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Strong-lensing of Gravitational Waves by Galaxy Clusters

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Abstract. Discovery of strongly-lensed gravitational wave (GW) sources will unveil binary compact objects at higher redshifts and lower intrinsic luminosities than is possible without lensing. Such systems will yield unprecedented constraints on the mass distribution in galaxy clusters, measurements of the polarization of GWs, tests of General Relativity, and constraints on the Hubble parameter. Excited by these prospects, and intrigued by the presence of so-called "heavy black holes" in the early detections by LIGO-Virgo, we commenced a search for strongly-lensed GWs and possible electromagnetic counterparts in the latter stages of the second LIGO observing run (O2). Here, we summarise our calculation of the detection rate of strongly-lensed GWs, describe our review of BBH detections from O1, outline our observing strategy in O2, summarize our follow-up observations of GW170814, and discuss the future prospects of detection.

Keywords. gravitational lensing, gravitational waves, galaxies: clusters: individual (MACS J0140.0−0555, MACS J1311.0−0310, RCS 0224−0002, Abell 3084, SMACS J0304.3−4401)

1. Strong-lensing of gravitational waves by galaxy clusters

The detection of strongly-lensed gravitational wave (GW) sources will create opportunities to explore binary compact objects at higher redshifts and/or that are intrinsically fainter than those that are detectable without assistance from lensing. This greater "reach" of GW detectors that can be achieved with lensing is due to the gravitational magnification, μ, that boosts the amplitude of the strain signal (A) at an interferometer by a factor $\sqrt{\mu}$ and the spectral flux density of any accompanying electromagnetic signal by a factor μ. In addition to increasing the sensitivity of observations, the gravitational

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magnification has important consequences for the interpretation of the strain and EM signals. In particular, there is a degeneracy between the luminosity distance (D_L) to the source and the gravitational magnification, such that $A \propto D_L^{-1}|\mu|^{0.5}$. Therefore, if it is assumed that $\mu = 1$ for a source that is actually lensed, then D_L and the redshift of the source (z) will be under-estimated. Moreover, given that the rest-frame mass of the source goes as $(1+z)^{-1}$, the mass of the source would be over-estimated if $\mu = 1$ is erroneously assumed (Wang, Stebbins & Turner 1996).

The early detections of binary black hole (BBH) GW sources by LIGO and Virgo are intriguing in the context of gravitational lensing because a large fraction of the reported BHs have rest frame masses larger than the most massive stellar mass BHs detected thus far (Abbott *et al.* 2016a, 2016b, 2017a, 2017b; Farr *et al.* 2011). This encourages speculation that one or more of the sources could have been gravitationally lensed.

The realisation that a GW source is strongly-lensed would also open up the possibility to detect the same GW source on more than one occasion by virtue of the different arrival times along multiple sight lines that connect an observer with a strongly-lensed source. Given the sub-millisecond accuracy of the measurement of the arrival time of a GW signal, it would be possible to measure the time delay between different sight lines through a galaxy cluster to a single GW source to a similar accuracy. Such accuracy is $\gtrsim 8$ orders of magnitude better than is achievable with multiply-imaged supernovae and quasars (Fohlmeister *et al.*, 2007; Rodney *et al.*, 2016). Discovery of one or more multiply-imaged GW sources would therefore deliver an unprecedented constraint on the local mass distribution in cluster lenses, and potentially offer a new and accurate probe of the Hubble parameter (e.g. Liao *et al.* 2017). Moreover, multiple detections of the same GW are unlikely to be made when the detectors are in the same orientations relative to the source. Therefore, observations of a multiply-imaged GW source should help to further constrain GW polarizations and potentially achieve new tests of General Relativity, since we would effectively observe the same signal with a greater number of detectors (Chatziioannou, Yunes & Cornish 2012).

2. The probability of strong-lensing

Given that the BBH GW sources are located at $z \sim 0.1 - 0.3$ (assuming $\mu = 1$), a magnification factor of $\mu \sim 30 - 300$ is required to reinterpret the strain signal as originating from a source at (say) $z \simeq 1$ (Smith *et al.* 2018). The physical region from which GWs emerge is $\sim 100\,\mathrm{km}$ in size. It is therefore possible for a GW source to be very closely aligned with the caustic of a gravitational lens, and thus achieve such a high magnification value (Ng *et al.* 2018) – i.e. we can treat GWs as point sources. In contrast, galaxies have typical physical sizes of $\sim 1 - 10\,\mathrm{kpc}$, and therefore cannot be treated as point sources at optical wavelengths. Hilbert *et al.* (2008) predicted that the optical depth to strong-lensing of point sources is dominated by galaxy clusters, with the optical depth peaking at $M \simeq 10^{14} M_\odot$. This peak, and the dominance of clusters, is predicted to be more pronounced for large lens magnifications, i.e. $\mu > 10$ (Figure 5 of Hilbert *et al.*). These predictions appear to be borne out by observations, in that the typical lens magnifications suffered by quasars – a class of point source, and thus directly relevant to lensing of GWs – that are strongly-lensed by clusters is typically $\mu > 10$ (Oguri *et al.* 2010, 2013; Sharon *et al.* 2017), whilst the magnification of quasars strongly-lensed by galaxies is typically $\mu < 10$ (Inada *et al.* 2014). Therefore, the available predictions and observations both point to galaxy clusters being more relevant than galaxies (Broadhurst *et al.* 2018; Li *et al.* 2018; Ng *et al.* 2018) to the discovery of strongly-lensed GWs with LIGO-Virgo.

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There are currently 130 known and spectroscopically confirmed cluster strong lenses (Smith *et al.* 2018 and references therein). It is important to stress that spectroscopic confirmation of the redshift of multiply-imaged galaxies seen through these cluster cores is essential to achieve robust constraints on the gravitational optics (e.g. Smith *et al.* 2009). Most of the cluster lenses are at redshifts of $z \sim 0.2-0.5$; at lower redshifts strong-lensing clusters become increasingly rare due to the small observable cosmic volume, and higher redshifts await systematic exploration.

The assumption of $\mu = 1$ in the LIGO-Virgo analysis of BBH detections in the first and second observing runs (O1 and O2) rightly reflects the fact that the probability of strong-lensing is small. This is due to a combination of factors including the large magnifications noted above, and existing constraints on the local BBH merger rate. Nevertheless, Smith *et al.* (2018) showed that the probability is non-zero. Based on the known population of cluster lenses and the GW detections from O1 (Abbott *et al.*, 2016b), they estimated a lower limit on the rate of detectable strongly-lensed GWs of $R_{\rm detect} \simeq 10^{-5}$ per detector year. This corresponds to rejecting the hypothesis that one of the O1 GW detections was multiply-imaged at $\lesssim 4\sigma$.

3. Known strong-lensing clusters and LIGO's O1 BBHs

Smith *et al.* (2018) identified three strong-lensing clusters with celestial coordinates consistent with the 90% credible sky localisations of GW sources detected in LIGO's O1 (Abbott *et al.*, 2016b), of which none are consistent with GW150914, two are consistent with GW151226 (MACS J0140.0−0555 and MACS J1311.0−0310) and one is consistent with LVT151012 (RCS 0224−0002). Following Jauzac *et al.* (2016) we used detailed parameterized models of the mass distribution in each of these cluster lenses to explore whether and when another appearance of GW151226 and LVT151012 would be detectable, if they have been strongly-lensed. In summary, the next appearance will be detectable at the current LIGO-Virgo sensitivity in roughly half of the cases, and on a timescale of up to 3 years from the initial detection. The "re-detection rate" of $\sim 50\%$ arises because the relevant strong-lensing configurations typically involve one caustic crossing, and thus produce three images, of which two are very highly magnified and detectable and the third is not. Therefore, if the initial GW detection corresponds to the first of the two highly magnified images, then the second of the two highly magnified images is generally detectable. If the initial GW detection corresponds to the second of two highly magnified images, then the next appearance corresponds to the third much less strongly magnified and thus undetectable image.

4. Gravitationally Lensed Gravitational Wave Hunters and O2

The Gravitationally-lensed Gravitational Wave Hunters collaboration began observing known strong-lensing clusters located within the 90% credible sky localisations of new GW detections in August 2017. The aim of these observations was to detect an EM counterpart to a GW based on the speculation that it had been strongly-lensed by a cluster. We used the GMOS instrument on Gemini-South and the MUSE instrument on VLT to examine the strong-lensing regions of clusters down to depths of AB $\simeq 25$ per visit. For a nominal gravitational magnification of $|\mu| = 100$, we therefore in principle reach a sensitivity of AB $\simeq 30$ in the search for an EM counterpart to GWs. This is the most sensitive search conducted to date. The first visit with each telescope took place as soon as possible after the LIGO-Virgo alert via a rapid target of opportunity observation, and subsequent visits took place up to ~ 1 week later.

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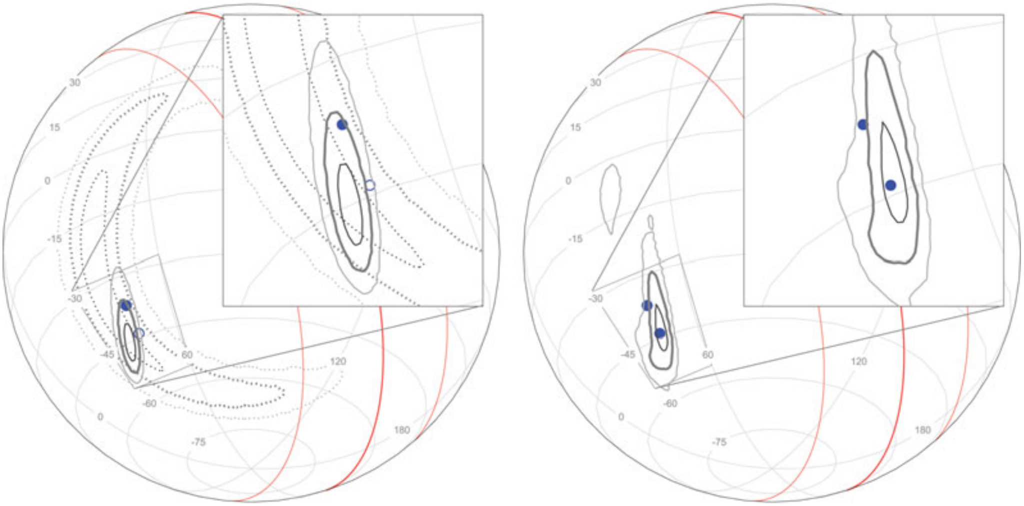

Figure 1. Left – Initial BAYESTAR skymap for GW170814 from GCN21474, showing the LIGO only contours (dotted), joint LIGO-Virgo contours (solid), Abell 3084 (filled blue), and SMACS J0304.3−4401 (open blue). Right – Initial LALInference skymap from GCN21493, showing updated sky localisation based on LIGO-Virgo data (solid) and the locations of both clusters. SMACS J0304.3−4401 is closer to the peak of the sky localisation than Abell 3084 in the revised map. In both panels the 90% credible region is shown as the thick solid contour, and galactic latitudes of ±20° are shown in red.

We observed two strong-lensing clusters associated with the sky localisation of GW170814 (Abbott *et al.* 2017b), namely Abell 3084 and SMACS J0304.3−4401 (Smith *et al.* 2017). Figure 1 shows the location of the clusters and the LIGO-Virgo credible regions on the celestial sphere. The small change in the sky localisation between the initial BAYESTAR and preliniary LALInference skymaps, and the relationship between these and the cluster coordinates explains why we initially observed Abell 3084 and subsequently switched to SMACS J0304.3−4401.

5. Future prospects

We consider the timescale on which the rate of detection of strongly-lensed GWs will approach $R_{\rm detect} \simeq 1$ per detector year. Two factors contribute to this timescale: (1) gains in sensitivity of the LIGO-Virgo detectors, and (2) expansion of the sample of known strong-lensing clusters. LIGO is scheduled to reach design sensitivity in 2020, by which time it will probe a $\sim 10\times$ larger volume than was the case in O1 and O2 (Abbott *et al.*, 2017c). This improved sensitivity will lead to less extreme magnifications being required to reinterpret GW signals as coming from redshifts higher than the cluster lenses. We estimate that the greater sensitivity and consequent reduced magnification requirement will together increase the rate to $R_{\rm detect} \simeq 10^{-2}$ per detector year, based on the same population of 130 known strong lensing clusters discussed above.

Clearly the incidence of strong-lensing of GWs is independent of the completeness of the available sample of strong-lensing clusters. However, ability to recognise GWs as being strongly-lensed does depend on knowledge of the lens population. Therefore $R_{\rm detect}$ will grow as more strong-lensing clusters are discovered. Forecasts for upcoming large-scale optical/near-infrared surveys indicate that *Euclid* and LSST will find of order 1 strong-lensing cluster per square degree in the redshift range $z \sim 0.2 - 0.5$ considered above

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(Boldrin *et al.*, 2016). It should therefore be possible to achieve a further two orders of magnitude gain to give $R_{\rm detect} \simeq 1$ per detector year during the 2020s. Precisely when this will be achieved will depend on the observing strategy of each survey, and the efficiency of strong-lensing cluster detection in the survey data.

Additional GW detectors, KAGRA and LIGO-India, are planned to begin operation in the period 2023-2025 (Abbott *et al.*, 2017c), i.e. in parallel with *Euclid*/LSST discovery of strong-lensing clusters. These detectors will increase the volume within which GWs can be detected by a further factor of 3 beyond the LIGO design sensitivity. This will help to increase the rate of strongly-lensed GW detections in the mid-2020s.

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