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Chasing X-ray counterparts of gravitational wave events with *Athena*

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Abstract. *Athena*, the next large X-ray observatory in the Cosmic Vision Program of the European Space Agency, constitutes an improvement in performance with respect to any existing of planned X-ray missions by more than one order of magnitude on several parameter spaces simultaneously: collecting effective area, sensitivity to the detection of weak emission lines, X-ray survey speed, accumulated spectroscopic counts for transient X-ray events, just to mention a few. Its scientific payload is therefore ideally suited to provide breakthrough contributions to multi-messenger astronomy in the 2030s. In this paper we summarize the main areas where *Athena* is expected to deliver transformational discoveries by identifying electromagnetic counterparts of Gravitational Wave events: the high-energy counterparts of neutron star-neutron star merger events; and the high-energy counterparts of super-massive black hole mergers to be discovered by LISA.

1. Introduction

Multi-messenger astronomy began with the discovery of the first binary neutron star (NS) 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 $\sim$ 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 position $\sim$9 and $\sim$16 days, respectively, after the merger (Abbott et al. 2017b).

This paper summarizes our current understanding of the revolutionary contributions that *Athena*, the future large X-ray observatory in the Cosmic Vision Program of the European Space Agency (ESA), will bring in the field of GW events EM counterparts.

2. Scientific goals and performance of *Athena*

Due to launch in early 2030s, *Athena* (Nandra et al. 2013) will embody the next step in the decade-long effort of the European space industry and scientific community to investigate the X-ray sky. Selected by the ESA Science Program Committee in 2014, *Athena* is a "Large" (L-)class mission designed to address the science theme of "The Hot and Energetic Universe". More specifically, *Athena* will address two fundamental questions in modern astrophysics:

– How does baryonic matter assemble in the large-scale structures we observe today?

How do the baryons locked in the cosmic web evolve from the structure formation epoch to the present day?
- How do black holes grow and shape galaxies?

While for the aforementioned science themes, core science objectives flow that drive the design of the mission, *Athena* is posed to produce breakthrough discoveries across all corners of astrophysics, through a community-driven observational program where a dominant fraction of the observing time during the nominal operational phase will be allocated through a competitive, peer-reviewed process.

In the context of multi-messenger astrophysics, a key feature of the *Athena* spacecraft is the fast response time of ≤4 hours to observe any Target of Opportunity (ToO) in a random position of the sky for at least 50 ks with a 50% efficiency.

The *Athena* science goals will be achieved through an innovative payload, constituted by an active pixel sensor Silicon detector, the **Wide Field Imager** (Meidinger et al. 2017) with a wide field of view of 40'×40' and spectral-imaging capability with an energy resolution ≤170 eV at 7 keV; and the **X-ray Integral Field Unit** (Barret et al. 2018), a cryogenic imaging spectrometer with ≤2.5 eV energy resolution at 7 keV (corresponding to a resolving power >2000 at 5 keV) over a 5' diameter effective field-of-view and a ≤5" pixel size. These two instruments are placed on the focal plane of a modular X-ray telescope based on the innovative, European-led Silicon Pore Optics technology (Bavdaz et al. 2018), with 12 m focal length and an effective area ≥1.4 m^2 at 1 keV and ≥0.25 m^2 at 6 keV.

This payload ensures that the prospective *Athena* science performance will exceed any operational or planned X-ray missions by at least one order of magnitude over several parameter spaces simultaneously. The effective area at 1 keV will exceed that of instruments with comparable energy resolution in *Chandra*, XRISM, or XMM-Newton by a factor ≥70 and ≥10 for the X-IFU and the WFI, respectively. This implies an X-IFU sensitivity to the detection of weak lines (as measured by the square root of the product of the effective area divided by the energy resolution) higher with respect to the *Resolve* instrument on XRISM by a factor of ≃10 and ≃5 at 1 keV and 6 keV, respectively (Guainazzi & Tashiro 2018). Furthermore, the X-IFU will be able to perform spatially-resolved spectroscopy on scales at least 30 times smaller (in area) than *Resolve* due to the smaller pixels (≤5" against ≃30"), well matching the *Athena* optics Point Spread Function (5" Half-Energy Width requirement). As far as the ToO performance is concerned, observations with *Athena* will accumulate one order-of-magnitude more counts on a typical GRB X-ray afterglow (assuming a total 50 ks exposure time) than the *Swift/XRT* or the XMM-Newton/EPIC-pn thanks to its optimal combination of large effective area and rapid response. This implies a sensitivity to the detection of weak lines in the afterglow spectra by the X-IFU a factor ≥15 larger than the XMM-Newton/RGS, and ≥20 with respect to the *Chandra*/LETG.

3. High-energy counterparts of NS-NS merging events with *Athena*

The discovery of the X-ray counterpart of the NS coalescence associated to the Gravitational Wave (GW) event GW170817 (Troja et al. 2017) has marked the birth of X-ray multi-messenger astronomy. The X-ray afterglow has been followed with extensive *Chandra* and XMM-Newton observational campaigns. The shallow increase of the radio, optical, and X-ray light curves, followed by a steep decline after about 150 days represent a clear signature of an off-axis relativistic structured jet (Troja et al. 2018), as confirmed by later high-resolution radio observations (Mooley et al. 2018; Ghirlanda et al. 2019). Thanks to its agility and large effective area, *Athena* will be able to chase X-ray afterglows corresponding to a flux density lower by a factor of 50 with respect to the *Chandra*/ACIS, and a by factor of ∼1000 with respect to the *Swift*/XRT. This implies that *Athena* will detect all GRB jets corresponding to a GW170817-like event (integrated energy of the jet $\sim 2\times10^{50}$ erg) for any line-of-sight ≥50° (Troja et al. 2018). The complete census of off-axis jet afterglows will permit to map the geometry of NS mergers and the role that different phases of the jet (relativistic versus non-relativistic) play in the system evolution; to probe the relation between the jet orientation and the binary inclination (derived from the GW signal); and even to provide independent constraints on the Hubble constant (Guidorzi et al. 2017). Furthermore, detecting weak flares in the afterglow light curve may signal the reactivation of the NS, breaking the degeneracy between NS and black hole (BH) remnants. A tentative detection of such a flare was reported by Piro et al. (2019) in the afterglow light curve of the GW170817 event at t = 155 d (see also the discussion in Lü et al. 2019; Lin et al. 2019). Such a miniflare would be easy to detect, and characterize spectrally with *Athena*. Long-lasting X-ray plateaus could be another observational signature of the merger remnant nature.

Another field where *Athena* may play a key role is the study of jets and/or X-ray afterglows produced by the highly anticipated mergers of a NS and a BH (Fernández et al. 2017; Ruiz et al. 2018; Barbieri et al. 2019).

4. High-energy counterparts of SMBH merger LISA events with *Athena*

Athena operations may partly overlap with LISA (Amaro-Seoane et al. 2017), the L-class space-borne GW observatory in the Cosmic Vision Program of ESA. LISA will be sensitive, among other events, to the merging of Super-Massive Black Holes (SMBHs) with total black hole mass in the range 10^{5-7} $M_\odot$. It will be able to observe such events across the cosmological history of the Universe up to redshift, z, $\simeq$20. While a SMBH merging signal could enter into the LISA frequency sensitive bandpass as early as several months before the coalescence time, only for the highest signal-to-noise events a localization better than 10 degrees^2 can be achieved a few days before the event, with a localization consistent with the *Athena* WFI field-of-view just a few hours before the merging occurs.

The detection of the EM counterpart prior to the merging is an extremely exciting and unprecedented opportunity to probe the behavior of matter in the variable space-time induced by the merging SMBHs. Models in the literature concur on the fact that a cavity with the size of a few tens of gravitational radii would surround the merging BHs. This cavity would be as such EM-silent. However, recent 2-D hydrodynamical simulations (Tang et al. 2018) indicate that soft X-ray ($\leq$1 keV) X-ray thermal emission could be produced in a circum-binary disk beyond the cavity. The cavity walls themselves would contribute with a slightly harder component. Furthermore, the merging black hole would accrete efficiently via mini-disk fueled by optically thick streams. These minidisks, if powering a corona, could shine in hard X-rays, up to and beyond $\simeq$10 keV. During the entire inspiral process the X-ray flux displays periodicities at twice the binary orbital frequency with a dynamical range of a factor of a few. Detecting such a periodic modulation in the X-ray signal would give the unambiguous "smoking gun" to identify the X-ray counterpart out of the the 2-3000 sources that a moderately deep *Athena*/WFI exposure may detect in a random sky field.

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 *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)

4.1. A possible *Athena* observational strategy

A few hours are sufficient for *Athena* to detect a standard Active Galactic Nucleus (AGN; cf. Tab. 1). However, detecting the counterpart would not be sufficient without an independent information on the location of the event host galaxy. It is unclear if even LSST will be able to provide suitable lists of candidates in real-time. Identifying the X-ray periodic signal predicted by theory (Tang et al. 2018) would require a sampling of the light curve that is probably beyond the operational capability of *Athena* given the time evolution of the LISA localization accuracy prior to merger, except perhaps in the most favorable cases. An optimized *Athena* observational strategy may start with a raster scan of a 10 degree^2 LISA error box. It can be covered by the WFI with about 20 observations of $\simeq$10 ks each (sufficient to detect a 10^6 $M_\odot$ BH at z = 1, or a 10^7 $M_\odot$ BH at z = 2; Tab. 1). The pointing can be optimized to cover the most likely event position with the improved LISA localization (assuming that LISA will be able to calculate and disseminate the refined event coordinates in $\leq$1 hour). When the localization error becomes comparable to the WFI field-of-view, *Athena* could stop scanning, and start staring a field centered at the most likely merging coordinates. Such a strategy may allow to observe a few percent of events at z$\lesssim$0.5 at least 5 times for an exposure time $\leq$10 hours (Fig. 1). However, these estimates are about one order of magnitude less favorable for the much more common events at z = 1, and extremely small at z = 2.

After merging, on the other hand, the LISA localization improves for the best signal-to-noise cases to a few arc-minutes up to redshift $\simeq$4. After slightly adjusting the pointing coordinates to ensure that the event is as close as possible to the telescope optical axis (to minimize vignetting), *Athena* may continue observing until the confusion limit is reached (in about 100 ks for a source on-axis), or follow a long-term monitoring strategy to sample different time-scales. No predictive theory exists of which kind of EM counterpart might be expected for a SMBH merging event. X-ray observations may trace the possible re-brightening of the accretion disk, or the heating of the interstellar medium by a prompt jet. This will offer the unique opportunity to observe the (re-)birth of an AGN, and even provide a direct measurement of the source redshift (via X-ray spectroscopy) that in turn would provide an independent calibration of the cosmic distance scale up to z~4 (because the GW signal provides an estimate of the luminosity distance). A few years of concurrent observations with the two space observatories may yield the detection of a $\geq$10 of such events (Tab. 2)

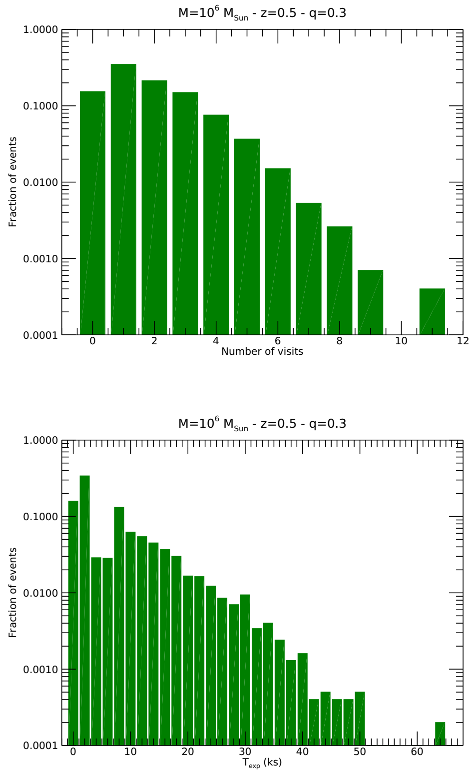

Fig. 1. Distribution of the number of exposures (*upper panel*) and of the total integrated exposure time (*lower panel*) for a possible strategy optimizing the *Athena* WFI follow-up of a SMBH merging event detected by LISA. Based on a Monte-Carlo simulation of the observing strategy described in text.

4.2. *Athena*-LISA synergy: summary

In summary, concurrent observations of SMBH merging events with *Athena* and LISA, while operationally challenging and affected by huge uncertainties as far as the predicted intensity and spectral nature of the X-ray counterpart is concerned, bear the potential of extremely rewarding new science. They may offer the opportunity of probing the behavior of matter in the variable space-time induced by the merging BHs; of studying the propagation velocity of photons vs. gravitons by phase-correlating time-modulated signals in the two bands; of performing an inde-

Table 2. Observational-based predicted rate per year of expected SMBH merging events visible by *Athena* and LISA. The estimates are based on the number density of galaxy at z≤2 with a 10^9-10^{10} $M_\odot$ mass (Ilbert et al. 2013), the intrinsic galaxy merging rate (Lotz et al. 2011), and assume that all galaxies leading to a SMBH merging host an AGN with sufficient gas in the nuclear region to fuel the BH accretion - a difficult to verify, but not unreasonable hypothesis (Koss et al. 2018).

	M=10^6 $M_\odot$	M=10^7 $M_\odot$
z = 1	0.3	0.1
z = 2	2.5	0.3

pendent calibration of the cosmic distance scale to z ≤ 4; and of witnessing the onset of relativistic jets and/or the formation of the AGN corona, two topics where the lack of observationally-based predictive theories has hampered our understanding for decades.

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