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Effects of supermassive binary black holes on gravitational lenses

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ABSTRACT

Recent observations indicate that many, if not all, galaxies host massive central black holes (BHs). In this paper, we explore the influence of supermassive binary black holes (SMBBHs) on their actions as gravitational lenses. When lenses are modelled as singular isothermal ellipsoids, binary BHs change the critical curves and caustics differently as a function of distance. Each BH can in principle create at least one additional image, which, if observed, provides evidence of BHs. By studying how SMBBHs affect the cumulative distribution of magnification for images created by BHs, we find that the cross-section for at least one such additional image to have a magnification larger than 10^{-5} is comparable to the cross-section for producing multiple images in singular isothermal lenses. Such additional images may be detectable with high-resolution and large dynamic range maps of multiply imaged systems from future facilities, such as the Square Kilometre Array. The probability of detecting at least one image (two images) with magnification above 10^{-3} is \(\sim 0.2f_{BH}(\sim 0.05f_{BH})\) in a multiply imaged lens system, where \(f_{BH}\) is the fraction of galaxies housing binary BHs. We also study the effects of SMBBHs on the core images when galaxies have shallower central density profiles (modelled as non-singular isothermal ellipsoids). We find that the cross-section of the usually faint core images is further suppressed by SMBBHs. Thus, their presence should also be taken into account when one constrains the core radius from the lack of central images in gravitational lenses.

Key words: black hole physics – gravitational lensing: strong – galaxies: formation – cosmology: theory.

1 INTRODUCTION

Recent observations suggest that many, if not all, nearby galaxies host massive central black holes (BHs). Empirical correlations have been discovered between the mass of the supermassive black hole (SMBH) and various galaxy properties such as the bulge mass (Laor 2001; Marconi & Hunt 2003; Häring & Rix 2004; Novak, Faber & Dekel 2006; Soker 2009), velocity dispersion (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002; Nipoti, Londrillo & Ciotti 2003; Robertson et al. 2006; Hu 2008; Graham et al. 2007; Feoli et al. 2011), luminosity (Magorrian et al. 1998; McLure & Dunlop 2001, 2002; Graham 2007) and concentration (Graham et al. 2001; Graham & Driver 2007). These correlations suggest that the growth of BH is closely related to galaxy formation (e.g. Kauffmann & Haehnelt 2000; Monaco, Salucci & Danese 2000; Wyithe & Loeb 2002; Yu & Tremaine 2002; Di Matteo et al. 2003; Volonteri, Haardt & Madau 2003; Haiman, Ciotti & Ostriker 2004; Ferrarese et al. 2006; Yu & Lu 2008; Bandara, Crampton & Simard 2009), although such a relation can also be a consequence of the central limit theorem in galaxy mergers with no significant physical meaning (Peng 2007).

Gravitational lensing is an independent, mass-based method to probe SMBHs. The lensing effects of single central and off-centre SMBHs have been studied previously (Mao, Witt & Koopmans 2001; Chen 2003a,b; Bowman, Hewitt & Kiger 2004; Rusin, Keeton & Winn 2005; Mao & Witt 2011). The effect of lensing by binary BHs has yet to be explored. Such systems are generated by the merging of galaxies (Yu 2002; Berczik et al. 2006; Johansson, Burkert & Naab 2009). Mergers between galaxies are observed and predicted in the hierarchical structure formation theory. The formation and evolution of binary BHs have been extensively studied using analytical and numerical methods (for reviews, see e.g. Merritt & Milosavljević 2005; Colpi & Dotti 2009, and references therein). We briefly discuss the processes below.

When two galaxies merge, the orbits of their associated BHs will first decay through dynamical friction. The critical separation where the binary rotation velocity equals the velocity dispersion of the host galaxy is often referred to in the literature as the ‘hardening radius’ of the binary (see equation 14). This radius plays an important role...
in binary BH evolution. At separations larger than the hardening radius, the BHs are ‘dressed’ with the inner cores of the stellar bulges belonging to their original host galaxies. The binary separation shrinks below the hardening radius due to the passage of individual stars which extract angular momentum from the binary. These stars are removed from their orbits after the interaction with the binary, leading to the appearance of a ‘loss cone’ in phase space. If this loss cone is not refilled, the orbital decay of the binary may stall, leading to a large population of galaxies with supermassive binary black holes (SMBBHs). The stalling radius is typically at several pc to several tens of pc (see, e.g., Yu 2002; Merritt & Milosavljević 2005; Colpi & Dotti 2009, for reviews).

Some other (e.g. gas) processes need to bring the binary BHs closer, so that gravitational radiation can rapidly merge the binary BHs into a single one. The problem of whether loss cones are refilled fast enough is still unsolved. It is, therefore, unknown how many SMBBHs there are in the Universe. Thus, any probe of this population will provide additional constraints on the formation and evolution of SMBBHs.

The purpose of this paper is to study the effects of SMBBHs on lensing properties using simple analytical models. We do not consider the effects of the inner stellar cores associated with the BHs. In these simple models, we show that the presence of SMBBHs can not only disturb the critical curves of the primary lens galaxy, but also create additional images. Many new lenses will be discovered with the next generation instruments, such as the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS)\(^1\) and the Large Synoptic Survey Telescope (LSST)\(^2\). Some of the more interesting cases will be observed with higher resolution and larger dynamical range using other instruments from which additional images, if detected, may provide direct evidence for the existence of SMBBHs or SMBBHs in galaxies. However, these images are usually very faint and close to each other. The Square Kilometre Array (SKA)\(^3\), if equipped with a very long baseline, which will provide high angular resolution and dynamic range images (maps), may provide the best possibility. If lenses have shallow (non-singular) central profiles (Trujillo et al. 2004), central core images are predicted, but they may be destroyed by the presence of SMBBHs (Mao et al. 2001; Rusin et al. 2005). We also touch upon this issue.

The outline of this paper is as follows. In Section 2, we present the basic lensing model of a galaxy with SMBBHs, i.e. the non-singular isothermal ellipsoid (NIE) with SMBBHs. The classification of SMBBHs is also discussed in Section 2. In Section 3, we focus on critical curves and caustics of a galaxy with SMBBHs. In Section 4, we discuss the cross-sections of BH images above a certain magnification threshold and estimate the probability of these images being detectable. In Section 5, we study the influence of SMBBHs on the core images in non-singular isothermal lens models. Conclusions and a discussion are given in Section 6. Throughout this paper, we assume a flat Λ cold dark matter cosmology with Ωm,0 = 0.3, ΩΛ,0 = 0.7 and a Hubble constant H0 = 100 h km s\(^{-1}\) Mpc\(^{-1}\), h = 0.7.

# 2 Lens Model with SMBBHs

We model the lensing galaxy as an NIE halo plus an SMBBH. This model includes the singular isothermal ellipsoid (SIE) model as a special case. The SIE model is not only analytically tractable, but also consistent with models of individual lenses, lens statistics, stellar dynamics and X-ray galaxies (Fabbiano 1989; Mao & Rix 1993; Kochanek 1995, 1996; Grogin & Narayan 1996a,b; Rix et al. 1997; Treu & Koopmans 2002; Keeton 2003; Rusin, Kochanek & Keeton 2003; Rusin & Kochanek 2005; Koopmans et al. 2006; Gavazzi et al. 2007; Parker et al. 2007; Czoske et al. 2008; Dye et al. 2008; Tu et al. 2009). In other words, the core radii are expected to be small in elliptical galaxies (Rusin & Ma 2001; Rusin & Tegmark 2001; Keeton 2003; Winn, Rusin & Kochanek 2004; Boyce et al. 2006; Zhang et al. 2007). In Section 2.1, we outline the lensing basics for an NIE plus an SMBBH. In Section 2.2, we focus on the classification of SMBBHs, which is important for understanding their influence on gravitational lenses.

## 2.1 Non-singular isothermal lens model with SMBBHs

The dimensionless surface mass density distribution of an NIE is given by

\[
\kappa = \frac{1}{\Sigma_{\text{eff}}} = \frac{1}{2g} \frac{1}{\sqrt{x_1^2 + x_2^2/q + r_c^2}},
\]

where \( r_c \) is the core radius, \( q \) is the axial ratio, \( \Sigma_{\text{eff}} = c^2 D_s/(4\pi GD_d D_a) \) is the critical surface density, \( D_s, D_d, D_a \) are angular diameter distances from the observer to the lens and source, respectively, and \( D_s \) is the angular diameter distance from the lens to the source. All the lengths \((x_1, x_2, r_c)\) are expressed in units of the critical radius, \( R_c \), which is also called the Einstein radius:

\[
R_c = D_d \theta_{E,SIS}, \quad \theta_{E,SIS} = 4\pi \left( \frac{\sigma_\text{s}}{c} \right)^2 \frac{D_d}{D_s},
\]

where \( \theta_{E,SIS} \) is the angle subtended by the critical radius on the sky (\( \theta_{E,SIS} \sim 0.2–3 \) arcsec for typical lens galaxies), and the velocity dispersion \( \sigma_\text{s} \) is related to, but not necessarily identical to, the observable line-of-sight velocity dispersion. We shall ignore this complication in our analysis and treat it as a parameter. For purposes of illustration, the source is taken to be at redshift 2, and the lens is at redshift 0.5. The velocity dispersion is \( \sigma_\text{s} = 200 \text{ km s}^{-1} \), and axial ratio \( q = 0.7 \), which is the most probable axial ratio of early-type galaxies (Choi, Park & Vogelezang 2007).

The lensing properties of the isothermal ellipsoid have been given by several authors (e.g. Kassiola & Kovner 1993; Kormann, Schneider & Bartelmann 1994; Keeton & Kochanek 1998). The lens equation including an SMBBH is given by

\[
y_1 = x_1 - \frac{\sqrt{q}}{\sqrt{1 - q}} \tan^{-1} \left( \frac{\sqrt{1 - q^2 x_1^2}}{\Phi + r_c/q} \right) - m_1 \left( \frac{x_1 - m_1 r_a}{r_a} \right) - m_2 \left( \frac{x_1 - v_1}{r_b} \right),
\]

\[
y_2 = x_2 - \frac{\sqrt{q}}{\sqrt{1 - q^2}} \tanh^{-1} \left( \frac{\sqrt{1 - q^2 x_2^2}}{\Phi + r_c q} \right) - m_1 \left( \frac{x_2 - u_2}{r_a} \right) - m_2 \left( \frac{x_2 - v_2}{r_b} \right),
\]

where \( \Phi^2 = q^2 x_1^2 + x_2^2 + r_c^2, \) and \( m_1, m_2 \) are the dimensionless mass of the two BHs, respectively. We label the two BHs of SMBBHs as ‘a’ and ‘b’. \( r_a, r_b \) are the dimensionless projected distances from the images to the BH ‘a’, ‘b’ on the lens plane. \((u_1, u_2), (v_1, v_2)\) are the coordinates of ‘a’ and ‘b’ on the lens plane:

\[
r = \sqrt{x_1^2 + x_2^2}.
\]

\(^1\) http://pan-starrs.ifa.hawaii.edu/public/home.html
\(^2\) http://www.lsst.org/lsst/scibook
\(^3\) http://www.skatelescope.org/
\[ r_a = \sqrt{(x_1 - u_1)^2 + (x_2 - u_2)^2}, \]
\[ r_b = \sqrt{(x_1 - v_1)^2 + (x_2 - v_2)^2}. \]

We also define
\[ m = \frac{M_{bh}}{M_{cl}}, \quad M_{cl} = \frac{\pi \sigma_c^2 R_{el}}{G}, \]
where \( M_{bh} \) is the total mass of the SMBBHs. Physically, \( M_{cl} \) is the mass of the galaxy contained within a cylinder with radius \( R_{el} \), hence \( m \) is the ratio of the total mass of the SMBBHs to the projected mass of the galaxy within \( R_{el} \). We assume that the correlation of the total mass of SMBBHs and velocity dispersion is the same as that for a single BH, which has been studied by many authors (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002; Nipoti et al. 2003; Robertson et al. 2006; Hu 2008; Gültekin et al. 2009). In our paper, we use the recent correlation found by Gültekin et al. (2009),
\[ M_{bh} \approx 10^{8-23} M_\odot \left( \frac{\sigma_v}{200 \text{ km s}^{-1}} \right)^{3.96}, \]
for elliptical galaxies, which dominate the lensing cross-sections. The dimensionless total mass of the SMBBHs is thus given by
\[ m = 2.5 \times 10^{-3} h \left( \frac{\sigma_v}{200 \text{ km s}^{-1}} \right)^{-0.04}. \]
Note that \( m \) has little dependence on the velocity dispersion, although we caution that there is substantial scatter around this correlation. The magnification (\( \mu \)) is given by
\[ \mu^{-1} = \frac{\partial y_1}{\partial x_1} \frac{\partial y_2}{\partial x_2} \frac{\partial y_1}{\partial y_2} \frac{\partial y_2}{\partial y_1}. \]
Throughout this paper, we quote the absolute magnification only (without parity).

Including the source position, the lens model has 11 degrees of freedom \((y, u, v, m_{bh}/m_2, \sigma_v, q, r_c)\), even if we ignore the scatter in the correlation between \( m \) and \( \sigma_c \). The parameter space is large, and thus in this paper we limit ourselves to illustrative examples. Also note that if we set the core size \( r_c = 0 \), the non-singular isothermal model becomes an SIE model, for which the influence of SMBBHs will be studied in Sections 3 and 4.

The lens equation has to be solved numerically to yield the image positions; their magnifications can then be found through equation (12). We can, however, study the influence of SMBBHs on gravitational lenses using critical curves and caustics. Critical curves are image positions where magnifications are infinite (\( \mu^{-1} = 0 \)). They map into caustics in the source plane. Caustics mark discontinuities in the number of images, so we can study the differences in critical curves and caustics, between lens models with and without SMBBHs to understand their lensing effects (see Section 3). In order to see whether additional images created by BHs are observable, we examine the cross-section when these images have magnifications above a certain threshold, e.g. \( \mu_{\text{th}} > 10^{-3}, 10^{-4} \) and \( 10^{-5} \) (see Sections 4 and 5).

### 2.2 Classification of SMBBHs

We classify each SMBBH in terms of the separation of its two members. First, we calculate the condition that the rotation velocity of SMBBHs is equal to the velocity dispersion. This case, the separation of the SMBBHs is called the ‘hardening radius’ \( (d_{\text{hard}}) \):
\[ \frac{G M_{bh}}{4 d_{\text{hard}}} = v^2 \approx 2 \sigma_v^2, \]
where \( M_{bh} \) and \( m \) are defined in equation (9). The hardening radius \( d_{\text{hard}} \) can be estimated as
\[ d_{\text{hard}} \approx 3.53 \text{ pc} \left( \frac{\sigma_v}{200 \text{ km s}^{-1}} \right)^{1.96}. \]
If the separation is smaller than this radius, we call these SMBBHs ‘hard’, otherwise ‘soft’. As discussed in Section 1, this may also be the most probable separation of SMBBHs (several pc to several 10 pc; Yu 2002) if the ‘loss cone’ is not refilled.

The ratio of the ‘hardening’ radius to the Einstein radius of its host galaxy is
\[ \frac{d_{\text{hard}}}{R_{el}} = \frac{\pi m}{8} \approx 6.87 \times 10^{-4} \left( \frac{\sigma_v}{200 \text{ km s}^{-1}} \right)^{-0.04}. \]

Two other ratios are relevant: the Einstein radius of BH to the Einstein radius of its host galaxy, and the ‘hardening’ radius to the Einstein radius of the BHs. Again assuming a lens redshift of 0.5 and a source redshift of 2, the first ratio is given by
\[ \frac{\theta_{\text{E,BH}}}{\theta_{\text{E,SIS}}} = \sqrt{m} \approx 4.18 \times 10^{-2} \left( \frac{\sigma_v}{200 \text{ km s}^{-1}} \right)^{-0.02}, \]
and the second by
\[ \frac{\theta_{\text{E,BH}}}{\theta_{\text{E,BH}}} = \frac{\pi \sqrt{m}}{8} \approx 1.64 \times 10^{-2} \left( \frac{\sigma_v}{200 \text{ km s}^{-1}} \right)^{-0.02}. \]
Both quantities are of the order of a few per cent.

### 3 CRITICAL CURVES AND CAUSTICS OF SINGULAR ISOTHERMAL ELLIPSOID LENS WITH SMBBHs

As discussed in the previous section, critical curves represent the positions of images of infinite magnification, while caustics mark discontinuities in the number of images. For singular potentials, there may also exist so-called pseudo-caustics: when a source crosses pseudo-caustic, the image number changes by one, rather than by two (Evans & Wilkinson 1998). In this section, we study how the SMBBHs affect the critical curves and caustics of singular isothermal gravitational lenses (i.e. \( r_c = 0 \)).

We show the critical curves and caustics of an SIE model with central SMBBHs at different separations in Figs 1 and 2, respectively. The separation \( (d_{\text{bh}}) \) is always expressed in units of the Einstein radius, which corresponds to about 5.1 kpc for our example. As can be seen, there are some critical curves near the BHs (which for convenience we will call them BH critical curves) when the separation of SMBBHs is \( 0 < d_{\text{bh}} \leq 1.6 \). The BH critical curves are a single continuous curve when \( d_{\text{bh}} \leq 0.05 \), while they become several disjoint curves when \( d_{\text{bh}} \geq 0.05 \) (Fig. 1). These behaviours are also reflected in the caustics (Fig. 2). When the separation becomes even larger \( (d_{\text{bh}} \approx 0.5) \), the BH critical curves become smaller and smaller. However, when the separation of SMBBHs becomes very large \( (d_{\text{bh}} \gtrsim 1.6) \), the critical curve of the primary lens can be disturbed by BHs, and the BH critical curves are merging into the primary critical curves, so we have peculiar caustics as shown in the bottom right-hand panel of Fig. 2. Such large separations are not expected to be common in SMBBHs (Yu 2002; Colpi & Dotti 2009).

We also show some examples of images in Fig. 1 and the positions of corresponding sources in Fig. 2. We can see that each BH of SMBBHs can generate BH images near itself (Fig. 1); if the source...
Effects of SMBBHs on galaxy lenses

Figure 1. Critical curves and examples of images for the case of an SMBBH in an SIE. The mass ratio for the binary system is $m_1/m_2 = 1$, and the separation $d_{bh}$ is indicated in each panel. $d_{bh}$ is in units of $r_{E,SIS}$, the Einstein radius of the singular isothermal sphere model. The black curves show the critical curves, red triangles show the image positions. We also plot the positions of the SMBBHs as black points. Each case has $m = 2.5 \times 10^{-3} h$, and the galaxy is modelled as an SIE with velocity dispersion $\sigma_v = 200$ km s$^{-1}$ and axial ratio $q = 0.7$. The BH image with the highest magnification is indicated as a larger triangle for each case.
Figure 2. Caustics for the case of an SMBBH in a singular isothermal galaxy for the same parameters as in Fig. 1. Some example source positions are shown with corresponding images shown in Fig. 1. The green curves show the caustics, while the blue triangles show positions of the sources. We also plot the positions of the SMBBHs in these panels (black points). All SMBBH cases have $m = 2.5 \times 10^{-3} h$, and the galaxy is modelled as an SIE with velocity dispersion $\sigma_v = 200 \, \text{km s}^{-1}$ and axial ratio $q = 0.7$.

is located in special positions (Fig. 2), e.g. near the pseudo-caustics, there can be multiple BH images for each BH. When the separation of the SMBBHs is zero (i.e. a single BH), and the source is outside the primary elliptical critical curve [also the pseudo-caustic, see panel (a) of Fig. 2], there is a BH image near the SMBBHs, which is shown in panel (a) of Fig. 1. As is well known for an SIE lens, if the source is located outside the pseudo-caustic, there are no multiple images, so the central image must be generated by the SMBH. When
the separations are not large, as illustrated in panels (b) and (c) of Fig. 1, the BH critical curve is continuous, and we find that there are three BH images for these two cases of source positions, as shown in panels (b) and (c) of Fig. 2. In panel (d) of Fig. 1, the SMBBH separation is larger than 0.05 and the BH critical curves as well as the caustics become disjoint [see panel (d) of Fig. 2]. The BH close to the source generates one BH image, while the BH farther away from the source generates three BH images. There is also another image around the position \((x = -0.081, y = -0.051)\) associated with the SIE lens. The cases in panels (e), (f) and (g) of Fig. 1 are similar: BH images are generated close to each BH in addition to a macro-image due to the SIE lens close to the primary critical curve. The most unusual case is shown in the bottom right-hand panels of Figs 1 and 2. The separation is such large that the two BHs distort the primary critical curve, eight images are created in total, including four BH images [see panel (h) of Fig. 1], when the source is located in a special position [see panel (h) of Fig. 2]. Some of these BH images are bright \((|\mu| > 0.425)\) enough to be potentially detectable, but the probability may be low because a large separation (11.6 kpc for our illustrative example) is required, and most BHs may not be at such large distances.

In the other extreme, we have very hard SMBBHs (i.e. with very small separations, \(d \lesssim 10^{-6}\) in the Einstein radius). In principle, the rapid rotation of the binary BH may lead to variations in the magnification. However, for this to be observable, its time-scale needs to be relatively short, \(T/4 \lesssim 10\) yr, where the period \(T = (d^3/(\text{GM}_{\text{bh}}))^1/2\). This requires a separation \(d \lesssim 0.04\) pc for a total BH mass of \(1.7 \times 10^8\) \(M_\odot\) corresponding to \(200\) km s\(^{-1}\). This separation is even smaller than \(d_{\text{crit}}\), and thus the binary BHs will essentially appear as a single one for lensing purposes. We conclude that in general the binary rotation effect will be difficult to detect using current or even future facilities.

### 4 CROSS- SECTIONS AND PROBABILITY

In this section, we investigate BH images with magnifications above several thresholds: \(\mu_{\text{th}} = 10^{-3}, 10^{-4}\) and \(10^{-5}\); such images are potentially detectable (see the discussion). We calculate cross-sections in the SIE model for producing at least one or two such BH images.

The cross-sections are calculated by constructing the magnification map (in the image plane) and identifying the region where the magnification is greater than some minimum value \(\mu_{\text{th}}\). We then map this region on to the source plane, from which we calculate the source cross-section. The cross-section in the case of having at least two BH images above a magnification threshold reflects the overlapping region where each member of the SMBBHs satisfies the condition. To do this, we first calculate the cross-section for the single BH case and then for binary BHs. The overlapping cross-section is obtained by subtracting the cross-section of the binary BHs from the total cross-section of the two single BHs.

Fig. 3 shows the cross-sections as a function of the separation between the binary BHs for three thresholds \(\mu_{\text{th}} = 10^{-3}, 10^{-4}\) and \(10^{-5}\). As expected, the higher the threshold, the lower the cross-section of the BH images. The peak of the cross-section also moves to a larger separation when the threshold increases.

Fig. 4 illustrates the cross-section that we can detect at least two BH images, which are generated by both members of the SMBBHs, respectively. As shown in Fig. 4, only when the separation is small enough, two BH images can be generated, and the higher the \(\mu_{\text{th}}\), the lower the cross-section of BH images, as expected.

### 5 SUPPRESSION OF CORE IMAGES IN A NON-SINGULAR ISOTHERMAL GALAXY WITH SMBBHs

In this section, we investigate how core images of the NIE lens model are affected by central SMBBHs. As is well known, non-singular isothermal model can generate a faint core image, and the magnification and position of the core images are sensitive to the core size. Observationally, very few central images have been observed (for more, see Section 6), which can be used to put an upper limit on the core radius (e.g. Rusin & Ma 2001; Rusin & Tegmark 2001; Keeton 2003; Winn et al. 2004; Boyce et al. 2006; Zhang et al. 2007). Not surprisingly, as in the case of a single central BH, the presence of SMBBHs can also demagnify and suppress the observability of central core images.

We again set the velocity dispersion \(\sigma_v\) equal to \(200\) km s\(^{-1}\), the axial ratio \(q\) equal to 0.7, and adopt a core size \(r_c = 0.05\). Fig. 5 shows the cumulative distribution function for the magnification of core images (\(\mu_{\text{core}}\)). SMBBHs suppress the faint end of the distribution,
leaving the bright end largely unaffected. A smaller separation will suppress the faint end of the distribution more effectively than a larger one. For $d_{bh} \lesssim 0.04$, the suppression is of the order of 12 per cent, and for $d_{bh} = 0.20$ the suppression is of the order of 7 per cent. Non-equal mass SMBBHs lead to smaller variations between different separations than equal mass systems. For example, for $d_{bh} = 0.20$ with $m_1/m_2 = 3$, the suppression is of the order of 7 per cent.

Fig. 6 shows the cumulative distribution function for the magnification of core images in non-singular isothermal lens with more massive SMBBHs ($m = 0.01$). As expected, the cross-sections of core images are suppressed more at the faint end of the distribution. To summarize, if double BHs exist in multiply imaged systems, then they will lead to small changes in the constraints on the central mass distributions in lenses.

6 DISCUSSION AND CONCLUSIONS

In this paper, we have studied the lensing configuration due to SMBBHs. We show typical examples of critical curves, caustics and image configurations. Similar to a single BH, SMBBHs can create additional images close to them. While we have adopted illustrative values for the axial ratio and orientation, we have also explored other values and found no significant dependence on these parameters.

For BH images to be observable, they have to be bright enough to be detected. We have examined the cross-sections for producing BH images with magnification above the thresholds, $\mu_{bh} = 10^{-3}$, $10^{-5}$ and $10^{-5}$ relative to that of producing multiple images, $\pi \theta^2_{E,SIS}$. We write this ratio as $R_{BH}$. The probability of being able to detect BH images in multiply imaged systems is given by $P_{BH}(\mu) \sim R_{BH}(\mu)$, where $f_{BH}$ is the fraction of galaxies with SMBBHs.

The values of $R_{BH}$ can be read off from Fig. 3. Thus, the observational probabilities of the BH images in a multiply imaged system for $\mu_{BH} = 10^{-3}$, $10^{-4}$ and $10^{-5}$ are about 0.2$\mu_{BH}$, 0.6$\mu_{BH}$ and 1.4$\mu_{BH}$, respectively. The probabilities, where both BHs generate at least one BH image for the same thresholds, are 0.05$\mu_{BH}$, 0.15$\mu_{BH}$ and 0.3$\mu_{BH}$, respectively, i.e. approximately a factor of 4 lower.

As shown in Fig. 1, BH images are very close to the BHs, so the separation between the brighter BH images is approximately the separation of the SMBBH, of which the most probable value is $\sim 10^{-4}$ in units of $R_{E,SIS}$ (see equation 16). Thus, the resolution must be better than $\approx 10^{-4}$ arcsec, which is already achievable by Very Long Baseline Interferometry (VLBI) techniques. On the other hand, we need very large dynamic range to detect the BH images. When the magnification of BH image is $10^{-3}$, the dynamic range required is $\mu_{max}/10^{-4}$, where $\mu_{max}$ is the magnification of the brightest image. For most cases, the largest magnification $\mu_{max}$ is about a few to ten. Thus, if we want to detect a BH image whose magnification is $10^{-3}$, as a conservative estimate, the dynamic range needs to be $\gtrsim 10^4$.

It is interesting to speculate what we can learn if we do observe two BH images. We have eight constraints (from the positions of two BH images and two macro-images produced by the SIE lens), while we have at least 10 parameters even if the core size is taken
to be zero. Clearly, the system is underconstrained. The number of parameters will be even larger in more complicated models, so we will not be able to determine the parameters uniquely. Furthermore, multiple BH images can also be produced by a single off-centre BH (Mao & Witt 2011), which may complicate the interpretation.

The presence of SMBBHs can suppress the faint end of the cumulative distribution for the magnification of core images while leaving the bright end largely unaffected. Their effects will need to be accounted for in the constraint on the central mass profiles (e.g. core radius). There are presently two known lenses with a core image [PMN J1632+0033 (Winn et al. 2004) and SDSS J1004+4112 (Inada et al. 2008)]. It is not surprising that SDSS J1004+4112 has a core image, because it is a cluster lens with a shallow Navarro–Frenk–White (Navarro, Frenk & White 1997) profile. For PMN J1632−0033, the evidence for the core image has been discussed in detail by Winn et al. (2004). At frequencies higher than 1.7 GHz, the logarithmic slopes of flux density ratio versus frequency for the three images are entirely consistent with the third image (C) being the elusive and long sought-after central image. At 1.7 GHz, image C is fainter than expected, which may be due to absorption and scintillation through the dense lens galaxy. In addition, they predict a fourth image induced by the central BH at <10 per cent level of the flux of image C, which, if detected with VLBI techniques, will provide a measurement of the BH mass (Winn et al. 2004).

To summarize, gravitational lensing can in principle be used to detect single BHs and SMBBHs in galaxies through the extra images they create. However, these images are usually very faint and close to each other, so they pose challenges for current instruments both in terms of resolution and sensitivity. For example, VLBI techniques may have sufficient resolution, but the dynamical range achievable currently may be insufficient to detect multiple, faint BH images. Another complication may arise because of the confusion of central images with radio emission from the lens galaxy. However, most lensing galaxies are ellipticals and so their central active galactic nuclei (AGNs) may be weak. Even so, at very high sensitivity/dynamical range, confusion with central AGNs may still be an issue. As discussed by Winn et al. (2004) and Rusin et al. (2005), we can use the usual tests – a common spectrum (or flux density ratio versus frequency), surface brightness and correlated variability (time delays) – to differentiate central images from an AGN in the lens galaxy. For example, for B2108+213 (McKean et al. 2005), More et al. (2008) compared the spectrum of the central radio source with those of lensed images and concluded that the central source is an AGN rather than a lensed image. Complications due to absorption and scintillation can be overcome by observing at high frequencies in the radio (since their effects scale as $\nu^{-2}$). Furthermore, if multiple BH images are discovered, then the confusion may be less of an issue since there is likely only one central AGN.

Future surveys using optical telescopes, such as Pan-STARRS and LSST, can provide a much larger sample of lenses, which may be used to identify particularly promising cases for further studies. Future generation of instruments, in particular the SKA, will provide very high-contrast ($\gtrsim 10^6$) and high-resolution ($\lesssim 10^{-2}$ arcsec) imaging capabilities. We remain cautiously optimistic that binary BHs can be independently discovered through careful observations of multiply imaged systems, especially in the radio.

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