Inference on gravitational waves from coalescences of stellar-mass compact objects and intermediate-mass black holes

Carl-Johan Haster,1* Zhilu Wang,1,2 Christopher P. L. Berry,1 Simon Stevenson,1 John Veitch1 and Ilya Mandel1

1School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK
2Department of Modern Physics, University of Science and Technology of China, 96 JinZhai Road, Baohe District, Hefei, Anhui 230026, People’s Republic of China

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ABSTRACT
Gravitational waves from coalescences of neutron stars or stellar-mass black holes into intermediate-mass black holes (IMBHs) of $\gtrsim 100$ solar masses represent one of the exciting possible sources for advanced gravitational-wave detectors. These sources can provide definitive evidence for the existence of IMBHs, probe globular-cluster dynamics, and potentially serve as tests of general relativity. We analyse the accuracy with which we can measure the masses and spins of the IMBH and its companion in intermediate-mass-ratio coalescences. We find that we can identify an IMBH with a mass above $10^2 M_\odot$ with 95 per cent confidence provided the massive body exceeds $130 M_\odot$. For source masses above $\sim 200 M_\odot$, the best measured parameter is the frequency of the quasi-normal ringdown. Consequently, the total mass is measured better than the chirp mass for massive binaries, but the total mass is still partly degenerate with spin, which cannot be accurately measured. Low-frequency detector sensitivity is particularly important for massive sources, since sensitivity to the inspiral phase is critical for measuring the mass of the stellar-mass companion. We show that we can accurately infer source parameters for cosmologically redshifted signals by applying appropriate corrections. We investigate the impact of uncertainty in the model gravitational waveforms and conclude that our main results are likely robust to systematics.

Key words: black hole physics – gravitational waves – methods: data analysis.

1 INTRODUCTION
The Advanced LIGO (aLIGO; Aasi et al. 2015) gravitational-wave (GW) detectors began their first observing run on 2015 September 18; the Advanced Virgo (AdV; Acernese et al. 2015) GW detector is expected to commence scientific observation in 2016 (Abbott et al. 2016). One of the key sources for the advanced-era detectors are compact binary coalescences (CBCs; Abadie et al. 2010), the inspiral and merger of binary systems including both neutron-star (NS) and black hole (BH) companions across a large mass spectrum.

Intermediate-mass black holes (IMBHs) fill the gap in the continuum between stellar-mass BHs and supermassive BHs, potentially representing an early stage in the evolution of supermassive BHs (Miller & Colbert 2004; Graham & Scott 2013). At present, the best evidence for their existence comes from observations of ultraluminous X-ray sources (Feng & Soria 2011; Pasham, Strohmayer & Mushotzky 2015).

IMBHs of a few hundred solar masses in a coalescing binary are a potential source of GWs for the advanced generation of ground-based detectors. If the IMBH’s companion is another IMBH, the system is referred to as an IMBH binary (IMBHB). If its companion is stellar mass, then the system undergoes an intermediate-mass-ratio coalescence (IMRAC). These are often also referred to as intermediate-mass-ratio inspirals (IMRIs); 1 however, we prefer IMRAC to highlight the importance of the entire coalescence, including the merger and ringdown phases in addition to the inspiral, to the detection and analysis of these high-mass systems (Smith, Mandel & Vechhio 2013).

IMRACs are most likely to be found in the dense cores of globular clusters (Leigh et al. 2014; MacLeod, Trenti & Ramirez-Ruiz 2015). They can form through a range of mechanisms, including hardening of existing binaries, through either three-body interactions or Kozai

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1 The inspiral of an IMBH into a supermassive BH is also referred to as an IMRI. GWs from such IMRIs are potential sources for a space-borne detector (Amaro-Seoane et al. 2007), as are the most massive (redshifted total masses of $\gtrsim 10^3 M_\odot$) IMBHBs (Fregaeu et al. 2006; Miller 2009).
oscillations as part of a hierarchical system, as well as through direct or tidal capture (Mandel et al. 2008). As a consequence of mass segregation in globular clusters, the stellar-mass companion to the IMBH will change throughout the evolutionary history of the cluster (MacLeod et al. 2015). Soon after the formation of the cluster, the companion will most likely be a stellar-mass BH, but for older clusters it could be an NS if the stellar-mass BH population has been depleted by mergers and dynamical ejections (Gill et al. 2008; Umbreit & Rasio 2013; Morscher et al. 2015). Consequently, there is a large variation in the possible mass ratios of detectable binaries.

The resulting IMRACs are estimated to have become largely circularized before entering the sensitivity band of the advanced GW detectors, and any residual eccentricity is expected to have a negligible effect on their detectability (Mandel et al. 2008). Estimates of the IMRAC detection rate in the advanced-detector era range up to tens of events per year, though rates of zero are possible given the absence of confirmed IMBHs in the few-hundred-solar-mass range where advanced detectors would be sensitive to emitted GWs (Brown et al. 2007; Mandel et al. 2008; Abadie et al. 2010). The IMBH spin distribution is not constrained. However, if IMRACs are common, and the IMBHs increase their mass by a significant fraction by capturing compact objects from an isotropic distribution of orbital inclinations, IMBHs will on average spin-down to dimensionless spin magnitudes $a \lesssim 0.2$ (Mandel 2007).

The dividing line between IMBHBs and IMRACs, just like the division between IMBHBs and stellar-mass BHs, is arbitrary; however, the evolution of the binary and the emitted GWs vary significantly with the mass ratio $q = m_2/m_1$, where $m_1 > m_2$ are the masses of the binary companions. Systems with more equal masses (IMBHBs with $q \sim 1$) inspiral more quickly than those with unequal masses (IMRACs with $q \ll 1$), and because of the difference in the scales associated with unequal masses, IMRACs are more challenging for numerical relativity to simulate (Lousto et al. 2010; Husa et al. 2016).

We perform a systematic parameter-estimation (PE) study for IMRAC signals using full inspiral–merger–ringdown waveforms. Details of our set up, which mirrors the analysis of Veitch, Purrer & Mandel (2015b) for IMBHBs, are described in Section 2. Results are given in Section 3 and discussed in Section 4, where we also examine the sensitivity of our analysis to systematics. Our main conclusions are summarized in Section 5; in particular, we find that the advanced GW detectors could unambiguously confirm the existence of IMBHs, should a suitable IMRAC ($m_1 \gtrsim 130 M_\odot$) be detected.

2 STUDY DESIGN

To determine how accurately properties of IMRACs could be measured in the advanced-detector era, we analysed a mock set of GW signals observed with aLIGO and AdV. The simulated GW signals (injections) and the detector properties are described in Section 2.1, and the data analysis is detailed in Section 2.2.

2.1 Sources and sensitivity

Following Veitch et al. (2015b), we simulated a set of IMRAC signals which systematically cover the mass range of interest. We explore a range of binaries with total mass $M_{\text{tot}} = m_1 + m_2$ between 50 and 350 $M_\odot$, sampled in 25 $M_\odot$ steps. For each total mass, three mass ratios $q$ of 1/15, 1/30, and 1/50 were used.

Each injection was assigned a sky position isotropically drawn from the celestial sphere, as well as an inclination $i$ drawn from a distribution uniform in $\cos i$. The distance to each source was then selected to yield a signal-to-noise ratio (SNR) of $\rho = 15$, distributed across the detector network, in order to give an indication of typical PE accuracy; the dependence of PE on $\rho$ is investigated in Section 4.2.

The injected signals were generated using a spin-aligned effective-one-body–numerical relativity (SEOBNR) waveform approximant, specifically SEOBNRv2 (Taracchini et al. 2012, 2014). These waveforms are constructed via the effective-one-body formalism (Buonanno & Damour 1999, 2000) for the inspiral dynamics, with the merger and ringdown portions calibrated to a suite of numerical relativity simulations (e.g. Mroue et al. 2013). The companion spins are assumed to be aligned; including effects of generic spin alignments (such that there is precession) is an area of active development (Pan et al. 2014). We only inject signals from non-spinning systems for this first study; we hope to include full spin effects in the future. Additionally, we assume the binaries to be fully circularized before they enter the detectors’ sensitive frequency band; as waveform approximants allowing for eccentricity effects become available for PE studies, we hope to include them as well.

The output of GW detectors is the sum of the GW strain and random detector noise. The particular noise realization present determines which GW template best matches the data. The best matching template may have parameters offset from the true value; over many different realizations of the noise, this shift in the parameter estimates should average to zero. However, at a given $\rho$, the measurement uncertainty should not be significantly influenced by the details of the noise realization.

We assume that AdV and aLIGO are operating at their respective design sensitivities (Acernese et al. 2009; Shoemaker 2010), which are expected to be realized at the end of the decade (Abbott et al. 2016). To fully utilize the detectors’ sensitivity to IMRAC sources, a lower frequency cut-off of $f_{\text{low}} = 10$ Hz was chosen for all three detectors; the importance of this low-frequency sensitivity is examined in Section 4.1.

2.2 Parameter estimation

The data, with injected signals, were analysed using the Bayesian PE pipeline LALINFERENCE (Veitch et al. 2015a). For each event,
LALINFERENCE computes a set of samples drawn from the joint posterior probability distribution spanning the signal parameters. To calculate the posterior, we need a model for the likelihood and prior probability distributions for the parameters.

The likelihood is calculated by matching a template signal to the data (Cutler & Flanagan 1994). The analysis was performed using the SEOBNRv2_ROM_DoubleSpin waveform approximant (Purrer 2014, 2015), a reduced-order model (ROM) surrogate of SEOBNRv2 implemented in the frequency domain. The development of this ROM has enabled PE studies previously deemed computationally infeasible, expanding the accessible parameter space for studies of CBC sources (cf. Veitch et al. 2015b). By using the same approximant for injection and recovery, we remove any systematic error caused by waveform uncertainty (cf. Section 4.3). SEOBNRv2 and its ROM surrogate only include the leading order quadrupolar mode of the GW radiation, but as it has been shown that higher order modes can significantly improve the PE for IMBHB systems (Graff, Buonanno & Sathyaprakash 2015), we hope to be able to include them in future IMRAC studies.

For this analysis, we adopted a flat prior distribution on the companion masses \( m_1, m_2 \in [0.6, 500] M_\odot \) with the constraints \( M_{\text{total}} > 12 M_\odot \) and \( q > 0.01 \). While all injections were non-spinning, we do allow for the exploration of dimensionless spin magnitudes \( a_1, a_2 \in [-1, 0.99] \), aligned with the orbital angular momentum, with uniform priors. We also assume an isotropic prior on the source position and orientation in the sky as well as a uniform-in-volume prior on the luminosity distance out to 4 Gpc.

GWs are redshifted in an expanding Universe. This corresponds to redshifting all masses from a source at redshift \( z \) by a factor of \( 1 + z \), and scaling the GW amplitude with the inverse of the luminosity distance. In this study, we report the injected and recovered masses as redshifted to the detector rest frame, rather than the physical source frame masses, except where otherwise noted. The implications of cosmological effects are discussed in further detail in Section 3.1.

### 3 Key Results

We characterize the posterior probability distributions produced by LALINFERENCE in terms of the innermost 90 per cent credible intervals CI\(_{90}\), spanning the 5th to the 95th percentiles, for one-dimensional marginalized parameter distributions (Aasi et al. 2013).

For low-mass systems, where the recovered SNR is dominated by the inspiral part of the coalescence (Aasi et al. 2013), the best constrained parameter is the chirp mass \( \mathcal{M} = m_1^{3/5} m_2^{3/5} M_{\text{total}}^{-1/5} \). The uncertainty on the chirp-mass measurement is shown in Fig. 1. For greater \( M_{\text{total}} \), the SNR becomes increasingly dominated by the merger and ringdown; the properties of the ringdown depend only on \( M_{\text{total}} \) and \( a_t \), the spin of the final BH (cf. Graff et al. 2015; Veitch et al. 2015b). High-mass systems, \( M_{\text{total}} \gtrsim 200 M_\odot \), are therefore better constrained in terms of their \( M_{\text{total}} \) (Fig. 2) than their \( \mathcal{M} \), as shown in Fig. 3. As discussed in Section 4.1, since the measurement accuracy of \( \mathcal{M} \) scales inversely with the number of in-band cycles of the inspiral, the specific mass of the \( \mathcal{M} \rightarrow M_{\text{total}} \) transition depends on the lower limit of the detector’s sensitive frequency band \( f_{\text{low}} \), either set explicitly as part of the analysis or implicitly by either a high noise floor or uncertain low-frequency calibration.

The mass measurements can alternatively be represented by the 90 per cent credible intervals for the companion masses. Fig. 4 shows that the larger mass \( m_1 \) is well constrained due to its near equivalence to \( M_{\text{total}} \) for these systems. At low \( M_{\text{total}} \), the mass ratio also provides tight constraints on \( m_2 \) compared to more equal mass.
Figure 4. The 90 per cent credible intervals for the larger and smaller companion masses, \( m_1 \) (left) and \( m_2 \) (right), respectively. The mass of the secondary \( m_2 \) is poorly measured and biased upward (towards stronger signals which can be observed at greater distances) when \( M_{\text{total}} \) is so large that little of the inspiral falls into the sensitive frequency band.

Figure 5. The 90 per cent credible interval for \( f_{\text{RD}} \). The true values are shown as dashed lines for each \( q \). For high-\( M_{\text{total}} \) systems, whose in-band signal is dominated by the ringdown, \( f_{\text{RD}} \) is better constrained than \( M_{\text{total}} \). The strong dependence of the number of waveform cycles (in the detector band) upon the mass ratio means that even a small shift away from the true \( q \) value causes a large dephasing between the signal and template waveforms (assuming that \( M_{\text{total}} \) or \( M \) is well constrained), and therefore a rapid decrease in the measured likelihood. At high \( M_{\text{total}} \) the detectors are only sensitive to the ringdown of the coalescence, where the mass-ratio dependence is only measured weakly through the final BH spin \( a_f \).

The remnant spin together with the final mass \( M_f \) determines the frequency of the quasi-normal modes (QNMs) of the ringdown of the merged BH. Following an approximate model for estimating \( M_f \) and \( a_f \) (Healy, Lousto & Zlochower 2014, equations 14 and 16) it is then possible to convert the posterior samples in the space of companion masses and spins into the frequency \( f_{\text{RD}} \) of the zeroth overtone of the dominant \((l, m) = (2, 2)\) QNM as (Berti, Cardoso & Will 2006, table VIII),

\[
 f_{\text{RD}} = \frac{c^3}{2\pi G M_f} \left[ 1.5251 - 1.1568(1 - a_f^{0.1292}) \right].
\] (1)

Fig. 5 compares the inferred \( f_{\text{RD}} \) to the value of the ringdown frequency of the injected waveform. It is the most accurately measured parameter for high-\( M_{\text{total}} \) systems (cf. Aasi et al. 2014 for IMBH systems), while \( M_{\text{total}} \) (cf. Fig. 2) suffers from a partial degeneracy with spin.

For these non-spinning injections, Fig. 6 shows the recovery of the combined effective spin \( \chi \equiv (m_1 a_1 + m_2 a_2)/M_{\text{total}} \) (Santamaria et al. 2010); \( \chi \) encompasses both the relatively well measured spin of the higher mass companion and the unconstrained spin of the lower mass companion. The effective spin can be constrained to \( \sim 1/5 \) of the prior range, always being consistent with \( \chi = 0 \). The trend towards larger positive \( \chi \) for high \( M_{\text{total}} \) is a consequence of the degeneracy between \( \chi \) and \( M_{\text{total}} \). There is a preference for systems at larger luminosity distances (as a consequence of our assumption of sources being uniformly distributed in volume), which makes signals quieter, but this can be compensated by an overestimation of \( M_{\text{total}} \). This, combined with \( q \) tending towards equal mass for those systems, forces \( \chi \) to higher positive values in order to correct for the in-band length of the observed signal, the end of the inspiral, and the well-measured ringdown frequency (cf. equation 1).

3.1 Effects of cosmology on inferring the presence of an IMBH

GW observations of IMRACs or IMBHBs may provide the first conclusive evidence for the existence of IMBHs. In order to infer...
the presence of an IMBH in an IMRAC, we need to be able to claim that $m_1$ is greater than a fiducial threshold $M_{\text{IMBH}}$ at a desired confidence level. Here, we follow Veitch et al. (2015b) and adopt a threshold mass $M_{\text{IMBH}} \geq 100 M_\odot$.\footnote{Veitch et al. (2015b) found that $m_1 \gtrsim 130 M_\odot$ was required to infer the presence of an IMBH in an IMBH at 95 per cent confidence.}

To infer the presence of an IMBH we must constrain the physical mass of the source. GWs are redshifted due to the expansion of the Universe. This corresponds to a redshifting of the companion masses as $m_{1,2} = m_{1,2}^{\text{source}}(1+z)$ for a signal at redshift $z$; thus far in the paper we have considered the redshifted masses as measured in the detector rest frame. Advanced ground-based detectors can observe IMRACs at maximum redshifts of $z\sim0.2$, depending on the mass ratio (e.g. Belczynski et al. 2014). A signal detected with $m_1 = 100 M_\odot$ and redshift $z = 0.2$ would correspond to a physical system with $m_{1,2}^{\text{source}} = 100/(1+0.2) \approx 83 M_\odot$, which would not be an IMBH by our definition. It is thus necessary to fold in redshift information in order to produce robust IMRAC mass measurements.

For each of our systems, we obtain a posterior on the luminosity distance $D_L$. The luminosity distance is related to the redshift by (Hobson, Efstathiou & Lasenby 2006, section 15.8)

$$D_L(z) = \frac{c(1+z)}{H_0} \int_0^z \frac{dz'}{\xi(z')}.$$  

(2)

where, if we assume zero curvature and neglect radiation energy density,

$$\xi(z) = \sqrt{(1+z)^3 \Omega_M + \Omega_\Lambda}.$$  

(3)

We invert equation (2) numerically to find $z(D_L)$, adopting standard cosmological parameters: $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 70.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$. We then calculate the primary mass in the source frame as

$$m_1^{\text{source}} = \frac{m_1}{1+z}.$$  

(4)

In Fig. 7, we show the fraction of the posterior distribution for $m_1^{\text{source}} > M_{\text{IMBH}}$ as a function of the injected primary source mass. We find that we can infer the presence of an IMBH with mass above $100 M_\odot$ at 95 per cent confidence when the system has $m_1^{\text{source}} \gtrsim 130 M_\odot$.

4 DISCUSSION

Having completed our PE study, validating our ability to measure the mass and spin parameters of IMRAC systems, we now focus on the sensitivity and robustness of our results to a selection of assumptions adopted in our analysis: the low-frequency sensitivity of the detectors (Section 4.1), the SNR of the signal (Section 4.2) and the accuracy of the waveform model (Section 4.3).

4.1 Impact of low-frequency sensitivity

As a consequence of the typical high total masses of IMRACs, the low-frequency sensitivity of the detectors is expected to be crucial for PE. IMRAC parameters are most precisely measured when they are determined by an inspiral with many in-band cycles, ending at the innermost stable circular orbit at a frequency $f_{\text{ISCO}}$. The transition in measurement accuracy seen in Fig. 3 will therefore be shifted to lower masses for decreased low-frequency sensitivity, caused by either a high noise floor or uncertain low-frequency calibration.

Fig. 8 shows a selection of frequency-domain IMRAC waveforms and the detector noise curves, represented as characteristic strain and noise amplitudes, respectively (Moore et al. 2015). The randomly chosen sky locations and orientations of our injections mean that for some mock events, the majority of the network SNR is contributed by AdV, with its relatively poorer low-frequency sensitivity, illustrated in Fig. 9. An example of this effect is seen in the $M_{\text{total}} = 275 M_\odot, q = 1/15$ event clearly visible in Fig. 1.

Low-frequency sensitivity is particularly critical for measuring the mass ratio, as the ringdown can only provide information on the total remnant mass and spin. For example, for an $M_{\text{total}} = 225 M_\odot, q = 1/15$ system which sits at the transition of inspiral detectability with the aLIGO noise spectrum with sensitivity starting at $f_{\text{low}} = 10\text{ Hz}$, the 90 per cent credible interval is $C_{1/2}^{90} \lesssim 0.05$. However, if sensitivity below 20 Hz is lost, $C_{1/2}^{90}$ spans half of the allowed range from 0 to 1, although more than 90 per cent of the SNR is
is robust under this systematic bias. Therefore, we expect this follows a trend, the, $= z$ (cf. Vallisneri $M_1$ 2016).

The SNR accumulated between 10 Hz and $f_{\text{cut}} \rho f_{\text{cut}}$ as a fraction of the total SNR $\rho$, for a system with $M_{\text{total}} = 225 M_\odot$ and $q = 1/15$ injected at $\rho = 15$. This illustrates the relative low-frequency sensitivity between aLIGO and AdV used in this analysis, cf. Fig. 8.

![Figure 9](https://example.com/figure9.png)

**Figure 9.** The SNR accumulated between 10 Hz and $f_{\text{cut}} \rho f_{\text{cut}}$ as a fraction of the total SNR $\rho$, for a system with $M_{\text{total}} = 225 M_\odot$ and $q = 1/15$ injected at $\rho = 15$. This illustrates the relative low-frequency sensitivity between aLIGO and AdV used in this analysis, cf. Fig. 8.

still available for detection (see Fig. 9). If $f_{\text{cut}} \rho f_{\text{cut}}$ increases to 30 Hz or above, $q$ becomes essentially unconstrained with CI $\chi(\rho)$ spanning 3/4 of its allowed range.

### 4.2 Uncertainty versus SNR

To investigate the effect of the loudness of the detected signal, a series of simulations at a range of SNRs were performed. For high $\rho$ the slope of which can be gauged by comparison with the magenta line.

![Figure 10](https://example.com/figure10.png)

**Figure 10.** The width of the 90 percent credible intervals as a function of injected network SNR $\rho$ for an example system ($M_{\text{total}} = 155 M_\odot$, $q = 1/30$), sampled at the indicated $\rho$. At high $\rho$ this follows a $1/\rho$ trend, the slope of which can be gauged by comparison with the magenta line.

4.3 Systematics

At the high mass ratios of IMRACs, the post-Newtonian expansion breaks down, an extreme-mass-ratio expansion in the mass ratio (the self-force problem; Poisson, Pound & Vega 2011) is not yet sufficient (e.g. Mandel & Gair 2009), and numerical-relativity solutions are extremely computationally expensive (e.g. Lousto et al. 2010; Husa et al. 2016). Therefore, possible model errors and the ensuing systematic bias in parameter recovery are a significant concern (Smith et al. 2013).

To validate our choice of SEOBNRv2 for this study, a subset of the events shown in Section 3 were repeated as injections with a different waveform family, but still recovered with SEOBNRv2_ROM_DoubleSpin. The injections were performed with IMRPhenomD (Husa et al. 2016; Khan et al. 2016), a phenomenological waveform model constructed in the frequency domain and calibrated against numerical relativity up to mass ratios $q \geq 1/18$. This calibration limit led to the exclusion of the most extreme mass ratio binaries ($q = 1/50$) from the injection set used to study of waveform systematics.

The systematic bias in the recovered $M_{\text{total}}$ introduced by the difference between IMRPhenomD injections and SEOBNRv2_ROM_DoubleSpin templates is small for all investigated systems, as shown in Fig. 11, confirming the results shown in Khan et al. (2016). In particular, it is comparable to or, in the majority of cases, much smaller than the statistical uncertainty shown in Fig. 2. Additionally, the width of the credible interval CI $\chi(\rho)$ remains largely unaffected by systematics, even outside the region where IMRPhenomD has been calibrated to numerical-relativity waveforms.

Using the same condition as in Section 3.1 for determining the presence of an IMBH, we find that the threshold of $m_{\text{source}}^\chi \geq 130 M_\odot$ is robust under this systematic bias. Therefore, we expect that, if the difference between IMRPhenomD and SEOBNRv2 is typical of the waveform model uncertainty in the IMRAC parameter space, then the systematic error introduced from waveform uncertainty should not hinder the identification of IMBHs from IMRAC observations. We evaluated the impact of systematics by comparing posterior probability distributions computed with different models of spin-aligned, circular templates without higher order modes; the impact of systematics will need to be re-evaluated once waveforms incorporating all of these effects are available.

### 5 SUMMARY

IMBHs may play an important role in the formation of supermassive BHs, and the dynamics of dense stellar environments like globular clusters (e.g. Trenti et al. 2007; Gill et al. 2008), yet conclusive evidence for their existence remains elusive. A network of advanced GW detectors can observe an IMBH as part of an IMRAC at cosmological distances, out to redshift $z \gtrsim 0.5$. Recent progress in the development of waveforms suitable for IMRAC systems has enabled the first systematic study of the measurement of the masses and spins of IMRACs. Despite the short in-band signal, we find that inference on the emitted GWs can provide interesting measurements of IMRAC systems.

For low-mass IMRAC systems, $M$ is the best constrained parameter. As total mass increases, the inspiral moves out of the sensitive frequency band of the detectors, after which most of the information comes from the ringdown of the merger remnant, so that the ringdown frequency is best constrained. For high-mass systems, $M_{\text{total}}$ is measured more precisely than $M$, but is still partly degenerate with the (poorly constrained) spin.

With a low and stable noise floor at low frequencies, it will be possible to infer the presence of an IMBH with mass $\geq 100 M_\odot$ at 95 percent confidence for systems with $m_{\text{source}}^\chi \geq 130 M_\odot$. This
relied on the assumption of standard cosmology to infer the source mass from the measured redshifted mass and luminosity distance. By using different waveform approximants for signal injection and PE, we confirm that our results, including the detectability of an IMBH, are robust against potential waveform errors so long as they fall in the range bracketed by these approximants.

Future investigations of IMRACs will benefit from ongoing waveform development to include spinning and precessing signals, possibly eccentric binaries, and higher order modes. Building upon improved confidence in PE with IMRAC waveforms, future studies could focus on using IMRAC observations to enhance our understanding of globular-cluster dynamics, and the suitability of IMRACs for high-precision tests of general relativity in the strong-field regime (e.g. Brown et al. 2007; Gair, Li & Mandel 2008; Rodriguez, Mandel & Gair 2012).

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Figure 11. Comparison of results recovered for IMRPhenomD (I) and SEOBNRv2 (S) injections. SEOBNRv2_ROM_DoubleSpin templates are used for PE in both cases. The left-hand panel shows the fractional difference in the recovered means of the $M_{\text{total}}$ posterior distributions $\Delta M_{\text{total}}^{I/S} = \langle (M_{\text{total}})^{I} \rangle - \langle (M_{\text{total}})^{S} \rangle$ as a function of $M_{\text{total}}$ and $q$. If the two injections were recovered with identical posterior means $\Delta M_{\text{total}}^{I/S} = 0$. The right-hand panel shows the natural logarithm of the ratio of 90 per cent credible intervals $R_{\text{CI}}^{I/S} = \ln(\text{CI}_{0.95}^{I}/\text{CI}_{0.95}^{S})$. If the posteriors have the same width, then $R_{\text{CI}}^{I/S} = 0$; $R_{\text{CI}}^{I/S} < 0$ indicates that the posterior distribution is narrow for the IMRPhenomD injection than for the SEOBNRv2 injection.

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