Gravitational-wave burst astronomy

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Abstract

To date, scientists have identified over one hundred gravitational-wave detections linked to collisions of neutron stars and black holes, while no other origins have yet been confirmed. Theoretical models suggest that some of the most energetic cosmic explosions should generate short gravitational-wave bursts, potentially paving the way for the next milestone in multi-messenger astronomy. These transient signals are typically characterized by uncertain waveforms and energy levels, owing to the poorly understood or highly complex nature of their progenitors. Candidate sources include core-collapse supernova events, cosmic string activity, fast radio bursts, eccentric compact binaries, and the phenomenon known as gravitational-wave memory. This review outlines the astrophysical characteristics of these predicted burst sources, describes what is currently known about their emission, explores the likelihood of future detections, and examines the difficulties in identifying such signals and decoding their astrophysical origins.

Introduction

What lies ahead in the realm of gravitational waves? So far, all terrestrial detections of these waves have come from the approach and merger of neutron stars and black holes (Abbott et al., 2019b, 2021b,a). Improved sensitivity of the LIGO-Virgo-KAGRA network (Aasi et al., 2015; Acernese et al., 2015; Akutsu et al., 2021) is rapidly and significantly expanding the cosmic volume under investigation, not only for compact binary mergers but also for other classes of sources. Confirming these categories could lead to major breakthroughs in our understanding of astrophysics and fundamental physics: from the physics of neutron stars and supernovae to even stranger phenomena such as cosmic strings.

Gravitational-wave sources can generally be classified according to the duration of their signals. For example, "bumps" on rotating neutron stars generate quasi-monochromatic signals lasting from months to thousands of years. Low-mass binary mergers remain within the LIGO-Virgo-KAGRA band for several minutes, while mergers of high-mass black hole binaries (~100 M⊙) stay in-band for only fractions of a second. Other possible transient gravitational-wave sources also cover these timescales, ranging from f-mode oscillations in neutron stars on the order of O(10–100 ms) to O(day) signals caused by fluid dynamics during pulsar glitch recovery. In this review, we focus on short bursts of gravitational waves lasting from a few milliseconds up to about 2000 seconds. Figure 1 presents a schematic diagram of the main sources of these bursts, with wave frequency plotted on the vertical axis and approximate duration on the horizontal axis.

Most candidate sources of gravitational-wave bursts are ideal targets for multi-messenger astronomy. Detecting gravitational waves from a transient source such as a core-collapse supernova (CCSN) could lead to the first joint observation combining electromagnetic radiation, neutrinos, and gravitational waves, giving us a comprehensive understanding of the underlying physical processes (Mezzacappa & Zanolin, 2024). Similarly, finding gravitational waves coincident with a fast radio burst (FRB) could provide the first clues to the nature of their progenitors (Abbott et al., 2022a). Other examples of transient sources with electromagnetic counterparts include magnetar flares, gamma-ray bursts (GRBs), and pulsar glitches. Gravitational-wave bursts may also arise from electromagnetically "dark" signals such as cosmic strings.

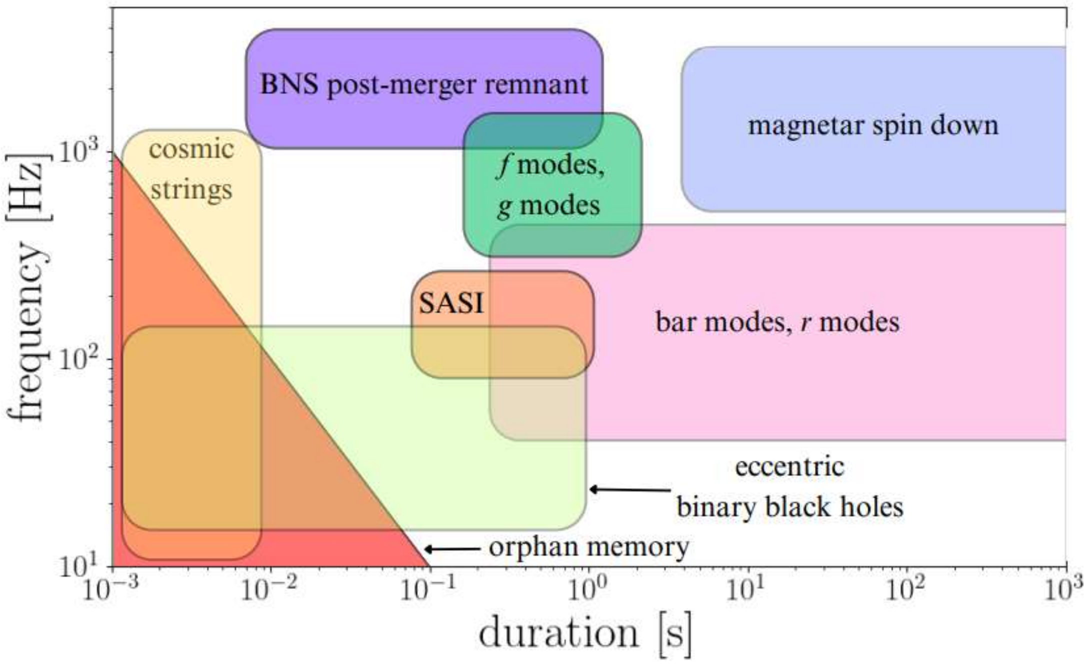


Figure 1. Characteristic timescales and frequency ranges of candidate gravitational-wave burst sources. Bursts lasting on the millisecond scale may originate from mergers of high-mass black hole binaries with eccentric orbits, from cusps/kinks of cosmic strings, and from "orphan" (unaccompanied) memory signals. Processes that can extend up to about 10^3 seconds include the spin-down of young magnetars with millisecond periods. Post-merger remnants and core-collapse supernovae can emit above 1 kilohertz, including the various emission channels of CCSNe discussed in Section 2.

Merger of a binary black hole on an eccentric orbit, or an astrophysical object of previously unknown nature.

Achieving the first detection of gravitational-wave bursts faces numerous challenges. Most importantly, modeling these signals is not straightforward: the difficulty may stem from the complexity of the physics of the progenitor, as in core-collapse supernovae (see Section 2), or from our ignorance of the very nature of the source, as in fast radio bursts (see Section 5). Without precise knowledge of the signal's morphology, relying on template-based search methods—such as matched filtering—becomes infeasible. The problem is further complicated because transient noise artifacts may mimic these short-lived signals.

Ongoing searches for gravitational-wave bursts typically rely on capturing coherent excess power across multiple gravitational-wave detectors (e.g., Klimenko et al., 2016; Lynch et al., 2017; Sutton et al., 2010), which helps reduce confusion from transient noise that may masquerade as a signal. These algorithms make minimal assumptions about the signal's form. Targeted searches have also been carried out for sources observed electromagnetically or through neutrinos (Abbott et al., 2024, 2022a; Abbasi et al., 2023; Abbott et al., 2022b). In addition, comprehensive all-sky and all-time surveys exist to ensure that no transient event without an electromagnetic counterpart is missed (Abbott et al., 2021d,c). So far, discoveries in unmodeled searches have been limited to binary black hole mergers, including the first detection of gravitational waves GW150914 (Abbott et al., 2016b), and no confirmed discoveries of new classes of sources have yet been made.

In this review, we present the potential spectrum of gravitational-wave burst sources and examine the prospects for their detection soon or with next-generation observatories such as the Einstein Telescope (Hild et al., 2011), the Cosmic Explorer (Evans et al., 2021), or a kilohertz-frequency–dedicated observatory like NEMO (Ackley et al., 2020). We illustrate how the anticipated signals could reveal the astrophysical properties of their sources, and what efforts are needed from the scientific community to be prepared for the first detection from a new source. We begin in Section 2 with a discussion of core-collapse supernovae, followed by Section 3 on post-merger remnants of neutron star binaries, Section 4 on highly eccentric or hyperbolic compact binaries, Section 5 on fast radio bursts, Section 6 on pulsar glitches, Section 7 on magnetars, Section 8 on gamma-ray bursts, Section 9 on "orphan" gravitational memory, Section 10 on topological defects, and finally Section 11 on "unknown unknowns," concluding in Section 12.

Core-Collapse Supernovae

Core-collapse explosions mark the violent end of stars with masses exceeding roughly 8 $M_\odot$. Once the stellar core surpasses the effective Chandrasekhar mass, it becomes gravitationally unstable and continues collapsing until it reaches nuclear densities. At that point, the central core launches an outward-moving shock wave, but the shock loses much of its energy and stalls at a radius of about ∼150 km. How this shock is revived remains unresolved, since electromagnetic observations cannot probe the star's inner depths. In contrast, gravitational waves and neutrinos are emitted directly from the core, potentially providing the first direct window into the driving mechanism of CCSN explosions (Müller, 2017).

Predictions of gravitational-wave waveforms in CCSNe come from numerical hydrodynamical simulations (see Abdikamalov et al., 2020; Müller, 2020; Mezzacappa & Zanolin, 2024 for recent reviews). These simulations, however, are extremely computationally demanding, requiring multi-dimensional modeling, accurate neutrino transport, stellar hydrodynamics, realistic equations of state, progenitor models from stellar evolution, as well as general relativity, rotation, and magnetic fields. Differences exist in predicted signal amplitudes across various code families (Andresen et al., 2017; Kuroda et al., 2017; Radice et al., 2019; Powell & Müller, 2019; Mezzacappa et al., 2020). Nevertheless, certain recurring features of CCSN signals are robust and have appeared consistently across multiple groups and simulation setups.

It is believed that most of these explosions proceed via a neutrino-driven mechanism, where the shock is revived by absorbing a fraction of the neutrino flux energy (Janka, 2017). More extreme scenarios are thought to be powered by a magnetorotational mechanism, in which the star's rotational energy is transferred to the shock via magnetic fields (Reichert et al., 2023; Müller, 2024). Several studies have demonstrated the possibility of inferring the explosion mechanism from the gravitational-wave signal itself, using model-selection methods trained on numerically generated waveforms (Logue et al., 2012; Powell et al., 2016, 2017; Saiz-Pérez et al., 2022; Powell et al., 2024). Based on currently available waveform sets, selection algorithms can determine the mechanism with high accuracy when the signal-to-noise ratio (SNR) $\gtrsim 20$.

At present, a large library of waveforms is available from three-dimensional simulations of neutrino-driven explosions (Andresen et al., 2017; Kuroda et al., 2017; Yakunin et al., 2017; O'Connor & Couch, 2018; Radice et al., 2019; Powell & Müller, 2019, 2020; Mezzacappa et al., 2020; Pan et al., 2021). On the other hand, the number of three-dimensional waveforms for magnetorotational explosions extending beyond core bounce remains limited (Bugli et al., 2022; Obergaulinger & Aloy, 2022; Powell et al., 2023; Powell & Müller, 2024). This class also exhibits significant variations between the outcomes of different simulations…

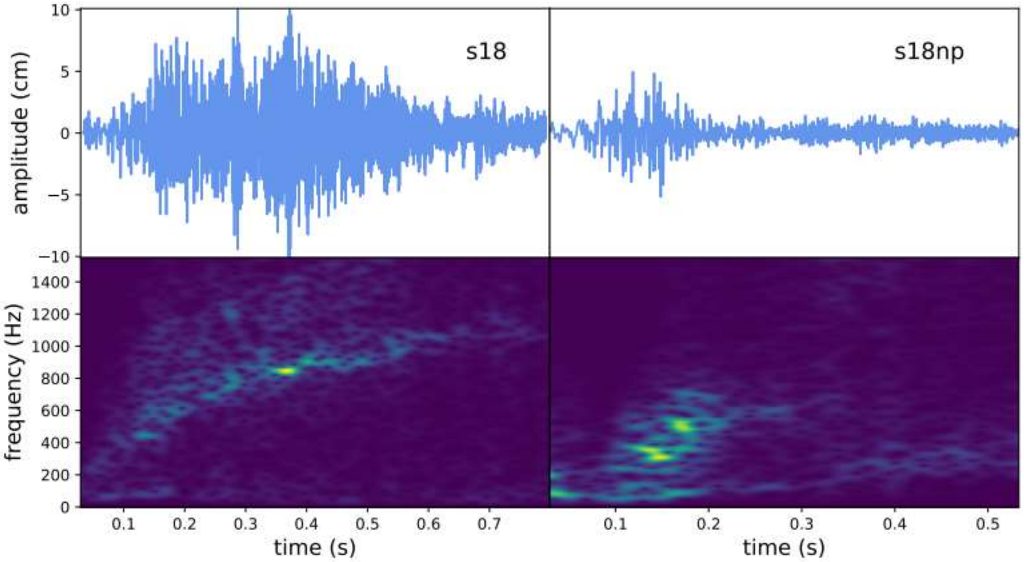


Figure 2. Examples of typical gravitational-wave signals from core-collapse supernovae. Both cases are based on 18 M⨀ progenitors from the work of Powell & Müller (2019, 2020). In model *s18* (left panels), the shock is revived quickly, whereas in model *s18np* (right panels) the stellar explosion fails to fully develop. The top row shows the time evolution of the signal, while the bottom plots display the time–frequency spectra of the signals. The most prominent feature is the high-frequency *g*-mode, whose frequency is linked to the properties of the proto–neutron star. The absence of shock revival in *s18np*

results in a smaller gravitational-wave amplitude and a prolonged low-frequency pattern arising from the standing accretion shock instability (SASI).

…Simulation suites (Varma et al., 2021). Thus, a broader development of waveforms in magnetorotational explosion scenarios is needed in order to accurately identify the explosion mechanism when a real CCSN event occurs.

The most prominent feature in gravitational-wave signals from CCSNe is the high-frequency *g/f*-mode oscillations in the proto-neutron star (proto-NS), which usually carry more gravitational energy than other components of the signal. These modes are clearly visible in time–frequency spectra, as shown in Figure 2; their emission frequency increases over time as the proto-NS contracts in radius and gains mass. This pattern typically begins about 100 ms after the moment of core "bounce." The maximum frequency can vary widely between simulations: for instance, Powell & Müller (2019) observed an upper limit of ~1000 Hz in neutrino-driven explosions, whereas Pan et al. (2021) found values up to ~3000 Hz. "Universal relations" have been developed linking the gravitational-wave frequency to the proto-NS mass and radius (Torres-Forné et al., 2019; Sotani et al., 2021, 2024), which have formed the basis for search and parameter-estimation tools for this mode (Powell & Müller, 2022; Bizouard et al., 2021; Bruel et al., 2023). These tools may allow the extraction of proto-NS properties from a positive detection. However, such relations currently neglect important physical aspects such as rotation and magnetic fields.

In rotating models, a "spike" appears in the time series at core bounce, followed by smaller oscillations (Dimmelmeier et al., 2008; Abdikamalov et al., 2014; Scheidegger et al., 2008). In the absence of rotation, the bounce signal is nearly absent. The spike arises when the equation of state stiffens and the proto-NS rings for a few milliseconds. The bounce phase appears only in the "+" polarization, with the optimal observation angle along the stellar equator; thus—even with rapid rotation—the bounce signal would not be visible if the line of sight is near the poles. If the bounce signal is detected, stellar properties can be constrained; for example, its amplitude is related to the oblateness of the core determined by the rotation rate. The subsequent oscillations after the spike may also reveal information about the equation of state. This frequency range is expected to lie between 100–1000 Hz. Since its physics is relatively well understood, matched-filtering searches and parameter estimation are possible

(Edwards et al., 2014; Richers et al., 2017; Pajkos et al., 2021; Edwards, 2021; Afle & Brown, 2021; Pastor-Marcos et al., 2023).

Another common feature in CCSN gravitational-wave emission is a lower-frequency mode associated with the standing accretion shock instability (SASI) (Blondin et al., 2003; Blondin & Mezzacappa, 2006; Foglizzo et al., 2007). SASI represents a perturbation in the shock front that can excite the proto-NS from above, generating pressure modes (p-modes). SASI frequencies fall within the most sensitive range of current gravitational-wave detectors (≈200 Hz), enhancing detectability. However, the gravitational-wave energy from SASI is usually far lower than that of the *g/f*-mode. The SASI frequency increases over time until shock revival; once the explosion begins, SASI growth ceases. Therefore, this mode typically does not appear in models where the shock is revived quickly.

The signal also contains a low-frequency component (below ~10 Hz) arising from gravitational-wave “memory.” Matter motions following shock revival can produce a small memory contribution, but anisotropic neutrino emission may enhance the memory amplitude significantly, increasing the detectability of CCSNe with low-frequency–sensitive detectors (Mukhopadhyay et al., 2021; Vartanyan et al., 2023; Powell & Müller, 2024). To determine the lower frequency limit and maximum amplitude of this component, long-term simulations are required, which are computationally challenging at present; some studies have attempted to extend the signal analytically (Richardson et al., 2022).

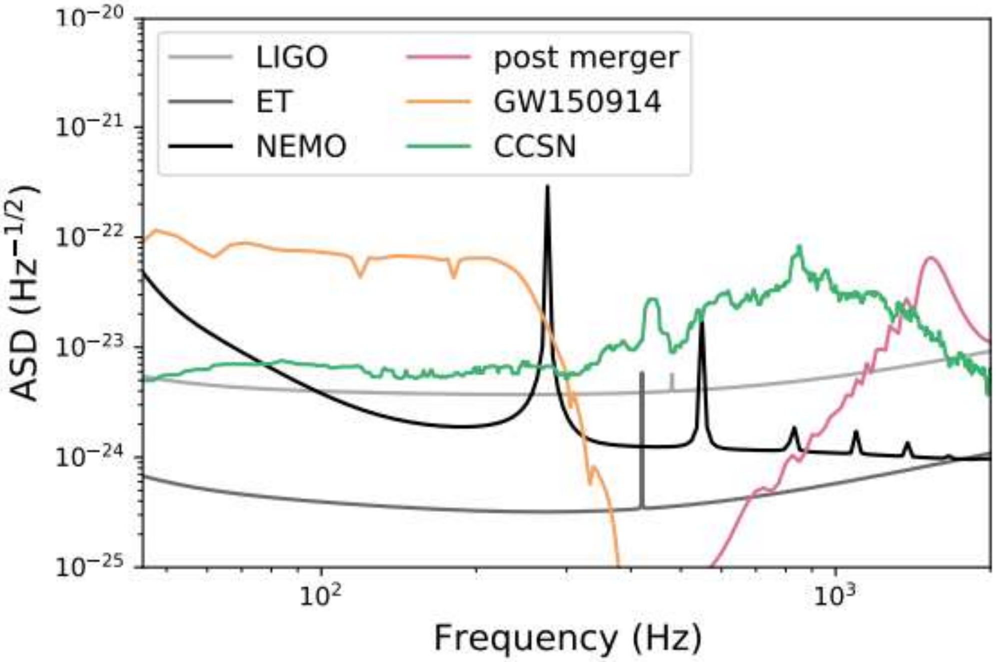
Several works have investigated detection prospects with current observatories using “unmodeled burst” algorithms (Gossan et al., 2016; Szczepańczyk et al., 2023). For recent waveforms of neutrino-driven explosions, the SNR typically needs to reach between ~15 and 20 before unmodeled searches can detect them. This implies that the expected detection distances are Galactic (within the Milky Way), with current ground-based observatories’ CCSN event rates amounting to only a few per century (Taylor et al., 2014). Magnetorotational explosions may be detectable at greater distances—out to the Magellanic Clouds—but this does not significantly raise event rates.

So far, no gravitational emission from CCSNe has been detected during the first three advanced observing runs of the LIGO-Virgo-KAGRA network using unmodeled burst searches (Abbott et al., 2020a; Szczepańczyk et al., 2023). For the next generation of ground-based gravitational-wave observatories, the expected detection distances will range from hundreds of kpc to several Mpc—depending on progenitor properties—which could raise the event rate to about one per year (Powell & Müller, 2019, 2024).

To enhance detection prospects in the future, further improvements in waveform predictions for CCSNe based on numerical simulations will be essential.

Figure 3. Amplitude spectral density (ASD) at design sensitivity for Advanced

Figure 3. LIGO, the Einstein Telescope (ET) configuration, and the proposed NEMO observatory, with



reference curves for a post-merger signal, the binary black hole event GW150914, and the core-collapse supernova model *s18* from Powell & Müller (2019) at a distance of 10 kiloparsecs (kpc). Post-merger signals appear at the high-frequency end of the LIGO–Virgo–KAGRA band, while compact binary mergers cluster around a few hundred hertz. CCSN signals are broadband, with most of their amplitude concentrated above 500 Hz.

It is also necessary to develop search algorithms for gravitational waves emitted from core-collapse supernovae (CCSN). The methods currently in use are "waveform-agnostic" and require a high signal-to-noise ratio (SNR) before a detection can be confirmed. If reliable features of the signal are incorporated into the search algorithms, this could lower the minimum SNR threshold needed to achieve the first CCSN detection.

Post-Merger Remnants of Binary Neutron Stars

The possible outcomes following the merger of two neutron stars are diverse, and the evolutionary path is largely determined by the remnant mass. If the mass is below the Tolman–Oppenheimer–Volkoff (TOV) limit, MTOV (Tolman, 1939; Oppenheimer & Volkoff, 1939)—the maximum mass a non-rotating neutron star can support before collapsing into a black hole—the collision results in a permanently stable neutron star. If the mass falls between MTOV and χMTOV, where 1.3 ≲ χ ≲ 1.6 depending on the unknown nuclear equation of state (e.g., Shibata et al., 2000, 2006; Baiotti & Rezzolla, 2017; Agathos et al., 2020; Bauswein et al., 2021), a meta-stable remnant forms, known as either a hypermassive or a supramassive neutron star. The former is supported against collapse by differential rotation and is expected to survive less than about one second before losing sufficient centrifugal support and collapsing into a black hole (e.g., Baumgarte et al., 2000; Shapiro, 2000). The latter is supported by uniform rotation that decays on longer timescales, potentially lasting up to ∼10^4 s (Ravi & Lasky, 2014). If the mass exceeds χMTOV, collapse to a black hole occurs promptly at merger. For recent reviews of post-merger remnants, see Bernuzzi (2020); Sarin & Lasky (2021).

Of the four scenarios above, the first three (stable, hypermassive, supramassive) are expected to emit strong gravitational waves for a short duration (≲1 s) immediately after merger, with amplitudes comparable to—or even exceeding—those of the inspiral phase. The characteristic emission frequencies fall mostly in the kilohertz range. Crucially, these frequencies encode imprints of the nuclear equation of state (Bauswein et al., 2012; Bauswein & Janka, 2012; Read et al., 2013), meaning that a positive detection of post-merger signals could significantly advance our understanding of nuclear physics under conditions inaccessible in terrestrial laboratories.

Although hypermassive remnants are expected to collapse on timescales similar to the gravitational-wave emission, estimates indicate that measuring the collapse time directly from the signal is difficult—even with third-generation observatories (Easter et al., 2021; Dhani et al., 2024). By contrast, supramassive and stable remnants may emit gravitational waves for much longer periods. This may arise from ellipticity induced by magnetic fields in the remnant (e.g., Cutler, 2002; Haskell et al., 2008; Dall'Osso et al., 2009; Lander & Jones, 2020) or from stellar oscillation modes such as *r* or *bar* modes (e.g., Bondarescu et al., 2009; Corsi & Mészáros, 2009). Nevertheless, the detectability of such long-lived signals remains hotly debated in the literature (see Sarin & Lasky, 2021), despite numerous searches for long-lived remnants after GW170817 (e.g., Abbott et al., 2017f, 2019g; Grace et al., 2024). Because of their long duration, searches for these signals borrow techniques from the continuous-wave community, which targets quasi-monochromatic, long-lasting signals. For this reason, we exclude this category from the present review and focus instead on short signals in the immediate aftermath (≲1 s) of merger.

From an astrophysical standpoint, the fraction of binary neutron star mergers that produce stable, hypermassive, or supramassive remnants—and thus the strong short-lived signals discussed here—remains unknown. Two key uncertainties hinder us: (1) the true value of the TOV mass, MTOV, and (2) the mass distribution of binary merger progenitors. The latter was once thought to be reasonably well understood, but the event GW190425 revealed a total mass of 3.4^{+0.3}_{−0.1} M⊙ (Abbott et al., 2020b), inconsistent with the observed mass distribution of Galactic binary neutron stars (Kiziltan et al., 2013; Keitel, 2019; Farrow et al., 2019). More events are therefore required to pin down this distribution with confidence.

And what about the fate of the remnant in the landmark event GW170817, observed by the LIGO–Virgo–KAGRA network (Abbott et al., 2017b, 2019a) and followed up with extensive electromagnetic observations (e.g., Abbott et al., 2017e,d)? It may seem surprising, but the matter remains under debate. Researchers have drawn sharply conflicting conclusions about the nature of the remnant based on the kilonova color (Margalit & Metzger, 2017; Radice et al., 2018; Yu et al., 2018), the absence of early X-ray emission (Piro et al., 2019; Ai et al., 2020), and later radio and X-ray observations (Piro et al., 2019; Lin et al., 2019; Troja et al., 2020); see the review in Sarin & Lasky (2021). The only certainty is the large uncertainty surrounding the long-term fate of the remnant. Nevertheless, it is likely that it did not collapse immediately into a black hole and therefore emitted kilohertz-frequency gravitational waves. Despite many searches, no secure identification of a post-merger signal has yet been made, and estimates suggest that observatories will need at least an order-of-magnitude improvement in sensitivity to achieve such a detection (Abbott et al., 2017f; Królak et al., 2023).

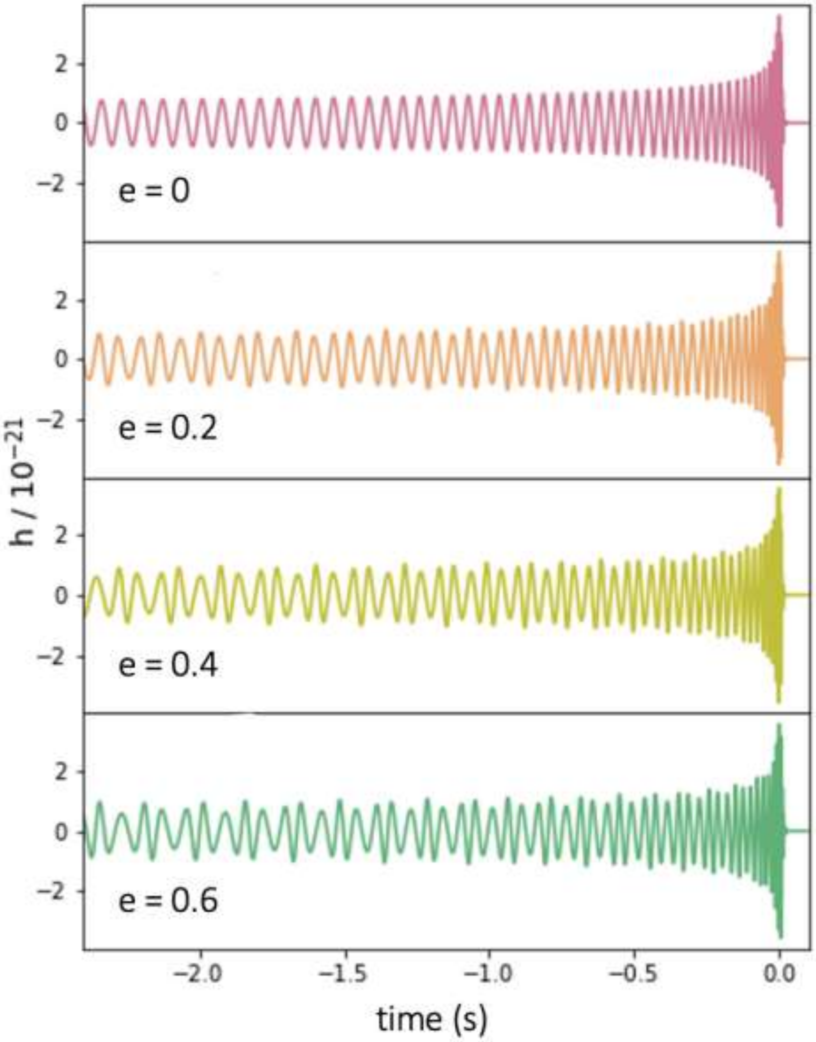


Figure 4.
Examples of wave strain time series for binary black hole mergers with a total mass of 30 M⊙ at four different eccentricities, computed at a reference frequency of 10 Hz. At high eccentricity, variations in strain near orbital periastron can resemble short burst-like signals, especially at higher masses where only about two cycles may appear within the LIGO–Virgo–KAGRA detection band.

Eccentric Binaries and Hyperbolic Encounters

Eccentric systems gradually lose their orbital irregularity through gravitational-wave radiation until they tend toward circularization (Peters, 1964). Thus, binaries formed through standard stellar evolution are expected to be nearly circular by the time they enter the LIGO–Virgo–KAGRA observation band (e.g., Hinder et al., 2008). However, some binary black holes may retain

eccentricity in two main ways:
(1) if they are formed dynamically within dense stellar environments such as globular clusters or active galactic nucleus (AGN) disks (Morscher et al., 2015; Samsing, 2018; Rodriguez et al., 2018);
(2) in hierarchical triple (Silsbee & Tremaine, 2017; Antonini et al., 2017) or quadruple systems (Liu & Lai, 2019; Fragione & Kocsis, 2019), where perturbations from the outer companion increase the eccentricity of the inner binary through Kozai–Lidov resonances (Kozai, 1962; Lidov, 1962).

At high eccentricities ($e \gtrsim 0.5$) and for intermediate-to-large masses, strain variations near periastron can resemble a short burst-like signal immediately preceding merger. If such signals are confidently detected, they could help distinguish between different formation channels (e.g., Lower et al., 2018).

Template banks in standard matched-filtering searches for binary black hole gravitational waves lack eccentricity modeling (Abbott et al., 2019b, 2021b,a), primarily due to the scarcity of waveform families that incorporate eccentricity effects (with only a few available: East et al., 2013; Gayathri et al., 2022) and the high computational cost of enlarging the parameter space. Nevertheless, "non-eccentric" templates remain effective at detecting systems with $e \lesssim 0.2$ (e.g., Brown & Zimmerman, 2010; Zevin et al., 2021).

For higher eccentricities ($\gtrsim 0.2$), unmodeled burst-search techniques are preferred, though template-based efforts also exist (Bustillo et al., 2021; Gayathri et al., 2022). Current LIGO–Virgo–KAGRA searches for eccentric sources use the model-independent cWB algorithm (Klimenko et al., 2016), but no confirmed eccentric candidates have yet been reported (Abbott et al., 2019e; Abac et al., 2023).

Black hole systems may also emit extremely short gravitational-wave bursts during hyperbolic encounters (Capozziello et al., 2008; De Vittori et al., 2012), which occur as mutual scatterings inside dense stellar clusters. If the objects pass sufficiently close, a sharp burst may fall within the frequency range of current detectors, appearing in the time series as a very brief solitary peak (Bae et al., 2020).

So far, two targeted searches for such encounters have been conducted: Morrás et al. (2022) examined fifteen days of data from the second observing run, and

Bini et al. (2024) searched during O3b. No reliable events were found. Both Bini et al. (2024) and Dandapat et al. (2023) estimated detection prospects for upcoming runs, suggesting that the fifth observing run could achieve a survey sensitivity corresponding to a volumetric rate of about 1.33 ± 0.052 × 10^7 Mpc^3/year.

Some repeating fast radio bursts (FRBs) have been detected, and a few have been localized to their host galaxies (Spitler et al., 2016; Chatterjee et al., 2017; Kumar et al., 2019). The astrophysical origin of most FRBs remains unresolved, with many proposed progenitor models—for both repeating and non-repeating cases—including scenarios that predict a gravitational-wave counterpart (see Platts et al., 2019). The extremely short timescales suggest that the source must be a compact object such as a black hole or a neutron star with strong magnetic fields or rapid rotation. However, the high observed rates make it impossible to attribute all FRBs to binary neutron star mergers (Wang & van Leeuwen, 2024).

Some FRBs may be catastrophic in origin—unlikely for repeaters—such as neutron star mergers, superluminous supernovae, or the collapse of a neutron star into a black hole. Non-catastrophic scenarios include magnetar flares or magnetars within binaries. Recently, an FRB was associated with a Galactic magnetar during an X-ray outburst, confirming that at least some FRBs originate from magnetars (Andersen et al., 2020). This event occurred between the third and fourth observing runs of current detectors. For magnetars to account for extragalactic and repeating FRBs, their radio luminosity would need to reach levels far higher than those observed in our own Galaxy.

Since binary neutron star mergers are proposed as candidates for non-repeating FRB sources, searches for gravitational counterparts use matched-filter methods for compact binaries along with unmodeled burst techniques. For repeaters, a binary-merger origin is unlikely, so only unmodeled methods are applied. If an FRB occurs within the detection range of neutron star binary mergers, a non-detection of gravitational waves could rule out merger as the source. Several FRBs are expected to fall within this range at the sensitivity of the fifth observing run, as illustrated in Figure 6.

It is unlikely that FRBs produced by magnetar flares outside our Galaxy would be detected via gravitational waves; we return to this point in Section 7.

To date, only one claimed coincidence between a gravitational wave and an FRB has been reported: GW190425 and FRB 20190425A observed by CHIME (Moroianu et al., 2023). The initial significance of the coincidence is about 2.8σ, but several issues undermine the claim, the foremost being the assumption that a supramassive neutron star remnant survived for 2.5 hours, which would require…

Pulsar Glitches

A "pulsar glitch" is defined as a sudden increase in the angular momentum of a neutron star's crust, observed as a rise in its rotation frequency (Radhakrishnan & Manchester, 1969; Reichley & Downs, 1969; Boynton et al., 1969). The driving mechanism is believed to be linked to superfluid physics in the interior (Anderson & Itoh, 1975). In simple terms: the superfluid does not lose angular momentum through the usual spin-down process because its vortices are pinned to the crystal lattice sites in the crust; this pinning prevents vortices from moving outward, keeping the superfluid's angular momentum nearly constant over long timescales. Over time, a differential builds between the angular velocities of the superfluid core and the crust until a sudden unpinning occurs, during which angular momentum is transferred from the core to the crust; this is observed as a pulsar glitch. For an extensive review of glitch physics, see Haskell & Melatos (2015), and for gravitational-wave emission associated with glitches, see Haskell & Jones (2024).

During glitches, there are two—and possibly three—mechanisms that may generate detectable gravitational radiation:

1. Large-scale oscillation modes can be excited, spanning a broad frequency range and being relatively short-lived.
2. The internal relaxation phase following a glitch is expected to drive bulk fluid flows within the star, producing current-quadrupole radiation.
3. A more speculative idea is that "starquakes" may accompany some glitches (Bransgrove et al., 2020), capable of exciting oscillation spectra and emitting gravitational waves. We briefly discuss each possibility.

Although the prevailing view is that glitches are triggered by accumulated differential rotation between the superfluid and the crust, the instantaneous mechanism of angular momentum transfer from the core remains unclear. Observations of the 2016 Vela glitch pulse-by-pulse (Palfreyman et al., 2018) showed that the rise time was shorter than 12 seconds (90% confidence) and possibly much less (Ashton et al., 2019). If the timescale is sufficiently short, energy can efficiently transfer from the excitation mechanism into subsequent fluid flows, as well as into the fundamental f-mode and higher-order p-modes (Kokkotas et al., 2001; Sedrakian et al., 2003; Sidery et al., 2010; Ho et al., 2020; Wilson & Ho, 2024), both of which couple to gravitational-wave channels. These modes are typically transient and damp out within $\lesssim 0.1$ s (Detweiler, 1975; Lindblom & Detweiler, 1983; McDermott et al., 1988). The sudden "kick" may also excite r-modes (Santiago-Prieto et al., 2012), which are unstable under the Chandrasekhar–Friedman–Schutz mechanism (Chandrasekhar, 1970; Friedman & Schutz, 1978), even at modest rotation rates (Andersson & Kokkotas, 2001), allowing growth to levels capable of significant gravitational-wave emission. Finally, spatially unpinned vortices may radiate through current-quadrupole emission, with possible detectability in current or future detectors (Warszawski & Melatos, 2012).

While the starquake scenario is theoretically less favored, the first direct pulsar observation of a glitch (Palfreyman et al., 2018) showed evidence for a momentary drop-out in the signal at the glitch epoch; this is difficult to explain without assuming strong motion or cracking of the crust (Bransgrove et al., 2020), which could excite a range of core oscillation modes. However, current estimates suggest their amplitudes lie below detection thresholds (Keer & Jones, 2015; Layek & Yadav, 2020).

Immediately after a glitch, the stellar core may begin to rotate more slowly than the crust, potentially driving axisymmetry-breaking Ekman flows capable of generating gravitational waves via current-quadrupole emission (van Eysden & Melatos, 2008; Bennett et al., 2010; Singh, 2017). Alternatively, glitches may create surface deformations ("mountains") on the neutron star, producing quasi-monochromatic gravitational waves tied to stellar rotation (Yim & Jones, 2020; Moragues et al., 2023), or transfer excess superfluid energy into gravitational radiation (Prix et al., 2011), or involve trapped ejecta masses radiating at the rotation frequency and its harmonics (Yim et al., 2024b).

Despite the many proposed mechanisms for gravitational-wave emission during and after glitches, no such emission has yet been observed (Abadie et al., 2011a; Abbott et al., 2022c, 2021d; Lopez, 2024). However, some glitch models are beginning to be constrained by these non-detections (e.g., Yim et al., 2024a), suggesting that the first detection of glitch-related gravitational waves may be within reach.

Figure 6. Estimated number of FRB bursts expected to be observed in the future assuming their rate traces star formation, predicted to fall within the detection range of binary neutron star systems during upcoming LIGO–Virgo–KAGRA observing runs. The absence of a counterpart detection within this range could exclude neutron star binaries as the source. This figure was prepared by Eric Howell, assuming a CHIME detection rate of two FRBs per day, NSBH binary masses of 1.4 and 10 $M_\odot$, and BNS binary masses of 1.4 and 1.4 $M_\odot$.

Magnetars

Neutron stars with extremely strong magnetic fields ($B \gtrsim 10^{13}$ G)—known as *magnetars*—exhibit recurrent bursts reaching luminosities of up to $\approx 10^{43}$ erg s^{-1} (see Kaspi & Beloborodov, 2017), and can release "giant flares" peaking at $\approx 10^{48}$ erg s^{-1}. Such extreme events in the magnetosphere may be accompanied by crustal fractures, large-scale magnetic field reconfiguration in the interior, and global fluid flows inside the star; all have been proposed as gravitational-wave emission mechanisms.

Early estimates of gravitational-wave energy suggested the possibility of wholesale reconfiguration of the internal magnetic structure. If the entire magnetic energy reservoir were converted into gravitational *f*-mode oscillations, the energy release could reach $\sim 10^{49}$ erg, potentially detectable by second-generation observatories (Ioka, 2001; Corsi & Owen, 2011). However, more recent analytic and numerical calculations present a less optimistic picture (Levin & van Hoven, 2011; Lasky et al., 2011; Ciolfi et al., 2011; Zink et al., 2012; Tsokaros et al., 2022), indicating that detecting kilohertz *f*-mode oscillations from a Galactic giant flare would require at least third-generation detectors.

f-mode oscillations are expected to be short-lived (≲100 ms; Detweiler, 1975; Lindblom & Detweiler, 1983; McDermott et al., 1988), making them relatively straightforward targets (see discussion below). In contrast, longer-lived modes may be excited, but detecting them requires algorithms capable of tracking phase evolution. Theoretically, these include *g*-modes and Alfvén waves, where the restoring forces are buoyancy and magnetic fields, respectively. Insufficient studies exist to firmly establish their amplitudes, evolution, and damping mechanisms, leaving their gravitational-wave energy and detectability highly uncertain. Furthermore, these modes are unlikely to be perfectly monochromatic; frequency and phase drifts over long durations make fully coherent searches unsuitable, leading to a significant gap between practical and optimal sensitivity.

Despite these challenges, the LIGO–Virgo–KAGRA network conducts searches for gravitational waves accompanying magnetar flares (Abbott et al., 2007, 2008, 2009; Abadie et al., 2011b, 2012; Abbott et al., 2019f, 2024). Of these, only one (Abbott et al., 2007) specifically targeted a giant flare: the 2004 event of the Galactic magnetar SGR 1806-20 (Hurley et al., 2005; Palmer et al., 2005), which was nearly 100 times brighter than the other two known giant flares, with an isotropic-equivalent energy of about 2 × 10^46 erg. Interestingly, the X-ray tail of that event showed quasi-periodic oscillations (Israel et al., 2005; Watts & Strohmayer, 2006; Strohmayer & Watts, 2006), attributed to vibrational modes of the core, crust, and crust–core interface. Many of these frequencies fall within the gravitational-wave detection band of LIGO–Virgo–KAGRA, but no gravitational waves were observed; upper limits were set at ≲10^47 erg.

Detector sensitivity has greatly improved since the 2004 flare, but no new Galactic giant flares have occurred. Searches have thus been limited to weaker flares with electromagnetic energies 5–6 orders of magnitude lower (e.g., Abbott et al., 2019f, 2024). The best upper limits on gravitational-wave energy from these campaigns are ≲10^44 erg for both short-lived (e.g., *f*-modes) and long-lived (e.g., *g*- or Alfvén modes) searches. For gravitational waves to be detectable from such flares, their gravitational energy would need to exceed the emitted electromagnetic energy by 3–4 orders of magnitude.

We therefore continue to await the next giant flare; but even at design sensitivity, there is no guarantee that the network will capture gravitational waves from these bursts.

Gamma-Ray Bursts (GRBs)

GRBs are intense flashes of gamma-rays followed by afterglows at multiple wavelengths. They are typically classified into two types with distinct progenitors and durations: “long” bursts, most lasting more than 2 s and sometimes up to hours with relatively soft spectra, and “short” bursts, which are dimmer, typically <2 s, and produce harder photons.

Long bursts can last minutes and are thought to be powered by extreme supernovae. Supporting evidence includes observational associations such as SN1998bw (Galama et al., 1998), which confirmed links to long GRBs. Possible progenitors include magnetorotational explosions (see Section 2), where rotational energy is extracted via magnetic fields, or more extreme scenarios such as accretion disks around black holes in collapsing stars (collapsars) (MacFadyen & Woosley, 1999).

Short bursts are often associated with compact binary mergers, as dramatically demonstrated by the multimessenger observation of GW170817, a binary neutron star merger accompanied by a short GRB (Abbott et al., 2017b,d). This GRB was several orders of magnitude less energetic than most of its peers, and joint interpretation of gravitational-wave and electromagnetic signals indicates an off-axis observation.

Recent observations are challenging the traditional “long/short” classification. GRB 211211A appeared long, with a soft spectrum and a duration exceeding 50 s, yet it was accompanied by a kilonova, suggesting a compact binary merger progenitor (Rastinejad et al., 2022; Troja et al., 2022). At a distance of no more than 350 Mpc, such an event would have been within the sensitivity of LIGO–Virgo–KAGRA’s fourth run if it involved a binary neutron star, or within the third run if it was a neutron star–black hole binary (Sarin et al., 2023; Yin et al., 2023). Similarly, GRB 230307A was a “long” burst with a kilonova; the James

Webb Space Telescope detected a tellurium emission line—a heavy *r*-process element attributed to compact binary mergers (Levan et al., 2024).

A simultaneous detection of a gravitational wave and a gamma-ray burst from a compact binary merger is highly anticipated. However, in gravitational-wave data analysis, these signals are not categorized as "bursts" because their morphology can be accurately modeled.

Past gravitational-wave searches have looked for counterparts to GRBs detected by *Fermi* and *Swift* (Abbott et al., 2017c, 2019h, 2021f, 2022b). Over six months of cumulative observing time, about 100 GRBs were recorded, most without known cosmological distances. Unmodeled search techniques are used for all GRBs regardless of type, while template banks for inspiral phases are applied only for short GRBs. A typical search window extends 600 s before to 60 s after the GRB trigger. It may be useful to extend this window given the unusual cases noted above and the observation of soft X-rays hundreds of seconds before gamma-ray emission (Liu et al., 2024). Previous searches have also been limited to the 20–500 Hz band, which is not optimal if GRBs are powered by extreme supernovae, since most of their gravitational energy—as discussed in Section 2—is emitted above 500 Hz.

Orphan Memory

Gravitational-wave "memory" represents a nonlinear hereditary effect arising from anisotropic gravitational radiation (Zel'dovich & Polnarev, 1974; Braginsky & Thorne, 1987; Christodoulou, 1991; Thorne, 1992). At frequencies below the characteristic source frequency, the strain spectral density follows the relation S_h^(1/2) ∝ 1/f. Thus, any burst with a characteristic frequency above the LIGO–Virgo–KAGRA band could appear through a low-frequency memory component in the signal (McNeill et al., 2017).

Hypothetical astrophysical sources radiating well above the ∼2 kHz upper limit of the LVK band include cosmic strings, dark matter collapse inside stars, and Kaluza–Klein modes in higher-dimensional theories (see Cruise, 2012 for review). An "orphan memory" from such high-frequency bursts could be detected within the LVK band, exhibiting the S_h^(1/2) ∝ 1/f behavior (McNeill et al., 2017). However, identifying the origin of such memory—or even confirming it as memory—may be challenging (see also Divakarla et al., 2020).

The absence of strong memory burst detections in LIGO–Virgo–KAGRA data places constraints on claims from specialized MHz/GHz-band devices (see Aggarwal et al., 2020). For example, the bulk acoustic wave (BAW) high-frequency gravitational-wave antenna reported “two highly significant events” (Goryachev et al., 2021; Goryachev & Tobar, 2014). If these had truly been gravitational waves, they would have produced memory signals in LIGO/Virgo with SNR > 10^6 (Lasky & Thrane, 2021). This reductio ad absurdum—along with its cosmological and astrophysical implications (Lasky & Thrane, 2021; Domènech, 2021)—demonstrates that those signals were not gravitational in origin, and that current MHz/GHz detectors remain far from the sensitivity needed to capture real astrophysical sources.

Conclusions

Current gravitational-wave observatories have revolutionized our understanding of the universe: delivering the first direct detection of gravitational waves, enabling strong-field tests of general relativity, and providing the first unambiguous evidence that binary neutron star mergers are the progenitors of short GRBs. Yet this is only the beginning. Next-generation facilities are expected to detect every binary black hole merger in the observable universe, and most binary neutron star mergers back to the peak of cosmic star formation.

Despite this progress, many classes of gravitational-wave sources remain undiscovered. Capturing a burst of a new type remains one of the most promising frontiers for future discoveries.

In this review, we have outlined the anticipated sources of gravitational-wave bursts, the prospects for their detection, and the insights they may provide into source physics. Some classes—such as core-collapse supernovae (CCSNe)—are modeled reasonably well, though detailed waveform predictions remain challenging due to complex and stochastic physical inputs. Hydrodynamic simulations have nevertheless enabled the community to understand the signals well enough to build tools that can extract astrophysical parameters such as spin rate and the nuclear equation of state. Strongly eccentric compact binaries are also understood fairly well, though not with the precision required to construct full template banks for strict matched filtering.

For other burst sources, waveform modeling is even more challenging, mainly due to the uncertainty in astrophysical progenitors. Fast radio bursts (FRBs), for instance, are associated with a broad range of proposed origins, leading to diverse predictions for signal morphology, duration, frequency, and amplitude. It is also possible that entirely unanticipated sources exist, neither theoretically predicted nor electromagnetically observed. Detecting a burst from such an "unknown unknown" class would mark a dramatic leap in our understanding of the cosmos.

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