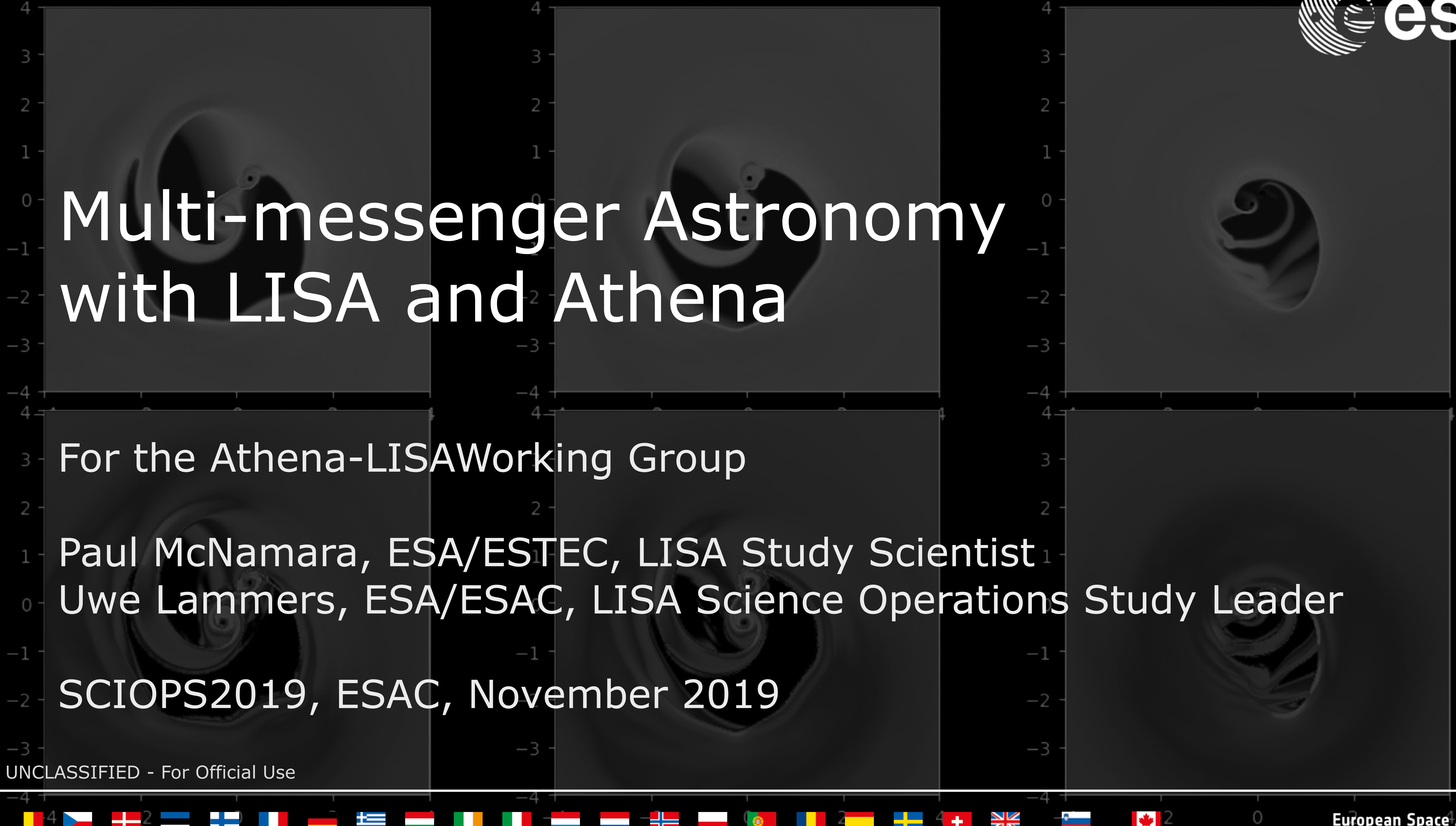
Multi-messenger Astronomy with LISA and Athena



Tang, et al [2018]

For the Athena-LISAWorking Group

Paul McNamara, ESA/ESTEC, LISA Study Scientist
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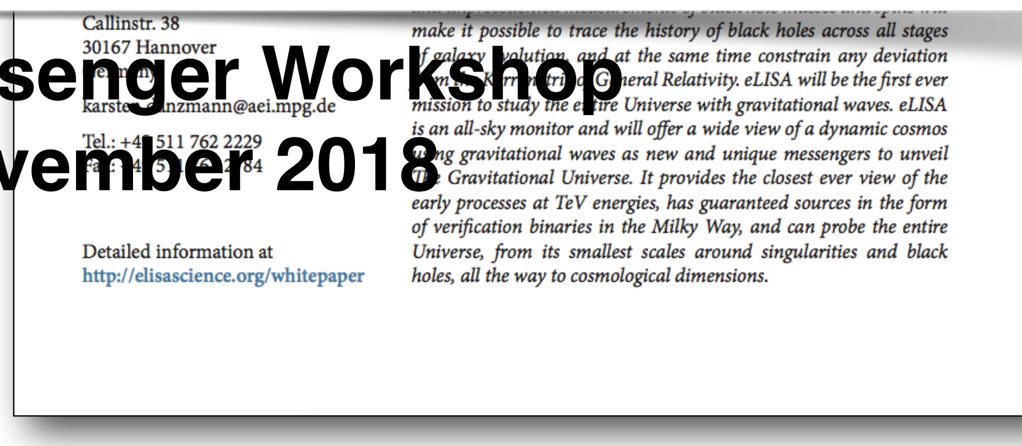
SCIOPS2019, ESAC, November 2019

Introduction

- 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


Callinstr. 38
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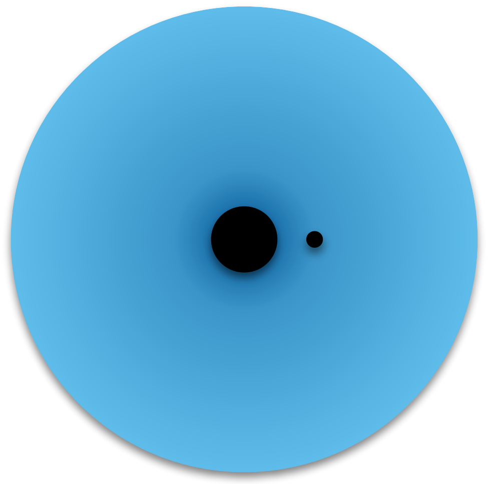
Detailed information at
http://elisascience.org/whitepaper

make it possible to trace the history of black holes across all stages of galaxy evolution, and at the same time constrain any deviation from the Kerr metric of General Relativity. eLISA will be the first ever mission to study the entire Universe with gravitational waves. eLISA is an all-sky monitor and will offer a wide view of a dynamic cosmos using gravitational waves as new and unique messengers to unveil The Gravitational Universe. It provides the closest ever view of the early processes at TeV energies, has guaranteed sources in the form of verification binaries in the Milky Way, and can probe the entire Universe, from its smallest scales around singularities and black holes, all the way to cosmological dimensions.

Athena Multi-messenger Workshop
Alicante, November 2018

Massive Black Hole binaries

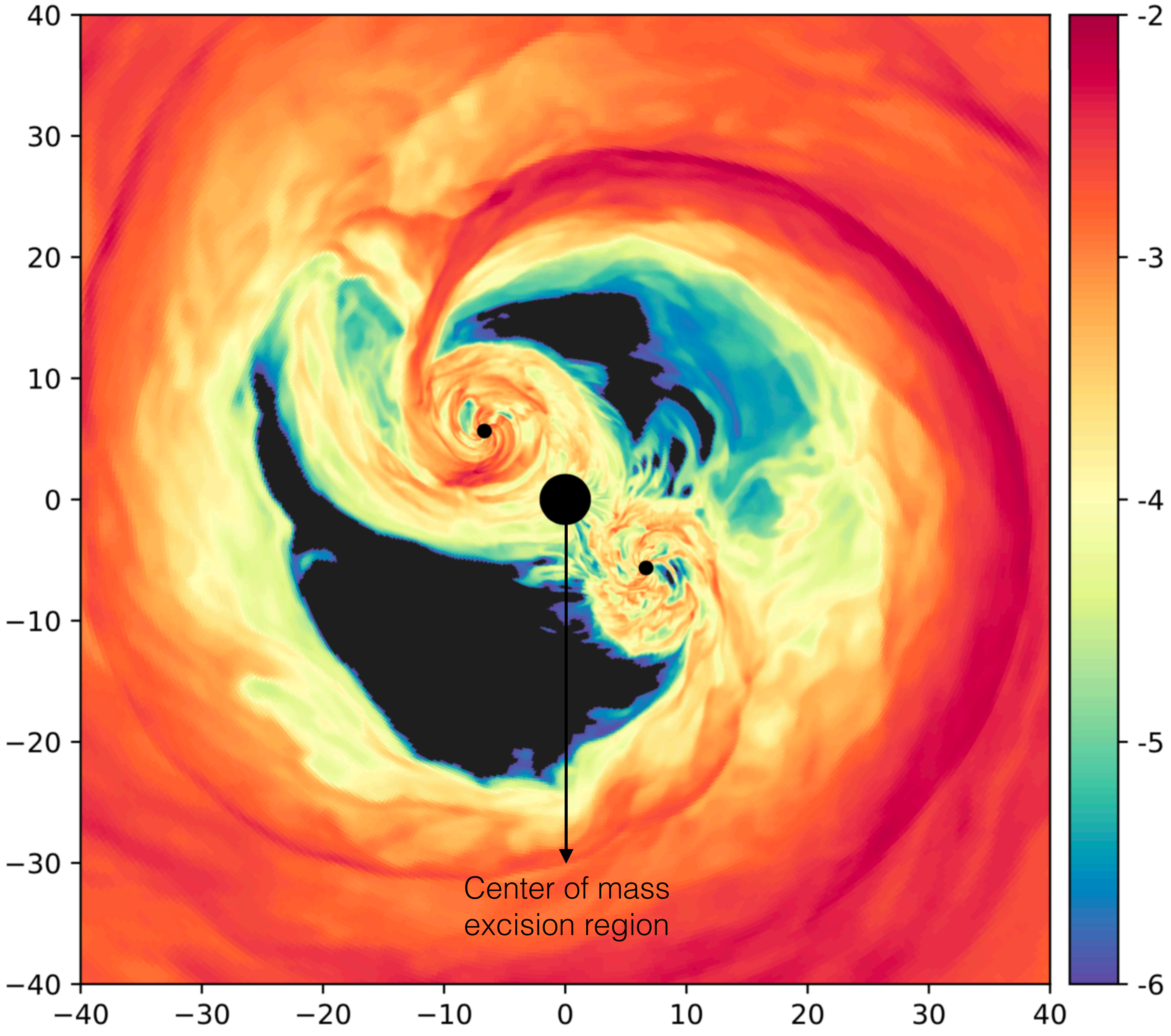
- Whitepaper does not consider formation channels of BH binaries
  - We assume MBH is in gas rich environment
- Depending on mass ratio, three scenarios are possible during the GW dominated phase:
  - Extreme Mass Ratio Inspirals (EMRI): SOBH embedded in SMBH disc
  - Intermediate Mass Ratio Inspirals (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 minidiscs around the two black holes



$q < 10^{-4}$
EMRI

$10^{-4} < q < 10^{-2}$
IMRI

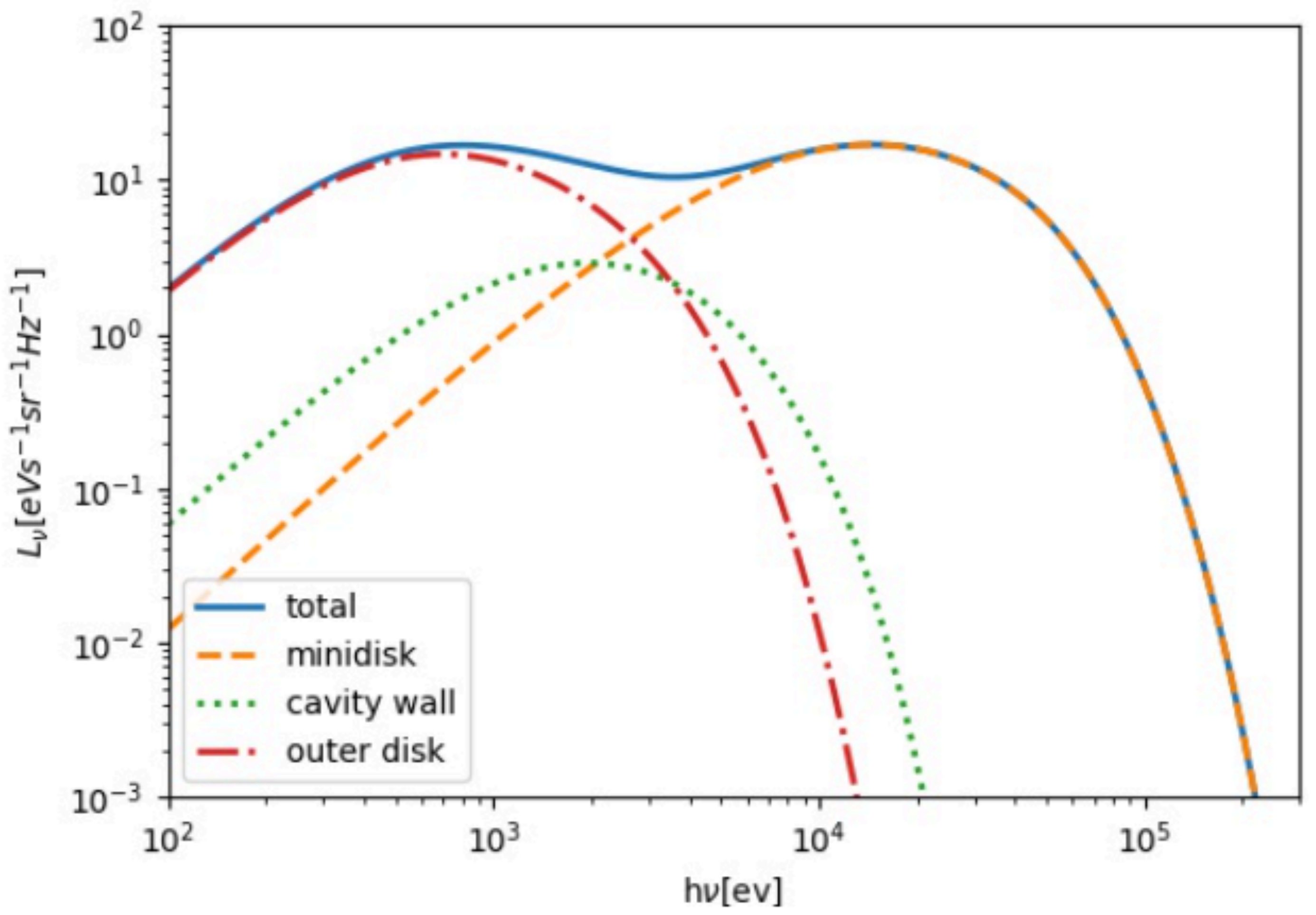
$q > 10^{-2}$
MBHB

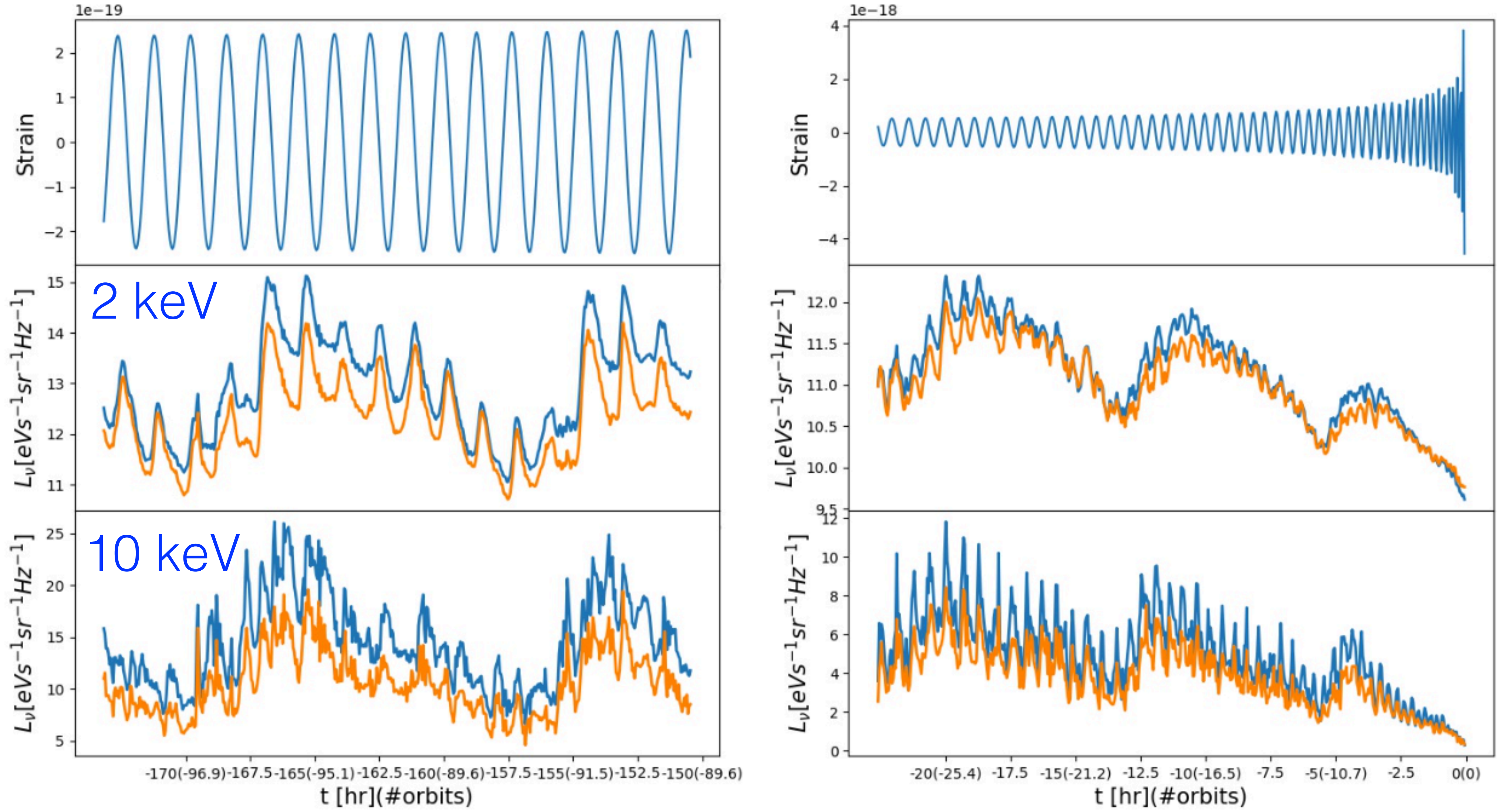


Bowen, et al [2018]

X-ray emission from MBH binary

- Circumbinary disc
  - X-ray emission in soft x-rays (≤1keV)
- Mini-discs around black holes
  - Hard x-ray emission (≥10keV) 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 (~2keV)
  - X-ray emission shows clear modulation which tracks the chirp frequency





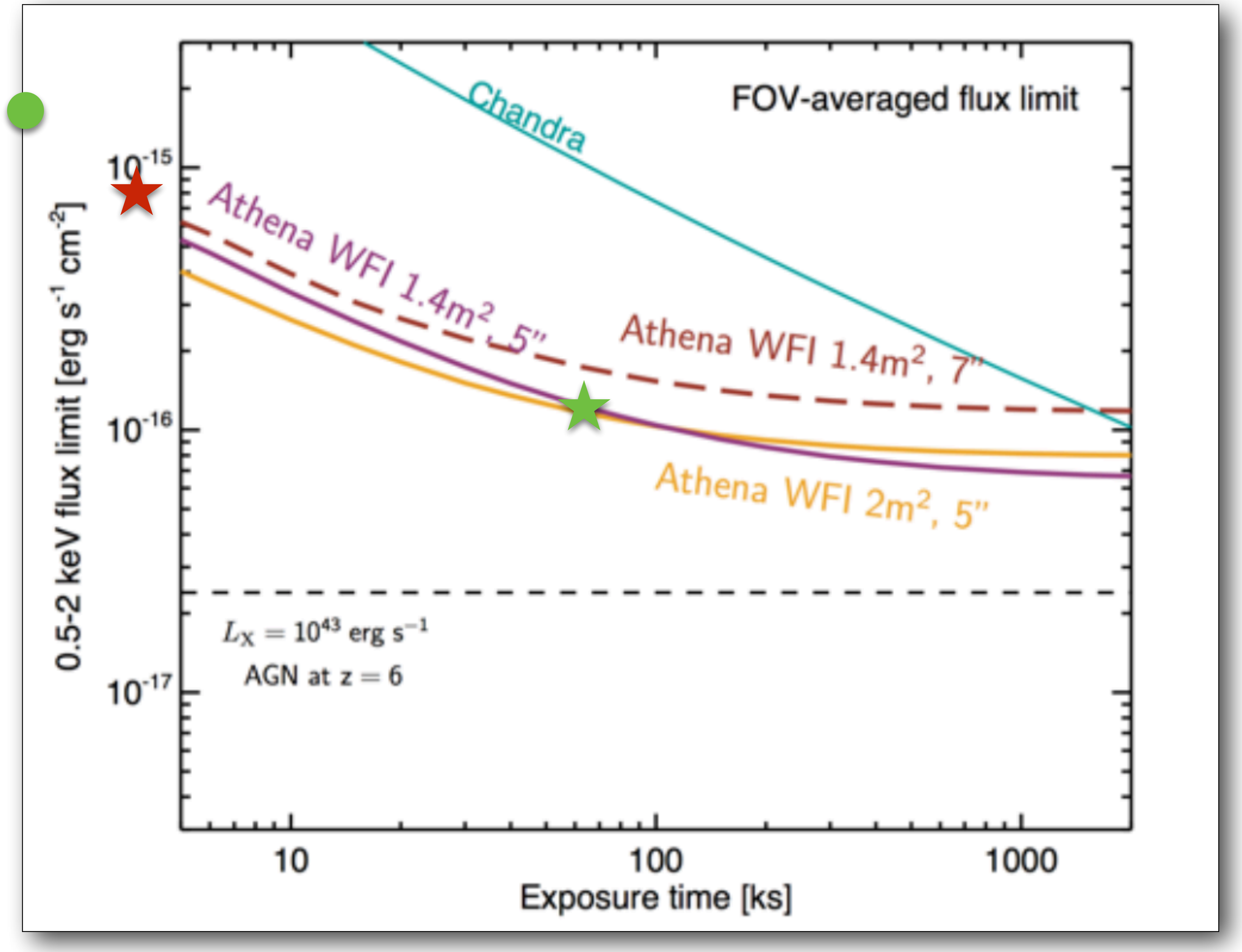
Tang, et al [2018]

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} erg cm^{-2} s^{-1}, then in 1 deg^2 there are ~3000 sources
  - At an equivalent optical magnitude (assuming $\alpha_{ox} = 1.3$) of ~24.2, in 1 deg^2 there are ~10^5 sources
  - Therefore ~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.

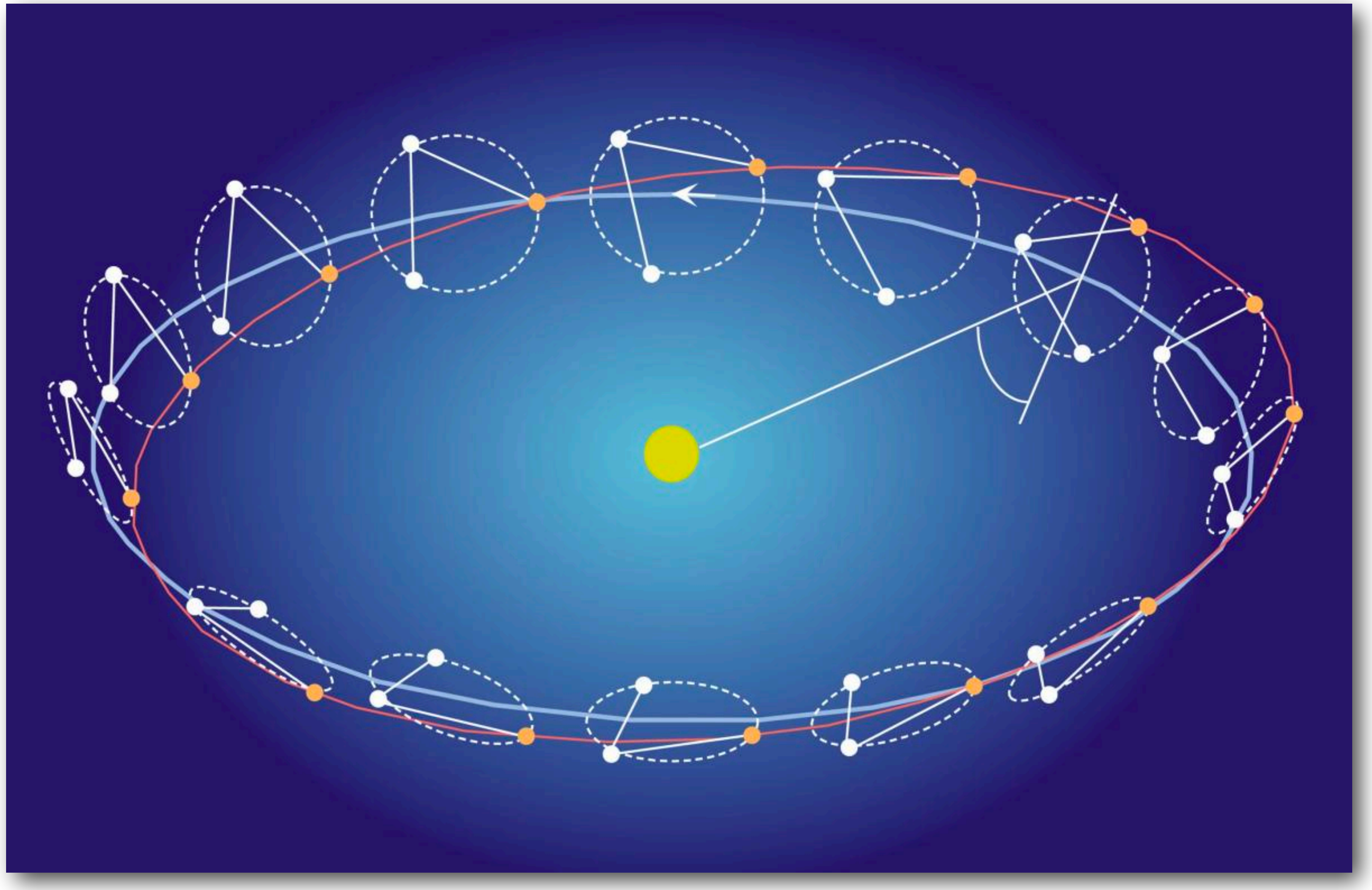
Athena flux limits (0.5-2 keV cgs) and exposure time (brackets) for 5σ

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



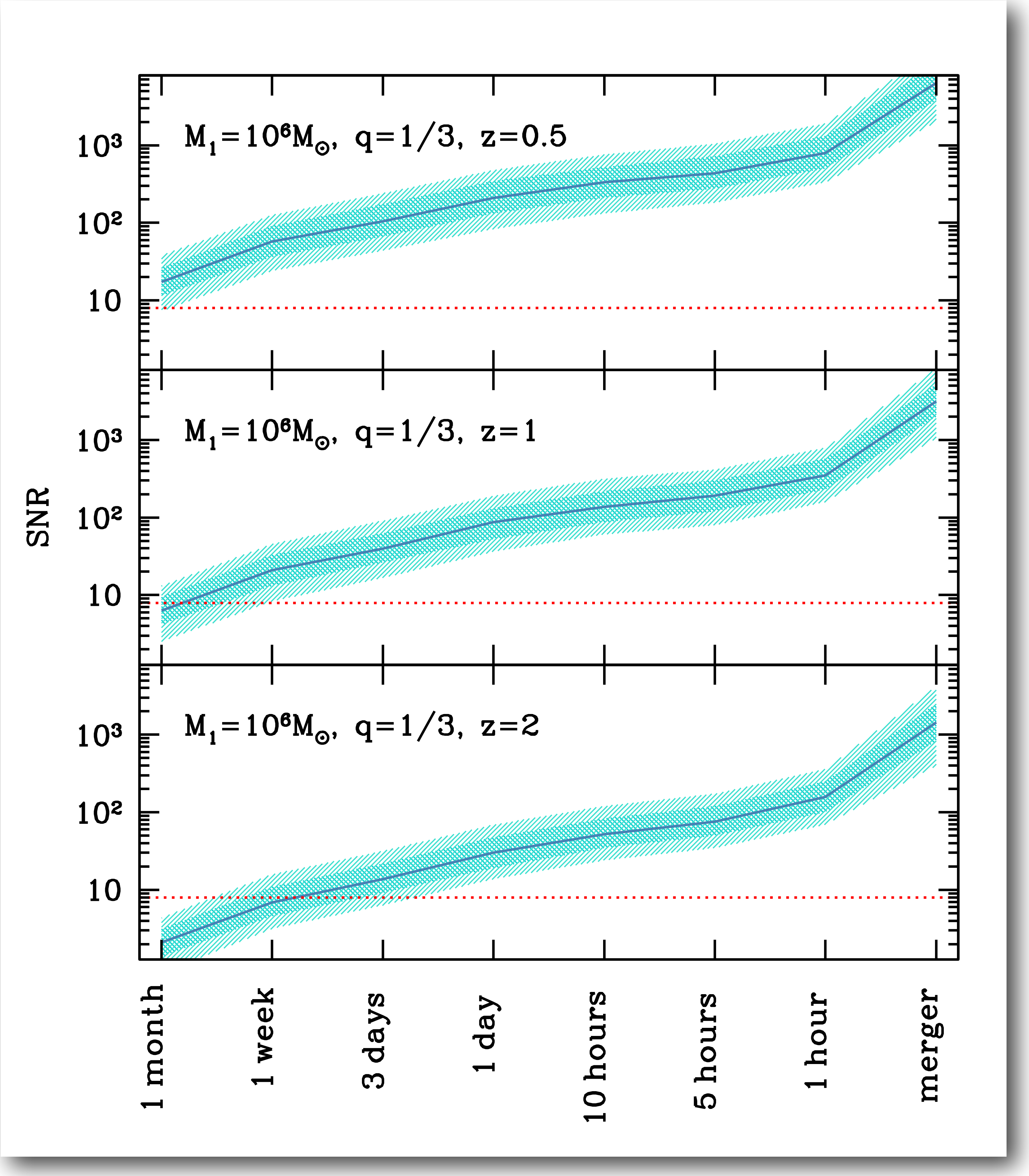
LISA sky localisation

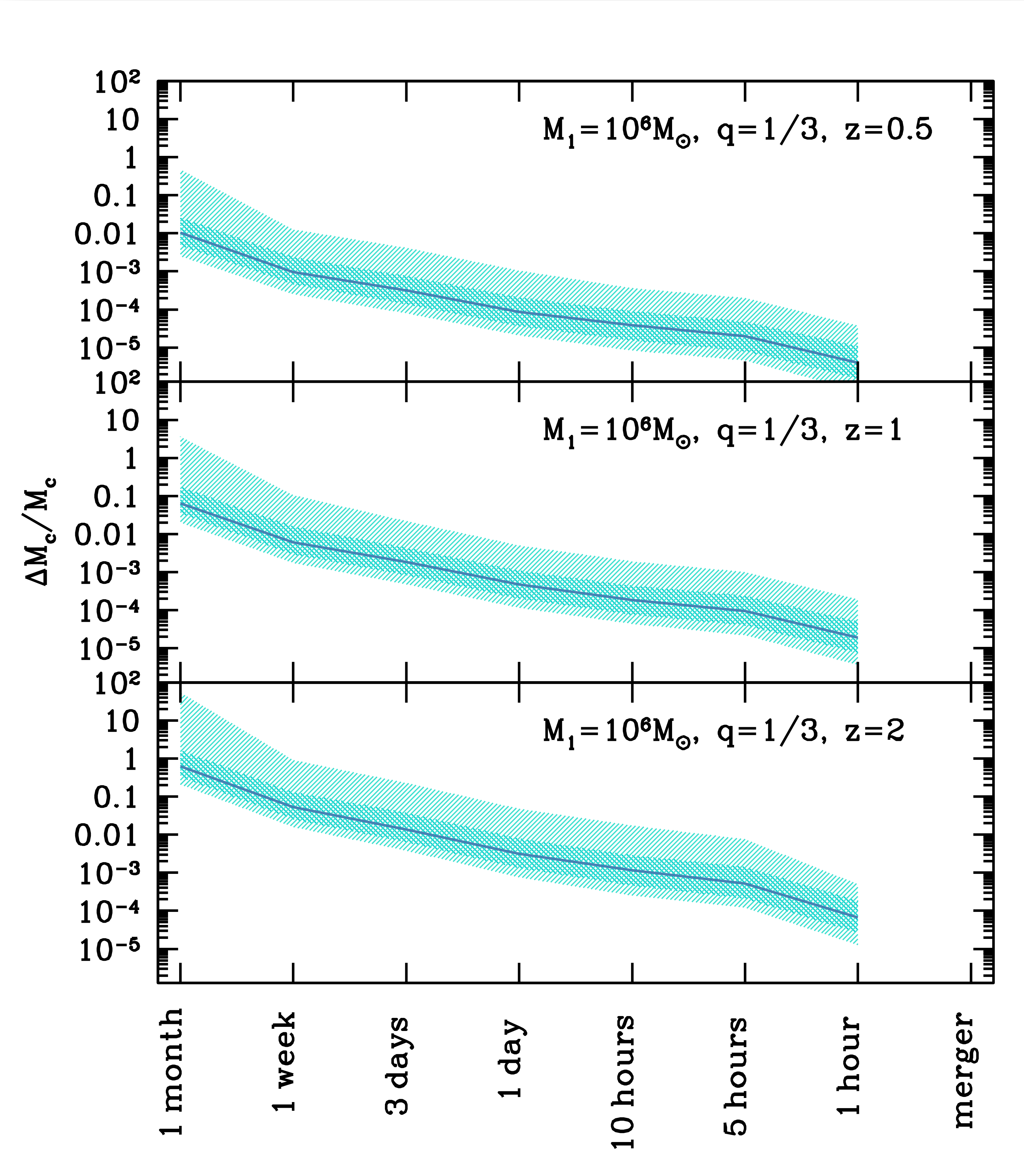
- Gravitational wave observatories are inherently poor at localising the source
  - GW observatories survey the entire sky simultaneously
- Unlike LIGO, LISA sources are long lived
  - Coupled with the orbit around the sun, and "tumbling" antenna pattern, the amplitude and frequency of the source is 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

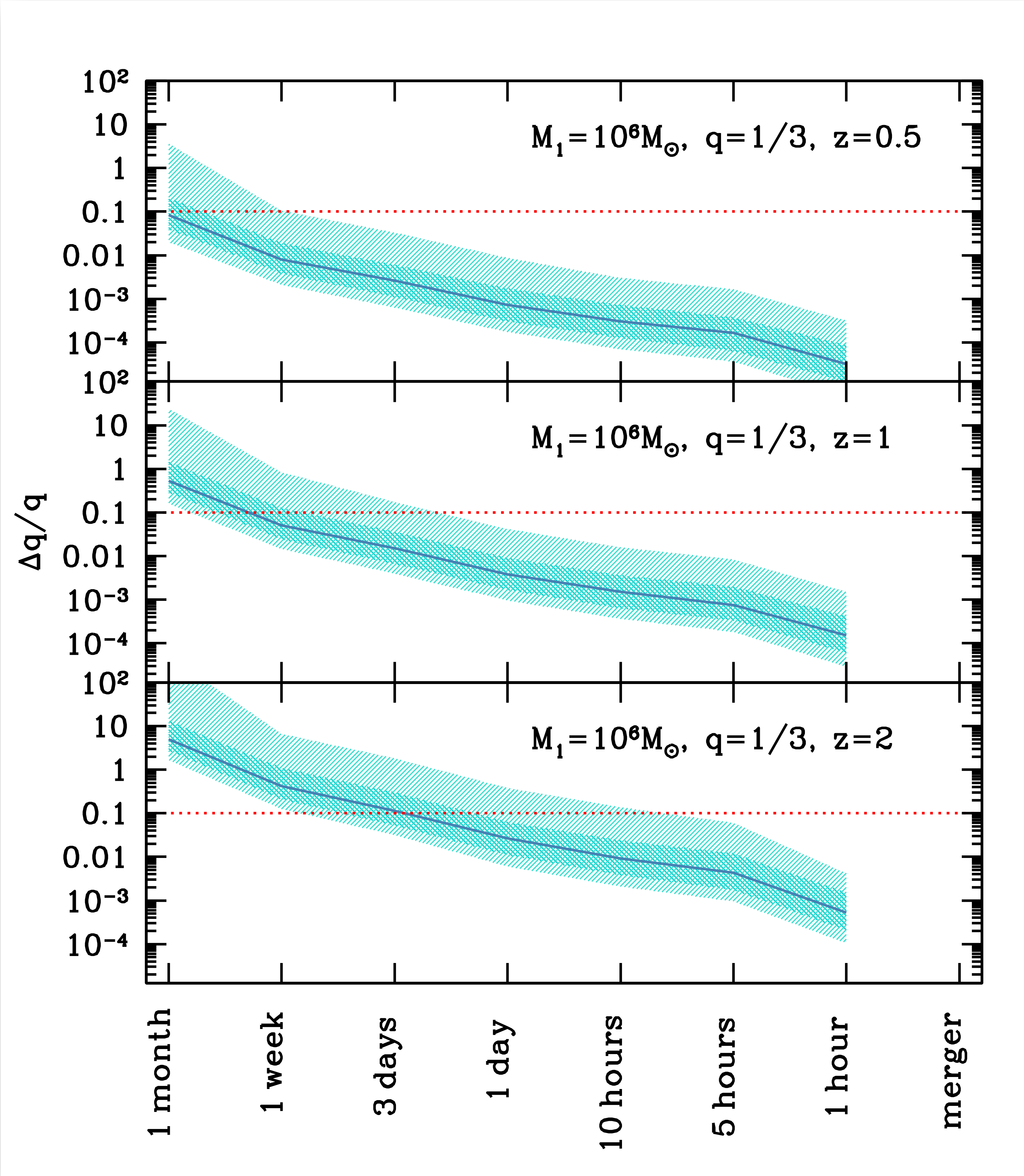


- The following charts show the sky localisation error box as a function of time to merger

Parameter Estimation ($10^6 M_\odot$, q = 1/3, z = 0.5-2)

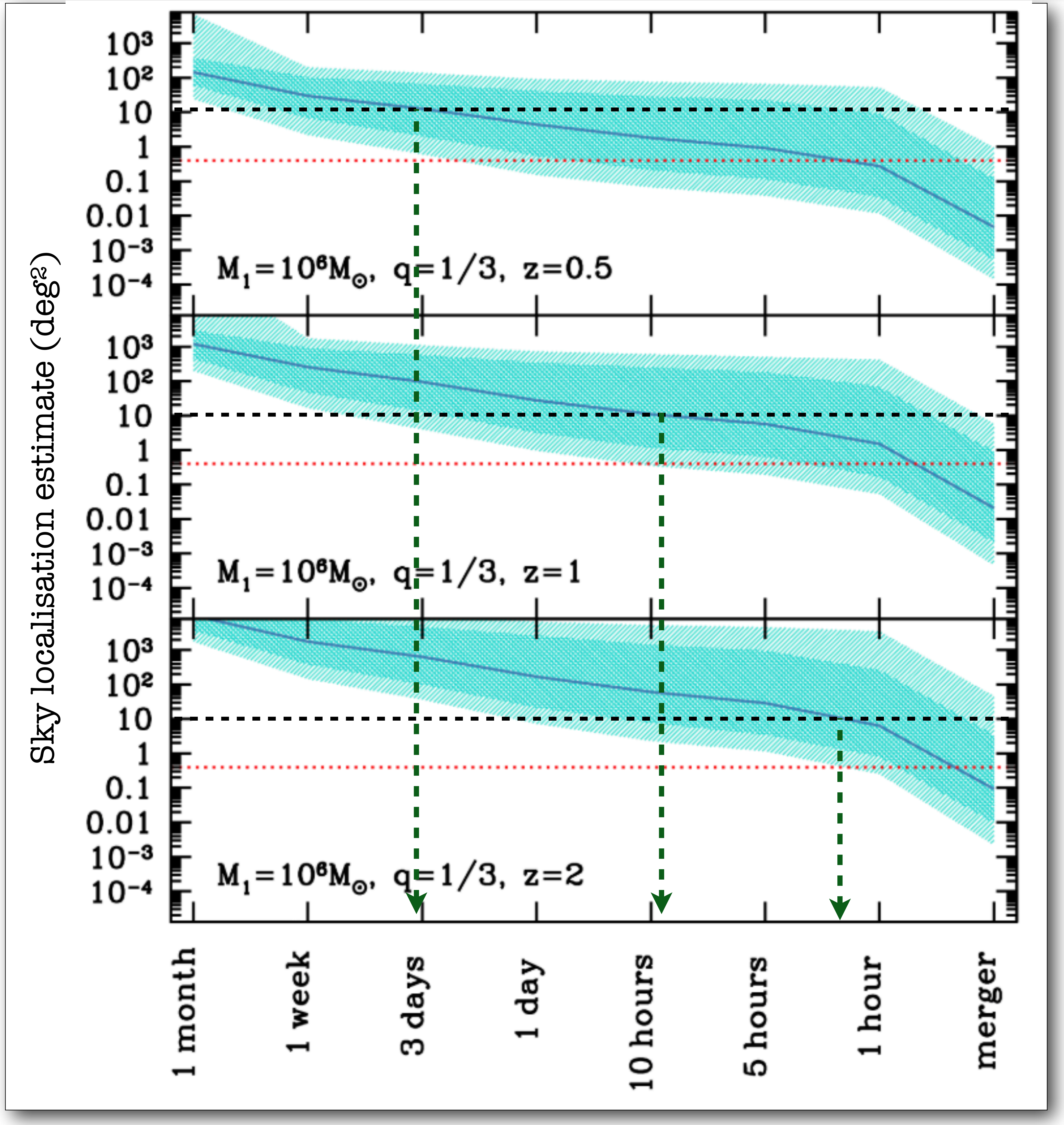




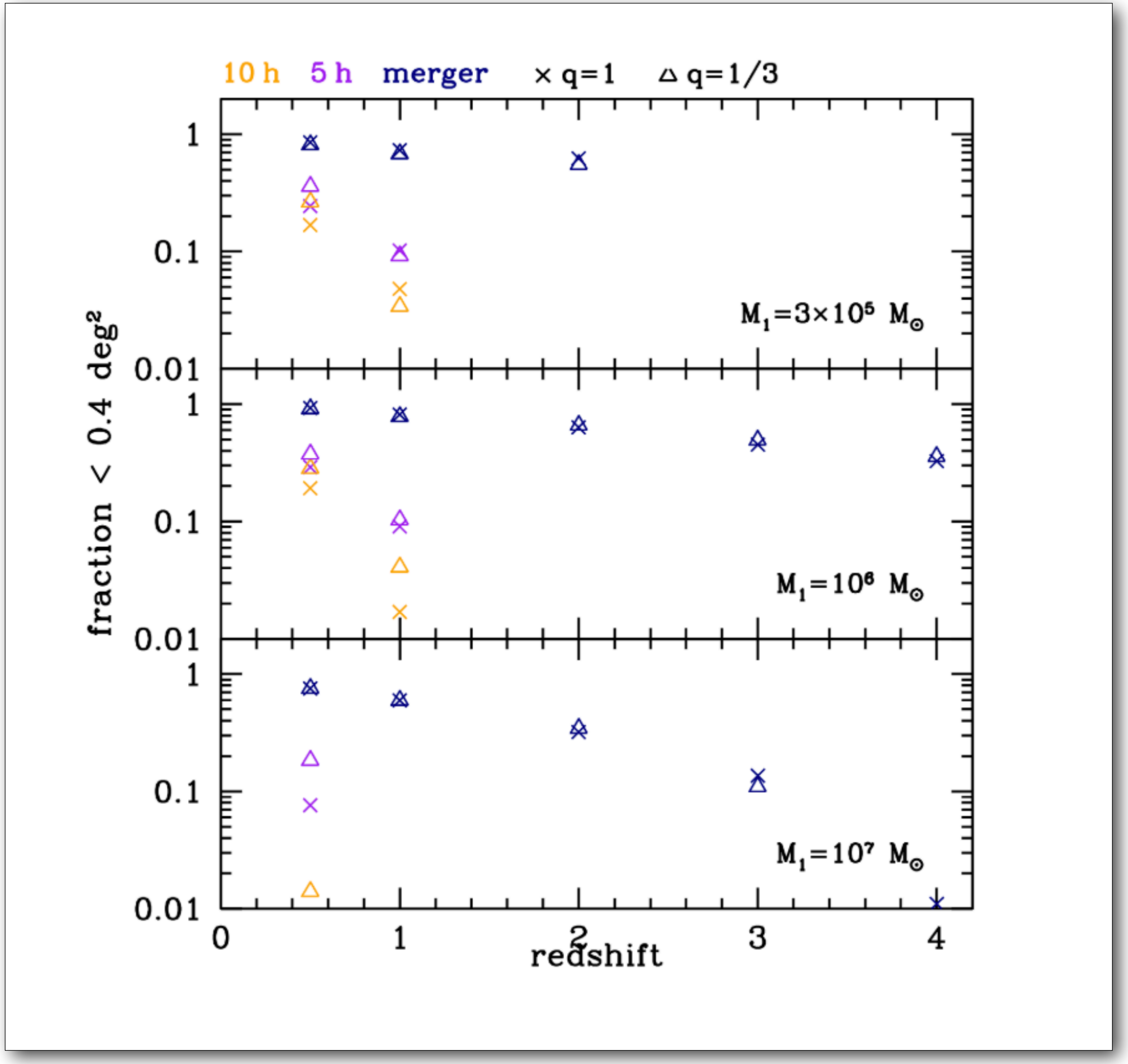


Sky localisation?

- 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 <10deg² hours before merger
- *Only for the 'golden binaries', we may get ~10deg² 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

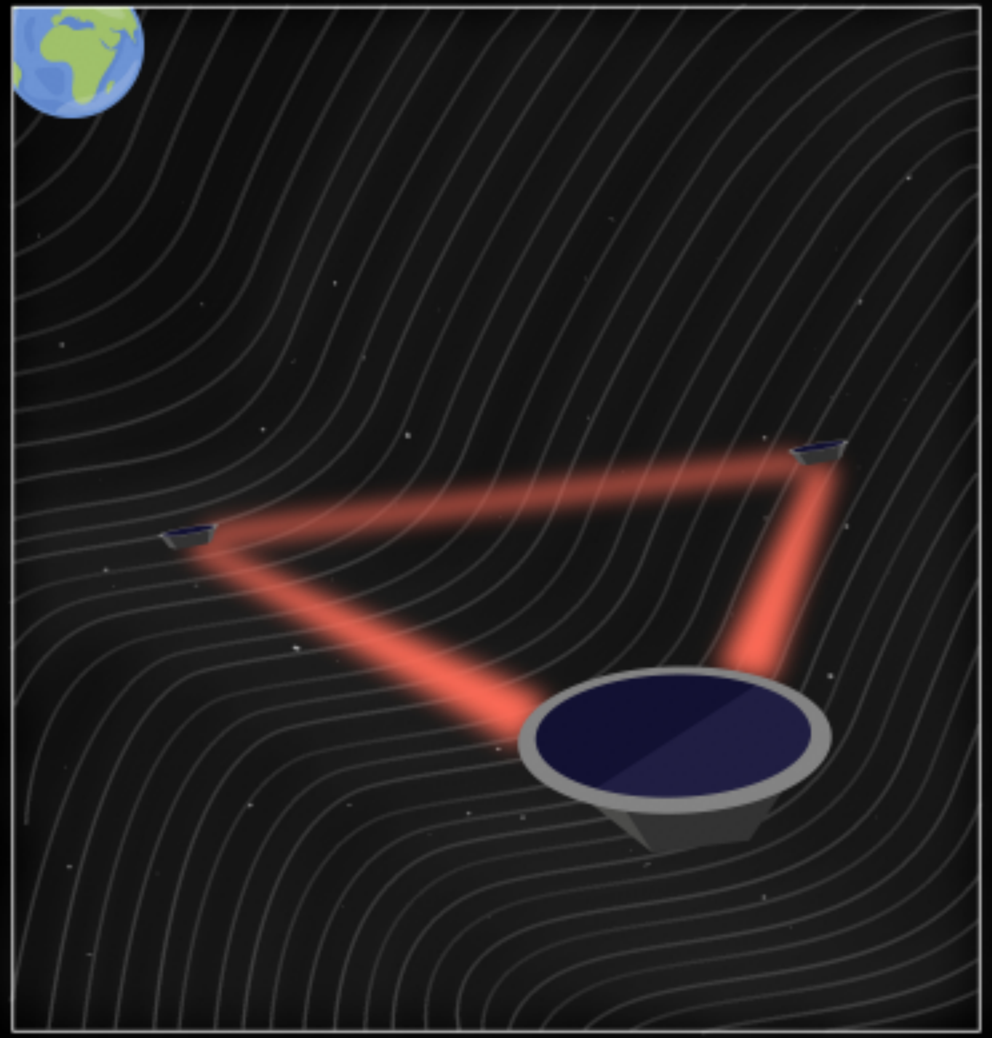


Fraction of sources in Athena WFI FoV



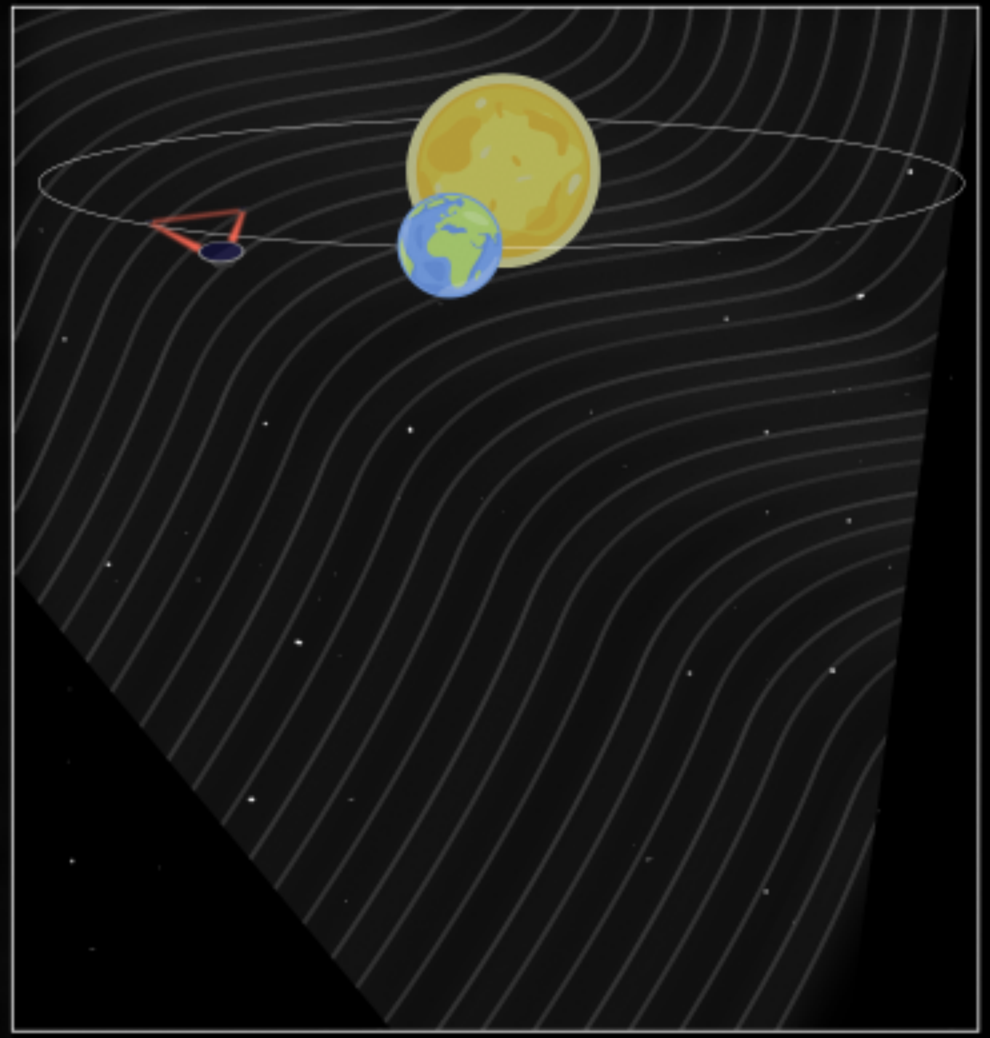
Observational Strategy

About 1 month before



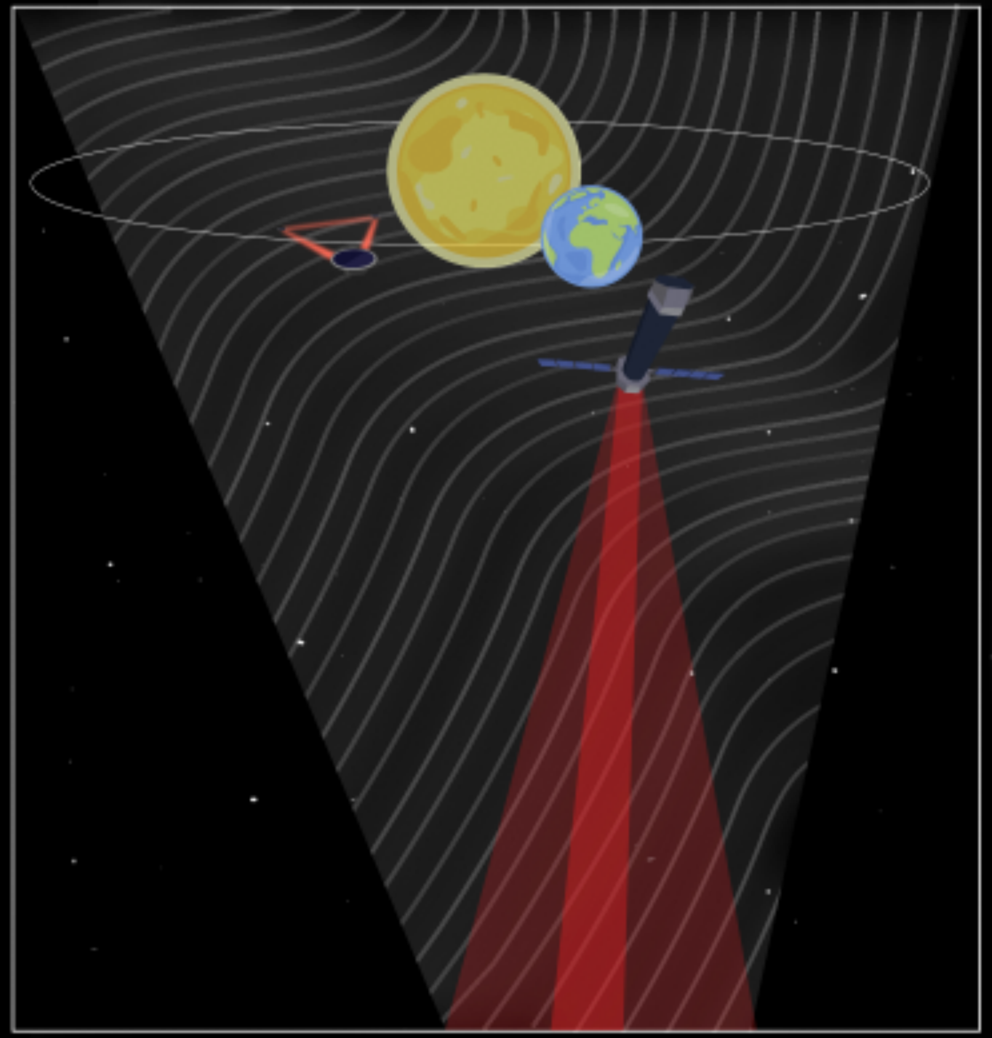
LISA low-latency pipeline identifies transient source

2 weeks before



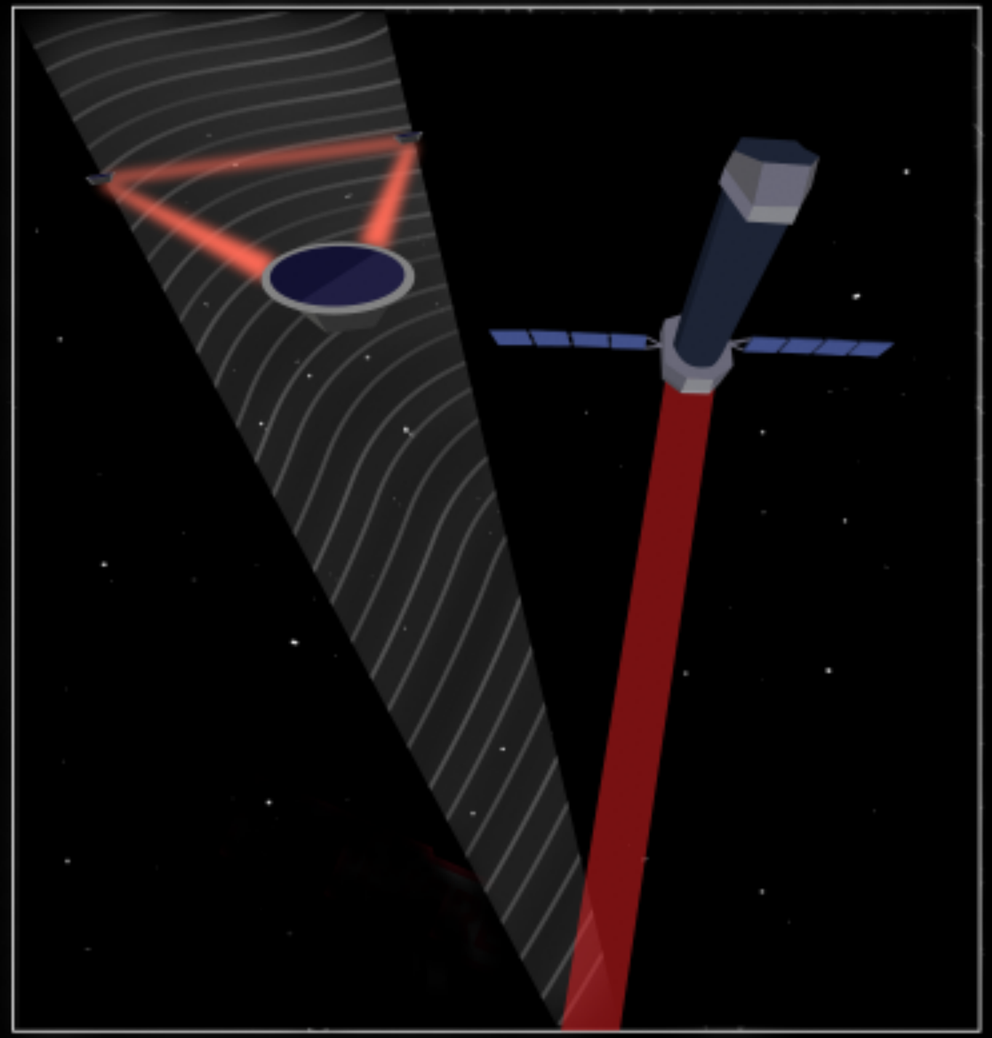
Sky localisation increases as constellation moves and SNR increases as binary approaches merger

1 week to several hours before



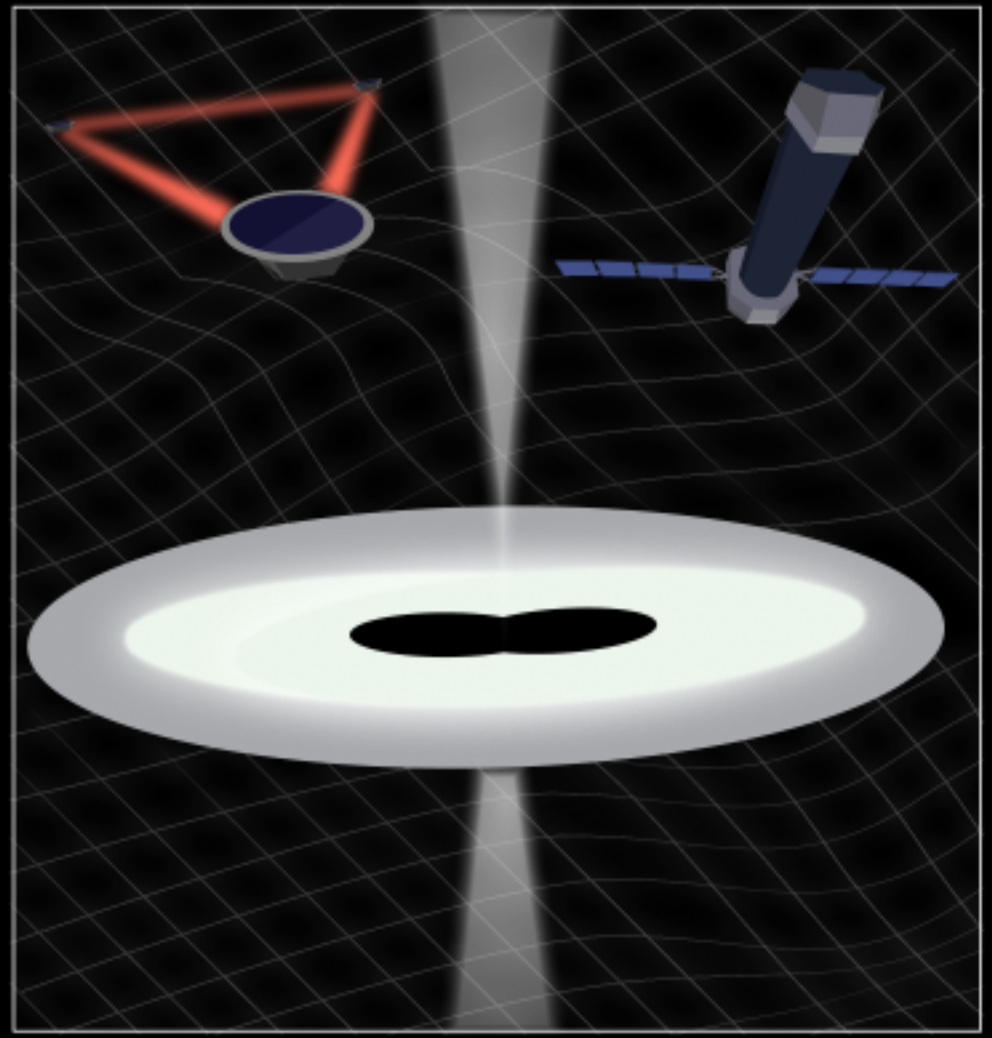
When sky localisation error reaches ~10deg^2, Athena scans the portion of sky with Wide Field Imager (WFI) (FoV = 0.4deg^2)

A few hours before



Shortly before merger, LISA locates the source to within ~0.4deg^2, 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):
  - $10^6 M_\odot$: $z=1 \Rightarrow 10^{-2} Mpc^{-3}$, $z=2 \Rightarrow 10^{-1.5} Mpc^{-3}$
  - $10^7 M_\odot$: $z=1 \Rightarrow 10^{-2.5} Mpc^{-3}$, $z=2 \Rightarrow 10^{-2.5} Mpc^{-3}$
- Probability (p) that a galaxy hosts an AGN with an Eddington fraction ≥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: $4x10^{-10}$ yr^{-1} (Lotz et al. 2011)
  - $z=1 \Rightarrow 4x10^{-10}/(1+z) = 2x10^{-10}\ yr^{-1}$
  - $z=2 \Rightarrow 4x10^{-10}/(1+z) = 1.3x10^{-10}\ yr^{-1}$
- 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 …

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

Conclusions

- The <u>additional</u> 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-LISA Synergies

Athena-LISA Synergy Working Group:

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Paul McNamara, Luigi Piro, Nial Tanvir
(with contributions by J.Aird, A.Klein, A.Mangiagli, E.M.Rossi, A.Sesana)

20 February 2019

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 $10^{5-7}M_\odot$ 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.

1

athena and lisa

→ OBSERVING SUPERMASSIVE BLACK HOLES COLLIDE