Multimessenger observations of black hole binaries: opportunities for LISA-Athena synergies

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The assembly of cosmic structure from baryons to black holes with joint gravitational-wave and X-ray observations

(ArXiv181100050)

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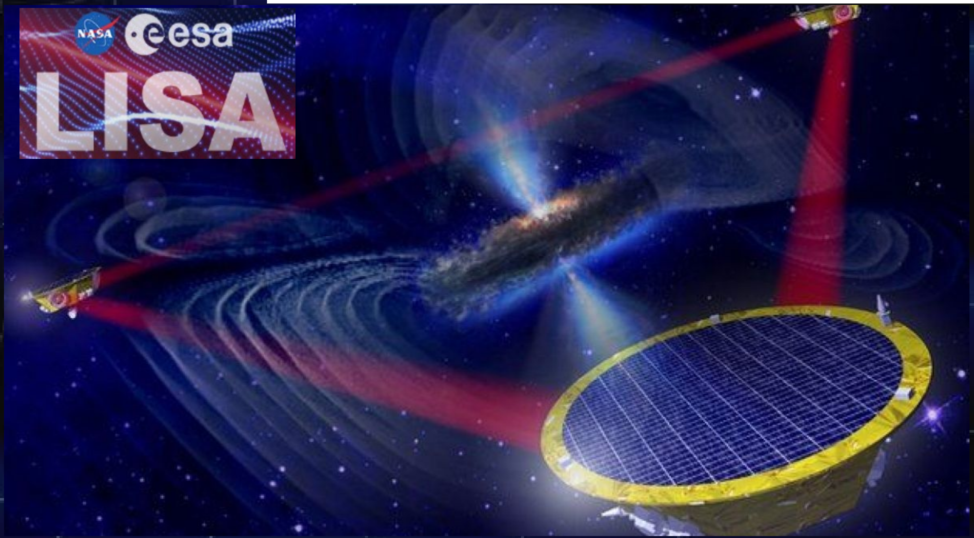
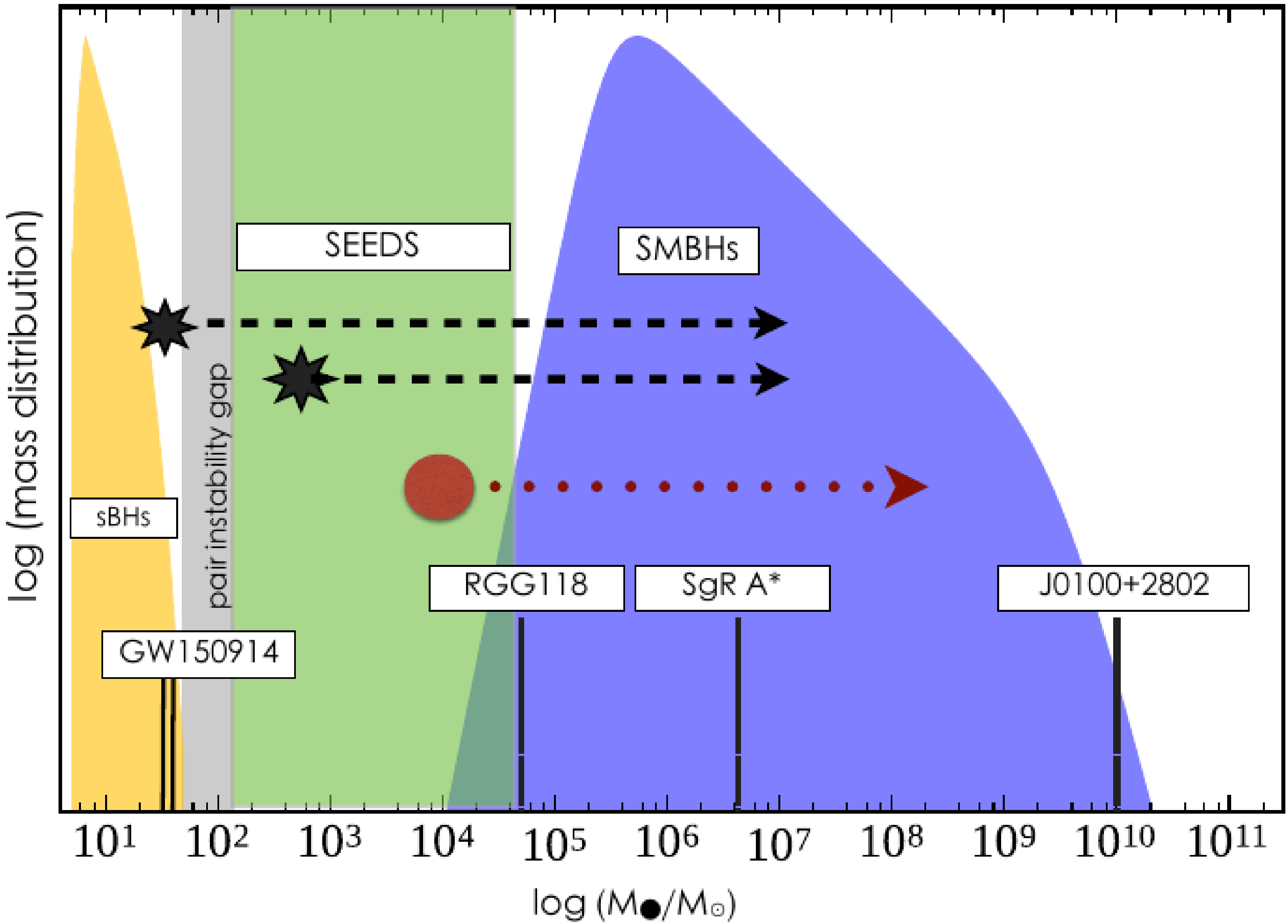
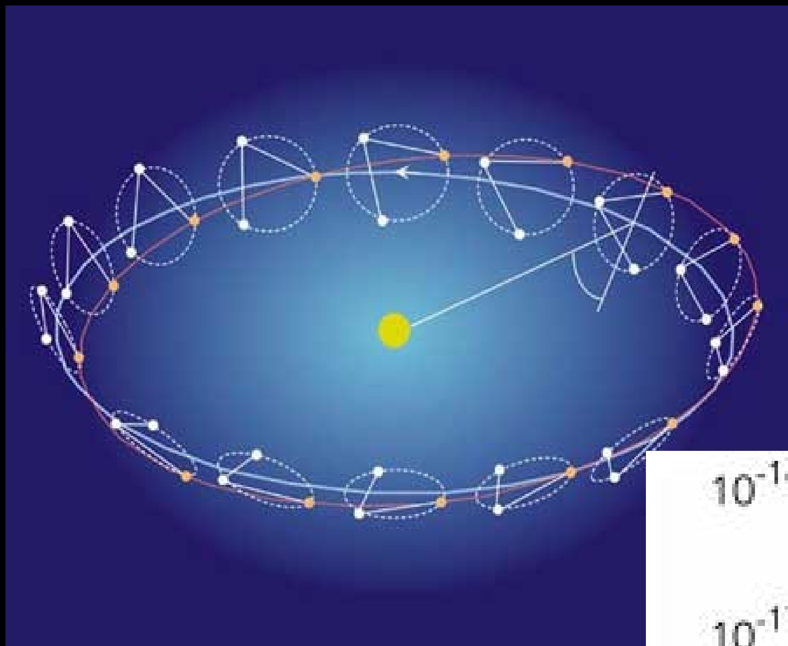




(From Barack al. 2018)

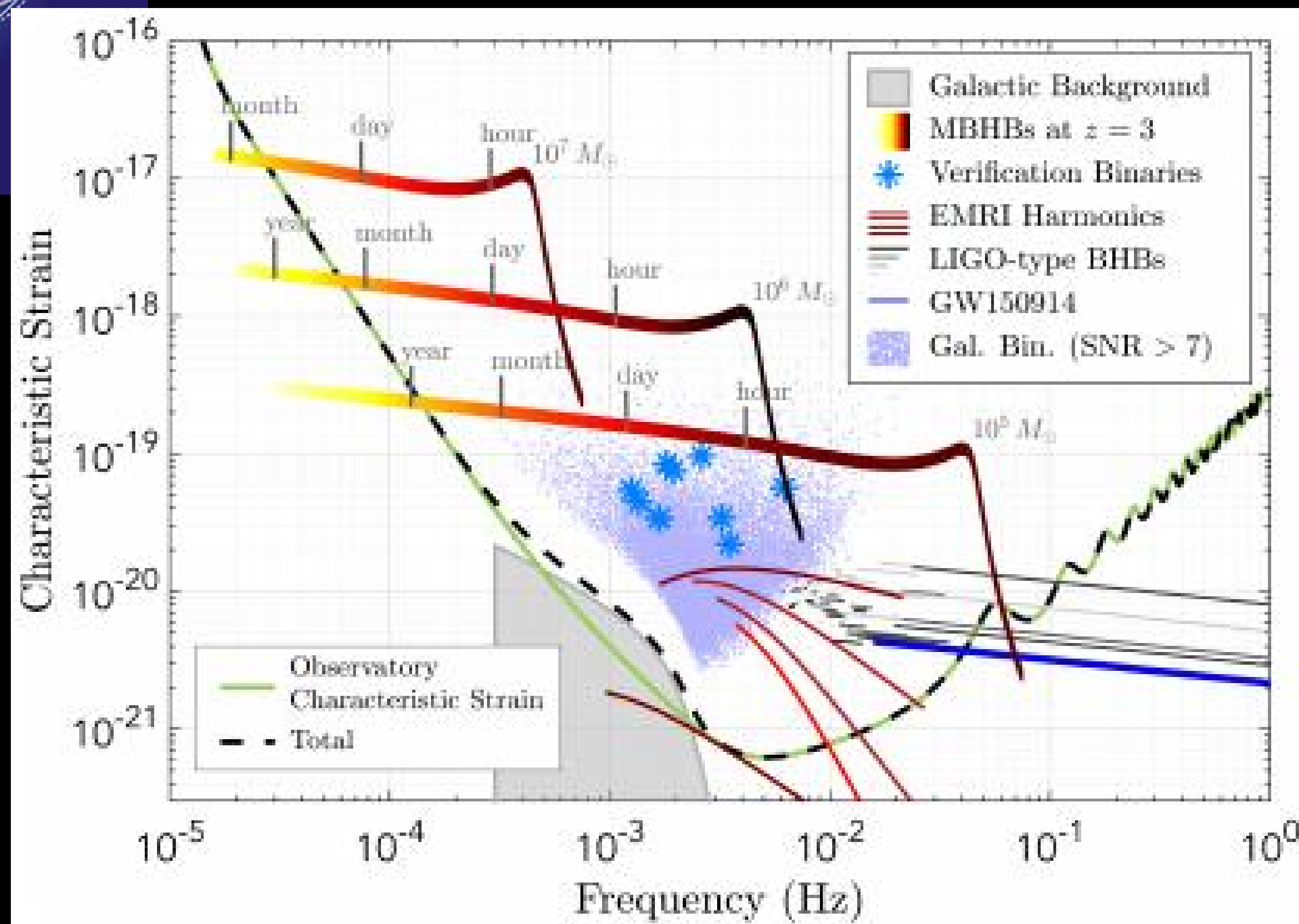
The Laser Interferometer Space Antenna

(Amaro-Seoane et al. 2017, arXiv:1702.00786)



Sensitive in the mHz frequency range where MBH binary evolution is fast (chirp)

Observes the full inspiral/merger/ringdown

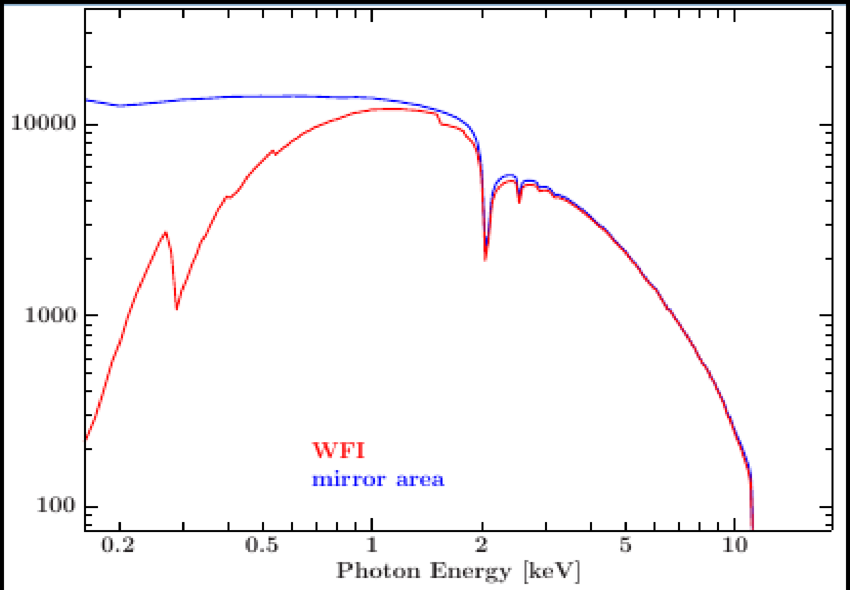


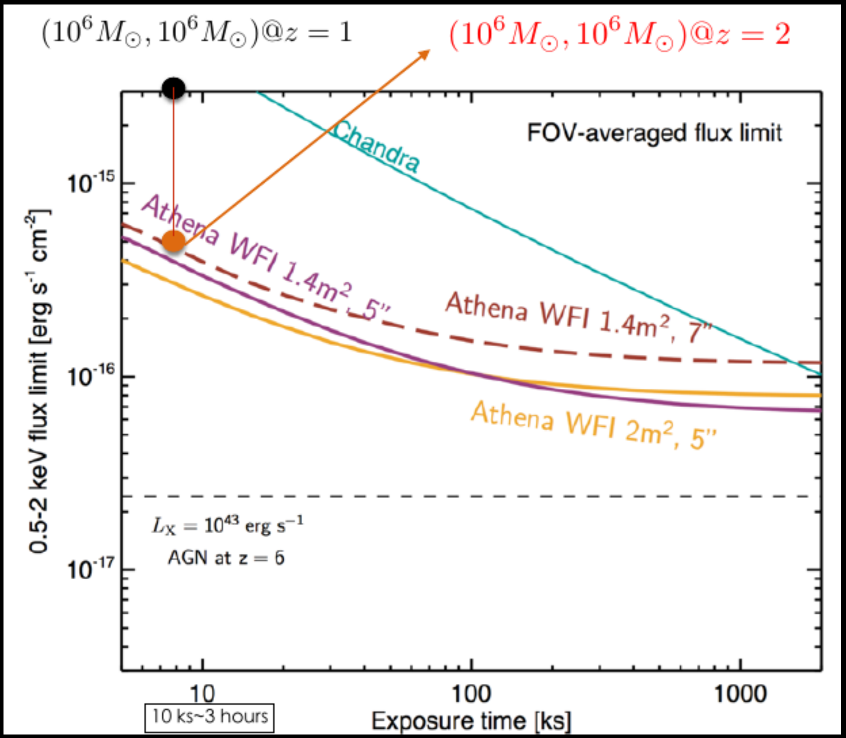
3 satellites trailing the Earth connected through laser links

Proposed baseline:
2.5M km armlength
6 laser links
4 yr lifetime (10 yr goal)

Athena Wide Field Imager (WFI)

Parameter	Characteristic
Energy Range	0.1-15 keV
Field of View	ca. 40' x 40' (baseline) ca. 50' x 50' (goal)
Array Format	Central chip: 256 x 256 pixel Outer chips: 4x 448 x 640 pixel (baseline) 4x 576 x 768 pixel (goal)
Pixel Size	Central chip: 100 x 100 μm² (1.8") Outer chips: 130 x 130 μm² (2.3")
Angular Resolution (onaxis)	<5 arcsec (oversampling by 2.8)
Quantum efficiency (incl. optical blocking filter)	277 eV: 24% 1 keV: 87% 10 keV: 96%
Energy Resolution	ΔE < 150 eV (FWHM) @ 6 keV
Readout rate	Central chip: 7800 fps Outer chips: 2200 fps
Fast timing, count rate capability	8 μs in window mode 0.5 Crab > 88 % throughput, <3 % pile-up 1 Crab > 80 % throughput, <5 % pile-up
Particle Background at L2	3×10^{-4} cnt/cm²/keV/s





(Rau+ 2015)

Three classes of sources considered

Massive black hole binaries

-observed by LISA everywhere in the universe
-likely occurring in gas-rich environment
-variety of possible counterparts (see Monica's talk)

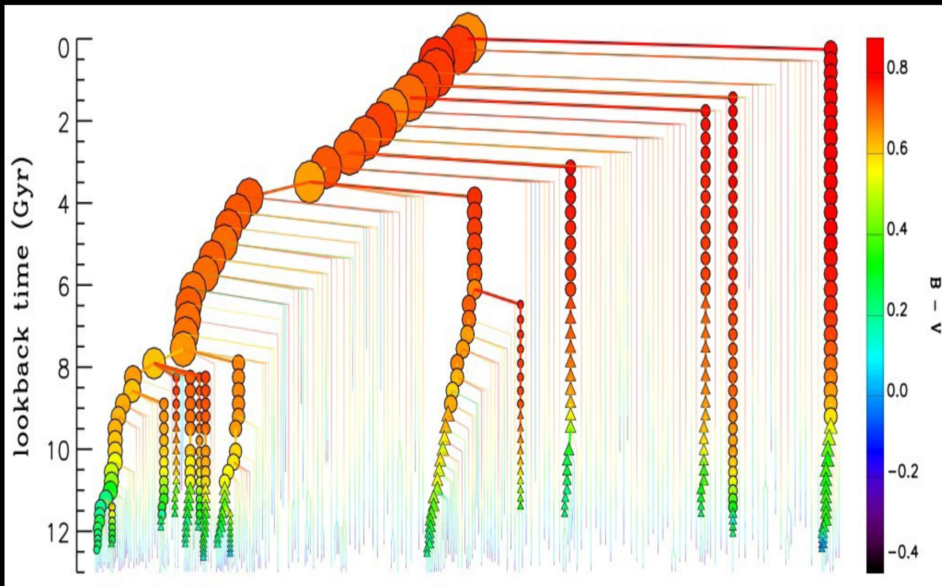
Extreme mass ratio inspirals

-observed by LISA up to z~2
-no obvious reason to expect a counterpart

Stellar mass black holes

-observed by LISA up to z~0.5
-no obvious reason to expect a counterpart

Structure formation in a nutshell



(From de Lucia et al. 2006)

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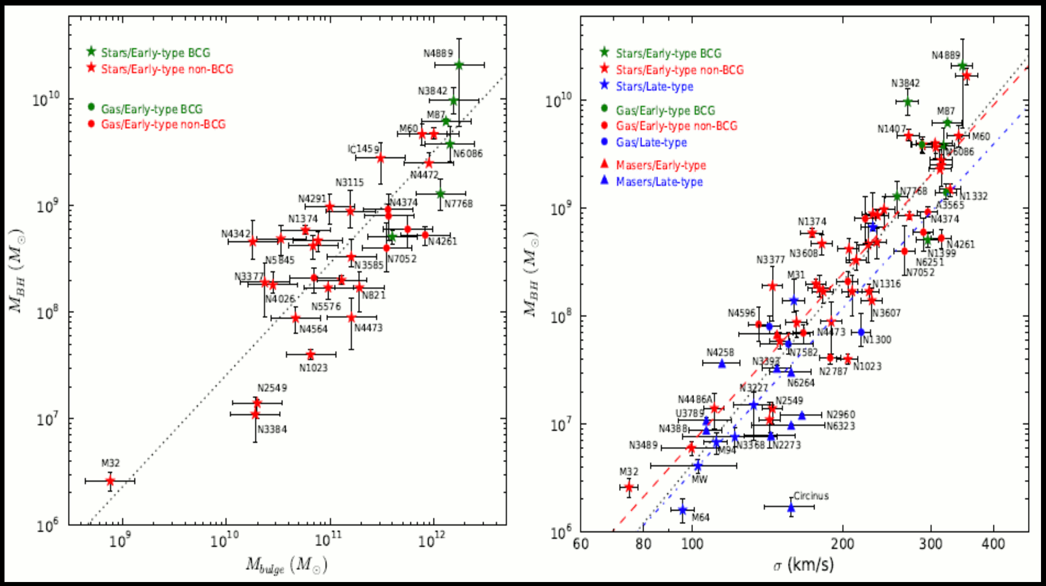

(Ferrarese & Merritt 2000, Gebhardt et al. 2000)

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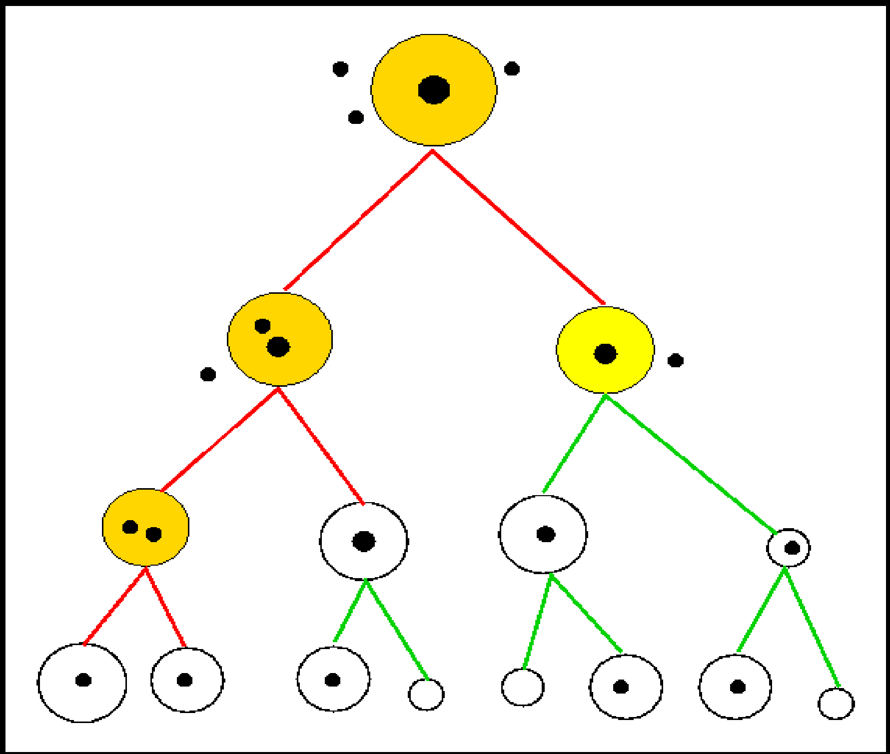
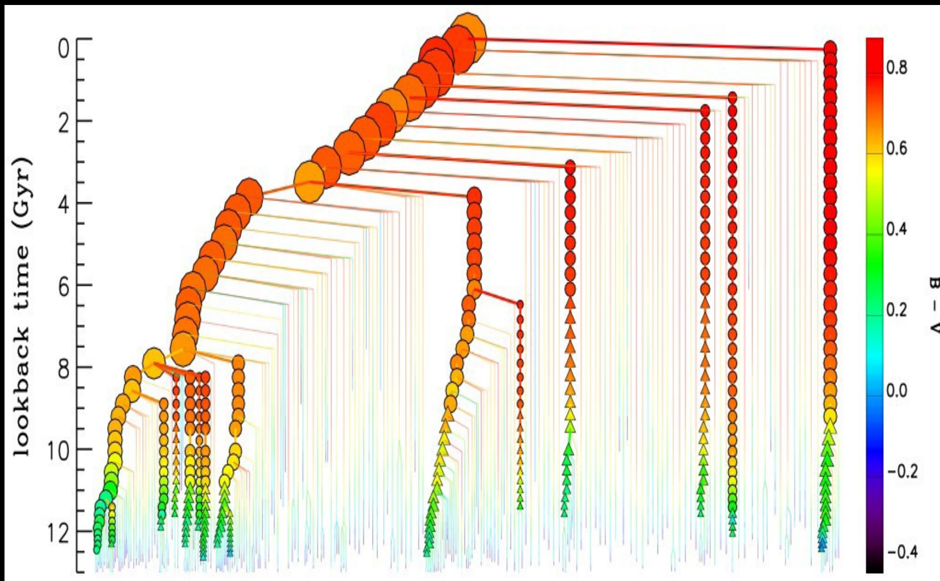


(Menou et al 2001, Volonteri et al. 2003)

Structure formation in a nutshell



(From de Lucia et al. 2006)

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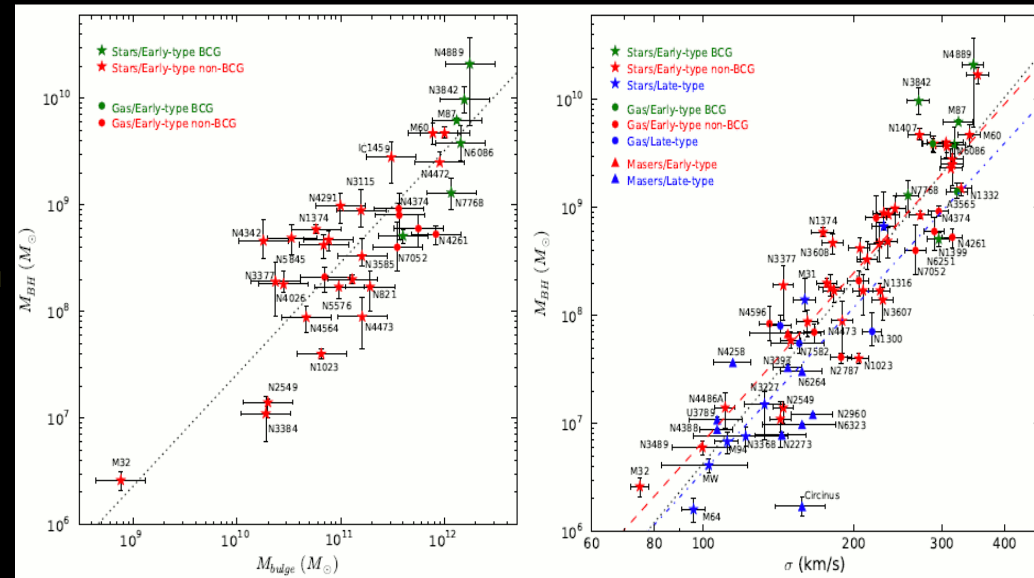

(Ferrarese & Merritt 2000, Gebhardt et al. 2000)

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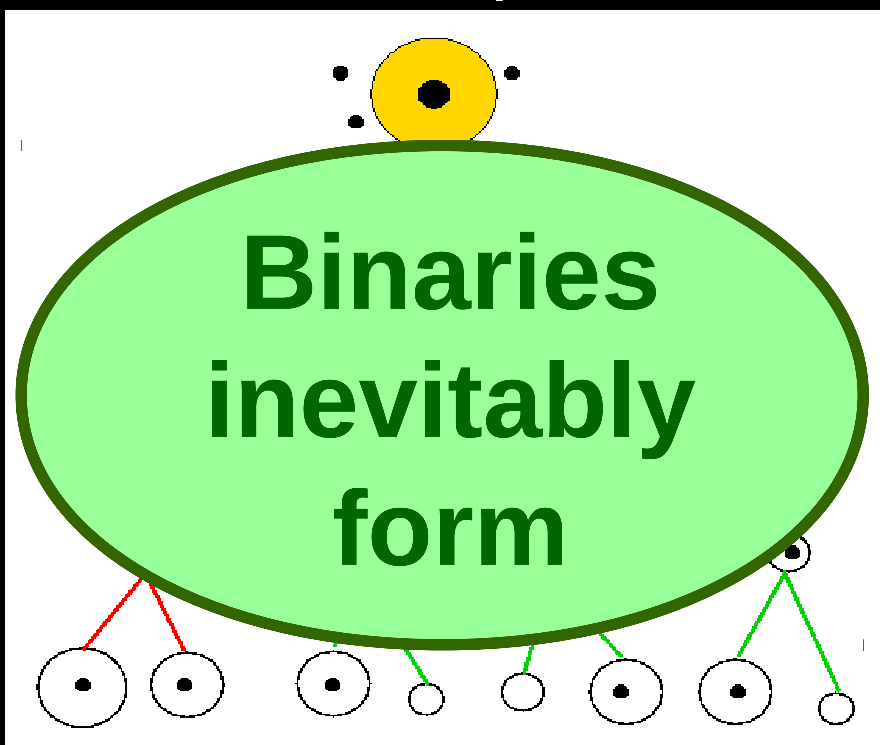
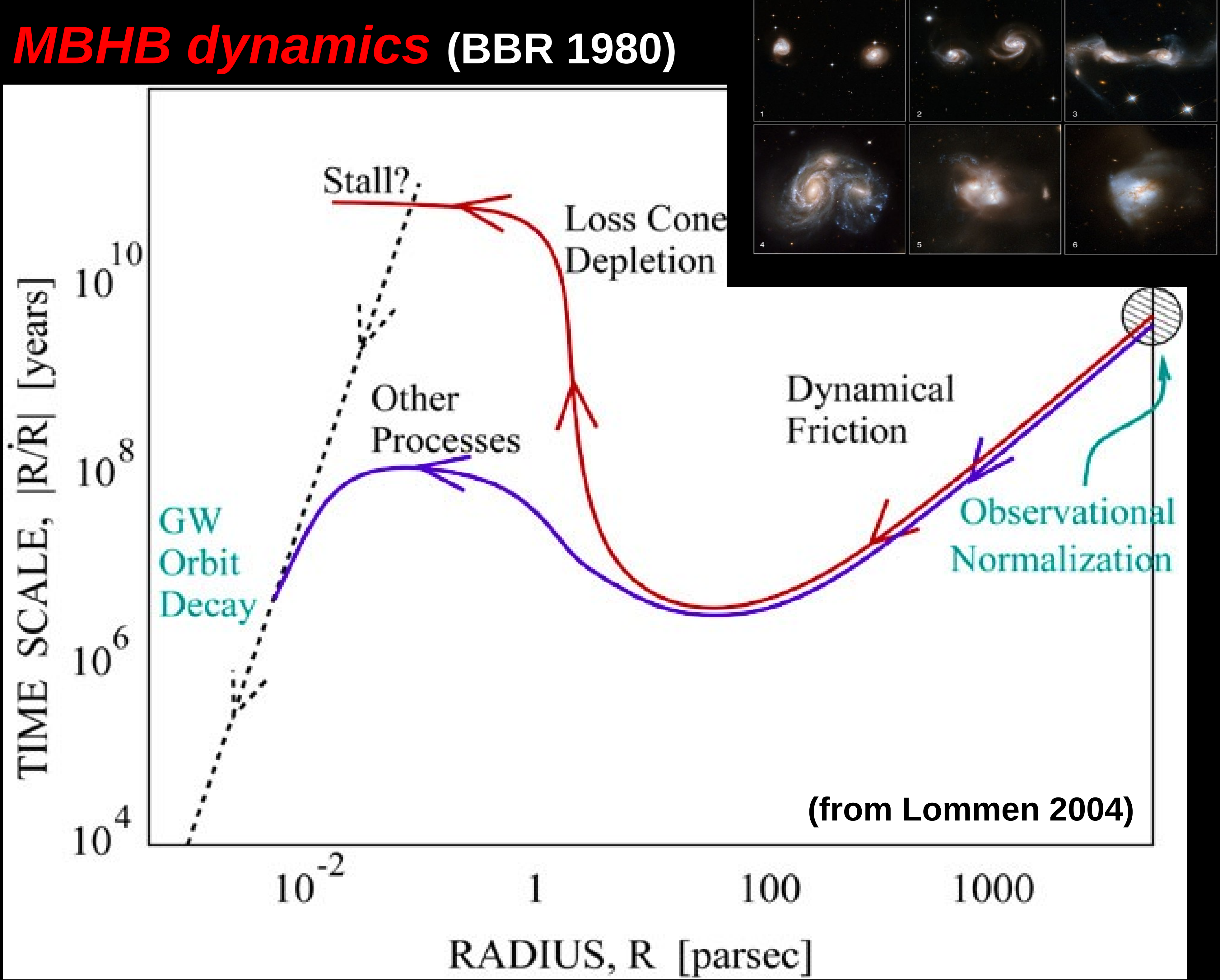


(Menou et al 2001, Volonteri et al. 2003)

- *Where and when do the first MBH seeds form?
- *How do they grow along the cosmic history?
- *What is their role in galaxy evolution?
- *What is their merger rate?
- *How do they pair together and dynamically evolve?

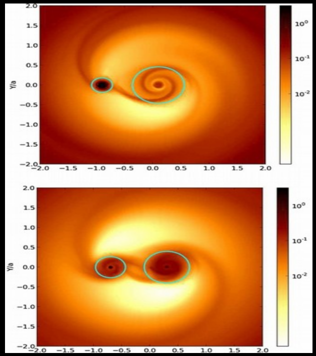
MBHB dynamics (BBR 1980)



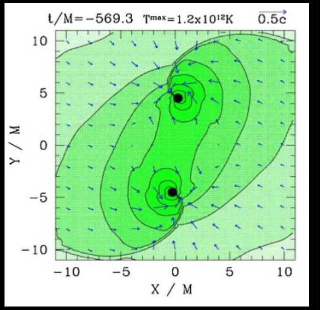
(from Lommen 2004)

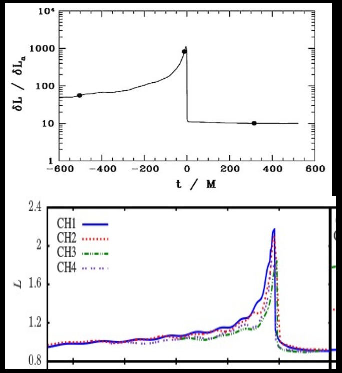
Associated electromagnetic signatures

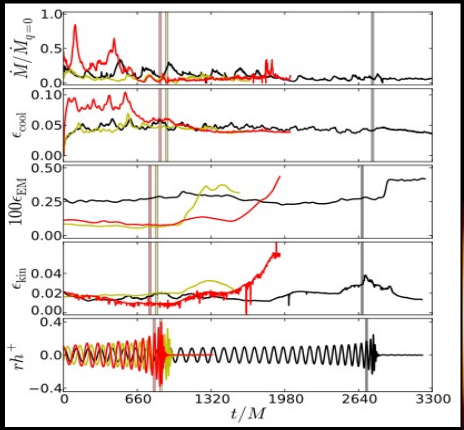
In the standard circumbinary disk scenario, the binary carves a cavity: no EM signal (Phinney & Milosavljevic 2005).
However, all simulations (hydro, MHD) showed significant mass inflow (Cuadra et al. 2009, Shi et al 2011, Farris et al 2014, Tang et al. 2018...)

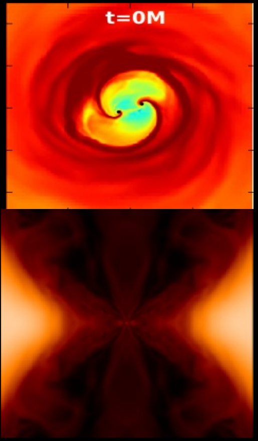


Simulations in hot gaseous clouds. Significant flare associated to merger (Bode et al. 2010, 2012, Farris et al 2012)



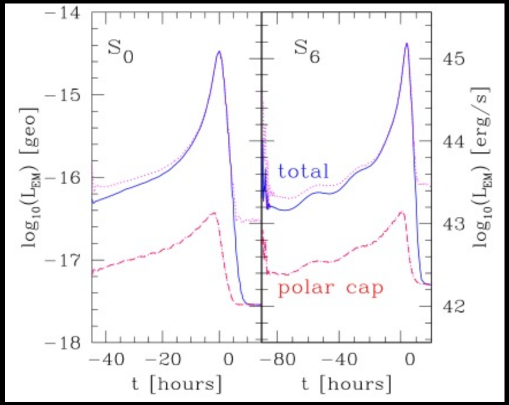


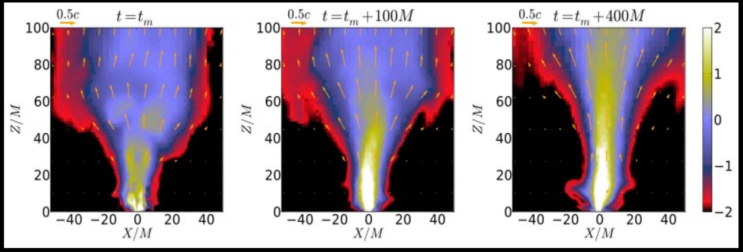




Simulations in disk-like geometry. Variability, but much weaker and unclear signatures
(Bode et al. 2012, Gold et al. 2014)

Full GR force free electrodynamics
(Palenzuela et al. 2010, 2012)





See Zoltan's talk!

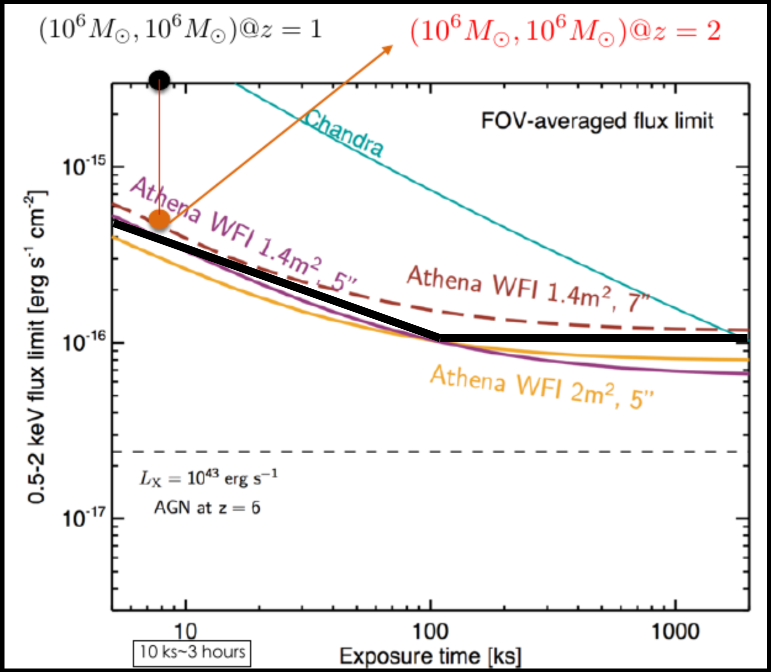
-Max ignorance approach: assume a generic post-merger persistent Eddington-limited emission $L_{\rm Edd} = 1.26 \times 10^{38}\,(M/M_\odot)\,{\rm erg\,s^{-1}}$ with 3% luminosity in the 2-10keV band. (Say a light-up of a persistent post-merger quasar).

-Assume nominal Athena flux limit

$$F_X = 3 \times 10^{-17} \left(\frac{10^6\,{\rm sec}}{T}\right)^{1/2} {\rm erg\,cm^{-2}\,s^{-1}}$$

-Using LISA PE from Klein et al. 2016 we derive the median, 10% and 90% sky location accuracy as a function of SNR

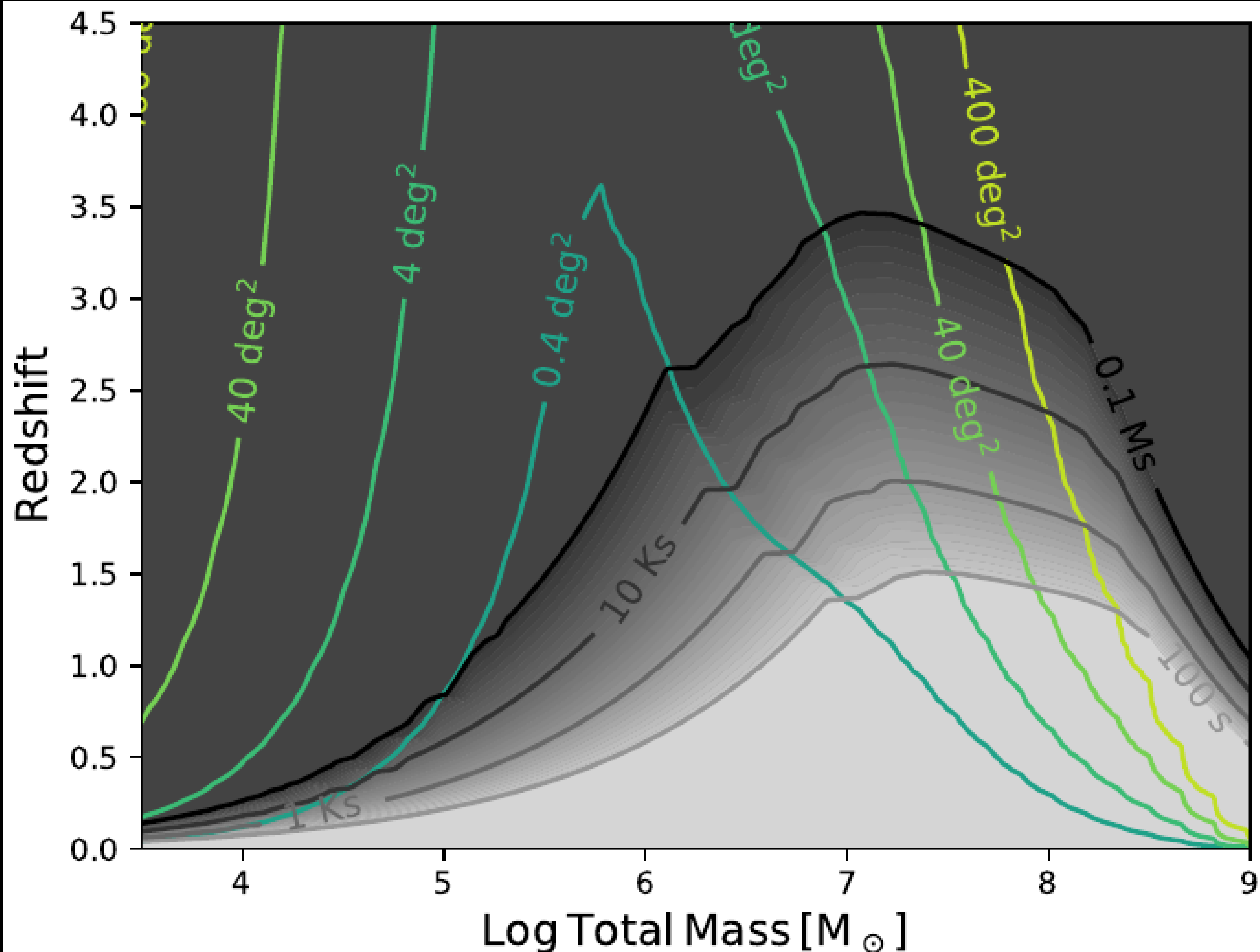
$$\Delta\Omega \approx 0.5 \left(\frac{\rho}{10^3}\right)^{-7/4} {\rm deg}^2$$



-We then compute rho (SNR) as a function of mass and redshift and convert that into $\Delta\Omega(M,z)$.

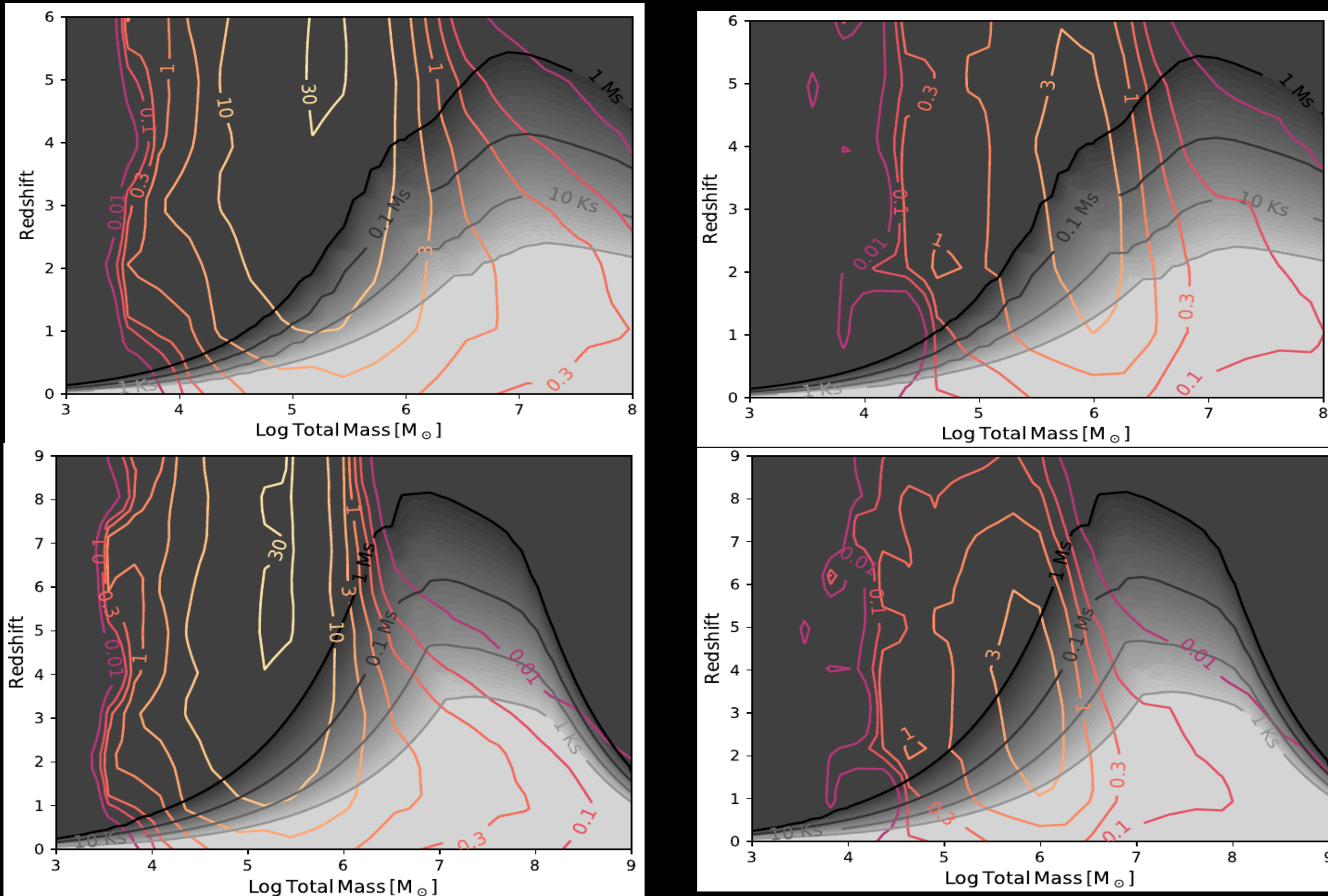
-finally we consider the total integration time required by Athena to cover $\Delta\Omega(M,z)$ at a depth allowing detection of the Eddington limited signal (including multiple pointings, when needed)

-We also check the DM halo mass of the merger host and compute the diffuse X-ray luminosity as $L_{X,\rm bol} = E(z)^{7/3} L_0 \left(\frac{M_{500}}{M_0}\right)^{\alpha}$



Redshift
Log Total Mass [M ⊙]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
4
5
6
7
8
9
40 deg²
4 deg²
0.4 deg²
400 deg²
40 deg²
0.1 Ms
10 Ks
1 Ks
100 s

How many events?



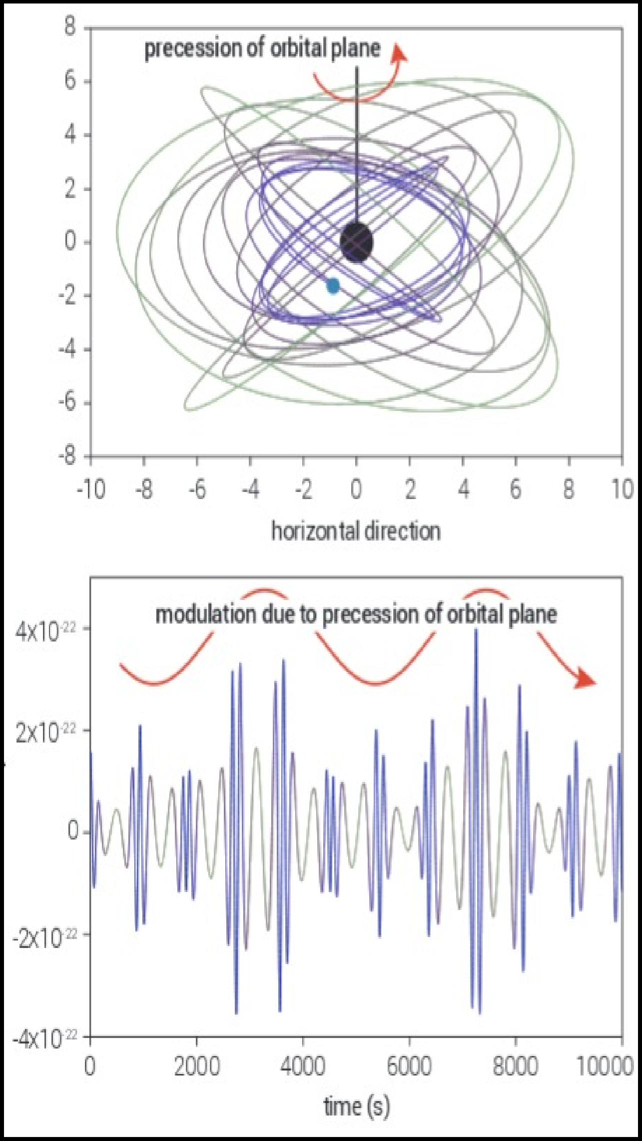
Several systems might be jointly detected by LISA and Athena

(Models from Klein+2016)

Extreme mass ratio inspirals (EMRIs)

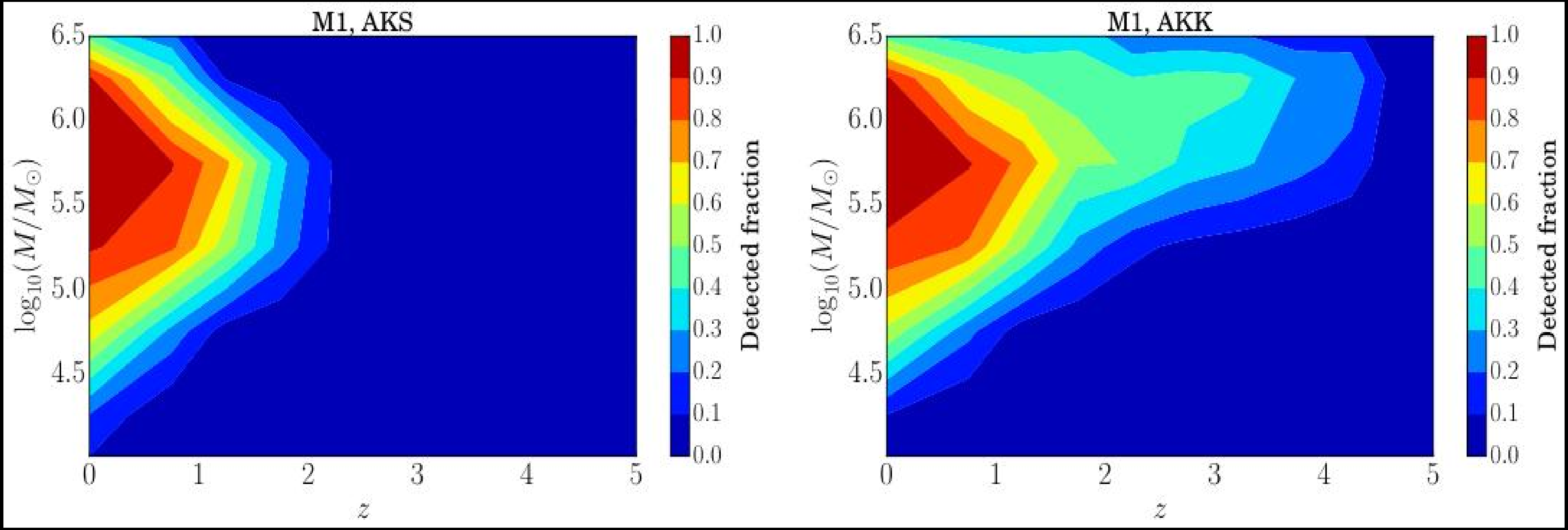
- *What is the mass distribution of stellar remnants at the galactic centres and what is the role of mass segregation and relaxation in determining the nature of the stellar populations around the nuclear black holes in galaxies?*
- *Are massive black holes as light as $\sim 10^5 M_\odot$ inhabiting the cores of low mass galaxies? Are they seed black hole relics? What are their properties?*

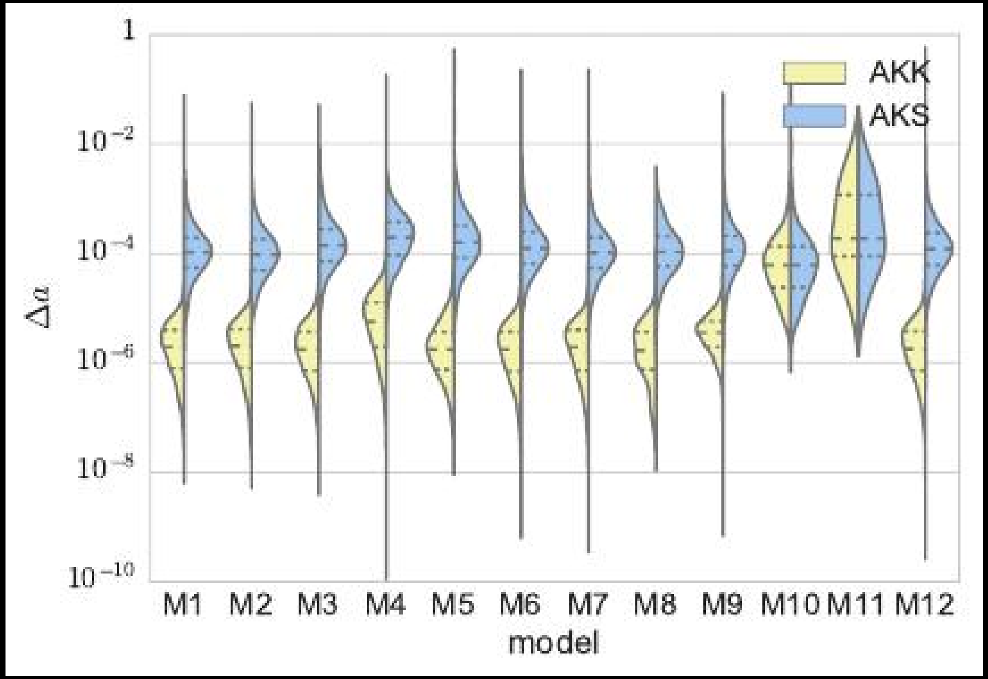
- *Does gravity travel at the speed of light ?*
- *Does the graviton have mass?*
- *How does gravitational information propagate: Are there more than two transverse modes of propagation?*
- *Does gravity couple to other dynamical fields, such as, massless or massive scalars?*
- *What is the structure of spacetime just outside astrophysical black holes? Do their spacetimes have horizons?*
- *Are astrophysical black holes fully described by the Kerr metric, as predicted by General Relativity?*

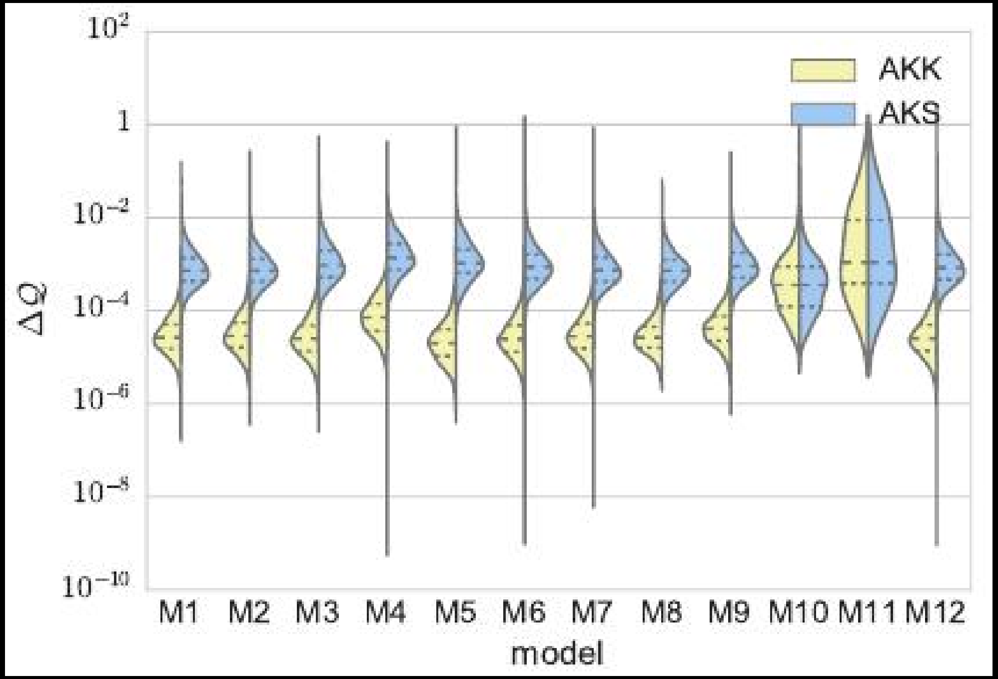


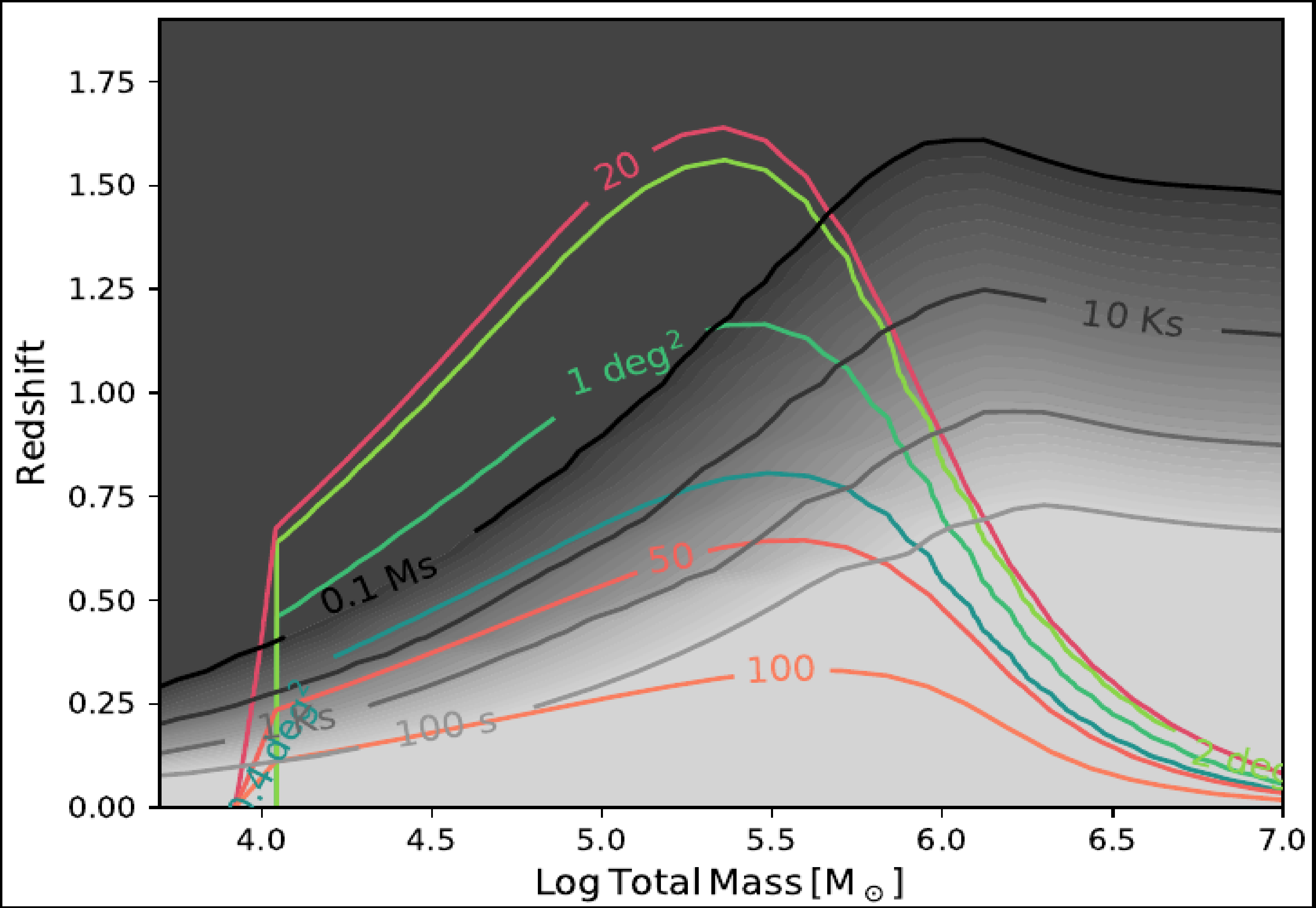
Selected results: LISA reach and parameter estimation

(Babak et al. 2018)

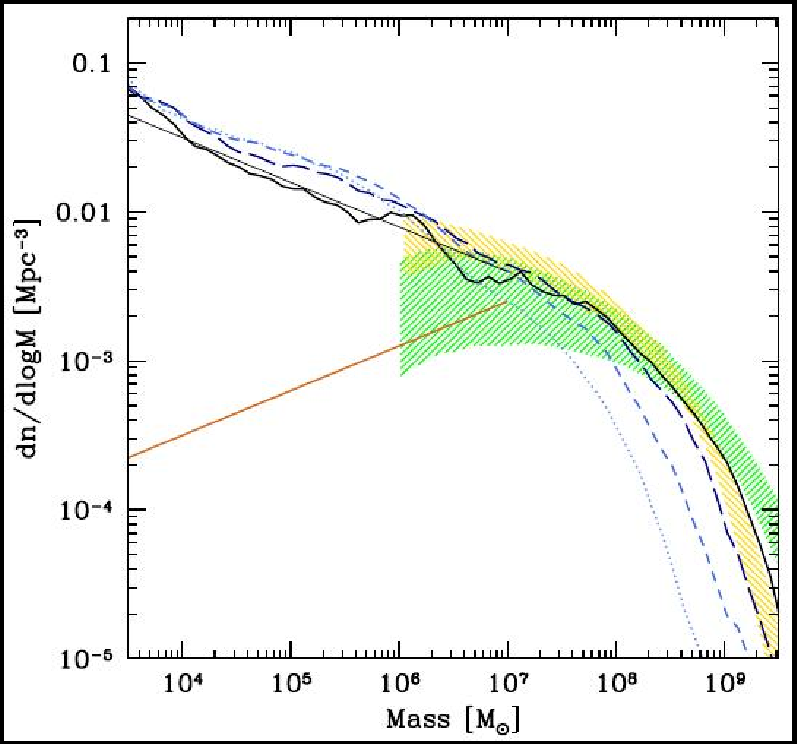








-Vast portion of parameter space can be covered with <10ks exposures
-if EMRI in AGN, drag can leave an imprint on the GW waveform
-some EMRIs at z<0.2-0.3 might have 1 single potential host in the errbox



Astrophysical uncertainties are huge:

-MBH mass function unknown below 10^6 solar masses

-distribution of compact objects (CO) around MBH (Preto & Amaro-Seoane 2010)?

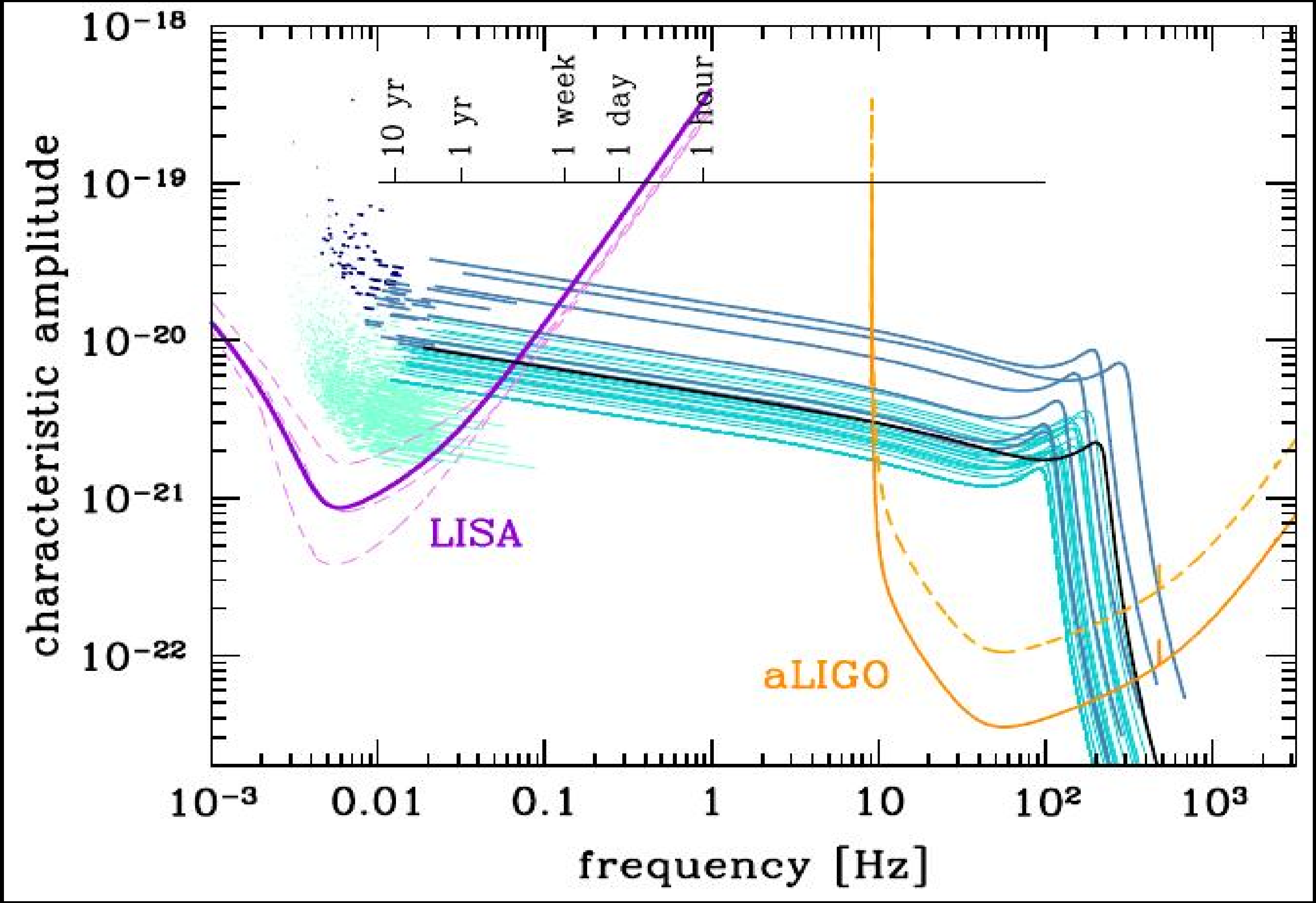
-are Cos inspiralling (thus producing EMRIs) or plunging (Merritt 2015)?

Using astrophysically motivated prescriptions we generated 12 models:

Model	Mass function	MBH spin	Cusp erosion	M–σ relation	N_p	CO mass [$M_\odot$]	EMRI rate [yr^{-1}] Total	Detected (AKK)	Detected (AKS)
M1	Barausse12	a98	yes	Gultekin09	10	10	1600	294	189
M2	Barausse12	a98	yes	KormendyHo13	10	10	1400	220	146
M3	Barausse12	a98	yes	GrahamScott13	10	10	2770	809	440
M4	Barausse12	a98	yes	Gultekin09	10	30	520 (620)	260	221
M5	Gair10	a98	no	Gultekin09	10	10	140	47	15
M6	Barausse12	a98	no	Gultekin09	10	10	2080	479	261
M7	Barausse12	a98	yes	Gultekin09	0	10	15800	2712	1765
M8	Barausse12	a98	yes	Gultekin09	100	10	180	35	24
M9	Barausse12	aflat	yes	Gultekin09	10	10	1530	217	177
M10	Barausse12	a0	yes	Gultekin09	10	10	1520	188	188
M11	Gair10	a0	no	Gultekin09	100	10	13	1	1
M12	Barausse12	a98	no	Gultekin09	0	10	20000	4219	2279

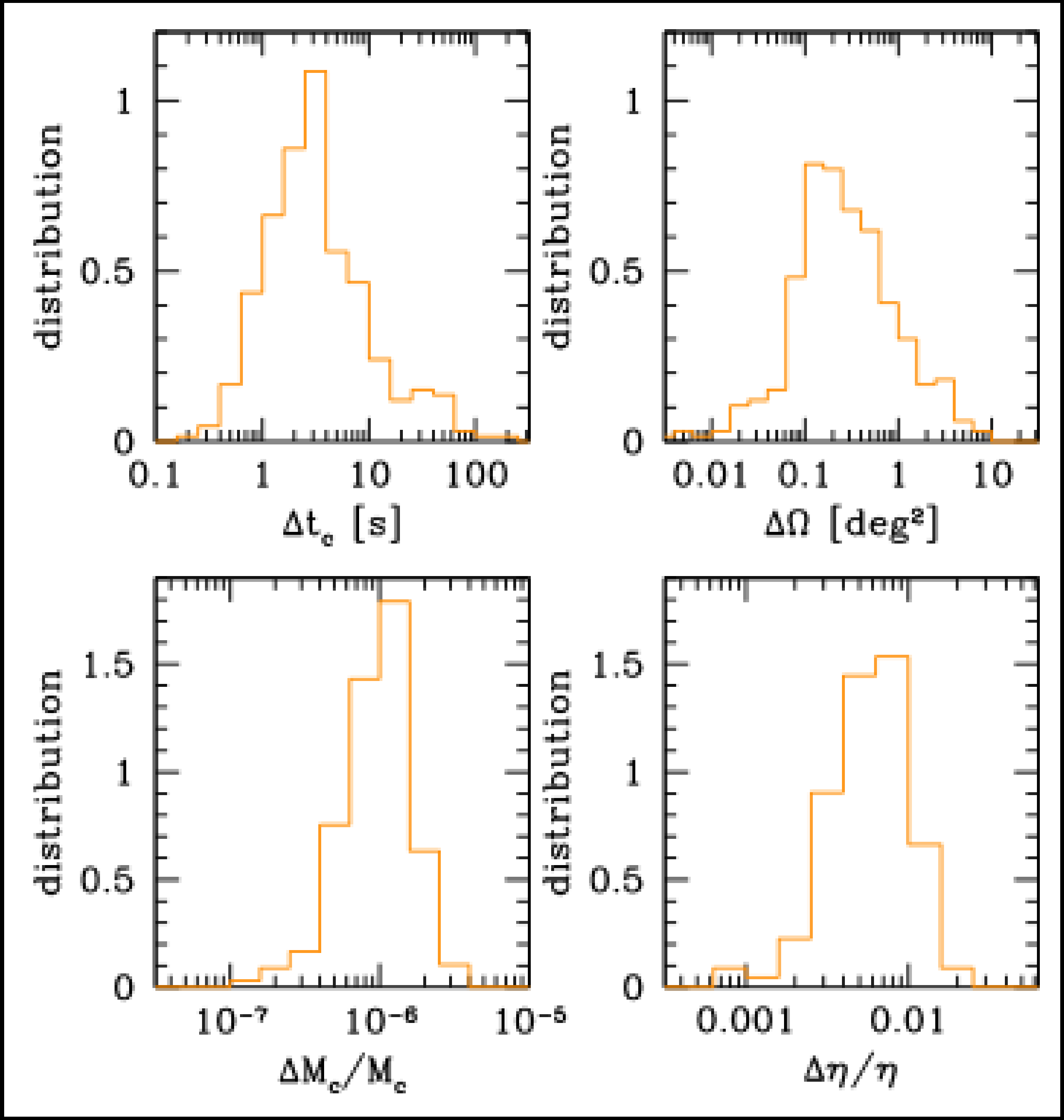
Implications of GW150914: multi-band GW astronomy

(AS 2016, PRL 116, 1102)



BHB will be detected by LISA and cross to the LIGO/Virgo band, assuming a 5 year operation of LISA.

Sky pre-localization and coincident EM campaigns



System crossing to the aLIGO/Virgo band can be located with sub deg^2 precision (Klein et al. In prep.)

Merger time can be predicted within 10 seconds (but see Bonvin et al. 2016)

Make possible to pre-point all instruments: open the era of coincident GW-EM astronomy (even though a counterpart is not expected).

The appeal of LISA is that it provides precise sky localizations and merger time weeks prior to merger!

Suppose that an exotic mechanism converts part of the rest mass in KeV photons

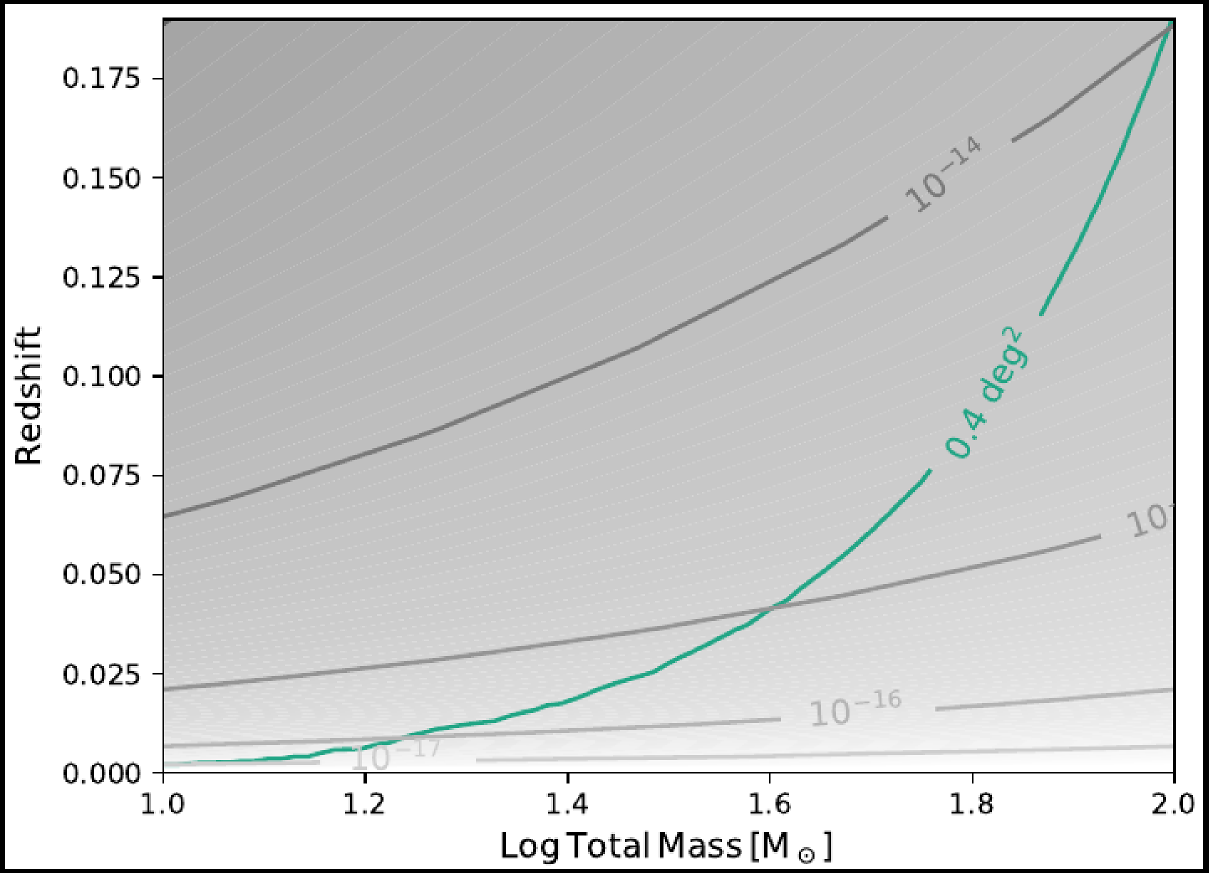
$$N_\gamma \approx 10^{63} \left(\frac{M}{M_\odot}\right) \left(\frac{E_\gamma}{1\,\mathrm{keV}}\right)^{-1}$$

$$N_{\rm WFI} = 10^{14} \left(\frac{M}{M_\odot}\right) \left(\frac{A_{\rm WFI}}{1\,\mathrm{m}^2}\right) \left(\frac{D_L}{300\mathrm{Mpc}}\right)^{-2} \mathrm{cts}$$

$$\bar{N}_{\rm bkg} \approx 0.5 \frac{M}{M_\odot} \left(\frac{\Delta E_\gamma}{1\,\mathrm{keV}}\right) \left(\frac{A_{\rm WFI}}{1\,\mathrm{m}^2}\right) \mathrm{cts}$$

Athena can provide stringent limits on the efficiency conversion (amend calculation)

$$\varepsilon_{\rm th} = \frac{N_{\rm min}}{N_{\rm WFI}} = 5\times 10^{-14} \left(\frac{M}{M_\odot}\right)^{-1/2} \left(\frac{D_L}{300\mathrm{Mpc}}\right)^{-2}$$



CONCLUSIONS

-LISA and Athena WFI capability overlap is significant in a large portion of the astrophysically interesting parameter space → Large discovery potential

-Joint observations of MBHB in the range 10^6-10^7 solar masses possible to z~3-4 for typical events and 6-7 for the best 10% of LISA localized events (post merger).

-AGNs associated to typical EMRIs (if any) detectable by Athena in less than 10ks

-For LIGO/Virgo–like events, mass to energy conversion efficiency down to 10^{-16} can be probed

-Counterparts?