Ripple effects & oscillations in the broad FeKα line as a probe of massive black hole mergers

B. McKernan$^{1,2,3,*}$, K.E.S. Ford$^{1,2,3}$, B.Kocsis$^{4,6}$ & Z.Haiman$^5$

$^1$Department of Science, Borough of Manhattan Community College, City University of New York, New York, NY 10007, USA
$^2$Department of Astrophysics, American Museum of Natural History, New York, NY 10024, USA
$^3$Graduate Center, City University of New York, 365 5th Avenue, New York, NY 10016, USA
$^4$Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA
$^5$Department of Astronomy, Columbia University, New York, NY 10027, USA
$^6$Einstein Fellow

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ABSTRACT

When a sufficiently massive satellite (or secondary) black hole is embedded in a gas disk around a (primary) supermassive black hole, it can open an empty gap in the disk. A gap-opening secondary close to the primary will leave an imprint in the broad component of the Fe Kα emission line, which varies in a unique and predictable manner. If the gap persists into the innermost disk, the effect consists of a pair of dips in the broad line which ripple blue-ward and red-ward from the line centroid energy respectively, as the gap moves closer to the primary. This ripple effect could be unambiguously detectable and allow an electromagnetic monitoring of massive black hole mergers as they occur. As the mass ratio of the secondary to primary black hole increases to $q \gtrsim 0.01$, we expect the gap to widen, possibly clearing a central cavity in the inner disk, which shows up in the broad Fe Kα line component. If the secondary stalls at $\gtrsim 10^2$ in its in-migration, due to low co-rotating gas mass, a detectable ripple effect occurs in the broad line component on the disk viscous timescale as the inner disk drains and the outer disk is dammed. If the secondary maintains an accretion disk within a central cavity, due to dam bursting or leakage, a periodic ‘see-saw’ oscillation effect is exhibited in the observed line profile. Here we demonstrate the range of ripple effect signatures potentially detectable with Astro-H and IXO/Athena, and oscillation effects potentially detectable with XMM-Newton or LOFT for a wide variety of merger and disk conditions, including gap width (or cavity size), disk inclination angle and emissivity profile, damming of the accretion flow by the secondary, and a mini-disk around the satellite black hole. A systematic study of ripple effects would require a telescope effective area substantially larger than that planned for IXO/Athena. Future mission planning should take this into account. Observations of the ripple effect and periodic oscillations can be used to provide an early warning of gravitational radiation emission from the AGN. Once gravitational waves consistent with massive black hole mergers are detected, an archival search for the FeKα ripple effect or periodic oscillations will help in localizing their origin.

Key words: galaxies: active – (stars:) binaries:close – planets-disc interactions – protoplanetary discs – emission: accretion

1 INTRODUCTION

Galactic nuclei host supermassive black holes ($> 10^6 M_\odot$) (Kormendy & Richstone 1995) and should be the sites of mergers of massive black holes. Major and minor galactic mergers in ΛCDM cosmology should inject supermassive and intermediate mass black holes (BH) into the dominant galaxy. Following the merger of two BH-harboring galaxies, the BHs sink to the bottom of the new galactic potential via dynamical friction in approximately a galactic dynamical timescale (Begelman, Blandford & Rees 1980). In addition to stellar interactions (e.g. Preto et al. 2011), many

E-mail: bmckernan at amnh.org (BMcK)

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studies have shown that gas in the vicinity of the binary could aid in hardening the binary down to \( \lesssim \) pc separations (e.g. Escala et al. 2007; Dotti et al. 2007; Mayer et al. 2007; Haiman et al. 2000; Lodato et al. 2004; Cuadra et al. 2009; Nixon et al. 2011; Chapron, Mayer & Tevsiier 2011). Black holes of intermediate mass can also grow quickly in gas disks in active galactic nuclei (AGN) via stellar/stellar remnant collisions and gas accretion (Levin 2007; McKernan et al. 2012) and orbital decay can generate a later merger with the central black hole. Massive black hole mergers should correspond to some of the strongest sources of gravitational waves in the Universe. Since we have yet to detect gravitational radiation directly, any electromagnetic signature that allows us to track massive mergers as they occur will be valuable for the study of strong gravity and the growth of the largest black holes in the Universe.

Gravitational torques from satellites in gas disks act to repel gas away from the satellite orbit. Sufficiently massive satellites can open empty annular gaps in protoplanetary disks (e.g. Lin & Papaloizou 1986; Pollack et al. 1996; Ward 1997; Armitage 2010; Duffell & MacFadyen 2012 & references therein). Analogously, sufficiently massive black holes can open gaps in AGN gas disks (e.g. Syer & Clarke 1993; Ivanov et al. 1999; Levin 2007; Dotti et al. 2007; Haiman et al. 2000; McKernan et al. 2012; Baruteau et al. 2013), leaving a number of unique observational signatures (McKernan et al. 2013). As the ratio of satellite black hole mass to central black hole increases to \( 10^{-2} \lesssim q \lesssim 1 \), the gap can widen to form a central cavity (e.g. Artymowicz & Lubow 1993; Liu, Wu & Cao 2003; Milosavljevic & Phinney 2003; MacFadyen & Milosavljevic 2003; D’Orazio, Haiman & MacFadyen 2012 & references therein). A gap-opening black hole in the innermost AGN disk, analogous to a gap-opening ‘hot Jupiter’ in a protoplanetary disk, can leave an imprint on a relativistically and gravitationally broadened Fe Kα line profile. The ripple effects and oscillations that result from a variety of black hole merger scenarios: (1) are potentially detectable with near-future X-ray detectors such as Astro-H, LOFT and IXO/Athena and possibly with present instruments such as XMM-Newton, (2) can be used to follow massive mergers as they happen, (3) provide advance warning of gravitational radiation from the source (Kocsis et al. 2008) and (4) can test models of extreme gravity, independent of the detection of gravitational radiation. However, detecting the effects outlined here with present and future proposed missions requires serendipity. To systematically survey sites of potentially merging massive binaries covering all the effects discussed here requires at a minimum, the planned effective area of LOFT combined with the planned spectral resolution of IXO/Athena.

In section 2 we review the broad FeKα line and outline the ripple effect caused by a narrow annular gap around the secondary’s orbit, deep in the potential well of a supermassive black hole. We also discuss several other different plausible configurations for the gas distribution around binaries. In section 3 we demonstrate the effects of an annular gap on the broad FeKα line profile for a range of basic observables (angle to observer, X-ray emissivity profile). In section 4 we discuss other possible circumbinary gas disk configurations for merging BHs including stalled migration, damming of the accretion flow, a central cavity and a secondary accretion disk around the gap-opening black hole. In section 5 we discuss the gravitational wave signals that may correspond to the FeKα broad line profiles. Finally in 6 we summarize our main results and present our conclusions.

2 A RIPPLE EFFECT IN THE BROAD FEKα LINE

2.1 The broad FeKα line component

Broad FeKα lines are observed in several nearby AGN (e.g. Nandra et al. 1997; Turner et al. 2002; Reynolds & Nowak 2003; Braito et al. 2007; Miniutti et al. 2007). The narrow core of the FeKα line observed in AGN (e.g. Yaqoob & Padmanabhan 2004) does not correlate significantly with outflowing gas (McKernan et al. 2007) and so presumably originates in fluorescing cold gas far from the supermassive black hole (Shu, Yaqoob & Wang 2010). We shall not discuss the narrow component further here. However, the broad FeKα line component in (AGN) is widely believed to originate in fluorescing Fe deep in the gravitational potential well of the central supermassive black hole. The broad FeKα line profile is complicated by ‘horns’ due to relativistic boosting and a strong red wing due to gravitational broadening (see e.g. Reynolds & Nowak 2003, for a review).

There is some recent controversy over the origin of the broad component of the line, with some suggestions that it originates in complex absorption (e.g. Miller, Turner & Reeves 2009). However, partial covering models do not eliminate the need for a broad FeKα component (Gallo et al. 2011) and Compton-thick outflows are ruled out in the innermost regions of the accretion disk (Reynolds 2012). Furthermore, the appearance of the broad line during transit events in AGN (McKernan & Yaqoob 1998) is consistent with an origin in the innermost accretion disk (Weaver & Yaqoob 1998). So it seems we should expect a broadened Fe Kα line component originating deep in the gravitational potential well around supermassive black holes.

Although the structure of the innermost accretion flow is unknown, it is common to assume a disk structure. The innermost parts of a disk must lie in the orbital plane of a massive merging binary (Ivanov et al. 1999). In this context, the broad FeKα line profile has been used to test models of warped disks (Hartnoll & Blackman 2004; Fragile, Miller & Vandervoot 2005), thick disks (Wu & Wang 2007), accretion rings (Sochora et al. 2011), spiral density waves (Hartnoll & Blackman 2002) and the presence of a binary with two disks (Sesana et al. 2014). Given the origin of the broad component of the FeKα line in the innermost regions of the AGN disk, a gap or cavity in the inner disk due to the presence of a massive (secondary) black hole will have an effect on the broad line profile. We discuss this effect in detail in the remainder of this paper.

Following Fabian et al. (1984), we calculate the flux emitted by a axisymmetric thin disk orbiting a Schwarzschild black hole. The ratio of the emitted energies

1 By ‘cold’ we mean Fe I-Fe XVII
from a point in the disk to the observed energy is given by \( \text{(Fabian et al. 1989)} \)

\[
(1 + z) = \left( 1 - \frac{6M}{r} \right)^{-1/2} \left[ 1 + \frac{\cos \beta}{r(1 + \tan^2 \xi)/M - 1} \right]^{1/2}
\]

where \((r, \phi)\) is the location of the emitting point in the disk (with \(r\) in units of \(r_g = GM/c^2\), the gravitational radius). In eqn. (1) \(M\) is the black hole mass, \(\beta\) is the angle between the disk plane and the plane of the photon trajectory, \(\xi + \pi/2\) is the angle between the emission of the photon and the line connecting the emitting point to the black hole. The quantity \(\cos \beta\) may be written as \(\text{(Fabian et al. 1989)}\)

\[
\cos \beta = \frac{\cos \phi \sin \theta}{\cos \theta + \cos \rho \sin \theta}^{1/2}
\]

with \(\theta\) the angle between the observer and the disk. The specific intensity in the frame of the emitting plasma is approximated as a delta function \(I_{\text{em}} = \delta(E - E_0)\) where \(E_0\) is the line rest energy. The structure of both the hot corona (source of the X-ray continuum) and the inner disk (source of the fluorescing Fe) is unknown, so \(\epsilon\) the disk emissivity is simply assumed to be \(\propto (r/M)^{-k}\). Therefore the specific flux measured by the observer from portion \(rdrd\phi\) of the disk is then given by \(\text{(Fabian et al. 1989)}\)

\[
dF_{\text{obs}} = \frac{1}{(1 + z)^3} I_{\text{em}} \frac{\partial \Omega}{\partial (r, \phi)} r^2 d\phi
\]

where the solid angle \(d\Omega = D^{-2} b^2 d\theta d\phi\) where \(D\) is the distance from the observer, \(b\) is the photon impact parameter and

\[
\frac{\partial \phi'}{\partial \phi} = \frac{\cos \theta}{\cos^2 \phi + \sin^2 \phi \cos \theta}.
\]

In the weak field limit, the photon geodesics can be approximated with straight lines, which means that not all relativistic effects are fully calculated at \(< 20 r_g\) in this approach \(\text{(Beckwith & Done 2004)}\). By integrating eqn. (3) as

\[
F_{\text{obs}} = \int_\Omega dF_{\text{obs}} = \int_0^{2\pi} \int_{r_{\text{inner}}}^{r_2} dF_{\text{obs}} + \int_0^{2\pi} \int_{r_2}^{r_{\text{outer}}} dF_{\text{obs}}
\]

where the disk extends from \(r_{\text{inner}}\) to \(r_{\text{outer}}\), with a gap excavated from radii \(r_1\) to \(r_2\), we obtain the observed broad line flux from a disk containing a gap. In the limit as \(r_1 \to r_2\), and if the disk extends to the innermost stable circular orbits (ISCO), \(r_{\text{inner}}\) to \(r_{\text{ISCO}}\), we recover the observed broad line flux from the total disk. In the limit as \(r_{\text{inner}} \to r_1\) we recover the observed broad line flux due to the inner disk minus a cavity spanning \(r_{\text{ISCO}}\) to \(r_2\).

### 2.2 Gap-opening in disks and merging black holes

The disk emissivity which produces the broad Fe Kα line component depends on both the structure of the X-ray continuum emitting corona plus the gas surface density distribution in the circumbinary disk. The geometry of both the corona and inner disk are poorly understood, particularly at the large stages of a merger with the central supermassive black hole. The main purpose of this paper is to illustrate that different possible gas configurations produce very different broad Fe Kα line profiles. Although our illustrations are based on toy models, the main features should be robust, and potentially distinguishable in observations with \(\text{Astr-H}\) and IXO/Athena. In this section, we outline possible models for the circumbinary gas, including those with a narrow annular gap, a fully empty central cavity, or a central cavity with possible minidisks inside the cavity. Throughout this discussion, we emphasize the very large existing theoretical uncertainties.

BH binaries are commonly believed to be surrounded by a thin \((H/r \lesssim 1)\) circumbinary disk. In models where the binary results from a galaxy-galaxy merger, the merger is expected to deliver the nuclear BHs \(\text{(e.g. Springel, Di Matteo & Hernquist 2005; Robertson et al. 2006)}\), along with copious amounts of gas \(\text{(Barnes & Hernquist 1992)}\). The central regions of the new galaxy. The gas cools efficiently, and loses angular momentum, creating a thin sub-parsec disk in which the pair of BHs are embedded \(\text{(e.g. Dotti et al. 2009; Hopkins & Quataert 2010; Chapon, Mayer & Teyssier 2011)}\). IMBHs with lower masses can also grow quickly in situ in the disk around a single supermassive black hole, again producing a pair (or more) of BHs embedded in a thin disk \(\text{(McKernan et al. 2012)}\).

A BH binary can exchange angular momentum with the disk, distorting the disk’s density profile, causing the secondary BH to migrate inward. In the limit of a very low mass secondary \(q = M_2/M_1 \ll 1\), the distortions, in the form of spiral density waves, remain in the linear regime \(\text{and the corresponding Type I migration is very rapid; e.g. (Goldreich & Tremaine 1980)}\). In this limit, the FeK line would be hardly affected by the presence of the low-mass secondary. As the mass of the secondary increases, gas is gravitationally torqued away from the orbit, lowering the co-rotating gas density and a particularly rapid form of migration (Type III) may occur \(\text{(Masset & Papaloizou 2003; McKernan et al. 2011b)}\). Once the secondary becomes sufficiently massive it will open an empty annular gap in the disk, analogous to gaps known to exist in protoplanetary disks. This happens above the critical mass ratio \(\text{(e.g. Armitage 2010)}\)

\[
q \geq \left( \frac{27\pi}{8} \right)^{1/2} \left( \frac{H}{r} \right)^{5/2} \alpha^{1/2}
\]

where \(H/r\) is the geometric thickness (aspect ratio) of the disk and \(\alpha\) is the disk viscosity parameter \(\text{(Shakura & Sunyaev 1973)}\). A black hole with \(q \gtrsim 10^{-4}\) should be able to open a gap in a fiducial AGN disk. This mass range spans massive stars or black holes of \(\gtrsim 10^3 M_\odot\) in accretion disks around \(\sim 10^6 M_\odot\) supermassive black holes \(\text{(McKernan et al. 2012)}\), all the way up to supermassive black hole binaries that form long after a major galactic merger has occurred. The radial extent of the gap would be of order a few Hill radii \(\pm R_H\). In this case, the secondary can be regarded as a particle in the disk, migrating inward on the viscous time-scale (so-called Type II migration).

When the secondary arrives at the radius where the local disk mass is too small to absorb the secondary’s angular momentum, its migration must stall (or at least slow 2

\[2\] However, if the local gas mass is low enough, or for low enough values of \(H/r\), it is likely that the innermost disk, even low-mass migrators expected in the AGN disk \(\text{(McKernan et al. 2011a, 2012)}\), could open a gap or cavity and affect the Fe Kα line as described here.
down). An important point is that "standard" thin disks have relatively low mass, and this stalling occurs at fairly large binary separations. With the exception of very unequal masses $q \lesssim 0.01$, the transition takes place well in the outer region of the disk, at $r >_{\text{several}} \times 10^3 r_g$. Even for $q < 1$ binaries, the transition is located at $r_{\text{stall}} = 260 (M_1/10^7 M_\odot)^{-2/7} (q/10^{-4})^{-2/7}$ (7)

Schwarzschild radii, which may lie outside the region of interest for producing broad FeKα lines depending on $r_{\text{outer}}$ (the above equation assumes standard disk parameters; see eqn. 25 in Haiman et al. 2009 for the full expression). Once inside this stalling radius, the secondary is no longer able to maintain steady Type II migration on the viscous time-scale, and the evolution of the binary+disk system from this point onward becomes very poorly known.

The inner disk - whose viscous time short is - is believed to drain onto the primary, creating a central cavity. Continued accretion from larger radii causes a pile-up of gas just outside the secondary’s orbit, analogous to a dam in a river (Syer & Clarke 1993; Ivanov et al. 1999; Milosavljevic & Phinney 2003; Zhang et al. 2012; Rafikov 2012). If the dam is 100% efficient in continuing to block the gas arriving from large radii, then the binary, at small separations, will be surrounded by an empty inner cavity, devoid of any gas. Such inner cavities have been seen in many numerical simulations (starting with the seminal work by Artymowicz & Lubow 1994). However, simulations do not follow the system on long enough timescales to determine whether such a cavity could persist for many viscous times. In the face of ongoing accretion, an initial cavity may be gradually refilled (if the “dam” is porous), or else the gas accumulated outside the orbit may eventually cause the dam to “burst” (Kocsis, Haiman & Loeb 2012b).

An empty cavity would of course strongly modify the shape of the FeKα line. However, this picture is over-simplified. Many numerical simulations imply that gas can enter such a cavity in narrow collimated streams (Artymowicz & Lubow 1994; Hayasaki, Mineshige & Sudou 2005; MacFadyen & Milosavljevic 2008; Cuadra et al. 2009; Roedig et al. 2011, 2012; Shi et al. 2011). Such streams may feed a “minidisk” around the secondary and perhaps also the primary BH (Hayasaki et al. 2008; Sesana et al. 2012; Farris et al. 2012). A minidisk around the secondary may be favored, but the details depend on the angular momentum and shocks in the material in the streams. The streamers and minidisks could create some additional FeKα emission. For example, if both disks emit, there would be a double FeKα line (Sesana et al. 2012). On the other hand, it is unclear whether such streams and minidisks may persist down to small binary separations. At separations of $\lesssim 200 r_g q^2$ (see eqn. 30 in Haiman et al. 2009 for the full expression, including dependencies on disk parameters), the binary BH emits GWs efficiently and is driven to merger by this GW emission. It effectively decouples from the disk (Lin, Wu & Cao 2003; Milosavljevic & Phinney 2003) and “runs away”. The merger timescale is given by (Peters 1964)

$$\tau_{\text{GW}} \approx 10^{12} \text{yr} \left(10^3 M_\odot/M_1\right)^{-2} \left(10^2 M_\odot/M_2\right)^2 \left(a/0.001pc\right)^4 (1-e)^{7/2} (8)$$

where $M_2$ is the mass of the secondary, $M_1$ is the mass of the primary, $a$ is the binary separation and $e$ is the secondary orbital eccentricity. For a secondary on a circularized orbit with $q = 3 \times 10^{-3}$ located at $a = (10)100 r_g$ in an AGN disk, $\tau_{\text{GW}} \sim (30yr)0.3\text{Myr}$ around a $10^6 M_\odot$ SMBH and $\tau_{\text{GW}} \sim (1yr)0.01\text{Myr}$ around a $10^4 M_\odot$ SMBH respectively. Simulations in the relativistic regime found that gas streams can follow the binary to small radii (e.g. Noble et al. 2012; Farris et al. 2011, 2012), but these simulations start with small binary separations, with gas assumed to have followed the BH to these initial separations.

As emphasized recently by Kocsis, Haiman & Loeb (2012a,b), even apart from possible streamers and minidisks inside the central cavity, the formation of the cavity itself, at large radii, is still uncertain. The coupled time-dependent processes of the secondary’s migration, inner cavity formation, and damming-up of gas outside the secondary’s orbit, has not been modeled self-consistently, even in one-dimensional calculations. However, using self-consistent steady-state solutions, Kocsis, Haiman & Loeb (2012b) have argued that in many cases, pile-up can cause a dam overflow at large binary separations. In this case, when the binary arrives at small radii relevant to the FeKα line, the gas configuration would presumably resemble a filled disk, with an annular gap (order the Hill radius). Although the above is yet to be demonstrated by a self-consistent calculation, it is at least suggested by recent simulations of Baruteau et al. 2013. This is the only existing simulation that looks at small binary separations, in the GW-driven regime, and does not manually insert an empty cavity in the beginning. They show that the secondary moves inward, “ice-skating” across the inner disk (with the inner disk material continually crossing the secondary’s orbit outward, on horse-shoe orbits). This simulation is in 2D, and assumes a constant kinematic viscosity physics, which may not be accurate. Nevertheless, it suggests that if the cavity filled in at large radius, it will remain filled until the end, except for a narrow annular gap around the secondary.

We are motivated by the above discussion to consider the impact on the Fe Kα line of four different circumbinary gas disk geometries, all variations on a standard single-BH accretion disk: (i) a narrow annular gap around the secondary, (ii) an empty central cavity, (iii) a central cavity surrounded by an overdense ring (‘dam’), and (iv) a central cavity with a small, circumbinary accretion disk (‘minidisk’) inside it. We regard (i) as our fiducial case, addressing it first in 2.3 and 3. We then examine the alternative scenarios (ii)-(iv) in 4.

### 2.3 A ripple effect in the broad FeKα line component

As a gap-opening black hole migrates inward in an AGN disk, the empty gap spans parts of the disk that produce ever bluer and redder parts of the broad Fe Kα line. Therefore we expect flux ‘notches’ to be removed from the broad line profile. As the annulus moves inward on the disk viscous timescale, we expect the notches to ripple red-ward and blue-ward respectively from the line centroid. Fig. 1 (from McKernan et al. 2013) demonstrates this ripple effect for a gap-opening black hole located at circularized orbit radius $R$ centered in an empty gap of width $2R_g$ (from McKernan et al. 2013)
Figure 1. From McKernan et al. (2013), showing Iron line flux in arbitrary units versus Energy in units of keV, binned at approximately the energy resolution (~7eV) expected for Astro-H. The curves demonstrate the progression of the 'ripple effect' in the Fe Kα line profile given the in-migration of a gap-opening black hole (mass ratio q = 3 × 10^{-4}) located at R in the inner disk. The empty gap has width 2R_H where R_H = (q/3)^{1/3}R. The disk has an assumed X-ray emissivity radial profile of r^{-2.5} and the angle to the observer's sightline is $\theta = 60^\circ$ (where $\theta = 0^\circ$ is face-on). The solid black curve indicates the unperturbed Fe Kα line profile (i.e. no gap). The turquoise solid curve corresponds to an annulus at 50$^\circ$-90$^\circ$ (dark blue curve) to 20$^\circ$-60$^\circ$ (red curve), the blue notch moves from 7.1keV to 7.6keV in the blue wing, and the red notch moves from 5.6keV to 4.2keV in the broad red wing. For a 3000M_☉ gap-opening IMBH around a 10^6M_☉ supermassive black hole, the progression from green to red curve in Fig. 1 via GW emission takes (eqn. 8) ∼ 16yrs and from red curve to final merger takes ∼ 1yr. Because of the shorter timescales, low mass AGN exhibiting broad Fe Kα line profiles (e.g. MCG-6-30-15) are the prime targets for observations searching for this ripple effect, and the massive mergers that cause it.

AGN that display this ripple effect in the broad Fe Kα line will be some of the most luminous sources of gravitational radiation in the Universe. By searching for the latter stages of a progression as in Fig. 1, we can follow the final stages of massive mergers electromagnetically. The final stages of a ripple effect in the broad FeKα line will provide advance warning of an outburst of gravitational waves from this AGN. Conversely, once gravitational waves consistent with an IMBH-supermassive black hole merger are actually detected, an archival search for the FeKα ripple effect can be used to localize the source.

We expect departures from the predicted progression in Fig. 1 at very small radii either as the disk profile changes or as the gravitational radiation luminosity increases dramatically and perturbs the disk ($\alpha$ and $H/r$ may change considerably). So the behaviour of the broad component of the Fe Kα line may be complicated in the final stages of the merger (in the limit of small disk radii). Variations from the predicted profile at small radii will include the effects of gravitational radiation on the accretion disk. So tracking the ripple effect may allow us to directly test models of massive mergers and gravitational radiation, without actually detecting gravitational radiation. The Fe Kα band can also be spectrally complicated by emission lines. By monitoring the monotonic change in energy of the blue and red dips, we can break the degeneracy associated with high energy Fe emission lines superimposed on the FeKα complex (e.g. McKernan & Yaqoob 2004). Curious 'notch'-like features have been observed in broad Fe Kα line components (e.g. Yaqoob & Serlemitsos 2002), but the collecting
area and the energy resolution of the high energy transmission gratings on board Chandra are insufficient to resolve these features and follow them over time. The broad component of the Fe Kα line can vary quite significantly over time (e.g. Iwasawa et al. 1996; de Marco et al. 2003; Svoboda et al. 2012), but it has been difficult to determine the nature of the variability given detector limitations.

The energy resolution of the micro calorimeter planned for the Astro-H mission will be \( \sim 7\)eV in the FeK band (Takahashi et al. 2010). This exceptional resolution combined with moderate collecting area should be sufficient to distinguish between absorption features and narrow, monotonically migrating notches of the kind depicted in Fig. 1 in long, repeated observations of nearby, X-ray bright AGN (e.g. Nandra et al. 1997). However, it is important to note that Fig. 1 displays only the predicted broad line flux. To systematically obtain broad line spectra that can distinguish between the different cases in Fig. 1 requires a minimum telescope effective area of that planned for LOFT \( \sim 10^{2} \) at 6.4keV, together with the planned spectral resolution of \((\sim 5 \text{ } - \text{ } 7\)eV at 6.4keV) for Astro-H and IXO/Athena. Vaughan & Fabian (2004) obtain \( \sim 18,000 \) counts in the broad red wing of the Fe Kα line in a \( \sim 320\)ks observation of MCG-6-30-15 with the EPIC detector on board XMM-Newton, yielding \( \sim 600 \) average counts at the limiting energy resolution of \( \sim 0.1\)keV per bin and very high signal to noise. An observation with a future Large Area High Resolution (L.A.H.R.) telescope with the effective area of LOFT would get \( \sim 6,000 \) average counts per \( \sim 0.1\)keV bin at very high signal to noise. In this case, observations with LAHR would have the signal-to-noise of XMM-Newton EPIC at binnings of \( \sim 10\)eV, which would be sufficient to at least systematically track the monotonic changes in the energy of the notches in Fig. 1. In the remainder of this paper we plot all figures at the \( \sim 7\)eV energy resolution expected for Astro-H (and IXO/Athena), to illustrate the details that might be observed in the Fe K broad line complex at sufficiently high signal-to-noise with future detectors. As we shall show below, the EPIC-pn detector on board XMM-Newton is most useful in testing models of oscillations in the broad Fe Kα line due to secondary mini-disks, until the advent of LOFT. In the case of oscillations, high energy resolution is less important than binned-up count-rates and the superior effective area of EPIC makes this the present detector of choice and we recommend that observers search for serendipitous oscillations in the Fe K band when observing with this instrument. The planned IXO/Athena mission will have both high energy resolution and large effective area. However, systematic testing of models of massive black hole mergers via the broad Fe Kα line will require Large Area High Resolution (LAHR) telescopes with minimum effective area that proposed for LOFT, together with the spectral resolution planned for IXO/Athena. We recommend that future mission planning take this into consideration.

A related issue to detectability is the expected rate of occurrence of binaries (of mass ratio \( q \)) in AGN. There are at present a small number of bright, nearby AGN that exhibit broad Fe Kα lines. Even with an order of magnitude increase in telescope effective area, our sample size would be \( \sim 10^{2} \) objects. The probability of seeing a close binary per AGN is \( N_{2}\text{rs} / N_{\text{AGN}} / t_{\text{disk}} \), where \( N_{2} \) is the number of secondaries (for a given range of mass ratios) in the AGN disk over its lifetime \( (t_{\text{disk}}) \), \( t_{\text{rs}} \) is the residence time of the secondary at the range of disk radii where we can observe the effects discussed here and \( N_{\text{AGN}} \) is the number of minimal S/N exposures of the AGN of duration \( (t_{\text{min}}) \) in which the effect could be detected. For the lowest mass (Type I) migrants we might expect \( N_{2} \sim 10^{4} \) in an AGN disk that lasts for \( t_{\text{disk}} \sim 10^{4}\text{Myrs} \) around a \( 10^{8}\)M⊙ SMBH, where \( t_{\text{rs}} \sim 1\text{yr} \) (McKernan et al. 2012). For a fiducial LAHR telescope, we might expect \( t_{\text{min}} \sim 10^{3}\text{ks} \) so in a total exposure over a mission lifetime of 1Ms, we would have a 10% chance of detecting a low-mass migrator in any one AGN. For SMBH binaries, \( t_{\text{rs}} \sim 10^{6}\text{yr} \) or more, so as long as \( N_{2} \) for massive SMBH is not vanishingly small, we will also have a reasonable likelihood of detecting SMBH binaries with future missions. For SMBH-IMBH binaries, \( N_{2} \) is likely to be of order several (McKernan et al. 2012), \( t_{\text{rs}} \) is likely to be \( \sim 10^{5}\text{yr} \) in the example above, so in a large sample of X-ray bright AGN, we may detect a small number of these binaries via effects in the broad Fe K line.

3 BROAD FEKα LINE PROFILES: BASIC OBSERVABLES

In this section we discuss the effects of a few basic observables on the expected broad Fe Kα line component profile, including angle to the observers’ sightline(\( \theta \)) assumed X-ray emissivity profile \( (\propto r^{-\beta}) \) and the width \( (\Delta r = r_{2} - r_{1}) \) of the annulus gap. In practice, the broad profiles discussed here will be those residuals in the Fe K band after the subtraction of a narrow (very slowly varying) Fe Kα component due to cold fluorescing material far from the supermassive black hole (e.g. Yaqoob & Padmanabhan 2004). The Fe K line complex actually includes two components (Kα1 and Kα2 separated by 13eV), centered at 6.0keV and an additional Fe Kβ component at 7.06keV. The Fe Kβ line should have \( \sim 13\% \) of the normalized flux of the FeKα line (Palmeri et al. 2003) and so adds a small percentage change in the profile of the overall broad Fe K line, particularly on the blue-wing. However, the line profiles that we generate here, distinguishing between various merger situations, are not materially effected by the addition of a broad Fe Kβ component, so we shall not discuss that component further. Furthermore, although individual highly ionized line components can appear in Fe K band spectra, these are sufficiently narrow that we can hope to disentangle their signature from broad components with Astro-H. For the purposes of the present discussion, in order to understand the sense in which different binary disk geometries affect the broad Fe K line component, we shall ignore the contribution of highly ionized Fe to the broad Fe Kα line complex.

We calculate the broad FeKα line profile around a Schwarzschild black hole using a modified version of the algorithm that generates the XPSEC DISKLINE model (Fabian et al. 1984) described in [27] above. We modify the DISKLINE algorithm by subtracting annuli of particular widths \( (\Delta r = r_{2} - r_{1}) \) or by introducing additional emission due to damming of the accretion flow or accretion disks around the secondary black hole (see discussion below). For ease of comparison of basic observables, in this section we discuss an empty gap opened at \( 20\alpha \) or \( 2\gamma \), in an accretion disk around a supermassive black hole (the green solid curve in

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3.1 Changing inclination angle

There is a relatively wide range of viewing angles (θ) possible for observations of Seyfert 1 AGN nuclei that display broad FeKα lines (Nandra et al. 1997). Indeed if disks are warped close to a spinning black hole, even face-on AGN may contain highly inclined inner disks (e.g. Bardeen & Petterson 1973; King & Pringle 2006; Nixon & King 2012). The most famous example of a broad Fe Kα line in an AGN (MCG-6-30-15) is best-fit with disk-inclination angle of θ = 27° (Reynolds & Nowak 2003), where θ = 0° corresponds to face-on.

Fig. 2 shows the effect of varying inclination angle (θ) on the ripple due to the annulus at 20 ± 2r_g (green curve) in Fig. 1. From Fig. 2 as the angle to the observers’ sightline increases to ∼ 60° (light blue curve), the FeKα line width increases and the ‘notches’ become more prominent. The ‘blue’ notch shifts away from the H-like Fe XXVI Lyα line at 6.97keV which prevents possible line confusion. However, at this inclination angle, we should expect that intervening material (the dusty torus, an outflowing wind or obscuring clouds) should absorb softer X-rays, influencing the shape of the continuum and therefore the broad component of the Fe Kα line. Thus, unless the AGN is ‘naked’ (i.e. without obscuring torus or clouds), or the inner disk is highly warped, a broad FeKα line at this inclination should be difficult to disentangle from absorption effects.

From Fig. 2 as θ decreases to nearer face-on (dark blue and red curves), the likelihood of obscuring structures decreases, but the blue wing of the Fe Kα shrinks back towards the rest-frame line energy (6.40keV). As a result the ‘blue’ notch becomes much narrower (and harder to detect with Astro-H). The ‘red’ notch remains prominent and should stand out clearly in observations with Astro-H, until obscuring material starts to absorb the continuum significantly at this energy.

3.2 Changing X-ray emissivity & gap width

The geometric structure of the corona (source of the X-ray continuum) and that of the inner disk (source of the fluorescent Fe) are unknown. Therefore the X-ray emission from the inner disk is simply parameterized as a radial power-law form (r^{-k}), where likely ranges for the emissivity span k ∼ 1.5 - 3 (e.g. Reynolds & Nowak 2003). The most famous example of a broad Fe Kα line is best-fit with X-ray emissivity profile of k ∼ 3 (Reynolds & Nowak 2003).

Fig. 3 shows the effect of varying the index (k) of the X-ray emissivity powerlaw ((r/M)^{-k}), on the ripple due to the annulus at 20 ± 2r_g (green curve) in Fig. 1. From
around a maximally spinning black hole, the Fe Kα line will extend redward to very low energies (<3keV [Iwasawa et al. (1996)]). In the final stages of merger, a gap-opening black hole could leave an imprint (at <6rg) on a very broad Fe Kα line. Around a low mass, rapidly spinning black hole such as in MCG-6-30-15 (∼10^6M⊙, McKernan et al. (2010)), the very late stages of a ripple effect could be observed, but would last only a few weeks. A gravitational wave trigger may therefore be useful in finding these late stage events. The possibility is intriguing, since tracking a massive merger electromagnetically to the very final stages would be a profoundly important advance in this field.

### 4 TESTING MERGER MODELS WITH THE BROAD FeKα LINE PROFILE

In this section we examine alternative models for the geometry of the innermost AGN disk, as discussed in §2.2 above, and ask how we might distinguish between these different models using the broad Fe Kα line component. In §4.1 we discuss cavity formation and how we might test the formation and presence of cavities using the broad FeKα line profile. In §4.2 we discuss observational consequences of ‘damming’ the disk due to pile-up of inflowing gas behind a stalled, migrating secondary black hole. In §4.3 we discuss the possibility of a disk around the secondary black hole and the effect this has on the overall broad Fe Kα line profile. In reality, a combination of all three effects is likely to be present simultaneously.

#### 4.1 Detecting cavities in the inner AGN disk

Fig. 3 shows the effect of a cavity in the innermost disk on the ripple due to the annulus at 20 ± 2rg (green curve) in Fig. 1. From Fig. 4 as we should expect, the notches in the Fe Kα line profile become more pronounced (detectable) as the gap width increases. In Fig. 5 below we discuss in more detail the effect on the broad Fe Kα line profile of increasing the gap width via disk drainage to form a cavity, damming the inflowing gas, and the possibility of an accretion disk around the secondary black hole.

#### 3.3 Changing black hole spin

In the discussion above, we have discussed broad Fe Kα line profiles that originate in fluorescent Iron deep in the potential well of a non-spinning (a = 0, Schwarzschild) black hole. In this case, the accretion disk extends inward as far as the innermost stable circular orbits (ISCO), which for a = 0 corresponds to r_{ISCO} = 6rg [Bardeen, Press & Teukolsky 1972]. Maximaly prograde spinning black holes (a ∼ M) allow the inner edge of the accretion disk to extend practically to the event horizon r_{ISCO} ∼ r_g. By contrast, black holes with retrograde spin compared to the disk (a ∼ −M) have r_{ISCO} ∼ 9rg. For all except the final stages of merger, the spin will make little difference to the ripple effect. However,
in the same AGN may also constrain the angle (θ) to the observer of the innermost disk and rule out e.g. near face-on disks.

In Fig. 6 we follow the draining of the inner disk due to a black hole migrator that has stalled at 50rg. The satellite black hole has opened a gap in the disk at 50rg ± 3rg, i.e. empty cavity (light blue curve); 20rg (green curve), 30rg (dark blue curve), 50rg (red curve). The progression from black curve to red curve (rinner = 10rg), to green curve (rinner = 20rg) occurs very quickly. The disk drainage progression in Fig. 6 spends most of its time between the dark blue and light blue curves. Observationally, the key characteristics to indicate this ‘inside out’ disk drainage are that the positions of the notches in the broad line (due to the gap) remain fixed, but the red and blue wings are suppressed monotonically as the line intensity diminishes. In this case, multiple repeated observations using the large effective area of XMM-Newton EPIC could be used to collect flux from the red and blue wings of the broad line. Even with the limited EPIC energy resolution (≥ 0.1keV), the equivalent width of the line wings (as well as the notch positions) can be measured down to fractions of individual exposures (~ 10ks intervals). However, we expect the monotonic decrease in the equivalent width of the wings to be most significant over longer intervals (~ yr) while the positions of the notches remain fixed. It is possible that disk drainage could occur on timescales faster than fiducial estimates of τg. For example, the sharp gradients at the cavity edge can cause viscous diffusion to be significantly faster than the local viscous timescale for uniform (non-piled-up) gas (Milosavljevic & Phinney 2005; Haiman et al. 2009). Furthermore, the effective viscosity α has been found to increase locally near the cavity edge by more than an order of magnitude (Shi et al. 2011; Noble et al. 2012); a similar increase is seen in the inner regions of single-BH disks (Penna et al. 2012). So, even for secondaries around very massive primaries, changes in the Fe Kα line due to disk drainage could be detectable over a period of several years.

If instead, we assume the drainage is ‘outside in’, the disk depletes first at larger radii and then at smaller radii in to rISCO, to form the cavity, the change in the line profile will be different. Outside-in drainage is unlikely, since the viscous timescale is shortest for small radii, although α(r) and H/r in eqn. (9) may change significantly with decreasing radius. Fig. 7 shows the effect of outside-in drainage, where r g decreases to rinner. For most of this time, the line profile will be somewhere between the black and green curves. The final stages of disk drainage will happen very fast and the rate of change in the broad FeKα line profile will be large (going from red curve to purple curve). As the inner gap edge decreases to 40rg (dark blue curve), 30rg (green curve), 20rg (red curve), 10rg (light blue curve) and rg (i.e. empty cavity; purple curve).

If the gap-opening black hole stalls further out, say at ≥ 100rg or greater as might be expected (Haiman et al. 2009), the inner disk will drain on the viscous timescale of the inner edge of the gap at ≥ 100rg, while the outer disk is damaged. In this case, for a q = 3 × 10−3 gap-opening black hole stalled such that r1 = 100rg in a α = 0.01, H/r = 0.1 gas disk around a 108M⊙ (108M⊙) supermassive black hole, the inner disk will drain in ~ 1.5(150)yr < τGW. If the disk drains ‘inside out’ (rinner → r1 over time), as we expect since...
the viscous timescale is shortest at small radii, the broad line component over that time will follow the progression in Fig. 3 assuming that disk gas at ≥ 100r\(_g\) is held up by the 'dam wall'. In our example of a q = 3 \times 10^{-3} secondary around a 10^{8}(10^{8} M_\odot) primary, the line profile will change from the black to green curve over 0.5(50) years, and from green to light-blue curve in 1(100) years. If the inner disk is draining 'inside out' in this way, the key observational characteristic to search for is the increasing suppression of the red and blue wings of the line over time. This model can be tested using archival and ongoing observations with the large effective area of XMM-Newton EPIC. In this case, the binned-up wings of the broad component will decrease in a consistent monotonic pattern over time (quickly at first, then more slowly). If instead, the α and H/r profiles of the disk mean that inside-out drainage does not occur, and an 'outside-in' disk drainage somehow manages to happen, the red and blue 'horns' of the line profile will ripple outward from the line centroid energy as the overall broad component intensity diminishes. In this case, the low energy resolution of XMM-Newton can capture the migration of the horns red-ward and blue-ward, but only over long timescales. The high energy resolution of Astro-H and IXO/Athena could resolve horn migration over much shorter timescales.

Note that if the X-ray continuum originates in a hot corona concentrated mostly above the innermost disk then during and after cavity formation, we should expect some fraction of the overall X-ray continuum to decline. If the inner disk drains 'inside out' to form a cavity, we should expect a rapid drop of the X-ray continuum together with a strong decrease in broad line intensity (most pronounced in the wings). Observing such an effect would allow us not only to test models of massive mergers, but also allow us to constrain the fraction of the X-ray continuum that originates in the central ~ 100r\(_g\). If the disk drains 'outside in' (much less likely), we expect the drop in the continuum to match the rippling apart of the horns of the Fe Kα line.

### 4.2 Detecting pile-up in AGN disks

In the discussion of disk drainage above, we ignored the effect of the continuing inflow of gas from the outer disk. As the migrating secondary stalls and the disk interior to it drains on the viscous timescale, mass is still flowing inward in the disk. Gas should build up at the outer gap or cavity edge on the viscous timescale (τ\(_g\)) at that disk radius (Syer & Clarke 1995; Ivanov et al. 1999; Kocsis, Haiman & Loeb 2012a). We can think of the outer...
The change in the broad FeKα line profile due to the draining of the entire inner disk due to a stalled gap-opening satellite black hole, where \( r_1 = 100r_g \). To replicate a draining inner disk, we assumed the broad FeKα emission originates entirely from within 100\( r_g \), with \( \theta = 60^\circ \) and \( r^{-2.5} \) X-ray emissivity profile as assumed above. We do not see ‘notches’ as in Fig. 6 since the gap does not imprint itself on the inner disk < 100\( r_g \). The solid black curve corresponds to the broad FeKα profile from the inner disk extending from 100\( r_g \) inward to 6\( r_g \). Since we expect the disk viscous timescale to increase with radius, we assume the disk drains in an ‘inside out’ manner, so \( r_{\text{inner}} \rightarrow r_1 \) and we ignore emission from gas ‘smeared out’ within \( r_{\text{inner}} \). As the inner edge of the disk increases radially to 20\( r_g \) (red curve), 40\( r_g \) (green curve), 60\( r_g \) (dark blue curve), 80\( r_g \) (light blue curve), the broad component of the line decreases in magnitude and the blue and red wings are increasingly suppressed. For a fiducial disk with \( \alpha = 0.01, (H/r) = 0.1 \) around a 10\(^6\) (10\(^8\)\(M_\odot\)) supermassive black hole, we expect the progression of profiles from solid black curve to light blue curve depicted here to last approximately \( \sim 1.5(150)\) yrs. Two-thirds of this time is taken up with the progression from green curve to light-blue curve. All curves are binned at approximately the energy resolution (\( \sim 7\)eV) expected for Astro-H.

Figure 8. The change in the broad FeKα line profile due to the draining of the entire inner disk due to a stalled gap-opening satellite black hole, where \( r_1 = 100r_g \). To replicate a draining inner disk, we assumed the broad FeKα emission originates entirely from within 100\( r_g \), with \( \theta = 60^\circ \) and \( r^{-2.5} \) X-ray emissivity profile as assumed above. We do not see ‘notches’ as in Fig. 6 since the gap does not imprint itself on the inner disk < 100\( r_g \). The solid black curve corresponds to the broad FeKα profile from the inner disk extending from 100\( r_g \) inward to 6\( r_g \). Since we expect the disk viscous timescale to increase with radius, we assume the disk drains in an ‘inside out’ manner, so \( r_{\text{inner}} \rightarrow r_1 \) and we ignore emission from gas ‘smeared out’ within \( r_{\text{inner}} \). As the inner edge of the disk increases radially to 20\( r_g \) (red curve), 40\( r_g \) (green curve), 60\( r_g \) (dark blue curve), 80\( r_g \) (light blue curve), the broad component of the line decreases in magnitude and the blue and red wings are increasingly suppressed. For a fiducial disk with \( \alpha = 0.01, (H/r) = 0.1 \) around a 10\(^6\) (10\(^8\)\(M_\odot\)) supermassive black hole, we expect the progression of profiles from solid black curve to light blue curve depicted here to last approximately \( \sim 1.5(150)\) yrs. Two-thirds of this time is taken up with the progression from green curve to light-blue curve. All curves are binned at approximately the energy resolution (\( \sim 7\)eV) expected for Astro-H.

The orbital time for the cavity wall. This can lead to an oscillation in the effect discussed below but we shall return to this in future work. In order to move the stalled secondary, we should expect a pile-up comparable to the mass of the secondary. We translated this into a simple density enhancement over a standard thin disk of a factor \( \sim 2 - 5 \) distributed uniformly within \( \sim 10\% \) of the cavity edge. This is roughly consistent with profiles of the pile-up seen in simulations (e.g. MacFadyen & Milosavljević 2008, Cuadra et al. 2009), although over time we might expect \( \Sigma(r) \propto r^{-1} \) build up to large radii behind the dam (Kocsis, Haiman & Loeb 2012a). We shall investigate the effects of different types of ‘damping’ in future work. Here we are not attempting to reproduce details of the damping; we neglect disk heating, pressure and expansion. Rather, we simply want to understand the sense in which the broad FeKα line component changes when we enhance the Fe Kα emission at the disk edge in a naive manner.

In the first case, where the inner disk at \( < r_1 \) is draining onto the primary as in Fig. 7, we assume that there is an enhancement of the emission from gas in an annulus immediately outside \( r_2 \). Fig. 8 shows the inner disk draining ‘outside in’, but now we uniformly enhance Fe Kα emission in an annulus spanning 55 – 60\( r_g \) immediately outside \( r_2 \) to model pile-up. As the inner gap edge (\( r_1 \)) decreases to 30\( r_g \) (red curve), we add a uniform (arbitrary) \( \times 2 \) enhancement of the Fe Kα emission from disk radii spanning...
By comparing Fig. 9 with Fig. 7, we can see that substantial branch in the observable Fe K line complex is emitting substantially more than the surrounding disk. In this case, the blue- and red-shifted horns of the line from the innermost annulus stand out relative to the blue- and red-shifted horns of the line from all until further out in the disk. At some point, when the pressure is large enough, the dam will overflow. If the overflow is continuous, we expect a dynamic equilibrium configuration of ‘double-peaked’ horns, where flux lost from the annulus is replaced by inflowing material. If the overflow is sudden, the outermost of the double-peaked horns will decay rapidly as flux gets redistributed blue-ward and red-ward of the horns. Thus, if we observe a broad Fe K component with double-peaked horns that do not change over the viscous timescale, there is a dynamic equilibrium between pile-up behind and leakage from the dam. The energy resolution of Astro-H is necessary to begin to detect the ‘double-peaked’ horns corresponding to ‘dammed’ accretion disks. However, to systematically study such effects (rather than rely on serendipity), future proposed missions will require much larger effective area than even that planned for IXO/Athena.

4.3 Detecting a disk around the secondary black hole

In our discussion of gaps and cavities above, we have ignored accretion onto the secondary. However (see §2.2), it is possible that the secondary’s accretion disk persists long after the inner disk has drained. An accretion disk within the Hill radius \(R_H = (q/3)^{1/3}R\) of a \(q = 0.03\) secondary located at \(50r_g\) in a cavity in the innermost AGN disk, has a radius of \(1r_g\) in units of the primary black hole mass or \(365r_g\), where \(r_g\) corresponds to gravitational radii in units of the secondary black hole mass. The viscous timescale in the disk around the secondary \(\tau_{\sigma,s} \approx (1/\alpha_s)(H_s/r_s)^{-1}/\omega_s\), where the parameters are as in eqn. (9), but the \(s\)-subscript refers to the accretion disk around the secondary (which may have different properties to the main AGN disk around the primary). Assuming \(\alpha_s \sim 0.01\), \(H_s/r_s \sim 0.1\), \(\tau_{\sigma,s} \sim 10^5\tau_{\sigma,s}\), where \(\tau_{\sigma,s}\) is the dynamical timescale in the secondary disk, a disk extending to \(365r_g\) around a \(q = 0.03\) secondary orbiting a \(10^{6(0)}\) mass supermassive primary black hole, will drain in \(\sim 2(200)\) yrs. Periodic dam overflows or continuous dam leakage could keep the disk persisting (see §2.2) around the secondary long after a cavity has formed. There could also be a small remaining inner disk around the primary in this case, which will add flux to the red and blue wings of the Fe complex. Since motion will be about the center of mass of the merging binary, a small disk component around the primary will wobble, which may be detectable for large mass secondaries (\(q \geq 0.01\)) with the energy resolution of future missions such as Astro-H and IXO/Athena, however, we shall leave discussion of the effect of oscillations of the primary component to future work. In the following discussion, we consider only flux from simple accretion disks around the secondary and ignore the flux contribution from the gas streamers within the cavity.

The secondary disk will add an additional component to the observed broad Fe K line as it orbits the primary. The observational effect will be most obvious at energies red-ward and blue-ward of the line component produced by
Ripple effect in broad FeKα lines

The secondary line component oscillates approximately between the red and blue horns of the primary component over the orbital timescale. For a secondary located at 50r_s from a 10^{6}\ M_\odot primary, one complete cycle of oscillation of the line centroid of the secondary component between the red and blue horns of the primary component will take ~ 2\pi R_s/v_s ~ 10^{10}\ s where R_s = 50r_s is the secondary orbital radius and v_s is the secondary orbital velocity.

In Fig. 11 we show the effect of adding an accretion disk around a secondary black hole located at 50r_s in a cavity which truncates the AGN disk at 55r_s. We assume that the circumbinary disk properties are identical to the circumbinary disk properties (emissivity, disk inclination) except for the cavity. We also assume that the secondary broad line flux is 10% of the primary flux without a cavity (the black curve in Fig. 8). In Fig. 11 the black solid curve corresponds to the superposition of the broad line profile from a AGN disk with cavity (purple curve in Fig. 4), with a secondary broad line component centered on the line centroid energy (6.40keV). The red-curve in Fig. 11 shows the AGN disk/cavity profile with the secondary disk line profile superimposed at the most red-shifted part of its orbit (line centroid is ~ 5.6keV). The blue curve in Fig. 11 shows the AGN disk/cavity line profile, with the secondary disk line profile superimposed at the most blue-shifted part of its orbit (line centroid is ~ 7.05keV). Thus, Fig. 11 shows the effect of one half of the orbit, as the secondary component centroid moves between the red horn to the blue horn of the primary component. The key observable for detecting disks around secondary, satellite black holes is therefore a periodic see-saw oscillation between the red and blue curves as in Fig. 11. If there were a weak circumprimary disk (say \lesssim 10r_g), it would add a very broad component to the red and blue wings of the Fe K line complex. Observationally this would be equivalent to adding a component to the red and blue wings that will vary on the timescale of the primary wobble around the binary center-of-mass. The wobble of the primary component depends on the mass ratio (q) of primary to secondary and may be detectable with the energy resolution of IXO/Athena in very long exposures. Here we shall focus on oscillations due to the secondary disk and we shall leave discussion of the effect of oscillations of the primary component to future work.

In Fig. 12 we show the same effect, this time for a secondary located at 30r_s inside a cavity the disk at 55r_s. In this case, we see a much more pronounced oscillation between the red and blue horns of the total observed broad line component. Here, the line centroid energy of the secondary oscillates between 5.2keV and 7.3keV. This oscillation can occur on the very short secondary orbital timescales (few-10s of ks in AGN with a primary 10^{6−8}\ M_\odot) and could easily be detected during an extended observation with Astro-H. Thus, the deeper the secondary accretion disk in the cavity, the easier it is to observe the oscillation effect. Fig. 12 looks quite different from the results of Sesana et al. (2012) (their Fig. 10), where there are two LAOR model disk components, corresponding to a 10^3\ M_\odot total-mass binary, with the secondary blue-shifted by 10^3\ kms^{-1} (corresponding to a separation of ~ 10^3r_g), much larger than the separations discussed here. The apparent difference is mostly driven by the lack of horns in the profiles in Sesana et al. (2012) which is due to their choice of steeper emissivity profile r^{-2} (see e.g. Fig.10 in Reynolds & Nowak 2003 for the impact of this choice on broad line profile).

In Fig. 13 we simulate a 350ks observation with XMM-Newton EPIC-PN of an AGN at z = 0.01 with a 2-10keV photon flux of 3.5 \times 10^{−11}\ photon\ cm^{-2}\ s^{-1}. We ignore the narrow line component in the model in order to illustrate the difference in best-fits to observations; in practice this model component would need to be fit to the data too. The XSPEC toy model was simply zphabs(zpowerlw+diskline+diskline) where the absorbing Hydrogen column was 10^{21}\ cm^{-2} and the power-

Figure 11. The change in the observed broad FeKα line profile due to an accretion disk around the secondary black hole located at 50r_s. The black curve corresponds to the Fe Kα emission from the main AGN disk (55 \sim 100r_g) plus a weak secondary broad component (10% of the intensity of the full disk profile) due to an accretion disk around the secondary black hole centered on the line centroid energy (6.40keV). The red curve shows the effect of shifting the centroid of the weak secondary component redward to 5.60keV. The blue curve shows the effect of shifting the centroid of the weak secondary component blueward to 7.05keV. The progression from red curve to blue curve occurs over half the orbital time of the secondary. Observationally, we expect a ‘see-saw’ oscillation between the blue and red wings of the line as the secondary accretion disk orbits the primary black hole inside the circumbinary disk cavity. All curves are binned at approximately the energy resolution (~ 7eV) expected for Astro-H.
The change in the observed broad FeKα line profile due to an accretion disk around the secondary black hole as in Fig. 11 except the secondary is located closer in, at 30\( r_g \). The black curve corresponds to the Fe Kα emission from the main AGN disk (55 – 100\( r_g \)) plus a weak secondary broad component (10% of the intensity of the full disk profile) due to an accretion disk around the secondary black hole centered on the line centroid energy (6.40keV). The red curve shows the effect of shifting the centroid of the weak secondary component red-ward to 5.2keV. The blue curve shows the effect of shifting the centroid of the weak secondary component blue-ward to 7.3keV. The progression from red curve to blue curve occurs over half the orbital time of the secondary. Observationally, we expect a 'see-saw' oscillation between the blue and red wings of the line as the secondary accretion disk orbits the primary. All curves are binned at approximately the energy resolution (∼7eV) expected for Astro-H.

The line profile was −1.8. The primary diskline was centered at 6.40keV and due to a truncated inner disk from 50–100\( r_g \), with \( \theta = 60^\circ \) and emissivity \( k = -2.5 \) as above, and a line normalization of \( 10^{-2} \) with respect to the continuum. The secondary diskline had similar parameters to the primary diskline except it ran from 6–100\( r_g, s \), where \( r_g, s \) represents gravitational radii of the secondary. We set the normalization of the secondary diskline to ∼0.2 of the primary to illustrate the difference between the best fits to two simulated observations. The simulated data in Fig. 13 corresponds to line centroid of the secondary at 7.3keV and the blue solid line is the best model fit to the data. The red solid line in Fig. 13 corresponds to the best model fit when the line centroid of the secondary lies at 5.2keV, although we do not show the simulated data in the latter case for ease of presentation. Flux differences in the red wing between the two models in Fig. 13 differ by a few percent and the key observational test in this case is that the best-fit model must oscillate between the blue and red curves on a regular orbital timescale. As we can see, even in two long simulated exposures with XMM-Newton and a relatively intense secondary disk component, it is difficult to disentangle the secondary disk component, even if we bin up the data.

However, repeated observations of bright AGN can build up statistical significance in the red and blue wings, allowing us to track the oscillation of the secondary over time. Thus, observations of AGN in the Fe K band with XMM-Newton EPIC-PN should be searched for serendipitous oscillations. A systematic study of models of secondary disks in AGN could be carried out with LOFT since the proposed effective area (10m²) is an order of magnitude larger than XMM-Newton and the spectral resolution (∼0.25keV) is sufficient for coarse binning of the red and blue wings of the broad Fe Kα line. For disentangling competing effects, ideally a Large Area High Resolution (LAHR) telescope should be used, with effective area greater than that of LOFT together with the proposed spectral resolution of IXO/Athena.
5 MULTIMESSENGER ASTRONOMY WITH GRAVITATIONAL WAVES AND THE RIPPLE EFFECT

Observations of a ripple effect or periodic oscillations in the broad FeKα lines will be an excellent leading indicator of gravitational radiation which can be detected directly independently. Depending on the orbital period of the binary, the GWs emitted by a supermassive black hole binary are detectable with pulsar timing or a space-based laser-interferometric instrument like LISA or NGC. The GW measurement can constrain the source parameters completely independently of the electromagnetic signal with different systematics. Furthermore, the GW measurement may independently indicate the presence of ambient gas around the binary as discussed below. A serendipitous binary detection in one channel can be used to do a targeted search in the other for verification (Kocsis et al. 2008). The comparison of these measurements can provide a consistency check for the central mass, inclination, and orbital radius. The combination of the electromagnetic and GW measurements may allow us to constrain the geometry of the accretion disk and the binary. In this section we discuss the gravitational wave signatures that may be coincident with the electromagnetic signatures.

The GW strain amplitude generated by a circular binary of separation $r$, distance $D$, inclination $i$ relative to the line of sight is

$$\left( \frac{h_+ (t)}{h_\times (t)} \right) = \frac{2 m_1 m_2}{r D} \left( \frac{1 + \cos^2 i}{2 \cos i} \sin 2\phi (t) \right)$$

where $\phi (t)$ is the orbital phase along the orbit. Here, the separation $r$ changes in a characteristic way due to GW losses and gas effects, which causes changes in the orbital frequency, $d\phi /dt$. The corresponding phase shift can be used to measure the binary parameters including the separation, eccentricity, masses, and spins (Cutler & Flanagan 1994) and the torques exerted on the binary by the accretion disk (Kocsis et al. 2013) Yunes et al. (2011) Hayasaki et al. (2012). The distance to the source and the binary inclination then follows from the amplitudes of the two GW polarizations $h_+$ and $h_\times$. The sky position of the source can be inferred by measuring the GW strain coincidently over multiple baselines.

5.1 PTA detections

Pulsar timing arrays (PTAs) can measure GWs of periods weeks to years (or frequencies between nHz to mHz) by detecting correlated variations in the time-of-arrivals (TOAs) of pulses in millisecond pulsars in the Galaxy. At these periods the binaries are relatively far from merger, so only four quantities are measurable for most of the sources: the GW amplitudes of the two polarizations (see Eq. (10)), the orbital period, and the eccentricity, but not the inspiral rate or $\phi$. However, the inspiral rate may be measurable for some sources (Lee et al. 2011). In the case of PTA detections, we expect to detect the binary when it is close to decoupling from the disk (Sohora et al. 2011) and therefore the signature of a gap or cavity in the broad Fe Kα line caused by disk drainage (outlined above) should be clearest. We expect to detect a few such binaries with PTAs out to $z < 1$.

These observations are mostly sensitive to the total stochastic background generated by many supermassive black hole binaries across the Universe at low frequencies (Phinney 2001; Sesana et al. 2009). However, the GWs of massive nearby binaries (e.g. $m_1 \sim m_2 \gtrsim 10^6 M_\odot$) within $z \lesssim 1 - 2$ are expected to rise well above the background level and may be individually resolved (Sesana et al. 2009; Kocsis & Sesana 2011). The individually detectable binaries are expected to be orbiting at separations $100 - 200 r_g$, where gas-driven migration is subdominant relative to gravitational wave losses (Kocsis & Sesana 2011). These GW observations would be able to localize such sources on the sky by comparing the TOAs of several pulsars in different directions. The sky localization and inclination measurement accuracy are of order degrees (Sesana & Vecchio 2014; Lee et al. 2011; Babak & Sesana 2012; Petiteau et al. 2012).

The individually resolvable massive binaries have a typically comparable mass-ratio ($q \sim 1$). These binaries are expected to open a large cavity in the disk. The FeKα profiles may show a double structure if the non-axisymmetric streams can penetrate the gap and create an accretion disk around the binary components (Sesana et al. 2012). These binaries may also exhibit periodic electromagnetic variability (MacFarwen & Milosavljević 2008; Haiman et al. 2008). With large cavities expected to be excavated in the inner disk, we expect to simultaneously detect broad Fe Kα profiles in these AGN similar to the individual curves shown in § 4. If we are lucky enough to detect a massive binary via PTA as the cavity is forming, we will simultaneously observe the variable broad Fe Kα profiles, together with ripple effects and oscillations outlined in § 7.

Since the inspiral rate is typically not available for these sources, one cannot directly measure the effects of gas for individual binaries from PTA observations. Gas driven migration may leave an imprint on the stochastic GW background by reducing the number of binaries in the Universe at large separations (Kocsis & Sesana 2011). For individual binaries, the effects of an accretion disk may be inferred from the GW signal indirectly by measuring a large orbital eccentricity and the absence of spin-orbit precession. The angular momentum exchange with an accretion disk leads to the excitation of orbital eccentricity for widely separated binaries if a cavity forms in the disk, while the eccentricity is predicted to quickly decrease in the absence of an accretion disk or during the later stages of the inspiral due to GW emission. However, the eccentricity is also increased by scattering of stars (Amaro-Seoane et al. 2008; Sesana 2010), albeit to a smaller level. The eccentricity may be detected with PTAs (Enoki & Nagashima 2007). SMBH binaries with a large orbital eccentricity may be indicative of an accretion disk. Secondly, spin-orbit precession may also be detectable if the spins are not aligned with the orbital plane (Mingarelli et al. 2012). Such a configuration would argue against the presence of a gas disk, which tends to align the binary spins (Bogdanović, Reynolds & Miller 2007).
5.2 LISA/NGO detections

LISA/NGO will be sensitive to much smaller periods between 10 hours to seconds, which corresponds to frequencies from $3 \times 10^{-5}$ to 1 Hz and SMBH masses of $M \sim 10^{7}$–$10^{9} M_{\odot}$ at separations from $\sim 100 r_g$ down to merger. In this frequency range, the inspiral of SMBH binaries is much more rapid and the astrophysical stochastic GW background is much more quiet, dominated by Galactic white dwarf binaries (Nelemans et al. 2001). In this case, for a massive binary very close to merger, if an annulus is maintained in the disk, we expect to simultaneously observe a broad Fe Kα component in the late stage of the ripple effect (e.g. the red curve in Fig. 1). If instead, the binary merger is occurring within a cavity, we expect a strongly damped cavity inner wall, and a simultaneous Fe Kα broad line profile similar to the green curve in Fig. 10.

The GW signal of an IMBH or an SMBH spiraling into a SMBH is much stronger than the background level, and may be detected to high significance to high redshifts into a SMBH is much stronger than the background level, the green curve in Fig. 10. If instead, the binary merger is occurring within a cavity, we expect a strongly damped cavity inner wall, and a simultaneous Fe Kα broad line profile similar to the green curve in Fig. 10.

6 CONCLUSIONS AND FUTURE WORK

If a gap-opening, migrating black hole ends up in the innermost regions of an AGN disk, analogous to a gap-opening 'hot Jupiter' in a protoplanetary disk, a unique and predictable pattern of variability appears in the broad component of the Fe Kα line. The ripple effect and oscillations in the Fe Kα line outlined in this paper are potentially detectable in long exposures with future missions such as Astro-H, IXO/Athena and LOFT. Oscillations may be detectable in long, repeated exposures with XMM-Newton EPIC-PN, such as may be found for popular sources in the archive. Here we have shown the range of ripple effects observable as a function of disk and merger properties, including inclination to observers’ sightline, gap-width (or cavity size), disk emissivity profile, damping of the accretion flow and a mini-disk around the secondary black hole.

Detection of a ripple effect or periodic oscillations in the broad component of Fe Kα from an AGN will provide advance warning of gravitational waves due to an impending merger in this AGN. For example, an observation of a broad FeKα line ripple profile given by the dashed red-curve in Fig. 10 from a supermassive black hole of mass $\sim 10^{8} M_{\odot}$ predicts a merger event in this source within a year. Once gravitational waves consistent with a binary black hole merger are detected, an archival search for a ripple effect or oscillations in a broad FeKα line will help localize the gravitational wave detection. Departures from the predicted ripple effect in the final stages of merger will allow us to test the predictions of strong gravity independent of the detection of gravitational radiation.

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