Athena-LISA Synergies

Athena-LISA Synergy Working Group:

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1 Executive summary

While the science cases of Athena and LISA are individually outstanding, the *additional* science that the concurrent operation of the two missions could achieve may provide breakthroughs in scientific areas beyond what each individual missions is designed for. They cover topics as diverse as high-redshift systems of merging black holes over a wide range of mass and mass ratios, and bright quasars in active galaxies. These topics are explicitly covered in this White Paper. The additional science encompasses a series of fundamental questions in modern physics and astrophysics, such as: the dynamics of fluid particles in time varying, strong gravity environments; the onset of nuclear activity in the core of galaxies hosting massive black holes; the physical origin of relativistic jets around spinning black holes, and their launch and interaction with the galactic environment; the cosmic distance scale; and the measurement of the speed of gravity.

Most of the literature work surveyed by this White Paper (and complemented by some state-of-the-art, and not yet published, simulations of event localisation by LISA; cf. Fig. 1 to 3) refers to the possible detection of *the X-ray counterpart of coalescing massive black holes* of $10^{5-7}\mathrm{M}_{\odot}$ that LISA will detect out to large redshifts. Predictions on the detectability of X-ray emission that may rise during the late inspiral and coalescence of the two black holes depend critically on the large uncertainties on the fueling rate and on the hydrodynamical properties of magnetized gas accreting onto the black holes. Within reasonable assumptions, *Athena* should be able to detect X-ray emission from sources at $z \lesssim 2$ (cf. Tab. 1 and 2)[1]. During the *inspiral phase* (*i.e.*, prior to the merger) X-ray emission could be produced over a wide X-ray spectral band as thermal (soft) emission from the inner rim of the circumbinary disk surrounding the binary and/or as coronal (hard) emission from each of the black hole mini-disks within the cavity evacuated by the spiraling black holes, as well as by shock-heated gas at the wall of the cavity. The X-ray emission could be modulated with frequencies commensurate with those of the fluid patterns and of the gravitational chirp, providing the "smoking gun" to identify the X-ray source through a characteristic variability pattern. This gives in principle the exciting possibility of directly probing, for the first time, the behaviour of matter in the variable space-time induced by the merging black holes.

After the merger, the X-ray monitoring of the LISA event error box (that could be as small as few arc-minutes for the most favorable events) may allow Athena to witness the re-birth of an Active Galactic Nucleus (AGN), or even the launch of a relativistic jet according to some theoretical predictions (Shapiro 2017). This will provide a new window for exploring the origin of some of the most powerful and fundamental events in the Universe.

[1] In this White Paper we assume the Athena nominal configuration at the time this document is being written, with an HEW angular resolution of 5", and an effective area of 1.4 m^2 at 1 keV and of 0.25 m^2 at 6 keV. Likewise, the LISA sensitivity used here corresponds to the "ESACall v1.1" configuration: the arm length is 2.5 million km, the laser power is set to 2 W, the constellation uses six laser links and the results of LISA Pathfinder have been included.

While these unique measurements will undoubtedly represent fundamental breakthroughs in various areas of physics and astrophysics, one shall bear in mind a series of caveats that make any prediction of the outcome of an actual experiment uncertain. The most significant among them are:

- the predictions on the nature, and even of the very existence of an X-ray counterpart of a massive black hole merging event detected by LISA are extremely uncertain. However, recent simulations predict vigorous X-ray emission with a characteristic variability pattern (Tang, Haiman, and MacFadyen 2018; d'Ascoli et al. 2018).
- as far as the *inspiral* phase is concerned, LISA will be able to provide a localisation of the events better then $\sim$10 deg^2 only a few days before, and a localisation consistent with the Athena WFI field-of-view only a few hours before the time of the merger for even the best SNR events. While the Athena pointing strategy can be optimised with the continuous improvement of the LISA localisation, it is conceivable that the WFI will be able to image the field including the event for at most a fraction of a day spread over a few visits. This may hamper to distinguish the modulation pattern in the X-ray light curve of the merging event from the common red noise observed in the field AGN
- *post-merger* LISA will provide sky localisation of a sizeable fraction of merging events (christened "*Golden Binaries*" in this WP) to arcminute precision, well within the Athena WFI field of view. However, there is, as yet, no observational-based predictive theory of the X-ray corona or relativistic jets, on which an estimate on the time scale of the formation of an AGN after a massive black hole merger can be based. Furthermore, while we do not have any observational data of binary supermassive black holes with separations lower than a parsec, it is known that binary AGN with separation $\geq$1 kpc are typically heavily obscured in X-rays (Koss et al. 2018). While a sizeable amount of gas in the environment of the binary black hole is required in order for electromagnetic radiation to be produced, gas can also conspire against the detectability of the X-ray counterparts via heavy obscuration suppressing the X-ray emission.

The expected rate of LISA mergers which are potentially also observable by Athena is encouraging, based on the observed galaxy density at $z \lesssim 2$ (Ilbert et al. 2013), and on the observed galaxy merger rates (Lotz et al. 2011). Predictions show the number of LISA massive black hole ($M \geq 10^6$ M$_\odot$) coalescence events is expected to be up to 30 averaged over a ten year period.

Predictions on the X-ray emission for other potential interesting sources are less optimistic (*i.e.*, no X-ray emission expected): Extreme Mass Ratio Inspirals, or stellar-origin ("LIGO-like") mergers that are detected in the LISA band a few years-months before they enter into the LIGO band. For these classes of objects, even an educated guess of the expected X-ray counterpart is highly speculative at this stage.

While in this White Paper we deal primarily with the additional science that will be brought by operating the two missions together, it should be born in mind that there are other science cases for which non strictly simultaneous observations with Athena and LISA are expected to bring breakthrough results (see, *e.g.*, Accreting White Dwarfs, Sect. 3.3).

2 Scope of document

The science cases of both Athena and LISA are outstanding, leading to the missions being selected as the 2nd and 3rd Large class (flagship) missions of the ESA Cosmic Vision Programme. Both missions will observe the most energetic and extreme objects in the universe, the supermassive black holes theorised to be powering the Active Galactic Nuclei (AGN) and to be, when in a binary system, the loudest sources of low-frequency gravitational waves in the Universe. Athena is a large area X-ray telescope, and can detect the emission of hot gas swirling around the massive black holes during the violence of a merger whereas LISA will detect the vibration of the spacetime emitted during their inspiral, merger and ringdown. Details of each mission can be found in Nandra et al. 2013 and Amaro-Seoane et al. 2017.

This White Paper (WP) describes the additional science which can be exploited with both Athena and LISA operating concurrently, observing the Universe, both in Gravitational Waves and X-rays.

3 Science Themes

Multi-messenger astronomy began with the discovery of the first binary neutron star coalescence on August 17th, 2017. The gravitational-wave event, named GW170817, was observed by the Advanced LIGO and Virgo detectors, and the short gamma-ray burst GRB 170817A was observed independently by *FERMI* and *INTEGRAL* with a time delay of ~ 1.7 seconds (Abbott et al. 2017a). An extensive observing campaign was then launched across the electromagnetic (EM) spectrum leading to the discovery of a bright optical transient in the nearby galaxy NGC4993, and X-ray and radio emission at the transient's position ∼9 and ∼16 days, respectively, after the merger (Abbott et al. 2017b). This one source allowed astronomers to confirm the origin of short GRBs, and that kilonovae are the sources of many heavy (r-process) elements in the Universe.

This white paper is focused on *future multi-messenger astronomy* combining low-frequency gravitational wave observations by LISA, and contemporary or follow-up X-ray observations of the same source by Athena.

3.1 Massive Black Hole Binaries

The scientific synergies related to the inspiral and merger of compact object binary systems fall under the following broad classes:

- Dynamics of merging massive black hole binaries
- Enhancement of the cosmic distance scale using GW standard sirens out to $z = 3$ (see Sect. 5)
- Fundamental physics

Theories of galaxy evolution predict that proto-galaxies started to form within dark matter halos at redshifts $z \sim 15 - 20$, and grew massive through repeated mergers and accretion of matter from filaments of the cosmic web (White and Rees 1978; White and Frenk 1991; Dekel et al. 2009). In these pre-galactic, low-metallicity structures, *black hole seeds* of $10^2\,\mathrm{M}_\odot$ (relics of population III stars) up to $10^{5-6}\,\mathrm{M}_\odot$ (from the direct collapse of massive clouds) were able to form, and grow at a high rate (Valiante et al. 2016; Volonteri 2010; Latif and Ferrara 2016). This is a necessary hypothesis to explain the existence of luminous quasars at redshifts as early as $z \sim 7$, representing the tip of an underlying population of massive black holes of $10^5\,\mathrm{M}_\odot$ up to a few $10^9\,\mathrm{M}_\odot$ that inhabit the galaxies we observe in the universe today. EM observations have also revealed the occurrence of tight empirical relations between the black hole mass and quite a few host galaxy properties (Kormendy and Ho 2013). It is now widely accepted that during quasar/AGN activity, the launch of powerful winds and emission of ultraviolet radiation by the black hole engine affected the hole's accretion cycles and star formation jointly, self-regulating their growth in the host galaxy. One of the best explanations for these correlations invokes *gas-rich galaxy mergers*. The high fraction of massive black holes in today's galaxies further suggests that mergers should invariably result in the formation of *massive black* *hole binary systems* at the centre of the newly formed galaxy. In this cosmological context, massive black hole mergers may occur in either gas-poor or gas-rich environments (Haiman, Kocsis, and Menou 2009).

Detecting the joint GW and EM emission during coalescence will have far reaching consequences in terms of knowledge on both black hole and accretion physics. Gas torques have been invoked to help hardening the binary down to tiny scales ($\sim 10^{-4}$ pc), letting the black holes to swiftly transit into the GW driven inspiral (Haiman, Kocsis, and Menou 2009; Colpi 2014 for a review). Thus, they may have played a key dynamical role, years to centuries prior to merging. Observing X-ray emission from hot gas in the vicinity of two black holes during the merger and aftermath of a coalescence will be challenging, but extremely rewarding.

The *additional science* resulting from the detection of an X-ray signal *contemporary* to the GW signal would be groundbreaking for the reasons explained in this document. For the first time we envision the possibility of detecting the simultaneous emission of X-ray and GW radiation to study the closest environment of a violent merger and the propagation properties of the GWs. The phases that precede and follow the coalescence are characterized by profoundly different spacetime geometries and the ability to detect both GW and EM signals in tandem in the two phases differs as well. Hence, in what follows we will distinguish two phases: the *pre-merger* phase associated to the binary late inspiral, which might lead to the detection of a long-lived *X-ray precursor* signal, and the *post-merger* phase associated to the merger proper and black hole ringdown, which might lead to an X-ray flare, disc re-brightening and jet formation. Late (weeks to years) follow-up observations might have also the chance of observing a recoiling black hole moving at high speed in the host galaxy, accreting residual, bound gas.

3.1.1 Pre-merger (Inspiral) phase

Environment around the massive black hole binary. As the massive black holes spiral-in, X-ray emission is expected to be modulated in time, with characteristic frequencies correlating with the binary orbital motion and with relativistic patterns rising in the non-axisymmetric circum-binary disc surrounding the two black holes (Farris et al. 2014; Tang, MacFadyen, and Haiman 2017; Bowen, Campanelli, et al. 2017; Bowen, Mewes, et al. 2018), described in Sect. 6. The GW signal during the inspiral provides the orbital frequency of the binary and chirp mass, necessary for the identification of the variable X-ray source in the Athena field of view, and for a preliminary consistency test on the extent of the expected luminosity (Tang, Haiman, and MacFadyen 2018; d'Ascoli et al. 2018).

Speed of gravity. As stated above, X-ray variability is expected during the inspiral phase. If one could correlate the X-ray modulation with the GW chirp, *i.e.* if the modulation would be dominated by Doppler and/or relativistic boosting, this would allow further tests on the speed of gravity on cosmological scales compared to photon propagation (Abbott et al. 2017a; Haiman 2017).

3.1.2 Post merger phase

The ability of LISA to locate the source in the sky improves dramatically with increasing SNR, during the merger and ringdown of the object (McWilliams et al. 2011). Post merger, many sources will be located to within a (few) arcmin precision. This will allow the host galaxy to be more easily identified, even if the inspiral phase was not recognised during the inspiral phase.

Cosmic distance scale. Coalescing binaries are standard sirens as the GW signal enables the direct measure of the luminosity distance to the source (Schutz 1986). By contrast it does not carry any information on the redshift that instead can be recovered from EM observations of the host galaxy. If from the X-ray signal and optical follow-up it will be possible to identify the host, then the distance-redshift relationship can be measured to high accuracy ($\approx 1\,\%$) to probe the late time background expansion of the universe (Tamanini et al. 2016).

AGN physics. The post merger observation of the AGN opens the door to better understanding the physical accretion process powering the AGN. The LISA observation will provide the parameters of the merging black holes (masses, spins, and orbital parameters) to the percent level, whereas the X-ray observations provide the high resolution details of the surrounding matter through the spectra/light curves.

3.2 Extreme Mass Ratio inspirals to study AGN disks

While electromagnetic (EM) observations probe the photosphere of AGN disks, the disk gas density and lifetime remain poorly constrained to within multiple orders of magnitude (Martini and Weinberg 2001), which limit our ability to estimate the average rate of SMBH growth due to gas accretion. Gravitational wave signatures of disk-driven mergers of stars and stellar remnants with the central supermassive black hole (SMBH) can provide this information, thus complementing EM data. This is because gas torques in AGN disks will cause stars and stellar remnants to become trapped by and migrate within the disk (e.g. Syer, Clarke, and Rees 1991; Artymowicz, Lin, and Wampler 1993). Differential migration then permits new binary formation and their rapid merger within the disk (e.g. McKernan, Ford, Lyra, et al. 2012; Secunda et al. 2018). The result is (overmassive) stellar black hole (sMBH) mergers detectable with LIGO (McKernan, Ford, Kocsis, Lyra, et al. 2014; Bartos et al. 2017; Stone, Metzger, and Haiman 2017). LIGO results already strongly constrain the presence of radiatively inefficient accretion flows in most weakly active LINER galactic nuclei (McKernan, Ford, J. Bellovary, et al. 2018). LISA on the other hand will directly probe the effect of gas drag on the GW waveform of these sMBH binaries but at wider separations. Even if they not form binaries, compact objects migrating within the disk will eventually inspiral and plunge onto the central SMBH. Due to the extreme difference in mass of the two objects, these events are named extreme mass ratio inspirals (EMRIs, Barack and Cutler 2004). The associated GW signal is at far too low frequencies for ground based detectors but well within the sweet spot of the LISA sensitivity. LISA will detect EMRIs out to $z \approx 2$ (Babak et al. 2017). Intermediate mass black holes (IMBHs) spiralling and eventually plunging onto the SMBH might be subject to a similar dynamics. Viscous torques within the disk might promote the formation of IMBH-SMBH binaries with a separation corresponding to migration traps (J. M. Bellovary et al. 2016). Subsequent inspiral and merger of the IMBH with the SMBH will give rise to an intermediate mass ratio inspiral (IMRI). Detection of these events is also well within LISA reach.

Athena may also be able to detect the presence of sMBH in AGN discs for mass ratios $q > 10^{-6}$ (i.e. an EMRI), via the "wobble" or "ripple" effect in broad X-ray emission lines (McKernan, Ford, Kocsis, and Haiman 2013). As the sMBH plunges through the disk, it exchanges angular momentum and excavates gas. Once the sMBH reaches an orbit such that the disk mass interior to it is comparable to its own mass, the sMBH will stall briefly, until GW emission or exterior gas buildup pushes it into the SMBH. This implies that the highest velocity gas will temporarily disappear. This will change the Fe K_α line profile, such that the broadest wings will fade on the viscous timescale (months to years depending on the BH mass and disc properties), and reappear on the same timescale, after a pause (the stalling timescale, an order of magnitude longer). So, if we detect GW we know that the missing high velocity wings are due to the presence of a sMBH and we can derive the disc properties. For IMBH-SMBH binaries with a mass ratio $q > 10^{-3}$, the imprint of the oscillations around the binary barycenter may also be detected in broad X-ray emission lines but as radial velocity shifts (McKernan and Ford 2015). The oscillation period is strongly dependent on the binary properties: for mass ratio q=0.1 and separation 100 gravitational radii the period is of ~ 1 yr around a 10^9 solar mass black hole primary and of ~ 8 hr around a 10^6 solar mass primary black hole, which falls in the sweet spot of the LISA sensitivity band. Interestingly, modulations of the oscillations are caused by the general-relativistic and Lense–Thirring precession of the periapse of the secondary SMBH's orbit, linked to mass and spin of the system. The Athena X-IFU will have the energy resolution to look for such oscillations and detection in multiple exposures of hundred of ks of the broad Fe K_α. For binaries with $q > 0.01$, separation less than 1000 gravitational radii and modest eccentricities (0.01-0.1) the shift has been estimated to be $\geq$25 eV, *i.e.* about ten times the instrumental resolution (McKernan and Ford 2015).

Athena is expect to detect relativistically broadened spectral features produced in a relativistic X-ray illuminated accretion disk up to z$\simeq$1.5–2 (Dovciak et al. 2013). We anticipate that Athena will be able to study these effects (wobbling and radial velocity shifts) with Fe K_α line around a few tens of systems. To increase this sample by a factor of several to $\sim 100 - 150$ systems, in principle one could look at relativistically blurred soft X-ray lines such as O VIII Lyα, (Ballantyne, Ross, and Fabian 2002), where the Athena effective area is one order of magnitude larger. However, it should be borne in mind that there is currently no observational evidence for relativistically broadened Oxygen lines in the spectra of AGN in the local Universe, the main evidence being for much more complex Fe-L line (Fabian, Zoghbi, et al. 2009). An additional complication may come from the effect of variable absorption with complex ionisation structure typically seen in the high-resolution spectra of nearby AGN.

3.3 Accreting white dwarf binaries

Our understanding of stellar evolution and of the stellar initial mass function imply that over 95% of all stars in the Milky Way will end their lives as white dwarfs (WDs). Between $\sim 5\% - 10\%$ of all WDs are in double WD (DWD) binaries (Maxted and Marsh 1999; Toonen et al. 2017; Maoz, Hallakoun, and Badenes 2018), with simulations predicting today over 10^8 systems (Nelemans, Yungelson, and Portegies Zwart 2004). In their evolution, DWD binaries do not always remain detached. A small and highly uncertain fraction ($\sim 10^{-3}$) of DWD survive the onset of mass-transfer and currently stable mass transfer occurs (called "AM CVn"). These short (< 30 min) period binaries are strong UV/X-ray and mHz gravitational waves emitters. Actually, the most compact binaries known today, HM Cnc (with orbital period of 5.4 min) and V407 Vul (9.5 min), are semi-detached AM CVn systems and currently the loudest guaranteed (i.e. we know they exist) LISA sources. Considering the predicted on-axis Athena sensitivity of $\simeq 2\times10^{-16}$ erg s^{-1} cm^{-2} in the 0.5–2 keV energy band in a typical 10 ks observation, we expect a few hundred systems with simultaneous X-ray and GW detection (Nelemans, Yungelson, and Portegies Zwart 2004). Combined EM (from optical to X-ray)-GW observations of accreting DWDs would allow us to uniquely study fundamental physical processes, related to WD accretion physics and mass transfer stability. For example, the largest uncertainties in predictions of the final fate of DWD binaries (merger versus stable mass transfer) and hence of SN Ia rates is the treatment of the onset of mass transfer when the larger WD fills its Roche Lobe and starts to accrete onto its companion. So far the space density of observed systems in EM is several order of magnitude below the theoretical predictions which challenges our theoretical understanding of their formation and evolution (Carter et al. 2013; Ramsay et al. 2018). The large statistical sample of accreting and non-accreting DWDs detected by LISA will provide us with space densities and system properties of each group individually. This in turn gives a direct measure on how many DWDs prevent the merger as well as what are the system properties of the surviving AM CVn binaries. Moreover, the angular momentum transport in accreting DWDs is a combination of gravitational wave radiation –which tends to shrink the system – and mass transfer, that typically widens a binary. The system properties derived from combined EM-GW data can disentangle the contribution from gravitational wave radiation and mass transfer from the overall period evolution ($\dot{P}$) and study, for the first time, the transport of angular momentum in accreting DWDs on a statistical significant number of systems. Finally, the amount of transport of angular momentum is intimately related to how much mass is being accreted in the system. A comparison of the accretion rate with the X-ray and UV luminosity and spectrum will allow us to get a deeper insight into the radiative property of matter.

4 Targets

Discovering the EM counterparts of GW sources that LISA will observe for the first time in human history will be groundbreaking *per se*. Athena likely offers the best opportunity to carry out a dedicated search of a counterpart in the electromagnetic domain. Two fundamental issues have to be folded in, to appreciate the problem at stake. This being an uncharted territory, any *prediction* on the rate of GW mergers and on the EM emission, in particular in the X-rays, have to rely on theory only, with a rather uncertain and widespread range of predictions (Roedig, Krolik, and Miller 2014; Tang, Haiman, and MacFadyen 2018; d'Ascoli et al. 2018).

Assuming that the counterpart is indeed a photon-emitter, and that it produces a flux above the instrumental threshold, the challenge is then to *identify* the counterpart in a field that will likely count hundreds to thousands of field sources. In this respect the X-ray band, the sensitivity and the field of view catered for by Athena offer the best combination. Assuming that the broad-band EM spectrum has an overall shape similar to that observed in massive black holes at the center of active galaxies ($\alpha_{OX} = 1.3$ in optical and $L_{1.4GHz}/L_x \approx 10^{-5}$ in radio (Panessa et al. 2007). one can relate the X-ray flux to a given optical magnitude or radio flux and then compare the number of field sources expected in the three bands. For example, the X-ray sky at a flux of $\approx 10^{-15}$ cgs is populated with about 3000 sources deg^{-2}, while at the corresponding magnitude m$\approx$ 24.2 and radio flux of $\approx$ uJy there are about or more than 10^5 source deg^{-2}, i.e. 30 times more contaminating objects in the optical and radio bands. Still, a proper *characterization* of the source behaviour (mostly in the time domain) is thus requested both from theory and observations to pin down the candidate.

In this section we summarize the class of sources that LISA is expected to detect, their rate, localization error box and associated uncertainties and the perspective to observe them with Athena.

- Massive black hole binary mergers (everywhere in the Universe). LISA is expected to detect binary black hole mergers from $\approx 10^{3-7}$ $M_\odot$ up to $z \approx 20$ (Amaro-Seoane et al. 2017). The detection rate is highly uncertain, in the range $\approx 10 - 300$ in 4 years (Sesana et al. 2011; Bonetti et al. 2018). The mass-redshift distribution is also subject to large uncertainties, and based on modelling, detections will be dominated in number by lower mass systems at redshift z> 5, with low S/N. However, up to several detections of black holes with masses $\geq 3 \times 10^5$ $M_\odot$ at $z < 2$ are expected per year. These events deliver the highest S/N in GW, with an error box small enough to be effectively observed by Athena. The GW signal increases with time, from the in-spiral phase to the merger event, thus the best localization is derived post-merging, with best cases localizations down to arcminutes. We define a *golden binary* as being composed of objects such that the error box derived *after* the merger is smaller than the WFI field of view (0.4 deg^2). This *golden sample* comprises the majority of binary mergers with mass within $3 \times 10^5\,M_\odot$ and $10^7\,M_\odot$ up to $z \approx 2$ (see section 5) and allows Athena to search for X-ray emission produced in the post-merger phase. For the highest S/N events the localization derived in-spiral phase can allow Athena to repoint *before* the merging takes place. We define a *platinum binary* as being composed of objects whose localisation error, determined 5 hours before the merger, is smaller than the WFI field of view. The timing is consistent with the Athena capability of carrying out a TOO in 4 hours. The *platinum binary* comprises a fraction of binary mergers with mass within $3 - 10 \times 10^5\,M_\odot$ below $z \approx 1$ (see section 5), and thus likely to be rare. For the *platinum binaries* both phases, in-spiral and merging can be observed with Athena, including the intriguing perspective to observe in X-rays the BH merging event in the act. With a proper observing strategy (see section 8), Athena can actually start observing few days before the final binary coalescence. At this time the localisation error of objects in the *platinum binary* is ≈ 10 deg^2, an area that can be effectively covered by tiling WFI observations in about 3 days.

  Models predict a very wide range of X-ray luminosity, from none to vigorous, with the major question being to which extent gas around BH exists and accretes onto it. Assuming that this happens at a few percent of the Eddington luminosity, the source will be easily detected by Athena.

- **Compact and Extreme Mass Ratio Inspirals and mergers**. EMRIs are low-mass compact objects (NS and stellar mass BHs) spiralling into Massive BH (Barack and Cutler 2004). It is not obvious if any EM counterpart exists. Events taking place in AGNs could affect the accretion disk inner orbits and thus possibly the associated X-ray broad line component. A few pointings of a few ks each could be sufficient to probe if there is an EM counterpart to an EMRI at $z \leq 0.3$.

- **Stellar mass black holes binaries ($z \leq 0.5$)**. They will be observed by LISA ~a few years in advance of final coalescence and will transition out of the LISA band weeks before the merger (Sesana 2016). At that point the merging time should be known with an accuracy ± 10 seconds, and the localisation with an accuracy $1\,\mathrm{deg}^2$. It is not obvious if an EM counterpart exists, however, some of them may be in the Milky Way (Lamberts et al. 2018) and could exhibit low-level of accretion (exact calculations still to be done). For a binary of a combined mass of $\approx 60 M_\odot$, at 10 kpc, the Eddington luminosity in X-ray corresponds to a flux of about $10^{-6}\mathrm{erg\,s^{-1}cm^{-2}}$. So Athena will be sensitive to X-ray luminosities down to $10^{-10} L_{\mathrm{Edd}}$.

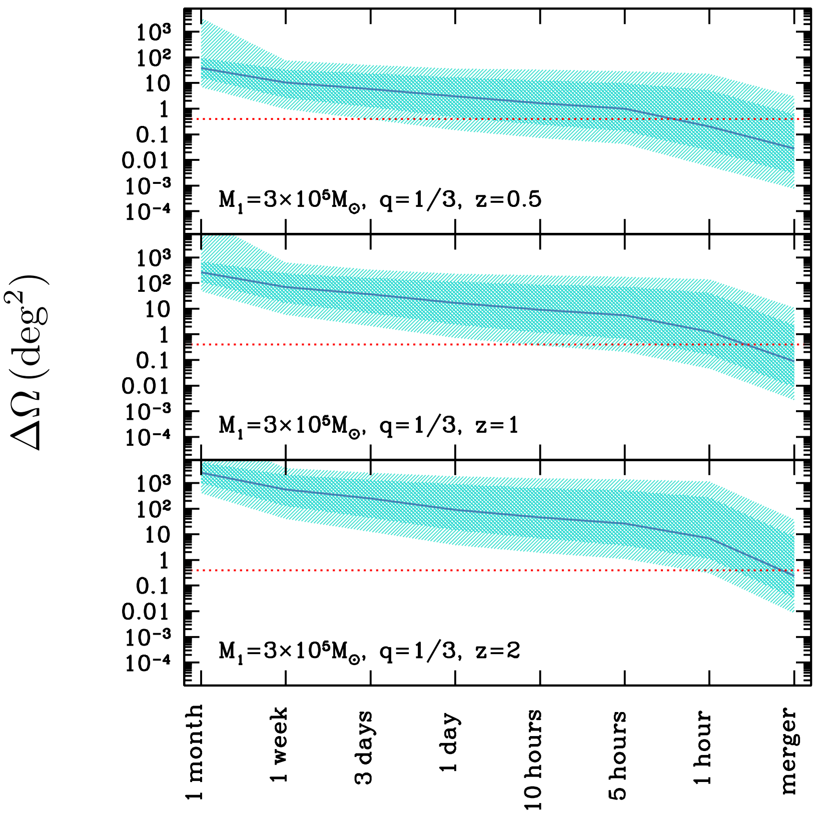

Figure 1: Sky localization error $\Delta\Omega$ in deg^2 versus time to merger for non-spinning black hole binaries with mass of the primary, in the source frame, equal to $3 \times 10^5\,\mathrm{M}_\odot$. The binary mass ratio q is set equal to 1/3. From top to bottom, the GW source is located at redshift $z = 0.5, 1$ and 2, respectively. Full inspiral (with higher harmonics), merger and ringdown waveforms are used to carry on the analysis (Klein, Cornish, and Yunes 2014). Shaded areas are the 68% and 95% confidence interval computed over 1000 systems and the dark solid line is the median value. The horizontal dotted line denotes the field of view (~ 0.4 deg^2) of the WFI onboard Athena.

5 LISA Massive Black Hole Coalescence: Sky Localization

LISA is an all sky monitor sensitive to sources at most points on the sky. To build localization information, LISA exploits the long duration of the GW signals, which characterize many of the prospected sources. Typically, massive black hole coalescences are observable months prior to merger, and during this time LISA's orbit around the Sun introduces frequency and amplitude modulations in the inspiral signal that can be used to determine the source position days in advance within few tens of deg^2 of uncertainty for relatively nearby sources. A number of studies have demonstrated that the sky localization error decreases significantly with measurement time when accounting for realistic LISA orbits and full high-frequency response of the LISA instrument, but most importantly when including the merger and ringdown portion of the GW signal, having a large power despite being short lived (see, e.g. McWilliams et al. 2011).

Here, we carried out the analysis of the sky localization uncertainties, using the current LISA design, for an ensemble of binaries with random orientations, sky positions and spins, using full waveform models for spinning and precessing massive black holes, including the contribution from higher harmonics in the inspiral

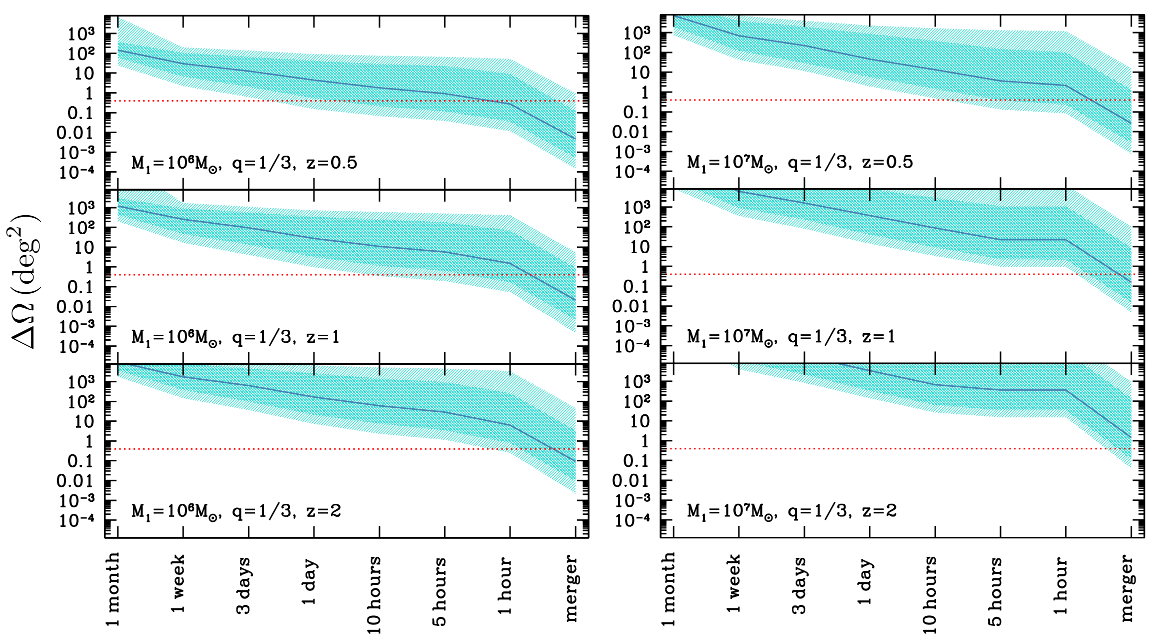

Figure 2: Sky localization error $\Delta\Omega$ in deg^2 versus time to merger for non-spinning massive black hole binaries with mass of the primary, in the source frame, equal to $10^6\,\mathrm{M}_\odot$ (left panel) and $10^7\,\mathrm{M}_\odot$ (right panel). The binary mass ratio q is set equal to 1/3. From top to bottom, the GW source is located at redshift $z = 0.5, 1$ and 2, respectively. Full inspiral (with higher harmonics), merger and ringdown waveforms for spinning and precessing black holes are used to carry on the analysis (Klein, Cornish, and Yunes 2014). Shaded areas are the 68% and 95% confidence interval computed over 1000 systems and the dark solid line is the median value. The horizontal dotted line denotes the field of view (~ 0.4 deg^2) of the WFI onboard Athena.

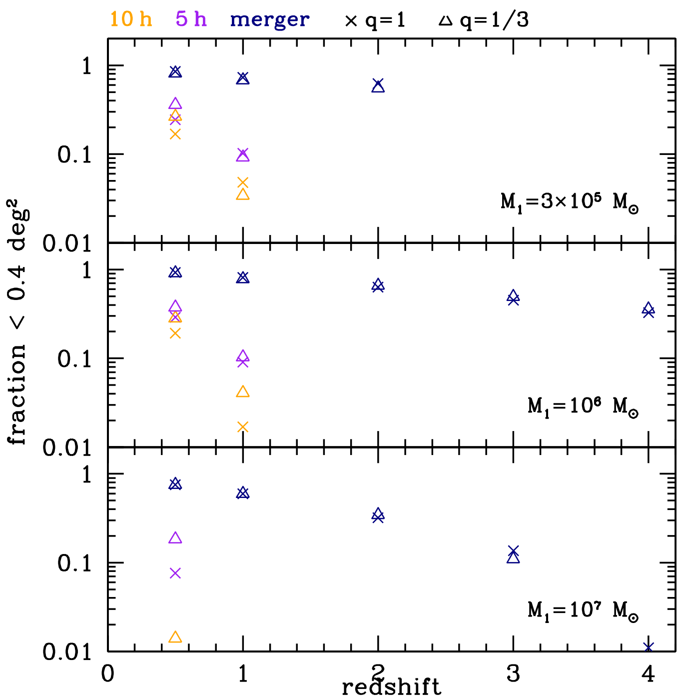

Figure 3: Fraction of massive black hole binaries with LISA sky localization better than 0.4 deg^2 at 10 hours before merger (orange) 5 hours before merger (purple) and after merger (blue). Each panel is for a different mass of the primary black hole ($M_1 = 3 \times 10^5\,\mathrm{M}_\odot$, $10^6\,\mathrm{M}_\odot$ and $10^7\,\mathrm{M}_\odot$). Crosses (triangles) refer to binaries with mass ratio $q = 1$ ($q = 1/3$). Results are shown as a function of redshift.

portion of the GW signal, which reduces the sky localization uncertainties in the early phases of the merger (Klein, Cornish, and Yunes 2014). In the analysis, we considered primary black holes with mass M_1 in the source frame of $3 \times 10^5\,\mathrm{M}_\odot, 10^6\,\mathrm{M}_\odot$, and $10^7\,\mathrm{M}_\odot$, respectively. The binary mass ratio is set equal $q = 1/3$, which is characteristic of LISA sources (Colpi 2014), but we also consider equal mass binaries. The binaries are placed at redshift $z = 0.5, 1$ and 2.

The results are illustrated in Fig. 1 and Fig. 2, where we plot the sky localization uncertainties as a function of time to merger. The figures show how sky localization improves as time progresses, for selected systems. Even for these loud sources, characterized by a cumulative SNR in the hundreds, the narrowing in the sky localization uncertainty (down to a few tens of a deg^2) occurs only in the last few days of the merger. By contrast at merger all systems, with the exception of binaries with primary mass of $10^7\,\mathrm{M}_\odot$ at $z = 2$, can be localized within fractions of a deg^2, with uncertainties that can be as low as a few arcminutes.

Fig. 3 summarizes our key findings, obtained simulating 1000 binaries for each set of intrinsic parameters. The figure shows the fraction of systems, as a function of redshift, that can be detected with LISA sky localization better than 0.4 deg^2 at 10 hours before merger (orange) 5 hours before merger (purple) and after merger (blue), allowing for the *Athena* follow-up. Each panel is for a different black hole primary masses as in Figures 1 and 2. Here we considered binaries with mass ratio $q = 1$ denoted with crosses, and binaries with $q = 1/3$ denoted with triangles.

The key result that emerges from this analysis is that localizing binaries within the Athena WFI during the late GW inspiral is possible only for low-redshift systems with $z < 1$. 20-40% of the binaries with primary $M_1 = 3 \times 10^5\,\mathrm{M}_\odot$ and $10^6\,\mathrm{M}_\odot$ at redshift $z < 0.5$, and 10% at $z = 1$ can be localized within the Athena WFI

5 hours before merger (purple marks). The results are weakly dependent on the value of the mass ratio q. Conversely, only about 10% of the $M_1 = 10^7\,\mathrm{M}_\odot$ systems at $z = 0.5$ can be pre-localized. Thus, *platinum binaries* are essentially a fraction of the $M_1 = 10^{5-6}\,\mathrm{M}_\odot$ binaries merging below $z \sim 1$, and thus are likely to be rare.

By contrast, post-merger sky localization is significantly better, increasing the chance of a detection of a prompt X-ray signal almost contemporary to the GW signal at its apex, i.e. during the merger proper. More than 60% of the binaries with $M_1 = 3 \times 10^5\,\mathrm{M}_\odot$ out to $z \sim 2$ can be localized within the Athena field of view. Similarly, 50% of the mergers with $M_1 = 10^6\,\mathrm{M}_\odot$ up to $z \sim 4$ can be observed in the post-merger phase within the Athena FoV, with the possibility of pinning down the localization to fractions of a deg^2. Also more massive systems, as those with $M_1 = 10^7\,\mathrm{M}_\odot$, can be well localized in the post-merger phase, out to $z \sim 3$.

The potential for post-merger Athena follow-ups of massive black hole binary mergers appears to be indeed promising.

In light of the above findings in the next section 6 we outline scenarios for the fueling of *Platinum* and *Golden* binaries, focusing first on the precursor emission and later on the post-merger prompt or afterglow emission.

6 Mapping matter in the space-time of merging massive binary black holes

6.1 Gas dynamics around coalescing binary black holes

The EM light-curve and spectrum of a coalescing massive black hole binary are unknown. No transient broad-band AGN like emission that could be attributed to the coalescence of a LISA binary has been observed in the variable sky yet, at any wavelength. Thus, we have to resort on theoretical models of gas dynamics around massive binary black holes to infer characteristics of their emission: (i) whether there are spectral variabilities and periodicities in the light curve related to the binary orbital motion and to non-axisymmetric patterns rising in the fluid flow, (ii) the launching of a (dual) jet(s), and (iii) accretion sustained at high enough rates to stand above the red background noise (Vaughan, Fabian, and Iwasawa 2005).

Joint and contemporary observations of the GW and EM signals require the presence of a rich reservoir of gas, possibly in the form of a *circumbinary disc* surrounding the binary and of *mini discs*, which feed the black hole engines. Circumbinary discs have been extensively studied in 2D and 3D hydro-dynamical simulations, in Newtonian and pseudo-Newtonian potentials when the binary is still far from coalescence, and most recently in full general relativity in proximity of the merger proper, when space-time is highly dynamical and accretion flows are far from equilibrium.

These studies show a richness of states and configurations as the flow pattern depends on the black hole mass, mass ratio and, to a higher level of sophistication, on the black hole spins. Spin-orbit and spin-spin relativistic precession may induce modulation in the accretion flows which are coupled to the spin via the Bardeen-Peterson effect. This might lead to variability and spectral signatures that are still difficult to quantify and separate. But despite these complexities, all models share important commonalities and basic traits that we summarize shortly.

Consider, with no loss of generality, the case of a black hole binary with total mass of $M_\mathrm{B} = 10^6\,\mathrm{M}_\odot$, mass ratio $q \lesssim 1$ surrounded by a circumbinary disc (of negligible mass and aspect ratio $H/R \lesssim 1$). Prior to its entrance in the LISA band, the binary may already have experienced a phase of accretion-driven inspiral. The picture is that the binary quadrupolar gravitational potential exerts a torque on the gas at the inner edge of the disc clearing a central cavity. Viscous torques in the circumbinary disc drive gas inwards and the balance between the binary and disc torques set, at twice the black hole binary separation, the location of the disc's inner edge, and thus size of the cavity. This is conducive to black hole migration inside this hollow region. For a long time accretion was thought to be negligible or absent, due to the presence of the cavity, preventing the possibility of emitting a multi-color spectrum. But, 2D and 3D numerical simulations have shown that the system evolves into a highly non-axisymmetric configuration with the cavity becoming highly lopsided and filled of tenuous, shocked plasma, in part ejected against the disc wall where it loses angular momentum to feed the black holes. This leads eventually to the formation of two narrow streams which periodically convey mass onto the black holes in the form of 'mini discs' extending down to the innermost stable circular orbit (ISCO) (e.g. Cuadra et al. 2009; Schnittman 2011; Roedig, Dotti, et al. 2011; Farris et al. 2014; Bowen, Campanelli, et al. 2017; Bowen, Mewes, et al. 2018; Tang, Haiman, and MacFadyen 2018). This feature appears to be universal.

A remarkable recent finding is that this type of environment appears to be present even when the binary dynamics are overwhelmingly dominated by its GW radiation, and the circumbinary disc decouples, due to the viscous time being longer than the GW timescale. Recent 2D and 3D general relativity magneto-hydrodynamic simulations have shown that accretion continues all the way to the merger. Accordingly, this type of environment is expected to be present also when the two black holes enter the LISA band around $\sim 10^{-4}$ Hz, at a distance of ~ 80 gravitational radii $GM_{\rm B}/c^2$. On these scales, relativistic effects have been shown to alter the gas dynamics in several ways. Bowen, Campanelli, et al. 2017 found that the gravitational potential between the two black holes is shallower than in the Newtonian regime so that gas is exchanged across the inner Lagrangian point. This mass transfer, termed sloshing, which increases sharply with decreasing binary separation, is quasi-periodically modulated at 2 and 2.75 times the binary orbital frequency, corresponding to timescales of hours. In addition, strong gravity adds an $m = 1$ over-density, a 'lump' at the inner edge of the circumbinary disc so that whenever each stream supplying the mini-disc comes into phase with the lump, at a frequency 0.74 times the binary orbital frequency, this creates a modulation in the accretion flow.

In summary, both sloshing and spiral waves may create periodicities in the accretion rates that uniquely mark massive binary black holes in the relativistic regime. These periodicities appear generic and may result in distinctive radiation features that could be detected by Athena in those nearby binaries (the *platinum binaries*) for which sky localization is so rapid to allow for the detection of precursor emission during the last hundred to tens of cycles prior to coalescence.

Concerning gas-dynamics during the merger and post merger phase, recent larger-scale hydrodynamic simulations of magnetized circumbinary discs onto non-spinning black hole binaries (Khan et al. 2018) have shown that collimated and magnetically dominated outflows emerge from the disc funnel independently of the size, extension and mass of the disc model. Incipient jets form and persist through the very late inspiral, merger and post-merger phases. During merger proper the magnetization in the funnel grows, and after merger the jet around the new black hole becomes magnetically powered. The region above and below the new black hole is nearly force-free, a prerequisite for the Blandford-Znajek (BZ) mechanism to be at work. Quite interestingly, after a few days from the merger, the EM luminosity reaches values comparable to the Eddington luminosity, enabling follow-up EM observations, after the GW source has been localized with the highest accuracy.

6.2 Light curves and spectra from coalescing binary black holes

There is no general consensus on the electromagnetic spectrum emerging from a coalescing black hole binary (Roedig, Krolik, and Miller 2014; Tang, Haiman, and MacFadyen 2018; d'Ascoli et al. 2018), nor on the extent of the modulation in the accretion luminosity which tracks the variability in the accretion rate. The broad-band emission is an uncharted territory, and there is no guidance from current observations of variable AGN.

6.2.1 Percursor emission

The *precursor emission,* hours prior to coalescence, is expected to come from the circumbinary disc, the mini discs around each black hole and the cavity wall filled of hot gas and accretion streams, each contributing at different wavelengths to a different extent. When the accretion rate makes the flow optically thick, and in the soft X-ray band (around 2 keV), thermal radiation is dominated by the inner edge of the circumbinary disc with clear periodicities in the early inspiral (Tang, Haiman, and MacFadyen 2018). By contrast, harder

X-ray emission (around 10 keV) comes from the mini discs with a light curve more noisy and less modulated, in particular in the imminent vicinity of the merger when the mini discs thin as their tidal radius shrinks to a size comparable to the hole's Innermost Stable Circular Orbit (ISCO), and accretion is highly non stationary being driven by pressure gradients at least as much as by internal stresses.

While it has been speculated that an optical/UV chirp would be present and evolve in tandem with the GW chirp in the very early inspiral phases due to the Doppler shift induced by the rapid black hole orbital velocity, this may not hold true very close to merger when the sky localization improves. Net Doppler shifts appears to be dominated by radial motions of the gas rather than orbital velocity, leading to an overall dimming of the light curve rather than a sinusoidal modulation (Tang, Haiman, and MacFadyen 2018). This makes extremely challenging any identification of pre-glow emission, unless it is tracked a few hours prior to coalescence. Thus a key prerequisite for a successful identification of precursor EM emission is a sky localization uncertainty of 0.4 $\deg^2$, a few hours prior to coalescence.

Outside thermalized regions and in case of low accretion rate, inverse Compton scattering for coronal emission around the mini discs produces hard X-ray emission (d'Ascoli et al. 2018). Additional X-ray variability may arise from refilling/depletion episodes caused by periodic passage of the black holes near the overdensity feature at the edge of the circumbinary disc. Also Doppler beaming (Haiman 2017) and gravitational lensing (D'Orazio and Di Stefano 2018) can modulate the observed light flux seen by near-plane observers. The emission is in general highly anisotropic, especially when the binary is seen edge-on, and thus with the lowest GW amplitude.

6.2.2 Prompt and post-merger emission

Concerning the *prompt, post-merger emission*, which is the most relevant for Athena, the launch of a jet from the spinning black hole (Shapiro 2017) might spark gamma-ray emission and the impact of the jet on the interstellar medium might give rise to broad-band afterglow emission.

At present, there is no clear prediction on the properties of the afterglow emission. Depending on the residual mass present near the newly formed black hole, jet emission can continue under stationary conditions to give rise to long-duration emission until gas consumption. The duration of this phase is unknown as no numerical simulations can track the joint disc evolution and jet emission, after merger, on such prohibitively long timescales.

As at coalescence the GW signal reaches a peak luminosity of the order of a few $\nu^2 10^{57}\,\mathrm{erg\,s^{-1}}$ (with ν the symmetric mass ratio, equal to the reduced total mass ratio of the binary) even a minuscule fraction of this luminosity could give rise to an observable prompt EM transient. Kocsis and Loeb 2008 argued that in the near zone GWs may induce shear motion in the surrounding gas disc (despite their tiny cross section with matter) so that a fraction of their power could be dissipated through viscosity, providing a prompt, post-merger EM counterpart. GWs carry away energy by an amount equal to $\sim 5-10\%$ of the reduced mass-energy of the binary, corresponding to $\lesssim 10^{59}$ erg, for a $10^6\,\mathrm{M_\odot}$ equal mass binary. This mass loss weakens the underlying gravitational potential. Thus, fluid particles, after the merger proper, carry more orbital angular momentum than required for equilibrium. In the perturbed disc, their orbits may intersect and shock heat the fluid which is radiating away some of the excess energy (Rossi et al. 2010; Schnittman 2011). This might again lead to a rebrightening of the disc. However, the extent of this dissipation might be insufficient to give rise to an Athena observable emission by several orders of magnitude (Rossi et al. 2010).

6.2.3 Long term dynamics of the new, remnant black hole and disc rebrightening

GWs not only carry away energy and angular momentum, but also net linear momentum which leads to *gravitational recoil* of the new black hole. This kick velocity is acquired near the time of formation of the common horizon of the merging black holes, and emerges when the two black holes carry either unequal masses, unequal spins, or a combination of the two. The recoil velocity can range between less than 100 km $\mathrm{s^{-1}}$ up to a few thousands km $\mathrm{s^{-1}}$ (Baker et al. 2008).

Numerical relativity experiments find that the recoil normal to the orbital plane (due to spin components lying in the orbital plane) can be larger than the in-plane recoil (originating either in unequal-masses binaries or for spin components normal to the orbital plane), and this may have consequences when considering the interaction of the black hole with the ambient gas.

Along these lines and quite interestingly, gravitational recoil may generate an EM disc rebrightening in the form of a late afterglow, as fluid particles which remain bound to the new, recoiling black hole modify their orbits not only in response to the change in the underlying gravitational potential but in response of the completely new arrangement that is imposed by the kick, particular when the recoil velocity has a large component in the disc plane, as the black hole excites shock in the fluid. This give rise to an EM transient rising a year to a few years after the merger proper, depending on the extent of the recoil, disc mass, and gas cooling (Rossi et al. 2010).

7 Observational strategy - priors

A key priority will be attempting to identify and characterise candidate LISA merger event host galaxies. This will be the route to redshifts and placing the merger in an astrophysical context. Identification may be possible prior to the merger, by searching for active galaxies, potentially with signatures of near merger dynamics. Alternatively, data gathered prior to the merger may be put together with post-merger localization to map the EM evolution through the merger phase. Although the X-ray view is of particular relevance to this paper, and has potential advantages of probing closer to the merger system itself, and being less confusion limited, it is likely that multiwavelength data will be important.

- Define a reference X-ray sky (eROSITA)
  - By the time Athena flies, eROSITA (Merloni et al. 2012) will have monitored the full X-ray sky with a sensitivity of $\sim 10^{-14}$ erg cm^{-2} s^{-1} in the 0.5-2 keV energy band. While this sensitivity is insufficient to detect even the highest SNR sources, eROSITA may provide a reference sky template to refine the selection of sources that are *unlikely* to be the SMBHM counterparts. It is unclear, however, which X-ray emission (if any) one should expect from a SMBHM system several years ($\geq$10) before the merging, hence whether the eROSITA reference sky can be used to efficiently point out counterpart candidates.
- The optical sky.
  - By the time of any joint Athena/LISA operations, LSST should have finished its wide area sky survey. This is intended to cover nearly half the sky (18000 sq-deg) to a point-source depth of ABmag$\sim$27.5 in each of six optical/nIR filters (*ugrizy*). Thus even without further LSST mapping of error regions, most galaxies of interest in the southern sky should already have useful photometry available. This will allow identification of galaxies with photometric redshifts consistent with the LISA distance estimate, and contribute to the characterisation of nuclear activity and variability.
  - The situation in the northern hemisphere is less clear cut, but facilities such as the Subaru HyperSuprimeCam has the capability to survey at about 1/3 the rate of LSST and so similar mapping may be available for much of the sky not observed by LSST.

8 Observational strategy - implementation

In this section we discuss the implementation of possible Athena observational strategies to follow-up different classes of GW sources

8.1 Super-Massive Black Hole Mergers

The localization of SMBHMs by LISA depends on the cumulative signal-to-noise ratio, and improves drastically in the week prior to merger. While the errors in sky localization depend on a number of factors (mass,

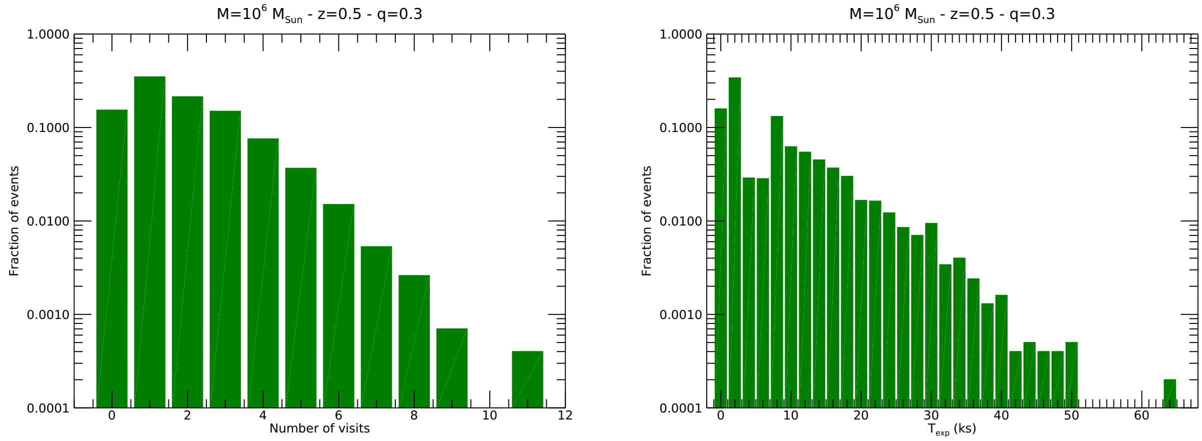

Figure 4: Distribution of the number of exposures (*left panel*) and of the total integrated exposure time (*right panel*) for a possible strategy optimizing the Athena WFI follow-up of a SMBHM event detected by LISA.

spin, binary inclination, location in the sky, redshift), for the best sources (*Platinum Binaries*) a localization better than $10\,\mathrm{deg}^2$ could be possible a few days prior to the merger. We consider hereby this accuracy as the threshold for the activation of a counterpart search strategy with the Athena WFI, and assume 3 days before the merging as the corresponding start time, following the results shown in Fig. 1 and Fig. 2.

An error box of 10 deg^2 can be covered with the Athena WFI in 3 days with a raster scan of at least 23 observations of $\simeq$9 ks each. The "at least" caveat is primarily driven by the sensitivity of the Athena telescope decreasing significantly off-axis due to the vignetting effect (Willingale et al. 2013). This implies that a certain overlap between adjacent pointing directions may be required to ensure that a given sensitivity is homogeneously achieved over the whole WFI field-of-view. This may increase the number of required pointing, decreasing the exposure time available for each of them. Once the LISA event localization is comparable to, or smaller than the Athena Wide Field Imager (WFI) field-of-view, Athena could stare to the predicted error box up to the time of the merger (and beyond; see Sect. 8.2). Because such a localization accuracy is estimated to occur about 5 hours before the merger for the *Platinum Binaries* (Fig. 1 and Fig. 2), an additional observation of $\simeq$15–20 ks could be performed immediately prior to the merger. With the improvement of the LISA localization the Athena pointing strategy can be optimized to cover the most likely location of the trigger at any time. The results of an example of this possible strategy[2] for a binary system with $M_{BH} = 10^6\ M_\odot$, q = 0.3, and z =0.5 are shown in Fig. 4. Only a few percent of these extremely favorable events can be covered with a number of exposures larger then 5, and a total exposure time larger than $\simeq$5 hours prior to merging. The fraction of events that can be observed 10 times with a total exposure time $\geq$50 ks is $\leq$0.1%. For the same events at redshift z = 1, only a fraction of the order of a few percent can be placed in the WFI field-of-view more than 3 times for a *total* exposure time of $\simeq$10 ks prior to merging. The LISA localization of such events at even larger redshift is basically too poor for Athena to have any reasonable probability of following them up.

How likely is it that the X-ray glow is sufficiently bright to be detectable in the WFI? The answer is in Tab. 1 and Tab. 2, where we show the expected fluxes and required Athena exposure time to detect an AGN at the Eddington limit, assuming an X-ray to bolometric luminosity ratio of 30the flux limit is reached over at least 90 percent of the Athena field-of-view in order for the object to be identified in a search. These

[2] Fig. 4 is the result of 10000 Monte-Carlo simulations, assuming: that Athena starts following the LISA-detected event once the localization is better than 10 deg^2 with a raster of WFI pointing of equal exposure time until merging; b) that the raster is centered to the best-fit LISA position whenever a new estimate of the merging coordinates is available; localization uncertainties as in Fig. 2, assuming a flat distribution in logarithmic space at each time. We assumed also 1 hour overhead time for the transmission and calculation of the LISA coordinates, a 4-hour response time for Athena to reach the initial position, and an Athena agility of 4 degrees per minute during the raster.

Table 1: Fluxes (in cgs units) and exposure times (in brackets, units of ks) to detect a X-ray unobscured AGN at the Eddington limit with the current configuration of the Athena mirror+WFI.

	M=10^6 $M_\odot$	M=10^7 $M_\odot$
$z = 1$	8×10^{-16} (5)	8×10^{-15} (<1)
$z = 2$	1.5×10^{-16} (70)	1.5×10^{-15} (2)

Table 2: The same as Tab. 1 for an AGN obscured by a column density $N_H=10^{23}$ cm^{-2}.

	M=10^6 $M_\odot$	M=10^7 $M_\odot$
$z = 1$	8×10^{-17} (200)	8×10^{-16} (5)
$z = 2$	5×10^{-17} (400)	5×10^{-16} (10)

results indicate that follow-up of BH of mass 10^6 $M_\odot$ could require considerable Athena observing time, particularly if the source is obscured. See Sect. 9 for a more detailed discussion of the expected luminosity and associated detection likelihood.

Even if a raster scan strategy of short observations could allow Athena to detect the counterpart of the GW-emitting SMBHM in *one of the WFI observations*, a significantly more challenging issue is identifying which of the hundreds of WFI sources is the true counterpart of the forthcoming merger. A possible "smoking gun" is the variability pattern in the soft and hard X-ray light curves, mirroring the GW strain (cf. Sect. 6). The expected variability time-scales could vary from minutes to hours. This implies that it may be hard to disentangle the variability pattern due to space-time deformation from the commonly observed variability in the X-ray light curves of many classes of celestial sources, most notably AGN, unless at least a few cycles are observed. The accurate measure of the strain pattern will represent a key prior in the analysis.

It comes naturally from the discussion so far that a strategy solely based on Athena rapid-response Target-of-Opportunity (ToO) is insufficient. Even for the *Platinum standard* events, and assuming an almost simultaneous transmission of the merging coordinates by LISA to the Athena Science Operation Center, only short observations of the order of a few ks at most would be possible if one would rely on ToO only, give the 4 hours response requirement for Athena. A full scanning of the predicted merging region as early as possible is mandatory, implying significant investment of the observatory's time for each precursor event.

In summary, our current understanding of the localization capability of LISA, of its operational constraints, of possible mechanisms producing X-rays in circum-binary disks and mini-disks, of the possible variability pattern of this emission, as well as (and not the least importantly) of AGN astrophysics conspire in making a measurement of the X-ray counterpart of a SMBH binary merging during the pre-merging phase an extremely challenging, albeit exciting, possibility.

8.2 Super-Massive Black Hole Merger post-merger emission

For large fraction of SMBH merging events, LISA will be able to localize the position using the merger and the ring-down within the field-of-view of the Athena WFI up to redshift $\sim$2, $\sim$4, and $\sim$2 for masses 3×10^5 $M_\odot$, 10^6 $M_\odot$, and 10^7 $M_\odot$, respectively (the *Golden Binaries* in this document; cf. Fig. 3). For 50% of the 10^6 $M_\odot$ sources, LISA will recover the sky location to a ~ 5 arc-minute side error box. For fraction of them (of the order of 10%, cf Fig. 2) an error box as small as 2 arc-minutes is possible. With predictions of tens of events over the mission lifetime (cf. Sect.9), several could be followed after the merging occurs to trace the re-brightening of the disk or the heating of the interstellar medium by a prompt jet (cf. Sect. 6.2), or a late afterglow due to gravitational recoil (cf. Sect. 6.2.3). This indicates the truly exciting opportunity to witness the birth of a AGN. A targeted strategy of the LISA error box would allow to achieve the confusion limit ($\sim3\times10^{-17}$ erg cm^{-2} s^{-1}) in $\leq$1.5 days. If Athena and LISA would be operated simultaneously, a strategy is conceivable whereby a certain numbers of Golden Binary fields are monitored periodically and *post-facto* to search for X-ray counterparts, coupled with deep Target of Opportunity observations if/after a counterpart is detected.

8.3 Stellar-origin ("LIGO-like") Black Holes (SOBH)

An exciting new perspective opened by the discovery of the first black-hole merging event by LIGO is the possibility that some BHBs will be detected by LISA a few years before the merging, and cross into the LIGO frequency band while the merging proceeds (Sesana 2016). 10 such mergers have now been observed by LIGO/VIRGO during the combined 13 months of the first two observing runs, setting robust estimates on the SOBH merger rate density of $\mathrm{R} = 53.2^{+58.5}_{-28.8}\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$ (Abbott et al. 2018). LISA will detect several of these binaries with signal-to-noise >8 during the inspiral phase, with many being localised to be better than 1 deg^2, and merger time predicted within 10 seconds. The prediction is that LISA will be able detect ∼100 BHBs in total, with ∼10 crossing to the LIGO band. Uncertainties are of about an order of magnitude, but it is very unlikely that LISA will see thousands of them. This opens the exciting possibility of a new era: the *coincident (concurrent) GW-EM astronomy*. However, it shall be borne in mind that no EM counterpart of such event is currently expected.

9 Caveats

There are many uncertainties involved in forecasting the number of Golden Binaries and in particular the number that will generate an X-ray flux detectable by Athena. "Known uncertainties" are discussed here, based on current observations of Active Galactic Nuclei (AGN).

In order that X-ray emission is generated during, or by, a merger of a pair of SMBH, gas must be present during the merger process and indeed may be instrumental in bringing the SMBH to a radius where gravitational radiation is strong enough to cause the pair of BH to spiral together. Theoretical predictions for the role and behaviour of gas are preliminary, but many papers suggest that accretion is likely to occur before the merger takes place. In other words, the SMBH binaries that will merge in the 2030s may currently be AGN

It should first be recognised that the X-ray emission detected from AGN by Athena is dominated by the X-ray corona, which is generally considered to be magnetically powered by an accretion disk orbiting about the black hole. The corona is relatively compact and contains energetic electrons with temperatures of tens to hundreds of keV that Compton upscatter blackbody photons from the accretion disk in to a power-law X-ray continuum. The observed fraction of the bolometric accretion power emerging in the 2-10 keV X-ray band (the bolometric fraction f_{bol}) ranges from about 10 to 2 percent or less as the bolometric power increases to the Eddington limit (Vasudevan and Fabian 2009; Lusso et al. 2012). There is as yet no predictive theory of the corona or f_{bol}. Additional 2-10 keV X-ray emission is seen if the object has jets (Blandford, Meier, and Readhead 2018). There is no observationally based predictive theory for jet occurrence in AGN; a rough guide is that approximately ten percent of quasars are radio-loud due to jets.

A complication to observing AGN is obscuration. The flat shape of the X-ray Background spectrum in the 2-10 keV band, which is largely the summed emission from all AGN, demonstrates that most accretion is obscured. Obscuration can occur in all types of AGN, but simulations suggest that both obscuration and luminous black hole accretion peak in the final merger stages when the two black holes are separated by less than 3 kpc (Hopkins et al. 2005). This is borne out by recent observations by Koss et al. 2018 who find obscured luminous BH show a significant excess (6/34) of nuclear mergers (i.e. a counterpart within 3 kpc) compared to a matched sample of inactive galaxies (2/176). The obscuration most affects the soft X-rays below 2-5 keV. Prolonged AGN emission at close to the Eddington limit can blow away most of the obscuring gas (Fabian, Churazov, et al. 2009; Ricci et al. 2017).

Violent accretion events such as Tidal Disruption Events (TDEs) could be an alternative template for accretion in the late stages of a SMBH merger. If so, then coronal emission may be weak or absent, with most of the accretion power emerging from a quasi-thermal blackbody disk, sometimes with jetted emission. Unless jets are formed, X-radiation from such objects is mostly confined to the soft X-ray band.

If we assume that accretion takes place in the late merger phase of a pair of SMBH, so that they appear as AGN, we can use the number densities of observed galaxies and AGN to predict the number of final mergers to be expected within a given interval of time. Concentrating on Golden Binaries with masses of

Table 3: Observational-based predicted number of expected SMBH merging events visible by Athena and LISA over 10 years.

	$M=10^6$ $M_\odot$	$M=10^7$ $M_\odot$
$z = 1$	3	1
$z = 2$	25	2.5

10^6 to 10^7 $M_\odot$ within redshift z=2, we start with the number densities of their host galaxies which will have stellar masses of approx 10^9-10^{10} $M_\odot$. Ilbert et al. 2013 gives number densities of 10^{-2}–$10^{-2.5}$ Mpc^{-3} at $z = 1$ and $10^{-1.5}$–$10^{-2.5}$ at $z = 2$, respectively for 10^9-10^{10} $M_\odot$ galaxies. The probability p that a galaxy is an AGN within 1 percent of the Eddington limit ($\lambda > 0.01$) as a function of BH mass and z has been estimated from observations by Aird, Coil, and Georgakakis 2018, giving $p = 0.003$ for 10^6 $M_\odot$ and $p = 0.01$ for 10^7 $M_\odot$ BHs. The intrinsic galaxy merger rate is about 4×10^{-10} yr^{-1} (Lotz et al. 2011) which means that over a 10 yr period of observation the rate is 2×10^{-9} and 1.3×10^{-9} at $z = 1$ and 2 respectively. The number densities are per comoving Mpc and the comoving volume out to $z = 1$ is 157 Gpc^3 and to 2 it is 614 Gpc^3. Gathering all these factors together, we predict that, per dex in mass and for an observation period of 10 yr, the number of BHs of mass 10^6 merging is 10^{-2} within $z = 1$ and within z=2 it is 7.5×10^{-2}. For BH of mass 10^7 the corresponding numbers are 10^{-2} and 2.5×10^{-2} detectable mergers per 10 yr interval. The above prediction assumes that the probabilities of a galaxy having an AGN and of it having had a merger are independent. If however we assume that all mergers lead to AGN, we can eliminate p, which raises the number to those listed in Tab. 3. These are the maximum predicted values, whether or not there is gas in the nucleus.

Note that the predictions decrease by a few (e.g. 3-5) if we assume that all the AGN are more luminous (e.g λ approaching 1), using the results of Aird, Coil, and Georgakakis 2018. Perhaps they are not AGN in the final stages having blown all gas away. Then the numbers correspond to the second set, but if there is no gas present then we do not expect to detect them as X-ray sources.

Further issues to be noted include source confusion and intrinsic source variability:

- Source confusion occurs when searching for faint objects at low fluxes. The rising number of even fainter sources increases the probability of 2 or more sources being present in the same detection pixel. This can lead to false detection and at least causes considerable uncertainty in sources fluxes, which become biased upward. For the Athena WFI with a central 5 arcsec PSF observing the extragalactic sky, source confusion sets in on average at a flux of $F_{0.5-2\mathrm{keV}} \approx 10^{-16}$ erg s^{-1} cm^2 for 90 percent of the FOV. It is a few times lower in the central 50 percent of the FOV. Sources at fainter fluxes have a higher probability of flux contamination by a second source. If a source position is precisely known (to a fraction of a source pixel) then it may be possible to go slightly deeper using a centred detection pixel. Moreover if the source has an unusual spectrum, or time signature then that can be used to extract source information at lower fluxes.

- One way in which SMBH pair in the final merger stage might be detected is through flux variability induced by the trans-relativistic orbits of the BH about each other causing aberration flux changes on the orbital timescale (or twice that if there are two accretion disks). If the GW signal gives the orbital period and its changes in advance of merger then that signal can be searched for even in a confused source. Intrinsic flux variability is however enhanced for systems with lower mass black holes (Miniutti et al. 2009; Ponti et al. 2012), making detection of periodic signals more difficult (Vaughan, Uttley, et al. 2016).

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