The future of gravitational wave detection: the low frequency band

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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

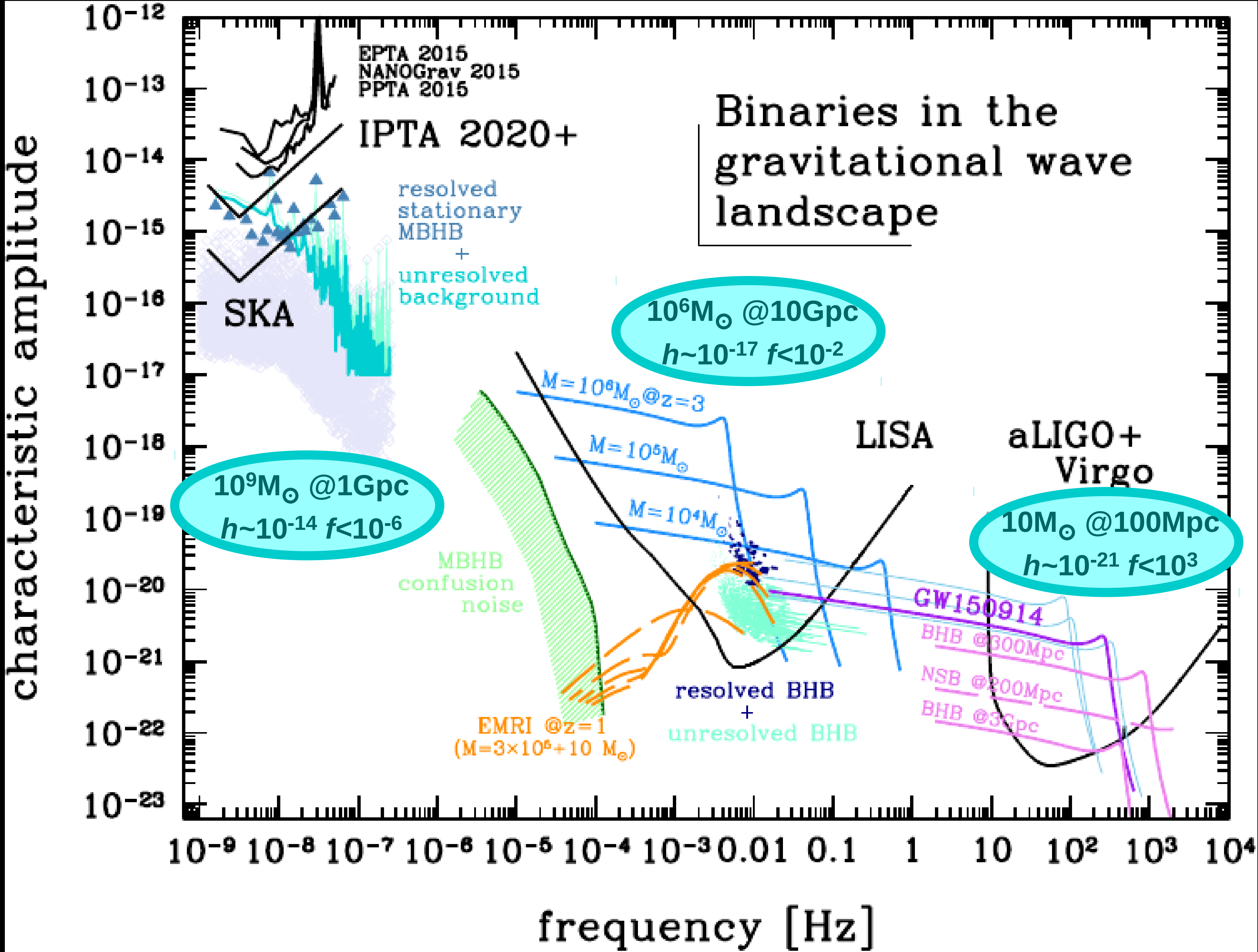
$$h \sim 10^{-20}\,\frac{M}{M_\odot}\,\frac{\mathrm{Mpc}}{D}$$

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

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

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

10^9 $M_\odot$ binary at 1Gpc: h~10^{-14}, f<10^{-5}



EPTA 2015
NANOGrav 2015
PPTA 2015
IPTA 2020+
SKA
resolved stationary MBHB + unresolved background
Binaries in the gravitational wave landscape
$10^6 M_\odot$ @10Gpc
$h \sim 10^{-17}$ $f < 10^{-2}$
$10^9 M_\odot$ @1Gpc
$h \sim 10^{-14}$ $f < 10^{-6}$
$10 M_\odot$ @100Mpc
$h \sim 10^{-21}$ $f < 10^3$
$M = 10^6 M_\odot$ @z=3
$M = 10^5 M_\odot$
$M = 10^4 M_\odot$
LISA
aLIGO+ Virgo
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]

Observational facts

1- In all the cases where the inner core of a galaxy has been resolved (i.e. In nearby galaxies), a massive compact object (which I'll call Massive Black Hole, MBH for convenience) has been found in the centre.

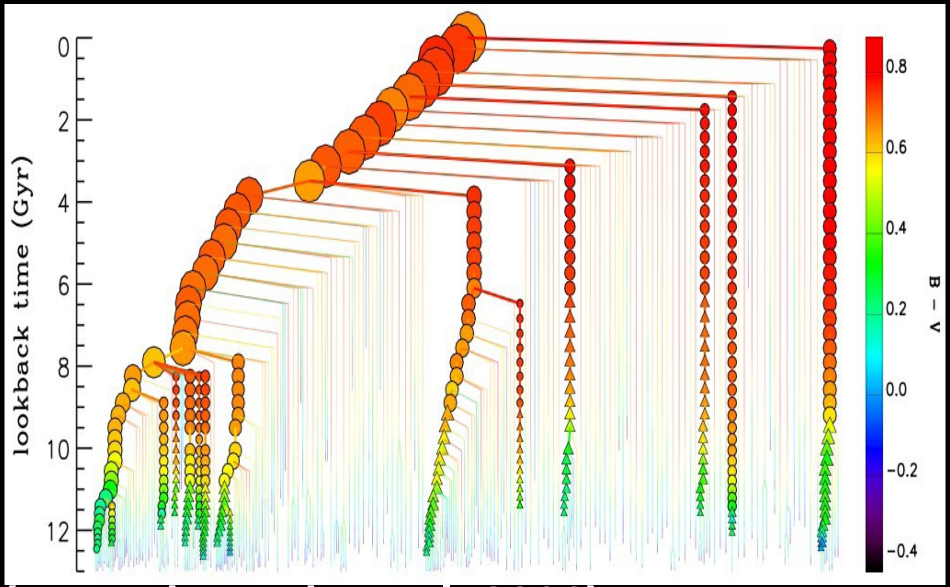
2- MBHs must be the central engines of Quasars: the only viable model to explain this cosmological objects is by means of gas accretion onto a MBH.

3- Quasars have been discovered at z~7, their inferred masses are ~10^9 solar masses!

THERE WERE 10^9 SOLAR MASS BHs WHEN THE UNIVERSE WAS <1Gyr OLD!!!

MBH formation and evolution have profound consequences for GW astronomy

MBH evolution in a nutshell



(From de Lucia et al. 2006)

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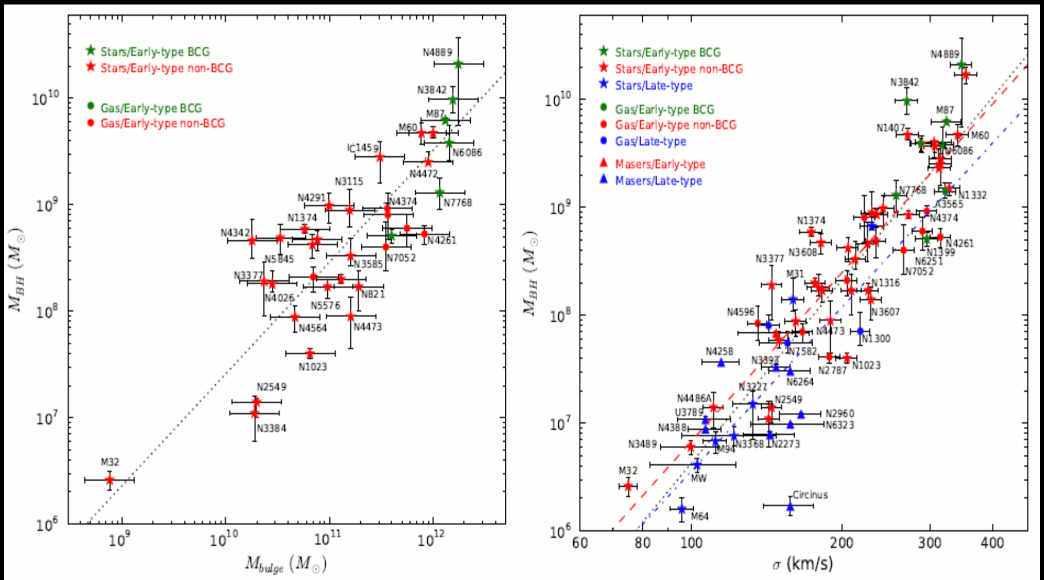

(Ferrarese & Merritt 2000, Gebhardt et al. 2000)

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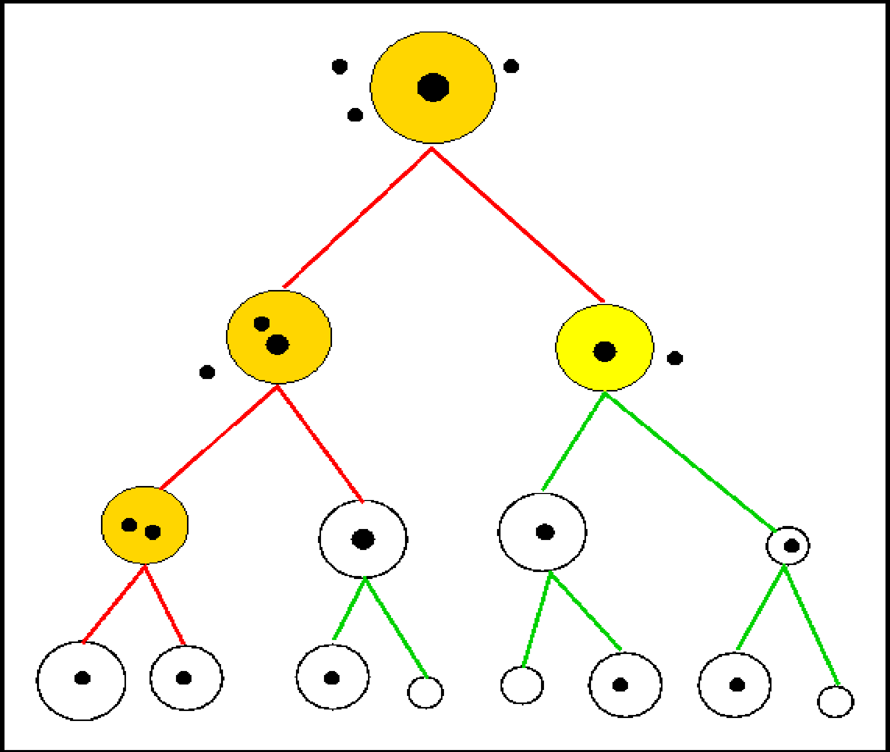

(Menou et al 2001, Volonteri et al. 2003)

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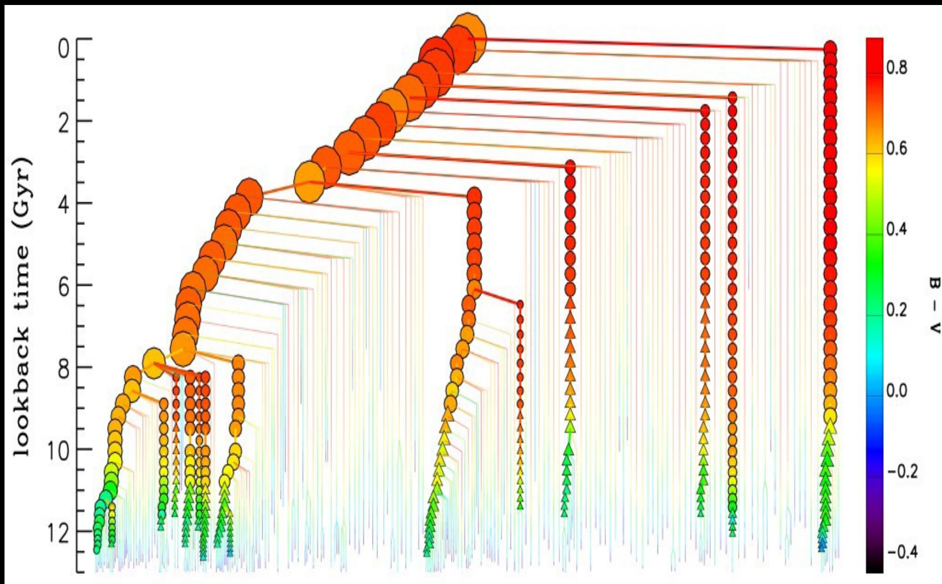

(From de Lucia et al. 2006)

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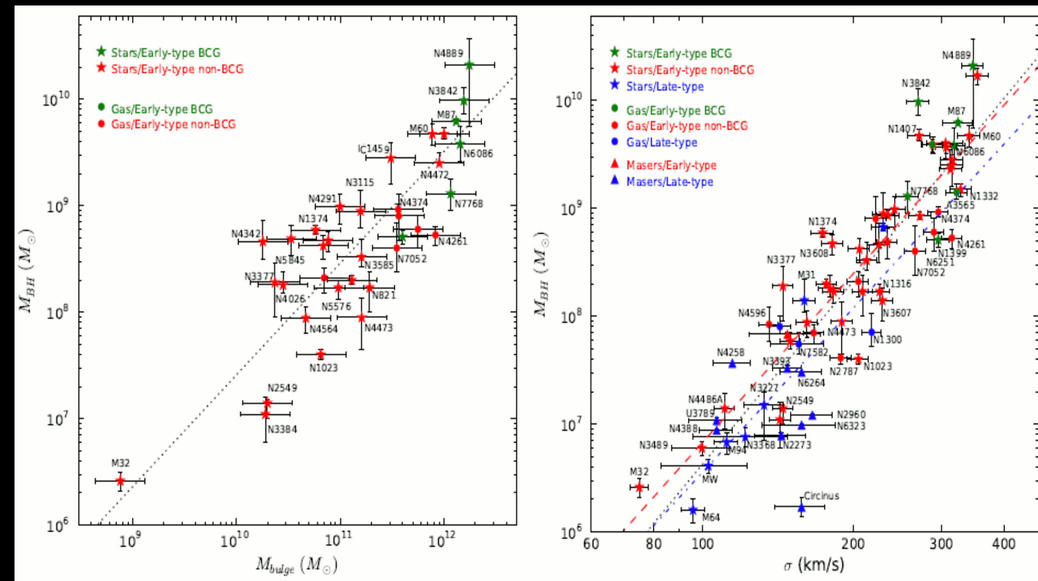

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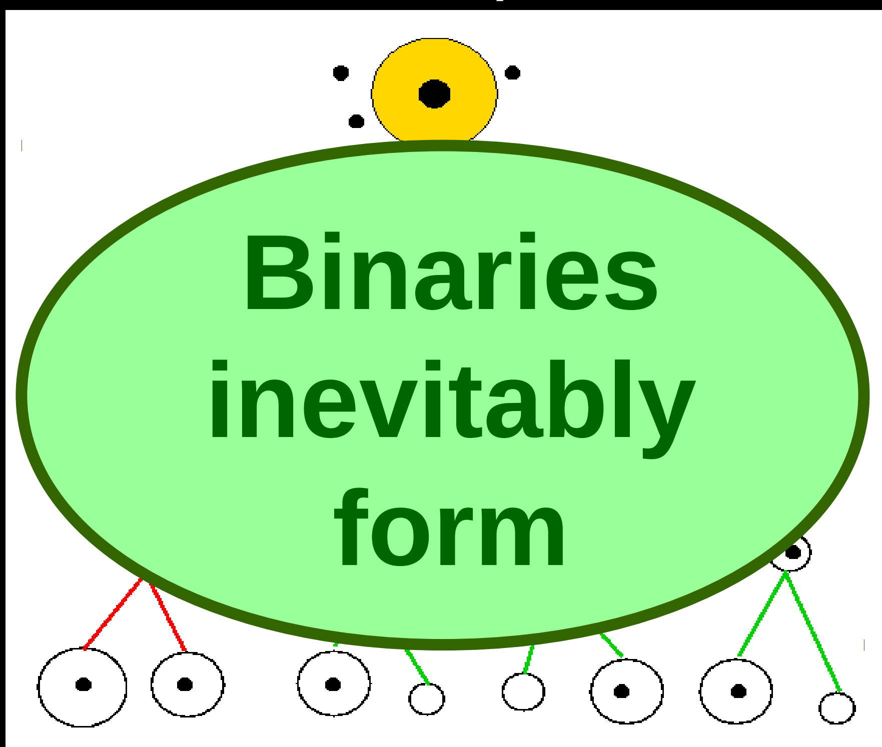
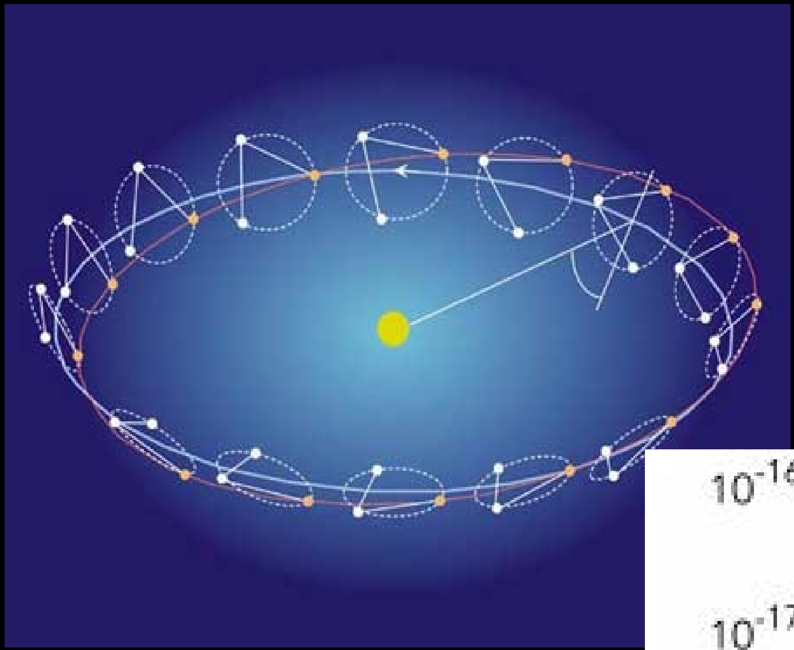


(Menou et al 2001, Volonteri et al. 2003)

*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?

The Laser Interferometer Space Antenna

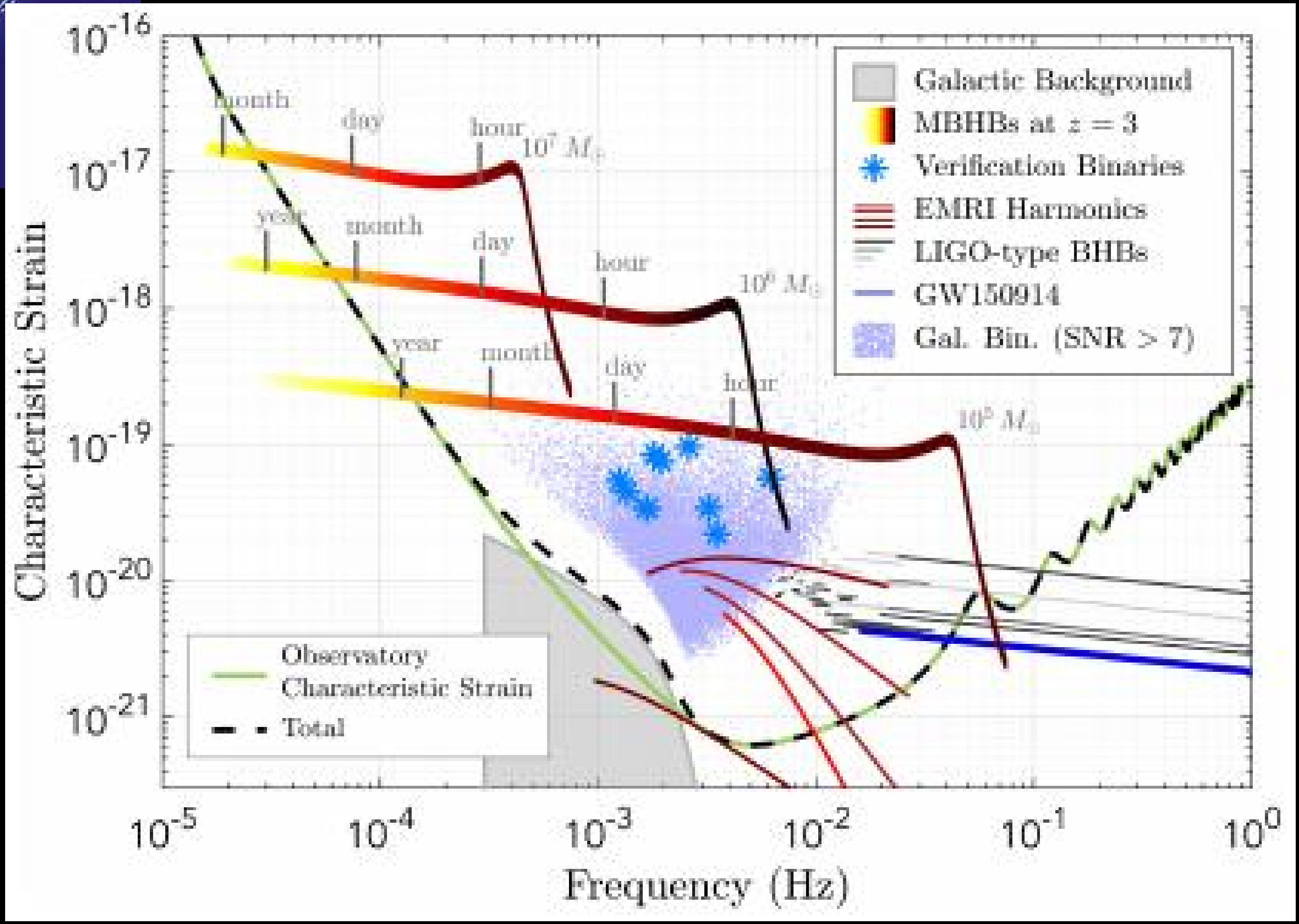


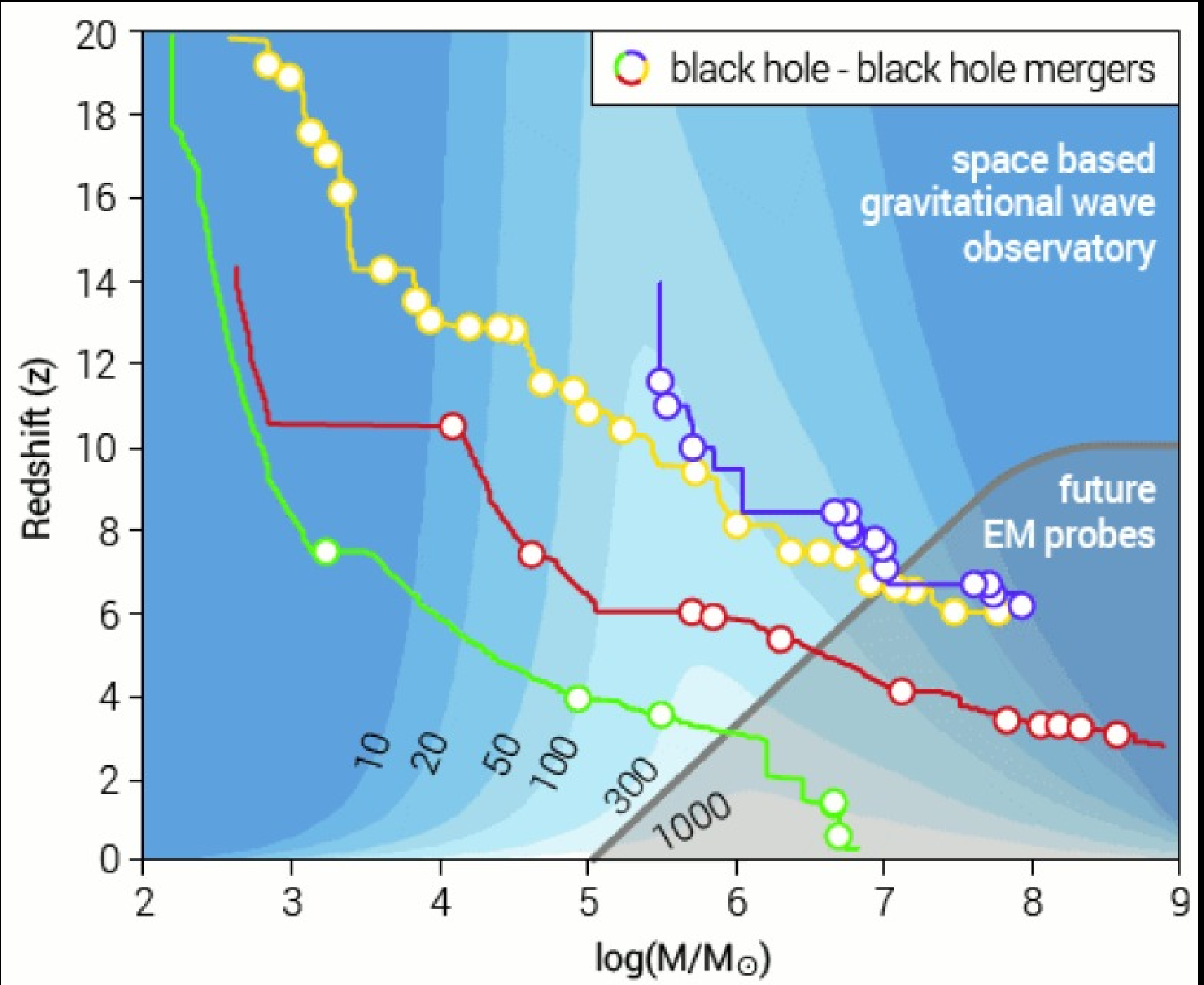
Sensitive in the mHz frequency range where MBH binary evolution is fast (chirp)

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)





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
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5
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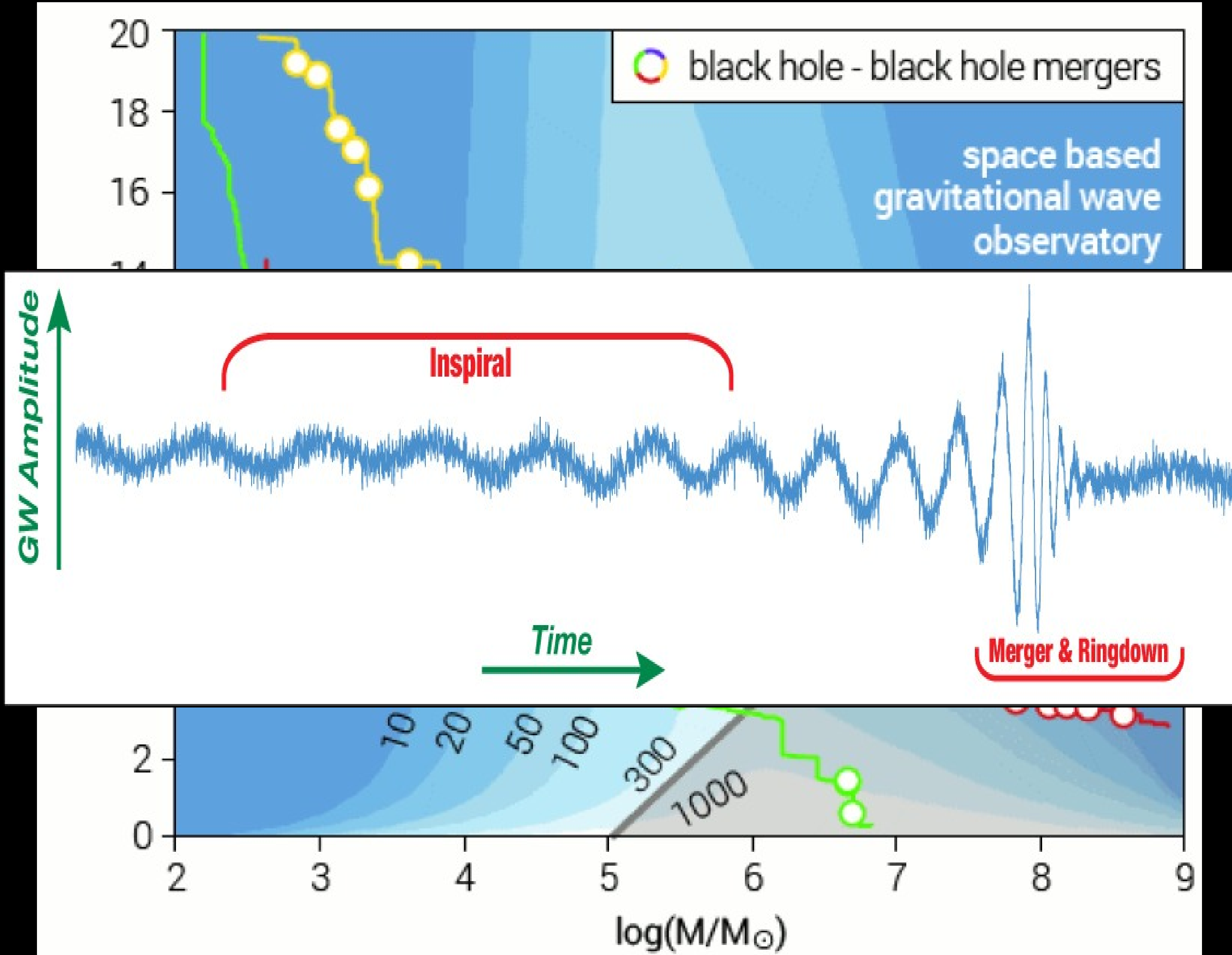
7
8
9



black hole - black hole mergers
space based
gravitational wave
observatory
GW Amplitude
Inspiral
Time
Merger & Ringdown
10
20
50
100
300
1000
log(M/M$_\odot$)

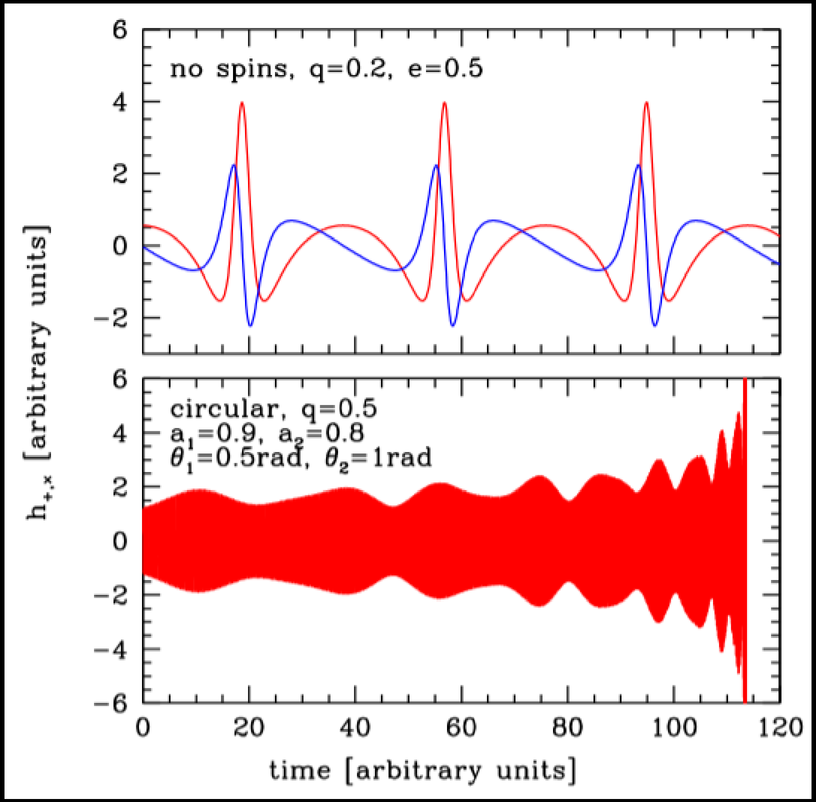
Extraction of information from the waveform

>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)

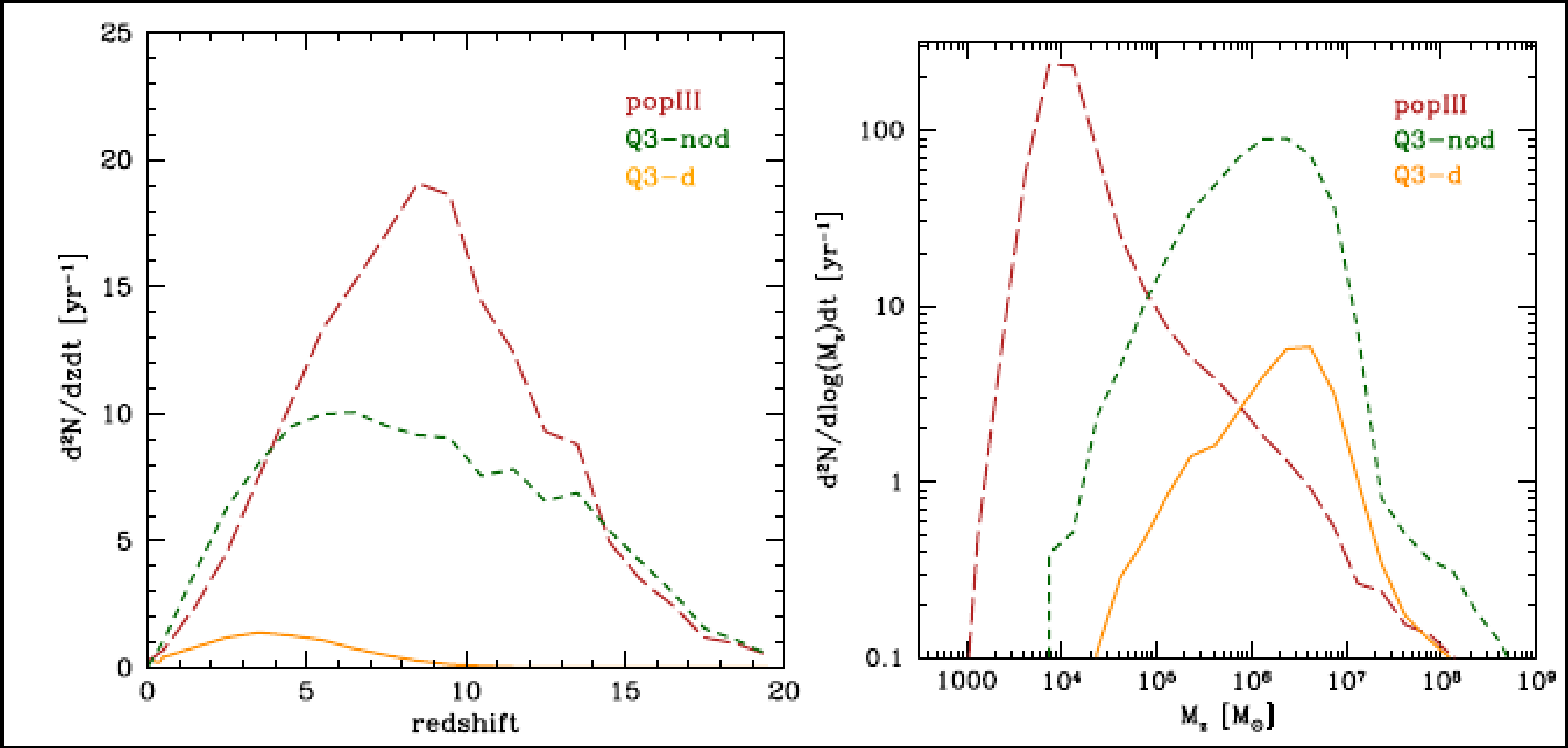
Depend on the time in band, polarization disentanglement, SNR.
Measurement is more difficult.
For MBH binaries, strong impact of having: 1) longer baseline
2) 6 laser links

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



MBHB: detections and parameter estimation

(Klein, Barausse, AS et al. 2016)

~100+ detections

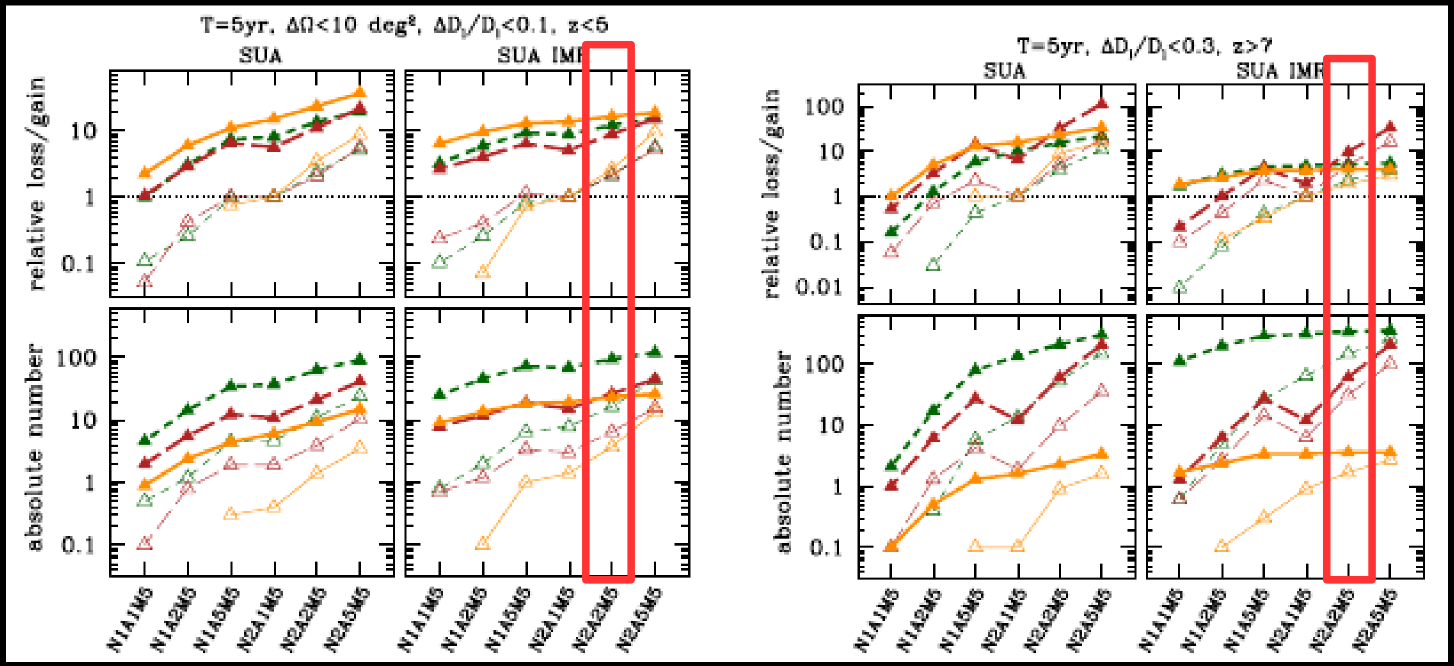
~100+ systems with sky localization to 10 deg2

~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

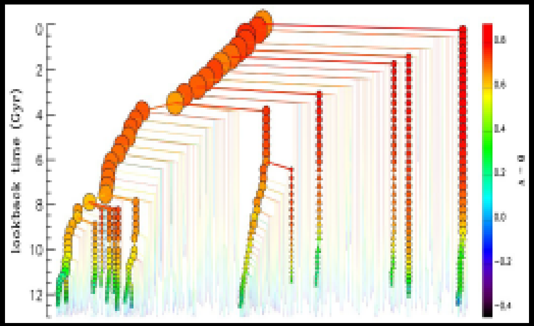
~50 systems with spin direction determined within 10deg



MBH astrophysics with GW observations

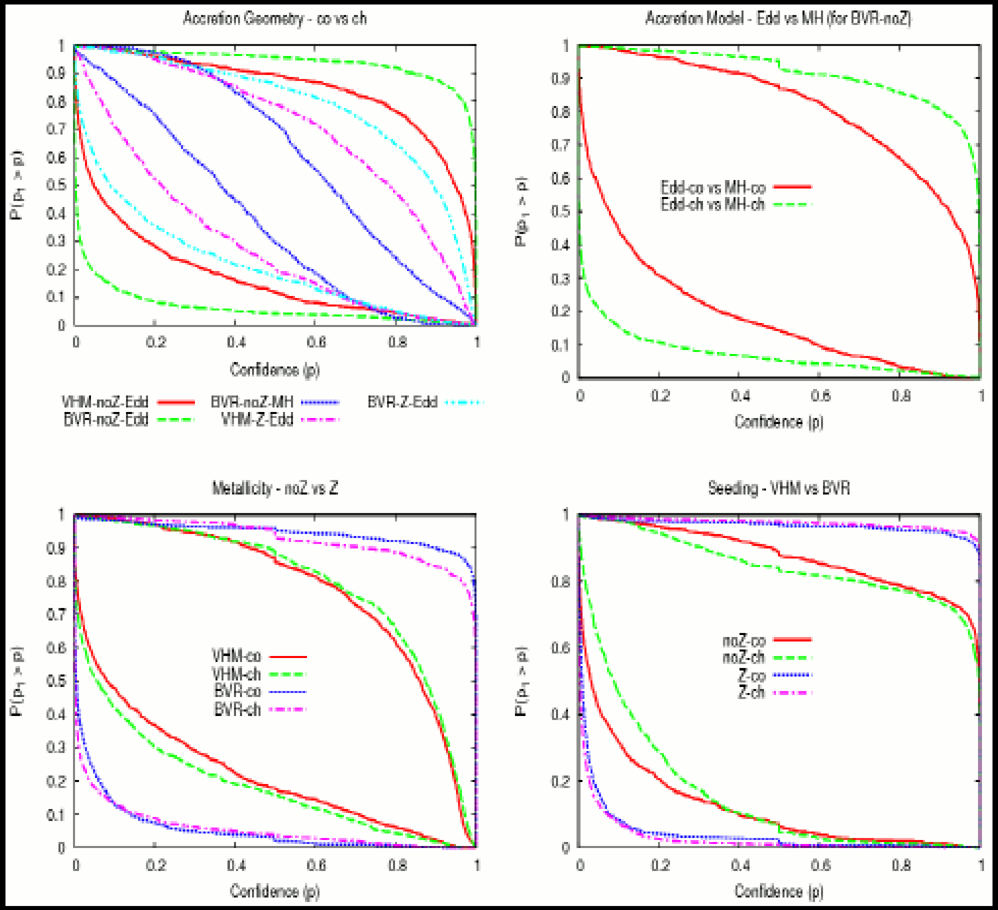
Astrophysical unknowns in MBH formation scenarios

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?

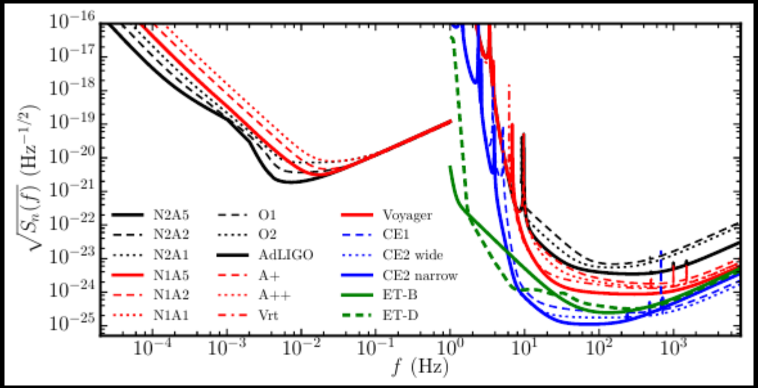
Create catalogues of observed binaries including errors from eLISA observations and compare observations with theoretical models



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

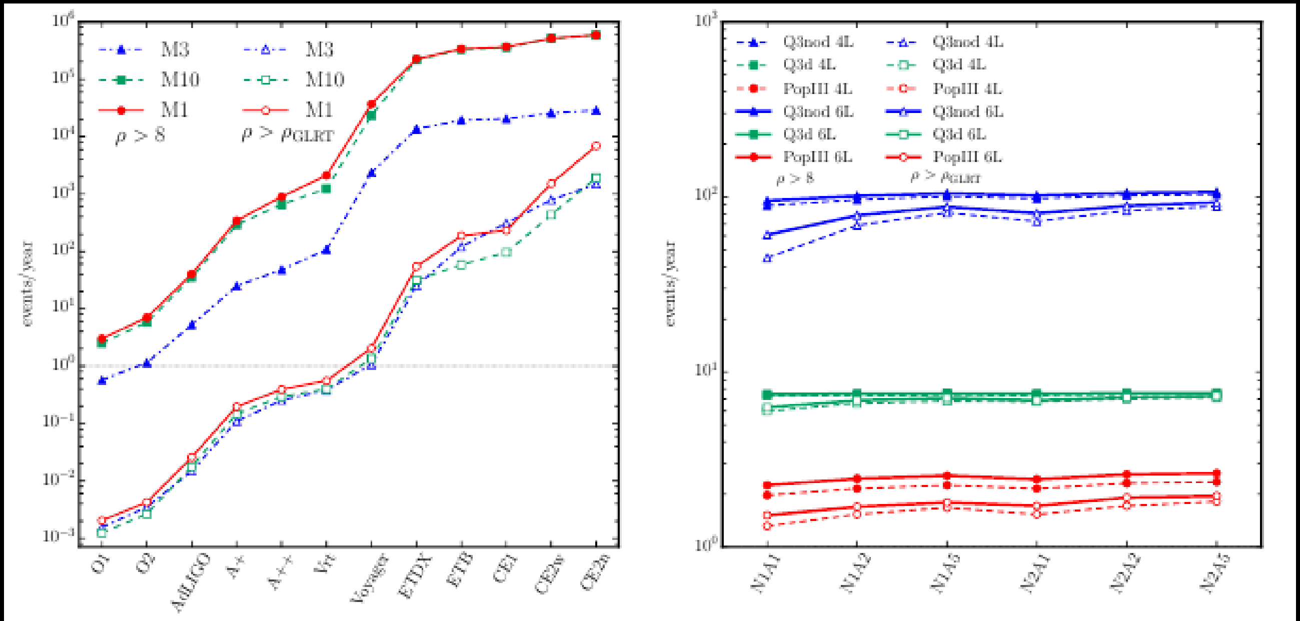
Resolving ringdown modes: BH spectroscopy

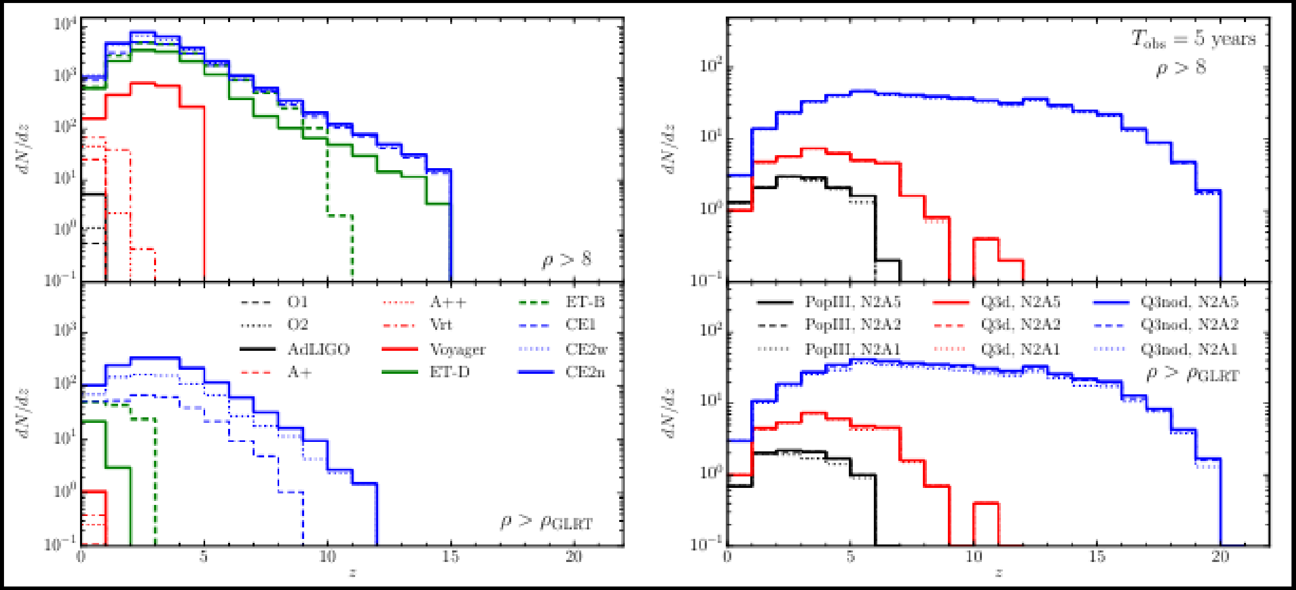
(Berti et al. 2016)



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

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





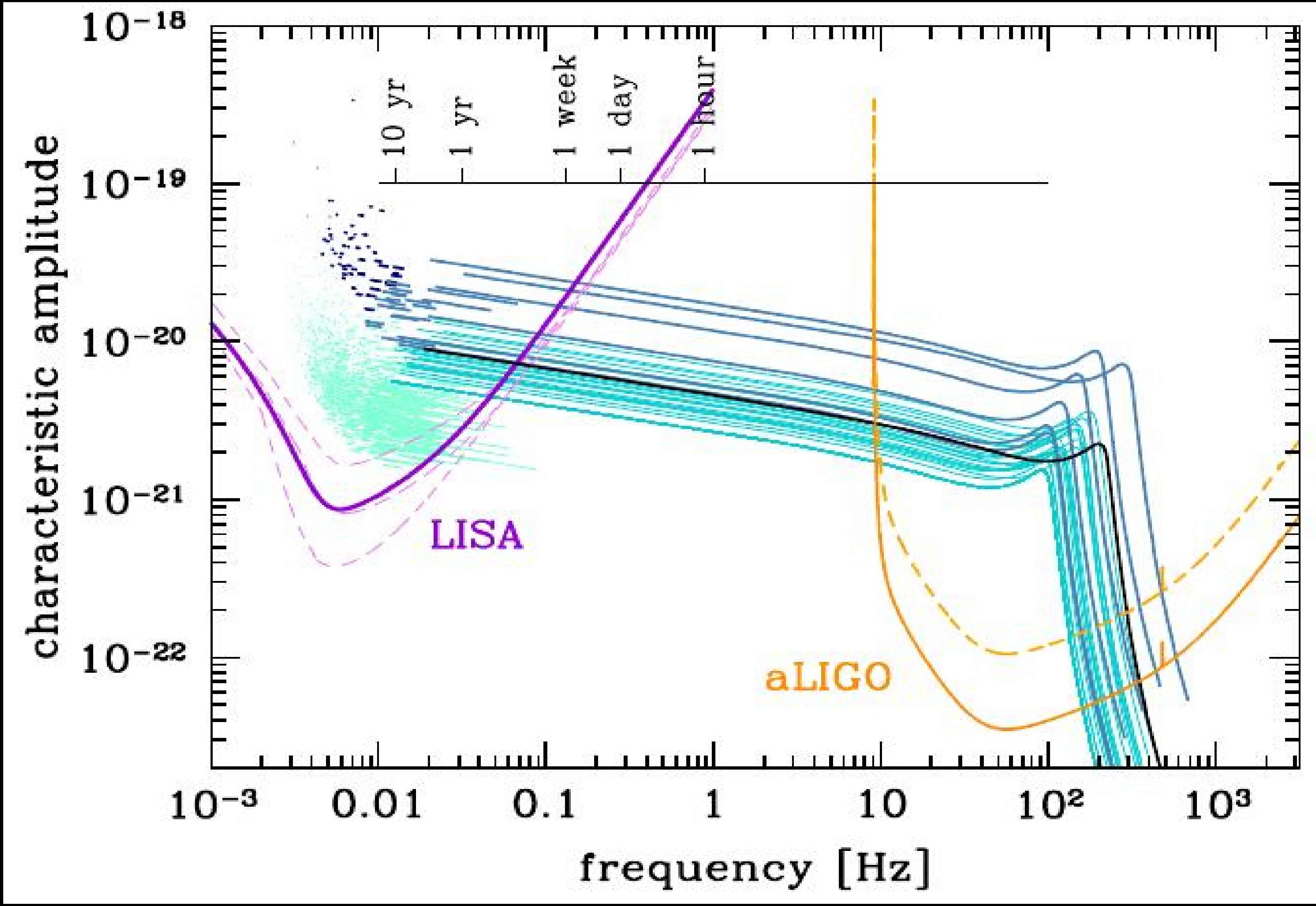
LIGO will not enable BH spectroscopy on individual BHB mergers

Voyager/ET type detectors are needed

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

Implications of GW150914: multi-band GW astronomy

(AS 2016, PRL 116, 1102)



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

What do we do with them?

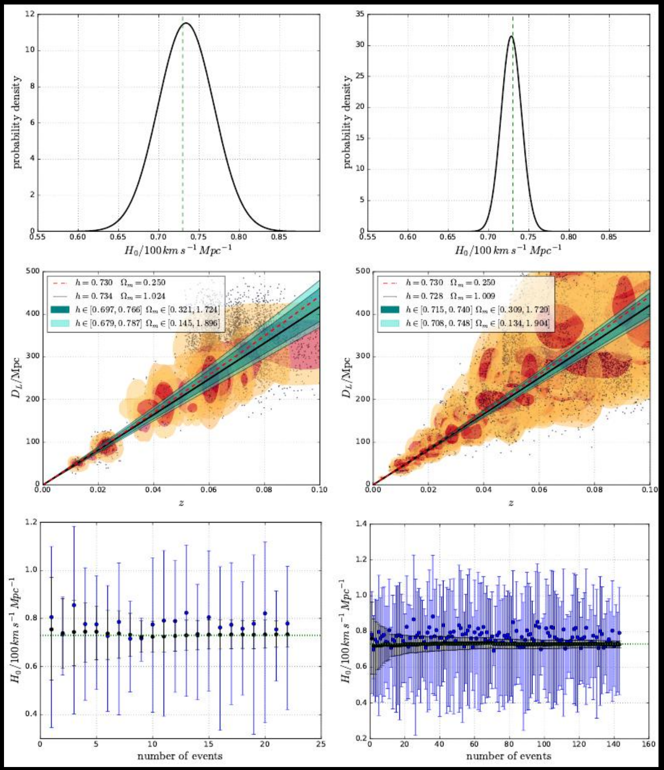
>Detector cross-band calibration and validation (LISA aLIGO)

>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**

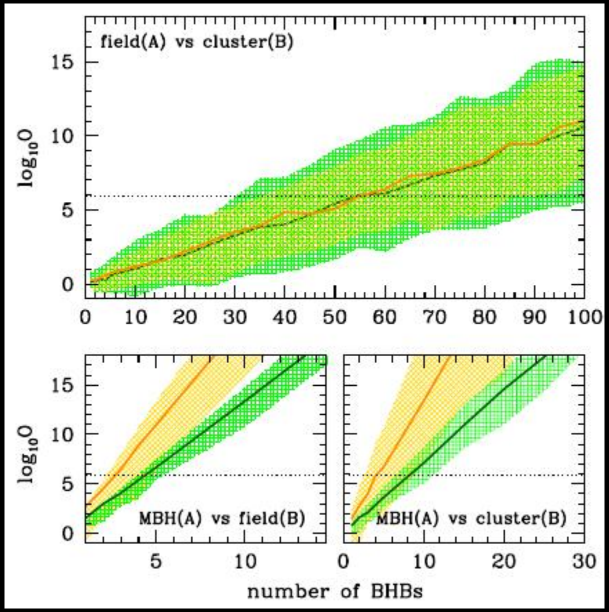
>Enhanced tests of GR: e.g. strongest limits on deviations from GR

(Barausse et al 2016)



>Astrophysics:
- **-independent measure of spins**
- **-measure of eccentricity**

(Nishizawa, AS, Berti, Klein 2017, Breivik et al 2017)



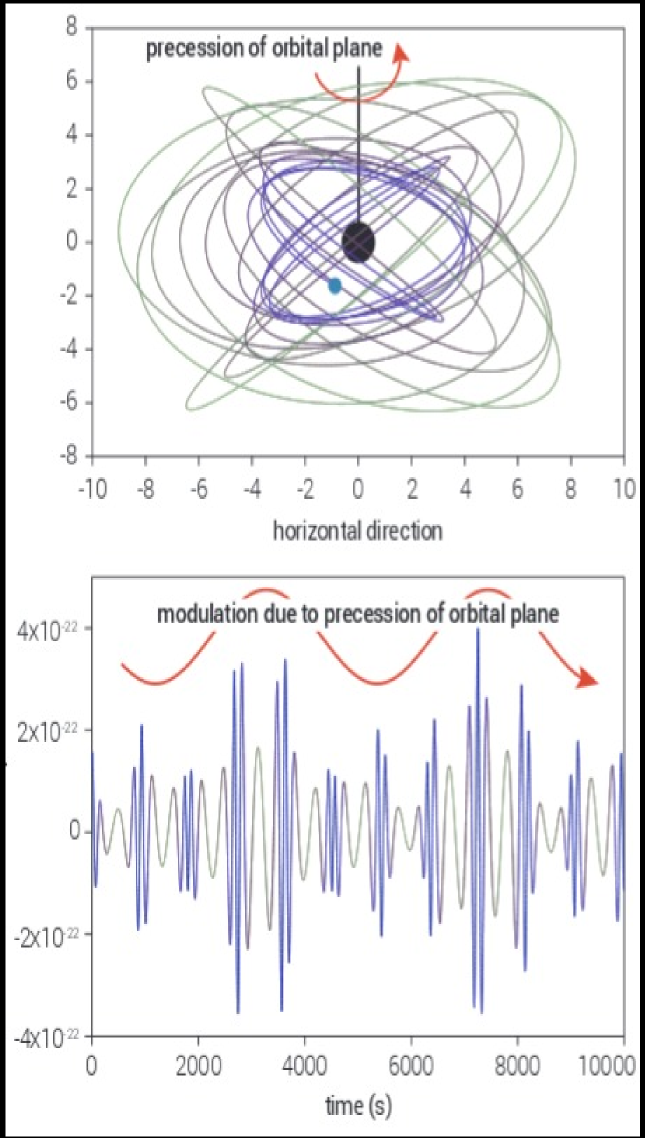
>Cosmology:
- **-new population of standard sirens?**

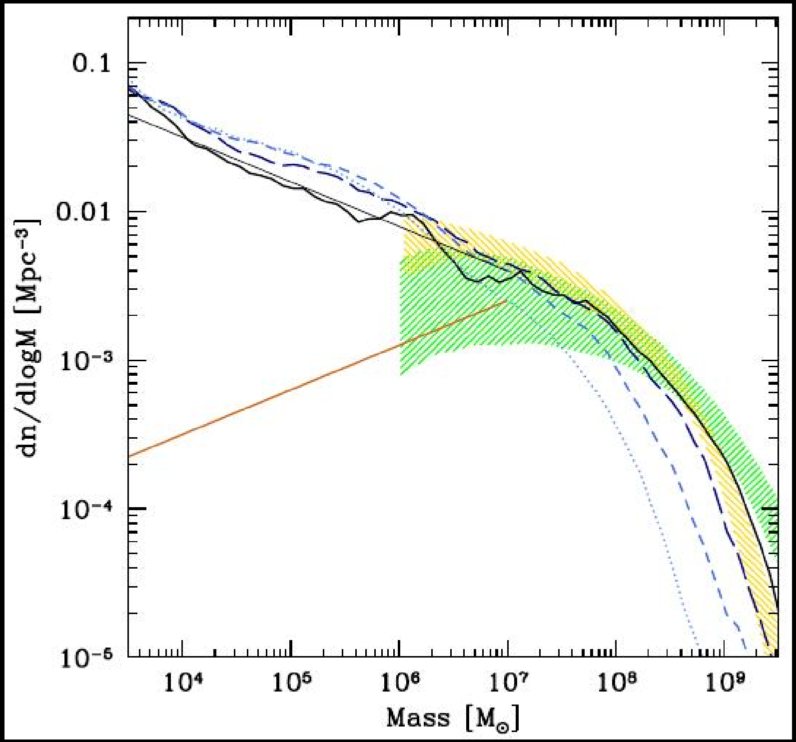
(Del Pozzo, AS, Klein 2017)

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?*





Astrophysical uncertainties are huge:

-MBH mass function unknown below 10^6 solar masses

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

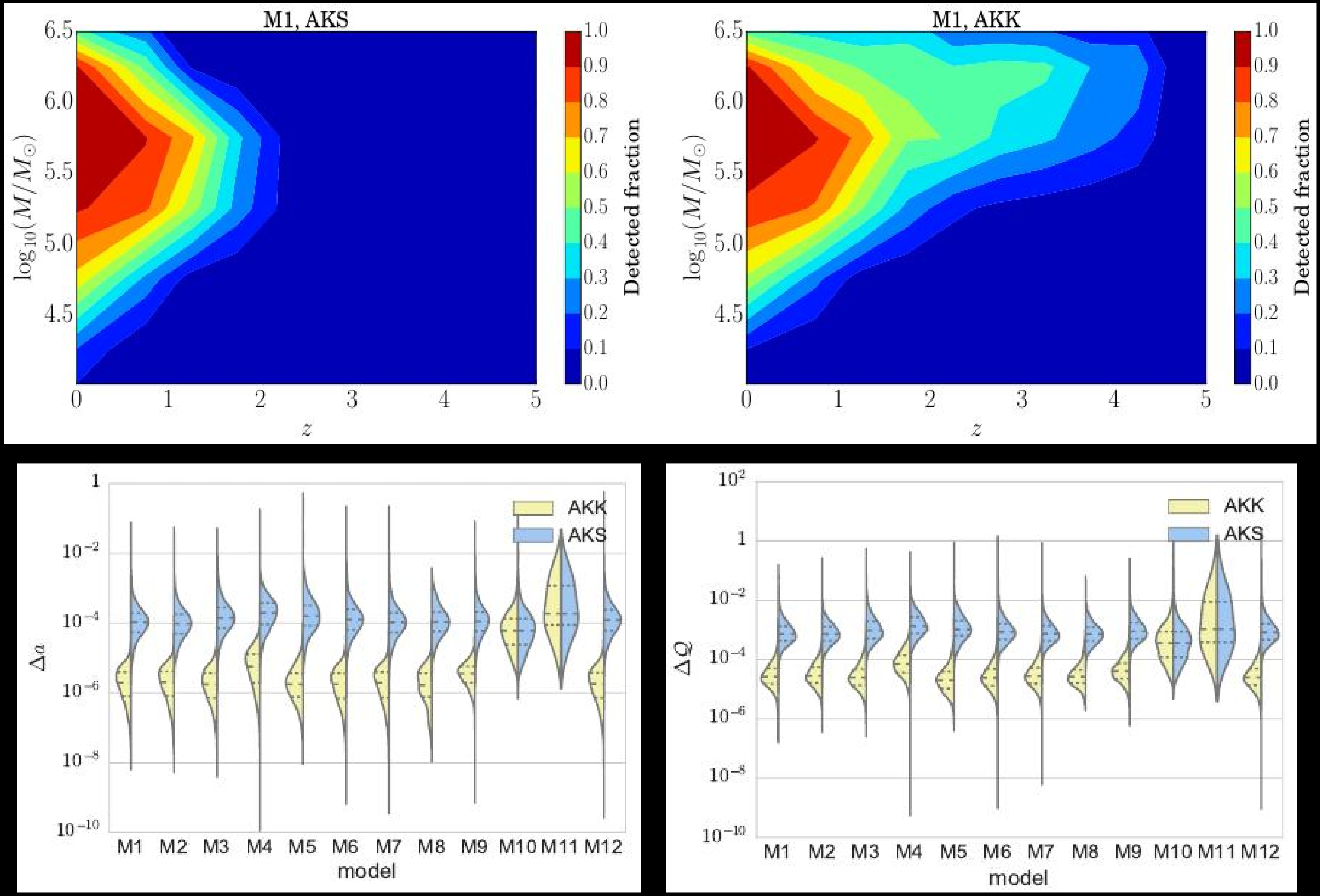
-are Cos inspiralling (thus producing EMRIs) or plunging (Merritt 2015)?

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

Selected results: LISA reach and parameter estimation

(Babak et al, almost submitted...finally!)



Summary of EMRI parameter estimation

~1-1000 detections/yr

~typical sky localization better than 10 deg2

~distance to better than 10%

~MBH mass to better than 0.01%

~CO mass to better than 0.01%

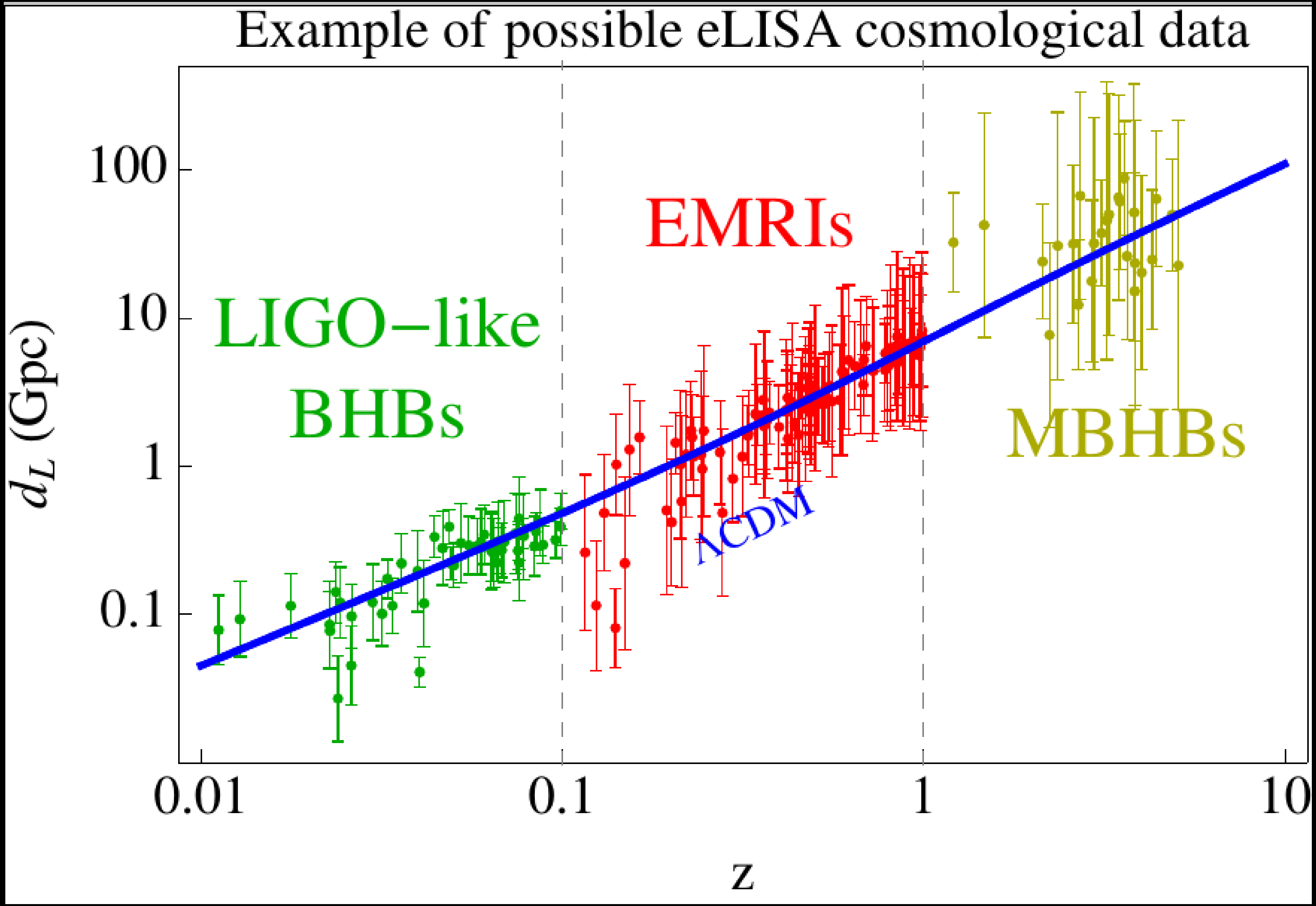
~MBH spin to better than 0.001

~plunge eccentricity to better than 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

Cosmology with gravitational waves



(Courtesy of N. Tamanini)

Different GW sources will allow an independent assessment of the geometry of the Universe at all redshifts.

Galactic binaries

- *How many ultra-compact binaries exist in the Milky Way?*
- *What is the merger rate of white dwarfs, neutron stars and stellar mass black holes in the Milky Way (thus better constraining the rate of the explosive events associated with these sources)?*
- *What does that imply for, or how does that compare to, their merger rates in the Universe?*
- *What happens at the moment a white dwarf starts mass exchange with another white dwarf or neutron star, and what does it tell us about the explosion mechanism of type Ia supernovae?*
- *What is the spatial distribution of ultra-compact binaries, and what can we learn about the structure of the Milky Way as a whole?*

Galactic binaries

- *How many ultra-c*
  Way?
- *What is the merger*
  and stellar mass bla
  ter constraining the
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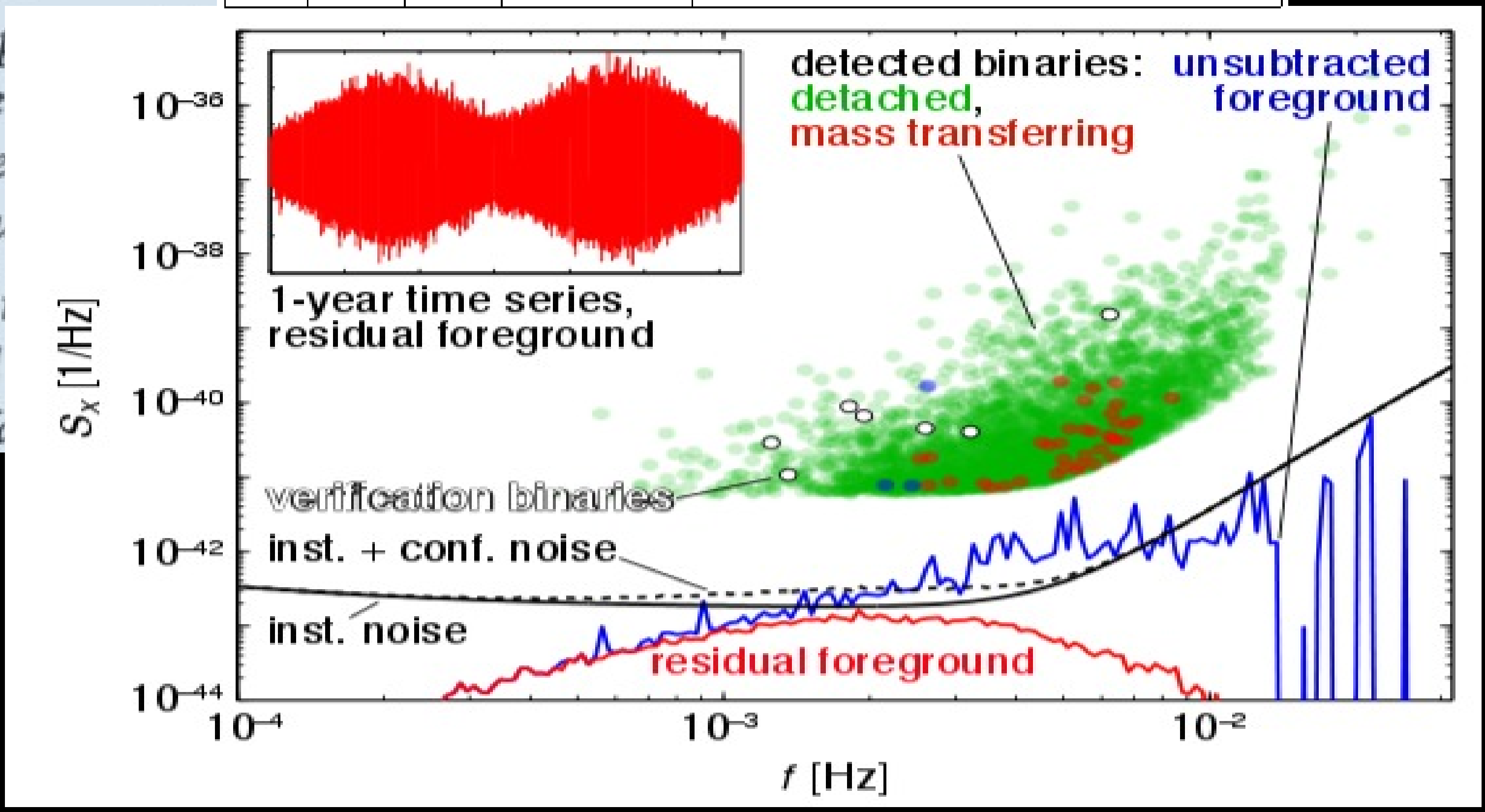
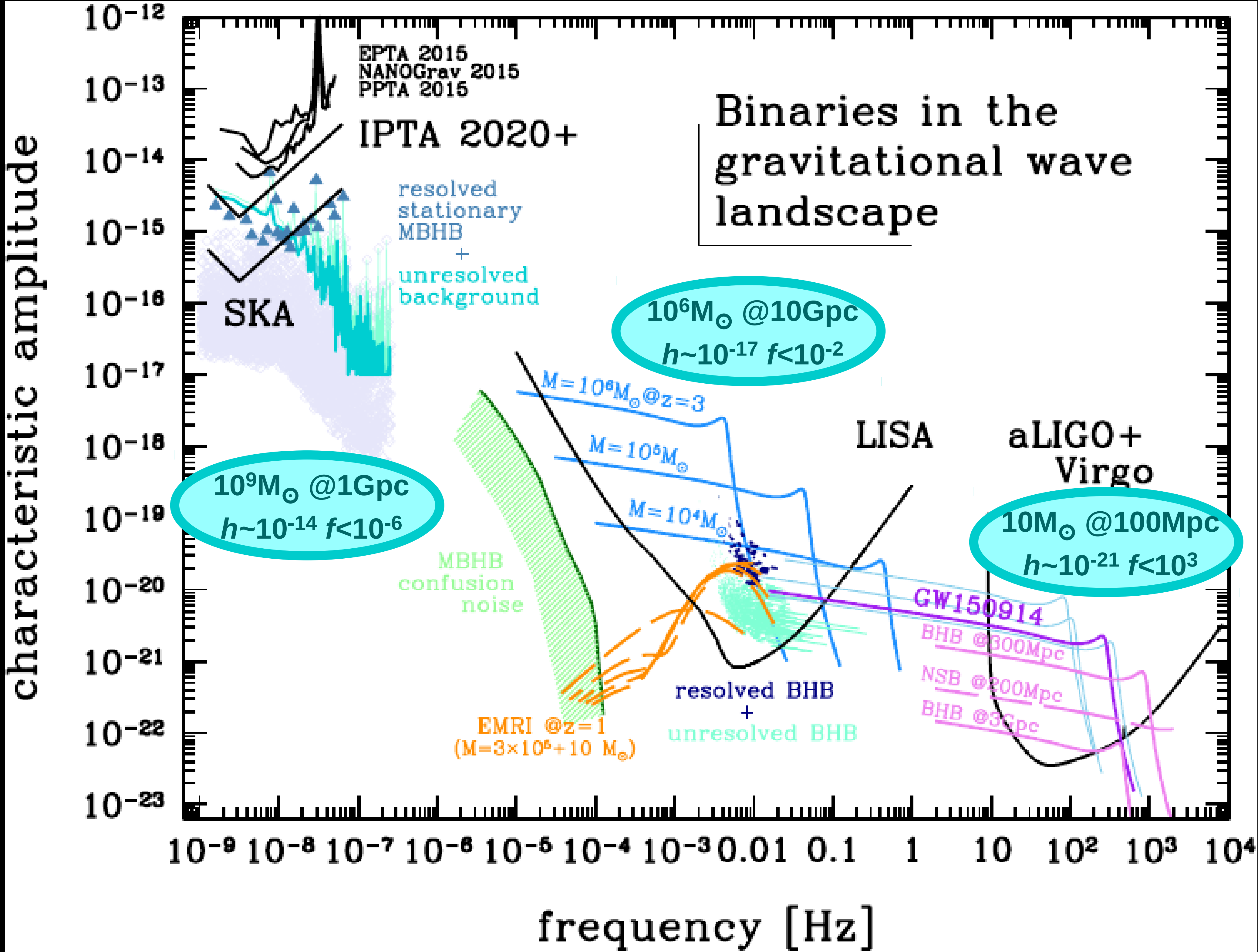
- *What does that imp*
  their merger rates i
- *What hap*
  exchange
  what doe
  type Ia s
- *What is*
  ries, and
  Milky W

Arm	Noise	Links	Full ID	S/N> 7	2-D	3-D	$\dot{f} < 20\%$	$\dot{f} < 20\%$
A1	N1	L4	L4A1M2N1	569	241	82	464	1
		L6	L6A1M2N1	952	418	103	672	3
	N2	L4	L4A1M2N2	5248	1366	452	1496	1
		L6	L6A1M2N2	8805	2390	600	1936	3
A2	N1	L4	L4A2M2N1	1298	498	205	809	3
		L6	L6A2M2N1	2043	800	246	1056	3
	N2	L4	L4A2M2N2	9189	2754	1001	2255	3
		L6	L6A2M2N2	14757	4562	1257	2804	3
A5	N1	L4	L4A5M2N1	3073	987	410	1275	3
		L6	L6A5M2N1	4987	1674	548	1604	3
	N2	L4	L4A5M2N2	13634	5558	1816	3287	3
		L6	L6A5M2N2	21744	8815	2127	3989	3

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resolved stationary MBHB
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LISA
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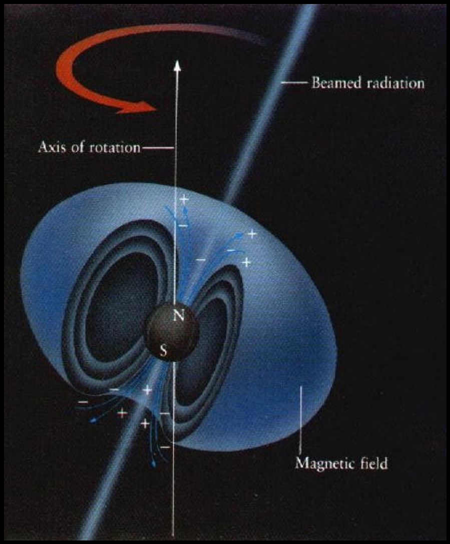
GW150914
BHB @300Mpc
NSB @200Mpc
BHB @3Gpc
resolved BHB
+
unresolved BHB
EMRI @z=1
($M=3\times10^5+10$ $M_\odot$)
characteristic amplitude
frequency [Hz]
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 0.01 0.1 1 10 10^2 10^3 10^4

What is pulsar timing

Pulsars are neutron seen through their regular radio pulses

Pulsar timing is the art of measuring the time of arrival (ToA) of each pulse and then subtracting off the expected time of arrival given by a theoretical model for the system



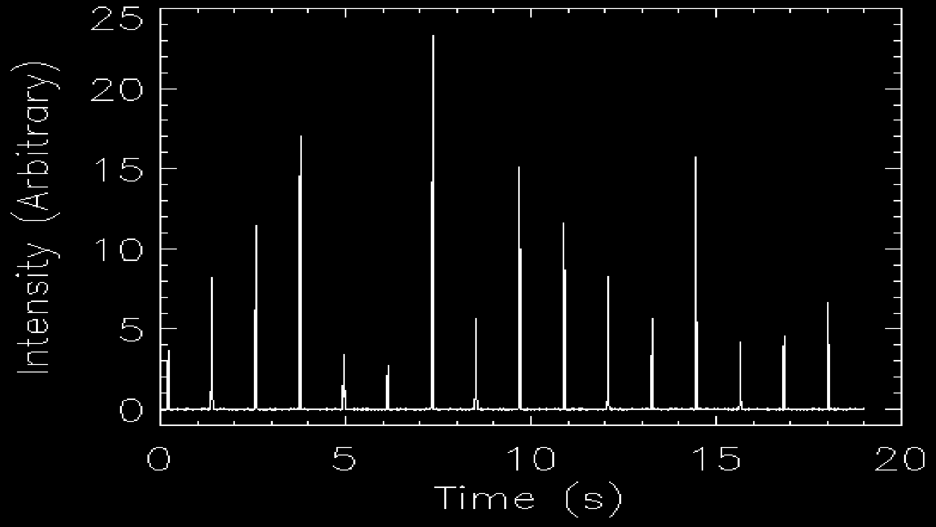
1-Observe a pulsar and measure the ToAs

2-Find the model which best fits the ToAs

3-Compute the timing residual R

$$R = \mathrm{ToA} - \mathrm{ToA}_m$$

If the timing solution is perfect (and observations noiseless), then *R*=0. *R* contains all uncertainties related to the signal propagation and detection, plus the effect of unmodelled physics, like (possibly) *gravitational waves*



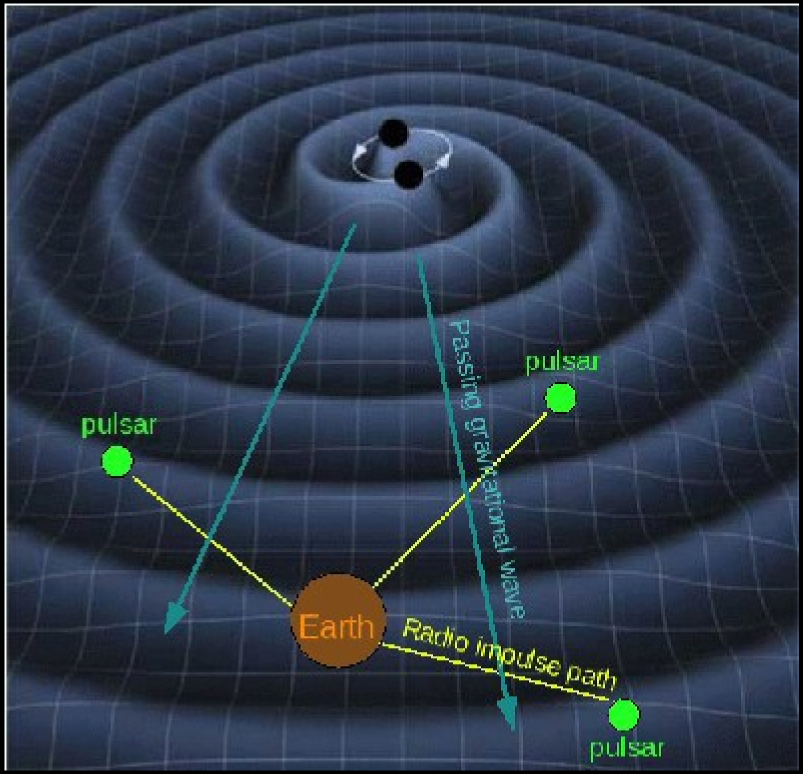
Effect of gravitational waves

The GW passage causes a modulation of the observed pulse frequency

$$\frac{\nu(t)-\nu_0}{\nu_0} = \Delta h_{ab}(t) \equiv h_{ab}(t_{\mathrm{p}},\hat{\Omega}) - h_{ab}(t_{\mathrm{ssb}},\hat{\Omega})$$

The residual is the integral of this frequency modulation over the observation time (i.e. is a de-phasing)

$$R(t) = \int_0^T \frac{\nu(t)-\nu_0}{\nu_0}dt$$



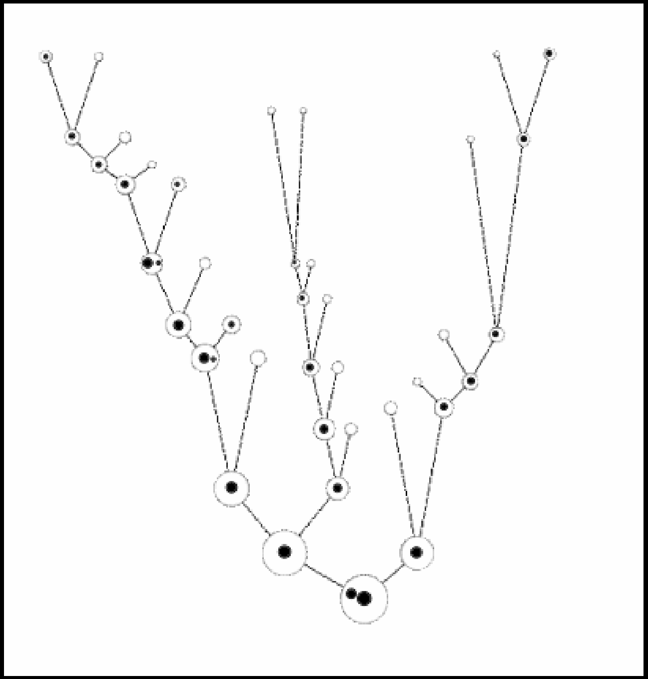
(Sazhin 1979, Hellings & Downs 1983, Jenet et al. 2005, AS et al. 2008, 2009)

10^9 $M_\odot$ binary at 1Gpc: h~10^{-15}, f~10^{-8}

Implies a residual ~100ns

100ns is the accuracy at which we can time the most stable millisecond pulsars today!

The expected GW signal in the PTA band



The GW characteristic amplitude coming from a population of circular MBH binaries

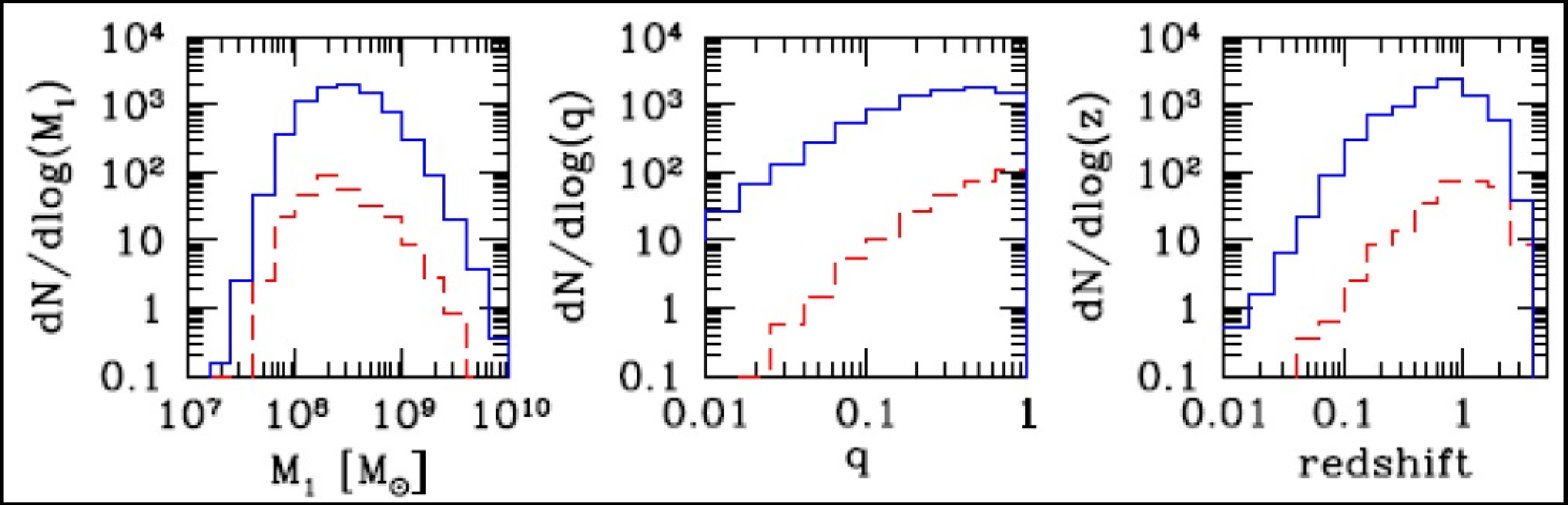
$$h_c^2(f) = \int_0^\infty dz \int_0^\infty d\mathcal{M} \, \frac{d^3N}{dz d\mathcal{M} d\ln f_r} h^2(f_r)$$

$$\delta t_{\rm bkg}(f) \approx h_c(f)/(2\pi f)$$

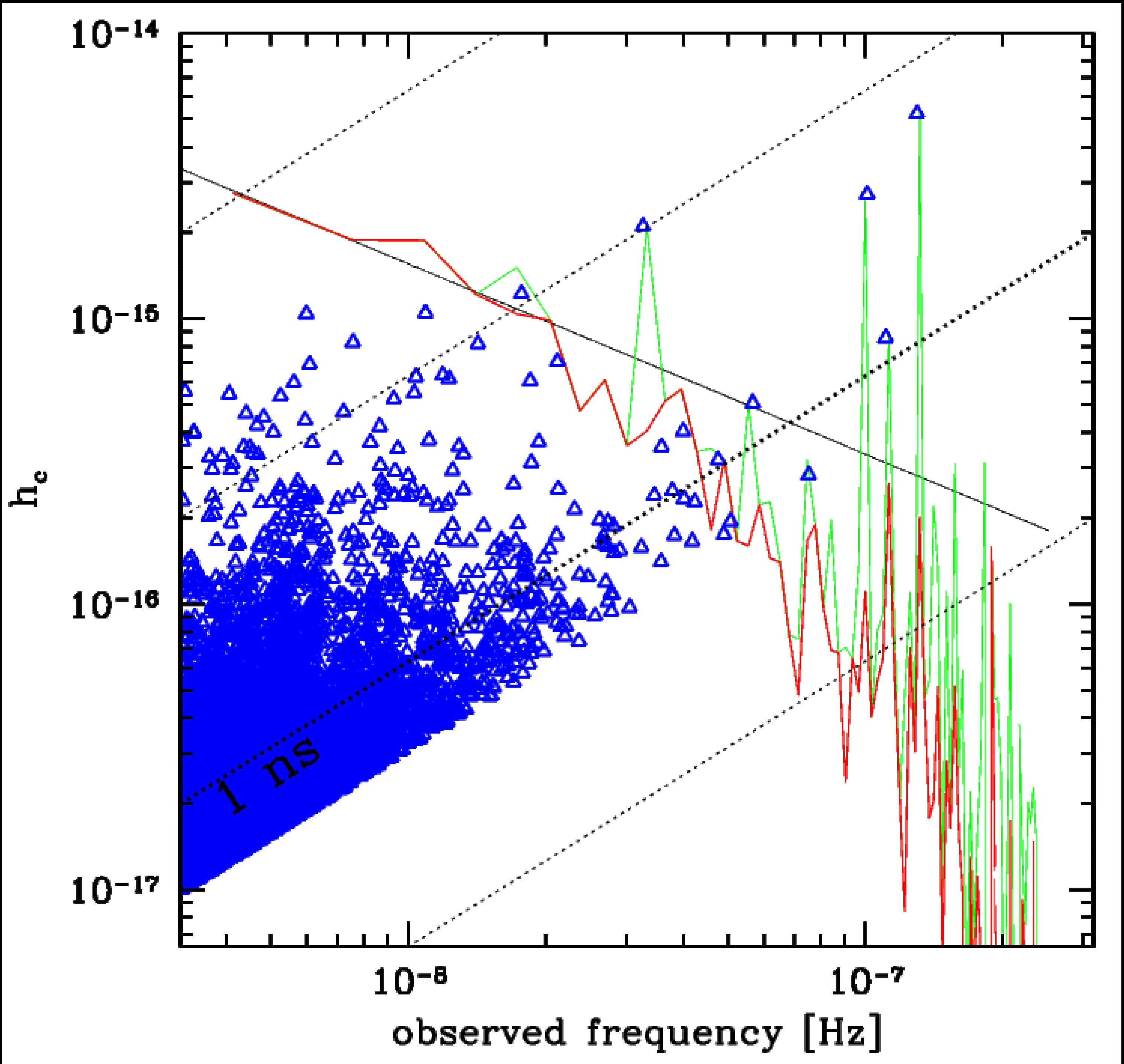
Theoretical spectrum: simple power law

(Phinney 2001)

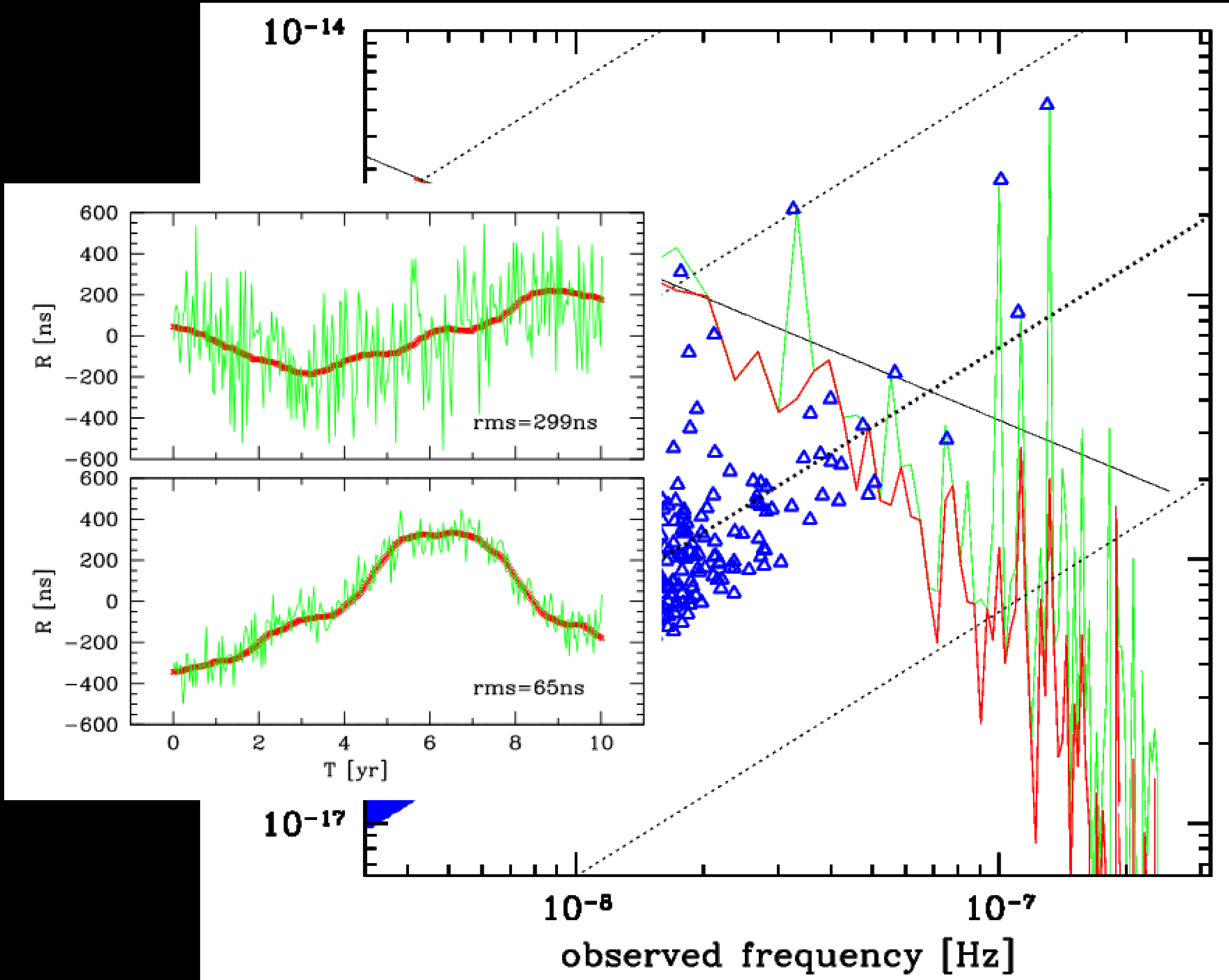
$$h_c(f) = A \left(\frac{f}{\mathrm{yr}^{-1}} \right)^{-2/3}$$



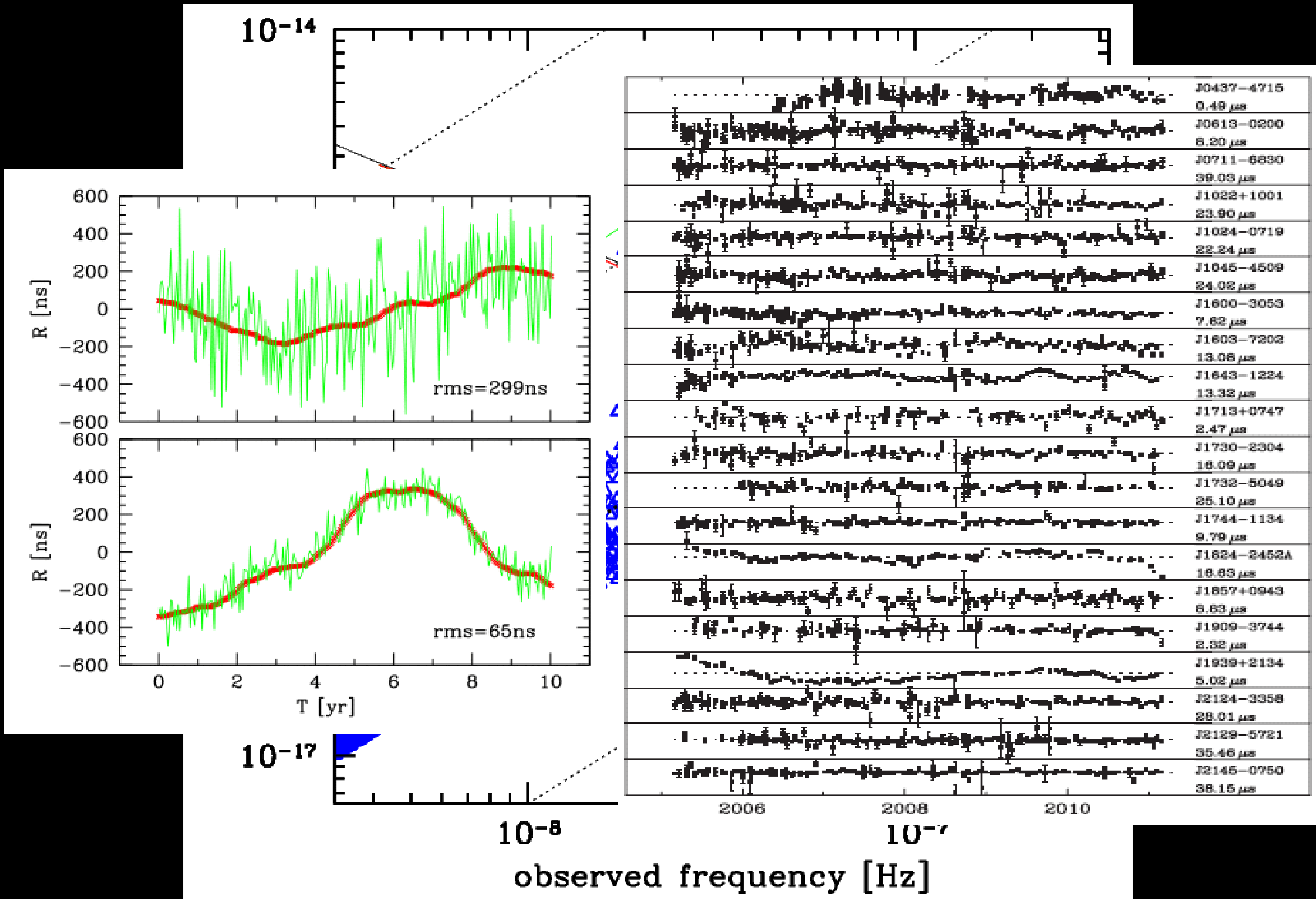
The signal is contributed by extremely massive ($>10^8 M_\odot$) relatively low redshift ($z<1$) MBH binaries (AS et al. 2008, 2012)



10^{-14}
10^{-15}
10^{-16}
10^{-17}
h_c
1 ns
10^{-8}
10^{-7}
observed frequency [Hz]

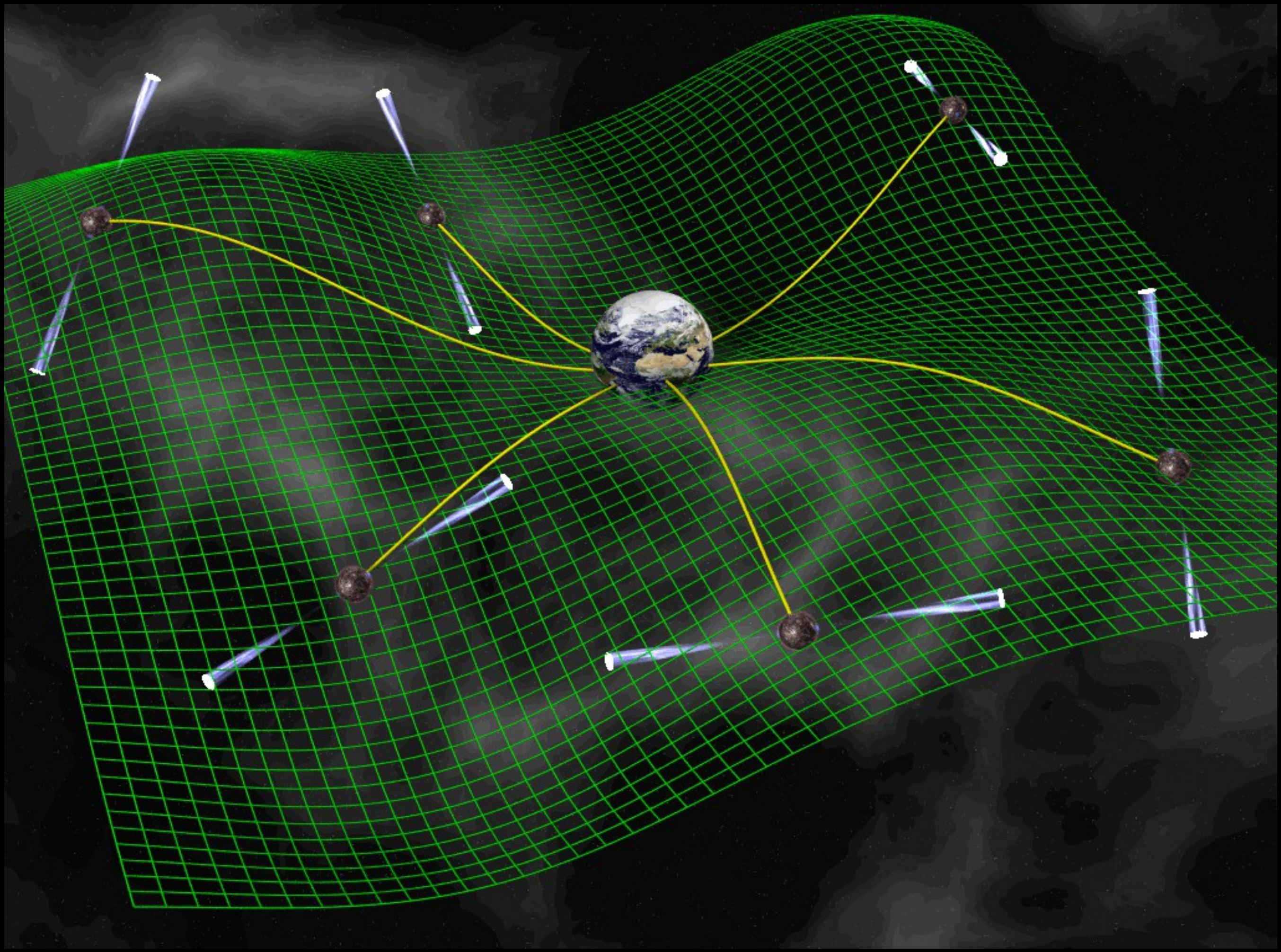


10^-14
10^-17
10^-8
10^-7
observed frequency [Hz]
600
400
200
0
−200
−400
−600
R [ns]
rms=299ns
rms=65ns
0
2
4
6
8
10
T [yr]

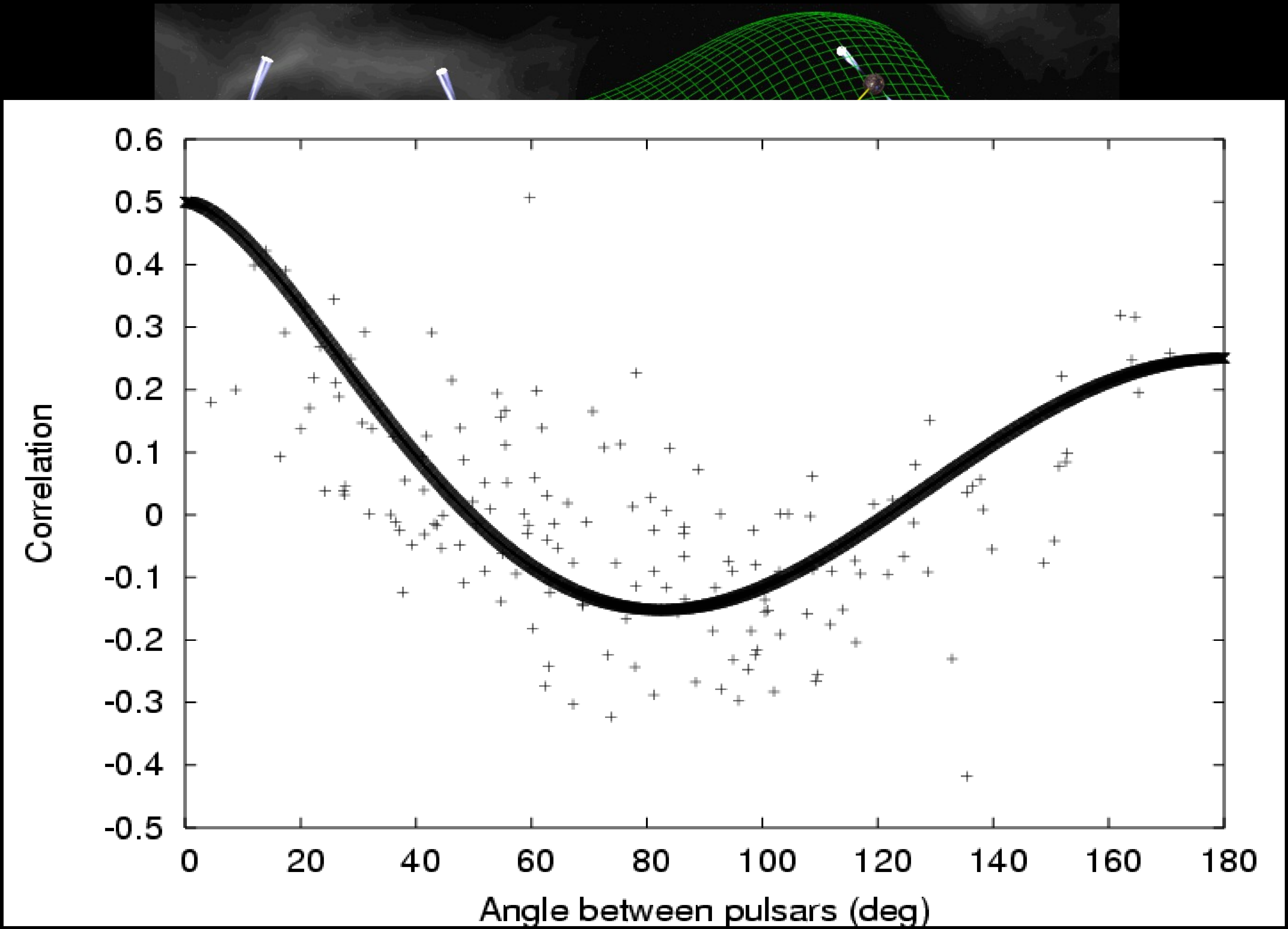


10⁻¹⁴
10⁻¹⁷
10⁻⁸
10⁻⁷
observed frequency [Hz]
R [ns]
rms=299ns
rms=65ns
T [yr]
600
400
200
0
−200
−400
−600
0
2
4
6
8
10
J0437−4715
0.49 μs
J0613−0200
6.20 μs
J0711−6830
39.03 μs
J1022+1001
23.90 μs
J1024−0719
22.24 μs
J1045−4509
24.02 μs
J1600−3053
7.62 μs
J1603−7202
13.06 μs
J1643−1224
13.32 μs
J1713+0747
2.47 μs
J1730−2304
16.09 μs
J1732−5049
25.10 μs
J1744−1134
9.79 μs
J1824−2452A
18.63 μs
J1857+0943
6.63 μs
J1909−3744
2.32 μs
J1939+2134
5.02 μs
J2124−3358
28.01 μs
J2129−5721
35.46 μs
J2145−0750
38.15 μs
2006
2008
2010

We are looking for a correlated signal



We are looking for a correlated signal



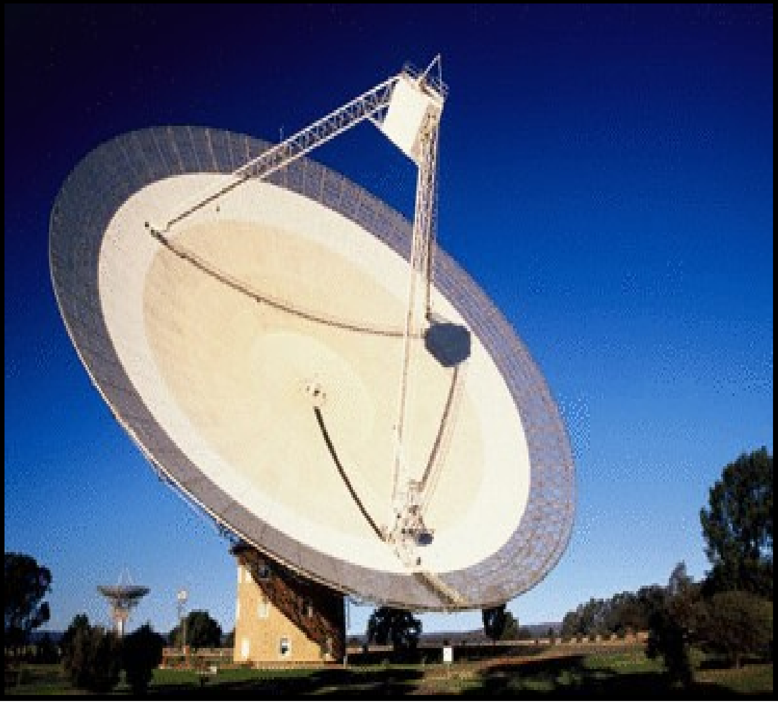
(Hellings & Downs 1983)

A worldwide observational effort

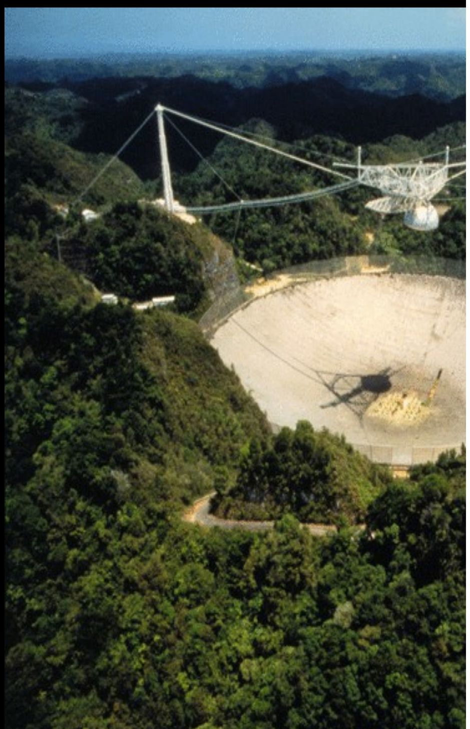
EPTA/LEAP (Large European Array for Pulsars)

NANOGrav (North American nHz Observatory for Gravitational Waves)

PPTA (Parkes Pulsar Timing Array)



A worldwide observational effort



INTERNATIONAL PULSAR TIMING ARRAY

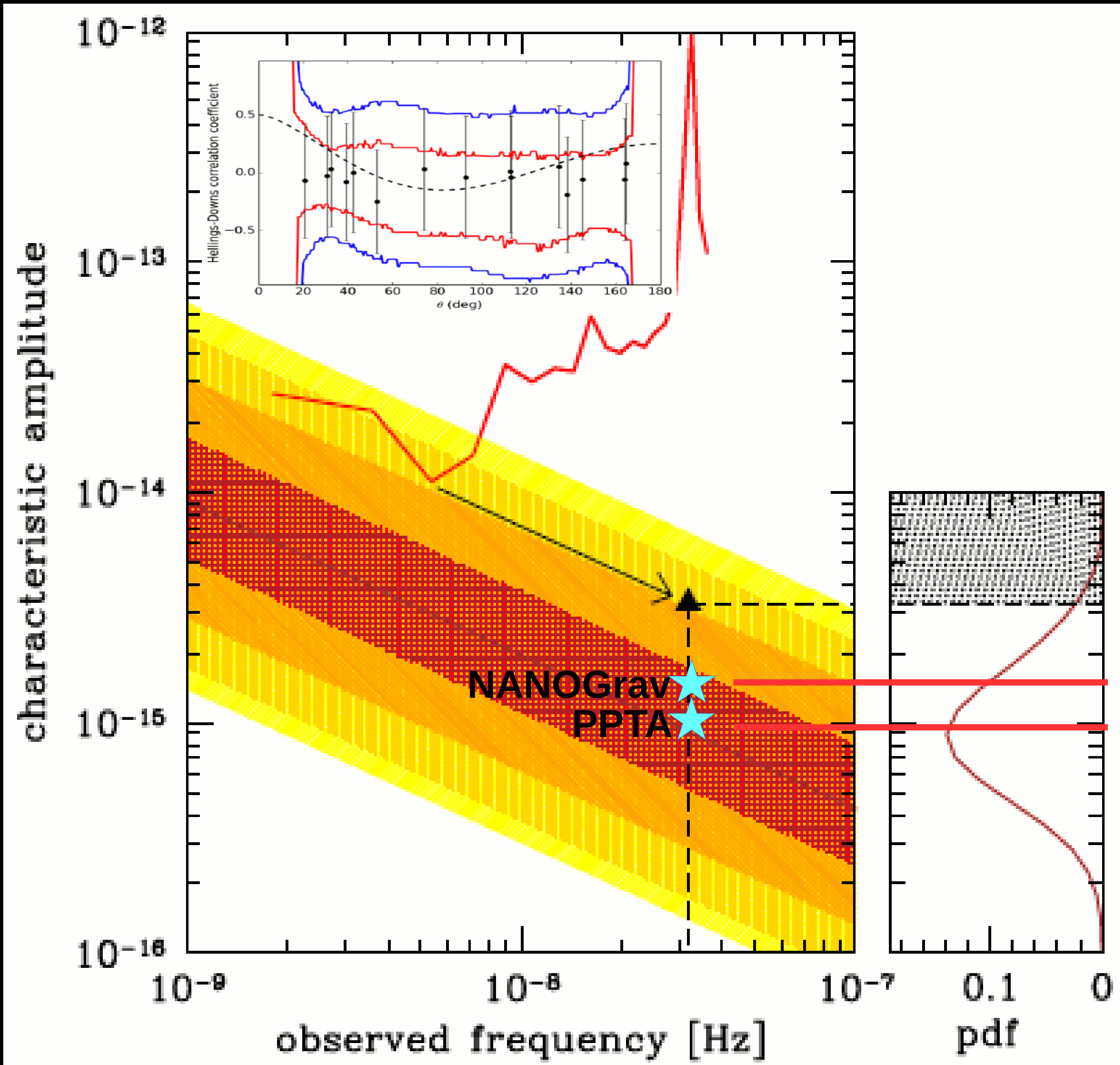
IPTA

nHz

aves)

PPTA

No detection: constraining SMBHBs?



(Lentati et al. 2015, Arzoumanian et. 2016, Shannon et al. 2015)

Predictions shown here (AS 2013):

>Assume circular GW driven binaries

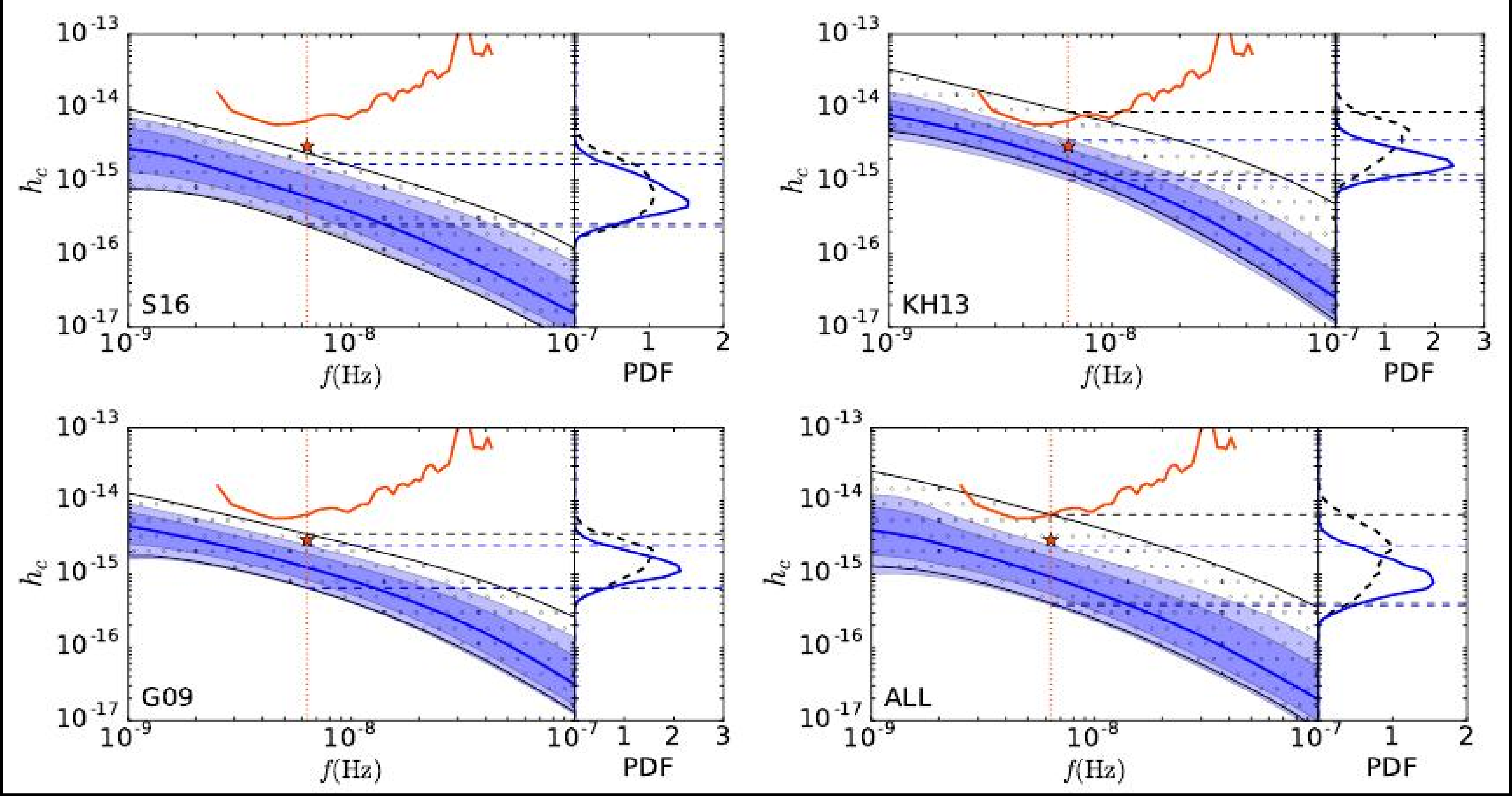
>Efficient MBH binary merger following galaxy mergers

>Uncertainty range takes into account:
- -merger rate
- -MBH-galaxy relation
- -accretion timing

(AS 2008, 2013; Ravi et al. 2012, 2015; Roebber er al. 2015; Kulier et al. 2014; McWilliams et al. 2014)

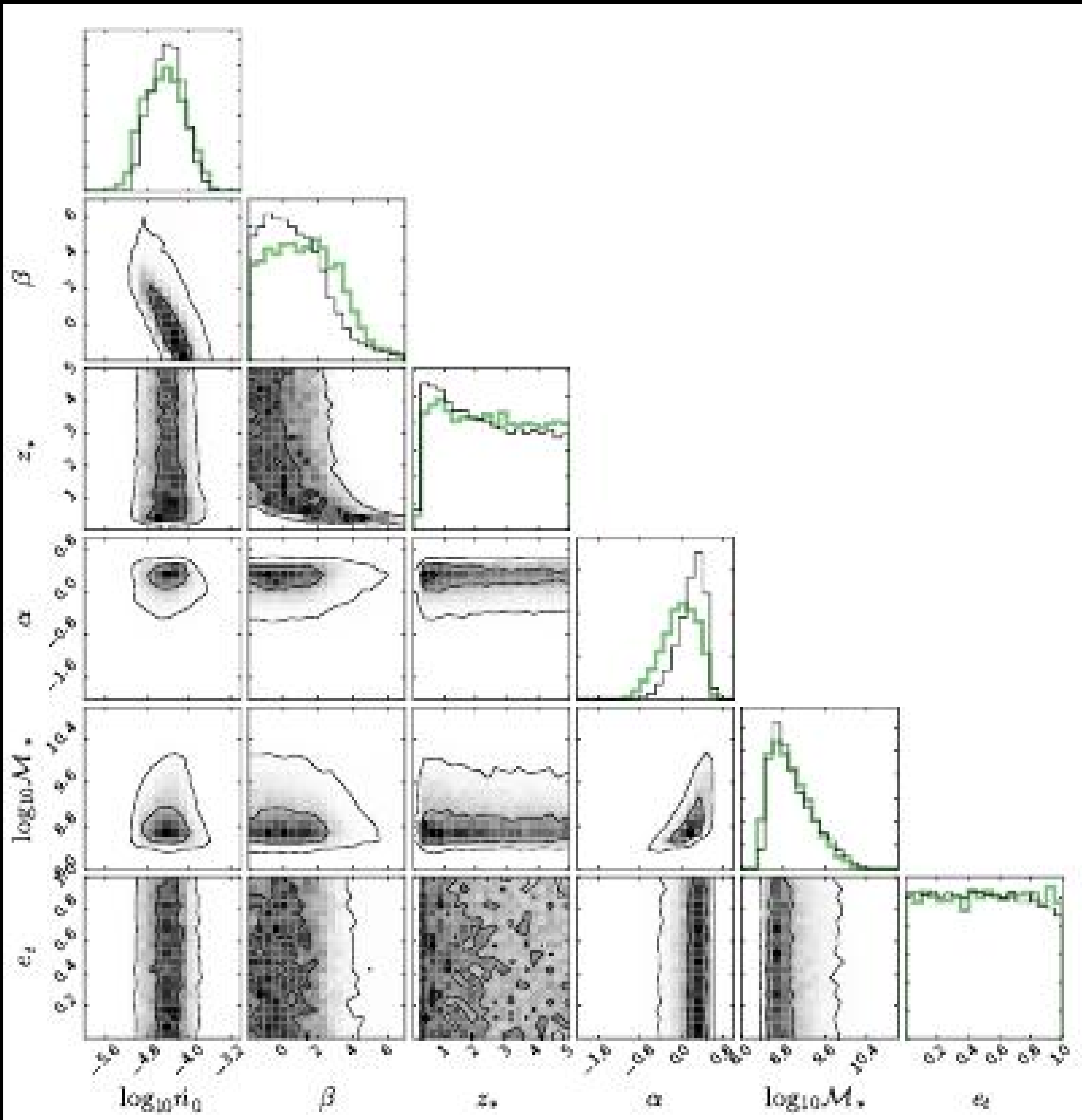
...not quite...

- -Comprehensive set of semianalytic models anchored to observations of galaxy mass function and pair fractions (AS 2013, 2016)
- -Include different BH mass-galaxy relations
- -Include binary dynamics (coupling with the environment/eccentricity)



(Middleton et al., submitted)

...not quite...



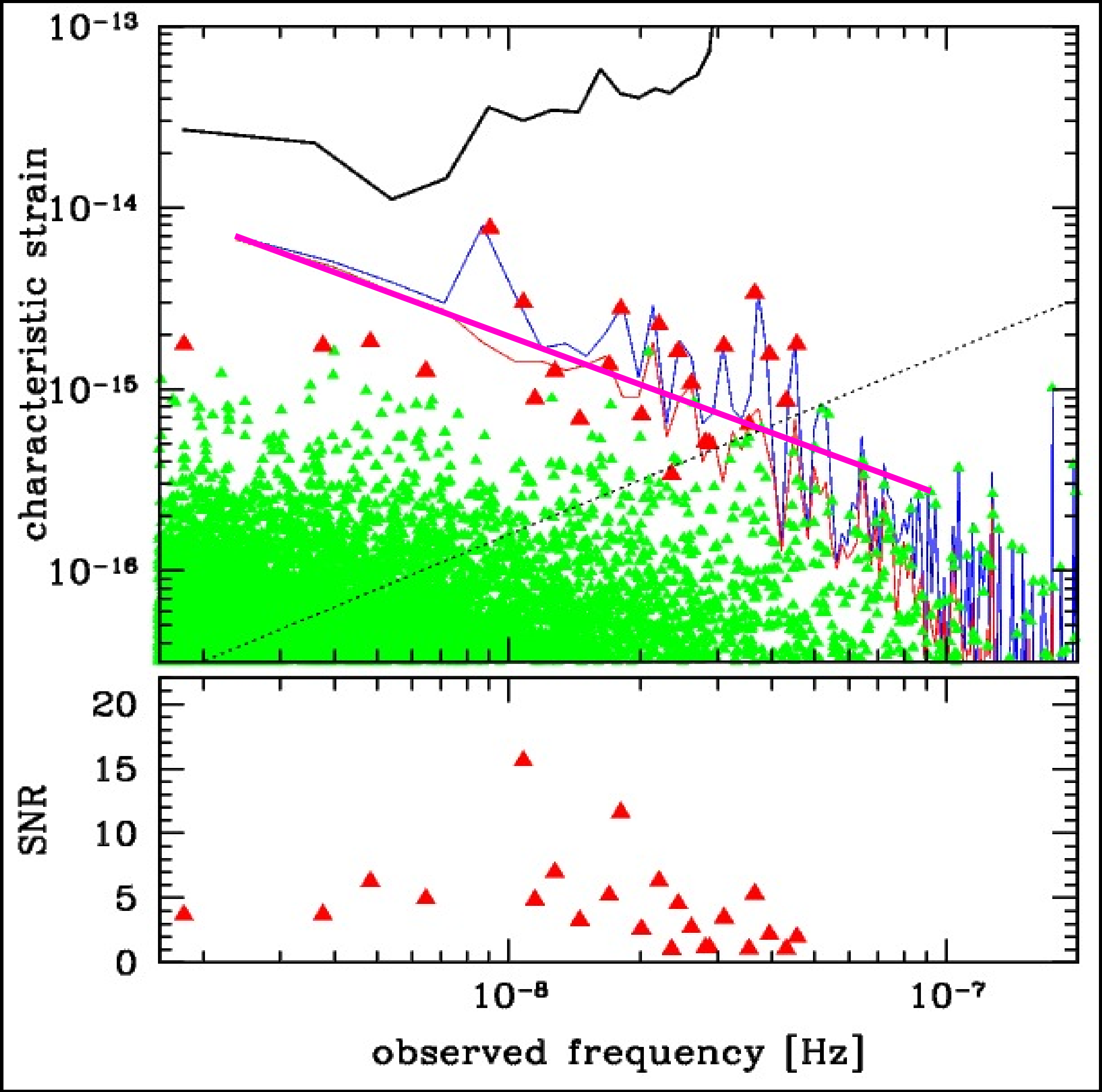
SMBHB population described by an analytic model (Chen et al. 2016, 2017)

Can put constraints on the parameters

Prior and posterior distributions on the parameters look pretty similar

The limit is not very informative (yet)

Resolvable sources (AS et al 2009)



*It is not smooth

*It is not Gaussian

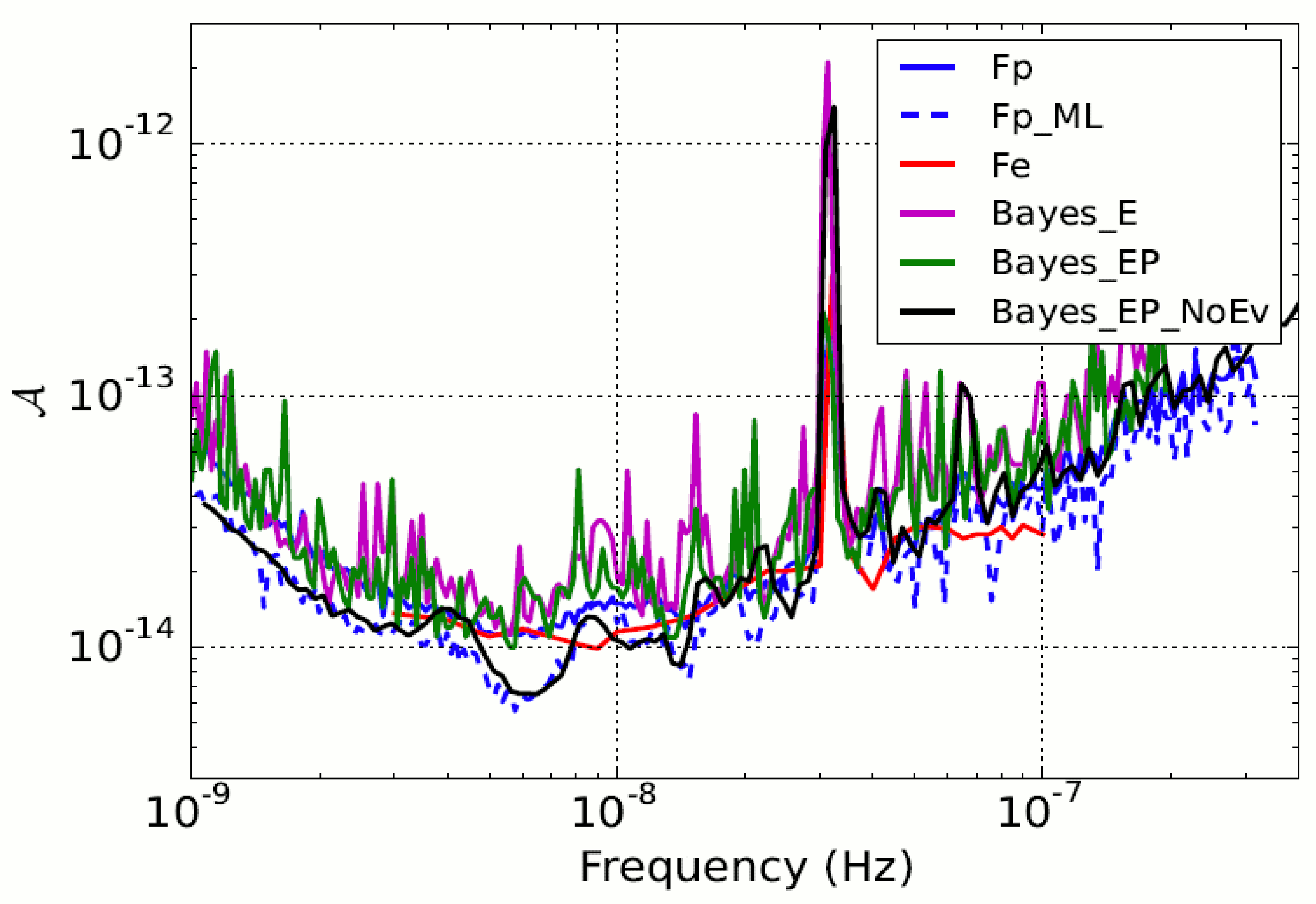
*Single sources might pop-up

*The distribution of the brightest sources might well be anisotropic

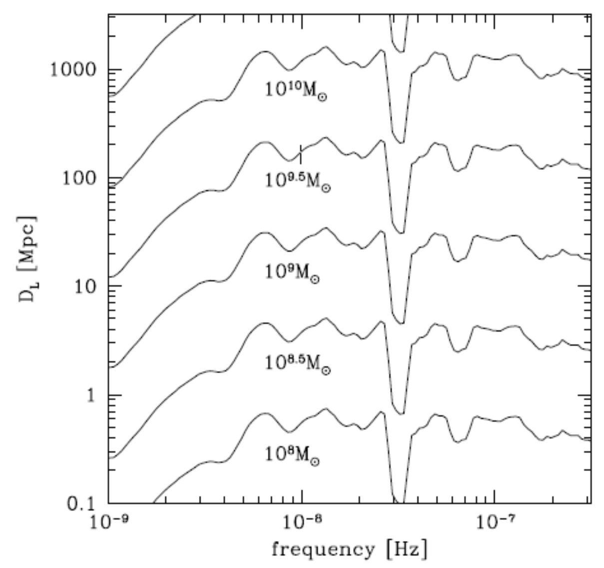
Limits on continuous GWs

(EPTA, Babak et al. 2015)

Search ID	Noise treatment	N pulsars	N parameters	Signal model	Likelihood
Fp_ML	Fixed ML	41	1	E+P NoEv	Maximized over 4 constant amplitudes plus pulsar phase
Fp	Sampling posterior	41	1	E+P NoEv	Maximized over 4 constant amplitudes plus pulsar phase
Fe	Fixed ML	41	3	E	Maximized over 4 constant amplitudes
Bayes_E	Fixed ML	41	7	E	Full
Bayes_EP	Fixed ML	6	$7+2\times 6$	E+P Ev	Full
Bayes_EP_NoEv	Fixed ML	41	7	E+P NoEv	Pulsar phase marginalization
Bayes_EP_NoEv_noise	Searched over	6	$7+5\times 6$	E+P NoEv	Pulsar phase marginalization

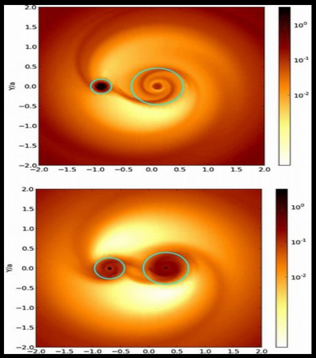


Data are not yet very constraining, we can rule out very massive systems to ~200Mpc, well beyond Coma

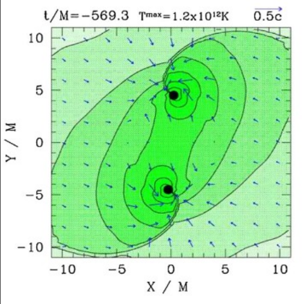


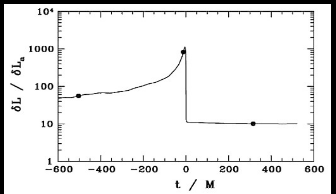
Associated electromagnetic signatures LISA

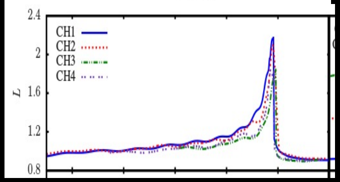
In the standard circumbinary disk scenario, the binary carves a cavity: no EM signal (Phinney & Milosavljevic 2005).
However, all simulations (hydro, MHD) showed significant mass inflow (Cuadra et al. 2009, Shi et al 2011, Farris et al 2014...)

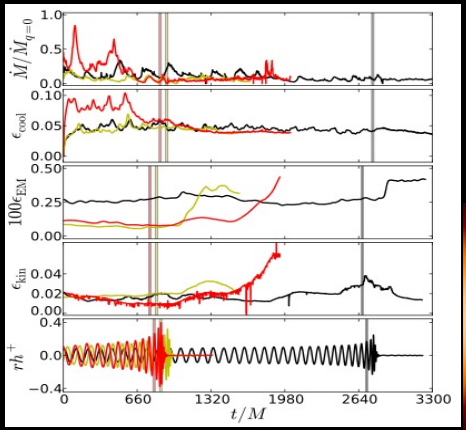


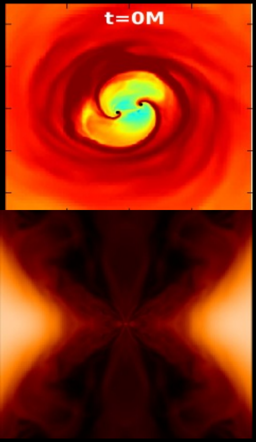
Simulations in hot gaseous clouds. Significan flare associated to merger (Bode et al. 2010, 2012, Farris et al 2012)





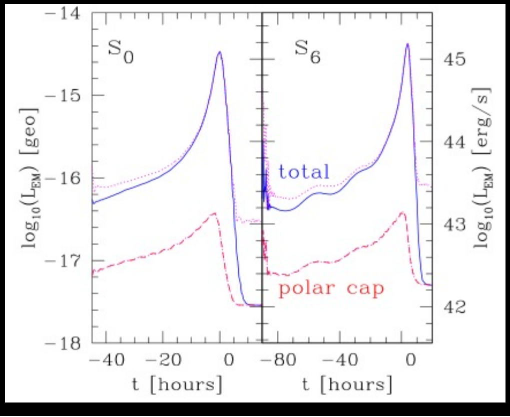


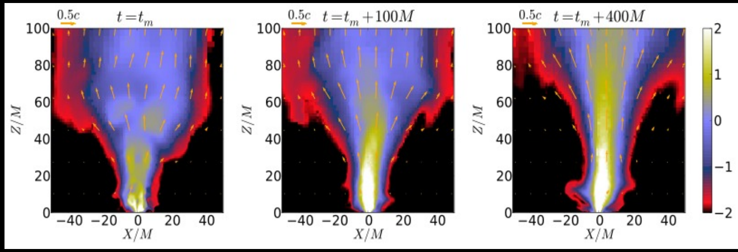




Simulations in disk-like geometry. Variability, but much weaker and unclear signatures
(Bode et al. 2012, Gold et al. 2014)

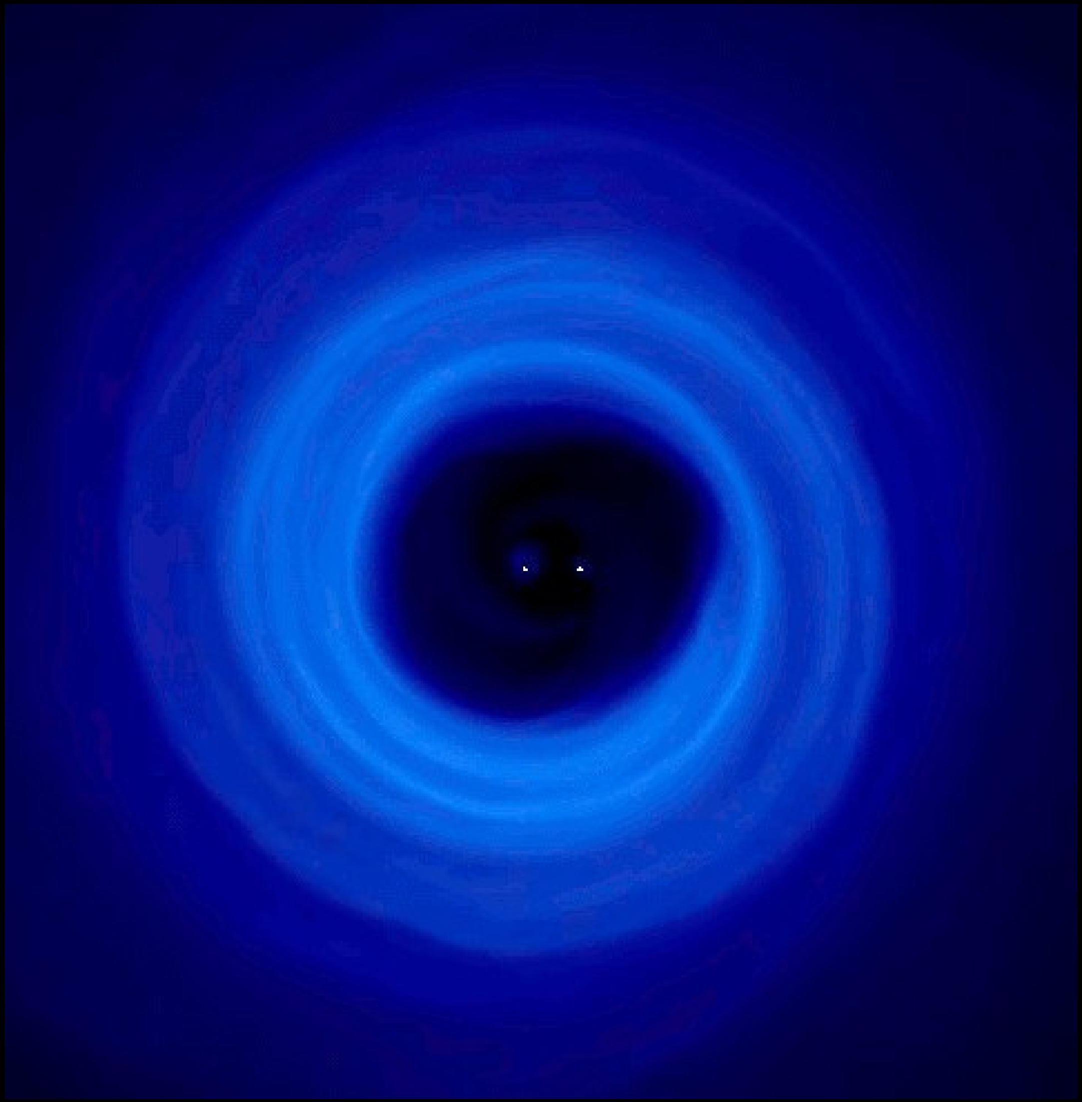
Full GR force free electrodynamics
(Palenzuela et al. 2010, 2012)





Associated electromagnetic signatures PTA

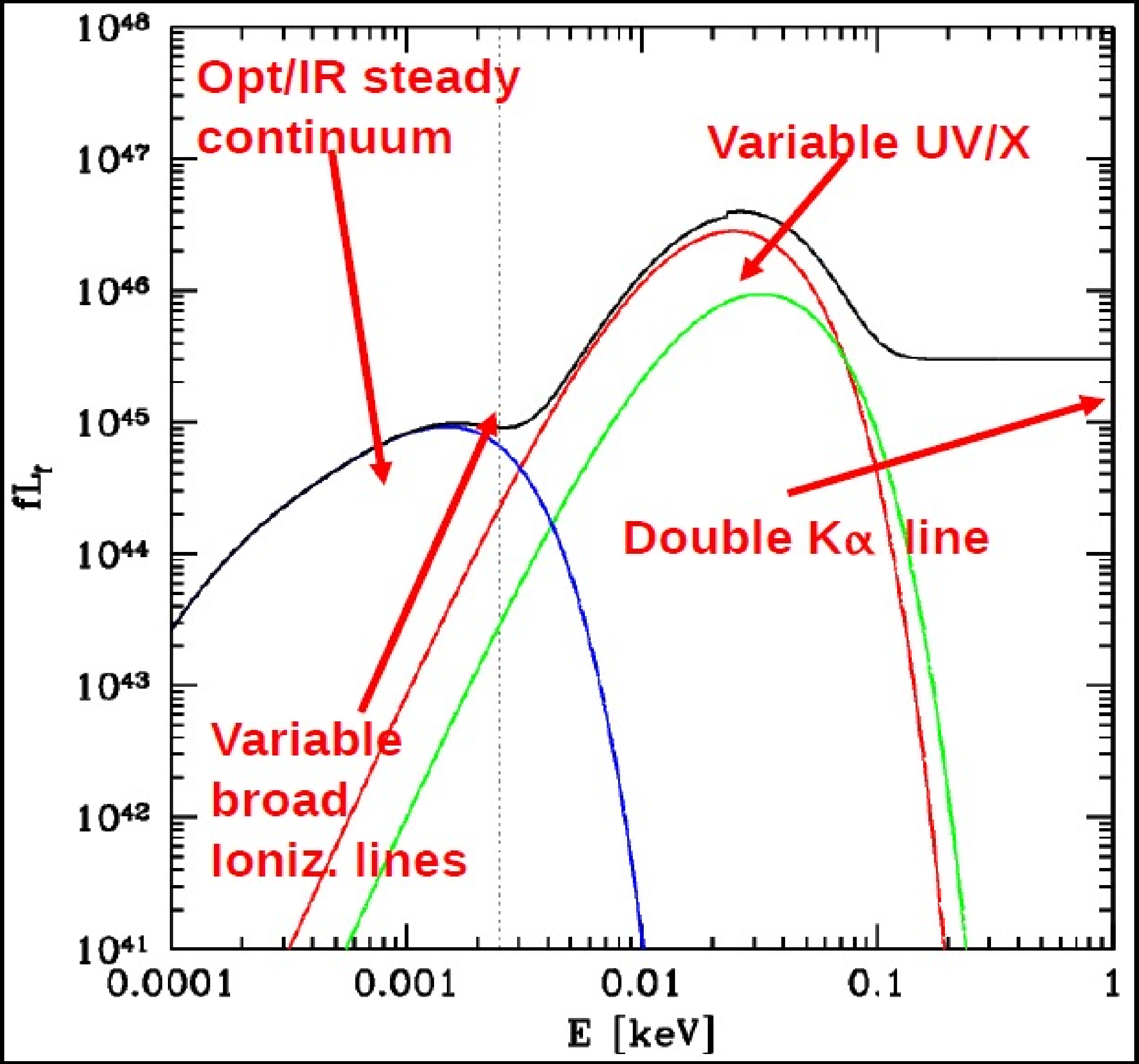
MBH binary + circumbinary disk



(Roedig et al. 2011, AS et al. 2012, Tanaka et al. 2012, Burke-Spolaor 2013)

Associated electromagnetic signatures PTA

MBH binary + circumbinary disk



(Roedig et al. 2011, AS et al. 2012, Tanaka et al. 2012, Burke-Spolaor 2013)

A variety of possibilities:

Optical/IR dominated by the outer disk: Steady/modulated?

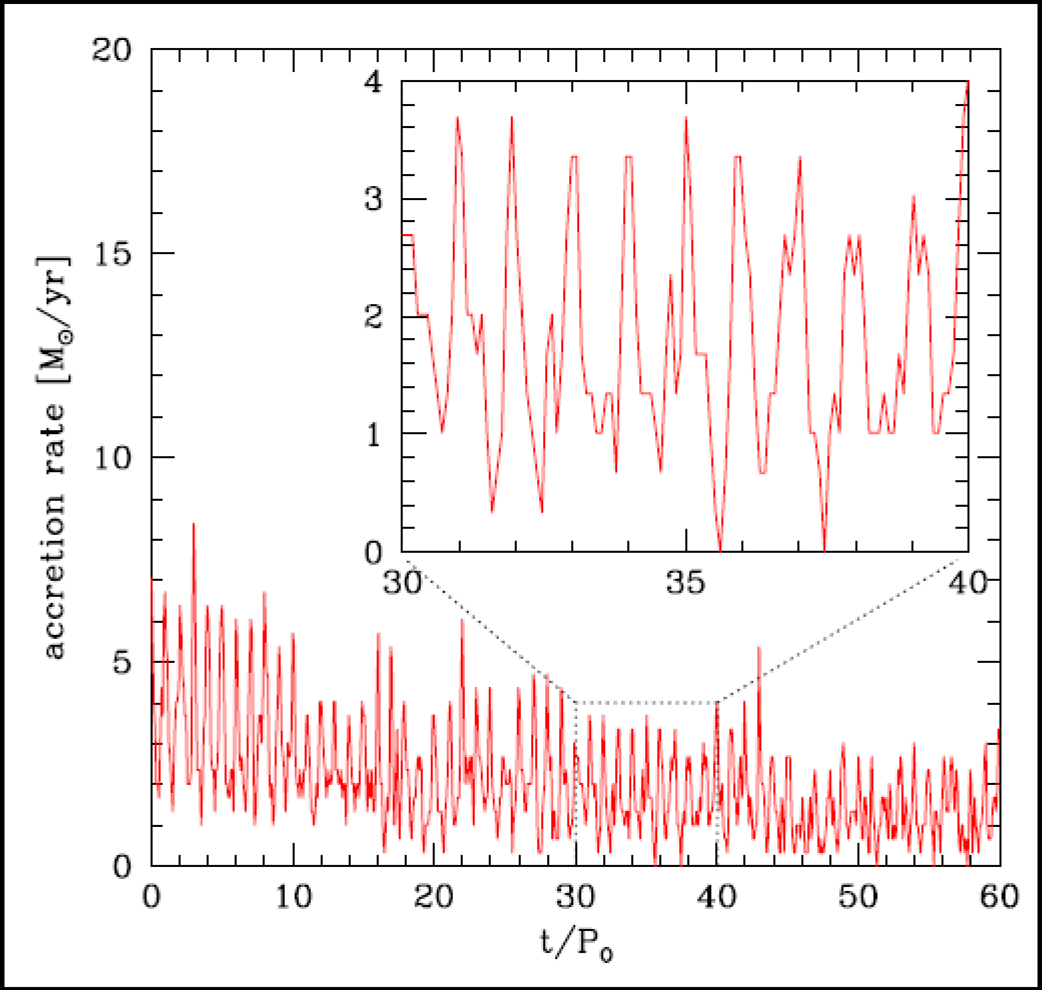
UV generated by inner streams/minidisk: periodic variability?

X rays variable from periodic shocks or intermittent corona?

Variable broad emission line in response to the varying ionizing continuum?

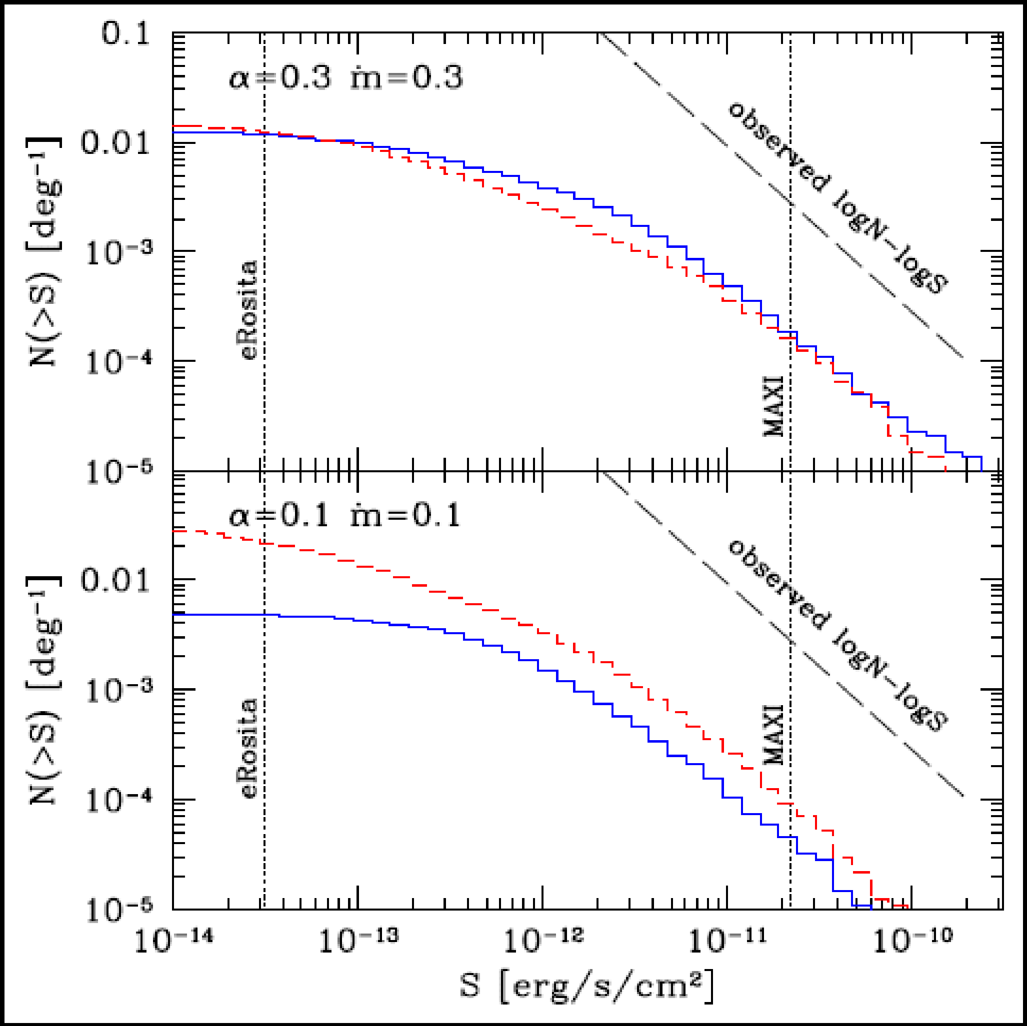
Double fluorescence lines?

Example: variability



Streams feed the inner minidisk
extremely intermittent mass inflow.

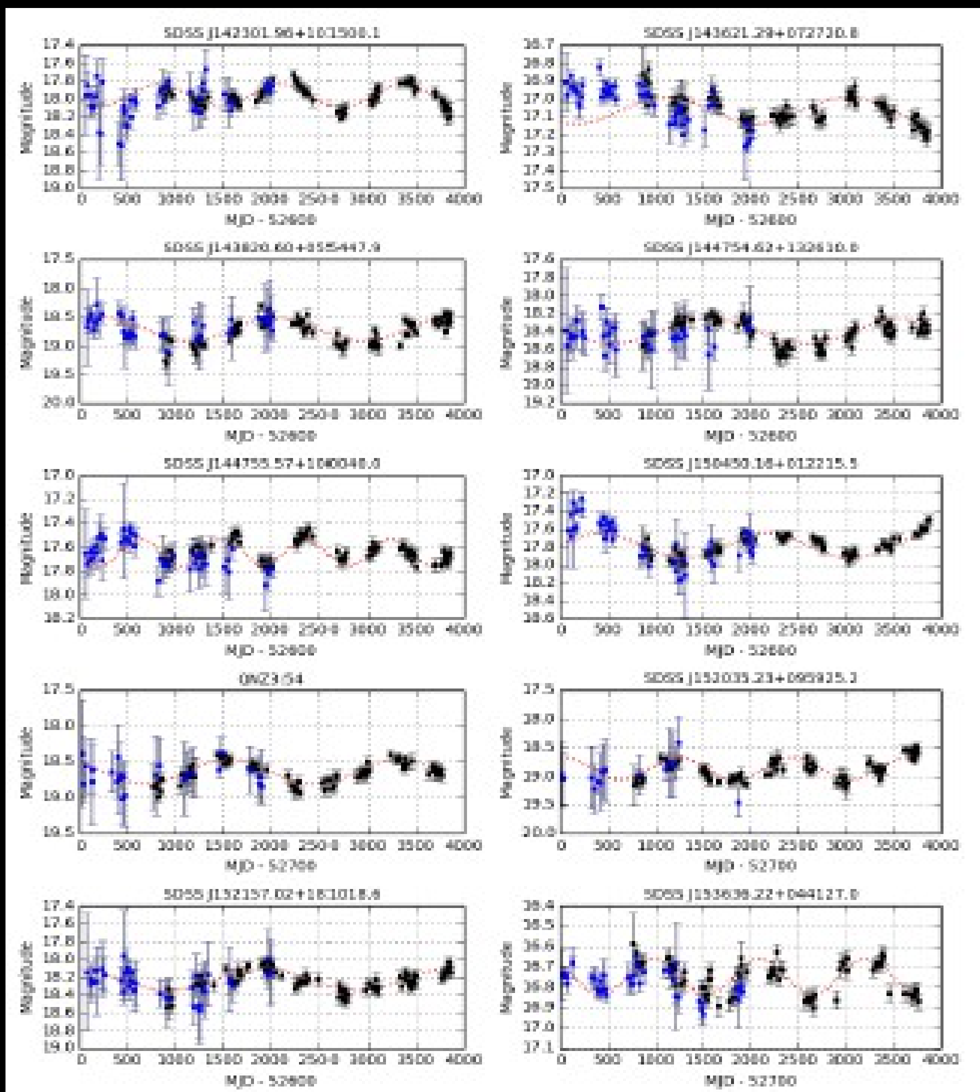
Applying this
model to a tipical MBH binary
population we get ~100 sources at
the eRosita flux limit



PTAs as a tool for astrophysics

A systematic search for close supermassive black hole binaries in the Catalina Real-Time Transient Survey

Matthew J. Graham,[1*] S. G. Djorgovski,[1] Daniel Stern,[2] Andrew J. Drake,[1]
Ashish A. Mahabal,[1] Ciro Donalek,[1] Eilat Glikman[3], Steve Larson[4], Eric Christensen[4]



Catalina survey:

9yr baseline, 250000 QSO

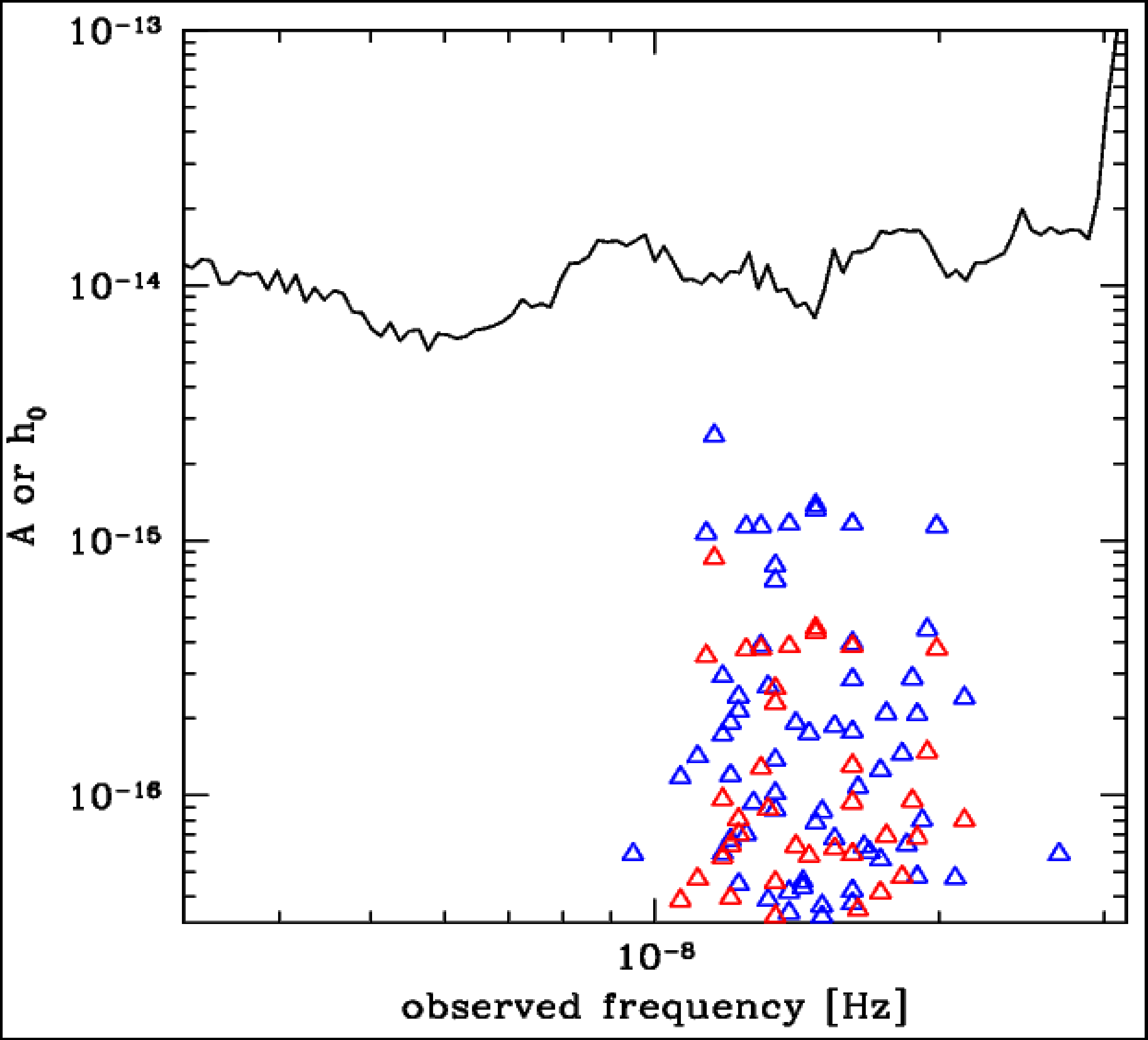
-required 1.5 cycles for periodicity identification.

-111 lightcurves showing periodic behaviour

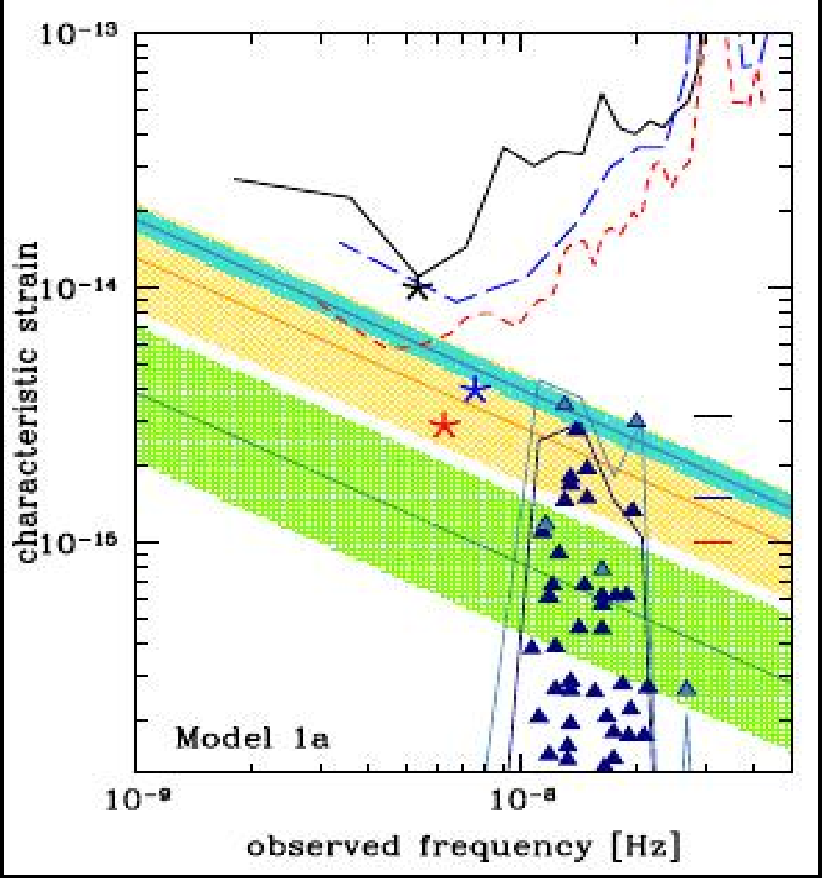
-For most of the systems we have: period, redshift, total mass, sky location, etc etc...

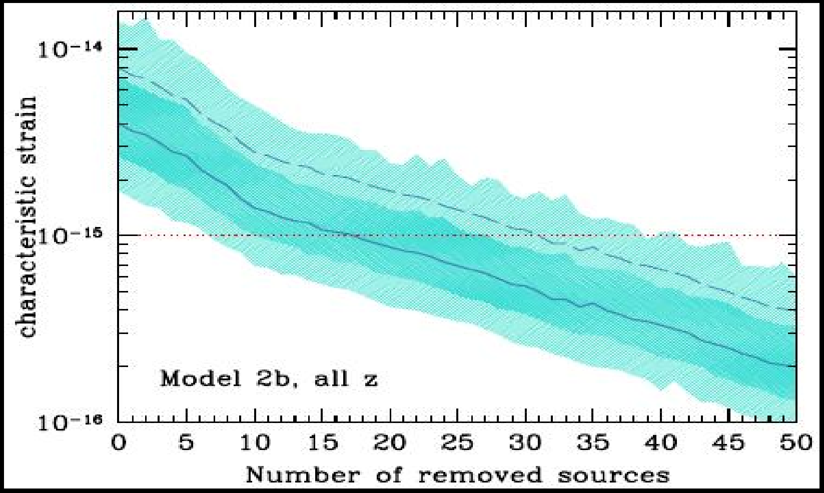
…not that I believe any of them, but...

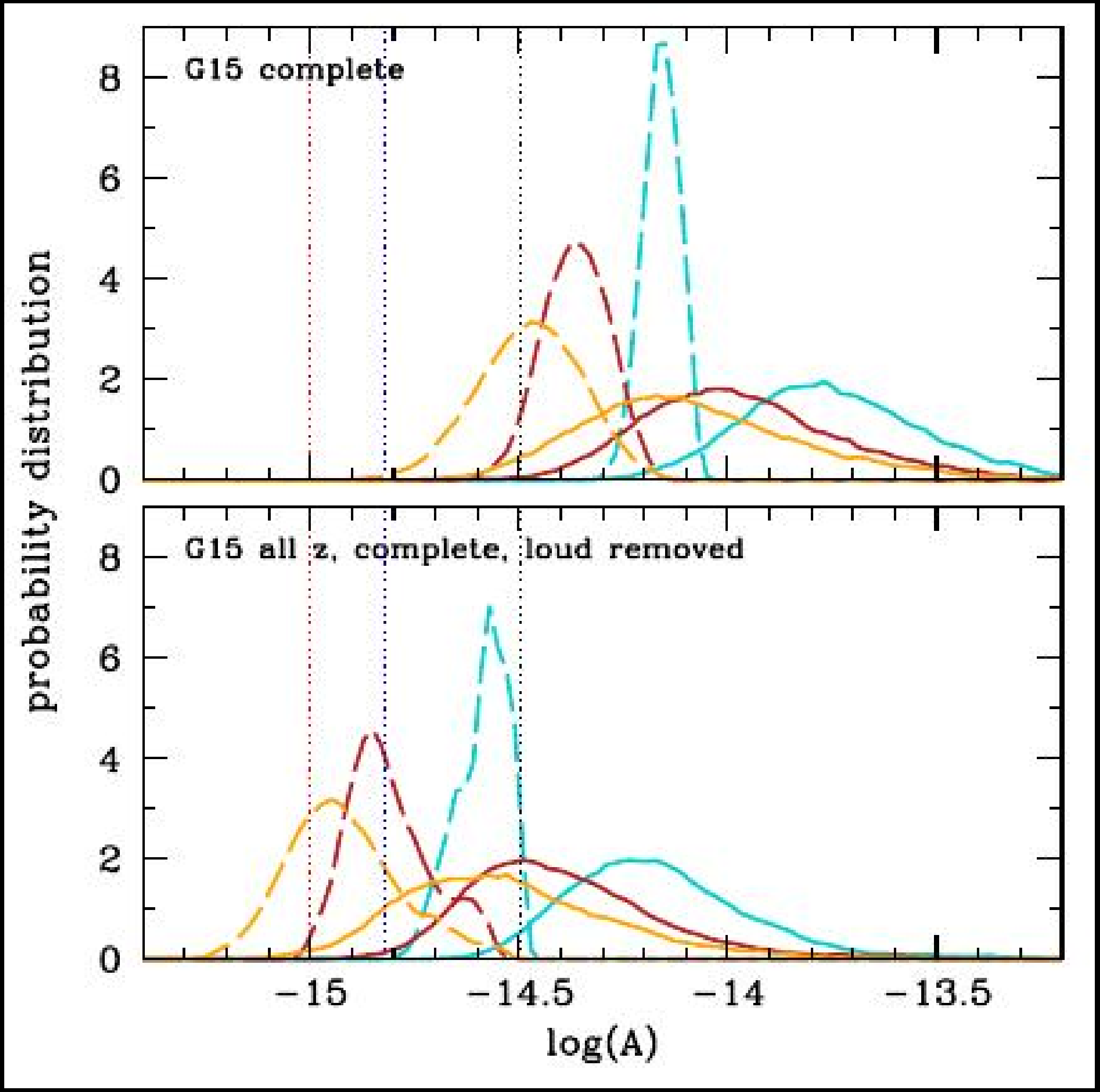
Strain amplitude of individual sources



Extrapolated GWB







GWB 3-to-15 times larger than PTA limits
Most of the candidates cannot be SMBHBs (AS et al 2017)

Doggybag

LISA will probe a number of GW sources at low frequency.

- -galactic binaries
- -extreme mass ratio inspirals
- -LIGO sources
- -SMBHB cosmic history

LISA sources will be invaluable tools for astrophysics, cosmology and fundamental physics

PTAs can provide unique information about the dynamics and merger history of MBHBs (e.g. merger rate density, environmental coupling, eccentricity, etc.)

Current PTA limits are getting extremely interesting, showing some tension with vanilla models for the cosmic SMBHB population, but nothing can be ruled out yet