Revealing the evolution of high-mass binaries using gravitational-wave observations

Christopher Berry(1,2)

Jim Barrett(2), Will Farr(3,4,2), Sebastian Gaebel(2), Vicky Kalogera(1), Ilya Mandel(5,2), Coenraad Neijssel(5,2), Simon Stevenson(6,2) & Alejandro Vigna-Gómez(5,2)

arXiv:1711.06287 • arXiv:1903.09220

christopher.berry@northwestern.edu • @cplberry

The binary black holes observed by LIGO and Virgo are a new source of information about the end-points of stellar evolution. Multiple potential formation channels have been suggested for these binaries, and each of these have associated physical uncertainties. The details of the formation channels leave imprints on the properties of the binary black holes. From these, we can infer how binary black holes form. With 1000 **detections**, we can use the chirp-mass distribution and merger rate to constrain population parameters for isolated binary evolution (such as common-envelope efficiency, natal kicks and mass-loss rates) to **precision of a few percent**. Next-generation gravitational-wave detectors will extend horizons such that we can measure the evolution of populations as a function of redshift.

Gravitational waves

From a gravitational-wave signal we can infer the source properties [1]. Best measured are the masses, as these have the largest impact on the waveform. Measurements to date show a family of black holes spanning from $7.6^{+1.3}_{-2.1} M_\odot$ to $50.6^{+16.6}_{-10.2} M_\odot$ [2].

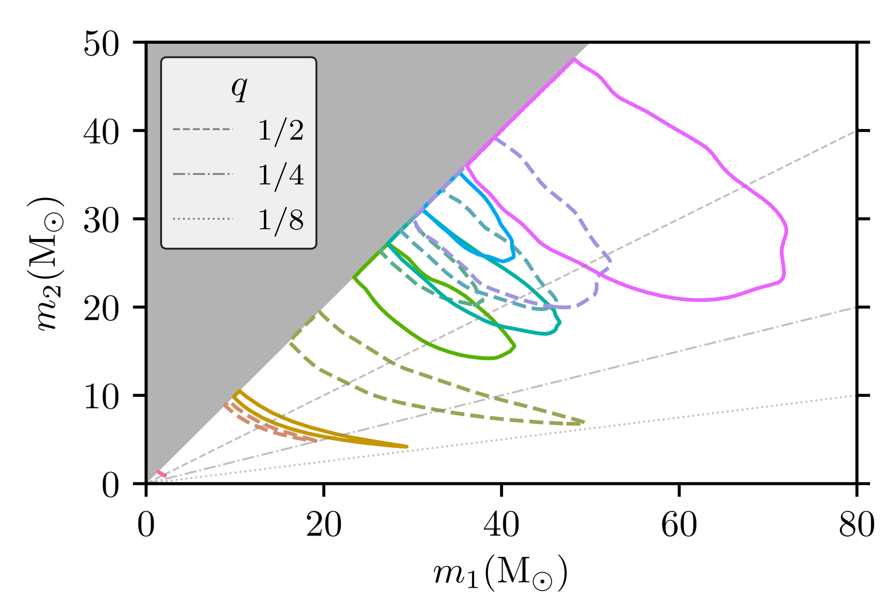

Figure 1. Inferred component masses $m_1 \geq m_2$ [2]. Contours show 90% credible regions. The evolution of the frequency during the inspiral is primarily determined by the chirp mass $\mathcal{M} = (m_1 m_2)^{3/5}/(m_1+m_2)^{1/2}$, while the merger and ringdown are primarily set by the total mass $M = m_1 + m_2$.

The number of detections provides information on the merger rate density. Translating from detections to mergers requires knowledge of the mass distribution, as this sets selection effects. We have inferred the mass distribution and rates together [3]. Assuming a power-law mass distribution with maximum and minimum cut-offs, the estimated rate density is $53.2^{+58.5}_{-28.8}\ \mathrm{Gpc^{-3}\,yr^{-1}}$, and the estimated power-law index is $-1.6^{+1.7}_{-1.5}$. We expect 16^{+21}_{-10} binary black hole detections in the current observing run (O3), which is planned to last one year [4].

Binary physics

Population-synthesis models can make predictions for expected binary populations. However, these models include processes which are currently uncertain. The range of uncertainties can be approximately captured by including variable parameters. These can have a significant impact on the predicted masses and merger rates.

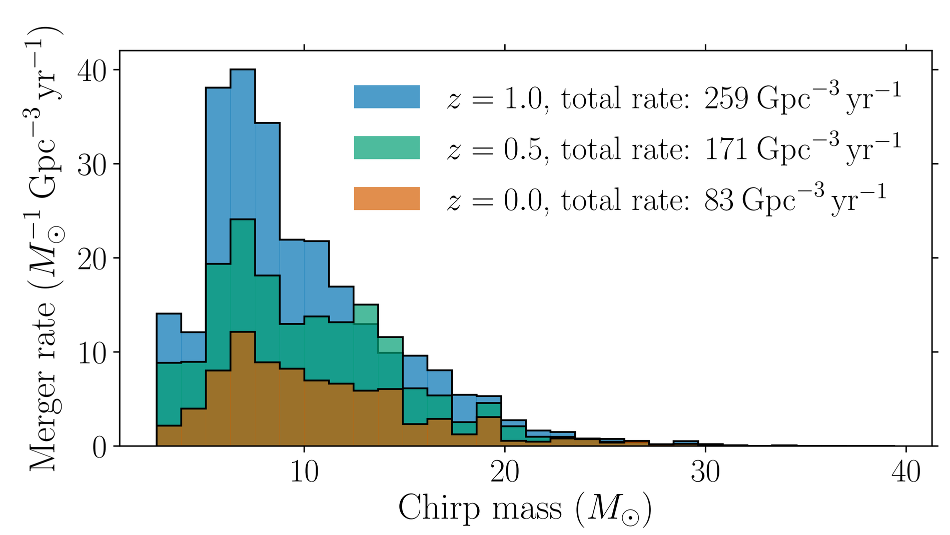

Figure 2. Predicted merger rate density as a function of chirp mass for different redshift bins from the COMPAS rapid population-synthesis code [5]. The detection rate for LIGO at design sensitivity is $480\ \mathrm{yr}^{-1}$.

By comparing the models with observations, we can constrain the uncertain parameters. These measurements would allow us the constrain the currently uncertain physical processes, such as common-envelope efficiency α_CE, black hole natal kicks σ_kick (the dispersion of a Maxwell–Boltzmann distribution), and Wolf–Rayet and luminous blue variable mass-loss rates f_WR and f_LBV (multipliers for a fiducial value).

We only consider binaries formed through isolated evolution, but it is possible to extend the analysis to consider dynamical formation as well, and place constraints on both the branch fraction and population-synthesis parameters [6].

Population inference

To compare population-synthesis models with gravitational-wave observations, consider the number of detections in a series of chirp-mass bins. Let c_k be the observed count in the k-th bin, and $N_\mathrm{obs} = \sum_k c_k$ the total number of observations. If a model predicts a detection rate μ and a proportion p_k in the k-th bin, then for an observing time t_obs, the expected number of observations is μt_obs, and the expected count in the k-th bin is $p_k \mu t_\mathrm{obs}$. The likelihood that the observed population was described by the given model is

$$\mathcal{L} = (\mu t)^{N_\mathrm{obs}} \exp(-\mu t_\mathrm{obs}) \prod_k \frac{p_k^{c_k}}{c_k!}, \tag{1}$$

Using this likelihood, we can estimate the precision we could measure the uncertain population-synthesis parameters, factoring in the degeneracies between parameters [5]. Best measured are α_CE and f_WR (which are anticorrelated) as these have the biggest effect on the detection rate.

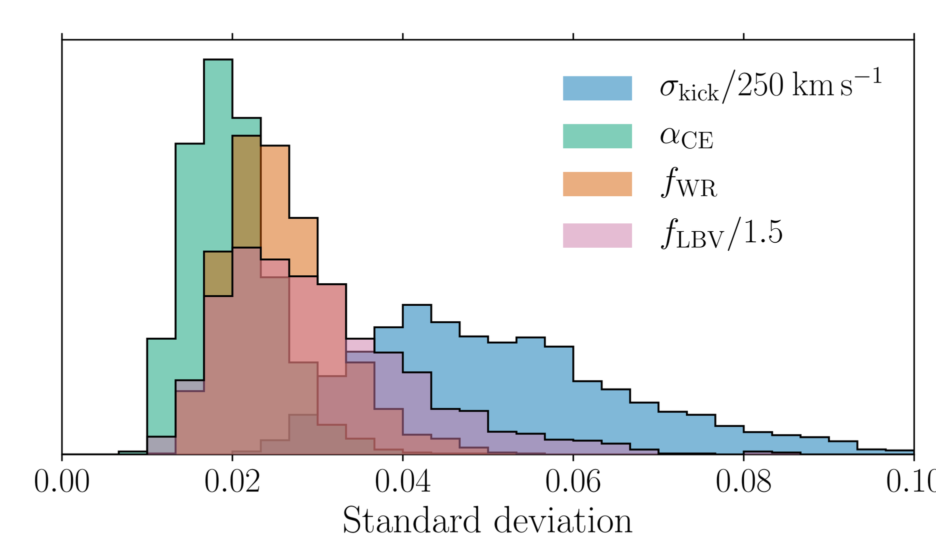

Figure 3. Fractional measurement precision after $N_\mathrm{obs} = 1000$ binary black hole detections for the four population-synthesis parameters [5]. The measurement precisions improve as $N_\mathrm{obs}^{-1/2}$. Results are shown for 1500 realisations of the Universe.

Future prospects

Advanced LIGO may detect $30 M_\odot + 30 M_\odot$ binaries out to redshift $z \sim 1$; the A+ upgrade may detect them out to $z \sim 2$. To push out further requires a new generation of detectors.

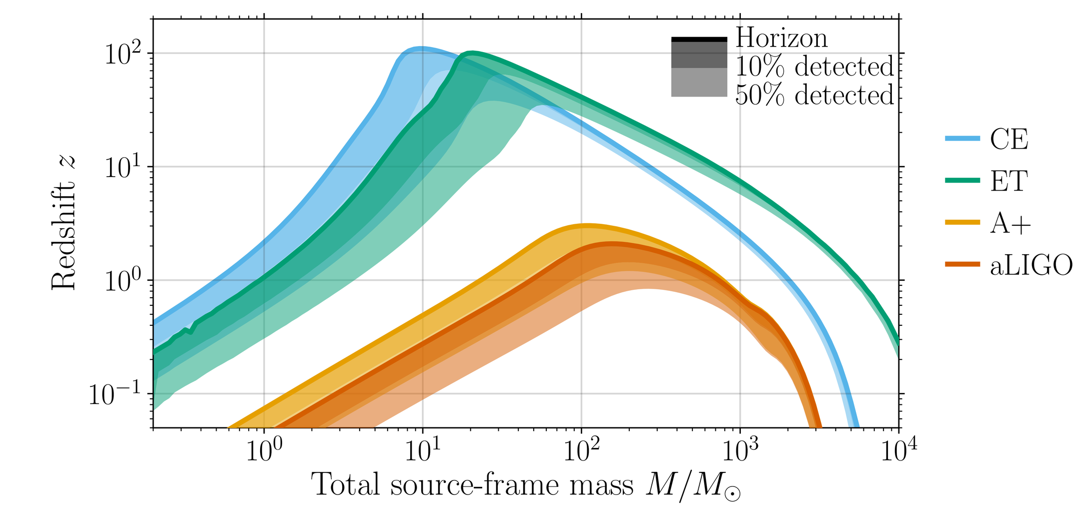

Figure 4. Detection horizon for equal-mass binaries with non-spinning components for Advanced LIGO (aLIGO) at design sensitivity [7], the A+ upgrade [8], the Einstein Telescope (ET) [9] and Cosmic Explorer (CE) [10]. Adapted from [11].

Future performance can be parametrized in terms of the boost relative to A+ [12]. A boost factor of $\beta_\mathrm{A+} \sim 10$ would capture effectively all the mergers out to $z \sim 2$. In a single redshift bin of width 0.1, we can collect 1000 detections in a few years of observing.

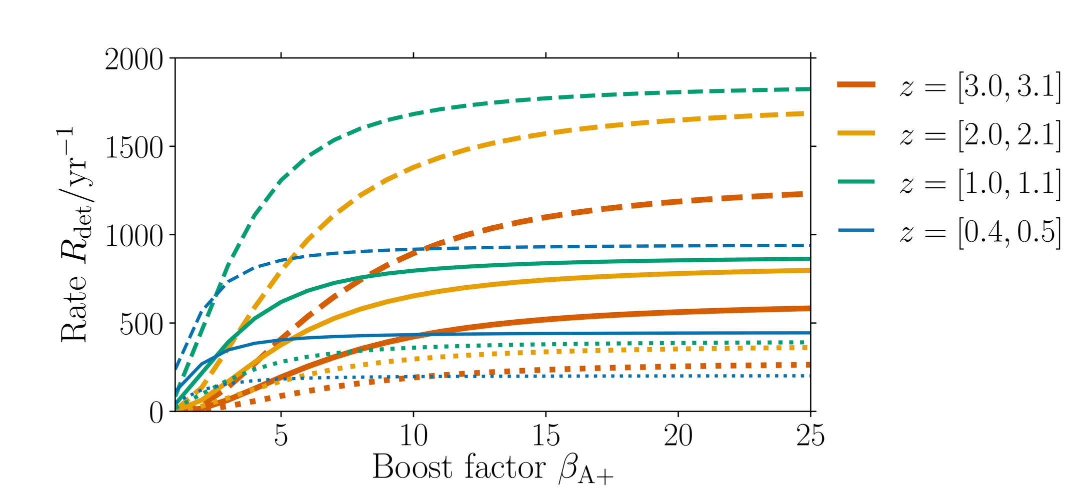

Figure 5. Number of detections per redshift bin as a function of sensitivity boost relative to A+ [12]. Assuming equal-mass non-spinning binaries with merger rates consistent with observations (median, lower and upper 90% shown with solid, dotted and dashed lines) [3].

Conclusions

- Gravitational waves are a new source of observational data for the properties of black holes.
- The catalogue of binary black hole observations will grow rapidly over the coming years.
- Masses and merger rates encode details of binary formation and evolution.
- Comparing population-synthesis models with observed populations can place precise constraints on physical processes.
- The next step is to use real observations to constrain binary-evolution parameters including multiple formation channels (isolated evolution and dynamical formation).
- Measurement precision will mean that systematic modelling uncertainty may soon dominate statistical measurement uncertainty.
- The next-generation of gravitation-wave detectors could further provide information on the evolution of the population back to cosmic dawn.

Affiliations: (1) Center for Interdisciplinary Exploration & Research in Astrophysics, Northwestern University; (2) Institute for Gravitational Wave Astronomy, University of Birmingham; (3) Center for Computational Astrophysics, Flatiron Institute; (4) Department of Physics & Astronomy, Stony Brook University; (5) School of Physics & Astronomy, Monash University; (6) Centre for Astrophysics & Supercomputing, Swinburne University of Technology.

References: [1] Abbott *et al.* (LVC); 2016; *PRL*; **116**:241102; arXiv:1602.03840. [2] Abbott *et al.* (LVC); 2018; arXiv:1811.12907. [3] Abbott *et al.* (LVC); 2018; arXiv:1811.12940. [4] Abbott *et al.* (LVKC); 2018; *LRR*; **21**:3; arXiv:1304.0670. [5] Barret *et al.*; 2018; *MNRAS*; **477**:4685; arXiv:1711.06287. [6] Zevin *et al.*; 2017; *ApJ*; **846**:82; arXiv:1704.07379. [7] Abbott *et al.* (LSC); 2015; *CQG*; **32**:074001; arXiv:1411.4547. [8] Barsotti *et al.* 2018; LIGO-T1800042. [9] Hild *et al.* 2011; *CQG*; **28**:094013; arXiv:1012.0908. [10] Abbott *et al.* (LSC); 2017; *CQG*; **34**:044001; arXiv:1607.08697. [11] Hall & Evans; 2019; arXiv:1902.09485. [12] Kalogera *et al.* 2019; arXiv:1903.09220.