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Cosmology with massive black hole binary mergers in the LISA era

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In $\sim$ 2034 the Laser Interferometer Space Antenna (LISA) will detect the coalescence of massive black hole binaries (MBHBs) from 10^5 to $10^7\,\mathrm{M}_\odot$ up to $z \sim 10$. The gravitational wave (GW) signal is expected to be accompanied by a powerful electromagnetic (EM) counterpart, from radio to X-ray, generated by the gas accreting on the binary. If LISA locates the MBHB merger within an error box < 10 deg^2, EM telescopes can be pointed in the same portion of the sky to detect the emission from the last stages of the MBHB orbits or the very onset of the nuclear activity, paving the way to test the nature of gas in a rapidly changing space-time. Moreover, an EM counterpart will allow independent measurements of the source redshift which, combined with the luminosity distance estimate from the GW signal, will lead to exquisite tests on the expansion of the Universe as well as on the velocity propagation of GWs. Here, I present some recent results on the standard sirens rates detectable jointly by LISA and EM facilities. We combine state-of-the-art models for the galaxy formation and evolution, realistic modeling of the EM counterpart and Bayesian tools to perform the parameter estimation of the GW event as well as of the cosmological parameters. We explore three different astrophysical scenarios employing different seed formation (light or heavy seeds) and delay-time models, in order to have realistic predictions on the expected number of events. We estimate the detectability of the source in terms of its signal-to-noise ratio in LISA and perform parameter estimation, focusing especially on the sky localization of the source. Exploiting the additional information from the astrophysical models, such as the amount of accreted gas and BH spins, we model the expected EM counterpart to the GW signal in soft X-ray, optical and radio. In our standard scenario, we predict $\sim$ 14 EM counterparts over 4 yr of LISA time mission and $\sim$ 6 ($\sim$ 20) in the pessimistic (optimistic) one. We also explore the impact of absorption from the surrounding gas both for optical and X-ray emission: assuming typical hydrogen and metal column density distribution, we estimate only $\sim$ 3 EM counterparts in 4 yr in the standard scenario.

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1. Introduction

In the next decade, the Laser Interferometer Space Antenna (LISA)[1] will detect gravitational waves (GWs) in between $[10^{-4}, 10^{-1}]$ Hz from the coalescence of massive black hole binaries (MBHBs) in the entire Universe [2]. The detection of GWs from these source will allow to reconstruct their merger history and distinguish the astrophysical processes and mechanisms affecting their evolution [3], to perform tests of general relativity and constrain cosmological parameters [4, 5].

Concerning MBHBs, the possibility of an electromagnetic (EM) counterpart together with the GW signal is still unclear, due to the lack of observations. If a sufficient amount of gas is present, an EM emission can be produced by the accretion of the gas onto the binary during the inspiral, merger and ringdown. While the orbital motion of the binary is expected to excavate a cavity in the circumbinary disk, the gas stream should fuel minidisks around each BHs, producing EM emission at different wavelengths. The EM emission might be modulated by the orbital motion of the binary during the inspiral, or it might appear at merger, or after, as a powerful radio jet emission [6–8]. I discuss here the potential of multimessenger observations combining LISA and future EM facilities under different scenarios for the EM counterpart of MBHB mergers. In particular, I present the work of [9].

2. General framework

Three different observational strategies are considered for identifying the EM counterpart (EMcp). The strategies require the identification of the galaxy hosting the merger as well as the determination of its redshift[1]. If an optical emission is present at merger, the galaxy can be identified with the Vera C. Rubin Observatory. The identification in radio is performed with the Square Kilometer Array (SKA) telescope while in X-ray we rely on the Advanced Telescope for High ENergy Astrophysics (Athena). After the identification of the host galaxy, its redshift can be obtained with the Extremely Large Telescope (ELT) or directly with the Rubin Observatory.

For the population of MBHBs, we adopt the results of semi-analytical models (SAM) that follow the evolution of MBH. We consider three different seed and time-delay prescriptions: (i) Pop3: a light-seed case where BHs form from the collapse of massive metal-poor stars. Time-delays are included; (ii) Q3d: a heavy-seed model with delays where BHs originate from proto-galactic disks; (iii) Q3nd: similar to the Q3d model but without time-delays. From the results of SAM, we have the expected merger rate as well as the binary parameters such as masses, spins, luminosity distance and the amount of gas surrounding the binary that can be used to compute the EM emission.

In order to detect the EM counterpart, telescopes have to be pointed in the direction of the source, estimated from the analysis of the GW signal. Therefore, we start selecting all the systems with a detectable EM counterpart and we then apply an additional cut on the signal-to-noise ratio (SNR > 10) and on sky localization, selecting only systems with $\Delta\Omega < 10\,\mathrm{deg}^2$ for the Rubin Observatory and SKA or $\Delta\Omega < 0.4\,\mathrm{deg}^2$ with Athena. In this way, we define *multimessenger candidate* (MMcand) as any systems that satisfy: (i) The system EM counterpart is detectable; (ii) SNR > 10. In other words, MMcands are events with a detectable EM emission but without the

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[1] We will explore in a following work the possibility to combine the luminosity distance information from the GW signal with the redshift information from the EM emission to constrain cosmological parameters.

sky localization condition. Combining the latter information, we can define *GW event with EMcp* (EMcp) as any system that satisfies: (i)The system is a MMcand; (ii) The system has $\Delta\Omega < 10\,\mathrm{deg}^2$ if the EMcp is detectable with the Rubin Observatory or LSST and/or $\Delta\Omega < 0.4\,\mathrm{deg}^2$ if the EM counterpart is detected with Athena.

2.1 Modeling of the EM emission

Here we limit to summarise the key points and we refer the reader to the more detailed description in [9]. We start computing the AGN bolometric luminosity $L_{\rm bol}$ as:

$$\dot{M}_{\rm acc} = \min\left(\frac{M_{\rm res}}{t_\nu}, \frac{L_{\rm Edd}}{\epsilon_{\rm rad} c^2}\right) \tag{1}$$

$$L_{\rm bol} = \min\left(\epsilon_{\rm rad} \dot{M}_{\rm acc} c^2, L_{\rm Edd}\right) \tag{2}$$

where $M_{\rm res}$ is the reservoir mass of gas available for accretion, t_ν is the viscous timescale, $L_{\rm Edd}$ is the Eddington luminosity and $\epsilon_{\rm rad}$ is the radiative efficiency. For the Rubin Observatory, we compute the apparent magnitude starting from $L_{\rm bol}$, applying a bolometric correction BC = 10 and we claim the detection of the EM counterpart if $m_{\rm AGN,Rubin} < 27.5$.

For the radio emission, we assume a flare emission with luminosity $L_{\rm flare} = 0.1 \epsilon_{\rm edd} L_{\rm edd}/q^2$ where $\epsilon_{\rm edd} = L_{\rm bol}/L_{\rm edd}$ is the Eddington ratio, $q = m_1/m_2 > 1$ is the mass ratio of the binary. We also take into account the possibility of a radio jet emission with luminosity:

$$L_{\rm jet} = \begin{cases} 0.8 \times 10^{42.7}\,\mathrm{erg\,s^{-1}} m_9^{0.9} \left(\frac{\dot{m}_{\rm jet}}{0.1}\right)^{6/5} \left(1 + 1.1 a_1 + 0.29 a_1^2\right), & \text{if } 10^{-2} \le \epsilon_{\rm edd} \le 0.3 \\ 3 \times 10^{45.1}\,\mathrm{erg\,s^{-1}} m_9 \left(\frac{\dot{m}_{\rm jet}}{0.1}\right) g^2 \left(0.55 f^2 + 1.5 f a_1 + a_1^2\right) & \text{otherwise} \end{cases} \tag{3}$$

where $m_9 = m_1/(10^9 \mathrm{M}_\odot)$, $\dot{m}_{\rm jet} = \dot{M}_{\rm acc}/(22\, m_9 \mathrm{M}_\odot \mathrm{yr}^{-1})$, a_1 is the spin magnitude of the primary BH, $f = 1$ and $g = 2.3$ are dimensionless parameters. The total luminosity is then computed as $L_{\rm radio} = L_{\rm flare} + L_{\rm jet}$ and we claim detection if $F_{\rm radio} \ge 1.7 \times 4\pi 10^{-20}\,\mathrm{GHz}\,\mu\mathrm{Jy}$ where $F_{\rm radio}$ is the flux obtained from $L_{\rm radio}$. For the radio emission, we also take into account the possibility of a collimated emission with an opening angle $\theta = 1/\Gamma$ with $\Gamma = 2$ and $\Gamma = 10$. Similarly, for the X-ray emission, we convert the bolometric luminosity $L_{\rm bol}$ into the X-ray luminosity and claim detection of the X-ray counterpart if $F_{\rm X} \ge 4 \times 10^{-17} \mathrm{erg\,s^{-1}\,cm^{-2}}$.

Finally for the optical and X-ray emission we also explore the possibility of AGN obscuration.

3. Results

For simplicity, we refer in the following to a *maximising* and *minimising* model. The former has (i) No AGN obscuration; (ii) Isotropic radio emission; (iii) X-ray emission at Eddington. The latter is defined as: (i) AGN obscuration included; (ii) Radio emission collimated with $\Gamma = 2$; (iii) X-ray accretion from the amount of gas surrounding the binary.

In Fig. 1 we show the average number of MBHBs as function of redshift and chirp mass. The Pop3 and Q3nd models predict a large fraction of event at $z > 10$, however most of the events are missed in the Pop3 scenario due to the intrinsic low chirp mass. The Q3d model predicts only events at $z < 12$ that are all detected by LISA because the mass distribution peaks at chirp mass $\mathcal{M} \simeq 10^{5-6}\,\mathrm{M}_\odot$.

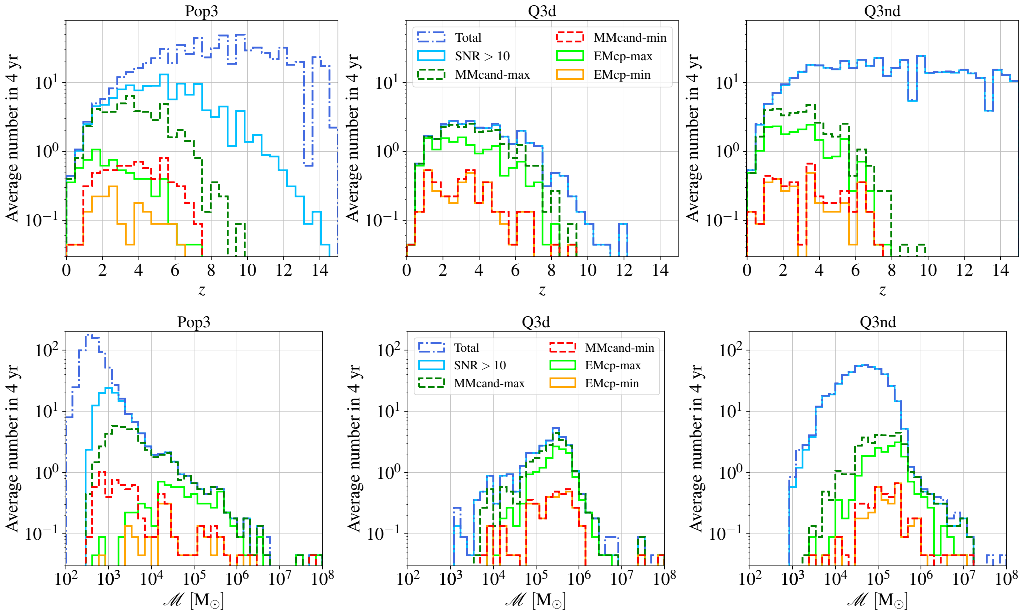

Figure 1: Average number of MBHB mergers (dark blue dotted-dashed line), MBHB mergers with SNR > 10 (light blue solid line), EMcps (light green and yellow solid lines), and multimessenger candidates (dark green and red dashed lines) , as function of redshift (upper panels) and chirp mass (lower panels).

(In 4 yr)	LSST, VRO	SKA+ELT			Athena+ELT		
		Isotropic	$\theta \sim 30°$	$\theta \sim 6°$	Catalog $F_{\mathrm{X,\,lim}}$ = 4e-17	Eddington $F_{\mathrm{X,\,lim}}$ = 4e-17	
	$\Delta\Omega = 10\,\mathrm{deg}^2$				$\Delta\Omega = 0.4\,\mathrm{deg}^2$	$\Delta\Omega = 0.4\,\mathrm{deg}^2$	
No-obsc.	0.84	6.8	1.51	0.04	0.49	1.02	Pop3
	3.07	14.9	2.71	0.04	2.67	3.87	Q3d
	0.53	20.6	3.2	0.04	0.58	4.4	Q3nd
Obsc.	0.27	6.8	1.51	0.04	0.04	0.37	Pop3
	0.84	14.9	2.71	0.04	0.22	0.18	Q3d
	0.22	20.6	3.2	0.04	0.09	0.4	Q3nd

Table 1: Average number of EMcps for each observational scenarios in 4 yr.

If we add the requirement on the detectability of the EM counterpart, we select only systems at $z < 8$ and at large value of chirp mass, independently from the astrophysical model. As expected only the closest systems produce a counterpart that can be detected. Moreover massive binaries are typically surrounded by a large amount of gas so the EMcp is brighter than the one produced by low mass systems. In the maximising scenario, we predict 48.7 (24.4) [38] MMcands for Pop3 (Q3d) [Q3nd] in 4 years. However if we include collimated radio emission and obscuration, the numbers of MMcands drop to 6.6 (3.6) [4.1].

Including the requirement on the source sky localization, we predict 6.8 (14.9) [20.9] and 1.7 (3.4) [3.4] EMcps for Pop3 (Q3d) [Q3nd] in 4 years in the maximising and minimising model, respectively. Comparing these numbers, it is clear that in the minimising model there are less MMcands, as expected, but a larger fraction of them is promoted to be EMcps respect to the maximising model because obscuration and collimated radio emission select only close events, for which LISA provides an accurate parameter estimation. Finally, in Tab. 1 we report the total number of EMcps in all the different strategies.

4. Conclusions

We have presented updated forecasts on LISA ability to perform multimessenger studies with future EM facilities. Starting from the results of SAM code, we modeled the EM emission from MBHB mergers in radio, optical and X-ray under different assumptions. We combined the information on the EM emission with an accurate parameter estimation to evaluate the typical sky localization uncertainty.

Overall, EMcps can be observed up to $z \sim 6-8$ with $\mathcal{M} \sim 10^{4-6}\,\mathrm{M}_{\odot}$. We predict between 7 and 20 EMcps in the best case scenario and only $2-3$ in the pessimistic one, i.e. with AGN obscuration and collimated radio emission. These results suggest that, in the future, every follow-up strategies between LISA and EM telescopes must be accurately planned in order to maximise the number of EMcps.

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