



Rapid and Bright Stellar-mass Binary Black Hole Mergers in Active Galactic Nuclei

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Abstract

The Laser Interferometer Gravitational-wave Observatory (LIGO) found direct evidence for double black hole binaries emitting gravitational waves. Galactic nuclei are expected to harbor the densest population of stellar-mass black holes. A significant fraction ($\sim 30\%$) of these black holes can reside in binaries. We examine the fate of the black hole binaries in active galactic nuclei, which get trapped in the inner region of the accretion disk around the central supermassive black hole. We show that binary black holes can migrate into and then rapidly merge within the disk well within a Salpeter time. The binaries may also accrete a significant amount of gas from the disk, well above the Eddington rate. This could lead to detectable X-ray or gamma-ray emission, but would require hyper-Eddington accretion with a few percent radiative efficiency, comparable to thin disks. We discuss implications for gravitational-wave observations and black hole population studies. We estimate that Advanced LIGO may detect ~ 20 such gas-induced binary mergers per year.

Key words: gravitational waves – stars: black holes

1. Introduction

The study of stellar-mass binary black holes (BBHs) is greatly limited by their expected lack of electromagnetic radiation. However, the merger of such systems produces luminous radiation in gravitational waves, making them prime targets for Earth-based detectors, including Advanced LIGO (LIGO Scientific Collaboration et al. 2015), Advanced Virgo (Acernese et al. 2015), and KAGRA (Aso et al. 2013). The detection of BBH mergers presents a unique opportunity to probe general relativity in the strong-field regime (Will 2006), to study the formation, evolution, and environment of black holes (BHs; Amaro-Seoane & Chen 2015), and may give us observational probes of the BH mass function and dynamics in galactic nuclei and globular clusters (O’Leary et al. 2016; Rodriguez et al. 2016). The recent discovery of a BBH merger by Advanced LIGO (Abbott et al. 2016c) has made the prospects of studying these systems particularly interesting.

A BBH system can form in isolated stellar binaries (Belczynski et al. 2002; Dominik et al. 2012; Mandel & de Mink 2016a; Marchant et al. 2016) and in dynamical interactions in dense stellar systems, including globular clusters and galactic nuclei (Miller & Hamilton 2002; Portegies Zwart & McMillan 2002; Portegies Zwart et al. 2004; O’Leary et al. 2009; Kocsis & Levin 2012; Naoz et al. 2013; Antognini et al. 2014; Antonini et al. 2014; Morscher et al. 2015). The binary subsequently loses energy and angular momentum and eventually merges via gravitational-wave radiation reaction. In the presence of stars or gas near the binary, its dynamical evolution may also be affected by energy and angular momentum exchange during stellar encounters (Pfuhl et al. 2014) or interactions with the gaseous medium. BBHs near supermassive black holes (SMBHs) are also subject to secular Kozai–Lidov processes, which can alter the inclination and eccentricity of their orbit, potentially decreasing the merger time (Antonini & Perets 2012; Stephan et al. 2016).

Active galactic nuclei (AGNs) represent a conceivable location where BBHs may be commonly embedded in dense gaseous environments. In AGNs, infalling gas cools radiatively

and forms a cold accretion disk around the central SMBH, which powers the observed highly luminous emission. Galactic nuclei are also expected to harbor large populations of stellar-mass BHs, which sink toward the central SMBH owing to dynamical friction on stars (Morris 1993; Rasio et al. 2004; O’Leary et al. 2009; Bartos et al. 2013b). Heavier objects sink faster. Nearby globular clusters, essentially behaving as even heavier objects, can also migrate into the galactic nucleus (Tremaine et al. 1975), carrying BHs with them. Further, massive stars can form near galactic centers, e.g., in AGN disks (Goodman & Tan 2004; Levin 2007; McKernan et al. 2012; Stone et al. 2016), providing an additional source of BHs to the nucleus.

A significant fraction of high-stellar-mass objects reside in binaries. As much as 70% of massive stars are observed to have a companion (Kobulnicky & Fryer 2007; Sana et al. 2012). In the Milky Way nucleus, the binary fraction of massive stars is observationally estimated to be $\sim 30\%$ (Pfuhl et al. 2014). BBHs can form via *isolated stellar binary systems* (Abbott et al. 2016a; Mandel & de Mink 2016b) if the two massive stars undergo core collapse, creating BHs without disrupting the binary or overly widening the orbit. Alternatively, BBHs can be formed *dynamically* through the chance encounters of BHs in dense stellar environments, such as galactic nuclei (O’Leary et al. 2009) or globular clusters (Kocsis et al. 2006; Rodriguez et al. 2015).

In this paper, we study the evolution of a BBH population in a newly activated AGN and its observational consequences. Galactic centers can experience a large influx of gas, e.g., in galactic mergers, or as a result of secular instabilities. The newly formed accretion disk will interact with nearby BBHs, accelerating their merger. Mergers within the disk can also be accompanied by amplified accretion by the BBH, producing an electromagnetic counterpart to the gravitational-wave signal.

In the following, we first show that BBHs within the disk can rapidly ($\lesssim 1$ Myr) merge by interacting with the gas in a typical AGN disk (Section 2). We then show that a significant fraction of the BBHs in the nucleus will rapidly ($\lesssim 10$ Myr) align their

orbital axes with the disk owing to loss of momentum upon disk crossings, increasing the number of BBHs that reside within the disk (Section 3). In Section 4, we discuss the expected rate of BBH mergers within AGN disks within the detectable range of Earth-based gravitational-wave detectors. We examine the production and detectability of X-ray and gamma-ray emission due to amplified accretion onto the binary from the disk (Section 5). We present our conclusions in Section 6.

2. Rapid Merger via Gaseous Torques

In the absence of a circumbinary medium and encounters with other stars, the orbital evolution of BBHs is dictated by gravitational-wave emission. Gravitational-wave emission diminishes rapidly with separation, and therefore a sufficiently wide binary spends most of its lifetime close to its initial separation following its formation. For instance, a circular $10 + 10 M_{\odot}$ BBH with a 13 hr period merges in a Hubble time, but one with a 1 hr period merges in 10 Myr.

The pace of the orbital decay can greatly increase within a gaseous environment, due to tidal and viscous angular momentum exchange between the binary and the surrounding gas (Kim et al. 2008; Stahler 2010; Baruteau et al. 2011). This interaction (either “dynamical friction” or resonant angular momentum transport) can harden the binary from wider separations to the point where gravitational-wave emission can take over, resulting in a rapid merger.

When gas is delivered to the nucleus and activates the central AGN, angular momentum conservation and radiative cooling lead to the formation of a thin accretion disk around the central SMBH. Stellar-mass BBHs may then be located in, or migrate into, a gaseous environment in the newly formed AGN disk. Since BHs are more massive than typical stars, BHs that formed in the local neighborhood of the Galactic center sink to the center owing to two-body encounters in the nuclear stellar cluster (Miralda-Escudé & Gould 2000; O’Leary et al. 2009). BHs may also be delivered to this region by star clusters that sink to the center owing to dynamical friction against dark matter, gas, and stars in the galactic disk and halo. Massive stars are also believed to form in the outer, unstable regions of an AGN disk (Goodman & Tan 2004; Thompson et al. 2005; Levin 2007; Kocsis et al. 2011; McKernan et al. 2012). As a result, BH binaries may also form in these regions, from massive stellar binaries that were created in the disk and/or grew massive through accretion from the disk (see also Stone et al. 2016).

Alternatively, BH binaries may form in the vicinity of the SMBH from binary stars that were scattered into the Galactic center and got captured through the Hills mechanism (Hills 1990). In this process, the binary gets scattered on a nearly radial orbit toward the SMBH and interacts with the SMBH, and the less massive component is ejected as a hypervelocity star, while the massive component gets captured on a close orbit representing the S stars in the Galactic center. Such stars may be dragged into the accretion disk through hydrodynamic drag and vector resonant relaxation (VRR) and eventually form BHs there (Rauch & Tremaine 1996; Šubr & Karas 2005). Single objects may form close binaries after dynamical multibody interactions or gravitational-wave capture. Binaries initially on wider orbits in the nuclear stellar cluster may also be dragged into the accretion disk if they get scattered onto orbits that cross the accretion disk (Syer et al.

1991; Karas & Šubr 2001). Triple disruption may also efficiently bring binaries into the nucleus (Perets 2009; Ginsburg & Perets 2011).

In the following we characterize the merger timescale of stellar-mass BBHs, embedded in an accretion disk around an SMBH. We consider a geometrically thin, optically thick, radiatively efficient, steady-state accretion disk (Shakura & Sunyaev 1973), which is expected in AGNs (Kocsis et al. 2011). We adopt the viscosity parameter $\alpha = 0.3$ (King et al. 2007). We assume a central SMBH with mass $M_{\bullet} = 10^6 M_{\odot}$, comparable to the SMBH mass within the Milky Way, accreting at $\dot{m}_{\bullet} = \dot{M}_{\bullet}/\dot{M}_{\bullet,\text{Edd}} = 0.1$ relative to the Eddington rate $\dot{M}_{\bullet,\text{Edd}}$ (Kocsis et al. 2011), with radiation efficiency $\epsilon = L_{\bullet,\text{Edd}}/\dot{M}_{\bullet,\text{Edd}}c^2 = 0.1$. These parameters determine the disk surface density $\Sigma(R)$, scale height $H(R)$, isothermal sound speed $c_s(R)$, and midplane temperature T (see Equations (26), (27), (28), (29), and (37) in Kocsis et al. (2011), with $b = 0$; and Equation (11) in Haiman et al. (2009), where we fix a typo of order unity, by multiplying the expression by $(3/4)^{1/4}$). At the characteristic distance from the SMBH $R_{\text{disk}} = 10^{-2}$ pc, we find⁴

$$\Sigma \approx 2000 \text{ g cm}^{-2} (R/10^{-2} \text{ pc})^{-3/5} (M_{\bullet}/10^6 M_{\odot})^{4/5}, \quad (1)$$

$$H \approx 10^{14} \text{ cm} (R/10^{-2} \text{ pc})^{21/20} (M_{\bullet}/10^6 M_{\odot})^{-3/20}, \quad (2)$$

$$c_s \approx 2 \text{ km s}^{-1} (R/10^{-2} \text{ pc})^{-9/20} (M_{\bullet}/10^6 M_{\odot})^{3/2}, \quad (3)$$

$$T \approx 800 \text{ K} (R/10^{-2} \text{ pc})^{-9/10} (M_{\bullet}/10^6 M_{\odot})^{7/10}. \quad (4)$$

2.1. Drag Force

Gas surrounding the BBH can provide a drag on the binary and facilitate its merger. The geometry of this gas is poorly understood, and we here employ two different simplified models to estimate the drag experienced by the binary.

First, we follow the semianalytic results of Kim & Kim (2007) and Kim et al. (2008). Kim et al. compute the drag force of an equal-mass binary perturber, with a circular orbit, embedded in a uniform and isothermal gaseous background medium, as a function of the perturbers’ Mach number $\mathcal{M} \equiv v_p/c_s$. Here v_p is the orbital velocity of the perturber, measured from the binary’s center of mass. The perturbers create density wakes within the gaseous medium, which act as a drag force, analogous to dynamical friction (Ostriker 1999). Because of the circular motion, the wakes from each perturber interact with the other perturber, reducing the total drag force, making the interaction important in estimating the binary evolution. We assume that the center of mass (COM) of the binary is orbiting the central SMBH at approximately the same speed as the gas bound to the binary. We also assume that the gas cloud around the BBH has no net rotation around the binary’s COM. The effect of the finite thickness of the accretion disk is expected to be small for our typical model parameters. At a distance $R = 0.01$ pc from the central SMBH, we find a disk scale height $H \sim 10^{14}$ cm, which is much greater than the characteristic distance $d_s = c_s t_{\text{orb}}$ sound travels within the gas during the orbital period t_{orb} . Kim et al. (2008) find that the gravitational drag force converges to its steady-state value within ~ 1 orbital period, indicating that dynamical friction is

⁴ These asymptotic radial scaling relations are only valid in the gas-pressure-dominated regime.

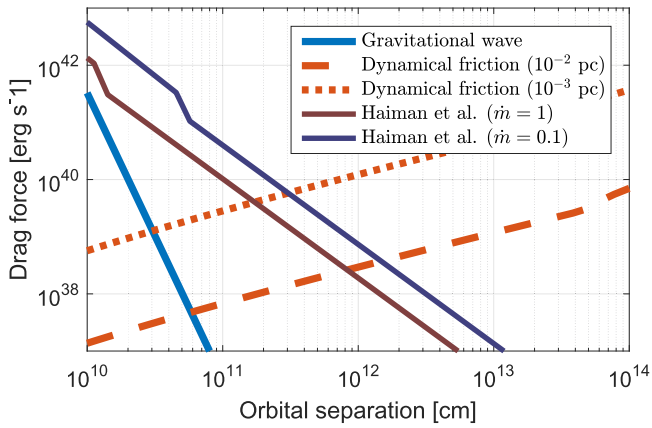


Figure 1. Drag force (energy-loss rate) for binary BHs within a gas disk as a function of orbital separation due to the emission of gravitational waves (solid lines) and dynamical friction at different orbital radii (see legend). The parameters adopted are $M_1 = M_2 = 10 M_\odot$ and $M_* = 10^6 M_\odot$.

mostly the effect of gas perturbations in the vicinity of the binary.

To calculate the drag force, we take an equal-mass binary with total mass $M_{\text{tot}} = M_1 + M_2 = 20 M_\odot$ in a gaseous environment with density $\rho_0 = \Sigma/2H$, i.e., the background density of the AGN disk around the binary. Note that we obtain similar results for other binary masses. We calculate the total drag force on the binary components using the approximations for the drag force from their own wakes and from the wake of the companion, given in Equation (14) of Kim & Kim (2007) and Equation (5) of Kim et al. (2008), respectively, as a function of the orbiting BHs’ Mach number. Beyond $\mathcal{M} = 8$, for which the numerical fits in Kim & Kim (2007) and Kim et al. (2008) are uncertain, we assume that the drag force is $F_{\text{df}} \mathcal{M}^2 = \text{const.}$, as expected in the $\mathcal{M} \gg 1$ limit (Ostriker 1999). To obtain the drag force, we define the characteristic size r_{min} (Kim & Kim 2007) of the perturbers to be the innermost stable circular orbit of the BHs, assuming no rotation. The drag force depends logarithmically on the choice of r_{min} . The obtained drag force is shown for $R = 10^{-2}$ pc in Figure 1. We see that the drag force slowly but monotonically decreases with decreasing separation, as $\mathcal{M} > 1$ for all orbital separations shown here.

An alternative and perhaps more realistic model is that the gas bound to the BBH has net angular momentum around the COM of the BBH and forms a circumbinary mini-accretion disk. Such a minidisk can be fed through streams of gas from the background AGN disk and has been seen to form in hydrodynamical simulations for a low-mass binary perturber (Lubow et al. 1999; D’Orazio et al. 2015). In this case, the background AGN disk can again be ignored, and the orbital decay of the BBH arises from the torques owing to the density perturbations it creates in the minidisk (Goldreich & Tremaine 1980; Cuadra et al. 2009; Roedig et al. 2012; D’Orazio et al. 2013). Note that unlike in the case of the gas drag in a nonrotating cloud, the orbital inspiral caused by a minidisk accelerates as the binary separation decreases.

For sufficiently small binary separations, the effective drag force in either case is dominated by gravitational-wave emission. We approximate the energy loss due to gravitational waves in the nonrelativistic limit assuming circular orbits (Peters 1964). We find that the resulting gravitational-wave

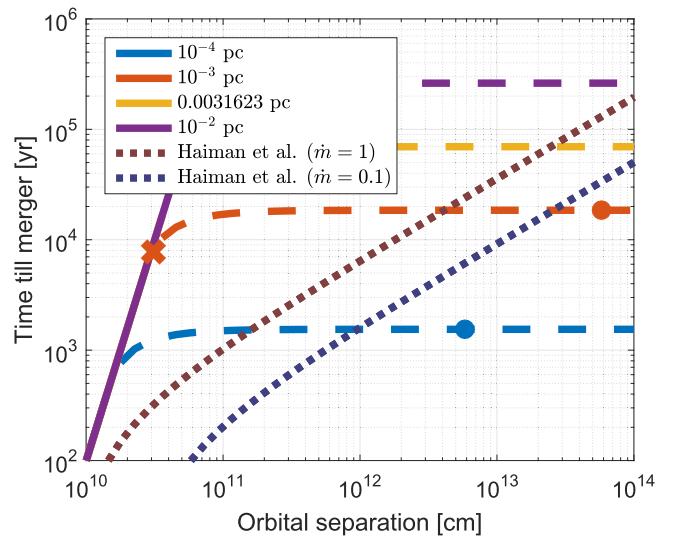


Figure 2. Time until merger for binary BHs as a function of their orbital separation, for different distances from the SMBH (see legend). The solid, dashed, and dotted curves indicate the dominant force behind orbital decay (gravitational waves, dynamical friction in a nonrotating cloud, or torques in a circumbinary minidisk, respectively). The circumbinary minidisks are assumed to have accretion rates $\dot{m} = 0.1$ and $\dot{m} = 1$ in Eddington units for the stellar-mass BHs. Filled circles and crosses indicate the separations that are equal to the Hill radius R_H and ionization radius r_{ion} , respectively, for each R considered. The adopted BH masses are $M_1 = M_2 = 10 M_\odot$ and $M_* = 10^6 M_\odot$.

drag force dominates for binary separations below $r \sim 10^{10-11}$ cm (Figure 1).

2.2. Merger Timescale

We saw above that the drag force due to dynamical friction decreases, while the drag force due to gravitational waves quickly increases with decreasing orbital separation. As a result, orbital decay will be the slowest at the separation where the gravitational-wave emission takes over. This central separation will dominate the merger time; see Figure 2. This transition at a separation around 10^{11} cm is only weakly dependent on R . Most importantly, we find that the total merger time from an initial separation $r \leq 10^{14}$ cm is $t_{\text{merge}} < 1$ Myr for $R \lesssim 1$ pc. This rapid merger time is much faster than expected purely from gravitational-wave emission and is much shorter than the typical lifetime (10^7 – 10^8 yr) of bright AGN accretion disks, or binaries outside of gaseous environments.

To estimate merger times in the alternative scenario, with the gas torques arising from a thin minidisk, we use the models in Haiman et al. (2009). They obtained the orbital decay of an SMBH binary by calculating binary–disk interactions, using simple thin-disk models (Syer & Clarke 1995). Adopting their fiducial disk parameters, we scale down their results to stellar-mass BBHs with our model parameters. To adopt their model to our case, we need to define the accretion rate \dot{M}_1 (and \dot{M}_2) onto the binary. We use the Eddington rate for the calculation; the actual rate can be super-Eddington, given the large disk density in the vicinity of the binary for the R range considered here, which would likely lead to more rapid orbital decay. For the binary separations considered here, we are in the “outer disk” regime, as defined in Equation (14) of Haiman et al. (2009), and we thus use Equation (26c) of Haiman et al. (2009). We find that the characteristic timescale of the merger is $t \sim 3 \times 10^4$ yr for $r = 10^{14}$ cm (see Figure 2). This result

also indicates that the binary merger within the inner AGN disk is expected to be very rapid.

2.3. Region of Validity

The above results are subject to the validity of the assumptions we made. First, the above thin accretion disk model for the SMBH is only valid if the self-gravity of the disk is negligible. This is valid for radii at which the disk's Toomre Q -parameter is $Q = c_s \Omega / (\pi G \Sigma) \gtrsim 1$, where Ω is the angular frequency of the gas around the SMBH. We find that $Q = 1$ around $R \sim 10^{-2}$ pc. Beyond 10^{-2} pc, the disk can be subject to fragmentation. The structure of the accretion disk is not well understood beyond this point. One possibility is that an additional source of heating from star formation stabilizes the disk with $Q = 1$ in the outer region (Sirko & Goodman 2003; Thompson et al. 2005), but we conservatively do not extend our calculations to this regime (see Stone et al. 2016 for a discussion of forming BBHs in this scenario).

The evolution of binaries can be affected by interaction with the central SMBH, as well as with field stars (Perets 2009; Antonini & Perets 2012; Pfuhl et al. 2014). Disruption by the SMBH, called *ionization*, can occur for binaries with separations larger than the Hill radius $R_H = (2M_{\text{tot}}/3M_*)^{1/3}R \approx 5 \times 10^{14}(R/10^{-2} \text{ pc}) \text{ cm}$. This effect will only be constraining for the binaries at the smallest R and greatest r we consider (see Figure 2). Close encounters with field stars will, on average, soften the binary until it is ionized if the binary's binding energy is smaller than the typical kinetic energy of field stars, $E_k \sim \langle M_* \rangle \sigma^2$, where $\langle M_* \rangle$ and σ are the average mass and the one-dimensional velocity dispersion of the stars, respectively. Approximating this dispersion with $\sigma^2 \sim GM_*/r$ (Pfuhl et al. 2014) and assuming $\langle M_* \rangle \sim M_{\text{tot}}$, we find that binaries are eventually ionized for separations larger than $r_{\text{ion}} \sim RM_{\text{tot}}/M_*$, where at the critical separation r_{ion} the binary's binding energy is equal to the typical kinetic energy of a field star (Pfuhl et al. 2014).

We find that, for the assumed parameters, r_{ion} could limit the available radii for which dynamical friction dominates, especially for $r \lesssim 10^{-3}$ pc (see Figure 2). However, ionization may not be a hindrance if it occurs on a sufficiently long timescale (Pfuhl et al. 2014). To estimate the ionization timescale t_{ion} of a binary, we consider a galactic nucleus within radius R in which stellar-mass objects with mass M_{tot} make up 10% of the mass of the central SMBH with mass M_* . The number density of objects is therefore $n = 0.1 M_* M_{\text{tot}}^{-1} / (4\pi R^3/3)$. Estimating the cross section of a softening encounter to be πr_{ion}^2 and taking the characteristic speed of field objects to be σ , the ionization time can be written as

$$t_{\text{ion}} \approx \frac{1}{n\pi r_{\text{ion}}^2 \sigma} \approx 10 \times \frac{M_*}{M_{\text{tot}}} t_{\text{orb}} \sim 10^8 \text{ yr}, \quad (5)$$

where t_{orb} is the orbital time for the BBH around the SMBH, and we obtained the numerical result for our fiducial parameters and $R = 10^{-2}$ pc. Similarly to Pfuhl et al. (2014), we conclude that the ionization timescale is long enough not to prevent mergers, unless the total mass of stars inside the orbit of the BBH is a significant fraction of the SMBH.

Ionization may also be important prior to the appearance of the AGN accretion disk, in determining the fraction of BHs residing in binaries. Stephan et al. (2016) find that 60%–80% of stellar binaries are ionized after a Hubble time. The ionization

fraction for heavier BH binaries, however, may be much lower. This effect will reduce the total number of BBHs available at the appearance of the AGN disk by less than a factor of 2.

For a sufficiently massive binary, its gravitational torque pushes gas away from its orbit around the SMBH faster than it can be replenished by viscosity, and a gap is opened (Duffell 2015). Following Kocsis et al. (2011) (their Equation (44)), we find for our adopted parameters that a gap will open for $R \gtrsim 10^{-3}$ pc, representing a significant fraction of the parameter space. Gap opening, nevertheless, does not mean that the amount of gas available for the binary needs to significantly decrease. For a single point-like low-mass perturber, hydrodynamical simulations have shown that even in the presence of a gap, the perturber can accrete gas from the background disk, through shocks occurring at the U-turns of horseshoe orbits inside the gap, at a rate comparable to the accretion rate in the unperturbed background disk (Lubow et al. 1999; D’Orazio et al. 2015). Similar nonaxisymmetric flows also develop across the gap and can fuel a gas disk around the perturber, even when the perturber itself is a binary (Lubow et al. 1999). Baruteau et al. (2011) have explicitly computed the binary hardening rate within a thin gaseous disk, for a 15–15 M_{\odot} stellar binary orbiting a $3 \times 10^6 M_{\odot}$ SMBH, similar to the system envisioned here. They found that binaries rapidly harden, despite the presence of a prominent gap in the disk, due to the formation of wound-up spiral wakes behind the stars in the minidisk. The merger timescale, based on the results of Baruteau et al. (2011), scaled to our fiducial parameters at $R = 10^{-2}$ pc and $r = 10^{14}$ cm, is $t_{\text{merge}} \sim 3 \times 10^5$ yr. This number is somewhat higher than our other two estimates based on Kim et al. (2008) and Haiman et al. (2009), although the long-term evolution of the stellar binary is not followed by Baruteau et al. (2011). Most importantly, these results confirm the rapid merger of binaries, corroborating our argument. We note here that the above investigations of gap opening were carried out for disk parameters different from our fiducial values. The simulation of gap opening in the thin-disk scenario considered here, in the vicinity of the SMBH, is difficult and has not yet been carried out (although see Duffell & MacFadyen (2013) for a simulation of a disk whose thickness is only an order of magnitude larger). Such a simulation will be an important step in better understanding the role of gap opening. Nonetheless, the examination of the simulation scenarios indicates that gap opening is unlikely to qualitatively change the results presented here.

High accretion rate for the binary can lead to mass increase that can affect the observed binary mass distribution. With accretion efficiency $\epsilon = 0.1$, at Eddington accretion, the BH would increase its mass by only 3% in 1 Myr. For our rapid merger scenario, the increase therefore is not expected to be significant. However, as mentioned above, the rate at which the BBH is diverting gas from the AGN disk could be comparable to the accretion rate in this disk and can therefore exceed the Eddington rate for the stellar-mass BHs by orders of magnitude (by a factor $\sim M_*/M_{\text{tot}}$). We here assume that the BBH (and the minidisk in its vicinity) can only accept a small fraction of this fuel and remains limited by the Eddington rate. A higher gas supply rate could accelerate the BBH merger and lead to a rapid increase in the component BH masses.

For our fiducial parameters, the total amount of gas within the binary's Hill radius is only about 0.1% of the binary's mass, which implies a significant slowdown of the binary's orbital

decay compared to the case when the mass of the circumbinary disk exceeds that of the binary. The migration rate we adopted includes this slowdown, following the prescription in Syer & Clarke (1995). Note that the total amount of gas available within $R_{\text{disk}} = 10^{-2}$ pc around the SMBH is greater than the binary's mass. The large influx of matter, given the accretion rate of the SMBH, ensures that gas is continuously replenished in the vicinity of the binary. For our fiducial parameters, gas with a total mass of about $2500 M_{\odot}$ flows through a given radius within 10^6 yr. This is ~ 100 times greater than the binary mass.

3. Orbital Alignment with Disk

As an accretion disk forms around an SMBH, typical stellar-mass BBHs in the galactic nucleus are expected to orbit the SMBH with nonzero eccentricity and nonzero inclination with respect to the disk plane. These binaries are not immediately immersed in the disk to undergo rapid merger. These binaries, however, will periodically cross the accretion disk, interacting with it at every crossing. These interactions gradually erode the inclination between the plane of the BBH's orbit around the SMBH and the plane of the SMBH accretion disk, similarly to stars piercing AGN disks along their orbits (Artymowicz et al. 1993; Karas & Šubr 2001; Miralda-Escudé & Kollmeier 2005).

To estimate the number of binaries crossing the accretion disk of radius R_{disk} , we assume that the orbital eccentricity of the COM of the binary is drawn from an isotropic thermal distribution with $f(e) = \frac{1}{2}e$ and a strongly mass-segregated number density $n(a) \propto a^{-2.5}$, which is also consistent with the massive O star distribution in the Galactic center (Alexander & Hopman 2009; Bartko et al. 2009). Note that the cluster around $M. \gtrsim 10^7 M_{\odot}$ may not be relaxed within a Hubble time at least for a single-mass-component (Merritt 2013). However, the core with massive components assembles in a shorter time (O'Leary et al. 2009), which is less than a Hubble time for $M. \lesssim 10^8 M_{\odot}$. To obtain the total number of relevant binaries, we consider objects within the radius of influence R_{inf} of the SMBH (within which the SMBH determines the motion and dynamics of the objects; O'Leary et al. 2009). At the radius of influence we take the enclosed mass in stars to be $2M.$ (Kocsis & Levin 2012). Using $M. = M_0(\sigma/\sigma_0)^k$ according to the $M.-\sigma$ relation and taking $\sigma_0 = 200 \text{ km s}^{-1}$, $M_0 = 1.3 \times 10^8 M_{\odot}$, and $k = 4$ (Binney & Tremaine 2008; Gültekin et al. 2009), we obtain

$$R_{\text{inf}} = \frac{GM.}{\sigma^2} = \frac{GM_0}{\sigma_0^2} \left(\frac{M.}{M_0} \right)^{1-(2/k)} = 1.2 M_6^{1/2} \text{ pc}, \quad (6)$$

where $M_6 \equiv M./10^6 M_{\odot}$.

We can express the fraction f_{cross} of objects within R_{inf} that will cross the SMBH accretion disk within R_{disk} as

$$f_{\text{cross}} = \iint_{\substack{a(1-e) < R_{\text{disk}} \\ a < R_{\text{inf}}}} n(a) f(e) 4\pi a^2 da de. \quad (7)$$

For $R_{\text{disk}} \ll R_{\text{inf}}$, this gives to leading order

$$f_{\text{cross}} = \frac{5}{6} \left(\frac{R_{\text{disk}}}{R_{\text{inf}}} \right)^{1/2} = 0.075 M_6^{-1/4}. \quad (8)$$

Evaluating Equation (8) shows that $f_{\text{cross}} = 13\%$ (2.4%) for $M. = 10^5 M_{\odot}$ ($10^8 M_{\odot}$).

To estimate the BH mass fraction within R_{inf} , we take the results of Miralda-Escudé & Gould (2000). They considered a Salpeter stellar initial mass function and assumed that stellar evolution will result in $0.6 M_{\odot}$ white dwarfs, $1.4 M_{\odot}$ neutron stars, and $7 M_{\odot}$ BHs for the mass ranges $1-8 M_{\odot}$, $8-30 M_{\odot}$, and $30-100 M_{\odot}$, respectively. They obtained a BH mass fraction of 1.6%. Assuming that BHs and neutron stars will dominate the central region owing to mass segregation, this mass fraction rises to $\eta_{\text{bh}} = 4\%$, which we will adopt in the following.

Another important parameter in our calculation is the fraction of BHs residing in binaries. While the binary fraction of massive stars is very large, some stellar binaries merge before forming two compact objects; they can be disrupted owing to natal kicks at core collapse, or in some cases only one of the stars becomes a BH. To estimate the fraction of BHs that will reside in binaries with other BHs, we neglect natal kicks as most BHs either are born through direct collapse without a supernova explosion or receive small natal kicks that will not disrupt the binary (Fryer et al. 2012). To count only those BHs whose companion will also be a BH, we calculate the fraction of binaries for which both stellar progenitors have a mass $> 30 M_{\odot}$. With this choice we also neglect the possibility of binary merger prior to core collapse, which is more likely in the case of highly unequal mass binaries, such as BH–neutron star progenitors (Dominik et al. 2012). We take a Kroupa initial mass function with $\xi(M) \propto M^{-2.3}$ in the relevant mass range (Kroupa 2001) and adopt a uniform binary mass ratio (Belczynski et al. 2014). With these selections, the fraction of stellar progenitors with mass $30-100 M_{\odot}$ whose companions also have masses in the range $30-100 M_{\odot}$ is ≈ 0.33 . With most massive stars residing in binaries, we adopt a BH binary fraction $f_{\text{bin}} = 30\%$. We note here that in addition to binary evolution, this fraction may further increase owing to dynamical binary formation channels in dense stellar environments.

With these parameters, the instantaneous number of BBHs crossing the disk is

$$N_{\text{cross}} = f_{\text{bin}} f_{\text{cross}} \frac{\eta_{\text{bh}} M.}{M_{\text{tot}}} = 45 \left(\frac{M.}{10^6 M_{\odot}} \right)^{3/4} \left(\frac{M_{\text{tot}}}{10 M_{\odot}} \right)^{-1}, \quad (9)$$

where all parameters are assumed to have the values in our fiducial model. BBHs that are initially not on disk-piercing orbits may later be scattered onto such orbits on the scalar resonant relaxation (Rauch & Tremaine 1996) timescale $t_{\text{rr}} = (M./M_{\text{tot}}) t_{\text{orb}}$, where $t_{\text{orb}} = 2\pi a^{3/2} M.^{-1/2} \text{ G}^{-1/2}$. This is $0.5 M_6^{1/2} \text{ Myr}$ at 0.01 pc, less than the lifetime of bright AGNs (10–100 Myr). The number of BHs that cross and migrate into the accretion disk can therefore further grow.

We estimate the timescale of orbital alignment by comparing the change in the binary's perpendicular velocity Δv_z with respect to the disk plane to the total perpendicular velocity v_z . The binary's velocity will change each time it crosses the disk owing to Bondi–Hoyle–Lyttleton accretion. For simplicity, we consider a single stellar-mass BH with mass M_{tot} orbiting the central SMBH at radius R on a circular orbit at inclination angle ψ with respect to the disk, with orbital velocity $v_{\text{orb}} = (GM./R)^{1/2}$. Results are expected to be similar for a binary. Matter in the disk at R will orbit at a comparable speed v_{orb} . The relative velocity of the gas and the BH upon crossing is $\Delta v = v_{\text{orb}} [(1 - \cos \psi)^2 + \sin^2 \psi]^{1/2}$, where ψ is the

inclination angle in the accretion disk plane. The duration of the crossing is $t_{\text{cross}} \approx 2H/(v_{\text{orb}} \sin \psi)$. Upon crossing, the BH will accrete mass within its Bondi–Hoyle–Lyttleton radius $r_{\text{BHL}} = 2GM_{\text{tot}}/(\Delta v^2 + c_s^2)$. The accreted mass can be written as $\Delta M_{\text{cross}} = \Delta v t_{\text{cross}} r_{\text{BHL}}^2 \pi \Sigma / (2H)$, so for supersonic encounters $\Delta M_{\text{cross}} \propto \Delta v^{-4} \Sigma$. Note that $r_{\text{BHL}} \approx (M_{\text{tot}}/M_*)R \ll R$, justifying the assumption of the formation and prompt accretion of a linear wake.

Since gas has, on average, zero velocity perpendicular to the disk, the velocity component of the BH perpendicular to the disk will change upon crossing:

$$\frac{\Delta v_z}{v_z} = \frac{\Delta M_{\text{cross}}}{M_{\text{tot}}}. \quad (10)$$

Neglecting the mass increase of the BH, the timescale of orbital alignment with the disk can be written as

$$\tau_{\text{align}} \sim \frac{t_{\text{orb}} v_z}{2\Delta v_z}, \quad (11)$$

where $v_z = v_{\text{orb}} \sin \psi$. The factor 2 is due to the two crossings per orbit. This alignment timescale is small for almost-aligned orbits, and it is long for misaligned orbits (maximum $\lesssim 10^9$ yr around 130° for our fiducial parameters). Assuming uniform distribution in $\cos \psi$ between -1 and 1 , we find that for our fiducial model $(M_{\text{tot}}, M_*) = (20, 10^6)M_\odot$, a fraction $f_{\text{capt}} \sim 2\%$, $\sim 6\%$, and $\sim 20\%$ of the stars align with the disk within 10^6 , 10^7 , and 10^8 yr, respectively. These percentages are even higher for lower M_* masses, e.g., for $10^5 M_\odot$, 4%, 14%, and 52% of the binaries get captured in less than 10^6 , 10^7 , and 10^8 yr, respectively, and vice versa for higher masses.

This simplified calculation neglected several potentially important effects. One is orbital eccentricity. Eccentric orbits crossing the inner edge of the disk may have orbital periods longer by a factor $(R_{\text{inf}}/R_{\text{disk}})^{3/2}$, and ΔM_{cross} decreases owing to the larger velocity by a factor of $\lesssim 4$, further prolonging alignment. On the other hand, the alignment time scales with $v_{\text{orb}}^{-4} \Sigma \propto R^{1.4}$ for orbits with a fixed orbital time, suggesting that the alignment is most efficient for circular orbits. We also neglected the effects of massive perturbers, which may efficiently excite the eccentricity and accelerate the rate of relaxation (Perets et al. 2007). Additionally, we neglected the effect of binary crossings on the disk. To check whether this assumption is justified, we computed the rate at which mass is removed from the disk by accretion onto the stellar-mass BHs during disk crossings. We find that this removal rate (corresponding to the total accretion rate onto all disk-crossing stellar-mass BHs) is $\sim 10^5$ times lower than the accretion rate onto the SMBH. We also estimated the heating of the disk due to (i) dynamical friction drag during disk crossings and (ii) absorption by the AGN disk of the radiation from accretion onto the stellar-mass BHs. We find that these are $\sim 10^3$ and ~ 10 times lower than the local viscous heating rate for our fiducial disk model. We conclude that the disk crossings do not significantly alter the mass or structure of the AGN disk.

Most importantly, stochastic torques from the spherical cluster cause chaotic orbital plane reorientation, a process called VRR (Rauch & Tremaine 1996; Kocsis & Tremaine 2015). If this process is much faster than alignment, alignment may be inhibited. On the other hand, VRR also reorients and warps the accretion disk (Kocsis & Tremaine 2011), which may change the piercing angle toward a favorable location

helping alignment; if so, it may increase the encounter rates. The timescale for VRR is of order

$$t_{\text{VRR}} = \frac{M_*}{N^{1/2} M_*} t_{\text{orb}} = 2 \times 10^5 M_6^{0.31} \text{ yr} \quad (12)$$

for the fiducial parameters (0.01 pc), where N is the enclosed number of stars and M_* is their rms mass, and we assumed that the stellar cluster density profile follows $n \propto R^{-1.75}$. Farther out at the radius of influence, this timescale is of the order $10^7 M_6^{3/4}$ yr (Hopman & Alexander 2006).

There may be additional avenues for forming BH binaries in accretion disks. Since the Bondi radius for our fiducial binary is $30 R_\odot$, comparable to the radius of massive stars or red giants, binary stars may get captured in the disk, accrete from it, and turn into BH binaries. Additionally, stellar binaries may be directly created in the outskirts of the accretion disk, grow into massive stars, get transported to the inner region by migration, and become BHs there (Goodman & Tan 2004; Levin 2007; McKernan et al. 2012).

We conclude that a significant fraction of stellar-mass BH binaries may align themselves with the accretion disk of the SMBH in a short time frame. In particular, the fraction of the N_{cross} disk-crossing BBHs that align with the disk by f_{capt} within an AGN lifetime, $\tau_{\text{align}} = 10^7$ yr, is $f_{\text{capt}} = (14, 6, 3, 1, 0.1)\%$ for $M_* = 10^{5,6,7,8,9} M_\odot$, respectively. We emphasize that AGN disks may be expected to exist for even longer, 10^8 yr or more, with a reduced density accretion disk, which may still be sufficient to drive the BBH to merge.

The value f_{capt} depends not only on M_* but also on M_{tot} . For BBH masses $M_{\text{tot}} \lesssim 100$, we find the approximate scaling relation $f_{\text{capt}} \propto M_{\text{tot}}^{1/2}$. We will use this relation in the next section.

The total BBH merger rate in a single AGN is

$$\Gamma(M_*) = \frac{f_{\text{capt}} N_{\text{cross}}}{\tau_{\text{align}} + \tau_{\text{merger}}} = \frac{f_{\text{capt}} f_{\text{bin}} f_{\text{cross}} \eta_{\text{bh}} M_*}{\tau_{\text{align}} + \tau_{\text{merger}} M_{\text{tot}}}, \quad (13)$$

where we have substituted Equation (9). This expression holds with our fiducial numbers until the BBHs on crossing orbits are all removed from the cluster. If this happens within the VRR timescale, the merger rate drops to zero until VRR can reshuffle the orbits. However, this never happens for our fiducial model parameters, which give $\Gamma = (10^{-7}, 2 \times 10^{-7}, 7 \times 10^{-7}, 1.3 \times 10^{-6}, 7 \times 10^{-7}) \text{ yr}^{-1}$ for $M_* = 10^{5,6,7,8,9} M_\odot$, respectively.

3.1. Stellar Dynamics prior to Black Hole Formation

The above description presumes that BH binaries are initially present outside of the accretion disk of the active galaxy, implying that the BHs' progenitor stars did not significantly interact with, nor were they formed within, the accretion disk. Regarding the latter case, for larger radii from the SMBH, the self-gravitating accretion disk can become fragmented, inducing star formation within the disk. This scenario can result in similar rapid merger discussed above if the formed stars have enough time to collapse and produce BBHs before merging themselves. We further refer the reader to Stone et al. (2016), who discuss in detail the possibility of binary formation within the accretion disk at $\gtrsim 0.1$ pc, outside of the region of interest discussed here.

Massive stars present within galactic nuclei could migrate into the accretion disk similarly to BHs. However, due to their very short lifetime ($O(10^6 \text{ yr})$), only those stars that are formed within the galactic nucleus will undergo this migration, and during the time in which the galaxy was active. BHs that were formed farther from the center and migrated in owing to mass segregation are therefore not affected by the progenitor stars' interaction with the accretion disk. Also, BHs that were formed prior to the onset of the SMBH accretion are not affected either. We therefore do not expect stellar interaction with the SMBH accretion disk to significantly affect our expected rate or dynamics.

4. Rate within LIGO's Horizon

To estimate the rate of BBH mergers within AGN accretion disks, we take into account the distribution of SMBH and BH masses. We use the lognormal fit to the observed AGN mass function in the local universe (Greene & Ho 2007, 2009)

$$\frac{dn_{\text{AGN}}}{dM} = \frac{3.4 \times 10^{-5} \text{ Mpc}^{-3}}{M} \times 10^{-[\log(M/M_{\odot}) - 6.7]^2 / 0.61}. \quad (14)$$

For simplicity, we consider only equal-mass BBHs. We take the number density of binaries to be $p(M_{\text{tot}}) \propto M_{\text{tot}}^{-2.5}$, with minimum and maximum masses of 10 and $100 M_{\odot}$, respectively (LIGO Scientific Collaboration et al. 2016). This mass distribution will modify N_{cross} (see Equation (9)). The number density of BBHs with masses M_{tot} will be

$$\frac{dN_{\text{cross}}}{dM_{\text{tot}}} = 2.3 f_{\text{bin}} f_{\text{cross}} \eta_{\text{bh}} M_{\text{tot}}^{-3.5}, \quad (15)$$

where the factor 2.3 comes from the normalization of $p(M_{\text{tot}})$. The corresponding BBH merger rate density in a single AGN is

$$\frac{d\Gamma}{dM_{\text{tot}}} = \frac{f_{\text{capt}}(M_{\text{tot}})}{\tau_{\text{align}} + \tau_{\text{merger}}} \frac{dN_{\text{cross}}}{dM_{\text{tot}}}. \quad (16)$$

The total merger rate density from all AGNs over all BBH masses is

$$\mathcal{R} = \iint \frac{dn_{\text{AGN}}}{dM} \frac{d\Gamma}{dM_{\text{tot}}} dM dM_{\text{tot}} \approx 1.2 \text{ Gpc}^3 \text{ yr}^{-1}. \quad (17)$$

We define the LIGO horizon distance as the luminosity distance at which the gravitational-wave signal-to-noise ratio of an optimally oriented source at an optimal sky location is $\rho = 8$ for a single detector (Abadie et al. 2010). We adopt a horizon distance of $D_{\text{h}} = 450 \text{ Mpc} (M_{\text{tot}}/2.8)^{5/6}$ for Advanced LIGO at design sensitivity (Dominik et al. 2015), which provides a good estimate for the relevant mass range, given that the binary is equal mass. Averaging over direction and orientation decreases this effective distance by a factor of 2.26 (Bartos et al. 2013a). The corresponding comoving volume is $V_c(M_{\text{tot}}) = 4/3\pi (D_{\text{h}}/2.26)^3 (1+z)^{-3}$, where z is the redshift corresponding to $D_{\text{h}}/2.26$ luminosity distance. Neglecting the merger rate evolution with redshift, we find an expected detection rate for these types of sources of

$$\Gamma_{\text{LIGO}} = \int V_c(M_{\text{tot}}) \frac{d\mathcal{R}}{dM_{\text{tot}}} dM_{\text{tot}} \approx 13 \text{ yr}^{-1}. \quad (18)$$

While this estimate is subject to uncertainties due to the approximations we adopted above, it is clear that detecting

gravitational waves from the merger of massive stellar binaries with Advanced LIGO may be feasible. More detailed modeling is needed to understand the implications of potential detections or nondetections.

5. Electromagnetic Signature

The inspiral and merger of BBHs within a gaseous medium can be accompanied by luminous electromagnetic radiation. In a uniform gas cloud, luminosity can be enhanced compared to a single BH with the same mass, by up to several orders of magnitude near the merger, due to shocks produced by the orbital motion of the binary (Farris et al. 2010). This uniform gas approximation, nevertheless, omits the effect of increased gas pressure due to the rotating AGN accretion disk, which can decrease total accretion. In a configuration similar to the one discussed in this paper, Stone et al. (2016) also find that accretion to the binary can exceed the Eddington rate by orders of magnitude.

Such super-Eddington accretion onto $10\text{--}100 M_{\odot}$ BHs can produce fast, bright (super-Eddington) electromagnetic transients through the disk's thermal emission (Jiang et al. 2014; McKinney et al. 2014; Murase et al. 2016), and possibly through driving relativistic outflows (Bosch-Ramon et al. 2005; Remillard & McClintock 2006).

For binaries buried within the accretion disk, emission can be reprocessed as it passes through the optically thick disk. This can convert high-energy emission to optical/infrared and spread out the emission in time. However, as we saw in Section 2.3, most of the binaries will open gaps within the AGN disk, enabling their emission to leave the AGN without needing to pass through the disk.

To characterize the detectability of high-energy emission from the accretion binary, let the bolometric luminosity of the binary shortly before the merger be $L_{\text{bol}} = \eta_{\text{bol}} L_{\text{Edd}}$, and assume that a fraction ϵ_{γ} of this luminosity is radiated in the gamma-ray band. The observed gamma-ray flux at Earth from a binary at luminosity distance D_L can then be written as

$$\Phi_{\gamma} = 10^{-14} \eta_{\text{bol}} F \left[\frac{M_{\text{tot}}}{100 M_{\odot}} \right] \left[\frac{D_L}{100 \text{ Mpc}} \right]^{-2} \text{ erg cm}^{-2} \text{ s}^{-1}. \quad (19)$$

Fermi-LAT is sensitive to gamma rays above $\sim 100 \text{ MeV}$, with source sensitivity $\sim 10^{-6} \text{ photons cm}^{-2} \text{ s}^{-1}$ for $\sim 1 \text{ hr}$ of exposure (Atwood et al. 2009). Estimating this sensitivity limit with $\Phi_{\text{LAT}} \sim 10^{-4} \text{ MeV cm}^{-2} \text{ s}^{-1} \approx 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$, we find that the detection of a BBH merger requires super-Eddington luminosity with $\eta_{\text{bol}} \gtrsim 10^4$, where we assumed $\epsilon_{\gamma} \sim 1$ and favorable source parameters. Although the studies mentioned above have shown that luminosities as high as $10\text{--}100 L_{\text{Edd}}$ can be achieved, the detection of a gamma-ray counterpart would require a further increase by at least two orders of magnitude above this value.

Alternatively, the source's effective luminosity can further increase if the large accretion rate results in the production of a beamed, relativistic outflow, in which internal dissipation results in nonthermal, high-energy emission. For a beaming factor $\mathcal{O}(100)$, comparable to that observed in gamma-ray bursts (Bartos et al. 2013a), detection prospects can significantly increase even for $10\text{--}100 L_{\text{Edd}}$ emission.

If the binary produces a comparable luminosity in X-rays, it could be observable with X-ray detectors, such as the *Chandra*

X-ray Observatory (Weisskopf 1999). With a point-source sensitivity of $4 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$ between 0.4 and 6 keV for 10^4 s of exposure, *Chandra* could detect a binary with $\eta_{\text{bol}} \sim 1$ and $\epsilon_X = 0.1$ out to 100 Mpc. Since *Chandra*'s field of view is very small compared to the localization uncertainty of LIGO-Virgo, additional directional constraints are needed from either a catalog of plausible host galaxies (Bartos et al. 2015, 2016; Abbott et al. 2016b) or other cosmic messengers with all-sky detection capabilities, such as gamma rays (Abbott et al. 2016b; Connaughton et al. 2016) and high-energy neutrinos (Baret et al. 2012; Aartsen et al. 2014; Adrián-Martínez et al. 2016). Alternatively, this scenario can be interesting because of the potential of observing a binary in an AGN nucleus that has not merged yet, allowing for a significantly longer observation window. Such a discovery would be informative of, e.g., the binary population within accretion disks. The proposed *X-ray Surveyor* satellite, with 30–100 times *Chandra*'s throughput and a significantly larger field of view, could be used to search for electromagnetic emission from similar BBH GW sources in the future (Weisskopf et al. 2015).

The above estimates show that emission from binaries within an AGN accretion disk may be a promising electromagnetic counterpart for BBH mergers. As key open questions remain, further numerical and theoretical investigations will be critical in better understanding the accretion and emission processes and detection prospects.

6. Conclusion

We examined the fate of stellar-mass BBHs within AGNs. We found that a significant fraction of the binaries migrate into the accretion disk around the SMBH in the center of the active galaxy. Within the accretion disk, we found that binaries rapidly merge ($\lesssim 1 \text{ Myr}$) via dynamical friction and, at the end stage, gravitational radiation. This scenario presents an interesting opportunity for gravitational-wave observations of BBHs within a high-density circumbinary medium. We estimate that the detection rate of gas-induced mergers observable with Advanced LIGO at design sensitivity is $\sim 20 \text{ yr}^{-1}$. This corresponds to a $\sim 20\%$ chance that such an event is detected during Advanced LIGO's first observation period O1.

We discussed the prospects of detecting the electromagnetic counterparts of these BBH mergers. We found that detectable radiation at the time of the merger would require a highly super-Eddington luminosity, which is unlikely, although not excluded, as the relevant emission physics is highly uncertain. Two interesting observation scenarios are (i) if high accretion rate gives rise to energetic outflows that produce nonthermal, high-energy emission within the outflow; and (ii) if one searches for nearby binaries that are within the accretion disk of an AGN but are not yet close to merging.

To better understand the gas-induced merger channel proposed here, as well as its prospects for producing an observable electromagnetic counterpart, it will be important to (i) carry out detailed simulations of BBH accretion close to merger, incorporating realistic AGN disk properties and gap opening by the binary; (ii) study the electromagnetic emission of such scenarios, in particular whether a relativistic jet can be driven by the system; and (iii) carry out a similar analysis for less dense accretion disks and other potentially gaseous environments, e.g., in globular clusters.

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