Multi-messenger Astronomy with LISA and Athena

For the Athena-LISA Working Group

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Athena and LISA are two of the ESA Science Programme’s Flagship missions.

Both missions were selected due to their (individual) outstanding science cases.

The ESA Director of Science (Günther Hasinger) posed the question:

- “What additional science can be achieved by operating both missions concurrently?”
  - Joint LISA-Athena working group set-up to answer this
  - Main topics covered include:
    - Black hole “engine”, cosmic distance scale, speed of gravity

Whitepaper considers:
- Coalescing massive black hole binaries
- EMRIs
- SOBH
- Galactic white dwarf binaries

Athena Multi-messenger Workshop
Alicante, November 2018
Whitepaper does not consider formation channels of BH binaries
- We assume MBH is in gas rich environment

Depending on mass ratio, three scenarios are possible during the GW dominated phase:
- Extreme Mass Ratio Inspirals (EMRI): SOBH embedded in SMBH disc
- Intermediate Mass Ratio Inspirals (IMRI): SMBH maintains disc, but IMBH evacuates a cavity in the circum-binary disc
- Massive Black Hole Binaries (MBHB): SMBH evacuate cavity in circum-binary disc

In the case of MBHB, General Relativistic MHD simulations show the formation of streams and minidisks around the two black holes
X-ray emission from MBH binary

- **Circumbinary disc**
  - X-ray emission in soft x-rays ($\leq 1$keV)

- **Mini-discs around black holes**
  - Hard x-ray emission ($\geq 10$keV) from accretion of mini-discs individually onto each black hole

- **Cavity wall**
  - Accretion of circumbinary disc onto mini-discs via optically thick streams
  - Thermal radiation dominated by the inner edge of the circumbinary disc, producing soft x-rays ($\sim 2$keV)
  - X-ray emission shows clear modulation which tracks the chirp frequency

 SCIOPS 2019 | November-2019 | Slide 4
Why x-rays?

- LISA will observe BH mergers throughout the universe out to redshifts, \( z \sim 20 \)
- However, only large signal-to-noise sources will be localised to within a few deg\(^2\)
  - “Golden Binaries” (high SNR), out to redshift, \( z < 2 \), will be localised to well within 1 deg\(^2\)
- Assume X-ray flux of \( 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1} \), then in 1 deg\(^2\) there are \( \sim 3000 \) sources
  - At an equivalent optical magnitude (assuming \( \alpha_{\text{ox}} = 1.3 \)) of \( \sim 24.2 \), in 1 deg\(^2\) there are \( \sim 10^5 \) sources
  - Therefore \( \sim 30 \) times more contaminating objects in the field
- Considering the above, Athena is the ideal instrument to identify, and simultaneously observe, the gravitational wave source object.

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**Athena flux limits (0.5-2 keV cgs) and exposure time (brackets) for 5\( \sigma \)**

<table>
<thead>
<tr>
<th>Flux (erg cm(^{-2}) s(^{-1}))</th>
<th>Exposure Time (ks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 8 \times 10^{-16} ) ( (5) )</td>
<td>( (5) )</td>
</tr>
<tr>
<td>( 8 \times 10^{-15} ) ( (&lt;1) )</td>
<td>( (&lt;1) )</td>
</tr>
<tr>
<td>( 1.5 \times 10^{-15} ) ( (2) )</td>
<td>( (2) )</td>
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Gravitational wave observatories are inherently poor at localising the source
- GW observatories survey the entire sky simultaneously

Unlike LIGO, LISA sources are long lived
- Coupled with the orbit around the sun, and “tumbling” antenna pattern, the amplitude and frequency of the source is modulated
- These are used to locate the source in the sky

Sky localisation improves with signal-to-noise ratio
- SNR increases rapidly shortly before merger
- Therefore, sky localisation error box shrinks shortly before merger

The following charts show the sky localisation error box as a function of time to merger
Parameter Estimation ($10^6 M_\odot$, $q = 1/3$, $z = 0.5-2$)
Sky localisation?

- Sky localisation will improve drastically in the week prior to merger.
- Errors in sky localisation estimation are huge.
  - Depends on mass, spin, binary inclination, location on sky, redshift, ...
- For the best sources, we will get to <10deg^2 hours before merger.
- Only for the ‘golden binaries’, we may get ~10deg^2 approx days before merger.
- However, for 50% of sources we will recover sky location to few arcminute accuracy using the merger and ringdown (and harmonics).
  - Too late to observe inspiral and merger with EM observatory.
  - Can be followed up for AGN rebirth or onset of relativistic jet.
Fraction of sources in Athena WFI FoV

![Graph showing fraction of sources in Athena WFI FoV with different masses and redshifts.]

- Masses: $M_i=3 \times 10^9 \, M_\odot$, $10^8 \, M_\odot$, $10^7 \, M_\odot$
- Redshift range: 0 to 4
- Source fractions are plotted against redshift for different mass scenarios.
LISA low-latency pipeline identifies transient source

Sky localisation increases as constellation moves and SNR increases as binary approaches merger

When sky localisation error reaches ~10deg², Athena scans the portion of sky with Wide Field Imager (WFI) (FoV = 0.4deg²)

Shortly before merger, LISA locates the source to within ~0.4deg². Athena stops scanning and stares at most likely location

After merger, sky localisation for "Golden Binaries" will be <10arcmin, allowing both WFI, and possibly X-IFU, to observe the system

Observational Strategy

- **About 1 month before**: LISA low-latency pipeline identifies transient source.
- **2 weeks before**: Sky localisation increases as constellation moves and SNR increases as binary approaches merger.
- **1 week to several hours before**: When sky localisation error reaches ~10deg², Athena scans the portion of sky with Wide Field Imager (WFI) (FoV = 0.4deg²).
- **A few hours before**: Shortly before merger, LISA locates the source to within ~0.4deg². Athena stops scanning and stares at most likely location.
- **During and after the merger**: After merger, sky localisation for "Golden Binaries" will be <10arcmin, allowing both WFI, and possibly X-IFU, to observe the system.
**Merger event rate estimates**

- Estimate the number of Golden Binaries based on what we observationally know of AGN and their host galaxy.
- A binary black hole with a $10^{6-7} \ M_\odot$ requires a host galaxy with $10^{9-10} \ M_\odot$ respectively.
- Galaxy number densities (Illbert et al. 2013):
  - $10^6 \ M_\odot$: $z = 1 \Rightarrow 10^{-2} \text{Mpc}^{-3}$, $z = 2 \Rightarrow 10^{-1.5} \text{Mpc}^{-3}$
  - $10^7 \ M_\odot$: $z = 1 \Rightarrow 10^{-2.5} \text{Mpc}^{-3}$, $z = 2 \Rightarrow 10^{-2.5} \text{Mpc}^{-3}$
- Probability ($p$) that a galaxy hosts an AGN with an Eddington fraction $\geq 1\%$ (Aird et al. 2018)
  - $M = 10^6 \ M_\odot$: 0.003, $M = 10^7 \ M_\odot$: 0.01
  - However, it is possible that all mergers lead to an AGN - let's try to ignore this factor.
- Intrinsic galaxy merge rate: $4 \times 10^{-10} \ yr^{-1}$ (Lotz et al. 2011)
  - $z = 1 \Rightarrow 4 \times 10^{-10}/(1+z) = 2 \times 10^{-10} \ yr^{-1}$
  - $z = 2 \Rightarrow 4 \times 10^{-10}/(1+z) = 1.3 \times 10^{-10} \ yr^{-1}$
- Comoving density volume: 157 Gpc$^3$ @ $z = 1$, 614 Gpc$^3$ @ $z = 2$
- Multiplying all these factors (and ignoring $p$), the event rate per 10 years are shown in the table for our Golden Binaries:
- Moreover, these galaxies shall have sufficient nuclear gas, but not too much along the line-of-sight not to obscure X-rays ...

<table>
<thead>
<tr>
<th></th>
<th>$M = 10^6$</th>
<th>$M = 10^7$</th>
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<tbody>
<tr>
<td>$z = 1$</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>$z = 2$</td>
<td>25</td>
<td>2.5</td>
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The additional science accorded by concurrent operation of LISA and Athena is substantial
- For the first time we may be able to observe the late stage inspiral of two massive black holes both in gravitational waves and X-rays
- Even if the inspiral is not observed by Athena, LISA will provide triggers (of the massive black hole mergers) allowing the possible observation of the onset of an AGN (accretion disk, jet ...)

Main issue will be identifying the host galaxy, in particular, during the late inspiral phase
- Requires low latency pipelines and issuance of alerts by LISA, and fast turnaround ToO for Athena

This is a unique multi-messenger opportunity to observe both the Hot and Energetic Universe and the Gravitational Universe using two of ESA’s flagship missions
athena and lisa

OBSERVING SUPERMASSIVE BLACK HOLES COLLIDE