

The transient gravitational-wave sky

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TOPICAL REVIEW

The transient gravitational-wave sky

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Abstract

Interferometric detectors will very soon give us an unprecedented view of the gravitational-wave sky, and in particular of the explosive and transient Universe. Now is the time to challenge our theoretical understanding of short-duration gravitational-wave signatures from cataclysmic events, their connection to more traditional electromagnetic and particle astrophysics, and the data analysis techniques that will make the observations a reality. This paper summarizes the state of the art, future science opportunities, and current challenges in understanding gravitational-wave transients.

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(Some figures may appear in colour only in the online journal)

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1. Introduction

The gravitational-wave (GW) sky is an unexplored frontier which holds a great potential for discovery and a promise for understanding one of the most mysterious interactions of nature: gravity. Predicted by Einstein's theory of general relativity, GWs are ripples in the fabric of spacetime, produced by the accelerated motion of masses. They carry information from the bulk, coherent motion of matter, complementary to the multi-wavelength electromagnetic (EM) spectrum of traditional astronomy and to the neutrinos and cosmic rays of particle astrophysics. Their observation will play a transformative role in our understanding of the Universe.

The existence of GWs was indirectly proven by over three decades of measurements of the orbit of the binary pulsar PSR1913+16, which has steadily been evolving due to the emission of gravitational radiation in agreement with the predictions of general relativity [1]. However, the direct measurement of GWs remains a challenge, due to their tiny amplitude once they reach Earth.

New and upgraded GW detectors are pursuing their first detection, which will transition gravitational physics to an observation-driven field and usher in a new GW astronomy. The instrumental landscape includes a new generation of ground-based laser interferometers [2–4], pulsar-timing arrays [5–7] and future detectors on the ground and in space [8–13]. In particular, the first generation of interferometric detectors has achieved design sensitivity [14–16], and next-generation ground-based interferometers are expected to be taking data within a few years.

The 'perfect storm' in the transient sky of short-duration cataclysmic events is about to arrive, with GW observations from stellar core collapse, gamma-ray burst (GRB) engines, rapidly rotating neutron stars (NSs) and mergers of compact-object binaries. The storm will be fueled by GW observations from advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) and advanced Virgo, but the success in interpreting observations will hinge on our ability to model the complex physics at the heart of these transient astrophysical sources. This includes GW emission mechanisms that, in general, are not yet fully understood. The importance of this enterprise was highlighted in *New Worlds, New Horizons in Astronomy and Astrophysics*, a Decadal Survey of Astronomy and Astrophysics by the National Research Council [17].

This paper summarizes the current state of the art, future science opportunities and open challenges for GW transients. In section 2, we review the main sources of the GW transient

sky: mergers of compact objects, core-collapse supernovae (CCSNe), and NS oscillations. For each burst source, we discuss its chances of detection and its connection with EM observations. In section 3, we describe GW antennas as well as traditional astronomical observatories available today and in the near future. We elaborate on the detection challenges and open questions of the GW transient Universe in section 4. Finally, section 5 summarizes our conclusions.

This review was conceived as the peroration of the *Gravitational Wave Bursts* workshop series. The first of these workshops was held in Chichen–Itza, Mexico on 9–11 December 2009 and the second in Tobermory, Scotland, on 29–31 May 2012. These meetings provided a forum for astrophysicists, GW data analysts and numerical relativists to explore transformative views of the GW transient sky, focused on: (i) critical examination of current methodologies to model, detect and characterize transients, (ii) current understanding of the physics behind burst sources, (iii) requirements on detector technology and data analysis, and (iv) imagining the future of GW transient science.

2. Sources of gravitational wave transients

Compact objects such as NSs and black holes (BHs) will likely be protagonists in most of the astrophysical events detectable by the next generation of ground-based GW interferometers. Their role could start at birth (CCSNe) or later in their life, either as members of binary systems or as isolated objects. This section provides an overview of what we know, observationally and theoretically, about compact objects as potential sources of transient GWs, including their predicted energetics and rates.

2.1. Compact object binaries and short gamma-ray bursts

Binaries of coalescing compact objects are the main target of ground-based GW astronomy. In many instances, their gravitational waveform is expected to contain many cycles in the sensitive band of the detectors. Therefore, with the aid of well understood models (and assuming that Einstein’s general relativity provides the correct description of gravity in dynamical, strong-field systems) they are ideal candidates for discovery via matched filtering. Given what we know about these sources and their merger rates deduced from known NS systems [18], binaries with either two NSs or a NS and a BH (also called *mixed binaries*) are expected to be bread-and-butter sources for ground-based detectors, even though recent population-synthesis calculations suggest that BH–BH binaries may be more numerous than initially expected [19, 20]. Unlike binary BHs, binaries containing at least one NS have an additional appeal: their potential to act as the central engine of short GRBs (SGRBs) (and possibly other observable EM signals). SGRBs are bursts with duration shorter than ~ 2 s, with most of them lasting a few hundreds of milliseconds. The expected properties of a population of SGRBs from double compact-object mergers have been estimated by several studies [21–23]. To date, only rough comparisons can be made between theory and observations [24, 25]. However, the theoretical predictions of compact-object merger rates are in general consistent with the observed SGRB rates [23, 26].

There are several pieces of evidence supporting the association of SGRBs with the merger of double NS or mixed binaries [27]. One is that SGRBs do not seem to be associated with supernovae, and some of them explode in ‘dead’ elliptical galaxies (i.e., galaxies with negligible ongoing star-formation). Long GRBs (LGRBs) have distinctly different host galaxies from SGRBs, and they mainly occur in star-forming galaxies. SGRBs appear more closely correlated with the rest-frame optical light (old stars) than the UV light (young massive

stars). Furthermore, offsets of SGRBs relative to their host galaxy centers are significantly larger than for LGRBs [28].

The observations listed above are promising, but several challenges remain to establish an unequivocal association between SGRBs and compact binary mergers. As we will see below, the answer to these questions for now can only be obtained via sophisticated numerical models including the relevant microphysics. For example, a problem that can only be resolved via numerical methods is whether mergers can produce accretion disks massive enough to power the observed EM emission. Other demanding aspects of the bursts are precursors [29] and extended emission phases [30] that happen on timescales larger than 10 s: these timescales are beyond the reach of current simulations, which presently last less than a second. Looking forward, a smoking gun for the association between SGRBs and binary mergers will be the coincident detection of EM signals and GWs. Such a coincident detection is one of the most exciting multi-messenger observations that could occur in the advanced detector era.

2.1.1. Neutron star–neutron star binaries. The last few years have witnessed remarkable progress in fully general relativistic simulations of compact-object binaries [31]. The first simulations of NS binaries were performed by Shibata and collaborators [32], but only recently have simulations been extended from the late inspiral up to the coalescence and eventual formation of a BH surrounded by a massive torus. Also recent is the inclusion of more sophisticated physics—realistic equation of state (EOS), magnetic fields and neutrino radiation—as well as the implementation of advanced numerical algorithms, such as adaptive mesh refinement (AMR) techniques.

New physics and AMR have been essential ingredients to accurately predict GW emission and to establish a possible connection with SGRBs. In particular, having AMR in place in the numerical codes has allowed various groups to model the inspiral and merger of NSs [34–37] and to study the formation of hydrodynamic instabilities in the presence of magnetic fields [34, 38, 39]. Similarly, the use of a realistic EOS has led to the suggestion [40, 41] that there are two broad classes of NS binary mergers. Binaries with initial total masses above $\sim 2.8\text{--}3.2 M_{\odot}$ (depending on the EOS) promptly form a BH soon after the merger. On the other hand, binaries with lower masses yield a metastable, hypermassive NS before collapsing to a BH. This difference has very important observational consequences. In the case of massive binaries, the GW signal shows a quick transition from ‘chirping’ during the inspiral to the characteristic quasi-normal ringdown of the final BH [42]. On the other hand, if the merger yields a hypermassive NS, the chirp in the GWs is followed by quasi-periodic oscillations (QPOs) at frequencies 2–4 kHz: see e.g. figure 1, adapted from [33]. Unfortunately this quasi-periodic signal will only be detectable by advanced LIGO and Virgo interferometers if the merger takes place within ~ 20 Mpc [43, 44], but these systems could be an interesting target for future detectors.

Recent studies [45, 46] have also addressed the association of binary NS mergers with SGRBs in the more general case of unequal-mass binaries. These investigations showed that the formation of a massive torus, which could lead to the emission of gamma rays, leaves a characteristic signature in the GW spectrum, consisting of an exponential decay followed by a hump in the $\sim 2\text{--}7$ kHz range. The cut-off frequency and the frequency and amplitude of the hump can be directly associated to the NS EOS and to the mass of the disk. While advanced LIGO and Virgo may not be sufficiently sensitive at these frequencies, a third-generation detector (such as the Einstein Telescope) would be sensitive to sources within 100 Mpc. Moreover, simulations have shown that unequal-mass binaries can produce tori with masses up to $\sim 0.35 M_{\odot}$, which would be more than sufficient to power SGRBs [33]. Notice

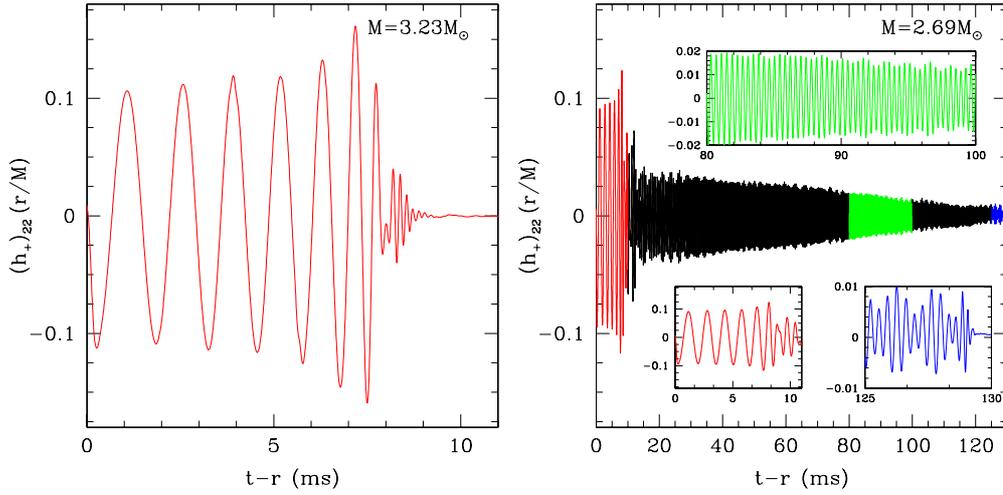


Figure 1. GW signal from the merger of equal-mass binary NSs. The left panel refers to a ‘high-mass’ case with a total gravitational mass of $3.23 M_{\odot}$; the right panel, to a ‘low-mass’ binary with a gravitational mass of $2.69 M_{\odot}$. In the ‘high-mass’ case the total mass of the system is large enough to produce a prompt collapse to BH soon after the merger, and the GW signal is characterized only by inspiral, merger and BH ringdown. In the right panel, on the other hand, the mass of the system is lower; a hypermassive NS is formed and survives for ~ 120 ms before collapsing to a BH (note the very different timescale between the two panels). In the right panel, different insets show zoom-ins on different parts of the signal. The bottom-left inset shows the inspiral and merger on the same timescale as the left panel. The top inset shows the signal emitted by the newborn hypermassive NS, which has a peak frequency at ~ 2.5 kHz. The bottom-right inset shows the final collapse to a BH. The figure was produced using data from [33].

however that simple equipartition arguments would suggest that even tori with masses as low as $\sim 0.01 M_{\odot}$ may be sufficient to power SGRBs (see e.g. [47] for a discussion).

Present estimates suggest that observations of lowest-order tidal perturbations in NS mergers with third-generation detectors would yield measurements of NS radii with ~ 1 km precision [48, 49], while observations of strong-field tidal effects during mergers might allow similar accuracies even with second-generation detectors if sufficiently accurate models are available [50]. Such GW observations, which probe the bulk properties of NSs and could make it possible to constrain the EOS of matter in the NS core, will be complementary to EM observations [51, 52], which are sensitive to surface properties. This enterprise will require a large number of GW templates. To reduce the computational burden, there have been successful attempts to construct semi-analytical GW templates (e.g. using the effective one-body approach) that include the influence of tidal deformation [53–55]. More recent studies in the conformally-flat approximation [56, 57] have suggested that the GW signal emitted by the hypermassive NS formed after merger may also be used to constrain the NS EOS. If the result of the merger is a long-lived hypermassive NS, the GW signal may be used to measure the NS radius with an accuracy of up to ~ 200 m already with advanced LIGO [56, 57]. While this is a very interesting result, a more accurate treatment of general relativistic effects and magnetic fields may affect the evolution of the hypermassive NS [34, 58] and make such measurements more difficult.

Our understanding of the potential role of magnetic fields in the dynamics of NS binaries has significantly improved in recent times [38, 39, 58–62]. These studies have provided

additional support to the view that the merger of magnetized NSs can provide the central engine for SGRBs; furthermore, one could have potentially observable emissions even in cases where a SGRB is not realized [60–62]. Unfortunately, the studies also showed that the effects of magnetic fields on the GW signal are most appreciable at frequencies larger than ~ 1 kHz, where advanced LIGO and Virgo are less sensitive.

Simulations of NS mergers that include the effects of neutrino cooling are in their infancy. Pioneering work in this direction [43, 44, 63] shows that for a stiff, finite-temperature EOS and with neutrino cooling, a hypermassive NS is the canonical outcome of the merger of NS binaries with masses smaller than $3.2 M_{\odot}$, and that thermal pressure support may be important. The neutrino luminosity associated with these events could potentially be detected for mergers within 5 Mpc by hyper-Kamiokande [44]. Finally, studies of the GW emission from NS mergers on eccentric orbits have also begun [64, 65]. These systems may be formed via dynamical capture in dense stellar environments, and they may account for a fraction of NS binaries [66].

2.1.2. Neutron star–black hole binaries. In the last few years, the interest in modeling mixed binary systems comprised of a BH and a NS has also intensified (see [67] for a recent review). The first simulations tracked the merger of a NS with a non-spinning BH [68–70]. These early simulations showed that the merger produced a torus with mass $\sim 0.2 M_{\odot}$ when the BH and the NS have comparable masses. Subsequent studies with higher numerical accuracy excluded the possibility of SGRBs in mixed binary mergers if the BH is non-spinning [36, 71–73], even in the case of equal-mass systems [72].

If the BH is spinning, the merger can potentially power a SGRB. Simulations show that a disk with mass $\sim 0.2 M_{\odot}$ can be formed for binary mass ratios of 1/3 and BH spins of $a/M_h = 0.75$ [74], where $a = J/M$ is the Kerr spin parameter (in geometrical units $G = c = 1$). Recently, the case of NSs merging with $10 M_{\odot}$ BHs was explored in [75]. If the BH is rapidly rotating ($a/M_h \sim 0.7$ – 0.9) the merger can result in accretion disks massive enough to power a SGRB [75]; however, we remark once again that even less massive tori may be able to power SGRBs in the presence of instabilities [47]. Furthermore, neutron-rich ejecta from BH–NS systems are possible, and it has been shown that the calculated flux and the time to return to the central engine are consistent with models for extended emissions from the r -process [76].

Analytic models have also been developed to compute the mass of the disk that can be formed after merger [77, 78], as well as other features of the merger remnant [79]. These studies have the main advantage that they allow us to explore a larger portion of the parameter space. They confirmed that massive tori can be formed even at low mass ratios ($q \sim 0.1$) if the BH is rapidly spinning [77, 78], and therefore that these binaries could in principle power SGRBs. GWs emitted from mixed binary systems can be grouped in three broad classes depending on their behavior near the innermost stable circular orbit (ISCO) [80]:

- Type I: the NS is disrupted outside the ISCO.
- Type II: the mass transfer from the NS to the BH takes place close to the ISCO.
- Type III: the NS is not disrupted outside the ISCO, and all of the matter falls immediately into the BH.

While gravitational waveforms from type-III mergers are difficult to distinguish from BH binary systems, type I and II will be sufficiently distinct that they could provide information about the mass ratio and the NS compactness. The likely frequency of these distinctive signatures is above 2 kHz, i.e. within the reach of third-generation detectors, such as the Einstein Telescope. In the case of non-spinning BHs and for large mass ratios between ~ 0.3 and 1 (i.e., type-I/type-II mergers), tidal deformations induced in the NS during the inspiral

may also allow for advanced LIGO measurements of the NS radius (and hence for constraints on the EOS) with accuracy $\sim 10\%$ – 50% for sources located at a distance of 100 Mpc [81–83].

While early simulations of mixed binary mergers adopted a simple ideal-fluid EOS, recent work accounts for more realistic EOSs [84–86], the effects of the orientation of the BH spin on the formation of the torus and GW signatures [87], and the presence of magnetic fields [88, 89]. Magnetic fields do not seem to have a detectable GW signature in the case of mixed binaries, but they could provide a mechanism for the production of relativistic jets when a torus is formed after the merger, and various models predict that they could induce possible observable EM counterparts [90–93].

Finally, recent studies considered eccentric orbits in mixed binary mergers [94, 95]. In particular, these simulations addressed the effect of eccentricity on the formation of the massive torus and on GW emission. While binaries in quasi-circular orbits emit a periodic signal during their inspiral phase, eccentric binaries emit a series of quasi-periodic GW bursts, detectable by advanced LIGO and Virgo up to distances of 300 Mpc.

2.1.3. Event rates. Techniques for estimating rates of compact binary mergers have been recently summarized in [96]. The rate of NS–NS binary mergers in our Galaxy can be estimated from measured parameters of known binary pulsars [97]. Given the lack of direct observations of NS–BH systems, their rates must be estimated by modeling, typically involving population-synthesis studies of large numbers of simulated binaries [98], or attempts to predict the future evolution of specific observed systems that represent possible progenitors of compact binaries [99].

Unfortunately, both methods currently suffer from significant uncertainties. Population-synthesis results depend critically on assumptions about common-envelope evolution, typical supernova kicks, mass-loss rates, metallicity, and other astrophysical parameters [19, 20]. Extrapolations from binary pulsar observations have fewer free parameters, but their accuracy is limited by small-number statistics due to the paucity of observed binary NS systems in the Galaxy, the imperfect understanding of selection effects in pulsar surveys, and uncertain knowledge of the pulsar luminosity function.

According to the compilation [100], NS–NS merger rates plausibly range from 1 to 1000 mergers per Milky Way Galaxy per million years. This range is also consistent with extrapolations from the observed rate of SGRBs assuming a relatively high correction for beaming [26]. Meanwhile, NS–BH merger rates fall in the range 0.05–100 per million years in the Galaxy.

The conversion of merger rates to detection rates depends on the assumed detector sensitivities, data quality, and details of the search pipelines. The uncertainties in these factors are typically small relative to the uncertainties considered above, but additional astrophysical uncertainties encountered when scaling up from the Galaxy, such as including the contribution of low-metallicity environments or elliptical galaxies, could be more significant [101]. The merger rate ranges quoted above correspond to detection rates of 0.04–400 per year for NS–NS binaries and 0.2–300 per year for NS–BH binaries in the era of advanced GW detectors operating at full sensitivity [100].

2.2. Binary black hole mergers

The defining characteristic of BHs is their event horizon: a ‘surface of no return,’ from within which not even light can escape. Until now, we have been able to infer the existence of BHs only indirectly, in particular by modeling phenomena associated with the neighborhood of the putative BH horizons [102]. The evidence gathered so far is from the behavior of astrophysical

objects, matter or fields that cannot be explained by other means than by appealing to the presence of a BH, under the assumption that Einstein's theory of gravity is correct. Examples are the emission from active galactic nuclei, the orbits of stars at the center of our Galaxy, x-ray sources and tidal disruptions of stars, to name a few. One rather extreme point of view is that no EM observation will ever provide conclusive proof of the existence of BHs [103]. On the other hand, there is general consensus that the detection and characterization of GWs from the merger of two BHs will offer compelling evidence for their existence: see e.g. [42, 104] and references therein.

Binary stellar-mass BHs can be formed either through the evolution of isolated binaries in galactic fields, or through dynamical formation scenarios in dense stellar environments, such as globular clusters or galactic nuclear clusters (see [96, 100] and references therein). Due to the lack of direct observations of any binary BHs, predictions about rates and mass distributions of these systems must rely on simulations.

In section 2.1.3 we referred to population-synthesis models for the evolution of isolated compact-object binaries. These models have particularly large uncertainties in the case of binary BHs, including the effects of metallicity (lower metallicity tends to decrease mass loss through stellar winds and increase the number of merging binary BHs), the uncertainty in supernova birth kicks for BHs (higher kicks may disrupt binaries), and the uncertain future of binaries that enter the common envelope as they are going through the Hertzsprung gap (such binaries may merge directly, without a GW signature). According to the compilation of predictions in [100], advanced detectors may observe GWs from merging binary BHs at a rate between one detection in a few years and a thousand detections per year. More recent simulations considering a wider range of updated models are presented in [20]. These simulations indicate that rate uncertainties still span several orders of magnitude, but also that rates appear more promising than in the past. Attempts to model the future evolution of BH–Wolf–Rayet binaries IC 10 X-1 and NGC 300 X-1 also indicate that advanced detectors may observe hundreds of events per year [105], even though the precise modeling of the evolution of such systems is still a difficult task.

Another possible channel to produce observable binary BH mergers consists of dynamical interactions in globular clusters and nuclear star clusters. In these systems, BHs are likely to sink to the center through mass segregation and replace other members of existing binary systems via three-body encounters, leading eventually to binary BH mergers. Several simulations (see e.g. [106–109]) have indicated that, although many BHs could be ejected from globular clusters during three-body encounters, dynamically formed BH–BH binaries could make significant contributions to the overall rates of detected systems.

Most BH binaries produced in population-synthesis models or via three-body encounters in globular clusters and nuclear star clusters have masses such that the binaries will inspiral in the band of interest for Earth-based GW detectors; some of them may also produce detectable ringdown signals in band. Post-Newtonian approximations and progress in numerical relativity since the 2005–2006 breakthroughs [110–112] are supplying accurate knowledge of the type of signal emitted in the coalescence, by providing waveforms with enough cycles to cover the inspiral, merger and ringdown (see e.g. [104, 113, 114] for recent reviews). Knowledge of the waveform allows for matched-filtering searches for these signatures in GW data. Efforts to create analytical and/or phenomenological models calibrated to numerical-relativity data are ongoing: see e.g. [115–120].

Beyond the mass range of stellar-mass BHs, binaries involving intermediate-mass black holes (IMBHs) could represent exciting GW sources. Detectable binaries in advanced LIGO and Virgo would have total mass in the range between ~ 100 and ~ 500 solar masses. Both theoretical formation scenarios and observational evidence for IMBHs are topics of active

research and debate [121, 122]. If IMBHs have a non-negligible occupation number in globular clusters, they could capture stellar-mass NSs or BHs, with GWs from the ensuing intermediate-mass ratio inspirals being detectable at rates of up to tens per year [123, 124]. It may also be possible to detect mergers of two IMBHs [125, 126]. The highly uncertain rates of these processes are summarized in [100].

The characteristic chirp-like signal from binaries in a quasi-circular inspiral could be radically modified if the BHs merge in a highly eccentric, precessing orbit. Such orbits could be the result of scattering events expected in the environment of dense galactic cores. The resulting GWs will appear as bursts of radiation near periastron, followed by quiescent phases while the BHs travel to and return from apoastron. The time elapsed between subsequent bursts decreases as the binary hardens and the eccentricity decreases [127–133]. Depending on the masses of the BHs, GWs from highly eccentric binaries should be visible by both ground- and space-based interferometers [134, 135].

2.3. Core-collapse supernovae and long gamma-ray bursts

CCSNe and LGRBs share a common origin: the collapse of stars with masses $\gtrsim 8 M_{\odot}$. Observational evidence comes from the positional and temporal association of several nearby LGRBs with supernovae of Type Ic: see [136, 137] for reviews. These SNe associated with GRBs are distinguished from other core-collapse events based on (i) the absence of hydrogen and helium in their optical spectra [138], characterized predominantly by broad absorption features of intermediate-mass elements, and (ii) a strong non-thermal afterglow component best studied at radio wavelengths [139]. Long-term monitoring of the afterglow reveals that the LGRB is characterized by a bipolar relativistic outflow, and jet opening angles $\lesssim 30^{\circ}$ are commonly inferred [140]. Intriguingly, comparing the collimation-corrected rates of LGRBs and Type Ic SNe, we find that *most* LGRBs are associated with a SN, but less than 1% of SN Ic are associated with a LGRB. This is confirmed through detailed radio studies of local Type Ic SNe, which indicate that only $\sim 0.7\%$ of SNe Ic drive relativistic outflows, some of which do not give rise to detectable ($E_{\gamma} \gtrsim 10^{48}$ erg; 25–150 keV) gamma-ray emission [141, 142].

While the progenitors of SNe Ic and/or LGRBs have yet to be directly detected in pre-explosion imaging [143], theoretical considerations point to massive stars that have been stripped of their hydrogen envelope prior to explosion, either by their own strong radiation-driven stellar winds [144] or through the interaction with a close binary companion [145]. The critical ingredient that enables only 1% of SNe to produce GRBs remains unclear, but a key component is probably low metallicity ($Z \lesssim 0.5 Z_{\odot}$), allowing the stellar core to retain angular momentum by suppressing the line-driven winds [146]. With the advent of new wide-field surveys (e.g., Pan-STARRS, Palomar Transient Factory), the rate of CCSN discoveries in metal-poor galaxies is growing. Combined with radio follow-up observations, the metallicity dependence of relativistic outflows in CCSNe can be directly tested.

GRB-associated SNe are not the only explosions with evidence for asphericity. Late-time spectroscopy of CCSNe in the nebular phase [147], polarization measurements of local CCSNe [148], and detailed high spatial resolution studies of Galactic SN remnants (SNR) such as Cas A [149] all suggest that ejecta asymmetries are in fact common place. Thus, it remains unclear what distinguishes the progenitors of ordinary CCSNe from GRBs, and it could be that a significant fraction of CCSNe (not just those associated with *detected* GRBs) could experience exotic explosion mechanisms.

2.3.1. Theoretical modeling. At the end stage of stellar evolution, the core of a massive star is supported against gravity by the pressure of relativistically degenerate electrons. Collapse

is initiated when the core exceeds its effective Chandrasekhar mass and continues until the inner core reaches nuclear density. There, the nuclear EOS stiffens, leading to core bounce and the formation of the hydrodynamic bounce shock. The shock runs into the supersonically collapsing outer core, losing its energy to the break-up of infalling heavy nuclei into nucleons and to neutrinos that are made by electron capture in the region behind the shock, and stream out freely as the shock reaches regions of low neutrino optical depth. The shock stalls, turns into an accretion shock, and must be revived by the *core-collapse supernova (CCSN) mechanism* to drive a CCSN explosion. This is the basic picture that has been established since Bethe's authoritative 1990 review [150].

A variety of mechanisms have been proposed in the literature (see, e.g., [151] for a recent review) and all leading candidates involve GW-emitting aspherical dynamics. The *neutrino mechanism* relies on the net deposition of energy by charged-current neutrino absorption in the region immediately behind the stalled shock. While the neutrino mechanism fails to blow up ordinary massive stars in spherical symmetry, the multi-dimensional phenomena of convection, turbulence, and the standing-accretion shock instability (SASI, an advective-acoustic instability of the stalled shock) very likely enhance the neutrino mechanism's efficacy [152–158].

The *magnetorotational mechanism* relies on rapid rotation and magnetic field amplification due to flux compression in collapse, rotational winding, and the magnetorotational energy that converts free energy of differential rotation into magnetic field [159–163]. These processes may lead to magnetic fields with strengths of order 10^{15} G, which would be sufficient to launch bipolar magnetohydrodynamic (MHD) jets, leading to an energetic, strongly aspherical explosion [164]. The key ingredient required for the magnetorotational mechanism is rapid progenitor star rotation, but most massive stars, perhaps up to 99%, are presently expected to be slow rotators [165, 166].

A third potential way of driving CCSN explosions is the *acoustic mechanism* proposed by [167, 168]. In their simulations, SASI-modulated turbulence and accretion downstreams hitting the protoneutron star (PNS) excited pulsations (predominantly of $l = 1$ spatial character) of the latter, that grew to non-linear amplitudes and dissipated in sound waves. Propagating along the density gradient behind the stalled shock, the sound waves steepened to secondary shocks, injecting additional heat into the postshock region, eventually leading to explosion. This mechanism is robust, but there are many unresolved issues with it. Explosions occur quite late and would imply NS masses and nucleosynthetic yields that are likely inconsistent with observations. Only one group and code have produced this mechanism to date. Though many see the necessary ingredients for this mechanism, including excitation of PNS pulsational modes, it is not clear whether the amplitudes obtained by [167, 168] are produced in nature. Furthermore, [169] showed that nonlinear parametric instabilities may limit the oscillation amplitudes of the PNS by funneling oscillation power into daughter modes.

The details of the LGRB central engine may be as uncertain as the CCSN mechanism, but the relativistic beamed outflows observed from GRBs strongly suggest that rapid rotation plays a major role in the central engine.

In the collapsar scenario, outlined first by [170], a rotating CCSN fails to explode or explodes weakly or very aspherically, leading to BH formation before (type-I collapsar) or after (type-II collapsar) an explosion by fallback accretion. Eventually, typically seconds after BH formation [171], an accretion disk is expected to form near the BH. Accretion energy or extracted BH spin energy, mediated via MHD processes [172, 173] and/or neutrino pair annihilation [174, 175], may then drive the relativistic GRB outflow, while MHD disk winds and viscous heating may power a GRB-accompanying energetic CCSN explosion [176, 177].

The rapid progenitor rotation required in the collapsar scenario may lead to an energetic magnetorotational explosion, preventing BH formation [178]. This possibility gives rise to the competing millisecond-protomagnetar model for the LGRB central engine [179–181]. In this model, a magnetorotational CCSN explosion excavates the polar regions, allowing the driving of an ultra-relativistic wind by the spin-down of the strongly magnetized neutrino cooling PNS (the protomagnetar). The protomagnetar model is able to explain the prompt GRB emission, and prolonged magnetar activity may explain long-duration x-ray afterglow observed in LGRBs.

2.3.2. Gravitational wave emission. The ubiquitous aspherical dynamics in stellar collapse, CCSNe and LGRBs gives rise to bursts of GWs with typical durations from milliseconds to seconds, whose waveforms are impossible to predict precisely by simulations. The reason is that much of the GW emission is influenced or dominated by stochastic dynamics (i.e. turbulence), and also that much of the input physics (e.g., the nuclear EOS) and the initial conditions are complicated and impossible to know exactly.

Aspherical stellar collapse was early on considered as a source of detectable GWs [182, 183] and has been studied extensively: see [184–186] for recent reviews. In nonrotating or only slowly rotating CCSNe, the GW emission is dominated by convective overturn in the PNS and in the region behind the shock, modulated by the SASI and enhanced by fast accretion downstreams that are decelerated in the stably stratified outer layers of the PNS. The emitted GW signal has random polarization, a broad spectrum with power at ~ 100 – 1000 Hz, and dimensionless strain amplitudes of order 10^{-22} at a source distance of 10 kpc [154, 187–190]. Contributions at low frequencies ($\lesssim 30$ Hz) come from anisotropic emission of neutrinos [187, 189–191] and explosion asphericities [154, 188, 189].

If the neutrino mechanism lacks efficacy and the explosion is delayed to late time, the strong PNS oscillations associated with the acoustic mechanism may be excited. Their quadrupole components emit GWs at momentarily fixed (secularly changing due to changes in the PNS structure) frequencies of ~ 600 – 1000 Hz, with strain amplitudes of 10^{-21} – 10^{-20} at 10 kpc [185, 192]. So far, all simulations of these pulsations have been axisymmetric, predicting linearly polarized signals, but in 3D correlated emission in the second GW polarization can be expected.

Rapid rotation, if present, will lead to a characteristic burst of GWs emitted at core bounce, when the inner core undergoes the greatest acceleration. This signal has been shown to be linearly polarized (i.e., the dynamics is axisymmetric) and increases in amplitude with increasing initial inner core angular velocity, up to the point where centrifugal forces become dominant and decelerate the bounce dynamics [193–197]. Typical signal amplitudes are of order 10^{-21} at 10 kpc for cores with precollapse central spin periods of 2–4 s; the GW emission peaks around 700–800 Hz, decreasing to below ~ 200 Hz for very rapid rotation. Simulations that take into account magnetic fields found that extreme precollapse iron core fields in excess of 10^{12} G would be necessary to modify the bounce dynamics and GW signal [163, 198–201]. More moderate initial fields can be amplified in the postbounce phase and will modify the postbounce dynamics and GW signal.

Subsequent to core bounce, nonaxisymmetric rotational instabilities may develop. These require rapid spin and/or differential rotation. A ratio of rotational kinetic to gravitational energy $T/|W|$ above $\sim 27\%$ is required for a classical high- $T/|W|$ dynamical instability, that leads to an $m = 2$ deformation of the PNS. A secular instability (driven by GW radiation reaction or viscosity) may set in at $T/|W| \gtrsim 14\%$ [202]. Typical rapidly spinning cores lead to PNS with $T/|W| \lesssim 10\%$ [193]. Core-collapse naturally produces a nearly uniformly spinning PNS core with a strongly differentially rotating outer mantle [166]. This

differential rotation can drive a rotational shear instability leading to angular momentum redistribution, nonaxisymmetric deformation and GW emission [196, 197, 203–209]. Typical signal characteristics are strain amplitudes of order 10^{-21} at 10 kpc and quasi-periodic emission at twice the frequency of the unstable mode—typically ~ 800 – 1000 Hz [196, 197, 208]—for a duration of 10—few 100 ms.

After the onset of an explosion, the GW signal emitted by dynamics between the PNS core and the shock will subside quickly, leaving the more gradually decaying GW signal from PNS convection and, potentially, nonaxisymmetric rotational dynamics behind. If the explosion fails, a BH forms after ~ 1 – 3 s (the exact time is determined by the nuclear EOS and the progenitor structure). If the PNS is spinning, this will give rise to a second pronounced peak in the GW signal, with strain of order 10^{-20} at 10 kpc and most GW power at frequencies above 1–2 kHz [210].

In a collapsar-type LGRB, the GW emission will be very similar to a rapidly spinning CCSN up to BH formation. The latter will be followed by a multi-second GW-silent phase after which instabilities in the inner accretion disk and/or outer accretion torus may give rise to GW emission lasting, possibly, for the duration of the GRB [211–213]. Detailed waveforms of such instabilities have yet to be predicted by simulations.

In a millisecond-protomagnetar LGRB, the signal from BH formation and the GW-silent phase would be absent. The GW emission due to nonaxisymmetric rotational dynamics of the protomagnetar may continue for the duration of the GRB and, if the instability is secular, possibly throughout the early afterglow phase [214, 215], and may be detectable by advanced LIGO out to ~ 100 Mpc [214].

2.4. Isolated neutron stars

The NS menagerie offers a rich variety of EM phenomenology and possibilities for GWs. In addition to the binary NS coalescences discussed in section 2.1, the birth of a NS following the death throes of a medium sized star in a supernova explosion may also be visible with advanced detectors. Each scenario may (depending on the maximum NS mass) lead to a hot, possibly rapidly spinning, remnant with violent dynamics. Initially this remnant is opaque to neutrinos, but after a few tens of seconds [216–218] it becomes transparent and cools, the thermal pressure drops and a NS is formed. During the initial phase, the GW signature of the newborn NS may evolve considerably [219], due to changes in thermal gradients and interior composition. This evolution, in fact, continues for the first few months of the NS life, as the crust freezes and the various superfluid/superconducting components establish themselves. At the end of the process, a mature NS has a complex structure, the modeling of which requires an understanding of much extreme physics.

In this section, we will focus on GW burst signals from isolated NSs. We take the, possibly simplistic, view that the related phenomena can be understood in terms of the star's oscillation modes. This is certainly the case for many of the mechanisms that have been discussed in the literature, ranging from various mode-instabilities to magnetar flares and radio pulsar glitches. The interest in instabilities is natural, since they provide an explanation for the excitation of the modes and the associated GW signal. Similarly, it is reasonable to consider scenarios associated with known EM phenomena, like magnetar flares and pulsar glitches. There are, however, issues with each of these scenarios. In the first case, the presence of an instability will not guarantee a detectable GW signal. The relevance of the mechanism depends on the physics that counteracts an unstable, growing mode. This involves both the mechanics of the problem—whether non-linear hydrodynamics saturates the instability [220–223]—and microphysics, as encoded in the relevant viscous damping channels [224].

While we have made good progress on understanding such issues in the last few years, it is clear that many challenges remain. In the second case, most estimates are based on simple energetics. However, the link between the observed EM signal and any GWs that may be generated by the underlying mechanism is not at all clear. This is rather obvious, since the detailed mechanisms leading to observed flares and glitches remain rather poorly modeled. Most current estimates are based on plausibility arguments. To make progress we need a better understanding of these enigmatic events. That this is a challenge is clear from the fact that the pulsar glitch mechanism and high-energy emissions from pulsars are not well understood, despite four decades of study [225].

NSs may radiate GWs through a range of mechanisms. For traditional reasons, the associated signals tend to be categorized either as ‘bursts’ or ‘periodic’ signals (mainly because of the different data analysis strategies used to look for the signals). However, this division is rather arbitrary. For example, rotating NSs with quadrupolar deformations (linked to the geological history of the elastic crust or the structure of the magnetic field) would produce continuous quasi-sinusoidal GW signals. Such signals have already been the subject of GW searches [226–228]. However, it is by no means clear that the signal will remain unchanged over a long-term observation lasting months to years. In fact, one may argue that NS ‘mountains’ ought to be transient, evolving due to plastic flow [229]. However, as the timescale and detailed behavior of the evolution is essentially unknown, this possibility has not been considered so far. A closely related problem concerns NSs that interact with their environment, as in the case of accretion from a binary partner in a low-mass x-ray binary. While it is natural to assume that the accretion of material leads to some level of quadrupole deformation and GW emission [230], it is far from clear how such ‘mountains’ are established and to what extent they evolve as the accretion rate changes. This is a key question that needs to be addressed if we are to search for signals from such systems. The problem is also linked to that of instabilities evolving on a secular timescale, as in the case of f - and r -modes discussed below. Instabilities may trigger a violent behavior, but they may also be rather subtle, leading to the system simmering on the threshold of stability. The latter behavior is, in fact, what is expected for the instability associated with inertial r -modes [221, 222, 231].

While searches for GWs from NSs have already been performed on data from first-generation detectors [226, 228, 232–236], it is generally expected that such signals will require third-generation detectors like the Einstein Telescope. A review of relevant sources of GWs, including isolated NSs, for the Einstein Telescope can be found in the design study [237] as well as recent review articles [238, 239]. Search techniques for long-duration transients have been proposed in [e.g., 240, 241]. Here, we will present a brief overview of the main mechanisms for ‘burst’ emission from isolated NSs touching on the science returns for observing such signals, and highlighting issues that require further attention.

2.4.1. Instabilities. NSs may suffer various instabilities as they evolve from hot remnants to cold mature objects. Some of these instabilities may be efficient GW emitters and so are of obvious interest for GW astronomy. The relevant instabilities can be broadly divided into two classes. Dynamical instabilities tend to grow rapidly, and do not require additional ‘physics’ for their existence. The most commonly considered such instability is the bar-mode instability associated with the star’s fundamental (f -) mode. Secular instabilities, on the other hand, are relatively subtle. They owe their existence to dissipative mechanisms and tend to grow on the associated dissipation timescale. The most important such instabilities (in the present context) are driven by GW emission via the so-called Chandrasekhar–Friedman–Schutz mechanism [242, 243] and are associated with the f -mode and the inertial r -mode in a rotating star. The basic picture is that an instability sets in at some threshold, say above a critical rotation rate,

leading to the growth of a non-axisymmetric perturbation. The existence of an instability and the early phase of its evolution are relatively easy to establish, since they can be studied within linear perturbation theory. Once the growing mode reaches a sizeable amplitude the situation becomes less clear, as one must account for the full nonlinear dynamics. At some point one would expect the instability to saturate. Understanding the mechanism for, and level of, saturation is key if we want reliable estimates of the emerging GWs.

The dynamical bar-mode instability has been studied in some detail via numerical simulations. As anticipated in section 2.3.2, this instability sets in once the ratio of rotational kinetic energy (T) to gravitational binding energy ($|W|$) exceeds a certain threshold. At that point, the f -mode grows and deforms the star into a (rotating) bar-shape. This would be a very efficient configuration for emitting GWs. However, it is not clear that real NSs exhibit this instability. The main problem is that the critical threshold requires a significant amount of differential rotation. Uniformly rotating NSs cannot get near the critical value of $T/|W|$, because they reach the break-up limit before this happens. There are, of course, situations where differential rotation is expected to develop, most notably a few milliseconds after core bounce in a supernova or tenths of seconds later, as the NS contracts due to cooling by neutrino emission. Present simulations [244–246] suggest that this may lead to $T/|W|$ becoming large enough to trigger the bar-mode instability, but unfortunately the system evolves away from this regime rather quickly. Recent simulations also cast doubt on the notion that the unstable bar-mode would last for many rotations [245], as required to make the effective GW amplitude detectable from sources outside our Galaxy. A closely related, somewhat more subtle instability may be more important. There is evidence that instabilities may be triggered at much lower values of $T/|W|$, provided that the system exhibits significant differential rotation [247–251]. This class of instabilities is much less well understood at the moment. Most importantly, we need to establish whether real astrophysical systems may evolve into the relevant part of parameter space.

In the last few years, the main focus has been on secular (GW driven) instabilities. This kind of instability sets in when the pattern speed of a given modes changes from counter- to co-rotating with respect to an inertial frame. This effectively means that the system radiates positive angular momentum, drawn from a negative angular momentum reservoir, leading to a runaway process.

Early work on this mechanism focused on the instability of the f -mode in Newtonian NS models [252–255]. The results suggest (perhaps somewhat optimistically) that the unstable modes could be observable from sources beyond our Galaxy. However, the f -mode instability only operates near the mass shedding limit, so NSs would have to be born rapidly spinning for the mechanism to kick in during their early life. Current observations suggest that the subset of NSs born spinning sufficiently fast may be rather small [256], but this is certainly not well understood at the present time. Another problem for the f -mode instability is that it may be completely quenched by dissipation. In particular, the so-called mutual friction associated with superfluid vortices may suppress the instability once the star cools below the threshold for superfluidity [254, 257]. This means that the f -mode instability is unlikely to operate in mature NSs, e.g. ones spun up by accretion in a low-mass x-ray binary. Our understanding of the f -mode instability has improved significantly recently, with accurate numerical simulations both at the linear and nonlinear level. In particular, we now have a clearer picture of the instability for relativistic stars [258, 259]. These results indicate an enhancement of the f -mode instability due to relativistic effects, renewing interest in the mechanism as a source for gravitational radiation [260].

In the last decade most work on secular instabilities has focused on the inertial r -modes. These modes are interesting as they radiate mainly through current multipoles, not mass

multipoles (as in the case of virtually all other GW sources). That these modes would also be unstable due to the emission of GWs came as some surprise, and by now many aspects of the associated instability have been considered: see [224, 261] for exhaustive reviews. The r -mode instability is interesting for many reasons. It may provide a natural explanation for the absence of NSs spinning faster than 720 Hz by preventing further spin-up once an accreting (recycled) NS reaches the instability threshold. This mechanism would lead to NSs in low-mass x-ray binaries being interesting targets for GW searches [262]. However, due to the varying accretion rate in these systems and the many unknown parameters, such searches will be very difficult [263]. As in the case of the f -modes, the unstable r -modes are counteracted by a range of dissipative mechanisms. It is generally thought that the most important damping mechanisms are associated with (i) a viscous boundary layer at the crust–core interface, (ii) superfluid mutual friction, and (iii) hyperon bulk viscosity in the deep core of the star. The star’s magnetic field may also have a decisive importance; this issue has not been studied in sufficient detail yet, but see [264]. Very recent work [265], comparing the predicted r -mode instability window to observed accreting systems, suggests that our understanding is far from complete. The generally accepted r -mode model would lead to a large number of observed systems in fact being unstable. This is an obvious problem that needs to be addressed by improving our models. It is, however, not clear what the missing piece of the puzzle may be.

Possibly in contrast with the f -mode, the r -mode is expected to saturate at low amplitudes due to nonlinear mode-coupling. The upshot of this is that the associated GWs are unlikely to be observed from outside our Galaxy [221]. The results also imply that the spin evolution of a NS with an unstable r -mode (at saturation) may be rather complex, making a GW search even more challenging.

2.4.2. Asteroseismology. In order to understand the observed NS phenomenology we need to account for much extreme physics, many aspects of which are poorly constrained. In fact, many relevant issues will never be tested in terrestrial laboratories. Consider, for example, the possibility of quark deconfinement at high densities. While colliders like the LHC at CERN and RHIC at Brookhaven probe the properties of quark–gluon plasma, they cannot reproduce the high-density/low temperature environment of a NS core. By exploring NS physics (making ‘sense’ of observations) we can hope to constrain theoretical physics in many useful ways. In fact, this is an exciting promise of GW astronomy. The basic idea is simple. If we observe GWs from an oscillating NS, then we can use the data to infer the state of matter in the star’s core. This prospect is particularly exciting as it provides a probe of the high-density region, not the surface (where most EM phenomena arise). Of course, there is a downside to this as well. It means that we need to construct models that faithfully represent the core physics. This is far from easy.

Due to their complex interior structure, NSs have many (more or less) distinct families of oscillation modes. Roughly speaking, one can associate different mode families with different pieces of physics [266]. Pressure gradients lead to the acoustic p -modes, composition (or thermal) stratification leads to g -modes, rotation leads to inertial modes, the dynamic spacetime leads to w -modes. There are modes associated with the crust, superfluidity, the magnetic field and so on. Of course, this means that the spectrum of a real NS is tremendously complicated and it may be very difficult to make sense of any data. However, for GW astronomy the situation may not be too bad, because most of the possible modes are unlikely to be efficient emitters of gravitational radiation. There are, essentially, two questions. Are there viable astrophysical scenarios where the oscillations of a star are excited to a large enough amplitude that the associated GWs may be detected? If so, what can

we learn from such observations? So far, most research in this area has focused on the second question. It has been demonstrated that global properties, such as mass and radius, can be constrained by observing f -modes (perhaps in some combination with p -modes and w -modes) [267–269]. It has also been shown that the rotational deformation, which may have a severe effect on the mode spectrum, can be ‘filtered out’ [270]. Thermal g -modes have been studied for PNSs [219], and superfluid modes have also been considered [271], but we do not yet have sufficiently realistic models that we can consider the combination of the different effects. However the relevant theory framework has been developed, so it is just a matter of time until the models we consider can be considered (at least moderately) realistic.

As far as realistic astrophysical scenarios are concerned, we know that isolated NSs suffer violent events like pulsar glitches or magnetar flares. The energetics of these events is such that they could plausibly be relevant for GW astronomy. The key question is whether sufficient energy is released gravitationally. To establish this, we need to develop models that account for the observed phenomenology. Following the exciting discovery of QPOs in the tails of giant magnetar flares [272–275], likely heralding the era of actual NS seismology, there has been significant activity aimed at understanding the dynamics of these events. Magnetars are strongly magnetized, slowly spinning NSs that exhibit high-energy emission, occasionally punctuated by bursts. The favored model contends that the energy of the magnetic field powers the observed activity, and is responsible for the bursts and occasional giant flares in soft-gamma repeaters and anomalous X-ray pulsars [276]. The observed QPOs have a complicated oscillation spectrum [277–281], the analysis of which may constrain both crust physics and the magnetic field structure [282–285]. However, the fact that these features are coupled makes the problem non-trivial. Perhaps optimistically, one may assume that GWs are also generated by the large-scale, dynamical rearrangement of the core magnetic field [286–289]. However, recent numerical simulations of MHD instabilities [290] suggest that there would not be any observable gravitational radiation [291] unless the magnetic field is unphysically large [292]. In fact, the detection of GWs from magnetars in the near future seems unlikely when based on triggering f -modes in the NS [289, 291].

The recurrent pulsar glitches are also interesting, especially since they set a relatively low energy threshold for events that happen regularly in our Galaxy. The general picture is that smaller glitches may be due to crust cracking, while the largest observed events are due to a transfer of angular momentum from a superfluid component to the crust (to which the magnetic field is anchored). These events could plausibly generate GWs as well, although to make definite statements about such signals is very difficult. This is not surprising, since the underlying glitch mechanism is not well understood. Available estimates range from pessimistic, suggesting that the radiated GWs will never be detected [293], to (overly) optimistic, where the signal would be borderline detectable with the first generation detectors [294]. It is quite easy to point to the flaws of each model, but to fix the relevant issues is not so straightforward. To make progress we need to improve our understanding of superfluid dynamics.

A closely related problem concerns the tidal interaction in a binary inspiral. It has been argued that the deviation from point-mass dynamics may be detectable at the late stages of inspiral [282, 295, 296]. Tidal stresses may also crack the crust, possibly leading to an EM signal that would precede the merger [297, 298]. This problem is interesting, and it requires the same computational technology as the seismology problem. Again, the challenge is to build truly realistic NS models, and assess the impact of the many different pieces of physics involved in the dynamics of the star. Possible EM precursors are also of obvious interest for GW searches.

3. Detectors and their capabilities

The observation of GWs, combined with astronomical observations from gamma-ray and X-ray satellites, optical/radio telescopes, and neutrino detectors, will enable a new, comprehensive multi-messenger astrophysics which will play a transformative role in our understanding of the Universe, with new constraints to source models combined with identification of the host galaxy, redshift and luminosity distance. In this section, we review present and prospected instrumental capabilities for multi-messenger observations in the foreseeable future.

3.1. Gravitational-wave interferometers

The inception of ground-based interferometers represented significant progress toward the detection of GWs. In 2005–2010 the LIGO [14] and Virgo [15] operated four detectors, sensitive to the merger of two NSs within ~ 30 Mpc of Earth [299, 300]. A GW interferometer uses lasers to monitor the relative distances between the beam splitter and mirrors located at the end of its two arms. A GW signal will stretch one arm of the interferometer and compress the other, causing a detectable change in the interference pattern at the output of the interferometer. First-generation GW interferometers were capable of observing a change in the arm length of 10^{-18} m, or about 1/1000 the diameter of a proton, around the most sensitive frequency (~ 100 Hz). Despite this impressive sensitivity no GWs have been detected so far, due to the low expected event rates, as discussed in section 2.1.3 for the merger of compact binary systems.

The second generation of GW interferometers, scheduled to start within this decade, will have improved seismic isolation, suspension, optics and laser systems, offering roughly a factor 10 sensitivity improvement over a wide frequency range [2]. These detectors could allow us to search for GWs from the rich class of transients discussed in section 2.

In general, transient searches for GW signals fall into two categories: modeled and unmodeled (or weakly modeled). Modeled searches rely on the availability of precise template waveforms for some signal classes, such as the known inspiral waveforms from compact binaries, against which data can be compared with matched-filtering techniques [301]. Unmodeled searches can use the coherence between excess power in multiple detectors to distinguish signals from noise [302]. Therefore, it is critical to have several detectors with comparable sensitivities operating with a high-coincidence duty cycle.

A network of detectors brings significant resistance against nonstationary noise due to environmental and instrumental disturbances, as well as sensitivity in a greater volume [302, 303]. Two advanced LIGO detectors [2] in Livingston, LA and Hanford, WA, and one advanced Virgo detector [3, 15] are currently under construction and will start operation in a few years. A large cryogenic GW telescope, KAGRA, [9, 304] is being constructed in Japan, and a third advanced LIGO detector is currently under consideration for being built in India [8]. The LIGO and Virgo collaboration have released a plan for the commissioning deployment of a network of second-generation GW detectors, which will start in 2015 with short (few months) science runs with two detectors, and will grow to stable operation of a network of four detectors by 2022 [305].

The GW detector network performance greatly depends on the number of detectors in the network, their geographical location, and the relative orientation of the detector arms. For each direction in the sky, the performance of the detectors is characterized by their antenna patterns, which can be combined into the network antenna factor [302]. For example, figure 2 (left plots) shows the distribution of the network antenna factor as a function of the sky coordinates. Note that the six-detector network provides more uniform coverage of the sky than the Hanford–Livingston or Hanford–Livingston–Virgo networks. The right-hand panel of figure 2 shows

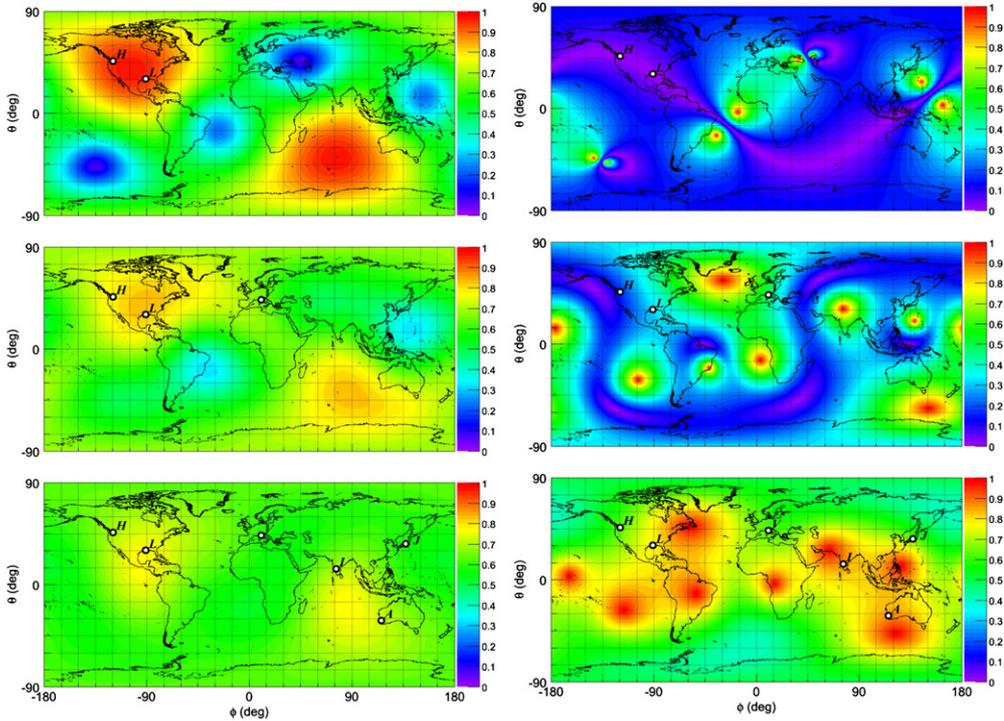


Figure 2. The distributions of the network antenna factor (left plots) and the network alignment factor (right plots) as a function of latitude (θ) and longitude (ϕ) for the Hanford–Livingston network, Hanford–Livingston–Virgo network and a six-detector network (from top to bottom).

the alignment factor between detectors in the network; networks of few detectors with similar arm orientations may only be sensitive to one of the two GW polarizations for some sources.

A worldwide GW detector network enables the reconstruction of source parameters and the localization of GW events on the sky [302, 306–310]. Accurate source localization is key to enabling multi-messenger astronomy, e.g., via joint observations with EM telescopes [311–314]. Meanwhile, measurements of other source parameters can enable studies of astrophysics and tests of general relativity [96, 315–317]. Reconstruction of source location and polarization requires geographically-separated detectors to make independent observations of the same GW event; recovery of intrinsic parameters such as binary component masses by modeled searches primarily depend only on the total network SNR [310].

Proposed future GW instruments will further enhance our astrophysical reach. These include third-generation ground-based detectors [318–321] that would be an order of magnitude more sensitive than second-generation instruments. Meanwhile, pulsar-timing arrays [322] would be sensitive to binaries composed of the most massive BHs in the Universe, while the Laser Interferometer Space Antenna (LISA) or a similar space-based detector [12, 13] could detect massive BH mergers, extreme mass ratio inspirals, and tens of thousands of Galactic white dwarf binaries.

3.2. Gamma-ray and X-ray instruments

The continued operation of high-energy, EM satellites in the coming decades is essential for the realization of the full science potential of joint GW–GRB observations discussed in

section 2. A GRB/x-ray trigger, possibly followed by optical observation to identify the host galaxy and source redshift, can be used as input for a GW transient search at a known time and location. In turn, the worldwide network of GW observatories will be able to reconstruct in near real time the sky position of GW candidates and trigger multi-messenger observations for apparent afterglows. The EM observations may identify the source's host galaxy, redshift and, assuming standard cosmology, the luminosity distance, while the GW measurement may offer enhanced constraints on the source engine; a joint observation will ultimately enable us to decipher science that would otherwise be inaccessible.

Currently, it is hard to know which GRB and x-ray sensitive instruments and all-sky transient surveys will be operating in the next two decades. Present GRB transient observation satellites such as AGILE [323], Fermi [324], INTEGRAL [325] and Swift [326] are not guaranteed to operate in the era of Advanced LIGO and Virgo. It is possible that the lifetime of some of these instruments will be extended, unless an operational constraint or accidental equipment failure necessitates end-of-life procedures for the satellites.

Ongoing x-ray missions such as *Chandra* [327] and *XMM-Newton* [328] are expected to continue to provide information on GRB properties by observing their x-ray afterglows, at least during the early years of the advanced GW detector era, but do require prior localization of the GRB. The Suzaku [329] orbiting x-ray observatory has a capability of detecting GRBs via its wide-band all-sky monitor. The recently launched NuSTAR [330], targeting the hard x-ray region, is likely to operate much beyond its originally planned lifetime of two years. MAXI [322] is an All-sky X-ray monitor, installed on the International Space Station by the Japan Aerospace Exploration Agency [331].

New projects include the Indian satellite ASTROSAT [332–334], a multi-wavelength mission that will monitor the x-ray sky for new transients and is currently scheduled for a 2013 launch, with an expected lifetime of 5 years. The next Japanese X-ray Astronomy mission, ASTRO-H [335], is scheduled to be launched in 2014; it can contribute to follow-up observations of GRB afterglows at high resolution [336]. The launch of SVOM [337–339]—a joint Chinese–French GRB monitor mission with an extended spectral coverage from the visible to a few MeVs, and with good GRB localization capability—is planned towards the end of the decade.

In addition, there are numerous high-energy astrophysics mission concepts targeting the X-ray and gamma-ray spectrum [340]. Some (e.g. AXTAR, EXIST, Xenia, GRIPS, A-STAR, JANUS) would allow the detection of x-ray or gamma-ray transients with potential GW burst counterparts. NASA's X-ray Mission Concept Study Report [341] states that it is feasible to start a next x-ray mission toward the end of the decade. In the study report, simplified missions that capture most of the recently terminated IXO (International X-ray Observatory) mission science goal elements were identified. The Lobster Transient X-ray Detector is a mature concept that was proposed to be deployed on the International Space Station in three to four years. Its unique technology would allow to detect transient x-ray emissions from a large portion of the sky at a wide field of view and high sensitivity. If approved, the instrument could work in conjunction with ground-based GW detectors, following up GW candidate events [342].

3.3. Electromagnetic instruments from radio to UV

Low-latency EM follow-up observations of GW event candidates will enable the identification of possible optical and other EM counterparts [90, 343–347]. The infrastructure for this type of analysis was tested during the most recent LIGO–Virgo data run, in 2010, when observation requests were sent to wide-field optical telescopes and other instruments, including QUEST,

TAROT, ZADKO, Pi in the sky, ROTSE, SkyMapper, LOFAR, the Palomar Transient Factory [311] and the Swift satellite [312].

Radio telescope arrays, such as LOFAR [348], EVLA [349], ASKAP [350] and the future Square Kilometre Array [351], have in most cases a wide field of view and are able to provide sub-arcsecond angular resolution, that is superior to the pointing of the advanced GW detector networks of the future.

In some theoretical models various mechanisms may give rise to a prompt pulse (see e.g. [90]), strong winds or bursts [61], flares [297, 298], intense Poynting fluxes and emissions through shocks [62, 352] or afterglow radio emission (see e.g. [353]) from some expected GW sources, particularly coalescing compact binaries, thus motivating coordinated observations. In addition, the use of GW detectors as a trigger for follow-up radio searches could provide a method of detecting faint radio transients that might otherwise be missed.

Prospects of EM counterpart observations of GW events were recently discussed in [354–359]. Gamma-ray observations will be critical for confirming a connection between SGRBs and NS–NS/NS–BH mergers. Optical and radio afterglows, even off-axis, as well as r -process nucleosynthesis ‘kilonovae’ are detectable in principle, provided that an optimized search strategy is used, taking into account the emission timescale and instrument parameters.

3.4. Low-energy neutrino detectors

CCSNe were discussed in section 2.3 as sources of GW radiation and engines for LGRBs. However most of their energy, about 99% of $\sim 10^{53}$ erg, is released in the form of neutrinos, within a few tens of seconds immediately following the collapse. The neutrinos in this burst are of all flavors, and their energy ranges from a few to tens of MeV. This prediction was confirmed by the detection of a burst of 19 neutrinos from SN1987A in the Large Magellanic Cloud by two water Cherenkov detectors: IMB in the United States [360] and Kamiokande II in Japan [361]. Scintillation detectors also reported observations [362, 363], and the main features of the signal [364, 365] confirmed the baseline model of stellar collapse (see e.g. [150, 186]).

Several existing neutrino detectors are sensitive to a neutrino burst from a galactic supernova [366, 367]. Super-Kamiokande [368], a 50 kT water Cherenkov detector in Japan, would observe ~ 8000 events from a supernova ~ 8.5 kpc away [369]. The LVD [370, 371] and Borexino [372, 373] scintillation detectors at Gran Sasso in Italy, KamLAND [374, 375] in Japan, and the upcoming SNO+ [376] in Canada would also observe hundreds of neutrino events interacting in 300–1000 tons of liquid scintillator. The IceCube detector [377] is a cubic-kilometer detector located at the geographic South Pole. IceCube is nominally a multi-GeV neutrino detector, but it is also sensitive to MeV-neutrinos from a Galactic supernova and could observe an increase in the count rate due to a diffuse burst of Cherenkov photons in the ice [378]. Super-Kamiokande, LVD, IceCube and Borexino operate as part of the SNEWS (SuperNova Early Warning System) network [379, 380], for a prompt alert to astronomers in the case of a supernova neutrino burst.

The distance reach of the global network of neutrino detectors covers the Milky Way and a significant fraction of its satellite system, up to $\sim O(100)$ kpc. This can be considered as a good match to the GW network reach for CCSNe [381–385] of GW detectors. A 50 kT detector like super-Kamiokande has a very low chance of detecting a SN in M31 (at ~ 770 kpc) on its own. Low-energy neutrino detectors have angular resolution comparable to advanced GW detector networks [306], and this makes synergetic observations particularly desirable [386, 387].

Long-term plans call for neutrino detectors with up to ~ 5 megatons of fiducial mass [388, 389] to enable observation of neutrinos from M31 and M33 [390, 391]. Proposals include MEMPHYS [392], LENA [393], and GLACIER [394] in Europe, DUSEL Long Baseline Neutrino Oscillation [395] in the US, hyper-Kamiokande [396] and Deep-TITAND [397, 390] in Japan. It is not unreasonable to expect that the lifetime of these detectors will coincide with the operation of third-generation GW detectors.

3.5. High-energy neutrino telescopes

High-energy neutrinos (HENs) in the GeV–PeV range could also unveil new physics in joint observations with EM and GW signatures [398, 399]. The detection of HENs is pursued in large Cherenkov detectors that exploit their charged-current interaction in large volumes of water or ice. Most of the neutrino energy is transferred to a single high-energy electron, muon, or tau particle, which will emit Cherenkov radiation as it travels through the detector medium. High-energy muons are most useful for neutrino astronomy, since they don't lose energy as rapidly as electrons and have longer lifetime than taus, so their path can be several kilometers long. The Cherenkov light emitted along this path can be detected and used to measure the direction and energy of the muon, and thus of the primary neutrino.

There are three HEN observatories currently in operation. The IceCube observatory [377] has recently been extended with an additional component called DeepCore [400], designed to be sensitive to neutrino energies below IceCube's lower limit of ~ 100 GeV, down to 10 GeV, effectively increasing the detector's astrophysics reach [401]. ANTARES [402], located in the Mediterranean sea, is scheduled for an upgrade to a cubic-kilometer detector called KM3NeT in the coming years [403]. A third HEN detector operating at lake Baikal is also planned to be upgraded to a km^3 volume [404].

The distance reach of HEN detectors is virtually infinite, although at larger distances the probability of detecting a neutrino from an individual source diminishes. The Waxman–Bahcall model [405], the benchmark model of HEN emission from GRBs, predicts about $n_{\text{HEN}} \approx 100$ neutrinos detected in a km^3 detector for a typical GRB at 10 Mpc [406], although recent upper limits from the IceCube detector disfavor GRB fireball models with strong HEN emission associated with cosmic ray acceleration [407]. However, milder HEN fluxes or alternative acceleration scenarios are not ruled out [408]. Moreover, the constraints weaken substantially when uncertainties in GRB astrophysics and inaccuracies in older calculations are taken into account, and the standard fireball picture remains viable [409, 410].

Models of HEN emission from mildly relativistic jets of CCSNe, and potentially from choked GRBs, predict HEN emission of $n_{\text{HEN}} \approx 10$ [411] (note that the result presented in [411] is three times higher, as it does not take into account neutrino flavor mixing). Horiuchi and Ando [412] estimate n_{HEN} from reverse shocks in mildly relativistic jets to be $n_{\text{HEN}} \approx 0.7\text{--}7$ for a km^3 neutrino detector (after taking into account neutrino flavor mixing). Razzaque *et al* [413] obtain $n_{\text{HEN}} \approx 0.15$ for supernovae with mildly relativistic jets with jet energy of $E \sim 10^{51.5}$ erg.

The most stringent observational constraints on transient GW+HEN sources so far has been obtained using searches with the latest initial LIGO–Virgo (S6-VSR2/VSR3) detectors and the IceCube detector in its 40-string configuration [414]. The derived constraints were also used to estimate the science reach of the advanced LIGO–Virgo detectors in combination with the completed IceCube detector, with promising results. The first joint search of ANTARES, LIGO, and Virgo data for coincident GW and HEN using LIGO, Virgo and ANTARES data derived limits on the rate density of joint GW–HEN-emitting systems in the local

Universe, comparing them with densities of merger and core-collapse events [415] that are compatible with previous results. While the available upper limits for initial detectors impose no constraints on joint emission models, the results [414] show that advanced detectors will be able to constrain some emission and population models, therefore also having the potential of detecting joint sources.

4. Challenges and open questions

The initial generation of GW detectors has targeted most of the transient sources described in section 2, yielding observational limits which already bear astrophysical interest. For instance, for two nearby GRBs, the non-detection of a GW signal made it possible to exclude a merger as the GRB central engine [416, 417], while constraints on GW emissions were produced for magnetars [418] and in a study of the 2006 Vela pulsar glitch [419]. Population constraints have been produced for GWs in coincidence with GRBs [420], and all-sky limits have been set on rates of binary mergers [300, 421, 422] and generic bursts [423]. A first coincidence search with HENs has been performed [415], and in the most recent data run (2009–2010) transient candidates have been broadcast for EM follow-up [311, 312]. The potential for extracting fundamental physics and astrophysics from GW data should be dramatically enhanced by the next generation of GW detectors, with a projected ~ 1000 times larger sensitive volume and the newly accessible ~ 10 – 40 Hz frequency band. Predictions for compact binary detection rates with next-generation detectors, based on astrophysical observations, population-synthesis and source models, are available in [100].

The engagement between the experimental and theoretical communities in the coming years will shape the future of GW astrophysics: to maximize their scientific output, GW transient searches will need to include more information from theoretical and computational astrophysics. In turn, robust source modeling will be required to provide a theoretical understanding of the mapping between signal characteristics and physics parameters, including the knowledge of potential degeneracies that may be broken by complementary information from multi-messenger observations. In this section we elaborate on what we identify as the main open challenges in the theoretical understanding of GW transient sources and in the ability to identify their signature.

4.1. Observations of gravitational-wave transients

Despite steady progress in relativistic astrophysics, there is still significant uncertainty in predicted waveforms for most GW transient sources. In some special cases, when an accurate signal model is available, the search relies on matched filtering with a bank of templates [300, 421, 424, 425]. In the more general case, GW bursts can be identified in the detector output data as unmodeled excess power localized in the time-frequency domain [423].

The principal challenge for the instruments is to achieve a 10-fold improvement in sensitivity compared to the first generation of GW interferometers, including a reliable calibration and a low rate of noise transients [e.g., 426, 427]. As soon as the second generation of GW detectors reaches design sensitivity, the main experimental challenge to GW burst science will be to discriminate between real GW signals and noise transients that happen to coincide in multiple detectors.

A fourth site, in addition to the existing facilities in the USA (LIGO Hanford and LIGO Livingston) and Italy (Virgo), is an additional instrumental challenge that will enable source localization and increase detection confidence. As discussed in section 3, the identification of a consistent signal in a network of instruments is a key ingredient in GW searches,

dramatically increasing the confidence in a candidate event. This is especially important for a GW burst, which otherwise may not be distinguishable from noise fluctuations of instrumental or environmental origin. A statistic built from the coherent sum over the detector responses is used to rank candidate events and discriminate between signal and noise, yielding better sensitivity (at the same false alarm rate) than individual detector statistics. Accurate timing information from multiple detectors also makes it possible to reconstruct the two GW polarizations and localize the source on the sky. The LIGO and Virgo collaborations outlined a timeline for the localization of GW transients by advanced detectors [305], in order to facilitate the formulation of joint detection strategies [428] with EM, neutrino, or other observing facilities.

The level of background, and, hence, the significance of a candidate event, is estimated empirically with time slides. Tests with simulated signals injected into LIGO and Virgo noise show that when a signal model can be assumed, this technique makes it possible to achieve high detection confidence. For instance, in a detection exercise during the most recent LIGO–Virgo run, the simulated coalescence of two compact objects with network signal-to-noise ratio of 12.5 was identified with a false alarm rate of 1 in 7000 years using matched filtering [300]. A completely unmodeled search instead yielded 1/1.1 years, after accounting for trial factors [423].

An important challenge for GW burst searches in the advanced detector era will be to incorporate partial information from theoretical models in order to constrain the false alarm rate and increase detection confidence in analyses tuned to specific sources, with perfectly modeled and completely general searches as extreme cases. Understanding what information can be incorporated in searches, and learning how to make inferences on source parameters from transients, starting from the frequency, bandwidth and duration of a coherent event, will require a close synergy with the modeling community. One particularly exciting possibility is the use of GW signals, possibly in coincidence with EM observations, as probes of strong-field dynamics and tests of general relativity itself (e.g., [429]).

We highlighted three key areas of cooperation for the relativistic astrophysics community:

1. *What can we understand about the source from the data?* Theorists and modelers can guide targeted analyses for a specific source, interpret the astrophysics of general searches, and (together with instrumentalists) determine what science can be extracted from the detector response. In return, the data analysis community should instruct astrophysicists/modelers on how to combine detector capabilities and theoretical waveforms into a prediction about the physics that can be extracted from a detection, and a realistic assessment of the extent to which these predictions are reliable.

2. *Can we improve the pipeline that moves theoretical advances in source modeling into the GW data analysis search methodologies?* Both theoretical and computational understanding of GW sources and GW search methodologies are rapidly advancing. There is, however, a time lag in implementing some of these advances into actual LIGO searches. One of the challenges in anticipation of the advent of GW astronomy is the development of better strategies to rapidly get the best models to data analysts.

3. *How to bring together GW, EM and astroparticle physics?* Searches for GW bursts in the advanced detector era will be a combination of untriggered, all-sky searches and externally triggered, localized searches. All-sky searches have the greatest potential for finding electromagnetically dark sources, and may discover unexpected signatures. They also provide triggers for follow-up studies of candidate events with EM observations. Externally triggered searches will have EM and/or neutrino counterpart observations. Strategies are needed to combine EM, neutrino, and GW information and foster collaborations between the GW community and ‘traditional’ astronomers, from data sharing to physics extraction.

4.2. Double neutron star and neutron star—black hole binaries and short gamma-ray bursts

While the most widely accepted model for SGRB progenitors is the merger of a NS with another NS or a BH [27], Swift and Fermi have observed only a few SGRBs per year, and therefore the prospect of observing a SGRB in association with a GW counterpart appears challenging. Furthermore, it is not easy to identify the host galaxy of a SGRB because the sky localization is poor unless an afterglow is detected, and even then, natal kicks could displace the binary system from the host galaxy [22, 430]. The nearest SGRBs may be the hardest to associate with their host, since angular offsets could be large. This uncertainty in host galaxy identification leads to an uncertainty in the progenitor distance, which, in turn, leads to an uncertainty in GW signal association. However, given the relatively small reach of advanced GW detectors, it is possible for GW observations to rule out potential host galaxies that are too distant.

There are many outstanding questions about the nature of observed GRBs. It is unclear how to best distinguish SGRBs associated with merging compact binary progenitors from soft gamma-ray repeater hyperflares. The energy budget for SGRBs is also unclear, although they have been identified (via their host galaxies) up to high redshifts. In particular, there are several uncertainties about the beaming of SGRBs, with very few measurements up to now [26]. Beaming is also a crucial ingredient to understand how many GW events could be associated to the observed rates of SGRBs (for a recent review of the properties of SGRBs, and the implications for their progenitors, see [431]).

There are several open problems in the astrophysics of the merging systems that are very important in the modeling of compact binary mergers. If magnetic fields are indeed responsible for the energy budget, where do these large fields come from in a merger scenario? The magnetic fields of the progenitor NSs are not large enough and the merger event can amplify them. Is this amplification sufficiently strong? Does the spin-down of the final BH cause any late emission signature? Shall we be able via more complete modeling to use GW or EM observations to distinguish between a NS or a BH as the companion compact object in the merger?

Observing GWs from compact binaries also challenges our understanding of binary evolution. If we can better understand merger events, we may be able to use GW and EM observations to understand physical mechanisms that are responsible for compact binary formation and the corresponding distribution of observed events. Another challenge is posed by the poorly known nuclear physics at the densities typical of NS interiors. Do we understand the physics of nuclear processes at NS densities well enough to accurately predict GWs from these systems? Even with an improved understanding of the properties of matter within NSs, adding an accurate treatment of magnetic fields, together with realistic NS EOS and neutrino radiation to get the right post-merger dynamics will be a significant technical and computational challenge to the numerical relativity community. It will be especially important to be able to efficiently generate a large number of data sets to be compared with GW observations. While the GW inspiral signal could probably be modeled analytically (e.g. using variants of the effective one-body model [53, 55]) facilitating the production of a large number of templates, the merger and post-merger dynamics will require a large and accurate set of numerical simulations.

4.3. Binary black-hole mergers as transient sources

Numerical relativity provides direct solutions of the Einstein equations for binary BH spacetimes. Numerical relativity plays a major role in two large collaborations using binary

BH waveforms. The NRAR (Numerical Relativity/Analytical Relativity) collaboration is working to provide templates that cover the inspiral, merger and ringdown phases of binary BH coalescence. The NINJA (Numerical INjection Analysis) project [432, 433] is using hybrid numerical relativity waveforms to test data analysis algorithms for the detection and characterization of GWs. The hybrid waveforms are made by stitching post-Newtonian and numerical relativity waveforms together. While the waveforms and templates created in these projects are useful for burst analysis, and in the case of NINJA unmodeled burst search algorithms are being tested, a burst-only focused study offers an opportunity and challenge to theory and data analysis.

For stellar-mass binary BH systems the challenge is to provide template coverage for modeled searches over a large parameter space using a combination of post-Newtonian techniques and numerical relativity. This includes the challenge of stitching the post-Newtonian and numerical waveforms together. The choice of where to make the stitching (i.e., how many cycles are supplied by post-Newtonian theory and how many cycles must be simulated numerically) depends on the physical parameters of the binary. The NRAR and NINJA collaborations are working systematically to address these problems.

More massive systems offer a different challenge to the numerical relativity and data analysis communities. Unmodeled or weakly modeled burst searches are most appropriate when we know little about the signal model. Rather than the exquisite accuracy in phase necessary for template building, a burst-only focus in numerical relativity offers the opportunity to survey the physical parameter space of binary BHs in a timely manner by reducing the resolution required compared with inspiral-focused simulations. The challenge, however, is learning to identify key features of the merger that will be useful to the data-analysis algorithms for transient sources, potentially improving glitch identification and reducing false-alarm rates. Only one of these studies, aimed at investigating the sensitivity of the Omega burst algorithm [434] to changes in the BH spin vector [435], has been completed, and more studies of this kind are needed.

Prior to the first science runs of the advanced detectors, we need information about the merging systems, including the energy, angular and linear momentum radiated (in total and in each harmonic mode), the polarization (such as ratios of circular to linear) and mode dependent merger timescales. This provides great opportunities: can we increase the likelihood of detecting GWs from binary BH mergers by employing weakly modeled burst searches? Can information gleaned from NR waveforms of merging BHs reduce the false-alarm rate for burst searches? Can a burst algorithm find sources of merging BHs for physical parameters that have not yet been modeled, or have not been modeled well enough? In order to answer these questions, we need to determine the smallest number of cycles we can simulate in numerical relativity while still representing actual signals reasonably well. We need to figure out how the inevitable lack of phase accuracy or length of numerical simulations propagates in the search for a transient source. This leads us directly to perhaps the most interesting and important challenge for a transient search of the binary BH merger sky: how well can such a search determine the physical parameters of the merging sources? Perhaps a burst-first approach (targeted at first finding a burst signal, and then digging through the data with matched-filtering parameter estimation techniques) can help in this regard.

4.4. Core-collapse supernovae and long gamma-ray bursts

Uncertainties abound in current GW estimates from CCSNe. These uncertainties include poorly known initial conditions, the relevance of 3D effects in the explosion mechanism, or the impact of detailed 3D neutrino transport on the GW signal from anisotropic neutrino

emission. Here we focus on two major issues in determining accurate GW signals: rotation of the progenitor and convective instabilities.

4.4.1. The role of rotation. Rapidly rotating systems have the potential to produce strong GW signals, especially if nonaxisymmetric instabilities develop. Whether or not such signals occur in nature depends upon the rotation profile of the precollapse star. Classic models of single stars produce a range of core rotation speeds, depending upon the initial angular momentum of the star and the magnetic field generation [165, 436–440]. In the absence of magnetic fields, the core can decouple from the rest of the star, retaining a high-spin rate even as the stellar envelope expands and decreases its spin rate. But if magnetic fields are produced at boundary layers, they tie the core to the stellar envelope, causing its spin to decelerate with the envelope.

The high-spin requirements of most LGRB progenitors have pushed stellar modelers to seek new ways to produce fast-spinning cores. Fast-rotating single star models often invoke extended mixing and generally require low metallicity, below $\sim 0.1 Z_{\odot}$ [439–441]. Others have devised a number of binary progenitors of LGRBs that may also produce fast-rotating cores invoking tidal interactions, mass transfer, and common-envelope mergers [442–446]. The fastest-rotating cores collapsing to form NSs could be produced in the merger of two white dwarfs [447–452], but we currently do not know whether such systems produce thermonuclear or CCSNe.

Uncertainties in the evolution of massive stars (especially rotating stars) and in binary evolution make it very difficult to predict the distribution of spin rates of collapsing cores. If fast-spinning pulsars also develop strong magnetic fields, selection biases make it difficult to use the observed pulsar distribution to constrain the birth spin rate of NSs. Similarly, high-spin rates are just one requirement for LGRB engines, and extrapolations to the spin rates of newly formed NSs from LGRB rates can only be done with specific model assumptions.

4.4.2. Convective instabilities. The detailed nature of the convective instabilities (both within and above the PNS) also remains an open question in estimates of GW emission. If low-mode large-scale convection develops and is modulated by the SASI, as is borne out by current simulations, we have a fairly strong picture of the GW signal. But the nature of this convection (and of the resulting GW signal) is different between 2D and 3D models. The current resolution in CCSN simulations, in particular in the first 3D simulations, remains roughly an order of magnitude lower (per dimension) than what computational fluid dynamicists argue is required to accurately model convective modes and turbulence [453, 454]. In addition, with few total turnover timescales in the model, initial perturbations (caused by convection in the Silicon burning layer) may have a strong impact on the convective motions. To more reliably predict the GW signal from convection, it will be necessary to gain a better understanding of convection, the SASI, and of the impact of perturbations from late convective burning stages.

4.5. Isolated neutron stars

It should be clear from our discussion that transients in isolated NSs provide a range of interesting prospects for GW astronomy. At the same time, it must be appreciated that the expected signals are likely to be weak. Because of the complexity of the physics involved in most realistic scenarios, these signals are also extremely difficult to model in detail. This means that it may be unrealistic to expect modeling to produce accurate search templates for matched filtering. Dealing with this difficulty is one of the main challenges for the next few years. Realistically, the sources that we have discussed here may only be borderline detectable with second-generation detectors. They may require future developments, like the Einstein

Telescope, with enhanced sensitivity in the high-frequency regime. However, such detectors could provide us with an unprecedented view into NS interiors [267, 268, 270, 455], especially if the signals are strong enough that the asteroseismology strategy is viable. The hope is that GW observations will complement EM data, helping us to place constraints on physics under extreme conditions.

On the theory side, it is easy to identify directions in which the current models need to be improved. Basically, we need to continue developing both the computational technology and our understanding/implementation of the relevant microphysics. In order to model the relevant astrophysical scenarios, we obviously need to build more realistic models. This is associated with a number of challenging issues. For the purposes of this summary, let us consider two specific problems.

First of all, it is clear that magnetars may be interesting target sources given their, sometimes rather violent, activity. However, even though there has been clear progress in recent years, we are still quite far from modeling ‘realistic’ magnetized stars. The difficulties range from fundamental to technical. We do not yet have reliable models of compact magnetic equilibria with the expected composition, and we must account for superconductivity (and the associated magnetic flux tubes) in the star’s core.

Secondly, recent work on instabilities, such as those of the r -mode, has shown that we do not, in fact, understand the relevant dissipation mechanisms well enough to explain the observed population of fast-spinning, accreting NSs. Given the amount of effort that has gone into modeling the r -mode instability, this is somewhat embarrassing. Another major problem concerns the nonlinear evolution of this kind of instability. The associated timescale is too long for the problem to be within reach of nonlinear simulations. At the same time, we need to account for nonlinear aspects (like the mode-coupling that is thought to saturate the r -mode). This is truly problematic, especially if we want to make the stellar models more realistic by including the appropriate microphysics. Similar issues relate to pulsar glitches, with a relaxation time of weeks to months but an initial rise time of tens of seconds, and NS mountains, which may evolve due to plastic flow.

These problems are clearly far from trivial, but they provide a good illustration of the kind of issues that we need to deal with if we want to extract as much physics as possible from future GW signals from NSs.

4.6. Multi-messenger astrophysics of transient sources

The success of the GW burst endeavor relies on a continued dialogue between source theory and detector expertise, or between predicted sources and what can be achieved in a practical instrument. On one side this drives detector design, on the other it determines which parts of parameter space theorists should focus on.

While GW bursts generally do not have well-defined waveforms, they have robust signal features when characterized by their energy. The duration, central frequency or even time-frequency characteristics of the signal energy can be used to tune source-specific searches. A GW burst search can be informed by source population or emission models to identify relevant regions of the parameter space to focus over. Moreover, any waveform estimates from potential sources can be used to characterize the efficiency of the developed searches. When a population of sources or repeating GW emitters are considered, it is possible to design an analysis to target the energy features to build up SNR and reject noise events.

While all-sky, untriggered GW searches are the principal mode of operation for GW detectors, triggered searches based on observations in other bands or theoretical guidance on the most important potential sources can yield to improved sensitivity. We will want to

revisit the issue of optimal sources for triggered GW searches as new astrophysical discoveries are made and GW detector performance and data analysis capabilities improve (e.g., [358]). Meanwhile, once potential GW sources have been identified, to facilitate efficient observations, it is highly desirable to exchange triggers between the GW and astronomy communities within 1 hour of the trigger, or even less.

Research on GRBs is now a mature subject. There are redshifts for hundreds of GRBs (all extragalactic). Despite this, many uncertainties remain. What is the nature of their progenitors? At least some LGRBs are confidently associated with CCSNe, but what about the other observations? GRB emission processes (both non-thermal and thermal) are quite uncertain, and the total energy budget is unclear.

A lot of infrastructure has been put in place and communication channels between the GW and astronomy communities opened in the preparation for the advanced LIGO era. It is worth asking, in the multi-messenger era, how should this momentum be maintained? A post-Swift mission with a comparable source localization error box will complement GW observations. Facilities with wide-field search capability (snapshot versus tiling) and a field of view covering advanced LIGO error regions may allow a rapid discovery of the EM transient counterpart, but it is equally important to have high-resolution instruments that can follow up the transient discovery with other observations, such as obtaining a source spectrum. There is also tension on the GRB requirements between the GW community and the broader GRB community: missions that suit multi-messenger astronomy would focus on rapid observations of closer GRBs, which may not be what other GRB astronomers (who may want to explore the oldest GRBs and cosmology) are after.

5. Conclusions and peroration

The era of GW astronomy is upon us. Advanced ground-based detectors are expected to reach their design sensitivity near 2019. The space-based GW detector eLISA may be selected in the EU as one of the next L2/L3 missions, with a launch possibly scheduled before the end of the next decade. IPTA may also detect GWs in the next few years [456, 457]. This paper has focused on transient GW sources for second-generation Earth-based detectors, particularly those amenable to unmodeled or weakly modeled burst searches.

We have reviewed the state of the art of theoretical and observational studies of several GW transient sources. Compact binaries composed of NSs and/or BHs are among the most promising sources, because they are detectable by advanced ground-based interferometers at distances of hundred of Mpc. In recent years, numerical simulations of these objects have increased our knowledge of their GW signals and, more recently, of their possible connection to EM observations. In particular, NS-NS and NS-BH binaries are thought to be linked to SGRB engines. A coincident detection of GWs and SGRBs would be the smoking gun that SGRBs are indeed caused by compact-object mergers. Another GW source that has a very important connection with EM observations are CCSNe, which are currently the main candidate LGRB engines. Unfortunately, GWs generated by such systems will be detectable only for events located in our Galaxy, hence the expected event rates are quite low.

Due to the possibility that the first GW detection may happen in the next few years, it is important to increase the current efforts in modeling GW sources. Significant progress has been made in modeling binary BHs, but covering the template space of generic precessing binaries is still a big challenge. New theoretical and computation insights are needed to tackle BHs spinning close to the Kerr limit, even for nonprecessing binaries with aligned spins. The study of non-vacuum sources, due to the higher level of complexity, still requires significant effort in order to better understand the effects of several different physical

mechanisms on their evolution (e.g. EOS, neutrino emission, magnetic fields, convection, turbulence). While part of this work will require the development of better and more efficient numerical codes, several studies will also require the use of larger computational resources. For example, the study of convective instabilities in CCSNe and of magnetic instabilities in NS mergers will require much higher resolutions, and hence more powerful computational resources than those used so far. Moreover, since the properties of matter in both NS mergers and CCSNe are not yet well known, it will be imperative to build a large and publicly available database containing GW signals generated by different models. This will be crucial in order to be able to extract physical information from the GWs that will be detected from these systems.

Detecting EM counterparts to GW events will lend greater confidence to GW searches and provide useful complementary information. This will considerably help in source localization and, in the case for example of SGRBs and LGRBs, allow us to better understand the engine of some of the most fascinating astrophysical phenomena. It will be particularly important that both x-ray and γ -ray satellites will be available and ready when the second generation of GW detectors will start to take data. For these studies to be successful, it will be necessary to increase the current level of collaboration between the GW and EM communities, and ideally better coordination between funding bodies.

After almost 100 years since the prediction of their existence, the direct detection of GWs is on the horizon. In the next decades GW astronomy may become one of the most important sources of information on high-energy astrophysics, providing us with an unprecedented level of information on NSs and BHs.

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