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DETECTION OF IMBHS WITH GROUND-BASED GRAVITATIONAL WAVE OBSERVATORIES: A BIOGRAPHY OF A BINARY OF BLACK HOLES, FROM BIRTH TO DEATH

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ABSTRACT

Even though the existence of intermediate-mass black holes (IMBHs, black holes with masses ranging between $10^{2-4} M_\odot$) has not yet been corroborated observationally, these objects are of high interest for astrophysics. Our understanding of formation and evolution of supermassive black holes (SMBHs), as well as galaxy evolution modeling and cosmography would dramatically change if an IMBH was observed. From a point of view of traditional photon-based astronomy, the *direct* detection of an IMBH seems to be rather far in the future. However, the prospect of detection and, possibly, observation and characterization of an IMBH has good chances in lower-frequency gravitational-wave (GW) astrophysics with ground-based detectors such as LIGO, Virgo and the future Einstein Telescope (ET). We present an analysis of the signal of a system of a binary of IMBHs (BBH from now onwards) based on a waveform model obtained with numerical relativity simulations coupled with post-Newtonian calculations at the highest available order so as to extend the waveform to lower frequencies. We find that initial LIGO and Virgo are in the position of detecting IMBHs with a signal-to-noise ratio (SNR) of ~ 10 for systems with total mass between 100 and $500 M_\odot$ situated at a distance of 100 Mpc. Nevertheless, the event rate is too low and the possibility that these signals are mistaken with a glitch is, unfortunately, non-negligible. When going to second- and third-generation detectors, such as Advanced LIGO or the ET, the event rate becomes much more promising (tens per year for the first and thousands per year for the latter) and the SNR at 100 Mpc is as high as $100 - 1000$ and $1000 - 10^5$ respectively. The prospects for IMBH detection and characterization with ground-based GW observatories would not only provide us with a robust test of general relativity, but would also corroborate the existence of these systems. Such detections would be a probe to the stellar environments of IMBHs and their formation.

Subject headings:

1. MOTIVATION

By following the stellar dynamics at the center of our Galaxy, we have now the most well-established evidence for the existence of a SMBH. The close examination of the Keplerian orbits of the so-called S-stars (also called S0-stars, where the letter "S" stands simply for source) has revealed the nature of the central dark object located at the Galactic Center. By following S2 (S02), the mass of SgrA* was estimated to be about $3.7 \times 10^6 M_\odot$ within a volume with radius no larger than 6.25 light-hours (Schödel et al. 2003; Ghez et al. 2003). More recent data based on 16 years of observations set the mass of the central SMBH to $\sim 4 \times 10^6 M_\odot$ (Eisenhauer et al. 2005; Ghez et al. 2005, 2008; Gillessen et al. 2009).

Massive black holes in a lower range of masses may exist in smaller stellar systems such as globular clusters. These are called intermediate-mass black holes (IMBHs) because their masses range between $M \sim 10^{2-4} M_\odot$, if we assume that they follow the observed correlations between SMBHs and their host stellar environments. Nevertheless, IMBHs have never been detected, though we have some evidences that could favor them (see Miller & Colbert 2004; Miller 2009, and references therein).

If we wanted to apply the same detection technique to detect IMBHs in globular clusters as we do with SMBHs in galactic centres, one would need ultra-precise astronomy, since the sphere of influence of an IMBH is $\sim$ few arc seconds. The number of stars enclosed in that volume is only a few. Currently, with adaptive optics, one can aspire – being optimistic – to have a couple of measurements of velocities if the target is about ~ 5 kpc away in the time basis of 10 yrs. The measures depend on a number of factors, such as the required availability of a bright reference star, in order to have a good astrometric reference system. Also, the sensitivity limits correspond to a K-band magnitude of ~ 15, (B- MS stars at 8 kpc, like e.g. S2 in our Galactic Center).

This means that, in order to detect an IMBH or, at least, a massive dark object in a globular cluster center with traditional astronomy by following the stellar dynamics around it, one has to resort to the Very Large Telescope interferometer and to one of the next-generation instruments, the VSI or GRAVITY (Gillessen et al. 2006; Eisenhauer et al. 2008). In this case we can hope to improve the astrometric accuracy by a factor of ~ 10. Only in that scenario we would be in the position of following closely the kinematics around a potential IMBH, so as to determine its mass.

The possibility of bringing GW astronomy into the picture constitutes a promising avenue towards detection. In the past years, the field has reached a milestone with the construction of an international network of GW interferometers that have achieved or are close to their design sensitivity. Moreover, the first-generation ground-based detectors LIGO and Virgo will undergo major technical upgrades in the next five years that will increase the volume of the observable universe by a

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factor of 1000[3].

The data that will be taken by the advanced interferometers are expected to transform the field from GW detection to GW astrophysics. The availability of accurate waveform models for the full BBH coalescence in order to construct templates for match-filtering is crucial in the GW searches for compact binaries. The construction of this kind of templates has recently been made possible thanks to the combination of post-Newtonian calculations of the BBH inspiral and numerical relativity simulations of the merger and ringdown.

GRAVITY, as well as Advanced LIGO, is planned to be operational in 2014. The potential detection of IMBHs with these two instruments would allow us to do multi-messenger astronomy. The optical examination of the kinematics in a cluster center could reveal the presence of a massive BH, which would then enable the possibility of complementing the information about the electromagnetic spectrum with the associated GW emission, if there was a binary of IMBHs, as we describe in next section.

The structure of this paper is as follows: In section 2 we will expand the astrophysical context to this problem and give a description of the different efforts made to address the evolution of a BBH in a stellar cluster, from its birth, to the final coalescence. Next, in section 3, we give an estimate for the number of events one can expect for Advanced LIGO and the Einstein Telescope, so as to motivate the rest of the work. In section 4 we give an updated description of the current and future ground-based lower-frequency GW detectors. In section 5 we depict current and some past efforts in the searches for binaries of BHs with LIGO and Virgo and the range of masses that they have targeted. In section 6 we introduce the techniques used in data analysis with respect to waveform modeling of BBH coalescences, we present our hybrid waveform and briefly discuss the advantages of hybrid PN-NR waveforms, whilst giving a short description of published and on-going work in this regard. In the next section 7, the angle-averaged signal-to-noise ratio for IMBHs as will be measured by various ground- and space-based detectors is calculated. Finally, we present the conclusions of our work in section 8.

2. LIFE OF A MASSIVE BINARY

The aim of this section is not to give a detailed explanation of the processes of formation of IMBHs and binaries of IMBHs (BBHs), but a description of the global picture so as to introduce the two different scenarios that play a role in the formation of BBHs.

2.1. *Birth*

Up to now the IMBH formation process which has drawn more attention is that of a young cluster in which the most massive stars sink down to the center due to mass segregation. There, a high-density stellar region builds and stars start to physically collide. One of them gains more and more mass and forms a runaway star whose mass is much larger than that of any other star in the system. Later, that runaway star may collapse and form an IMBH (Portegies Zwart & McMillan 2000; Gürkan et al. 2004; Portegies Zwart et al. 2004; Freitag et al. 2006a).

We can theoretically explain the formation of a binary of two IMBHs in a cluster in two different ways.

(i) The double-cluster channel :

[3] http://www.ligo.caltech.edu/advLIGO/, http://wwwcascina.virgo.infn.it/advirgo/

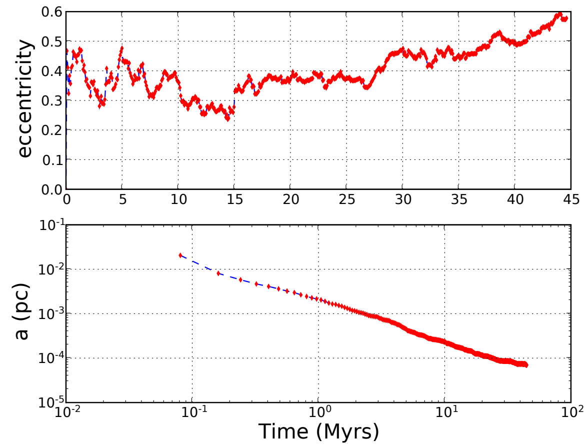

FIG. 1.— Evolution of the orbital parameters of a born-in (second channel of formation) BBH of total mass $600 M_\odot$, which is taken from the direct N–body model C of Amaro-Seoane et al. (2009b). Initially the BBH had a semi-major axis of 0.1 pc and we used for the initial conditions a King model of profile $W_0 = 6$ (King 1966). The cluster follows an initial-mass function of Kroupa, more specifically a 5-Myrs evolved Kroupa IMF of masses 0.2, 0.5, 50 and exponents 1.3 and 2.3 (Kroupa 2001). The BBH semi-major axis shrinks slowly and its eccentricity e increases

In this scenario, two clusters born in a cluster of clusters, such as those found in the Antennæ galaxy, are gravitationally bound and doomed to collide (see Amaro-Seoane & Freitag 2006, for a detailed explanation of the process and their references). When this happens, the IMBHs sink down to the center of the resulting merged stellar system due to dynamical friction. They form a BBH whose semi-major axis continues to shrink due to slingshot ejections of stars coming from the stellar system. In each of the processes, a star removes a small fraction of the energy and angular momentum of the BBH, which becomes harder. At later stages in the evolution of the BBH, GW radiation takes over efficiently and starts to circularize, though one can expect these systems to have a residual eccentricity when entering the LISA band (Amaro-Seoane & Freitag 2006). For this detector and channel, the authors estimated an event rate of $4-5\ \mathrm{yr}^{-1}$.

(ii) The single-cluster channel : Gürkan et al. (2006) added a fraction of primordial binaries to the initial configuration in the scenario of formation of a runaway star in a stellar cluster. In their simulations they find that not one, but two very massive stars form in rich clusters with a binary fraction of 10%. Fregeau et al. (2006) investigated the possibility of emission of GWs by such a BBH and estimated that LISA and Advanced LIGO can detect tens of them depending on the distribution of cluster masses and their densities. More recently, Gair et al. (2009) addressed the event rate that the proposed Einstein Telescope could see and quoted a few to a few thousand events of comparable-mass IMBH mergers of the single-cluster channel.

2.2. *Growing up (shrinking down): The role of triaxiality on centrophilic orbits*

We show in Figure 1 the evolution in a cluster of 30002 $N_\star$ of a BBH of IMBHs for the single-cluster channel. The semi-major axis of the BBH shrinks slowly, the binary becomes harder and the eccentricity increases to $e \sim 0.6$.

A problem into which one runs when simulating the scenario of two bound IMBHs on their way to coalescence with direct N–body techniques is that numerically it is out of the question to integrate the system down to the frequencies of interest for us. In the case of the double-cluster channel, the cluster, which is in rotation, results from the merger of the two initial clusters has a triaxiality which is not sufficient to produce enough centrophilic orbits. These "boxy" orbits, as seen by Berczik et al. (2006), are typical of systems that do not possess a symmetry around any of their axes. On the contrary to loop orbits, a characteristic of spherically symmetric or axisymmetric systems, "boxy" orbits bring stars arbitrarily close to the centre of the system, since it oscillates independently along the three different axes. Therefore, such stars, due to the fact of being potential sling-shots, can feed the process of shrinkage of the BBH semi-major axes by removing energy and angular momentum out of it after a strong interaction. In the strong triaxial systems of Berczik et al. (2006), the rotation caused in the process of merger creates an unstable structure in the form of a bar. Within the bar the angular momentum will not be conserved and thus the BBH loss-cone is full due to the stars on centrophilic orbits, independently of the number of stars $N_{\star}$.

In the models of Amaro-Seoane & Freitag (2006), the initial conditions are a realistic parabolic merger of two stellar clusters. The resulting merged cluster does not show the strong axisimmetry of Berczik et al. (2006). Whilst the loss-cone is not empty, because we see a shrinkage due to stellar encounters, the flow of stars is too low to integrate such systems with direct N–body down to the moment of interest for the observation of GWs, the moment at which the BBH enters the first detection possibility in the LISA window. One reason for this low flow in this case could be that the initial angular momentum given to the clusters was not sufficient for it. In any case, it does not make sense to integrate a whole cluster for a very long time in order to follow the evolution of two single particles, the IMBHs, that interact only with a star from time to time. One has to resort to a semi-analytical approach, such as in Amaro-Seoane & Freitag (2006) to understand what the orbital parameters of the BBH will be when it enters the LISA bandwidth.

In Figure 2 we show the role of the cluster symmetry explicitly by depicting the evolution of the triaxiality of the cluster formed as a result of the merger of the two clusters for our fiducial model in the case of the double-cluster channel (which is the reference model of Amaro-Seoane & Freitag 2006). After a merger which is the result of a parabolic orbit, the final system is oblate rather than prolate; i.e. $a \sim b > c$, where a, b and c are the cluster axes. At the outskirts the resulting merged cluster is flatter and at the centre the binary of IMBHs makes it rather spherical. This is true for the case of the double-cluster channel. In the single-cluster channel, where we do not have two merging clusters, the situation is even worse, because of the absence of the initial triaxiality in the system. Amaro-Seoane et al. (2009b) addressed this scenario and used additional simulations to further evolve the BBH. They used scattering experiments of three bodies including relativistic precession to 1st post-Newtonian order, as well as radiation reaction caused by GW, so that they did not have to integrate every single star in the cluster to understand the posterior evolution of the BBH. In their work, between the strong encounters, a and e of the BBH were evolved by resorting to the quadrupolar formulæ of Peters (1964).

In Figure 3 we show the ulterior evolution of such a BBH starting from the last point of an N–body simulation. We see that the eccentricity in this case decays to $e = 0.01$ in the moment in which the BBH reaches the LISA sensitivity window.

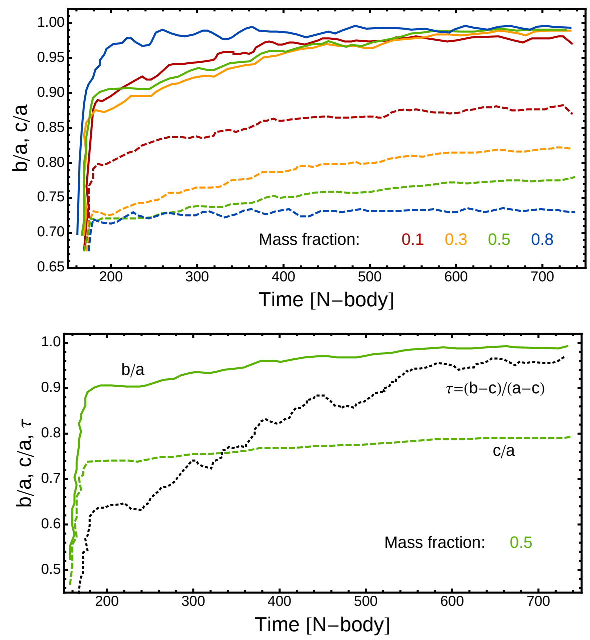

FIG. 2.— Triaxiality of the resulting merged cluster for different mass fractions (upper panel) and the mass fraction 0.5. We calculate the semi-major axes of the ellipsoid of inertia a, b and c (where $a > b > c$) according to four different mass fractions which, in turn, are distributed on the basis of the amount of gravitational energy. The shorter the distance to the center of the resulting cluster, the lower the mass fraction. Displayed are b/a (solid lines) and c/a (dashed lines). The lower panel shows the shape indicators for the mass fraction 0.5, together with the evolution of the parameter τ, an indicator for the triaxiality of the system, which tends to one as time elapses; i.e. the system tends to be oblate. The evolution of τ is similar for the rest of mass fractions

In other cases of Amaro-Seoane et al. (2009b), though, the final eccentricity was as large as $e \sim 0.2$. This is an important point, because this eccentricity could be a finger-print to this process. The BBH will have completely circularized when it reaches the frequencies probed by Advanced LIGO and the ET, because the emission of GWs takes over the dynamics of the system.

2.3. *Death*

While the emission of GWs is present all the time from the very first moment in which the BBH is formed, the amplitude and frequency of the waves is initially so low that no present or planned detector would be able to register any information from the system. Only when the semi-major axis shrinks sufficiently, the frequency increases enough so as to "enter" the LISA band, which we assume starts at 10^{-4} Hz. The BBH then crosses the entire detector window during its inspiral phase, as we can see in Figure 4. We depict the evolution of a BBH of mass $439.2 + 439.2\,M_{\odot}$. The reason for this particular choice of masses is to give the reader a point of reference to understand the whole picture. Recently, Amaro-Seoane et al. (2009a) included the effect of rotation of the host cluster and addressed the dynamical evolution of the global system. They found some cases which led to high eccentricities at the entrance of the detector LISA. The authors also made a parameter estimation for these high-eccentricity sources and found with Monte Carlo realizations that LISA will observe some of them with signal-to-noise ratios (SNRs) of 300 or greater, though the median SNR should be between 10 and 20. The chirp-mass was estimated to be detected with

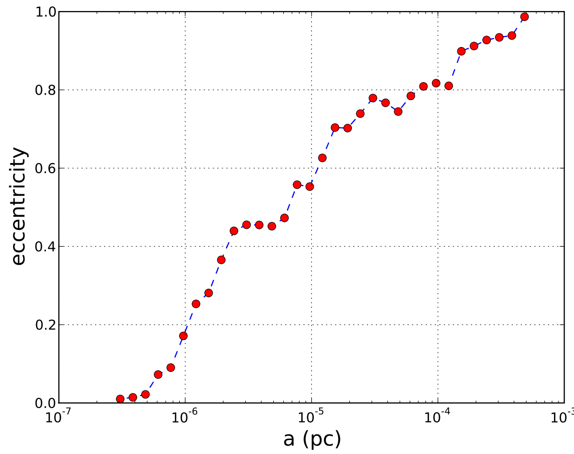

FIG. 3.— Ulterior evolution of a BBH of masses $1000\,M_\odot - 1000\,M_\odot$. For this particular model of Amaro-Seoane et al. (2009b), a King model of $W_0 = 6$ with an initial semi-major axis of 400 AU and $e = 0.5$ embedded in a stellar cluster with a Kroupa mass function. The last point of their N−body simulation was used to feed the relativistic scattering processes to follow the evolution of the orbital parameters down to the moment in which the GW frequency is 10^{-4} Hz and, hence, in the LISA band. At that moment, $e = 0.01$

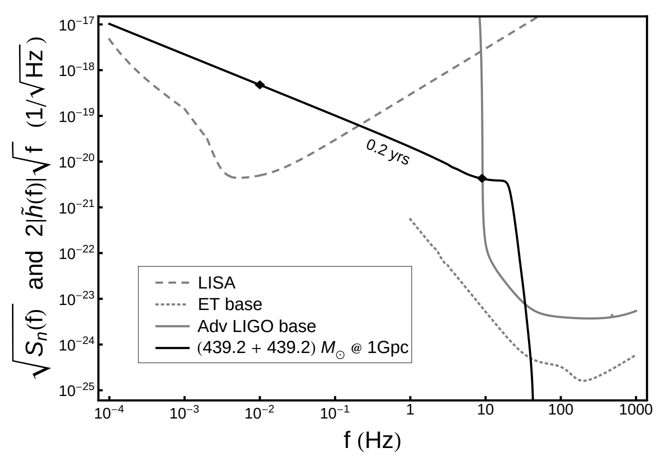

FIG. 4.— Amplitude of the GW emitted by a system of two equal-mass IMBHs of total mass $878.4\,M_\odot$ as seen by different GW observatories. Note that we have multiplied $|\tilde{h}(f)|$ by a factor $2\sqrt{f}$, with f the frequency of the system. This is required in order to be able to compare it with the sensitivity curve of the different detectors (see section 7 for more details). From left to right we depict the sensitivity windows of the future space-borne LISA (dashed, grey curve), the Einstein Telescope (dotted, grey curve) and Advanced LIGO (solid, grey line starting sharply at 10 Hz). The strain of the BBH of IMBHs spends most of its inspiral in the LISA band, whilst the ringdown and merger occur at higher frequencies, only observable by ground-based detectors. Notably, the ET captures an important extent of the inspiral as well as the whole ringdown and merger. The BBH system spends approximately 0.2 yrs to go from $f = 0.01$ Hz (well into the LISA band) up to the lower cut-off frequency of Advanced LIGO, 10 Hz. These two points are pinpointed on the plot

median fractional errors of 10^{-4}, the reduced mass on the order of 10^{-3} and the luminosity distance on the order of 10^{-1}. In order to follow the system at this early stage of its evolution in the LISA band, a simple post-Newtonian approach suffices for modeling the GW radiation. We are far enough from the highly relativistic regime and only the inspiral phase of the BBH coalescence is visible to the space antenna.

As the IMBH system depicted in Figure 4 leaves the LISA band and enters the strong field regime, higher order post-Newtonian corrections and eventually input from numerical relativity simulations need to be considered in order to model the GW waveform. Three reference frequencies in the evolution of a compact BBH that approaches its merger are the innermost stable circular orbit ($f_{\rm ISCO}$) of a test particle orbiting a Schwarzschild black hole, the light-ring frequency ($f_{\rm LR}$) corresponding to the smallest unstable orbit of a photon orbiting a Kerr black hole and the fundamental ringdown frequency ($f_{\rm FRD}$) of the decay of the quasi-normal modes computed by Berti et al. (2005).

For the binary system shown in Figure 4, the values of these three frequencies are $f_{\rm ISCO}|_{878.4M_\odot} \simeq 5$ Hz, $f_{\rm LR}|_{878.4M_\odot} \simeq 14.2$ Hz and $f_{\rm FRD}|_{878.4M_\odot} \simeq 21.4$ Hz. Should such a binary exist at a distance of 100 Mpc, and if it was to be detected with Advanced LIGO, it would produce a sky-averaged SNR of ~ 450, assuming a low frequency cut-off of 10 Hz. To that total SNR, the contribution of parts of the inspiral happening before the system reaches the characteristic frequencies $f_{\rm ISCO}$, $f_{\rm LR}$ and $f_{\rm FRD}$ would be 0%, 37% and 95% respectively. Figure 5 illustrates the same percentages for binaries with total masses between 100 and $2000\,M_\odot$. It is immediately noticed that, for the IMBHs of interest in this study, most of the SNR that these binaries will produce in Advanced LIGO comes from the last stages of the the BBH coalescence.

Amaro-Seoane et al. (2009a) have shown that LISA will see the system of Figure 4 with a median SNR of few tens. The fact that the system merges outside its band prevents LISA from observing the loudest part of the BBH coalescence. Nevertheless, the future generations of ground-based interferometers are in an excellent position to observe the merger of IMBH systems, which will conveniently fall inside their sensitivity bands.

We can estimate the time that the IMBH system takes to evolve from $f = 0.01$ Hz, a frequency where the BBH can be seen by LISA, to the lower cut-off frequency of 10 Hz of Advanced LIGO or of 1 Hz of the ET. A lower order approximation based on the Newtonian quadrupole formula (Peters 1964) leads to the following expression for the evolution of the frequency in terms of the chirp mass $\mathcal{M} = (m_1 m_2)^{3/5} M_{\rm tot}^{-1/5}$ and frequency of the system

$$\frac{df}{dt} = \frac{96}{5}\pi^{8/3}\mathcal{M}^{5/3} f^{11/3}. \qquad (1)$$

We find a delay of only 0.2 yrs (80 days) for a BBH with total mass $M = 878.4\,M_\odot$ to go from 0.01 Hz to the beginning of the Advanced LIGO band and almost similar numbers to the beginning of the ET band (the evolution of the system is extraordinarily quick in the late inspiral phase, which explains the fast evolution from 1 to 10 Hz). In view of these figures, LISA could be used as an “alarm” to prepare ground-based detectors to register in detail the final coalescence, the death of the BBH as such, by adjusting their *sweet spots* (the most sensitive part of the detector) to the particular BBH. The high accuracy of which LISA is capable for parameter estimation during the inspiral phase could be combined with the information obtained from the large-SNR triggers that the BBH merger and ringdown will produce in Advanced LIGO or ET to achieve a more complete characterization of the system.

3. EVENT RATES

Fregeau et al. (2006) calculated the number of events that initial and Advanced LIGO (and LISA) could see from the single-cluster channel. In their estimation, they assume that

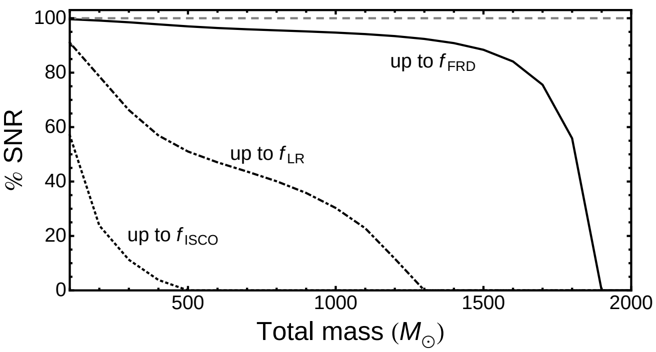

FIG. 5.— Percentage of the total SNR produced by IMBH inspiralling signals cut at the three reference frequencies f_{ISCO}, f_{LR} and f_{FRD}. The SNRs have been calculated using the noise curve of Advanced LIGO for signals placed at 100 Mpc of the detector starting at 10 Hz and with a total mass between 100 and $2000\,M_\odot$. Whereas the SNR computed up to f_{ISCO} constitutes more than 50% of the total SNR for systems with total mass below $100\,M_\odot$, it is the merger and ringdown parts of the coalescence (after f_{LR} and f_{FRD}) that contribute most to the SNR as the total mass of the system increases above a few hundreds of solar masses

the very massive stars formed in the runaway scenario do not merge into one, but evolve separately and eventually each form an individual IMBH, following the numerical results of the Monte Carlo experiments of Gürkan et al. (2006). Amaro-Seoane & Freitag (2006) gave a prescription to get an estimate of the event rates for the double-cluster channel by resorting to the detailed calculation of Fregeau et al. (2006). This was based in the fact that the only difference between both astrophysical scenarios in terms of the event calculation involves (i) the fact that in the double-cluster channel one has one single IMBH in one cluster and (ii) these two clusters have to collide so that the IMBHs form a BBH when they sink to the center due to dynamical friction.

The two different works assumed that the probability that a cluster gets into the runaway phase is P_{ra} ($P_{ra} = 1$ meaning that all of them evolve to it). Fregeau et al. (2006) took this value as a parameter because of the large uncertainties and set it to 0.1 as an example. Nevertheless, as proven in the simulations of Freitag et al. (2006b), it could be *as large as 0.5*.

As explained in section 4 of Amaro-Seoane & Freitag (2006), the connection between the event rate estimation of the two channels is

$$\Gamma^{\rm doub} = P_{\rm merg}\, P_{\rm ra}\, \Gamma^{\rm sing}, \tag{2}$$

where $\Gamma^{\rm doub}$ is the event rate of the double-cluster channel, $\Gamma^{\rm sing}$ of the single-channel and $P_{\rm merg}$ is the probability for two clusters to collide in the scenario of Amaro-Seoane & Freitag (2006). As explained in their work, $P_{\rm merg} \in [0.1, 1]$

$$\Gamma^{\rm sing}_{\rm Adv.\,LIGO} = 10 \cdot \left(\frac{P_{\rm ra}}{0.1}\right) \,{\rm yr}^{-1} \tag{3}$$

$$\Gamma^{\rm doub}_{\rm Adv.\,LIGO} = P_{\rm merg} \cdot 10 \left(\frac{P_{\rm ra}}{0.1}\right)^2 \,{\rm yr}^{-1}. \tag{4}$$

We therefore can define the (absolute) "optimistic" upper limit and "pessimistic" lower limit of the event rates by assigning all parameters their maximum and minimum values.

For initial LIGO, even taking into account the second channel of forming binaries of IMBHs, the double-cluster channel, the event rate seems to be negligible, even when considering the most optimistic assumptions for the uncertain parameters. For Advanced LIGO,

$$\Gamma^{\rm total}_{\rm Adv.\,LIGO} \in [(0)\,11, 300]\,{\rm yr}^{-1}. \tag{5}$$

We can apply the same argument in the case of the ET detector by following the recent calculation of Gair et al. (2009) for the single-channel and extend it to the double-channel, so that we have

$$\Gamma^{\rm sing}_{\rm ET} = 2000 \left(\frac{P_{\rm ra}}{0.1}\right)\left(\frac{g_{\rm gl}}{0.1}\right) {\rm yr}^{-1} \tag{6}$$

$$\Gamma^{\rm doub}_{\rm ET} = P_{\rm merg} \cdot 2000 \left(\frac{P_{\rm ra}}{0.1}\right)^2 \left(\frac{g_{\rm gl}}{0.1}\right) {\rm yr}^{-1}, \tag{7}$$

where $g_{\rm gl}$ is a certain redshift-independent fraction of the total star formation rate per comoving volume. Its value is unknown. We follow Gair et al. (2009) in their estimation and set it to $g_{\rm gl} = 0.1$. Thus, the "optimistic" upper limit and "pessimistic" lower limit in the event rates for the ET are

$$\Gamma^{\rm total}_{\rm ET} \in [(0)\,4000, 6 \cdot 10^4]\,{\rm yr}^{-1} \tag{8}$$

Even though the optimistic upper limit is to be taken carefully, these event rates are obviously more than encouraging to address the problem of detection and characterization of systems of IMBH binaries with ground-based detectors of GWs, particularly with Advanced LIGO and the ET. On the other hand, one should bear in mind that the existence of IMBHs altogether has not yet been corroborated, so that the pessimistic estimate is still somewhat optimistic. This is why we have added a (0) in the previous rates.

4. GROUND-BASED GW DETECTORS

An international network of first-generation ground-based GW detectors – LIGO (Abbott et al. 2007), Virgo (Acernese et al. 2008), GEO600 (Grote 2008) – recently finished taking data at or close to design sensitivity. In late 2007 the LIGO detectors completed their fifth science run, S5, during which one year of triple-coincident data was collected at design sensitivity. The addition of the Virgo and GEO600 interferometers to the joint data taking has given rise to the most sensitive GW-detection effort to date. The currently operating ground-based detectors are Michelson interferometers with the additional feature of Fabry-Perot arms and have been designed to be most sensitive to GW signals in the 10^{1-4} Hz band. The analysis of the detectors' data by the Virgo and LIGO scientific collaborations has already lead to astrophysically-relevant results, such as a lower upper limit on the gravitational radiation emitted by the Crab pulsar (Abbott et al. 2008a) and the statement that GRB070201 was unlikely to have originated from the merger of a neutron star binary in M31 (Abbott et al. 2008b).

As of summer 2009, the two 4 km LIGO and the 3 km Virgo detectors have undergone their respective upgrade programs, known as Enhanced LIGO and Virgo+. A one- to two-year joint S6/VSR2 science run with these enhanced interferometers has recently begun in July 2009 and will finish at the beginning of 2011.

The following years will however see significant sensitivity improvement of the detectors and more extensive upgrades in what will constitute a second generation of GW interferometers. Advanced LIGO and Virgo will replace their existing hardware with new technology, with the goal of gaining a factor of 10 in improved sensitivity with respect to the first-generation detectors. One of the most significant consequences of the upgrades in the suspension systems of LIGO will be the reduction of the seismic cut-off frequency from the existing 40 Hz value in initial LIGO to 10 Hz for the advanced

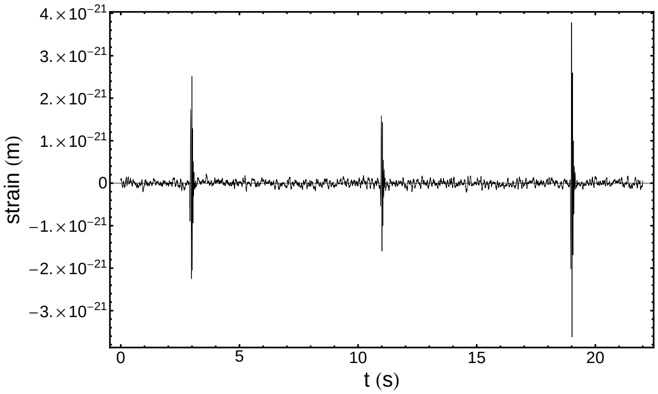

FIG. 6.— IMBH systems as will be seen in the time-domain output strain of the detector by the Advanced LIGO interferometer at the Livingston site. Three signals corresponding to equal-mass, non-spinning IMBH systems with total mass $400M_{\odot} \leq M_{\rm total} \leq 700M_{\odot}$ and random orientations and polarization angles have been placed at 1 Gpc from the detector with a starting frequency of 10 Hz. The L1 interferometer strain has been modeled by Gaussian noise colored with the design sensitivity curve expected for Advanced LIGO. Depending on their distance and orientation, the signals could be spotted by eye, which gives an intuitive idea of the kind of "bright" (in terms of GW emission) sources they are

detector. To improve the sensitivity limited by the quantum noise, the laser power will be increased from the 10 W of initial LIGO to $\sim$ 200 W. A signal recycling mirror will give the advanced detectors the ability to tune the interferometer frequency response, so that the sensitivity can be optimized for detection of different kinds of astrophysical sources. The second generation of ground-based interferometers will most likely inaugurate an era of routine GW observations, as its physical reach during their first several hours of operation will exceed the integrated observations of the first year LIGO science run. If the current instruments do not make the first detection of GWs, the second-generation interferometers should succeed.

The fundamental low-frequency limitations of the second-generation detectors are given by thermal, gravity gradient and seismic noise. To circumvent these problems, yet a third generation of GW interferometers to be operated underground is currently being proposed. The Einstein Telescope[4] will be a 10 km laser-interferometer with a sensitivity 100 times larger than that of the current detectors. Moreover it will cover the frequency range between 1 Hz and 10^4 Hz, increasing the ability to detect massive BBHs which merge at frequencies lower than the cut-off values of LIGO and Virgo. Once the design study and the technical preparation phase are completed, construction could begin after the second-generation observatories have started operation, probably before the end of the next decade.

The frequency range that the ET will be able to probe and its expected sensitivity could make this third-generation, ground-based interferometer a complementary companion for the space antenna LISA, a very advantageous fact, since these two detectors might well be operating simultaneously. Whereas the geometry of the current ground-based detectors requires a multi-site network to measure the polarization of the GW signal, the ET design will be able to do so by itself, benefiting from two coaligned, coplanar detectors at a single site. The currently favored design contains three independent detectors arranged in an equilateral-triangle geometry. The expected sensitivity curve for this "baseline" design of the ET is shown in Figure 8. An alternative "xylophone" configuration of the ET has been proposed by Hild et al. (2009), which trades off improved sensitivity near 10 Hz for decreased sensitivity at higher frequencies. The ability to operate either in broad- or narrow-band mode – within the frequency range where the noise budget is limited by photon-shot noise – in order to optimize the sensitivity to targeted astrophysical sources is a common characteristic of the proposed ET and the Advanced LIGO and Virgo detectors.

[4] http://www.et-gw.eu/

5. CURRENT SEARCHES FOR BBH SIGNALS WITH LIGO AND VIRGO

Data taken prior to May 2007 by the LIGO and GEO600 detectors has been or is currently being analyzed by the international LIGO Scientific Collaboration. Due to an agreement between the LSC and the Virgo collaboration, all data collected after that date are to be analyzed and published jointly. Depending on the GW sources to be searched for, different analysis techniques are employed. For transient, modeled sources such as compact binaries, for which an accurate theoretical understanding of the waveforms exists, searches based on matched filtering are the optimal analysis choice. To this category belong binary inspirals formed by neutron stars and/or black holes. If the sources can only be modeled imperfectly, as is the case of core-collapse supernovae and neutron-star quakes, a more general approach to detection of GW burst needs to be taken. Searches for continuous waves and stochastic GW background are also underway, for sources others than the IMBH systems of interest for the work presented here.

Past LIGO searches for coalescing binaries have traditionally split the total mass parameter space in several regions, partially due to lack of a complete theoretical model of all the stages of the coalescing process and also because different triggers rates are expected for different mass ranges. Post-Newtonian calculations that describe well the adiabatic inspiral of a binary, when the two coalescing objects are far apart and the gravitational field is weak, have been available for more than a decade (see the review by Blanchet 2006, and references therein) and are continuously being improved with the publication of higher post-Newtonian terms in the series expansion (Blanchet et al. 2004, 2008). This approximation is valid up to the innermost circular stable orbit (ISCO) which happens at a mass-dependent frequency $f_{\rm ISCO} = \left(2.8M_{\odot}/M_{\rm total}\right)1600\,{\rm Hz}$.

The latest results corresponding to an inspiral search for binaries with total masses between 2 and $35M_{\odot}$ in the first year of the S5 LIGO data (Abbott et al. 2009b) and the subsequent half year prior to the joint LIGO/Virgo data taking (Abbott et al. 2009c) making use of 2nd order PN templates have been recently published. No GW signals were detected and therefore an upper limit of $1.4\times10^{-2}, 7.3\times10^{-4}$ and $3.6\times10^{-3}{\rm yr}^{-1}{\rm L}_{10}^{-1}$ on the rates of binary neutron star systems, binary black hole systems and black hole-neutron star binary systems respectively is computed. L_{10} is 10^{10} times the blue solar luminosity. In addition to this BNS, BBH, and NSBH low-mass search, an externally triggered search associated to short-hard GRBs is also being performed in S5 data with the help of PN templates, for these processes are thought to originate in the merger of a neutron star with another compact object.

IMBH binaries with a total mass of $10^{2\text{–}4}M_{\odot}$ reach the ISCO at frequencies ranging from 45 to 0.45 Hz, which makes the inspiral phase of their coalescence effectively invisible to the currently operating first-generation detectors, hence an alternative to matched filtering with PN waveforms is necessary. A perturbative calculation of the ringdown phase of the BBH coalescence can be done assuming that the post-merger BBH results in a final Kerr black hole (Leaver 1985; Echeverria 1989), for which an analytical family of damped sinusoidal waveforms can be used to construct a template bank as shown by Creighton (1999). Such a search has been performed in the S4 LIGO data stream for BBH systems with masses between 85 and 390$M_\odot$ assuming a uniform distribution of sources(Abbott et al. 2009a), again leading to a null result and a upper limit of $1.6\times10^{-3}\mathrm{yr}^{-1}\mathrm{L}_{10}^{-1}$ on the rate of BBH ringdowns in the local universe. The corresponding results for a similar search in the LIGO S5 data are in progress.

As it has already been pointed out, the above-mentioned searches are targeted towards detection of a specific part of the BBH coalescence, be it the adiabatic inspiral or the final ringdown. With the success of numerical relativity codes in computing the late inspiral, merger and ringdown of a BBH system, pioneered by Pretorius (2005); Campanelli et al. (2006); Baker et al. (2006), the prospects for performing a search that benefits from a template bank modeling the full coalescence process have become promising. A search for binary systems with total mass between 25 and 100$M_\odot$ in S5 using this kind of approach is currently in progress. For a review of the ongoing activities of the LIGO and Virgo collaborations see Abbott et al. (2007) and Acernese et al. (2008). With respect to the binary systems of interest for this work, it will suffice to say that no current LSC or Virgo matched-filter search is specifically targeted to IMBH systems with masses in the $10^{2-4}M_\odot$ range. In our opinion, due to their astrophysical relevance and the advent of the second-generation detectors within the first half of next decade, future searches ought to be carefully designed to pursue detection of this kind of system.

6. WAVEFORM MODEL

Accurate theoretical modeling of the gravitational radiation $h(t)$ emitted by an IMBH system is key to improving its detectability and parameter estimation. Wiener optimal filter (“matched filter”) is the standard algorithm currently used in GW searches of BBH coalescences for which a template bank of waveforms is available. While post-Newtonian (PN) theory is valid to model the early inspiral phase of the BBH evolution, an exact description of the merger and ringdown stages is only possible via numerical relativity (NR) calculations. For comparable-mass scenarios, simulations are available that model the late inspiral, merger and ringdown by numerically solving the vacuum Einstein equation. Gravitational waves can be extracted from the numerically-simulated space-time by means of the Newman-Penrose scalar Ψ_4 via the electromagnetic decomposition of the Weyl tensor, see for instance Bruegmann et al. (2008). If the boundary of the numerical grid is placed far enough from the inspiralling BHs, the GW radiation as a distant detector would see it can be computed and extrapolated. Moreover, a recent implementation of the Cauchy characteristic extraction (CCE) method by Reisswig et al. (2009a) allows the first unambiguous, gauge-free determination of the gravitational waveforms for the late inspiral, merger and ringdown of a black-hole binary at null infinity $\mathscr{I}^+$. This general procedure has been applied to the particular equal-mass, non-spinning case and it is this NR data that we use for the construction of our BBH waveform model and in the computation of the results of section 7. The equal-mass, non-spinning system that we model and use in our SNR

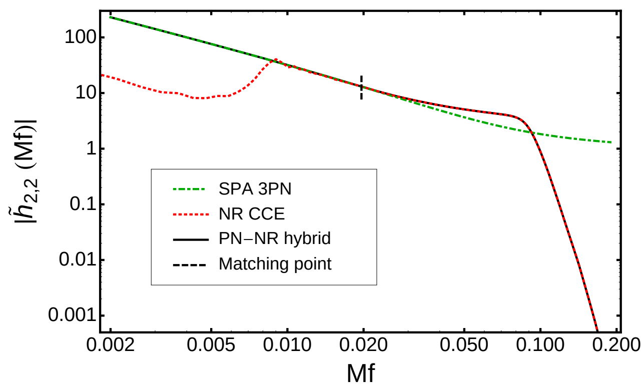

FIG. 7.— Waveform model employed in the SNR calculations of section 7 for the equal-mass, non-spinning BBH scenario. The amplitude of the numerically simulated and $\mathscr{I}^+$-extrapolated $\ell=2, m=2$ mode (Reisswig et al. 2009a) is attached to a PN calculation based on the stationary phase approximation that incorporates terms up to 3rd PN order. The amplitudes are stitched at a frequency $Mf = 0.0196$ to produce a full inspiral-merger-ringdown waveform. Note that the magnitudes displayed in the plot are dimensionless and can be scaled to account for different BBH masses

calculations is a simplification of the more general case, however we will take our results as a zero-order step in the characterization of IMBH systems, a more complex picture of which would involve higher modes and different mass ratios and spin configurations.

Due to the characteristics of the gravitational radiation, the quantity Ψ_4 is usually decomposed into modes using spin weighted spherical harmonics of weight −2:

$$Mr\Psi_4 = Mr\sum_{\ell=2}^{\infty}\sum_{m=-\ell}^{\ell} {}^{-2}Y_{\ell m}(\theta,\phi)\,\psi_{\ell m}\,. \tag{9}$$

In the comparable-mass case, most of the radiation (in particular $> 98\%$ for equal-mass systems) is emitted in the dominant $\ell=2, m=\pm2$ modes, being the contribution of the higher harmonics negligible (Berti et al. 2007).

The effect of a GW on a detector in the far field of a source is given by transverse-traceless part of the metric, the two polarizations of which are related to the Newman-Penrose scalar Ψ_4 by

$$\Psi_4(t) = \ddot{h}_+(t) - i\ddot{h}_\times(t) \tag{10}$$

or its equivalent in the frequency domain

$$\tilde{\Psi}_4(f) = -4(\pi f)^2\left[\tilde{h}_+(f) - i\tilde{h}_\times(f)\right]. \tag{11}$$

The strain induced in the detector by the GW of the binary can be reconstructed as

$$h(t) = F_+(t;\theta,\phi,\psi)\,h_+(t) + F_\times(t;\theta,\phi,\psi)\,h_\times(t) \tag{12}$$

where F_+ and $F_\times$ are the antenna response functions of the detector and depend on the orientation angles between the radiation and detector frames.

The high computational cost of current NR simulations makes it unfeasible to numerically model the full BBH coalescence process over hundreds of orbits. It is in fact also unnecessary to do so, because PN theory provides a valid description of the system when the black holes are sufficiently separated and the gravitational field is weak. Several procedures have been proposed in the past years to produce long inspiral-merger-ringdown waveforms by combining together the results from NR with PN and perturbation theories. The effective-one-body (EOB) approach of Buonanno & Damour (1999, 2000) has been calibrated to NR results, yielding the waveforms presented in Buonanno et al. (2007). Alternative methods for constructing phenomenological waveforms have been carried out for non-spinning BBHs and more recently also for systems with non-precessing spins by Ajith et al. (2007, 2008, 2009).

For the purpose of the SNR calculations shown in this paper, we have chosen a new procedure for constructing hybrid PN-NR waveforms in the frequency domain proposed by Santamaría et al. (2009). The amplitude of the $\ell = 2, m = 2$ mode, which dominates the GW emission in the comparable-mass scenario, is modeled in the frequency domain by a 3rd-order PN calculation based on the stationary phase approximation at low frequencies followed by a numerical simulation extrapolated to null infinity via Cauchy characteristic extraction (Reisswig et al. 2009a). This hybrid waveform models the dominant mode of the GW radiation $h_{22}(t)$ for the full BBH coalescence and can be rescaled to BBH systems of any total mass. Details of the construction procedure sketched in Figure 7 will be presented elsewhere.

Assuming that most of the GW emission is carried away by the dominant mode and considering an optimally oriented source, we can write down the expression of our model waveform $h(t)$ in terms of the $\ell = 2, m = 2$ mode only, as

$$h(t) = 4\sqrt{\frac{5}{64\pi}}\, h_{22}(t) \approx 0.6308\, h_{22}(t), \qquad (13)$$

which allows us to compute $h(t)$ and hence the expected signal-to-noise ratio for IMBH binaries as we show in the next section.

7. SNR CALCULATION

The signal-to-noise ratio (SNR) of a model waveform with respect to the output stream of the detector is the quantity typically quoted to signify the detectability of a signal. The SNR ρ obtained from matched filtering can be computed as

$$\rho^2 \equiv 4\int_0^\infty \frac{\tilde{h}(f)\tilde{h}^*(f)}{S_n(f)}\,df = \int_0^\infty \frac{|2\tilde{h}(f)\sqrt{f}|^2}{S_n(f)}\,d\ln f, \qquad (14)$$

(see Thorne 1989; Finn 1992, e.g.). In the last equation $S_n(f)$ represents the one-sided noise spectral density of the detector.

Because the strain induced in the detector by the binary depends on its orientation and sky position as shown in Equation 12, the SNR varies with the angle between the source and the detector. It is therefore convenient to introduce an angle-averaged SNR $\langle\rho\rangle$, which can be computed after decomposing the signal in modes via the spherical harmonics ${}^{-2}Y_{\ell m}$

$$\langle\rho^2\rangle = \frac{1}{\pi}\sum_{\ell m}\int_0^\infty \frac{|\tilde{h}_{\ell m}(f)|^2}{S_n(f)}\,df. \qquad (15)$$

Whereas the relation between the SNR given by an optimally-oriented source (a source located directly above or below the detector with an inclination angle of $\iota = 0$) and the averaged SNR is in general dependent on the higher-harmonics structure of the signal, a simple relation arises assuming that the radiation is entirely modeled by the dominant $\ell = 2, m = 2$ contribution, in which case $\rho_{\max} = \sqrt{5\langle\rho^2\rangle_{(\ell=2,m=2)}}$. This assumption is made in all our calculations throughout this paper, see

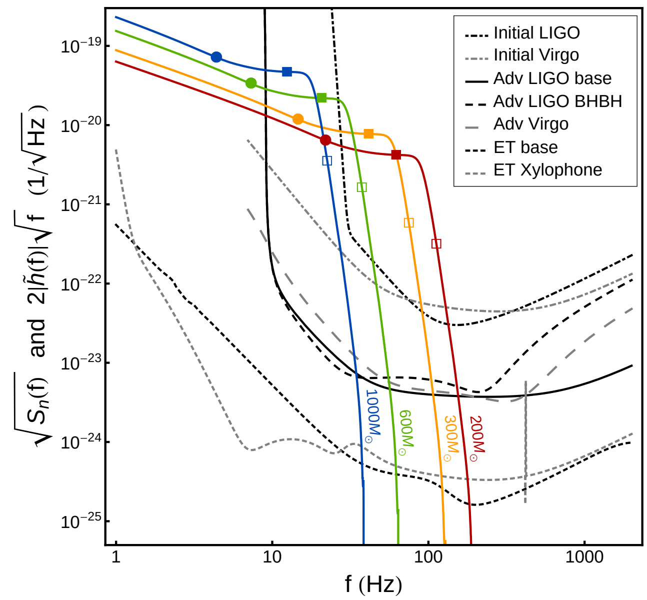

FIG. 8.— Hybrid PN-NR(CCE) waveform for equal-mass, non-spinning BBH systems scaled to various IMBH masses. From top to bottom we show BBH systems with total mass $1000, 600, 300$ and $200 M_\odot$, in blue, green, orange and red respectively. The sources are optimally oriented and placed at 100 Mpc of the detectors. The symbols on top of the waveforms mark various stages of the BBH evolution: solid circles represent the ISCO frequency, squares the light ring frequency and open squares signal the Lorentzian ringdown frequency (corresponding to 1.2 times the fundamental ringdown frequency $f_{\rm FRD}$), when the BBH system has merged and the final BH is ringing down. Currently operating and planned ground-based detectors are drawn as well: plotted are the sensitivity curves of initial LIGO and Virgo, two possible configurations for Advanced LIGO (zero detuning and $30-30M_\odot$ BBH optimized), Advanced Virgo and the proposed Einstein telescope in both its broadband and xylophone configurations

Reisswig et al. (2009b) for computations of maximal and averaged SNRs in the general, multi-mode case.

Figure 8 provides a graphical representation of the detectability of several IMBH binaries by current and future generations of ground-based GW detectors. Displayed are the design sensitivity of current initial LIGO and Virgo (sensitivities that have been met or approximately met during the S5/VSR1 data taking), the proposed noise curves of Advanced Virgo and two possible configurations of Advanced LIGO (broadband or "base" and optimized for $30-30 M_\odot$ BBHs) and the designed noise budget for the Einstein Telescope in its "base" (broadband) and xylophone configurations. The hybrid waveform described in section 6 has been conveniently scaled to represent equal-mass, non-spinning BBH systems with total mass $200, 300, 600$ and $1000 M_\odot$. Since IMBH systems with total masses in this range merge at frequencies well within the reach of the ground-based detectors, an accurate modeling of the final stages of the BBH coalescence and a correct PN-NR hybrid construction are crucial for computing correct values of the SNR and for good parameter estimation.

As the right-hand-side of Equation 14 suggests, plotting the quantity $2|\tilde{h}(f)|\sqrt{f}$ versus $\sqrt{S_h(f)}$ allows for direct visual comparison of the importance of each of the stages of the BBH coalescence. The three frequencies $f_{\rm ISCO}, f_{\rm LR}$ and the Lorentzian ringdown frequency $f_{\rm LRD} = 1.2 f_{\rm FRD}$ – used as reference frequency in some of the LIGO searches described in Section 5, for it captures the decay of the quasi-normal modes – are marked on top of the curves with solid circles,

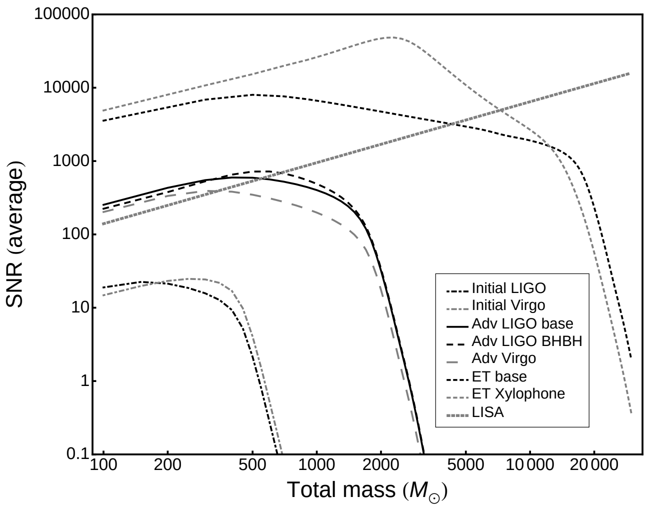

FIG. 9.— Signal-to-noise ratio as a function of the total mass of the BBH for the present and future generations of GW detectors and LISA. The sources are placed at a distance of 100 Mpc and the SNRs are angle-averaged

squares and open squares respectively. One can immediately appreciate that systems with total mass above $600\,M_\odot$ fall almost completely below the 40 Hz "seismic wall" of the initial LIGO detectors; however they will become very interesting sources for the second generation of GW interferometers and the proposed Einstein Telescope. Indeed, as we show in Section 2, they will also be seen by the future space-borne LISA.

In Figure 9 we show the angle-averaged SNR expected for these sources in each of the above-mentioned detectors as a function of the total mass of the system. The sources are placed at a distance of 100 Mpc simply because this is a handy number which is easily scalable. The redshift z in this case can therefore be neglected. For more distant sources however, the total mass $M_z = (1+z)M$ would need to be considered.

Unsurprisingly, the SNRs calculated for the third generation of ground-based detectors beat the expectations for initial and Advanced Virgo and LIGO at all masses. SNRs of the order of 10 are expected for current LIGO and Virgo interferometers for binaries with total mass up to a few hundreds of solar masses at 100 Mpc. The first-generation detectors are most sensitive to neutron star binaries and stellar-mass back holes, hence they miss most of the inspiral part of an IMBH binary coalescence and can only see a fraction of its merger and ringdown phases. Advanced LIGO and Virgo will be able to measure averaged SNRs of the order of 10^{2-3} at 100 Mpc, with a maximal response to BBH systems with total mass in the range of 400 to $1000\,M_\odot$. For the Einstein Telescope the SNR values are expected to lie within the 10^{3-5} range, and it is expected to be sensitive to binaries with total masses of the order of $10^4\,M_\odot$, a significantly larger range than that surveyed by Advanced LIGO and Virgo. It is noticeable how the ET xylophone configuration increases the detectability of binaries with masses above $600\,M_\odot$ with respect to the broadband ET configuration. This is due to its improved sensitivity precisely at frequencies in the range of $1-30$ Hz, which is where systems of mass above hundreds of solar masses accumulate most of their SNR (see Figure 8). As for LISA, IMBH binaries with masses of hundreds of solar masses will be seen by the space antenna with a moderate SNR – it is only at masses above tens of thousands of solar masses that LISA will start taking over the ground-based observatories, as can be seen in Figure 9. Although the space antenna will be most sensitive to BBH binaries with masses in the range of $10^{6-7}\,M_\odot$, the possibility that it can act as a complementary observatory to the Einstein Telescope for IMBH binaries is a very promising one. Parameter accuracy studies for IMBHs in LISA are already available using the inspiral part of the coalescence (including also relatively high eccentricities; see Amaro-Seoane et al. 2009a), and indicate that masses and sky positions will be recovered with a high accuracy level. In order to complete the characterisation of IMBHs with the information given by the second and third generations of ground-based detectors, a comprehensive study of parameter recovery that takes the BBH coalescence into account is very much desirable.

8. CONCLUSIONS

The existence of IMBHs is a subject of particular interest in theoretical astrophysics. Even though we do not have any evidence of these objects so far, a number of theoretical works have addressed their formation in dense stellar clusters. If we were to follow the same techniques that have led us to discover the SMBH in our Galaxy, we would need the Very Large Telescope interferometer and next-generation instruments, such as the VSI or GRAVITY, which should be operative in the next ~ 10 yrs. An alternative, or even complementary way of discovering IMBHs is via their emission of GWs when they are in a BBH system.

We present the current status of the problem from the point of view of astrophysics, as well as analyze the symmetry of the merged system in the case of the double-cluster channel. For this, we examine the structure of the resulting stellar system and find that it is oblate and not prolate. This results in a reduced number of stars on centrophilic orbits; therefore we find that the loss-cone is not populated as fast as suggested by previous works (Berczik et al. 2006). The authors found an unstable structure in the form of a bar that guaranteed a repopulation of the loss-cone, so that it is always full and their binary of supermassive black holes does not stall. In the simulations we address for the results of this work, the BBH (of IMBHs, which is the case of our interest) is not stalling, in spite of the reduced number of centrophilic orbits due to the architecture of the stellar system.

We then calculate the contribution to the event rates from the single- and double-cluster channels and find that, whilst the current ground-based detectors LIGO and Virgo will not be able to observe these systems, next-generation observatories, such as Advanced LIGO, Advanced Virgo and the proposed Einstein Telescope will be ready to detect tens per year (Advanced LIGO/Virgo) up to thousands per year (ET). Whereas the space-borne LISA will see these binaries with moderate SNRs and should be able to estimate the physical parameters of the system with high accuracy (Amaro-Seoane et al. 2009a), it is the advanced interferometers and the ET that will measure the loudest triggers associated to IMBH binaries, for they merge completely within their sensitivity bands.

The identification and characterization of these systems relies on accurate waveform modeling of their GW emission, which has been made possible due to the success of numerical relativity in simulating the last orbits of the BBH coalescence and the coupling of these results to analytical post-Newtonian calculations of the inspiral phase. We use a PN-NR hybrid waveform model of the BBH coalescence based on a construction procedure in the frequency domain, see Santamaría et al. (2009) for details. The ingredients for its construction are the highest available PN corrections to the amplitude (3PN) and phase (3.5PN) and the most accurate, Cauchy-characteristic NR data at spatial infinity $\mathscr{I}^+$, corresponding to the last orbits before merger up to the plunge and ringdown of the binary.

Using this hybrid waveform, we have computed the sky-averaged SNR corresponding to the current and Advanced LIGO and Virgo detectors, the proposed ET and the space-based LISA. The results show that binaries up to $500\,M_\odot$ will be seen by the initial interferometers with SNRs of tens at 100 Mpc (but their event rate is, unfortunately, negligible); binaries up to $\sim 1000\,M_\odot$ will produce SNRs of 10^{2-3} in Advanced LIGO and Virgo at 100 Mpc; finally, ET will see IMBH binaries up to tens of thousands of solar masses with SNRs of $\sim 10^{3-5}$. These observations could be complementary to those of LISA, which is expected to detect these systems with moderate SNRs and to be more sensitive to SMBH binaries instead. More remarkably, in principle if LISA and the ET are operative at the same time, they could complement each other and be used to track a particular event. The time for a BBH of $M \sim 800\,M_\odot$ to get from frequencies well inside the LISA bandwidth to within the ET sensitivity window is only 80 days. In such circumstances, one could use LISA to forewarn ground-based detectors, so that they could be tuned to get as much information (SNR) from the BBH as possible, optimizing the parameter extraction.

Current LIGO and Virgo matched-filter searches for BBH coalescences are solely targeted to stellar-mass black holes, for those are one of the types of systems that first-generation ground-based detectors are most sensitive to. The elevated rates of IMBHs events that we predict for Advanced LIGO and Virgo (tens per year) and the ET (thousands per year) should bring these more massive systems to the attention of the GW data analysis community. Future matched filter searches specifically targeted towards detections of IMBH binaries with ground-based detectors should be able to shed light into the question of their existence and corroborate or invalidate the current theoretical estimations on their event rate.

Advanced ground-based detectors are designed to be able to operate in different modes so that their sensitivity can be tuned to various kinds of astrophysical objects. Considering the importance of an eventual detection of an IMBH binary, the design of an optimized Advanced LIGO configuration for systems with $M \sim 10^{2-4}\,M_\odot$ would be desirable in order to increase the possibility of observing such a system. In case an IMBH binary coalescence was detected, the recovery and study of the physical parameters of the system could serve to test general relativity and prove or reject other alternative theories, such as scalar-tensor type or massive graviton theories.

A number of assumptions and simplifications have been made in the waveform model used here that can certainly be improved in subsequent works on this topic. Further work will benefit from a more sophisticated model that includes a larger number of mass ratios and the incorporation of the spins of the black holes, which will change their expected SNR. By including those corrections we do not, however, expect a major change in the orders of magnitude of the figures that we have drawn here. The high-SNR triggers that IMBHs will produce in the advanced detectors should in any case guarantee their detection, should they exist. Nevertheless, a full study on the accuracy of parameter estimation with advanced ground-based detectors when the merger and ringdown come into play remains to be performed. In that regard, accurate modeling of spins and higher modes are expected to be crucial for precise determination of masses, spins, location and distance of the sources. These and other questions regarding parameter estimation will be the core of further work in this topic.

The *direct* identification of an IMBH with GWs will be a revolutionary event not only due to the uncertainty that surrounds their existence and their potential role to test general relativity. The information encoded in the detection will provide us with a detailed description of the environment of the BBH/IMBH. Freitag et al. (2006b,a) described in detail the requirements from the point of view of the host cluster to form an IMBH in the center of the system. By starting with a cluster of main-sequence stars with a determined initial-mass function, the authors find that, after the cluster reaches core-collapse due to mass segregation in the system, if there are not "too hard" binaries, the time to reach core collapse is shorter than 3 Myrs and the environmental velocity dispersion is not much larger than $\sim 500\,\mathrm{km\,s^{-1}}$, the runaway formation of a very massive star (VMS) with a mass larger than $\gg 100\,M_\odot$ is possible. Not yet well understood are the later evolution of the VMS and the conditions to impose upon it, so that it does not evolve into a super-massive star (SMS) (see for instance Amaro-Seoane & Spurzem 2001; Amaro-Seoane et al. 2002; Amaro-Seoane 2004, and the references in their work) in this particular scenario, as well as the factors that could limit the mass of such an object so that it could collapse and turn into an IMBH. The process depends on a number of factors and assumptions, such as e.g. the role of metallicity, winds (see e.g. Belkus et al. 2007, though it is rather unclear how to extrapolate the results they obtain, which are limited to stars with masses of maximum $150\,M_\odot$ to the masses found in the runaway scenario works, which are typically at least one order of magnitude larger) and the collisions on to the runaway star from a certain mass upwards. On the other hand, Suzuki et al. (2007) investigated the process of growing up of a runaway particle by coupling direct N–body simulations with smooth particle hydrodynamics (SPH) to analyze the evolution of the star and found that stellar winds would not inhibit the formation of a very massive star. More recently, Glebbeek et al. (2009) considered the effects of the stellar evolution on the runaway collision product. They find that for their low-metallicity models, the final remnant of the merger tree is expected to explode as a supernova, and in their high-metallicity models the possibility of forming an IMBH is negligible and end up with a mass of 10–14 $M_\odot$ at the onset of carbon burning. Nevertheless, these develope an extended envelope, so that the probability of further collisions is higher. In any case, self-consistent direct-summation N-body simulations with evolution of the runaway process are called in to investigate the final outcome.

The information which we will recover from the data analysis of these systems, once they have been detected with GWs, will provide us with restrictions on the models which will constrain the various unknowns. Also, by combining this information with that from forthcoming instruments such as the Very Large Telescope interferometer and next-generation observatories, as e.g. VSI or GRAVITY, we will have a more accurate description of the stellar environment surrounding the IMBH. Thanks to an accurate identification of the system, we will be in position to "reverse-engineer" the astrophysical history of the stellar cluster, since this will leave a fingerprint in the detected IMBHs.

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