

DETECTABILITY AND IDENTIFICATION OF MASSIVE BINARY BLACK HOLES WITH NEWATHENA

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Abstract.

One of the key targets of the future space-based interferometer LISA (Laser Interferometer Space Antenna) are the gravitational waves emitted during the merger of massive black holes. The surrounding of these massive binary systems, potentially gas-rich, could be powerful X-ray sources detected by the upcoming X-ray observatory NewAthena (New Advanced Telescope for High ENergy Astrophysics). To prepare for these joint observations of gravitational waves and electromagnetic counterparts, we are interested in the specific X-ray spectral signatures of these massive binaries (10^4 to $10^7 M_{\odot}$) which can be used to distinguish them from single black holes in active galactic nuclei. This work focuses on their detectability and identification through the thermal signature of the circumbinary disc and mini-discs configuration based on analytical models depending on the binary mass, mass ratio, orbital separation and spins. We identify two main features, a notch pattern for low mass and small separation binaries and a broadened high-energy emission for unequal mass or spin binaries.

Keywords: Massive binary black holes, X-ray spectral signature, NewAthena, multi-messenger astronomy

1 Introduction

Observations of central massive black hole at the heart of most galaxies (Magorrian et al. 1998), correlated with the hierarchical model of galaxy growth through successive mergers, suggests the existence of massive binary black holes (MBBH) in galaxy merger remnants (Hopkins et al. 2008). In the final stage towards coalescence of these massive black holes, their orbital evolution is dominated by gravitational wave (GW) emission which may be detected by the upcoming Laser Interferometer Space Antenna LISA (GW frequency from 0.1 to 100 mHz) days to weeks before merger (Amaro-Seoane et al. 2023). Galaxy mergers are also expected to be the scene of large gas motions and may provide a very gas-rich environment to the binary, favourable to black hole accretion and consequently to electromagnetic counterpart emission. X-ray observations, by probing the inner regions of massive black hole accretion discs are of paramount importance for these challenging studies. The forthcoming NewAthena satellite should lead to significant progress, thanks to its enhanced sensitivity and the WFI (Wide Field Imager) large field of view ($40^{\circ} \times 40^{\circ}$) tailored to detect transient sources (Cruise et al. 2025). To disentangle binaries from single active galactic nuclei (AGN), the identification must bring together different clues across several features, either temporal or spectral. Here we present the potential of the thermal signature arising from the combined mini-discs around each black hole (BH) and the circumbinary disc around the binary, as a means to distinguish a binary system from an isolated BH.

The next section describes this thermal continuum. Section 3 presents the simulated observations and the detection limits. Section 4 dives into BBH identification versus AGN. Section 5 summarizes and discusses.

2 Thermal signature

Some recent fluid simulations describe the close environment of the binary in the shape of two mini-discs around each black hole, a larger circumbinary disc encompassing the binary system and between them a low-density

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cavity (for example d’Ascoli et al. 2018, see the insert in the left panel of figure 1). We are interested in the thermal emission of this three-discs configuration. Based on the seminal work of Shakura & Sunyaev (1973) modelling the thermal emission of an AGN disc as a multi-colour blackbody, Roedig et al. (2014) has suggested a flux deficit, the so-called ”notch”, due to the low-density cavity between the circumbinary disc emitting at lower energy and the mini-discs emitting at higher energy. Our model completes this approach in the high energy range by tacking into account the fast decline at the innermost stable circular orbit (ISCO) and the impact of the BH spins.

The left panel of figure 1 shows the contributions of the circumbinary disc and mini-discs, as well as the combined flux for a $q = 0.3$ ($q = m_2/m_1$) mass ratio binary without rotation. We observe the notch (dashed red line) between the lower energy circumbinary disc emission (blue line) and the higher energy mini-discs emission (more massive, primary BH in yellow and less massive, secondary BH in green). The smaller the BH mass (secondary BH in green), the higher the energy of the disc flux decline. The right panel of figure 1 shows the notch energy as a function of the two main influencing parameters, binary mass and orbital separation. About one day (~ 90 ks) before merger the notch energy reaches 0.1 keV and is potentially detectable with NewAthena.

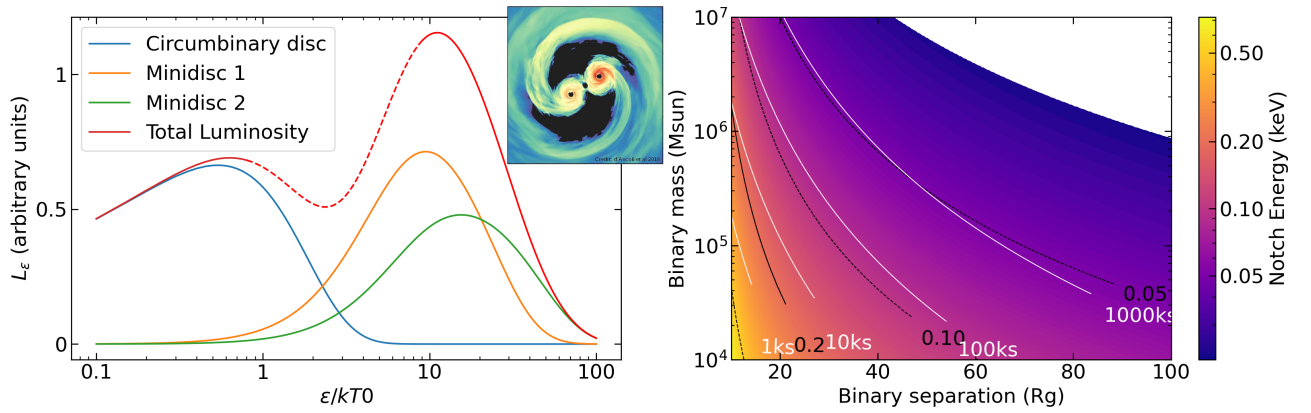


Fig. 1. Left: Detailed blackbody contributions of the various components of the model for a $q = 0.3$ binary, expressed in term of flux (in arbitrary units) as a function of normalised energy (to T_0 the characteristic temperature of the notch). The insert reproduces d’Ascoli et al. (2018) simulation as an example of the geometry under consideration. **Right:** Evolution of the notch energy versus binary mass and separation, expressed in gravitational radius R_g . The black lines indicate the notch energy contours in keV, with 0.2 keV representing the NewAthena detection limit. The white lines indicate the time before merger in ks.

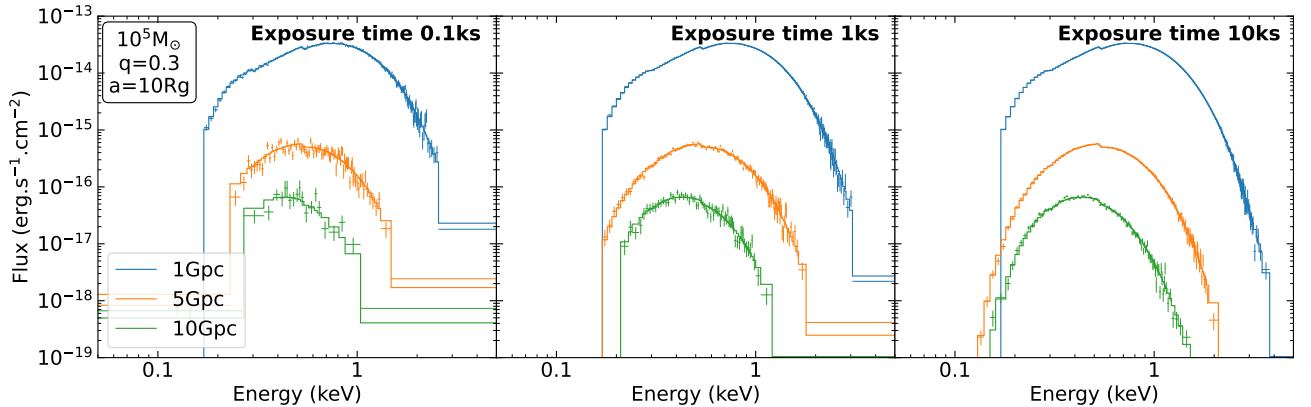


Fig. 2. Simulated X-ray spectra for a $M = 10^5 M_\odot$, $q = 0.3$, $a = 10R_g$ binary with no spins. Each plot represents an exposure time, from left to right: 0.1 ks, 1 ks and 10 ks. Three luminosity distances are plotted: 1 Gpc (blue), 5 Gpc (orange) and 10 Gpc (green). Significant detections are achievable for exposures of 0.1 ks, 1 ks, and 10 ks at 1 Gpc, 5 Gpc and 10 Gpc respectively.

3 Detectability of the binary

We implement our model in the X-ray spectral fitting package Xspec (Arnaud 1996) and develop simulated observations based on the NewAthena/WFI instrumental response matrices “NewAthena_WFI13rows_LDA_wo_filter_OnAxis_20240209”. We are able to explore the binary mass, mass ratio, orbital separation, spins and luminosity distance. For the simulations we consider Galactic absorption with a column density of $N_{\text{H}} = 3 \cdot 10^{20} \text{ cm}^{-2}$ (Xspec phabs model).

Figure 2 shows one of these simulations, evolving luminosity distance and exposure time, for a binary with a mass $M = 10^5 M_{\odot}$, a mass ratio $q = 0.3$, a separation in gravitational radius $a = 10R_g$ and no spins. For plotting purposes, bins are combined to have a minimum significance $\sigma = 3$. We observe significant detections with exposure times as short as 0.1 ks for a 1 Gpc object, 1 ks for a 5 Gpc object and 10 ks for a 10 Gpc object.

4 Identification against AGN

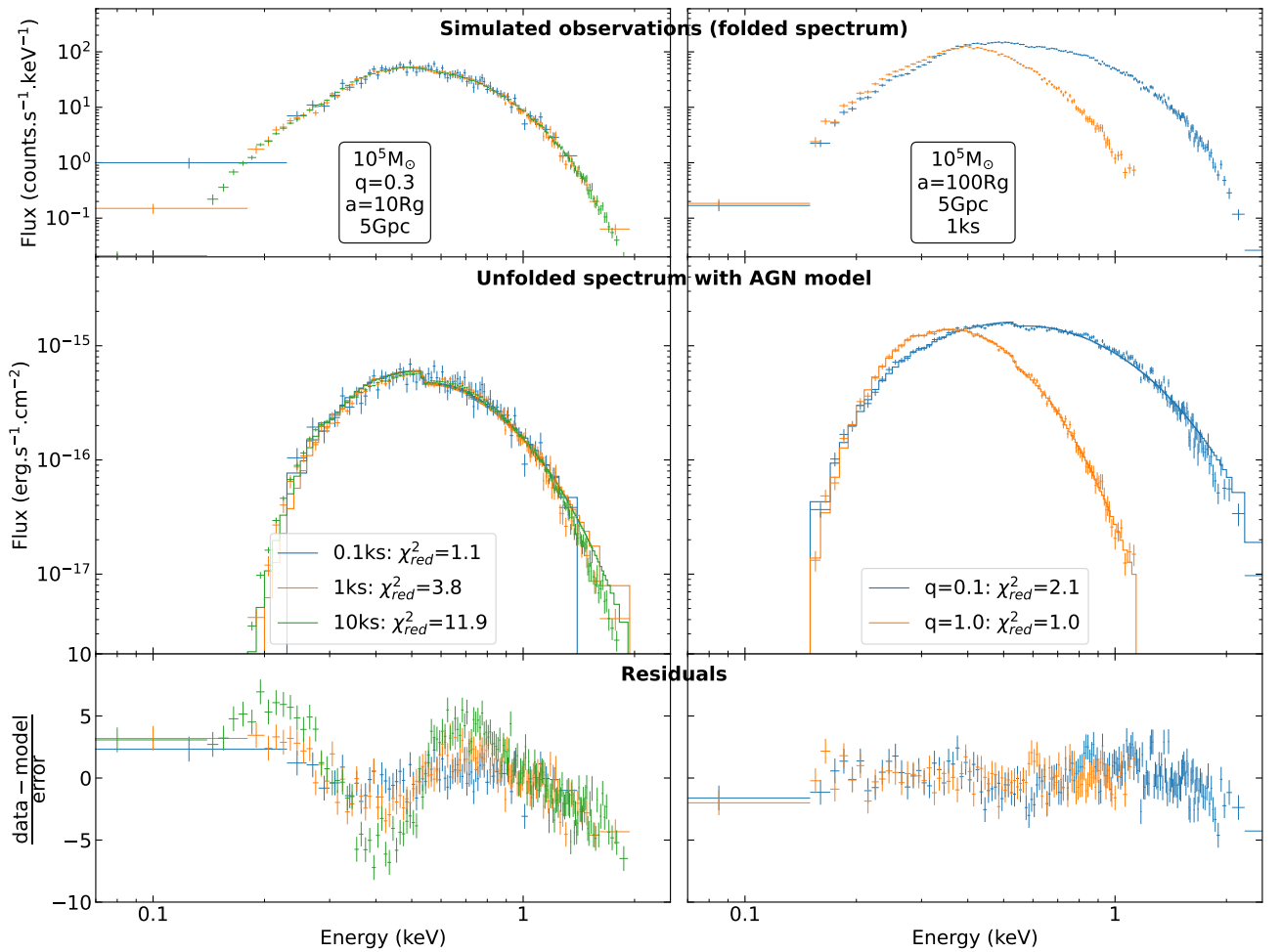


Fig. 3. Spectral fitting statistics on simulated observations: the first row shows the simulated observations for a given binary / exposure configuration. Then second row shows a spectral fitting of these observations with a single BH model and returns the reduced χ^2 and the residuals in the third row. We present two cases here, with and without notch in the NewAthena range. **Left:** a $M = 10^5 M_{\odot}$, $q = 0.3$, $a = 10R_g$ binary with no spins, located à 5 Gpc. With this short separation the notch is fully in the NewAthena energy range and we explore the exposure time needed to distinguish a binary from an isolated AGN: for 1 ks the single BH model is unable to reproduce the binary spectrum. **Right:** a $M = 10^5 M_{\odot}$, $a = 100R_g$ binary with no spins, located à 5 Gpc. Taking a reasonable exposure time of 1 ks, we outline the impact of mass ratio on binary/AGN distinction : efficient for small mass ratio but failed for equal mass binary.

We perform spectral fitting of simulated observations (group until a minimum of 20 cts/bin) and use χ^2

statistics to evaluate the fit quality and hence test our ability to discriminate between a binary system and an isolated AGN. Starting from the simulation of a selected binary, we fit it using a single BH model, describing the thermal component of an isolated accretion disc with a multiple blackbody (similar to Xspec diskbb model).

Let us first distinguish two main cases according to the notch energy, in or out NewAthena energy range. For low mass binaries and/or binaries with small orbital separation, the notch falls into the energy range targeted by NewAthena, and the spectrum shows this identified notch pattern. The questions then concern the capability to detect this feature after taking into account the photoelectric absorption of the X-rays, the minimum exposure time required to detect it unambiguously, and the maximum distance at which it can be observed. An example is given in the left panel of figure 3, with a $M = 10^5 M_\odot$, $q = 0.3$, $a = 10R_g$ binary with no spins, located at 5 Gpc. For a very short exposure time (0.1 ks, blue line), the simulated observation data can be correctly adjusted by the single BH model (reduced $\chi^2 = 1.1$). Therefore, it is not possible to distinguish binaries from single AGNs with such a short exposure time. However, for an exposure time of 1 ks (orange line), the single BH model is unable to correctly reproduce the notch pattern with great confidence in the results (reduced $\chi^2 = 3.8$). This is confirmed for longer exposure time (reduced $\chi^2 = 11.9$ for a 10 ks exposure time).

On the other hand, for large binary separations, the notch slides towards the UV domain, out of NewAthena's reach. It remains to determine whether other features in the thermal signature can help identify the binary. Some clues come from the high-energy part of the thermal emission, i.e. the emission of mini-discs. For a given total mass, the two black holes in a binary system are less massive, and the inner edge of their accretion discs emits at a higher energy than in the case of an isolated black hole. This is particularly noticeable given that the secondary black hole is light (small mass ratio) and/or spins rapidly (high secondary spin). Furthermore, a significant difference between the two black holes in the binary system, linked to a large mass difference (small mass ratio) or a counter-rotation (opposite high spins), broadens the high-energy emission, forming a plateau that is difficult to reproduce using a single BH model. In the right panel of figure 3, we show the case of a $M = 10^5 M_\odot$, $a = 100R_g$ binary, hence having its notch out of NewAthena energy range. Identification depends on the mass ratio: for equal mass binary ($q = 1$ in orange), the single BH model provides a fitting solution tailored to the observation data, with a reduced $\chi^2 = 1.0$. In this case we are not able to distinguish a binary from an single AGN. A contrario for a smaller mass ratio ($q = 0.1$ in blue), the two mini-discs emit at different energies and this broadened emission band can not be properly fitted with single BH model (reduced $\chi^2 = 2.1$).

5 Conclusions

Through this study we examine the thermal continuum emission from accreting binary black holes and report a good detectability over the parameter space with reasonable exposure times with the forthcoming NewAthena satellite. Beyond that we are deeply interested in the binary/AGN distinction with this thermal continuum emission and look for specific patterns which enable unambiguous identification. The notch signature, due to a flux deficit between circumbinary disc and mini-discs, is efficient for low mass ($M_{\text{BBH}} < 10^6 M_\odot$), small separation ($a < 30 R_g$) binaries. Furthermore, the broadening of the high-energy emission part allows for clear identification when the mini-discs differ from each other in mass or spin. These promising results still need to undergo final verifications, one concerning the ratio of inspiral / observation time and the other concerning the impact of non-thermal emissions on the capability of distinguishing binary black holes from isolated AGNs.

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