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Dawes Review

The Dawes Review 12: Gravitational-wave burst astrophysics

Jade Powell[1,2] and Paul D. Lasky[3,4]

[1]Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Hawthorn, VIC, Australia, [2]OzGrav: The ARC Centre of Excellence for Gravitational-Wave Discovery, Hawthorn, VIC, Australia, [3]Monash Astrophysics, School of Physics and Astronomy, Monash University, Melbourne, VIC, Australia and [4]OzGrav: The ARC Centre of Excellence for Gravitational-Wave Discovery, Clayton, VIC, Australia

Abstract

Over a hundred gravitational-wave signals have now been detected from the mergers of black holes and neutron stars, but other sources of gravitational waves have not yet been discovered. Some of the most violent explosive events in the Universe are predicted to emit bursts of gravitational waves and may result in the next big multi-messenger discovery. Gravitational-wave burst signals often have an unknown waveform shape and unknown gravitational-wave energy, due to unknown or very complicated progenitor astrophysics. Potential sources of gravitational-wave bursts include core-collapse supernovae, cosmic strings, fast radio bursts, eccentric binary systems, and gravitational-wave memory. In this review, we discuss the astrophysical properties of the main predicted sources of gravitational-wave bursts and the known features of their gravitational-wave emission. We summarise their future detection prospects and discuss the challenges of searching for gravitational-wave burst signals and interpreting the astrophysics of the source.

Keywords: Gravitational waves; transients

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1. Introduction

What comes next in gravitational-wave astronomy? To date, all ground-based gravitational-wave observations have come from the coalescence and merger of neutron stars and black holes (Abbott et al. 2019b, 2021b, a). The increased sensitivity of the LIGO-Virgo-KAGRA (Aasi et al. 2015; Acernese et al. 2015; Akutsu et al. 2021) network of gravitational-wave observatories implies a significant and rapid increase in the volume of the Universe being surveyed, not only to compact-binary coalescences, but also to other types of sources. The positive detection of these other source types has the potential to vastly increase our understanding of different aspects of astro- and fundamental physics, from neutron star and supernova physics, to more exotic aspects such as cosmic strings.

Different gravitational-wave sources can be loosely divided into categories based on the duration of their signals. For example, 'mountains' on rotating neutron stars create nearly monochromatic gravitational-wave signals that are persistent for months to millennia. Low-mass compact binary mergers last in the LIGO-Virgo-KAGRA band for many minutes, while relatively high mass binary black hole mergers ($\sim 100\mathrm{M}_{\odot}$) are in band for less than tenths of a second. Other potential transient sources of gravitational waves also cover these timescales, from $\mathcal{O}(10-100\mathrm{ms})$ f-mode oscillations of neutron stars to $\mathcal{O}(\mathrm{day})$ long signals from fluid dynamics associated with pulsar glitch recovery. In this review, we focus on *bursts* of gravitational waves with short durations from a few ms up to around 2000 s. In Fig. 1, we show a schematic plot of the main sources of gravitational-wave bursts as a function of their gravitational-wave frequency on the vertical axis and approximate duration on the horizontal axis.

The majority of potential gravitational-wave burst sources are perfect targets for multi-messenger astronomy. A detection of gravitational waves from a burst source such as a core-collapse supernova (CCSN) may result in the first electromagnetic, neutrino, and gravitational-wave joint detection, providing us with a comprehensive understanding of the underlying astrophysical processes (Mezzacappa & Zanolin 2024). A detection of gravitational waves from a fast radio burst (FRB) may provide us with some of the first insights into the nature of the source of these events (Abbott et al. 2022a). Some other examples of potential burst sources with electromagnetic counterparts are magnetar flares, gamma-ray bursts (GRBs) and pulsar glitches. Gravitational-wave bursts could also be emitted from an electromagnetically dark signal like a cosmic string, an eccentric binary black hole merger, or a previously unknown astrophysical object.

Making the first detection of gravitational-wave burst signals has many challenges. First and foremost, they are difficult to model. This may be due to complicated astrophysical processes in the progenitor, for example in CCSNe (see Section 2), or because of a lack of knowledge of the nature of the source, such as FRBs (see Section 5). A lack of understanding of the exact signal morphology means that typical template-based search techniques such as matched filtering cannot be used. Additional problems arise in that transient noise artefacts could potentially mimic these short-lived signals.

Current searches for gravitational-wave bursts tend to search for excess power that occurs coherently between multiple gravitational-wave detectors (e.g., Klimenko et al. 2016; Lynch et al. 2017; Sutton et al. 2010), which mitigates transient noise

Corresponding author: Jade Powell; Email: dr.jade.powell@gmail.com

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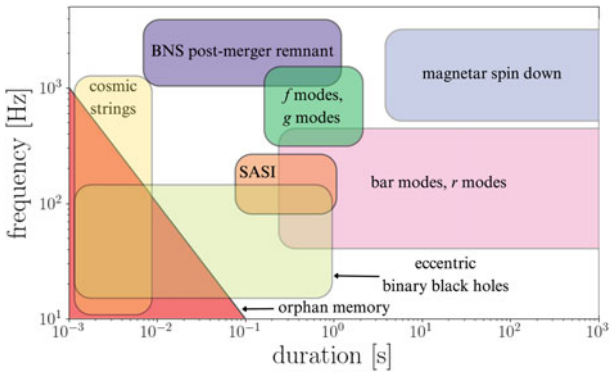


Figure 1. The duration and frequency of different potential sources of gravitational-wave bursts. Bursts that last only a few ms include high mass eccentric binary black hole mergers, cosmic strings and orphan memory. Sources that last up to a few thousand seconds include the spin down of millisecond magnetars. Gravitational waves from post mergers remnants and core-collapse supernovae can occur at frequencies above 1 000 Hz, including the different types of emission modes for core-collapse supernovae discussed in detail in Section 2.

artefacts parading as gravitational-wave signals. These searches make minimal assumptions about the morphology of the signal. Previous work has performed targeted searches for sources observed electromagnetically or through neutrinos (e.g., Abbott et al. 2024, 2022a; Abbasi et al. 2023; Abbott et al. 2022b). There are also all-sky and all-time searches to ensure that no gravitational-wave burst event is missed if there are no electromagnetic counterparts (Abbott et al. 2021d,c). To date, unmodelled burst searches have only made detections of binary black hole mergers, including the first gravitational-wave detection GW150914 (Abbott et al. 2016b). They have not made any confident detections of any new types of gravitational-wave sources.

In this review, we describe the various potential sources of gravitational-wave bursts. We discuss the probabilities of making a detection of these burst sources in the near future, or in next generation gravitational-wave observatories such as the Einstein Telescope (Hild et al. 2011), Cosmic Explorer (Evans et al. 2021), or a dedicated kilohertz frequency observatory such as NEMO (Ackley et al. 2020). We describe how potential gravitational-wave signals can be used to interpret the astrophysical properties of the and discuss what work still needs to be done for the community to be ready for the first detection from a new source. We begin in Section 2 with a discussion of CCSNe. We discuss binary neutron star post merger remnants in Section 3, highly eccentric and hyperbolic compact binaries in Section 4, FRBs in Section 5, pulsar glitches in Section 6, magnetars in Section 7, GRBs in Section 8, orphan memory in Section 9, topological defects in Section 10, and unknown unknowns in Section 11. We conclude in Section 12.

2. Core-collapse supernovae

Core-collapse supernovae are the explosive deaths of stars more massive than $\approx 8\,M_\odot$. When a stellar core exceeds its effective Chandrasekhar mass it becomes gravitationally unstable and collapses until the core reaches nuclear densities. A shock wave is launched outwards from the core, loses energy, and stalls at a radius of ~ 150 km. The mechanism to revive the shock is not fully understood as electromagnetic observations cannot probe the inner regions of the star. However, gravitational waves and neutrinos are emitted directly from the core, and may provide us with the first direct probe of the mechanism that powers CCSN explosions (Müller 2017).

Predictions of gravitational waveforms for CCSNe come from numerical hydrodynamical simulations (see Abdikamalov, Pagliaroli, & Radice 2020; Müller 2020; Mezzacappa & Zanolin 2024 for recent reviews). However, CCSN simulations are extremely computationally challenging and need to include multi-dimensions, accurate neutrino transport, stellar hydrodynamics, realistic equations of state, progenitor models from stellar evolution, general relativity, rotation and magnetic fields. There are some variations in gravitational-wave amplitude predictions between different simulation codes (Andresen et al. 2017; Kuroda et al. 2017; Radice et al. 2019; Powell & Müller 2019; Mezzacappa et al. 2020). However, there are many features of gravitational-wave signals from CCSNe that are considered to be robust and have been seen in simulations made by many groups using different codes and different numerical set-ups.

The majority of CCSNe are thought to explode by the neutrino-driven explosion mechanism, where the shock wave is powered by absorbing some of the energy from the neutrinos (Janka 2017). More extreme supernovae are expected to explode by the magneto-rotational explosion mechanism, where the rotational energy of the star is transported into the shock wave by the magnetic fields (Reichert et al. 2023; Müller 2024). Several studies have shown how we can determine the explosion mechanism from the gravitational-wave signal using model selection techniques trained on waveforms from numerical simulations (Logue et al. 2012; Powell et al. 2016; Powell, Szczepanczyk, & Heng 2017; Saiz-Pérez, Torres-Forné, & Font 2022; Powell et al. 2024). Using currently available waveforms, different model selection algorithms are able to determine the explosion mechanism with high accuracy for gravitational-wave signals with a signal-to-noise ratio (SNR)$\gtrsim 20$.

There are currently a large number of waveforms 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; Powell & Müller 2020; Mezzacappa et al. 2020; Pan et al. 2021). On the other hand, there are only a small number of three-dimensional waveforms available for magneto-rotational explosions that extend beyond the core-bounce phase (Bugli et al. 2022; Obergaulinger & Aloy 2022; Powell et al. 2023; Powell & Müller 2024). There are also significant differences in the magneto-rotational waveforms from different simulation codes (Varma, Müller, & Obergaulinger 2021). More waveform development for magneto-rotational explosions is therefore needed to ensure we are ready to accurately determine the explosion mechanism for a real CCSN event.

The main feature in CCSN gravitational-wave signals is the high frequency g/f-mode oscillations of the proto-neutron star, which usually has higher gravitational-wave energy than the other signal components. These modes have very clear features in signal spectrograms, as shown in Fig. 2, where the gravitational-wave emission rises in frequency with time as the proto-neutron star radius shrinks and its mass increases. The mode typically starts around 100 ms after the core-bounce time. The maximum gravitational-wave frequency of the mode can vary significantly between different simulations. For example, Powell & Müller (2019) see a maximum frequency of $\sim 1\,000$ Hz in their neutrino-driven explosions, but Pan et al. (2021) see a maximum frequency of $\sim 3\,000$ Hz.

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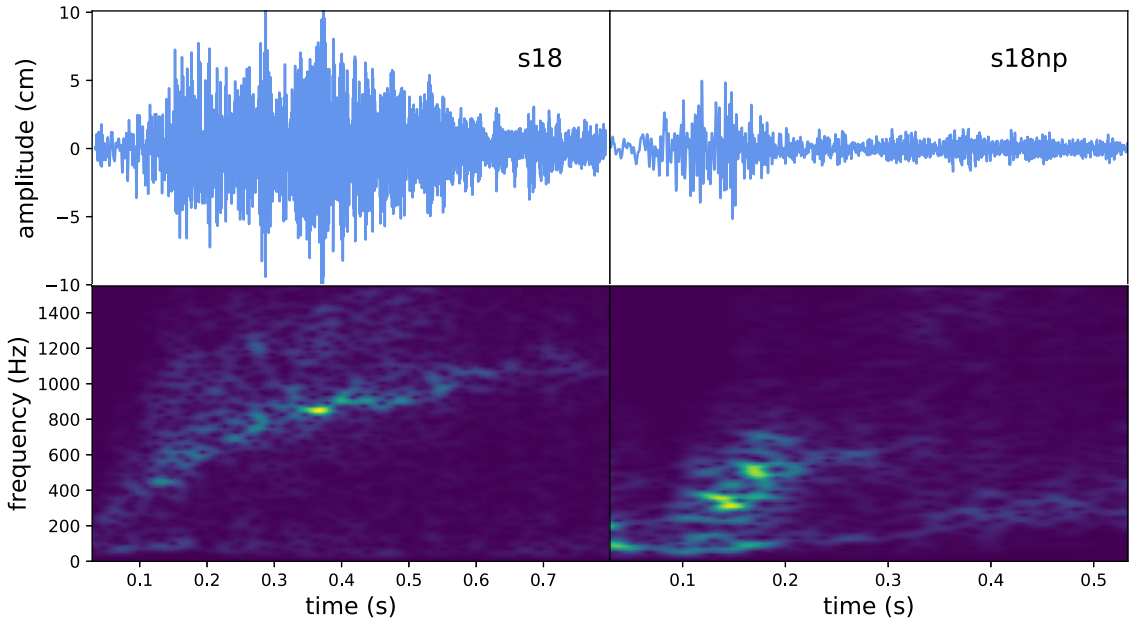


Figure 2. Examples of typical gravitational-wave signals from core-collapse supernovae. Both models are 18 $M_{\odot}$ stars from Powell & Müller (2019, 2020), where model s18 (left panels) rapidly undergoes shock revival, and model s18np (right panels) fails to power a full supernova explosion. The top panels show the time series, and the bottom panels are spectrograms of the gravitational-wave signals. The main feature in the spectrograms is the high frequency g-mode, which has a frequency that is related to the properties of the proto-neutron star. The lack of shock revival in model s18np results in lower gravitational-wave amplitude and a longer duration low frequency mode due to the SASI.

Universal relations have been developed that describe the relationship between the gravitational-wave frequency and the mass and radius of the proto-neutron star (Torres-Forné et al. 2019; Sotani, Takiwaki, & Togashi 2021; Sotani, Müller, & Takiwaki 2024), which has led to development of search and parameter estimation tools for this signal mode (Powell & Müller 2022; Bizouard et al. 2021; Bruel et al. 2023). These tools may enable us to learn proto-neutron star properties from a positive gravitational-wave detection. However, current universal relations ignore some aspects of the physics behind CCSNe, for example rotation and magnetic fields.

In rotating models, there is a spike in the gravitational-wave time series at the time of core-bounce followed by smaller oscillations (Dimmelmeier et al. 2008; Abdikamalov et al. 2014; Scheidegger et al. 2008). If the star is non-rotating, then the gravitational waves at the core-bounce time will be effectively zero. The spike occurs when the equation of state stiffens and the proto-neutron star oscillates for a few ms. The bounce signal only occurs in the plus polarisation and the most optimal observer angle is from the equator of the star. So even if the star is rapidly rotating, there will be no core-bounce signal visible if we detect the gravitational waves from an observer angle near the poles. If the core-bounce signal is detected, it can be used to constrain properties of the star. For example, the amplitude of the bounce signal is related to the oblateness of the core that is determined by the rate of the rotation. Oscillations after the initial spike may tell us about the equation of state. The core-bounce signal is expected to be in the frequency range between 100-1000 Hz. As this part of the signal is well understood, it is possible to perform template-based searches and parameter estimation (Edwards, Meyer, & Christensen 2014; Richers et al. 2017; Pajkos et al. 2021; Edwards 2021; Afle & Brown 2021; Pastor-Marcos et al. 2023).

Another common feature found in CCSN gravitational-wave emission is a lower frequency mode due to the standing accretion shock instability (SASI; Blondin, Mezzacappa, & DeMarino 2003; Blondin & Mezzacappa 2006; Foglizzo et al. 2007). The SASI is an instability in the shock wave that can result in the proto-neutron star being excited from above producing pressure (p) modes. The SASI modes occur in the most sensitive frequency band of current gravitational-wave observatories ($\approx$ 200 Hz), which can aid in the signal's detectability. However, the gravitational-wave energy caused by the SASI is usually significantly lower than the energy in the g/f-mode. The gravitational-wave emission mode from the SASI usually increases in frequency with time up to the time of shock revival where the explosion prevents further growth of the SASI. Therefore, there is usually no SASI mode visible in models that quickly undergo shock revival.

The gravitational-wave signal will also have a low-frequency component (below $\sim$ 10 Hz) due to gravitational-wave memory. Matter motion post shock revival can result in a small memory component in the signal. However, asymmetric emission of neutrinos creates much stronger memory amplitudes, resulting in increased CCSN detection rates for gravitational waves in low-frequency detectors (Mukhopadhyay, Cardona, & Lunardini 2021; Vartanyan et al. 2023; Powell & Müller 2024). Long-duration simulations are needed to fully understand the limits on the minimum frequency and maximum amplitude of this aspect of gravitational-wave emission. As this is currently not computationally feasible, some groups have tried to extend the duration of the gravitational-wave emission analytically (Richardson et al. 2022).

A few studies have determined the detection prospects for CCSNe in current gravitational-wave observatories with unmodelled burst search algorithms (Gossan et al. 2016; Szczepańczyk et al. 2023). For modern neutrino-driven CCSN explosion

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waveforms, the SNR needs to be approximately between 15 and 20 before the signal can be detected by an unmodelled burst search. This translates to Galactic detection distances and puts the rates of CCSNe at a few per century for current ground based observatories (Taylor et al. 2014). Magneto-rotational explosions may be detected at much greater distances, to beyond the Magellanic Clouds, but this does not add a significant improvement to the detection rates.

No gravitational waves from CCSNe have been detected during the first three Advanced LIGO-Virgo-KAGRA observing runs using unmodelled burst searches (Abbott et al. 2020a; Szczepańczyk et al. 2023). In the next generation of ground based gravitational-wave observatories, the detection distances for CCSNe will vary from hundreds of kpc to a few Mpc, depending on the progenitor properties, potentially increasing the detection rates to as much as one per year (Powell & Müller 2019; Powell & Müller 2024).

To enhance the prospects for further detections, further improvements need to be made to CCSN gravitational waveform predictions from numerical simulations, and also to the search algorithms for gravitational waves from CCSNe. The current searches are waveform agnostic and need a relatively high SNR signal before the gravitational waves can be detected. If the known features of the gravitational-wave signals are incorporated into the search algorithms, then it may decrease the minimum SNR needed for the first CCSN detection.

3. Binary neutron star post merger remnants

There are multiple potential outcomes for the remnants of binary neutron star mergers that primarily depend on the remnant's mass. If the remnant is below the so-called Tolman-Oppenheimer-Volkoff mass $M_{\rm TOV}$ (Tolman 1939; Oppenheimer & Volkoff 1939), which is the maximum mass a non-rotating neutron star can attain without collapsing to a black hole, then an infinitely stable neutron star will be born from the collision. If the remnant mass is between $M_{\rm TOV}$ and $\chi M_{\rm TOV}$, where $1.3 \lesssim \chi \lesssim 1.6$ depending on the unknown nuclear equation of state (e.g., Shibata, Baumgarte, & Shapiro 2000; Shibata et al. 2006; Baiotti & Rezzolla 2017; Agathos et al. 2020; Bauswein et al. 2021, and references therein), then the remnant will be a meta-stable neutron star known as either a hyper- or supramassive neutron star. Hypermassive neutron stars, supported from collapse by differential rotation, are expected to survive for less than about one second (e.g., Baumgarte, Shapiro, & Shibata 2000; Shapiro 2000) before losing sufficient centrifugal support and collapsing to a black hole. Supramassive stars are supported from collapse by rigid rotation which is quenched on a longer timescale, and hence can survive for up to $\sim 10^4$s (Ravi & Lasky 2014). Remnants with mass above $\chi M_{\rm TOV}$ will immediately form a black hole as a direct result of the merger. For recent reviews of post-merger remnants, see Bernuzzi (2020), Sarin & Lasky (2021).

Of the four stages mentioned above, the first three (stable, hypermassive, and supramassive) are all expected to emit large-amplitude gravitational waves that may be detectable in current- or next-generation gravitational-wave observatories for a short time ($\lesssim$ s) after the merger. The amplitude of the emission is expected to be comparable, if not larger, than the amplitude of the inspiral strain. The characteristic frequency of emission is, on the other hand, almost predominantly in the kHz regime as shown in Figure 3. Importantly, the specific frequencies emitted can be used to trace the nuclear equation of state (Bauswein et al. 2012; Bauswein & Janka 2012; Read et al. 2013), implying the positive detection of post-merger remnants have the potential to significantly advance our understanding of nuclear physics in conditions inaccessible to terrestrial experiments.

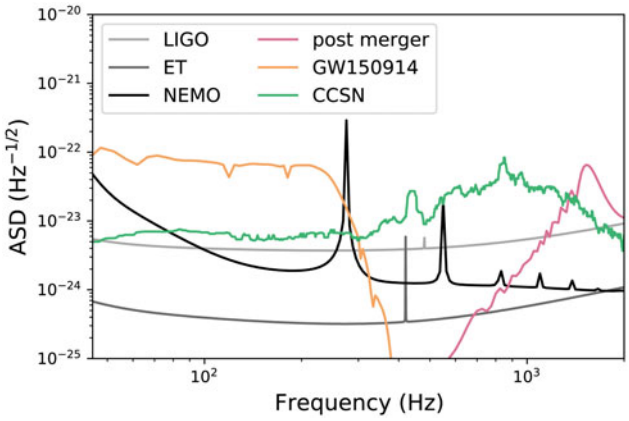


Figure 3. The amplitude spectral density (ASD) of Advanced LIGO at design sensitivity, the Einstein Telescope (ET), the proposed NEMO observatory, a typical post merger signal, the binary black hole merger GW150914, and core-collapse supernova (CCSN) model s18 from Powell & Müller (2019) at a distance of 10 kpc. Post merger signals occur in the higher end of the frequency range of the LIGO-Virgo-KAGRA observatories. Binary mergers typically occur at frequencies of a few hundred Hz. CCSN signals are broadband, with the majority of their amplitude above 500 Hz.

While hypermassive remnants are expected to collapse on a timescale similar to that in which the gravitational-wave emission is expected to be visible, it looks unlikely that the collapse can be directly measured from the gravitational-wave signal even in third-generation observatories (Easter, Lasky, & Casey 2021; Dhani et al. 2024). Long-lived supramassive and stable remnants, on the other hand, are expected to emit gravitational waves for significantly longer periods of time. These may be generated through magnetic-field-induced ellipticity of the remnant (e.g., Cutler 2002; Haskell et al. 2008; Dall'Osso, Shore, & Stella 2009; Lander & Jones 2020), or stellar oscillation modes such as r or bar modes (e.g., Bondarescu, Teukolsky, & Wasserman 2009; Corsi & Mészáros 2009). However, the prospects of detection of these longer-lived signals has been vigorously debated in the literature (see Sarin & Lasky 2021, for a review), although many authors have tried searching for the long-lived remnant of the binary neutron star merger GW170817 (e.g., Abbott et al. 2017f; Abbott et al. 2019g; Grace, Wette, & Scott 2024). The long-lived nature of the emission in this case implies such gravitational-wave searches typically adopt methods from the community also searching for long-lived, nearly-monochromatic gravitational waves. As such, we declare these longer-lived signals out-of-scope for this review, and focus only on the short-lived signals in the immediate ($\lesssim$ s) aftermath of the merger.

Astrophysically, what fraction of binary neutron star mergers create either a stable, hypermassive, or supramassive neutron star, and therefore emit the short-lived but loud gravitational-wave signals that we are discussing in this Section is currently unknown. There are two primary unknowns limiting our ability to answer this question: (1) the unknown TOV mass $M_{\rm TOV}$ and (2) the unknown mass distribution of binary neutron star merger progenitors. While the latter was believed to be reasonably well understood, the binary neutron star merger GW190425 has a total

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mass of $3.4^{+0.3}_{-0.1}M_{\odot}$ (Abbott et al. 2020b), which is inconsistent with the Galactic mass distribution of double neutron star systems (Kiziltan et al. 2013; Keitel 2019; Farrow, Zhu, & Thrane 2019). We therefore wait patiently for more binary neutron star mergers to confidently determine this mass distribution for merging systems.

So what became of the neutron stars in the landmark merger event GW170817 that was observed by the LIGO-Virgo-KAGRA collaboration (Abbott et al. 2017b, 2019a) and across the electromagnetic spectrum (e.g., Abbott et al. 2017e, 2017d)? It is somewhat contentious to say that this is contentious. However, there are multiple authors who make definite claims that are in direct contradiction of one another about the nature of the remnant from e.g., the colour of the kilonova (Margalit & Metzger 2017; Radice et al. 2018; Yu, Liu, & Dai 2018), the lack of early-time x-ray observations (Piro et al. 2019; Ai, Gao, & Zhang 2020), and late-time radio and x-ray observations (Piro et al. 2019; Lin, Dai, & Gu 2019; Troja et al. 2020); for a review, see Sarin & Lasky (2021). What is certain is the uncertainty about the long-term fate of the remnant, but it is highly likely that the remnant did not promptly form a black hole, and therefore emitted kHz gravitational waves. Despite multiple searches, reliable identification of gravitational waves from a post-merger remnant have not been identified, and estimates indicate the gravitational-wave observatories required at least an order of magnitude of additional sensitivity to make a detection (Abbott et al. 2017f; Królak et al. 2023).

4. Eccentric binaries and hyperbolic encounters

Eccentric inspiralling systems circularise due to the emission of gravitational waves (Peters 1964). Systems born through binary stellar evolution are therefore expected to lose all detectable eccentricity by the time they enter the LIGO-Virgo-KAGRA observing band (e.g., Hinder et al. 2008). However, there are two main ways in which a black hole binary system could still be eccentric. First, if the binary system formed dynamically in a dense stellar environment such as a globular cluster or AGN disk (Morscher et al. 2015; Samsing 2018; Rodriguez et al. 2018). Second, from hierarchical field triples (Silsbee & Tremaine 2017; Antonini, Toonen, & Hamers 2017) and quadruples (Liu & Lai 2019; Fragione & Kocsis 2019) in which the inner binary's eccentricity is driven up through perturbations from the outer component through Kozai-Lidov resonances (Kozai 1962; Lidov 1962). For high eccentricities $e \gtrsim 0.5$ (see Fig. 4) and moderately large masses, modulations of the gravitational-wave strain when the binary is at periapsis imply the signal resembles a short-lived burst immediately prior to merger. The confident detection of such bursts may therefore allow us to distinguish between different formation channels (e.g., Lower et al. 2018).

Current standard matched filter searches for gravitational waves from binary black holes do not include the effects of eccentricity in their template banks (Abbott et al. 2019b, 2021b, 2021a). This is mainly due to a lack of available waveforms that include the effects of eccentricity, although there are a small number of waveforms currently available (East et al. 2013; Gayathri et al. 2022). There is also a significant increase in computational expense when more waveform parameters are added to the template bank. Templates without eccentricity are still effective at discovering black hole binaries with low ($\lesssim 0.2$) eccentricity (e.g., Brown & Zimmerman 2010; Zevin et al. 2021).

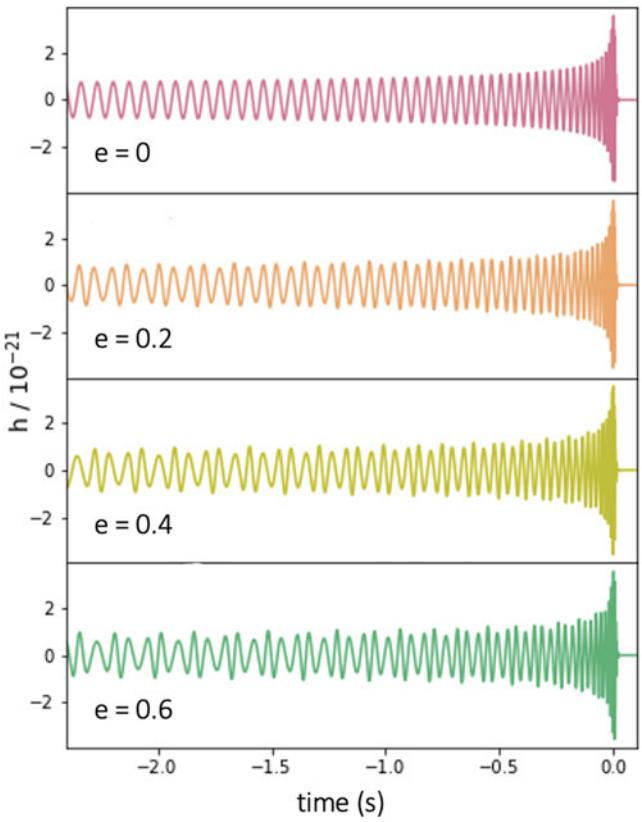


Figure 4. Example strain time series' of 30 $M_{\odot}$ binary black hole mergers with four different eccentricities calculated at a reference frequency of 10 Hz. At relatively large eccentricity, modulations of the strain at periapsis can resemble short-lived burst signals, especially at relatively large masses where only a couple of cycles may be present in the LIGO-Virgo-KAGRA observing band.

For binary black holes with larger eccentricities ($\gtrsim 0.2$), burst-search techniques are required to discover their gravitational-wave signals (although see e.g., Bustillo et al. 2021; Gayathri et al. 2022). Current LIGO-Virgo-KAGRA searches for gravitational waves from eccentric binaries use the unmodelled burst search algorithm cWB (Klimenko et al. 2016), however they have not identified any bona fide eccentric candidates (Abbott et al. 2019e; Abac et al. 2023).

Black hole systems may also produce short bursts of gravitational waves from hyperbolic encounters (Capozziello et al. 2008; De Vittori, Jetzer, & Klein 2012). A hyperbolic encounter occurs when black holes in dense star clusters scatter off of one another. If the two black holes pass close enough, then a burst of gravitational waves should occur in the frequency band of current gravitational-wave observatories. The gravitational-wave signal is very short duration, resulting in a single spike in the time series (Bae, Lee, & Kang 2020), as shown in Fig. 5.

To date, two gravitational-wave searches have been performed that specifically target hyperbolic encounters. Morrás et al. (2022) searched fifteen days of data during the second LIGO-Virgo-KAGRA observing run, and Bini et al. (2024) searched for hyperbolic encounters during O3b. Neither search detected gravitational waves from hyperbolic encounters. Bini et al. (2024), and Dandapat et al. (2023), explored the prospects for detecting these events in future gravitational-wave observing runs. They predict

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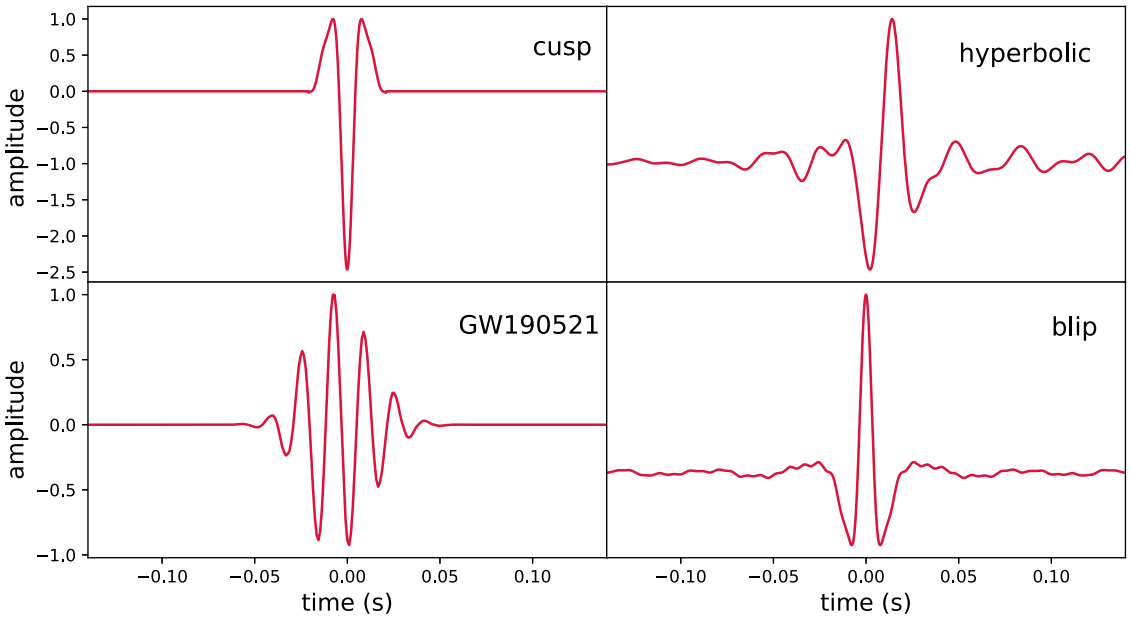


Figure 5. Examples of gravitational-wave bursts from different sources. Top left, a cosmic string cusp. Top right, a hyperbolic encounter. Bottom left, a numerical-relativity simulation of the high-mass binary black hole signal GW190521. Bottom right, a blip glitch. Detecting very short duration astrophysical signals is difficult due to their similarity to short duration detector noise glitches.

that the fifth observing run of LIGO-Virgo-KAGRA may be sensitivity to hyperbolic encounters out to a volume of $1.33 \pm 0.052 \times 10^7 \mathrm{Mpc}^3$ yr.

5. Fast radio bursts

FRBs are milli-second duration bursts of radio waves that are often detected at cosmological distances (see Petroff et al. 2022; Bailes 2022 for recent reviews). The first FRB was discovered by the Parkes/Murriyang telescope (Lorimer et al. 2007), with over a thousand more FRBs discovered to date (Petroff et al. 2016; Amiri et al. 2021). Some FRBs have been found to repeat, and a few have been localised to their host galaxies (Spitler et al. 2016; Chatterjee et al. 2017; Kumar et al. 2019).

The astrophysical progenitor of the majority of FRBs is currently unknown. There are a significant number of publications predicting different possible origins of repeating and non-repeating FRBs, some of which predict gravitational-wave counterparts (e.g., see Platts et al. 2019). The short time scales of FRBs suggest their origin is some kind of compact object such as a black hole or neutron star, possibly with a strong magnetic field or rapid rotation. However, the FRB detection rates are too high for every FRB progenitor to be a binary neutron star merger (Wang & van Leeuwen 2024).

Potential sources of FRBs could be cataclysmic, although this is likely not the case for repeating FRBs. Examples of cataclysmic potential origins of FRBs are neutron star mergers, extreme supernovae, or neutron star collapse to a black hole. Examples of non-cataclysmic sources include magnetar flares or magnetars in binary systems. Recently, a detection was made of an FRB associated with a galactic magnetar that was found during an X-ray outburst, showing that at least some FRBs originate from magnetars (Andersen et al. 2020). This event occurred between the current gravitational-wave observatories' third and fourth observing runs. For magnetars to be the origin of extragalactic repeating FRBs, they would need to have a radio luminosity significantly brighter than what we observe from magnetars in our own galaxy.

As binary neutron star mergers are one of the proposed progenitors for non-repeating FRBs, searches for their gravitational-wave counterparts use both modelled matched filter compact binary searches and unmodelled gravitational-wave burst search techniques. On the other hand, current searches for repeating FRBs use only unmodelled burst search methods, as it is not possible for a binary neutron star merger to be the progenitor. If an FRB occurs within the gravitational-wave observatories' binary neutron star detection range, then a non-detection could rule out neutron star mergers as the origin. Several FRBs are expected to occur within such a detection range at the expected sensitivity level of the current observatories fifth observing runs, as shown in Fig. 6.

Fast-radio bursts created by magnetar flares are unlikely to be detected in gravitational waves beyond our galaxy. We explore this more in Section 7.

To date, there has been only one claim of a coincident gravitational-wave signal with an FRB; that of GW190425 and the CHIME-detected FRB 20190425A (Moroianu et al. 2023). The originally-claimed association has a relatively low probability of coincidence of 2.8σ. However, the association has at least four problems. First, it relies on a long-lived supramassive neutron star surviving 2.5 h, which requires an incredibly stiff nuclear equation of state given the total inferred mass of the progenitor (Magaña Hernandez et al. 2024). Second, the 400 MHz radio signal is unlikely to traverse the merger ejecta without significant attenuation (Bhardwaj et al. 2023). Third, if the association is true then the gravitational-wave data strongly prefer an off-axis system, whereas the FRB requires an on-axis system to be detectable (Bhardwaj et al. 2023). Fourth, based on the most likely host galaxy

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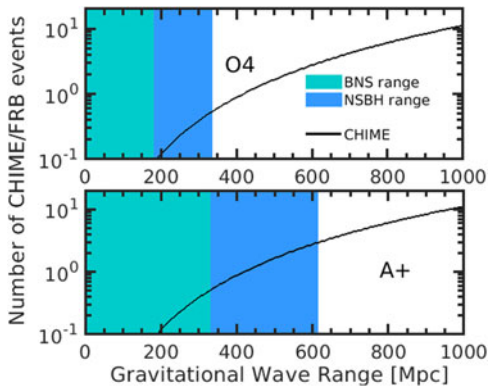


Figure 6. The predicted number of future FRB observations, calculated assuming FRBs track the star formation rate, expected to occur within the binary neutron star detection range of the upcoming observing runs of the LIGO-Virgo-KAGRA observatories. A non-detection could rule out a binary neutron star as the FRB progenitor. This figure was produced by Eric Howell, assuming a CHIME detection rate of 2 FRBs per day, and masses of 1.4 $M_\odot$ and 10 $M_\odot$ for neutron star black hole (NSBH) binaries, and masses of 1.4 $M_\odot$ and 1.4 $M_\odot$ for binary neutron stars (BNS).

(Panther et al. 2023; Bhardwaj et al. 2023) and a proper common-source odds statistic (Ashton et al. 2018), the significance of the FRB and gravitational-wave event is significantly reduced (Magaña Hernandez et al. 2024).

LIGO-Virgo-KAGRA and GEO searches have not discovered any gravitational-wave counterparts to FRBs to date (Abbott et al. 2016a, 2022a). The first search used only the GEO and Virgo gravitational-wave observatories and searched for gravitational-wave burst emission ± 2 min around the time of FRBs discovered by the Parkes/Murriyang telescope (Abbott et al. 2016a). Searches for gravitational-wave counterparts to FRBs discovered by CHIME (CHIME/FRB Collaboration et al. 2018) started during the third observing run (Abbott et al. 2022a). They searched for gravitational waves from the closest 22 non-repeaters, and for eleven repeating bursts from the closest three repeating sources. The search for binary neutron stars covered gravitational-wave observatory data from 10 s before and 2 s after the FRB, and the unmodelled search covered 600 s before the FRB and 120 s after. This is to ensure that the search window would cover the expected time frame for emission from all theoretical FRB progenitors. Although the previous searches were not able to rule out any possible progenitor sources, this is expected to soon be the case, as the gravitational-wave observatories increase in sensitivity during their next observing runs.

6. Pulsar glitches

Pulsar glitches are sudden increases in the angular momentum of the crust of a neutron star causing an inferred increase in the stellar spin frequency (Radhakrishnan & Manchester 1969; Reichley & Downs 1969; Boynton et al. 1969). The glitch mechanism is believed to be related to internal superfluid dynamics (Anderson & Itoh 1975). Broadly speaking, the internal superfluid does not lose angular momentum through the usual spin down process as the superfluid vortices are pinned to lattice sites in the crust; the pinning implies the vortices cannot move outward, and hence the superfluid angular momentum does not change on secular timescales. A lag between the superfluid core and the crystalline lattice in the crust builds up until it is eventually released with angular momentum transferring back from the core to the crust, which is seen as a pulsar glitch. For a more detailed review of glitch dynamics, see Haskell & Melatos (2015), and for associated gravitational-wave emission, see Haskell & Jones (2024).

There are two, maybe three, primary mechanisms during a glitch that could generate substantial gravitational waves. First, the spin-up event is expected to ring up multiple large-scale oscillation modes across a broad range of frequencies that would be relatively short lived. Second, relaxation of the stellar interior following the glitch is expected to generate interior bulk-motion fluid flows that can generate gravitational waves through the current quadrupole. And third, but perhaps more speculatively, recent evidence suggests starquakes may accompany glitches (Bransgrove, Beloborodov, & Levin 2020), which could also generate gravitational waves. We discuss each of these potential mechanisms presently.

While it is generally believed glitches are triggered by a lag between the superfluid core and the crust, the exact mechanism that triggers the angular momentum transfer from the core is ill-understood. Regardless, recent pulse-to-pulse observations of the Vela 2016 glitch (Palfreyman et al. 2018) show that the glitch rise time is less than 12 s (at 90% confidence), although it could be substantially shorter (Ashton et al. 2019). If the timescale is short enough there could be efficient energy conversion between the trigger mechanism and subsequent fluid flow and the fundamental f mode and higher-order p modes (Kokkotas, Apostolatos, & Andersson 2001; Sedrakian et al. 2003; Sidery, Passamonti, & Andersson 2010; Ho et al. 2020; Wilson & Ho 2024), which both couple to the gravitational-wave channel. These modes are short lived, typically damping on timescales $\lesssim 0.1$ s (Detweiler 1975; Lindblom & Detweiler 1983; McDermott, van Horn, & Hansen 1988). The sudden glitch rise could also generate inertial r modes (Santiago-Prieto et al. 2012) that are unstable to the Chandrasekhar-Friedmann-Schutz (Chandrasekhar 1970; Friedman & Schutz 1978) mechanism, even at low rotation rates (Andersson & Kokkotas 2001) and hence could grow to produce significant gravitational-wave emission. Finally, the spatially inhomogeneous vortex unpinning could generate a current-quadrupole gravitational-wave signal, potentially also observable with current or next-generation observatories (Warszawski & Melatos 2012).

While starquake-induced glitch mechanisms are generally disfavoured, the first pulse-to-pulse observation of a glitch (Palfreyman et al. 2018) showed evidence for a null at the time of the glitch. This is difficult to interpret without significant crustal motion or cracking (Bransgrove et al. 2020), which could generate a spectrum of core oscillation modes. Current estimates, however, indicate these could be too small for detection (Keer & Jones 2015; Layek & Yadav 2020).

Immediately following a glitch, the stellar core may be rotating slower than the crust, which could lead to non-axisymmetric Eckman flows that could generate gravitational waves through the current quadrupole (van Eysden & Melatos 2008; Bennett, van Eysden, & Melatos 2010; Singh 2017). Alternatively, glitches could induce neutron star mountains that could generate nearly-chromatic gravitational waves as the star spins (Yim & Jones 2020; Moragues et al. 2023), excess superfluid energy could drive gravitational-wave emission (Prix, Giampanis, & Messenger 2011), or trapped ejecta mass could cause emission at once and twice the star's spin frequency (Yim et al. 2024b).

Despite the oodles of proposed mechanisms for generating gravitational waves during and immediately following a neutron

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star glitch, no such gravitational waves have been observed (Abadie et al. 2011a; Abbott et al. 2022c, 2021d; Lopez 2024). Some glitch models are already being constrained by these non-observations (e.g., Yim, Shao, & Xu 2024a), implying a future detection of gravitational waves from a glitch may be just around the corner.

7. Magnetars

Highly magnetised ($B \gtrsim [10^{13}]$G) neutron stars – magnetars – exhibit regular bursting events emitting luminosities up to $\approx [10^{43}]\text{erg s}^{-1}$ (e.g., see Kaspi & Beloborodov 2017, for a review), with so-called giant flares emitting peak luminosities up to $\approx [10^{48}]\text{erg s}^{-1}$. Such extreme events in the stellar magnetosphere may come with crust-cracking, large-scale internal magnetic field rearrangements, and global fluid flows inside the star; all of which are mechanisms proposed to generate gravitational waves.

Initial estimates for the gravitational-wave energy release proposed that the magnetic field inside the star could be globally rearranged. If the full energy reservoir of this magnetic-field topology change could be converted into gravitational waves as f-mode oscillations, then up to $\sim 10^{49}$erg could be released, making them potentially observable with second-generation observatories (Ioka 2001; Corsi & Owen 2011). Unfortunately, more realistic calculations, both analytic and numerical, tell a more pessimistic story (Levin & van Hoven 2011; Lasky et al. 2011; Ciolfi et al. 2011; Zink, Lasky, & Kokkotas 2012; Tsokaros et al. 2022). These works indicate kHz f-mode oscillations will require at least third-generation observatories for galactic giant flares to be detectable.

The f-mode oscillations are expected to be short-lived ($\lesssim$ 100ms; Detweiler 1975; Lindblom & Detweiler 1983; McDermott et al. 1988) and therefore relatively easy to search for (see discussion below). On the other hand, longer lived modes may be excited, but would require detection algorithms that track the phase of the signal. From a theoretical perspective, such longer lived modes include g modes and Alfven waves, where the restoring forces are respectively buoyancy and magnetic fields. Not much theoretical work has been done estimating the potential amplitude, evolution, and damping mechanism of these waves, implying estimates for their total gravitational-wave emission energy and their gravitational-wave detectability are largely unknown. Moreover, searches for such mode oscillations are extremely difficult given the modes are not likely to be exactly chromatic; unknown frequency and phase evolution over long timescales implies fully-coherent search algorithms are not applicable, and there is a significant difference between actual and optimal sensitivity to these signals.

Despite the challenges, the LIGO-Virgo-KAGRA collaboration undertakes searches for gravitational waves from magnetar flares (Abbott et al. 2007, 2008, 2009; Abadie et al. 2011b, 2012; Abbott et al. 2019f, 2024). Of these searches, only one (Abbott et al. 2007) has been for gravitational waves associated with a giant flare, which was the 2004 giant flare of galactic magnetar SGR 1806-20 (Hurley et al. 2005; Palmer et al. 2005). That flare was approximately 100 times brighter than the other two giant flares observed, emitting total isotropic energy of 2×10^{46}erg. Importantly, quasi-periodic oscillations were observed in the x-ray tail of the flare (Israel et al. 2005; Watts & Strohmayer 2006; Strohmayer & Watts 2006), which have been attributed to a number of mechanisms associated with oscillation modes in the core, crust, and at the crust-core interface. Despite many of these identified x-ray oscillations having frequencies in the LIGO-Virgo-KAGRA gravitational-wave observing band, no gravitational waves were detected, with upper limits on the gravitational-wave energy emission being $\lesssim 10^{47}$erg.

The sensitivity of gravitational-wave observatories has greatly improved since the 2004 giant flare, but unfortunately no more galactic giant flares have been observed during this time. We have therefore had to suffice searching data associated with magnetar flares emitting some five or six orders of magnitude less electromagnetic energy (e.g., Abbott et al. 2019f, 2024). The best gravitational-wave energy upper limits from these searches are $\lesssim 10^{44}$erg for both short (e.g., f mode) and long (e.g., g or Alfven mode) searches. For gravitational waves to have been detected from such flares, the gravitational-wave energy emitted from the flare would have had to exceed the electromagnetic energy emitted by some three or four orders of magnitude.

And so we continue to wait for the next giant flare, although there are still no guarantees the network operating at design sensitivity will observe gravitational waves from such bursts.

8. Gamma-ray bursts

GRBs are powerful bursts of gamma-rays that are followed by emission in multiple different wavelength bands. There are two classes of GRB, with different progenitors and emission durations. Long GRBs have typical duration larger than 2 s, and potentially as long as a few hours, and a soft spectral hardness. Short GRBs are dimmer, have duration typically less than 2 s, and produce hard gamma-rays.

Long GRBs can last for as long as a few minutes and are thought to be powered by extreme supernova explosions. There is observational evidence for this association through supernovae, such as SN1998bw (Galama et al. 1998), which have confirmed long GRB counterparts. Potential progenitors could be the magneto-rotational explosions discussed in Section 2, which gain some of the energy from the rapid rotation through the magnetic field, or other extreme models such as black hole accretion disks in collapsars (MacFadyen & Woosley 1999; Gottlieb, Levinson, & Levin 2024).

Short GRBs are generally attributed to compact binary mergers; this was certainly the case for the only multi-messenger gravitational-wave observation that came from the binary neutron star merger GW170817 with an accompanying short GRB (Abbott et al. 2017b, 2017d). The GRB was several orders of magnitude less energetic than most other GRBs; the combined gravitational-wave and full spectrum of electromagnetic observations suggest the source was detected off-axis.

Recent electromagnetic observations of some GRBs is now challenging the conventional long/short GRB divide. For example, GRB 211211A was a typical long GRB with a soft spectrum and burst duration more than 50 s, albeit with a kilonova counterpart, and therefore strongly suggestive that the progenitor was a compact binary merger (Rastinejad et al. 2022; Troja et al. 2022). That GRB was at a distance of only 350 Mpc, implying it could have potentially been observed in gravitational waves with LIGO-Virgo-KAGRA fourth observing run sensitivity if it was a binary neutron star merger, and third observing run sensitivity if it was a neutron star-black hole merger (Sarin, Lasky, & Nathan 2023; Yin et al. 2023). The GRB 230307A was another 'typical' long GRB, again with a kilonova; this time, James Webb Space Telescope observations revealed an emission line associated with tellurium,

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an *r*-process heavy element thought to only be produced through compact binary mergers (Levan et al. 2024).

The search for a coincident gravitational-wave and GRB signal from a compact binary merger is much anticipated. That said, in gravitational-wave data analysis parlance, these sources are not considered 'burst' gravitational waves because the gravitational-wave signal can be precisely modelled.

Previous gravitational-wave searches have looked for counterparts to GRBs detected by Fermi and Swift (Abbott et al. 2017c, 2019h, 2021f, 2022b). Approximately 100 GRBs occured during 6 months of gravitational-wave observation time, and the majority do not have a known redshift. A model agnostic burst search is used to search for all GRBs regardless of their classification. On the other hand, compact binary searches using template banks of binary inspiral signals were only used to find gravitational-wave counterparts to short GRBs. In general, the gravitational-wave burst searches look for events that occur in a window of 600 s before and 60 s after the time of the GRB. It may be worth considering expanding this window given the exotic nature of some recent GRB detections, including those mentioned in previous paragraphs, as well as the recent discovery of soft x-rays preceding gamma-ray observations by several hundred seconds (Liu et al. 2024). Previous searches have only searched in the frequency band of 20–500 Hz, which is not optimal if the source of the GRB is an extreme supernova because, as described in Section 2, they are expected to emit most of their gravitational-wave energy at frequencies above 500 Hz.

9. Orphan memory

Gravitational-wave memory is a non-linear hereditary effect caused by the anisotropic emission of gravitational waves (Zel'dovich & Polnarev 1974; Braginsky & Thorne 1987; Christodoulou 1991; Thorne 1992). At frequencies below the characteristic frequency of the gravitational-wave source physics, the gravitational-wave strain amplitude spectral density scales as $S_h^{1/2} \propto 1/f$. Any gravitational-wave burst with characteristic frequency above that of the LVK observing band is therefore potentially observable through the low-frequency memory component of the signal (McNeill, Thrane, & Lasky 2017).

A number of speculative astrophysical sources have been proposed as emitting gravitational-wave signals at frequencies significantly higher than the ≈ 2 kHz observing band of the LIGO-Virgo-KAGRA observatories. These include cosmic strings, dark-matter collapse in stars, and Kaluza-Klein modes in higher-dimensional theories; for a review, see Cruise (2012). The so-called 'orphan memory' signals from these high-frequency bursts may be observable in the LIGO-Virgo-KAGRA observing band (McNeill et al. 2017) with strain $S_h^{1/2} \propto 1/f$. In such a scenario, distinguishing the source of the memory burst, and even whether it is a memory burst in the first place, could be difficult (although see Divakarla et al. 2020).

The non-existence of loud memory bursts in LIGO-Virgo-KAGRA data can be used to constrain potential signals in dedicated MHz and GHz gravitational-wave observatories; for a review of these observatories see Aggarwal et al. (2020). For example, the Bulk Acoustic Wave High Frequency Gravitational Wave Antenna (Goryachev & Tobar 2014) recently announced the detection of 'two strongly significant events' (Goryachev et al. 2021) that they interpreted *could* have been gravitational waves. However, if those two events are interpreted as gravitational-wave signals, the corresponding memory signals in LIGO/Virgo would have had SNRs in excess of 10^6 (Lasky & Thrane 2021). This *reductio ad absurdum* (together with the cosmological and astronomical implications Lasky & Thrane 2021; Domènech 2021) show that the signals could not have been gravitational waves, and that the current generations of MHz and GHz observatories are a long way from the required sensitivity to observe real astrophysical signals.

10. Topological defects

Cosmic strings are topological defects that may have formed during symmetry breaking phase transitions in the early Universe (Hindmarsh & Kibble 1995). Measurements of the cosmic microwave background have shown no evidence for cosmic strings, however gravitational waves may be the best way to provide the first direct evidence for their existence (Damour & Vilenkin 2000). As well as being a source for gravitational-wave burst searches, a superposition of cosmic strings are also a potential source of a gravitational-wave stochastic background (Siemens, Mandic, & Creighton 2007). Upper limits placed on the emission of gravitational waves from cosmic strings are typically more stringent from stochastic background searches than from gravitational-wave burst searches (Abbott et al. 2021e).

When a cosmic string crosses itself it can form a loop that becomes detached from the string. The loop will then radiate gravitational waves and eventually disappear (Vachaspati & Vilenkin 1985; Casper & Allen 1995). A cosmic string cusp is the part of the loop that has detached from the string. The cusps are expected to produce a burst of gravitational waves with an amplitude related to the size of the loop and the tension in the string (Stott, Elghozi, & Sakellariadou 2017). An example of a gravitational-wave signal from a cosmic string cusp is shown in Fig. 5.

Gravitational waves can also be produced by cosmic string kinks, which are localised distortions in the cosmic string that propagate at the speed of light (Damour & Vilenkin 2001). When two strings cross, they can create a loop that contains several kinks. Gravitational waves from the cusp are emitted in the forward direction of the cusp, and kinks can produce repeating bursts as they move around the cusp. There can also be an isotropic burst of gravitational waves caused by the collision of two kinks on the same cusp.

The gravitational-wave signals from cosmic strings are understood well enough for a templated matched filter search to be performed. There were no gravitational-wave detections from cosmic strings in the first three LIGO-Virgo-KAGRA observing runs, which searched for cusps, kinks and kink-kink collisions (Abbott et al. 2018b, 2021e).

The biggest challenge for the detection of cosmic strings is the short duration of the gravitational-wave signal. In the time series, they look very similar to the most common transient noise glitches in gravitational-wave detectors (Cabero et al. 2019), which may lead to a large number of false alarms in searches. They also look very similar to the gravitational-wave emission expected from other very short duration astrophysical sources, for example the merger of an intermediate mass black hole binary system. An example of a binary black hole merger identified by a cosmic string search is GW190521, which produced a very short duration gravitational-wave signal in the LIGO-Virgo frequency band due to the high component masses of 85 $M_\odot$ and 66 $M_\odot$ (Abbott et al. 2020c). However, the SNR for the source was much higher

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in the compact binary search than in the cosmic string search, and Bayesian model selection was also used to rule out a cosmic string origin for this event (Abbott et al. 2020c; Aurrekoetxea, Hoy, & Hannam 2023).

Another potential cosmological source of gravitational-wave bursts is a domain wall passing through a gravitational-wave detector (Jaeckel, Khoze, & Spannowsky 2016). Quantum field theory tells us that the vacuum is full of fields with an average value of zero. When the Universe expands and cools it results in the production of local minima in the field; domain walls are the boundaries between the areas with different vacuum topology.

The signal morphology and amplitude is dependent on the direction of the domain wall. Due to this, the signal may not have the same morphology in multiple gravitational-wave detectors, implying it could easily be missed by traditional search methods. The duration of the signal is determined by the thickness of the domain wall and the time taken for it to pass through the detector. The speed of the domain wall is typically the speed of the dark matter halo of the galaxy ~ 300 km s^{-1}.

In gravitational-wave searches, where the travel time of the gravitational-wave is equal to the speed of light, a lot of gravitational-wave transient noise can be rejected because of the time coincidence between the detectors. Because the travel time for a domain wall is much slower than the speed of light, every detector noise glitch is now going to be coincident with other glitches in the data from the other gravitational-wave detectors. This would result in a huge number of false alarms for a domain wall search. Therefore, efforts to reduce detector noise glitches or understand their cause from first principles, are essential to make the first detection of domain walls passing through a gravitational-wave observatory.

11. Unknown unknowns

Every time the Universe has been explored at a new electromagnetic wavelength, new astrophysical objects have been discovered that were not theoretically predicted, and their origins were at least at first unknown. Some examples are GRBs (Klebesadel, Strong, & Olson 1973) and FRBs (Lorimer et al. 2007). As gravitational-wave observatories become more sensitive, it is likely that they may also begin to detect gravitational waves from sources that have not already been theoretically predicted. This is arguably the most exciting aspect of this burgeoning field.

Searching for completely unknown gravitational-wave sources presents significant detection challenges. Searches for unknown bursts are divided into short-duration searches of less than a few seconds, and long-duration searches of up to a few hundred seconds. The burst search algorithms (e.g., Klimenko et al. 2016; Lynch et al. 2017; Cornish & Littenberg 2015; Sutton et al. 2010; Skliris, Norman, & Sutton 2020; Thrane et al. 2011; Thrane & Coughlin 2015) typically use one or more sine Gaussian, sine Gaussian wavelet, or other common wavelet types as basis functions for their signal model. An example of a typical sine Gaussian is shown in Fig. 7. These types of generic signal models are good at adapting to fit an unknown shape. The duration and frequency can be altered to cover the burst signal parameter space, with the typical frequency range of such burst searches covering $\sim$ 30–2 000 Hz; the most sensitive frequency band of the current observatories.

Gravitational-wave data contains many transient noise artifacts, known as glitches, that can mimic gravitational-wave burst signals. Some of the most typical types of glitches that limit the background of gravitational-wave burst searches are shown in Fig. 8. Due to these glitches, a coincident detection between multiple interferometers is needed for confidence that a gravitational-wave burst signal has an astrophysical origin. For this reason, gravitational-wave burst searches look for signals with common shape and arrival time (within the light-travel time of the observatories) in multiple detectors (Klimenko et al. 2016; Lynch et al. 2017; Cornish & Littenberg 2015). They then estimate the gravitational-wave background by time-sliding the data to measure how often glitches accidentally occur at the same time in multiple detectors (Was et al. 2010). The imperfect duty cycles imply only one gravitational-wave observatory is operational about 20% of the time. To ensure we do not miss a gravitational-wave burst during single-detector observing time, better methods for the elimination of glitches are required (Cavaglia et al. 2020). To date, the current gravitational-wave all-sky burst searches have only detected gravitational waves from binary black holes (Abbott et al. 2017a, 2019d, 2021d, 2018a, 2019c, 2021c). For the LIGO-Virgo-KAGRA third observing run, the all-sky short duration burst searches were sensitive to sources with gravitational-wave energy as low as $10^{-10}M_{\odot}c^2$ at a distance of 10 kpc and a frequency of 70 Hz.

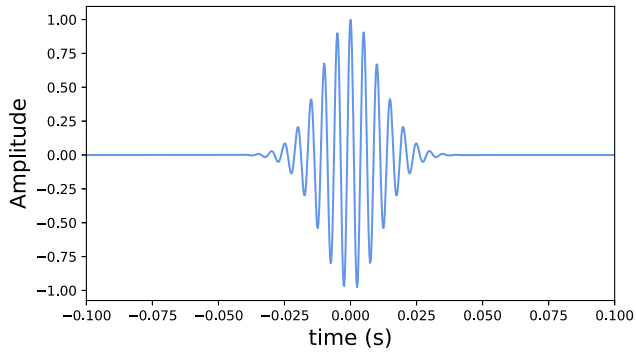


Figure 7. A typical sine Gaussian wavelet with a frequency of 200 Hz, and a duration of 0.05 s. Sine Gaussian wavelets are often used as signal models for searches and waveform reconstruction of gravitational-wave bursts with an unknown signal shape.

The all-sky searches for unknown gravitational-wave bursts can produce parameter estimates for the sky location, the gravitational-wave amplitude, central frequency, and duration (Essick et al. 2015; Bécsy et al. 2017). They can also reconstruct the waveform of the gravitational-wave signal (Millhouse, Cornish, & Littenberg 2018; Raza et al. 2022). As for compact binary signals, the accuracy of the sky location is largely dependent on the number of gravitational-wave observatories operating. How well the overall signal morphology can be reconstructed depends primarily on the SNR and the complexity of the signal. In general, longer duration bursts and more broadband signals are more difficult to reconstruct.

Understanding the astrophysical source properties from the parameters measured by the burst searches will be difficult in the case of an unknown source, especially if there is no electromagnetic or neutrino counterpart. The observed waveform could, in principle, be used to place limits on the characteristic mass and size of the progenitor system, albeit contingent on the likely unknown distance (Bécsy et al. 2020). Such constraints would be based on there being a maximum compactness and a maximum luminosity for any potential gravitational-wave source.

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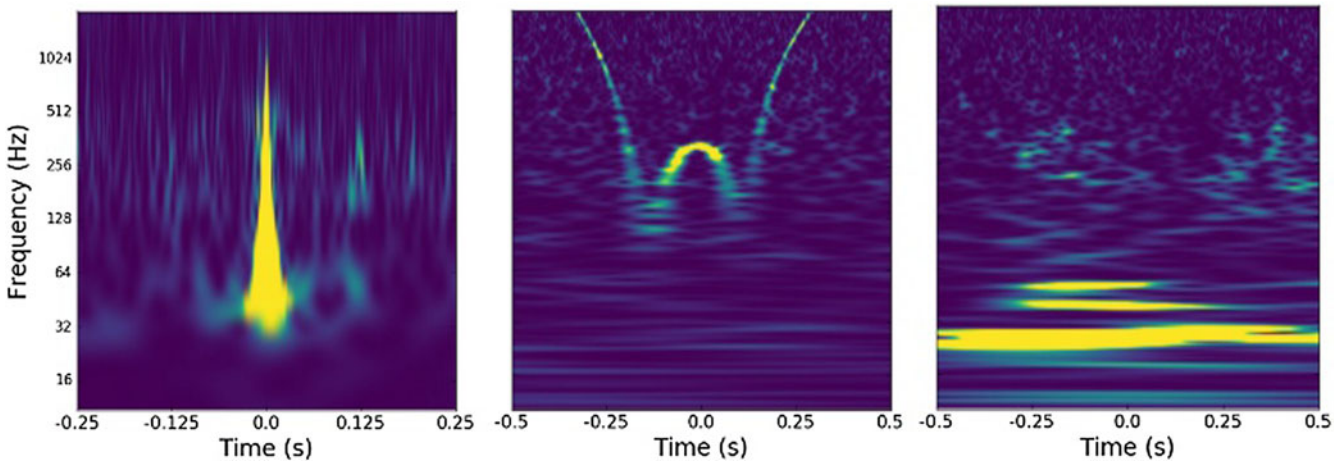


Figure 8. Examples of detector noise glitches from Advanced LIGO. Glitches limit the gravitational-wave search sensitivity, and can contaminate astrophysical signals. From left to right, a blip glitch, a whistle glitch and scattered light. Figure reproduced from Powell (2018).

If the luminosity distance to the source is known from an electromagnetic counterpart, we could also place constraints on the gravitational-wave energy, and set lower limits on the mass and size of the astrophysical source.

12. Conclusions

The current gravitational-wave observatories have already transformed our understanding of the Universe, producing the first direct detection of gravitational waves, the first strong field tests of general relativity, and the first direct evidence that binary neutron stars are the progenitors of short GRBs. However, this is just the beginning. The next generation of observatories will hear every binary black hole merger in the observable Universe, and almost all of the binary neutron star mergers well back before the peak of star formation. However, there are many other potential sources of gravitational waves that have yet to be discovered. A detection of a burst of gravitational waves from a different type of source is one of the most promising potential next gravitational-wave discoveries.

In this Review, we describe the expected future sources of bursts of gravitational waves, the prospects for their detection, and what we might learn about the astrophysics of the source. The gravitational-wave signals of some astrophysical burst sources, such as CCSNe, are fairly well modelled, however their exact waveforms are difficult to predict due to complex input physics and stochastic processes. Hydro-dynamical simulations of these systems have allowed us to understand their gravitational-wave signals enough to enable the community to develop tools to extract astrophysical parameters of the source, such as the stars rotation and equation of state. Gravitational-wave signals from highly eccentric compact binaries are also fairly well understood, but not well enough to produce a full template bank to perform a matched filter search.

Gravitational-wave burst signals from other sources are significantly more difficult to model, as not enough is known about their astrophysical progenitors. FRBs currently have many theories for their potential progenitors, which translate to a large range in different predictions for the gravitational-wave signal shape, duration, frequency, and amplitude. It is also possible that there may be sources of gravitational waves that have not been predicted theoretically or observed electromagnetically. A detection of a gravitational-wave burst signal from this type of unknown source would result in a significant advancement in our understanding of the Universe.

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