Localization of binary black hole mergers with known inclination

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ABSTRACT

The localization of stellar-mass binary black hole mergers using gravitational waves is critical in understanding the properties of the binaries' host galaxies, observing possible electromagnetic emission from the mergers, or using them as a cosmological distance ladder. The precision of this localization can be substantially increased with prior astrophysical information about the binary system. In particular, constraining the inclination of the binary can reduce the distance uncertainty of the source. Here, we present the first realistic set of localizations for binary black hole mergers, including different prior constraints on the binaries' inclinations. We find that prior information on the inclination can reduce the localization volume by a factor of 3. We discuss two astrophysical scenarios of interest: (i) follow-up searches for beamed electromagnetic/neutrino counterparts and (ii) mergers in the accretion discs of active galactic nuclei.

Key words: gravitational waves – stars: black holes – galaxies: active..

1 INTRODUCTION

So far, Advanced LIGO (Aasi et al. 2015) and Advanced Virgo (Acernese et al. 2015) have discovered 10 stellar-mass binary black hole (BBH) mergers (Abbott et al. 2018a), a number that is expected to grow by two orders of magnitude in the next few years (Abbott et al. 2018b). Such a high detection rate will soon enable constraining binary formation channels, probing the environments of the mergers, and studying the expansion of the Universe, among other possibilities.

Identifying the host galaxies of BBH mergers is particularly useful in these and other endeavours. The properties of host galaxies provide additional information on these events. For example, the association of some BBH mergers with rare host galaxy types – such as active galactic nuclei (AGNs) – can reveal the binaries' formation channel (Bartos et al. 2017a). Host galaxies are also essential in utilizing BBH mergers as standard cosmological candles (Schutz 1986b).

Beyond the gravitational wave (GW) signal and host galaxies, further information could be gained of BBH systems if their merger also produces detectable electromagnetic/neutrino counterpart. Such emission can be produced for binaries residing in a dense gaseous environment from which they can accrete at super-Eddington rates. This may be the case in a few astrophysically plausible scenarios, including mergers in the accretion discs of AGNs (Bartos et al. 2017a,b; Stone, Metzger & Haiman 2017), gas or debris remaining around the black holes from their prior evolution (Kotera & Silk 2016; Moharana et al. 2016; Murase et al. 2016; Perna, Lazzati & Giacomazzo 2016; de Mink & King 2017; Kimura, Takahashi & Toma 2017), and BBH formation inside a collapsing star (Loeb 2016; Dai, McKinney & Miller 2017; Fedrow et al. 2017).

The identification of host galaxies is limited by the localization accuracy of GWs. This accuracy primarily depends on the signal-to-noise ratio of the GW signal, the number of detectors, the masses of the black holes, the sky direction, and any prior information available of the event.

Prior studies of GW localization have overwhelmingly focused on binary-neutron-star and neutron-star-black-hole mergers (Abbott et al. 2018b and references therein), which are known to produce

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electromagnetic/neutrino emission (Metzger & Berger 2012; Bartos, Brady & Márka 2013; Abbott et al. 2017b; Albert et al. 2017). Further, using prior information to improve localization has been considered only recently following the discovery of binary neutron star merger GW170817 (Abbott et al. 2017a). The inclination of GW170817, inferred from the short gamma-ray burst and its afterglow produced by the merger (Abbott et al. 2017c; Mooley et al. 2018; Abbott et al. 2019), was greater than what was anticipated for joint GW and gamma-ray burst observations. The motivation behind these studies is the degeneracy between orbital inclination and luminosity distance in GW parameter estimation (Nissanke et al. 2010; Veitch et al. 2015; Usman et al. 2019). Constraints on the inclination can therefore improve distance measurement, which is the relevant quantity for measuring Hubble's constant with GWs (Schutz 1986a). Improved estimates on the binary inclination can be achieved by combining information from gravitational waves with other electromagnetic observations, in particular a gamma-ray burst afterglow (Mooley et al. 2018; Wu & MacFadyen 2018). A previous study (Chen & Holz 2016) also looked the localization volumes of BBH mergers. However, this work only considered representative binary masses and no prior information on inclination.

Knowing the inclination of BBH mergers could help their localization similarly to the case of neutron star mergers. This has, however, not been previously studied as constraining the inclination of BBHs is only possible if more information can be collected about the merger than what is available in GWs. There are two possibilities: electromagnetic emission from the binary through gas accretion from a dense environment, and information from the binary's host galaxy.

In this paper, we use inclination priors for stellar-mass BBH mergers in AGN environments to infer the expected probability density of GW localization for realistic mass distributions, for the network of Advanced LIGO and Virgo detectors at design sensitivity, and for a five-detector network including LIGO-India (Ilyer et al. 2011) and KAGRA (Aso et al. 2013). We derive localizations both with and without prior information on localization. We then discuss these results in the context of two relevant search scenarios: (i) the search for a beamed electromagnetic/neutrino counterpart and (ii) BBH mergers in AGN discs.

2 UTILITY OF INCLINATION PRIORS

Having prior information on the inclination of BBH mergers can significantly reduce the GW localization volume of the mergers. This reduction has multiple advantages. Below we discuss two such advantages: in follow-up observations searching for the electromagnetic/neutrino counterparts of the merger, and the identification of a sub-class of mergers occurring in AGNs.

2.1 Electromagnetic/neutrino follow-up

The search for electromagnetic/neutrino emission from a source can benefit from the use of host galaxy candidates by reducing the part of the sky that needs to be scanned and by reducing the number of false positives (Nissanke, Kasliwal & Georgieva 2013; Bartos, Crotts & Márka 2015; Evans et al. 2016; Singer et al. 2016; Coulter et al. 2017). A reduction of the search volume therefore proportionally reduces the number of host galaxy candidates that need to be searched for.

We envision two particular scenarios in which prior information on the inclination of the source can be available. First, high-energy gamma-ray and neutrino emission from the source is likely

highly beamed. Therefore, if a high-energy counterpart of the GW signal is observed, one can carry out follow-up observations of this joint source by making use of the fact that the orbital axis of the binary is likely pointing close to Earth. Taking cosmological GRBs as an example, high-energy emission will be visible within $\lesssim 10°$ (Berger 2014; Goldstein et al. 2016). While in the case of GW170817/GRB 170817A, high-energy emission has been observed at about $20°$ (Ghirlanda et al. 2018; Mooley et al. 2018), this will probably only be the case for the most nearby events (Abbott et al. 2017c; Goldstein et al. 2017; Gupte & Bartos 2018), which will be known in advance from the GW signal. A possible caveat is that jets driven by accretion discs around orbiting black holes may be precessing with the motion of the black hole, producing high-energy emission in a changing direction that is offset from the orbital axis (Palenzuela, Lehner & Liebling 2010; Britzen et al. 2017; Khan et al. 2018). This can introduce an additional offset over the jet opening angle, however this will not be significantly increase the $\lesssim 10°$ offset.

As a second possibility, we envision a merger whose orbital axis is pointing away from Earth. While high-energy emission is not detected from such an event, if the merger drives a relativistic outflow it will produce afterglow emission that spreads to greater angles. The profile of this off-axis afterglow emission is dependent, among other parameters, on time (van Eerten & MacFadyen 2011). Therefore, for a given time, one can estimate the inclinations for which the afterglow emission should be observable at that time, making it possible to optimize the follow-up observation schedule of host galaxy candidates. For example, there can be some galaxies within the gravitational wave localization volume that are too far to be host galaxies unless the binary inclination is close to zero. These galaxies should be looked at first as afterglow has no time delay. Some other galaxies that are closer may only be host galaxies if the binary inclination is large. For large inclinations, afterglow should be delayed, and therefore these galaxies are only worth following up with a time delay after the merger.

2.2 Inclination prior from AGNs

AGNs represent a special promising case of BBH mergers in which the inspiral of the BHs is accelerated and guided by the AGN disc (McKernan et al. 2012; Bartos et al. 2017b; Stone et al. 2017; Yang et al. 2019b,a). As the BHs migrate into the AGN disc's plane, the binary orbital axis becomes aligned with the AGN disc's orbital axis. Therefore, information on the orientation of the AGN disc will inform the expected inclination of the BBH merger.

The orientation of the AGN disc may be measured with several distinct methods. This includes fitting the observed iron K α line profile with accretion disc models (Nandra et al. 1997); using the broadening of the H β emission line with known SMBH mass from, e.g. reverberation mapping (Wu & Han 2001) (for the inclination of the broad-line region); polarization measurements (Schmid, Appenzeller & Burch 2003); and others (see Marin 2014 and references therein). Some of these methods produced inclination estimates with uncertainty $\lesssim 5°$ for some of the studied AGNs (e.g. Marin 2014).

The above information can be utilized as follows. We first localize a detected BBH merger using no prior information. Then, within its localization volume, we identify AGNs, either using a galaxy catalogue or by follow-up observations (Bartos et al. 2015). For each of these AGNs, we determine the AGN disc's inclination with a suitable technique, and localize the GW signal with this reconstructed inclination as prior. An AGN will only remain a

candidate if it remains within the new localization volume derived using the AGN's inclination.

3 METHODS

Our methods include generating a sample of realistic BBH merger events and localizing them with various priors on inclination. Below, we discuss BAYESTAR, the localization algorithm used in this study, and our method of computing BBH localization volumes.

3.1 BAYESTAR

We performed our localizations of simulated BBHs using BAYESTAR (Singer & Price 2016). BAYESTAR performs a Bayesian analysis using the maximum-likelihood parameter estimates from matched filter searches to compute GW localization.

Previously, BAYESTAR computed posteriors assuming a uniform distribution in $\cos(\iota)$ within $[-1, 1]$, where ι is the inclination angle [see equation (38) in Singer & Price 2016]. We modified the analysis method to include prior information on the binary inclination. In the following, we use prior distributions that are uniform in $\cos(\iota)$ within $[\cos(\iota_{high}), \cos(\iota_{low})]$.

3.2 Computation of BBH localization volumes

We adopted a realistic BBH mass model in which each BH mass follows $m \propto m^{-2.35}$, with a minimum mass of $5\,M_\odot$ and a maximum mass of $50\,M_\odot$ (Abbott et al. 2016). We did not consider any correlation between the two masses. We drew the locations of BBH mergers assuming a uniform distribution in comoving volume, and we assigned a random orientation to the binary. We used reduced-order-model (ROM) SEOBNRv4 waveforms (Bohé et al. 2017). We assumed black hole spins aligned with the orbital axis, and we did not include precession. We adopted cosmological parameters from the 9-yr WMAP observations (Hinshaw et al. 2013).

We consider two network sensitivities: (i) the Advanced LIGO and Virgo detectors (HLV), all at design sensitivity (Abbott et al. 2018b), and (ii) LIGO-Virgo-India-KAGRA network (HLVIK), with HLV at A+ sensitivity (Barsotti et al. 2018) and IK at design sensitivity. We assigned each detector an independent duty cycle of 70 per cent.

We generate samples of BBH parameters as described above and determine whether each injection is detectable. We compute the time of arrival, phase of arrival, and SNR in each detector, and we add Gaussian measurement error to the SNR. We calculate network SNR as the quadrature sum of the individual SNRs, and to consider an event discovered, we use a threshold network SNR of 12 and require at least two detectors to contribute an SNR of 4. For discovered signals, we use BAYESTAR to derive 3D localizations, also using our inclination priors when applicable.

4 RESULTS

We discuss two results of the localization studies below: first, the reduction in localization volumes obtained using inclination priors, and second, the improved study of AGNs as a BBH formation channel.

4.1 Localization distribution with inclination priors

We used the simulations described above to obtain the cumulative probability density of BBH merger localization volumes. Fig. 1
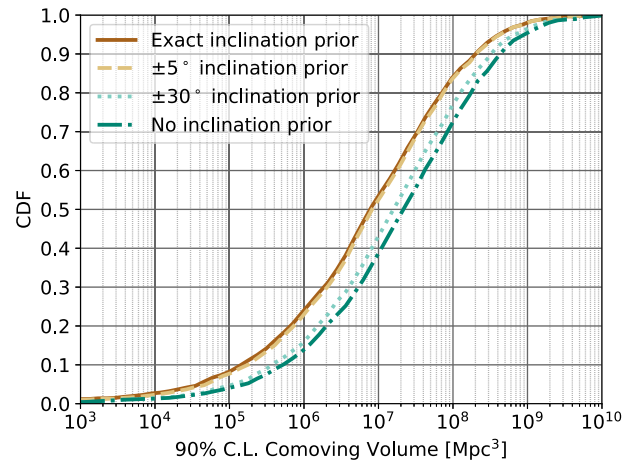

Figure 1. Cumulative density function (CDF) of the 90 per cent confidence-level localizations in comoving volume for BBHs detected by the HLV network at design sensitivity, assuming various inclination priors. We find similar distributions for the HLVIK network, due to the simultaneous effects of greater source distances and improved sky localization.

shows how localization depends on prior information on the binary inclination. We see that knowing the inclination to $5°$ precision or better (e.g. Marin 2014) reduces the localization volume by a factor of about 3, while knowing the inclination to a precision of $30°$ reduces the localization volume by about 35 per cent.

While not shown separately, we find that this improvement comes from better distance estimation. The improvement of distance estimation is practically the same as the improvement in 3D localization. The 2D sky localization is practically unaffected.

4.2 Population constraints on AGN-assisted BBH mergers

We can convert the expected improvement using inclination priors into improved population constraints on the subset of BBH mergers occurring in AGN discs. For this, we adopted the method of Bartos et al. 2017a, who used the correlation of AGN locations and GW localization volumes to derive the number of GW detections needed to statistically indicate the presence of an AGN-assisted BBH sub-population. We carried out their calculation with our localization volume distribution assuming that the inclination of the merger is known within $5°$.

The number of mergers needed for identifying a sub-population as a function of the sub-population's fractional contribution to the total event rate is shown in Fig. 2. Comparing these results to those of Bartos et al. 2017a, we find that the number of events needed is reduced by about a factor of 3 (i.e. proportionally to the improvement in localization).

4.3 The role of BH spins

For AGN-assisted mergers, large BH spins that are misaligned from the orbital axis can mitigate the precision of this technique. In such cases, the binary undergoes orbital precession, which can reduce the alignment of the orbital plane from the AGN disc plane.

In addition, for some precessing binaries, precession can help reconstruct the inclination of the orbit, decreasing the advantage of having additional information on the inclination through other means. However, it is difficult to substantially constrain pre-merger inclination for precessing binaries using Earth-based GW
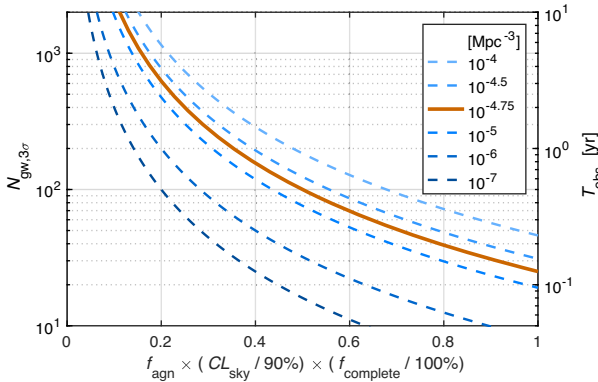
Figure 2. Number of BBH detections required to obtain 3σ evidence for the fraction of BBH mergers originating in AGNs with known inclination priors, at various galaxy number densities.

instruments (Brown, Lundgren & O'Shaughnessy 2012; Vitale et al. 2017), unless the BH masses are low (Vitale et al. 2014). This is due to the fact that lower mass BHs undertake more orbits and therefore more precession in the LIGO band.

In our studies, we neglected these effects as the spin distribution and alignment of merging black holes is highly uncertain, with no evidence so far for a sufficiently high spin to necessitate accounting for precession (Abbott et al. 2018a). Nevertheless, we note that if a large fraction of the merging black holes had large misaligned spins, it would need to be accounted for in inclination studies.

5 CONCLUSIONS

We computed the expected probability distribution of GW localization volumes of stellar-mass BBH mergers using a new localization algorithm BAYESTAR[i], using prior information on the inclination of the binary. We examined two particular cases in which inclination priors can be expected: electromagnetic emission and AGN-assisted mergers. Our takeaways are as follows:

(i) Knowing the inclination of the merger a priori to at least $5°$ reduces the localization volume by about a factor of 3. This factor comes primarily from the reduced distance uncertainty. Knowing the inclination to $30°$ results in a 35 per cent reduction.

(ii) Inclination priors can be used in electromagnetic follow-up searches when beamed high-energy emission or its afterglow is searched for.

(iii) The inclination of BBH mergers in AGNs can be constrained by assuming that the merger plane is aligned with the AGN disc plane. Using these aligned inclinations can reduce the number of BBH detections needed to identify an AGN-assisted sub-population by a factor of 3.

The results above represent a first step in the development of methods to incorporate astrophysical prior information in the localization of BBH mergers.

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