LISA science

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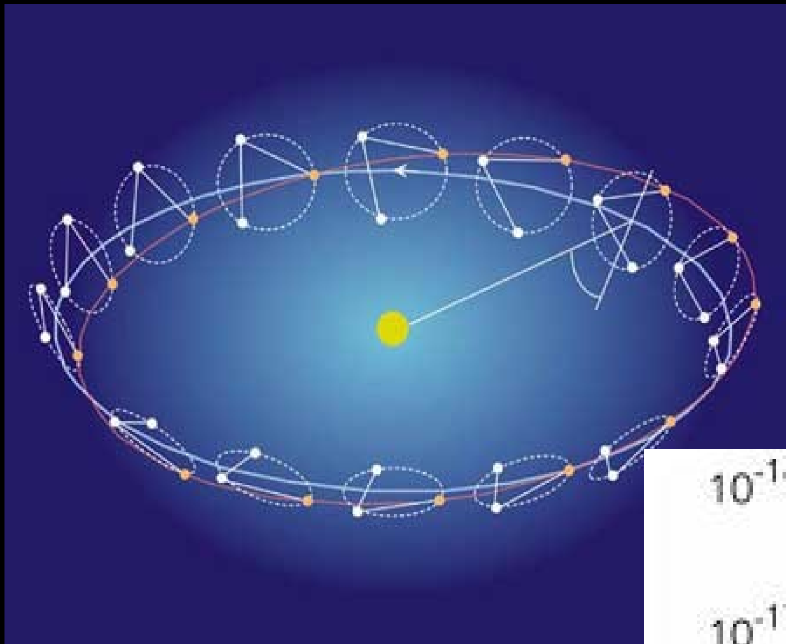
The Laser Interferometer Space Antenna

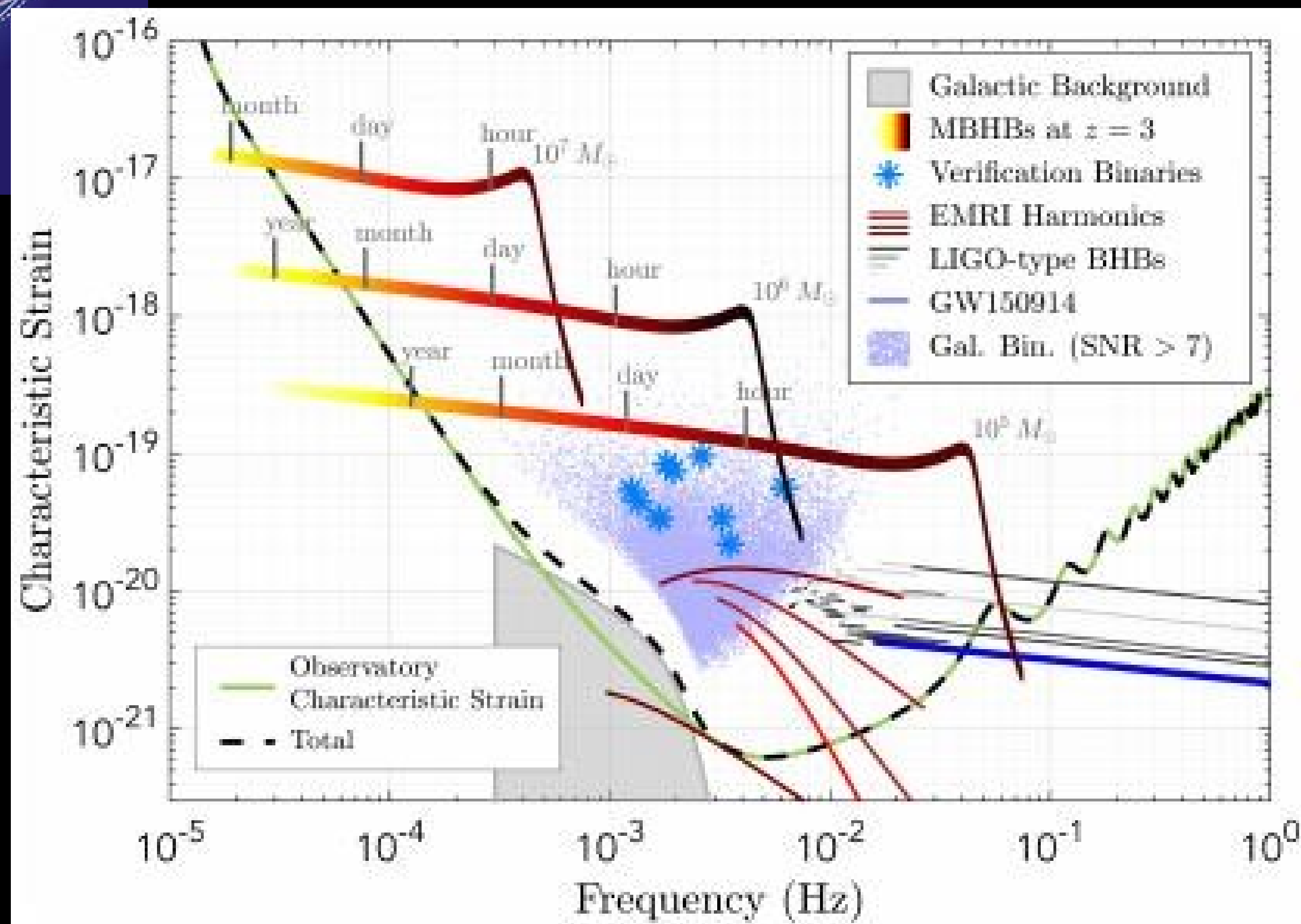


Sensitive in the mHz frequency range where massive black hole (MBH) binary (MBHB) evolution is fast (chirp)

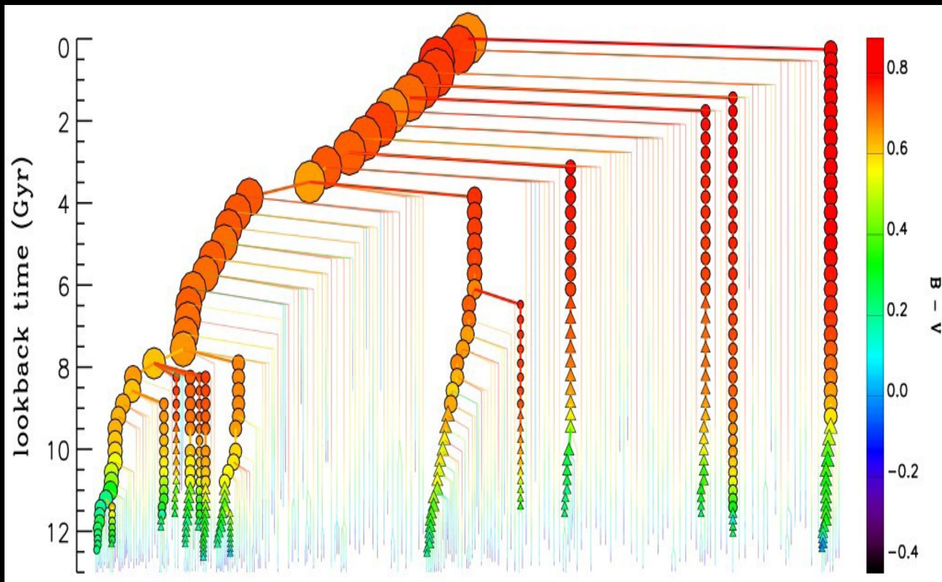
Observes the full inspiral/merger/ringdown

3 satellites trailing the Earth connected through laser links

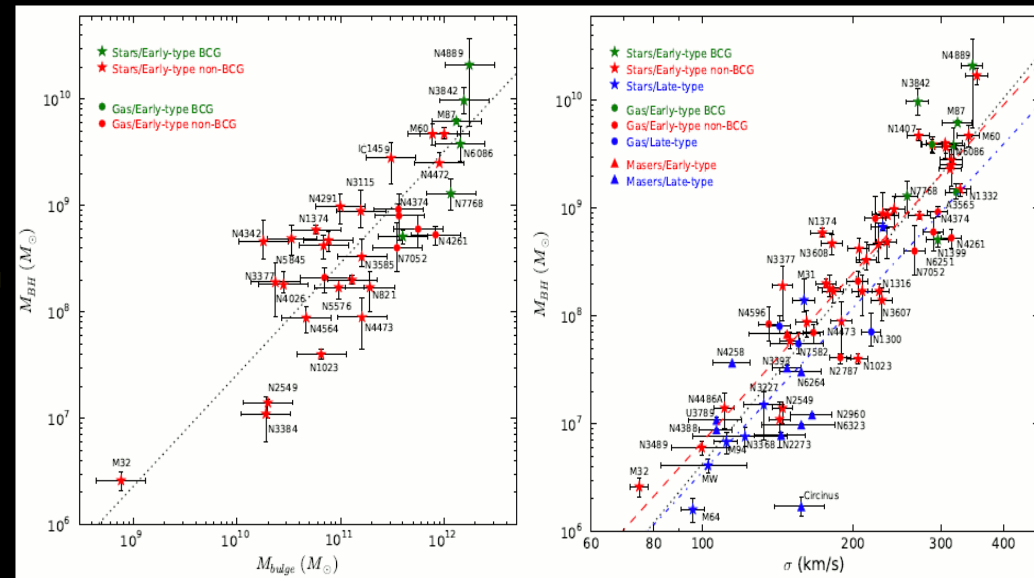
Proposed baseline:
2.5M km armlength
6 laser links
4 yr lifetime (10 yr goal)



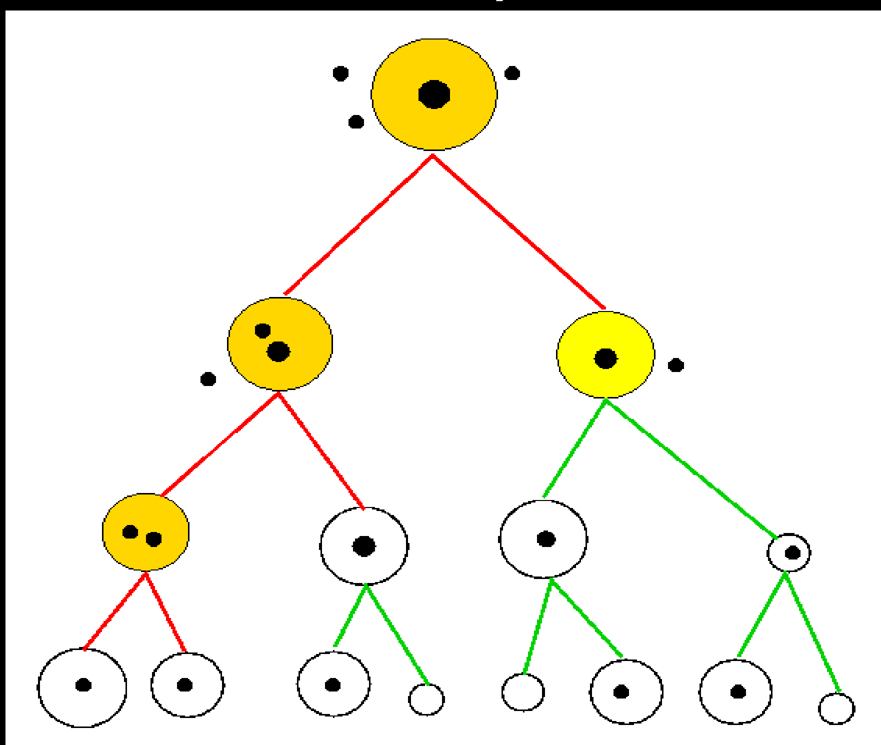
MBH evolution in a nutshell



(From de Lucia et al. 2006)

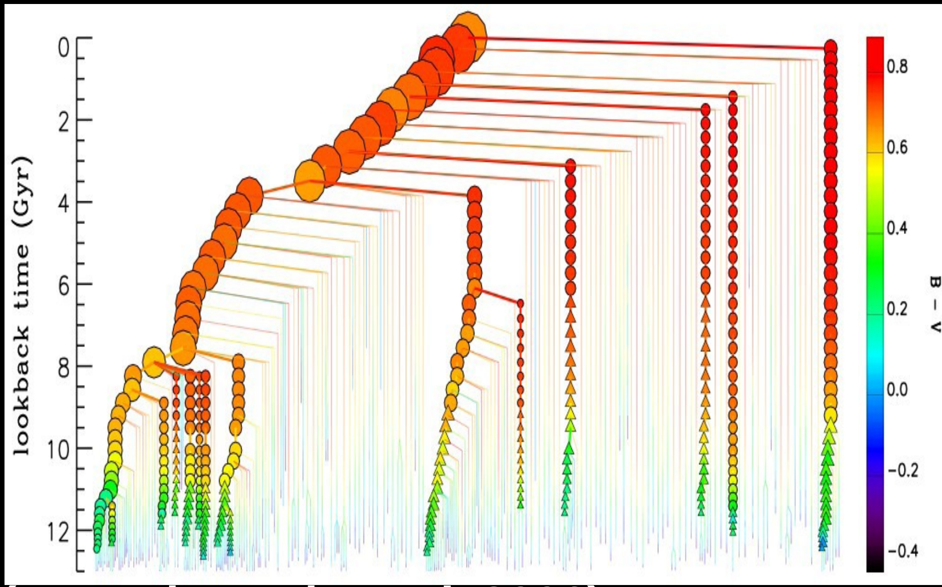


(Ferrarese & Merritt 2000, Gebhardt et al. 2000)



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

MBH evolution in a nutshell



(From de Lucia et al. 2006)

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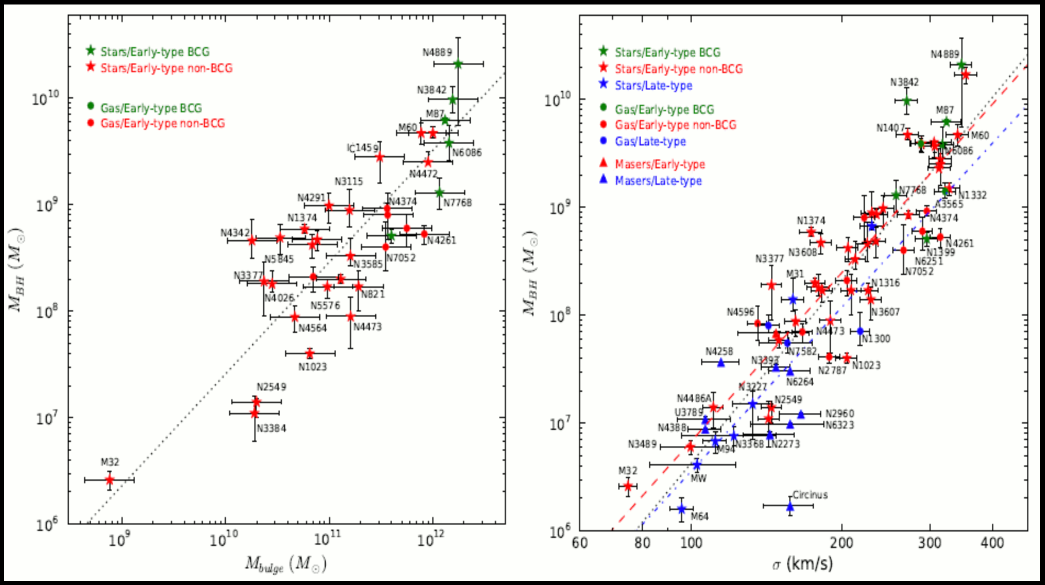

(Ferrarese & Merritt 2000, Gebhardt et al. 2000)

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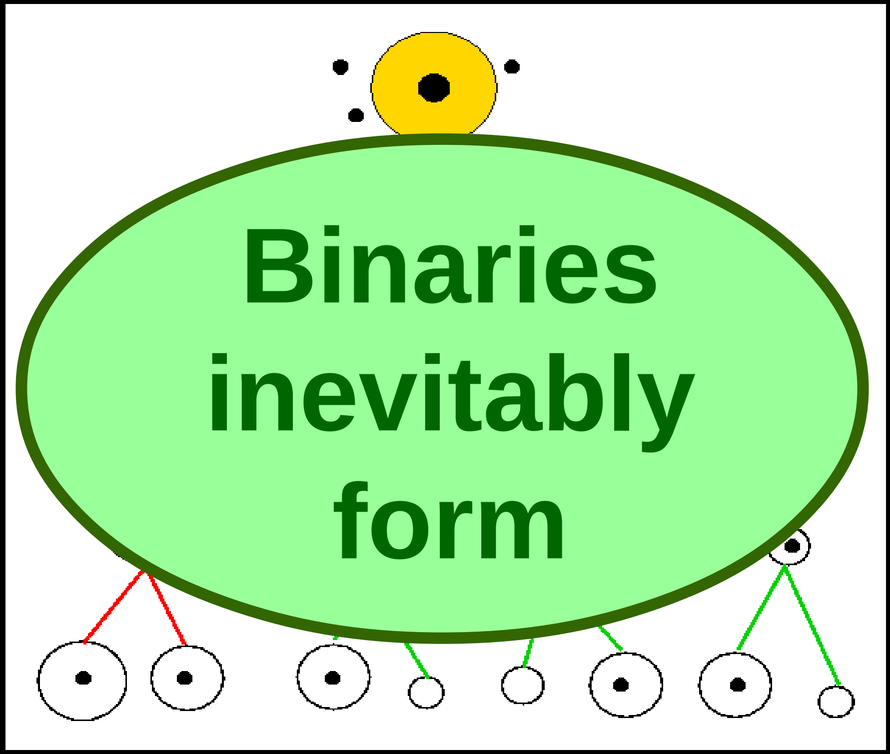
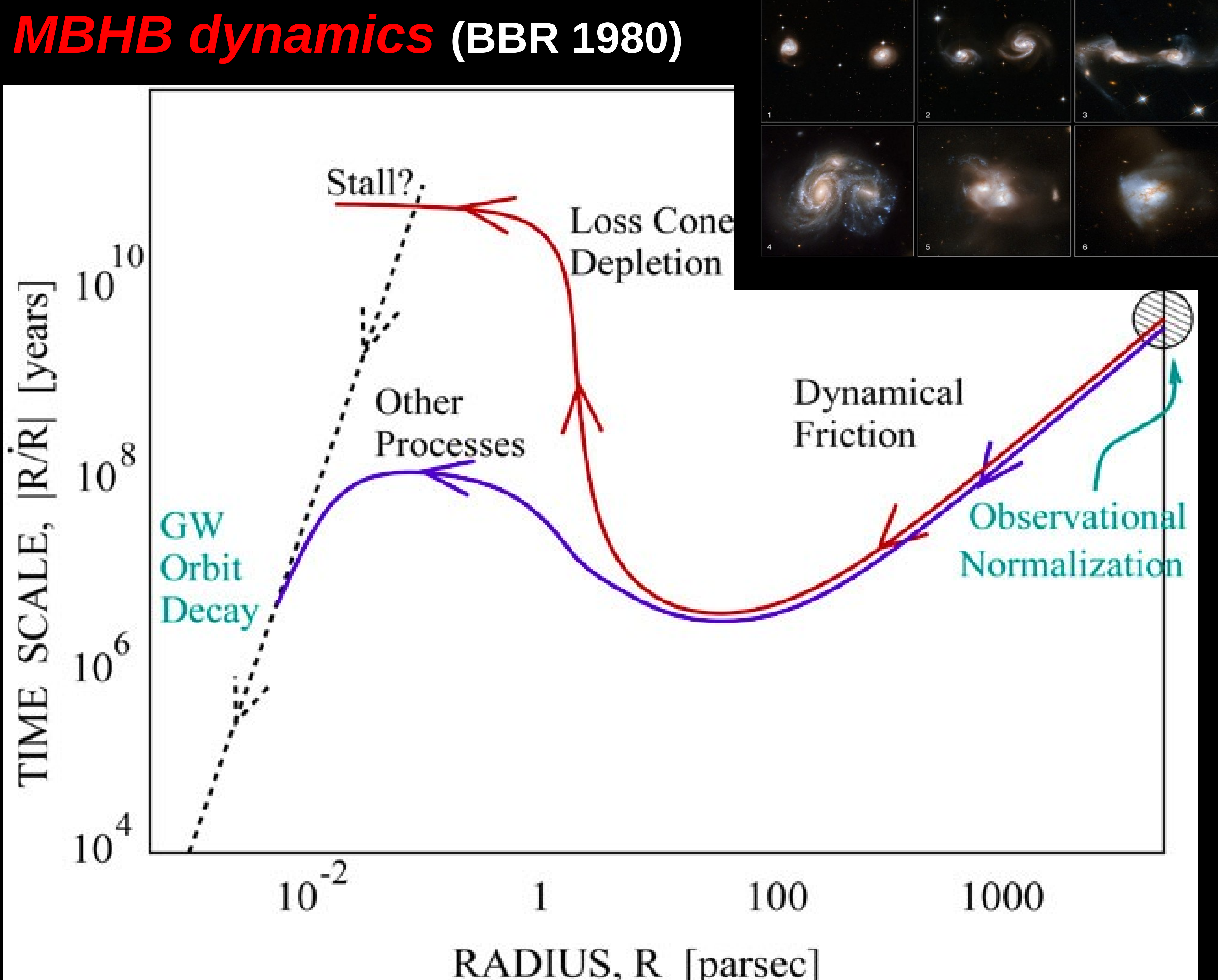
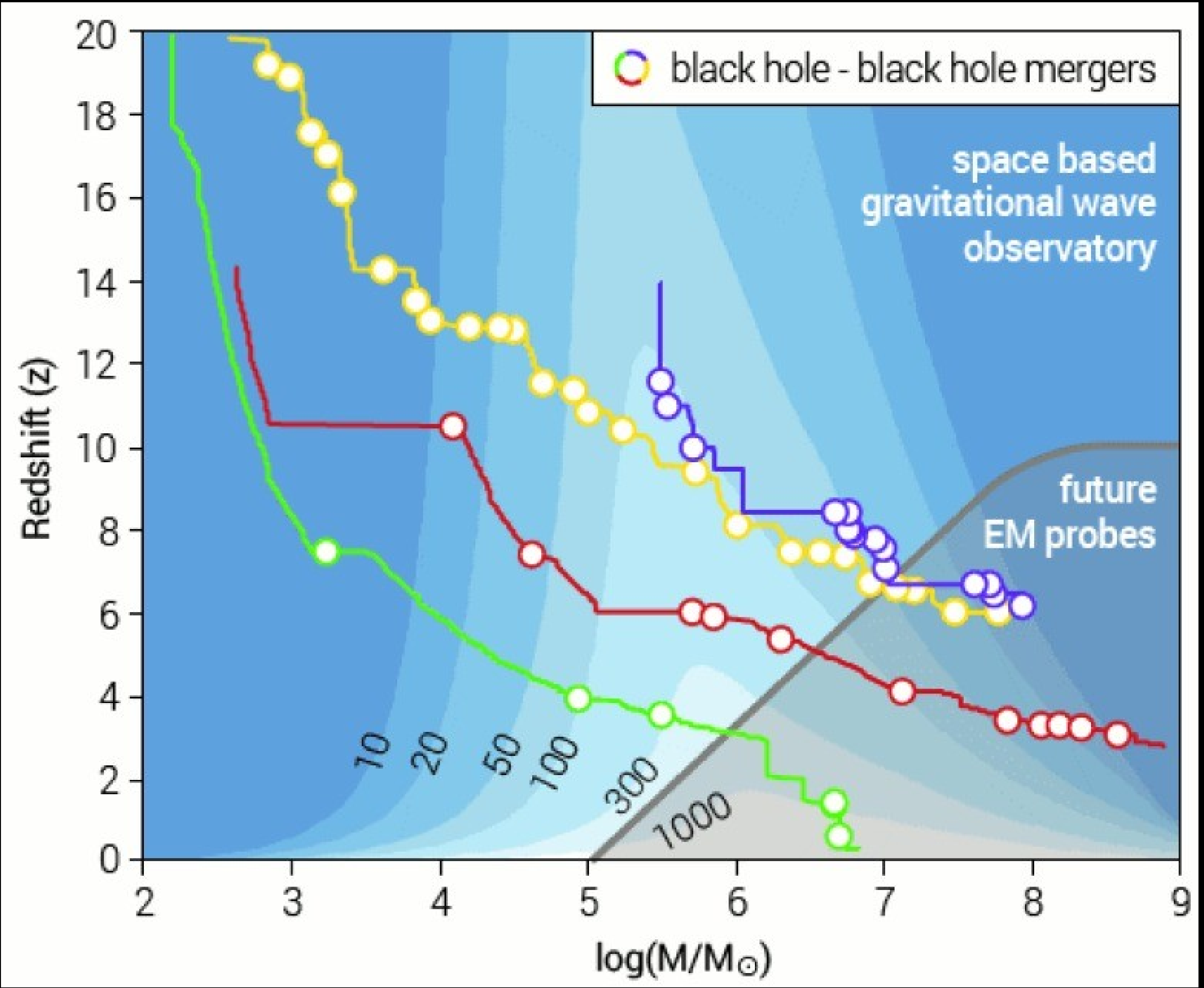


(Menou et al 2001, Volonteri et al. 2003)

*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)**





black hole - black hole mergers
space based
gravitational wave
observatory
future
EM probes
10
20
50
100
300
1000
Redshift (z)
log(M/M⊙)

Summary of LISA parameter estimation

Assuming 4 years of operation and 6 links:

~100+ detections

~100+ systems with sky localization to 10 deg2

~100+ systems with individual masses determined to 1%

~50 systems with primary spin determined to 0.01

~50 systems with secondary spin determined to 0.1

~50 systems with spin direction determined within 10deg

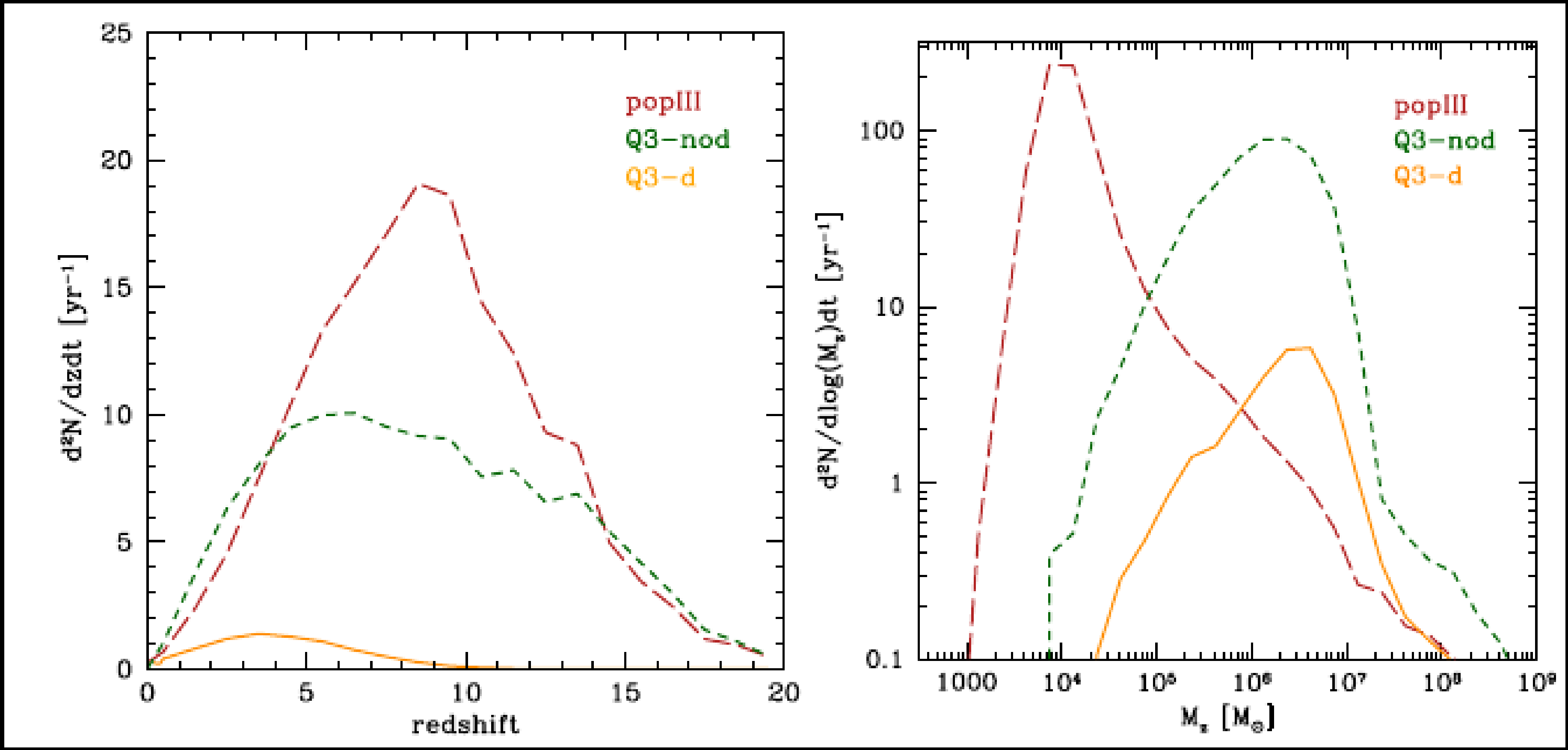
~30 events with final spin determined to 0.1

MBHB population models

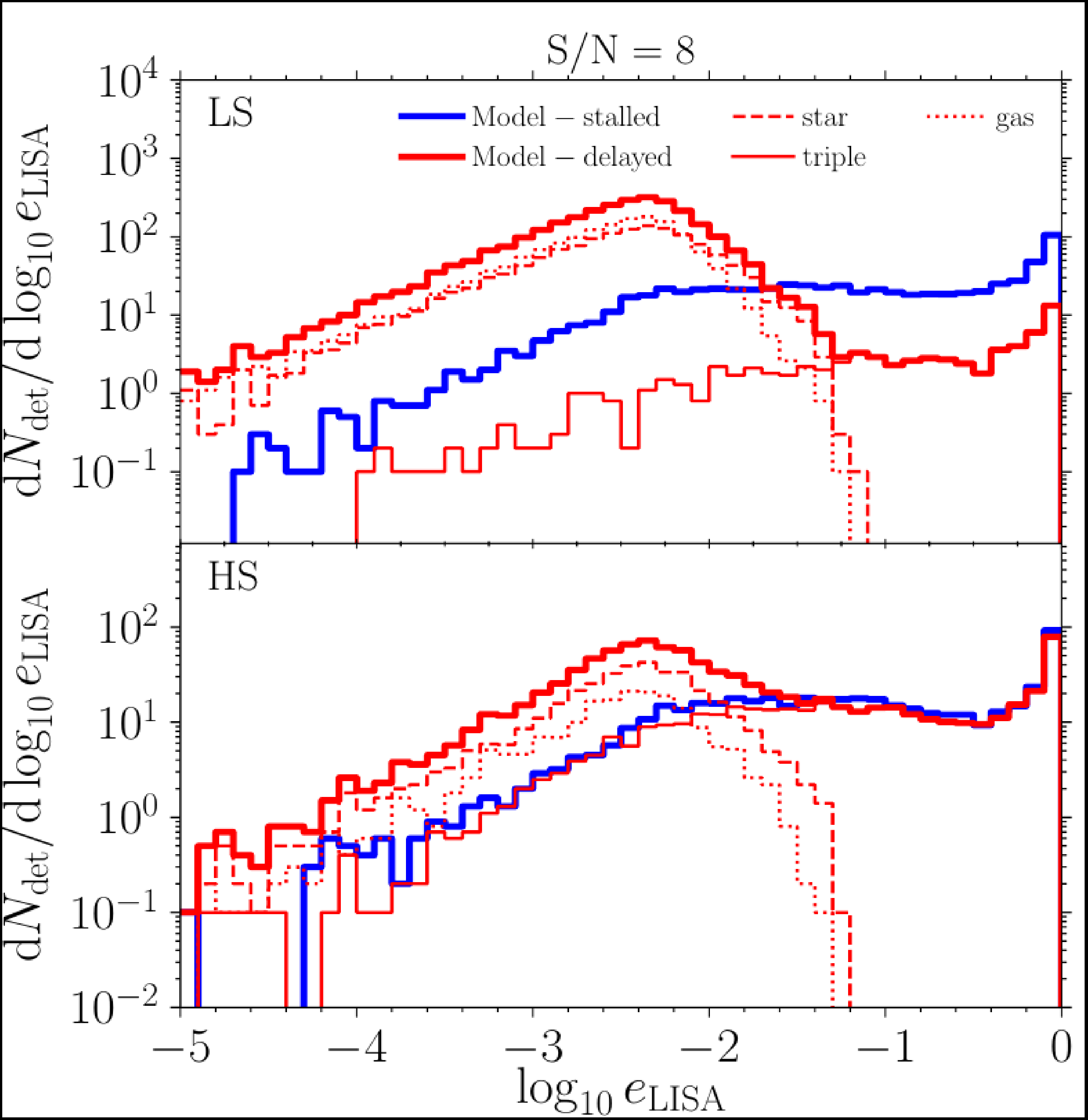
Semianalytic models for galaxy and MBH formation and evolution (Barausse).

The explored scenarios cover a wide range of merger histories:

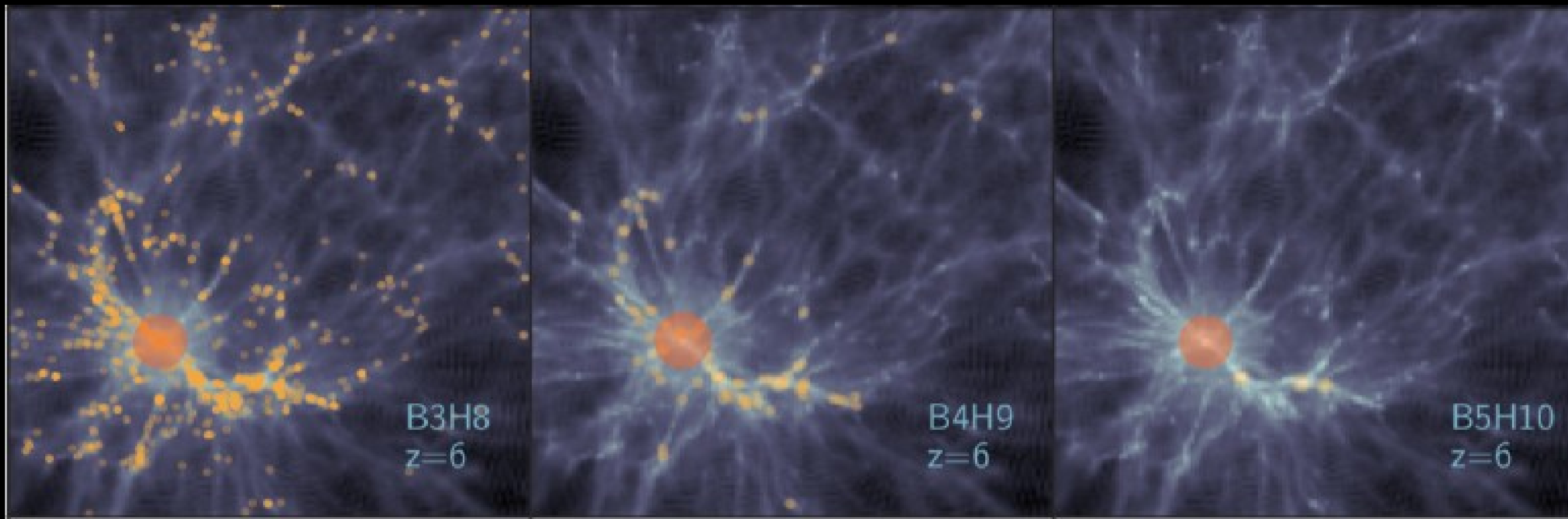
- -Heavy seeds no time delays
- -Heavy seeds time delays
- -PopIII seeds time delays



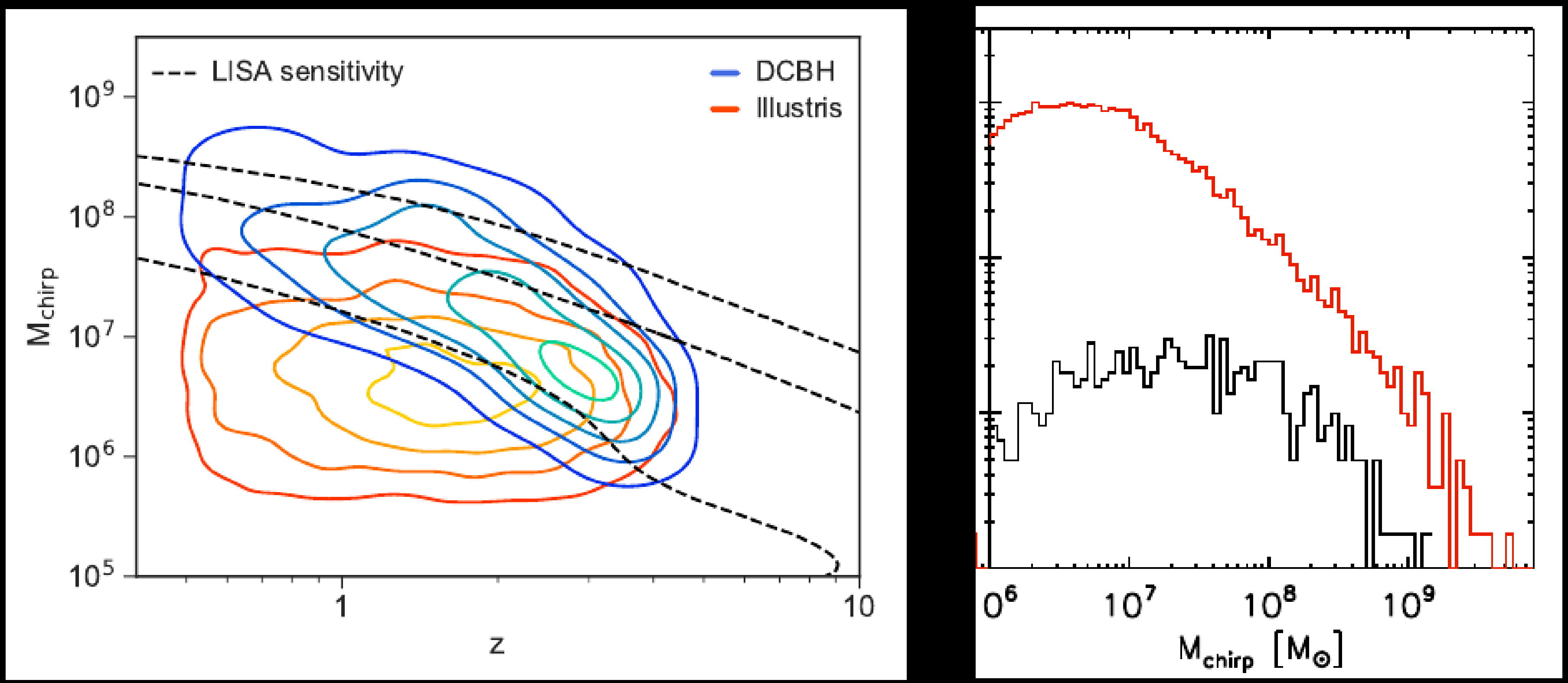
(Bonetti+ 18)



S/N = 8
LS
Model – stalled
Model – delayed
star
triple
gas
HS
$\mathrm{d}N_{\mathrm{det}}/\mathrm{d}\log_{10} e_{\mathrm{LISA}}$
$\log_{10} e_{\mathrm{LISA}}$



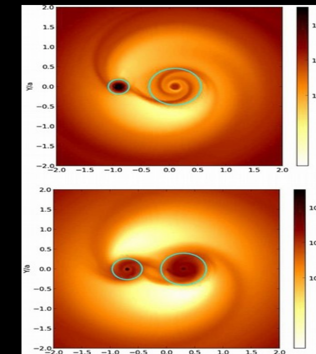
(Huang+, BlueTides sim)



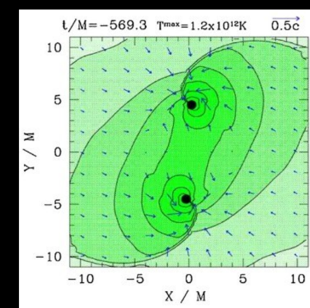
(De Graf & Sijacki, Illustris sim….see also Salcido+, EAGLE sim)

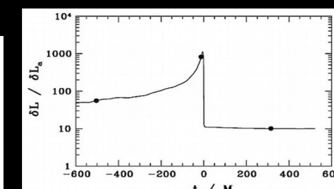
Associated electromagnetic signatures?

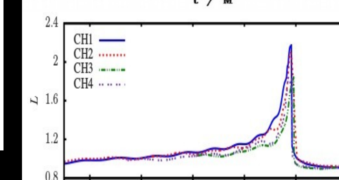
In the standard circumbinary disk scenario, the binary carves a cavity: no EM signal (Phinney & Milosavljevic 2005).
However, all simulations (hydro, MHD) showed significant mass inflow (Cuadra et al. 2009, Shi et al 2011, Farris et al 2014...)

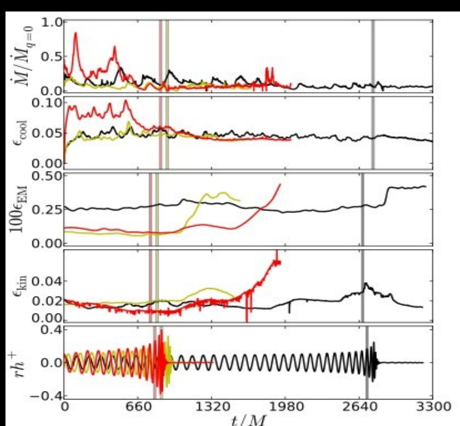


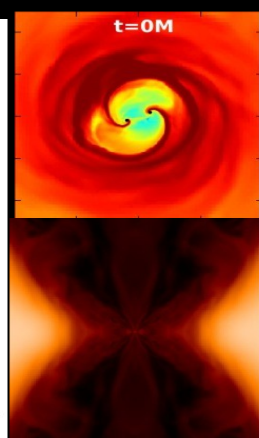
Simulations in hot gaseous clouds. Significant flare associated to merger (Bode et al. 2010, 2012, Farris et al 2012)





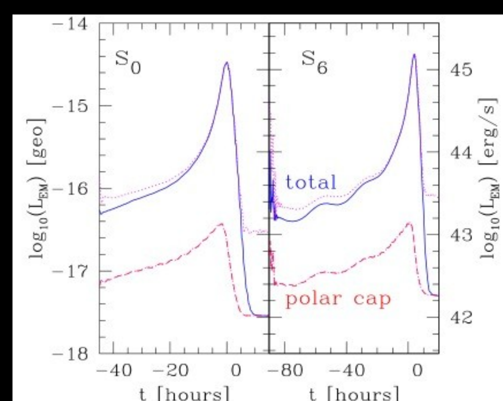


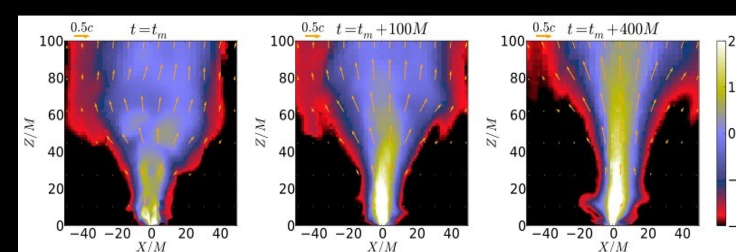




Simulations in disk-like geometry. Variability, but much weaker and unclear signatures (Bode et al. 2012, Gold et al. 2014)

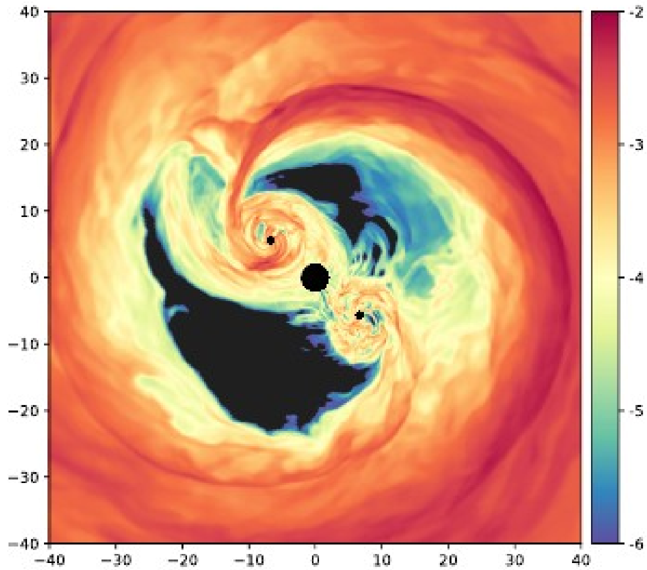
Full GR force free electrodynamics (Palenzuela et al. 2010, 2012)

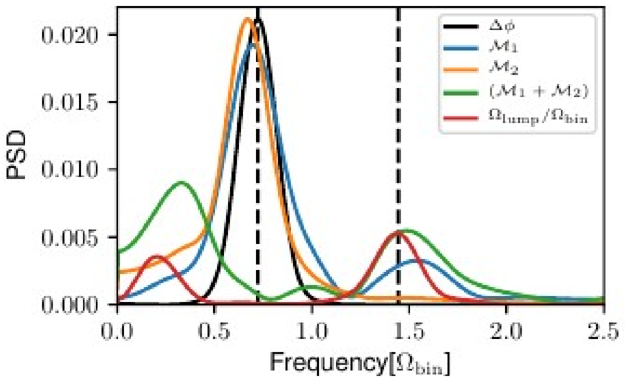




Pre-merge/post-decoupling phase
probing accretion in variable spacetimes with GR MHD simulations

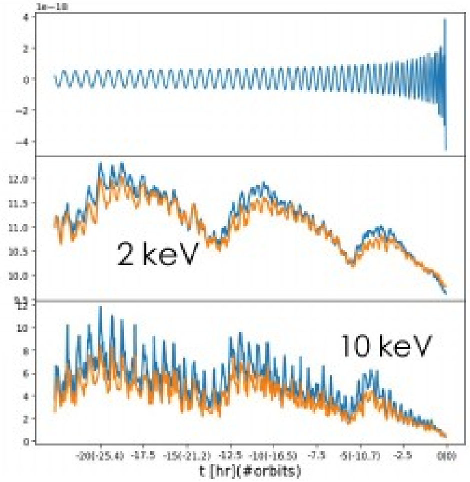
- cavity contains considerable amount of gas (thick discs)
- black holes remain surrounded by gas that follows the binary - dense streams feed the two black holes - mini discs
- expected periodicity commensurate with the fluid patterns - beat frequency: lump and orbital period
- discs are not any longer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



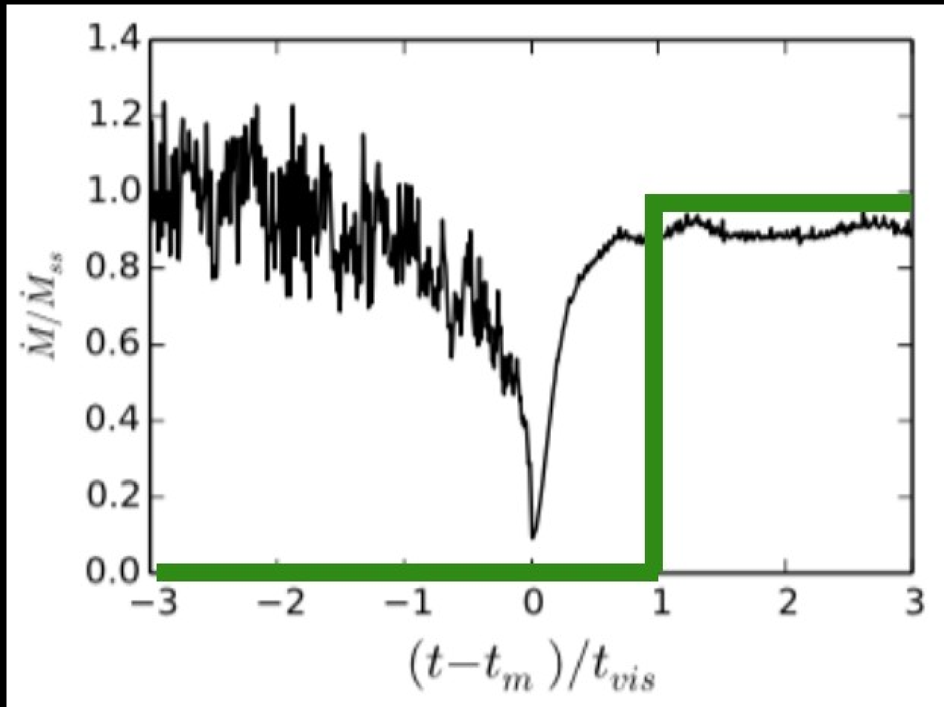


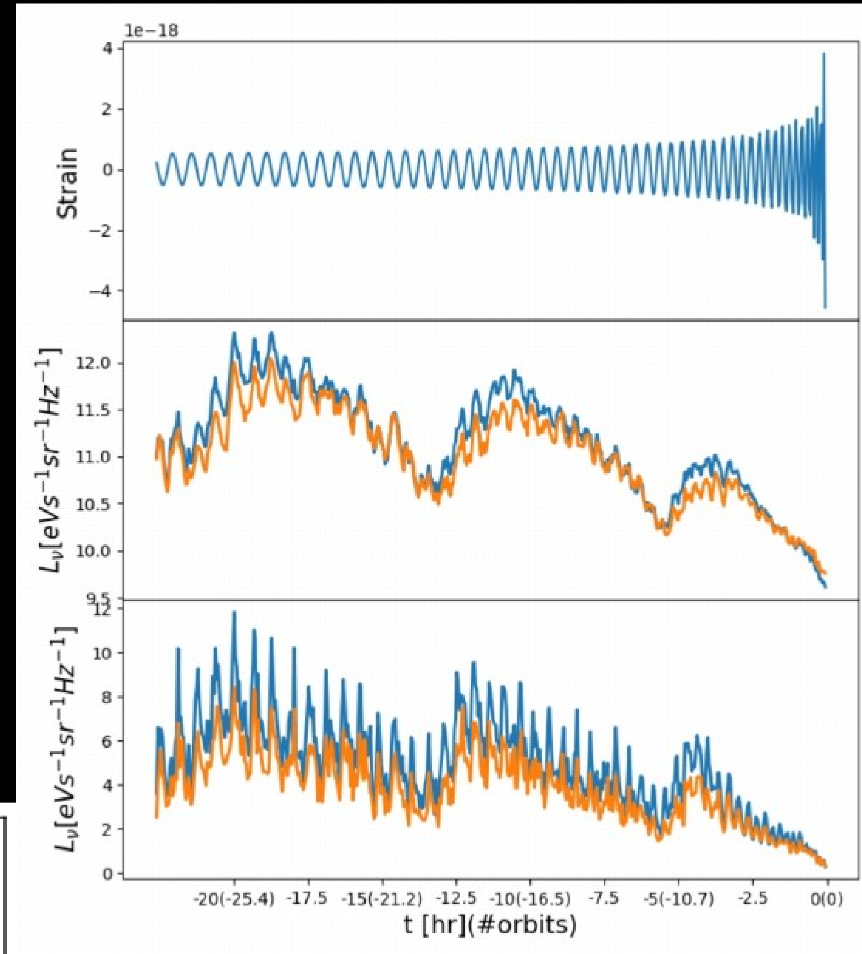
GRMHD simulations: BOWEN et al. 2018, 2019

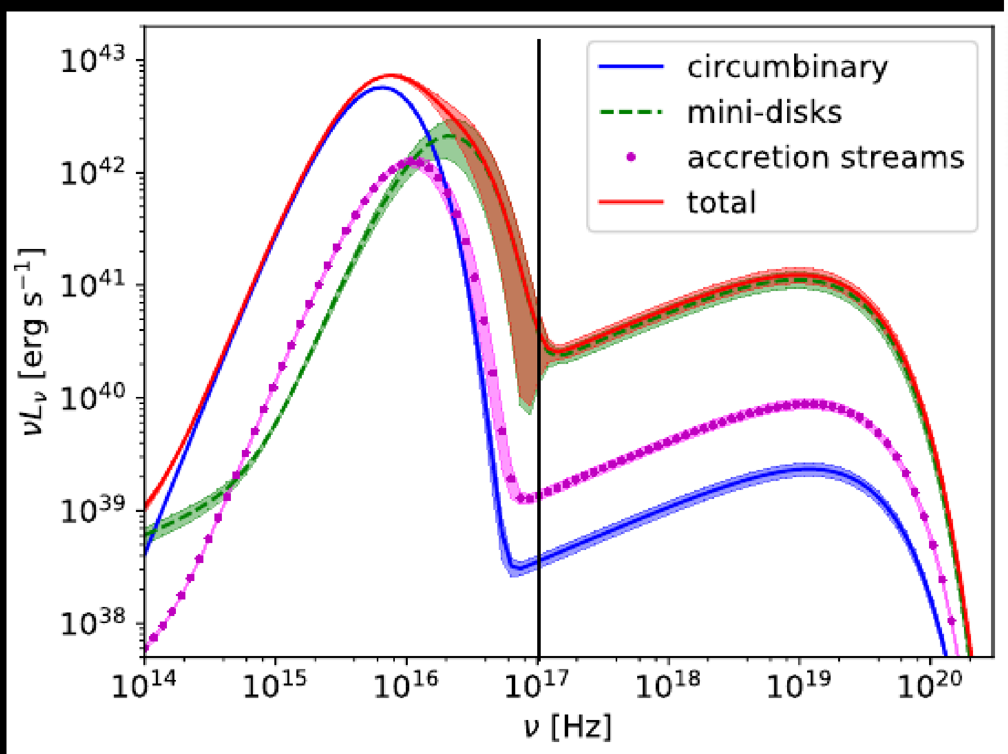
20 h before merging



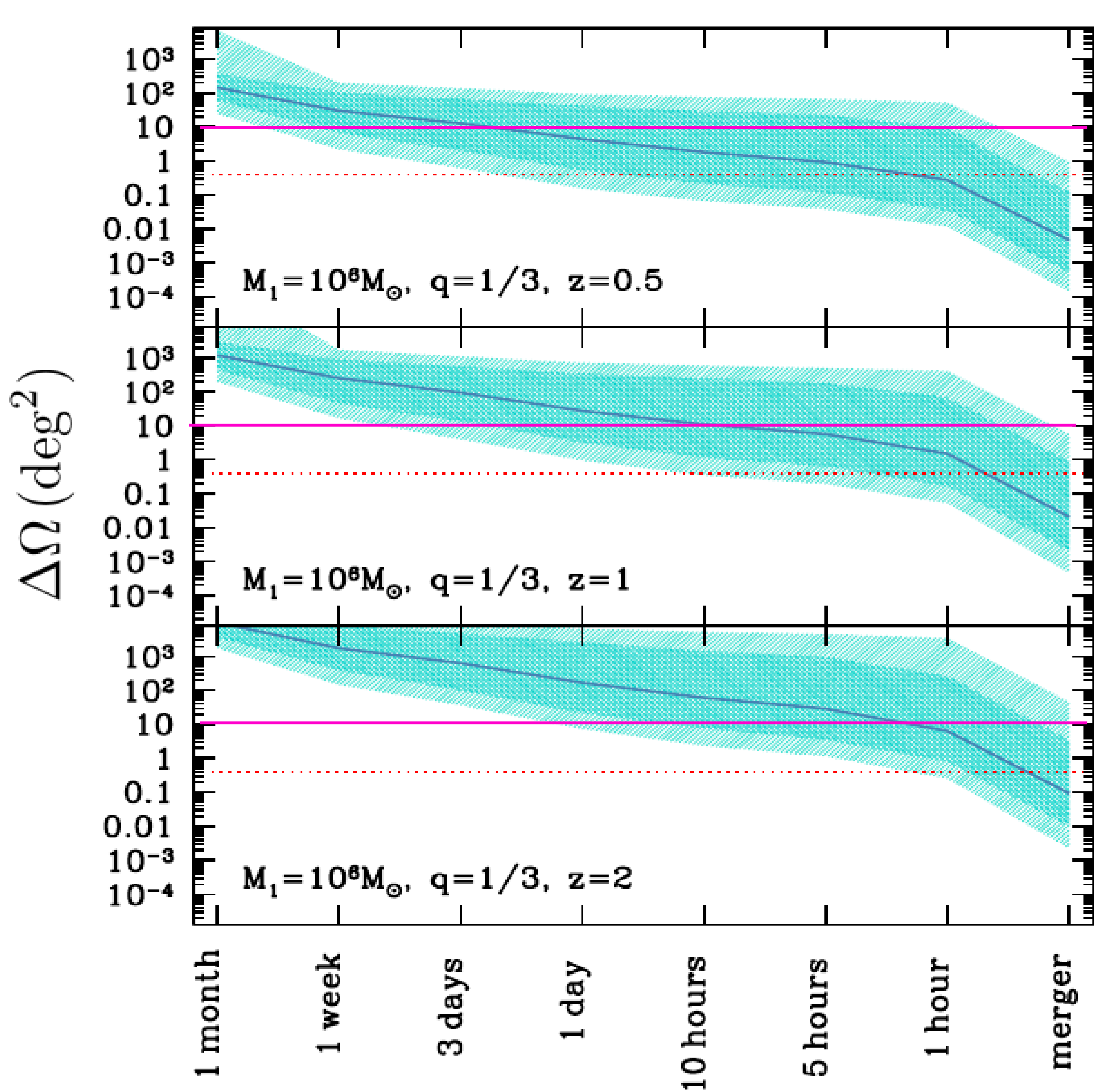
TANG et al. 2018



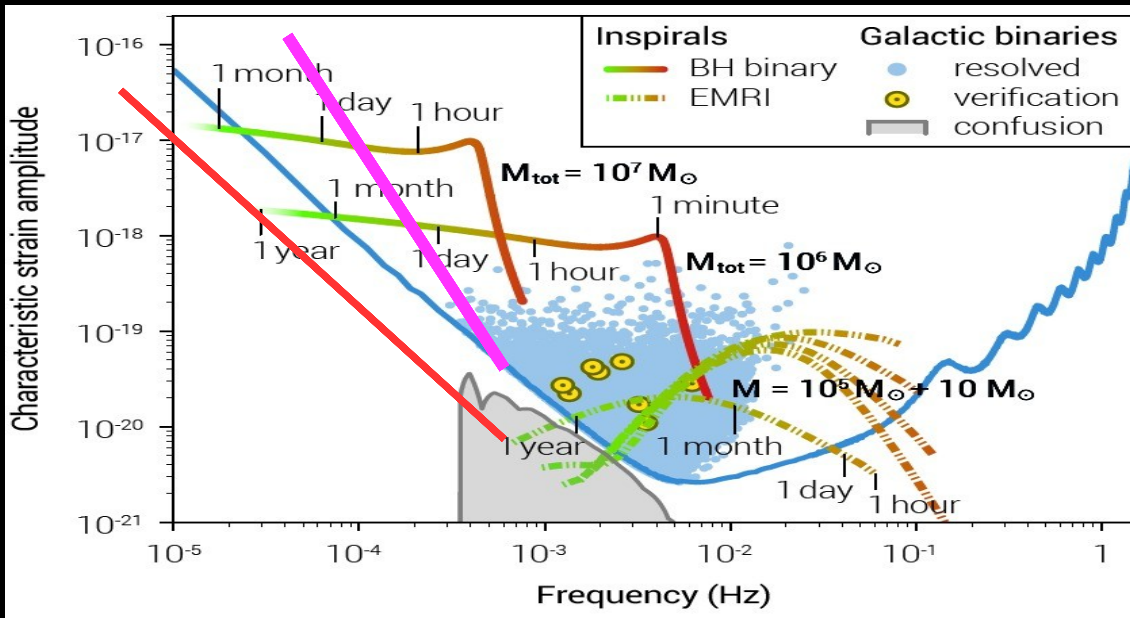


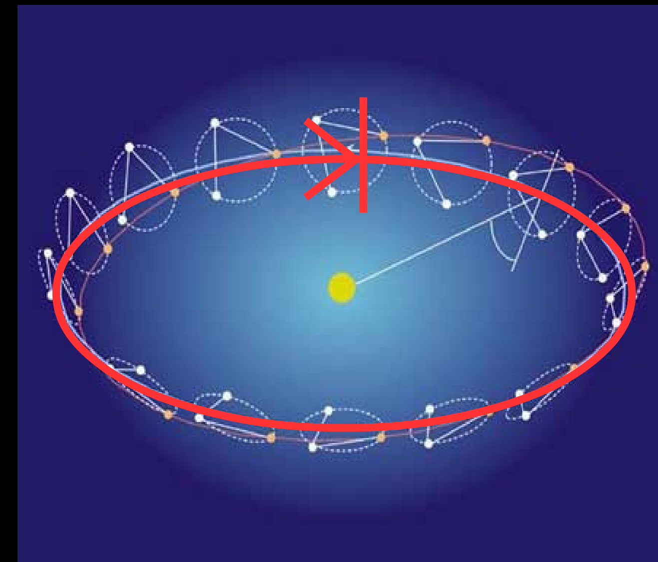


D' Ascoli et al. 2018

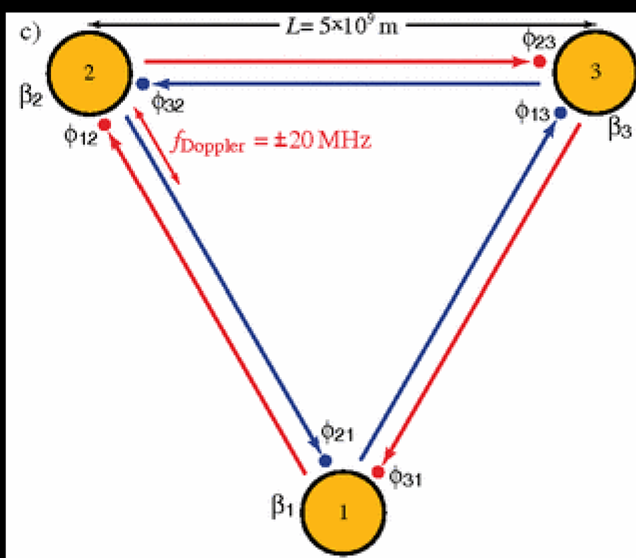

ΔΩ (deg²)
M₁=10⁶M⊙, q=1/3, z=0.5
M₁=10⁶M⊙, q=1/3, z=1
M₁=10⁶M⊙, q=1/3, z=2
10³
10²
10
1
0.1
0.01
10⁻³
10⁻⁴
1 month
1 week
3 days
1 day
10 hours
5 hours
1 hour
merger

Baseline

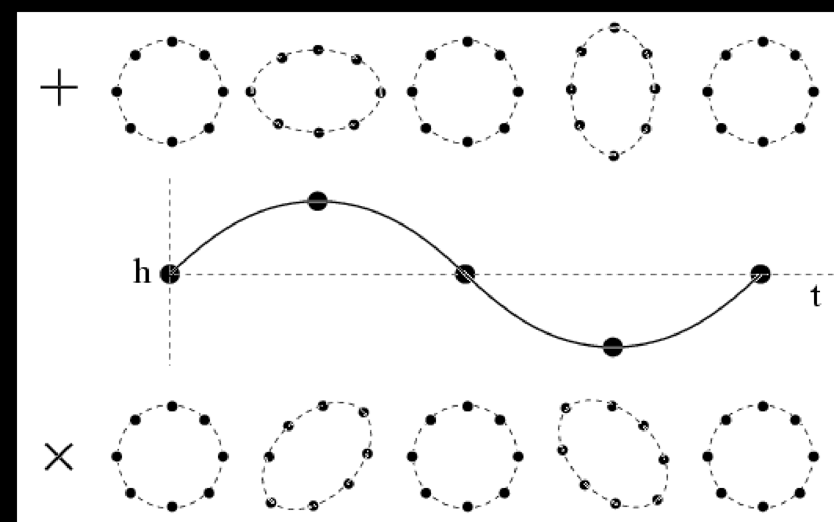




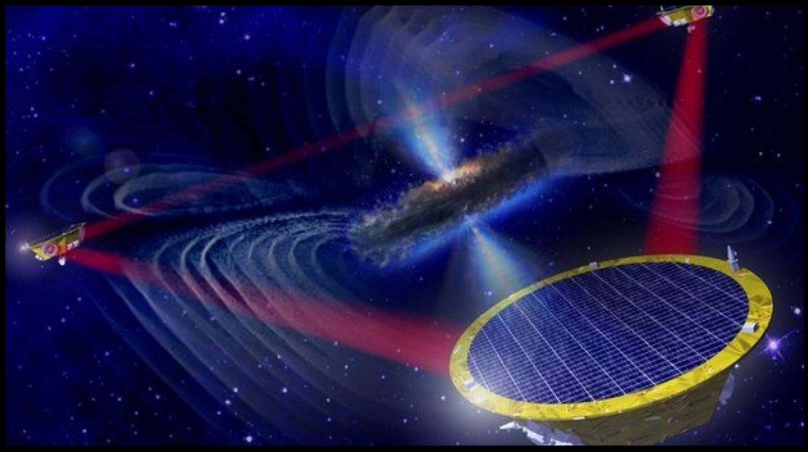
Number of laser links

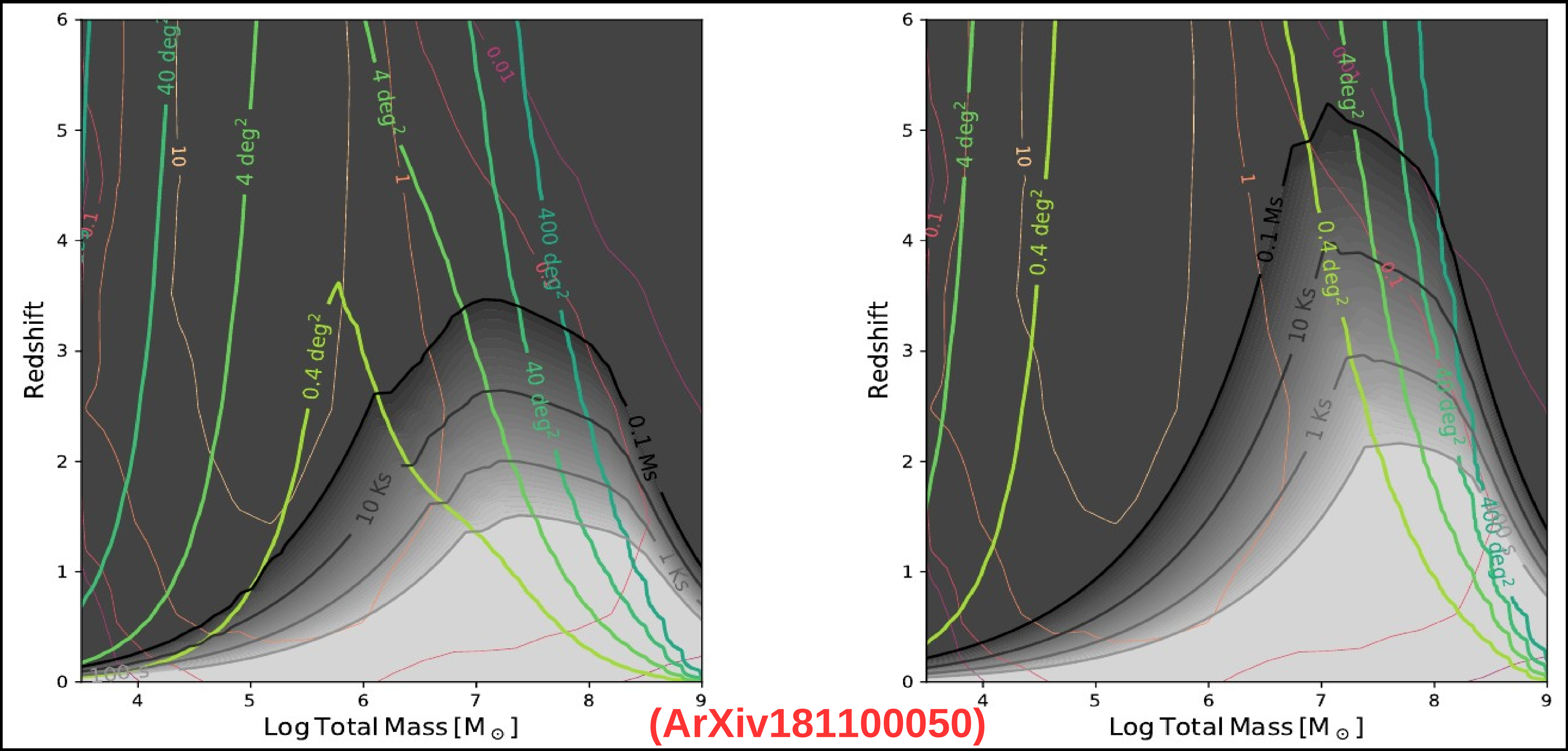


$$g_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1+h_+^{TT} & h_\times^{TT} \\ 0 & 0 & h_\times^{TT} & 1-h_+^{TT} \end{pmatrix}$$



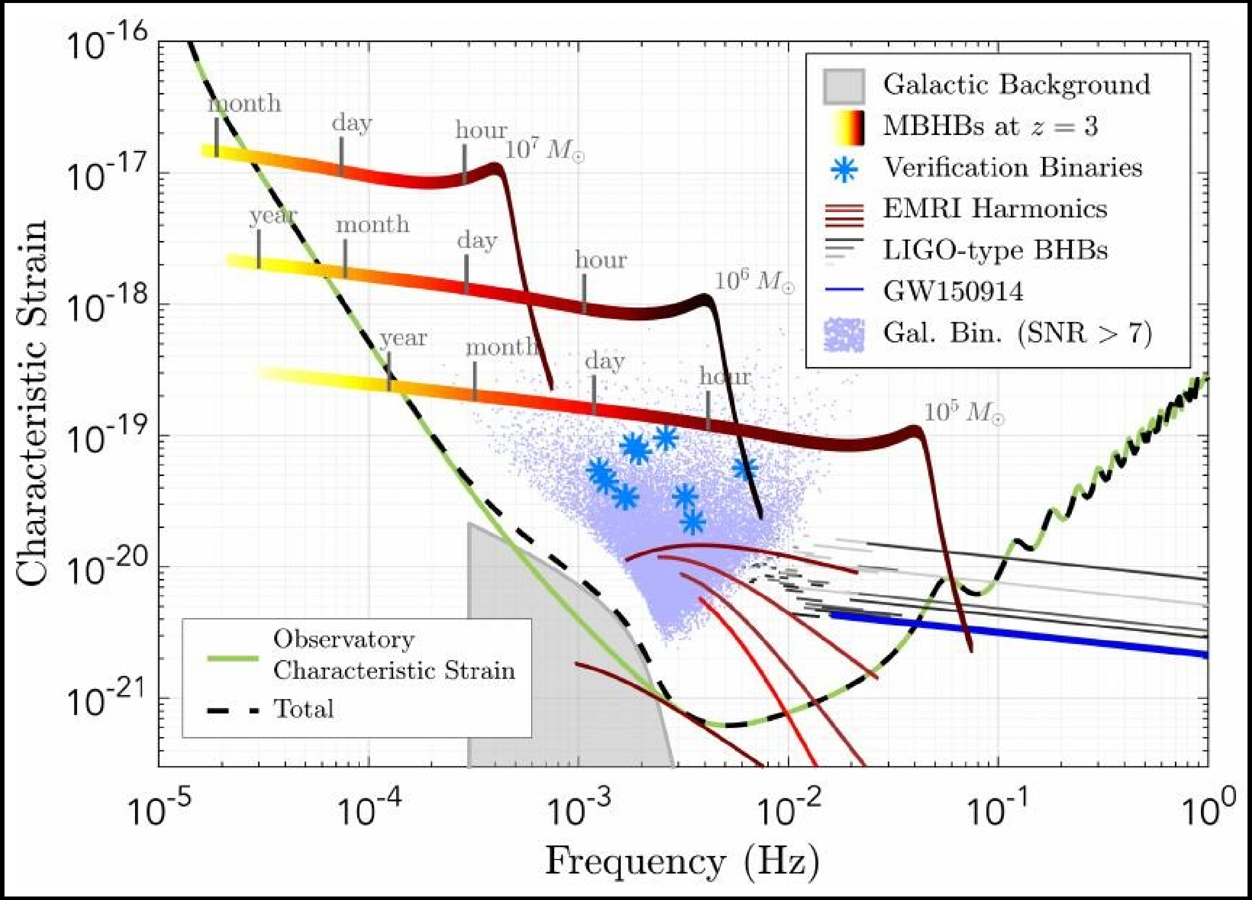
Athena & LISA in space together?





(ArXiv181100050)

Massive objects inspiralling and merging: freqeuncy set by the Most massive object so we have:
1-massive black hole binaries (MBHBs)
2-extreme mass ratio inspirals (EMRIs)



Light objects far from coalescence: monochromatic or slowly inspiralling
1-Galactic binaries (all flavours, most prominent WD-WD)
2-Extragalactic stellar BHBs (multiband astronomy)

Binary evolution with frequency

$$E = \frac{M_1 v_1^2}{2} + \frac{M_2 v_2^2}{2} - \frac{G M_1 M_2}{r} = \frac{\mu v^2}{2} - \frac{G M \mu}{r} = -\frac{G M \mu}{2a}$$

$$\frac{dE_{\rm rad}}{dt} = \frac{32}{5}\frac{G^4}{c^5}\frac{\mu^2 M^3}{a^5}F(e) = \frac{32}{5}\frac{G^4}{c^5}\frac{M_1^2 M_2^2 (M_1 + M_2)}{a^5}F(e)$$

Equating $dE_{rad}/dt = -dE/dt$ and solving for a we get

$$\frac{da}{dt} = -\frac{64}{5}\frac{G^3}{c^5}\frac{M_1 M_2 (M_1 + M_2)}{a^3}F(e)$$

Using Kepler's law we finally get

$$\frac{\mathrm{d}f_{\rm r}}{\mathrm{d}t_{\rm r}} = \frac{96}{5}\pi^{8/3}\mathcal{M}^{5/3} f_{\rm r}^{11/3}$$

1-Mass proportionality: at a given *f*, low mass binaries live longer

2-Frequency proportionality: at low *f* binaries live muuuuuch longer

3-Redshift: $f_{obs}=f_r/(1+z)$: high *z* binaries are observed at lower *f*

How many binaries?
WD binary merger rate in the galaxy is estimated to be ~10^{-2} 10^{-3}/yr

Remember:

$$\frac{\mathrm{d}f_\mathrm{r}}{\mathrm{d}t_\mathrm{r}} = \frac{96}{5}\pi^{8/3}\mathcal{M}^{5/3}f_\mathrm{r}^{11/3}$$

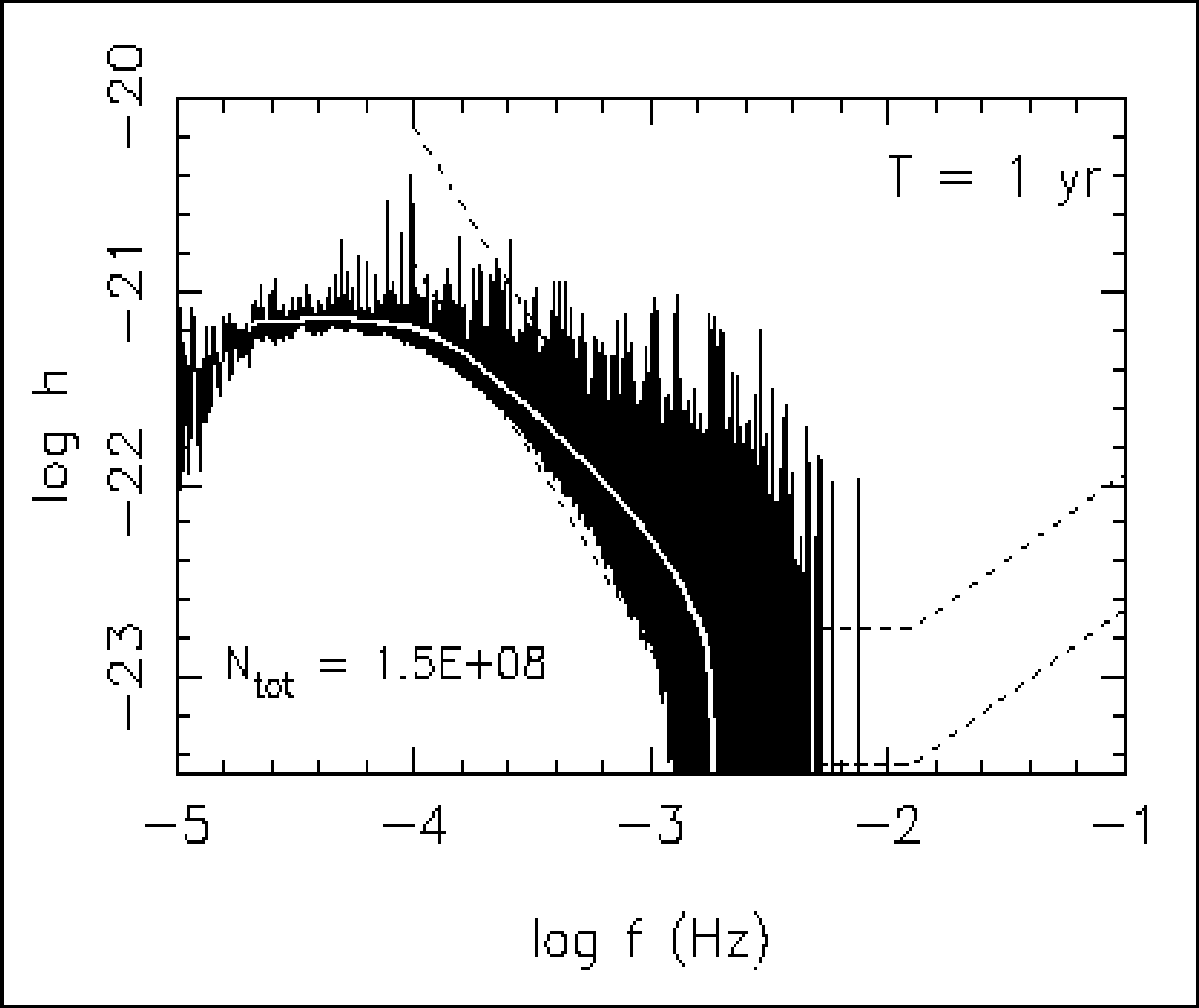
dN/df=dN/dt x dt/df **→ proportional to** $f^{-11/3}$

$$\frac{dt}{d\ln f} \approx 8\,\mathrm{s}\left(\frac{\mathcal{M}}{\mathrm{M}_\odot}\right)^{-5/3}\left(\frac{f}{100\mathrm{Hz}}\right)^{-8/3}$$

So at *f*~0.1mHz we have, ~10^{-9} x 10 x 10^{16}~100M
There are ~100M WD binaries estimated in the MW

One can make a similar calculation for NS and BH binaries to get
~10-100 BHBs at *f*>0.1mHz in the MW
~10^5 NSB at *f*>0.1mHz in the MW

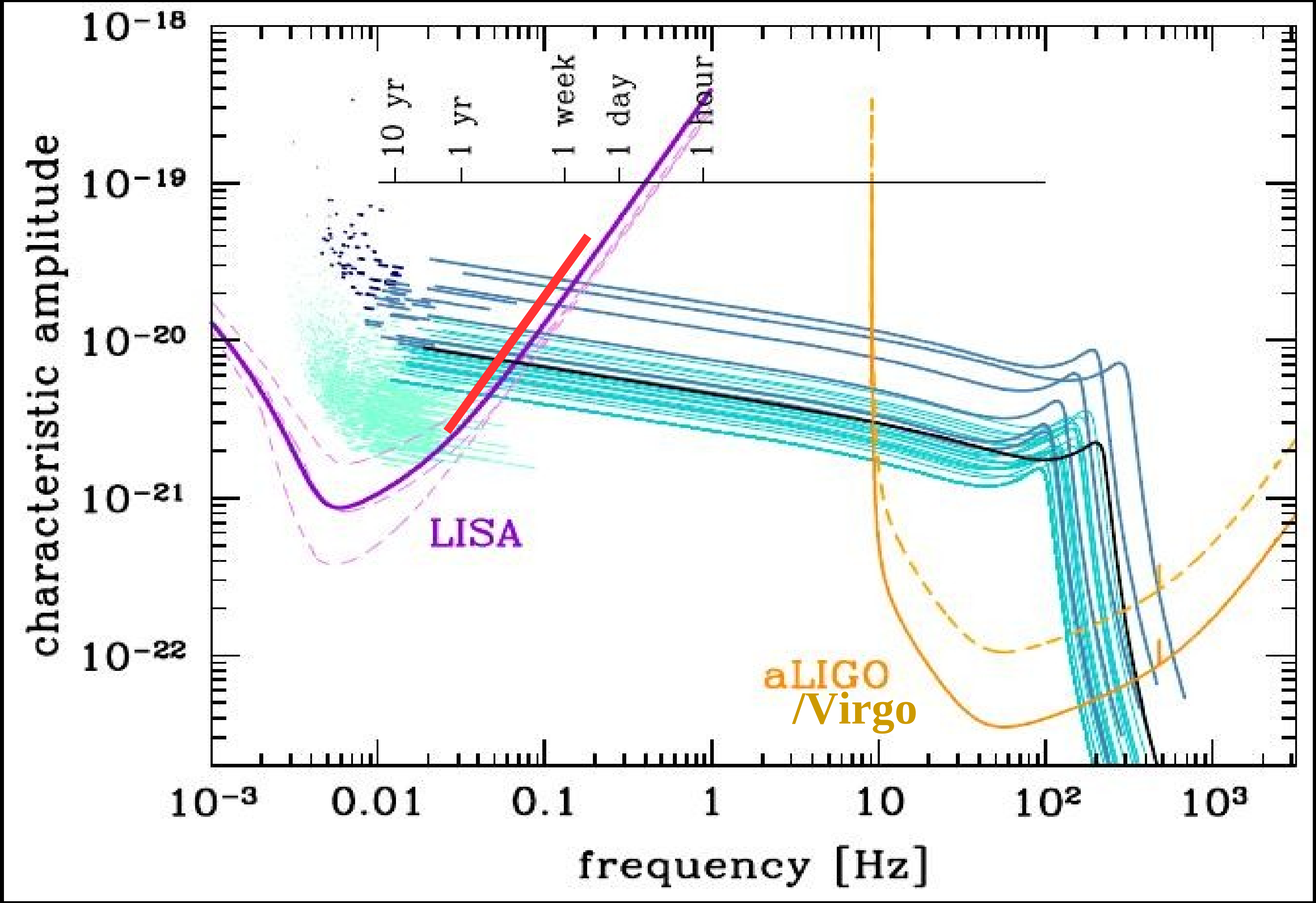
The signal looks like a ‘forest’ of lines piling up



Rates?
Eccentricity?
Triplets?
Type Ia?

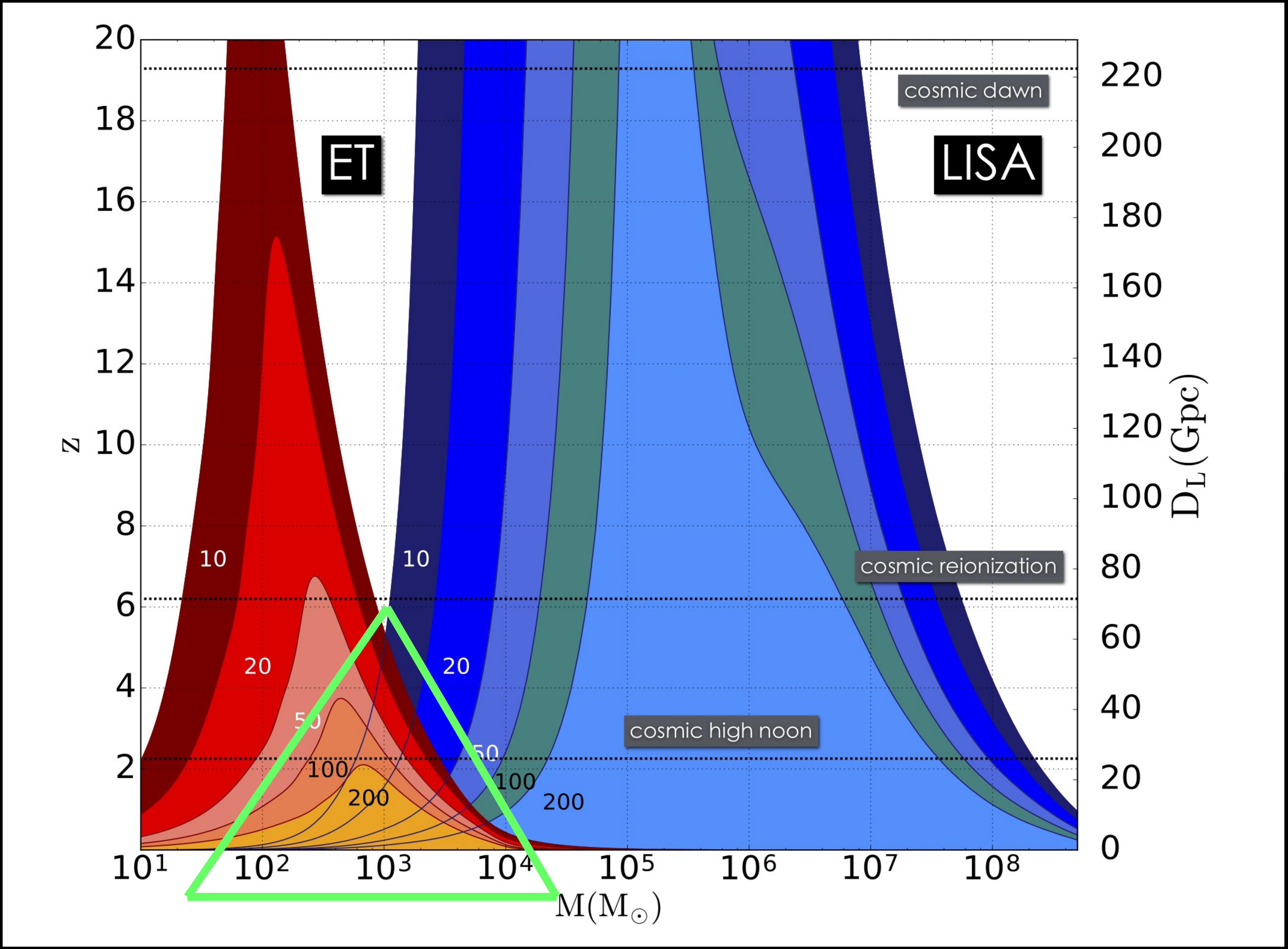
Implications of GW150914: multi-band GW astronomy

(AS 2016, PRL 116, 1102)



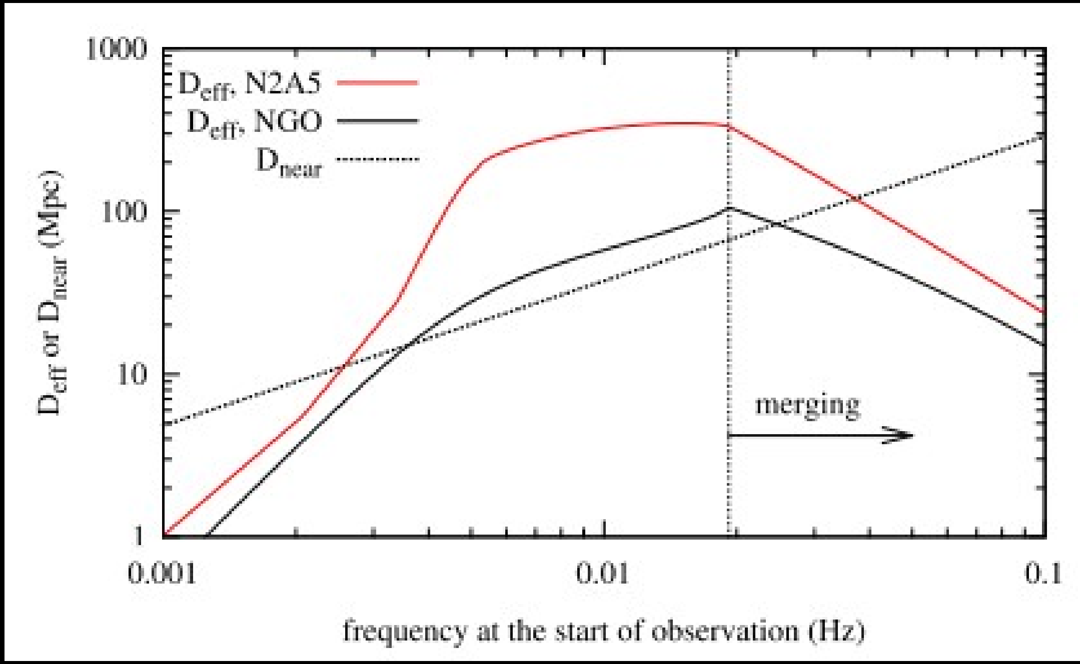
BHB will be detected by LISA and cross to the LIGO/Virgo band, assuming a 5 year operation of LISA.

The parameter space of black holes



Distribution of sources across the band

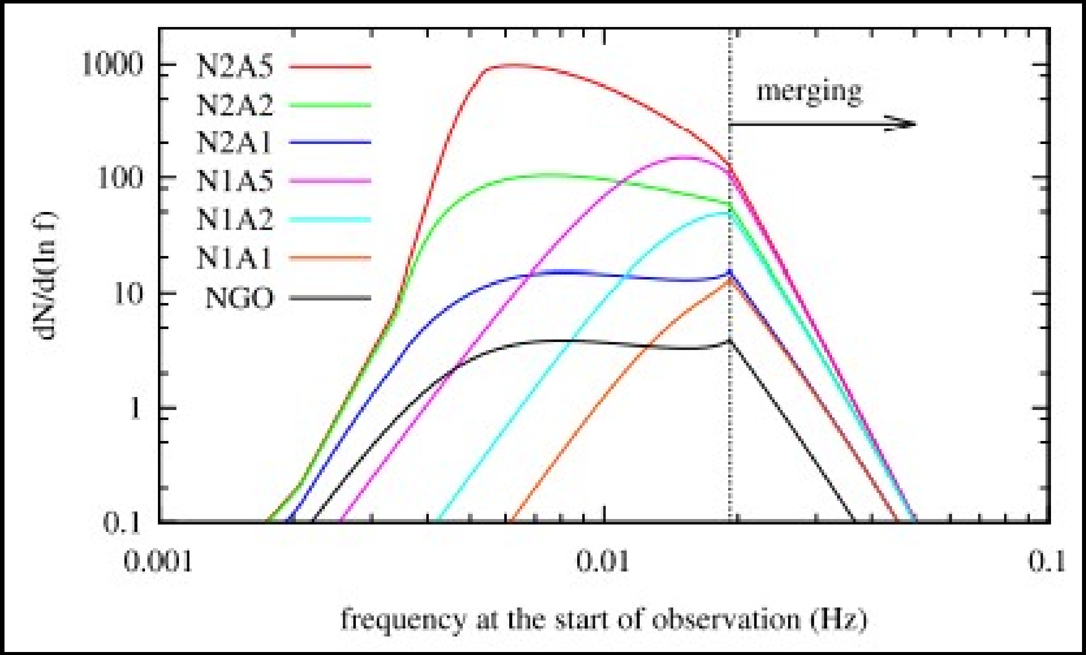
(Kyutoku & Seto 2016)



$$\frac{dt}{d\ln f} \approx 8\,\mathrm{s}\left(\frac{\mathcal{M}}{\mathrm{M}_\odot}\right)^{-5/3}\left(\frac{f}{100\mathrm{Hz}}\right)^{-8/3}$$

Reach of eLISA for GW150915. Up to z~0.1 at *f*~0.01Hz

-Almost stationary at *f*<0.02 Hz
-Evolving to the LIGO band for *f*>0.02 Hz

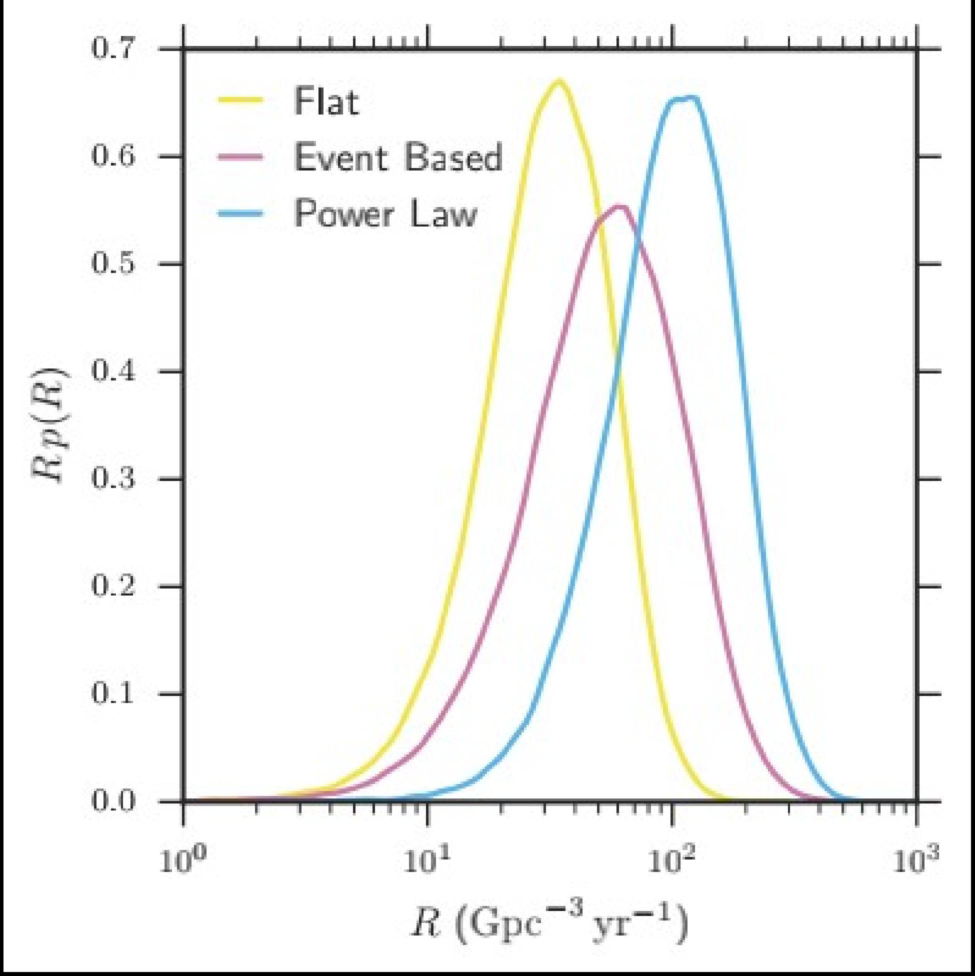


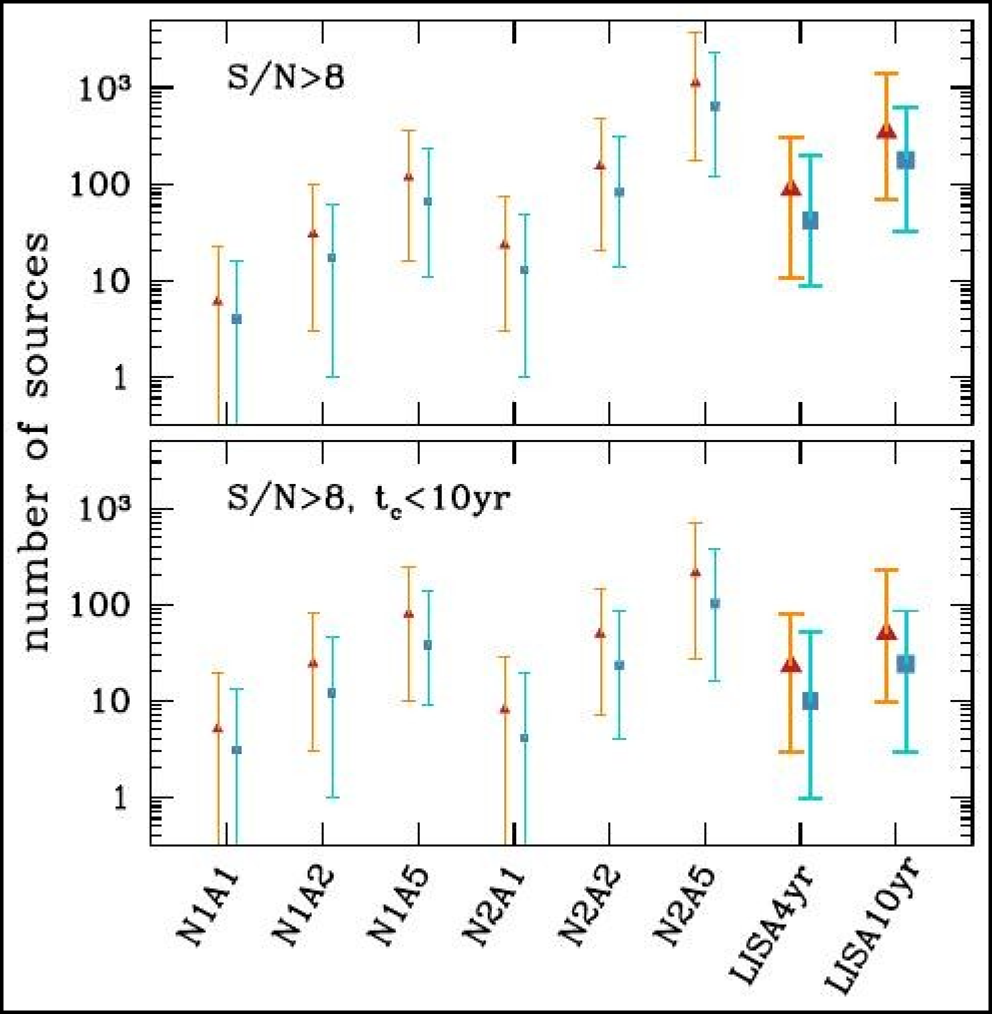
Number of observable sources (S/N>8) is a strong function of frequency*.

***that is the main reason of rather pessimistic initial estimates about the observability of these sources by eLISA**

How many BHBs in the eLISA band?

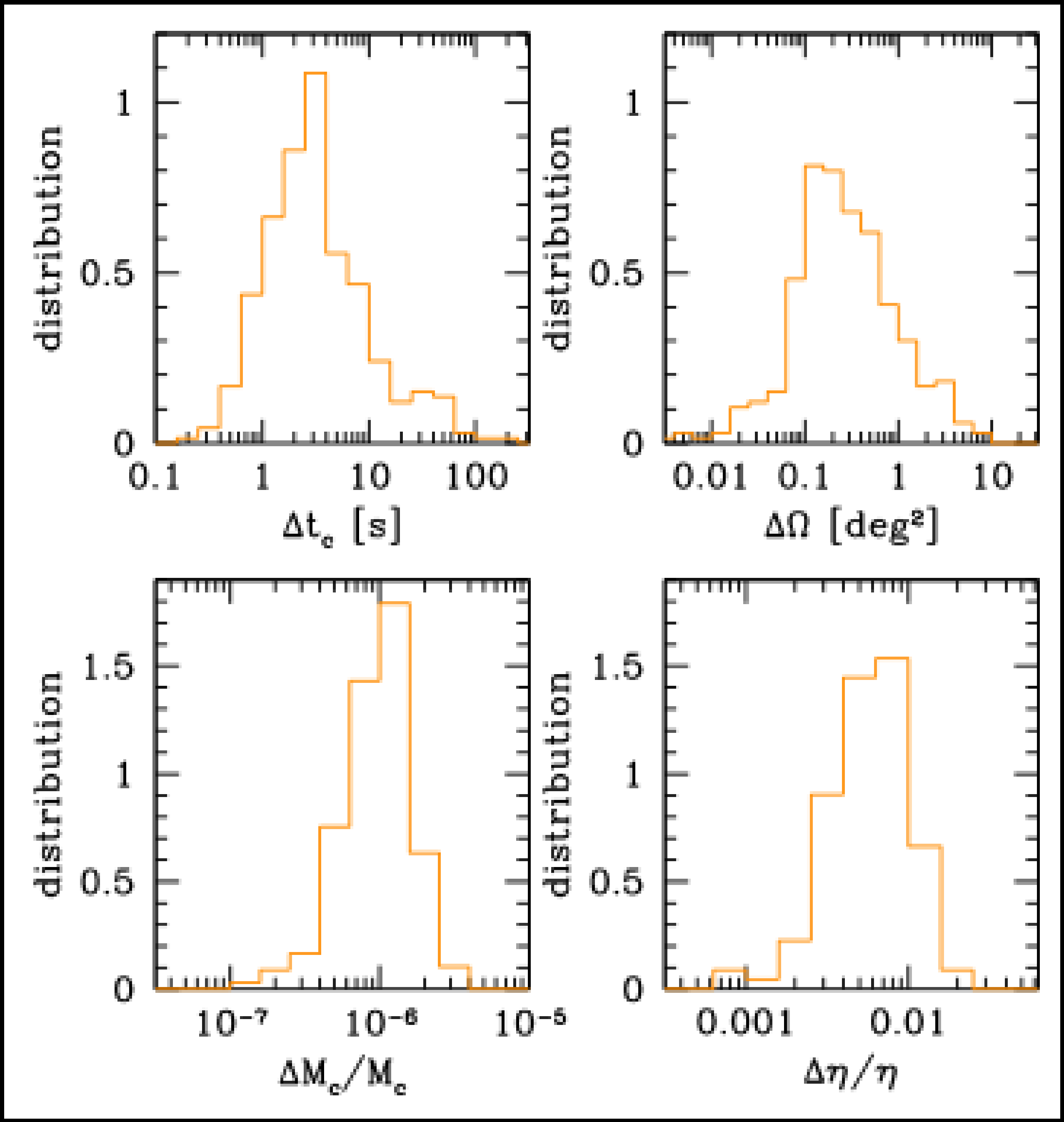
Implied BHB mass distributions and merger rates higher than previously thought and BHs are more massive





eLISA will detect up to thousands of BHBs with S/N>8 up to few hundreds crossing to the aLIGO band in 5yr

Sky pre-localization and coincident EM campaigns

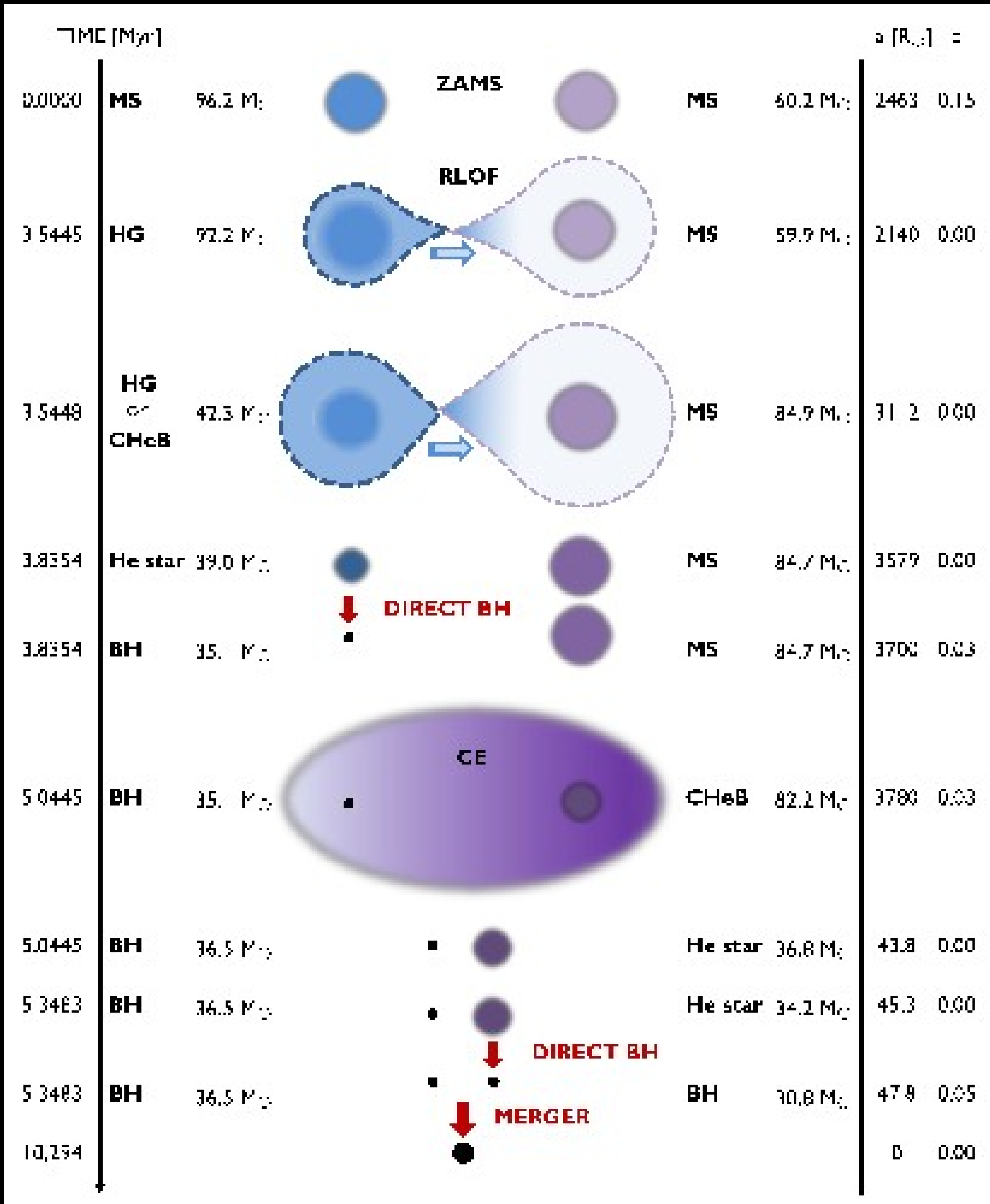


System crossing to the aLIGO band can be located with sub deg^2 precision **(Klein et al. In prep.)**

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).

Astrophysics: BHB origin



(Belczynski et al. 2016 + many many others)

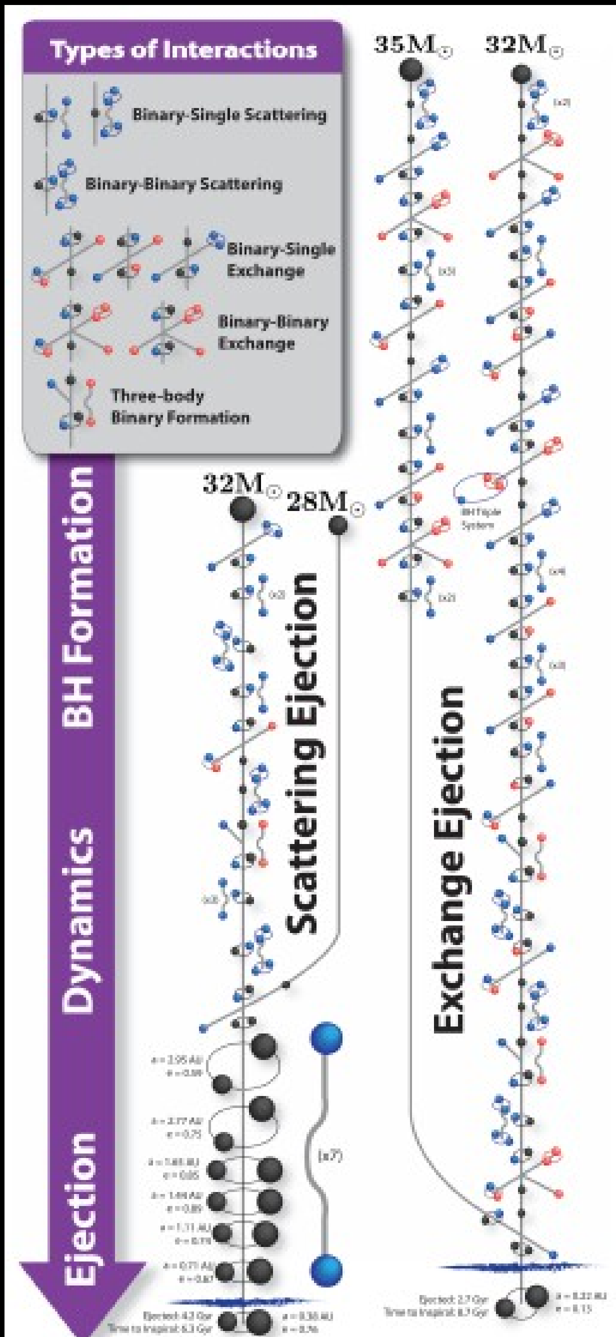
$$a_0 = 1.6\ R_\odot \left(\frac{M_1}{M_\odot}\right)^{3/4} \left[q(1+q)F(e)\left(\frac{t_{\rm coal}}{1{\rm Gyr}}\right)\right]^{1/4}$$

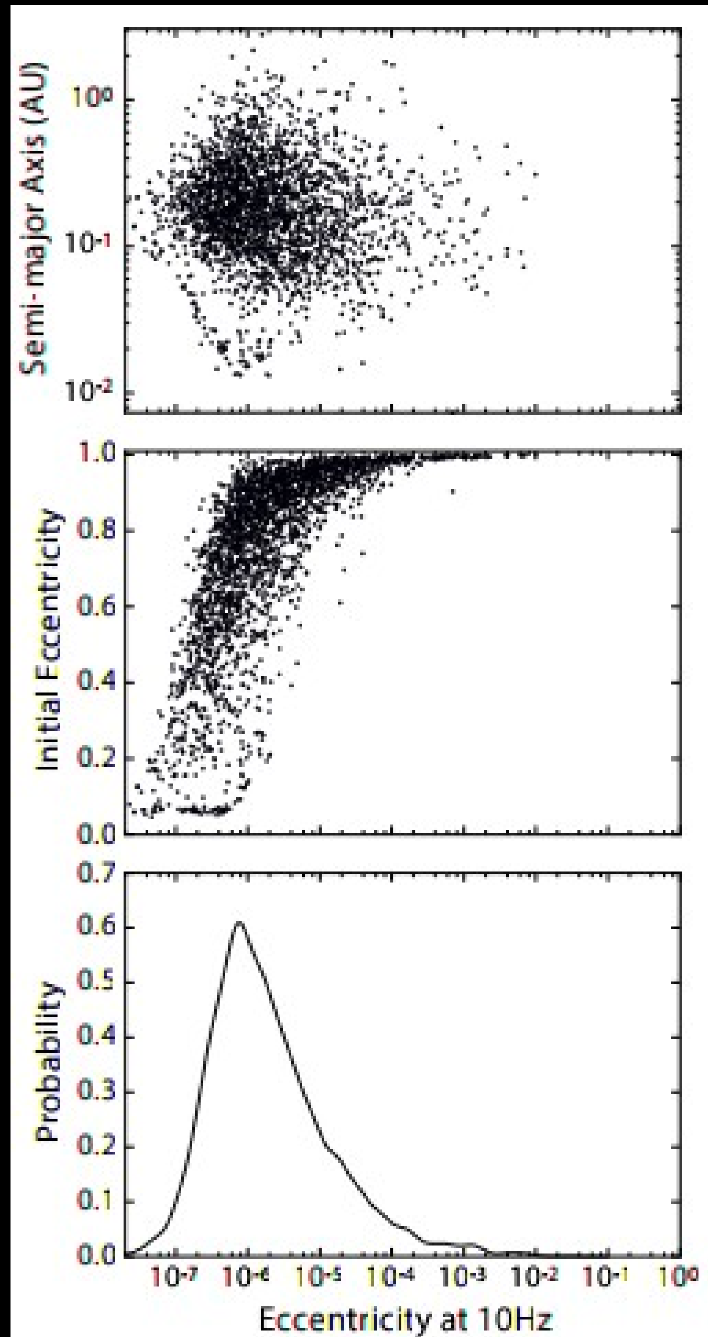
Evolution of massive Binaries

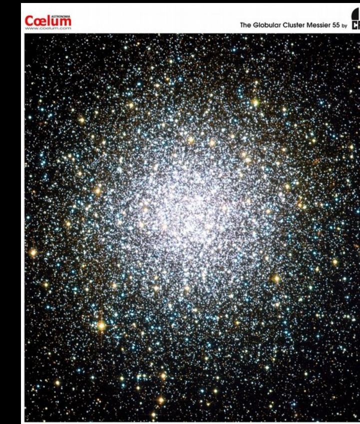
Complications
- **common envelope**
- **kicks**
- **metallicity**
- **rotation**

Features:
- **Preferentially high, aligned spins?**
- **small formation eccentricity**

Astrophysics: BHB origin







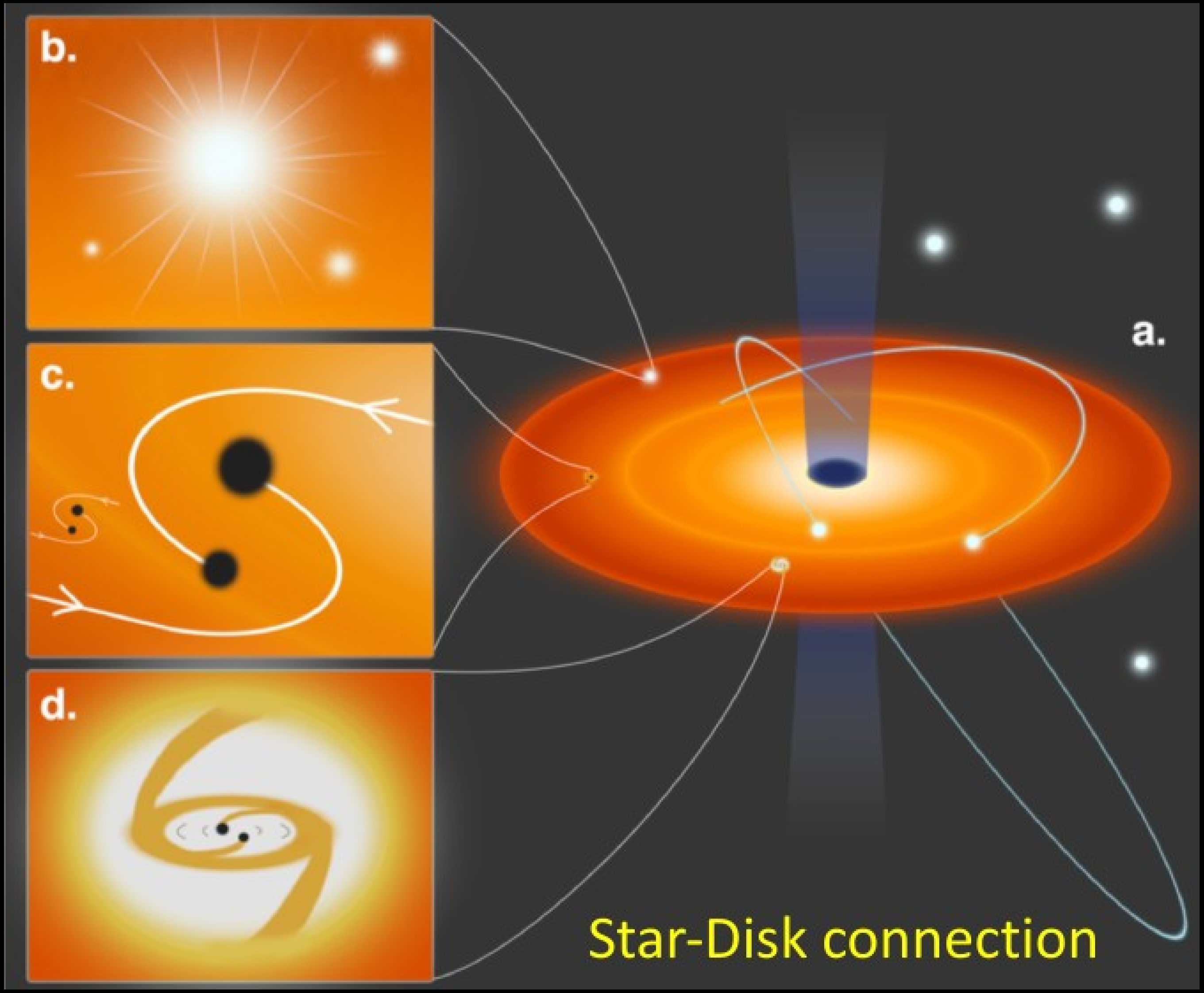
Dynamical capture

Complications
- -mass segregation
- -winds
- -ejections
- -multiple interactions
- -resonant dynamics (Kozai-Lidov)

Features:
- -randomly oriented spins?
- -high formation eccentricities

(Rodriguez et al. 2016, Samsing, D'Orazio, Mapelli...)

Astrophysics: BHB origin



(Ford, McKernan, Haiman, Lin, Antonini….)

GALACTIC NUCLEI

AGN disks

Complications
-capture
-evolution
-migration traps
-multiple interactions

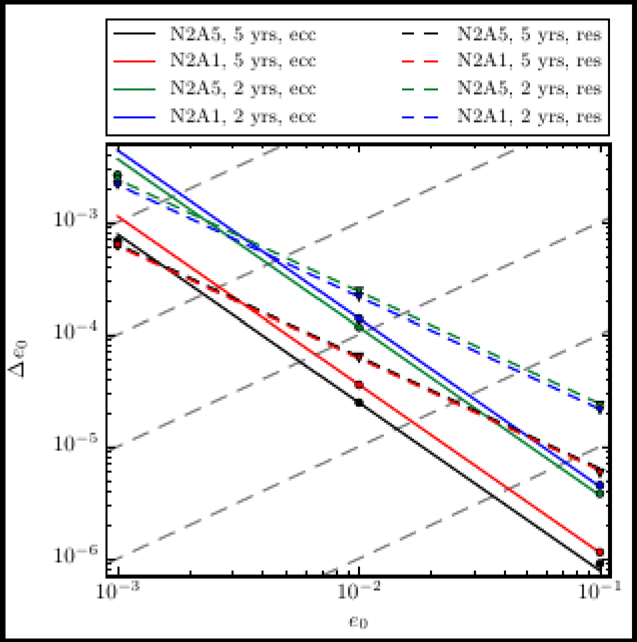
Features:
-accelerated by large MBH potential
-EM counterparts?
-associated to galactic centers

Kozai by SMBH

-very eccentric
-associated to galactic centers

Measuring eccentricity with eLISA

(Nishizawa et al. 2016)

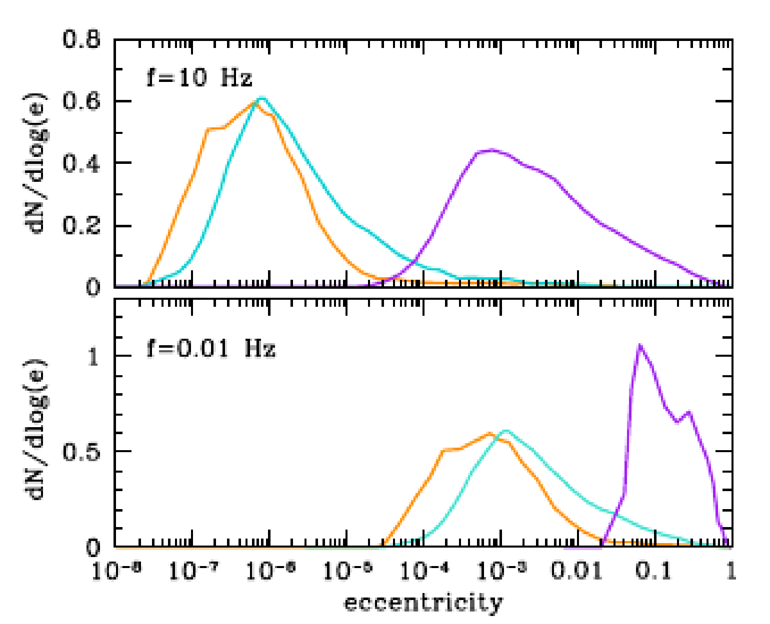


>aLIGO can only place upper bounds on *e*, but eLISA can measure *e* if >10^{-3} (NOTE: $1-e^2$)

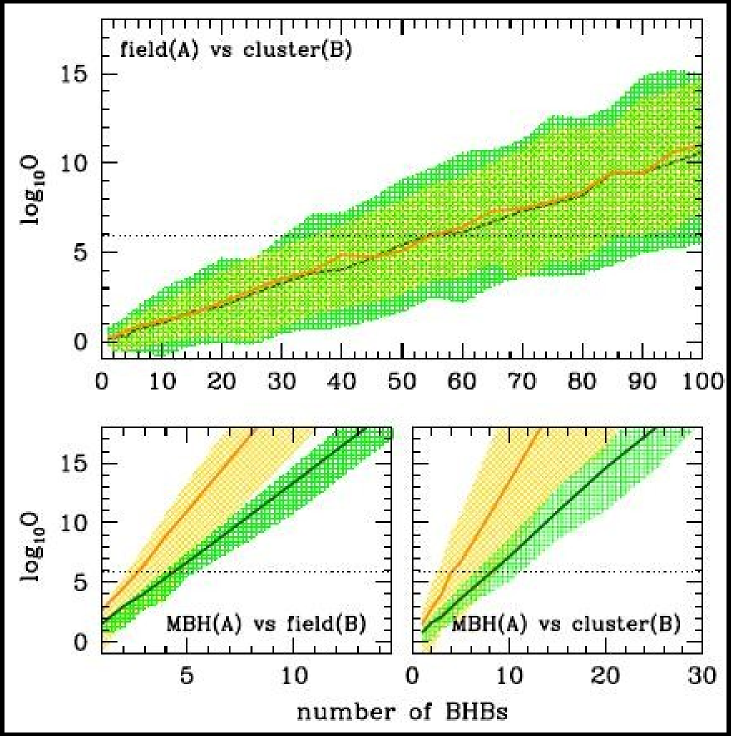
>GW circularization implies much higher eccentricities in the eLISA band

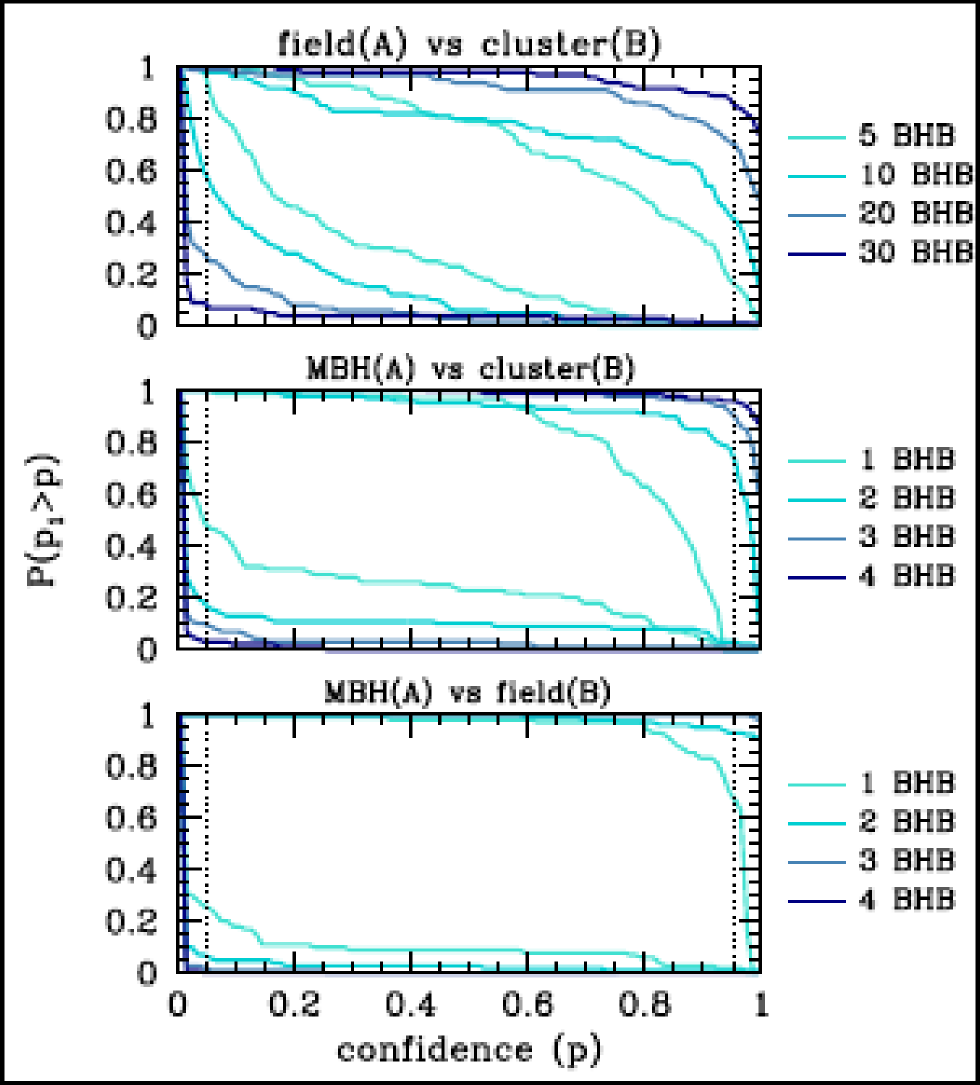
Different formation channel imply different e distributions.
Too small to be measured by LIGO but accessible to LISA

Proof of concept: three BHB formation scenarios
- -field binaries (Kowalska et al 2011)
- -dynamical formation in Gcs (Rodriguez et al. 2016)
- -Kozai resonances around a MBH (Antonini & Perets 2012)



Assessing BHB origin using eccentricity



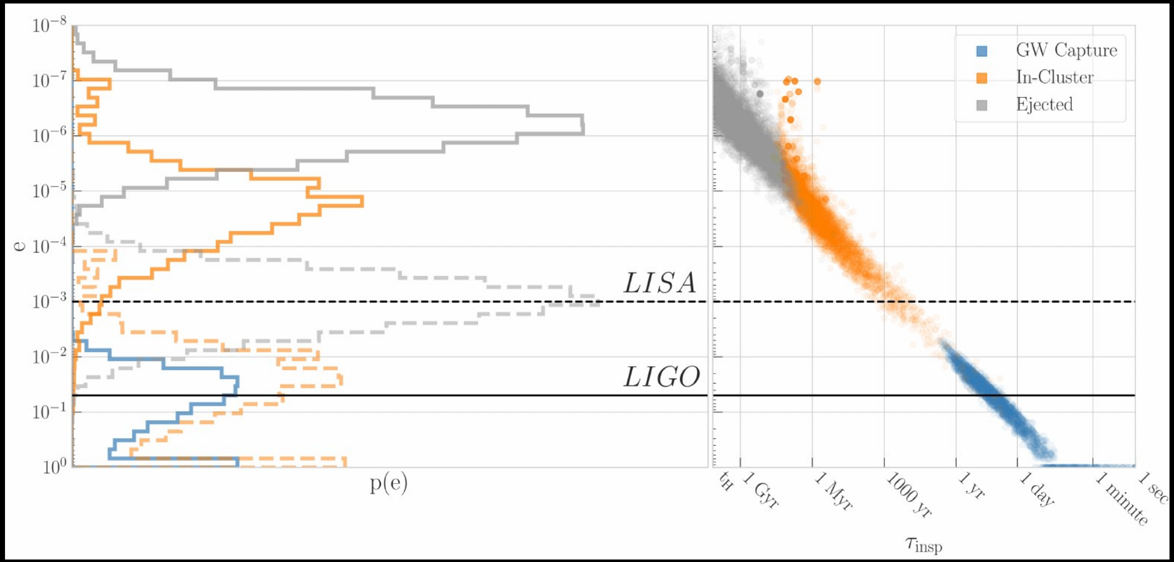


Different formation channels result in different *e* distributions in the eLISA band, (see also Breivik et al. 2016)

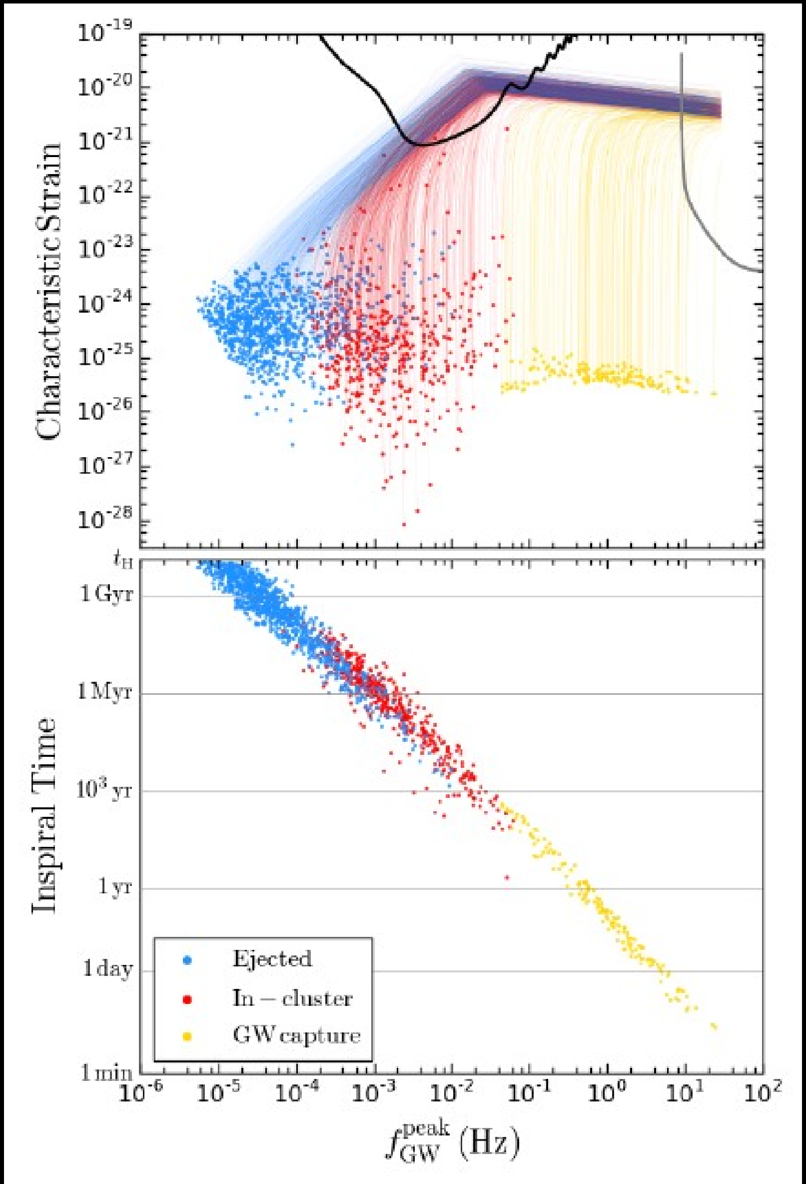
eLISA can tell formation scenarios apart with few tens of observations (Nishizawa et al. 2016)

Can be complemented to aLIGO spin measurements.

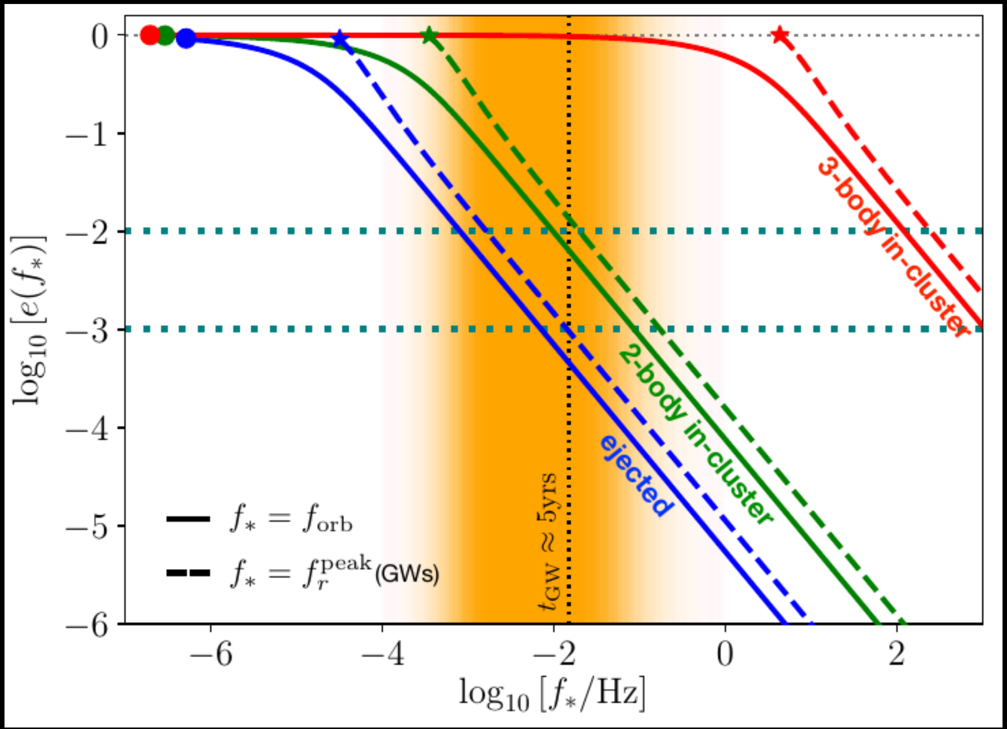
Binary triplets quadruplets...



(Zevin+)

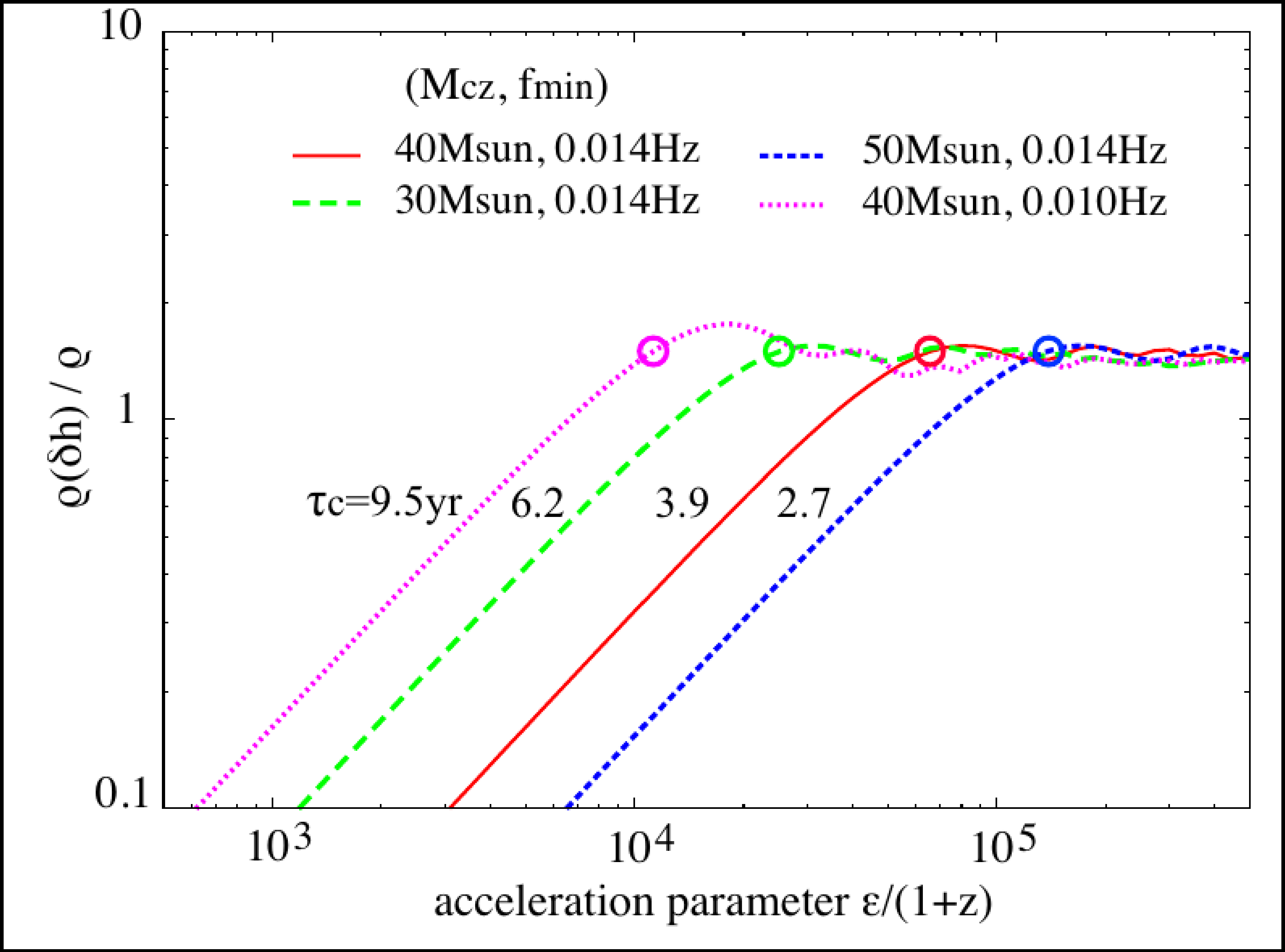


(Kramer+)



(D'Orazio & Samsing)

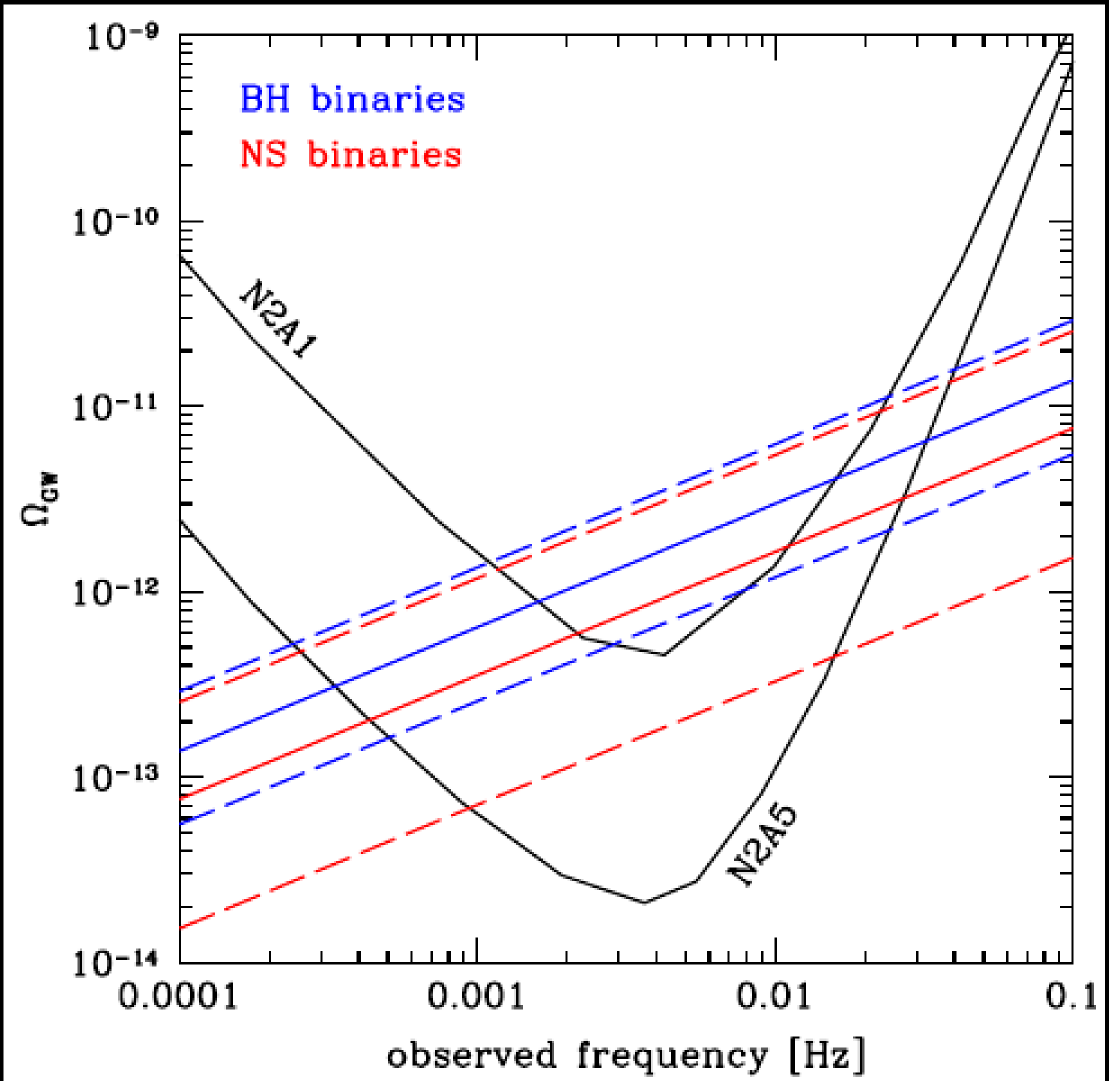
CoM acceleration detectable by LISA



$$\rho(\delta h) \simeq 16\ \epsilon_{z,4}\ d_{L,100}^{-1}\ \delta t_5^{1/2}\ M_{cz,40}^{-5/3}\ f_{14}^{-11/3}.$$

(Inayoshi+)

Hey, what about those NSBs?

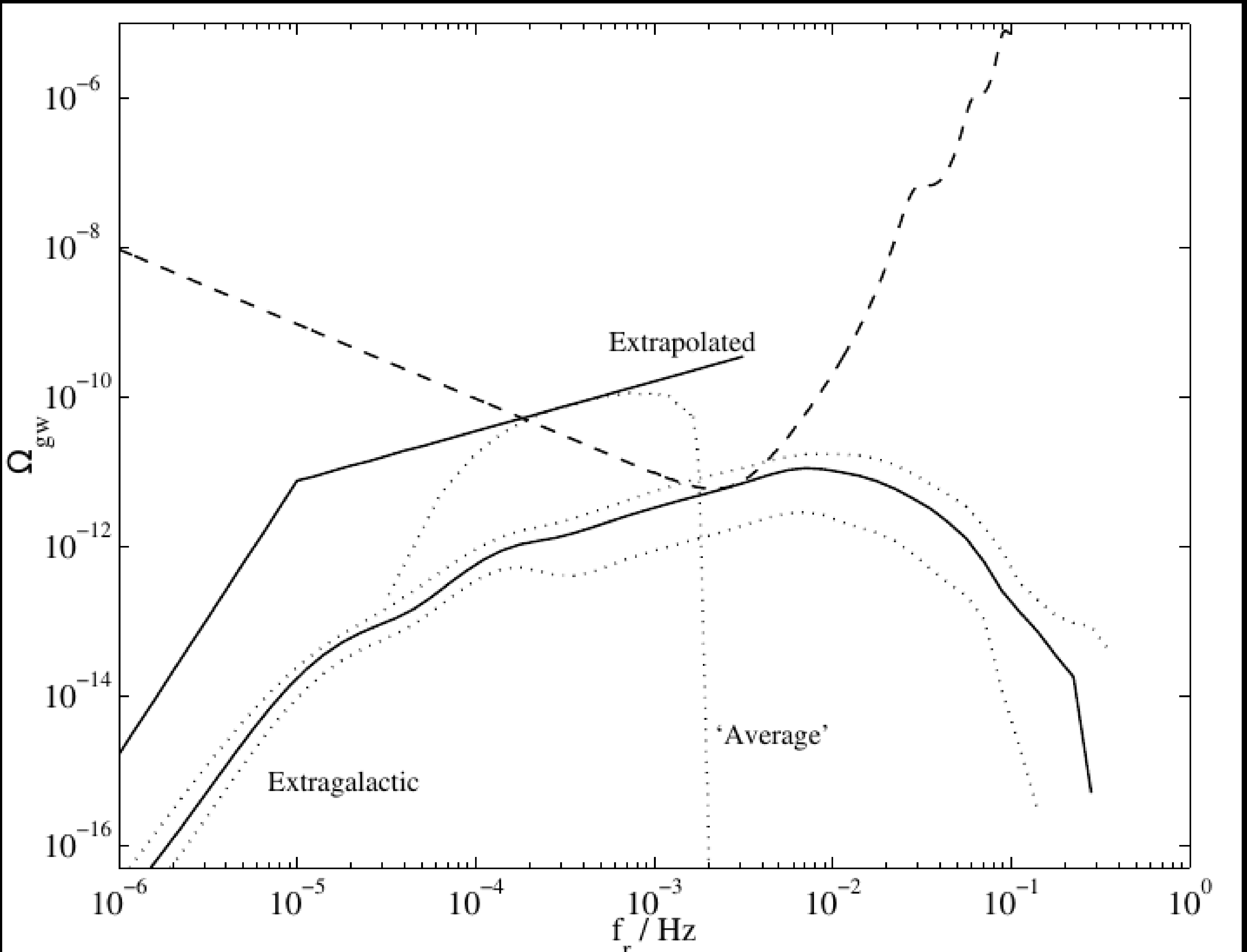


Source	lower90%	median	upper90%
BBH	13.8	34.5	72.5
BNS	3.8	19.0	63.4

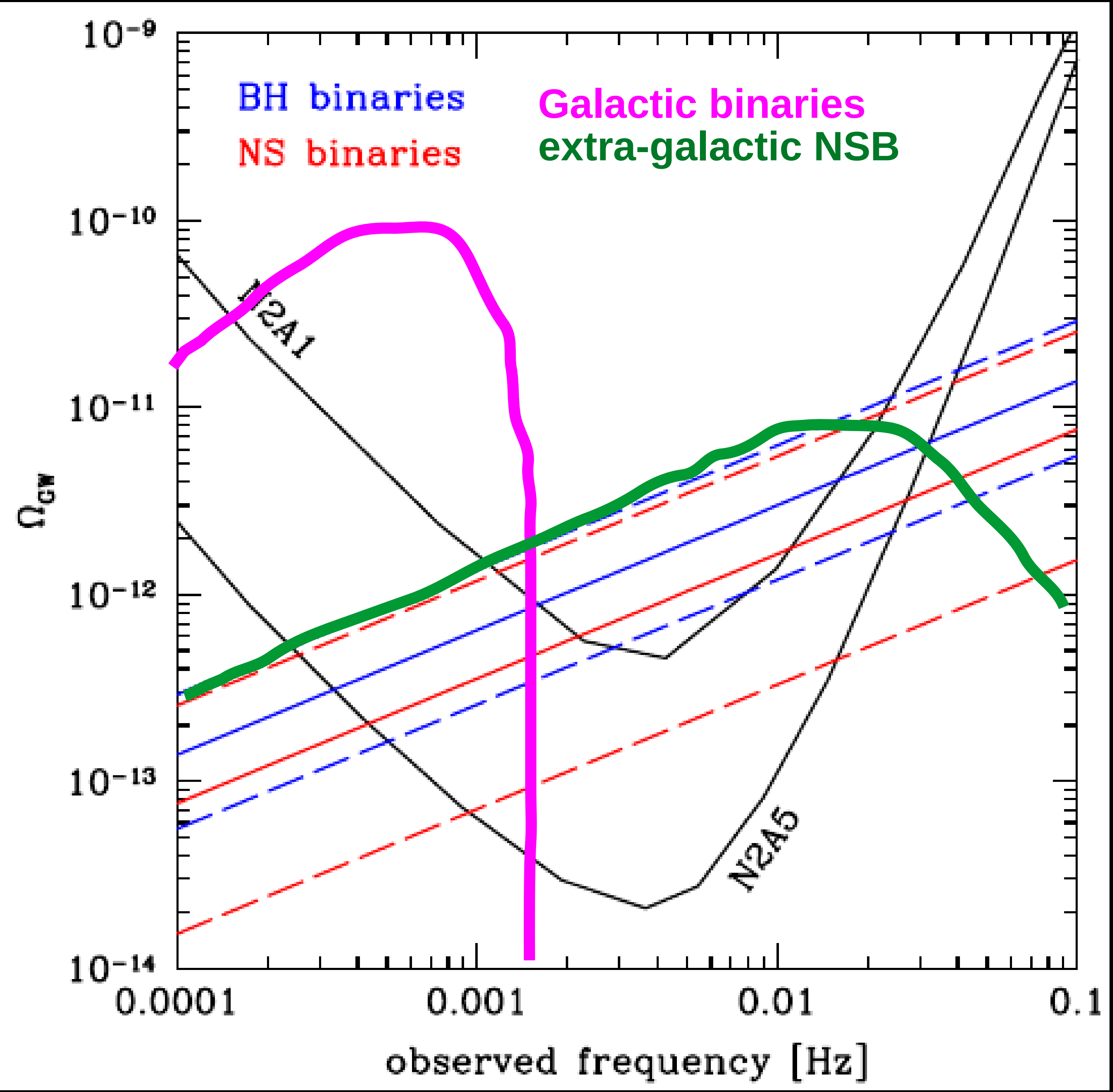
GW170817 has interesting consequences for the NSB merger rate

GWB in the LISA band expected to be similar to the one produced by SOBHBs

Note: nothing new here really, just rediscovering Farmer & Phinney 2003

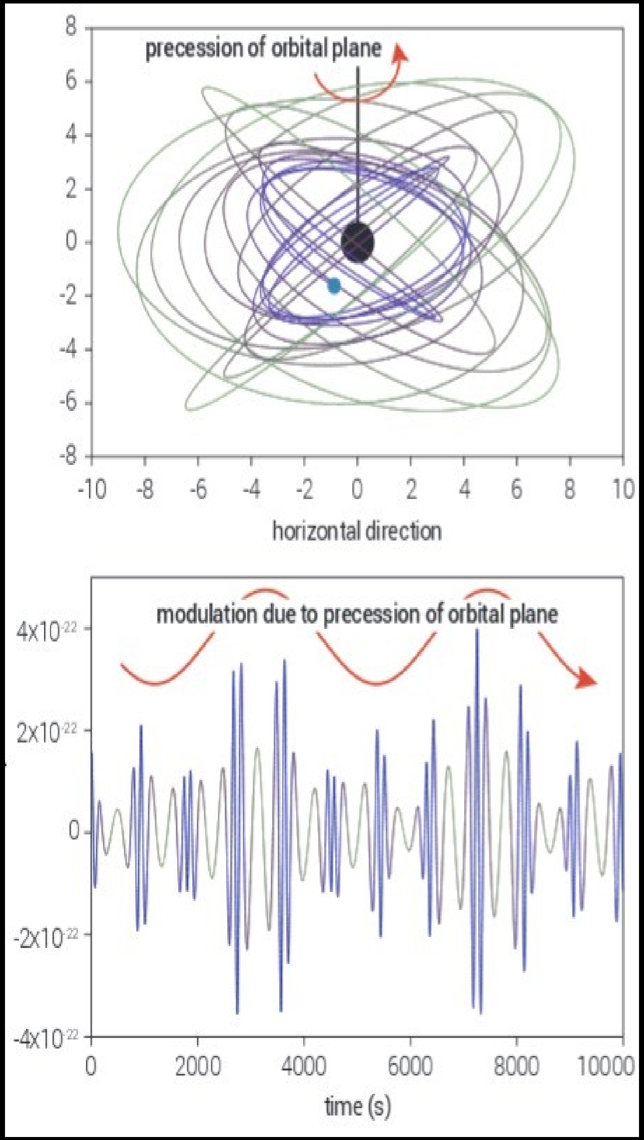


Ω_{gw}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
Extrapolated
'Average'
Extragalactic
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
f_r / Hz

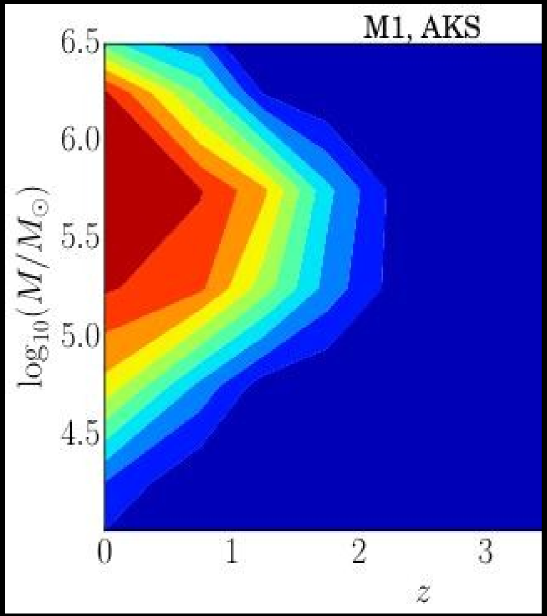


BH binaries
NS binaries
Galactic binaries
extra-galactic NSB
N2A1
N2A5
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
Ω_{GW}
0.0001
0.001
0.01
0.1
observed frequency [Hz]

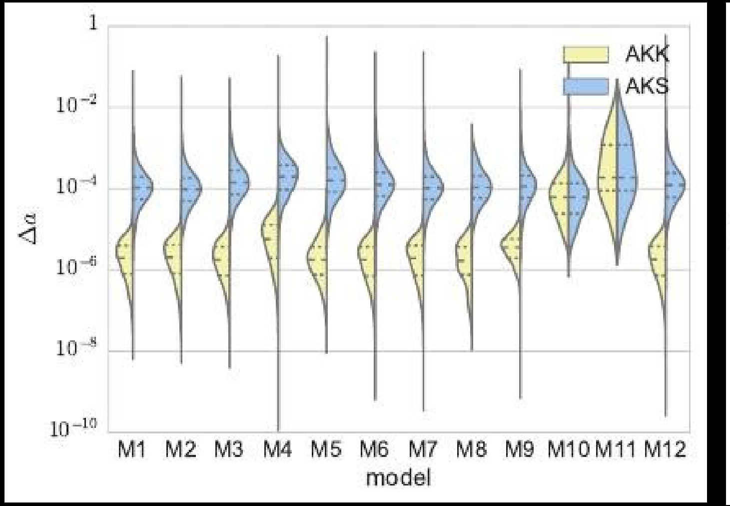
Extreme mass ratio inspirals (EMRIs)

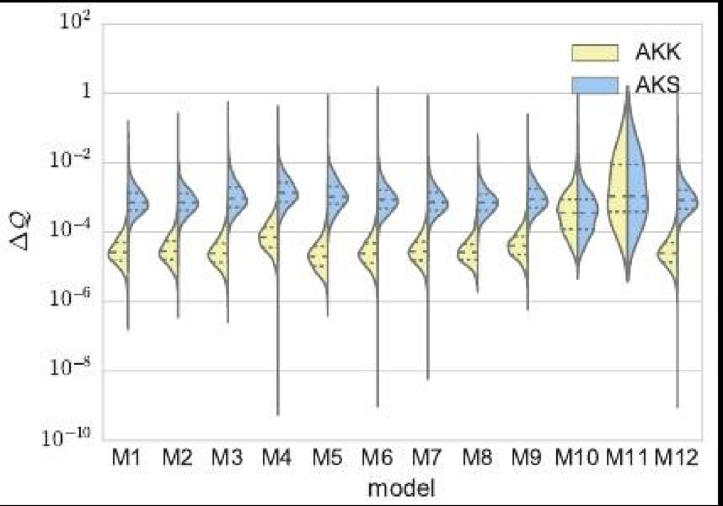


- 1-1000 detections/yr
- sky localization <10 deg2
- distance to better than 10%
- MBH mass to better than 0.01%
- CO mass to better than 0.01%
- MBH spin to better than 0.001
- plunge eccentricity <0.0001
- deviation from Kerr quadrupole moment to <0.001

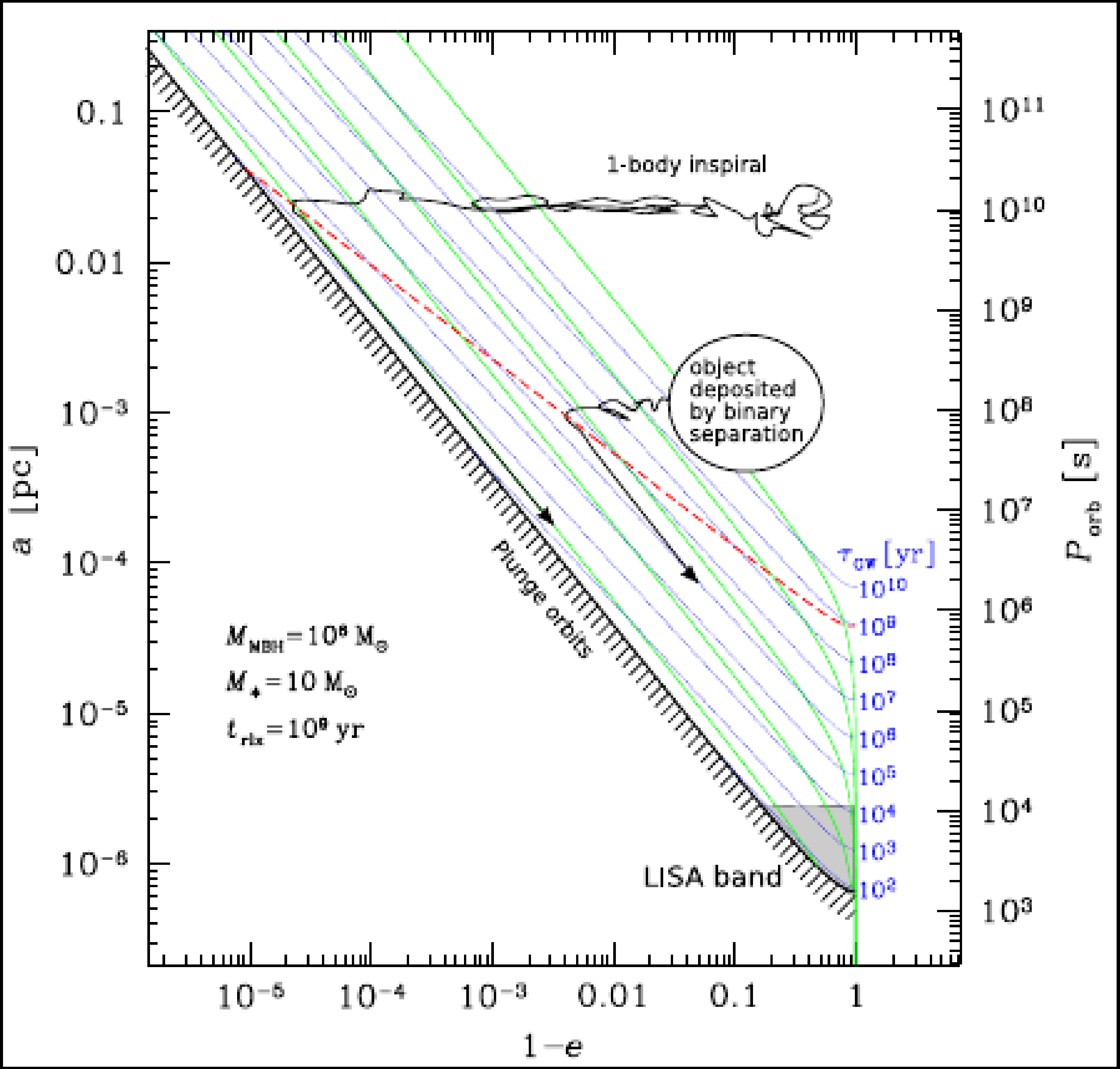


New tool for astrophysics (Gair et al 2010) **cosmology** (McLeod & Hogan 2008), **and fundamental physics** (Gair et al 2013) …
to be further explored





(Babak et al, 2017)



(Amaro Seoane et al. 2007)

Equating the two timescales give

$$a_{\rm EMRI} = 5.3\times10^{-2}\,{\rm pc}\,C_{\rm EMRI}^{2/3}\times\left(\frac{t_{\rm rlx}}{10^9\,{\rm yr}}\right)^{2/3}\left(\frac{m}{10\,M_\odot}\right)^{2/3}\left(\frac{\mathcal{M}_\bullet}{10^6\,M_\odot}\right)^{-1/3}$$

$$1-e_{\rm EMRI} = 7.2\times10^{-6}\,C_{\rm EMRI}^{-2/3}\times\left(\frac{t_{\rm rlx}}{10^9\,{\rm yr}}\right)^{-2/3}\left(\frac{m}{10\,M_\odot}\right)^{-2/3}\left(\frac{\mathcal{M}_\bullet}{10^6\,M_\odot}\right)^{4/3}$$

Note that for $\rho \,\alpha\, r^{-2}$, $dn/dr \,\alpha\, r$

Moreover, the time it takes to scatter things in and out of the 'capture loss cone is $(1\text{-}e)t_{rlx}$.

$(1\text{-}e)$ is proportional to $1/r$, so that

$(1\text{-}e)t_{rlx}$ is proportional to $r^{-1/2}$

In practice the largest contribution to capture comes from a_{EMRI}!

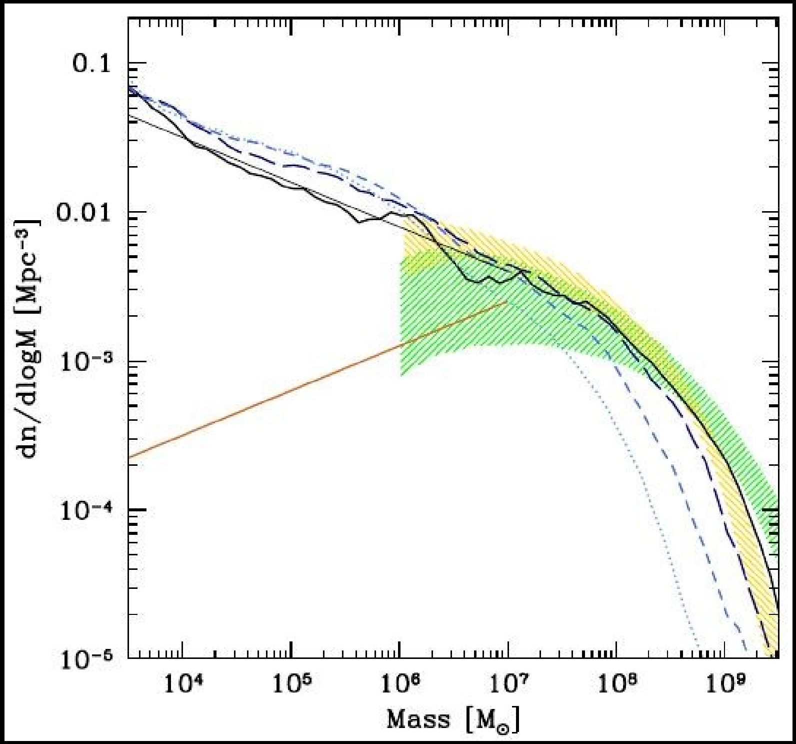
What is the rate? The rate can be approximated as

$N_{CO}(<a_{EMRI})/T_{rlx}(a_{EMRI})$

For a MW cusp, $N_{CO}\sim10^4$, $T_{rlx}(a_{EMRI})\sim10^{11}$yr

So the rate is $\sim10^{-7}$/yr or 100/Gyr

$$R_0 = 300\left(\frac{M}{10^6\,M_\odot}\right)^{-0.19}\,{\rm Gyr}^{-1}$$



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)**?
- -Scaling with mass too naive! **(Babak+17)**

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