

# Can we disentangle between the emission of an accretion disc around a single black hole and a circumbinary disc?

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## ABSTRACT

The detection of gravitational waves from binary black holes (BBHs) started the hunt for their pre-merger electromagnetic emission. In that respect, numerical simulations have been looking for the ‘smoking gun’ signal that could help identify pre-merger systems. Here, we study if any of the expected features of circumbinary discs, such as the periodic modulation from the orbiting ‘lump’, could be used to identify pre-merger BBHs or if they could be easily confused with other systems. Indeed, while the timing feature associated with the ‘lump’ seems to be present for a large part of the parameter space defined by the binary separation and mass ratio in circular binaries, it was recently proposed to form thanks to an instability occurring naturally at the edge of accretion discs around single black holes (SBH). In order to check if features of a circumbinary disc could be reproduced by a SBH system, we search for at least one SBH fit able to replicate the given synthetic observations of a circumbinary disc. We found that many of the features from a circumbinary disc can be reproduced by an SBH system with different masses, distances, or inner disc positions. Interestingly, while we can always find an SBH model providing a good enough fit to the data, the presence of two variabilities, associated with the lump and the binary, or binary-lump beat, period, is a necessary condition for a wide range of BBH system parameters and should be used as a test to disqualify some BBH candidates.

**Key words:** accretion, accretion discs – black hole physics – hydrodynamics.

## 1 INTRODUCTION

The detection of gravitational waves (GW) from the merger of compact objects and their electromagnetic counterparts has opened a new era of multimessenger astronomy both in observations (Abbott et al. 2017; Graham et al. 2020) but also in numerical simulations as they are currently the only way to constrain what observables would help us detect a BBH system before or during the early stage of gravitational wave detection. The major part of the numerical studies of pre-merger binary black-holes (BBHs) is looking at the system between the moment a circumbinary disc is formed down to the merger (e.g. reviews by Gold 2019; D’Orazio & Charisi 2023). Those numerical studies converged towards a system where the circumbinary disc is feeding the individual black holes through two streams which might form some intermittent disc-like structures around each black hole (MacFadyen & Milosavljević 2008; Shi et al. 2012; Noble et al. 2012; D’Orazio, Haiman & MacFadyen 2013; Gold et al. 2014; Shi & Krolik 2015; Armengol et al. 2021; Tiede et al. 2022; Liu 2021). One of the most interesting features is the presence of a strong  $m = 1$  azimuthal mode at the inner edge of the circumbinary disc leading to an overdensity that was dubbed ‘lump’ by Shi et al. (2012). Such an overdense lump is promising

as it could lead to an observable feature in the form a modulation of the electromagnetic flux, especially in the case of a high inclination system (Noble et al. 2012, 2021; D’Orazio et al. 2013; Farris et al. 2014), in turn this signal could allow us to identify pre-merger systems with a circumbinary disc. It is worth noting that this overall structure is also seen in Newtonian simulations (see the extensive review on circumbinary disc by Lai & Muñoz 2023) and across codes (as is shown in the Santa Barbara Binary-Disc code comparison in Duffell et al. 2024), hence making it a robust feature of circumbinary discs around circular binaries.

In Mignon-Risse, Varniere & Casse (2023b), we proposed an instability (the Rossby-Wave Instability; RWI; Lovelace & Hohlfield 1978; Lovelace et al. 1999; Li et al. 2000) to be at the origin of the  $m = 1$  mode that gives rise to the lump at the edge of the circumbinary disc which would create a quasi-periodic modulation of the light curve (e.g. Tang, Haiman & MacFadyen 2018). This was a beneficial step as it gives us a better understanding of what causes the lump, hence we can better predict in which systems it would occur, which in turn tells us that such observables are expected for a large range of mass-ratio and time-to-merger. At the same time, it also raises the issue of how to distinguish those observables from the ones arising from the accretion disc orbiting around a single black hole (see e.g. Varniere, Vincent & Casse 2020). Indeed, if one wants to use the lump-induced variability as a way to identify pre-merger BBHs, we need to make sure that no other systems, namely

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an SBH system, could exhibit the same observational features. If the observable cannot be untangled, it could not only mean that some BBHs have been misclassified as single black holes, but also that some of our candidate BBHs are in fact single black-hole systems with quasi-periodic variability. Hence, a more thorough examination is required.

To that effect, we will first briefly present which stage of the pre-merger BBH system we are focusing on and what are the potential observables that are associated with it. We will also briefly present the simulations from which our synthetic observations were computed. As we are looking for a possible match between observables from circumbinary discs and SBH accretion discs, the actual origin of the lump is not relevant in this study but rather its impact on the observables. As such we will not discuss in detail these simulations but only display the basic set-up from which they originate. In the following two sections, we will focus on specific circumbinary observables and their potential matches from SBH systems. Our approach will be to take each observable and check if the SBH model can be disproved or shown to lack some ingredients hinting at a more complex system. The first one will be the full spectral energy distribution (SED) of the circumbinary disc that will be confronted with a few SBH systems able to fully reproduce its observed SED. Then we will focus on the temporal variability of circumbinary discs and compared it with SBH systems that could match it. Here, the aim is to see how easy it would be simply fit the BBH's observables with an SBH. Lastly, we will look at what combination of observables would be needed in order to distinguish both systems. In turn, this will allow us to check when the lump's impact on the observables can be confirmed as a key component to identify pre-merger systems.

## 2 BINARY BLACK HOLE VERSUS SINGLE BLACK HOLE SYSTEM

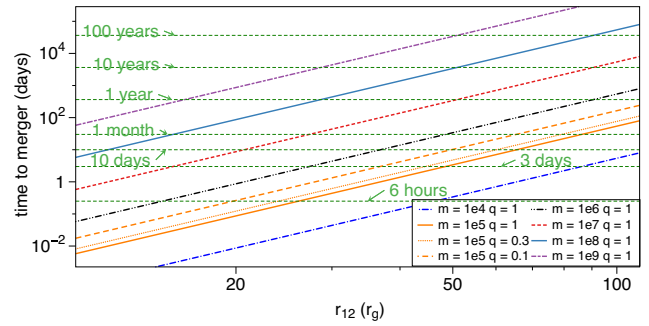
For both systems, we are using the units where the gravitational constant  $G$  and velocity of the light  $c$  are set to unity  $G = c = 1$  and the gravitational radius  $r_g = GM/c^2$  is computed with the total mass  $M$  of the system while the mass ratio between masses in a BBH system is labelled by  $q$  (with  $q \leq 1$ ).

### 2.1 Explored stage of the pre-merger BBH system

In this paper, we choose to focus on the pre-merger stage where the BBHs are surrounded by a circumbinary disc while being separated by up to a few tens of gravitational radii, prior to binary–circumbinary disc decoupling (Armitage & Natarajan 2002).<sup>1</sup> A consensus has arisen on this pre-decoupling stage where it is believed that it exhibits a promising variability coming from the ‘lump’ which could be used to distinguish binary systems from SBHs (MacFadyen & Milosavljević 2008; Shi et al. 2012; Noble et al. 2012; D’Orazio et al. 2013; Gold et al. 2014; Shi & Krolik 2015; Armengol et al. 2021; Tiede et al. 2022; Liu 2021).

The existence of a circumbinary disc around the BBH imposes an upper limit upon the binary separation between the two black holes as, at very large separation, the original individual accretion discs are not yet rearranged into a circumbinary disc by the tidal forces of the binary. While there is no firm consensus on the separation

<sup>1</sup>The separation at decoupling depends on various parameters and processes, e.g. the ability of the circumbinary disc to transport angular momentum, and can occur at very small separation in some cases (Noble et al. 2012). Here, by assuming circular orbits we focus on the pre-decoupling stage.



**Figure 1.** Time to merger for BBHs as a function of the binary separation (in units of  $r_g$ ) for several binary total masses (in solar masses) and mass ratios.

below which a circumbinary disc is likely to exist, we have decided to restrain ourselves to separations no larger than  $100 r_g$ . Setting such maximal separation leads to binary time-scales that provide interesting estimates of the time period during which such systems can potentially be detected. Considering such maximum separation, Fig. 1 displays the upper limit of the timespan corresponding to our assumption, under the condition of the existence of a circumbinary disc, computed using the lowest-order post-Newtonian formula (Peters 1964). We see that systems with total mass  $M > 10^5 M_\odot$  will spend a long enough time in this pre-merger stage to reach detectability for current and future high-energy observatories (Mangiagli et al. 2022), especially if the system has been flagged as a BBH candidate prior to forming a circumbinary disc (see for example Varniere, Casse & Dodu, in preparation, for a study of pre-circumbinary disc system). For that reason, we will focus the rest of the paper on those supermassive BBH systems, even though the results presented here are independent of the system’s mass.

### 2.2 Origin of the synthetic observations used in the paper

The main objective of this paper is to confront observables characterizing accretion discs orbiting an SBH to observables characterizing circumbinary discs. In order to do so, it is desirable to have synthetic observations based on GR fluid simulations, as analytical models (Roedig, Krolik & Miller 2014) are unable to describe the complex flow morphology we described above and Newtonian fluid description failing in the relativistic regime. In our previous works, such synthetic observations were already performed with the exception of the lightcurve for the SBH case which was not produced for a supermassive BH system in the original publication. All of the fluid simulations and synthetic observations were produced by NOVAS, our Numerical Observatory of Violent Accreting systems (Varniere, Casse & Vincent 2018) for the SBH system, or by e-NOVAS, its extension to BBHs (Mignon-Risse, Varniere & Casse 2023a). As a result, we only succinctly present the code below and orient the reader to the original publications of the different simulations for more details.

Fluid simulations were performed in a 2D framework with GRAMRVAC (Casse & Varniere 2018; Mignon-Risse et al. 2023a), a general-relativistic hydrodynamical code using either a Kerr metric for SBH systems or a newly implemented approximated BBH metric (Ireland et al. 2016) for circumbinary disc simulations. Synthetic observations associated with the aforementioned fluid simulations were obtained by the use of a ray-tracing code `gyoto` (Vincent et al. 2011), in which we implemented the very same metrics as in the GR fluid simulations. `gyoto` ray-traces the emissions back from the observer toward the disc where it uses the temperature map produced

by the GR simulation to compute the disc blackbody emission. All the synthetic observations of circumbinary discs used in this paper were obtained using the method of Mignion-Risse et al. (2023a), with the fluid simulations presented in Mignion-Risse et al. (2023b). For the SBH case, the synthetic observations and the fluid simulations (Varniere et al. 2020) were performed using the simpler Kerr metric. Both types of synthetic observations were obtained using the same procedure as presented in Varniere et al. (2020), namely calculating the synthetic emission without the fast-light approximation. It is noteworthy that the inner edge location of the surrounding disc depends on the nature of the central object (near the last stable orbit for SBH systems and approximately twice the orbital separation in BBH system; Artymowicz & Lubow 1994). The aforementioned GR fluid simulations initial set-up was with gas everywhere close to gravitocentrifugal equilibrium and we let the gravity carve out the inner edge of each disc while having similar mass distribution. In those simulations, an inner edge of the disc forms near its expected radius and was able to form a lump for the explored mass ratio  $q \in [0.1, 1]$  (Mignion-Risse et al. 2023b). At the separation of twenty gravitational radii, this gave a lump period of about six binary periods. When producing the light curves, and spectral energy distribution, of each systems we only use snapshots after the instability has reached saturation until the end of the simulation,<sup>2</sup> i.e. tens to hundreds of inner edge orbits. The light curves are computed over the entire blackbody spectrum so that different masses will have the same light curve but with their maximum emissivity pointing in a different band (see Figs 4 and 3). We then followed the dynamical evolution of the discs leading to time-varying synthetic observations. The time-variability in both types of simulation is induced by the presence of a fluid instability (e.g. the RWI) leading to a non-axisymmetric pattern in the disc that directly affects the luminosity of the respective discs.

### 2.3 Observables of BBH and SBH systems

According to previous works focusing on the dynamics of the circumbinary discs in BBH systems (in a wide variety of gravity, thermodynamics, and excision set-ups see for example MacFadyen & Milosavljević 2008; Shi et al. 2012; Noble et al. 2012; D’Orazio et al. 2013; Gold et al. 2014; Shi & Krolik 2015; Armengol et al. 2021; Tiede et al. 2022; Liu 2021; Duffell et al. 2024), two strong observables can be found, namely

- (i) the thermal spectrum from the circumbinary disc whose inner edge lies around twice the binary separation leading to a peak in the UV/optical for binary masses in the range  $M = 10^{4-10} M_{\odot}$  (Roedig et al. 2014; Farris et al. 2015; D’Ascoli et al. 2018; Gutiérrez et al. 2022; Krauth et al. 2023; Franchini et al. 2024).
- (ii) a dominant flux modulation, linked with the presence of the lump at the inner edge of the circumbinary disc, and related to the Keplerian frequency around the position of the lump. A smaller modulation, related to the much shorter binary period (owing to the spiral arms or to the binary-lump beat), is also present (Tang et al. 2018; D’Ascoli et al. 2018; Duffell et al. 2020; Westernacher-Schneider et al. 2022; Franchini et al. 2024; Cocchiararo et al. 2024).

In order to reproduce the first observable in the SBH case, full GR simulations are not required as simple observational models like

`diskbb`<sup>3</sup> or `kerrbb`<sup>4</sup> are often used for fitting accretion discs around SBHs. Only when we consider the timing aspect of SBH systems, we do turn towards GR numerical simulations as we are still lacking observational model for quasi-periodic oscillations (QPO) beyond a sinusoidal fit. In the post-processing step, emission and BH parameters are chosen to be consistent with a supermassive BH disc.

### 3 REPRODUCING A CIRCUMBINARY DISC SPECTRUM WITH A SINGLE BLACK HOLE SYSTEM

One of the first observables we are able to obtain for any supermassive BH system is its SED, generally comprised of several non-continuous bands that cover the overall behaviour of the source. It is therefore interesting to explore how different the SED of a circumbinary disc will be from a disc around a single BH. The presence of the lump and spiral structure in the circumbinary disc causes a relatively strong modulation of the flux, hence emphasizing that a non-negligible part of the flux is present within those structures. It is therefore not entirely straightforward that a featureless monotonic disc could reproduce the SED of a circumbinary disc. We are particularly interested to see under which conditions one could match a circumbinary SED to an SBH one, basically looking at the possibility that we have already observed a BBH system which was ‘misclassified’ as a single BH if solely basing the comparison upon the SED of the system.<sup>5</sup>

We choose to focus only on the emission from the disc versus circumbinary disc as we want to see if they are distinguishable. In a more realistic system, contaminants would be added to both emissions which would complexify the fit, but by showing how well we can fit the disc spectrum, any added structure on top of them would only amplify our inability to distinguish between the two. Among those potentially added structures there are the individual accretion structures around each BH which are not accessible through the simulation of Mignion-Risse et al. (2023b) in which the inner region is excised. Nevertheless, it was shown in the Santa Barbara Binary-Disk code comparison (Duffell et al. 2024), that having an excision region does not impact the existence of either lump or spiral arms in the simulation. In the presence of individual accretion structures and streams, those would be at higher energy than the CBD (see for example the representation by Roedig et al. 2014; Cocchiararo et al. 2024) and both components, CBD and individual structures, would be separated by a ‘notch’ or at least a lower emission<sup>6</sup> in the full SED.

Hence, we chose to focus on the circumbinary disc spectrum which has the advantage of staying present, though decoupled from the binary evolution in later stage, even after individual accretion structure become unstable as the binary separation shrinks (Krauth et al. 2023).

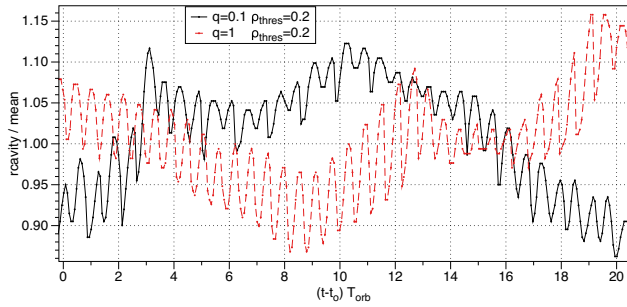
<sup>3</sup>spectrum from an accretion disc consisting of multiple blackbody components <https://heasarc.gsfc.nasa.gov/xanadu/xspec/manual/node166.html>

<sup>4</sup>multitemperature blackbody model for a thin, steady state, general relativistic accretion disc around a Kerr BH <https://heasarc.gsfc.nasa.gov/xanadu/xspec/manual/node189.html>

<sup>5</sup>In theory, this also means that some BBH candidates could actually be a single black-hole systems. But, as BBH candidates are more often identified through their variability than their SED, such misclassification is less likely to happen when looking at the SED fitting.

<sup>6</sup>compared to a full accretion disc without cavity.

<sup>2</sup>While we stopped the runs due to computational time limits, we still have up to a hundred orbits of the inner edge of the disc in some of the runs.

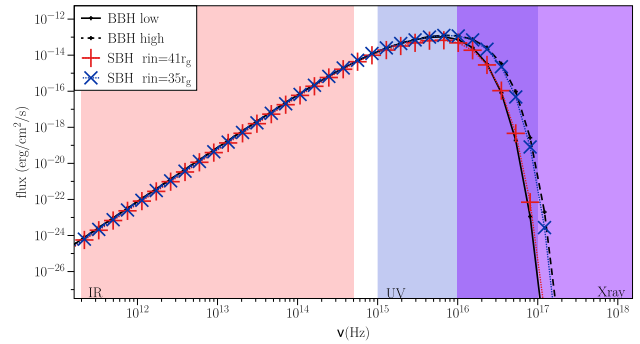


**Figure 2.** Temporal evolution of the ratio of the outer radius of the cavity carved by the BBH divided by its mean value, for the equal-mass  $q = 1$  case (dashed line) and for the  $q = 0.1$  case (full line). In both cases, the binary separation is  $20 r_g$  with a lump period of about six binary periods, and both simulations are shown at a similar stage where the ‘lump’ is well established (with  $t_o^{q=0.1} = 144 T_{\text{orb}}$  and  $t_o^{q=1} = 110 T_{\text{orb}}$  respectively to show both curves on the same axis).

### 3.1 Evolution of the circumbinary disc edge

As the system we are looking to identify is comprised of the central object, either a binary or single BH, and its associated disc, it is important to first characterize the disc position in our BBH simulations as it will directly impact the energy spectrum. We showed in Mignon-Risse et al. (2023b) that the inner region of the circumbinary disc has a fast evolution which might be hard to reproduce with an SBH disc. It is therefore interesting, even before looking at the circumbinary disc emission, to look at the instantaneous evolution of the outer edge of the cavity carved by the BBH which, in turn, determines the position of the inner edge of the disc and hence its overall emission.

Hitherto, as can be seen in all numerical simulations of circumbinary BBH discs (see e.g. Duffell et al. 2024 and references therein), the inner region of the circumbinary disc is not circular. In order to get an estimate of the position of the inner edge of the disc, we first average azimuthally the density and then follow the position of the outer edge of the cavity defined using a density threshold. Fig. 2 shows this radius in the latter stage of circumbinary disc simulations, meaning when the lump is fully developed and has a strong impact on the edge of the disc (with  $t_o^{q=0.1} = 144 T_{\text{orb}}$  and  $t_o^{q=1} = 110 T_{\text{orb}}$ , respectively). In these simulations, the separation is  $20 r_g$  while the inner edge of the disc is initially located at a radius smaller than two times the separation. As simulations go on, material below two times the separation is rapidly swept away leading to a non-axisymmetric inner edge of the circumbinary disc. To facilitate the comparison between the typical symmetric case,  $q = 1$ , and a more strongly asymmetric mass distribution case with  $q = 0.1$ , we show the evolution of the inner edge of the disc with respect to its mean value. We can see on Fig. 2 that, while the azimuthally averaged inner edge of the disc oscillates, following both the movement of the lump (which is less noticeable for the  $q = 0.1$  case) and the beat frequency with the binary period, this overall variation is at most  $\pm 15$  per cent and even smaller along one binary orbit. Nevertheless, we also see that the variation of the azimuthally averaged inner edge shows wider variation for the  $q = 0.1$  case. For that reason, we will use this case as an example in the rest of the paper as it gives us a wider range of modifications for the azimuthally averaged inner edge, which in turn will lead to a wider range of changes in the SED that we are trying to reproduce.



**Figure 3.** Evolution of the energy spectrum along one orbit of the ‘lump’ (the full line for the low point, and dashed line for the high point) and how it can be reproduced by a moving truncated disc around a single Schwarzschild black hole (cross and plus representing an inner edge of the disc at  $35 r_g$  and  $41 r_g$ , respectively). The BBH source is  $M_{\text{BBH}} = 10^6 M_{\odot}$  with a mass ratio of  $q = 0.1$  and a separation of  $20 r_g$ , seen at a distance  $D = 500$  Mpc and under an inclination of  $70^\circ$ .

### 3.2 Comparing SED from a BBH circumbinary disc with a truncated inner disc around an SBH of the same total mass

In fig. 10 of Mignon-Risse et al. (2023a), we showed that the *averaged* energy spectrum of a circumbinary disc, with all its structure, computed in a full BBH metric could be reproduced by truncating the inner region of an axisymmetrical disc around a single BH of the total mass of the binary. Here, we want to explore if the change at most  $\pm 15$  per cent seen in the azimuthally averaged inner edge position translates into a noticeable impact on the instantaneous energy spectrum of the entire circumbinary disc.

It is therefore interesting to see if a simple disc around an SBH can reproduce the emission expected from the circumbinary disc and its associated ‘lump’. For the rest of the paper, we will compute observables for a fiducial BBH of a total mass of  $M_{\text{BBH}} = 10^6 M_{\odot}$  (which is a mass enabling the system to stay in the pre-merger phase for a long enough time for a potential detection, see Fig. 1) with a binary separation of  $20 r_g$ , seen at a distance  $D = 500$  Mpc and under an inclination of  $70^\circ$ . We see in Fig. 3 that even for the 15 per cent variation of the  $q = 0.1$  case, the full energy spectrum can be reproduced by having an axisymmetric disc around a Schwarzschild BH with the same mass if the inner edge of that disc is further away than its last stable orbit and matches the average position of the circumbinary cavity as seen in Fig. 2. This is related to the fact that the differences due to the GR effects between a BBH and an SBH of the same total mass are relatively small at that distance (this can be seen in fig. 3. of Mignon-Risse et al. 2023a), hence the overall instantaneous spectra for a disc at the same distance are similar and do not allow us to distinguish between the different central objects.

The drawback of that fit is that it leaves the need to explain the reason for such truncation of the disc. On top of that, if we have access to more than one spectrum of the system, we will find that the inner edge of the disc is moving which also needs to be explained.

### 3.3 Comparing SED from a BBH circumbinary disc with a disc reaching the last stable orbit of a heavier SBH

As a consequence it is interesting to look for the possibility to match the SED of a circumbinary disc with the one produced by an SBH disc extending up to its last stable orbit. Following the similitude between the circumbinary spectra and truncated discs shown previously (also raised by Roedig et al. 2014), we use the

temperature scaling from Shakura & Sunyaev (1973) to estimate its distribution in the circumbinary disc as well. Hence, the temperature profile for a black hole of mass  $M_{\text{BBH}}$  with an inner edge of the disc at  $r_{\text{in}}^{\text{BBH}}$  is given by

$$T^{\text{BBH}}(r) \propto \left( \frac{M_{\text{BBH}}}{M_{\text{Edd}}} \right)^{1/4} (M_{\text{BBH}})^{-1/4} \left( \frac{r}{r_{\text{in}}^{\text{BBH}}} \frac{r_{\text{in}}^{\text{BBH}}}{r_g^{\text{BBH}}} \right)^{-3/4} \quad (1)$$

with  $r_g^{\text{BBH}}$  the gravitational radius of the binary,  $M_{\text{BBH}}$  its accretion rate and  $M_{\text{Edd}}$  the Eddington accretion rate. In order to be able to fit the same SED, we need to have the same effective temperature profile but for a disc reaching its last stable orbit. This translates into a relation between the BBH total mass, its circumbinary disc inner radius and the required mass for an SBH whose disc reaches its last stable orbit, denoted  $r_{\text{LSO}}^{\text{SBH}}$ , namely

$$M_{\text{SBH}} = \left( \frac{r_{\text{in}}^{\text{BBH}}}{r_g^{\text{BBH}}} \right)^{3/2} \left( \frac{r_g^{\text{SBH}}}{r_{\text{LSO}}^{\text{SBH}}} \right)^{3/2} M_{\text{BBH}}. \quad (2)$$

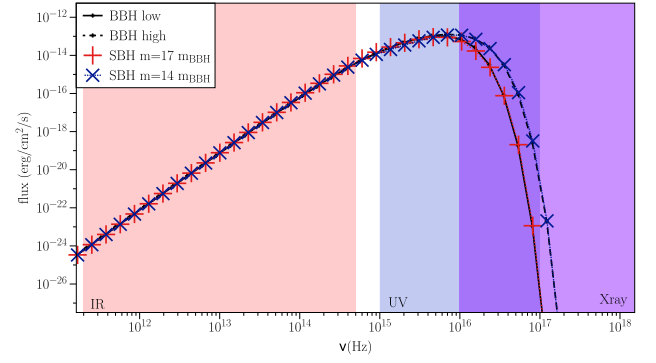
Since we focus on the pre-decoupling phase,  $r_{\text{in}}^{\text{BBH}} \approx 2b > 20r_g^{\text{BBH}}$  for all cases depicted in Fig. 1, with  $b$  the orbital separation. Similarly, for the SBH case we have, depending on its spin,  $1 \leq r_{\text{LSO}}^{\text{SBH}} \leq 9r_g^{\text{SBH}}$ , with  $r_g^{\text{SBH}}$  the gravitational radius of the SBH. This gives us  $M_{\text{SBH}} > M_{\text{BBH}}$ . It is interesting to note that the ratio is at the power of three-half which means that even a small,  $\pm 15$  per cent, change in the inner radius of the circumbinary disc will require a larger, but still mostly within typical error bars, change for the single BH mass. This is valid for any spin of the SBH but adding another unknown, will only increase the complexity of the fit and would only make sense if we had an independent constraint on the spin of the object we are trying to fit. For that reason, in the following we only show results for a Schwarzschild SBH but the calculation can be done for any value of  $r_{\text{LSO}}^{\text{SBH}}$ .

When applying this for our previous circumbinary disc where the inner radius fluctuates between  $34r_g$  and  $44r_g$ , we see that it can cause the needed SBH mass to change by a maximum of 30 per cent along the orbit. Nevertheless, when looking at the instantaneous case, it predicts a good fit by a single BH with a mass varying between 14 and 17 times that of the binary, as is shown in Fig. 4. In the case where we have only one instantaneous energy spectrum of the circumbinary disc, and therefore only one value for its inner edge radius, it will be well approximated by a single, but heavier, Schwarzschild BH with a disc reaching its last stable orbit. Without any other information, such as an estimate of the central object mass, there is no need for a more complex system than an SBH. Alternatively, if we get a large enough set of observations to follow the shrinking of the binary orbit, hence observations on a long enough time-scale to follow the dynamical change of the separation, we could see the needed mass change at a rate compatible with equation (2) which could be used to hint at the presence of a binary.

## 4 REPRODUCING THE TEMPORAL VARIATION IN BBH: QPOS IN SMBH

### 4.1 Interest of timing studies for BBH candidates

While the SED is the first and most common observable for supermassive BHs, another common observable of BH systems is their time variability, especially when a close to periodic signal exists. Because of the difference in time-scale, such studies tend to be more frequent for low-mass X-ray binaries, with a modulation in the range of seconds to 100 s, while it is at least hours for the lowest



**Figure 4.** Evolution of the energy spectrum along one orbit of the ‘lump’ and how it can be reproduced by a heavier single Schwarzschild BH with a disc at its last stable orbit. The BBH source is  $M_{\text{BBH}} = 10^6 M_{\odot}$  with a mass ratio of  $q = 0.1$  and a separation of  $20r_g$ , seen at a distance  $D = 500$  Mpc and under an inclination of  $70^\circ$ . An equivalent SBH system whose mass is between 14 and 17 times heavier would provide a good fit for the circumbinary disc.

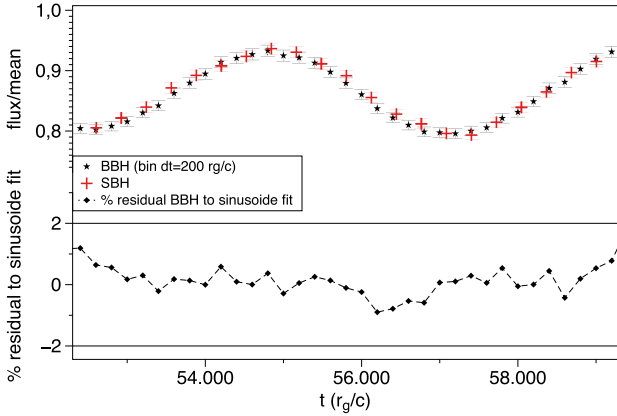
supermassive BH and up to hundreds of days in the highest mass systems (see for example Varniere 2023). Studying such variability is technically challenging and requires long spanning observations to constrain, which is the reason that we have only limited variability studies in supermassive BHs.

Nevertheless, looking at the ‘fast’ temporal variability of SMBH is becoming particularly interesting with the rise of the lump feature and its variability as a potential signature of near-merger BBHs (Shi et al. 2012; Noble et al. 2012, 2021; D’Orazio et al. 2013; Farris et al. 2014) among other periodic-like signatures (D’Orazio & Charisi 2023; Franchini et al. 2024). As we have excised the inner region, close to the black-holes, focusing on the circumbinary disc only, we lack any variability linked to the presence of individual accretion structures. While studies of those ‘mini-disc’ exist (D’Orazio, Haiman & Schiminovich 2015; Krauth et al. 2024), their variability cannot be easily estimated from the literature. Nevertheless, their flux should be modulated either at the (semi-)orbital period or beat with the lump, which is different from the lump period (Westernacher-Schneider et al. 2022). Hence, having this region does not change the existence of the lump modulation, though it would change the amplitude ratio between the two modulations (linked with the lump and the orbital period of the binary) depending on the energy band where the light curve is computed (Westernacher-Schneider et al. 2022). While this last point could be a novel way to detect binary black-holes, we are focusing here on the longer-lasting circumbinary disc (Krauth et al. 2023).

At the same time, in order to check the viability of the lump variability as a pre-merger signature, we need to search (1) if there is a way to mimic the periodic signal predicted to come from the orbiting lump in a system with only one BH, (2) how probable those would be, and (3) if there is any way to distinguish between them.

### 4.2 Comparing the light-curve modulations from the lump in BBH systems and from QPOs in SBH systems

Similarly to what was done for the thermal spectrum observable, here we aim to match the light curve modulation frequency, induced by the presence of the lump in circumbinary discs, to the variability frequency sometimes observed in SBH systems. Indeed SBH accretion discs are known to exhibit QPOs, quasi periodic modulation of their light curve, likely induced by a fluid instability (see e.g. Remillard & McClintock 2006).



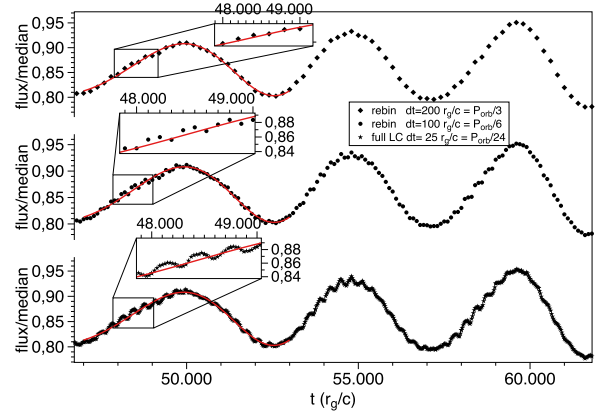
**Figure 5.** Comparing the light curve from an SBH prone to an instability occurring at the last stable orbit of its disc versus a lower mass BBH system exhibiting the so-called lump at the inner edge of its circumbinary disc. The error bar corresponds to a one per cent error. The bottom panel shows the percent residual of fitting the BBH light curve with a simple sinusoid often used to represent the RWI induced periodic variability in black hole systems in a model-independent way. Those light curves were computed at an inclination of  $70^\circ$ .

Even before having a model to explain the observed variability, we might try if a model-independent variability for the SBH case (i.e. we do not explain its origin) gives an acceptable fit. Indeed, this might be the first ‘model’ tried on such observations as to not add model-dependent hypotheses (D’Orazio et al. 2015). The bottom of Fig. 5 shows the residual from fitting the BBH’s light-curve variability with a simple sinusoid (the full fit can be seen on the top of Fig. 6). Not only do the residuals stay within a few per cent of the data but they also lack any strong additional feature pointing out to a missing component.

The next option to fit such variable light curve would be to have a QPO-inducing instability in an SBH system with a similar BBH mass and the inner edge of its accretion disc far from its last stable orbit (so their respective SEDs are similar, Section 3.2). This would be indistinguishable from the circumbinary case as the gravitational field of the central object is unlikely to affect quantitatively the modulation. Nevertheless, this would, as in the SED case, raise the question of what causes this sharply truncated inner disc.

Similarly to what was done for the spectrum, another possibility would be to try to reproduce the observed light curve with an SBH having its disc reaching its last stable orbit, hence removing the need for an additional mechanism to truncate the inner disc. For that we need to see if not only the frequency of the lump variability can be matched, but more importantly, how well the variability induced by an instability, such as the RWI (Varniere et al. 2020), occurring at the edge of a disc for a single BH could be confused with the light-curve modulation coming from the lump at the edge of the circumbinary disc. By equating the orbital Keplerian frequency at the edge of the circumbinary disc with the one at the last stable orbit of a single Schwarzschild BH, we get the requirement for the SBH to be more massive as  $M_{\text{SBH}} = (r_{\text{in}}^{\text{BBH}}/r_{\text{LSO}}^{\text{SBH}})^{3/2} M_{\text{BBH}}$  (with both radii given in units of their respective  $r_g$  in order to remove the mass scaling). Here, we see that the needed mass of the SBH inferred from the modulation is the same as the one needed for the SED fitting, meaning that the full SED will also be reproduced.

Looking at the light curves of both systems, we need to see how well the light curve of such SBH would be able to match the light curve from the circumbinary disc. Using e-NOVAs and the



**Figure 6.** Light curve for the BBH simulation binned at different time resolutions,  $P_{\text{orb}}/3$ ,  $P_{\text{orb}}/6$  and  $P_{\text{orb}}/24$ , showing the need for a good time resolution and signal-to-noise ratio in order to identify both frequencies. Those light curves were computed at an inclination of  $70^\circ$ .

previous mass estimate, we can compute the SBH light curve (with the appropriate mass using simulations from Varniere et al. 2020) and compare it with the corresponding circumbinary lightcurve. The top of Fig. 5 shows how little the light curve depends on the nature of the central object, indeed, the light curve computed from the more massive SBH is easily within the 1 per cent error bar of the lightcurve computed from the circumbinary simulation.

The similitude of both light curves makes it very difficult to differentiate between a BBH and a heavier SBH purely based on the fitting of the modulation. This will also stay difficult if we take into account the change in frequency that will occurs has the binary separation decreases. Indeed, as can be seen on Fig. 1, the less massive of the supermassive BBHs will go through the inspiral too fast for us to detect the change in frequency induced by the edge of the circumbinary disc moving inward. Similarly, the higher mass systems will have too slow of an evolution to produce a detectable change in the inner edge of the circumbinary disc. Only BBHs around  $10^{6-7} M_\odot$ , if caught early, might give us enough observations of the period evolution that the inferred SBH mass for each observation would become incompatible with each other.

## 5 A GENERAL VIEW ON ALL THE OBSERVABLES TOGETHER

We have seen that neither the spectrum nor the light curve independently can differentiate between a circumbinary or a SBH, here we want to explore if, and how, we could push those in order to have enough tension between the SBH fits to the data to rule that explanation out, hence leaving us with only the BBH explanation.

### 5.1 Can mass determination help lift the degeneracy?

A way to lift that issue is possible, at least for the larger circumbinary disc, hence the wider binary. Indeed the mass needed for the different fits presented above are greater than the actual mass of the binary by  $M_{\text{SBH}} = (r_{\text{in}}^{\text{BBH}}/r_{\text{LSO}}^{\text{SBH}})^{3/2} M_{\text{BBH}}$ ; hence, for the wider separation, creating a discrepancy that might be too large to be within an acceptable range of mass based on the quality of the SEDs and light curves. In the case used to illustrate the fitting in the previous examples, this leads to a mass difference of  $M^{\text{SBH}} \simeq 15M^{\text{BBH}}$  which could put a strain on the interpretation that the system hosts a single BH. This might be enough for the larger circumbinary disc, i.e.

binary with larger separation, if we also have access to a good and independent mass determination of the system as fitting the SED with an SBH at its last stable orbit requires a black hole that could be more than one order of magnitude heavier than the BBH is.

Nevertheless, if we lift the requirement for the disc to be at its last stable orbit then it will be impossible to distinguish a circumbinary system from a {SBH + truncated disc} system as the metric at such distance is too similar and there is little difference in the behaviour of the instability. This would raise the question of what causes the receding of the inner disc but would give a great fit of the data and be hard to refute using only the data presented here.

## 5.2 Detecting the binary period

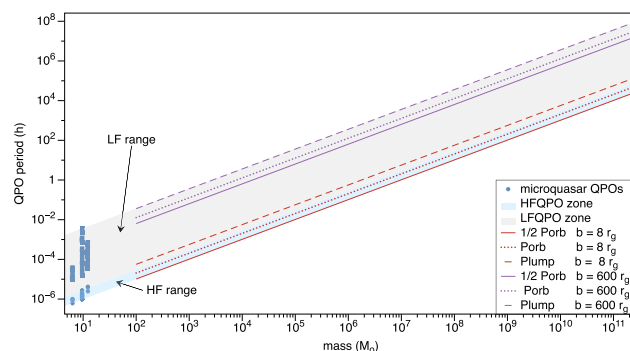
We now turn to look how improving the data could help distinguish between a single BH and a binary, focusing on what is unique to the binary, namely its period and features related to it, such as the spiral density waves and the binary-lump beat, both producing a signal close to the (semi-) binary period.

Following this idea, we binned the light curve for the BBH simulation at different time resolutions,  $P_{\text{orb}}/3$ ,  $P_{\text{orb}}/6$ , and  $P_{\text{orb}}/24$ . As the BBH rotates at a larger frequency than the plasma in the circumbinary disc, the binary modulation is expected to have a smaller period than the lump induced modulation of the disc. Fig. 6 shows how we can see half the binary period directly on top of the main variability once we have enough data points per binary period. The red curve on each LC represents a simple sinusoidal fit of the main modulation and the zoom-in plots give an idea of how that secondary modulation would become visible in the residual if a model-independent sinusoid was used to fit the LC. It is important to note that, while a good time resolution is necessary, it is not enough as the lower-amplitude modulation is only of the order of 1 per cent of the total flux for a wide range of separations, hence much smaller than the lump's one and will be hard to detect without a good signal-to-noise ratio for the light curve. It is worth noting, that this secondary modulation might be strengthened if also present in the individual accretion structure of each black-hole, though we will see an evolution of the respective amplitude depending on the energy band where the LC is computed (Westernacher-Schneider et al. 2022).

While being able to directly observe the impact of the binary period on the light curve will be a great step toward distinguishing between a single BH system and a binary system, it does not create a unique enough impact on the light curve. Indeed, such small modulation seen on top of a stronger, lower frequency, modulation is similar to what is seen in low-mass X-ray binaries in the state where both the low-frequency and high-frequency quasi-periodic oscillations (LF and HF QPOs) are present. This is especially important as most models for those QPOs could be applied to SMBH (see e.g. Varniere, Tagger & Rodriguez 2011; Varniere 2023) and would reach a similar frequency zone in the late stage of merger.

Indeed, if one extends the range of observed low-frequency and high-frequency QPOs to higher masses using a simple mass scaling (see e.g. Smith, Tandon & Wagoner 2021), we see on Fig. 7 that the expected lump and binary period will be in the 'QPO range' for a wide variety of orbital separations<sup>7</sup> making the presence of both variabilities, associated with the lump and the binary period, a

<sup>7</sup>The upper limit of a binary separation of  $600r_g$  is only there to show what would be the equivalent to the upper limit of LFQPOs and not as a realistic limit for the existence of a circumbinary disc.



**Figure 7.** Range of modulation periods as a function of mass for the circumbinary modulation, namely the lump and binary period (also indicative of the binary-lump beat period) and how they compare to an extension of the LF and HF QPO frequency of low mass X-ray binaries (data for GRO J1655 – 40, GRS 1915 + 105 and XTE J1550 – 564 from Rodriguez et al. 2002; Mikles et al. 2009; Varniere & Vincent 2017). The  $600r_g$  separation is to show that all binary separations with a disc will fall into the QPO range.

necessary condition for a BBH but not sufficient as they could be originating from instabilities or phenomena similar to the case in low-mass X-ray binaries.

## 6 CONCLUSION

In this paper, we explored the difficulty of identifying if a source hosts a binary system or a single black-hole using either/both the SED and light curve from their disc's thermal emission without a priori on its nature. The aim was to show the potential issues and pitfalls of disentangling between BBH and SBH based only on their disc's emission and to show potential steps to resolved that. Indeed, while the periodic modulation predicted to originate from the orbiting lump at the edge of a circumbinary disc is often presented as a way to detect pre-merger BBHs, it raises the question of our capacity to distinguish between the lump induced modulation of a circumbinary disc and an SBH disc exhibiting temporal variability due to the presence of a fluid instability (such as the RWI) occurring near its inner edge. In this paper, we show that the modulation caused by the lump will be hard to use as the ultimate signature of BBHs. Indeed, it requires a good, independent mass determination, as well as a precise time resolution and a good signal-to-noise ratio in the wavelength where the lump modulates the flux, while not being unique to BBH systems. Nevertheless, it can be used as a first criterion when looking for BBHs. Indeed, while not unique to those systems, its presence is a requirement for a large number of mass ratio and pre-merger times (Mignon-Risse et al. 2023b) and can help reduce the number of sources that could be BBH candidates.

It is interesting to note that what limits the usage of this double variability as a unique signature of BBH is our limited knowledge of supermassive single BH QPOs which prevents us from quantifying the differences between both variabilities. Hence, we need to improve our understanding of supermassive single BH QPOs at the same time as we explore the variability linked with the presence of a BBH if we want to be able to differentiate between them in the near future. Similarly, the spectra could not be used to uniquely point towards a BBH, even in case of a good, independent mass determination, but it is worth noting that the existence of a truncated disc could also be used to trigger more thorough observations to look for the double variability. Though, if the separation is wide enough, some accretion

structures could be present closer to each black-hole, hence *filling* some of that cavity making it harder to detect its presence.

Hence, we see that while neither timing nor spectral features of circumbinary discs are uniquely linked with the presence of a binary, they would be useful in weeding out false binary candidates and should be used as a test on all existing candidate-binaries.

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## DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, P.V., on request and will also be part of a data release in 2025.<sup>8</sup>

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- <sup>8</sup>Which will be available for download at [https://apc.u-paris.fr/~pvarni/eN\\_OVAs/LCspec.html](https://apc.u-paris.fr/~pvarni/eN_OVAs/LCspec.html)  
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