reddest filters. If such mergers occur in the globular cluster cores it will be difficult to identify host clusters much beyond Virgo, and those in Virgo do not require a 3G GW detectors for discovery.

Based on our current understanding, galaxies are assembled by the merger of smaller proto-galaxies and star formation peaks near $z \sim 2$ [195]. Identification of kilonovae beyond $z \sim 0.5$ requires hour-long integrations on 8m class facilities like LSST or Subaru and therefore determining the host galaxies of BNS mergers near the peak of star formation will not be routine in the absence of a gamma-ray burst jet pointing towards the Earth, even with ELTs. Nevertheless, at redshifts $z < 0.5$ 3G detectors will work in concert with astronomy facilities to enable thousands of host galaxy identifications from BNS and NSBH mergers thanks to the identification of a kilonova. At larger distances, the identification will be possible only through the detection of an associated gamma-ray burst afterglow, which can be much more luminous than a kilonova if the jet is directed towards the Earth.
2.3 Nucleosynthesis in Binary Neutron Star Mergers

A long standing puzzle in astrophysics is how the elements heavier than iron came into being. About half of these elements are believed to have been created by a process of rapid neutron capture (the r-process), but it is unclear which astrophysical sites are the main contributors. Neutron star mergers have long been proposed as a possible site [165]. GW170817 and its associated thermal EM counterpart provided the first direct identification of a prolific site of r-process nucleosynthesis [196]. However, determining the degree to which BNS mergers contribute to cosmic chemical abundance and evolution will require a more extensive determination of the rates, locations, timescales, and nucleosynthetic yields of the various types of merger events. Even the basic question of whether all three r-process abundance peaks were synthesized by GW170817 is debated [197, 198].

Heavy elements can be synthesized in BNS or NSBH mergers when clouds of neutron-rich material are expelled, either dynamically during the merger or later in the form of winds blown off the remnant accretion disk. The subsequent radioactive decay of the freshly synthesized elements powers the kilonova thermal optical/infrared transient. Theoretical modeling has demonstrated how measurements of the brightness and color of the kilonovae are diagnostic of both the total mass of r-process elements and the relative abundance of lighter to heavier elements [199].

Whereas historical studies of chemical evolution have relied on observing fossil traces of r-process elements mixed into old stars, multimessenger observations provide the unique opportunity to study heavy element formation at its production site and to determine how the initial conditions of an astrophysical system map to the final nucleosynthetic outcome. Answering the basic question of the extent to which BNS and NSBH mergers are the dominant site of r-process production will require multimessenger observations of a large sample of events. GW measurements would pin down the rate of mergers and the binary properties, such as the binary type (BNS or NSBH), companion masses, the merged remnant lifetime and the spin–orbit alignment, while optical/infrared photometry of the associated kilonovae would determine the average r-process yields. Detailed infrared characterization would probe the relative abundance distribution and how similar or different it is from the solar abundance distribution of heavy elements. These observations would also illuminate the key physics driving the r-process and kilonova, such as the equation of state of dense matter, the fundamental interactions of neutrinos and the magneto-hydrodynamics of accretion.

Statistical studies of multimessenger observations will reveal how r-process production in BNS and NSBH mergers depends on host galaxy type, location and redshift, allowing us to piece together the history of when and where the heavy elements were formed over cosmic time. Such studies can determine the distribution of delay times between star formation and merger, thereby addressing whether some BNS and NSBH mergers occurred promptly enough to explain the enrichment of the oldest metal poor stars and the extent to which compact binaries receive strong kicks that move them within, or expel them from, their host galaxies, a factor that is important for understanding whether mergers can explain the unusually high r-process enhancement seen in some dwarf galaxies [200].

In addition to discovering BNS and NSBH mergers beyond the peak of star formation, 3G detectors, because of their wide band sensitivity, will track the full inspiral, merger and ringdown signal. This could enable exquisite measurements of the intrinsic masses prior to coalescence, and determine companion spins and the nature of the remnant, key parameters to fully determine the dynamics of the merger, the nature of the relic star, and the type of debris responsible for panchromatic emission of radiation. State of the art numerical magneto-hydro-dynamical simulations will provide key insight into the geometry and physical state of the debris, in the form of ejecta, winds and discs that can be used to model the EM signal. Thus, the combination of information derived independently from the EM and GW signals will be immensely powerful to build a complete, self-consistent astrophysical picture. In the era of 3G detectors, optical kilonovae will be detectable by LSST out to 3 Gpc and infrared characterization photometrically by WFIRST/Euclid and spectroscopically by JWST/GMT/TMT/E-ELT would be out to 1 Gpc ($z < 0.2$).
Facilities for Observing EM Counterparts to GWs

Table 2.2: Present (P) and future (F) EM facilities that are able to observe faint/distant counterparts to GWs. Detection Limit (DL, 1 hr exposure time) for UV, optical, and near-IR facilities are expressed in AB magnitudes, for X-rays in $10^{-16}$ erg s$^{-1}$ cm$^{-2}$, and for radio in $\mu$Jy. Distance reach (D in Mpc) of facilities for GW170817-like events are shown.

<table>
<thead>
<tr>
<th>Facility</th>
<th>Gamma-rays</th>
<th>X-rays</th>
<th>UV</th>
<th>Optical</th>
<th>Imaging</th>
<th>IR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><em>Fermi P</em></td>
<td><em>Swift P</em></td>
<td><em>HST (im)</em></td>
<td><em>Subaru P</em></td>
<td><em>WFIRST F</em></td>
<td><em>Euclid F</em></td>
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<tr>
<td></td>
<td>S/N 5</td>
<td>S/N 5</td>
<td>26</td>
<td>27</td>
<td>27.5</td>
<td>25.2</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>~80</td>
<td>2000</td>
<td>3200</td>
<td>4800</td>
<td>1700</td>
</tr>
</tbody>
</table>

Component of GW170817-like

<table>
<thead>
<tr>
<th>Facility</th>
<th>Gamma-rays</th>
<th>X-rays</th>
<th>UV</th>
<th>Optical</th>
<th>Imaging</th>
<th>IR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><em>AMEGO F</em></td>
<td><em>Chandra P</em></td>
<td><em>HST (spec)</em></td>
<td><em>LSST F</em></td>
<td><em>WFIRST F</em></td>
<td><em>Euclid F</em></td>
</tr>
<tr>
<td></td>
<td>S/N 5</td>
<td>30</td>
<td>23</td>
<td>27</td>
<td>27.5</td>
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<td></td>
<td>130</td>
<td>150</td>
<td>400</td>
<td>3200</td>
<td>4800</td>
<td>1700</td>
</tr>
</tbody>
</table>

Jet Physics in BNS and NSBH Mergers

Relativistic explosions and compact-object mergers can generate collimated, energetic jets of material and radiation. Our understanding of jet physics thus far comes from studies of gamma-ray bursts, active galactic nuclei and X-ray binaries. Multimessenger observations provide an entirely new perspective on this topic.

The panchromatic study of GW170817 revealed that there was both a wide-angle mildly relativistic cocoon [201, 137, 202] as well as a narrow ultra-relativistic jet [139, 203–205]. This was not seen in previous studies of cosmological short-hard gamma-ray bursts. Combining the EM and GW allowed to directly constrain system parameters with unprecedented precision. GW170817 opened up many questions for future events to answer. Specifically, what is the connection to the class of cosmological short hard gamma-ray bursts? Does a wide-angle mildly relativistic cocoon always accompany a BNS merger? Does the jet always successfully escape the cocoon or is it sometimes choked? How do the observed jet properties vary as a function of viewing angle, mass ratio, hypermassive NS lifetime, remnant spin, and ejecta mass? Do mergers produce prompt EM signals? What is the distribution of the time delays between the EM and GW signal arrival times? What are the characteristics of a jet from a NSBH merger? With the first census of BNS and NSBH coalescences, and full GW and EM coverage of the signals, joint multimessenger parameter inference will be key in understanding the physical origin of jets, ubiquitous around relativistic sources [206–209]. For the first time, a direct measurement of the black hole spin in a source emitting a collimated jet, will enable to establish the close correlations between the jet power, the spin and the inflow rate from the debris disk, which determines the conditions for launching the jet.

The 3G GW network combined with new, powerful EM facilities can further revolutionize our understanding of the physics of jets. 3G network will enable the detection of NS mergers out to redshifts of $z \sim 10$. Even with the planned upgrades, we are limited by the sensitivity of gamma-ray, X-ray and radio telescopes to study jet physics to only out to 500 Mpc. To build a sample large enough to map the full parameter space, we would need of order of a thousand events localized to better than few sq deg. This is a realistic goal with the proposed 3G network.
3. Observing Stellar-mass Black Holes Throughout the Universe

**SCIENCE TARGET**

*Reveal the population of merging black holes throughout the Universe and search for the seeds of supermassive black holes*

The first two observing runs of Advanced LIGO and Advanced Virgo have yielded the discovery of ten BBH systems. Already these detections have revolutionized astrophysics of stellar-mass black holes [210, 211] and provided new tests of GR [11, 9, 48, 212, 6].

Through to the end of the next decade, the advanced detector network will continue to be enhanced as sensitivities reach design goals and new detectors come online [213]. In the BBH domain, we will be able to detect a pair of $10M_\odot$ BHs out to a redshift of $z \approx 1$ [213]. The annual BBH detection rates are forecast to be several hundreds of mergers and science benefits will compound through accumulated observing time and growing detected samples [214–218].

3G gravitational-wave observations will uncover binary black holes throughout the entire Universe back to the beginning of star formation, and will detect new source types (if they exist) beyond stellar-mass binaries, such as intermediate-mass black holes.

- **Discover binary black holes throughout the observable Universe.** What is the merger rate as a function of redshift to the beginning of the reionization era, and how does it correlate with massive star formation, metallicity, and galaxy evolution?
- **Reveal the fundamental properties of black holes.** What are the mass and spin demographics of black holes throughout the Universe, are they correlated, and do they evolve with redshift? What do they reveal about the formation and evolutionary origin of binary black holes?
- **Uncover the seeds of supermassive black holes.** Do intermediate-mass black hole mergers occur in nature, and can such black holes serve as the long sought seeds of supermassive black holes? Is there a single thread which connects the formation of stellar-mass and supermassive black holes?

Beyond this horizon, step-wise sensitivity improvements with the next generation of ground-based GW observatories will be required if we are to pursue major science questions that cannot be answered by the current and near-term GW facilities [e.g., 219, 220]. Current-generation GW detectors are able to provide constraints on the merger-rate densities in the local Universe and approximate distributions of component masses [211]; however, precise measurements of, for example, spin magnitudes and tilts are of paramount importance to understand their origin and the evolutionary physics of the binary system [214, 221, 222, 215, 216, 223, 224]. This information is essential to obtain insights on the formation channels of compact binaries. While instrumental designs are an active area of research, we highlight here how 3G GW ground-based detectors will enable us to survey deeper, to observe a wider range of frequencies, and to make more precise physical measurements; how observations can be synergistically combined between 3G and space-based GW observatories, and how these results will transform the study of BBH astrophysics.
Chapter 3. Observing Stellar-mass Black Holes Throughout the Universe

3.1 A survey of black holes throughout cosmic time

With a 3G GW detector network, for the first time, we will detect BBH mergers at redshifts beyond $z \sim 1$ and we will measure the evolution of the BBH merger rate out to redshifts of $z \gtrsim 10$ [213, 225, 144]: over the entire history of the Universe. GW astronomy would thereby gain a synoptic view of the evolution of BHs across cosmic time, beyond the peak in star-formation rate at $z \sim 2$ [226] back to the cosmic dawn around $z \sim 20$ when the Universe was only 200 Myr old.

Measurements of merger rate vs. redshift combined with measurements of the black holes’ physical properties at unprecedented accuracies will enable conclusive constraints on BBH formation channels. Stellar-origin BBH formation tracks cosmic star formation [227–230], while the density of primordial BHs is not expected to correlate with the star formation density [105, 231]; different binary channels are predicted to lead to different distributions of delay times between formation and merger [232–236, 217, 237–239]. Therefore, determining the merger rate as a function of redshift provides a unique insight into the lives of BBHs. Only next-generation GW detectors can survey the complete redshift range of merging BBHs and provide a sufficiently large catalog of detections to constrain the full BBH population and their origins.

To capture BBH mergers across the stellar mass spectrum (up to total masses of $M \approx 200M_\odot$) all the way back to the end of the cosmological dark ages ($z \sim 20$), a major advance in GW detector sensitivity is required. This cannot be delivered by the maximal sensitivity planned for the current ground-based detector facilities. We quantify this sensitivity step by the boost factor $\beta_{A+}$ relative to the LIGO A+ design [240] between 5 Hz and 5 kHz (and no sensitivity outside this range). In Figure 3.1, we show this boost factor, required to detect an optimally-oriented, overhead binary at a SNR of 8, as a function of the binary’s total mass and redshift.

![Figure 3.1: Color maps show the boost factor relative to the LIGO A+ design $\beta_{A+}$ required to see a binary with a given total source mass $M$ out to given redshift. The color bar saturates at $\log_{10}\beta_{A+} = 4.5$; some high-mass systems at high redshift are not detectable for any boost factor as there is no signal above 5 Hz. Panels are for mass ratios $q = 1$ (left) and $q = 0.1$ (right). The blue curve highlights the reach at a boost factor of $\beta_{A+} = 10$. The solid and dashed white lines indicate the maximum reach of Cosmic Explorer [220] and the Einstein Telescope [219], respectively; sources below these curves would be detectable.]

The boost factors $\beta_{A+}$ needed to acquire a complete census of BBH mergers throughout the Universe are well within the design aspirations for next-generation designs such as Cosmic Explorer [220] and the Einstein Telescope [219]; for these specific sensitivity assumptions, BBH mergers of total mass $M \sim 10–40M_\odot$ can be detected out to $z \sim 10^2$.

Observations of the cosmological distribution of coalescing binaries would complement planned EM surveys designed to study stars and stellar remnants back to cosmic dawn [241–245], as well as millihertz GW observations made by the Laser Interferometer Sapce Antenna (LISA) [246], which can observe systems ranging from local stellar-mass binaries (days to years before they enter the frequency range of terrestrial detectors) [247, 248] to supermassive black hole systems in the centers of galaxies [249, 250]. Athena [251]
and the mission concept Lynx [252] would detect supermassive black holes back to high redshift \(z \gtrsim 7\); Lynx would observe \(10^3 M_\odot\) black holes to \(z \sim 5\) and \(10^2 M_\odot\) black holes to \(z \sim 2\), while Athena would survey these in the nearby Universe. Next-generation GW detectors have the unique potential to observe stellar-mass black hole systems back to the early Universe.

### 3.2 Expanding the black hole mass spectrum

EM astronomy has benefited enormously from advancing observing facilities to cover an expanded range of frequencies. These enable new probes of previous known sources, and allow for the discovery of new types of previously unobserved sources. 3G GW detectors have the unique capability to push the frequency range down to \(\sim 1\) Hz and up to \(\sim 5\) kHz, while improving performance across the band in between.

The merger frequency for a coalescing binary scales inversely with the mass of the binary, hence observing at lower frequency opens up the potential of detecting more massive black holes. Reaching down to frequencies of \(\sim 1\) Hz is the most robust means to prove the existence of intermediate-mass black holes in binaries with masses in excess of \(100 M_\odot\) [253, 254]. The discovery of intermediate-mass black hole [255, 256] would be uniquely impactful: these could be formed through dynamical processes in star clusters [257, 258] or from the collapse of massive metal-poor stars [259–261], and may potentially be the seed black holes which grow into supermassive black holes [262–265]. Supermassive black holes are observed up to redshift \(z = 7.54\) [266] as quasars, at lower redshifts as active galactic nuclei [267], and today in massive galaxies in their quiescent state [268], and cover a mass range from \(\sim 10^4 M_\odot\) [269–272] up to \(> 10^{10} M_\odot\) [273–275]. Supermassive black holes may have light seeds, formed from massive stars in low metallicity halos which evolve into black holes beyond the pair instability gap [276], or heavy seeds, formed from supermassive (proto)-stars of \(\sim 10^4\)–\(10^6 M_\odot\) growing through continued and fast accretion within their birth clouds, which eventually collapse down to black holes [277–282] Determining the seeds of supermassive black holes will help us chart how they grow, and hence the role they play in the evolution of their host galaxies [283–286]. In particular, the observation of high-redshift black holes with mass \(\gtrsim 100 M_\odot\), beyond the (pulsational) pair-instability mass gap [287–291], would be key to understand not only the properties of very massive (\(\gtrsim 250 M_\odot\)) metal-poor stars [292], but also the assembly of the first massive black holes in the Universe [293].

![Figure 3.2: Left: The waveform from the final stages of inspiral, merger and ringdown of a 100\(M_\odot\)+100\(M_\odot\) BBH at a redshift of \(z = 10\). Highlighted is the time evolution of the waveform from 3, 5 and 7 Hz. Right: Requirements on the low-frequency noise power spectrum \(S_n(f)\) necessary to detect an overhead, face-on 100\(M_\odot\)+100\(M_\odot\) BBH merging at \(z = 10\). We assume a power-law form \(S_n(f) \propto f^\alpha\) extending down to a minimum frequency \(f_{\text{min}}\) with the specified normalization \(S_{10}\) at \(f = 10\) Hz.](image)

In Figure 3.2, we illustrate the importance of sensitivity in the 1–10 Hz regime. Even with detectors sensitive to 3 Hz, we see only one cycle of a 100\(M_\odot\)+100\(M_\odot\) circular binary with non-spinning components at \(z = 10\) before merger. This system is not observable above 10 Hz. Therefore, the objective to observe the most massive stellar-origin BBHs and the potential seeds of supermassive black holes early in the Universe...
requires new detectors sensitive to currently inaccessible frequencies below \( \sim 10 \text{ Hz} \), which are inaccessible to current detectors. The detectability of intermediate-mass black holes places requirements on low-frequency sensitivity. We can model the low-frequency noise power spectral density of the detector as a power-law \( S_n(f) = S_{10}(f/10 \text{ Hz})^\alpha \) and assume that the power law extends to some minimal frequency \( f_{\text{min}} \), below which the detectors have no sensitivity. In Figure 3.2, we show the combination of power law \( \alpha \), minimum frequency \( f_{\text{min}} \) and the normalisation \( S_{10} \) necessary to detect an optimally located and oriented merger of two \( 100M_\odot \) intermediate-mass black holes at \( z = 10 \). There is a trade-off between the power-law slope, minimal frequency, and overall normalization, such that a range of specifications can fulfil the science requirements.

For binaries in the currently detectable mass range, observing across a broader range of frequencies gives a more complete picture of their properties. The precession of component spins misaligned with the orbital angular momentum occurs over many orbits [294, 295]. Its imprint is easier to discern over longer inspirals, and hence becomes more apparent with low-frequency data. Orbital eccentricity is rapidly damped through GW emission [296]. This means that it is near unmeasurably small for current GW detectors [297]; however, by monitoring the earlier parts of inspiral, it will be easier to detect traces of eccentricity. Both the spins and the orbital eccentricity are indicative of the formation channel; enabling their measurement for large samples will have a transformative effect on our ability to answer questions about BBH origins.

### 3.3 High-precision measurements of binary properties

Both the sensitivity and the bandwidth of next-generation detectors will enable high-precision measurements of the properties of individual binaries [73, 298, 299]. Parameter uncertainties are inversely proportional to the SNR [300]. The increase in SNR made possible by the increased sensitivity will lead to exquisite measurements of the loudest events. Increased bandwidth enables the coalescence to be tracked for a longer time, improving estimates of quantities like the spins. Masses, spins, merger redshifts, orbital eccentricities and (where possible) associations with host galaxies all give complementary insights into binary physics. High-precision measurements of individual systems allow us to make detailed studies of their origins and fundamental physics [301, 89, 302, 10]. Combining many events together lets us study the properties of the population. The unique and critical advantage of GW BBH observations with 3G detectors is the combination of high-precision measurements for a very large number of detected sources, something that cannot be delivered by the current detectors.

As an example, consider a highly precise reconstruction of the black hole mass spectrum. At high masses, there is predicted to be a gap between \( \simeq 45M_\odot \) and \( \simeq 130M_\odot \) due to (pulsational) pair-instability SN [303, 289, 291]. At lower masses, there is potentially a gap between the maximum neutron star mass and the minimum stellar black hole mass [304–307]. Determining the precise bounds for these gaps would provide insight into the mechanics of SN explosions [308–310] and insights into the neutron star equation of state [311, 15, 141, 312, 16].

Federal holidays 2019 It can be shown [313] that: (i) for the high-mass gap, if the desired accuracy on the mass gap boundary measurement is \( \sigma_g \sim 1M_\odot \), with a conservative individual
mass uncertainty for near-threshold detections of order $\sigma_m \sim 10M_\odot$, $N \gtrsim 500$ detections are required; (ii) for the low-mass gap, $\sigma_g \sim 0.3M_\odot$ and $\sigma_m \sim 3M_\odot$, which would require $N \gtrsim 1500$ BBH detections. To provide robust answers to questions regarding massive star evolution and BBH formation, we need to trace the dependence of the boundaries of the mass gaps on metallicity and hence redshift. Therefore, it is desirable to observe $\sim 1000$ sources in each redshift bin of width $\Delta z = 0.1$, since we may expect knowledge of the star formation rate and metallicity distribution at this resolution on the timescale of next-generation detectors [226]. Observing $1000$ sources in a given redshift bin would provide $\sim 3\%$ fractional accuracy on merger rate per redshift bin, sufficient to determine the redshift evolution of the merger rate, and constrain details of binary evolution at that redshift [218, 217].

With this in mind, we plot the number of expected BBH detections for a next-generation detector as a function of its boost factor relative to A+ in Figure 3.3. This assumes a BBH merger rate that does not evolve in redshift and is roughly consistent with current GW observations [211]. From this, the target of $\sim 1000$ detections per redshift bin is achievable with boost factors of $\beta_{A+} \sim 10$ after only 2 years of observing time. These factors are possible only with next-generation GW detectors.

### 3.4 Multiband gravitational-wave observations

Joint observations of GW events by the *LISA* at millihertz frequencies and 3G detectors at audio frequencies could maximise their science potential. If *LISA* had been observing in 2010, it would have detected GW150914 years before it was observed by LIGO [314]. Indeed, *LISA* will see up to thousands of stellar-mass BBH mergers of $M > 20–30M_\odot$, up to $z \approx 0.3$ [314, 315]. A small fraction of them will sweep across the detector band within few years that will eventually be detected by ground-based detectors. The benefit of multiband observations of such events will be significant.

*LISA* would provide a precise measurement of the source system’s eccentricity (to a precision of $\Delta e < 0.001$ [316]), sky localization to $0.1 \text{ deg}^2$, and time to coalescence within few seconds, several weeks prior to coalescence [314]. This will help point an EM telescope in the right direction before the merger, providing a much deeper coverage from radio to gamma-ray than what might be possible without any early warning alert. This could also allow real time optimization of 3G detectors to tune their sensitivity to observe the ringdown signal, thus enhancing the potential for black hole spectroscopy [317]. On the other hand, one can use the information extracted by 3G network to dig out sub-threshold *LISA* events [318]. From an astrophysical standpoint, the eccentricity information delivered by *LISA* can be combined with the spin measurement obtained from 3G detectors to better constrain different formation channels [319–321]. Multiband observations will also facilitate tests of GR [322] by enhancing the sensitivity to specific deviations arising in the long adiabatic inspiral as predicted, for example, from dipole radiation [323].

Figure 3.4 shows the sensitivity of *LISA* and the Einstein Telescope as a function of binary mass. Both observatories have the capability of detecting events at redshifts as large as $z \sim 20$. Therefore, they can probe the epochs where the seeds of supermassive black holes were formed and grown in a complementary way. Combining the observations in the two different frequency domains will provide the first ever census of coalescing black hole binaries forming in the Universe. The comparison between the detection rate between light and heavy BBHs in the two GW bands will be instrumental in determining, at statistical level, the relative contribution of light and heavy seeds in building up the population of supermassive black holes, and the role of mergers versus accretion in determining their growth. As well as both 3G and space-based detectors being able to see the same intermediate-mass black hole binary signal at different phases in the inspiral, the two GW bands allow the intermediate-mass black hole population to be explored in different regimes.
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Figure 3.4: Lines of constant SNR in the redshift $z$ (luminosity distance $D_L$, left ordinate axis) and $M_B$ plane, where $M_B$ is the (source-frame) mass of the binary. The green points show simulated merging halos which host light (circle) and heavy (triangle) seeds at their center at different redshifts. Should BBHs reach coalescence, after dynamical pairing under the action of stellar and gas-dynamical torques [324], these points describe cosmologically-driven BBH coalescences.

Figure 3.4 highlights that intermediate-mass black holes are a prime multiband GW astronomy target [325, 326]. While LISA will be sensitive to mergers of $M \geq 10^3 M_\odot$ binaries out a redshift of $z > 20$, 3G detectors can access $M \sim 100 M_\odot$ population at comparable redshifts. If 3G detectors see a $\sim 100 M_\odot$ merger at high $z$, one question that arises is whether those are the seeds of supermassive black holes or a different population that will not evolve into supermassive black holes [327]. Multiband GW observations will quantify the continuity between the two putative populations.

3.5 Outlook for black hole gravitational-wave astronomy

Next-generation ground-based GW detectors fulfilling the scientific objectives described here will enable the measurement of the cosmological evolution of the mass and spin distributions of BBHs and will allow us to probe their dependence on star formation history and metallicity evolution with redshift. With sensitivity increases by factors of $\sim 10$ we will be able to probe the complete mass spectrum of black holes formed in merging binaries. Such detectors will enable the robust discovery of intermediate-mass black holes, if they exist, and will allow us to measure the boundaries of any mass gaps. The precise measurements of physical properties for large numbers of black hole systems back to the cosmic dawn would lead to constraints on the physics of massive star evolution in single and binary systems (in connection to massive stellar winds, uncertain phases of binary interactions, as well as core-collapse SNe and associated natal kicks), as well as to constraints on different formation channels of merging black hole binaries. The potential of also revealing the nature of seed black holes for supermassive black holes through the unique, independent perspective of GW observations is exciting. Such data would complement those from from future EM and space-based GW observatories, enabling the maximum scientific return from these facilities.

3G GW detectors offer a unique opportunity to advance the frontiers of stellar astrophysics, the fundamental physics of compact objects, and multimessenger astronomy.
4. Sources at the Frontier of Observations

**SCIENCE TARGET**

*Understand the physical processes and mechanisms that underlie the most powerful astrophysical phenomena*

Black holes and neutron stars have been detected as chirping GW sources [4, 5], the latter also as a multimessenger source with emission across the EM spectrum [8]. However, black holes and neutron stars are predicted to be GW sources of burst or continuous-wave character, in isolation or in binary systems. These GW sources can also be multimessenger sources, and combined multimessenger observations will reveal richer details of the source astrophysics. Signal strengths are highly uncertain, but generally low, low enough that detection with the 2nd-generation detectors even at design sensitivity are far from guaranteed, if not impossible. The 3G network will be necessary certainly for the reliable study of (i) bursts from the birth of compact objects when massive stars collapse as core-collapse SN, (ii) bursts from magnetars or glitching radio pulsars, (iii) continuous GWs from neutron stars, isolated or in interacting binaries.

**KEY SCIENCE GOALS**

Observations with the 3G network further enhanced with multimessenger analyses of EM and possibly neutrino detections will allow us to probe new extreme astrophysics and answer key questions:

- **Gravitational Waves from Core-Collapse Supernovae.** Which core collapse SN phases dominate the GW emission? Do the progenitors rotate and how fast? Does the event form a black hole?
- **Continuous GW Emission from Isolated or Accreting Neutron Stars.** What magnitude of deformations can neutron star crusts sustain and what are the implications for nuclear matter equation of state? Is the spin equilibrium of accreting neutron stars determined by GW emission and through what mechanism?
- **Bursts from Magnetars and Other Pulsars.** Can GW detections help us probe the role of magnetic fields in transient emission from neutron stars and further constrain the equation of state of ultra dense matter?

4.1 Core-Collapse Supernovae

GWs are generated in core collapse SNe by time-dependent rotational flattening, proto-neutron-star pulsations, non-axisymmetric bulk mass motions due to convection, non-radial accretion flows and instabilities, and other asymmetries associated with the effects of strong magnetic fields. The dominant GW emission occurs during the phase of neutrino-driven convection with the standing accretion shock instability (SASI) and by $\ell = 2 f$- and g-modes in the near-surface layers of the proto-neutron star [328–330]. At later times (of the order or a few hundred ms), a single f-mode manifests itself in GW amplitude spectrograms as a narrow frequency band whose location and width are determined by proto-neutron star properties [330–333]. The 3D models predict a well-defined structure in the time–frequency domain, but the quadrupole amplitudes
Each core collapse SN phase has a range of characteristic signatures in its GW signal that can provide diagnostic constraints on the evolution and physical parameters of the explosion and on the dynamics of the nascent proto-neutron star. **Core Collapse and Bounce:** General-relativistic studies [335–337] showed that the GW burst signal from core bounce has a generic shape [338] for a wide range of rotation rates and rotation profiles; therefore, it is best for probing the bulk parameters of the collapsing iron core [339, 340]. **Neutrino-driven Turbulent Convection Outside and Inside the proto-neutron star:** Milliseconds after core bounce, prompt convection in the cavity between the proto-neutron star and standing shock produces a short period (of the order of tens of ms) of GW activity peaking at $\sim 100$ Hz. Several tens of ms post bounce, stochastic mass motions can lead to significant broadband emission (10–500 Hz with a peak at about 100–200 Hz) [341, 342, 334, 343, 328, 344, 345, 329, 330]. On the other hand, the typical properties of the inner proto-neutron star convection zone translate into a turnover timescale of ms, so the corresponding GW signal, also broadband, emerges in the range 500 Hz to a few kHz [346, 347, 344, 345, 330, 334]. **proto-neutron star Oscillations:** Fundamental modes driven by gravity and pressure forces can generate GW emission. Most dominant are the quadrupolar g-modes [348] and the fundamental f-mode of the nascent proto-neutron star excited by the aspherical accretion of plumes of matter crashing onto it during the stalled accretion phase, as well as after explosion by the continuing fallback of matter [349, 350, 330, 348]. The f- and g-modes can also be excited by convection inside the proto-neutron star [334]. The time–frequency trajectory of the dominant f-mode follows a well-defined path that is a direct function of the proto-neutron star mass, radius, and temperature [342, 348] and, hence, of the equation of state and of integrated neutrino losses. The excited frequencies are $\sim 200–500$ Hz in the early stage (within the first few hundred ms after bounce) and of $\sim 500–2000$ Hz in the later stage (hundreds of ms to s after bounce) [330]. **SASI:** This is an instability of the supernova (SN) shock itself. It exists in both 2D and 3D simulations, defined by a nonlinear, sloshing mode in 2D, and by both sloshing and spiral modes in 3D [351]. The SASI modulates the shock position on a time scale $\sim 50$ ms—in turn modulating the accretion flow in the region below it—i.e., the post-shock region, at frequencies $\sim 100–250$ Hz in both 2D and 3D [343, 328, 344, 329, 352, 334, 345]. Importantly, the onset of the neutrino emissions in core collapse SNe coincides (to within ms) with the onset of GW emission [334, 352, 329, 328, 353]. The detection of neutrinos by Super-K/Hyper-K [354], DUNE [355], JUNO [356], IceCube [357], LVD [358], Borexino [359], KamLAND [360], and yet more sensitive neutrino detectors anticipated for the 2030’s, will allow to optimally extract the GW signal [361]. Both signals are produced at the same interior locations resulting to not only in time coincidence, but are also correlated timescale modulations and polarization, which aids with signal extraction and interpretation. If the progenitor core is rotating, there are additional, distinctive modulation signatures [362]. Joint multimessenger analyses can not only enhance detectability but also more reliably probe physical processes, including those producing EM emission necessary for useful localization, for identification of host galaxies, progenitors, and potential progenitor binary companions. Synergistic observational strategies for optimizing multimessenger campaigns for a future core collapse SN event have been articulated in various situations. The 3G network will be critical to extracting all the physics from observable core collapse SNe and will take advantage of EM/particle detectors synergistically.

The detection of GW signals from core collapse SNe will enable us to measure the progenitor mass, as it is one of the major determinants for parameters that affect the various signal components directly, such as the proto-neutron star mass or the violence of convective/SASI motions. Simulations show a qualitative trend in successful SN explosions towards stronger and longer GW emission for more massive progenitors [344, 345, 330]. The energy radiated in GWs is predicted to vary by several orders of magnitude. The core spin could be measured with GW and neutrino multimessenger detections, as the GW frequency is twice the modulation frequency of the neutrino signal [363, 364, 361, 362]. Hot, nuclear matter EOS constraints

of these models are smaller than those of 2D models [334, 333], as the downflows are decelerated before striking the proto-neutron star surface and also lack the necessary rapid time variability needed for resonant excitation of the f-mode.
are best obtained from the proto-neutron star modes and the SASI signals at $\sim 100$ to $250$ Hz [330, 352]. Time evolution of the GW frequency may allow us to probe the mass accretion history before and after shock revival, unless the process is purely stochastic. Bounce and explosion times are much harder to pin point, and if at all, require neutrino detections. A fundamental question is whether the core collapse SN explosion mechanism is neutrino- or MHD-driven but until MHD models are further developed, we are limited in our efforts. If black hole formation takes place in a rapidly spinning progenitor, it will be accompanied by an intense spike-like burst of GW emission at the point of relativistic collapse, followed by a fast ringdown as the newly formed black hole settles down to a Kerr spacetime [365]. By contrast, black hole formation during the first seconds after collapse in non-rotating or slowly rotating progenitors is likely to manifest itself only as an abrupt cutoff of GW emission after a long period of moderate-amplitude GW emission. Prior to black hole formation, the characteristic frequencies of proto-neutron star oscillation modes in the spectrum will increase to several kHz [366, 367].

No core collapse SN GW signals have been detected so far. Even at design sensitivity, 2nd-generation detectors are not expected to reach outside our own Milky Way [368].

Typical predicted 3D core collapse SN GW signals shown in Fig. 4.1 for a source placed at 100 kpc have SNRs for Advanced LIGO at design in the range 0.5–6, i.e., below reliable detectability levels. In contrast, they reach values in the range of 12–130 for example designs of the 3G network. Therefore a range of $\sim 100$ kpc is a reasonable order-of-magnitude for the maximal detection distance of core collapse SN events. The goal of the 3G network is not only to detect the signal (most likely aided by multimessenger observations), not only to reconstruct the GW signal waveform and the location of the source, but more importantly to determine with precision its intrinsic physical progenitor and explosion parameters (e.g., [369, 370]).

4.2 Sources of Continuous Gravitational Waves

The emission of continuous high-frequency GWs at detectable amplitudes requires a time-varying mass quadrupole in a fast rotating compact object. They are expected whenever there is a sustained non-axisymmetric distribution of matter in a rotating compact object [374]. This can happen due to a variety of mechanisms. Most prominent examples include elastic stresses building up in the crust and giving rise to local deformations, deformations due to magnetic fields, which can occur in isolated neutron stars, and the growth of r-modes in accreting neutron stars (a fluid mode of oscillation for which the restoring force is the Coriolis force) [375, 376]. Whereas the amplitude of a GW signal depends on the details of the emission mechanism and on the source, the possible signal morphologies do not differ much. Typical continuous GWs are sinusoidal signals with a small spin-down or spin-up ($|\dot{f}|$ no larger than $10^{-7}$ Hz s$^{-1}$ and most often smaller than $10^{-9}$ Hz s$^{-1}$) and a duration of at least a few weeks and most typically years. As the loss rate
of rotational energy caused by GW radiation is proportional to the sixth power of the spin frequency, the most powerful sources must possess rapid spin. Such large amounts of spin angular momentum can be a birth property of a newborn neutron star, or it may result from the recycling of an old neutron star via accretion of matter and angular momentum from a companion star.

The timescale over which such a deformation can be sustained is crucial for detectability. In young neutron stars that are observable as radio pulsars and magnetars, a significant magnetic field is indeed present. Such neutron stars lose additional rotational energy to magneto-dipole radiation and magnetospheric currents, which reduces their GW luminosity considerably. From long-term monitoring of the braking index, it might be possible to distinguish between GW sources which spin down solely due to GW radiation from those which in addition spin down due to EM radiation.

The recycling of old neutron stars in interacting binaries may, in principle, allow for a population of neutron stars spinning at sub-ms spin periods—and, equally important, supply the material needed to produce thermal or magnetic mountains. Whereas the fastest spinning ms pulsar is spinning at a frequency of 716 Hz, the mass-shedding frequency is still larger by a factor of 2. However, it is currently unclear whether magnetosphere-disk interactions can allow for the existence of sub-ms pulsars among the populations of low-mass X-ray binaries and radio ms pulsars.

No continuous GW signal has so far been observed. The most current upper limits over the entire sky corresponds to a canonical neutron star at 10 kpc, emitting GWs above 500 Hz (150 Hz) due to an ellipticity smaller than $10^{-5}$ ($10^{-7}$) [377]; and upper limits on searches targeting known pulsars can be even stricter, with the limit for J0711–6830 at $1.2 \times 10^{-8}$ [378]. However, in order to detect strains factors of $≈ 100$ lower than the current ones, new detectors, with a substantially lower noise floor are needed. Such sensitivity requires new, 3G detector facilities.

The detection of continuous GWs from neutron stars in the 3G network would be a fundamental breakthrough in our attempts to peer into the ultra-dense interiors of neutron stars. It would provide clues about neutron star properties (isolated) or accretion and magnetosphere physics (binaries), their spin, thermal and magnetic field evolution, the nature of cold dense matter, and phase transitions in QCD. Concurrent EM observations and input microphysics such as the transport coefficients and neutrino cooling rates will be essential to interpret these observations and harvest these fundamental insights.

**Isolated Neutron Stars:** As first pointed out by Ruderman [379], a solid neutron star crust can sustain (nonaxisymmetric) deformations. The maximum possible size of these deformations depends on the composition and structure of the crust. A fully general-relativistic calculation [380] (building on the Newtonian calculation in [381]) gives maximum fiducial ellipticities of $≈ 2 \times 10^{-6}$ for the SLy EOS and its associated crustal model [382]; this EOS is consistent with LIGO observations of GW170817 (see, e.g., [16]). Nevertheless, the fiducial ellipticities of $≈ 10^{-9}$ that are suggested to provide a floor on the spin-down of ms pulsars in [383] seem more likely to occur in a large population of stars than deformations near the theoretical maximum, particularly if one is only considering crustal deformations. Magnetic fields significantly complicate the modeling of neutron star interiors. However they play an important role in determining the spin evolution of neutron stars and possibly continuous GW emission. This is largely uncharted territory: developing fully relativistic MHD evolution models will be crucial to guide and interpret observations.

**Accreting Neutron Stars in Binaries:** neutron stars in binary systems can also emit continuous GWs. In fact, these systems might be more likely to present large deformations than their isolated siblings, as it may be possible for the neutron star surface magnetic field to be compressed by infalling material, such that a large quadrupolar ellipticity could be created [384]; asymmetric heating of the interior due to accretion could lead to sufficient thermal deformations that GWs are produced [385]; high-frequency oscillations during an X-ray burst or outburst, could be due to a GW-emitting unstable r-mode [386, 387], e.g. as detected in two accreting neutron stars [388, 389]. In fact, the emission of GWs could be the reason why we do not observe neutron stars spinning at their theoretical limit [390–392]. GWs from neutron stars in a binary could also uncover effects that may not be studied in isolated neutron stars. Long-term monitoring of the neutron star
4.3 Other GW Bursts from Magnetized Neutron Stars

Neutron stars can produce GW bursts, for example via magnetar giant flares or pulsar glitches. If detected (e.g., after an EM trigger), they can provide insights into the properties of high density matter. Current GW detectors have searched for such signals with no positive result.

Magnetars, highly magnetised neutron stars with magnetic fields exceeding $10^{14}$ G, are observed as anomalous X-Ray pulsars or soft gamma-ray repeaters [393]. Soft gamma-ray repeaters show recurrent X-ray activity that include frequent short-duration bursts ($10^{36} - 10^{43}$ erg s$^{-1}$ with durations of $\sim 0.1$ s) and, in some cases, energetic giant flares [394] ($10^{44} - 10^{47}$ erg s$^{-1}$ within 0.1 s with X-ray tails that can extend to several 100 s). Since they are thought to involve substantial structural changes within the neutron stars and due to the large involved energy, magnetars are potential GW sources, see [395, 396] for recent reviews. They may, however, only be detectable if an energy corresponding to a significant fraction of the X-ray energy is channelled into GWs.

To date, three giant flares [397–399] have been detected, and several bursts [400, 401] have been observed that showed quasi-periodic oscillations. A detection of magneto-elastic quasi-periodic oscillations together with GW would provide incomparable information on the oscillation spectrum of neutron stars and thus allow to study their deep interior with unprecedented detail. For a neutron star at 10 kpc with a magnetic field at the pole of $B_{\text{pole}} \sim 10^{15}$ G, this corresponds to a strain of $h \sim 10^{-27}$ at the detector. Typical GW signals consist of two major contributions, a high frequency signal, corresponding to the f-mode around 1–2 kHz and a low frequency contribution associated to Alfvén oscillations in the neutron star core around $f \sim 100$ Hz, which depends on the magnetic field strength.

Radio pulsars known for their very stable spin periods can occasionally undergo a sudden increase in their rotation frequency. These are called glitches and several hundred glitches have been observed in over 100 pulsars [402]. There two main physical models for the explanation of glitches and both models involve a substantial rearrangement of the neutron star structure on a short time scale, therefore one can expect a bursts of gravitational radiation, both from the glitches themselves and from subsequent relaxation of the neutron star structure. The dynamics and duration of these phases, however, is to date not well understood and the predictions of the emission of GWs and their detectability vary widely. The most pessimistic ones expect that not even 3G instruments can detect the signal [403], moderately optimistically ones [404] predict the signals to be detectable by the Einstein Telescope while the most optimistic ones [405–407] expect that the signals should be marginally detectable even by Advanced LIGO and Virgo. One can therefore from both detection, or non-detection by 3G instruments expect to constrain the physics of the neutron star interior.

Given the predicted strengths, sensitivity improvements of factors 10–100 compared to current facilities are required for the detection and study of these sources. This necessity extends for all of the sources discussed in this white papers: uncovering the inner workings of stellar core collapse events and SNe and reliably studying the equation of state of both hot and cold ultra-dense nuclear matter, supported by a sample of several sources and different types of signals, can be achieved only with a dramatic advance of GW sensitivity at high frequencies, that only 3G ground-based GW detectors can deliver.
Science Target

Investigate the particle physics of the primeval Universe and probe its dark sectors

Gravity assembles structures in the Universe from the smallest scale of planets to galaxy clusters and the largest scale of the Universe itself. Yet, until recently gravity played only a passive role in observing the Universe. Almost everything we know about the Universe, from its hot primeval phase to recent accelerated expansion, the most powerful explosions such as hypernovae and brightest objects like quasars, comes from EM waves. Important exceptions include cosmic rays and neutrinos that have allowed to probe complementary phenomena. GW observations forever changed the role of gravity in our exploration of the Universe; moreover, the detection of EM counterparts to GW170817 [132, 8] generated a treasure trove of data that has ushered in a new era in cosmology [138].

Merging binaries of NSs and BHs are standard sirens [408]: GR completely determines the time evolution of the GW’s amplitude and frequency, which give the GW’s apparent and absolute luminosities, respectively. Matched filtering the data with the predicted GR waveform, therefore, allows us to readily infer the luminosity distance to a host galaxy, without the aid of the cosmic distance ladder. Thus, BBHs and BNSs have been hailed as standard sirens and they provide a completely independent tool for observational cosmology.

The merger rate of BBHs and BNSs inferred from LIGO and Virgo [211, 7] imply that future detectors will observe a stochastic background formed from the astrophysical population of binaries at cosmological distances [210, 409]; such observations will reveal the history of star formation from a time when the Universe was still assembling its first stars and galaxies. Buried under this background could be stochastic signals of primordial origin that could provide insights into the physics and energy scales of the earliest evolutionary phases in the history of the Universe—scales that are not accessible to current or planned particle physics experiments (see, e.g., [410–433]). The 3G network will probe those energy scales with its excellent sensitivity to stochastic background.

Key Science Goals

Future GW observations will enable exploration of particle physics, early Universe and cosmology:

- **Early Universe.** What evolutionary phases took place in the early Universe, their energy scales? How did they transition from one into another and the Universe observed today?
- **Standard Siren Cosmology.** Is dark energy just a cosmological constant, or does the dark energy equation-of-state vary with redshift?
- **Modified Theories of Gravity.** Do gravitational waves propagate from their sources in the same way as electromagnetic waves do? How do extra dimensions and other modified theories of gravity affect the propagation of gravitational waves from their sources?
5.1 Early History of the Universe

GW observations could inform us about the history and structure of the Universe in at least two ways: by studies of individual sources at cosmological distances that give information about its geometry and kinematics and by direct observation of a stochastic GW background. In turn, a stochastic background could either be astrophysical in origin, generated by any of a myriad of astrophysical systems or it could come from the Big Bang itself, generated by quantum processes associated with inflation or with spontaneous symmetry breaking in the early Universe. Figure 5.1 shows examples of energy density spectra for some of the cosmological background models in comparison with the best current upper limits and future expected detector sensitivities. Cosmological background is probably the most fundamentally important observation that GW detectors can make. However, the astrophysical background may mask the primordial background over much of the accessible spectrum, while still carrying important information about the evolution of structure in the Universe. Techniques are being developed to identify and estimate these various contributions to the stochastic GW background.

Irreducible GW background from inflation Inflation represents the leading framework to explain the properties and initial conditions of the observed Universe. During inflation massless fields experience quantum fluctuations, and due to the accelerated expansion small fluctuations with wavelengths initially smaller than the Hubble radius are amplified and stretched to super-Hubble scales. This applies, in particular, to tensor metric perturbations [410–413]. The resulting spectrum of tensor modes is quasi scale-invariant with a small red-tilt, spanning over a wide range of scales, from the Hubble scale at the end of inflation to (at least) the Hubble scale today.

When the tensor modes re-enter the horizon after inflation, they turn into a proper classical (yet stochastic) background of GWs, with a quasi scale-invariant red-tilted spectrum. This background constitutes an irreducible emission of GWs expected from any inflationary model. The expected background assuming the standard slow-roll inflationary model is shown in Figure 5.1. Thus, even when considering an ideal case of an exact scale invariant tensor spectrum today’s amplitude of this irreducible background is likely below the proposed sensitivity of the 3G network. However, follow-up upgrades of 3G detectors could be sufficiently
sensitive to observe this background—this should be factored into the site selection and facility design of the 3G detectors.

**Beyond the irreducible background from inflation** Additional processes during or immediately after inflation could lead to significant amplification of the stochastic background in the frequency band of 3G detectors. For example, efficient gauge field excitation due to axionic coupling to the inflaton could extend inflation and boost GW production with a significant blue tilt [414, 415, 442–444]. Furthermore, the resulting background has distinctive properties, namely it is highly chiral (i.e. only one polarization is excited) and non-Gaussian. Both of these properties enjoy specific predictions unique to this scenario, which, therefore, can be used to differentiate it unambiguously from other GW backgrounds. An example of the background spectrum produced in this model is also shown in Figure 5.1. Similar large blue tilts in the background spectrum are also possible if inflation is followed by another (presently unknown) phase with a stiff equation of state ($w > 1/3$), again resulting in possible detectability with 3G detectors [416–421].

**Preheating and non-perturbative phenomena:** After inflation ends the Universe must be reheated, converting the energy responsible for inflation into the particles that fill up the Universe. Following inflation the inflaton typically oscillates around the minimum of its potential, producing particle species coupled to it. This corresponds to a non-perturbative effect, referred to as preheating. In the case of bosonic species the production is resonant and it is known as parametric resonance. This phenomenon, and in general other similar non-perturbative particle production stages (unrelated to reheating), are energetic and produce a large amount of GWs. The spectrum is typically characterized by a single peak, with the peak frequency determined mostly by the energy scale and the coupling constants involved. Both the amplitude and the characteristic frequency of this GW background today increase with the energy scale at which the parametric resonance occurs. Consequently, in order to obtain an appreciable amplitude of this GW background it is necessary to have a large energy scale, which results in a peak at frequencies far above the range in which terrestrial GW detectors operate. At lower energy scales, even though the peak frequency is shifted into the band of terrestrial detectors, the spectral amplitude is too small to be detectable. In summary, GW backgrounds from preheating and from similar particle production phenomena in the early Universe are likely not accessible to 3G detectors.

**First order phase transitions:** Following the end of inflation, the Universe has undergone the QCD, electroweak, and potentially other phase transitions. Currently, an experimentally verified physical model is lacking for energy scales higher than the electroweak one, where several proposed extensions of the Standard Model of Particles predict the occurrence of phase transitions. Any experimental confirmation that such phase transitions took place in the early Universe would therefore constitute an invaluable piece of information for our understanding of particle theory underlying the Universe at very high energies. To be an efficient direct source of GWs, a phase transition must be of first order. First-order phase transitions proceed through the nucleation of bubbles of the true vacuum, energetically more favourable, in the space-filling false vacuum.

The dynamics of the bubble expansion and collision is phenomenologically rich, and the sources of GWs are the tensor anisotropic stresses generated by these multiple phenomena: the bubble wall’s expansion [423–427], the sound waves in the plasma [428–430], and the subsequent magnetohydrodynamic turbulence [431–433].

**Cosmic Strings:** If the broken vacuum manifold is topologically non-trivial, topological defects such as cosmic strings may arise in the aftermath of a phase transition. Cosmic strings are expected to form in the context of grand unified theories applied in the early Universe [98]. For Nambu-Goto strings the string tension is the only free parameter; it defines the energy scale of the phase transition accompanied by the spontaneous symmetry breaking scale leading to the cosmic strings formation. It is also possible to form a network of fundamental cosmic (super)strings, in which case the network is also affected by the probability that two strings would reconnect when they intersect.

Cosmic strings predominantly decay by the formation of loops and the subsequent GW emission by cosmic string cusps and kinks [445, 446]. Searches for individual bursts of GWs due to cosmic string cusps
and for the stochastic background due to cusps and kinks have placed a strong constraint on the string tension for the three known Nambu-Goto string models [447–450], $G\mu \lesssim 10^{-11}$. The 3G network will improve on these bounds, by 8 orders of magnitude, depending on the model (see Fig. 5.1).

**Dark Photons:** A dark photon is proposed to be a light but massive gauge boson of a $U(1)$ extension of the Standard Model. If sufficiently light, the local occupation number of the dark photon could be much larger than one, so it can then be treated as a coherently oscillating background field that imposes an oscillating force on objects that carry dark charge. The oscillation frequency is determined by the mass of the dark photon. Such effects could result in a stochastic background that could be measured by 3G detectors, potentially exploring large parts of the parameter space of such models [451].

### 5.2 Astrophysical Binary Foregrounds and Large Scale Structure

The cosmological population compact binary mergers will give rise to a stochastic foreground of GWs [452–457]. The predicted amplitude of the background from BBH and BNS mergers is $\Omega_{GW}(f = 25\text{Hz}) = 1.8 \times 10^{-9}$ compared to $\Omega_{GW}(f = 25\text{Hz}) = 1.1 \times 10^{-9}$ from BBHs alone [458]. Such a signal is likely to be detected by Advanced LIGO-Virgo. 3G detectors, thanks to their better low-frequency sensitivity, could detect backgrounds at levels approaching $\Omega_{GW} \sim 10^{-12}$ around frequencies of 10–30 Hz [459]. This implies the 3G network could detect anisotropies of the dominant component of the background in this frequency range [434, 460–463]. The energy density of the background is likely to be non-gaussian in the sensitivity band of 3G detectors [464] and they could measurements the bispectrum and of higher order correlation functions, which would be extremely useful in understanding the large scale structure of the Universe.

The compact binary background could potentially mask the cosmological backgrounds discussed before. Figure 5.1 shows that the amplitude of this foreground is several orders of magnitude stronger than most cosmological backgrounds. However, a large fraction of the binary merger signals will be individually detected by the 3G detector network, allowing for the possibility to subtract this foreground to probe a cosmic background of $\Omega_{GW} \sim 10^{-13}$ [465, 452]. Small errors in subtraction could lead to a substantial residual foreground, although novel methods might allow for a more effective subtraction [466]. BNS signals, given their longer duration and the fact that on average many signals will overlap in time, pose greater challenge for subtraction as it is necessary to keep in phase over a longer period of time.

Effective subtraction techniques would be required to minimize the residual signal and dig deeper to detect other stochastic backgrounds. Indeed, sources other than compact binary mergers could also contribute to the astrophysical background including isolated NSs [467–469], stellar core collapse supernovae [470, 471] and population III binaries [472]. Studying the properties of such a background will allow us to place new types of constraints on astrophysical models and can impact astrophysics as much as the CMB did for cosmology. In particular, it will be possible to extract precise data on galactic and stellar physics and their evolution.

### 5.3 Hubble Parameter

Joint GW and EM observations provide a completely independent tool for measuring the dynamics of the universe and to constrain cosmological parameters such as the Hubble parameter, dark matter and dark energy densities, and the equation of state of dark energy [408, 138, 473–475]. It is estimated that about 10 compact BNS or NSBH mergers with EM counterparts are required to reach $H_0$ measurements at the 5% level, and 200 to reach 1% [476–478]. While BNS events are promising based on GW170817, NSBH mergers, due to precession of the orbital plane because of spin–orbit coupling, can break the degeneracy between the orbital inclination and luminosity distance, and provide accurate distance measurements [479]. In addition, EM observations could also break this degeneracy [480].

There is significant potential in statistical methods as well, where sources without EM counterparts are combined with galaxy catalogs to make inferences [481]. For example, 3G detectors will localize some BBHs within a volume where on average only one galaxy is present [298, 482], although the method is limited by
5.4 Dark Energy and Cosmological Parameters

Dark energy has been studied by investigating its effect on the expansion of the universe, specifically by probing the relationship between the luminosity distance and redshift of standard candles, such as Type Ia SNe. GWs offer another approach to this problem, using compact binary mergers as standard sirens. The GW signal from coalescing binaries allows a direct measurement of their luminosity distance \( d_L \) [408]. Dark energy can then be probed either by using redshift measurements from EM counterparts, or by using statistical methods [483–486, 473, 474, 481, 487–491, 475, 492, 493]. 3G detectors will measure standard sirens up to large redshifts, \( z \sim 10 \), significantly farther than what is possible with the standard candles, while never having to rely on the cosmological distance ladder. Studies have shown that measuring cosmological parameters with 1–2\% uncertainties will be possible, for example by using 1000 observed BNSs with EM and/or GRB counterparts [492, 493]. This level of uncertainty is comparable to what is achievable with EM measurements, but it is susceptible to a completely different set of systematic errors from those due, e.g., to SNe, offering an independent measure.

Standard sirens are sensitive to another powerful signature of the dark energy sector that is not accessible to EM observations. A generic modified gravity theory induces modifications with respect to the standard model of cosmology both in the cosmological background evolution and in the cosmological perturbations. Indeed, theories with extra dimensions [494], some scalar-tensor theories of the Horndeski class (including Brans–Dicke) [495–499], as well as a nonlocal modification of gravity [500–502, 492, 493], are characterized by GWs propagating at the speed of light but with their amplitude decreasing differently with the scale factor than in GR. Consequently, the standard sirens would measure a GW luminosity distance as opposed to the standard EM luminosity distance. The 3G detectors will be sufficiently sensitive to search for this deviation, and thereby probe multiple classes of modified theories of gravity in the context of their dark energy content [492, 493]. Modified gravity theories also induce modified cosmological perturbations in the scalar sector, which then leave measurable signatures via the integrated Sachs–Wolfe effect [503], the effect of the integrated Sachs–Wolfe on a primordial stochastic background [504–507], the effect of peculiar velocities [508, 509], and of lensing [510–513]. 3G detectors may also be sensitive to these effects for some of the modified gravity theories [514].
6. Science Requirements: Source Modelling and Data Analysis

6.1 Challenges in Waveform Modeling

With larger bandwidth and greater sensitivity, the 3G network will allow us to address and solve several outstanding questions in cosmology, astrophysics and fundamental physics. It will permit us to infer source parameters with unprecedented accuracy, unveil binary formation scenarios, carry out spectroscopy of black holes and neutron stars, perform stringent tests of GR, disclose existence of ECOs, pin down the equation of state of ultra-high dense matter and measure cosmological parameters. This science will be possible because those astrophysical and physical effects are imprinted in the GWs. To be successful those physical effects must be included in the models that are employed in data-analysis studies. Here we list some open questions, highlighting the need of building accurate and genuine source models.

Birth, life and death of compact-object binaries. 3G detectors will allow us to probe the existence of BBHs in a much larger region of parameter space than advanced detectors—for example up to component masses of \( \sim 10^4 M_\odot \), and mass ratios in the range \( 1 \leq q \lesssim 10^3 \), and observe many more binaries, some of which will sweep in band for longer times, with binary’s orbital plane oriented randomly with respect to the line-of-sight, thus exposing a much richer and complex GW signal. Properties of such a large population of compact binaries will offer the unique opportunity to unveil the binary’s formation scenarios and their astrophysical environment. In particular, the main astrophysical formation channels can be distinguished by extracting information about spins, notably their magnitude and orientation, and eccentricity [214–216, 221–224, 515, 516]. Current state-of-art models [517–523] do not include all the relevant physics. In parts of the parameter space, however, current models will not be accurate enough to detect the signals when mass ratios are \( \sim 10^3 \) or higher, lasting for tens of thousands of cycles in the sensitivity band. Current models are limited to quasi-circular orbits, spins aligned or anti-aligned with the orbital angular momentum, include a handful number of higher modes, and have not been calibrated to numerical simulations. Models that do treat spin precession [517–519] do not yet include higher modes and not adequate to describe intermediate mass-ratio inspirals (IMRIs), composed of a \( 10^2–10^4 M_\odot \) BH and a stellar-mass companion, a source that will be seen orbiting for a few thousand cycles in the strong-field regime, tracing complicated trajectories for a generic choice of eccentricity, spins and binary orientation (see Fig. 6.1).

Resonances: Orbital resonances can occur in binary inspirals when the periods associated with spin-precession and eccentric radial oscillations form commensurate ratios [524–527]. Because the radial and precession periods evolve at different rates, each inspiral will have resonant episodes, during which the resonant dynamics can increase or decrease the dissipation of energy and/or angular momentum. Resonant episodes act as phase microscopes enhancing the effects of phase differences accumulated during the inspiral. Those phase differences could be caused by astrophysical environmental effects, e.g., perturbations from other stars, deviations from GR and existence of eccentric compact objects [528, 525]. The size of the effect depends on how long a resonant episode lasts and the strength of the resonant dynamics controlled by eccentricity and spin orientations [524, 529–532, 527]. Resonances live longer in large mass-ratio systems and negligible for comparable-mass systems [533]. Correctly accounting for resonance in IMRI waveforms will be necessary for the 3G network to detect astrophysical environmental effects and deviations from GR.
Probing the astrophysical environment of binary systems. Gravitational radiation tends to efficiently circularize orbits [296]. This leads to the expectation that isolated compact-object binary systems that have evolved over a long time scale will have a negligible eccentricity shortly before merger, when their signals enter the sensitivity band of terrestrial detectors. However, a number of processes can induce a significant eccentricity at small separation: (i) binary formation from primordial BHs [102, 534], (ii) dynamical interactions in dense stellar environments such as galactic cores or globular clusters [535–538, 515, 539–544, 516], and (iii) the nonsecular evolution of isolated triple systems [545–547], can lead to eccentricities \( \sim 1 \) at GW frequencies in the millihertz range, and can retain appreciable eccentricities in the \( \sim 1 \) Hz regime for a nonnegligible fraction of the population of merging compact objects.

GWs from an eccentric binary are richer in structure than those from nearly circular motion [548]. They contain invaluable information about the binary’s formation channel and reveal new phenomena such as zoom–whirl dynamics [549–551], orbital resonances and, for ECOs, the excitation of internal oscillation modes [552–554, 544] and enhance otherwise small matter-effects from neutron stars and fundamental fields [72, 63]. Measuring eccentricity is an important science goal for which the unprecedented access to information at lower frequencies offered by 3G detectors is extremely important. Models that include the effects of eccentricity are essential in order to measure the physics and astrophysics described above, for mitigating biases in determining the source properties [555, 556], to correctly identify potential eccentric multi-band sources [319, 320] and, for binaries with a large total mass where only the signal’s higher modes are in the detector’s sensitive band [557, 558].

Current models with eccentricity [559–581] remain severely limited in accurately describing the relevant physics over a wide range of the parameter space. Even for the simplest case of black holes, devising complete models that include precessing spins, arbitrary eccentricity, and full inspiral-merger-ringdown signals, and that are tested and refined based on information from numerical relativity (NR), will require a substantial further effort in the field. Methods for designing efficient approximations will require further advances to cover the higher-dimensional parameter space for eccentric binaries.

Probing matter at extreme density and pressure. Analogous to particle colliders, GWs from binary coalescences are able to uniquely probe internal structure of neutron stars and/or ECOs, the nature of subnuclear forces, and potential signatures beyond GR or the Standard Model of particle physics. As a BNS system collides close to the speed of light, the density rises, temperatures increase to \( \sim 100 \) MeV (\( \sim 10^{12} \) K), and complex microphysics like neutrino processes and magneto-hydrodynamical instabilities become important [582, 167]. This extreme physics is imprinted in the GWs, with complementary information from EM and neutrino counterparts [583].

Precision measurements at increased sensitivity of 3G detectors will require substantially more accurate waveform models than are currently available to avoid systematic bias [584]. Modeling the complex and parameter-dependent merger process can only be accomplished with NR simulations. These must include GR, relativistic magneto-hydrodynamics [585–591], neutrino processes [592–594, 589, 595], temperature and composition changes in the equation of state [596, 597], small-scale turbulences [598, 599], and high-order
high-resolution shock capturing schemes [600, 601]. Additionally, simulations will need to be performed over a wide range of parameter space [602] to categorize the different possible outcomes. Current simulations indicate dominant matter-dependent features in the GWs remain relatively unaffected by changes in the detailed microphysics [603–605, 189]. Understanding the origin, robustness, and parameter dependence of sub-dominant features remains a topic of ongoing research. A systematic comparison of results from different NR simulations is another key goal requiring organized community effort [606]. Yet, even without high-precision models, GW measurements based on parameterized models [607] or on an unmodeled search [608], together with information from the inspiral and multimessenger counterparts [142, 609, 610], may lead to new insights and physics constraints.

Likewise, the GW models of tidal disruption in NSBH binaries require further improvements. Although the microphysical processes are less complex than BNS mergers, new challenges arise such as the disparate spatial scales due to the larger mass ratios [611, 612], and effects of black hole and neutron star spins [613]. Current models focus on aligned black hole spins, and recent NR simulations indicate challenges extracting the tidal disruption signature when the black hole spin precesses [614, 612].

**Precision gravity with GWs.** 3G detectors will probe a range of phenomena that are not accessible to current detectors. The GW memory manifests itself as a nonoscillatory piece of a transient GW burst, which permanently changes the relative distances between a set of freely-falling test masses. Predicted by GR, the GW memory [615, 616] and GW spin memory [617] are closely connected with asymptotic symmetries and conserved quantities at null infinity, and potentially with the black hole information paradox [618]. Observing the memory part of a burst waveform not only provides important means to test these areas of fundamental physics, but also complementary information on astrophysical sources.

Generic binary black holes radiate GWs anisotropically. Linear momentum is therefore dissipated in some preferential direction, imparting a recoil, or *kick*, velocity to the merger remnant [619, 620]. Black-hole kicks can reach thousands of km s$^{-1}$ [621–624], thus ejecting black holes from their astrophysical hosts [625–628]. Besides many interesting astrophysical consequences [629, 630, 628, 631–633, 626, 627, 634–644], GW observation of recoiling black holes will constitute a measurement of fundamental interest. Kicks are encoded in the differences between the dominant and higher order modes of the emitted GW [645]. 3G detectors can reach the sensitivity required to detect kicks as small as $\sim 120$ km s$^{-1}$ [646].

Some models of semiclassical and quantum gravity predict that the horizon does not form at all (e.g., fuzzballs, gravastars, dark stars). However, they lack a robust theoretical framework to set up an initial-value problem and to study the dynamical formation of ECOs in a self-consistent way [79]). This is arguably the strongest limitation for current studies of ECOs and its resolution should have high priority.

ECOs might be unstable both at linear level, if they spin sufficiently fast (due to the ergoregion instability [647–650]), and probably at nonlinear level, even without spin [651, 652]. The ergoregion instability is totally quenched if the absorption rate of ECOs is larger than the maximum superradiant amplification factor for the corresponding Kerr black hole with the same mass and spin at a given frequency. For highly spinning objects, this requires at least 0.4% absorption rate for scalar fields, but up to 100% absorption rate for gravitational perturbations and almost maximal spins [653, 654]. While these numbers reduce to $\lesssim 0.1\%$ for spins $\chi \lesssim 0.7$, they are still several orders of magnitude larger than achievable with viscosity from nuclear matter [655]. An open theoretical problem is to understand whether current ECO models are consistent with such level of GW absorption. Each subsequent echo has a smaller frequency content, smaller amplitude, and inverted phase.

Recently, there has been considerable progress in modeling echo waveforms that result in the aftermath of the merger of certain ECOs [656–663] (see Fig. 6.2). Searches for such signals can be performed without knowing the details of the waveform [664, 665], although extraction of the best possible information from the data would require an accurate model of the signal. For example, with reliable templates absence of an echo signal in the detector can be used to set stringent constraints on the models.
A preliminary analysis [663] suggests that perfectly-reflecting ECO models can be detected or ruled out at 5σ confidence level with an SNR ≈ 10. However, such models are already ruled out by the ergoregion instability and by the absence of GW stochastic background in LIGO O1 [666]. Excluding/detecting echoes for models with smaller values of the reflectivity (for which the ergoregion instability is absent [655]) will require SNRs in the post-merger phase of $\mathcal{O}(100)$, which will be possible with the 3G network.

**Precision cosmology with GWs.** The 3G network will observe compact-object binary systems out to cosmological distances of $z \lesssim 15$, with possible EM counterparts up to $z \sim 3$. These multimessenger events will enable us to extract cosmological parameters using EM counterparts or statistical methods [408, 667, 668, 510, 484, 473, 486, 669–673, 138], perform tests of GR on cosmological scales, and probe dark energy and dark matter [102, 674, 672, 112, 675] with much better precision than advanced detectors.

The 3G network is expected to observe $\sim 10^4$–$10^5$ GW binary mergers per year of which $\sim 10^2$ may be lensed [676]. If the wavelength of the GW is much smaller than the characteristic scale of the gravitational field of the intervening lens, lensing will magnify/demagnify the GW signal without changing its frequency profile. A lens of magnification $\mu$ will bias the inferred luminosity distance, introducing a systematic error $\Delta D_L/D_L = 1 - 1/\sqrt{\mu}$. Lensing must be taken into account in order to correctly interpret observations.

It is crucial that gravitational waveforms include all genuine signatures predicted by GR, and are sufficiently accurate so that systematics due to modeling are smaller than statistical errors. To extract cosmological information from the complete population of BBHs, NSBH binaries and BNS, which span a large region of parameter space, spin effects, tidal effects, and eccentricity must all be correctly modelled. The inclusion of these physical effects is necessary to avoid biases, but it also improves the precision with which parameters can be extracted—for example including higher harmonics [677–679, 521, 522] beyond the dominant mode reduces the uncertainty in the distance and breaks the degeneracy between distance and inclination [680]. Similarly, spin-precessional effects can lead to more precise measurements of parameters.

BNS could be used to measure cosmological parameters without the need to identify EM counterparts, but rather exploiting the physics of NSs [667, 681, 671, 488, 682, 683]. In particular, if the NS equation of state or its mass range is constrained with sufficient accuracy then it is possible to directly obtain the source redshift from GW observations. This interesting methods would potentially allow us to use all detected BNSs as luminosity-distance and redshift tracers, dramatically improving our ability of constraining cosmological parameters with the 3G network. To successfully carry out this science it is necessary to accurately model spin effects, tidal effects, and possible eccentricity in BNSs.

### 6.2 Novel and efficient methods to solve the two-body problem in gravity

The science from GW experiments stems on our ability to make precise predictions for the waveforms, which implies solving accurately for the two-body dynamics and gravitational radiation. Waveform models (or templates) are employed to detect, identify and infer source’s properties, and test GR.
The main analytical and numerical approaches employed to solve the two-body problem are summarized in Fig. 6.3. Post-Newtonian (PN) theory [295] expands the Einstein equations and gravitational waveforms in powers of $v/c$, where $v$ is the characteristic velocity of the companion stars and $c$ the speed of light. For bound orbits this expansion is intertwined with the expansion in $GM/rc^2$, where $M$ is the binary’s mass and $r$ the radial separation. The formalism of gravitational self-force (GSF) [684] is used to treat the motion of a small mass $m$ in the field of a large mass $M$ by expanding the dynamical equations in the ratio $q = m/M$. At leading order, the motion of the small object follows geodesics in the background of the large body; however, accurate modeling of relativistic dynamics must include back-reaction effects due to the interaction of the small object with its own perturbation field.

So far, this technique has been developed mainly for systems with $q \lesssim 10^6$ (expected in space-based detectors) but it could play a central role also for intermediate mass-ratio inspirals (i.e., $q \lesssim 10^3$) for 3G detectors. Intermediate mass-ratio inspirals probe for a few thousand cycles the strong-field regime of the orbital evolution. To accurately describe the emitted waveforms one might need GSF results at next-to-leading order or beyond, or approaches that efficiently combine different analytical approximations. NR (e.g., [685, 686]) can, in principle, solve the target system of equations but it cannot span the full parameter space.

The successful development of waveform models during the last decade is based on a synergistic approach between analytical and numerical relativity: (1) extending the validity of PN and GSF dynamics close to merger [687–690], and building analytical models for the plunge phase of the dynamics [688, 691–694]. (2) developing an approximate ansatz for the merger-ringdown waveform [688, 689, 695], (3) improving the analytical waveform model by matching it to NR simulations [696, 697, 517–520, 677, 521–523] and (4) constructing fast and efficient representations of the full waveforms using reduced-order modeling techniques [698, 699, 520] or frequency-domain, phenomenological closed-form expressions [700, 518]. So far, the models are sufficiently accurate to identify and infer source parameters for events observed by advanced LIGO and Virgo. However, the accuracy requirements of 3G detectors are much more stringent, some of which can be solved by including physical effects that are currently missing (e.g. spin precession and eccentricity), but the full parameter space may not be accessible to NR simulations on the right time scale (e.g., Ref. [520]). The need for more accurate waveforms is, on the one hand, driving the computation of higher-order corrections in PN [701, 702] and GSF [703] formalisms, while fostering the development of novel techniques. In particular, results in post-Minkowskian (PM) theory, which expands the Einstein equations and gravitational radiation in powers of $G$, could be obtained more efficiently using modern scattering methods of quantum fields [704–707] through a conjectured duality between GR and non-Abelian gauge theory, e.g., QCD (see Fig. 6.4). Scattering amplitudes for gravity are square of the non-Abelian gauge-theory amplitudes. A synergistic combination of PN, GSF and PM results may lead to more accurate, highly precise models using results from NR simulations in sparse regions of the parameter space.

Data-analysis methods rely on fast-to-compute waveform models. Reduced order and surrogate models [708, 578, 709–712, 699, 698, 713–717] have proven critical to accelerate waveform generation. They have also been applied to directly interpolate NR waveforms, resulting in very accurate models of the of a
binary’s evolution [709, 710, 712]. These research avenues would need to be continued and improved in the future to take advantage of the discovery potential of 3G detectors. In addition, to understand how GR could be violated in the highly-dynamical, strong-gravity regime the synergistic approach of combining results from analytical techniques and numerical simulations would need to be extended to theories of gravity that violate the principle and symmetries embraced by GR.

\[
\begin{align*}
\text{On the right, the springy line represents a gluon, in a non-Abelian gauge theory (e.g., QCD) and straight lines represent massive color charges (e.g., quarks). On the left, the wavy line represents a graviton, and straight dashed lines represent a massive body (e.g. a BH).}
\end{align*}
\]

Current NR codes have an associated computational cost tightly coupled to the spatial resolution needed to capture the relevant physics, increasing in inverse proportional to the desired target error. However, the cost also rises when simulations become longer with increased mass-ratio since phase’s accuracy must be preserved over more cycles. In addition, for high spins the size of the black hole apparent horizons shrink dramatically, which can increase the computational cost by an order of magnitude. The computational cost for a BBH simulation increases roughly as the square of the mass-ratio and cube of the starting frequency. Thus, order-of-magnitude reduction in mass-ratio or starting frequency will increase the computational cost by \(O(10^2–10^3)\). Moore’s law will only help the simulations marginally in the coming decade, except for some specific regions of the parameter space. Thus, novel analytical techniques to solve the two-body problem would need to be accompanied by the development of new computational algorithms in NR.

### 6.3 Challenges in Data Analysis

To observe and understand gravitational-wave sources we need efficient and accurate data analysis techniques. Current methods were developed for initial and advanced detectors. Compact binary coalescence signals are identified by matched-filtering the detector data with a set of templates or filters that are essentially copies of the expected waveforms from these sources [718–720]. A number of different implementations [721–726] of the method has allowed the detection of signals both in real time, to alert potential multimessenger observations, and offline, to dig out weaker signals and improve parameter inferences. Strain sensitivity of 3G detectors, compared to current detectors, are expected to increase by at least an order of magnitude and they will have far greater bandwidth. This increased sensitivity and bandwidth results in a number of new challenges that must be addressed before 3G detectors become operational.

**Long and overlapping signals.** In 3G detectors signals from BNS can last for days, so motion of the detector relative to a source is nonnegligible and antenna responses cannot be assumed to be constant. This would introduce sky position as additional parameters in a matched filter search. With an expected median detection rate of roughly two BNS mergers every minute the detector will have numerous overlapping signals in the data. Although this problem poses no problem for identifying individual events [727], the number of templates increases enormously and parameter inferences will be formidable. Optimal solution of this problem would not only ensure optimal detection efficiency, in addition it would automatically enable the identification of a source’s approximate sky location often before the merger, providing an early warning to electromagnetic facilities [728]. Further exploration and development of this possibility is needed in the coming years.

**Inclusion of all relevant physics in template banks.** In the case of BBHs it has been shown that for large mass ratios and large precessing spins, the aligned-spins searches that are currently used may miss up to 20% of events [729]. Residual eccentricity for signals entering the 3G detector band may need to be taken into
6.4 Identifying Signatures of New Physics

An important goal for the 3G network is to search for new physics and phenomena which broadly fall into four categories: tests of the dynamics of coalescence; finding evidence for anomalies in the compact objects or in the ringdown, or echoes; GR violations in the propagation of GWs; searching for non-standard polarizations.

**Tests of the dynamics of coalescence.** One test involves estimating masses and spins from different portions of the waveform, and checking for consistency or lack thereof with the predictions of GR [740, 741]. Another
class of tests allows for parameterized deformations away from GR waveforms, and measuring the free parameters associated with them [742–748]. Thus, efficient tools are already exist to search for violations of GR in a model-independent way. However, should a GR violation be found, then we will also want to know its precise nature and origin. Currently only an approximate mapping is possible from the test parameters to quantities that characterize particular modified theories of gravity [9]. This is not ideal; while one expects deviations from the GR dynamics to be prominent in the merger regime itself, full inspiral–merger–ringdown waveforms are currently not available for modified theories of gravity. If they were, then in the event that a GR violation is found, one could perform hypothesis ranking on a list of modified theories according to their relative Bayesian evidences and see which one ends up on top.

**Searching for anomalies related to compact objects.** Various alternatives to black holes in GR have been proposed as well as the accumulation of dark matter particles around an ordinary black hole, or the formation of boson condensates of light scalars through superradiance. Their nature will have an impact on the inspiral dynamics through, e.g., tidal effects or gravitational drag. A similar question then arises as in the interpretation of a priori general anomalies in the dynamics of coalescence, namely how to reliably distinguish between a potentially wide range of qualitatively different scenarios given that even with 3G detectors and at relatively high SNRs, the observed strength of the anomaly need not be large [749]. Additional information is likely to come from the observation of anomalies in the ringdown, for which analysis techniques are already under development [95, 94]. These look for deviations in the way the quasi-normal mode frequencies \( \omega_{lmn}(M, a) \) and damping times \( \tau_{lmn}(M, a) \) depend on the mass \( M \) and spin \( a \) of a newly formed compact object; this can be viewed as an indirect test of the no-hair conjecture. Here too it is possible to combine information from multiple sources, and using golden binaries with advanced detectors, it will be possible to constrain deviations in the dominant mode frequency at the few percent level. What will be qualitatively new with 3G detectors is that individual modes can in principle be separated [91], and methods will need to be developed to make optimal use of this. The emission of GW echoes would again bring further information. In the latter case, concrete waveforms only exist for selected types of objects, and even then in approximate form. More importantly, there may exist echo-emitting compact objects of a type that has not yet been envisaged. Thus, alongside template-based searches [750, 751], a morphology-independent method to search for, and characterize, echoes is also called for [665]. There is also the possibility of testing the black hole area increase law. One proposal is to measure masses and spins of the initial and final black holes and compute from these the areas using the expression for Kerr black holes [752]. A question that arises is whether it is possible to measure the areas more directly; a method for doing this has yet to be developed.

**Searching for anomalies in GW propagation.** 3G detectors will see signals that have propagated over distances comparable to the size of the universe, and hence be ideal to find anomalies in the propagation of GWs that accumulate with distance. This includes dispersion due to a non-zero graviton mass or a violation of local Lorentz invariance [753, 754] and leakage of GWs into large extra dimensions [494, 755]. In both cases, current methods assume that the underlying violation of GR indeed predominantly manifests itself as a propagation-related effect and that modifications in the dynamics of the source can be neglected, which may not be the case; here too a more complete analysis framework is not yet in place.

**Searching for non-GR polarizations.** Alternative polarizations in GW signals (from any type of source, not just coalescing binaries) can be searched for in two ways. One is Bayesian model selection [756–758], another, which can be applied when the sky location can be accurately determined (either through an EM counterpart or a large detector network), involves the construction of null streams: particular combinations of the outputs of multiple detectors in a network that are guaranteed not to contain tensorial modes [759]. For both methods, the science that can be extracted will be limited by the number of detectors; for example, with three interferometers and a sky position from an EM counterpart, one would only be able to establish the presence of additional polarizations in a signal, but not their type. This is then a particular example of how the design choices of 3G observatories (e.g., the number of interferometers in ET) will affect the science that can be accomplished.


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