On the search of electromagnetic cosmological counterparts to coalescences of massive black hole binaries

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ABSTRACT

We explore the nature of possible electromagnetic counterparts of coalescences of massive black hole binaries at cosmological distances detectable by the Laser Interferometer Space Antenna (LISA). An electromagnetic precursor, during the last year of gravitational wave (GW)–driven inspiral, or an afterglow within few years after coalescence, may highlight the position in the sky of galaxies hosting LISA sources. We show that observations of precursors and afterglows are mutually exclusive, depending on the mass of the primary black hole. Precursors are expected to occur in binaries where the primary (more massive) black hole is heavier than \( \sim 10^7 M_\odot \). They may correspond to on–off states of accretion, i.e., to a bright X–ray source decaying into quiescence before black hole coalescence, and are likely associated to disturbed galaxies showing signs of ongoing starbursts. Coalescences of lighter binaries, with masses \( \lesssim 5 \times 10^6 M_\odot \), lack of any precursor, as gas is expected to be consumed long before the GW-driven orbital decay. Such events would not be hosted by (massive) galaxies with an associated starburst, given the slow binary inspiral time compared to the typical time scale of starbursts. By contrast, coalescence, for such light binaries, is followed by an electromagnetic afterglow, i.e., an off–on accretion state rising in \( \lesssim 20 \) yrs. Using a cosmological merger tree algorithm, we show that future X–ray missions such as XEUS will be able to identify, in 20 yrs operation, almost all the massive BH binary detectable by LISA, and, in only 5 yrs, all the LISA sources at \( z > 6 \).

Key words: accretion, accretion discs – black hole physics – gravitational waves – quasars: general – galaxies: starburst

1 INTRODUCTION

Massive black hole (BH) binaries are considered primary sources of gravitational waves (GWs) detectable, throughout the entire Universe (up to redshifts \( z \gtrsim 10 \), Hughes 2002, Bender & Hils 2003), by the space–based Laser Interferometer Space Antenna (LISA; Bender et al. 1994, Hils & Bender 1995), designed to operate in the low–frequency range \((3 \times 10^{-5} – 0.1 \) Hz). LISA will observe the signal, emitted during the last year of inspiral and at coalescence, by BH binaries of characteristic masses between \( 10^4 M_\odot/(1+z) \) and \( 10^9 M_\odot/(1+z) \) (Haehnelt 1994; Jaffe & Backer 2003; Wyithe & Loeb 2003; Sesana et al. 2004, 2005; Alcubierre et al. 2005). In standard hierarchical cosmogonies, a large number of BH binaries is predicted to form along the cosmic history, through collisions of (pre–)galactic structures (Begelman, Blandford, & Rees 1980; Kauffmann & Haehnelt 2000; Volonteri, Haardt, & Madau 2003).

LISA will operate as an all–sky monitor, and its data stream will record the signals from a large number of sources belonging to different populations of both galactic and cosmological origin (Nelemans, Yungelson & Portegies Zwart 2001; Benacquista et al. 2003; Farmer & Phinney 2003; Barak & Cullter 2004). Given the difficulty in disentangling the different signals, and the large number of noise sources, the degree of precision for the determination of the source position on the sky is still an open issue (Cutler 1998; Hughes 2002; Vecchio 2004; Kocsis et al. 2005). Analysis of LISA data alone will provide a measure of a number of binary parameters not corrected for the source redshift (Vecchio 2004; Holtz & Hughes 2005, Baker et al. 2006). Thus, pinpointing the GW source to its electromagnetic (EM) counterpart within the LISA error cube would be of great importance. Although the detection of a GW signal from coalescing BHs would be an extraordinary event by itself, the identification of an EM counterpart would greatly increase the scientific payoff, allowing: (1) to improve our un-
understanding of the nature of the galaxy hosting coalescing massive BH binaries (e.g., galaxy type, colors, morphology, etc.), (2) to reconstruct the dynamics of the merging galaxies and of their BHs, and, most importantly, (3) to break the degeneracy between the luminosity distance, which is directly measurable from the GW signal and the source redshift. In this last case, LISA sources could be used (1) as “standard candles” (“standard sirens”, Schutz 1986) to estimate fundamental cosmological parameters (Schutz 2002; Holz & Hughes 2005), (2) to distinguish between the measured redshifted BH masses and their rest-frame values, and (3), to improve our understanding of the accretion history of massive BHs comparing the EM luminosity with the BH masses and spins.

Different possible EM counterparts of coalescing massive BHs have been proposed in the last few years. Kocsis et al. (2005) proposed that LISA events are associated to the brightest quasar in the LISA error box, provided that the volume explored is limited to \( z \lesssim 1 \) (\( z \lesssim 3 \) in case of rapidly spinning BHs), guaranteeing an unambiguous identification. Armitage & Natarajan (2002) suggested that a strong, potentially observable accretion episode should anticipate the BH collision: gas trapped inside the binary orbit may produce a surface density spike, and a bright flare with outflows just prior coalescence. Finally, Milosavljevic & Phinney (2005) argued that a near–Eddington X–ray afterglow should appear, delayed by few years from the LISA detection. On such timescale, residual circumbinary gas accumulated during the viscous–migration of the less massive BH has time to refill the accretion volume, and feed the central BH.

In this paper, we explore the proposed EM counterparts to LISA events, relating their characteristics to the physical properties of binary BHs and of their host galaxies. We restrict our analysis to the BH binaries with mass ratios \( q \gtrsim 0.01 \), i.e. covering the expected range in hierarchical scenario of supermassive BH assembly (Sesana et al. 2005). Although coalescences of binaries with more extreme mass ratio could be important sources of GW emission, the physical conditions for these events might be really different with respect to the cases here explored. We address a number of questions: (1) What are the BH masses for which we can potentially see an EM precursor or/and an EM afterglow? (2) Does the host galaxy show visible signs of a collisional interaction (a starburst) during the last–year of BH inspiral? (3) Will the next–generation of X–ray missions be able to identify LISA events at cosmological distances?

The paper is organized as follows. In Sect. 2 we introduce characteristic radii and times associated to the circumbinary disc surrounding the BHs, and describe the latest stages of orbital decay, before GW–driven coalescence. In Section 3 we infer relations that are necessary (not sufficient) for the occurrence of an EM precursor phase, and explore the possibility that tidal disruption of bound stars may trigger an episode of mass transfer leading to an X–ray flare. Then we study the detectability of EM afterglows with XEUS. In Section 4, we discuss on the potential link between starburst–host–galaxies and LISA events. In Section 5 we derive our conclusions with a sketch of the domains where EM preglows and afterglows can occur, in the BH mass parameter space.

2 BH DYNAMICS

Coalescences of massive BHs are thought to be events associated with mergers of (sub–)galactic structures at high redshifts, so that the orbital decay, from the large distance scale of a merger (\( \sim 100 \) kpc) to the subparsec–scale, likely occurs in a gas–rich, dissipative environment. In cosmological models of structure formation the typical mass ratio of close BH binaries observable by LISA is \( q \sim 0.1 \), with a tail extending down to \( \sim 0.01 \) (Sesana et al. 2005). Thus, we will not consider here more extreme mass ratios.

Recently, Kazantzidis et al. (2005) explored the effect of gaseous dissipation in mergers between gas–rich disc galaxies with central BHs, using high resolution N–Body/SPH simulations. The authors show how the presence of a cool gaseous component is essential in order to bring, in minor mergers, the BHs to parsec scale separations. Gas infall deepens the potential well, preserving the less massive galaxy against tidal disruption, and leading to formation of a close BH pair. Moreover, the interplay between strong gas inflows and star formation seems to lead naturally to the formation, around the two BHs, of a massive circumnuclear gaseous disc on scales of \( \lesssim 100 \) pc, close to the numerical resolution limit. Despite these advances, it is still difficult to establish the dynamical properties of such self–gravitating discs at sub–parsec scales, as well as to assess the characteristics of the BH orbits.

Escala et al. (2005; see also Escala et al. 2004) and Dotti, Colpi, & Haardt (2006) have recently studied the dynamics of double massive BHs (in the range \( 10^5 M_\odot \leq M_{BH} \leq 2.5 \times 10^9 M_\odot \)) orbiting inside a circumnuclear disc modeled with a Mestel profile. They found that orbital angular momentum losses via dynamical friction against the gaseous background are sufficient to pair the BHs into a bound Keplerian orbit (on distances of a few pc), and to drive initially eccentric orbits into circular before the two BHs form a bound state (Dotti et al. 2006). Escala et al. (2005) have also shown that gravitational torques excited by ellipsoidal deformations of disc inner regions can bring the binary to even closer distances. Torques can reduce the separation down to \( \sim 0.1 \) pc, the scale (for \( M \gtrsim 10^5 M_\odot \)) at which GW emission can bring the two BHs to the coalescence in less than an Hubble time. In extrapolating the results of the highest resolution simulations available to date, Escala et al. (2005) suggested that gas–driven orbital decay leads the binary to coalescence in \( \lesssim 10^7 \) yr. All these simulations lack of enough spatial resolution to detail the transition boundary separating the self–gravitating region of the disc from the region dominated by the gravity of the binary. Inside this transition zone, the disc surrounding the binary is expected to be accreting through viscous stress. If the mass ratio \( q = M_2/M_1 \leq 1 \) of the binary BHs is \( q \ll 1 \), then we may estimate the position of the radius

* In collisionless mergers, the bulge of the lighter galaxy is tidally disrupted before the merger is completed, leaving its central BH wandering in the outskirts of the remnant galaxy (Kazantzidis et al. 2005).

† See Mayer et al. 2006 for new preliminary simulations at higher resolution, which are designed to solve for the spatial and velocity structure of the circumnuclear discs and dynamics of the BH pairing process.
Thus, we expect that within $\alpha$ where

$$R_\alpha \sim 3.5 \times 10^8 M_\odot \left( \frac{M_7}{\alpha} \right) ^{4/5} f_E^{1/5} R_7^{7/5},$$  

(1)

where $f_E$ is the luminosity in Eddington units (computed using a radiative efficiency $\epsilon = 0.1$), and $M_7$ is the reference mass of the central, more massive BH in units of $10^7 M_\odot$. Thus,

$$R_\alpha \sim 8 \times 10^{-2} \text{pc} \left( 1 + q \right)^{0.71} M_7^{0.14} \alpha^{0.57} f_E^{-0.43}. \quad (2)$$

Given our estimate of $R_\alpha$, one can fairly assume that dynamical friction can shrink the BH binary down to this separation. Indeed, on the bases of known results of disc–planet interactions (see e.g. Papaloizou et al. 2006 and references therein) we expect that $M_7$ perturbs gravitationally the surrounding viscous gas creating a low density, hollow region, called “gap”, which separates the outer–circumbinary disc from an inner gas–poor region around the primary BH. At $a_{\text{gap}}$, the gravitational torque from the secondary BH balances the gas–viscous torque.

In the case considered here, the appearance of the gap would occur at a BH binary separation $a_{\text{gap}} \gtrsim a_\text{tr} \sim 0.6 R_\alpha$, 

(3)

where the prefactor 0.6 is taken from the numerical simulations of Artymowicz & Lubow (1994). The scale $a_\text{tr}$ defines naturally the time for binary coalescence set by the GW back–reaction, which corresponds to the longest time in absence of other processes of orbital angular momentum loss:

$$t_{\text{GW}}(a_\text{tr}) \sim 2.5 \times 10^{12} \text{yr}$$

$$\times M_7^{-2.43} \alpha^{2.29} f_E^{-1.71} \left( 1 + q \right)^{1.86} F(e)^{-1},$$

(4)

where $F(e)$ takes into account the dependence of $t_{\text{GW}}$ on the binary eccentricity $e$ (Peters 1964; following the result of Dotti et al. 2006 on BH circularization, we consider $F(e) \sim 1$ hereafter). Note that at $a_\text{tr}$, $t_{\text{GW}} \lesssim 10 \text{Gyr}$ for $M \gtrsim 3 \times 10^7 M_\odot$ ($q = 0.1, \alpha = 0.1, f_E = 1$). To accomplish coalescence on a shorter time, additional angular momentum losses are necessary.

For $q \ll 1$, Armitage & Natarajan (2002) have shown that, once the gap opens, gravitational torques exerted by the inner edge of the circumbinary disc can still shrink the orbit, so that the inspiral time is set by the disc–driven migration timescale. For their choice of binary and disc parameters, coalescence is reached in $\sim 10^7 \text{yr}$. If we assume in our study that this process is efficient even for $q \lesssim 0.1$, and that migration continues down to the binary separation at which the disc mass inside the orbit equals $M_2$ (Armitage private communication), i.e.,

$$a_{\text{crit}} \sim \left[ \frac{q}{(1 + q)} \right]^{0.71}$$

$$\sim 4.7 \times 10^{-2} \text{pc} \left( 1 + q \right)^{0.71} M_7^{0.14} \alpha^{0.57} f_E^{-0.43},$$

(5)

then the time needed to migrate from $a_{\text{gap}}$ to $a_{\text{crit}}$ would be

$$t_{\text{torque}} \sim 4.2 \times 10^8 \text{yr} \alpha^{-0.8} M_7^{-0.2} f_E^{0.4} (a_{\text{crit}} - a_{\text{gap}}).$$

(6)

(see eq. 1 of Armitage & Natarajan 2002). From $a_{\text{crit}}$ inwards, GWs can drive the binary to coalescence on a timescale

$$t_{\text{GW}}(a_{\text{crit}}) = t_{\text{GW}}(a_\text{tr})(a_{\text{crit}}/a_\text{tr})^4.$$  

(7)

Note that now $t_{\text{GW}} \lesssim 10 \text{Gyr}$ for $M_7 \gtrsim 2 \times 10^6 M_\odot$ ($q = 0.1, \alpha = 0.1, f_E = 1$). According to eqs. 6 and 7, the coalescence time of the binary BHs can be approximated as

$$t_{\text{coal}} = \min\{t_{\text{GW}}(a_\text{tr}), [t_{\text{torque}} + t_{\text{GW}}(a_{\text{crit}})]\}. \quad (8)$$

### 3 NUCLEAR ACTIVITY AS EM COUNTERPART

#### 3.1 Circumbinary disc accretion: the precursor

A galaxy showing nuclear activity can be a peculiar EM counterpart of a LISA event. In order to have an AGN precursor, part of the gas has to remain bound forming a small accretion disc at least around the more massive BH when the gap opens. The time of gas consumption, $t_{\text{duty}}$, is given by

$$t_{\text{duty},1} = \frac{\epsilon}{1 - \epsilon} \frac{M_{\text{disc},1}(a_{\text{gap}})/M_1}{F_E^{-1}} \ln[1 + (M_{\text{disc},1}(a_{\text{gap}})/M_1)],$$

(9)

where $\epsilon$ is the radiative efficiency, and $M_{\text{disc},1}$ is the mass of the disc when the gap opens. $M_{\text{disc},1}$ is obtained from eq. 1, using the estimate of the disc radius around $M_1$ as given by Artymowicz & Lubow (1994), viz. $< 0.45 a_{\text{gap}}$ for our choice of parameters. The AGN is still in an “on” state at binary coalescence only if

$$t_{\text{duty}}(a_{\text{gap}}) > t_{\text{coal}}.$$  

(10)

The presence of an AGN precursor varies with $M_1$ and $q$ as shown in Figure 1 (for $q = 0.1$) and Figure 2 (for $q = 0.01$). The solid curve, labeled with $t_{\text{coal}} = t_{\text{duty}}$ in both figures, defines the critical BH binary separation below which gap opening still ensures nuclear activity at coalescence (assuming $\alpha = 0.1, f_E = 1$, and $\epsilon = 0$). If the gap opens at larger separations, all the gas in the accretion disc around $M_1$ is consumed before coalescence (assuming negligible refilling of gas through the gap). As reference, in the same figure we plot also $a_{\text{tr}}$, to show the closest binary separation at which we expect the gap to open. So, for $M_1 < 1 - 5 \times 10^7 M_\odot$, assuming $q = 0.01 - 0.1$, the gap is opened well before $t_{\text{coal}} = t_{\text{duty}}$, implying that the accretion is completed long before coalescence. Larger masses, instead, imply that gas accretion is still going on. In this case, a bright X–ray counterpart could be present in the error–box of $\text{LISA}$, given the large mass of the BHs. During the last year of inspiral, and during the BH plunge–in phase, gas dynamical perturbations and space–time curvature effects strongly affect the disc structure. Armitage & Natarajan (2002) have shown that, if some residual gas is present around the BHs just before coalescence, the accretion rate could be enhanced during the final GW driven inspiral. This process might trigger an episode of short–lived nuclear activity, so a transient, highly variable on–off precursor can anticipate the BH merger, making easier the identification of the galaxy hosting the $\text{LISA}$ event.

#### 3.2 Tidal disruption of bound stars

A burst of nuclear activity might be excited by the tidal disruption of a star bound to a BH, lasting $\sim 1$ yr (Rees 1988). In order to produce an X–ray flare associated to a
lines correspond curves of constant coalescence time for GW emission. We assume here $q = 1$, i.e., $a = 1$, $f_K = 1$, and $e = 0$. 

To assess the possible occurrence of such disruption within one-year prior coalescence two points must be satisfied: (a) the possibility for a star to survive in an orbit so bound that can interact with the secondary BH one year before coalescence; (b) the 3-body interaction must lead to the stellar tidal disruption instead of its ejection because of slingshot mechanism.

To select binaries matching point (a), we can compare three length scales: (1) the tidal disruption radius of a solar type star orbiting around $M_1$, $r_{td} \sim 8.3 \times 10^{-5}$ pc $M_1^{0.7} \times q^{0.25};$ (2) the separation at which a massive BH binary coalescence occurs in 1 yr: $a_{GW, BH} \sim 3.7 \times 10^{-5}$ pc $M_1^{0.75}[q(1 + q)]^{0.25} F(e)^{0.25};$ (3) the separation at which a solar type star orbiting around the primary BH decays because of GW emission in, say, $10^7$ yr which is the expected (shortest) lifetime of a BH binary in a galaxy nucleus: $a_{GW, \star} \sim 3.7 \times 10^{-5}$ pc $M_1^{0.7}$. The radius $a_{GW, \star}$ gives the dimension of the empty–cusp around the primary BH. A star can be perturbed in its motion and be disrupted during the last year of BH binary inspiral only if $r_{td} < a_{GW, BH}$. The region in the $M_1$ $-$ $q$ plane for which this condition holds is shown in fig. 3 as horizontally shaded area, and is bounded on the right by the condition $r_{td} = 6 G M_1/c^2$: Note that for $M_1 > 2 \times 10^8 M_\odot$ a solar–type star has a tidal radius smaller than the radius of the last–stable circular orbit so that it would be swallowed by the BH rather than being disrupted. In addition, the existence of stars around the two BHs on the verge of merging, requires the size of the empty–cusp to be inside the BH binary separation at one–year from coalescence, i.e., $a_{GW, BH} > a_{GW, \star}$. This region in the $M_1$ $-$ $q$ plane is indicated with the vertically shaded area. The superposition of the two areas defines the parameter space of binaries that are allowed to host a star so bound to $M_1$ that feels the presence of $M_2$ during the last year of the binary inspiral.

The point (b) is investigated by means of three body scattering experiments. A detailed description of the 3–body procedure can be found in Sesana, Haardt & Madau 2006. Here we briefly review those technical features which are of interest for the present application. The three masses are treated as point–like particles, and the tidal disruption radius considered for the two BHs. We integrate the nine coupled, second order, differential equations of motion, assuming Newtonian gravity, and the mutual force acting on the two BH induced by gravitational wave in emission in quadrupole approximation (Iwasawa, Funato & Makino 2005). We set the initial conditions as follows: we consider circular BH orbits, at initial separation $a_{GW, BH}$; bound stars are then drawn from an isotropic velocity distribution spherically symmetric around $M_1$, with the constrain that the distance from $M_1$ at periastron is $> r_{td}$, and at apoastron is $< a_{GW, BH} - r_{td,2}$, where $r_{td,2}$ is the tidal disruption radius of $M_2$. The integration is stopped as soon as one of the following conditions is met: (1) the star is kicked out by the binary with positive total energy; (2) the star crosses $r_{td}$ or $r_{td,2}$. During the integration of the orbit, as the binary shrink because of GW emission, $M_2$ perturbs the stellar orbit around $M_1$. Typically the star is tidally disrupted by $M_1$ or $M_2$ well before it gets a positive energy because of slingshot mechanism. In a sample of about 5000 simulated

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orbits, we recorded $\sim 4950$ disruption events, i.e. $\sim 99\%$ of the total. In other words, (almost) all binaries satisfying our condition (a) above, are also producing a tidal disruption event.

3.3 Disc accretion: the afterglow in the era of next generation X–ray satellites

Right after coalescence, the central relic BH is embedded in a hollow region surrounded by a gaseous disc. The gap will be re–filled on a time scale comparable to the gas viscous timescale. Milosavljevic & Phinney (2005) have shown that the AGN turns on after a time $t_{\text{on}} \sim 7(1 + z)(M_{\text{BH}}/10^6 M_{\odot})^{1.32}$ yr, creating an Eddington–limited X–ray source of luminosity $L \sim 10^{45.5}(M_{\text{BH}}/10^6 M_{\odot})$ erg s$^{-1}$. Such a turn–on of nuclear activity could be the clear signature of a very recent coalescence, and would allow for the unambiguous EM counterpart identification among other X–ray sources in the LISA error cube (see Hughes 2002, Vecchio 2004 and Kocsis et al. 2005 for a discussion on the LISA spatial resolution). The next generation of X–ray missions (such as XEUS$^\ddagger$ and Constellation–X$^\S$), expected to be operating simultaneously to LISA, will be able to detect these objects up to $z \sim 20$ (Milosavljevic & Phinney 2005).

The afterglow delay $t_{\text{on}}$ is a function of BH mass. and, as an example, only BHs lighter then $3 \times 10^6 M_{\odot}$ can be observed during an operation time of $\sim 30$ yr. To quantify the number of X–ray afterglows detectable during the operation lifetime of next generation satellites, we must rely on a model for the BH assembly in hierarchical models of structure formation. To this aim, we started with the results of Sesana et al. (2004, 2005), which calculate the rate of BH binary coalescences as a function of redshift and mass (see their fig. 1). The contribution of massive BH binaries to the LISA data stream was computed using an extended Press–Schechter merger tree code able to follow the assembly of massive BHs (Volonteri, Haardt & Madau 2003$^\parallel$). The total number of coalescences that can be detected in a 3 years LISA mission assuming a signal to noise threshold for detection $S/N=5$ is shown with a solid line in fig. 4, and turns out to be $\sim 35$, with a peak of detection around $z \sim 5$. Now, if we (i) assume that the disc spectrum is described by a thermal modified blackbody for a nearly maximal spinning BH, so that most of the luminosity is emitted at rest–frame energies $h\nu \sim (0.5–5)$ keV (Milosavljevic & Phinney 2005); (ii) neglect photo–electric absorption in the X–ray observed band $\parallel$, and (iii), take as fiducial value for future X–ray mission a $0.5–2$ keV flux limit $\sim 10^{-18}$ erg s$^{-1}$ cm$^{-2}$, we can compute the number of LISA sources detectable by XEUS in 1, 5, and 20 yrs operation time (fig. 4). Already after 1 yr from the LISA detection, almost $25\%$ of the coalescence can be identified as X–ray sources. This fraction increases up to $60\%$ ($80\%$) if longer lifetime for XEUS are considered. It is interesting to note that almost all the coalescences observed by LISA at $z \gtrsim 6$ have an EM counterpart detectable by future X-ray missions within the first 5 yrs after the GW burst. At these redshifts, LISA error cube will be crowded by a large number of X–ray sources, so the sudden turn–on of a new X–ray source can give a peculiar fingerprint of the coalescence event. We also verify that increasing the flux limit (i.e., increasing the BH mass threshold for the afterglow identification) of future X–ray missions by a factor of, say, 10, our predicted counts remain valid, as afterglows are expected to have fluxes typically exceeding $10^{-17}$ erg/s/cm$^2$ in the X–ray band.

As far as EM counterparts in other wavelengths are concerned, we can speculate that a wiggling radio jet could be observable during the last phases of spiral in of the BHs (see as a review Komossa 2006 and references therein) in particular when the precursor is present that guarantees the feeding of the BHs over most of their inspiral. This particular feature could also persist for several years after the LISA detection.

4 STARBURST GALAXY AS EM COUNTERPART

In standard hierarchical scenario of structure formation, the assembly of massive BH is connected to galactic mergers.

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$\ddagger$ www.rssd.esa.int/index.php?project=XEUS

$\S$ constellation.gsfc.nasa.gov

Note that Volonteri et al. (2003) assume a short coalescence time invoking stellar dynamical processes with a continuous supply of low angular momentum stars.

$\parallel$ This assumption is justified particularly for high redshift sources, since in this case we sample the high energy tail of the spectrum.
Figure 4. Number of coalescences as a function of redshift detectable by LISA in three years of operation (solid line; S/N $>5$) and expected number of X-ray counterpart identifications by XEUS in 1, 5, and 20 yrs with dashed–dotted, short dashed, and long dashed line, respectively (neglecting absorption). The standard ΛCDM cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$ has been assumed.

Kazantzidis et al. (2005) have performed N-body SPH simulations of binary equal– and unequal–mass (1:4) mergers of disc galaxies following the BH decay down to a separation $\lesssim 100$ pc, comparable to the numerical resolution. These simulations show an intense burst of star formation excited when the two BHs form a pair. Almost 90% of the central gas is converted into stars in less than $t_{\text{burst}} \sim 10^8$ yr, implying a star formation rate of 30–100 $M_\odot$ yr$^{-1}$, comparable to that observed in (ultra-)luminous infrared galaxies ((U–)LIRGs).

The existence of such an intense burst of star formation associated with a merger event (see also Di Matteo, Springel & Hernquist 2005; Springel, Di Matteo, & Hernquist 2005), could be, in principle, a peculiar feature of galaxies hosting coalescing BH binaries. The peculiar correspondence is observable if BH coalescence is attained before starburst is completed, i.e., if BHs merge in less than $10^9$ yr. As seen in Section 2, dynamical friction against stellar and gaseous background is able to bring the BHs to the gap opening in only $\sim 10^7$ yr. As we already pointed out, for $q \lesssim 0.1$, the interaction between the BHs and the inner edge of the circumbinary disc can lead to coalescence on a timescale $t_{\text{coal}}$ given in Eq. (8).

In Fig. 5 we show the run of $a/a_t$ with time $t$, assuming that dynamical friction have driven the BHs to a separation $a_t$ (see eq. 3) in $\sim 10^7$ yr. The vertical solid line marks $a = a_{\text{crit}}$ (eq. 5), the separation at which viscous torques become inefficient. For smaller separations, the evolution of the binary is dominated by GW emission. Different curves refer to different masses of the primary BH. The solid horizontal line indicates the typical starburst duration, $t_{\text{burst}}$. The top (bottom) panel shows the results for $q = 0.1$ ($q = 0.01$). We find that the starburst is likely to be still active at the coalescence (i.e. $t_{\text{coal}} \lesssim t_{\text{burst}}$) only for $M_1 > 10(2) \times 10^6 M_\odot$.

On the contrary, for smaller masses, the starburst is consumed before the BHs merge. In case dynamical friction is inefficient until $a_t$, the starburst activity at coalescence is still possible as shown in figs 1 and 2. The dot-dashed line marks, in the $M_t - a$ plane, the locus $t_{\text{coal}} = t_{\text{burst}}$, assuming that at these separations the gap is already open, and that the dynamics is dominated by viscous torques. Following this argument, the identification of a (U-)LIRG in the LISA error cube could be a probable EM counterpart of the GW event. Some caveat to this analysis has to be discussed: (i) the more massive BHs ($\gtrsim 10^8 M_\odot$) are preferentially hosted in gas poor early type galaxies that could be the outcome of a gas-rich major merger. However there is the possibility that dry mergers are important, i.e., mergers between gas poor galaxies, and in this case an intense burst of star formation is not expected; (ii) binaries with small $q$ may correspond to small mass ratio of the interacting host galaxies, so that the associated starburst might be less powerful then what typically observed in (U-)LIRG; (iii) the presence of an intense starburst event in the last phases of galaxy mergers could depend on the morphology of the two galaxies and in particular on the relative size of the bulges, poorly addressed by numerical simulations up to now. Nevertheless, the presence of a starburst galaxy in the LISA error cube may indicate a preferential host of the BH coalescence.
5 SUMMARY AND CONCLUSIONS

We have explored a number of possible EM counterparts of the coalescence of massive BH binaries at cosmological distances, assessing their detectability with future X-ray missions. Our main findings are summarized in Fig. 6.

EM precursor is expected to occur in binaries with primaries heavier than $\sim 10^7 M_{\odot}$. Coalescences involving less massive BHs will lack of any precursor and, for $M_1 \lesssim 3 \times 10^6 M_{\odot}$, are followed within 20 yr by an EM afterglow. The small triangle labeled as “tidal” shows the region of the parameter space where tidal disruption events of bound stars may be associated to the LISA detection. Finally, an intense starburst event may be still present at the coalescence of massive BHs ($M_1 \gtrsim 2 \times 10^6 M_{\odot}$) embedded in gas rich galaxies.

AGN precursors, detectable during the last year of inspiral, can be identified as variable X-ray sources switching to an off state. X-ray flares due to accretion of matter pushed by the incoming secondary BH might be the fingerprint of the LISA event. This on–off preglow would help in identifying the host galaxy within the error cube. Note that the extrapolation of our results to $q > 0.1$ are only speculative, and demands more detailed studies (solid lines ending with dots in fig. 6 indicate uncertain extrapolation). EM afterglows associated to these massive binaries require onset times in excess of $> 100$ yr, and so exceedingly long expectant times. The triangle involving the heaviest BHs denotes the region where a tidally disrupted star may be accreted in the last year before coalescence, potentially causing a X-ray episode of accretion. This would again appear as a preglow.

Smaller BHs ($M_1 \lesssim 3 \times 10^6 M_{\odot}$) will lack of any precursor, since we have found that the gas around the BHs is consumed long before coalescence. Moreover, the starburst activity is also unimportant, since the merging time of the BH binary is longer than the typical starburst timescale. By contrast, a LISA event involving light BHs is followed by an afterglow with rise–time less than 20 yr, i.e. the expected operation time of XEUS. Using cosmological merger tree algorithm, we have shown that XEUS will be able to identify almost all the predicted LISA events in 20 years of operation, and the totality of the events at $z > 6$ in only 5 years. There is a small transition region in between the light and heavy BHs considered in this paper, where a LISA event may be only associated to a starburst but shows no precursor.

The association of an EM counterpart to a LISA event should be linked to a variable on–off (precursor) or off–on (afterglow) state. In addition, we predict that the precursor is related to mergers of heavy BHs, whereas afterglows are detectable only for lighter BHs. This dichotomy may be tested by comparing the redshift of observed EM counterpart hosts with the redshifted masses estimated analysing the LISA data stream (see, e.g., Vecchio 2004).

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