CHASING X-RAY COUNTERPARTS OF

LISA

MASSIVE BLACK HOLE COALESCENCES

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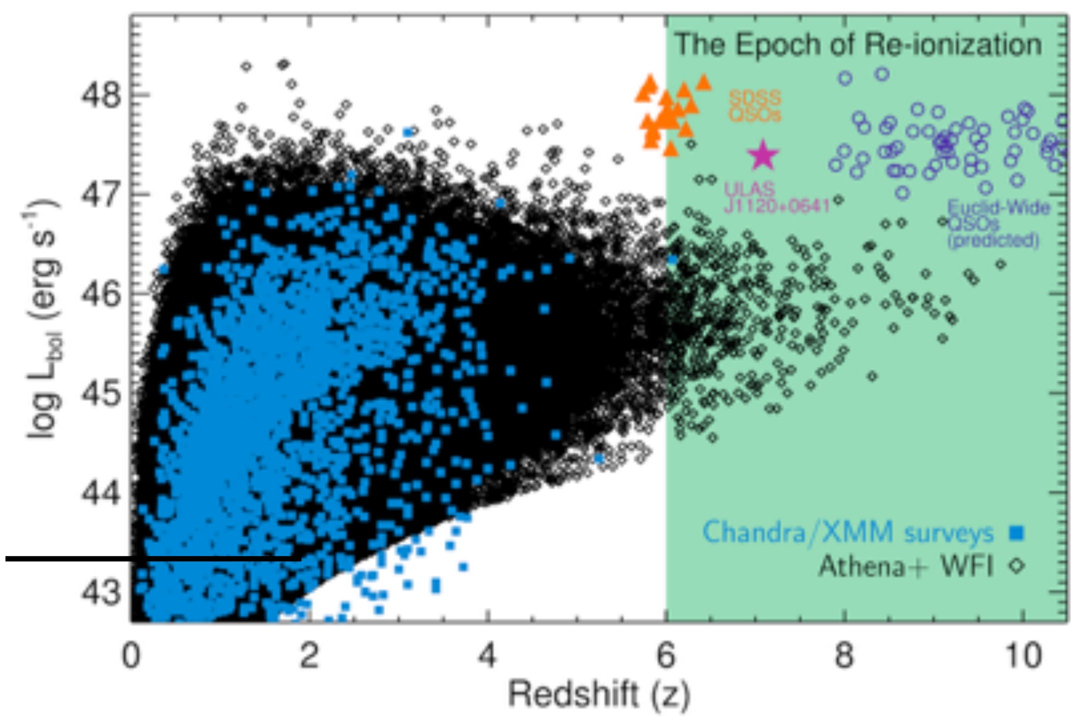
MERGING VISIONS: EXPLORING COMPACT-OBJECT BINARIES WITH GRAVITY AND LIGHT
Kavli Institute for Theoretical Physics, Santa Barbara
June 27th 2019

Athena & LISA science cases

Exploring the violent high-z universe from two different perspectives

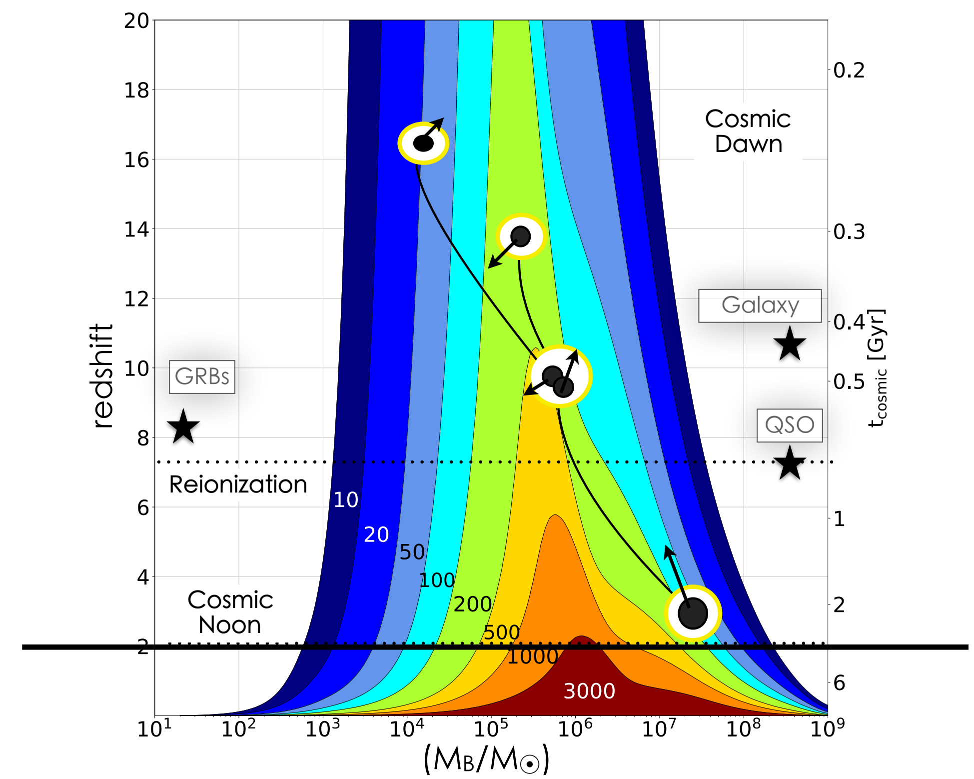


How do solitary (obsucred) accreting black holes grow and shape **galaxies**?

400,000 AGN

Dimmest, low redshift X-ray transient AGN

Athena white paper 2013
2020 DECADAL WP Tombesi+ 2019

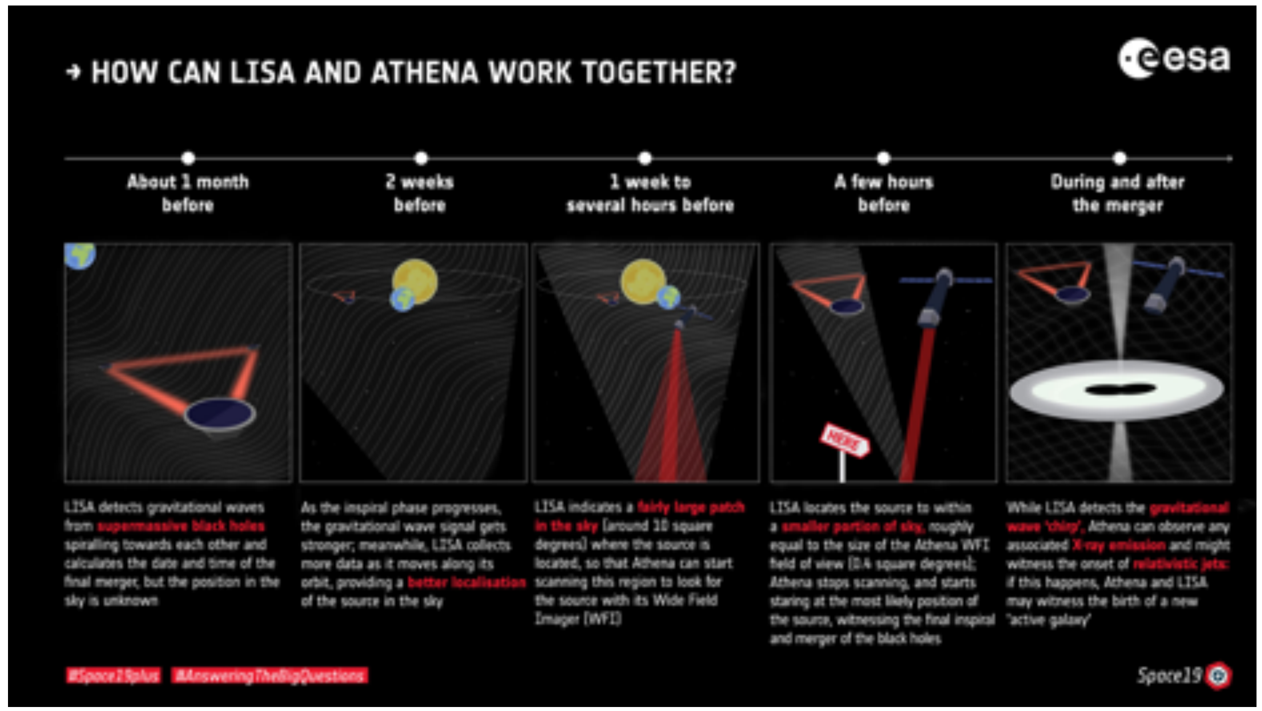


How do massive **black holes** binaries form in concordance with **galaxy assembly**?

Loudest, low redshift GW events

LISA white paper 2013,2017
2020 DECADAL WP Colpi + 2019

What can LISA and Athena do together?



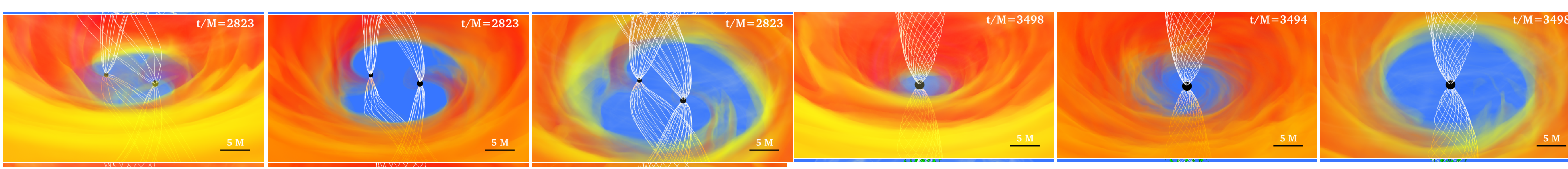
ESA- LISA-Athena joint WG:
Paul McNAMRA, Matteo GUAINAZZI, Luigi PIRO, Andy FABIAN, Nial TANVIR
Alberto MANGIAGLI, Alberto SESANA, Antoine KLEIN

Which additional science to anticipate
LISA launch ?

https://www.cosmos.esa.int/documents/678316/1700384/Athena_LISA_Whitepaper_Iss1.0.pdf

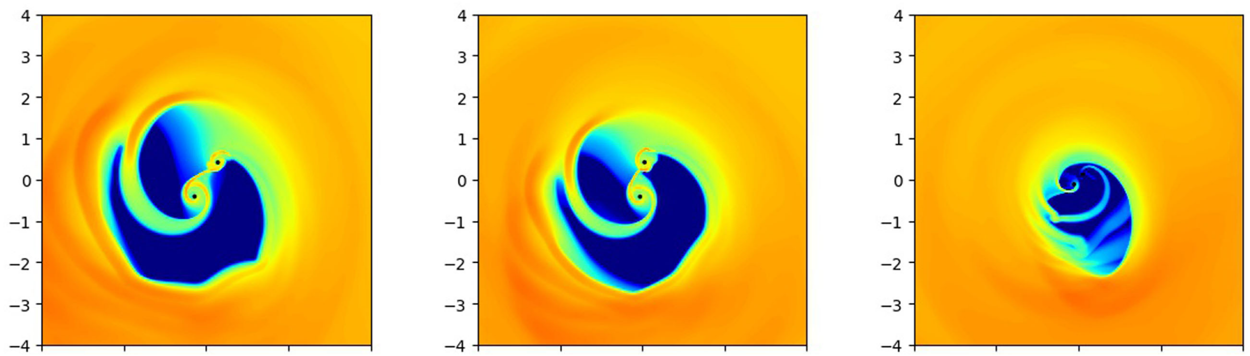
MERGING VISIONS
Detecting X-ray light and GW radiation from the violent merger between two massive black holes

- UNCHARTED TERRITORY
- No transient broad band AGN-like emission have been observed yet in the variable sky that could be attributed to a LISA coalescence event consumed over a timescale of days/hours
- No observational guide as far as the EM light curves and spectra of coalescing binary black holes are concerned
- Resort on theoretical models of gas dynamics around massive binary black holes CLOSE to merging

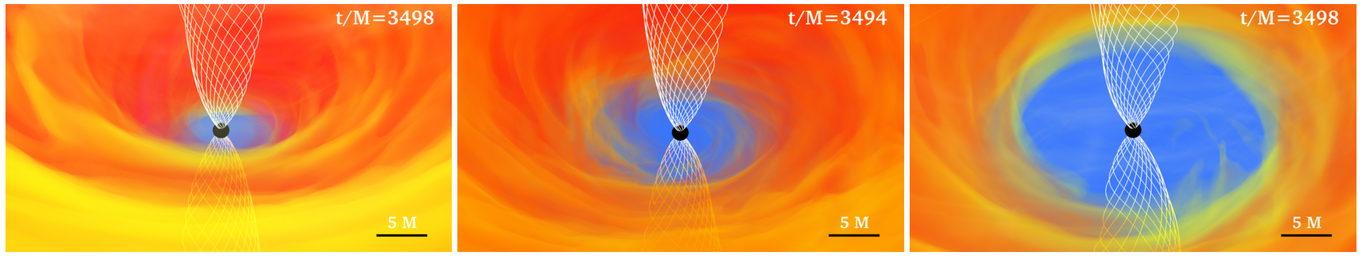


Gold et al. 2014; Farris et al. 2014; Tang, MacFadyen, and Haiman 2018; Hainan 2017;Bowen, Campanelli, et al. 2017; Bowen, Mewes, et al. 2018; Khan et al. 2018, Kelly et al. 2018

BINARIES
in gas rich mergers
CIRCUMBINARY ACCRETION DISCS



- Inspiral GW phase - X-ray precursor (correlating X-ray variability pattern with GW chirp (separations <50 M)
- Post-merger GW phase: merger proper, the ring-down, the new spinning black hole - disc X-ray re-brightening, launch of an incipient jet, X-ray afterglow (?)



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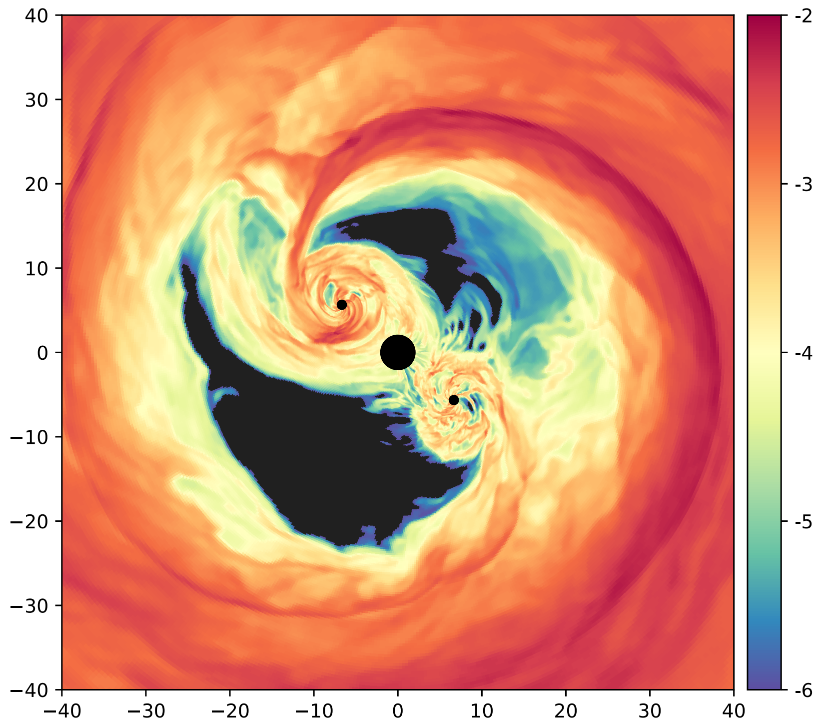
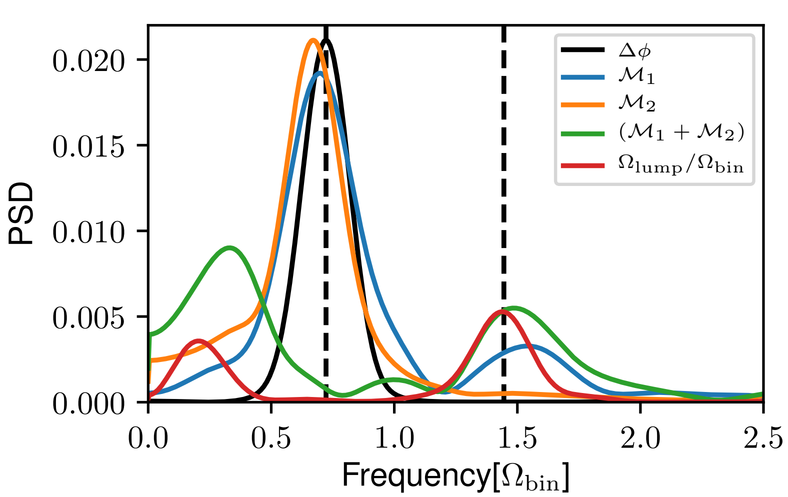
Pre-merge/post-decoupling phase
probing accretion in variable spacetimes with GR MHD simulations

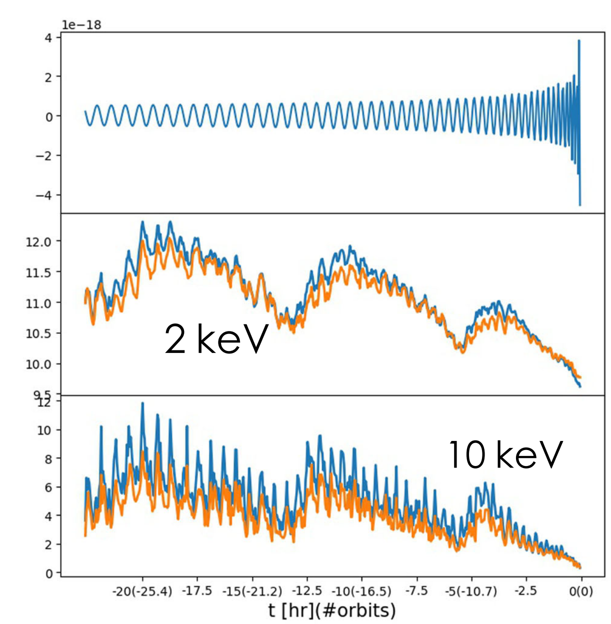


- cavity contains considerable amount of gas (thick discs)
- black holes remain surrounded by gas that follows the binary - dense streams feed the two black holes - mini discs
- expected periodicity commensurate with the fluid patterns - beat frequency: lump and orbital period
- discs are not any longer stationary-(mass sloshing)
- tidally truncated
- decrease in the accretion rate across the horizon (might depend of q - EM chirp?)



GRMHD simulations: BOWEN et al. 2018, 2019

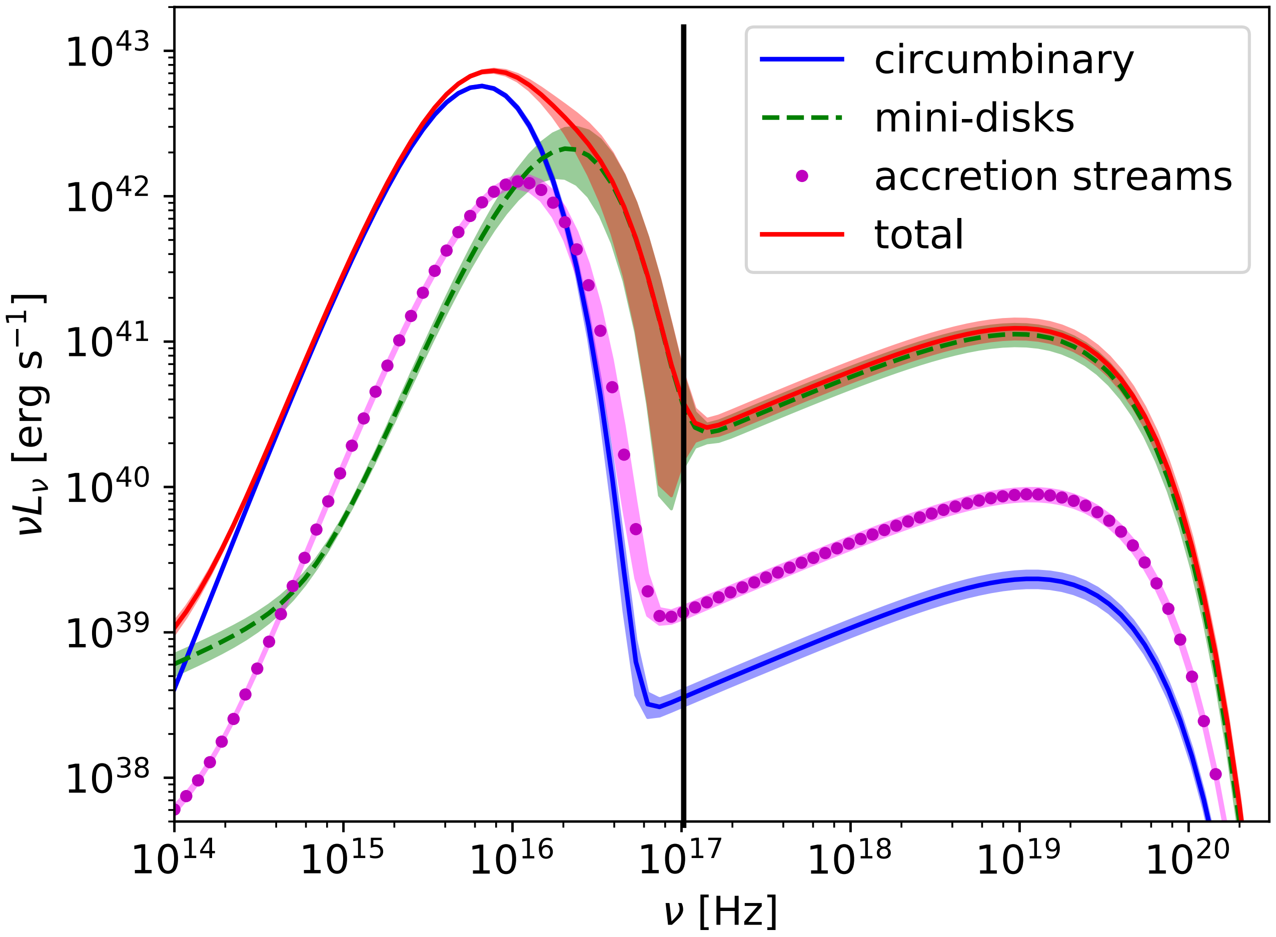
20 h before merging



TANG et al. 2018

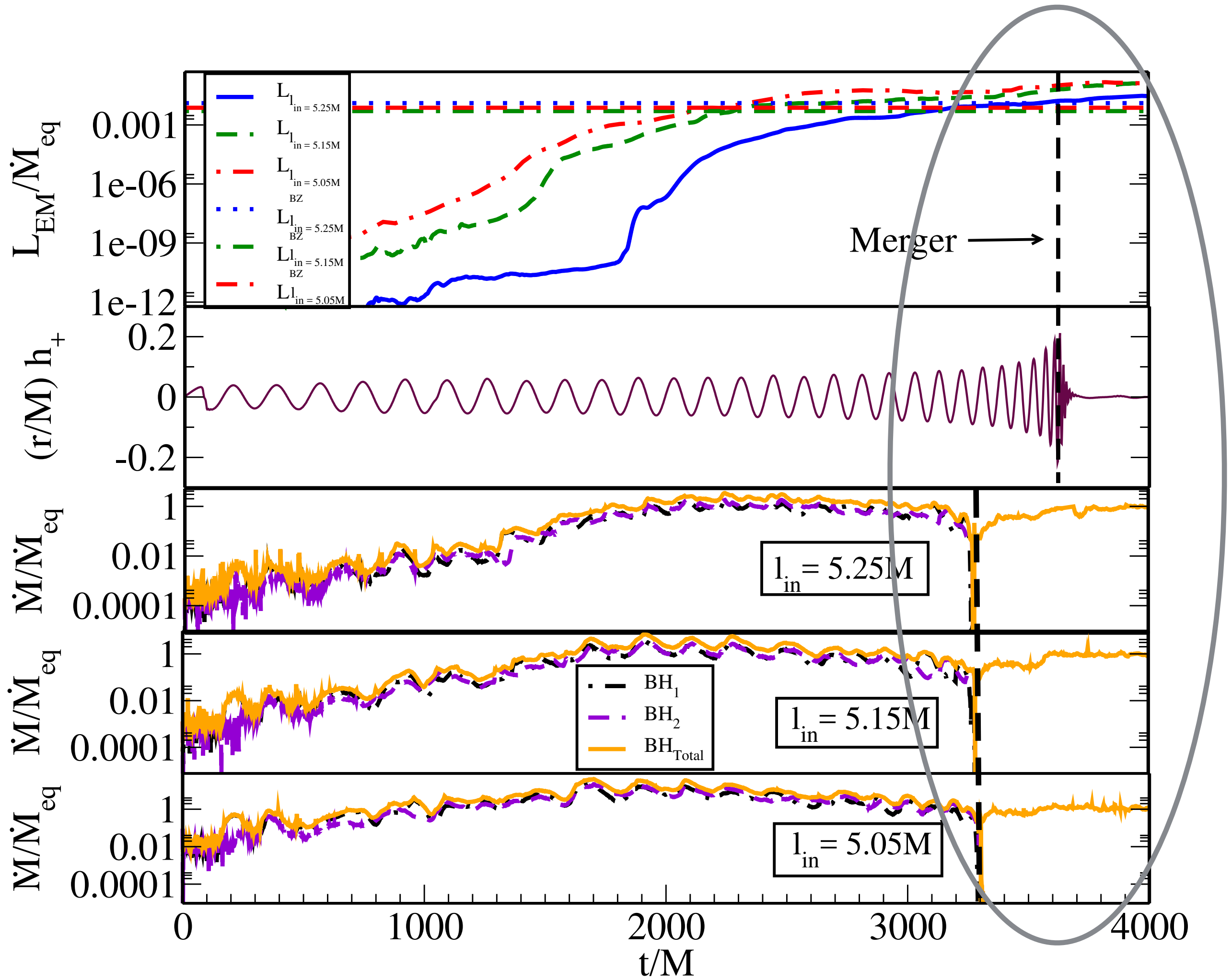
Broad Band Spectrum

- Using a ray-tracing code to post-process the data from the GR simulation, D' Ascoli+2018 generate images and spectra / inclination effects - relativistic Doppler, gravitational redshift and light bending
- Posit a thermal Compton hard X-ray spectrum from coronal emission on top of the mini discs

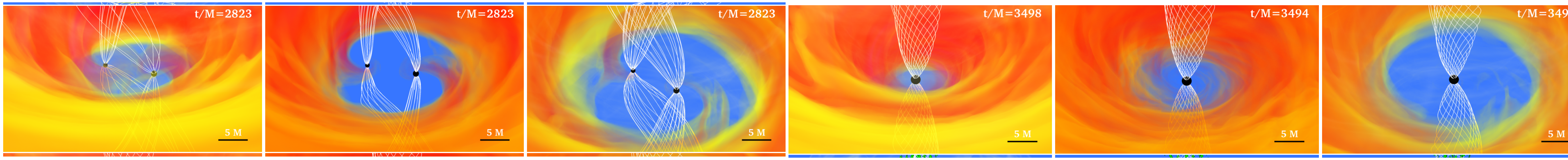


D' Ascoli et al. 2018

Post-merger phase

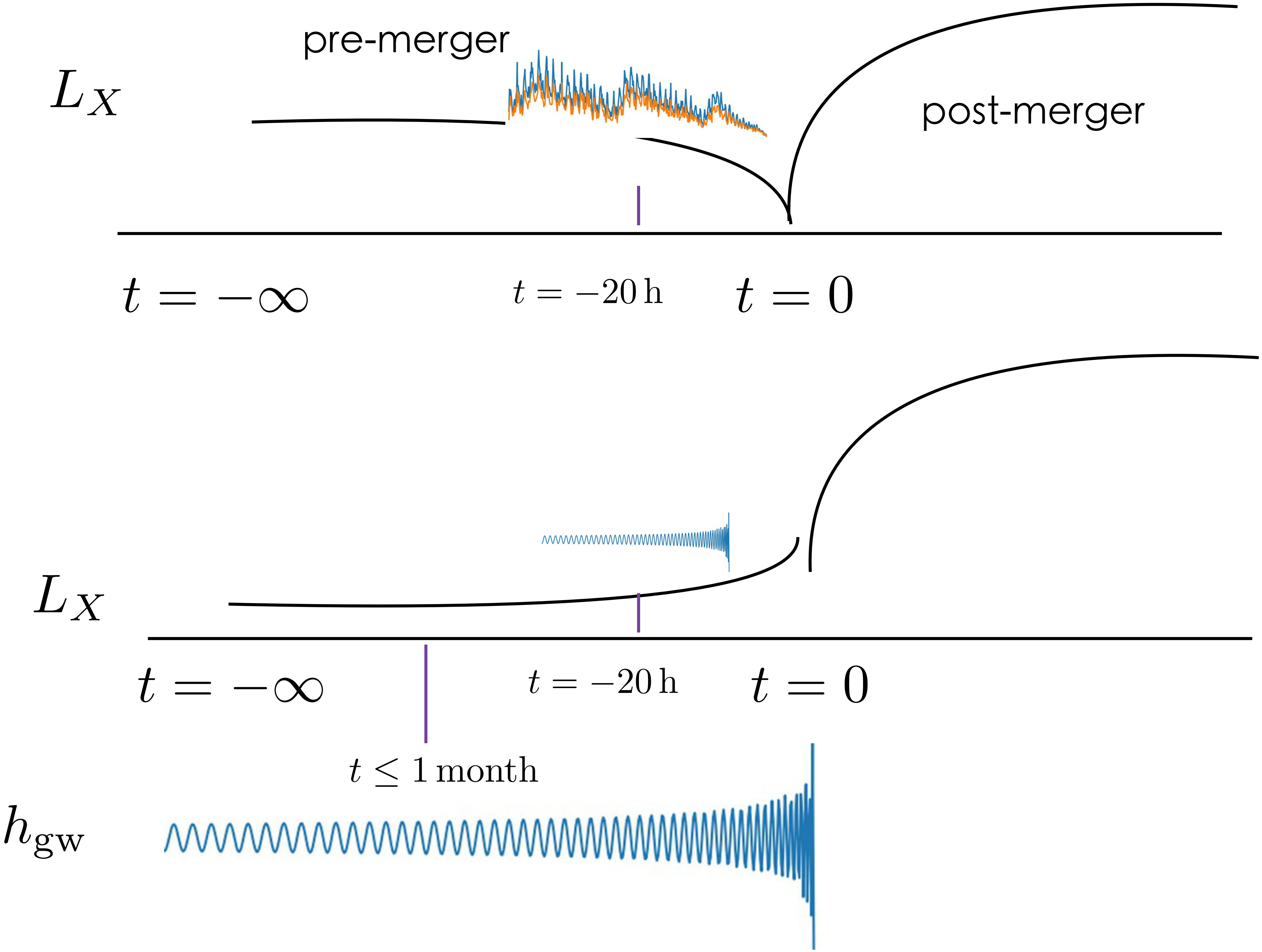


- collimated magnetized outflows in the polar regions even prior merging
- new black hole is highly spinning
- Poynting luminosity rises in the early merger aftermath and stays constant (jet from a million sun back hole?)
- need of microphysics to model calling, radiative transport and extract light curves and spectra

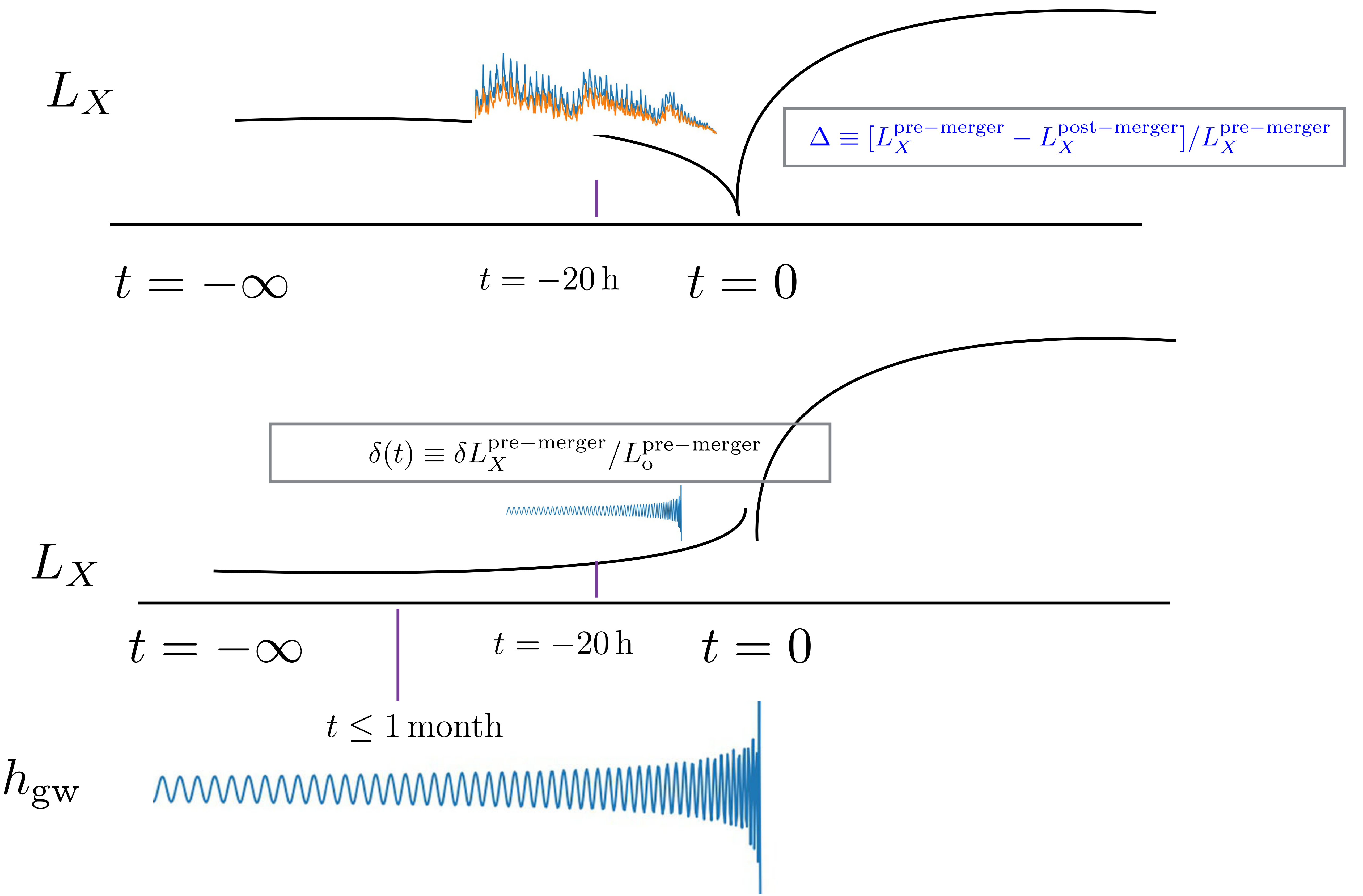


KHAN et al. 2018

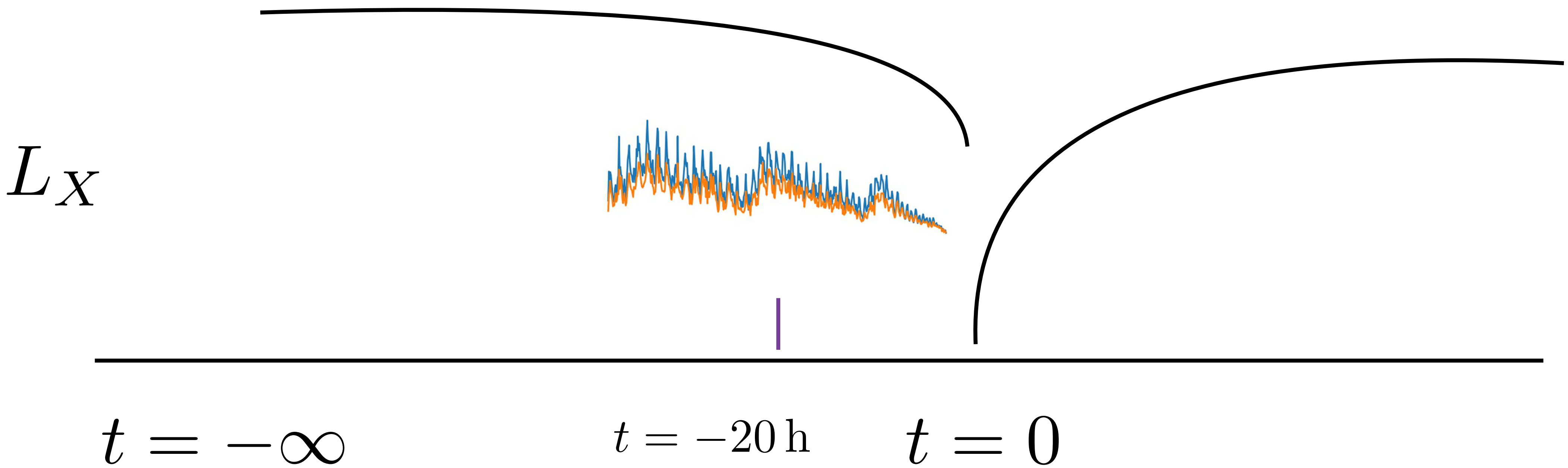
- LISA black hole binaries with EM counterpart are always "on"



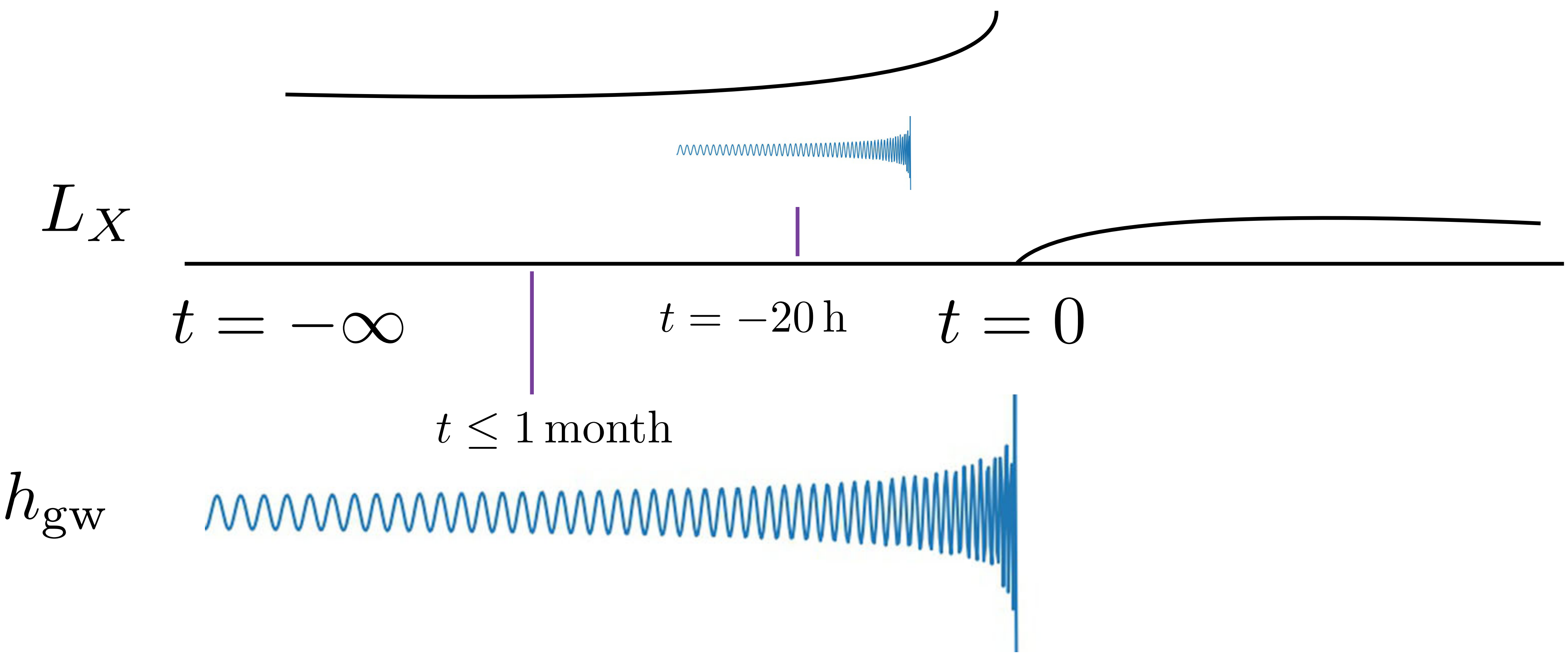
- Level of VARIABILITY during inspiral and merger is critical



- ON-OFF case



L_X
$t = -\infty$
$t = -20\,\mathrm{h}$
$t = 0$



L_X
$t = -\infty$
$t = -20\,\mathrm{h}$
$t = 0$
$t \leq 1\,\mathrm{month}$
h_{gw}

- observing strategy pre/post merger

- how early can we determine the parameters of the GW source?
- how early can we localize the source with LISA to inform Athena?

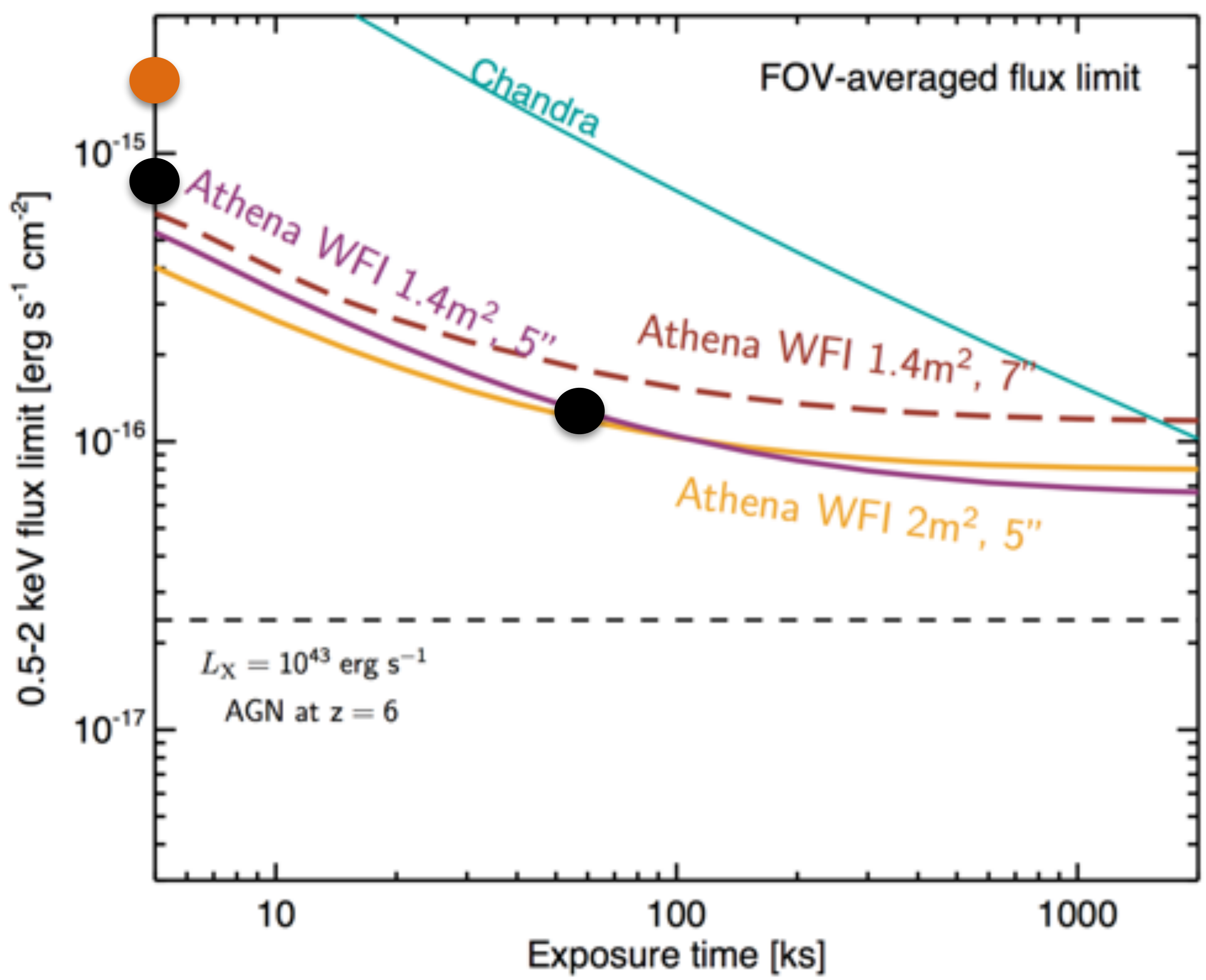
Athena Wide Field Imager (WFI)

- Energy range between 0.2 keV to 15 keV
- Field of view of 0.4 square degrees (40’ x40’)
- Time resolution of 5 milliseconds
- Angular resolution of 5” on axis
- Averaged flux sensitivity limit ~ $7x10^{-17}$ (cgs units)
- Slew rate of 4 deg/s
- FAST RESPONSE TIME comparable to or less than 4 hours, to enable observing any Target of Opportunity in a random field of the sky
- Athena covers a 10 square degree field of view in 3 days with a raster scan of at least 23 observations in sequence of 10 ksec each (it can be faster we can reduce tiling the sky to 5ksec each if the source is indeed brighter)

http://www.mpe.mpg.de/ATHENA-WFI/
MEIDINGER et al. 2015

Vanilla emission model
Eddington limited sources+bolometric correction (0.3%)

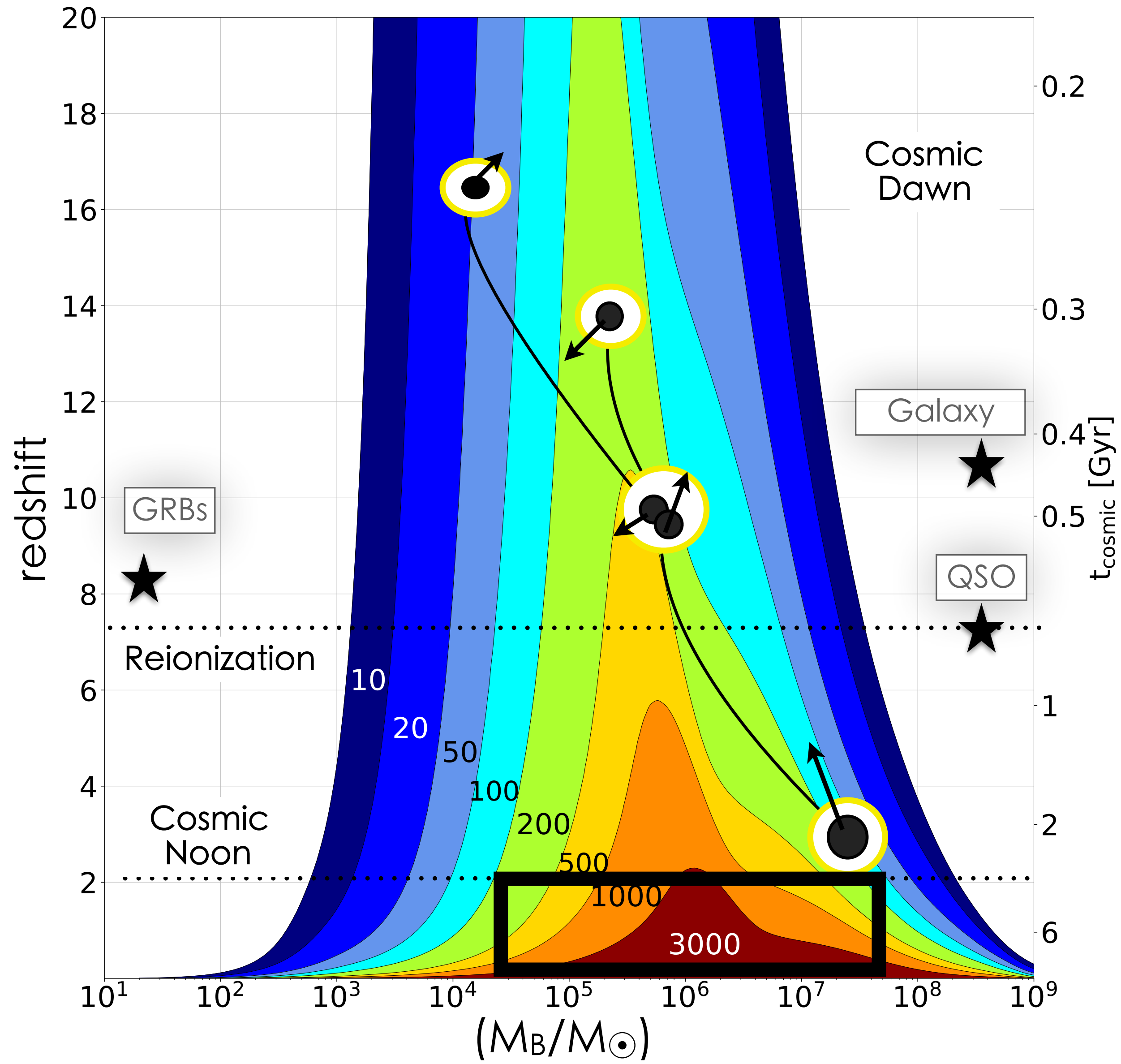
	● $M=10^6\ M_\odot$	● $M=10^7\ M_\odot$
$z = 1$	8×10^{-16} (5)	8×10^{-15} (<1)
$z = 2$	1.5×10^{-16} (70)	1.5×10^{-15} (2)
	Kilo seconds	Kilo seconds



10 ks~3 hours
100 ks ~ 28 hours

LISA-a sky monitor

$$\Delta\Omega \approx 0.5 \left(\frac{\rho}{10^3}\right)^{-7/4} \mathrm{deg}^2$$



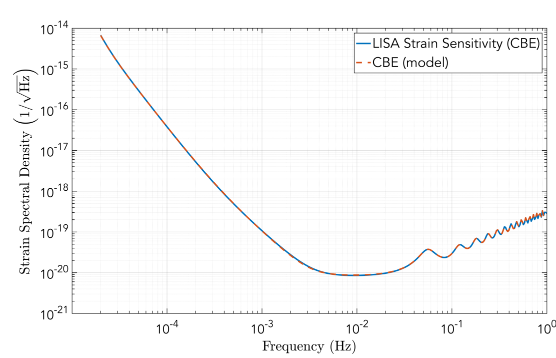
Joint observations of nearby "very GW bright" and" X-ray dim" events !

- LISA antenna pattern is time dependent and long lasting sources are localized better by exploiting LISA motion around the sun
- sky localization error decreases with measurement time and improves significantly @ merger

McWilliams et al. 2011

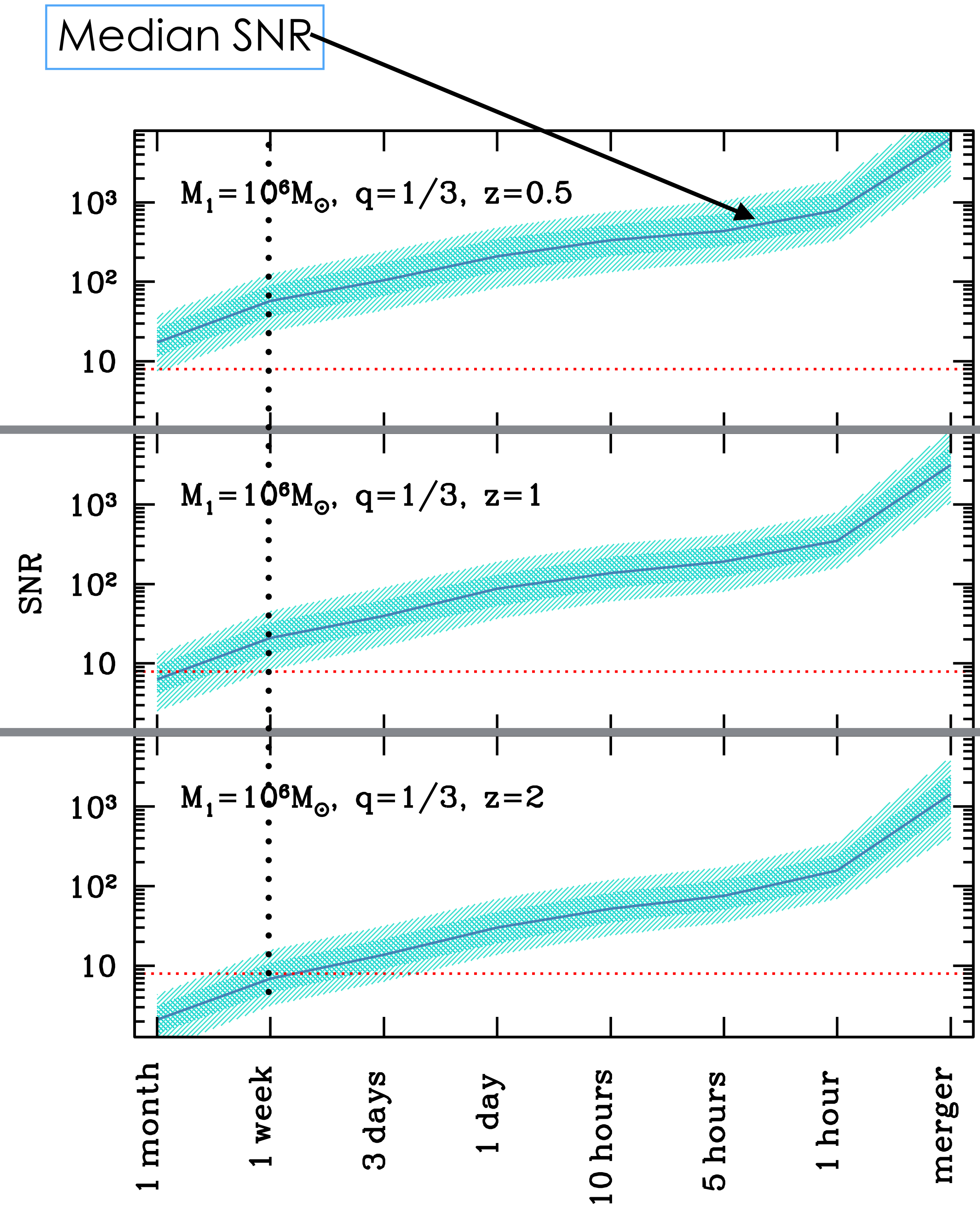
- an ensemble of binaries with random: sky position, orientation and spin, using precessing waveforms including contribution of higher harmonics in the inspiral portion of the signal (Klein, Cornish and Yunes, 2014)
- match the SNR with that of the merger and ring-down PhenomC waveform

Mangiagli et al. in preparation



Robson, Cornish, Liu 2018

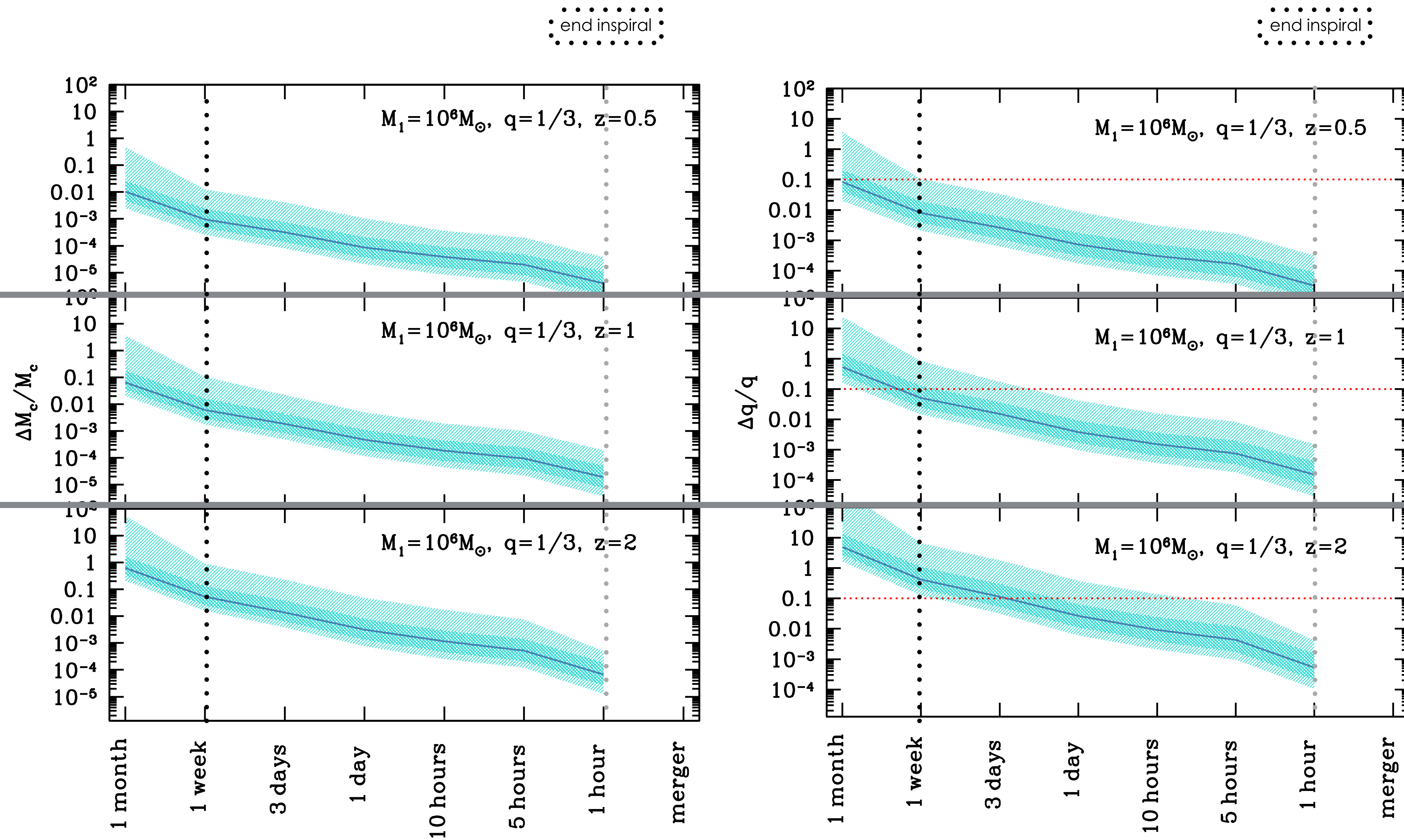
$M_{\rm BHB} = 10^6\,{\rm M}_\odot \qquad q = 1/3$



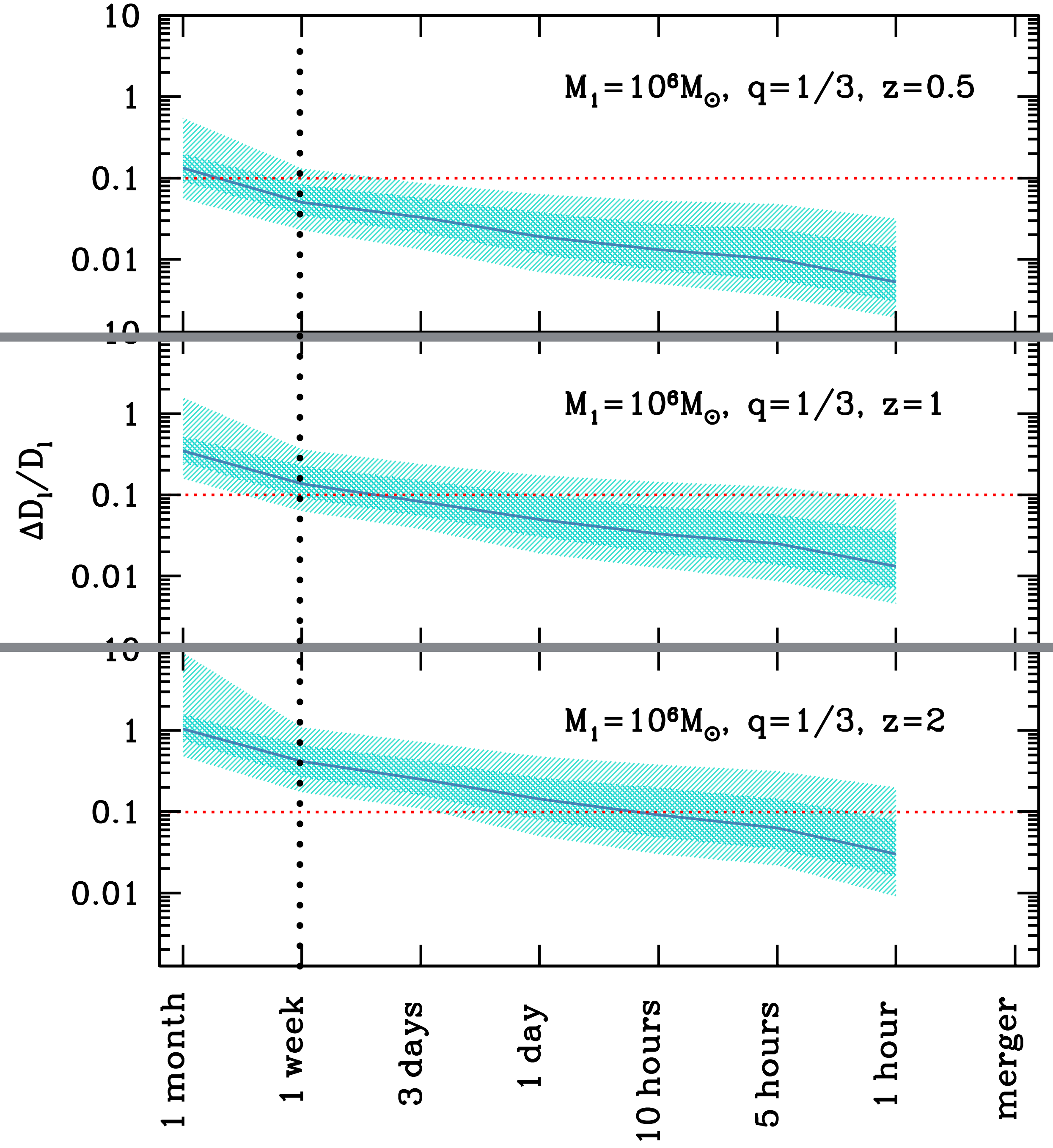
"merger" time determined precisely

shaded areas are
our 68% and 95% confidence intervals

Mangiagli et al. in preparation

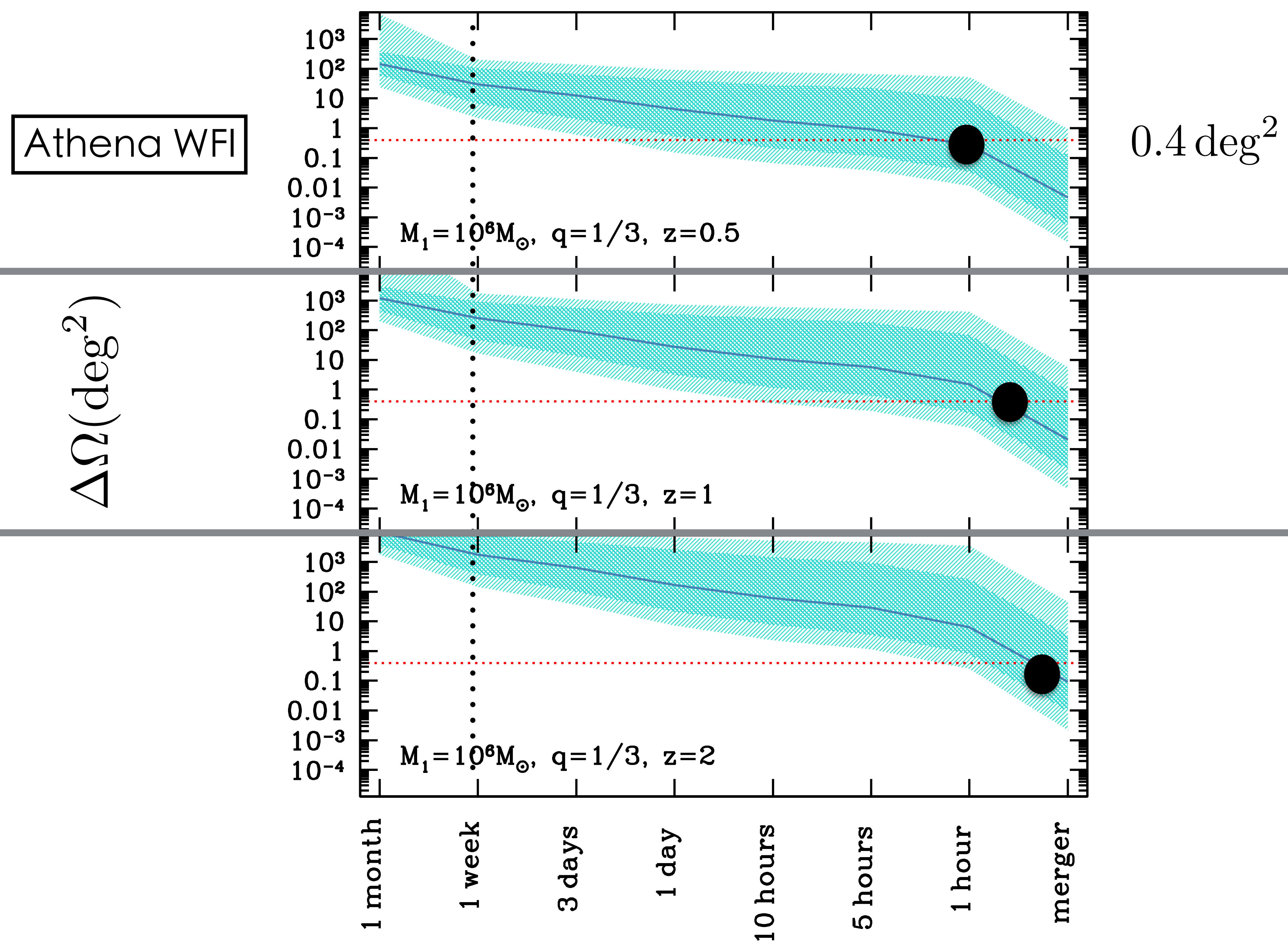


end inspiral
end inspiral
$M_1=10^6 M_\odot$, $q=1/3$, $z=0.5$
$M_1=10^6 M_\odot$, $q=1/3$, $z=1$
$M_1=10^6 M_\odot$, $q=1/3$, $z=2$
$\Delta M_c/M_c$
$\Delta q/q$
10^2
10
1
0.1
0.01
10^{-3}
10^{-4}
10^{-5}
1 month
1 week
3 days
1 day
10 hours
5 hours
1 hour
merger



$M_1=10^6M_\odot$, $q=1/3$, $z=0.5$
$M_1=10^6M_\odot$, $q=1/3$, $z=1$
$M_1=10^6M_\odot$, $q=1/3$, $z=2$
$\Delta D_l/D_l$
10
1
0.1
0.01
1 month
1 week
3 days
1 day
10 hours
5 hours
1 hour
merger

sky localization uncertainties

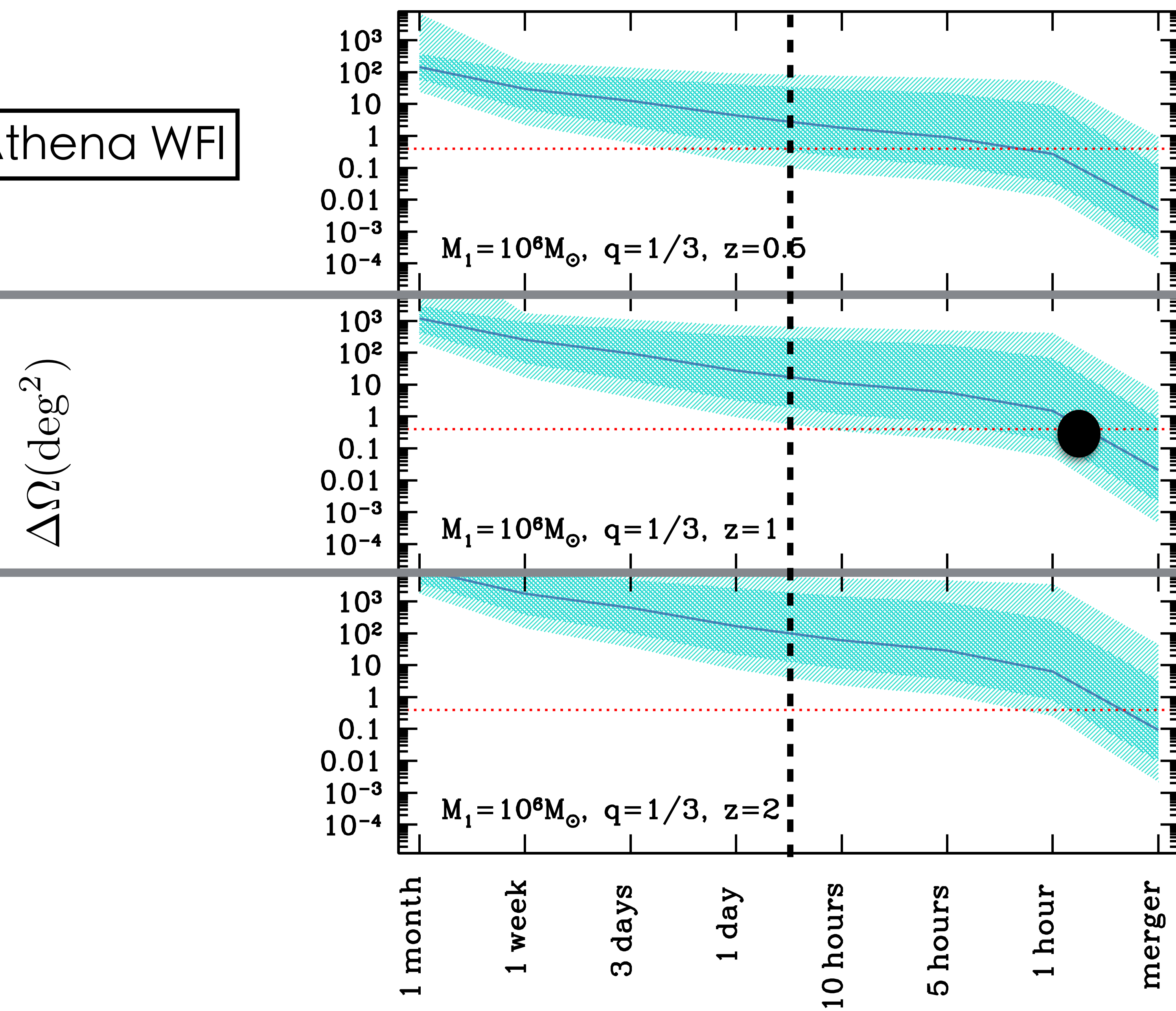


- Athena can start tiling the sky 12 hours prior merging with a raster scan of 5ksec (depending on the source luminosity instructed by the LISA PE + modeling)
- Athena wants to keep on exploreing the wider field of view a few times in search for periodicity patterns

$\delta(t) \equiv \delta L_X^{\rm pre-merger} / L_{\rm o}^{\rm pre-merger}$

Athena WFI

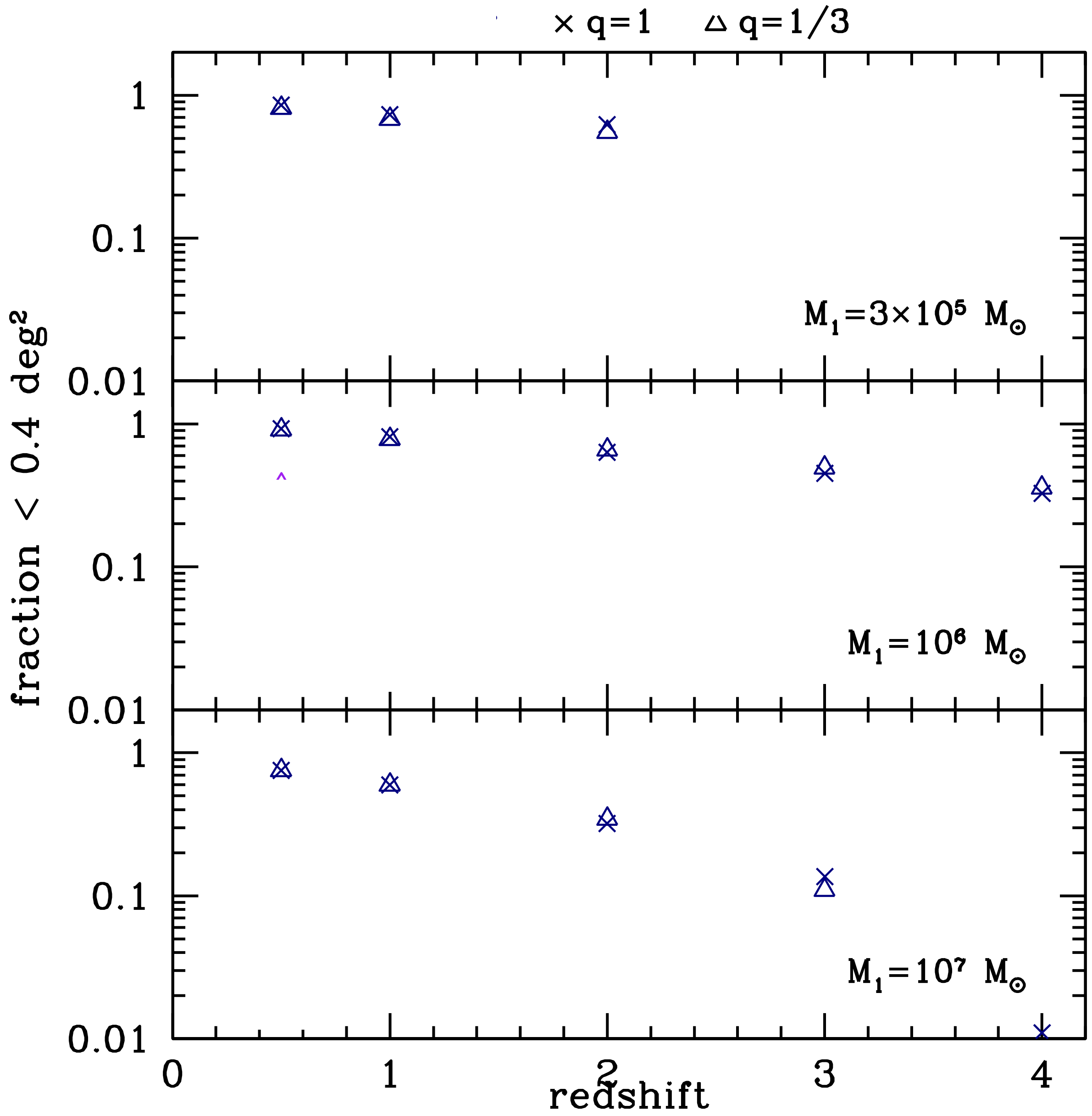
$0.4\,\mathrm{deg}^2$



0.1%

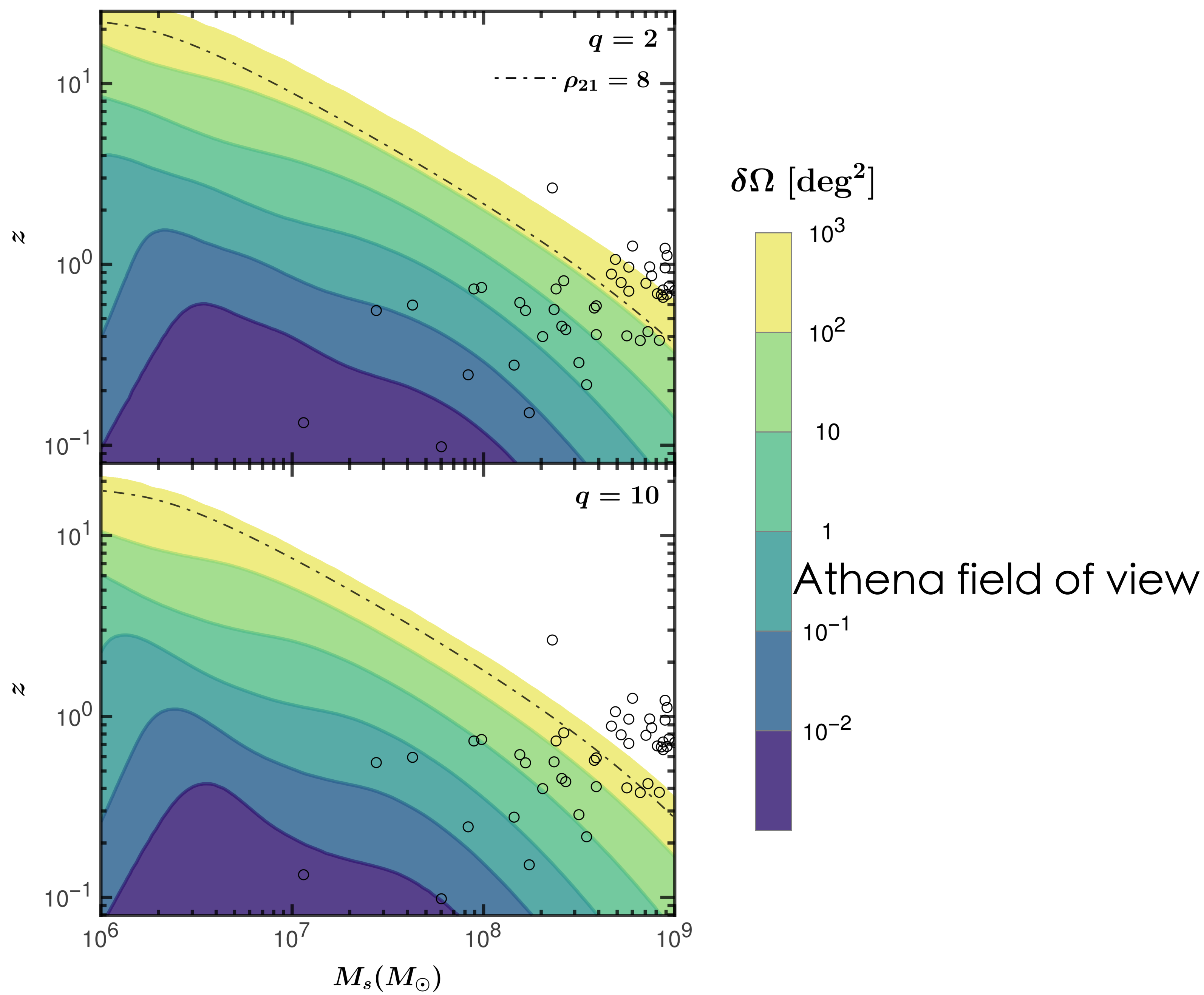
0.1% success

Post-merger phase



Post-merger phase strategy is significantly better

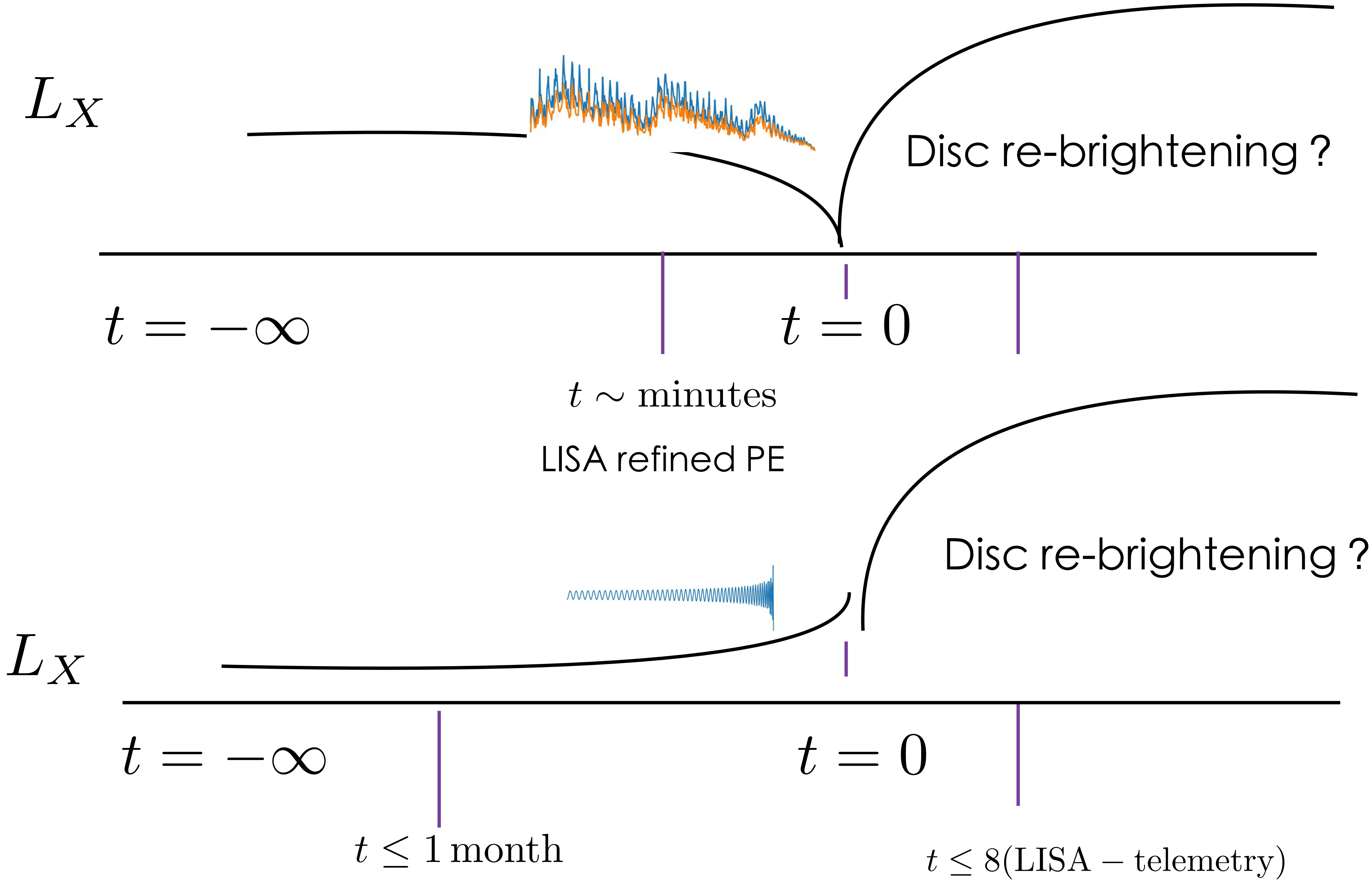
- By exploiting the power of higher harmonics in the ring-down signal, sky localization can be improved significantly for the most massive, unequal mass black hole binaries



Vishal Baibhav et al. in preparation

- POST-merger
  Timescales -hours

$$\Delta \equiv [L_X^{\rm pre-merger} - L_X^{\rm post-merger}]/L_X^{\rm pre-merger}$$



Caveat

- In absence of a periodicity detected during the inspiral phase, it will be difficult to identify the X-ray source
- Extremely challenging to observe the X-ray precursor: Knowing masses and spins of the merging black holes and an "X-ray" template we might succeed in identifying the host
- Source confusion (two or more sources in the same pixel)
- LSST and eROSITA provide the "reference" sky, and LSST photometric redshifts - galaxy selection knowing the luminosity distance
- Euclid will provide a census of galaxies out to z~1
- Rates are uncertain: upper limit is ~10 in 10 years of operation
- Obscuration matters
- Need of numerical simulations to infer X-ray light curves and spectra template bank as a function of masses, spins, mass ratios …

Summary and Conclusions

- The potential for post-merger followups of LISA binary mergers appears promising indeed, enabling detection of sources up to z~2
- @merger: sky localization error can be reduced down to fractions of a square degree
- @merger: also the "heaviest" LISA massive binaries can be detected within the Athena field of view (Bahibav+ in preparation) by exploiting the richness of the higher harmonics in the ring-down
- LISA can provide key priors for selecting the X-ray properties of the putative source
- Inspiral- X-ray precursor phase is detectable at very low z, which limits the number of potential events
- Big uncertainties - luminosities - rates - identification host galaxy