Techniques for gravitational-wave detection of compact binary coalescence

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***Abstract*—In September 2015, the Advanced Laser Interferometer Gravitational-wave Observatory (LIGO) came online with unprecedented sensitivity. Now with two observation runs completed, LIGO has detected gravitational waves from five binary black hole mergers and one neutron star merger. The Advanced Virgo detector also recently came online in August 2017, significantly improving the sky localization of two of these events. The identification of these signals relies on techniques that can clearly distinguish a gravitational-wave signature from transient detector noise. With the next LIGO and Virgo observation run expected to begin in the fall of 2018, more detections are expected with the potential for discovery of new types of astrophysical sources.**

***Index Terms*—gravitational waves**

I. Introduction

The Advanced Laser Interferometer Gravitational-wave Observatory (LIGO) is a gravitational-wave detector network composed of two Fabry-Perot-Michelson interferometers with 4-km arms in Hanford, WA and Livingston, LA [2]. The Advanced Virgo detector in Cascina, Italy [19], with 3-km arms, recently joined this network. These detectors measure the effect of a passing gravitational wave as a spacetime strain. This effect results in a varying phase difference between the laser light propagating in perpendicular arms of the interferometers.

During the first observation run (O1) of Advanced LIGO from September 12, 2015 to January 19, 2016, the first direct detection of gravitational waves was made with GW150914 [6] from the inspiral and merger of two black holes with component masses of $36.2^{+5.2}_{-3.8} M_{\odot}$ and $29.1^{+3.7}_{-4.4} M_{\odot}$ (90% credible interval). A second detection of GW151226 from a lighter black hole system [5] as well as the possible third signal LVT151012 further revealed a population of stellar-mass binary black hole systems [3]. At the time of this publication, the second observation run of Advanced LIGO from November 30, 2016 to August 25, 2017 yielded three further binary black hole detections [12]–[14]. Advanced Virgo joined this observation run on August 1, 2017 providing the first triple-detector observation of gravitational waves [14], also from a binary black hole system, as well as the most precisely localized gravitational-wave signal yet, GW170817 [15] from the inspiral of a binary neutron star system. This last event was exceptional due to the association of the gravitational-wave event with the γ-ray burst GRB 170817A [11] and the subsequent identification of counterparts across the electromagnetic spectrum [16].

Detection of gravitational-wave signals from the coalescence of binary neutron star and stellar-mass black hole systems requires an understanding of the detector noise as well as gravitational waveform models. While it is possible for the short signals from heavy stellar-mass black hole binaries to be uncovered by searches for generic gravitational-wave transients [6], [7], longer, lower amplitude signals and subsequent parameter estimation [1], [9] of the sources rely on precise waveform models of the two-body dynamics.

Searches for un-modeled transient gravitational-wave signals employ other methods than those described in this paper. Short-duration transient gravitational-wave searches use minimal assumptions regarding the expected waveform and source direction. More details about these techniques and how they can also detect signals from compact binary coalescence can be found in [8], [10].

II. Compact Binary Coalescence

Advanced LIGO and Virgo are sensitive to gravitational waves that pass through their sensitive frequency band, where the maximum sensitivity occurs near 100Hz. This can be seen in Figure 1 where representative O2 amplitude spectral densities, are plotted estimated using 4096 s of data around the time of GW170814 [14], [27]. Gravitational-wave signals from the coalescence of compact binaries with total masses less than a couple hundred solar masses will be detectable. The types of binaries in this mass range include binary neutron stars, binary stellar-mass or intermediate-mass black holes, or a combination neutron star-black hole system. General relativity provides the model for the inspiral and coalescence of the two compact objects, particularly in the last few seconds that are visible to LIGO and Virgo. The gravitational-wave signal increases in frequency and amplitude, taking the form of a chirp. At early times, the evolution of the chirp frequency is determined primarily by a parameter called the chirp mass:

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} \tag{1}$$

where m_1 and m_2 are the component masses. The inspiral phase evolution is also driven by each objects' angular

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momentum, or spin $\mathbf{S}_{1,2}$ (magnitude and orientation), and, if the spin is misaligned with respect to the orbital angular momentum, the signal can have amplitude and phase modulations. Right before merger, as the orbit shrinks and the gravitational-wave frequency grows rapidly, the signal is additionally influenced by relativistic effects related to the mass ratio $q = m_2/m_1$ where $m_1 \geq m_2$. If the binary components include a neutron star, tidal effects can also affect the phase. After the objects have merged, a ringdown signal could be seen if a black hole was formed or a more complicated signal might be seen if a short- or long-lived neutron star was formed. The inspiral, merger and ringdown signal for a binary black hole system can be seen in Figure 2.

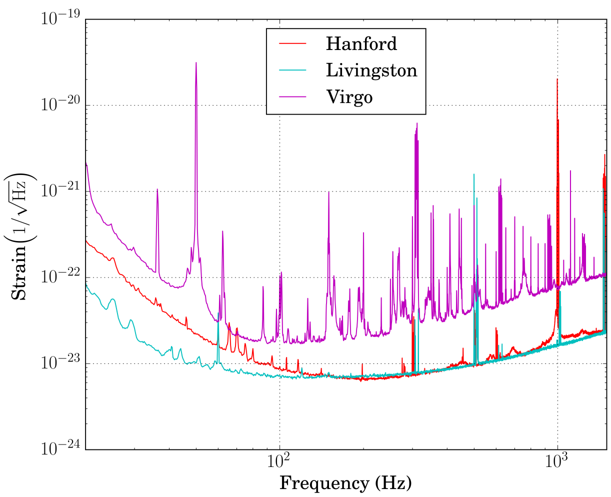

Fig. 1. Amplitude spectral densities of the Advanced LIGO-Advanced Virgo detector network, estimated using 4096 s of data around the time of GW170804 [14], [27]. This data is publicly available from the LIGO Open Science Center (https://losc.ligo.org).

Signals from heavier black hole systems spend less time in the detectors' sensitive band. In this case, we are more sensitive to the late inspiral, merger and ringdown part of the signal. Signals from lower mass systems are dominated by the inspiral and can spend significantly longer time in the detectors' sensitive band. For example, GW150914 from a heavy stellar-mass binary black hole system lasted about $\sim$ 0.2s while GW170817 from a binary neutron star system lasted $\sim$ 100s.

III. Matched-Filtering Based Pipelines

The process of matched filtering correlates a gravitational waveform model with the data over the detectors' sensitive band. Several matched-filter-based searches [20], [24]–[26] are employed both on a low-latency timescale of seconds and a longer latency timescale of days. The low-latency searches aim to make detections on a timescale that allows rapid electromagnetic followup. The longer latency searches are typically deeper searches, benefitting from improved calibration and data quality information not available in low latency.

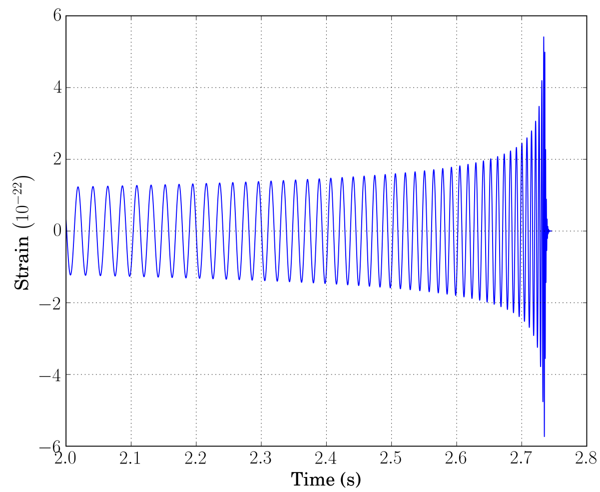

Fig. 2. Time-domain chirp gravitational-wave signal for a (10., 10.) $M_\odot$, non-spinning binary black hole system. In the last second before merger that we see here, the system is undergoing the inspiral where the signal increases in frequency and amplitude. After merger, a brief ringdown signal is seen.

Matched filtering is the preferred method for extracting modeled signals from Gaussian and stationary detector noise. The correlation of a signal $h(t)$ with detector strain data $s(t)$ can be expressed as

$$\langle s|h\rangle (t) = 4 \int_0^\infty \frac{\tilde{s}(f)\tilde{h}^*(f)}{S_n(f)} e^{2\pi i f t} \mathrm{d}f \tag{2}$$

where $\tilde{s}(f)$ is the Fourier transform of $s(t)$ and $S_n(|f|)$ is the one-sided average power spectral density of the detector noise. The square of the matched-filter signal-to-noise ratio (SNR) $\rho(t)$ is defined as

$$\rho^2(t) \equiv \frac{1}{\langle h|h\rangle} \left|\langle s|h\rangle (t)\right|^2 \tag{3}$$

where $\langle h|h\rangle$ is the autocorrelation of the signal waveform. The SNR in each detector is tracked as a function of time and when there is a peak above a predetermined threshold, a trigger is stored. Each search pipeline determines the SNR threshold independently although values usually range between 4 and 5.5. Typically, a trigger will be defined by its GPS time, the parameters of the signal waveform, or template, that it most closely matched, as well as its SNR.

A. Template Banks

It is not computationally feasible to search for gravitational waves over the continuous mass and angular momentum parameter space that describe the compact binaries accessible to LIGO and Virgo. Instead, we construct a discrete grid of waveforms, or a template bank, and perform matched filtering with these templates. Typically, the template banks are constructed in such a way that the loss in matched-filter SNR is $\leq 3\%$ for any signal with parameters that fall within the boundaries of the template bank. Currently, the gravitational

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waveforms are typically represented in a four-dimensional space that includes the two component masses $m_{1,2}$ as well as a measure of the angular momenta $S_{1,2}$ of each component. This measure typically takes the form of the component spin aligned with the direction of the orbital angular momentum L of the binary

$$\chi_{1,2} = \frac{c}{Gm_{1,2}^2} S_{1,2} \cdot \hat{L}. \tag{4}$$

Studies have shown that this simplified parameter space can recover systems with precessing, misaligned spins in the equal mass range [4] but may not provide good coverage for neutron star-black hole systems with large mass ratio and spin magnitude [22]. To refine the system parameters, we use coherent Bayesian analyses in post-processing to derive posterior distributions of the source parameters, including the initial and final masses, final spin, distance, redshift, and tides for neutron star systems [1], [9].

The top panel of Figure 3 shows the template bank used in the O1 search for gravitational waves from compact binary coalescences [4]. Each point represents a unique template waveform represented by four parameters: $\{m_1, m_2, \chi_1, \chi_2\}$. There are 249077 templates in total. The bank covers a total mass between $2M_\odot$ and $100M_\odot$. The range of $\{\chi_1, \chi_2\}$ are represented by the different colored regions: binary neutron stars (green), neutron star-black hole systems (red), and binary black holes (blue). Among binary neutron star systems that will merge within a Hubble time, the most extreme spin has been found to be less than ~ 0.04 [23], hence the constraint on the χ value of the neutron star. The constraints on binary black hole spins are not as strong, hence we allow for near maximal χ values.

For comparison in the bottom panel of Figure 3, we see the O1 template bank used to search for intermediate-mass black hole binaries [17]. This bank covers a total mass between $50M_\odot$ and $600M_\odot$, mass ratios less extreme than 1:10, and aligned spins$|\chi_{1,2}| \leq 0.99$. There are 44902 templates in total. The higher density of templates at lower masses results from computing the 3% loss in matched-filter SNR from a lower frequency.

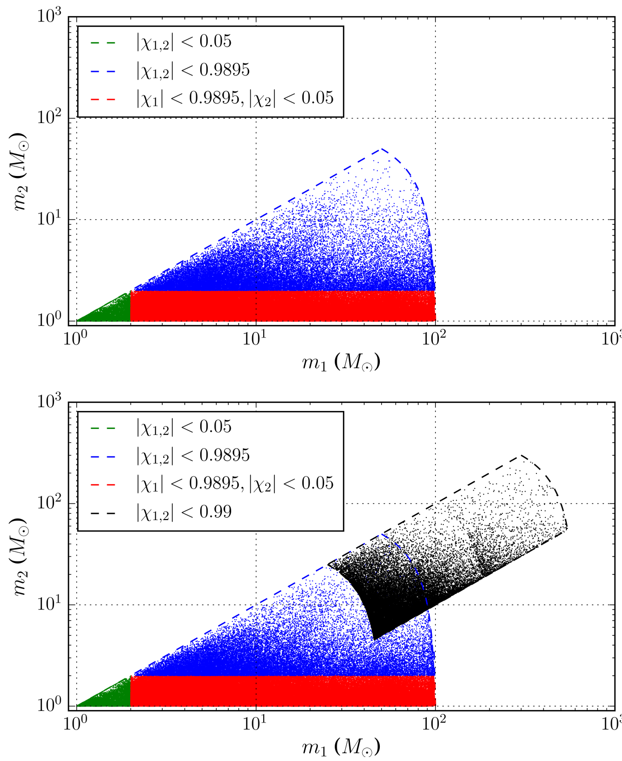

Fig. 3. *Top panel:* the template bank used in the O1 search for gravitational waves from compact binary coalescences [4]. *Bottom panel:* the O1 template bank used to search for intermediate-mass black hole binaries [17] overlain. In each case, dashed straight lines correspond to constraints on the mass ratio m_2/m_1 and dashed curved lines correspond to constraints on $m_1 + m_2$.

B. Signal-consistency Checks

Detector data contains many short noise transients, called glitches. These often trigger high SNR output. Thus it is not sufficient to rank gravitational-wave candidates by SNR. Several methods can be employed to combat these glitches. If the glitches arise from known instrumental or environmental issues, it is possible that the data can be removed from the searches. The detector and its environment are carefully monitored with hundreds of sensors. If a coupling can be established between noise visible in a sensor and glitches in the data, then a data-quality veto can be created to exclude the data from the search [18].

Search algorithms may also include an automated gating procedure. For example, if a glitch has an extraordinary amplitude in whitened detector strain data, it can safely be removed. Real gravitational wave signals will not produce such large excursions unless the source is extremely close by.

Finally, signal-consistency tests can also be used to down weight glitch-like triggers. These tests typically consider the unique time-frequency evolution of a chirp signal and penalize any triggers not following this evolution. Examples include a χ^2 time-frequency test for broad-band signals [21] and a matched-filter SNR versus template autocorrelation consistency check [24].

C. Coincidence

Requiring coincidence in time and template parameters for the triggers identified in each detector is a powerful tool for identifying real gravitational-wave signals. Events found by both LIGO detectors must fall within the same 15ms time window. This window is determined by the 10-ms inter site propagation time plus a 5-ms allowance for uncertainty in the arrival time of weak signals. With the inclusion of Virgo and other detectors, the allowed time window will need to be retuned but will still be motivated by the allowed inter site propagation time between all the detectors in the network.

D. Ranking Statistics

Coincident triggers that have passed the coincidence test will be ranked by the search algorithms, typically using a

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likelihood-ratio-based statistic. Given a set of values that characterize the trigger in each detector (i.e. SNR, signal-consistency checks, timing differences, etc.), we can compute the probability that this set of values came from a signal model and the probability that this set of values came from a background model. For example, the likelihood-based ranking statistic for the LIGO detector network can be generically written as

$$\mathcal{L} = \frac{P(\{d_{\mathrm{H}}, d_{\mathrm{L}}\}|\mathrm{signal})}{P(d_{\mathrm{H}}|\mathrm{noise})P(d_{\mathrm{L}}|\mathrm{noise})} \tag{5}$$

where $\{d_{\mathrm{H}}, d_{\mathrm{L}}\}$ are the coincident triggers' characteristic values in the Hanford and Livingston detectors, respectively. The numerator will contain conditional and joint probabilities due to the fact that a signal's parameters will be strongly correlated in each detector. However, the denominator can be factored since we assume the detectors' noise distributions are independent of each other. This expression can be expanded to include N-detectors.

The signal model can typically be constructed semi-analytically. However, the noise model must be constructed from the search background. Several methods exist for measuring a matched-filter search background. For example, one can collect statistics from the non-coincident triggers and use them to simulate accidental coincidences. Similarly, the method of time-shifting the triggers in each detector relative to the others provides a way of generating accidental coincidences.

Search background estimation is typically done separately across the target signal space. For example, long signals from binary neutron stars have a lower background than short signals from binary black hole candidates. Thus, candidate and background events are often divided into different search classes based on template length.

It is convenient to express the significance of gravitational wave candidates in terms of how often the noise is expected to yield an event with a ranking statistic $\mathcal{L}$ larger than some predetermined threshold $\mathcal{L}^*$. This is the false-alarm rate (FAR). For an experiment of length T, we define this as

$$\mathrm{FAR} = \frac{C(\mathcal{L} \geq \mathcal{L}^*|\mathrm{noise})}{T} \tag{6}$$

where $C(\mathcal{L} \geq \mathcal{L}^*)$ is a cumulative distribution.

IV. Conclusion

Matched-filter-based searches can detect gravitational-wave signals from the coalescence of binary neutron star and stellar-mass black hole systems as demonstrated by the successes of O1 and O2. Work is ongoing to prepare these searches for the LIGO-Virgo detector network that will begin a third observation run later this year. We also are steadily working towards search algorithms that support N-detectors. Finally, with confident detections becoming a regular occurrence, we will start to explore other parameter spaces, potentially uncovering new types of astrophysical sources.

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References

[1] J. Aasi et al. Parameter estimation for compact binary coalescence signals with the first generation gravitational-wave detector network. *Phys. Rev. D*, 88:062001, Sep 2013.

[2] J Aasi et al. Advanced ligo. *Classical and Quantum Gravity*, 32(7):074001, 2015.

[3] B. P. Abbott et al. Binary black hole mergers in the first advanced ligo observing run. *Phys. Rev. X*, 6:041015, Oct 2016.

[4] B. P. Abbott et al. Gw150914: First results from the search for binary black hole coalescence with advanced ligo. *Phys. Rev. D*, 93:122003, Jun 2016.

[5] B. P. Abbott et al. Gw151226: Observation of gravitational waves from a 22-solar-mass binary black hole coalescence. *Phys. Rev. Lett.*, 116:241103, Jun 2016.

[6] B. P. Abbott et al. Observation of gravitational waves from a binary black hole merger. *Phys. Rev. Lett.*, 116:061102, Feb 2016.

[7] B. P. Abbott et al. Observing gravitational-wave transient gw150914 with minimal assumptions. *Phys. Rev. D*, 93:122004, Jun 2016.

[8] B. P. Abbott et al. Observing gravitational-wave transient gw150914 with minimal assumptions. *Phys. Rev. D*, 93:122004, Jun 2016.

[9] B. P. Abbott et al. Properties of the binary black hole merger gw150914. *Phys. Rev. Lett.*, 116:241102, Jun 2016.

[10] B. P. Abbott et al. All-sky search for short gravitational-wave bursts in the first advanced ligo run. *Phys. Rev. D*, 95:042003, Feb 2017.

[11] B. P. Abbott et al. Gravitational waves and gamma-rays from a binary neutron star merger: Gw170817 and grb 170817a. *The Astrophysical Journal Letters*, 848(2):L13, 2017.

[12] B. P. Abbott et al. Gw170104: Observation of a 50-solar-mass binary black hole coalescence at redshift 0.2. *Phys. Rev. Lett.*, 118:221101, Jun 2017.

[13] B. P. Abbott et al. Gw170608: Observation of a 19 solar-mass binary black hole coalescence. *The Astrophysical Journal Letters*, 851(2):L35, 2017.

[14] B. P. Abbott et al. Gw170814: A three-detector observation of gravitational waves from a binary black hole coalescence. *Phys. Rev. Lett.*, 119:141101, Oct 2017.

[15] B. P. Abbott et al. Gw170817: Observation of gravitational waves from a binary neutron star inspiral. *Phys. Rev. Lett.*, 119:161101, Oct 2017.

[16] B. P. Abbott et al. Multi-messenger observations of a binary neutron star merger. *The Astrophysical Journal Letters*, 848(2):L12, 2017.

[17] B. P. Abbott et al. Search for intermediate mass black hole binaries in the first observing run of advanced ligo. *Phys. Rev. D*, 96:022001, Jul 2017.

[18] B P Abbott et al. Effects of data quality vetoes on a search for compact binary coalescences in advanced ligo's first observing run. *Classical and Quantum Gravity*, 35(6):065010, 2018.

[19] F Acernese et al. Advanced virgo: a second-generation interferometric gravitational wave detector. *Classical and Quantum Gravity*, 32(2):024001, 2015.

[20] T Adams, D Buskulic, V Germain, G M Guidi, F Marion, M Montani, B Mours, F Piergiovanni, and G Wang. Low-latency analysis pipeline for compact binary coalescences in the advanced gravitational wave detector era. *Classical and Quantum Gravity*, 33(17):175012, 2016.

[21] Bruce Allen. χ^2. *Phys. Rev. D*, 71:062001, Mar 2005.

[22] Ian W. Harry et al. Investigating the effect of precession on searches for neutron-star–black-hole binaries with advanced ligo. *Phys. Rev. D*, 89:024010, Jan 2014.

[23] Ryan S. Lynch, Paulo C. C. Freire, Scott M. Ransom, and Bryan A. Jacoby. The timing of nine globular cluster pulsars. *The Astrophysical Journal*, 745(2):109, 2012.

[24] Cody Messick et al. Analysis framework for the prompt discovery of compact binary mergers in gravitational-wave data. *Phys. Rev. D*, 95:042001, Feb 2017.

[25] Alexander H. Nitz, Thomas Dent, Tito Dal Canton, Stephen Fairhurst, and Duncan A. Brown. Detecting binary compact-object mergers with gravitational waves: Understanding and improving the sensitivity of the pycbc search. *The Astrophysical Journal*, 849(2):118, 2017.

[26] Samantha A Usman et al. The pycbc search for gravitational waves from compact binary coalescence. *Classical and Quantum Gravity*, 33(21):215004, 2016.

[27] M Vallisneri et al. The ligo open science center. *proceedings of the 10th LISA Symposium, University of Florida, Gainesville*, May 18-23, 2014.

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