LISA science

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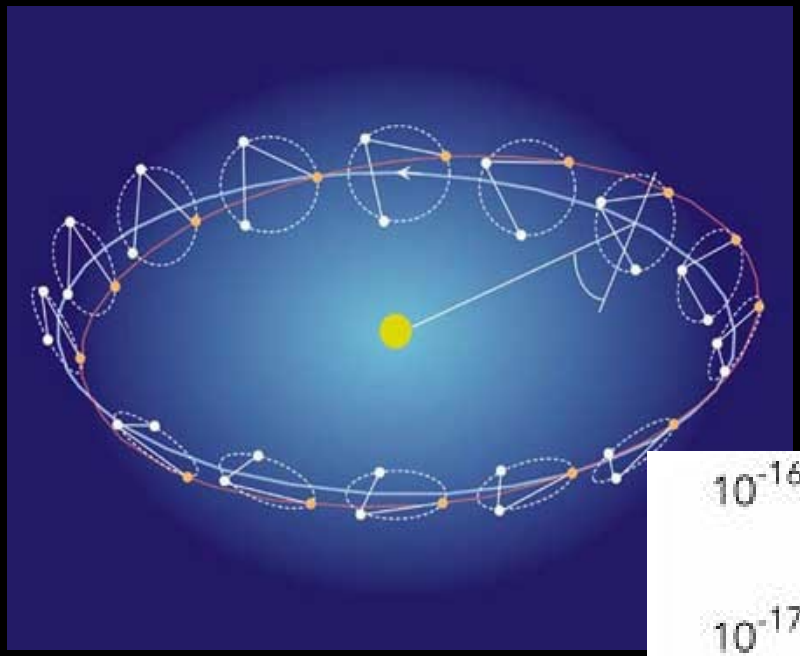
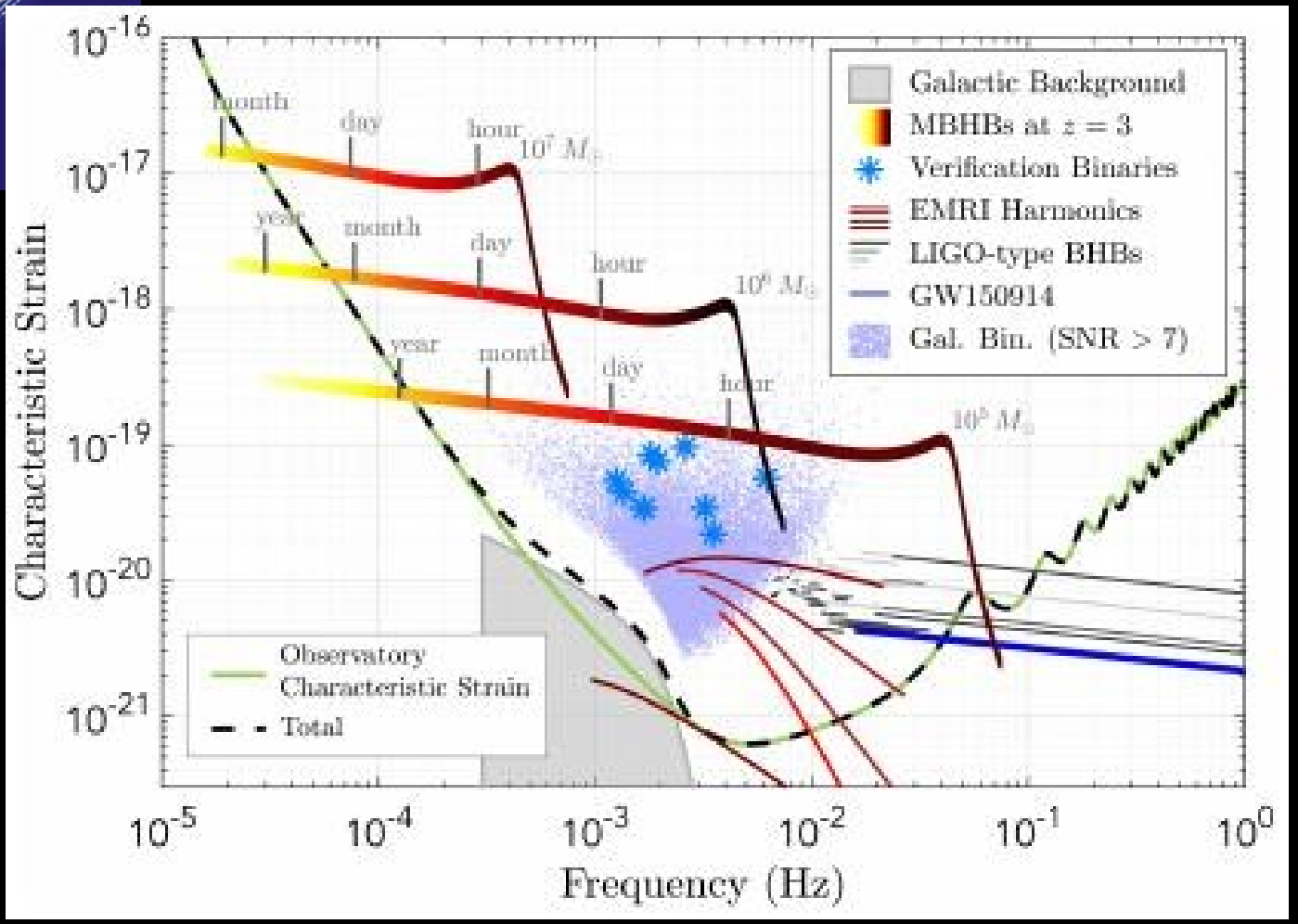
The Laser Interferometer Space Antenna



Sensitive in the mHz frequency range which is anticipated to be the richest frequency band in terms of GW sources

3 satellites trailing the Earth connected through laser links

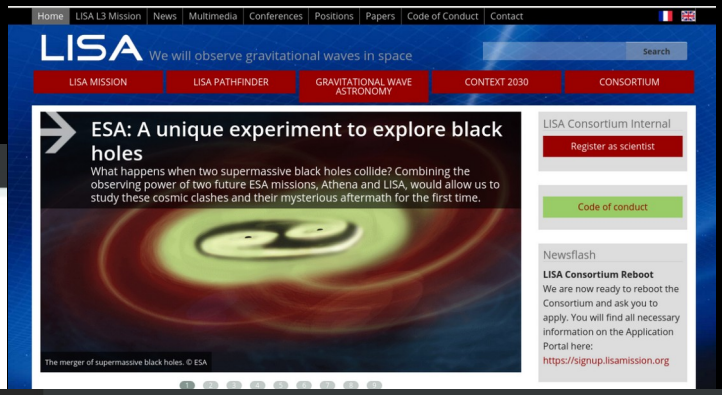
Proposed baseline:
2.5M km armlength
6 laser links
4 yr of science data

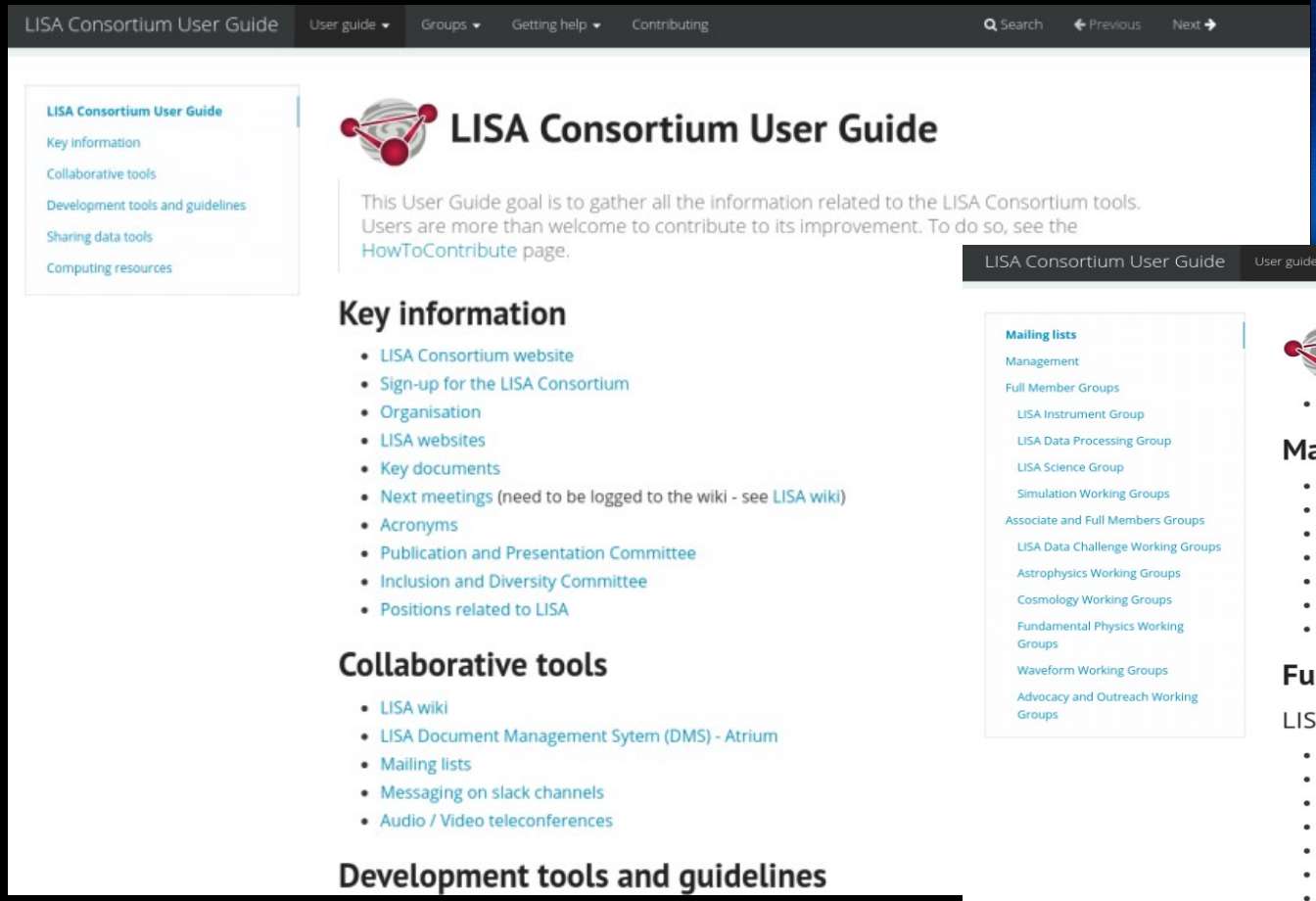


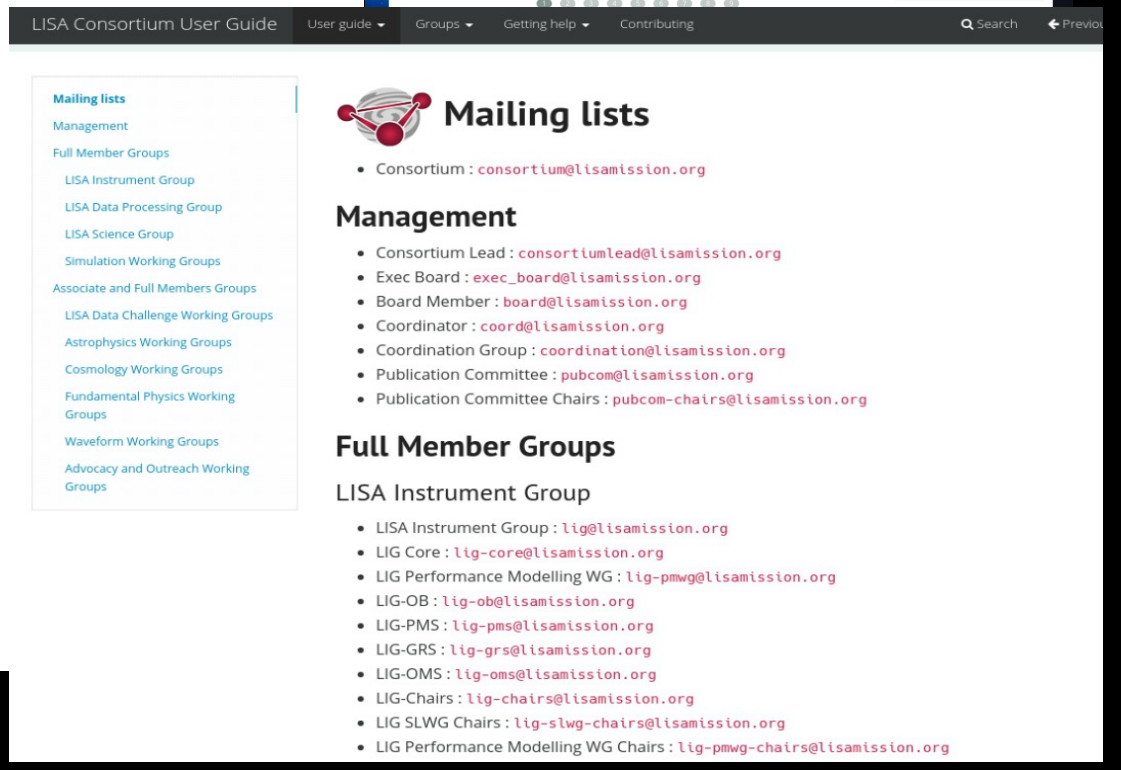
The LISA Consortium

- Now a thriving community: 1300+ among full and associate members
- Several working groups connecting to the community: astrophysics, fundamental physics, cosmology, waveforms
- Several working packages defining deliverables
- 2 consortium meetings/yr, LISA symposium every 2 years, dedicated WG meetings every year

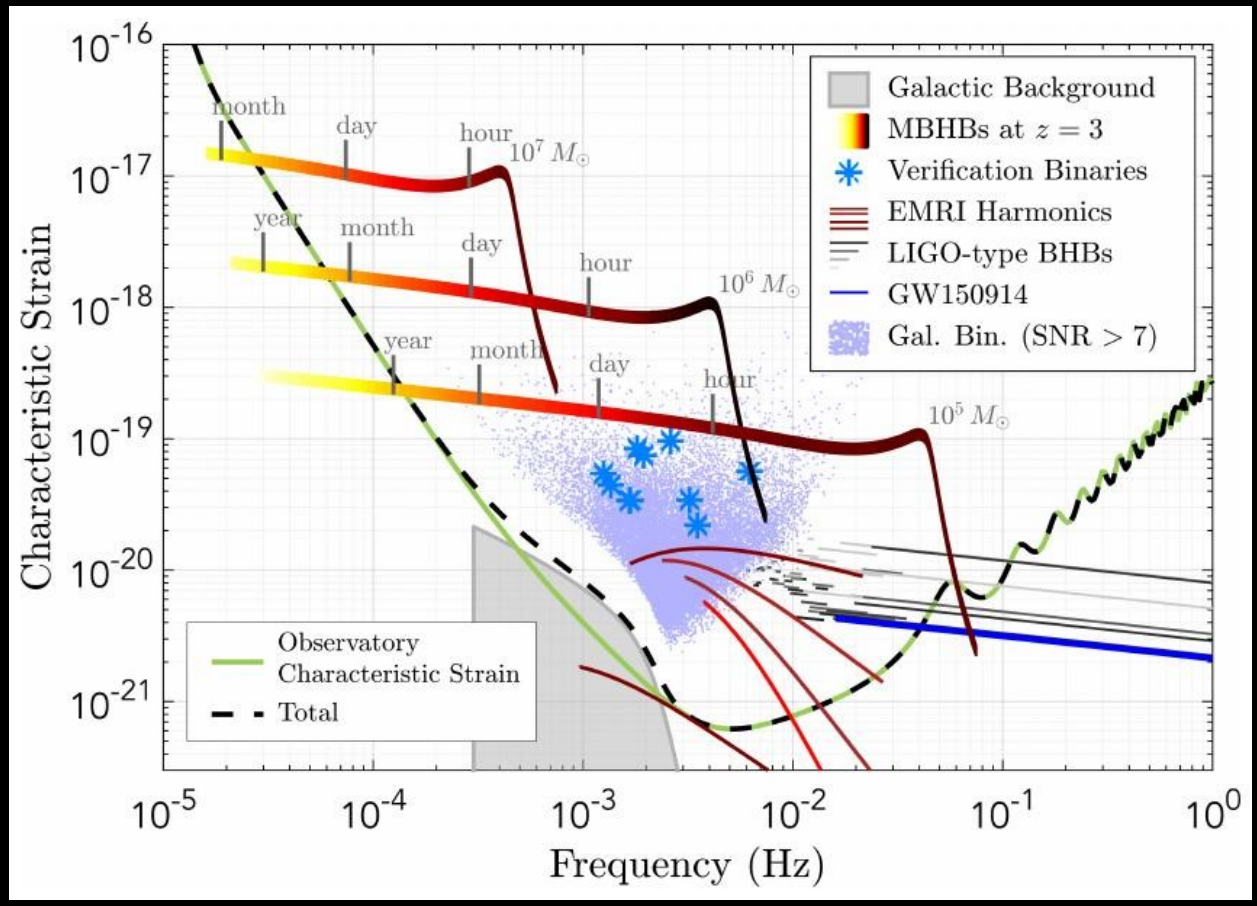
https://www.lisamission.org/





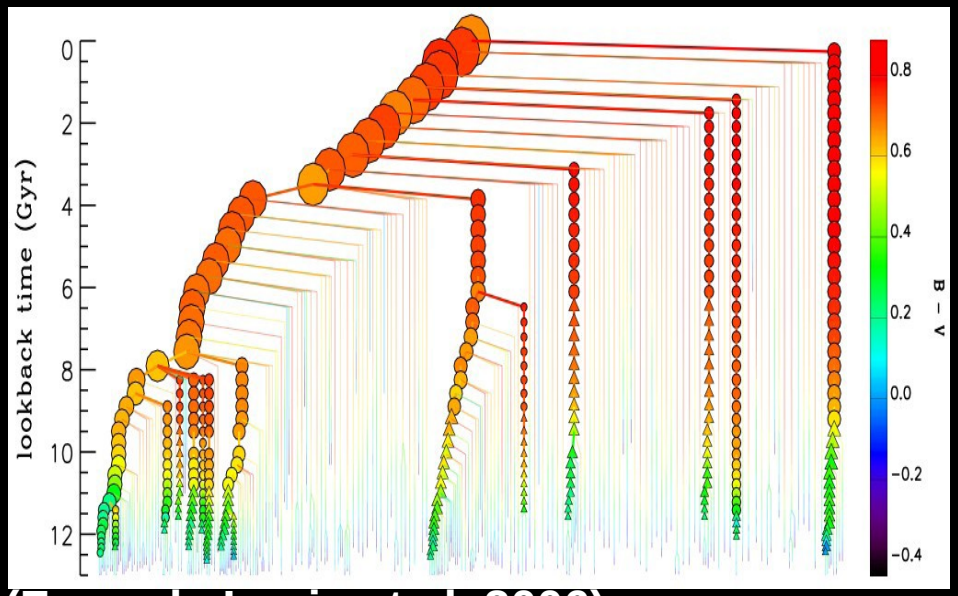


Massive objects inspiralling and merging: freqeuncy set by the Most massive object so we have:
1-massive black hole binaries (MBHBs)
2-extreme mass ratio inspirals (EMRIs)



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

MBH evolution in a nutshell



(From de Lucia et al. 2006)

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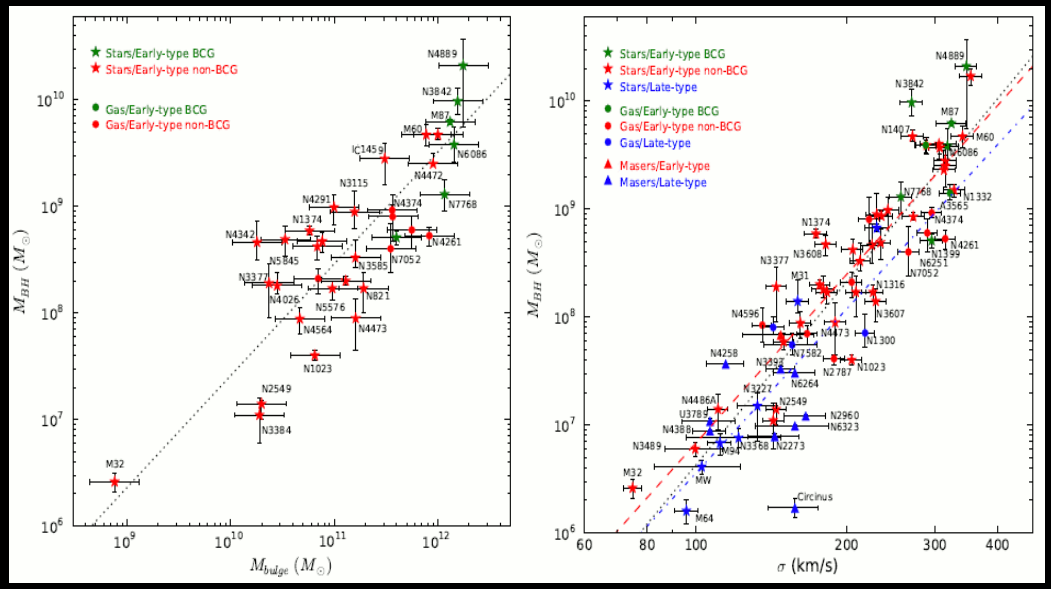

(Ferrarese & Merritt 2000, Gebhardt et al. 2000)

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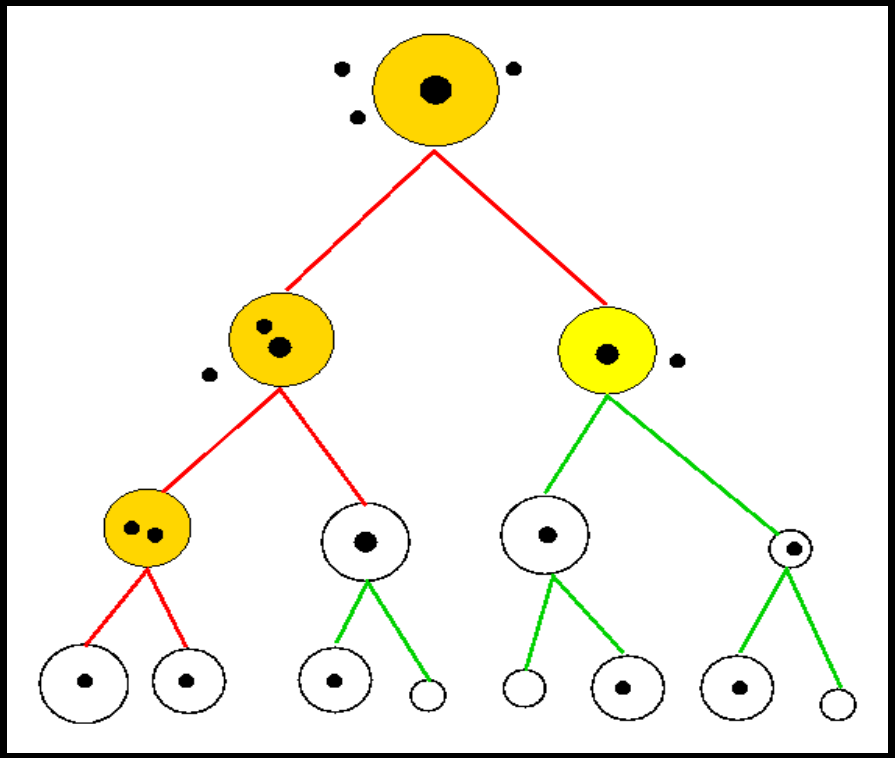
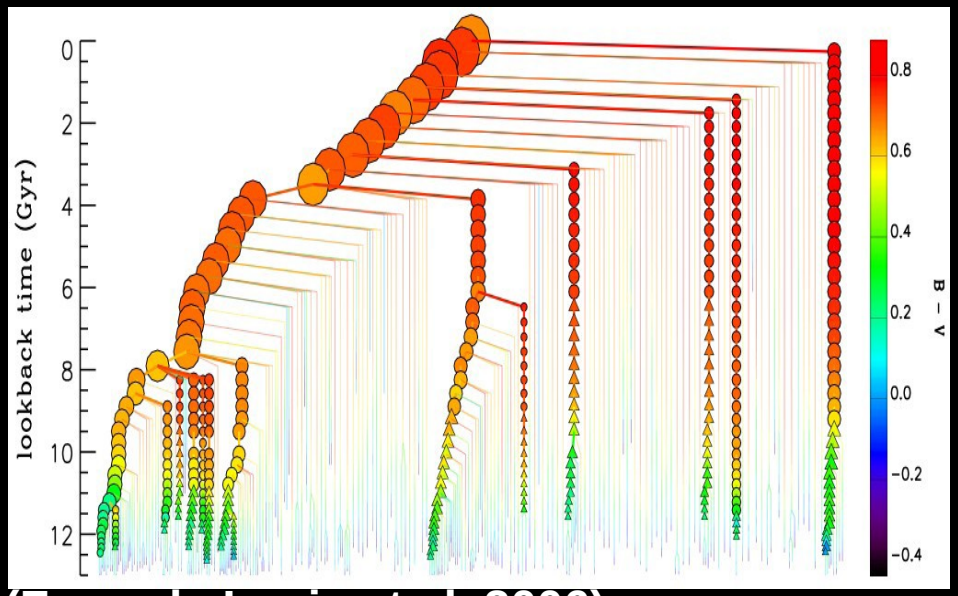


(Menou et al 2001, Volonteri et al. 2003)

MBH evolution in a nutshell



(From de Lucia et al. 2006)

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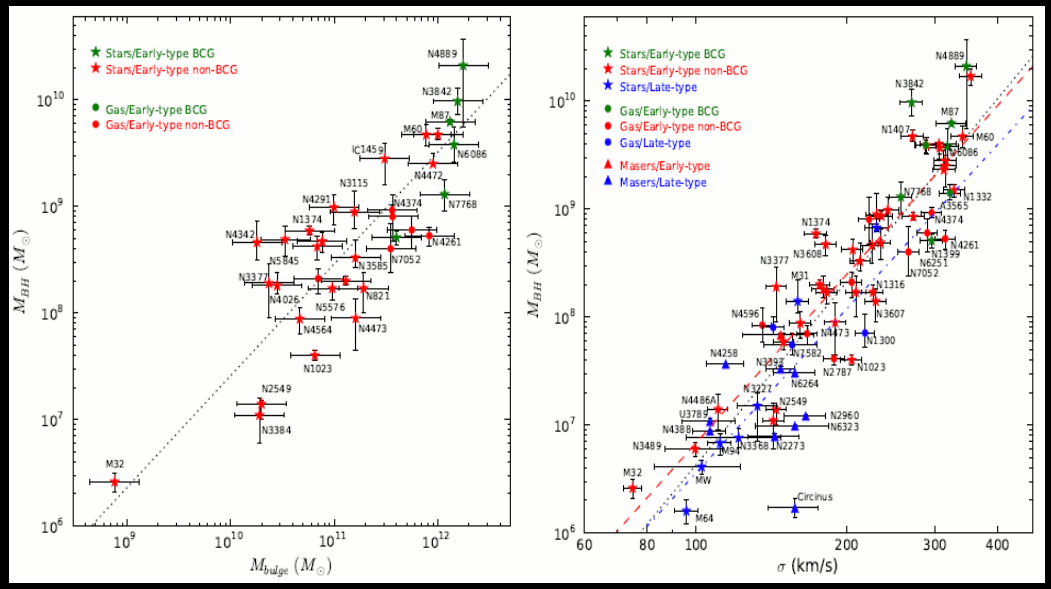

(Ferrarese & Merritt 2000, Gebhardt et al. 2000)

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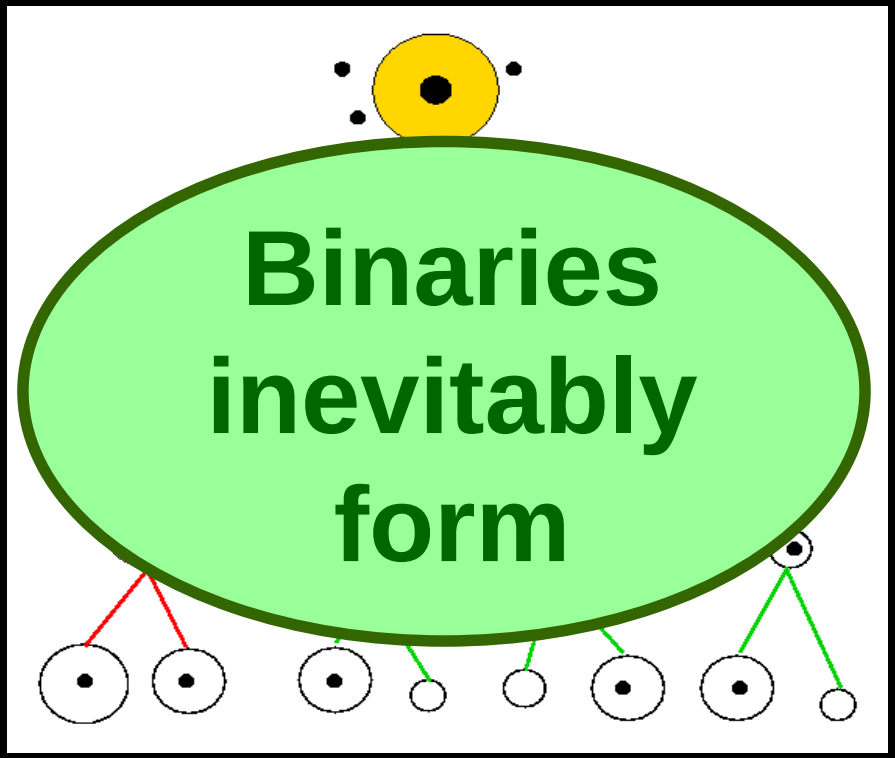
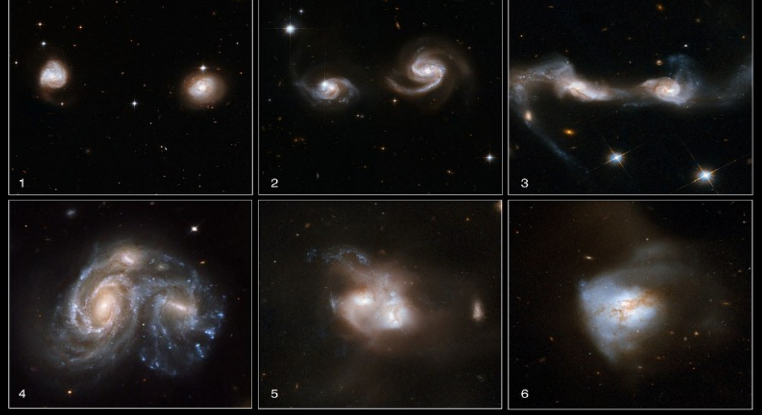


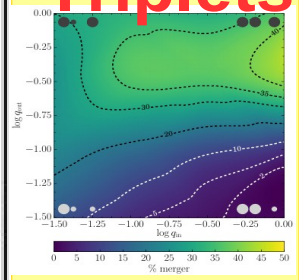
(Menou et al 2001, Volonteri et al. 2003)

*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)



Triplets



(Bonetti+18
Ryu+18)

Stall?

Loss Cone
Depletion

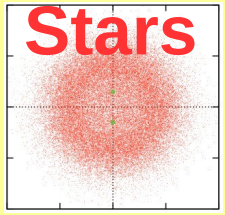
Other
Processes

Dynamical
Friction

Observational
Normalization

GW
Orbit
Decay

Stars



(Kahn+11,
Preto+11,
AS&Khan15,
Vasiliev+15)

Gas

(Hayasaki+07,
Cuadra+09,
Roedig+11,
AS+12...)

TIME SCALE, $|\dot{R}/R|$ [years]

10^{10}

10^{8}

10^{6}

10^{4}

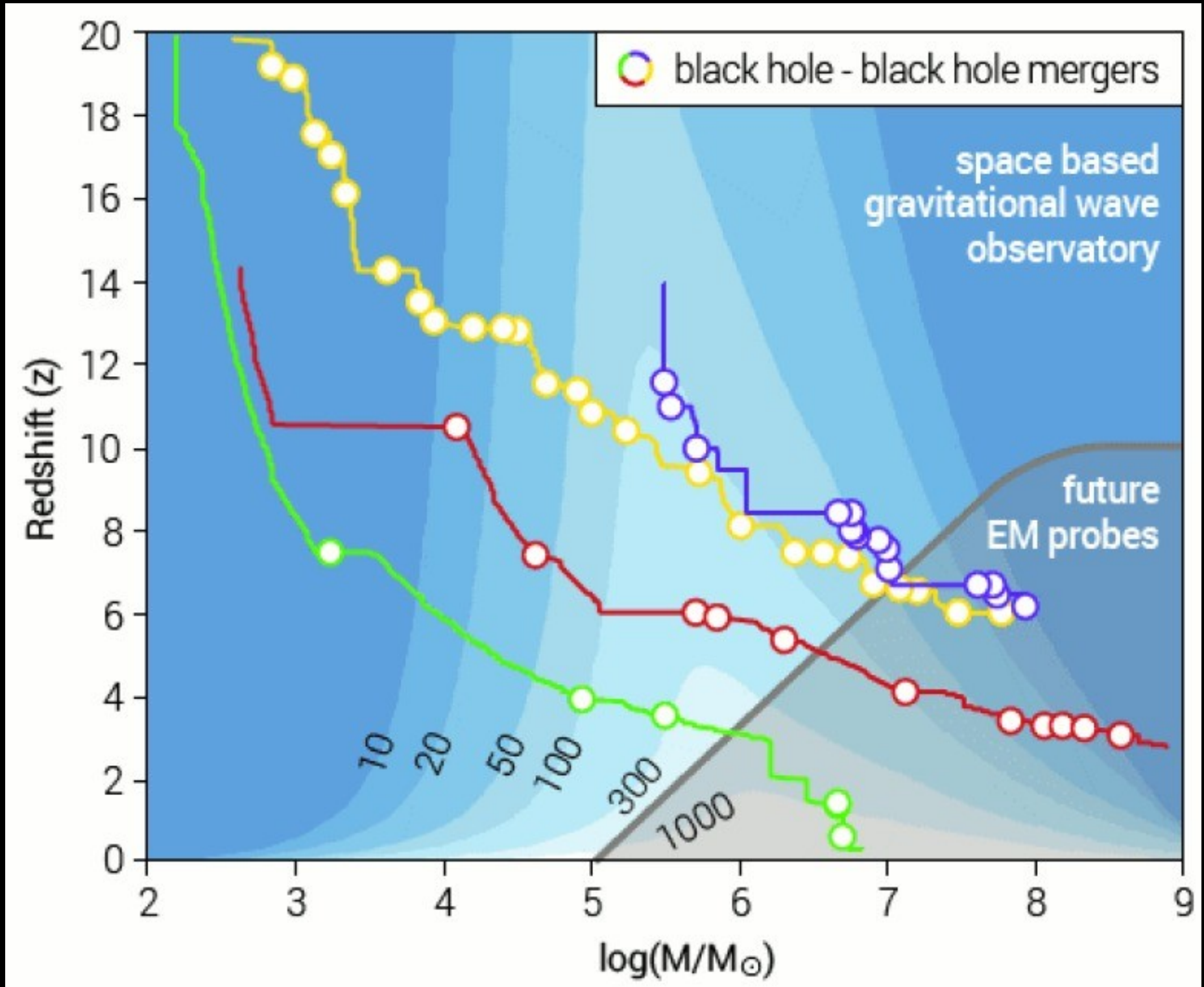
10^{-2}

1

100

1000

RADIUS, R [parsec]

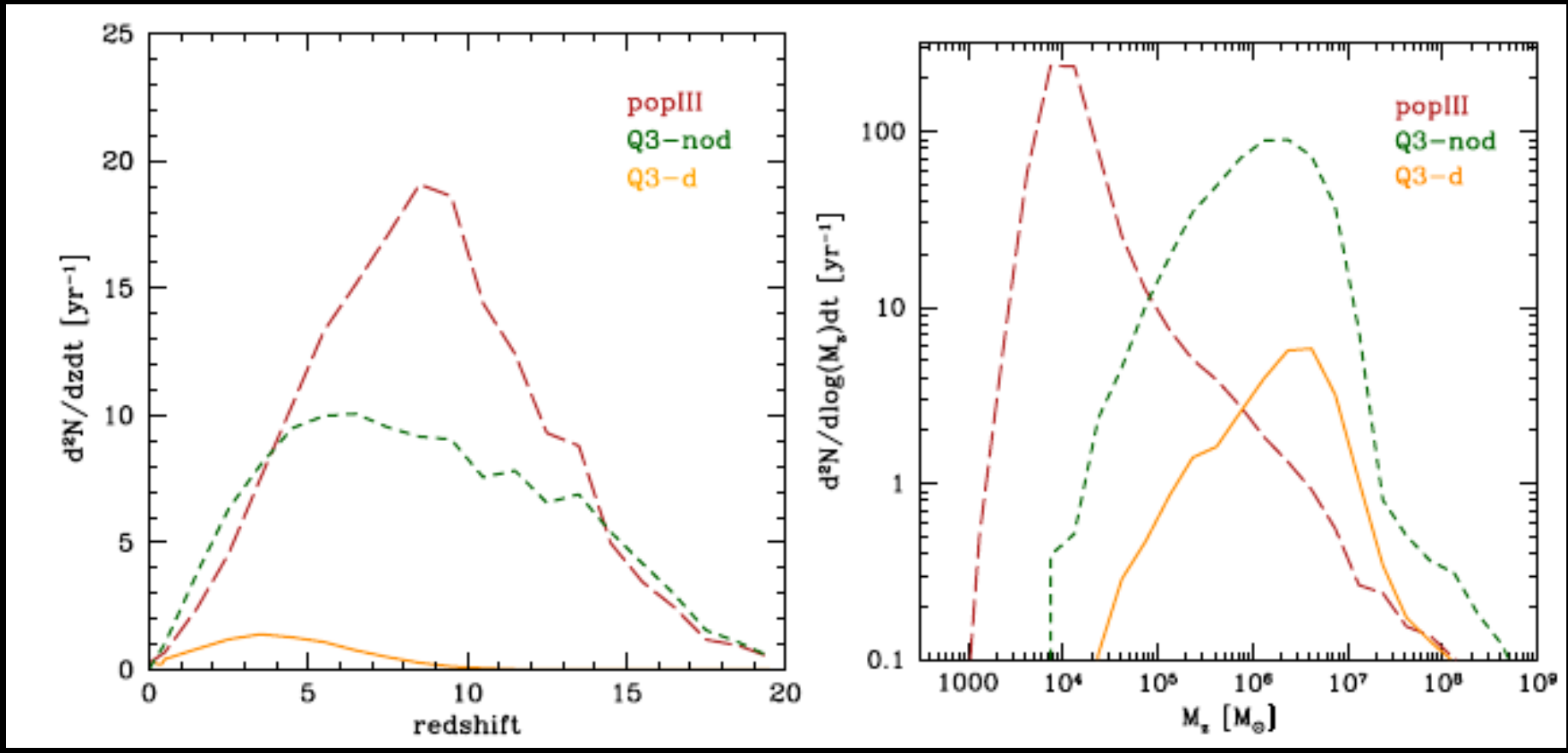

black hole - black hole mergers
space based
gravitational wave
observatory
future
EM probes
10
20
50
100
300
1000
Redshift (z)
log(M/M⊙)
0
2
4
6
8
10
12
14
16
18
20
2
3
4
5
6
7
8
9

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**



Summary of LISA parameter estimation

LISA is anticipated to detect:

~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

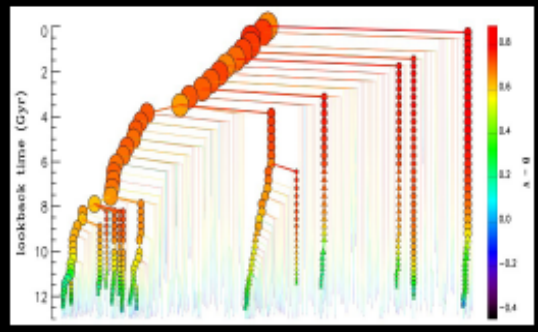
~50 systems with spin direction determined within 10deg

~30 events with final spin determined to 0.1

MBH astrophysics with GW observations

Astrophysical unknowns in MBH formation scenarios

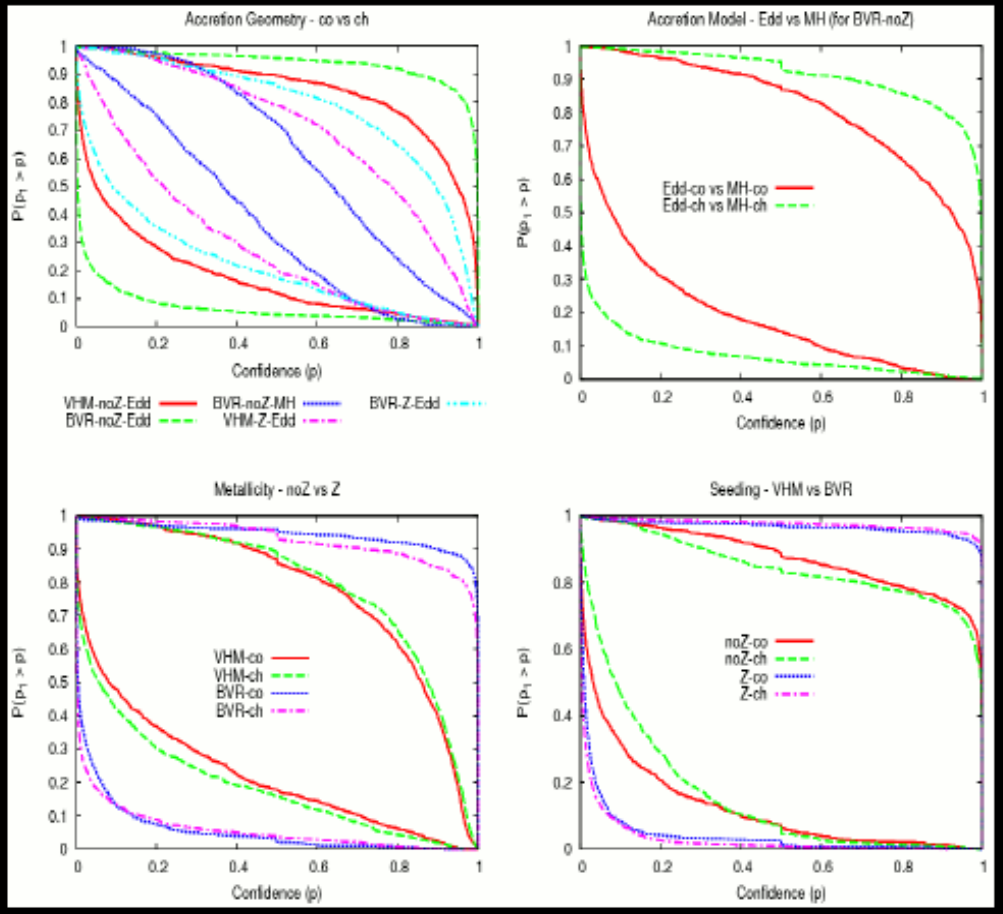
1- MBH seeding mechanism (heavy vs light seeds)
2- Metallicity feedback (metal free vs all metalliticies)
3- Accretion efficiency (Eddington?)
4- Accretion geometry (coherent vs. chaotic)



CRUCIAL QUESTION:
Given a set of LISA observation of coalescing MBH binaries, what astrophysical information about the underlying population can we recover?

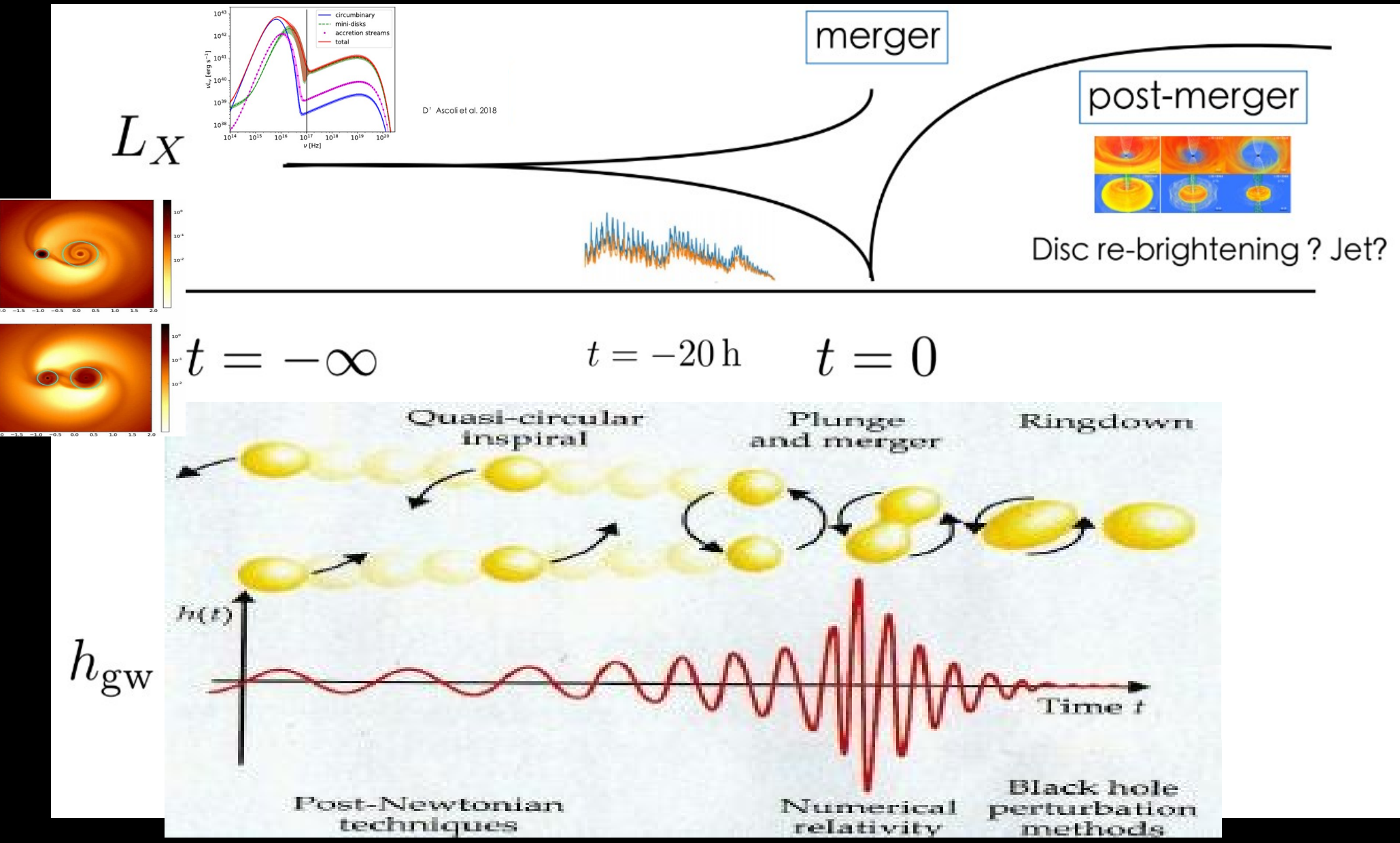
Create catalogues of observed binaries including errors from eLISA observations and compare observations with theoretical models

(see also Toubiana+ 2021)



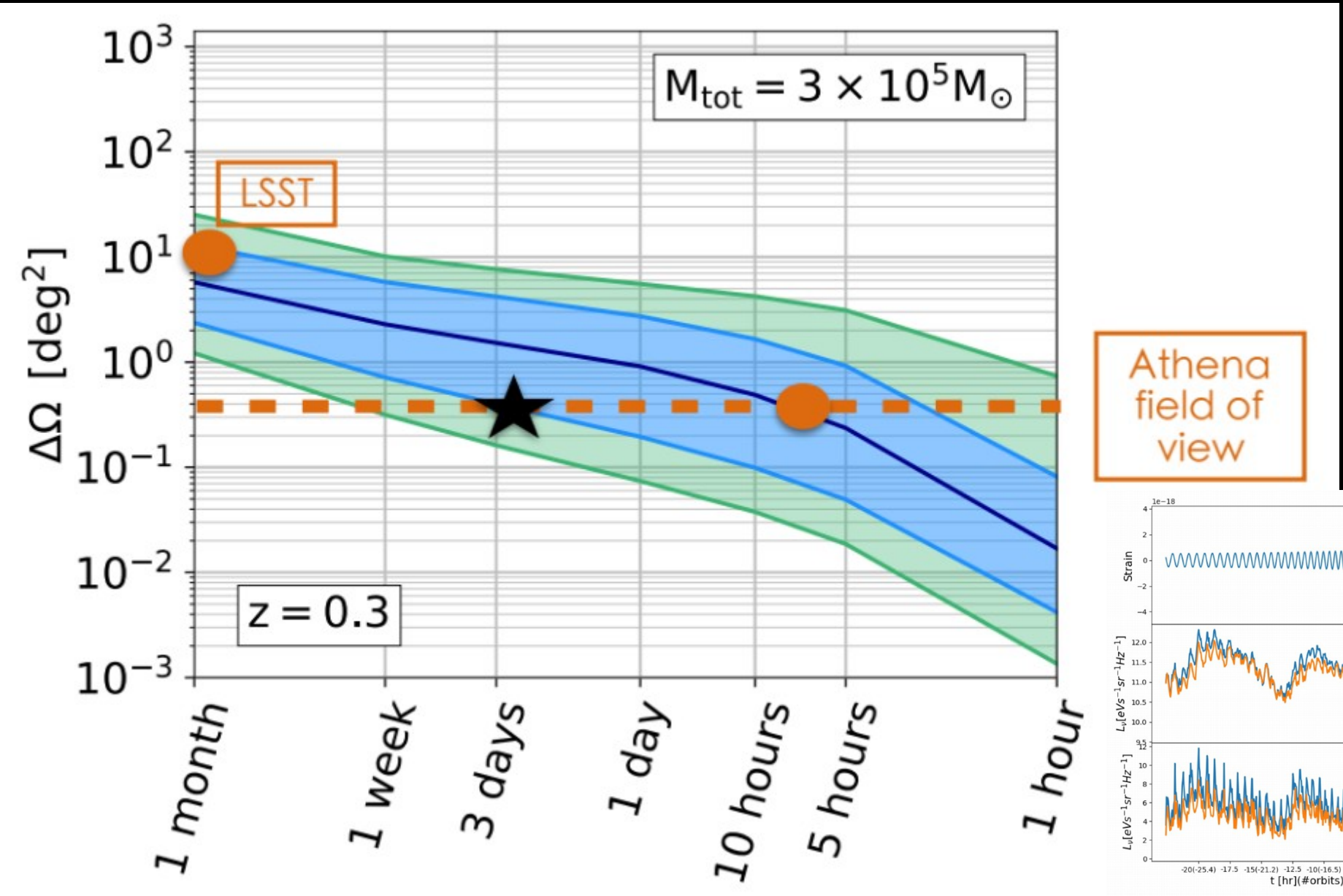
AS et al. 2011, see also Plowman et al 2011

Associated electromagnetic signatures



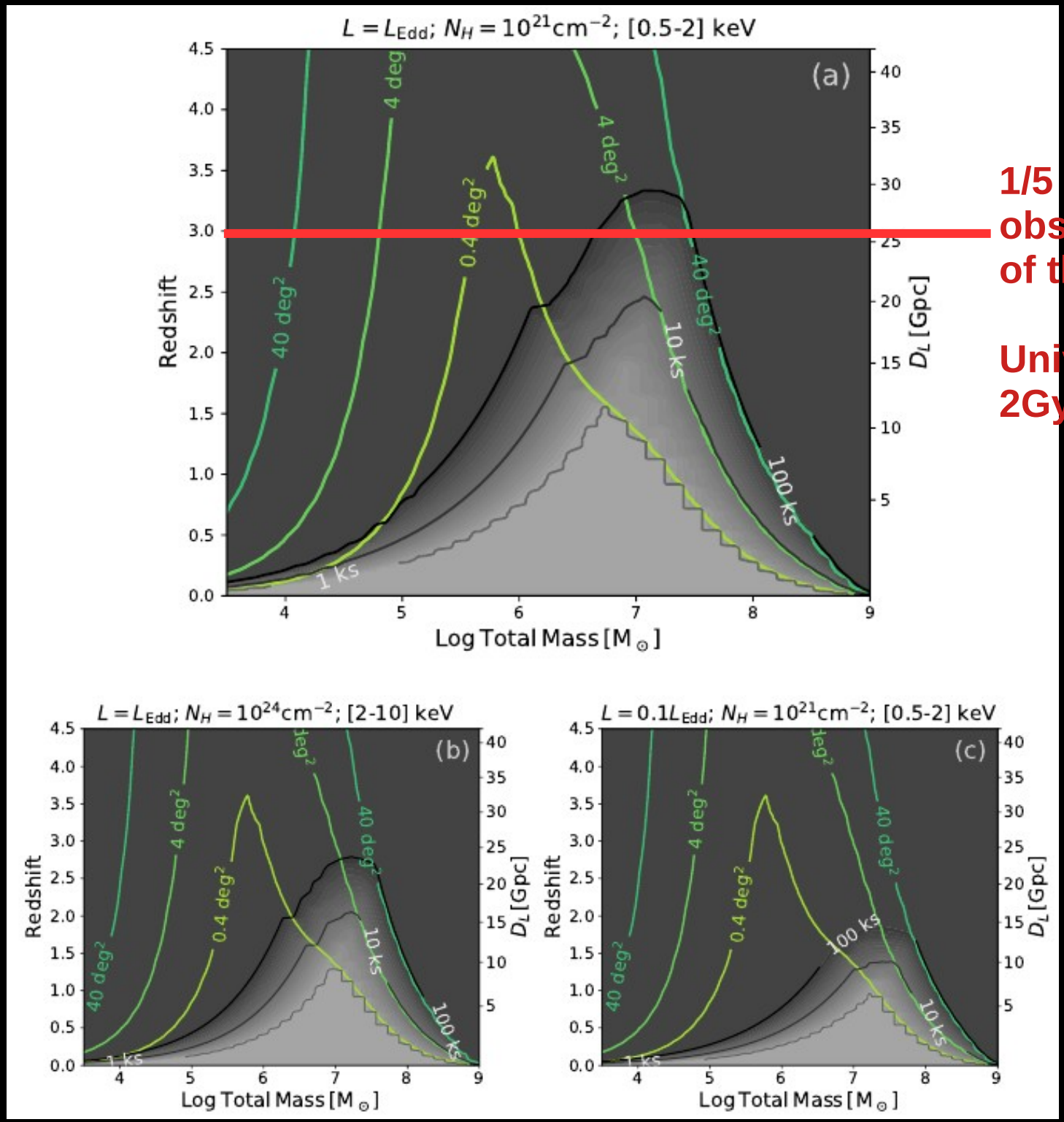
(Palenzuela+ 2010, Gold+ 2014, Farris+ 2014, Tang+ 2017, 2018, D'Ascoli+ 2018, ...)

Sky localization



(Mangiagli+ 2020, Piro+ in prep.)

-Athena pre-pointing only possible for very low z sources
-LSST/Rubin more suitable for tracking inspiral periodicity (but optical)



1/5 of the observable volume of the universe.

Universe was 2Gyr old.

(McGee+ 2020)

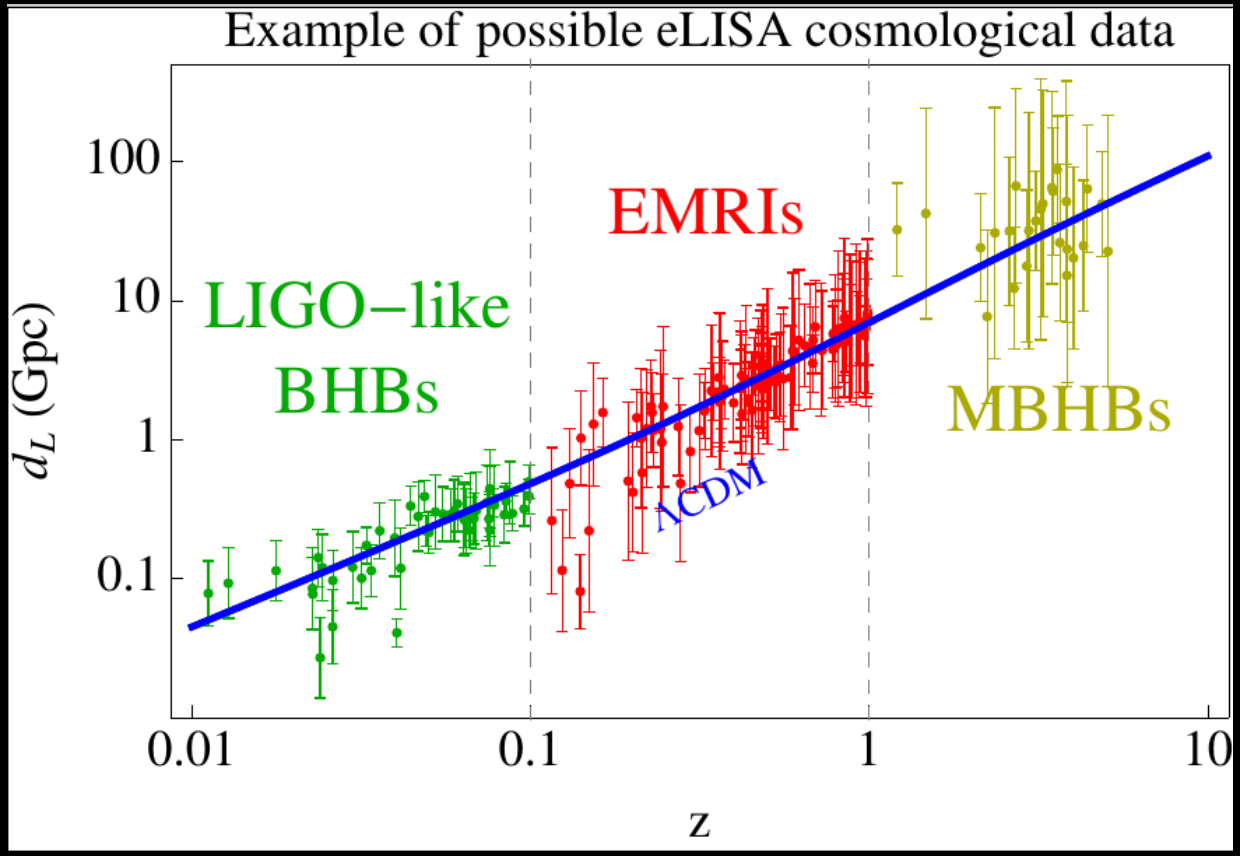
Why multimessenger?

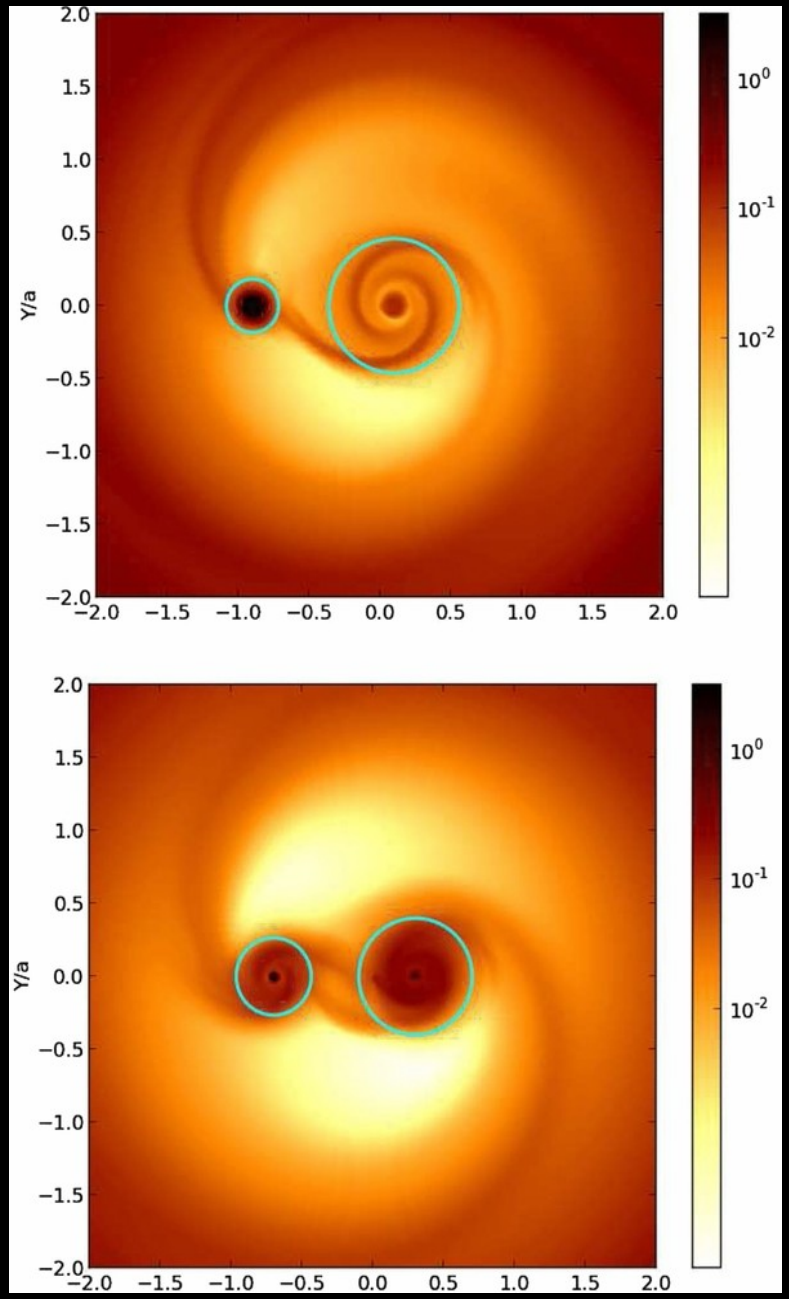
- Cosmology and cosmography at high *z*

- Study of accretion on MBHs with known mass and spins

- Study of the interplay between MBHs and gas (torques, disk structure, disk models)

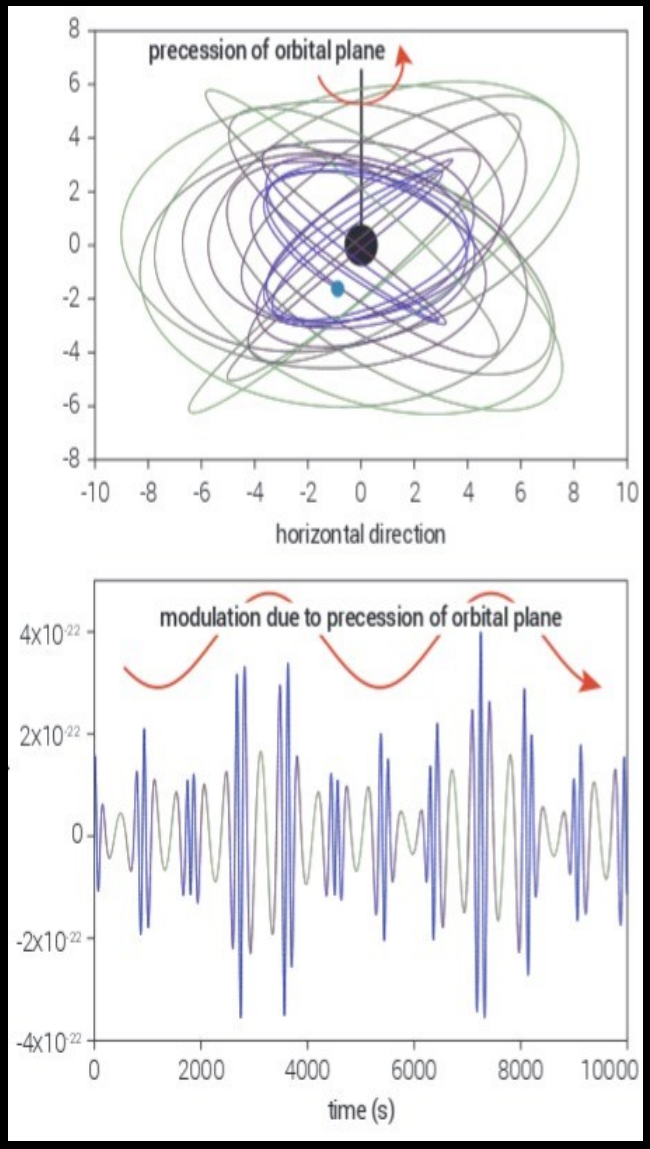
- Host galaxy, Jet launches, AGN lightup...





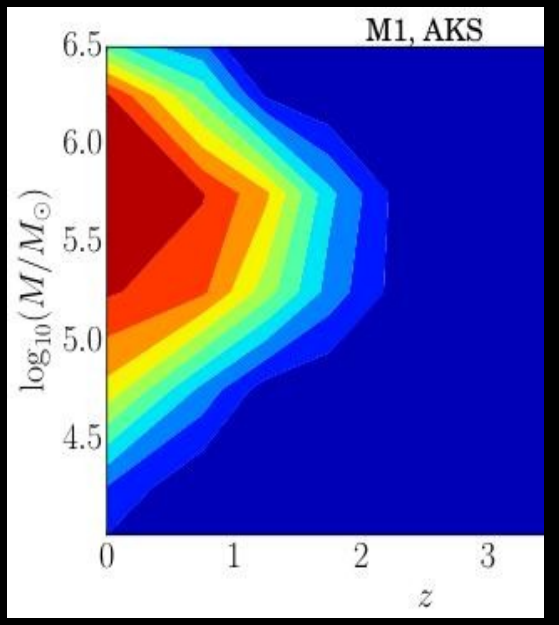
Courtesy of N. Tamanini

Extreme mass ratio inspirals (EMRIs)

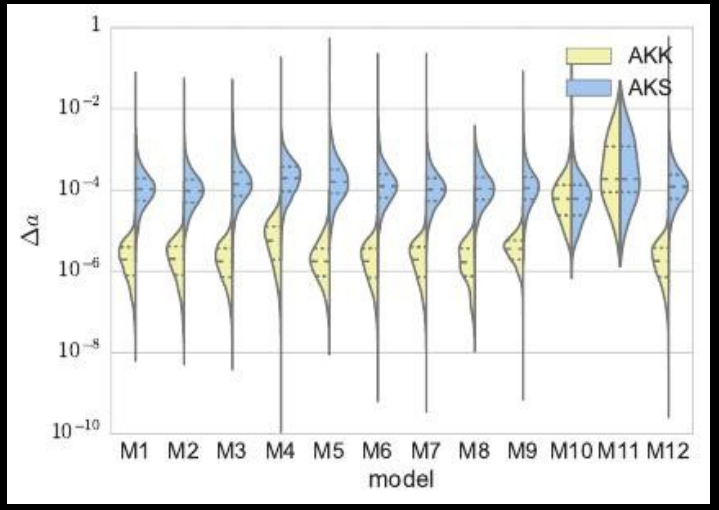


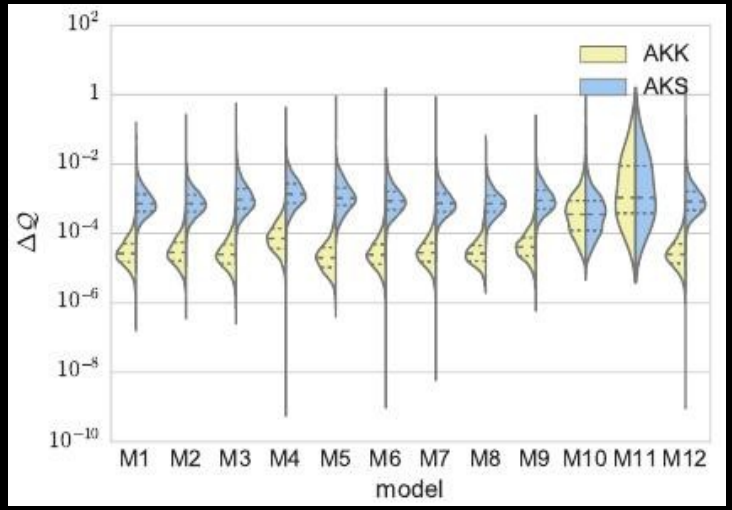
(Babak et al, 2017)

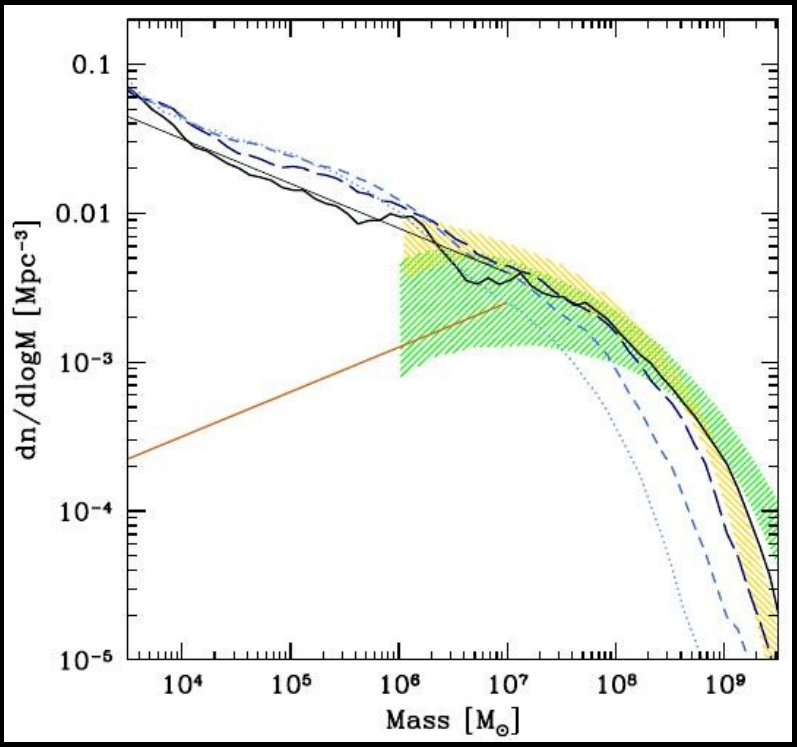
- 1-1000 detections/yr
- sky localization <10 deg2
- distance to better than 10%
- MBH mass to better than 0.01%
- CO mass to better than 0.01%
- MBH spin to better than 0.001
- plunge eccentricity <0.0001
- deviation from Kerr quadrupole moment to <0.001



New tool for astrophysics (Gair et al 2010) **cosmology** (McLeod & Hogan 2008, Laghi+ 2021), **and fundamental physics** (Gair et al 2013) **…**
to be further explored







Astrophysical uncertainties are huge:

-MBH mass function unknown below 10^6 solar masses

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

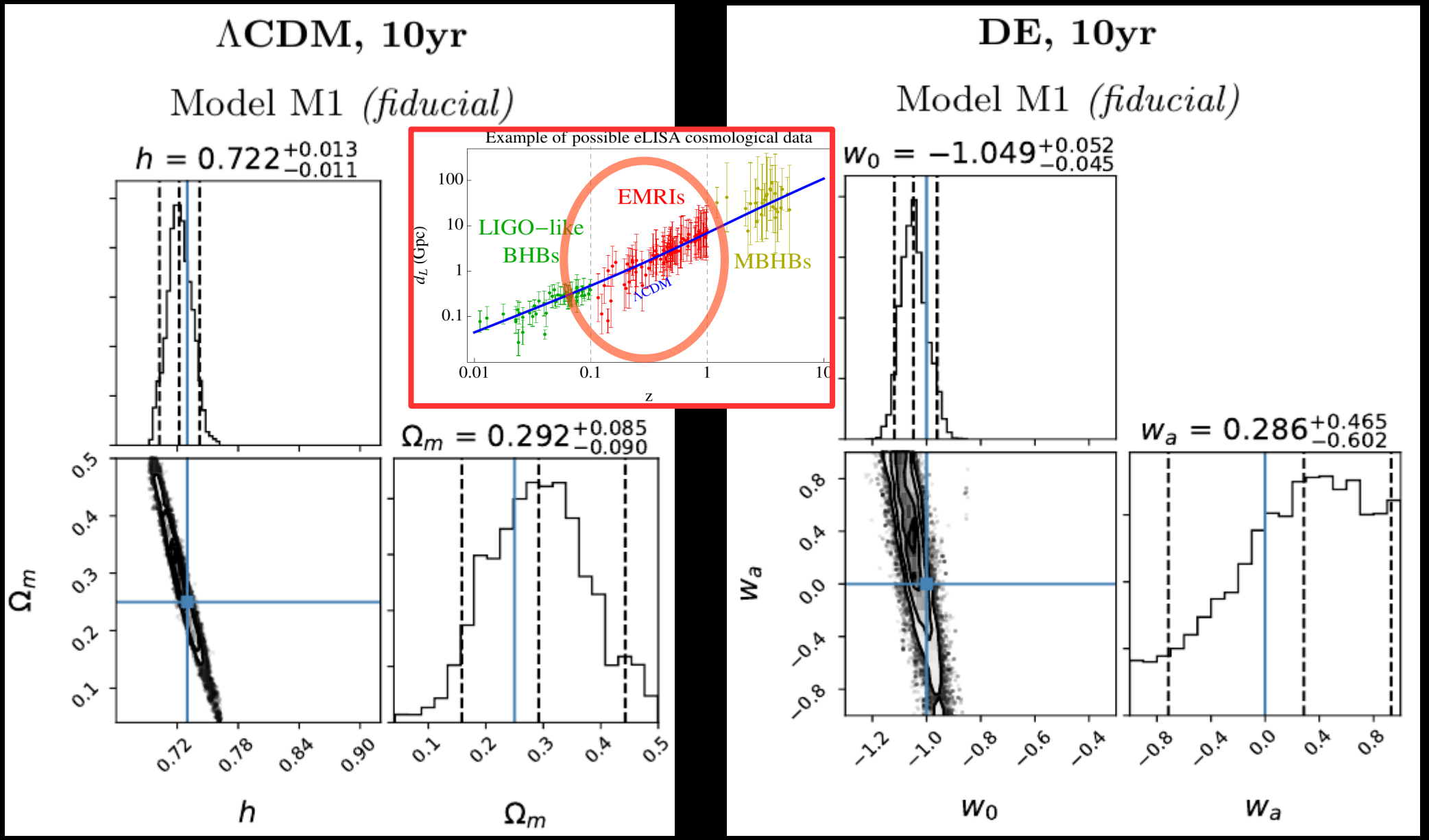
-are COs inspiralling (thus producing EMRIs) or plunging (Merritt 2015)?

-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

Example: cosmology with EMRIs



(Laghi+21)

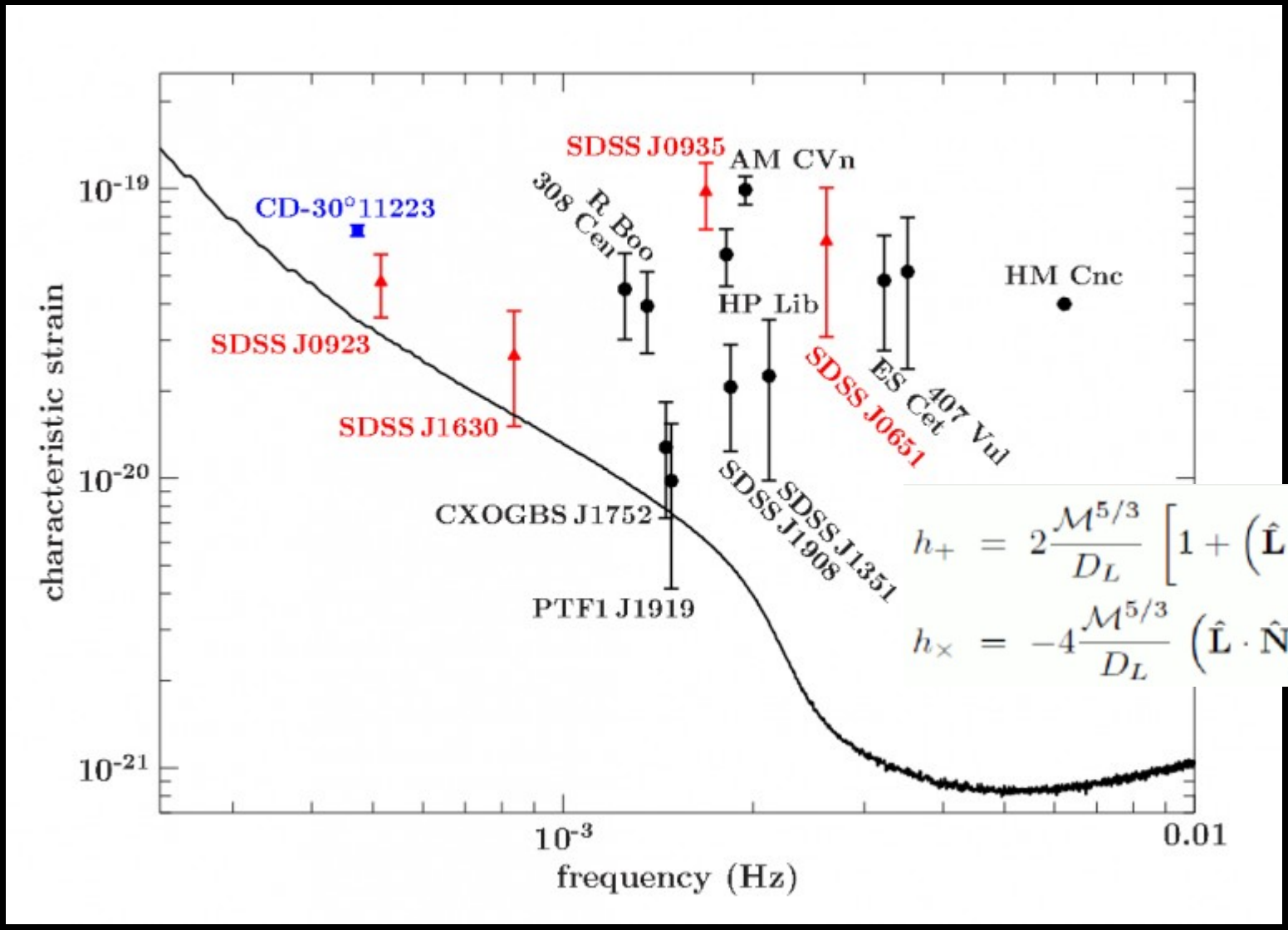
> Independent measurement of H_0 at 1.5% level

> Independent measurement of w_0 at 5% level (assuming H_0 known)

Galactic binaries

There are WD binaries for which we know period masses and distance (to some extent): verification binaries.

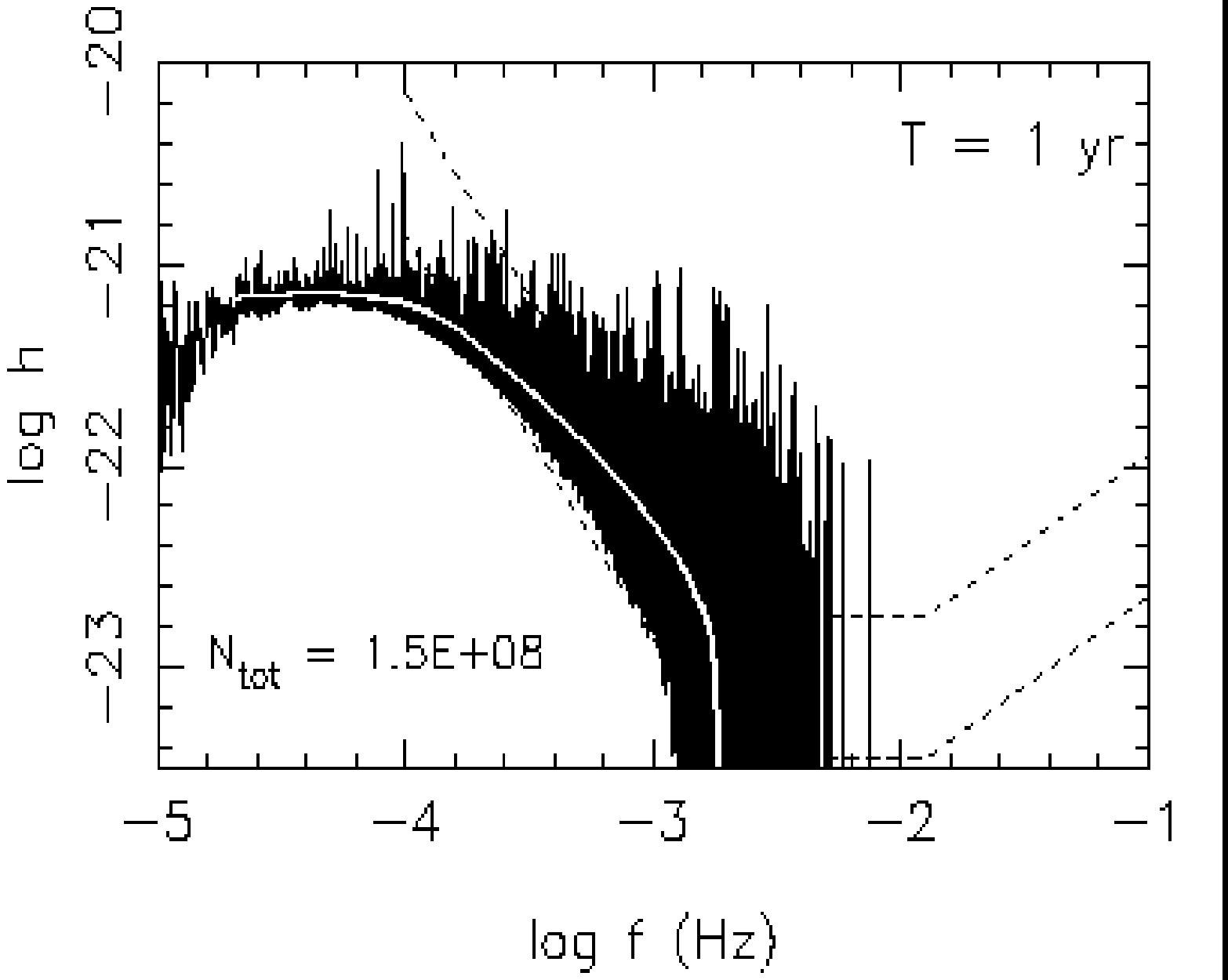
These systems are known to produce a high S/N signal in LISA. Many more expected to come with GAIA



$$h_+ = 2\frac{\mathcal{M}^{5/3}}{D_L}\left[1+\left(\hat{\mathbf{L}}\cdot\hat{\mathbf{N}}\right)^2\right](\pi f)^{2/3}\cos\phi(t)$$

$$h_\times = -4\frac{\mathcal{M}^{5/3}}{D_L}\left(\hat{\mathbf{L}}\cdot\hat{\mathbf{N}}\right)(\pi f)^{2/3}\sin\phi(t)\,,$$

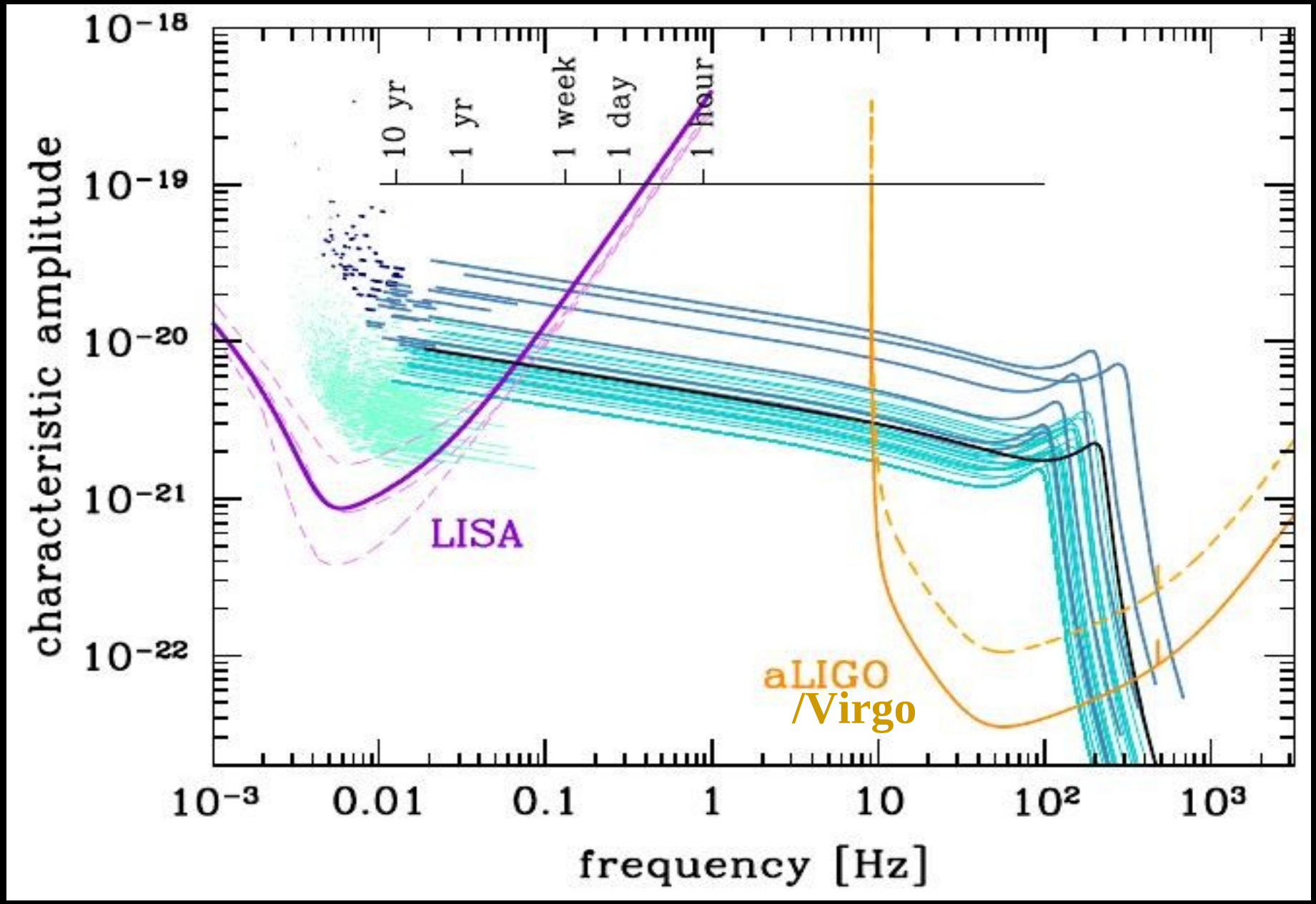
The signal looks like a ‘forest’ of lines piling up



Rates?
Eccentricity?
Triplets?
Type Ia?

Stellar origin BHs: multi-band GW astronomy

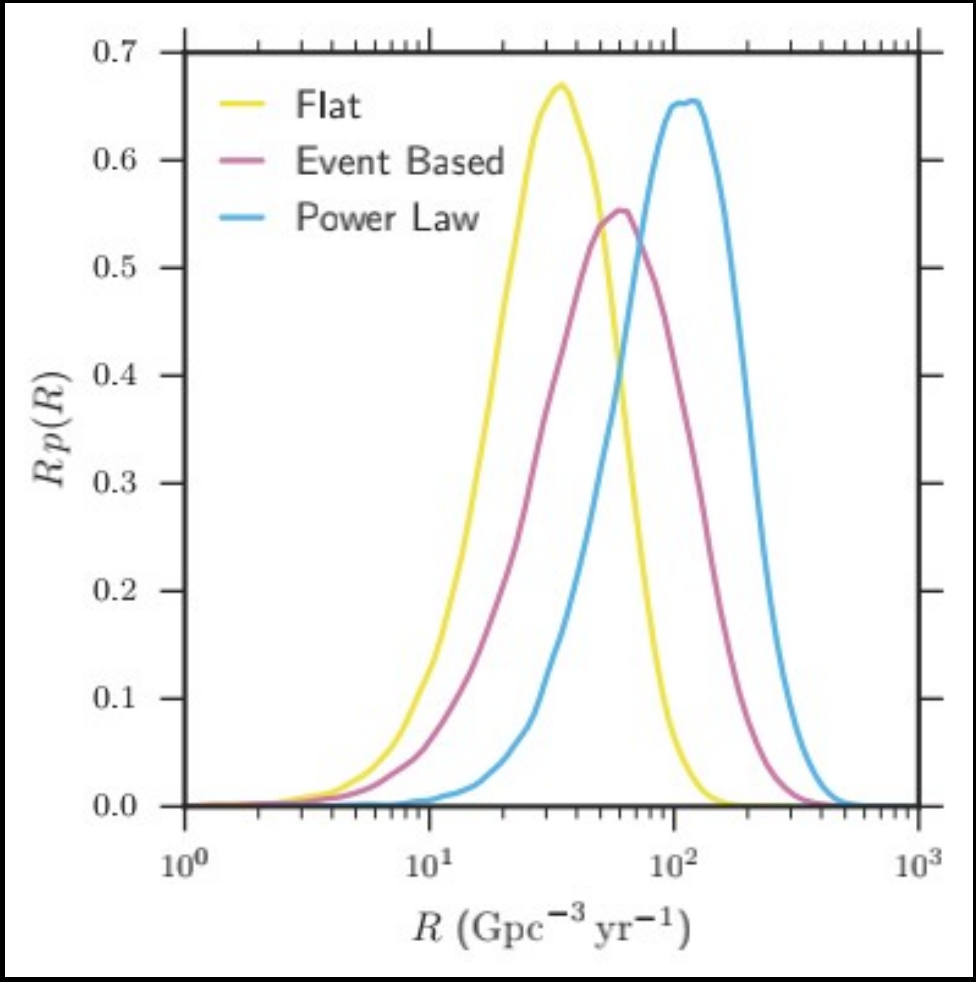
(AS 2016, PRL 116, 1102)

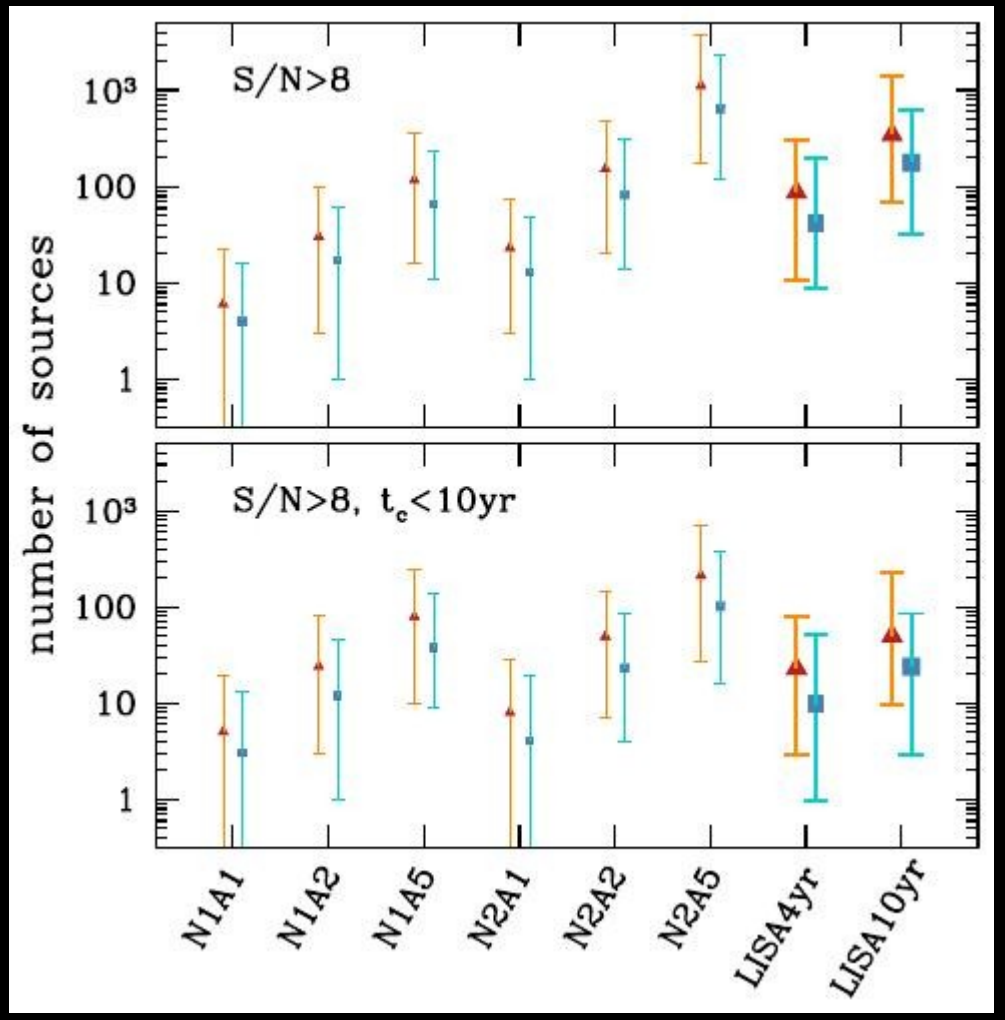


BHB will be detected by LISA and cross to the LIGO/Virgo band, assuming a 5 year operation of LISA.

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

What do we do with them?

>Detector cross-band calibration and validation (LISA - L-V-K)

>Multiband GW astronomy:

LISA → L-V-K: *alert L-V-K to ensure GW detectors are on

***inform L-V-K with source parameters: makes detection easier**

L-V-K → LISA: *identify sub-threshold source that can be dug out of the LISA data streams

>Multimessenger astronomy:

-point EM probes at the right location before the merger

>Enhanced tests of GR: e.g. strongest limits on deviations from GR

>Astrophysics:

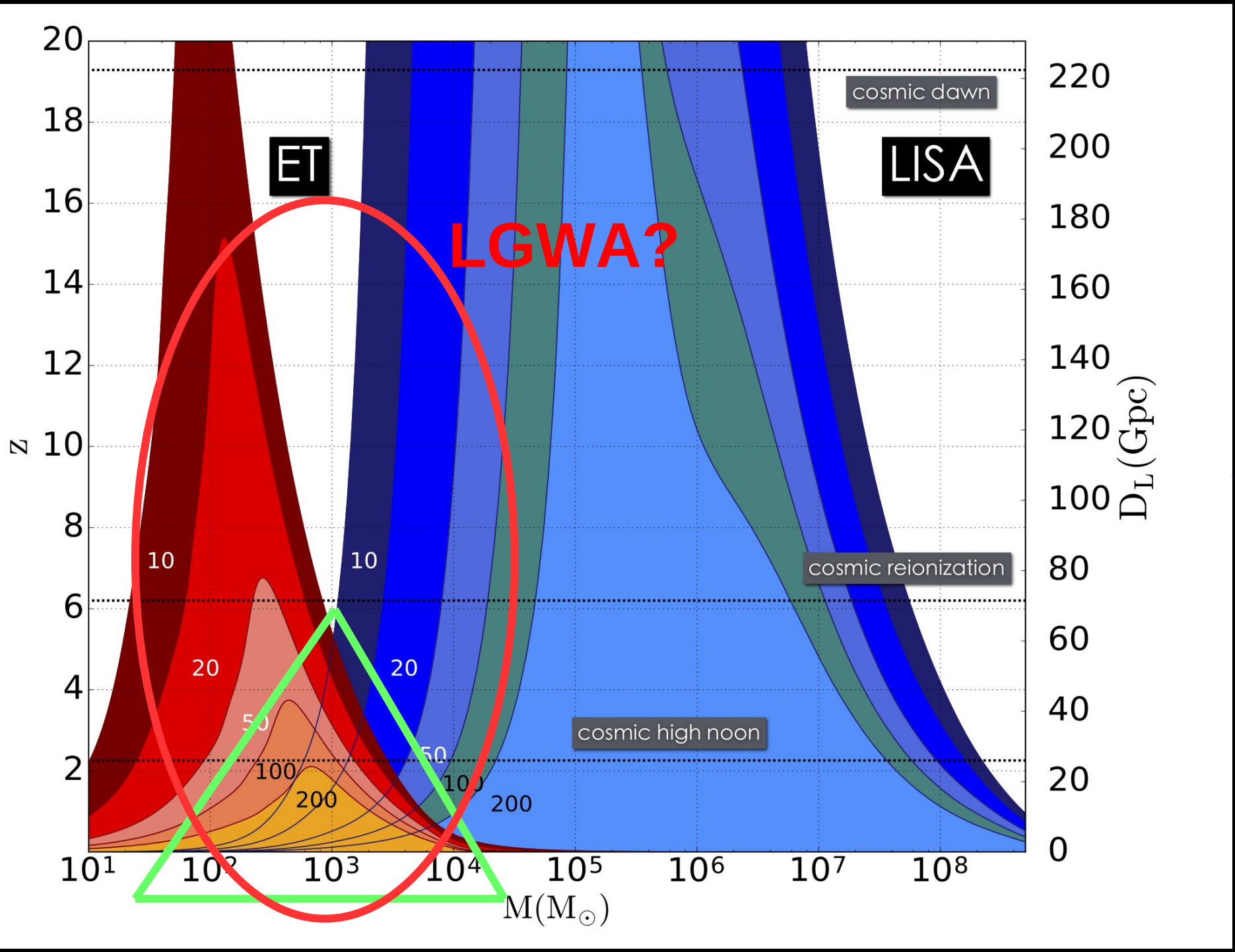
-independent measure of spins

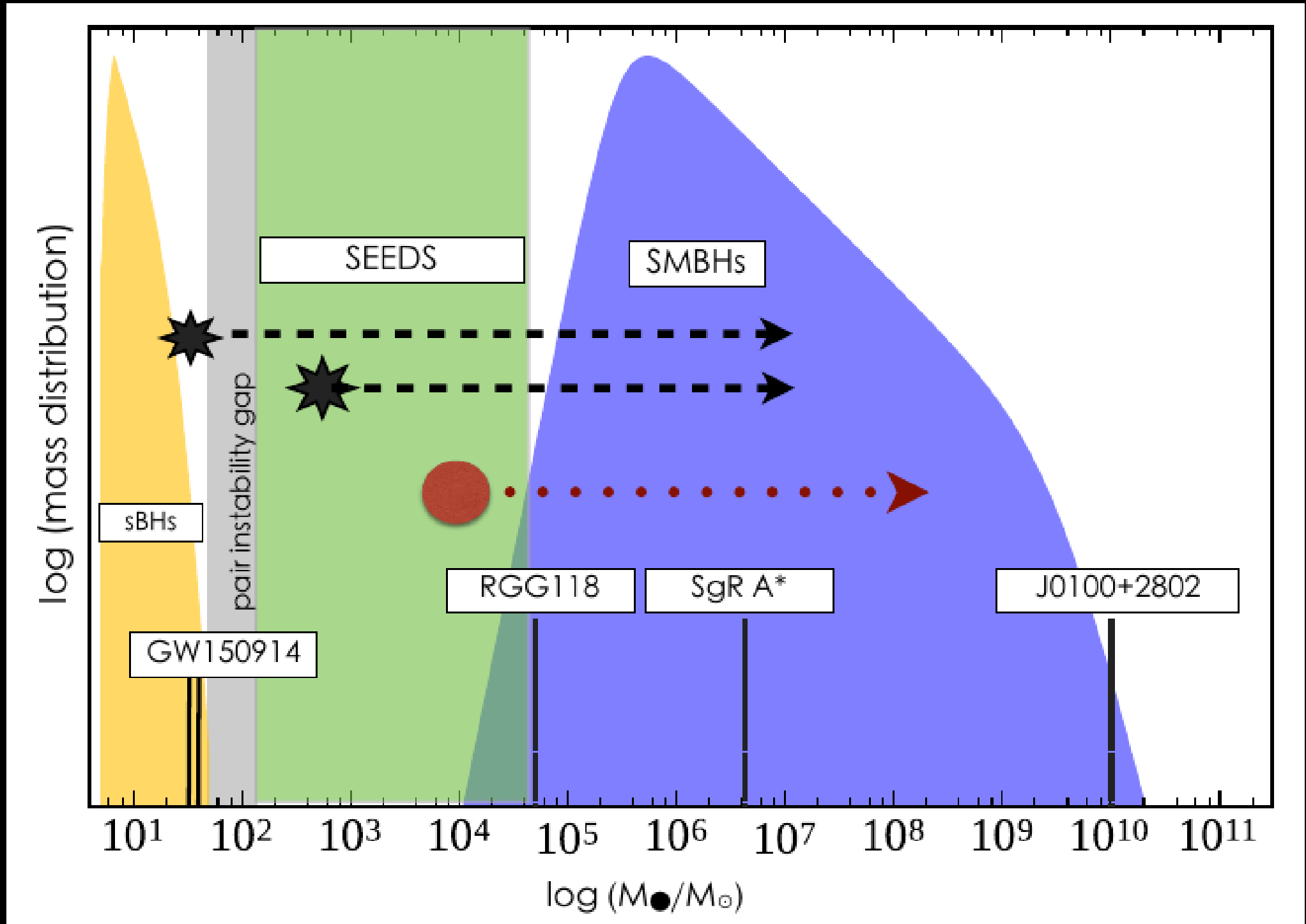
-measure of eccentricity

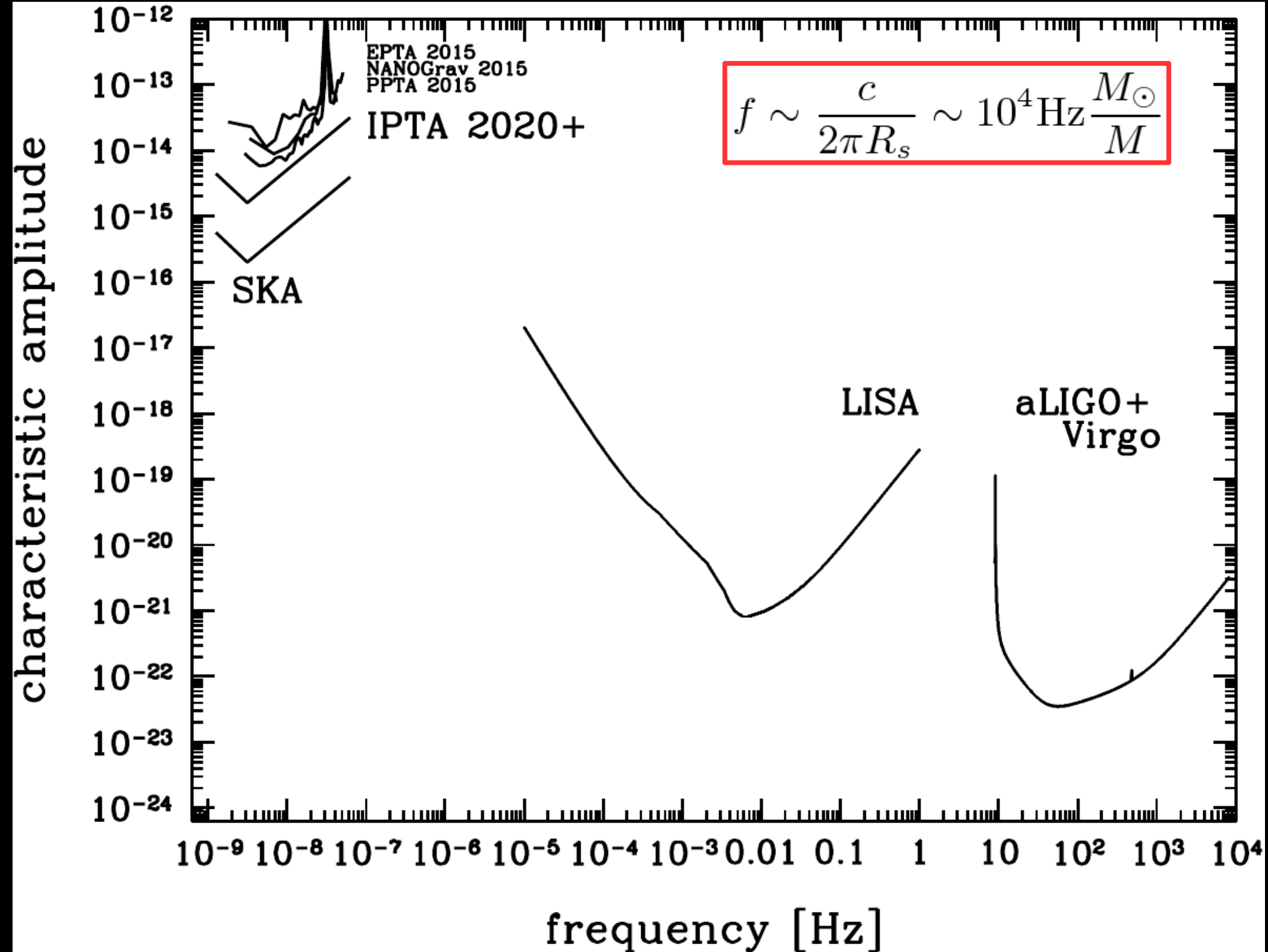
>Cosmology:

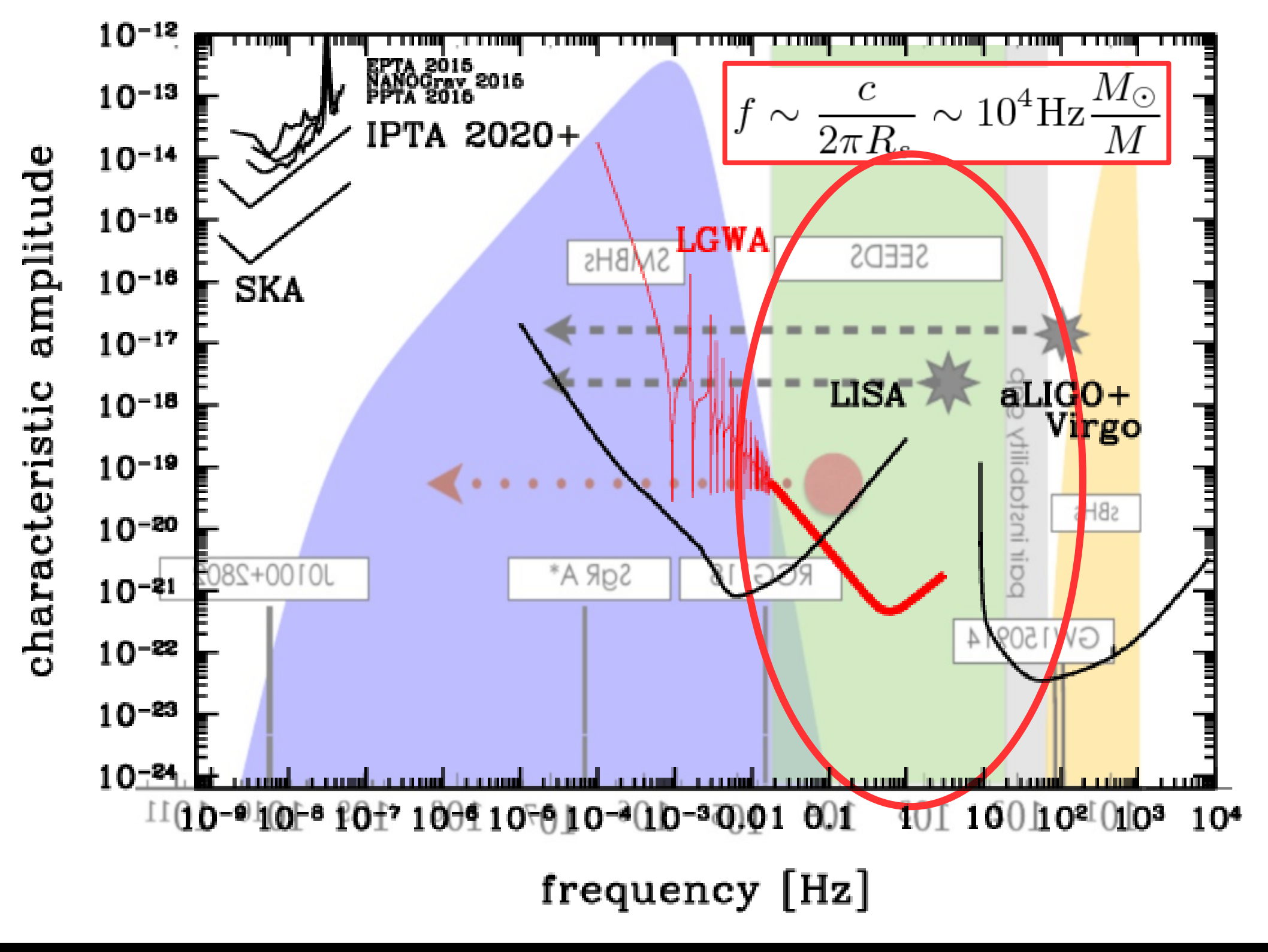
-new population of standard sirens?

MULTIBAND SYNERGIES

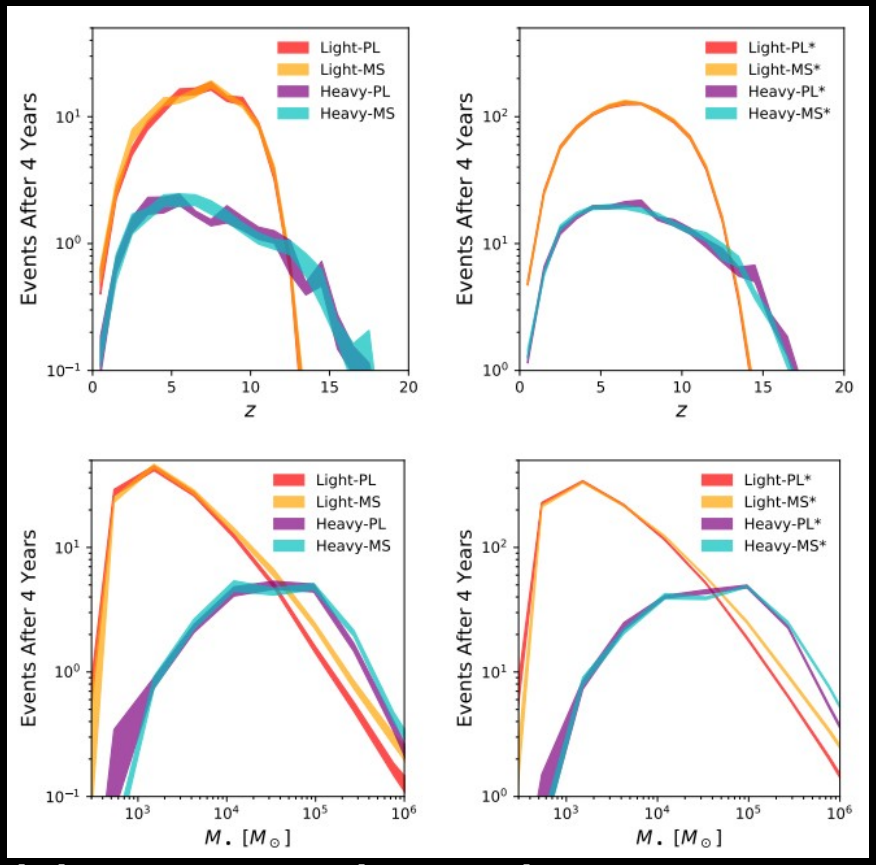



log (mass distribution)
SEEDS
SMBHs
pair instability gap
sBHs
RGG118
SgR A*
J0100+2802
GW150914
10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11}
log ($M_\bullet/M_\odot$)

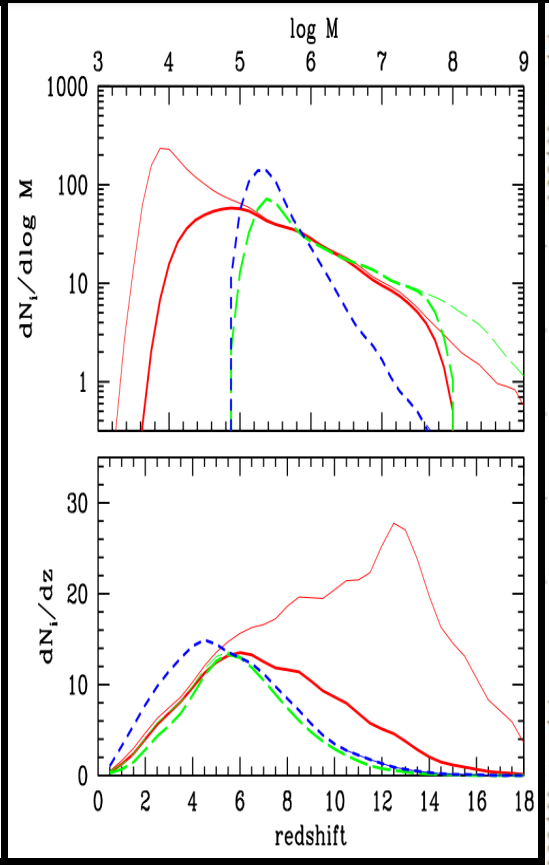

EPTA 2015
NANOGrav 2015
PPTA 2015
IPTA 2020+
SKA
LISA
aLIGO+
Virgo
$f \sim \frac{c}{2\pi R_s} \sim 10^4 \mathrm{Hz} \frac{M_\odot}{M}$
characteristic amplitude
frequency [Hz]
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 0.01 0.1 1 10 10^2 10^3 10^4


EPTA 2015
NANOGrav 2016
PPTA 2015
IPTA 2020+
SKA
LGWA
LISA
aLIGO+
Virgo
$f \sim \frac{c}{2\pi R_s} \sim 10^4 \mathrm{Hz} \frac{M_\odot}{M}$
characteristic amplitude
frequency [Hz]
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 0.01 0.1 1 10 10^{2} 10^{3} 10^{4}

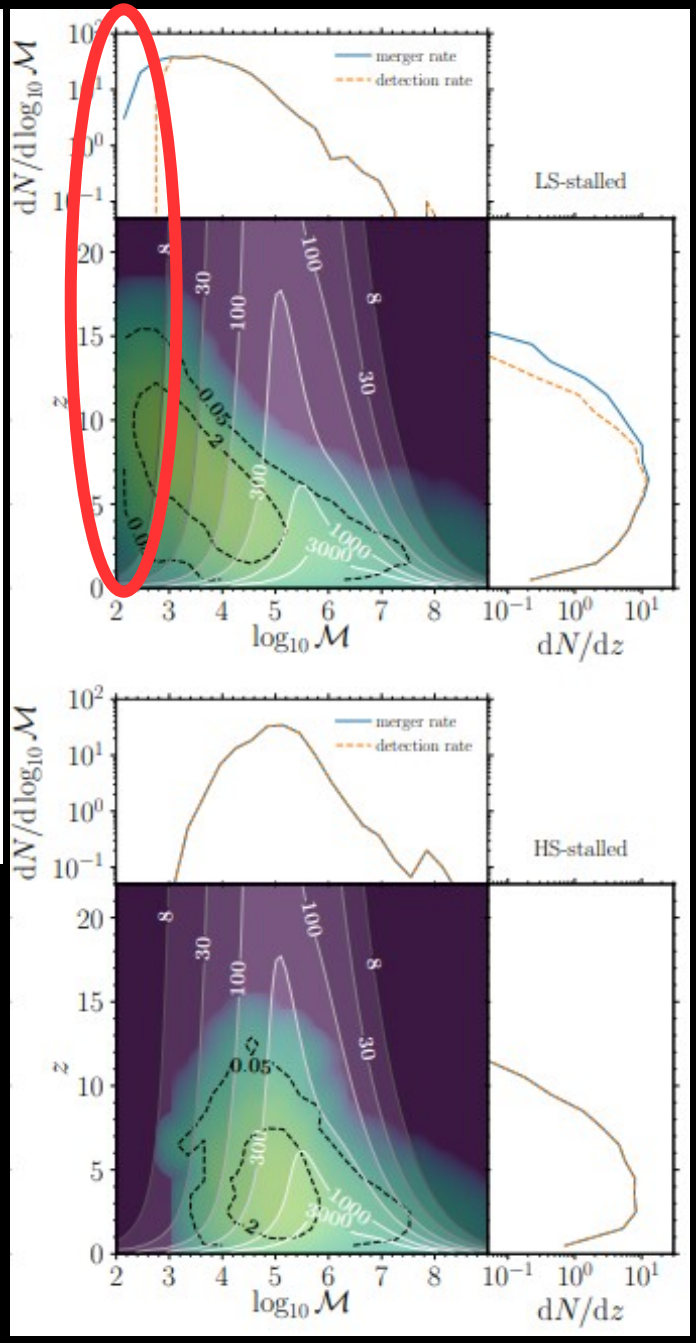
LISA capabilities



(Ricarte & Natarajan 2018)



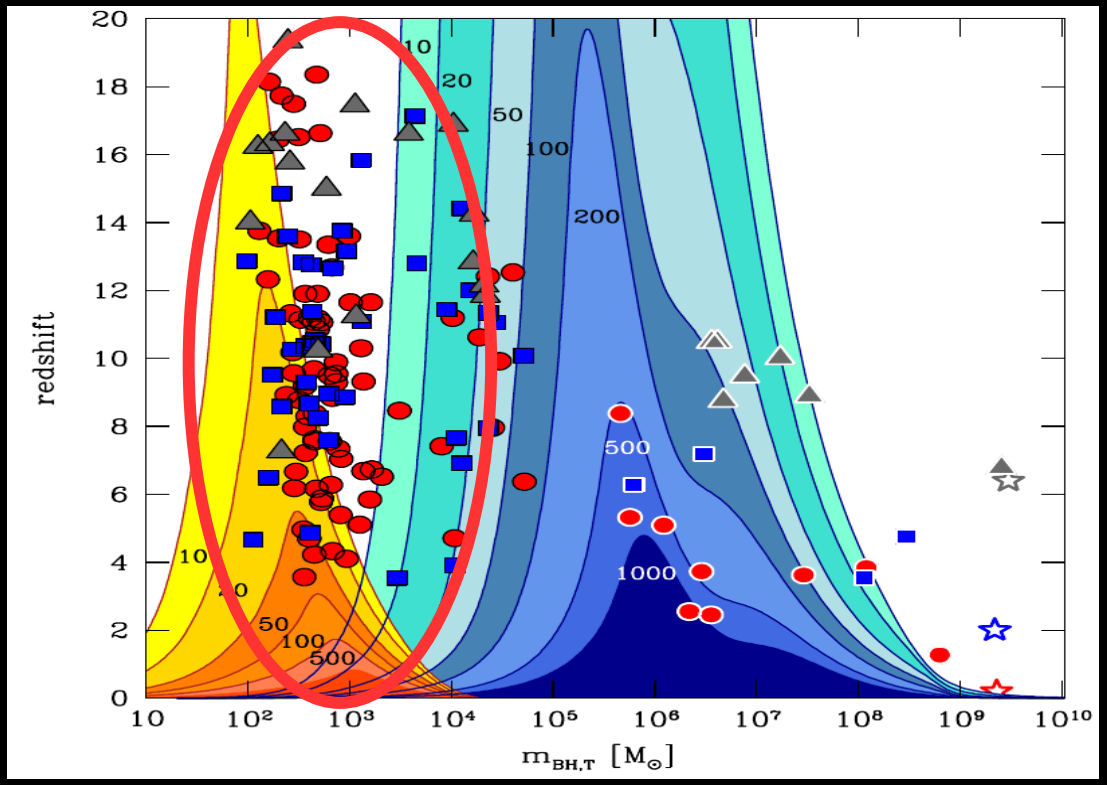
(Sesana+ 2011)

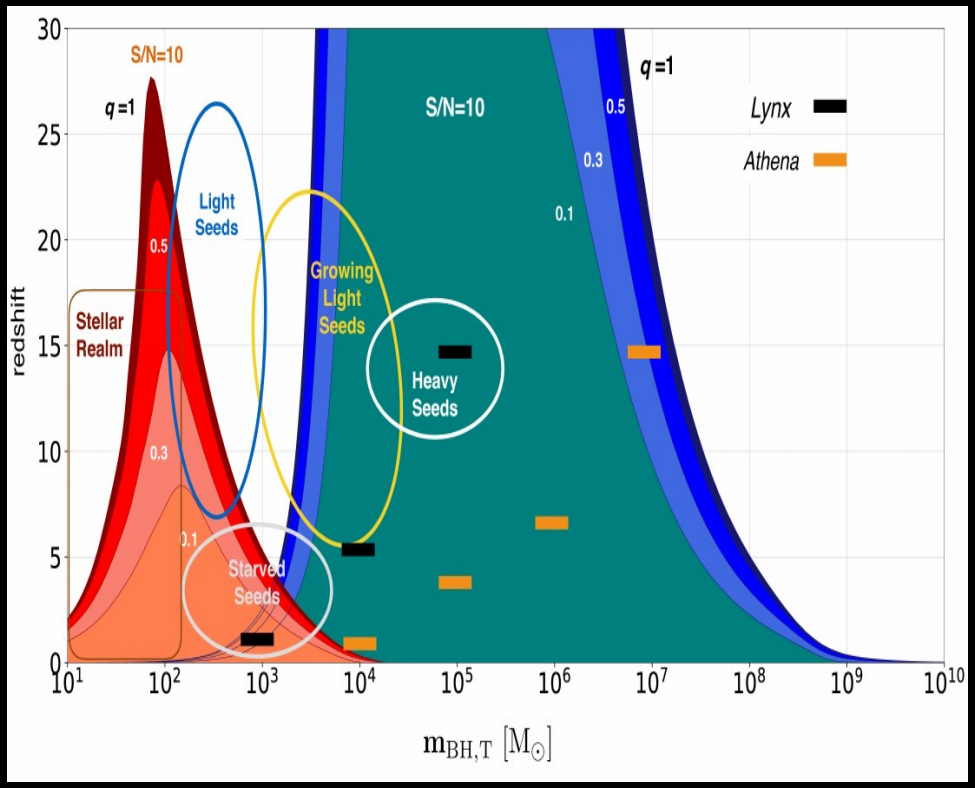


(Bonetti+ 2019)

- LISA can see BH seeds up to z~10-15, down to ~1000 solar masses
- LISA can distinguish among a set of defined seed models (Sesana+ 2011) but:
  - → highly idealized
  - → did not consider 'other BH populations'
- LISA cannot see the first popIII seed mergers

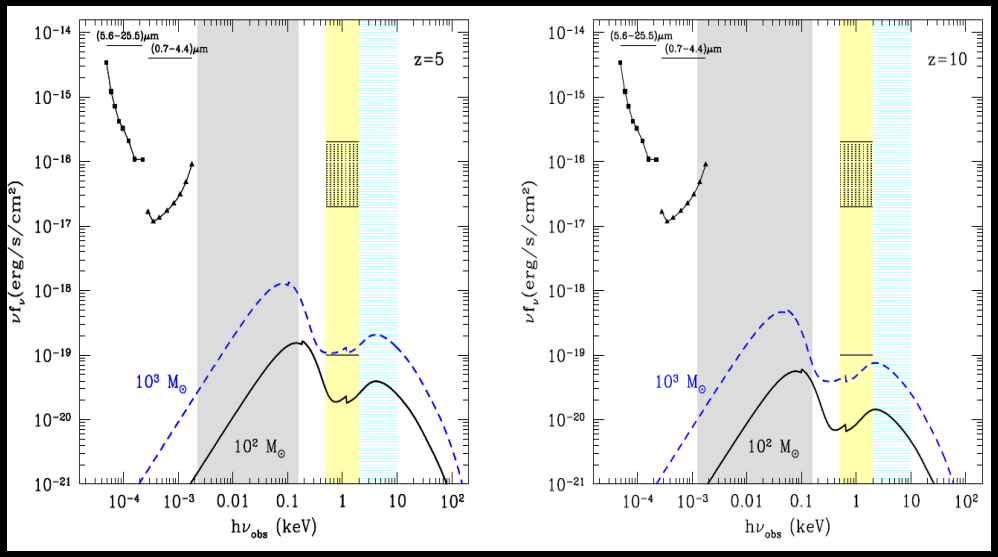
3G and LGWA as important as LISA for seeds!





-ET is in principle almost perfectly Complementary to LISA
-can see the first mergers of popIII seeds up to high z
-it reaches deeper than EM probes

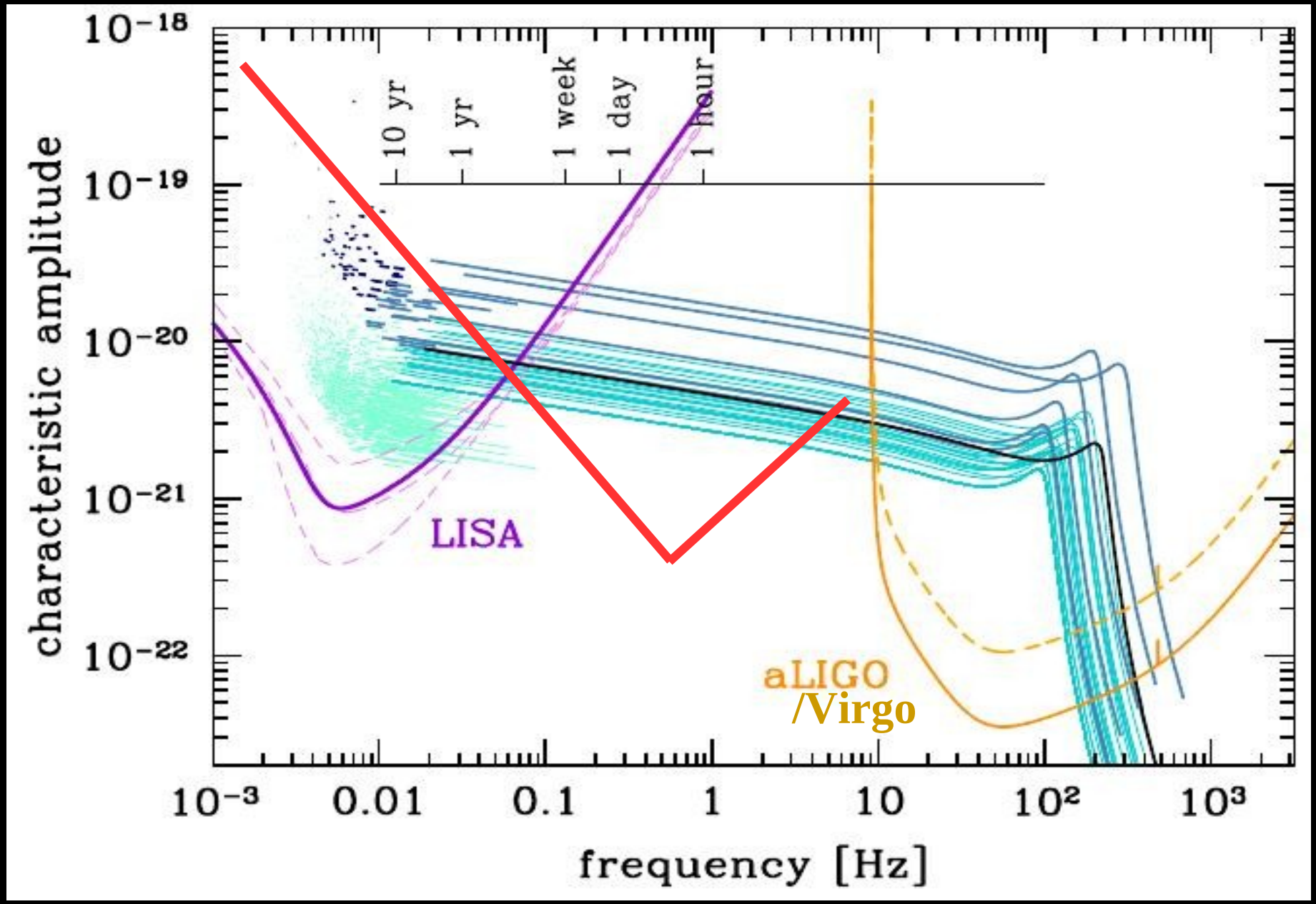
However:
-can we pin down the popIII nature of the detecte sources?
-can we connect popIII with SMBHs?



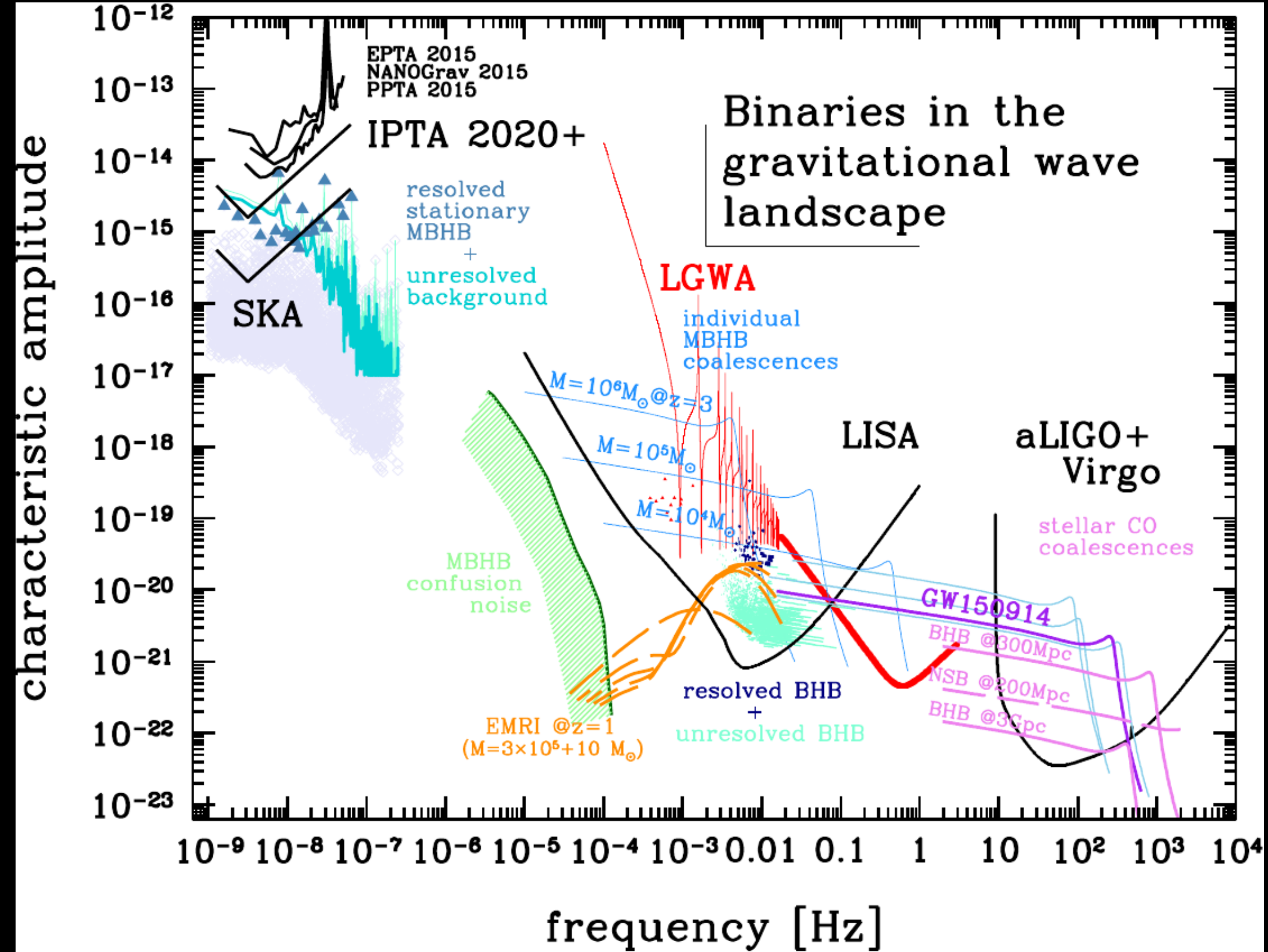
(Valiante+ 20)

multi-band SOBH (and NS) GW astronomy

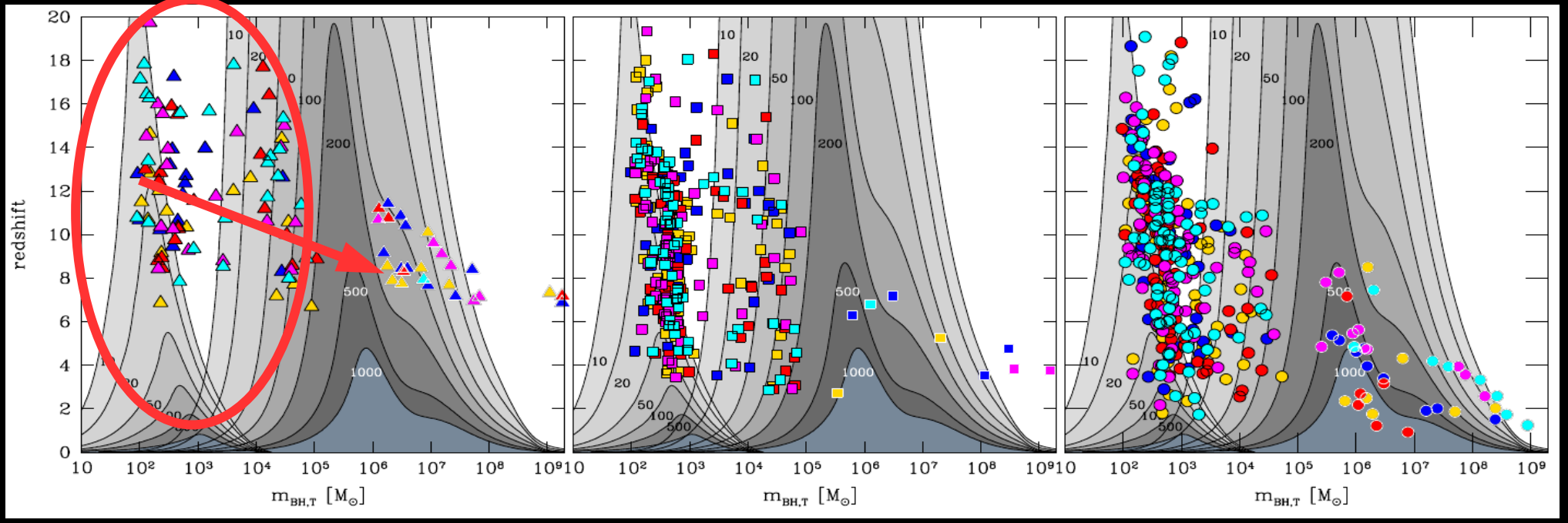
(AS 2016, PRL 116, 1102)

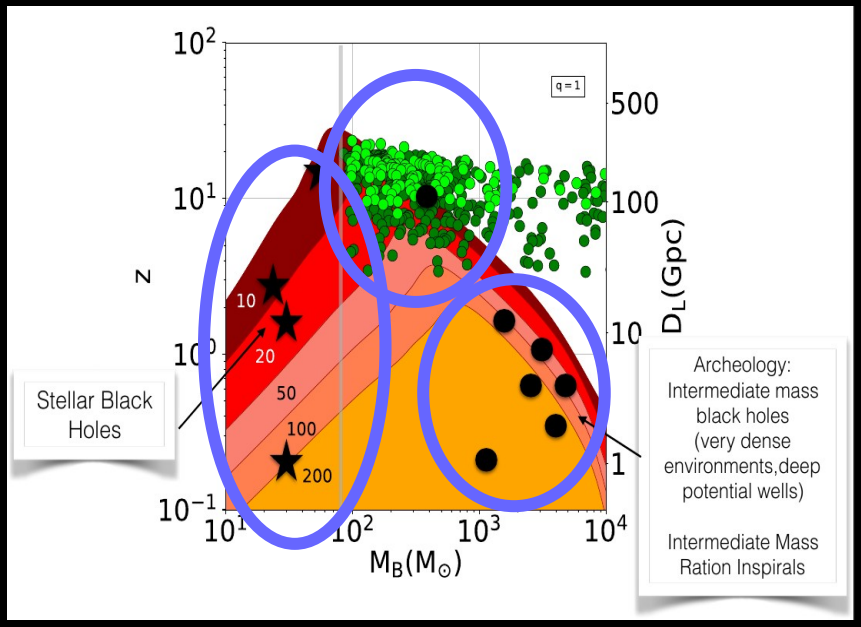


BHB will be detected by LISA and cross to the LIGO/Virgo band, assuming a 5 year operation of LISA.


Binaries in the gravitational wave landscape
EPTA 2015
NANOGrav 2015
PPTA 2015
IPTA 2020+
SKA
resolved stationary MBHB + unresolved background
LGWA
individual MBHB coalescences
$M=10^6M_\odot@z=3$
$M=10^5M_\odot$
$M=10^4M_\odot$
LISA
aLIGO+ Virgo
stellar CO coalescences
MBHB confusion noise
GW150914
BHB @300Mpc
NSB @200Mpc
BHB @3Gpc
resolved BHB + unresolved BHB
EMRI @z=1 ($M=3\times10^5+10\ M_\odot$)
characteristic amplitude
frequency [Hz]
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 0.01 0.1 1 10 10^2 10^3 10^4

The importance of combining 3G LGWA and LISA





-How to connect seeds to SMBHs?

-statistical consistence between LISA and ET detection?

-combination with high z X-ray LF?

-identification of separate subclusters in the ET detected sources?

-Combining MBHs and SOBHs in SAMs? What's the way to go?