Gravitational wave astrophysics at all scales with eLISA

Alberto Sesana
(University of Birmingham)

Gravitational Wave Astronomy in Space
eLISA/NGO

OUTLINE

>Gravitational waves (GWs) across the frequency spectrum

>astrophysics of massive black hole binaries (MBHBs) with eLISA

>GW150914: a gift from LIGO

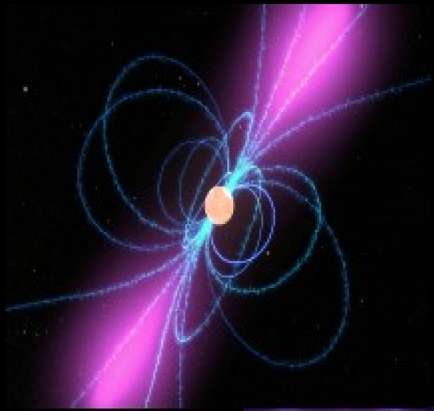
>Stellar Bhs in the eLISA band: Multi-band GW astronomy with eLISA and LIGO

Gravitational wave sources

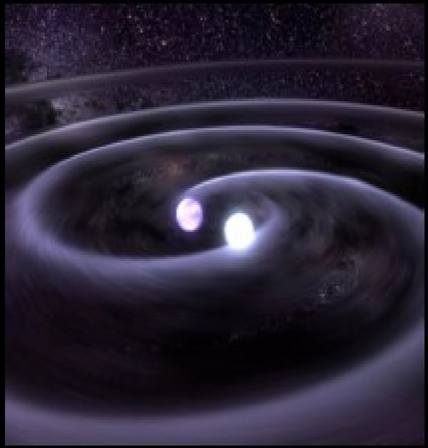
Massive compact systems with a time varying mass quadrupole momentum:

1-collapses and explosions (supernovae, GRBs)

2-rotating asymmetric objects (pulsars, MSPs)

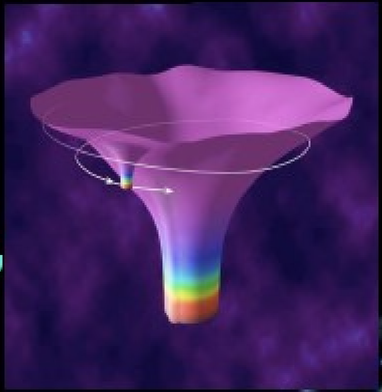


3-binary systems:



a-stellar compact remnants (WD-WD, NS-NS, NS-BH, BH-BH)

b-extreme mass ratio inspirals (EMRIs), CO falling into a massive black hole



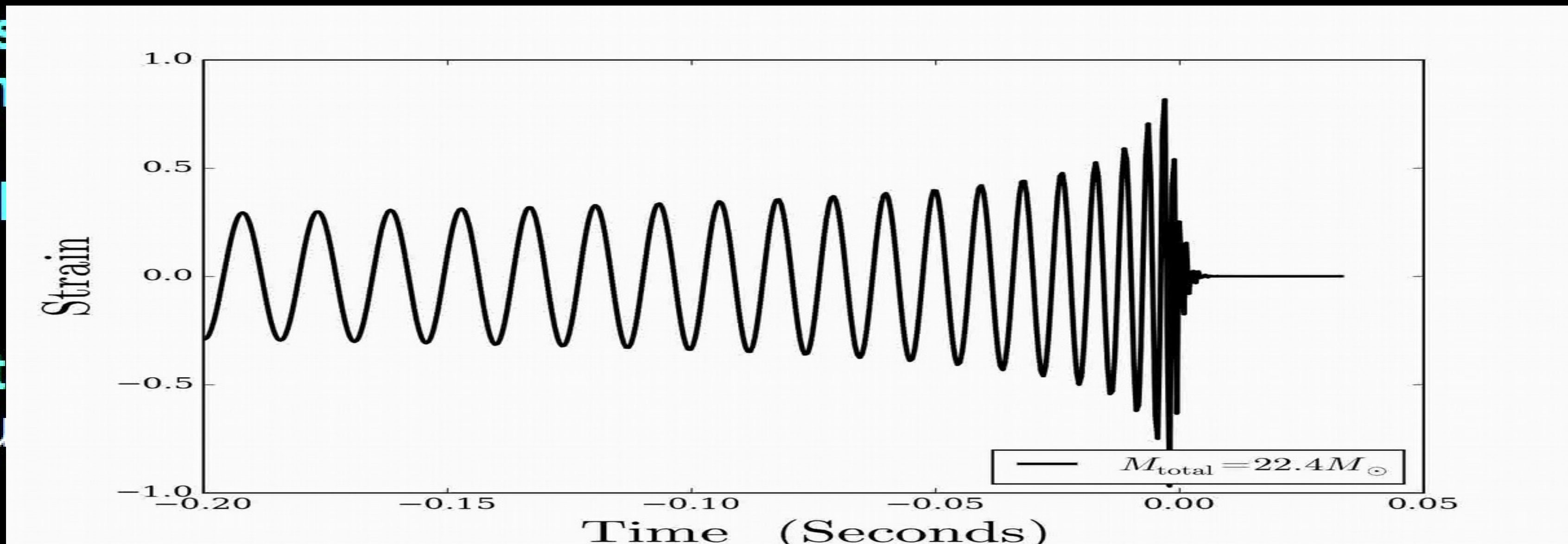
c-massive black hole binaries (MBHBs) forming following galaxy mergers

Gravitational wave sources

Mass
mom

1-col

2-rot
(pu

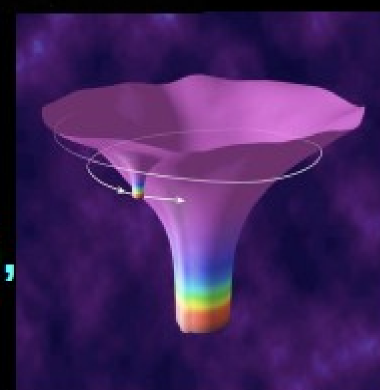


3-binary systems:

a-stellar compact remnants
(WD-WD, NS-NS, NS-BH, BH-BH)

b-extreme mass ratio inspirals (EMRIs),
CO falling into a massive black hole

c-massive black hole binaries (MBHBs)
forming following galaxy mergers



Heuristic scalings

We want compact accelerating systems
Consider a BH binary of mass M, and semimajor axis a

$$h \sim \frac{R_S}{a}\frac{R_S}{r} \sim \frac{(GM)^{5/3}(\pi f)^{2/3}}{c^4 r}$$

In astrophysical scales

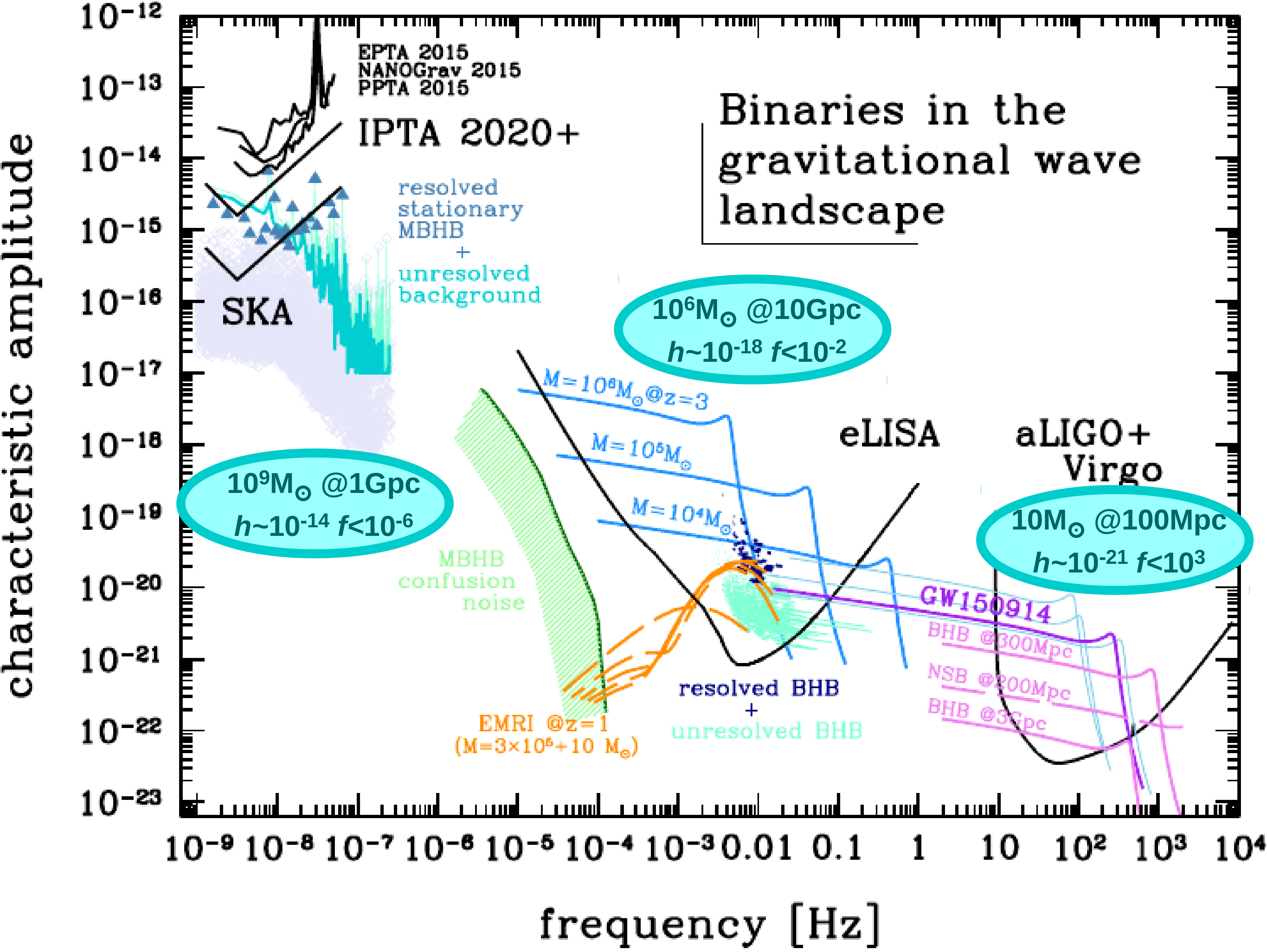
$$h \sim 10^{-20}\frac{M}{M_\odot}\frac{\mathrm{Mpc}}{D}$$

$$f \sim \frac{c}{2\pi R_s} \sim 10^4\,\mathrm{Hz}\frac{M_\odot}{M}$$

10 $M_\odot$ binary at 100 Mpc: $h \sim 10^{-21}$, $f < 10^{3}$

10^6 $M_\odot$ binary at 10 Gpc: $h \sim 10^{-18}$, $f < 10^{-2}$

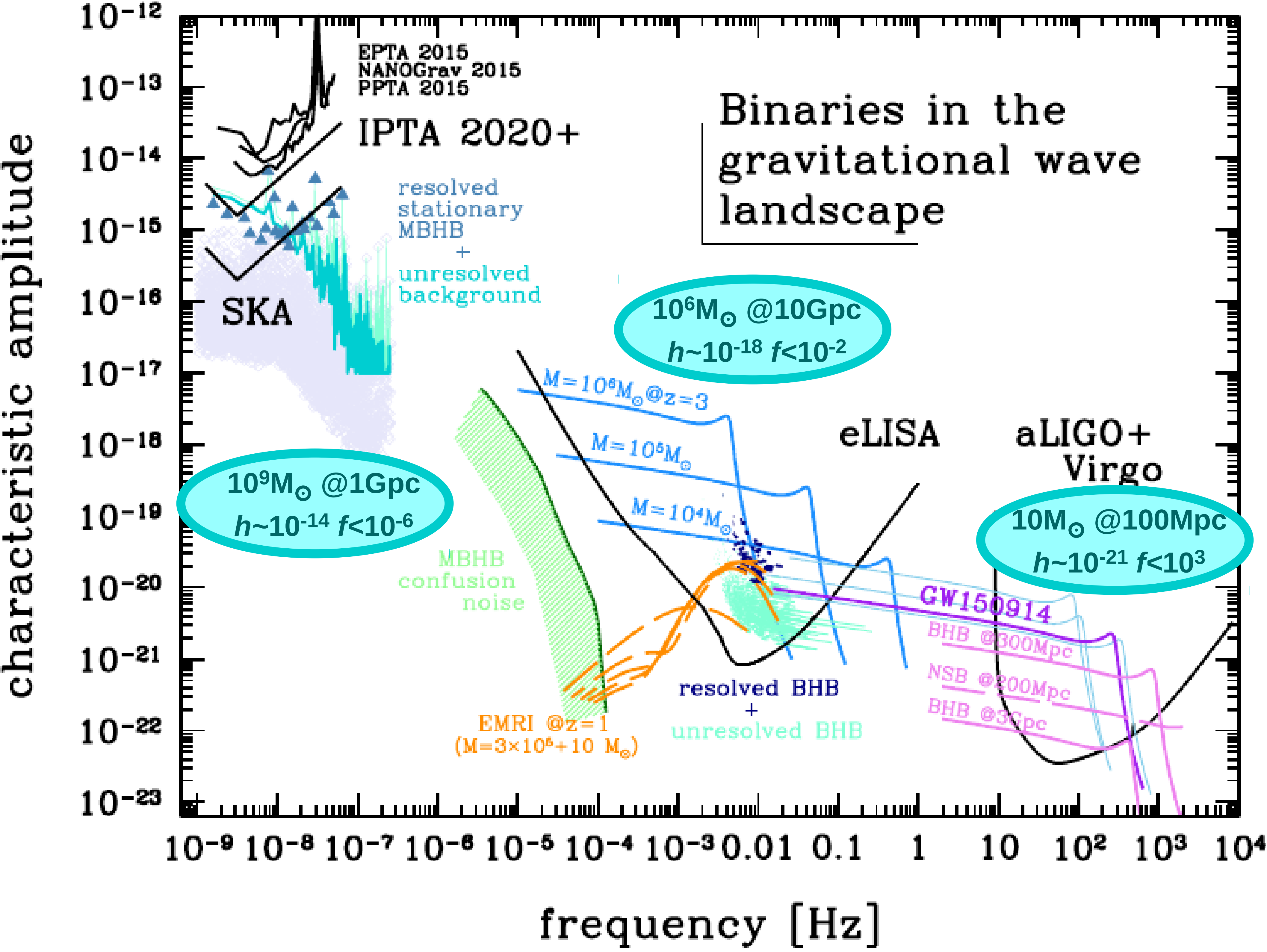
10^9 $M_\odot$ binary at 1Gpc: $h \sim 10^{-14}$, $f < 10^{-6}$



characteristic amplitude
frequency [Hz]
EPTA 2015
NANOGrav 2015
PPTA 2015
IPTA 2020+
SKA
resolved stationary MBHB
+
unresolved background
Binaries in the gravitational wave landscape
10⁶M⊙ @10Gpc
h~10⁻¹⁸ f<10⁻²
10⁹M⊙ @1Gpc
h~10⁻¹⁴ f<10⁻⁶
10M⊙ @100Mpc
h~10⁻²¹ f<10³
M=10⁶M⊙@z=3
M=10⁵M⊙
M=10⁴M⊙
eLISA
aLIGO+ Virgo
MBHB confusion noise
GW150914
BHB @300Mpc
NSB @200Mpc
BHB @3Gpc
EMRI @z=1
(M=3×10⁵+10 M⊙)
resolved BHB
+
unresolved BHB

eLISA: a privileged GW window

> It has the potential to observe sources at all relevant astrophysical masses (unlike LIGO and PTA)

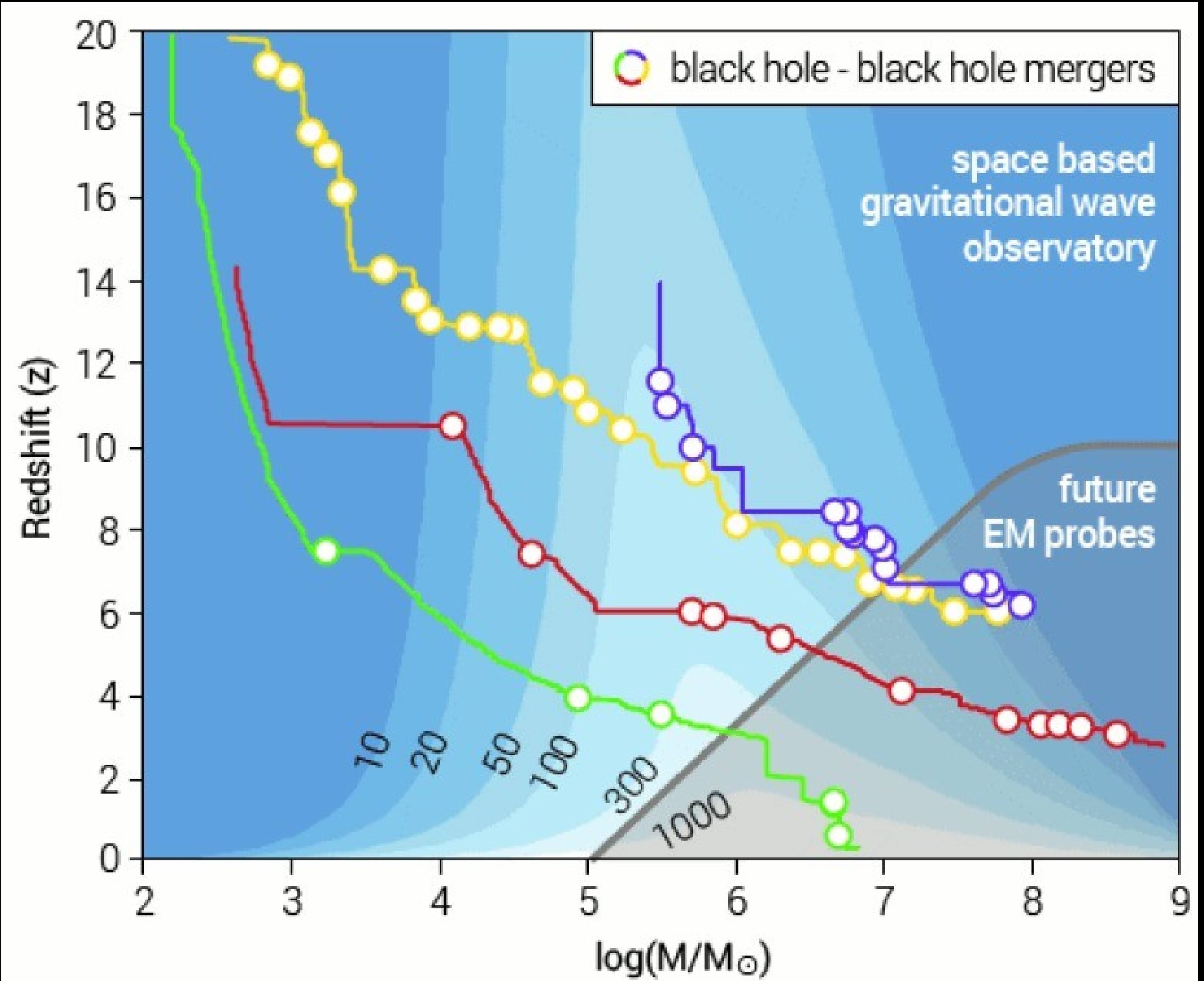


Binaries in the gravitational wave landscape
EPTA 2015
NANOGrav 2015
PPTA 2015
IPTA 2020+
SKA
resolved stationary MBHB
+
unresolved background
10^6M⊙ @10Gpc
h~10^-18 f<10^-2
10^9M⊙ @1Gpc
h~10^-14 f<10^-6
10M⊙ @100Mpc
h~10^-21 f<10^3
M=10^6M⊙@z=3
M=10^5M⊙
M=10^4M⊙
eLISA
aLIGO+ Virgo
MBHB confusion noise
GW150914
BHB @300Mpc
NSB @200Mpc
BHB @3Gpc
EMRI @z=1
(M=3×10^5+10 M⊙)
resolved BHB
+
unresolved BHB
characteristic amplitude
frequency [Hz]

eLISA: a privileged GW window

> It has the potential to observe sources at all relevant astrophysical masses (unlike LIGO and PTA)

>It has the potential to observe sources at all redshifts (unlike LIGO and PTA)



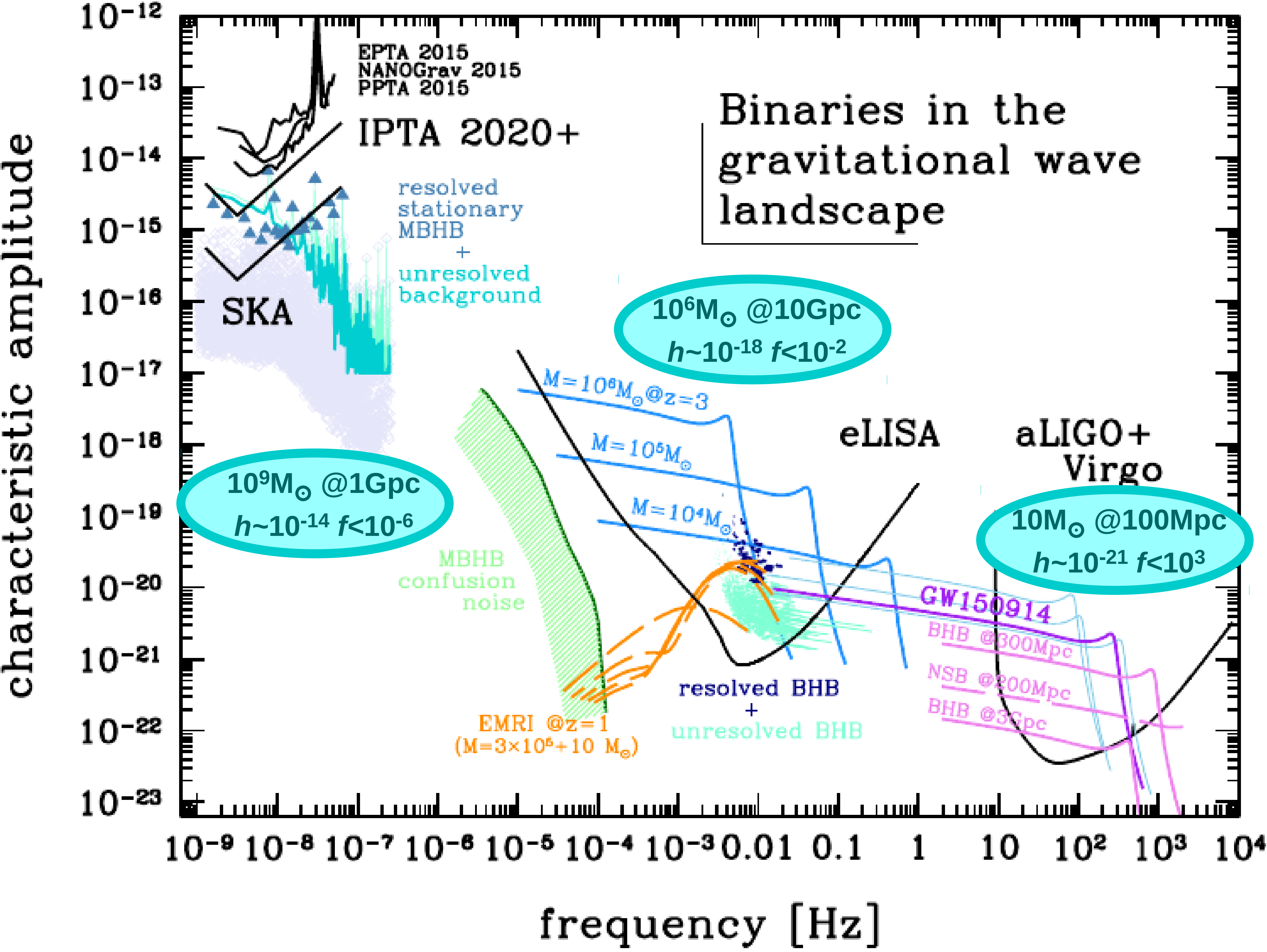
black hole - black hole mergers
space based gravitational wave observatory
future EM probes
Redshift (z)
log(M/M⊙)
10
20
50
100
300
1000
0
2
4
6
8
10
12
14
16
18
20
2
3
4
5
6
7
8
9

eLISA: a privileged GW window

> It has the potential to observe sources at all relevant astrophysical masses (unlike LIGO and PTA)

>It has the potential to observe sources at all redshifts (unlike LIGO and PTA)

>It has the potential to observe sources down to extreme mass ratios (unlike LIGO and PTA)



Binaries in the
gravitational wave
landscape
EPTA 2015
NANOGrav 2015
PPTA 2015
IPTA 2020+
SKA
resolved
stationary
MBHB
+
unresolved
background
10⁶M⊙ @10Gpc
h~10⁻¹⁸ f<10⁻²
10⁹M⊙ @1Gpc
h~10⁻¹⁴ f<10⁻⁶
10M⊙ @100Mpc
h~10⁻²¹ f<10³
M=10⁶M⊙@z=3
M=10⁵M⊙
M=10⁴M⊙
eLISA
aLIGO+
Virgo
MBHB
confusion
noise
GW150914
BHB @300Mpc
NSB @200Mpc
BHB @3Gpc
EMRI @z=1
(M=3×10⁵+10 M⊙)
resolved BHB
+
unresolved BHB
characteristic amplitude
frequency [Hz]

eLISA: a privileged GW window

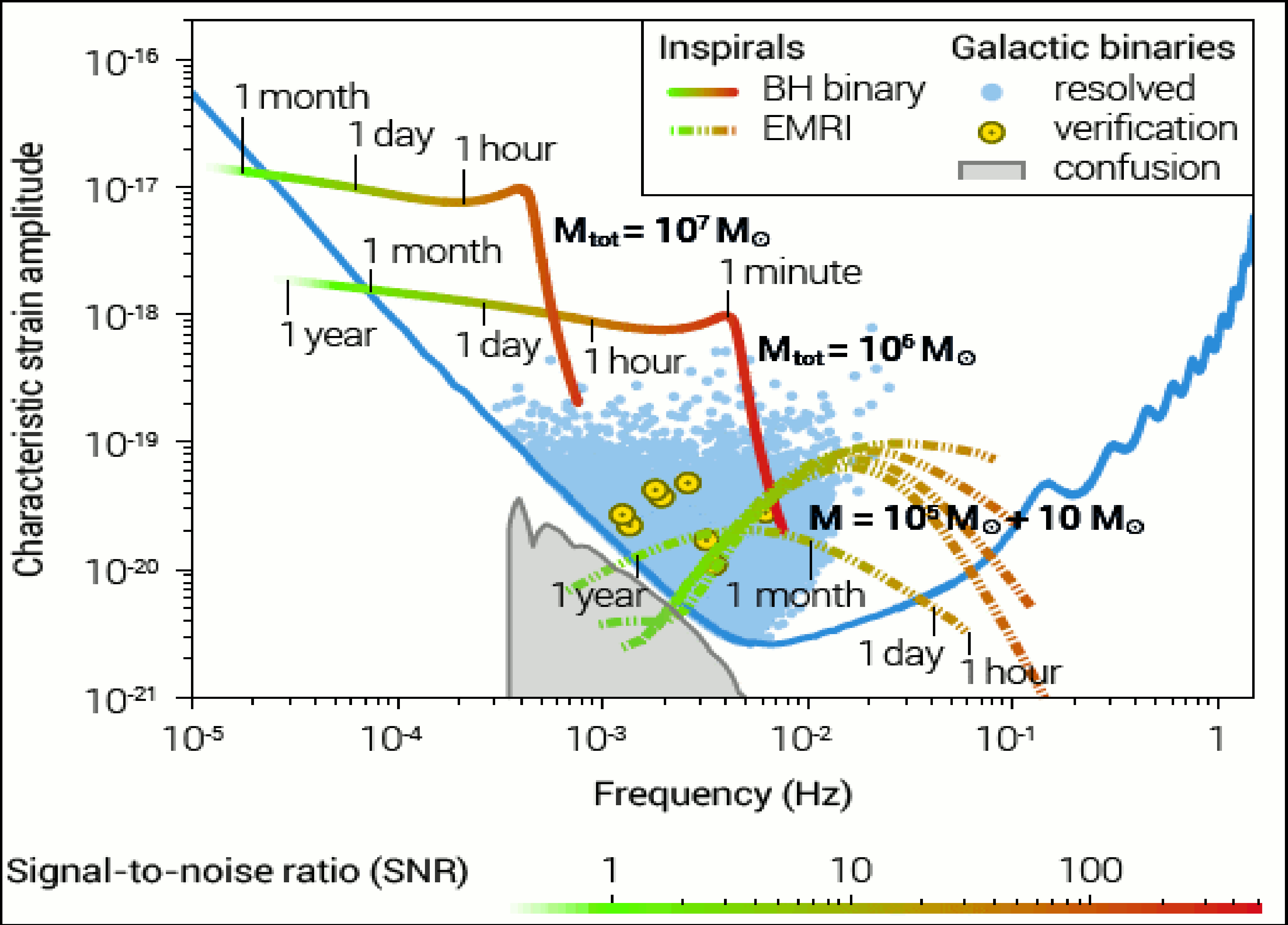
> It has the potential to observe sources at all relevant astrophysical masses (unlike LIGO and PTA)

>It has the potential to observe sources at all redshifts (unlike LIGO and PTA)

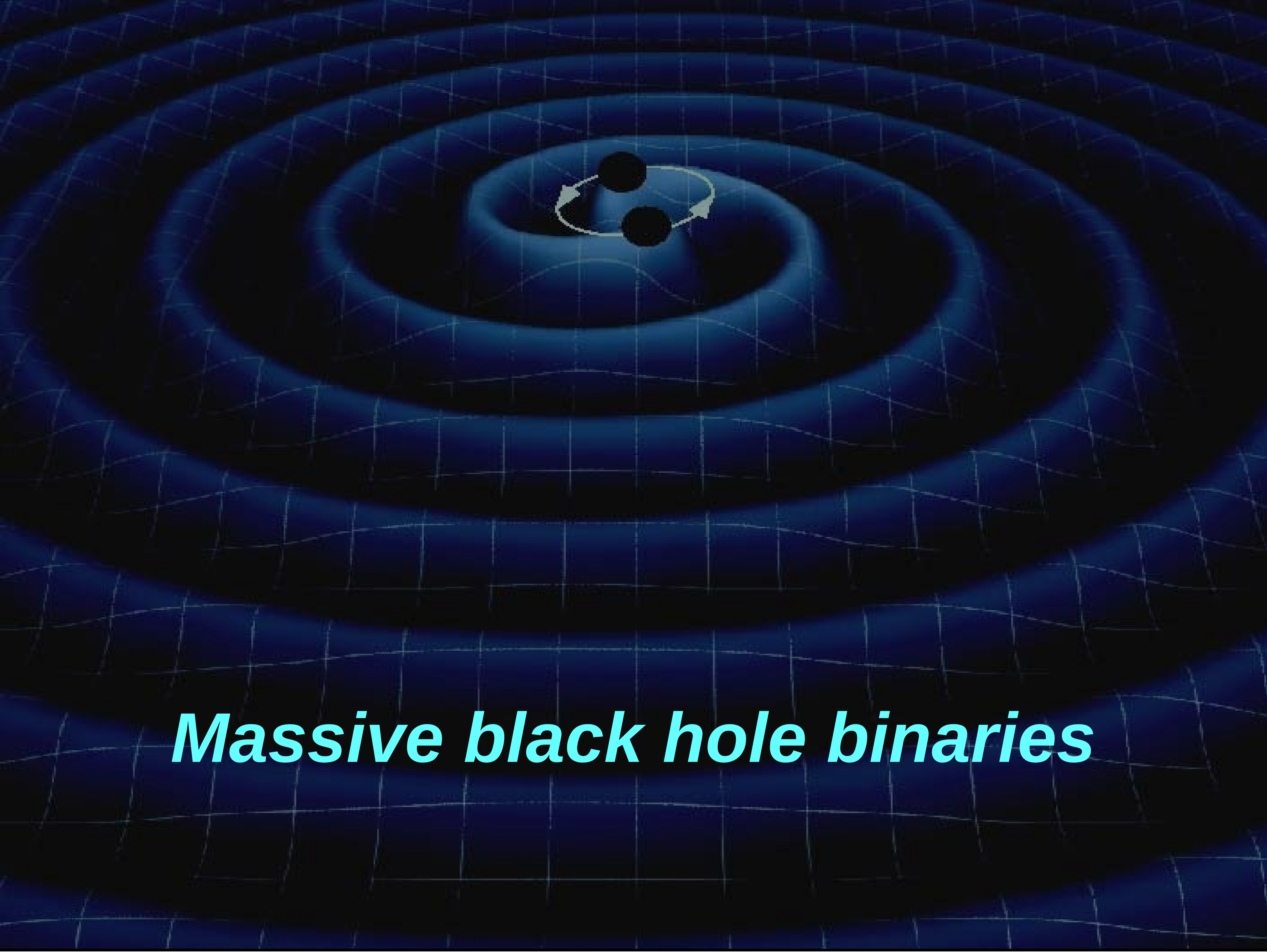
>It has the potential to observe sources down to extreme mass ratios (unlike LIGO and PTA)

>It has the potential to see vacuum (BHs) and matter (WD NS) (unlike PTA)

>It has the potential to probe the Galaxy (unlike LIGO and PTA)

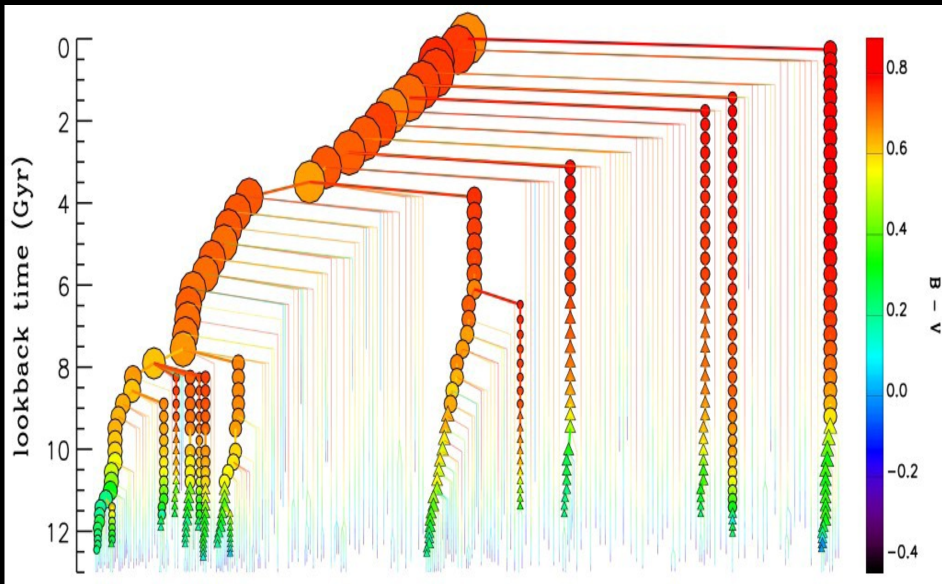


Inspirals
BH binary
EMRI
Galactic binaries
resolved
verification
confusion
1 month
1 day
1 hour
$M_{tot} = 10^7 M_\odot$
1 month
1 minute
1 year
1 day
1 hour
$M_{tot} = 10^6 M_\odot$
$M = 10^5 M_\odot + 10 M_\odot$
1 year
1 month
1 day
1 hour
Characteristic strain amplitude
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
Frequency (Hz)
Signal-to-noise ratio (SNR)
1
10
100



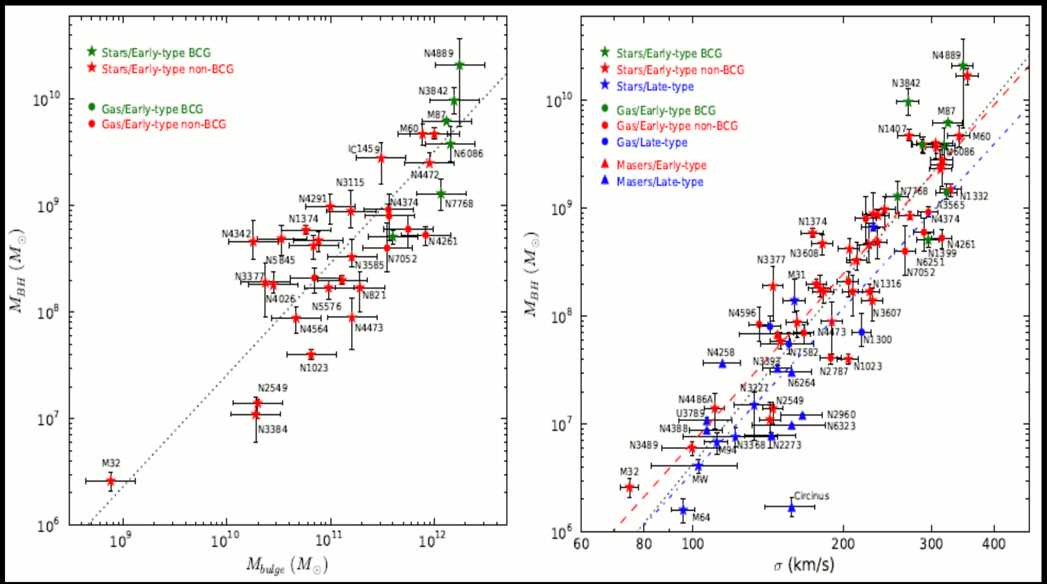
Massive black hole binaries

Structure formation in a nutshell



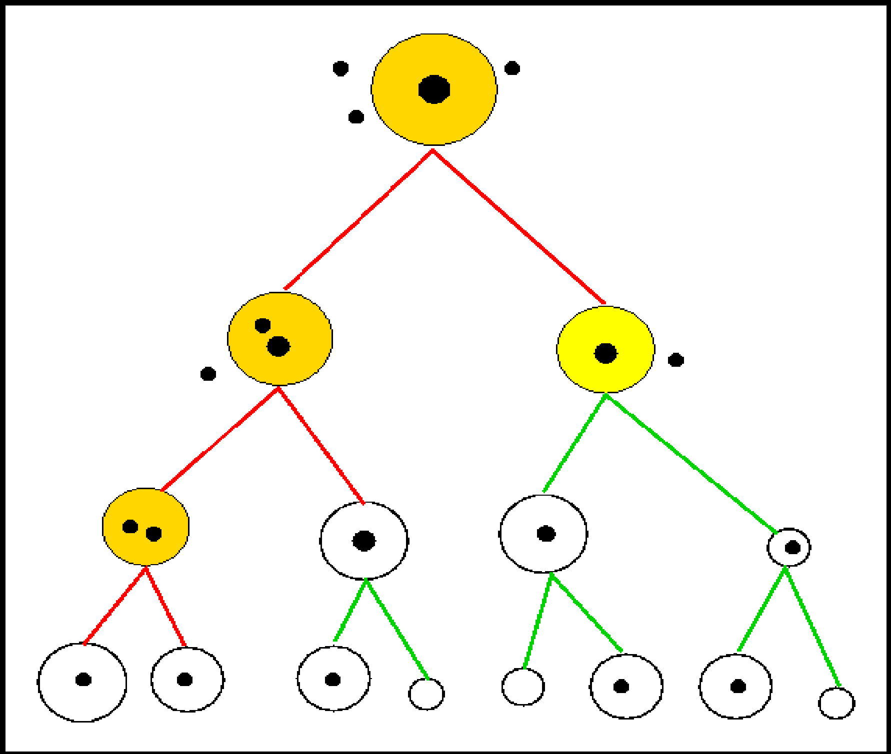
(From de Lucia et al. 2006)

+



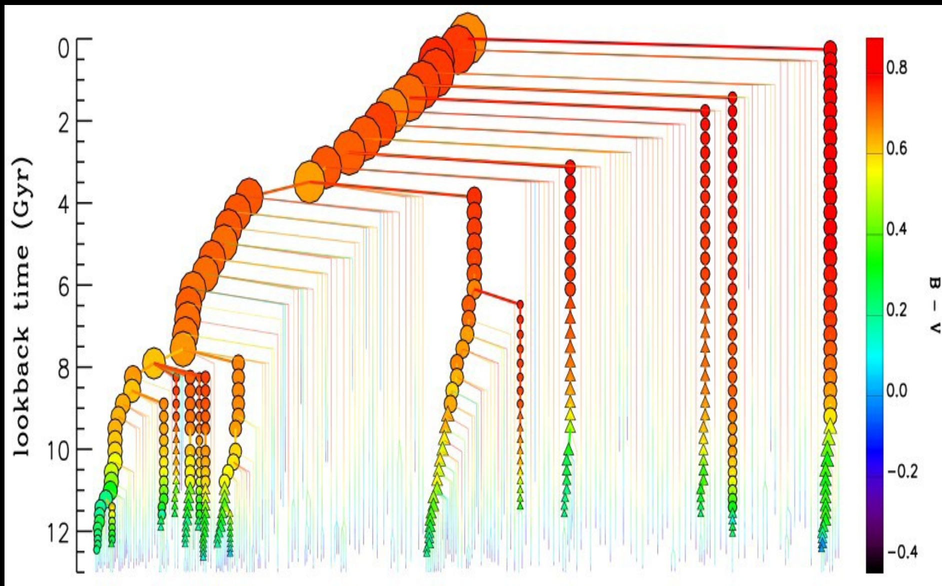
(Ferrarese & Merritt 2000, Gebhardt et al. 2000)

=

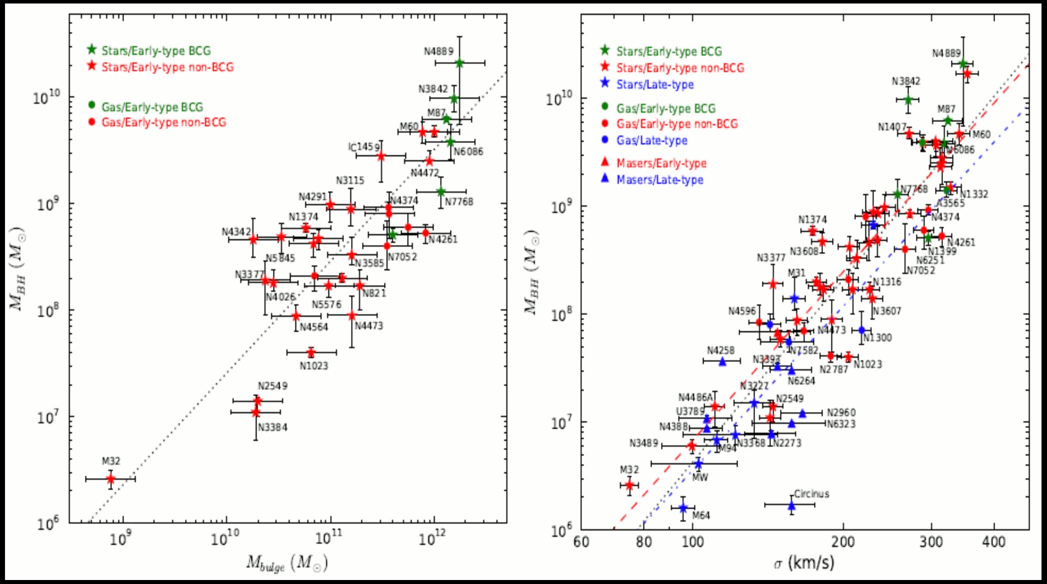


(Menou et al 2001, Volonteri et al. 2003)

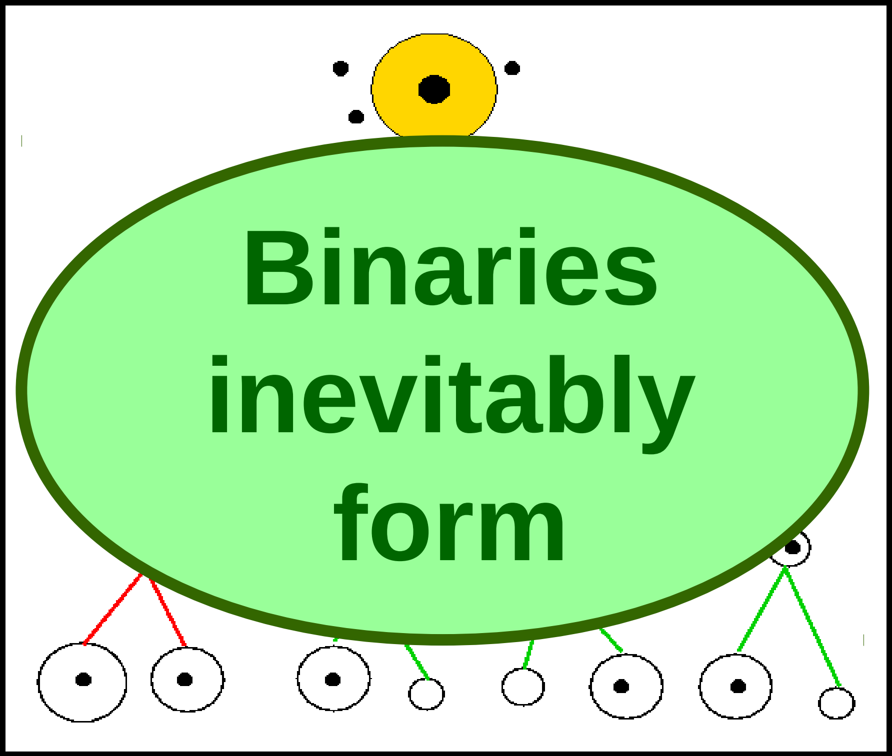
Structure formation in a nutshell



(From de Lucia et al. 2006)

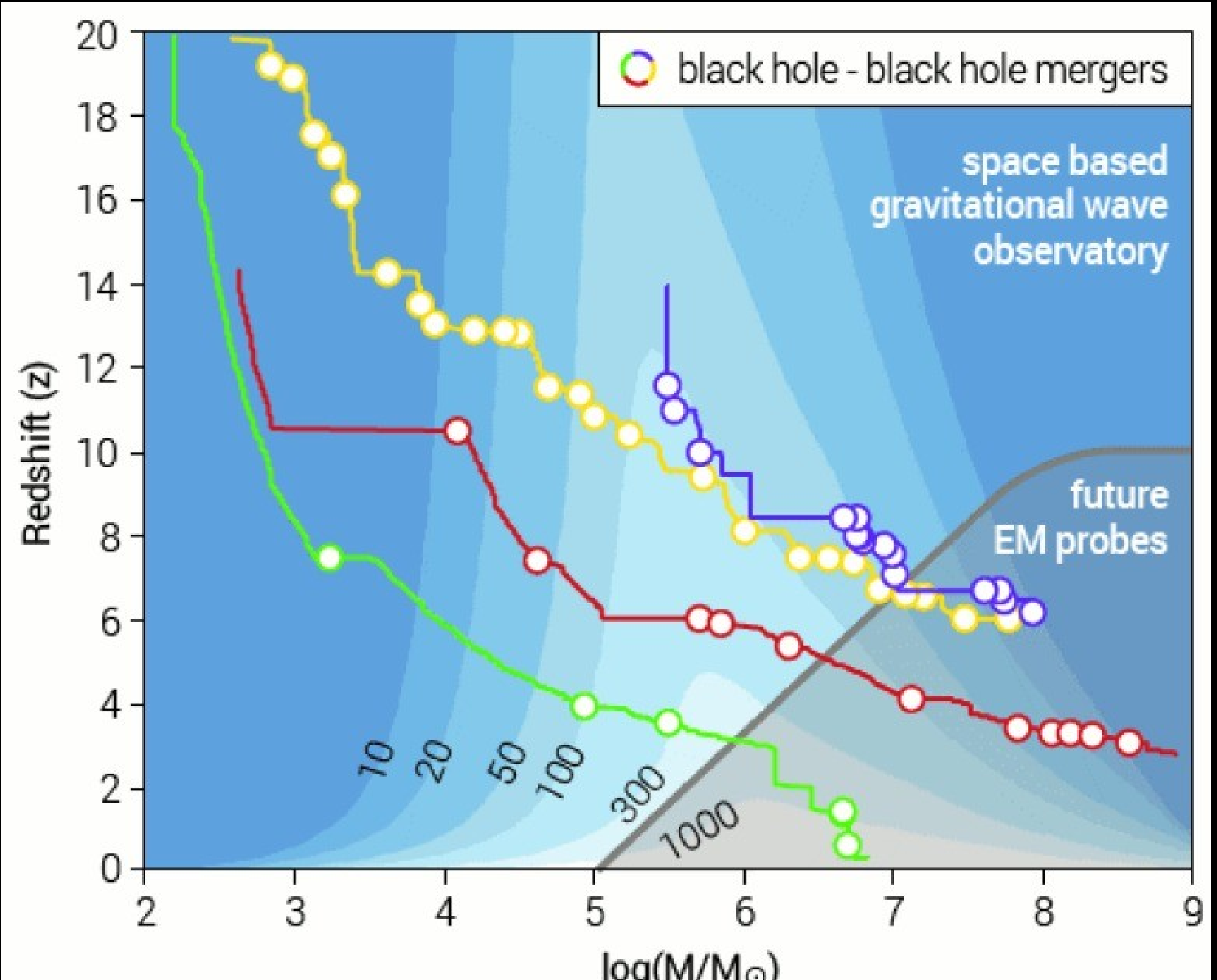


(Ferrarese & Merritt 2000, Gebhardt et al. 2000)

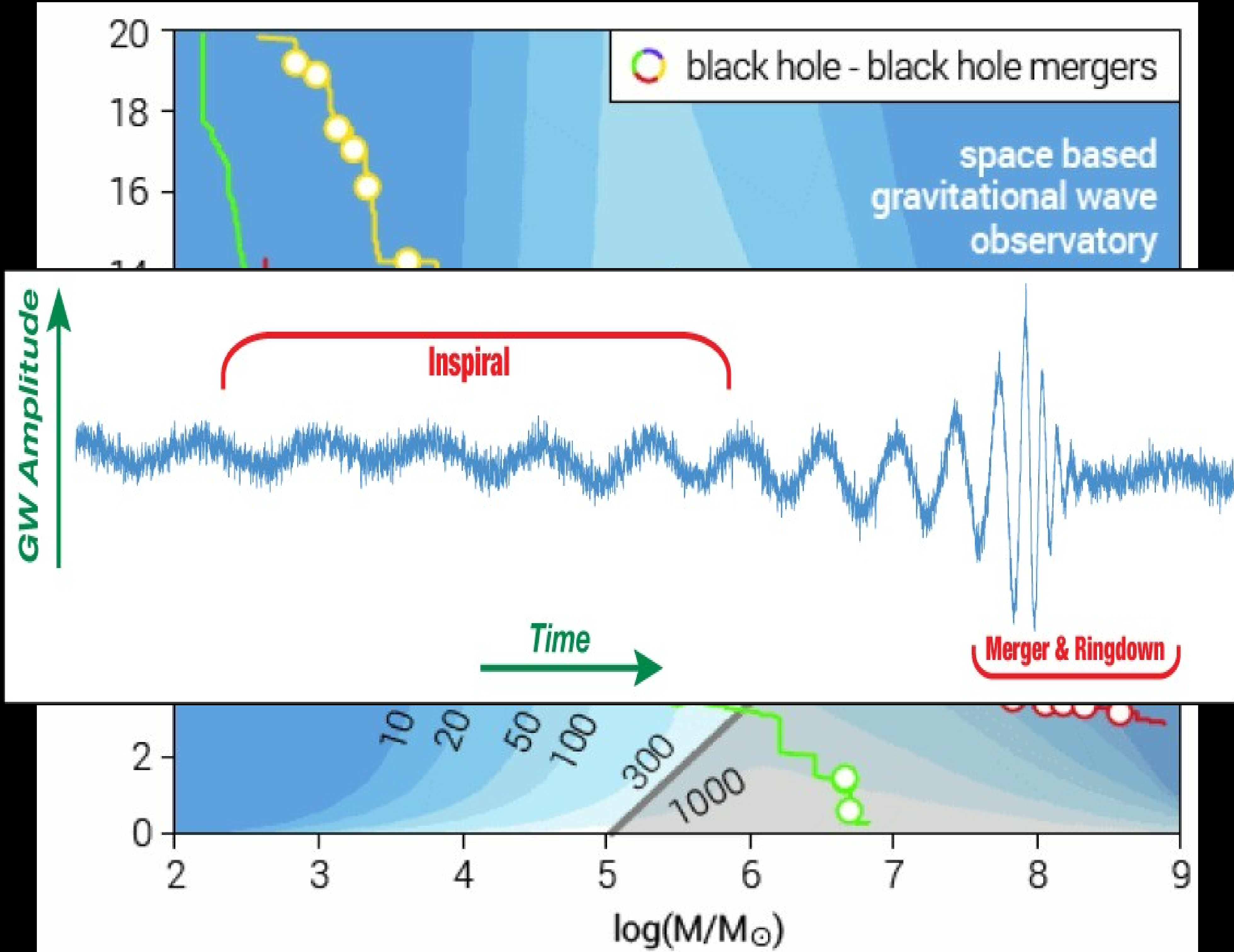


(Menou et al 2001, Volonteri et al. 2003)

*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?



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



black hole - black hole mergers
space based
gravitational wave
observatory
GW Amplitude
Inspiral
Time
Merger & Ringdown
10
20
50
100
300
1000
20
18
16
2
0
2
3
4
5
6
7
8
9
log(M/M⊙)

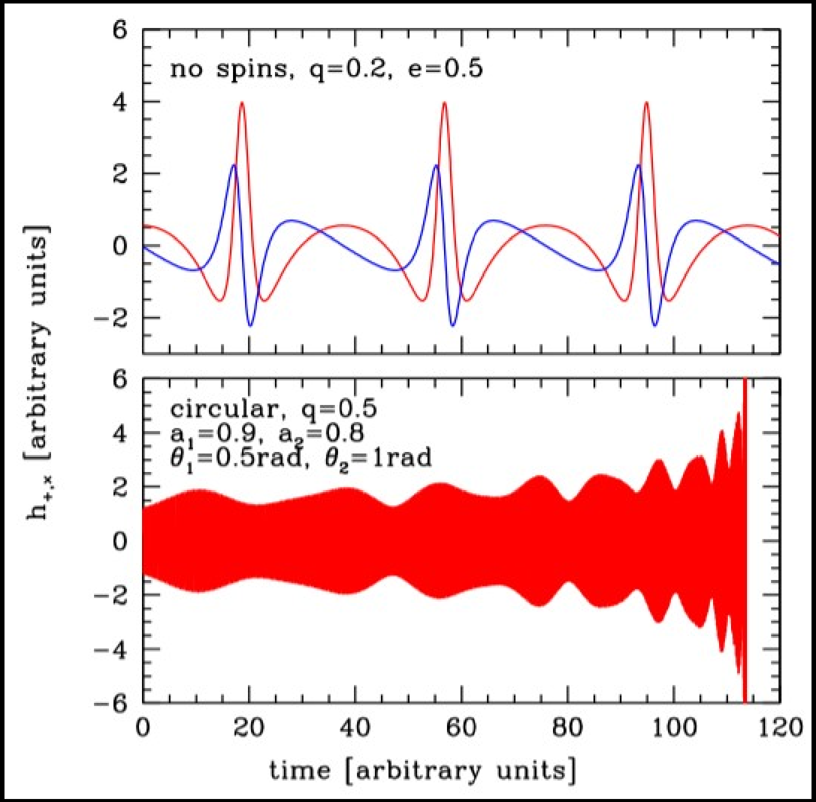
Extraction of information from the waveform

>Masses have the largest impact on the phase modulation

>Eccentricity impacts the waveform and the phase modulation

>Spins impact the waveform and the phase modulation (but weaker effect)

Depend on the number of cycles and SNR, can be easily measured with high precision



>Sky location impacts the waveform modulation over time through antenna beam pattern

>Distance impacts the waveform amplitude (degenerate with masses, and sky location, inclination)

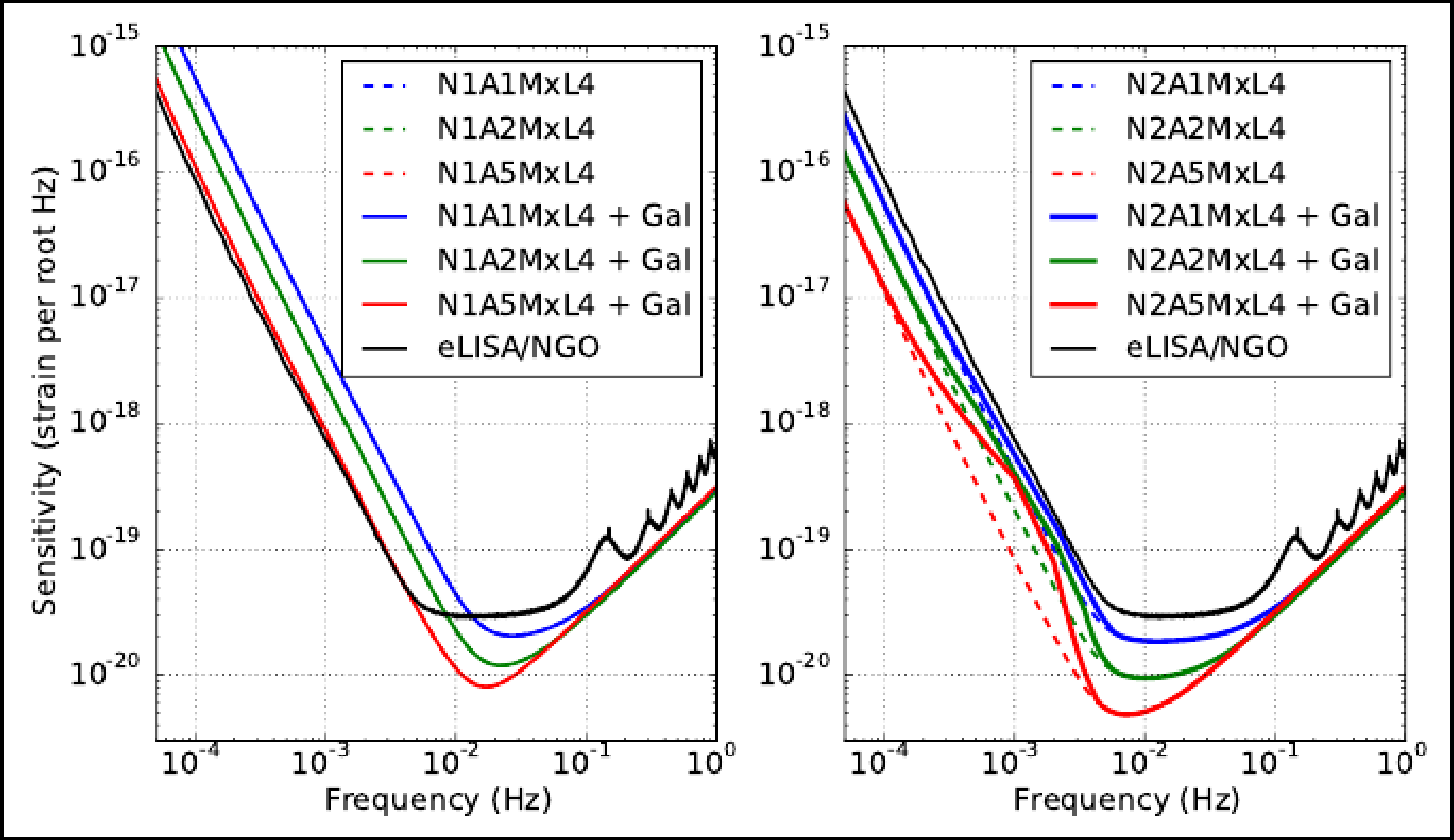
Depend on the time in band, polarization disentanglement, SNR.
Measurement is more difficult.
For MBH binaries, strong impact of having: 1) longer baseline
2) 6 laser links

GOAT study: sensitivity curves

12 detector configurations:

- **-1 2 5 Mkm armlength**
- **-two different low frequency noise levels**
- **-4 and 6 lase links**

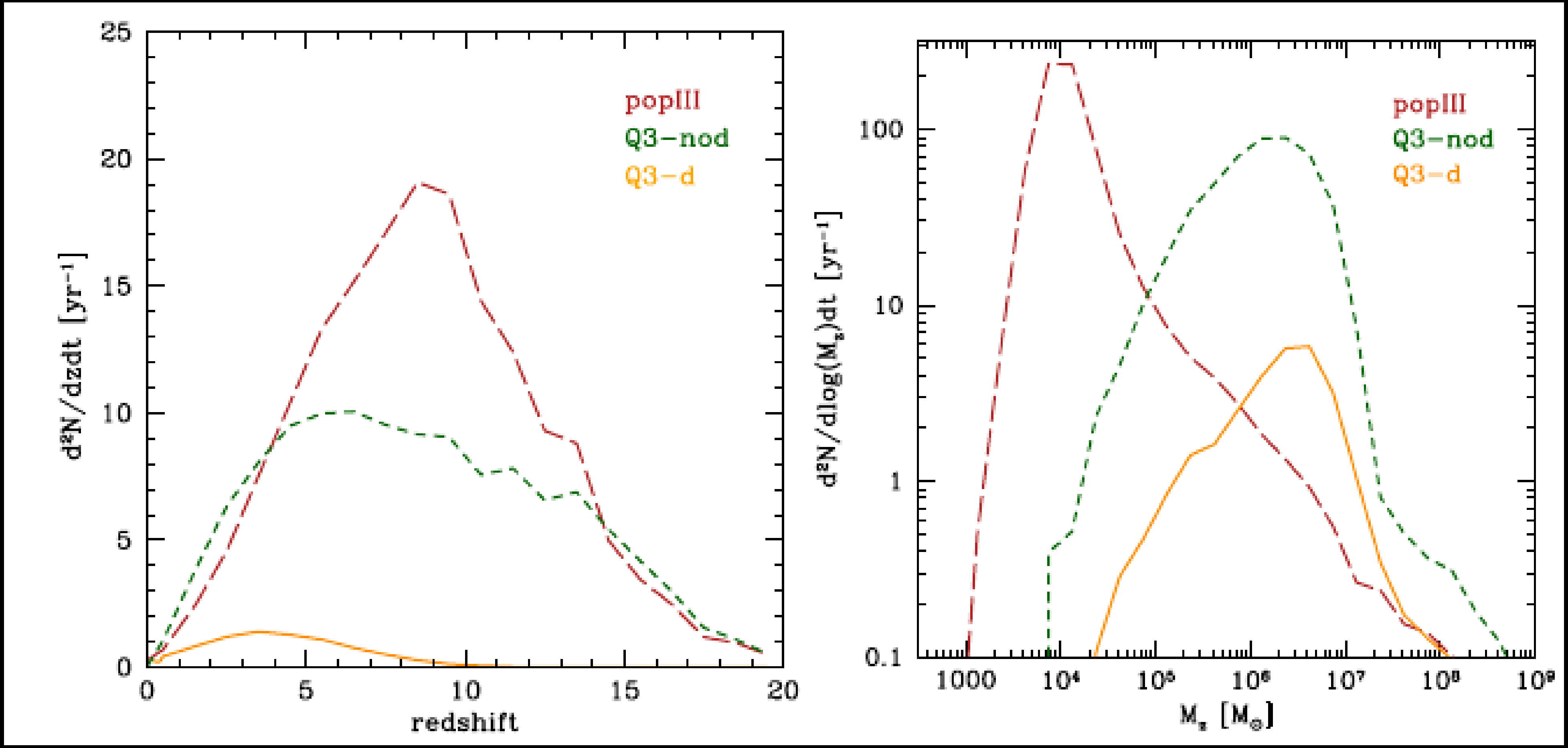
(for each configuration 2 and 5 yr mission considered)



GOAT study: MBHB population models

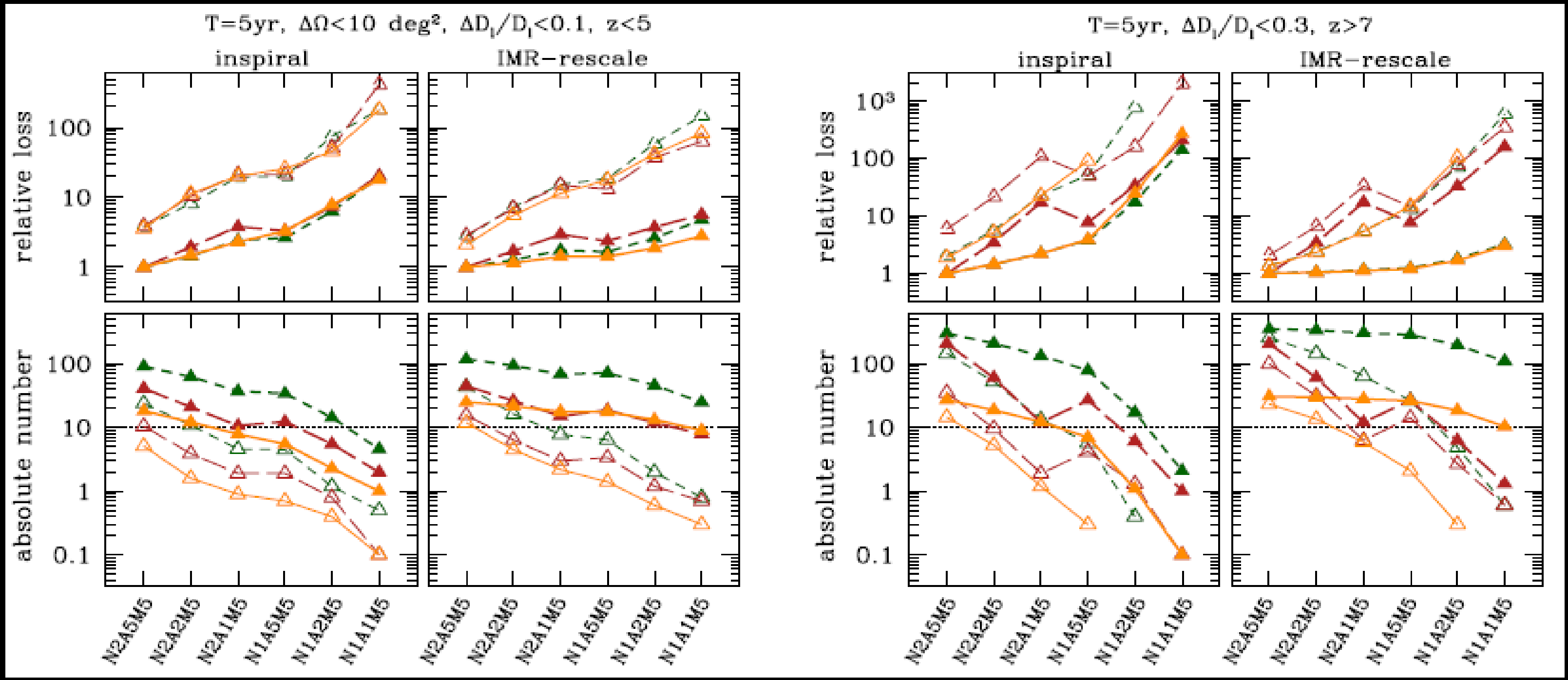
3 main MBH cosmic population models
- **popIII vs direct collapse seeds**
- **no delays vs delays of MBHB merger following galaxy mergers**

Representative of some of the main uncertainties in determination of the MBHB merger rate (Marta's and Monica's talks)



Example: source sky localization

(Klein et al. 2016)



Arm	Noise	Links	Config ID	$\Delta\Omega < 10\text{deg}^2$ & $\Delta d_l/d_l < 0.1$ & $z < 5$						$z > 7$ & $\Delta d_l/d_l < 0.3$					
				Precession+ HH			Precession+ HH IMR			Precession+ HH			Precession+ HH IMR		
				popI	Q3-nod	Q3-d	popI	Q3-nod	Q3-d	popI	Q3-nod	Q3-d	popI	Q3-nod	Q3-d
N2	A5	L6	N2A5M5L6	41.0	90.6	14.8	45.0	119.6	26.1	207.1	299.4	3.4	207.1	352.4	3.6
		L4	N2A5M5L4	10.5	23.9	3.5	15.7	43.9	13.4	35.3	147.6	1.6	100.6	258.8	2.7
	A2	L6	N2A2M5L6	21.0	62.9	9.3	26.4	94.2	23.1	60.6	210.0	2.3	60.6	338.4	3.6
		L4	N2A2M5L4	3.9	11.0	1.4	6.4	16.4	3.7	9.7	53.1	0.9	31.4	147.4	1.7
	A1	L6	N2A1M5L6	10.7	37.5	6.0	15.2	68.4	19.2	12.1	134.1	1.6	12.1	306.0	3.4
		L4	N2A1M5L4	1.9	4.6	0.4	3.0	7.8	1.4	1.9	13.4	0.1	6.3	64.6	0.9
N1	A5	L6	N1A5M5L6	12.3	34.3	4.4	18.9	72.2	18.0	26.9	79.1	1.3	26.9	286.7	3.4
		L4	N1A5M5L4	1.9	4.5	0.3	3.4	6.4	1.0	4.2	5.8	0.1	14.4	26.8	0.3
	A2	L6	N1A2M5L6	5.5	14.3	2.4	12.0	45.8	13.5	6.1	17.2	0.5	6.3	197.7	2.4
		L4	N1A2M5L4	0.8	1.2	0.0	1.2	2.0	0.1	1.3	0.4	0.0	2.7	4.9	0.1
	A1	L6	N1A1M5L6	2.0	4.6	0.9	7.9	24.9	9.0	1.0	2.1	0.1	1.3	110.8	1.7
		L4	N1A1M5L4	0.2	0.5	0.0	0.7	0.8	0.0	0.1	0.0	0.0	0.6	0.6	0.0

Summary of eLISA parameter estimation

Assuming 5 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

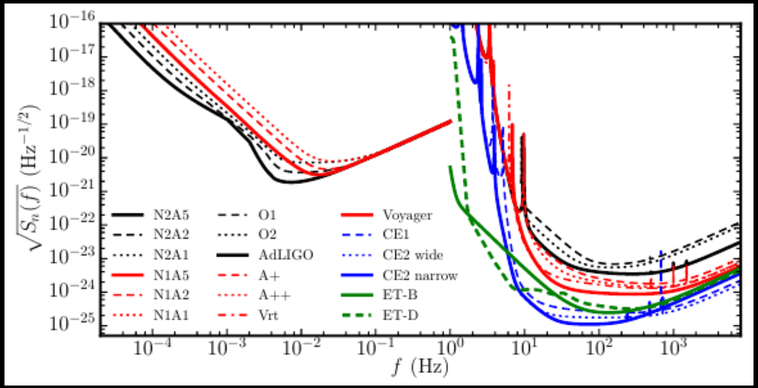
~50 systems with secondary spin determined to 0.1

~50 systems with spin direction determined within 10deg

~30 events with final spin determined to 0.1

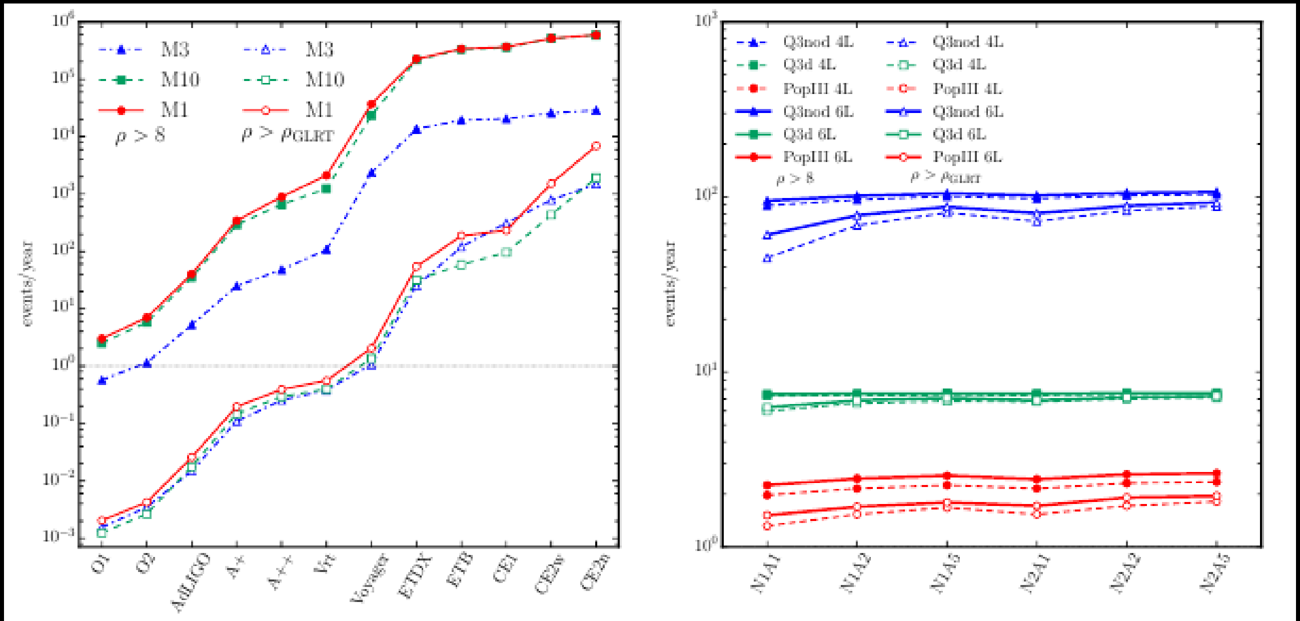
Resolving ringdown modes: BH spectroscopy

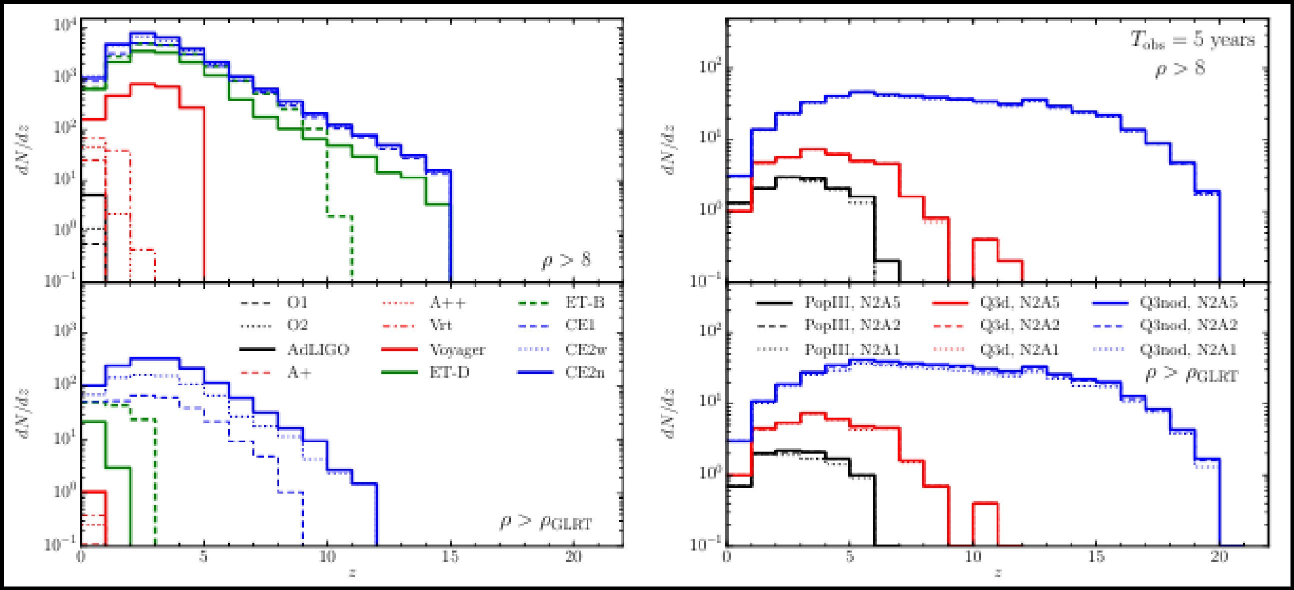
(Berti et al. 2016)



$$\rho^{2,3}_{\rm GLRT} = 17.687 + \frac{15.4597}{q-1} - \frac{1.65242}{q}\,,$$

$$\rho^{2,4}_{\rm GLRT} = 37.9181 + \frac{83.5778}{q} + \frac{44.1125}{q^2} + \frac{50.1316}{q^3}$$





LIGO will not enable BH spectroscopy on individual BHB mergers

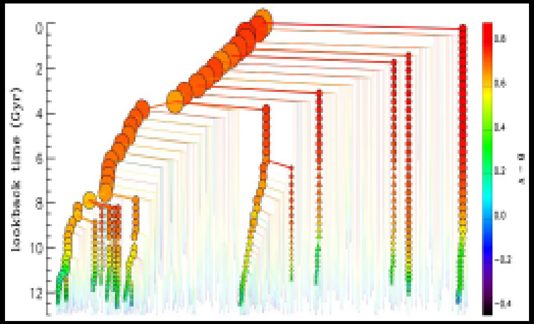
Voyager/ET type detectors are needed

eLISA will enable precise BH spectroscopy on few to 100 events/yr also at very high redshifts

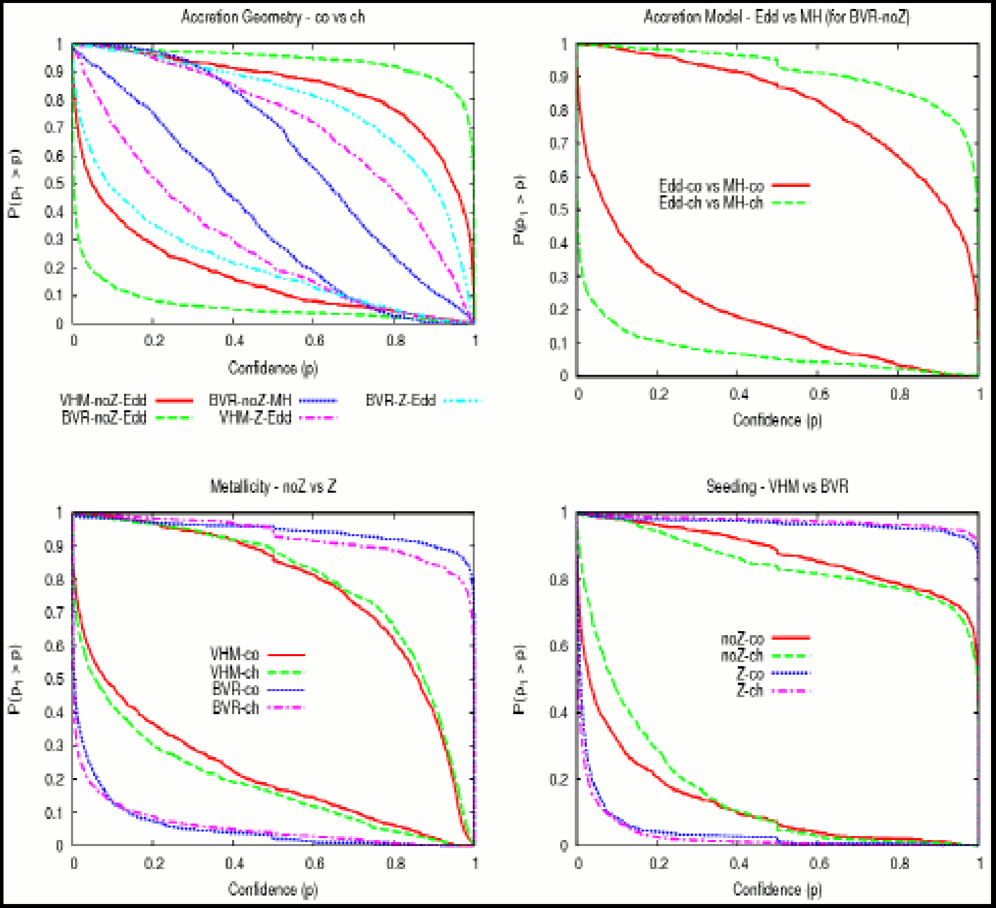
MBH astrophysics with GW observations

Astrophysical unknowns in MBH formation scenarios

1- MBH seeding mechanism (heavy vs light seeds)
2- Metallicity feedback (metal free vs all metallicities)
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?

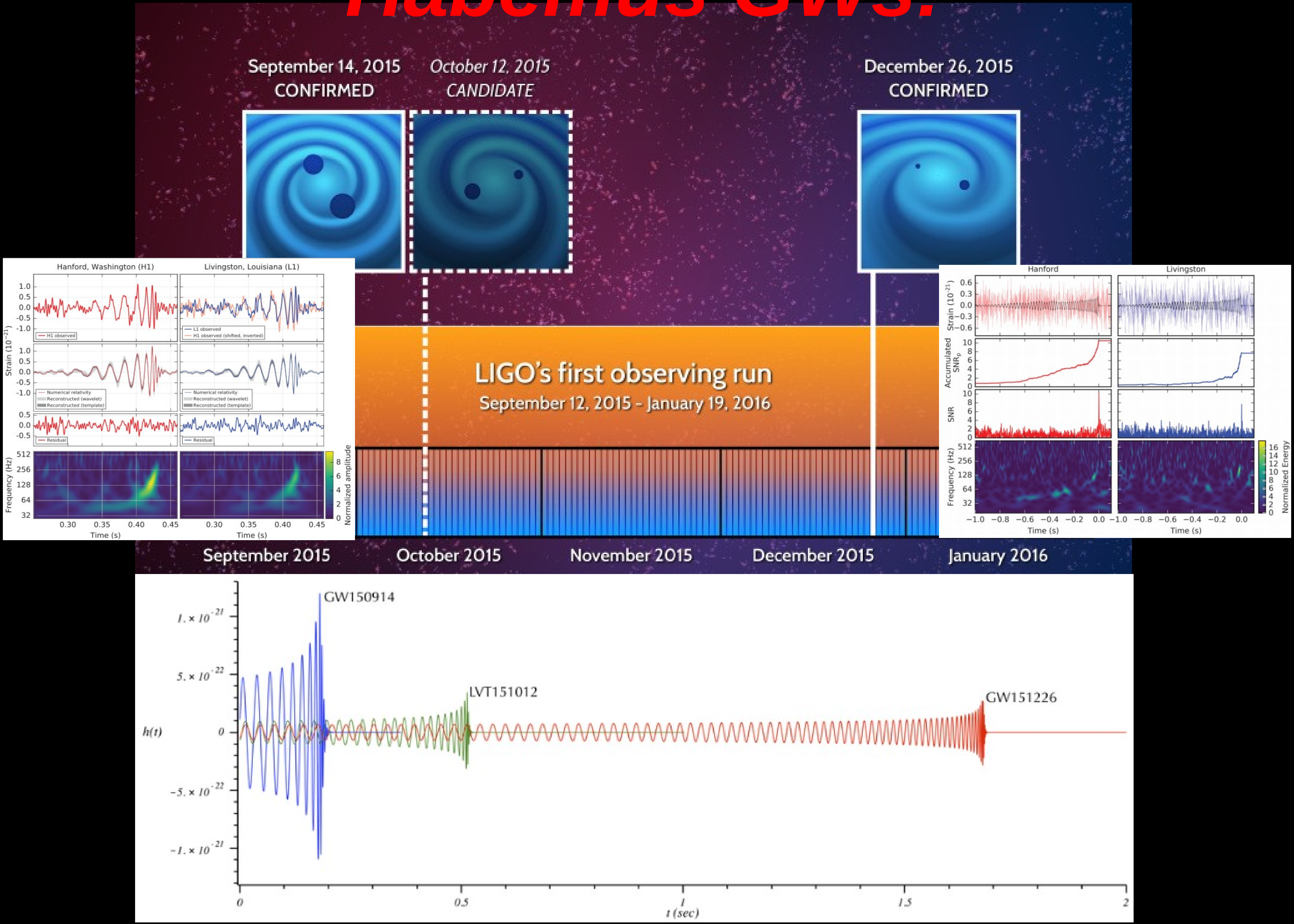


Create catalogues of observed binaries including errors from eLISA observations and compare observations with theoretical models

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

Stellar black hole binaries

Habemus GWs!



September 14, 2015
CONFIRMED
October 12, 2015
CANDIDATE
December 26, 2015
CONFIRMED
LIGO's first observing run
September 12, 2015 - January 19, 2016
September 2015
October 2015
November 2015
December 2015
January 2016
Hanford, Washington (H1)
Livingston, Louisiana (L1)
Hanford
Livingston
GW150914
LVT151012
GW151226
h(t)
t (sec)

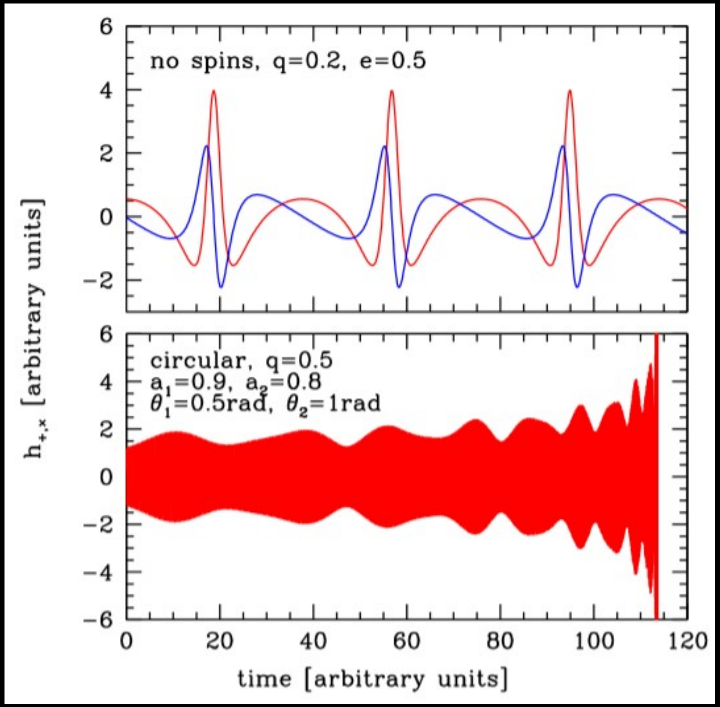
Extraction of information from the waveform

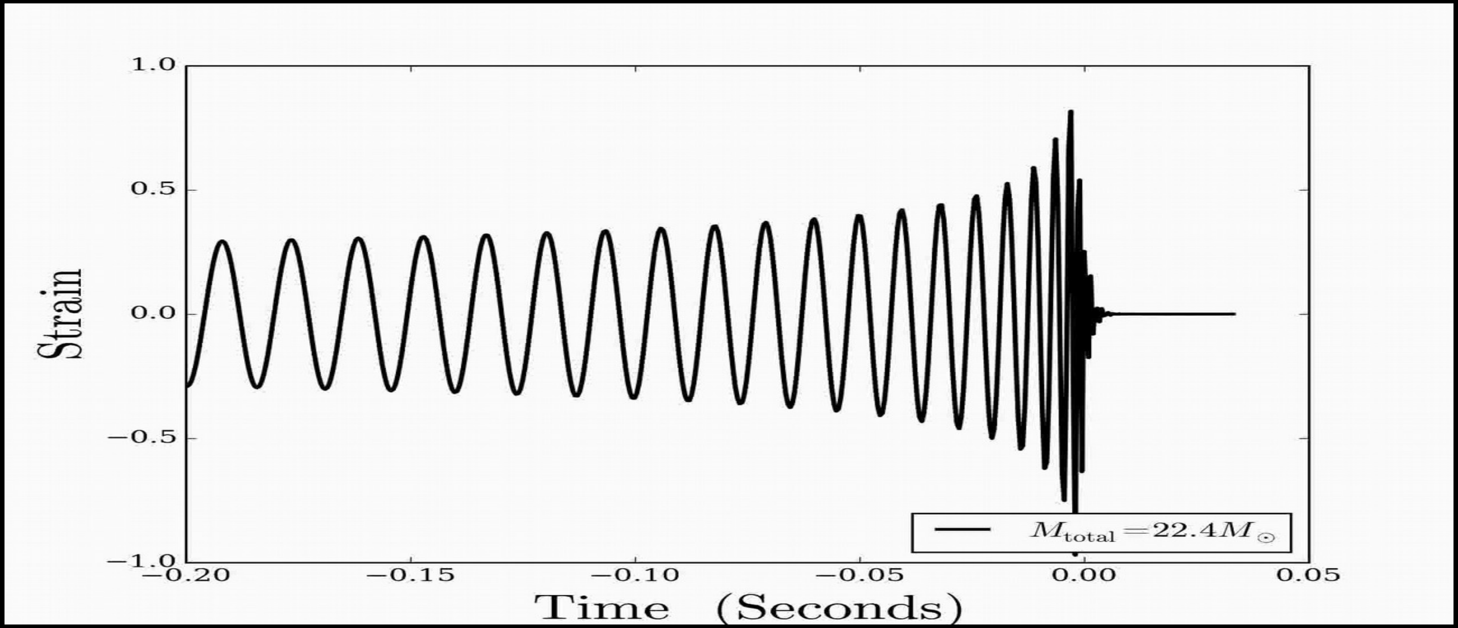
>Masses have the largest impact on the phase modulation

>Eccentricity impacts the waveform and the phase modulation

>Spins impact the waveform and the phase modulation (but weaker effect)

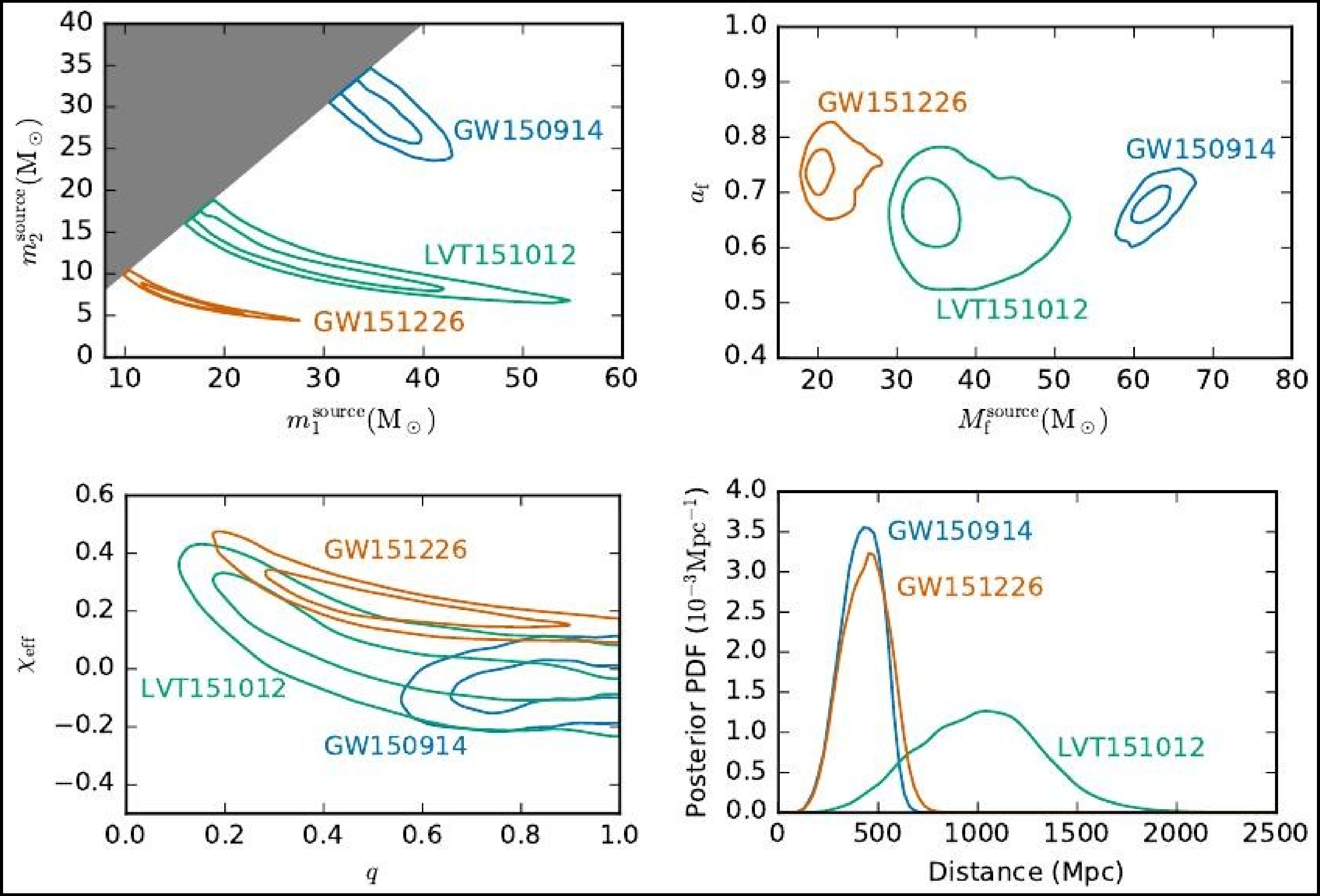
Depend on the number of cycles and SNR, can be easily measured with high precision



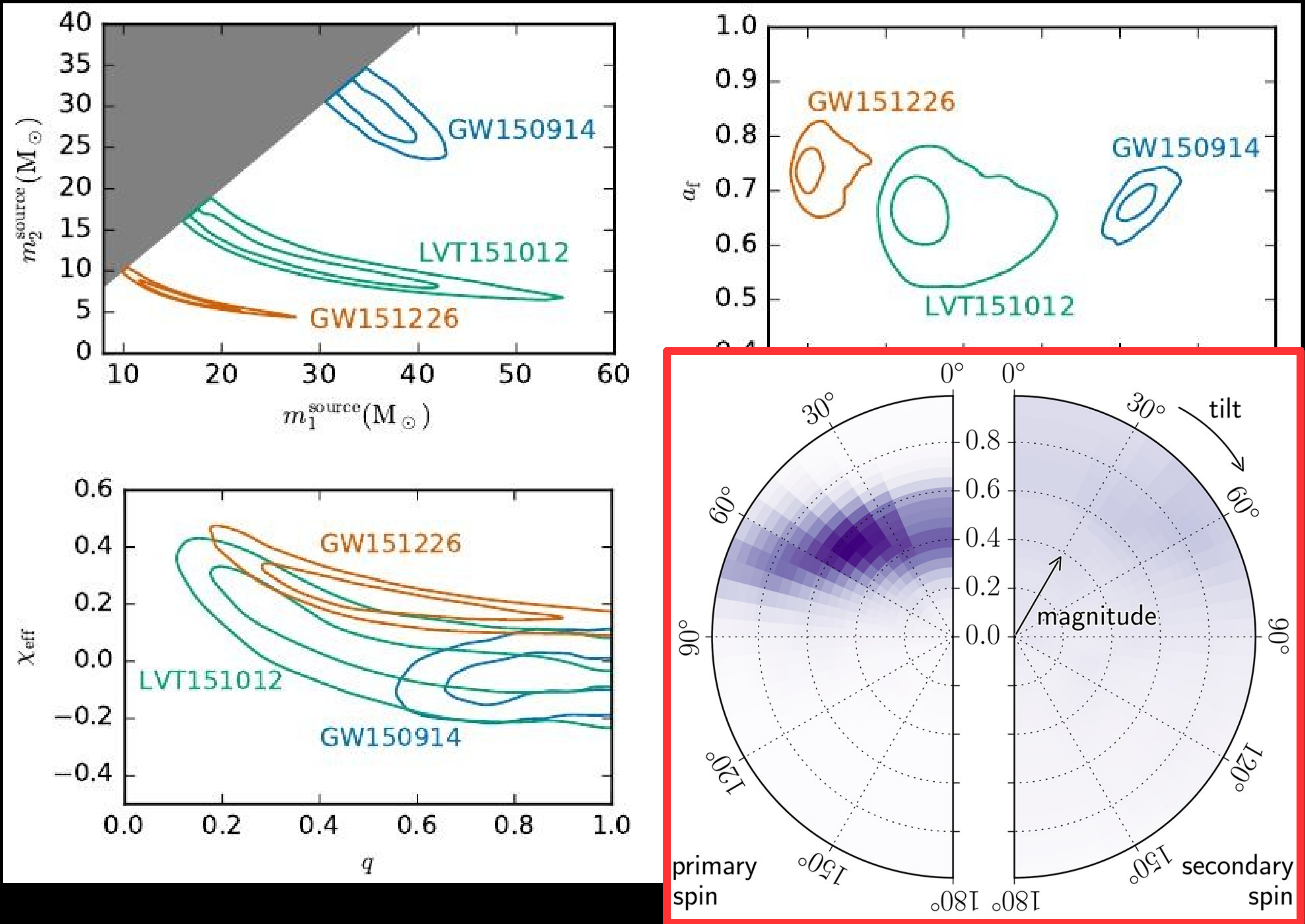


(Courtesy W. del Pozzo)

(astro)physical properties



(astro)physical properties

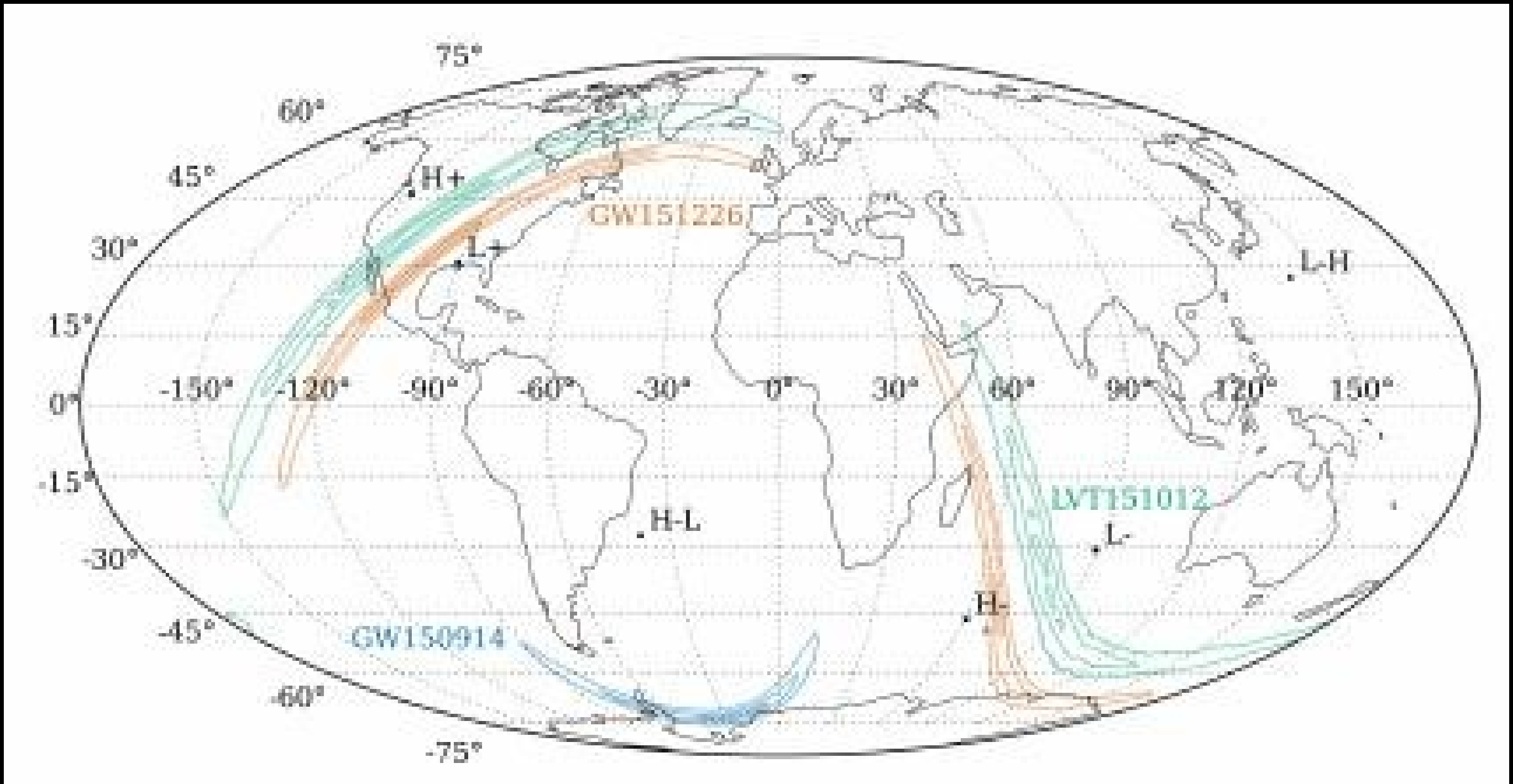


Extraction of information from the waveform

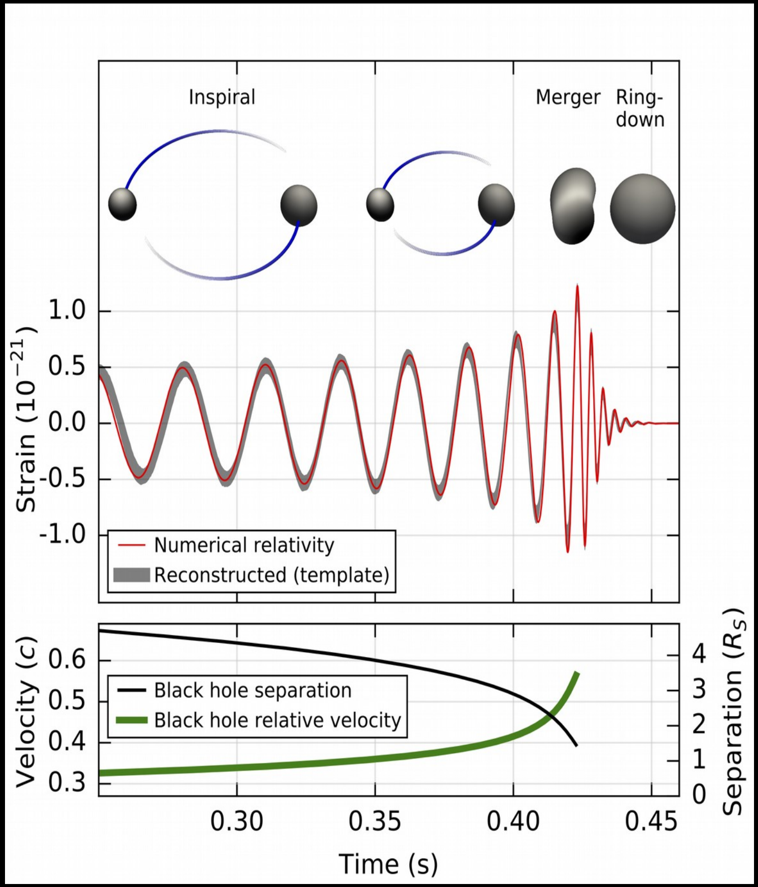
>Sky location essentially measured through triangulation:
two detectors ⟶ poor information

>Distance impacts the waveform amplitude (degenerate with masses, and sky location, inclination)

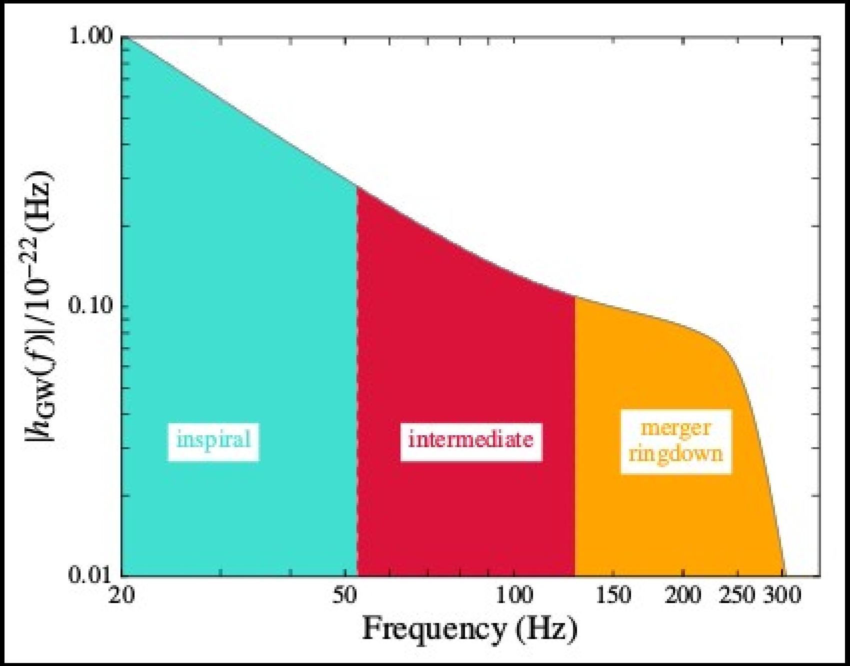
Depend on number of detection, polarization disentanglement, SNR.
Measurement is more difficult.

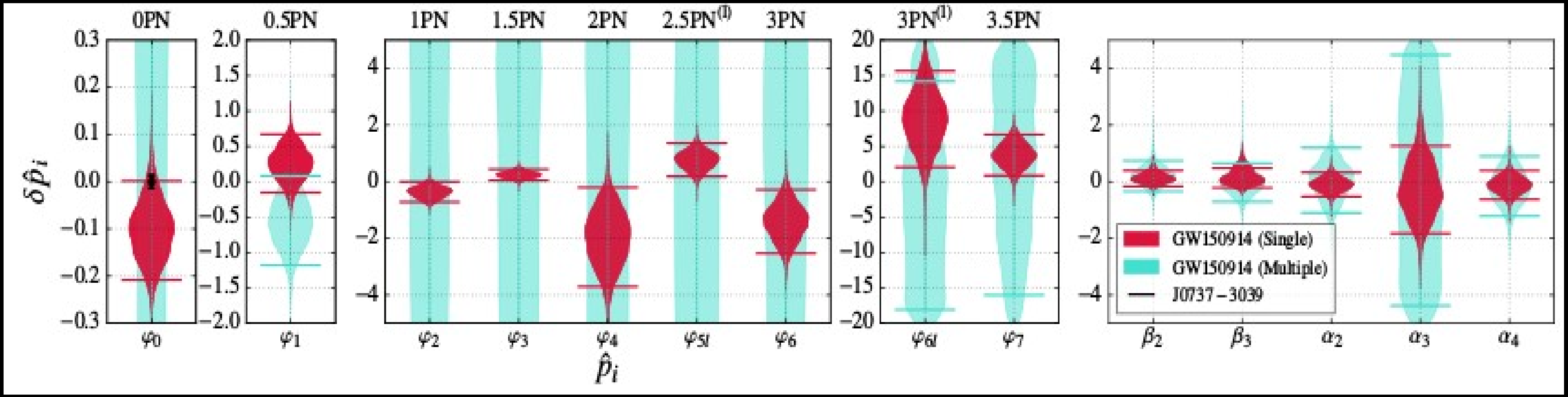


Testing GR with GW150914



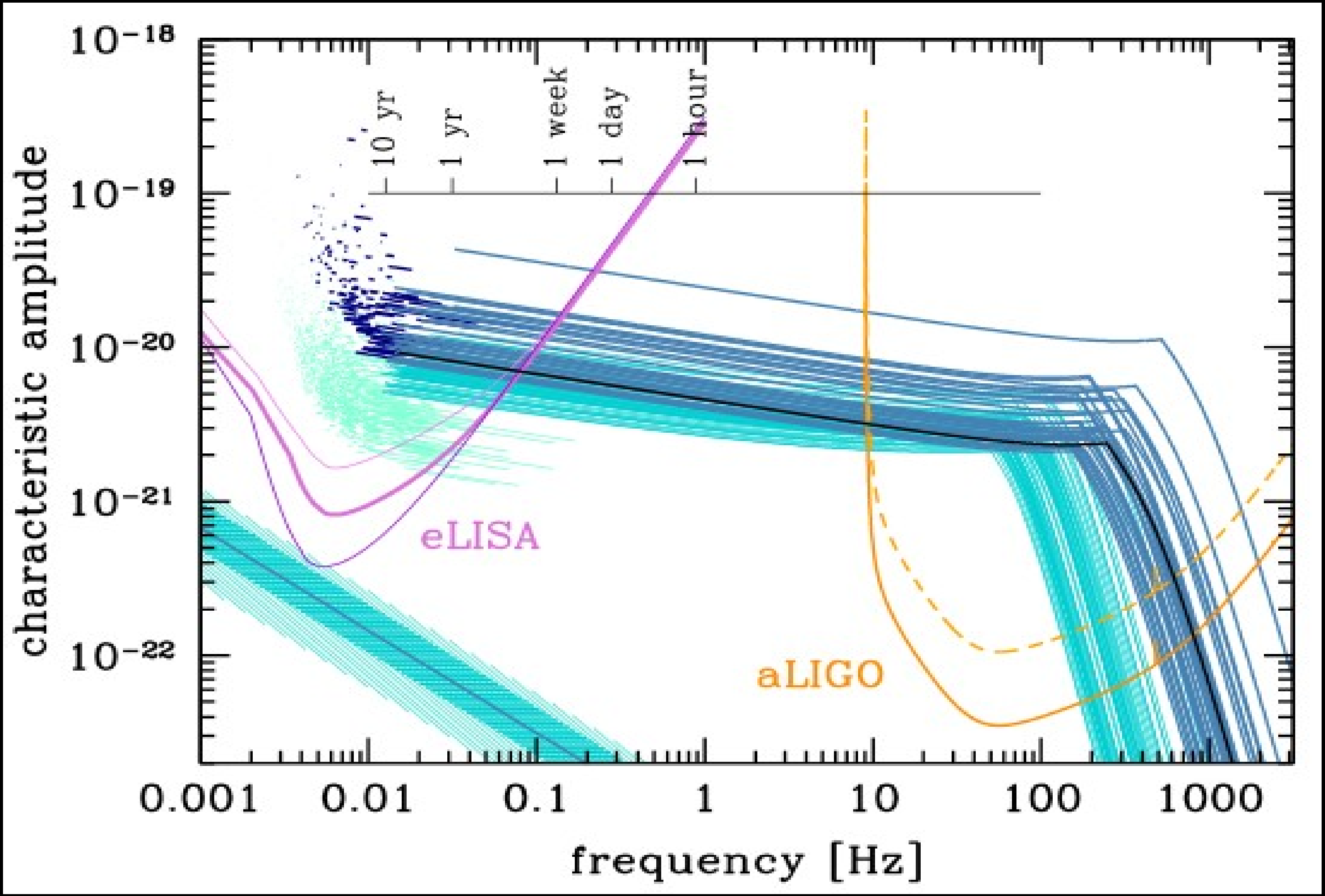
GW150914 provides the most stringent tests of gravity in the strong field regime:
NO EVIDENCE FOR DEVIATIONS FROM GR





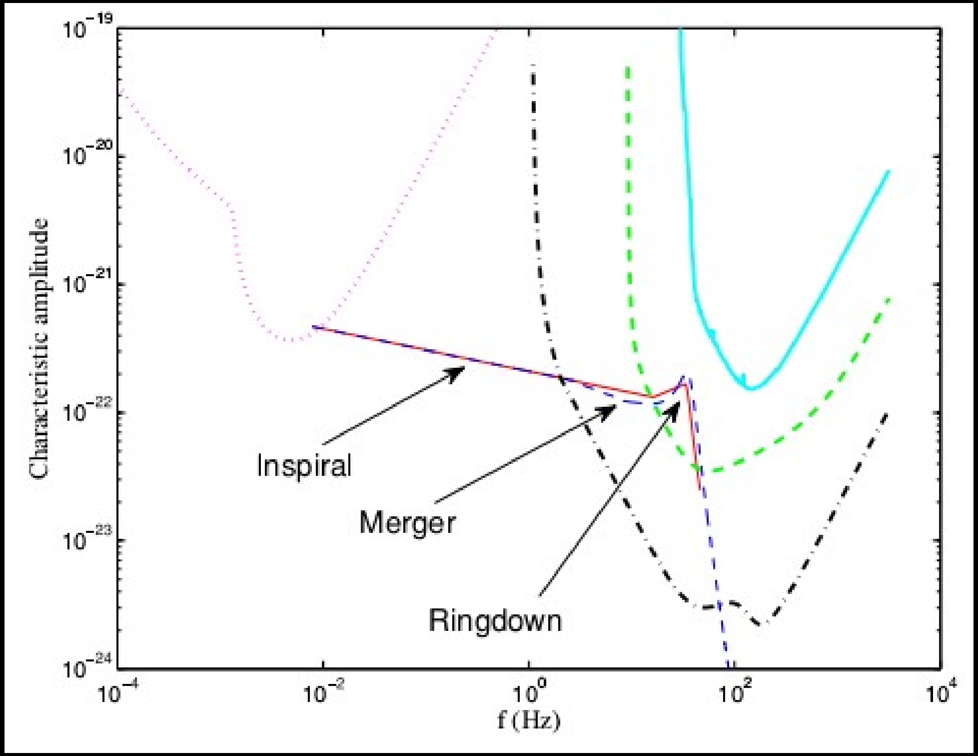
An unexpected implication: multi-band GW astronomy

(AS 2016, PRL 116, 1102)

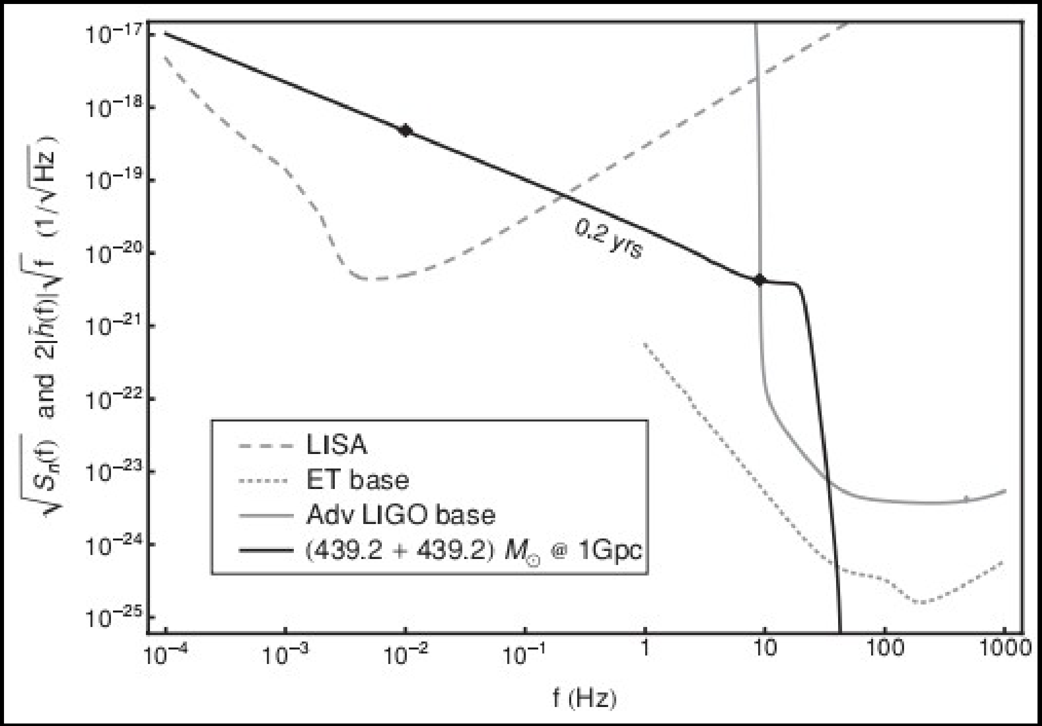


BHB will be detected by eLISA and cross to the LIGO band, assuming a 5 year operation of eLISA.

The idea was already around in the literature



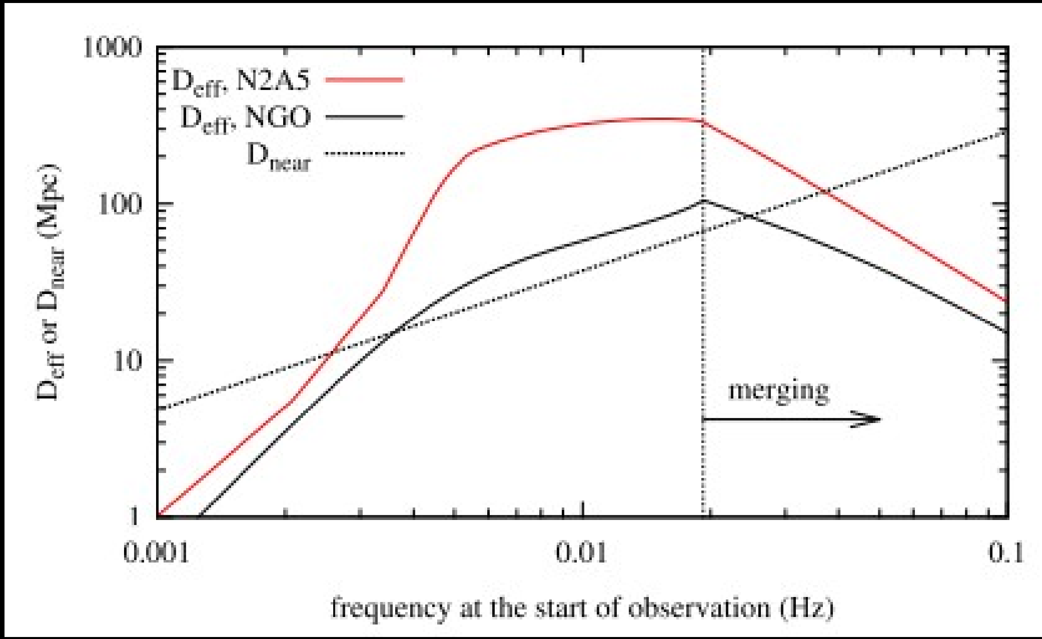
PopIII seeds merging at late times (z~2) could be seen both in LISA and aLIGO/ET **(AS et al. 2009)**



IMBH binaries formed in star cluster can also cross from LISA to LIGO/ET in a short timescale **(Amaro-Seoane & Santamaria 2010)**

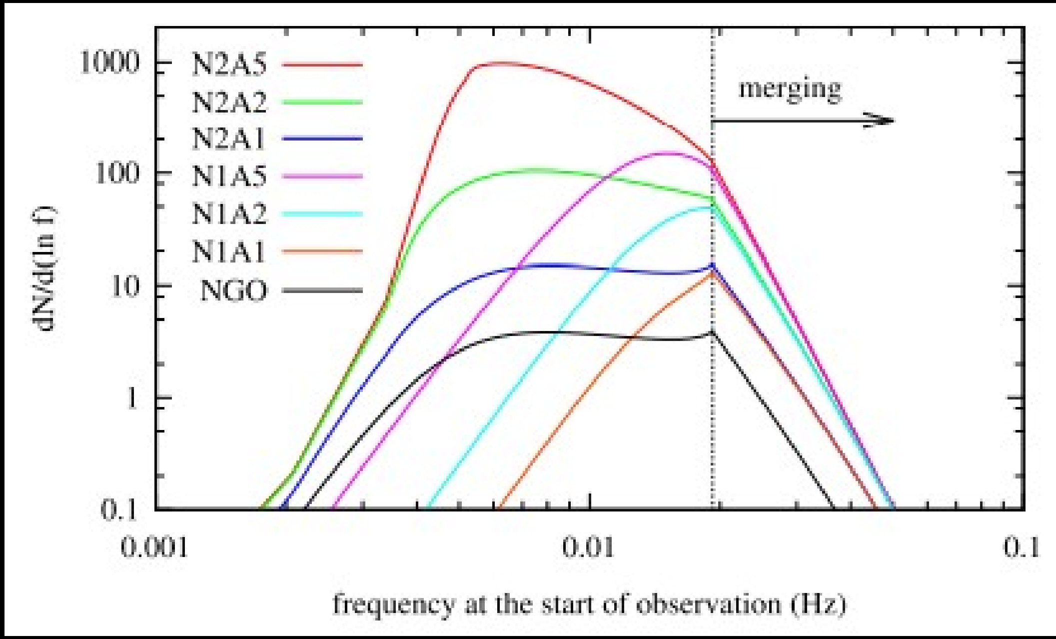
Distribution of sources across the band

(Kyutoku & Seto 2016)



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

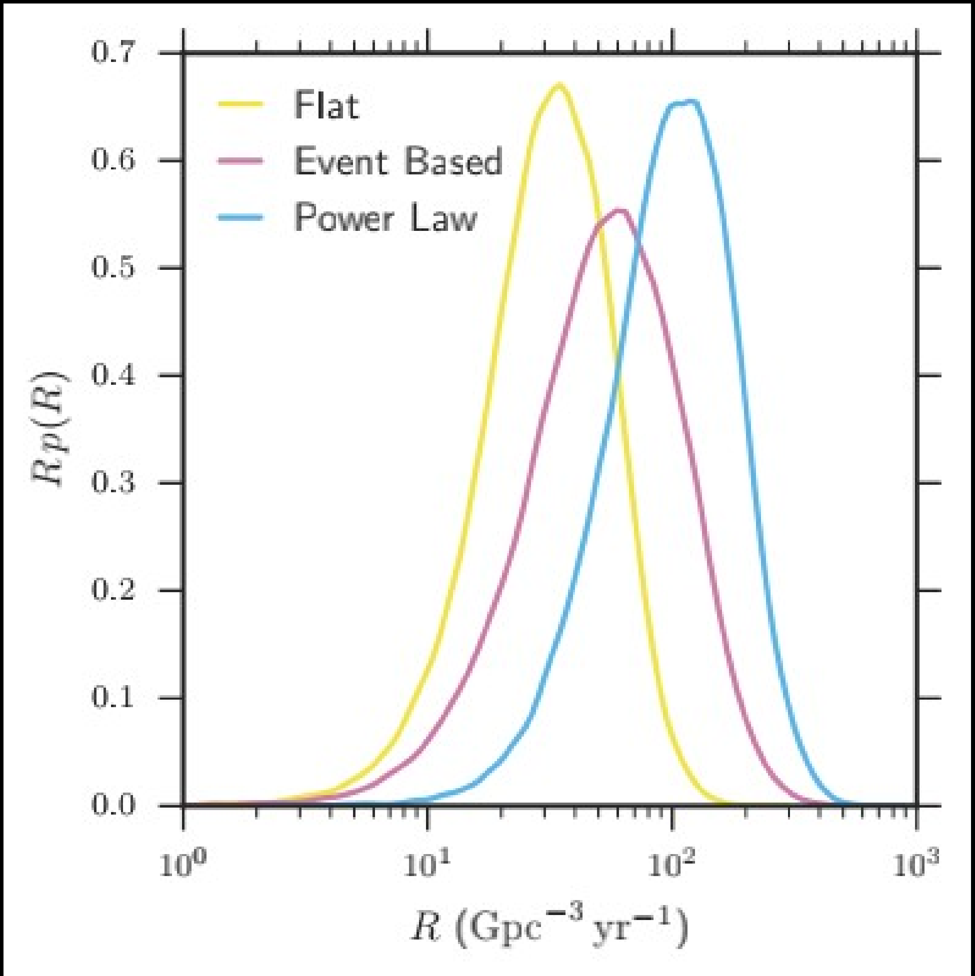


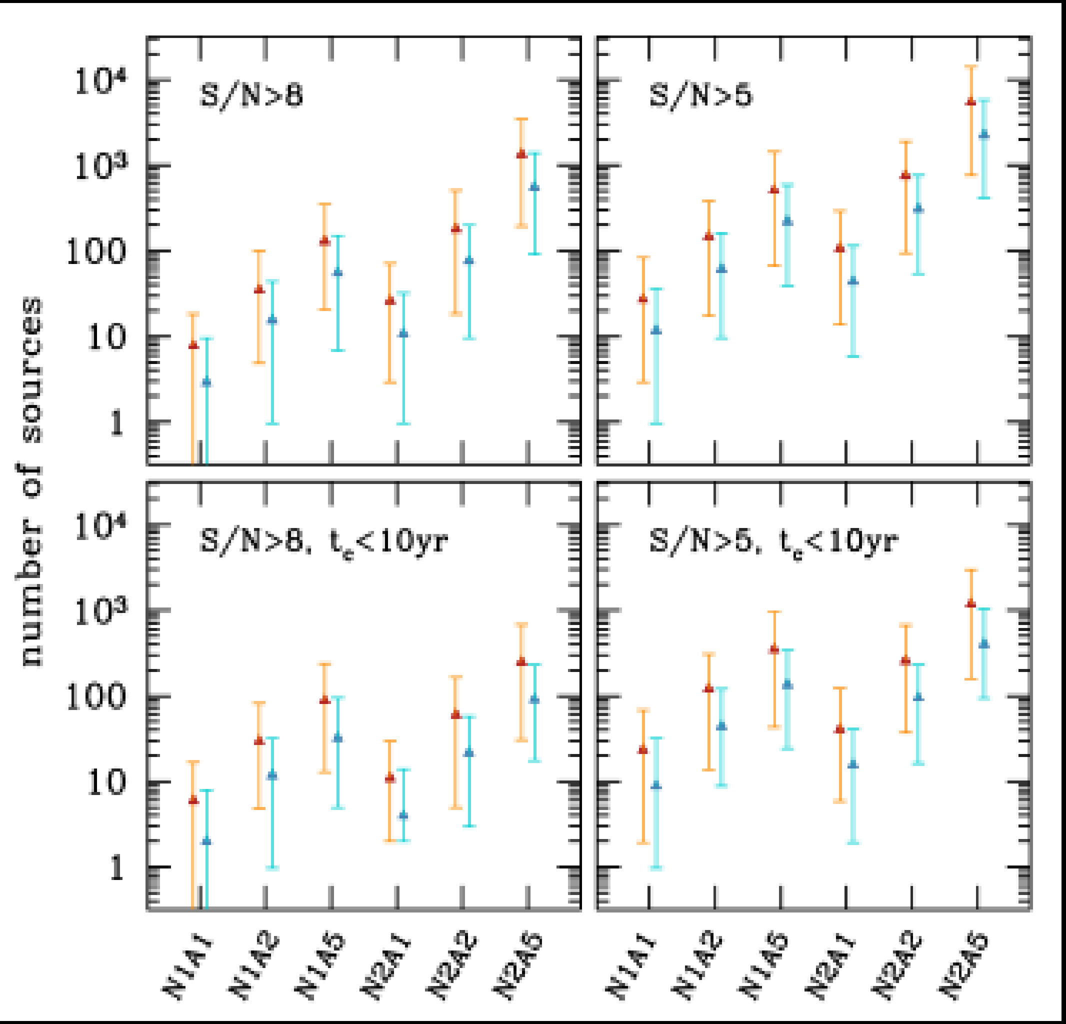
Number of observable sources (S/N>8) is a strong function of frequency*.

*that is the main reason of the erroneous initial claims about the observability of these sources by eLISA

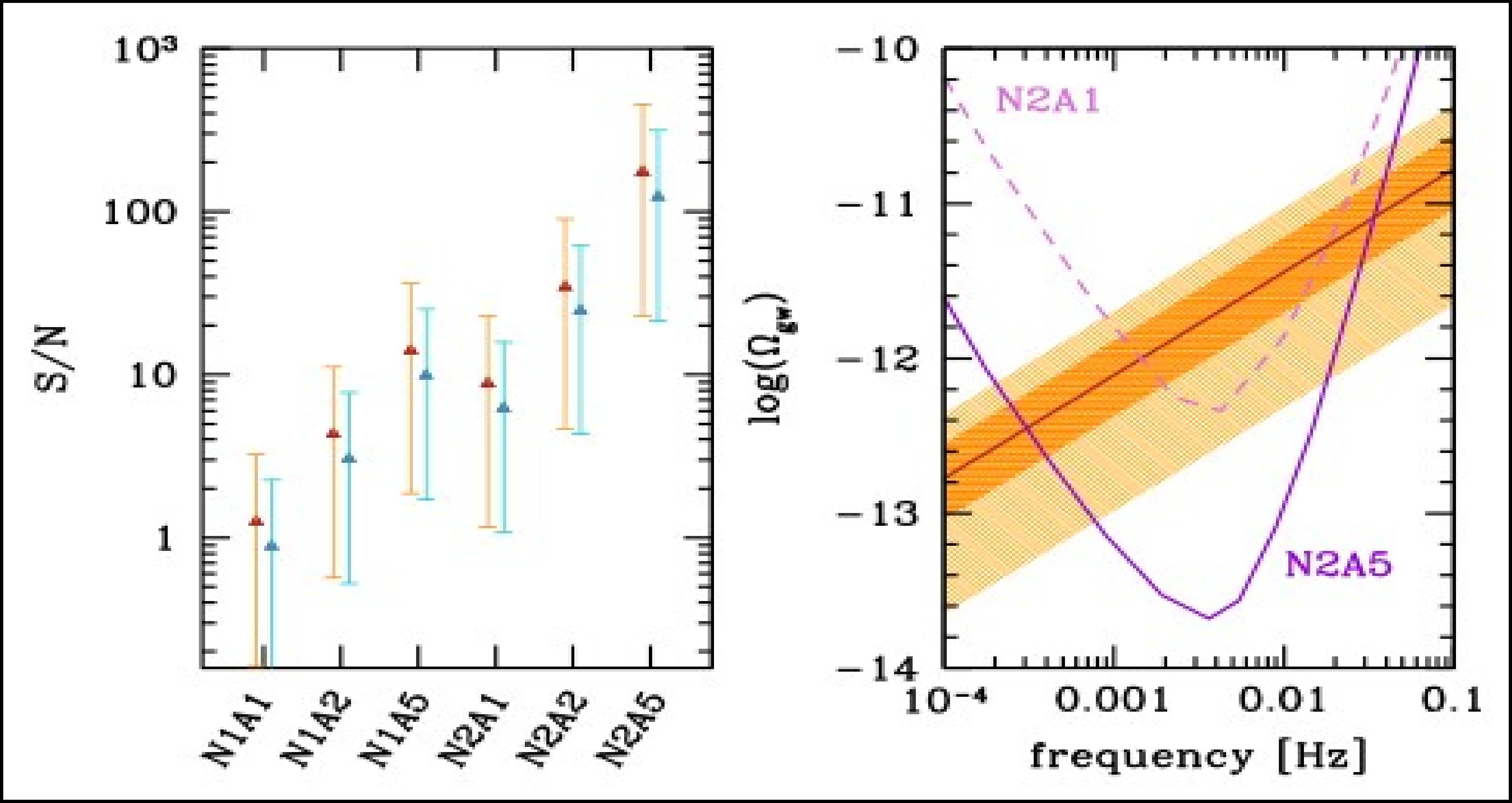
How many BHBs in the eLISA band?

Implied BHB mass distributions and merger rates much higher than previously thought!





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



Unresolved sources will form a confusion noise detectable with high S/N

What do we do with them?

>Detector cross-band calibration and validation (eLISA aLIGO)

>Multiband GW astronomy:

-alert aLIGO to ensure multiple GW detectors are on

-inform aLIGO with source parameters: makes detection easier

>Multimessenger astronomy:

-point EM probes at the right location before the merger

>Enhanced tests of GR: e.g. strongest limits on dipole radiation

>Astrophysics:

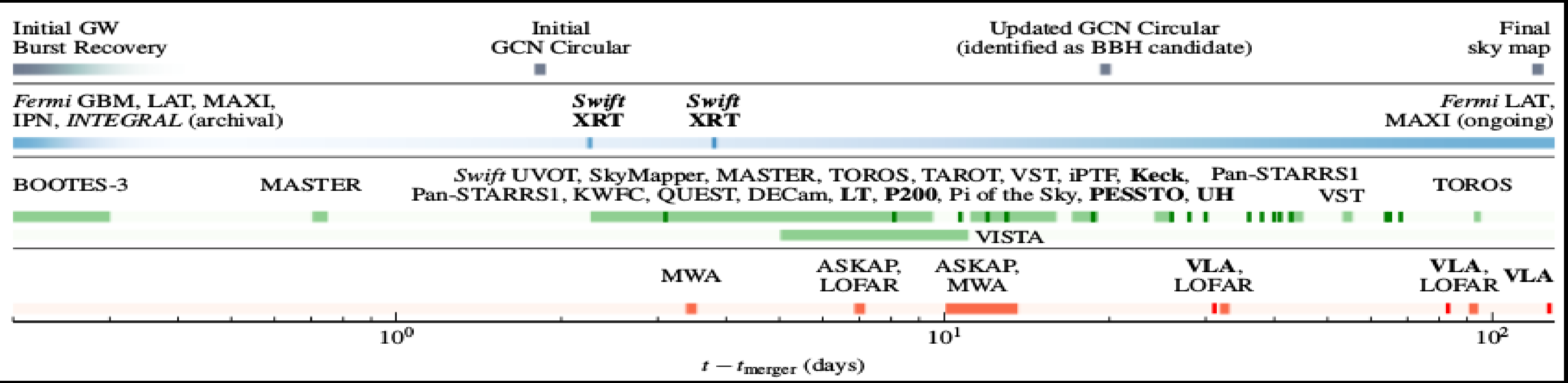
-independent measure of spins

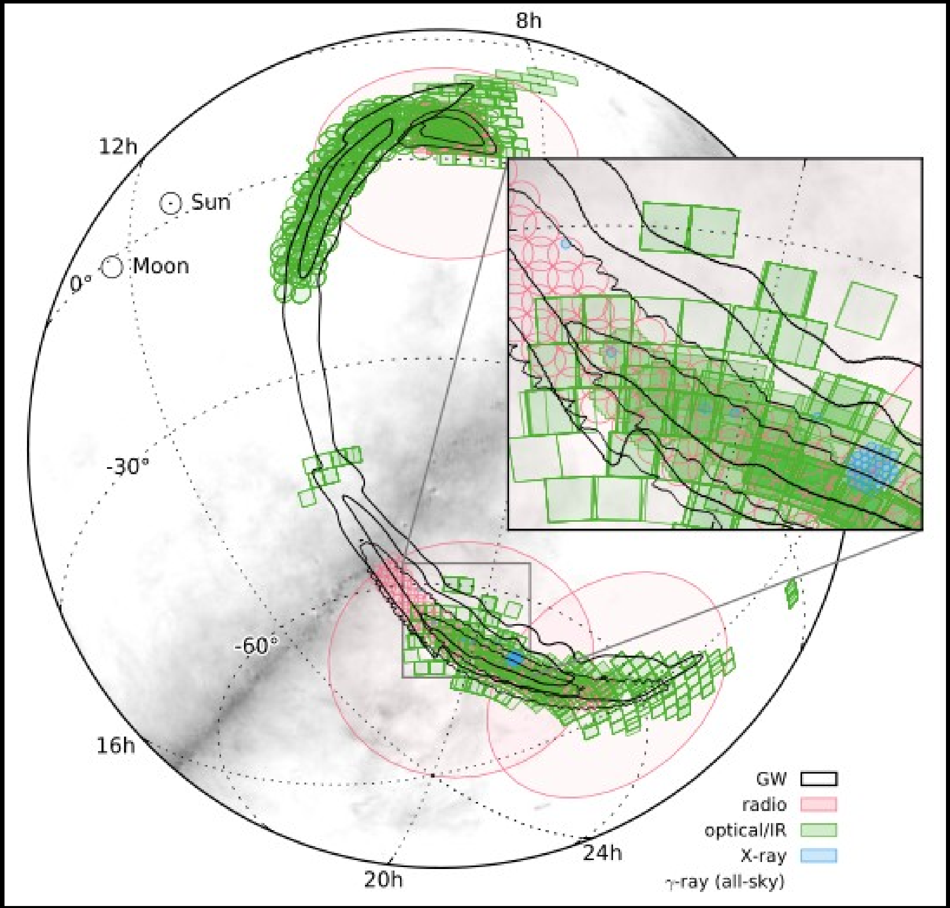
-measure of eccentricity

>Cosmology:

-new population of standard sirens?

Skylocalization and follow-up EM campaigns





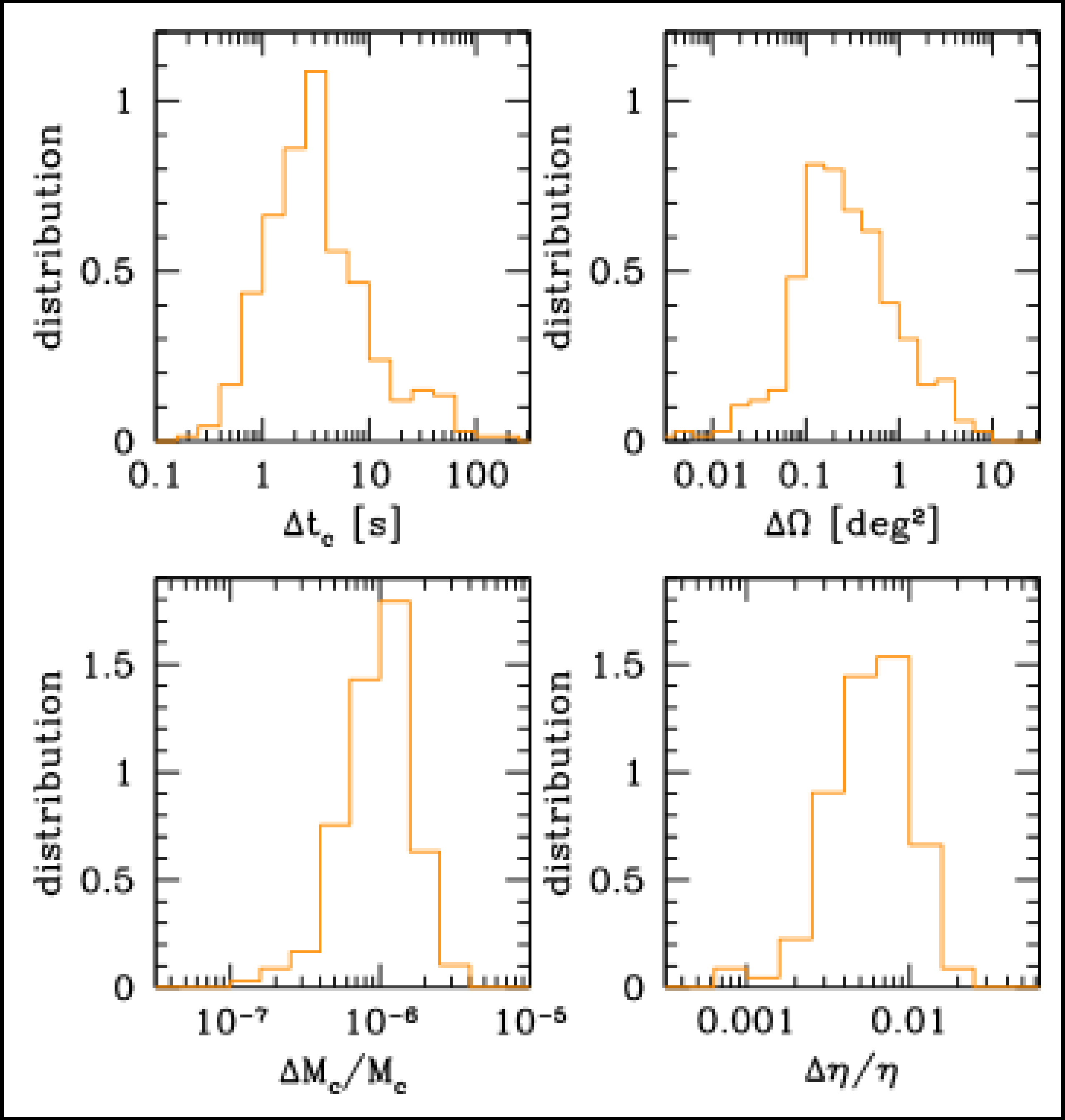
GW150914: huge error box!

Nevertheless everybody jumped on the event for follow-ups

Those campaigns are however very unlikely to succeed because of:
1-wide error box
2-delay wrt the coalescence

1 will improve with more detectors, 2 is bound to remain a limitation (unless....see later)

Sky pre-localization and coincident EM campaigns

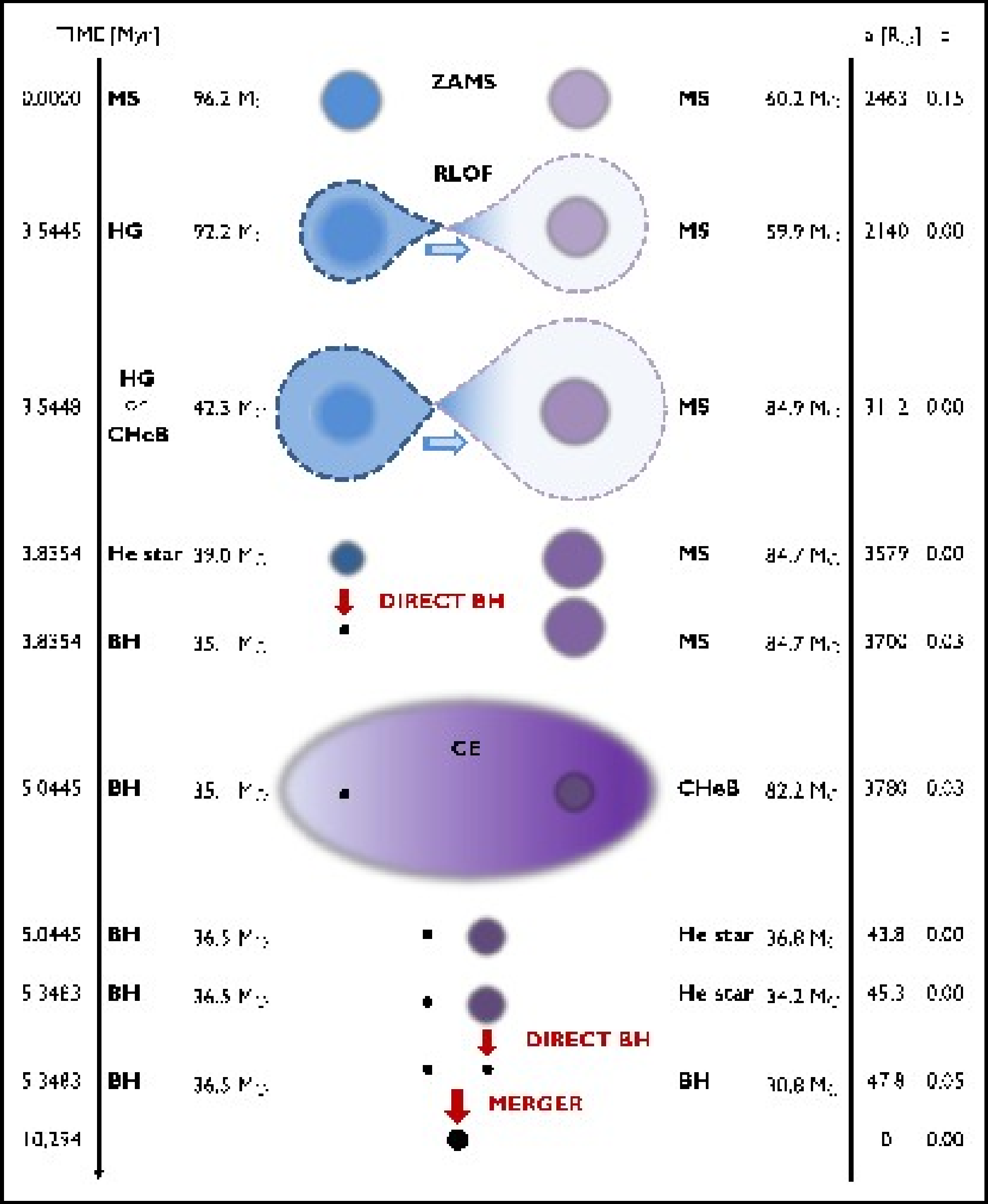


System crossing to the aLIGO band can be located with sub deg2 precision

Merger time can be predicted within 10 seconds

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



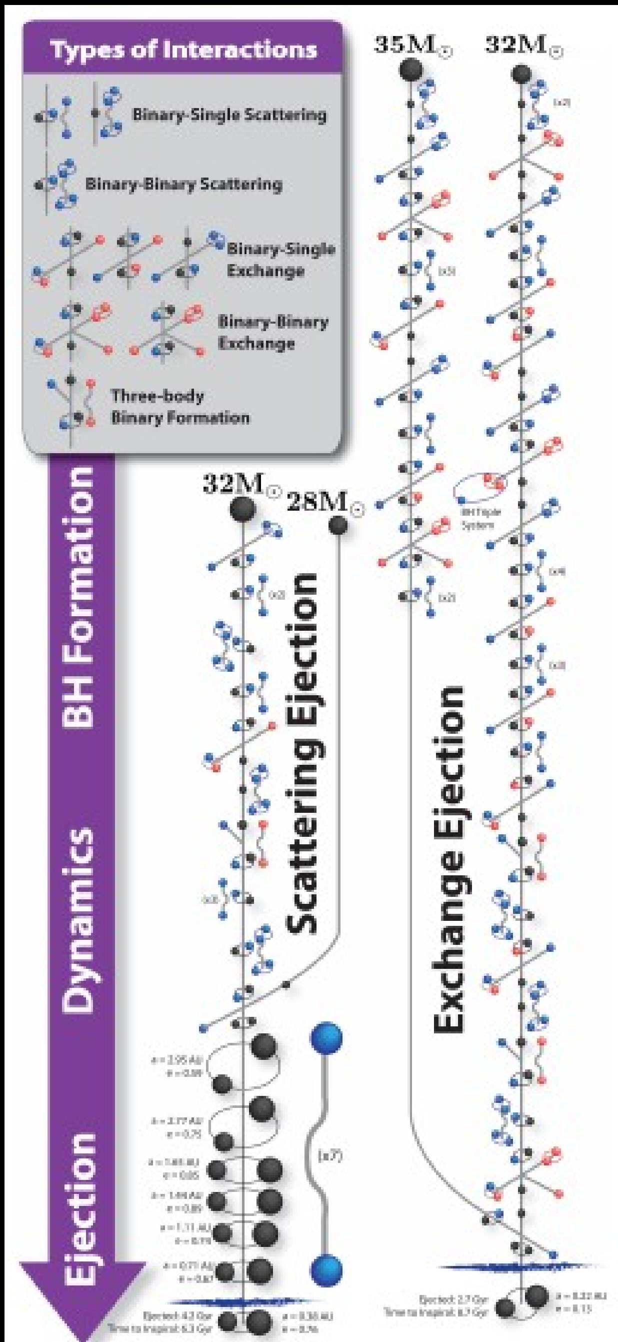
(Belczynski et al. 2016)

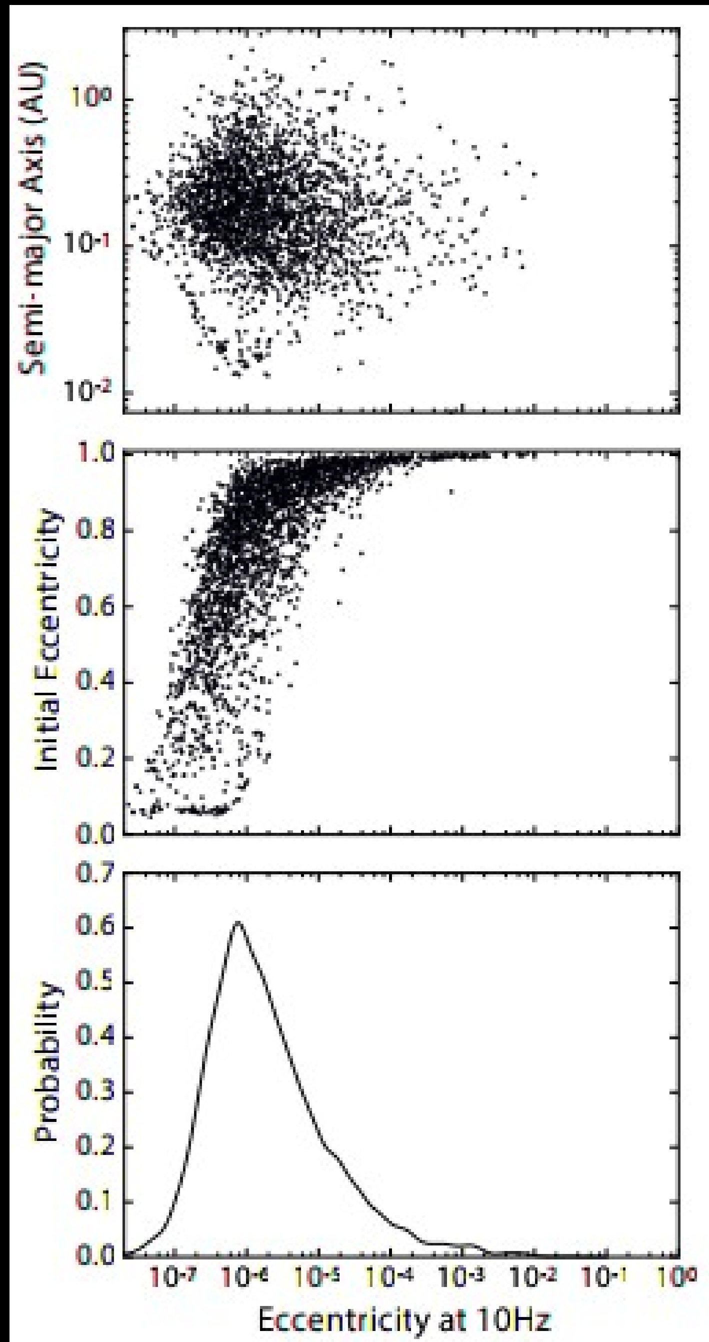
Evolution of massive Binaries

Complications
- common envelope
- kicks
- metallicity
- rotation

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

Astrophysics: BHB origin





(Rodriguez et al. 2016)

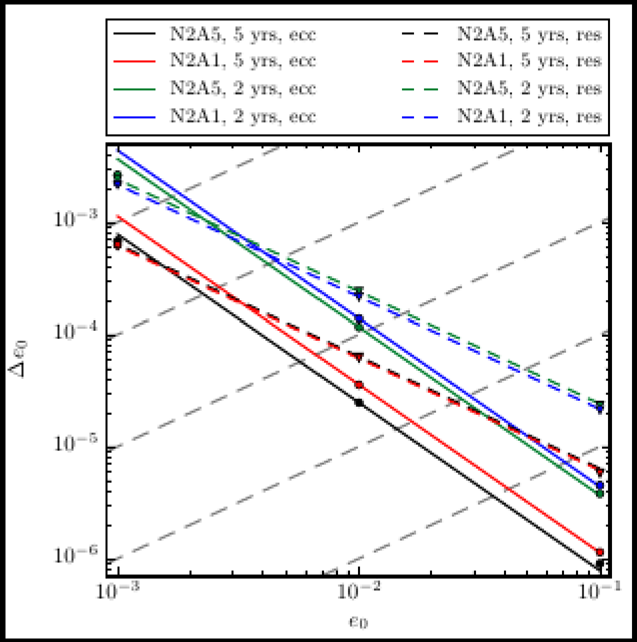
Dynamical capture

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

Features:
- randomly oriented spins?
- high formation eccentricities

Measuring eccentricity with eLISA

(Nishizawa et al. 2016)



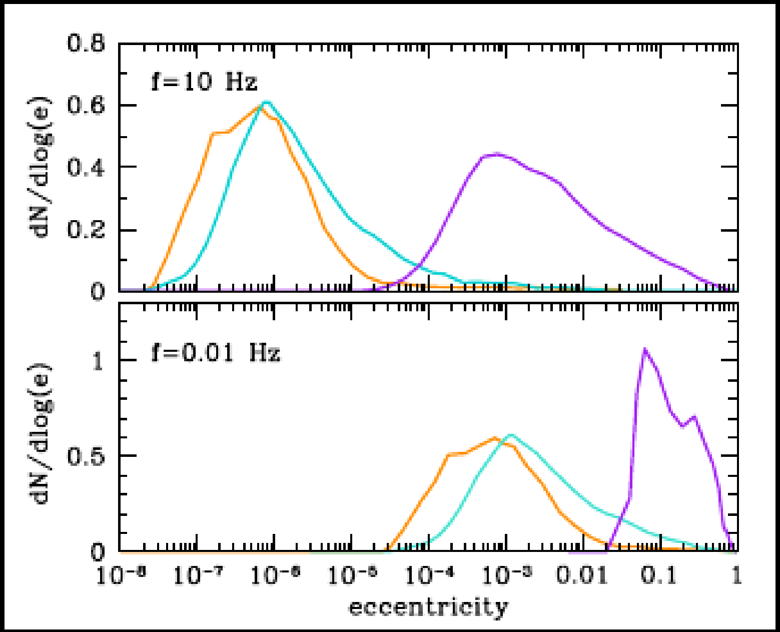
>aLIGO can only place upper bounds on *e*, but eLISA can measure *e* if >10^{-3}

>GW circularization implies much higher eccentricities in the eLISA band

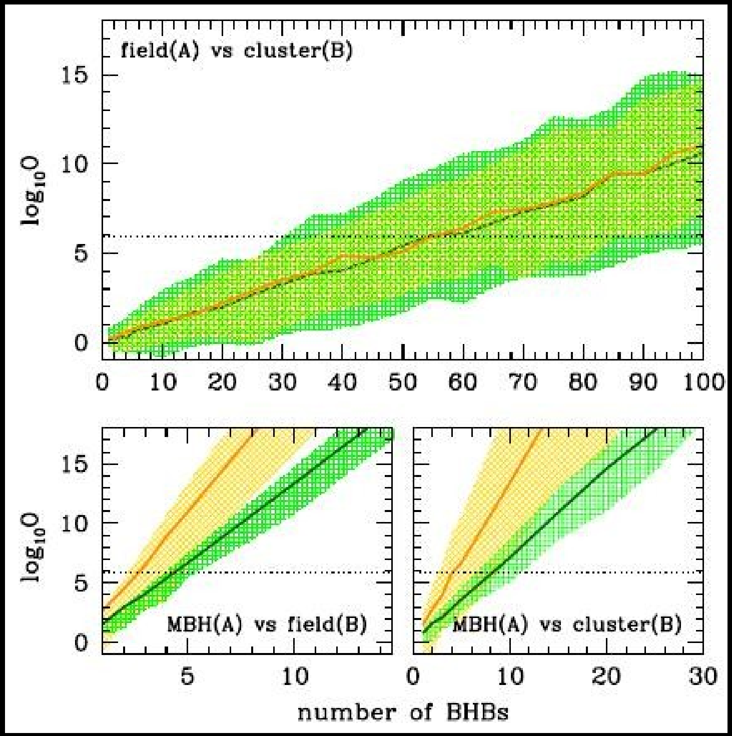
Different formation channel imply different e distributions.
Too small to be measured by LIGO but accessible to LISA

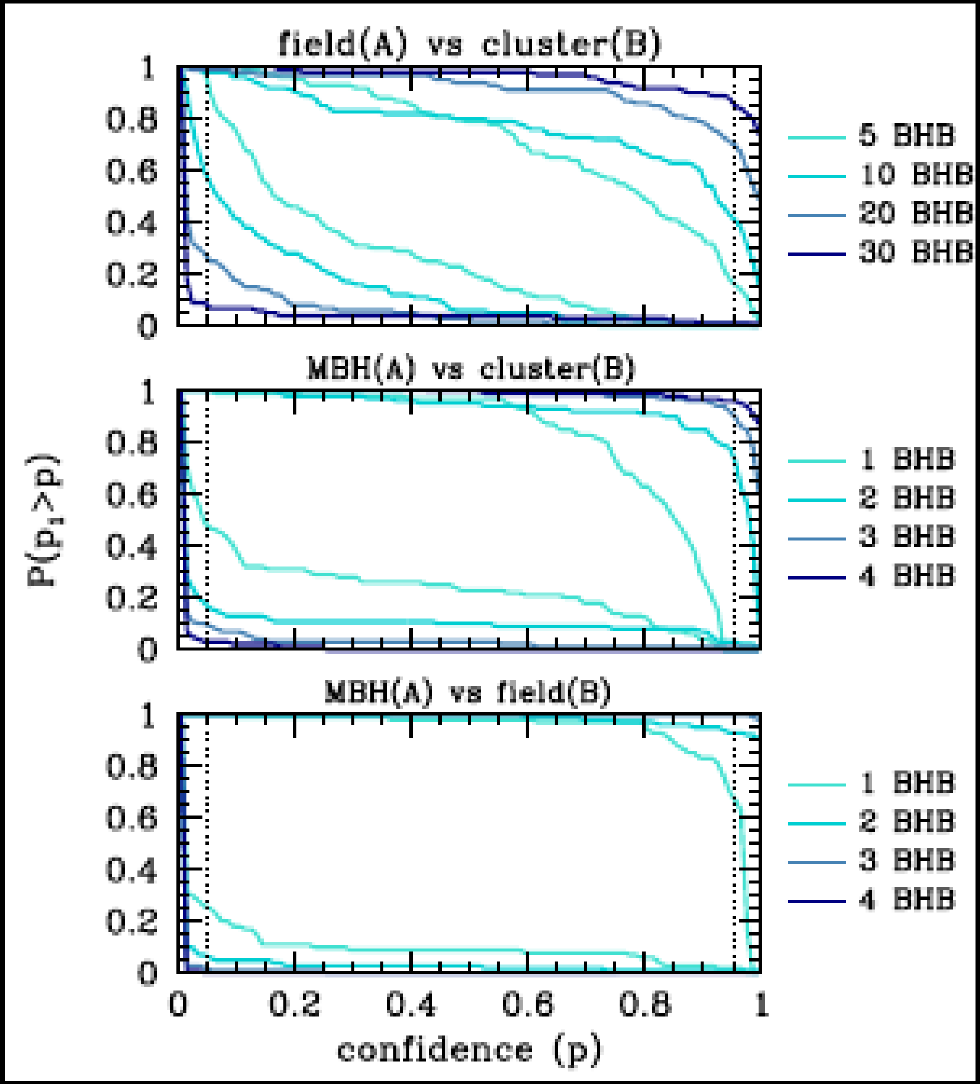
Proof of concept: three BHB formation scenarios

- -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



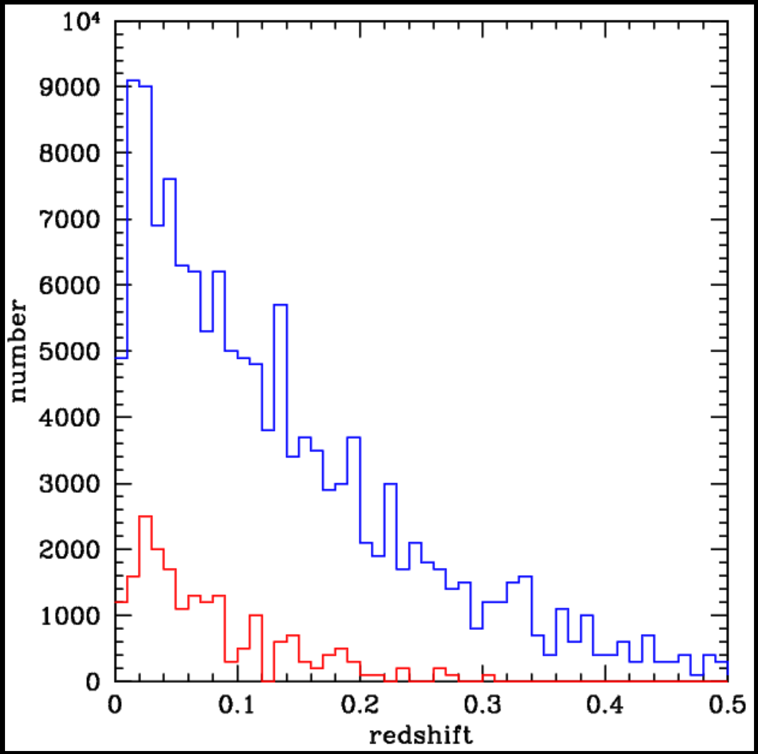


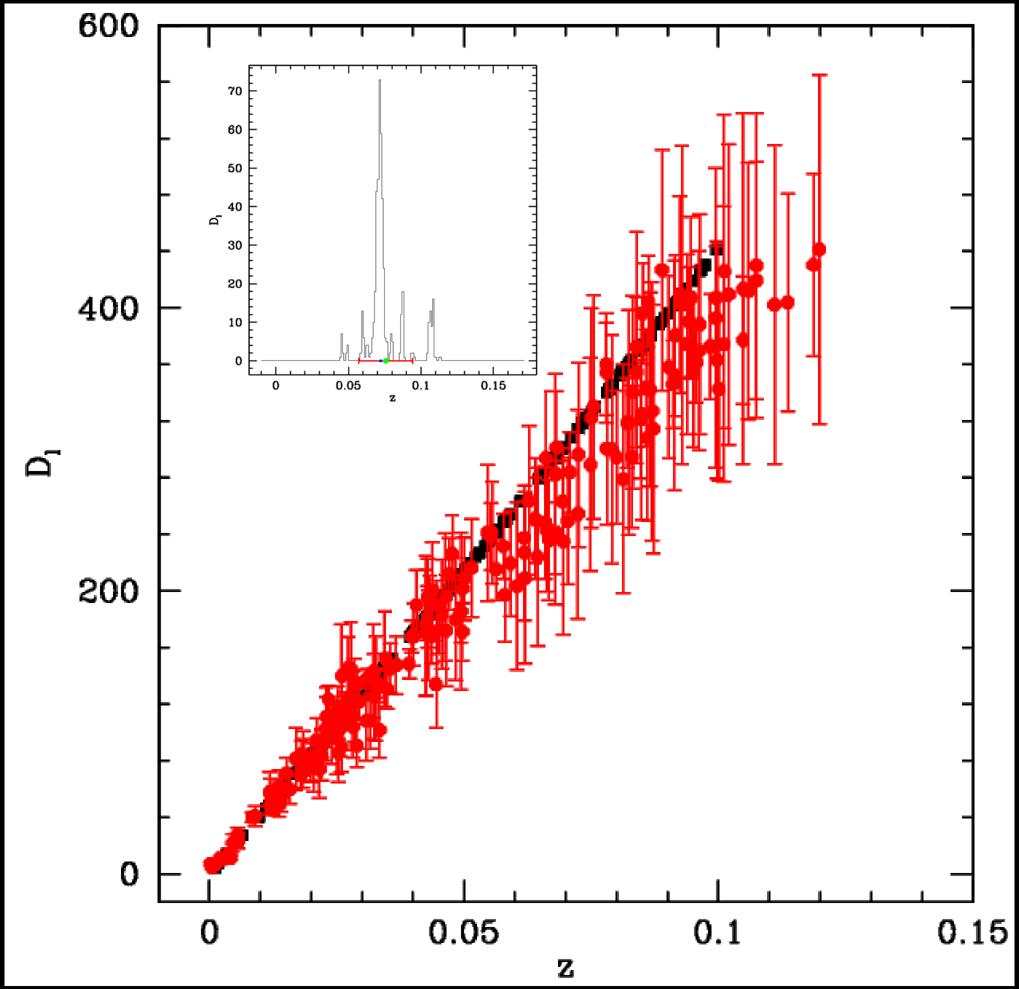
Different formation channels result in different *e* distributions in the eLISA band, **(see also Breivik et al. 2016)**

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

Can be complemented to aLIGO spin measurements.

BHBs as standard sirens: measuring H_0





No counterpart required

(McLeod & Hogan 2008, Petiteau et. al 2011)

- **Many sources at z<0.1**
- **small errorbox consider all possible hosts within the errorbox assuming a broad prior on *h***
- **combine statistically the likelihood of the hosts in each errorbox to determine *h***

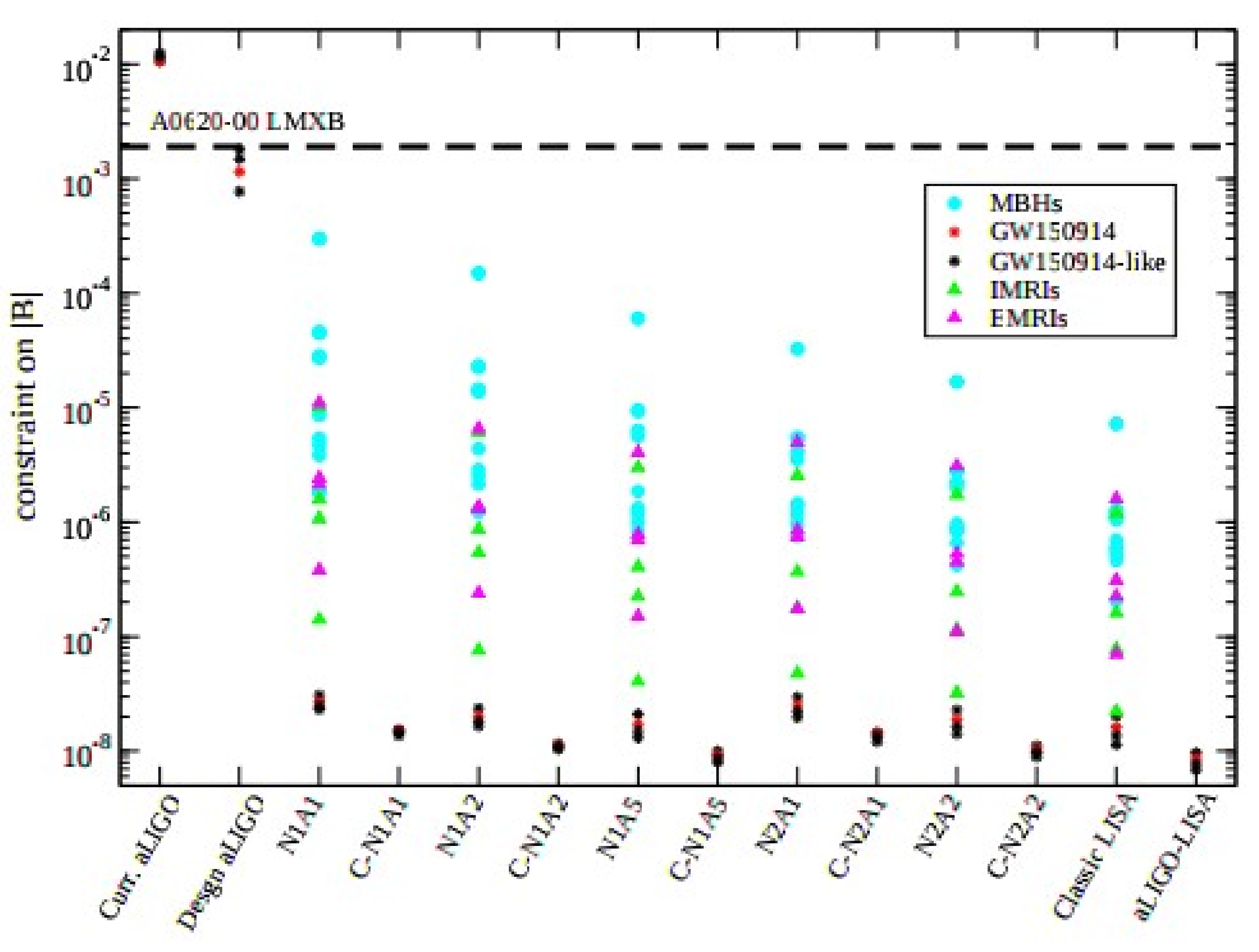
Work in progress, h determined to up to 1%

AstroBonus: few local events have 1 galaxy in the errorbox

Tests of Gravity combining eLISA and aLIGO

BH dipole emission will cause a de-phase observable over several decades in frequency

$$\dot{E}_{\rm GW} = \dot{E}_{\rm GR}\left[1 + B\left(\frac{Gm}{r_{12}c^2}\right)^{-1}\right]$$



(Barausse et al. 2016)

Summary

>eLISA will enable GW physics and astrophysics at all scales

>Reconstruct the cosmic history of MBHs and gain insights in the underlying astrophysics

>GW150914 is the prototype of eLISA/aLIGO multiband GW sources

>number of sources very uncertain but vast scientific potential (most of it yet to be explore)