The first gravitational wave detection and the future of multimessenger astronomy

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OUTLINE

>Gravitational waves (GWs): theory and detection

>GWs across the frequency spectrum

>GW150914: LIGO first detection

>Multi-band GW astronomy with eLISA and LIGO: the future of multimessenger astronomy

>the eLISA potential

>probing the lowest frequencies with pulsar timing arrays

Gravitational waves: a short intro

Consider a small metric perturbation

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, \qquad h_{\mu\nu} \ll 1$$

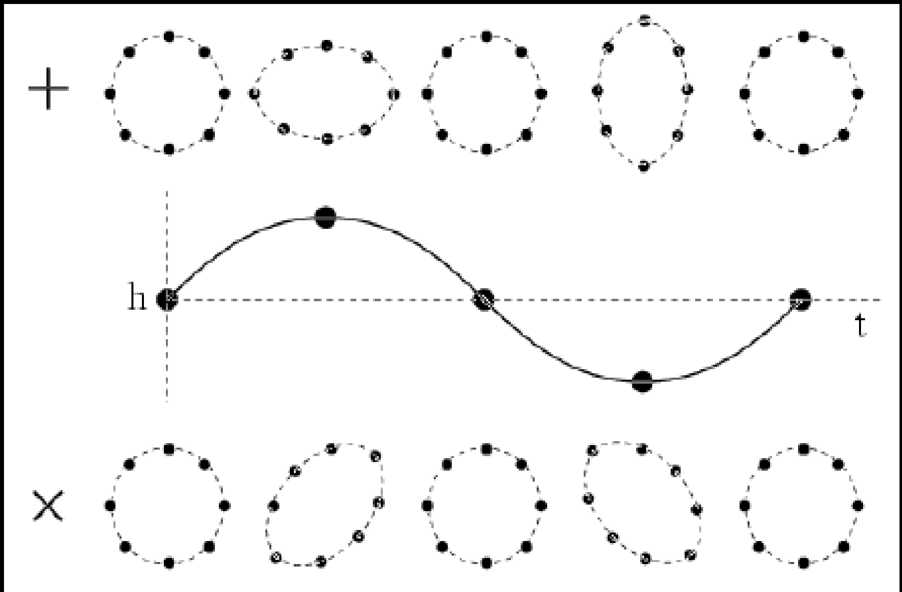
The linearization of the EEs results in a wave equation

$$\Box \overline{h}_{\mu\nu} = -\frac{16\pi G}{c^4} T_{\mu\nu}$$

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

The solution is a wave travelling
At the speed of light:
GRAVITATIONAL WAVES

$$\overline{h}^{ij}(t,r) = \frac{2G}{c^4}\left[\frac{d^2}{dt^2} q^{ij}\left(t - \frac{r}{c}\right)\right]$$



They are proportional to the
Second derivative of the mass quadrupol moment and they carry an energy given by

$$L_{gw} = \frac{G}{5c^5}\left\langle \sum_{ij} \frac{d^3}{dt^3} Q_{ij}\left(t - \frac{x}{c}\right) \frac{d^3}{dt^3} Q^{ij}\left(t - \frac{x}{c}\right)\right\rangle$$

GWs are transversal and have two independent polarizations

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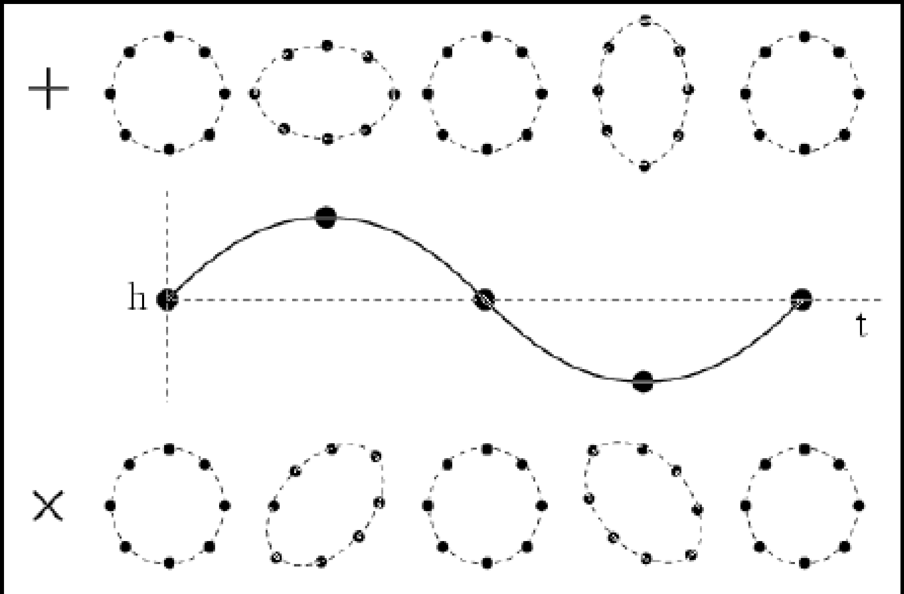


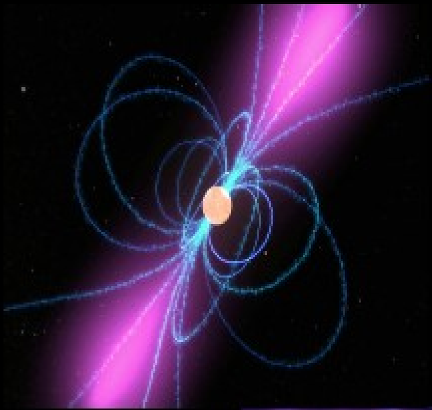
GWs are transversal and have two independent polarizations

Gravitational wave sources

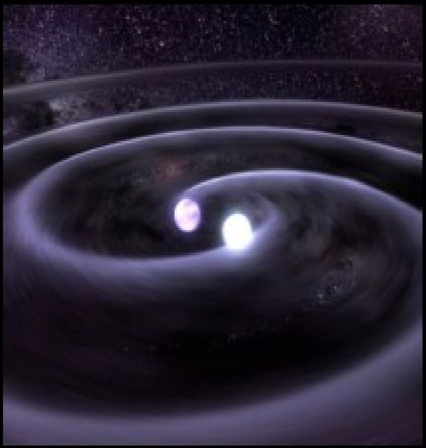
Massive compact systems with a time varying mass quadrupole momentum:

1-collapses and explosions (supernovae, GRBs)

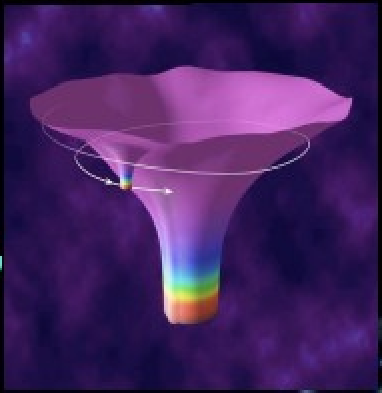
2-rotating asymmetric objects (pulsars, MSPs)



3-binary systems:



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

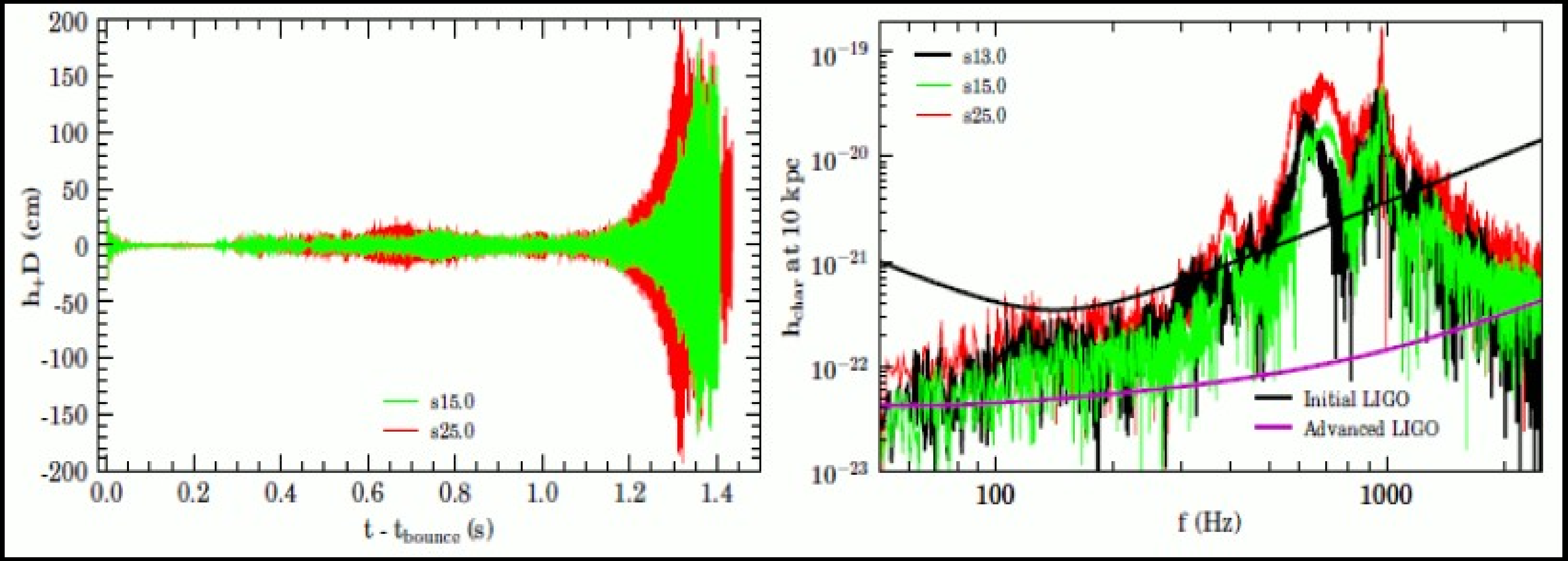


b-extreme mass ratio inspirals (EMRIs), CO falling into a massive black hole

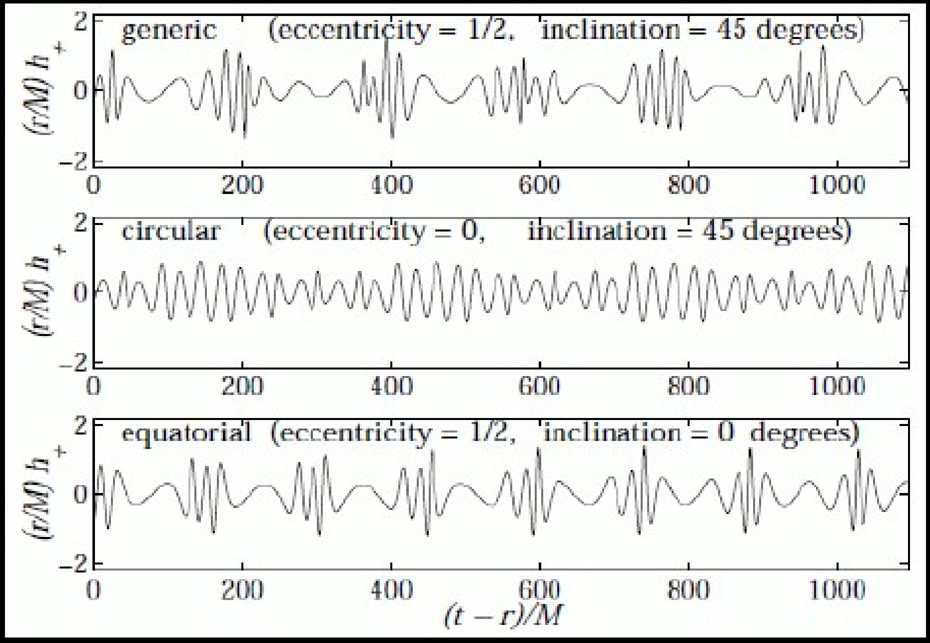
c-massive black hole binaries (MBHBs) forming following galaxy mergers

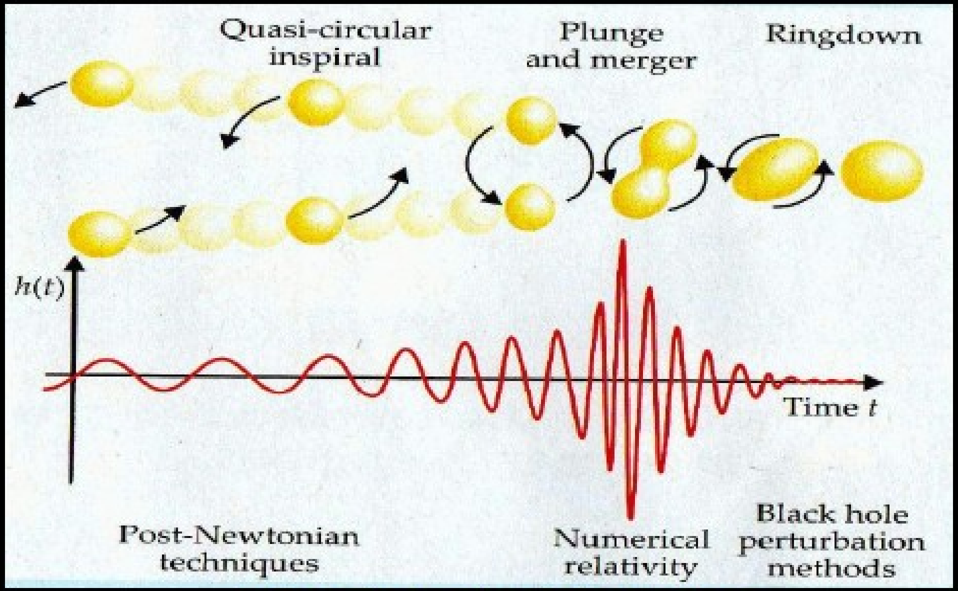
Example of gravitational waveforms

Supernova explosion (credits C. Ott)



EMRIs (credits Drasco & Hughes)





Black hole binaries

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

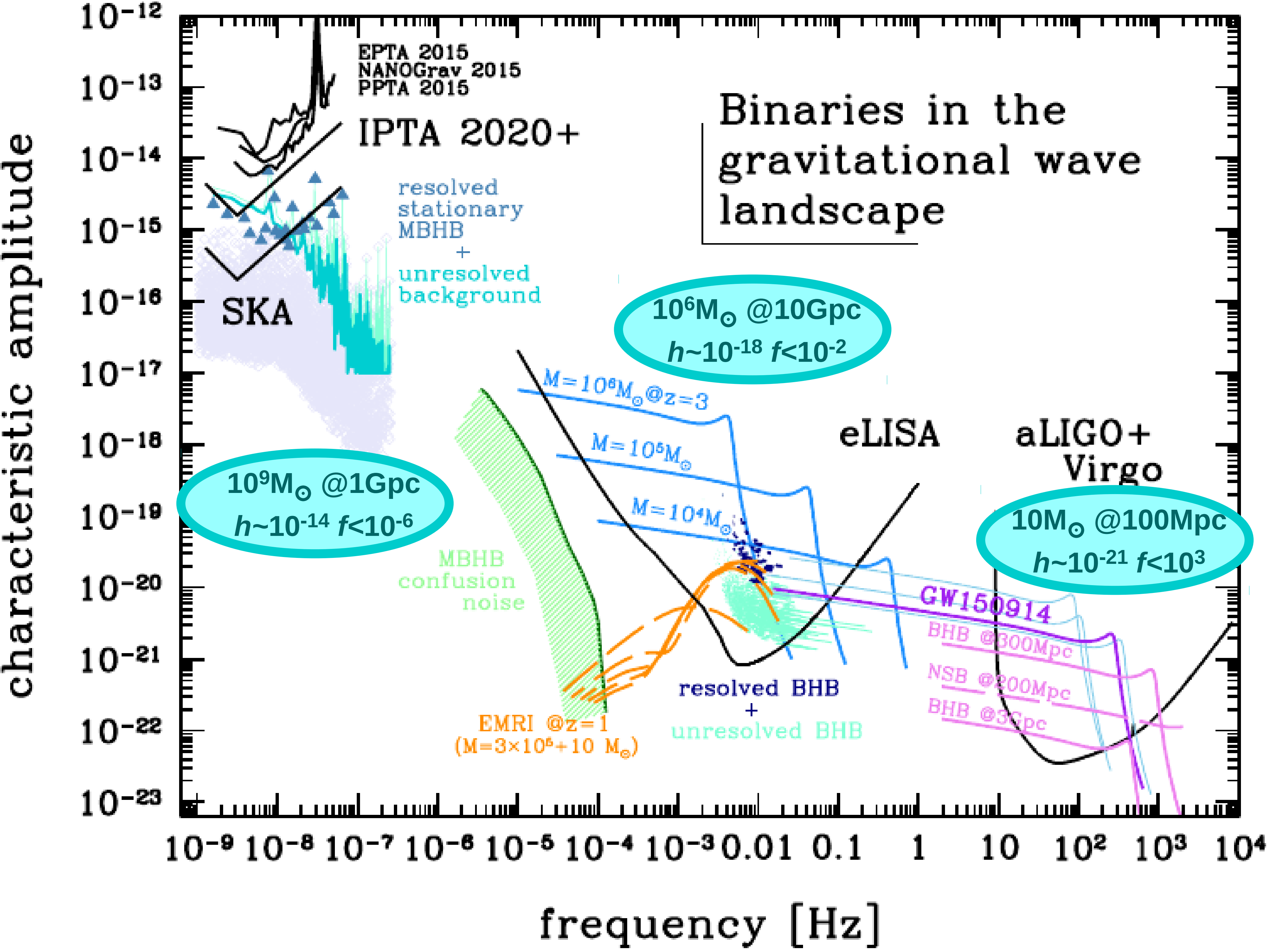
$$h \sim 10^{-20}\frac{M}{M_\odot}\frac{\mathrm{Mpc}}{D}$$

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

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

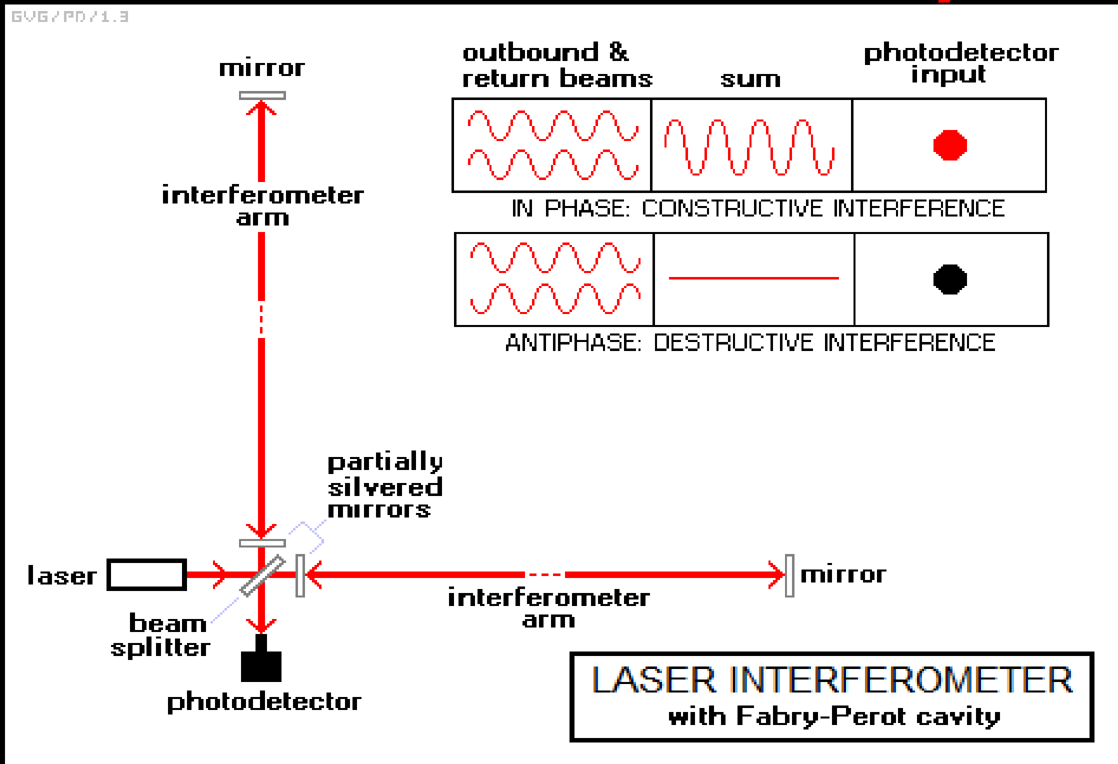
10^6 $M_\odot$ binary at 10 Gpc: $h \sim 10^{-18}$, $f < 10^{-2}$

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

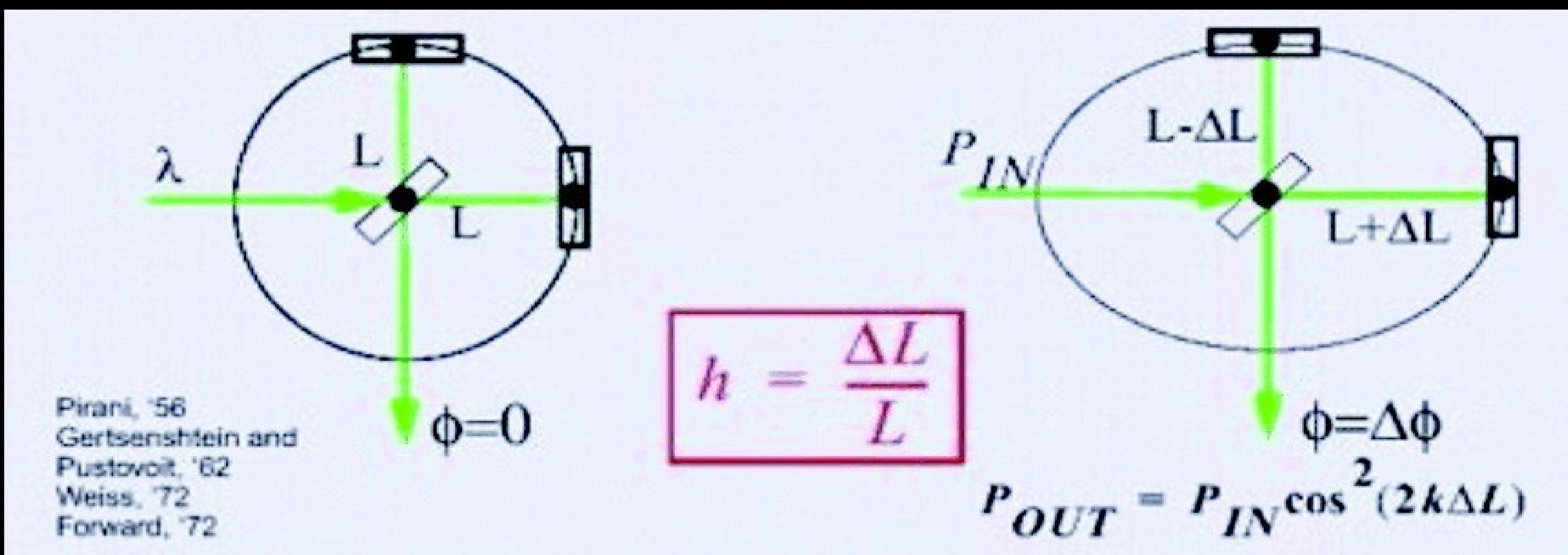


characteristic amplitude
frequency [Hz]
EPTA 2015
NANOGrav 2015
PPTA 2015
IPTA 2020+
SKA
resolved stationary MBHB + unresolved background
Binaries in the gravitational wave landscape
10⁶M⊙ @10Gpc h~10⁻¹⁸ f<10⁻²
10⁹M⊙ @1Gpc h~10⁻¹⁴ f<10⁻⁶
10M⊙ @100Mpc h~10⁻²¹ f<10³
M=10⁶M⊙ @z=3
M=10⁵M⊙
M=10⁴M⊙
eLISA
aLIGO+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

Main detection technique: laser interferometry

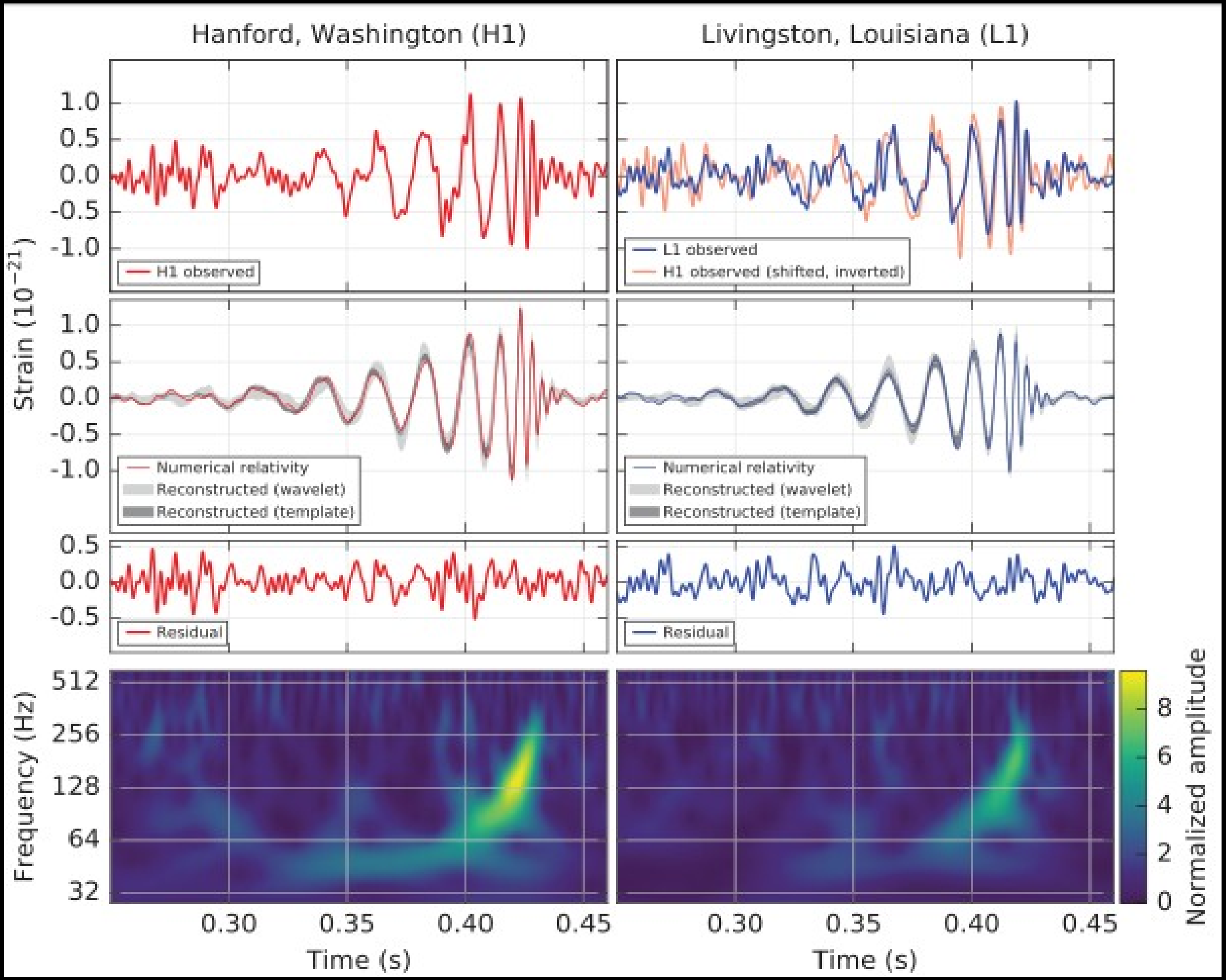


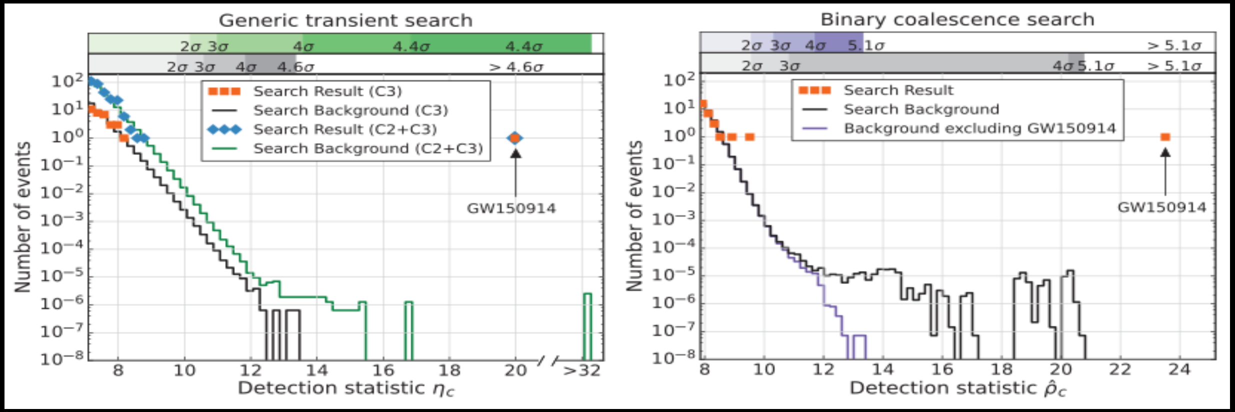
The passing waves change the relative path of the photons. This results at a de-phasing of the beams at recombination that can be detected....



Ground-based interferometer network

Making history: 14 September 2015





On September 14 2015, the two LIGO detectors detected a coincident signal.

It lasted about 0.2 seconds.

The signal was so strong that it was detected by the 'burst' pipeline.

Nominal S/N: 24

Significance: 5.1σ

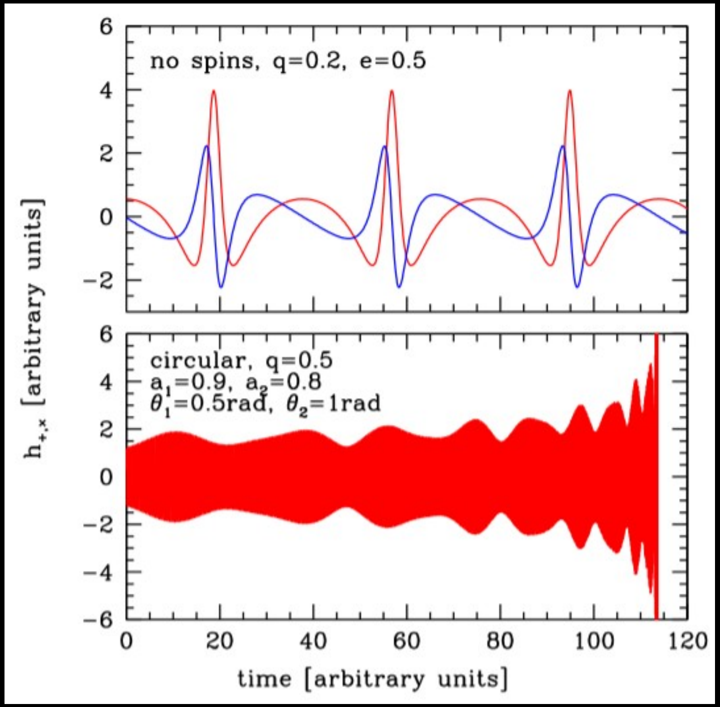
Extraction of information from the waveform

>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



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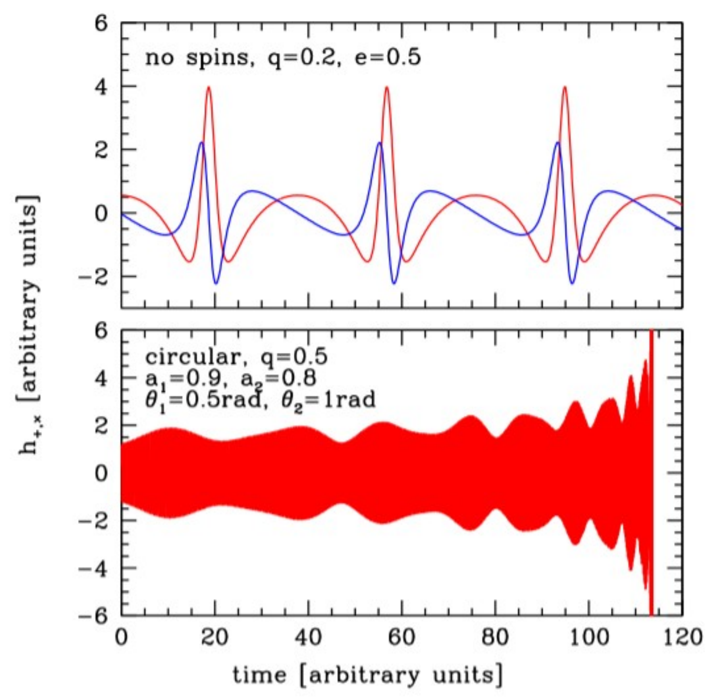

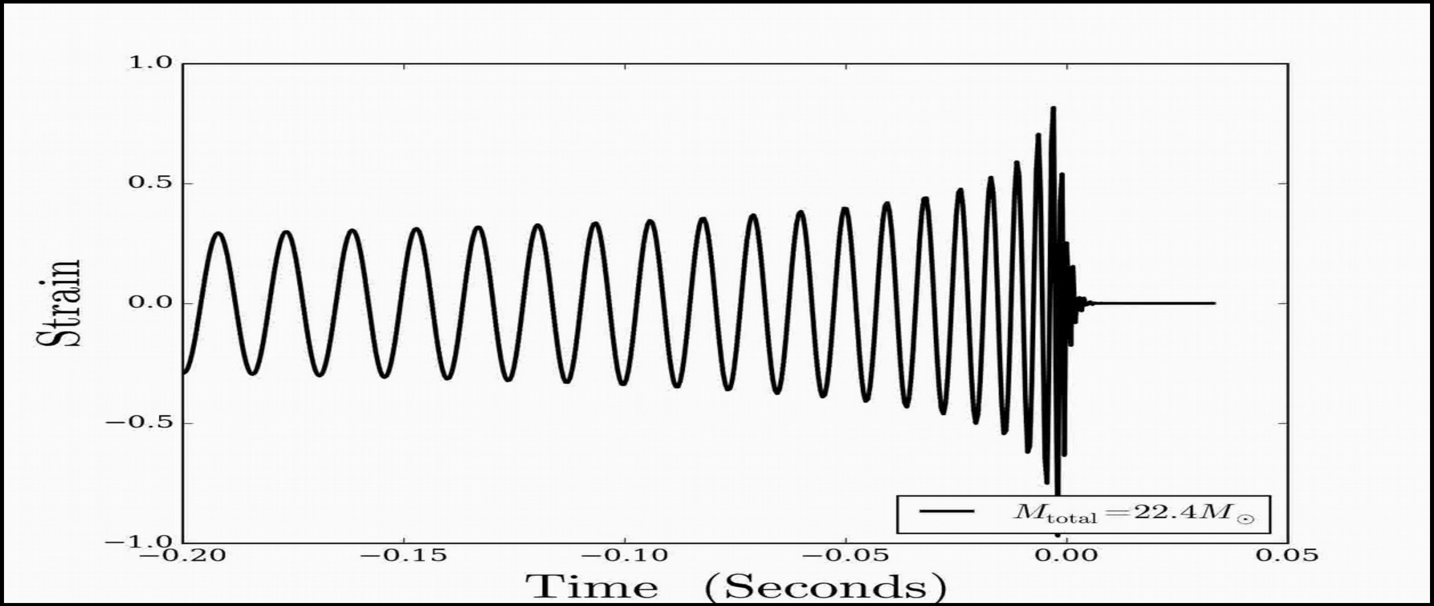

(Courtesy W. del Pozzo)

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.

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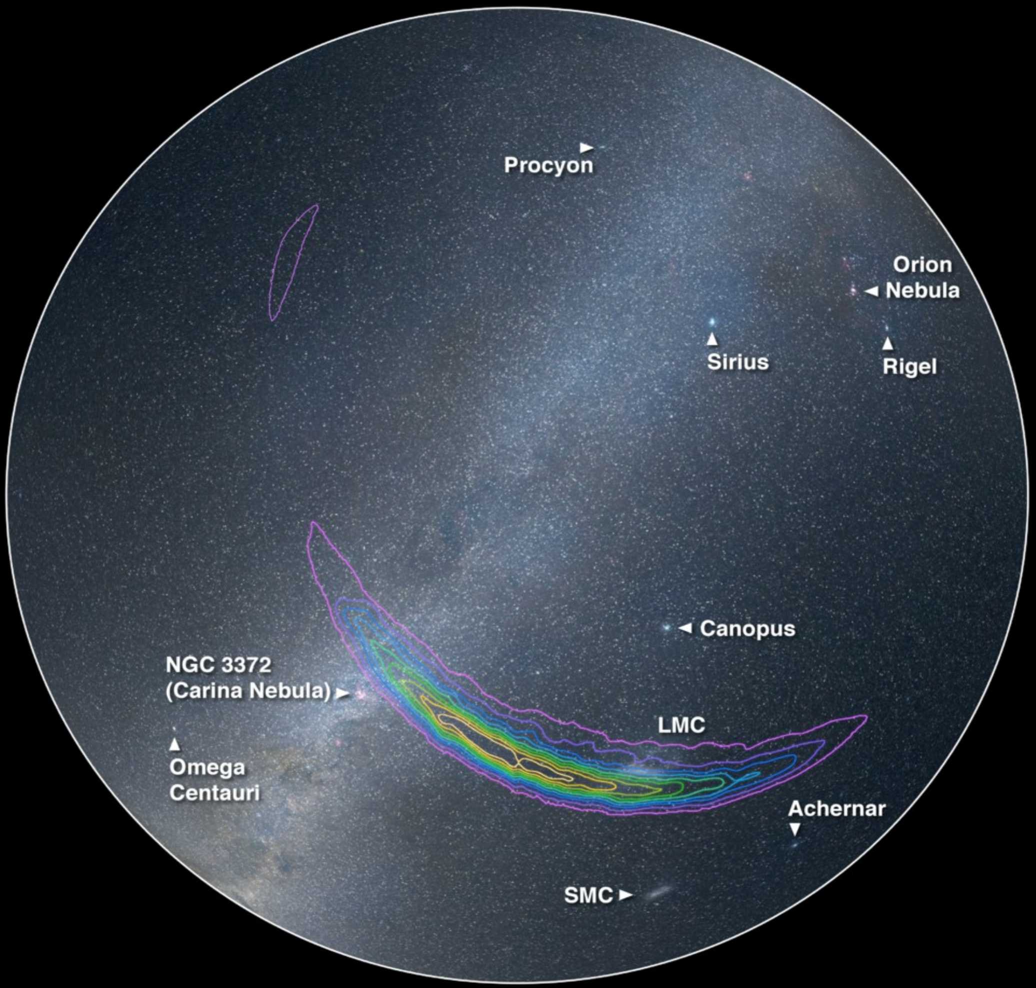
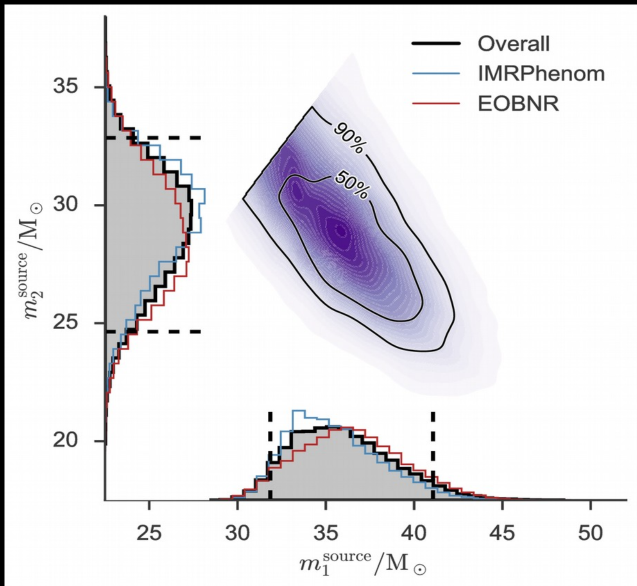
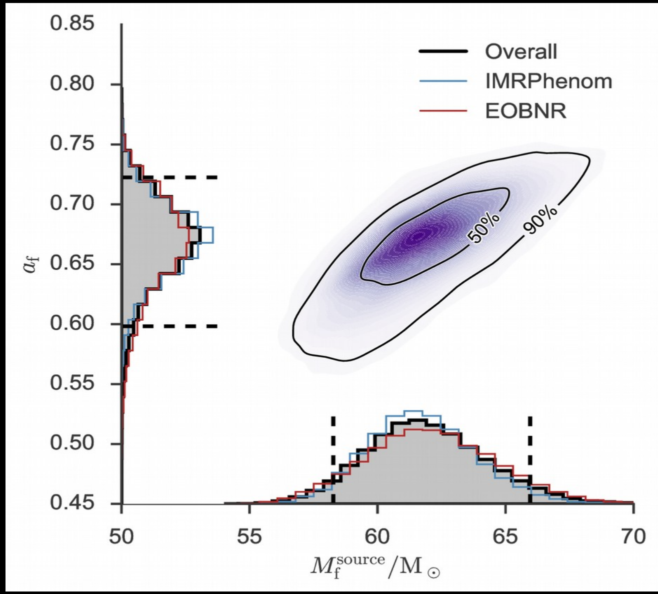
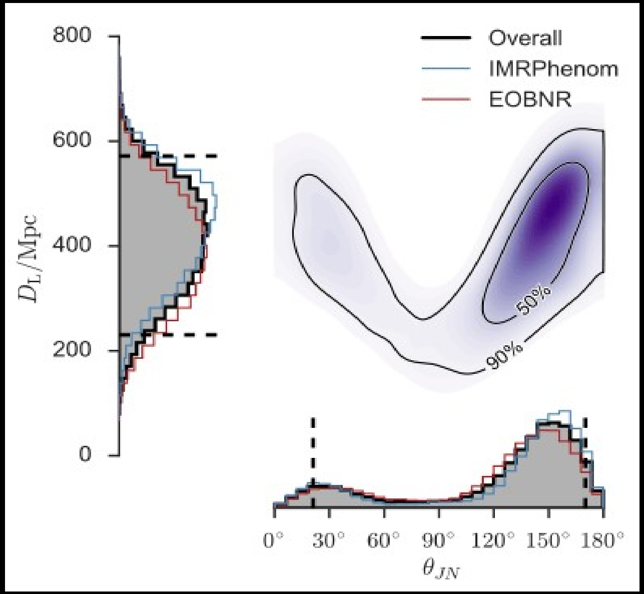
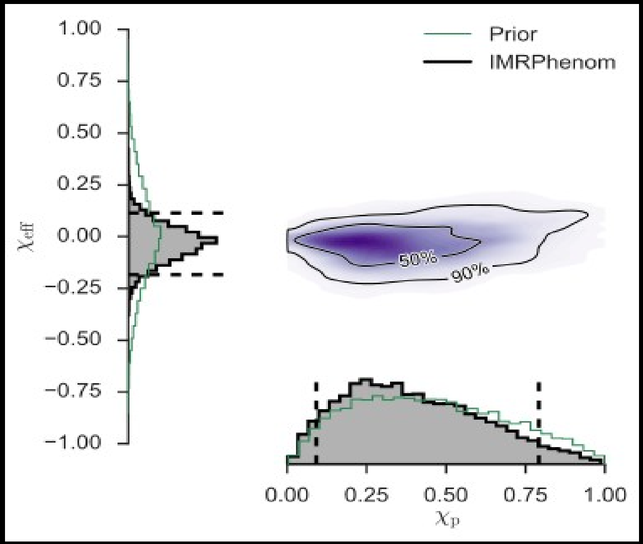


GW150914 (astro)physical properties









$$\chi_{\rm p} = \frac{c}{B_1 G m_1^2} \max(B_1 S_{1\perp}, B_2 S_{2\perp}) > 0$$

$$\chi_{\rm eff} = \frac{c}{G}\left(\frac{\boldsymbol{S}_1}{m_1} + \frac{\boldsymbol{S}_2}{m_2}\right)\cdot\frac{\hat{\boldsymbol{L}}}{M},$$

The signal came from a coalescing BHB!

- **Masses M_1=36M$_\odot$ M_2=29M$_\odot$ M_f=62M$_\odot$**
- **Distance D=400Mpc, z=0.09**
- **Spins low**
- **Eccentricity small**

The system radiated ~3 solar masses in energy during coalescence at a luminosity L~3x10^{56}erg/s

GW150914: FACTSHEET

BACKGROUND IMAGES: TIME-FREQUENCY TRACE (TOP) AND TIME-SERIES (BOTTOM) IN THE TWO LIGO DETECTORS; SIMULATION OF BLACK HOLE HORIZONS (MIDDLE-TOP), BEST FIT WAVEFORM (MIDDLE-BOTTOM)

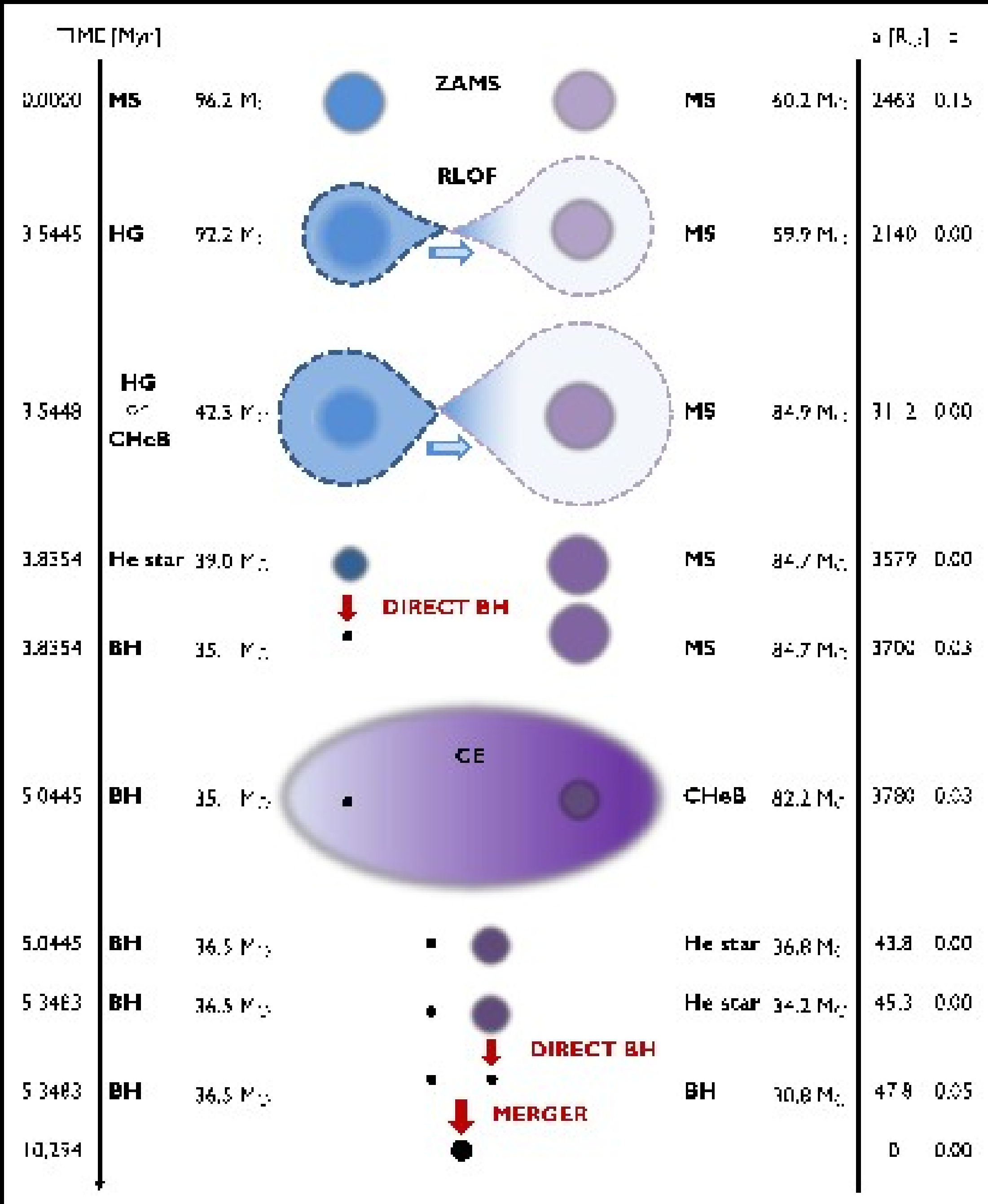
first direct detection of gravitational waves (GW) and first direct observation of a black hole binary

observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc
redshift	0.054 to 0.136
signal-to-noise ratio	24
false alarm prob.	less than 1 in 5 million
false alarm rate	1 in 200,000 yr
Source Masses	M⊙
total mass	65
chirpmass	28
primary BH	32 to 41
secondary BH	25 to 33
remnant BH	62
mass ratio	0.6 to 1
primary BH spin	< 0.7
secondary BH spin	< 0.9
remnant BH spin	0.7
signal arrival time delay	arrived in L1 7 ms before H1
likely sky position	Southern Hemisphere
likely orientation	face-on/off
resolved to	~600 sq. deg.

duration from 30 Hz	~ 200 ms
# cycles from 30 Hz	~10
peak GW strain	1×10^{-21}
peak displacement of interferometers arms	±0.002 fm
frequency/wavelength at peak GW strain	150 Hz, 2000 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	3.6×10^{56} erg s^{-1}
radiated GW energy	2.5-3.5 M⊙
remnant ringdown freq.	~ 250 Hz
remnant damping time	~ 4 ms
remnant size, area	180 km, 3.5×10^5 km^2
consistent with general relativity?	passes all tests performed
graviton mass bound	$< 1.2 \times 10^{-22}$ eV
coalescence rate	2 to 400 $Gpc^{-3} yr^{-1}$
online trigger latency	~ 3 min
# offline analysis pipelines	5
CPU hours consumed	~ 50 million (=20,000 PCs run for 100 days)
papers on Feb 11, 2016	13
# researchers	~1000, 80 institutions in 15 countries

Detector noise introduces errors in measurement. Parameters with a range (e.g. distance) are 90% credible bounds; fractional error on parameters without a range is less than 10%. Acronyms: L1=LIGO Livingston, H1=LIGO Hanford; Gly=giga lightyear=9.46×10^{12} km; Mpc=mega parsec=3.2 million lightyear, Gpc=10^3 Mpc, fm=femtometer=10^{-15} m, M⊙=1 solar mass=2×10^{30} kg

Astrophysical origin



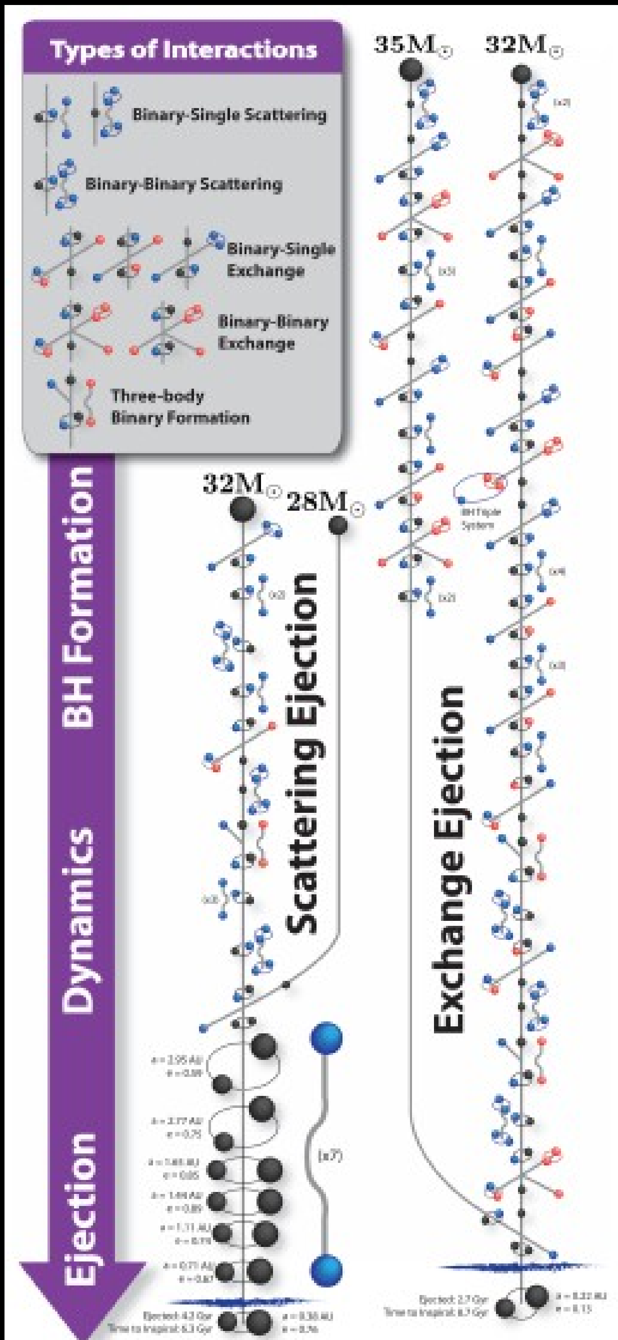
(Belczynski et al. 2016)

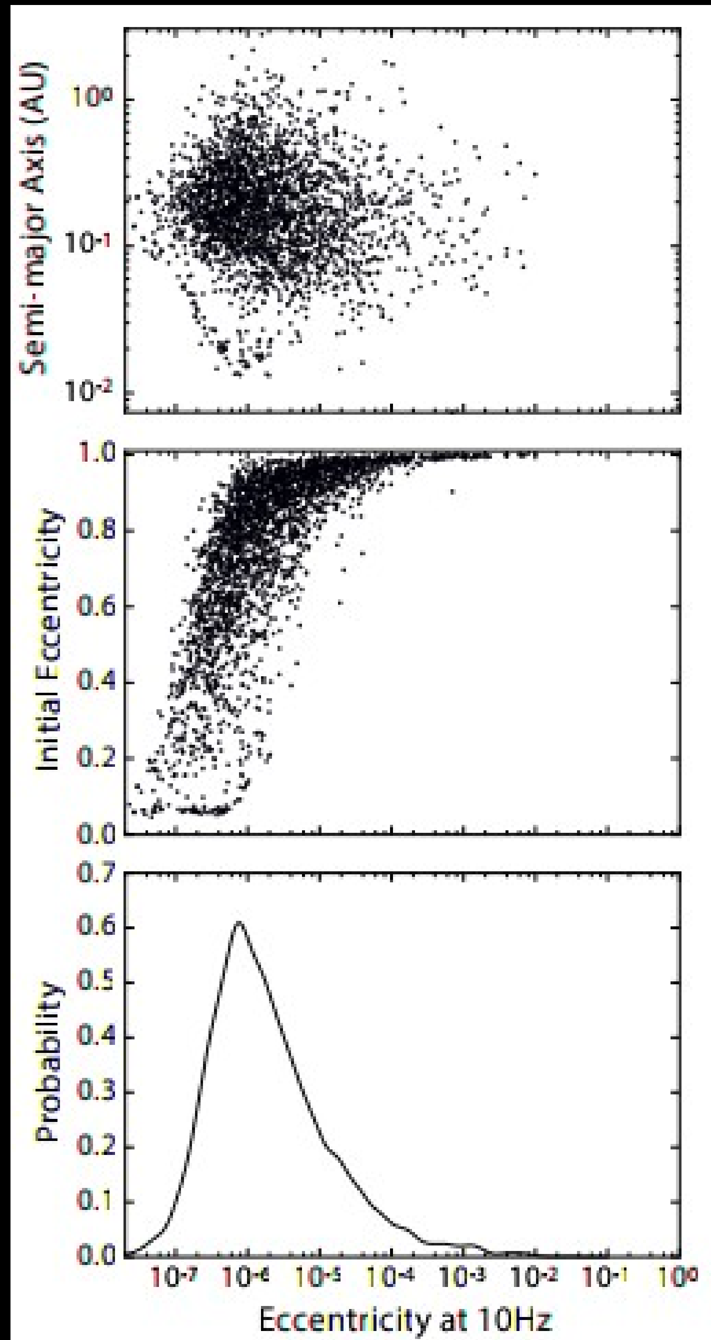
Evolution of massive Binaries

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

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

Astrophysical origin

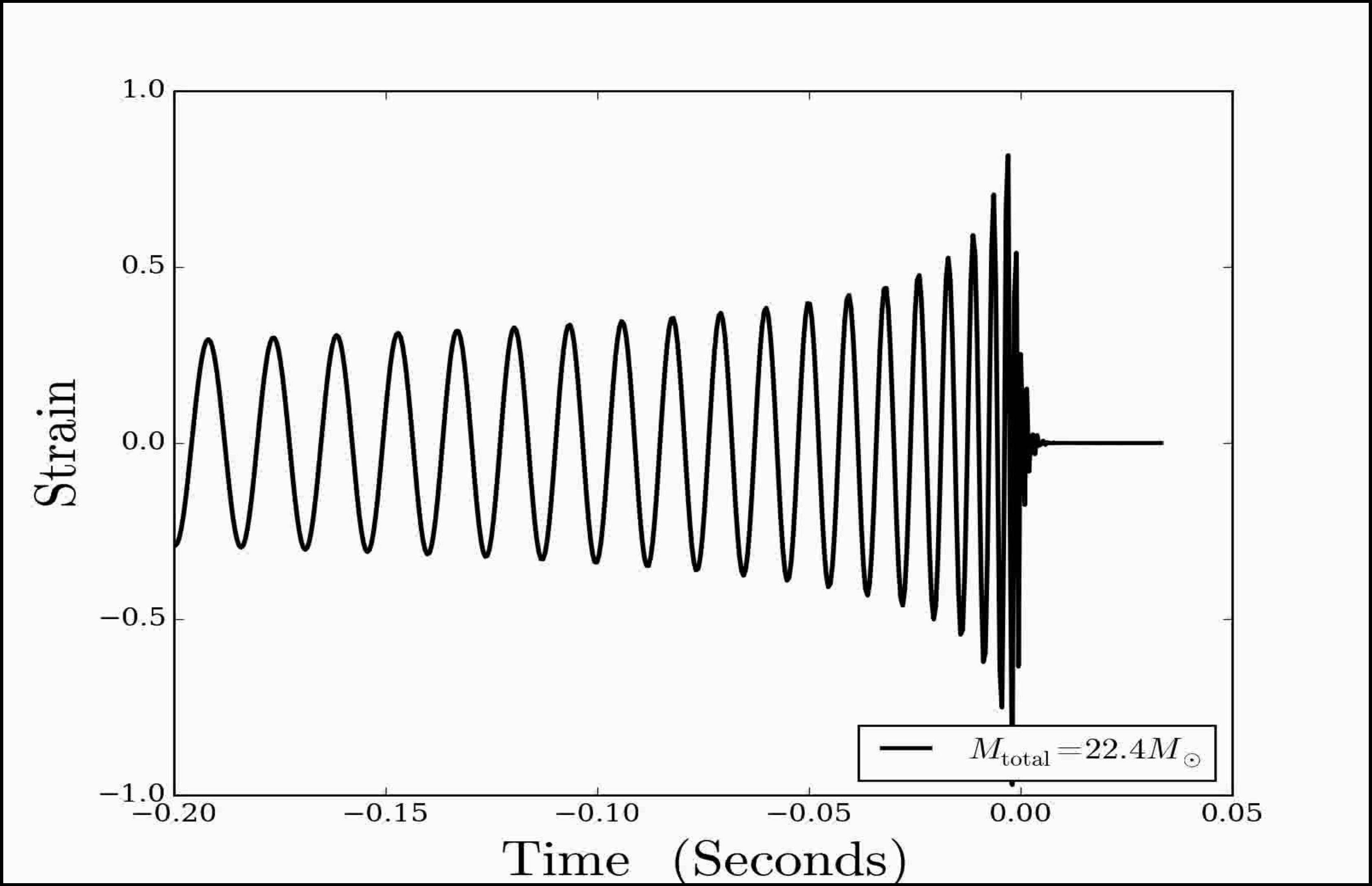




Dynamical capture

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

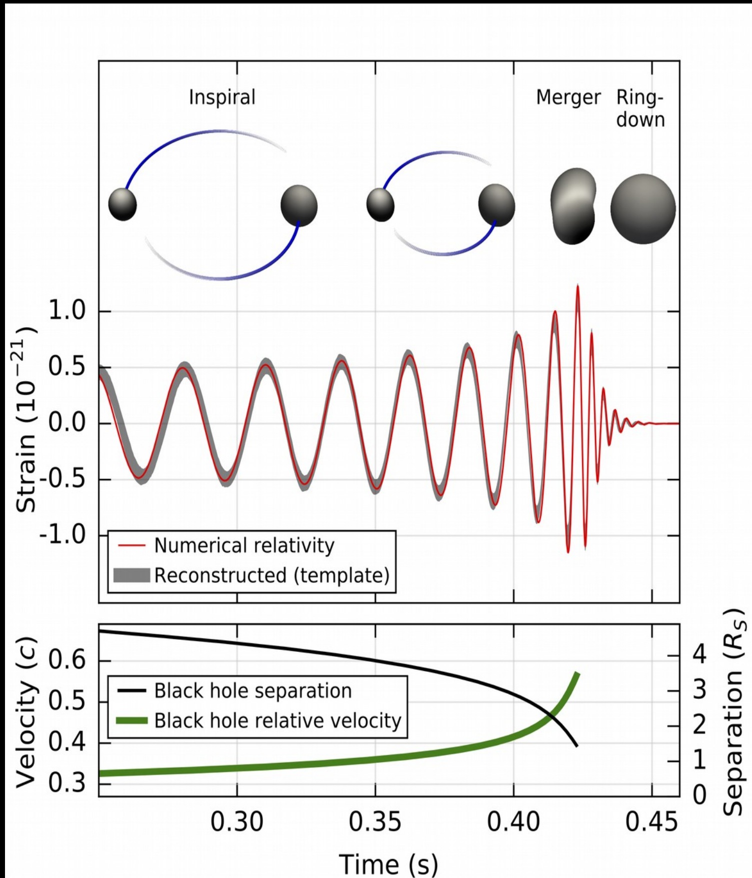
Features:
- -randomly oriented spins?
- -high formation eccentricities



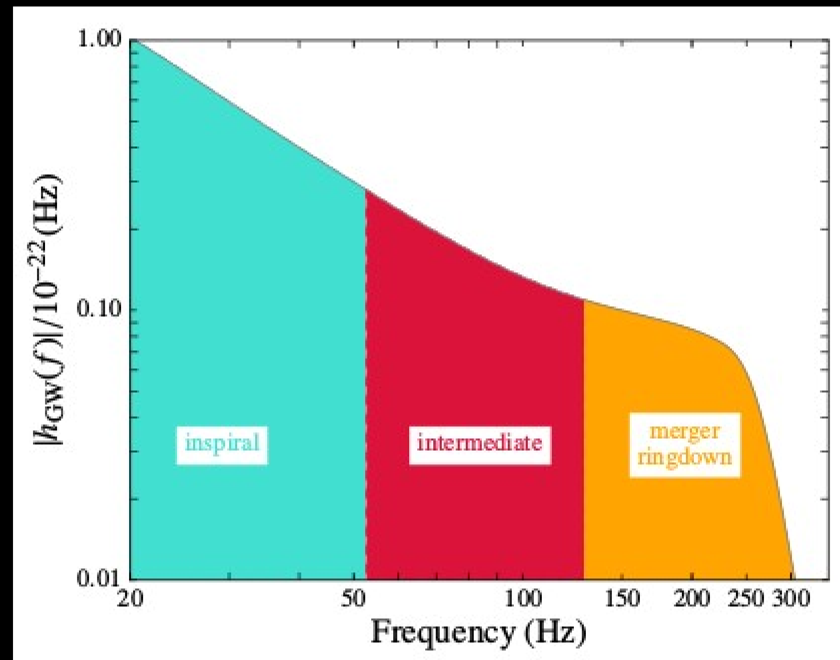
Waveforms also look different in alternative theories of gravity

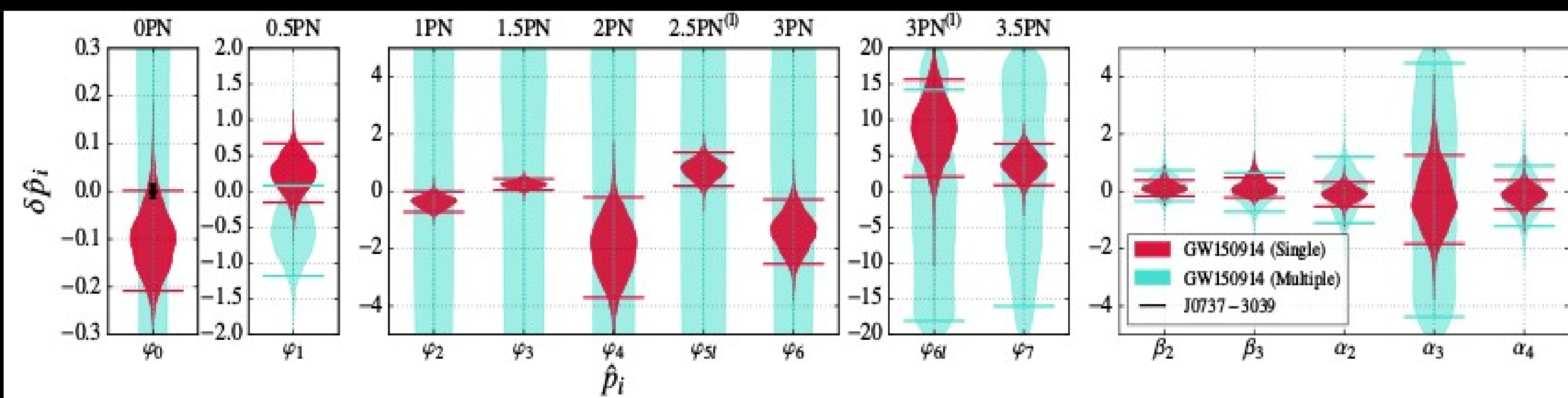
We can test GR in the strong regime!

Testing GR with GW150914



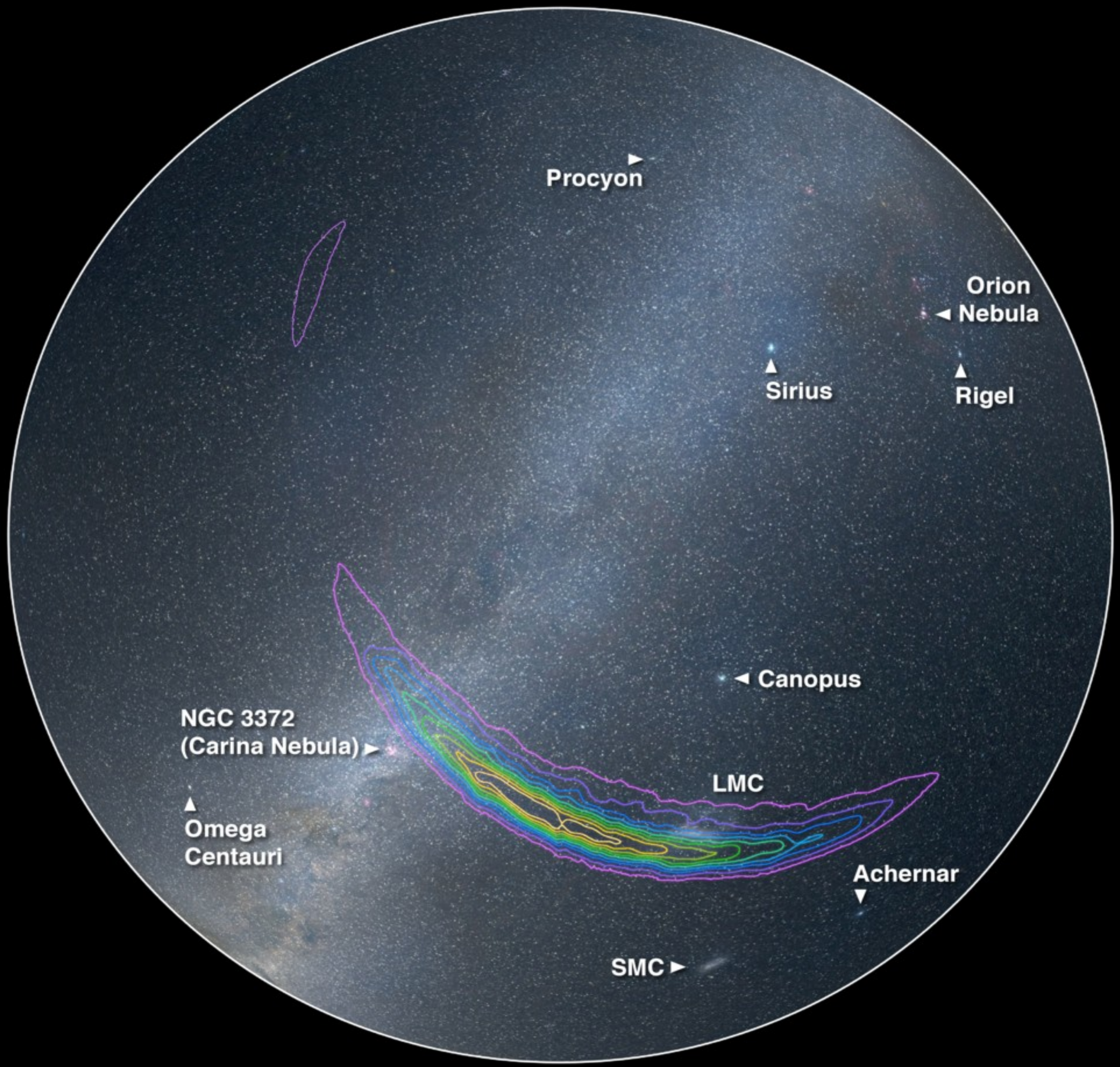
GW150914 provides the most stringent tests of gravity in the strong field regime:
NO EVIDENCE FOR DEVIATIONS FROM GR



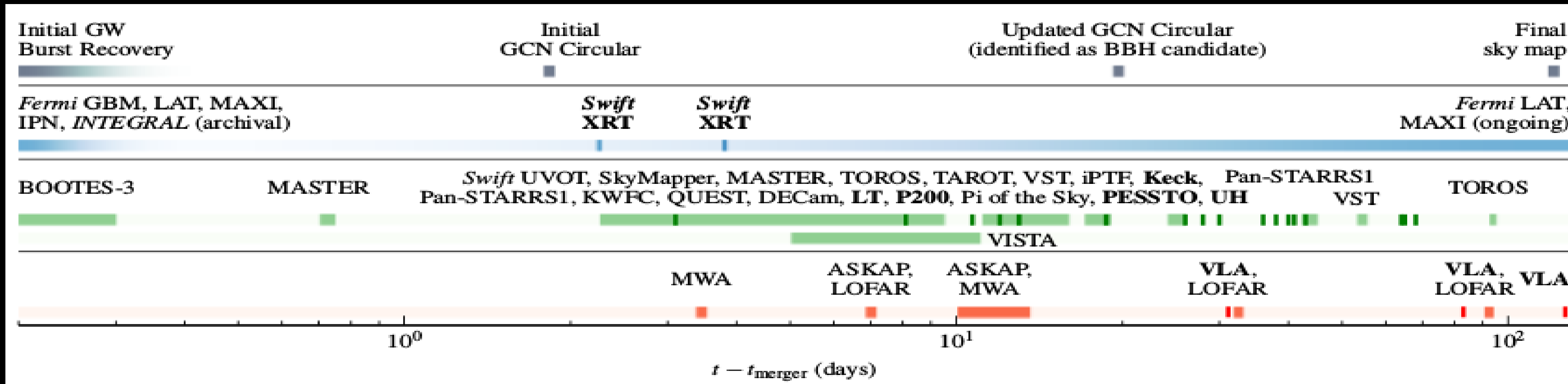


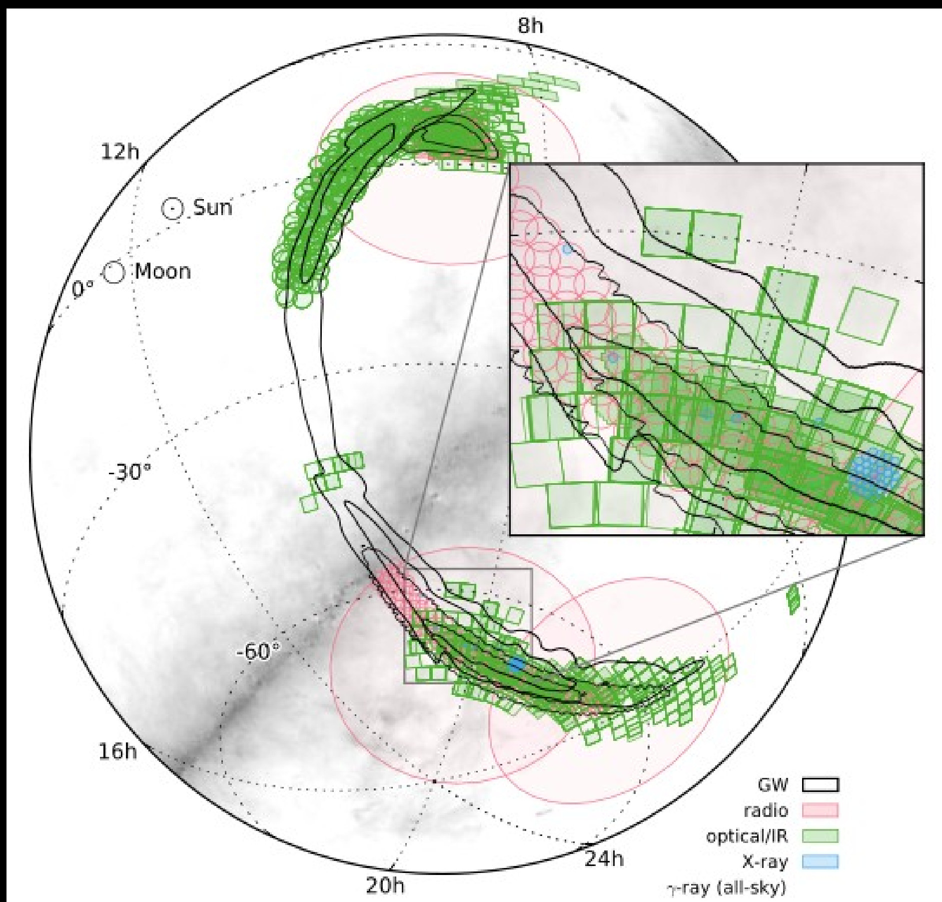
Sky localization and follow-up campaigns

(LIGO & friends 2016, arXiv:1602.08492)



With two detectors only sky localization is very poor: more than 500 sq degrees in the southern sky





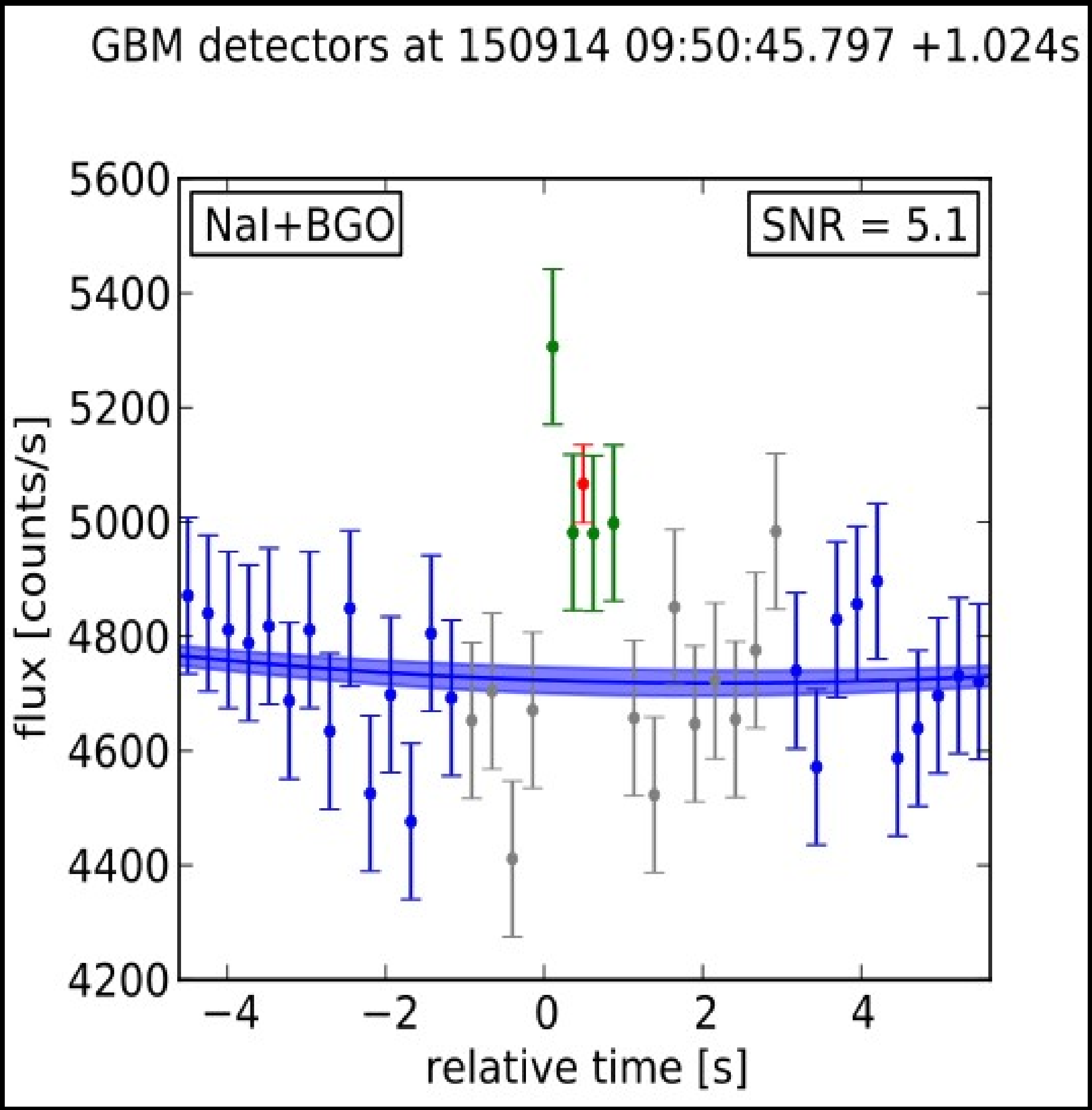
Nevertheless everybody jumped on the event for follow-ups

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)

Fermi association

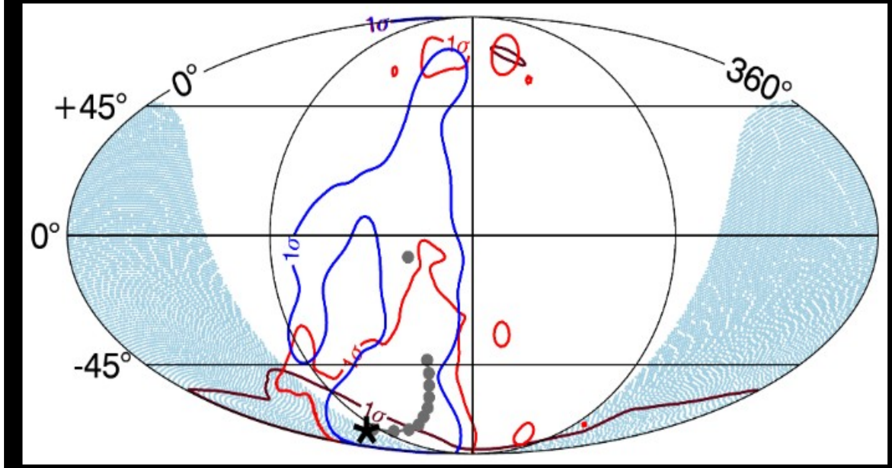
In fact the only tentative signal associated to GW150914 came from a nearly all-sky high energy monitor: GBM on board Fermi



GBM detected an excess flux in the second following GW150914, with claimed FAP=0.0022

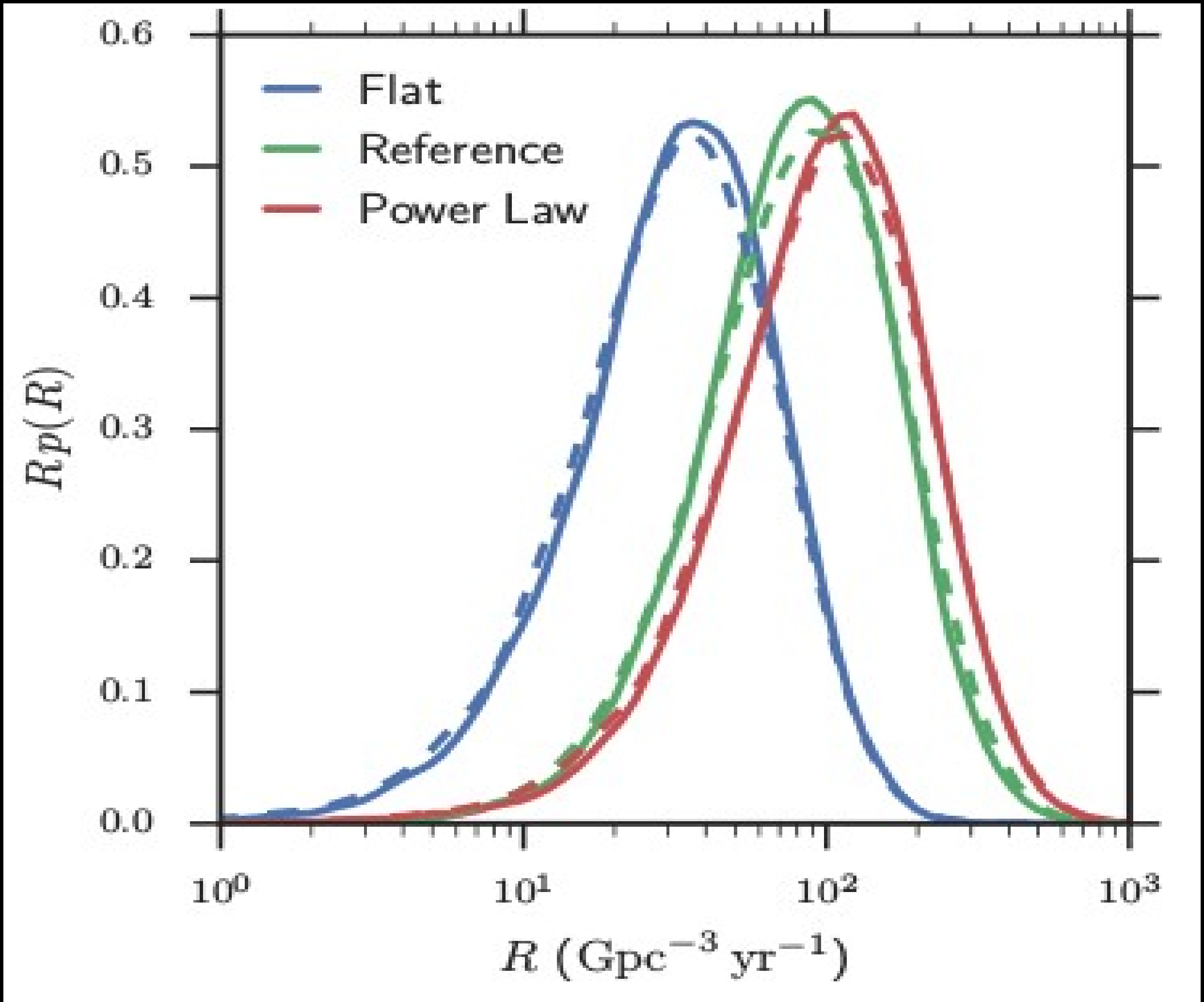
However no other wide field high energy instrument (BAT, MAXI, INTEGRAL...) detected any signal

(Savchenko et al. 2016)



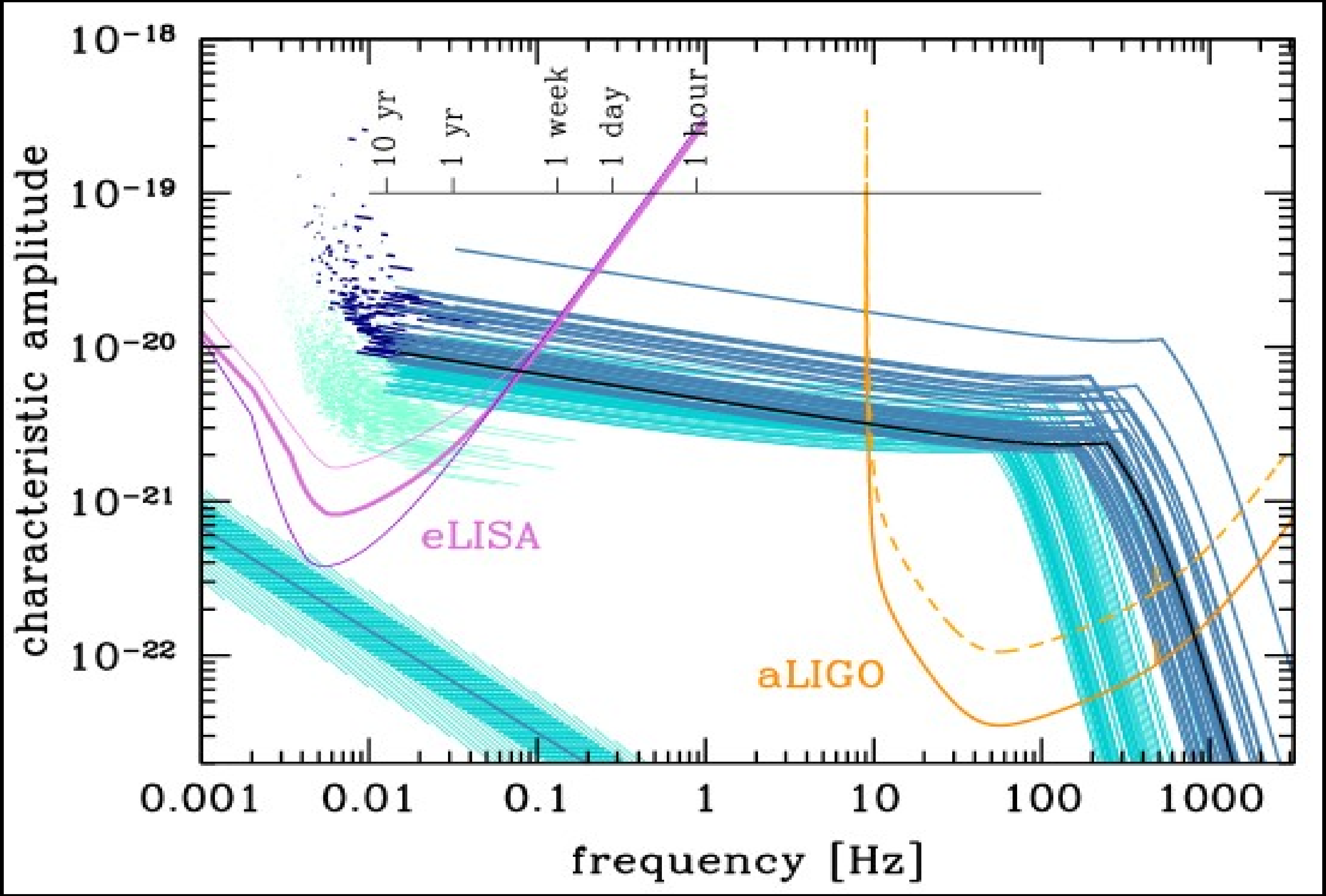
(Connaughton et al. 2016)

Empirical merger rate determination



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

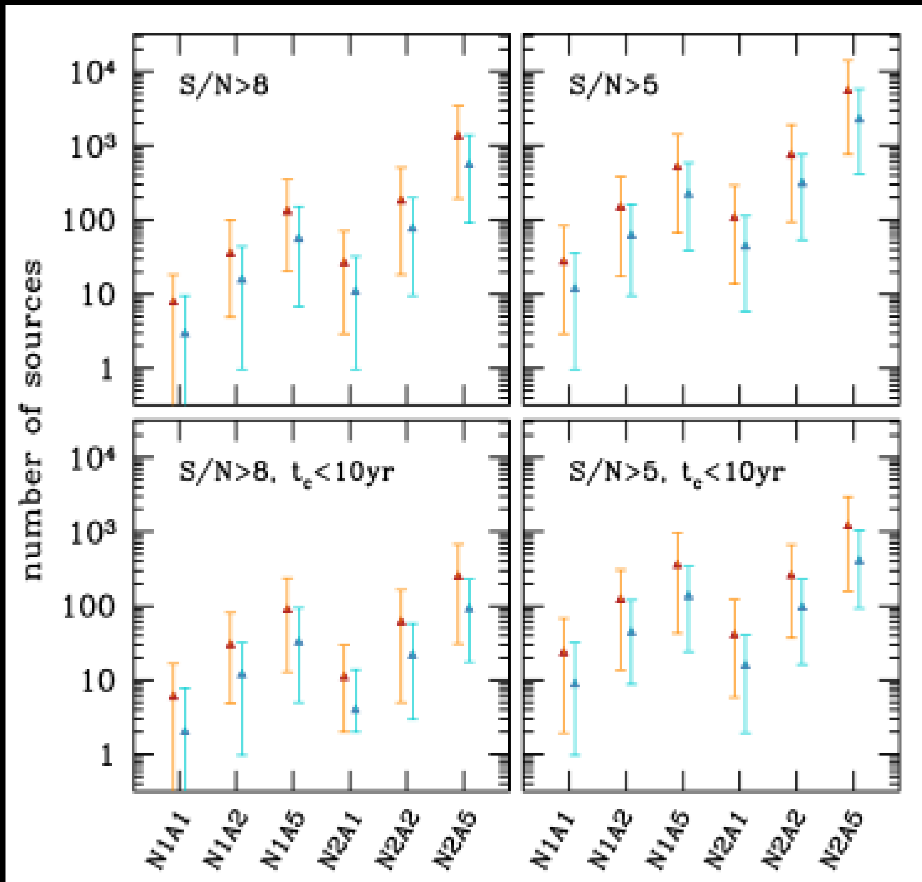
An unexpected implication: multi-band GW astronomy



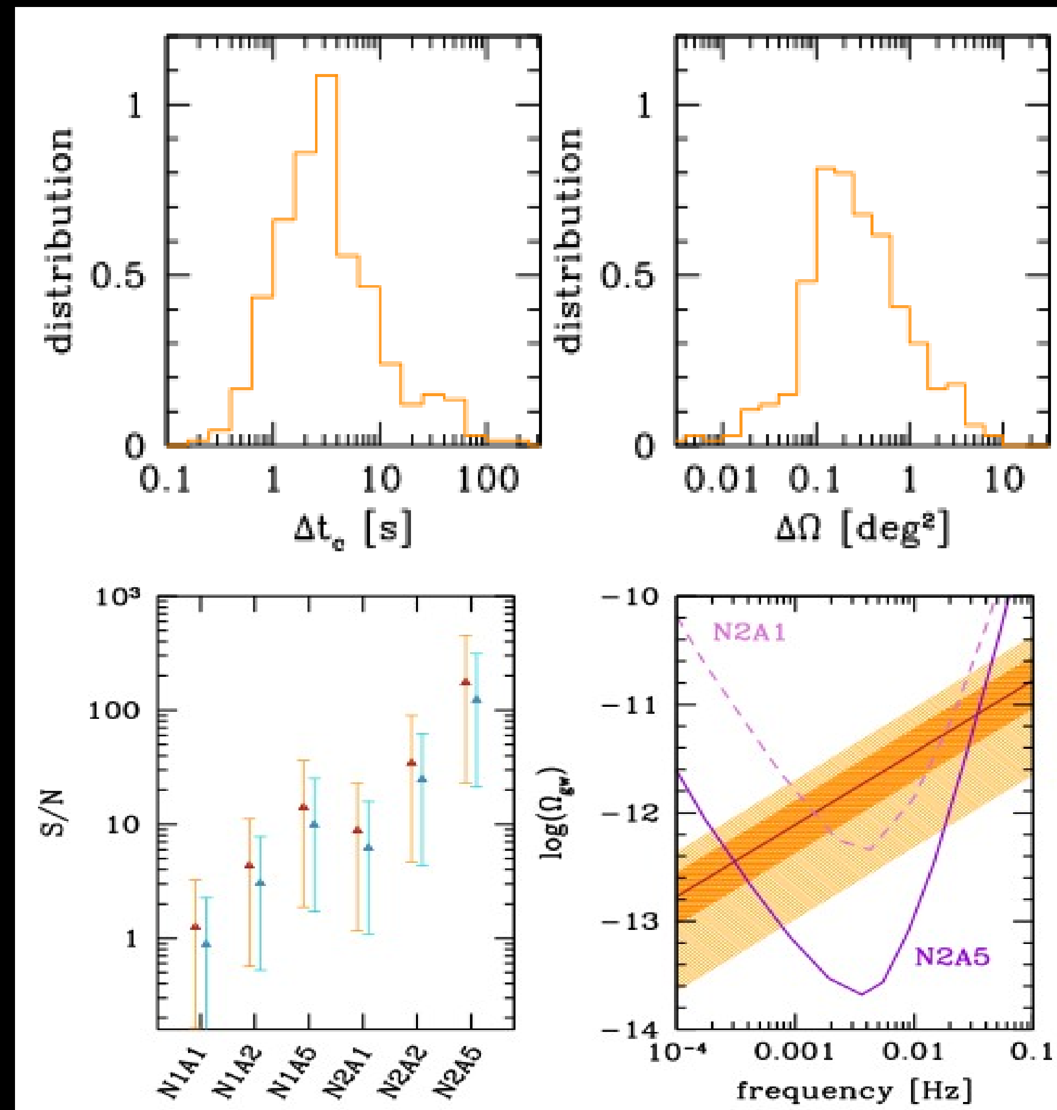
(AS 2016, arXiv:1602.06951)

Up to 100 BHB will be detected by eLISA and cross to the LIGO band, assuming a 5 year operation of eLISA.

Number of sources and parameter estimation



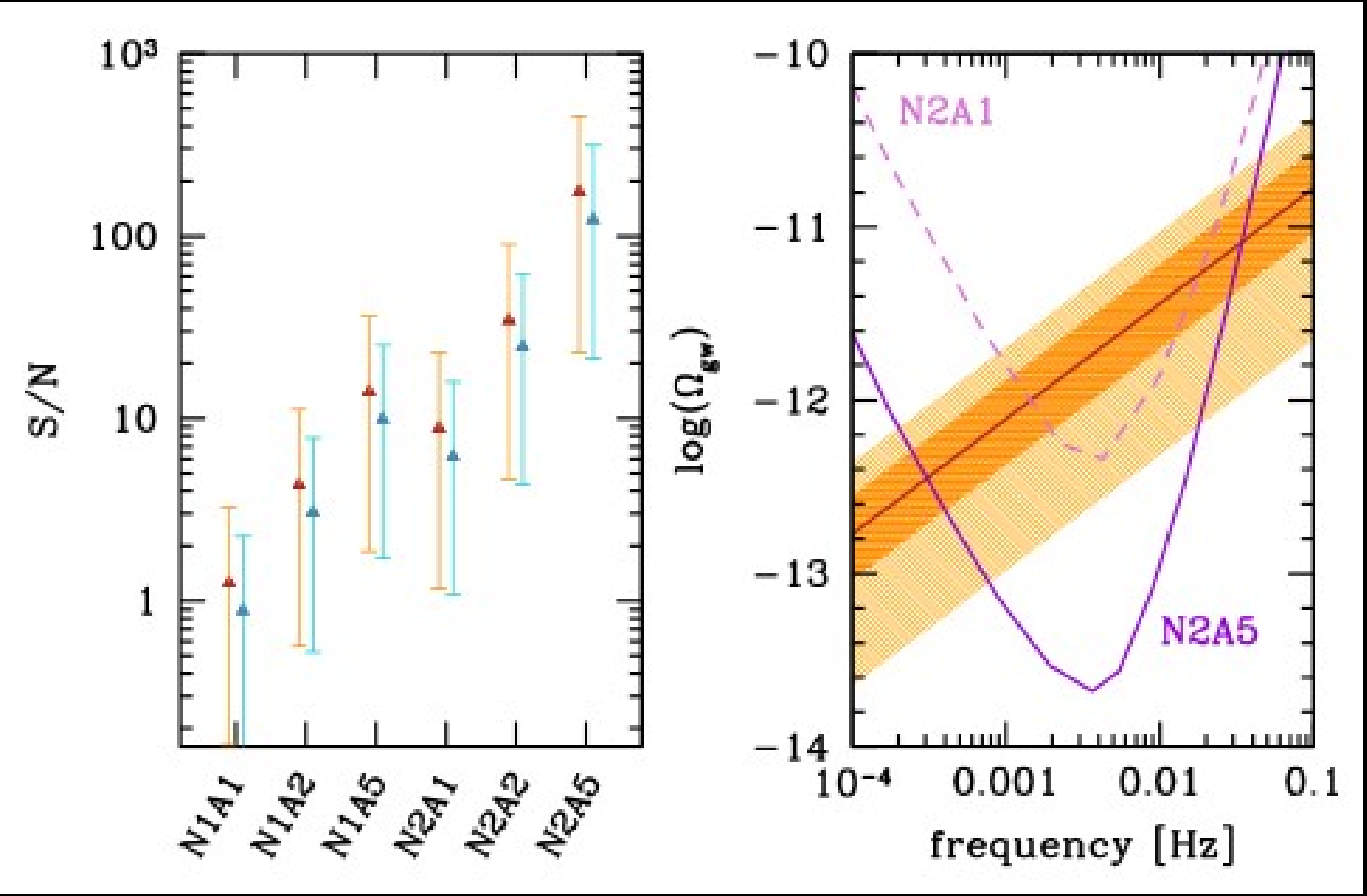
eLISA will detect up to a thousand BHBs with S/N>8



System crossing to the aLIGO band can be located with sub deg2 precision and the merger time can be predicted within 10 seconds

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

Bonus: unresolved background



eLISA will detect an unresolved background with S/N~1-100

Benefits

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

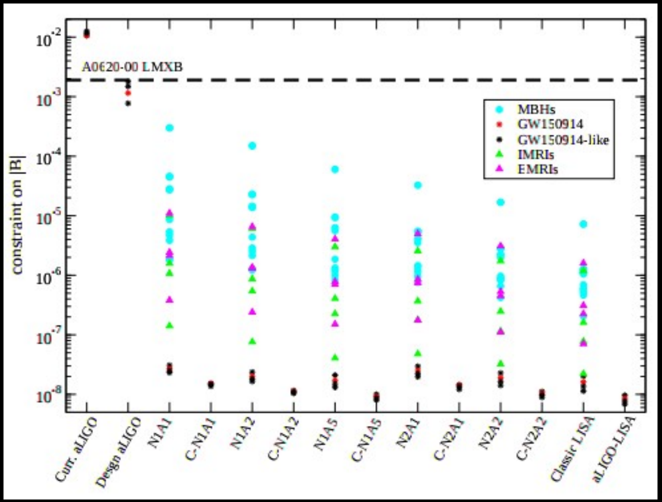
>Multiband GW astronomy:

- **-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**

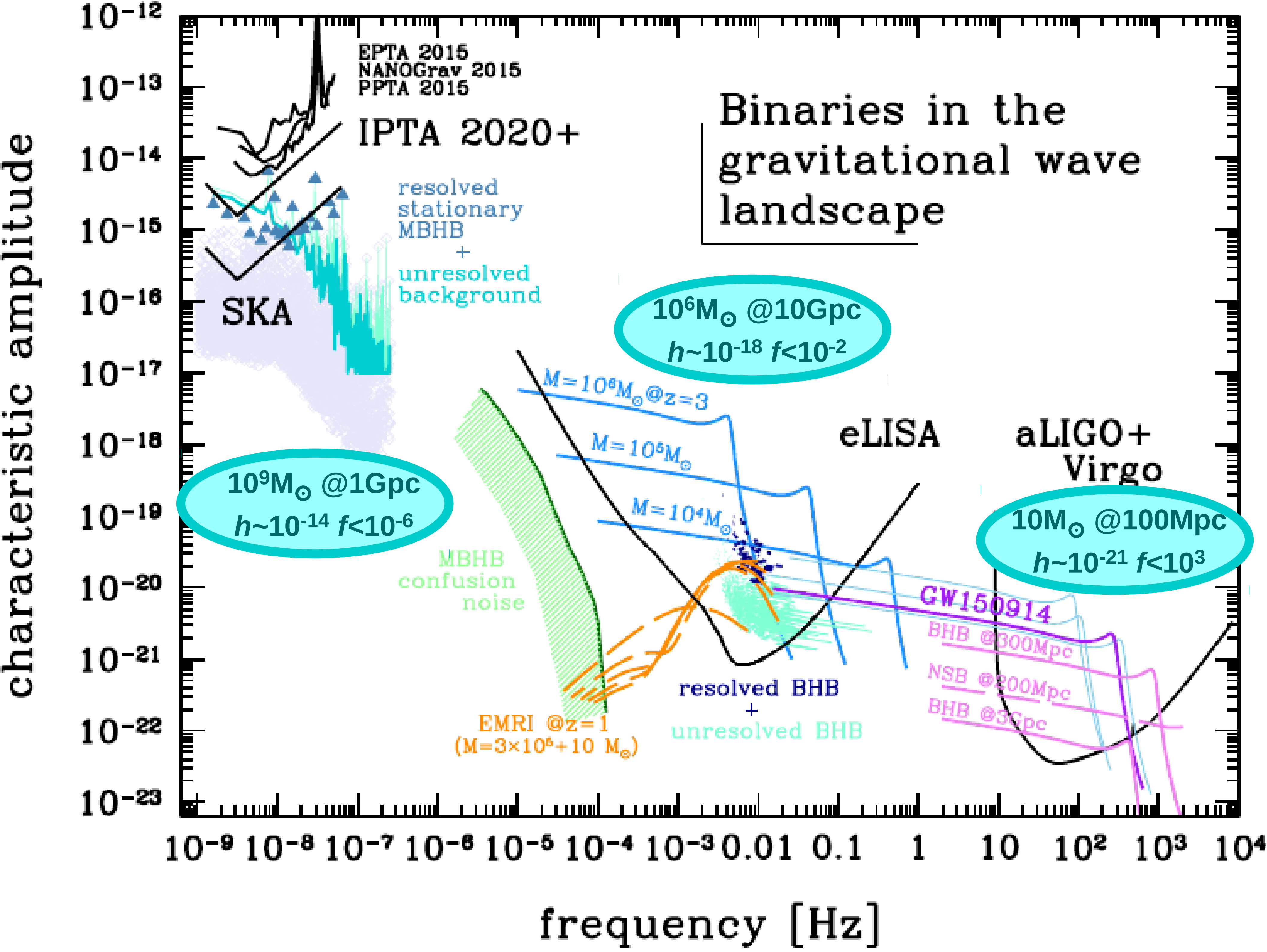
>Enhanced tests of GR: e.g. strongest limits on dipole radiation



>Astrophysics:

- **-independent measure of spins**
- **-measure of eccentricity**

>Cosmology: new population of standard sirens?



characteristic amplitude
frequency [Hz]
EPTA 2015
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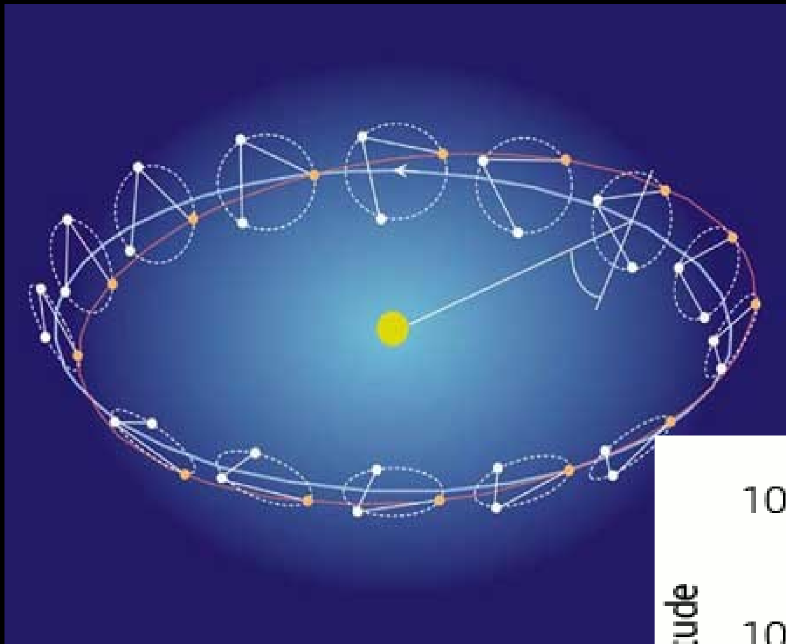
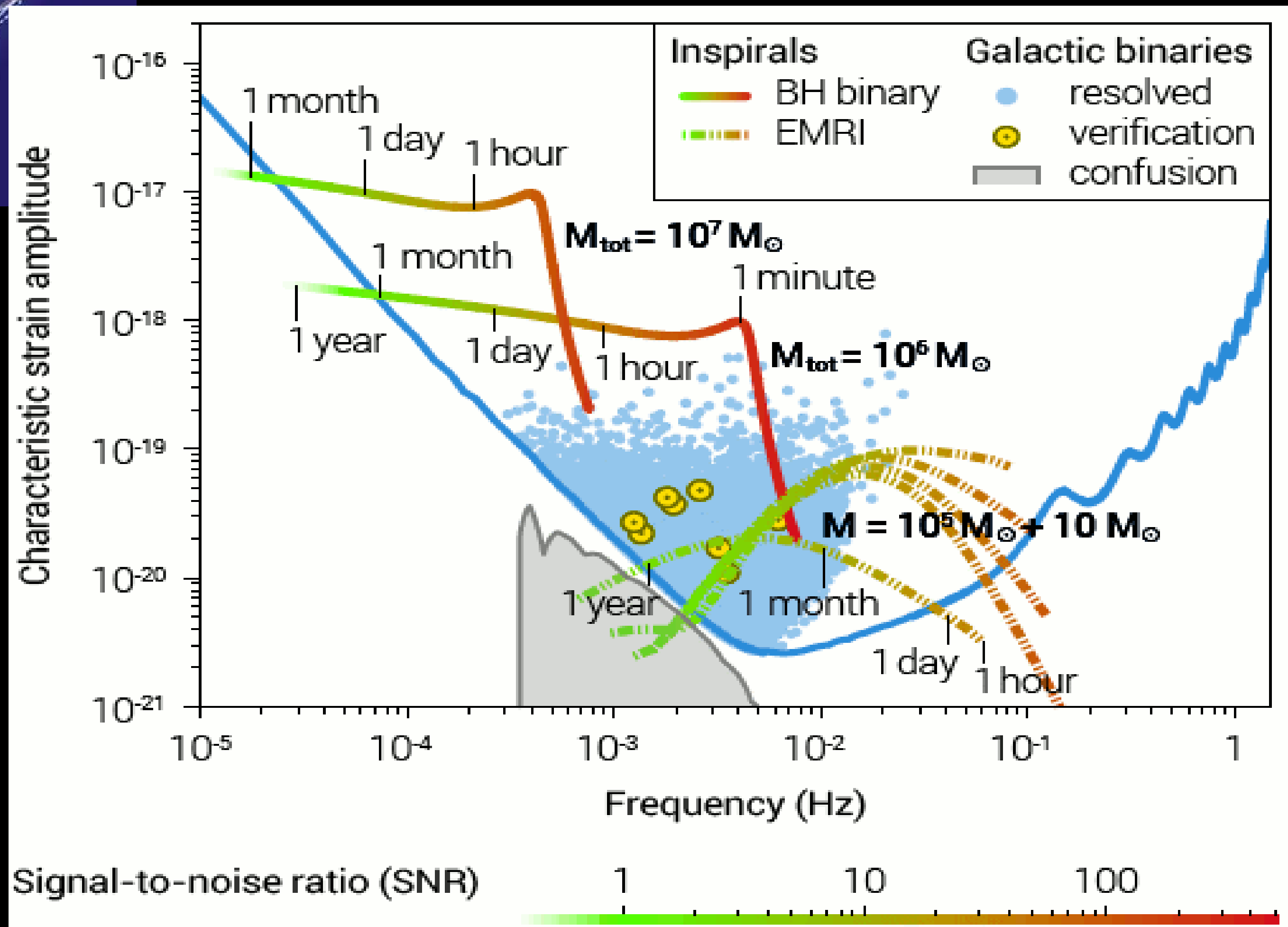
PPTA 2015
IPTA 2020+
SKA
resolved stationary MBHB + unresolved background
Binaries in the gravitational wave landscape
$10^6 M_\odot$ @10Gpc
$h \sim 10^{-18}$ $f < 10^{-2}$
$10^9 M_\odot$ @1Gpc
$h \sim 10^{-14}$ $f < 10^{-6}$
$10 M_\odot$ @100Mpc
$h \sim 10^{-21}$ $f < 10^{3}$
$M=10^6 M_\odot$ @z=3
$M=10^5 M_\odot$
$M=10^4 M_\odot$
eLISA
aLIGO+ Virgo
MBHB confusion noise
GW150914
BHB @300Mpc
NSB @200Mpc
BHB @3Gpc
EMRI @z=1
($M=3\times10^5+10$ $M_\odot$)
resolved BHB + unresolved BHB

The evolving Laser Interferometer Space Antenna



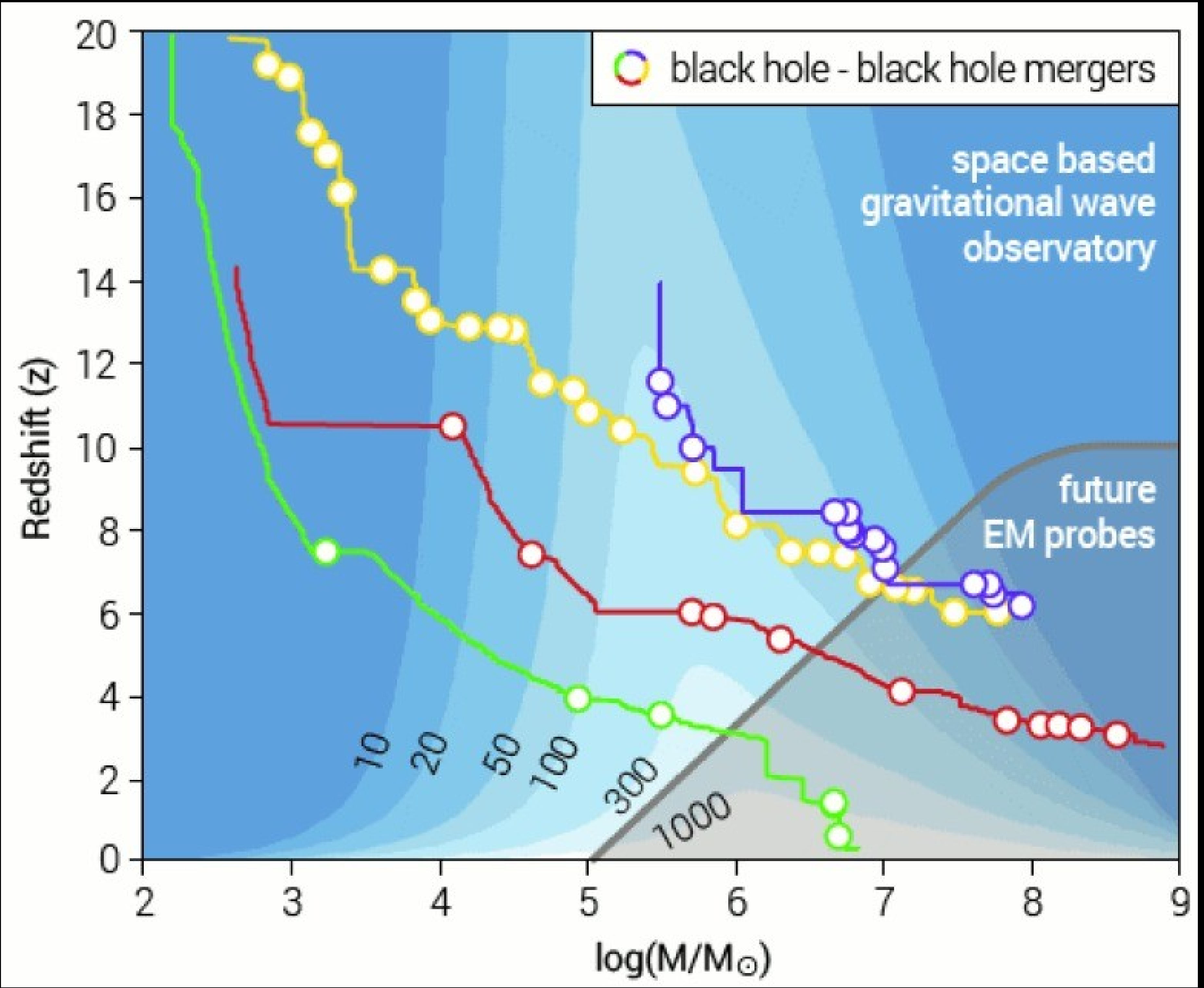
Sensitive in the mHz frequency range where massive black hole binary (MBHB) evolution is fast (chirp)

Observes the full inspiral/merger/ringdown



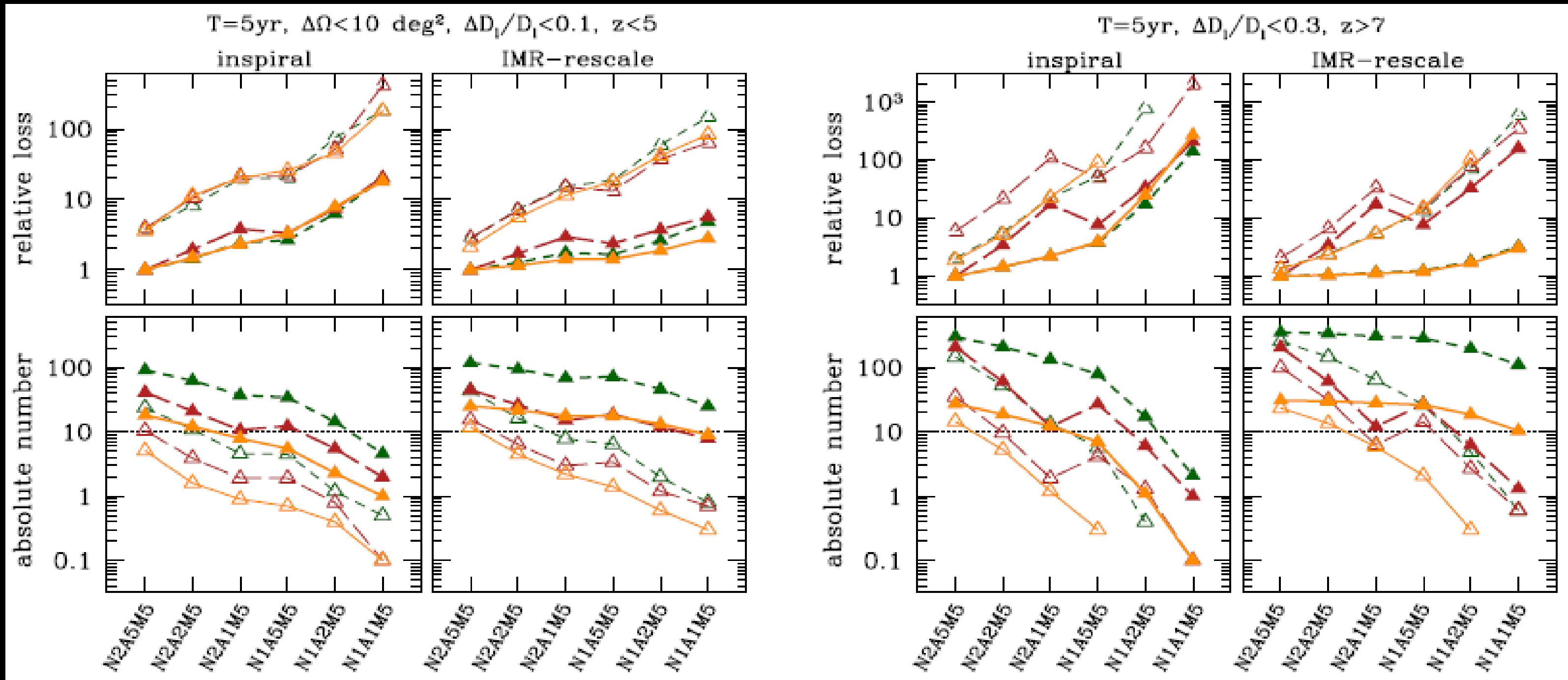
3 satellites trailing the Earth connected through laser links

Baseline not yet decided, currently under study


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

Example: source sky localization

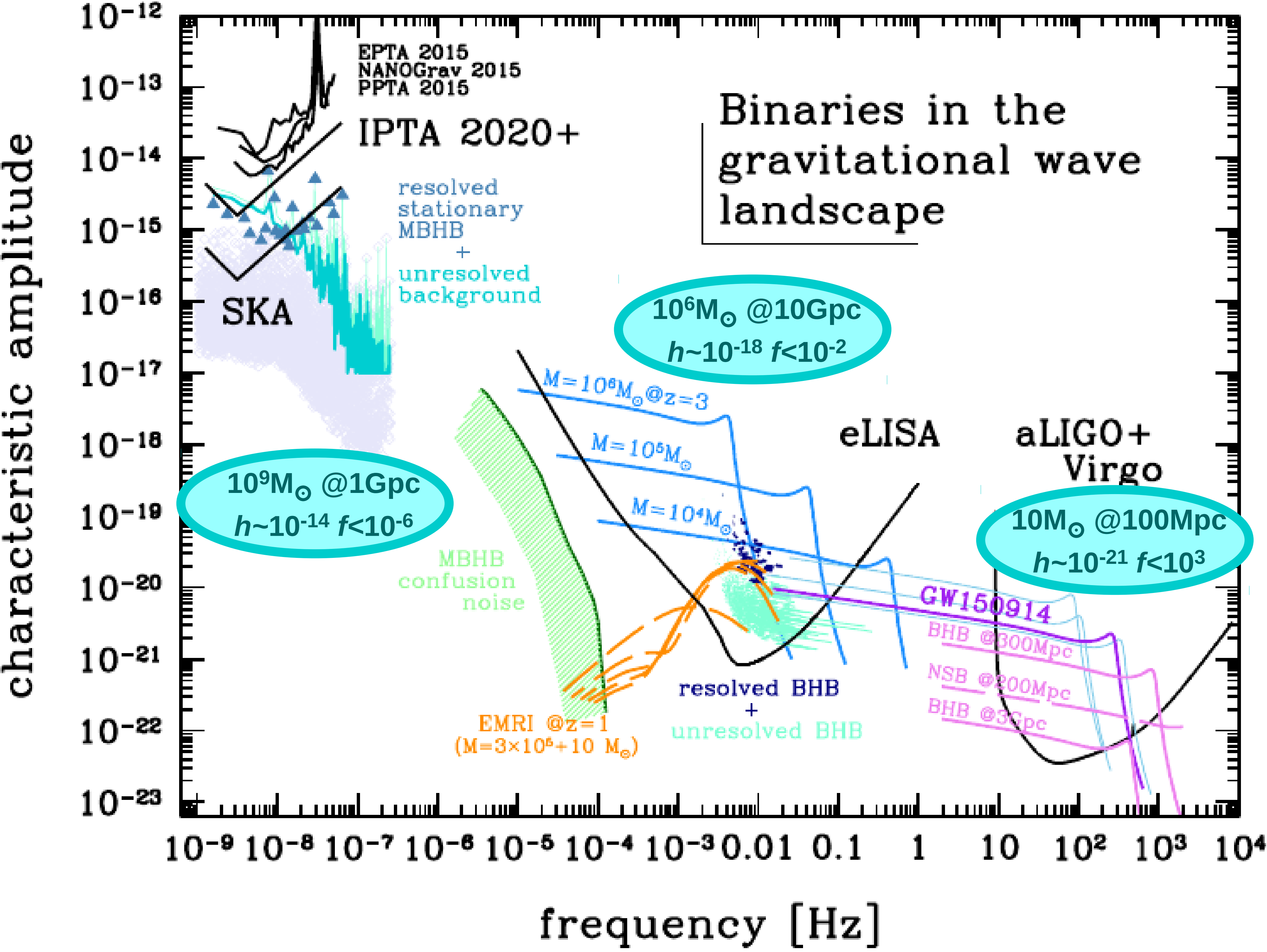
(Klein et al. 2016)



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

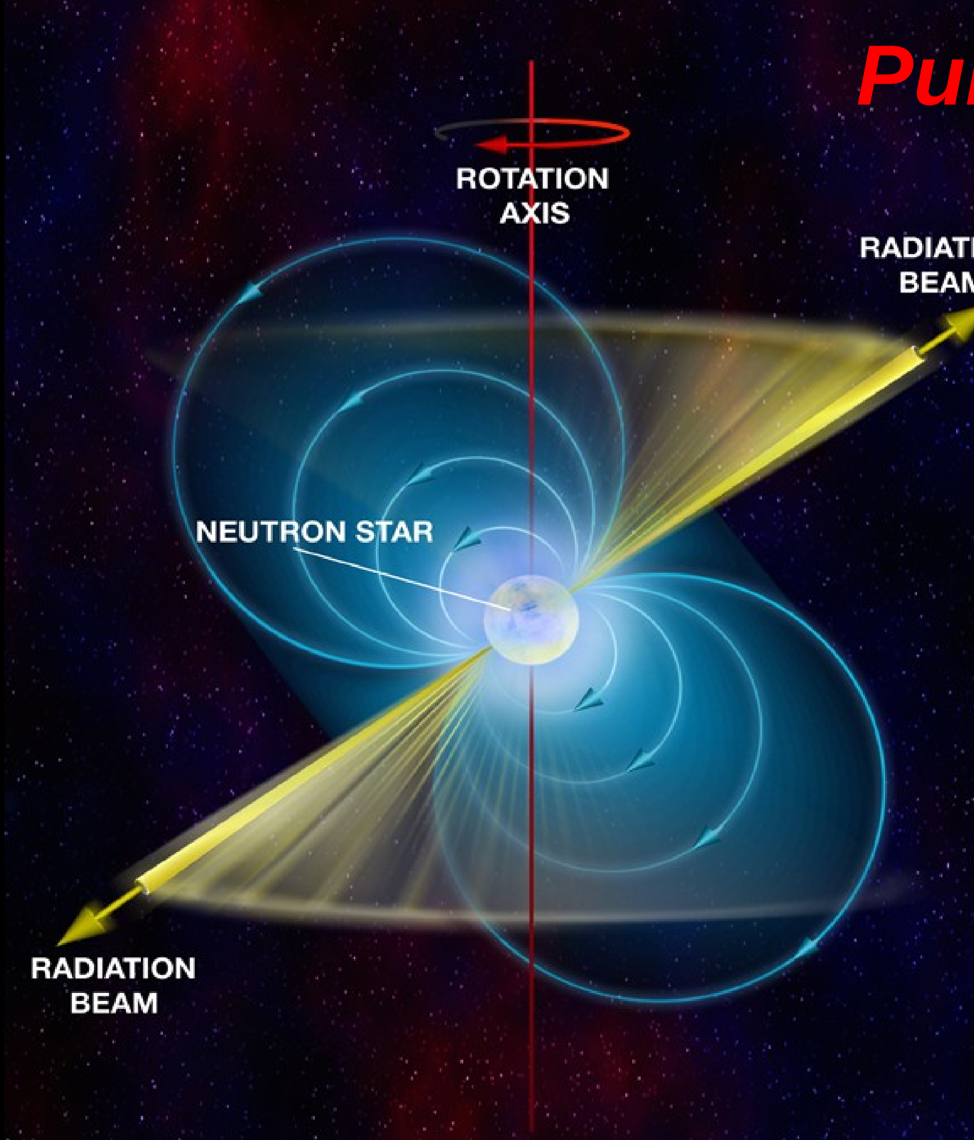
LISA Pathfinder lift off!!!

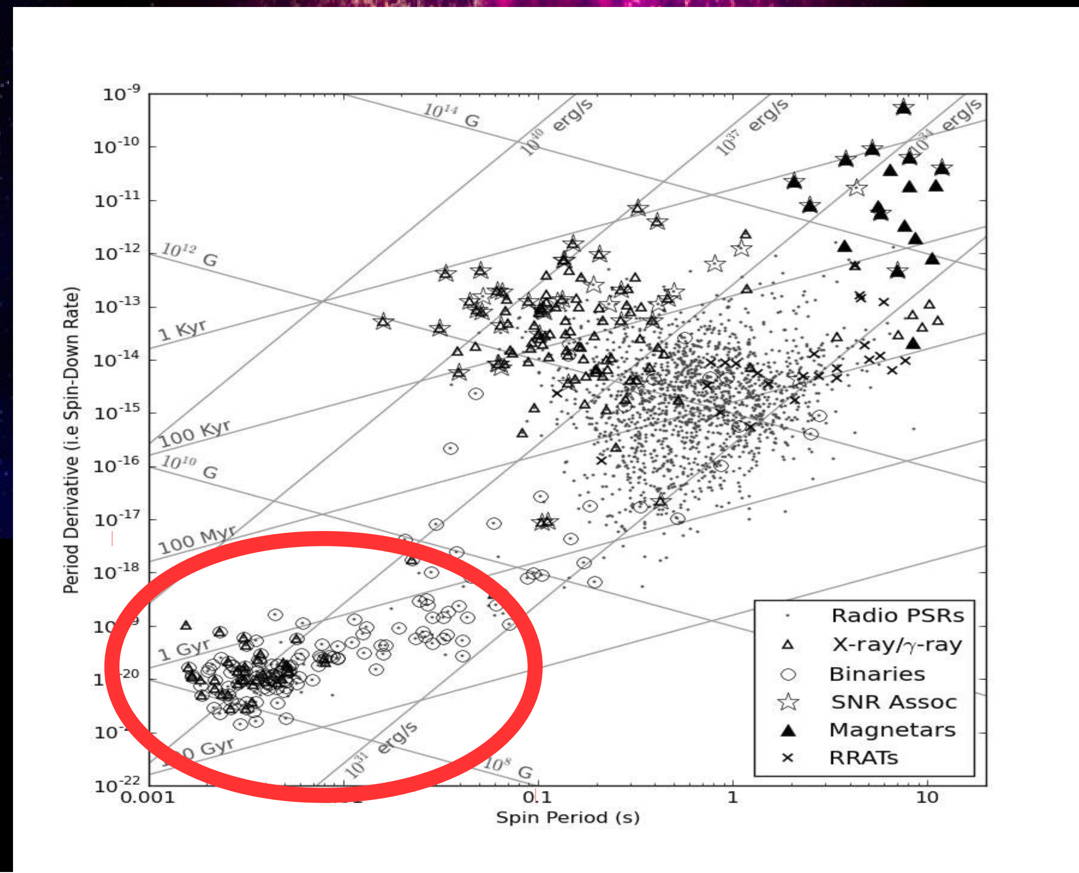
LISA Pathfinder lift off!!!



characteristic amplitude
frequency [Hz]
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
$h \sim 10^{-18}$ $f<10^{-2}$
$10^9 M_\odot$ @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
$M=10^5 M_\odot$
$M=10^4 M_\odot$
eLISA
aLIGO+ Virgo
MBHB confusion noise
GW150914
BHB @300Mpc
NSB @200Mpc
BHB @3Gpc
EMRI @z=1
($M=3\times10^5+10\ M_\odot$)
resolved BHB + unresolved BHB

Pulsars



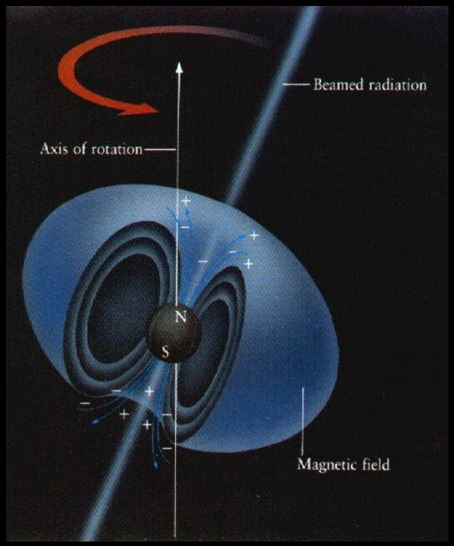


- M ~1.4 solar mass
- R~10 km
- P~0.0014-10 s
- B~10^8 -10^{15} G

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



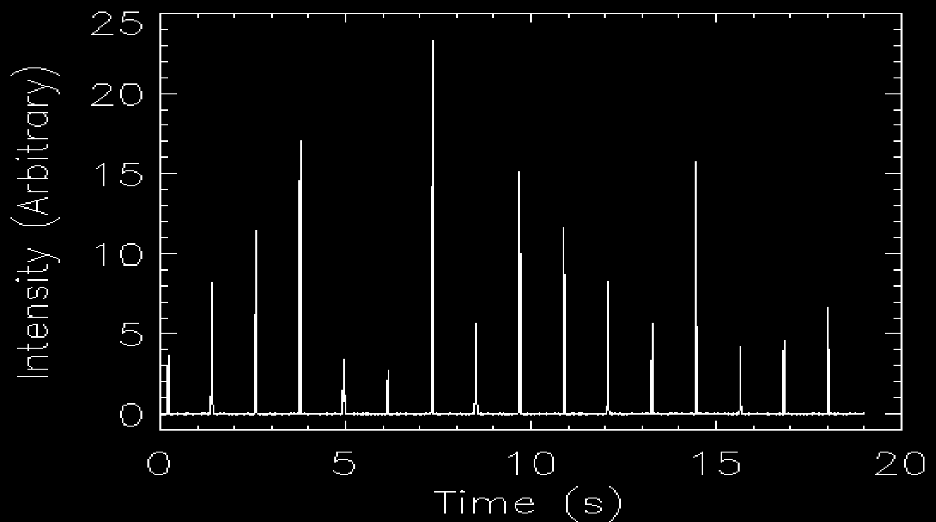
1-Observe a pulsar and measure the ToAs

2-Find the model which best fits the ToAs

3-Compute the timing residual R

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

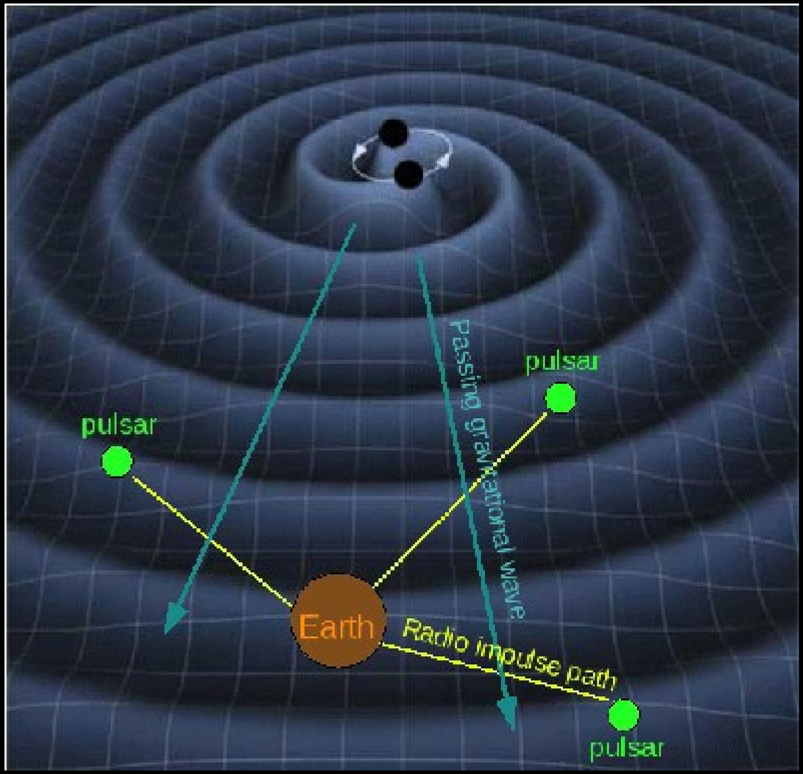
If the timing solution is perfect (and observations noiseless), then *R*=0. *R* contains all uncertainties related to the signal propagation and detection, plus the effect of unmodelled physics, like (possibly) ***gravitational waves***



Effect of gravitational waves

The GW passage causes a modulation of the observed pulse frequency

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



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

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

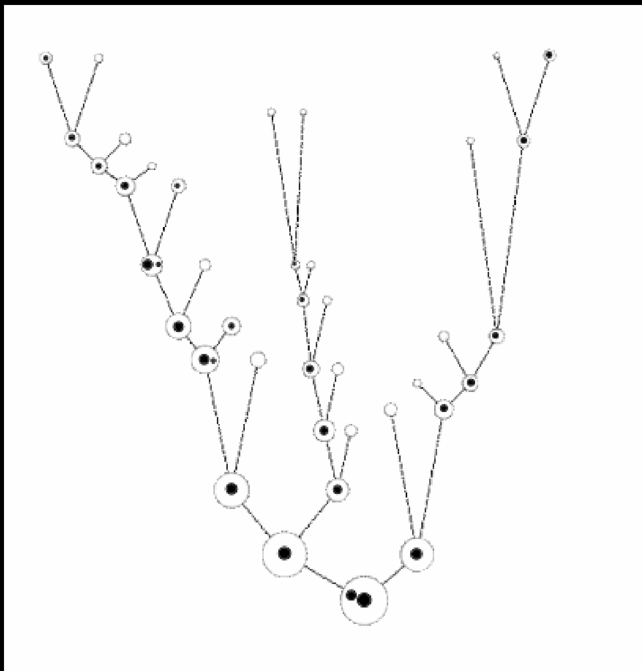
(Sazhin 1979, Hellings & Downs 1983, Jenet et al. 2005, AS et al. 2008, 2009)

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

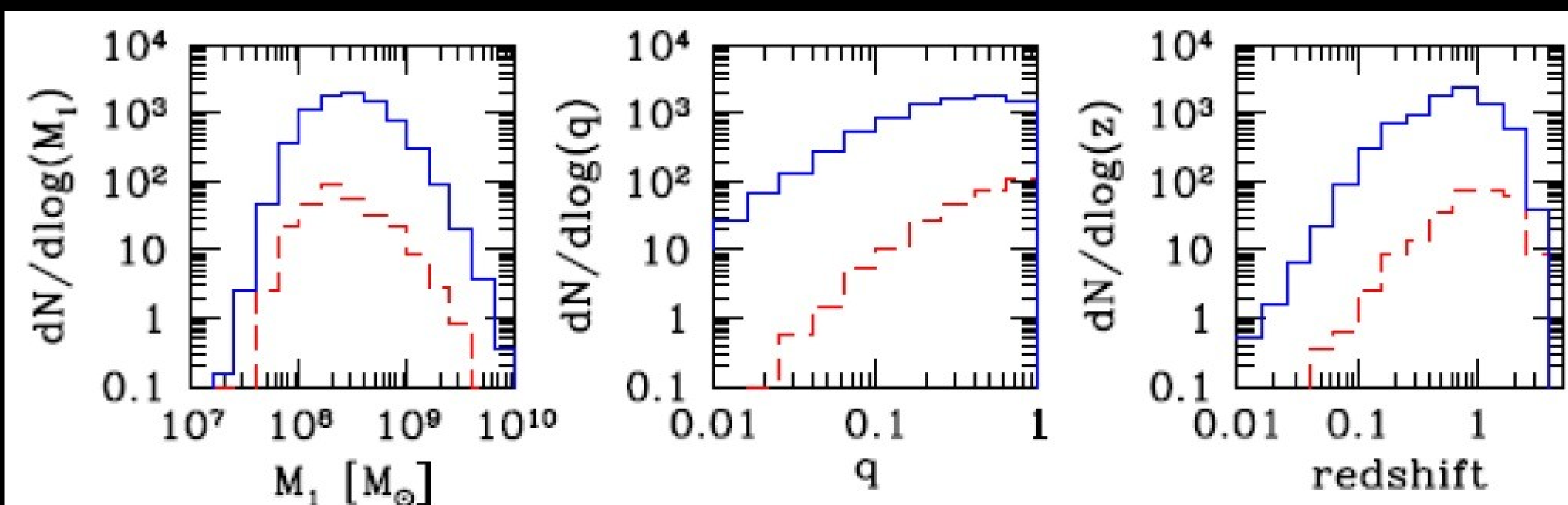
$$h_c^2(f) = \int_0^\infty dz \int_0^\infty d\mathcal{M} \, \frac{d^3N}{dz\,d\mathcal{M}\,d\ln f_r} h^2(f_r)$$

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

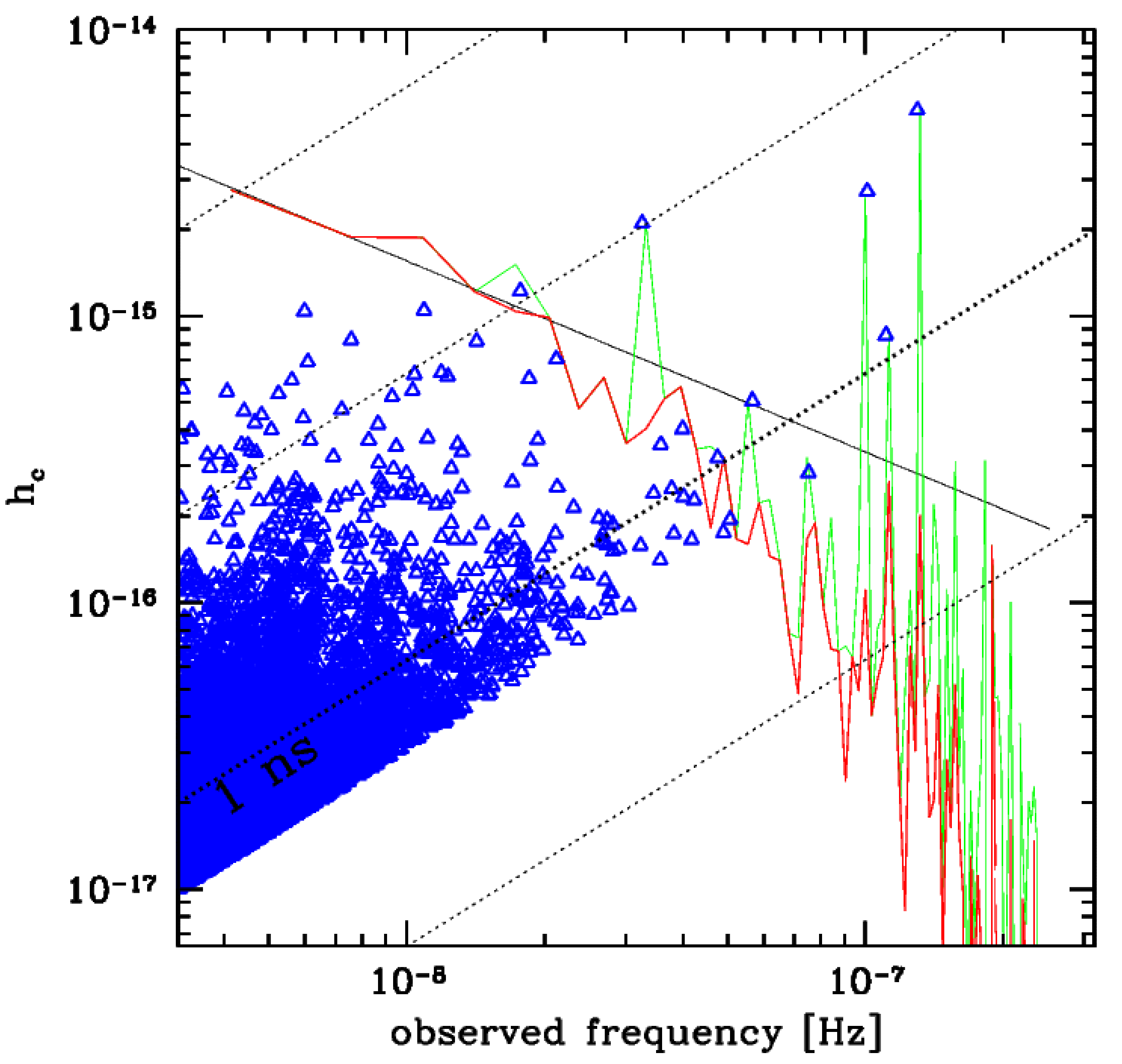
Theoretical spectrum: simple power law

(Phinney 2001)

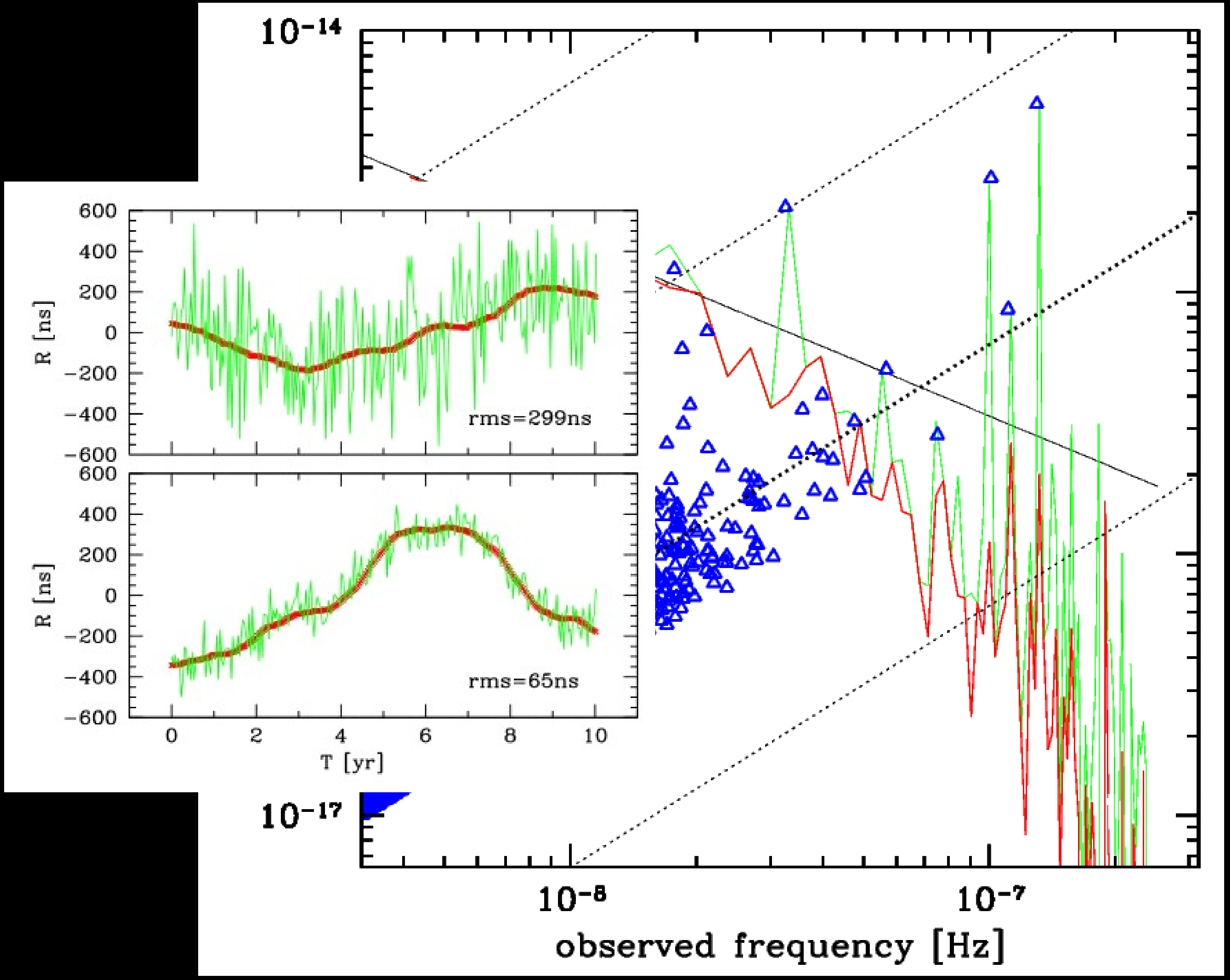
$$h_c(f) = A \left(\frac{f}{\rm yr^{-1}} \right)^{-2/3}$$



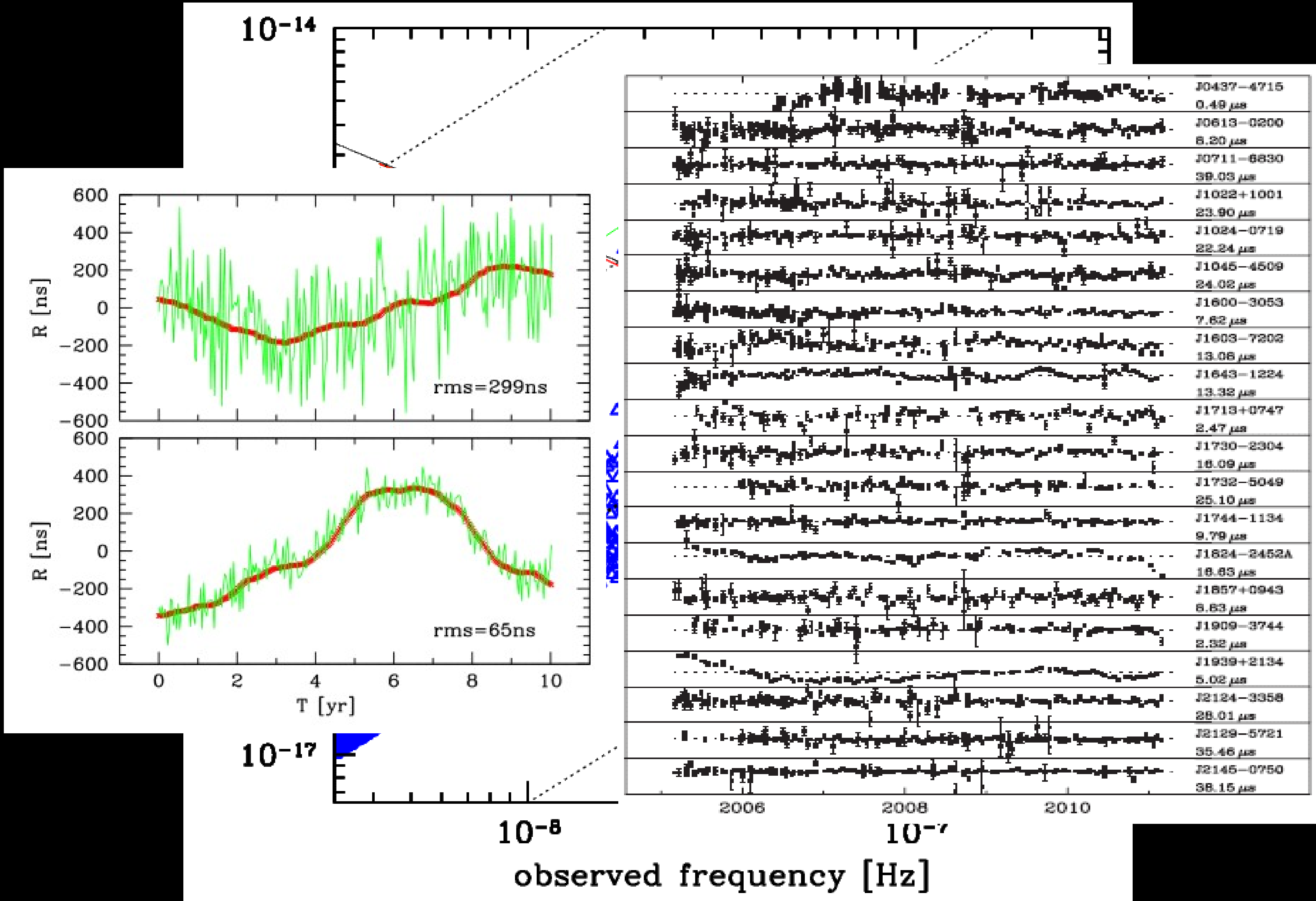
The signal is contributed by extremely massive ($>10^8 M_\odot$) relatively low redshift ($z<1$) MBH binaries **(AS et al. 2008, 2012)**



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

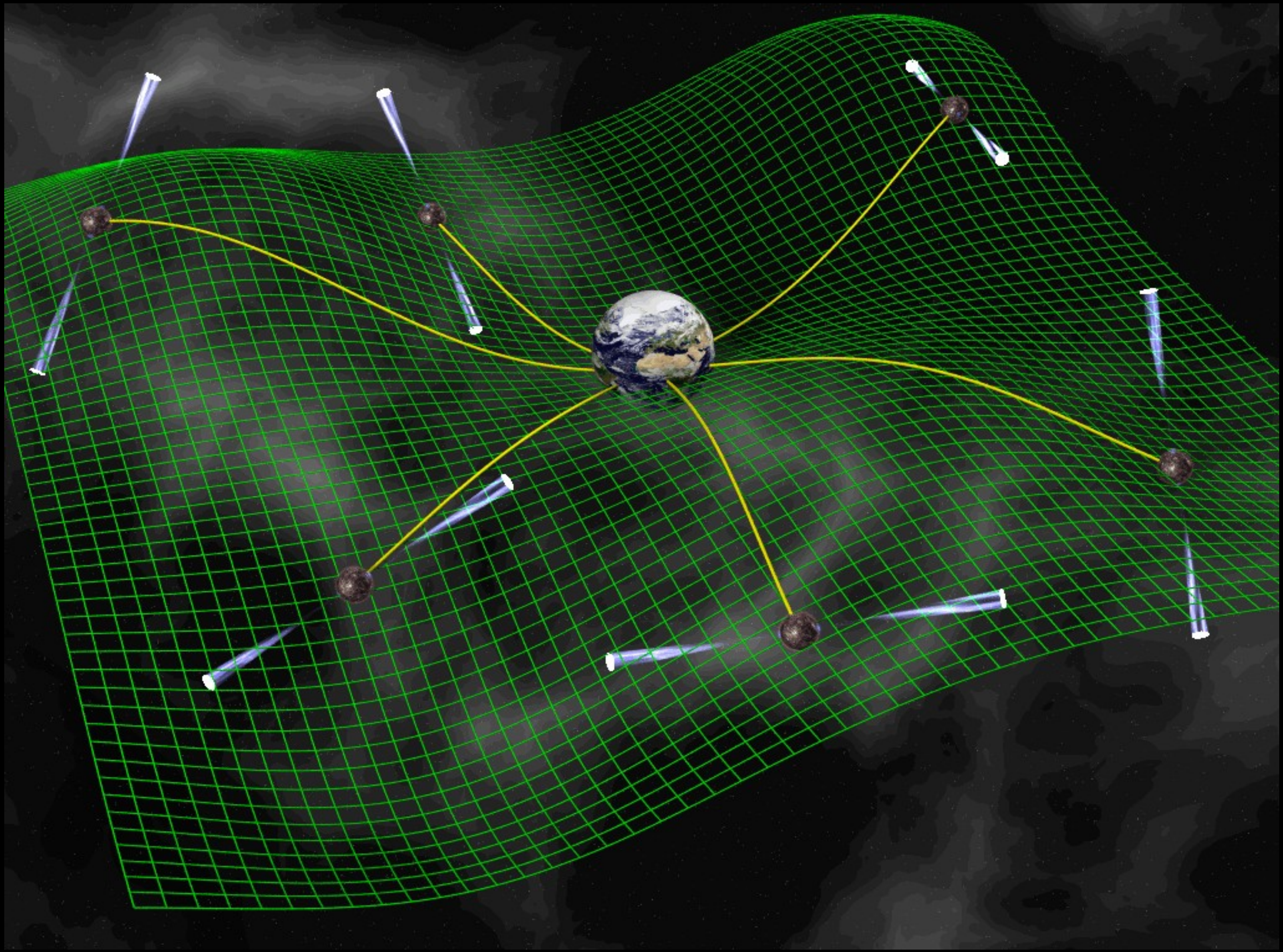


10^{-14}
10^{-17}
10^{-8}
10^{-7}
observed frequency [Hz]
R [ns]
T [yr]
rms=299ns
rms=65ns
600
400
200
0
−200
−400
−600
0
2
4
6
8
10

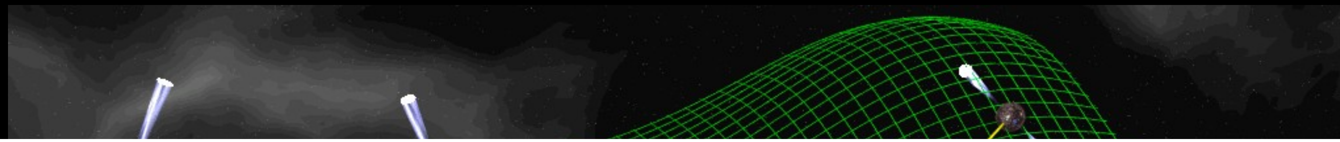


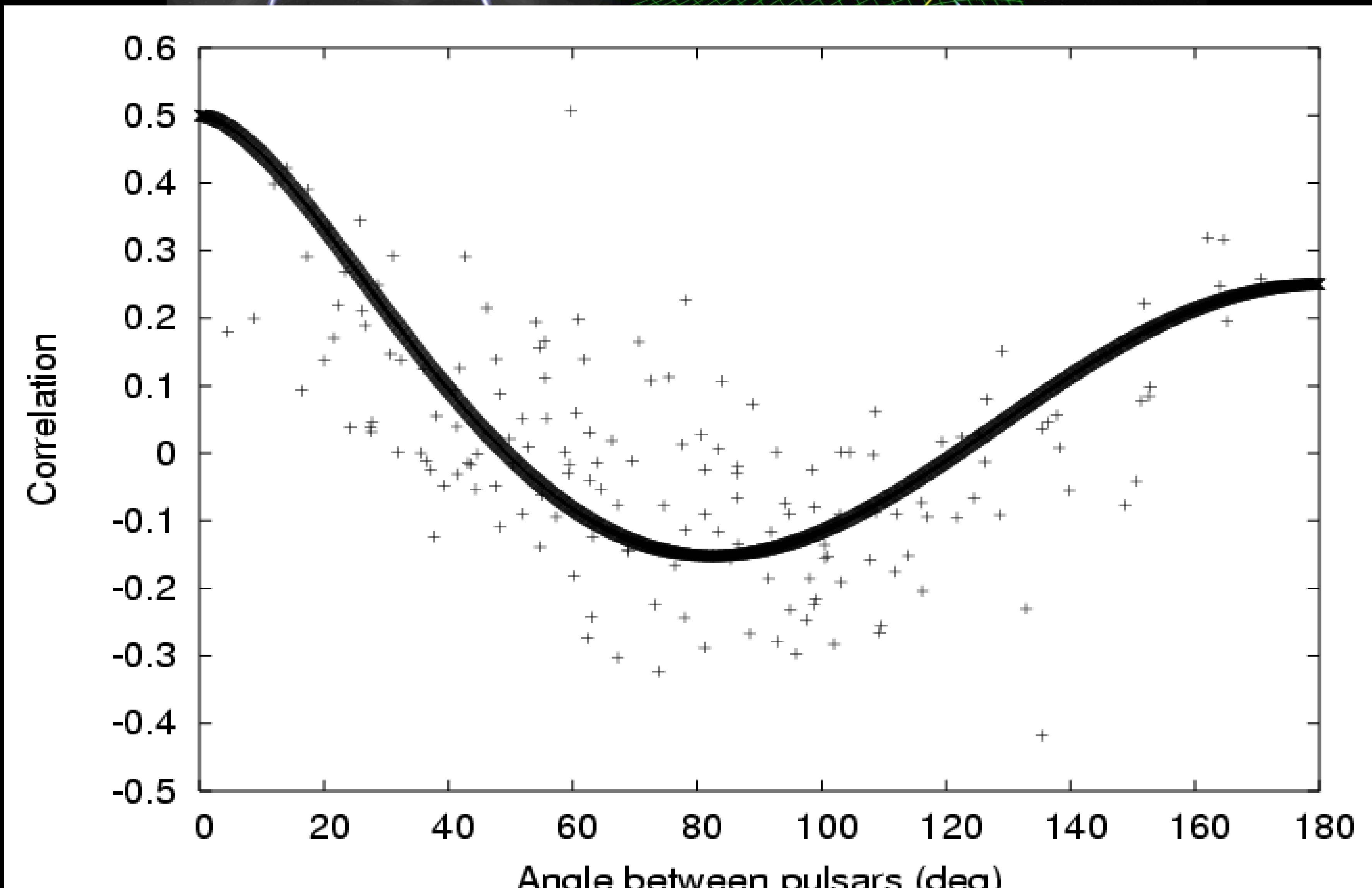
10−14
10−17
10−8
10−7
observed frequency [Hz]
R [ns]
600
400
200
0
−200
−400
−600
rms=299ns
rms=65ns
0
2
4
6
8
10
T [yr]
J0437−4715
0.49 μs
J0613−0200
6.20 μs
J0711−6830
39.03 μs
J1022+1001
23.90 μs
J1024−0719
22.24 μs
J1045−4509
24.02 μs
J1600−3053
7.62 μs
J1603−7202
13.06 μs
J1643−1224
13.32 μs
J1713+0747
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)

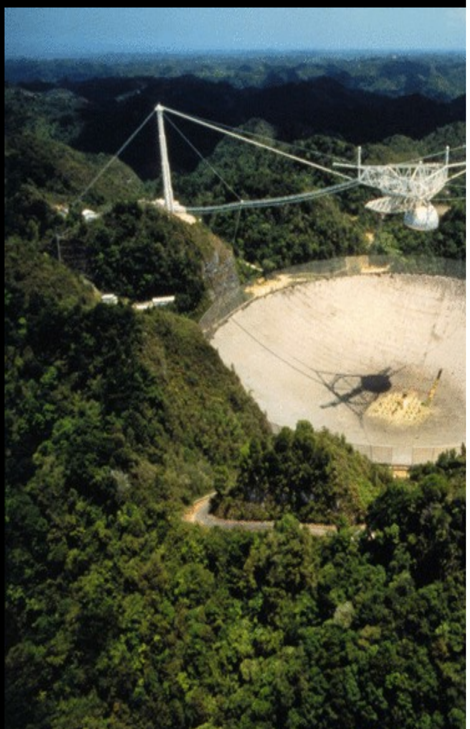
A worldwide observational effort

EPTA/LEAP **(Large European Array for Pulsars)**

NANOGrav **(North American nHz Observatory for Gravitational Waves)**

PPTA **(Parkes Pulsar Timing Array)**

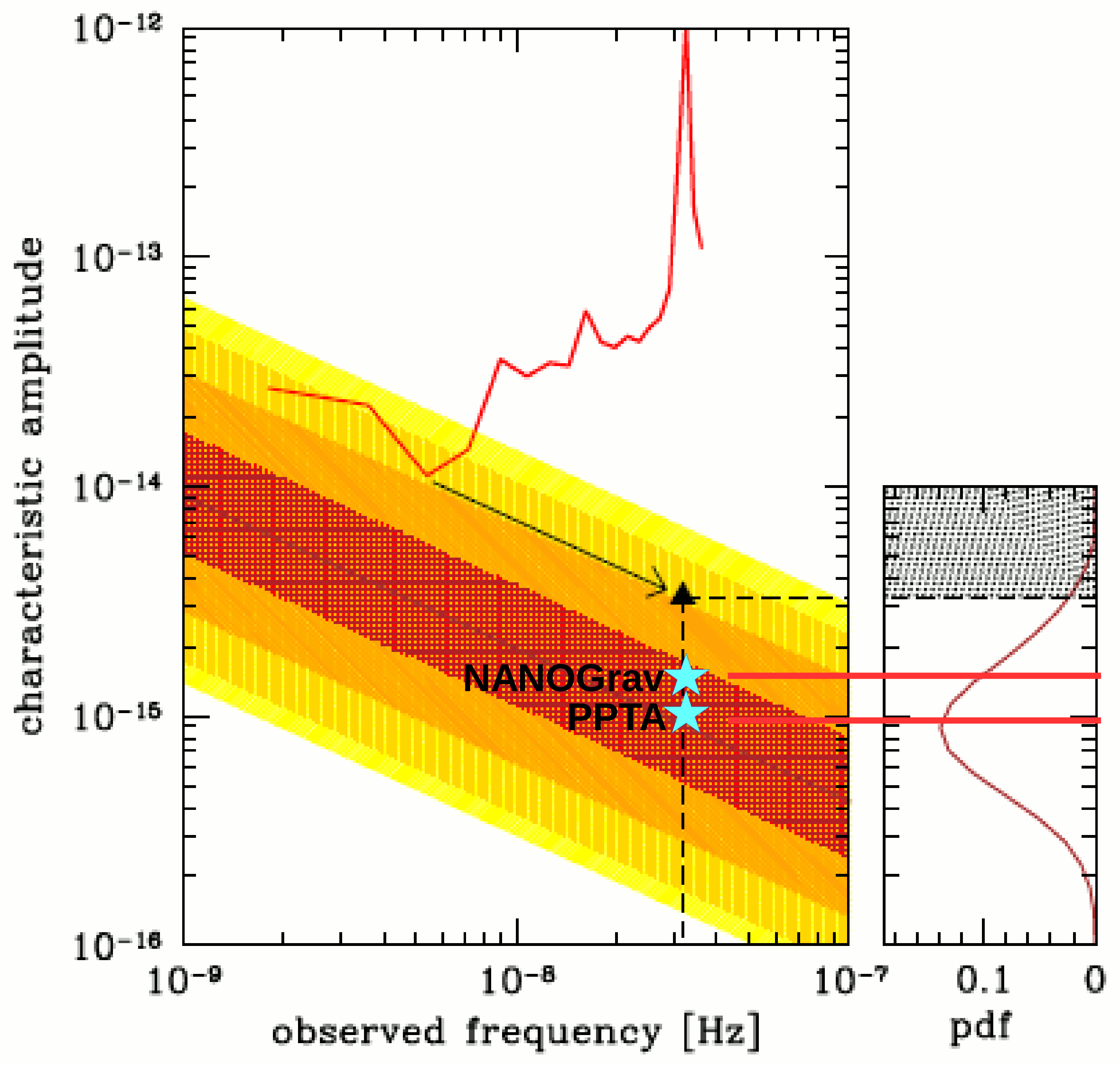
A worldwide observational effort



nHz
aves)

PPTA

Uncertainty in the GW background level



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

Predictions shown here (AS 2013):

>Assume circular GW driven binaries

>Efficient MBH binary merger following galaxy mergers

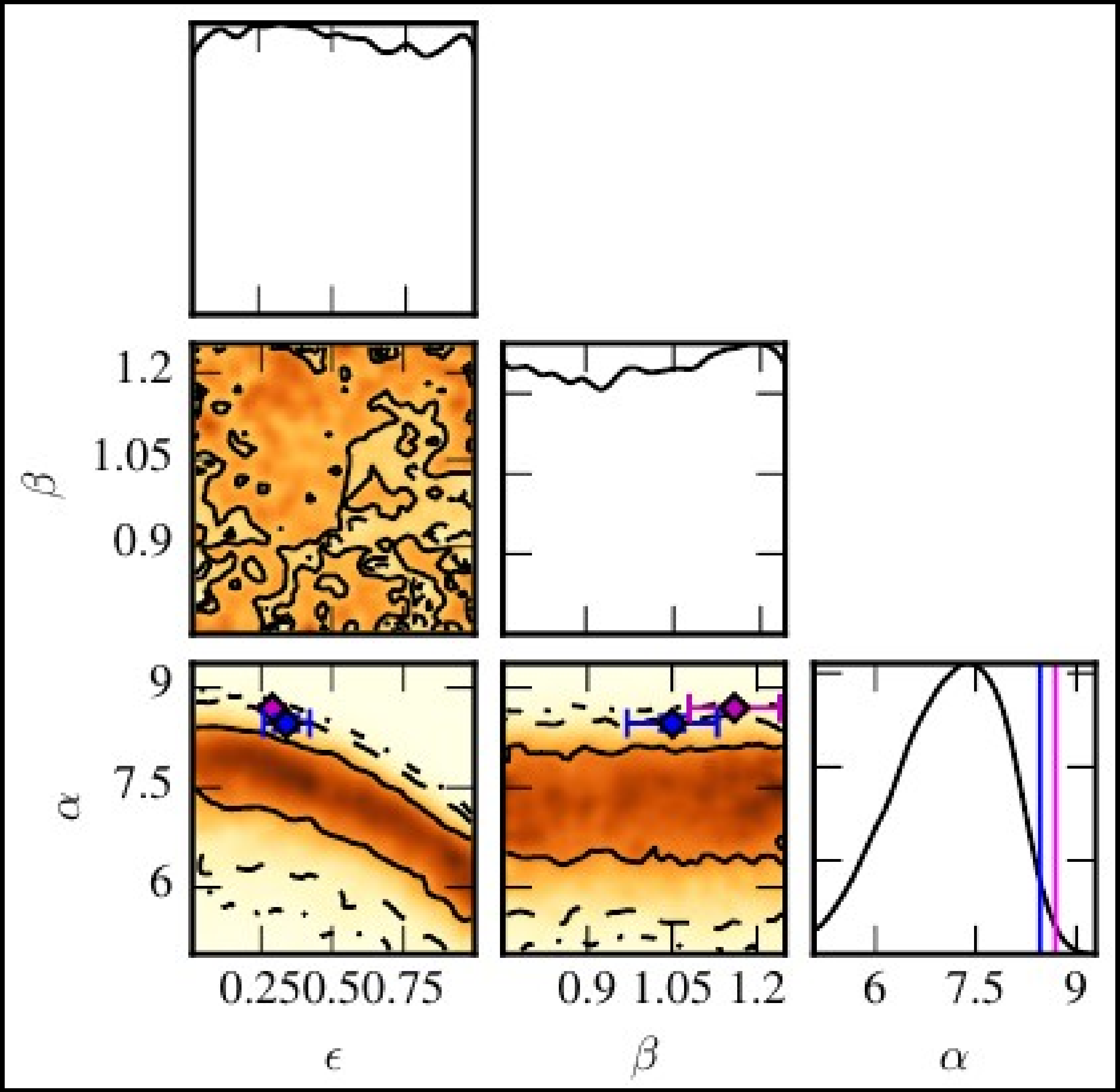
>Uncertainty range takes into account:
- **-merger rate**
- **-MBH-galaxy relation**
- **-accretion timing**

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

Constrains on the BH-galaxy relations

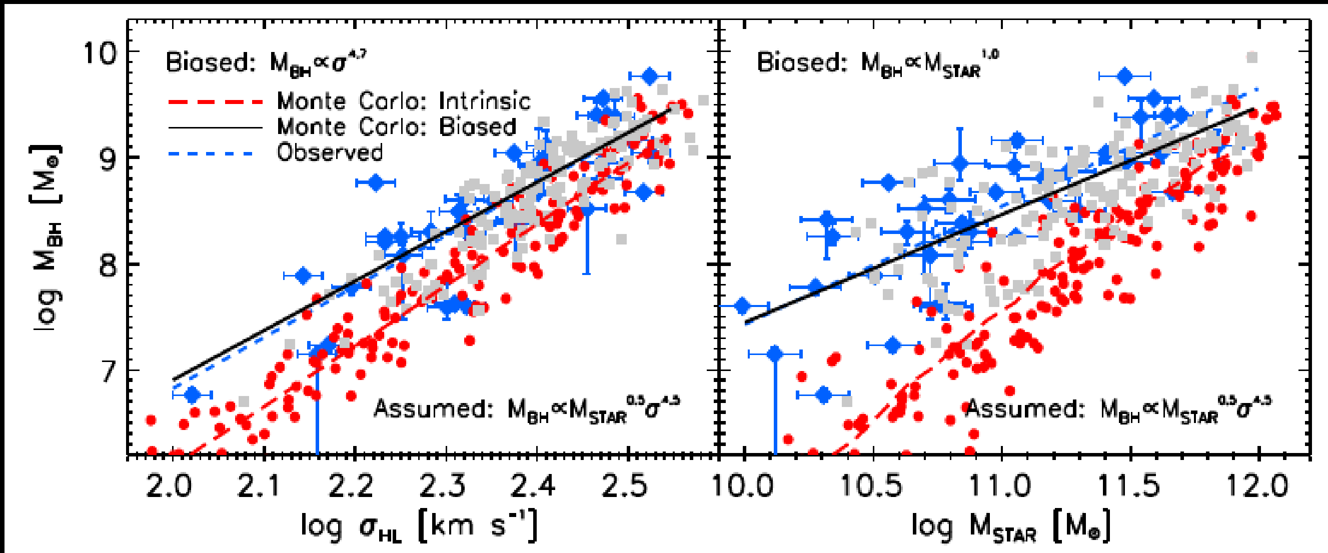
$$\log_{10} M_\bullet = \alpha + \beta \log_{10}\left(\frac{M_{\rm bulge}}{10^{11}{\rm M}_\odot}\right)$$

Parametric MBH-galaxy relation (plus a scatter ε)

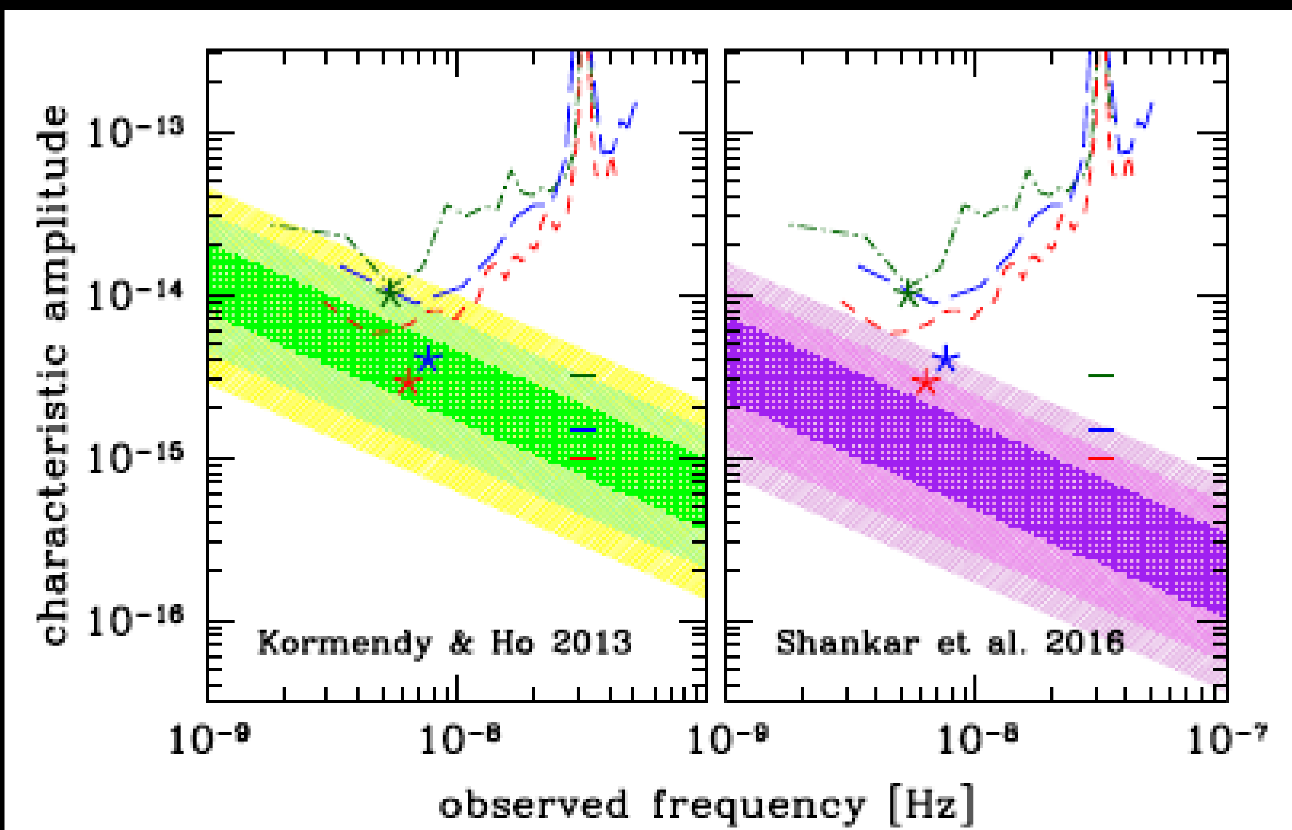


The measured upper limit on the signal results in a posterior distribution on the parameters.

Can be used to constrain MBH-galaxy relations *within the assumptions of the model* (Simon & Burke-Spolaor 2016)



The MBH-galaxy relations might be biased-high
(Shankar et al. 2016)

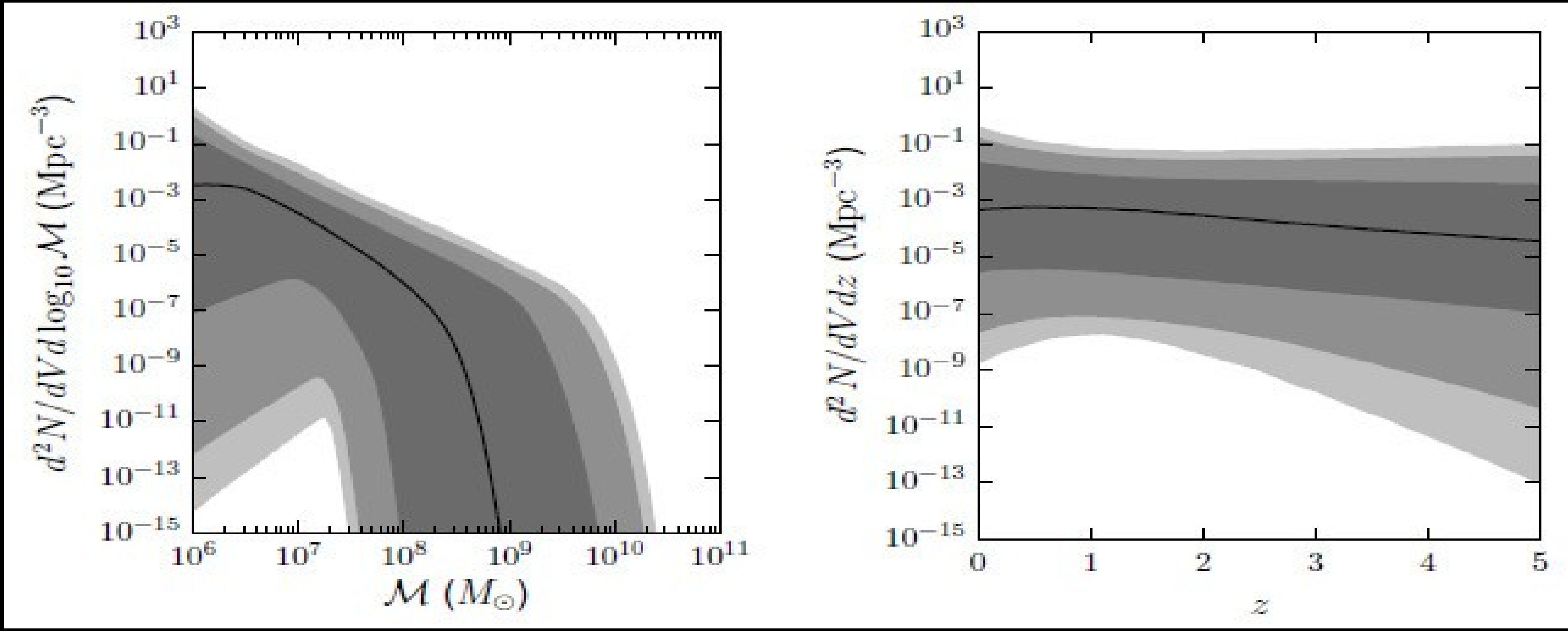


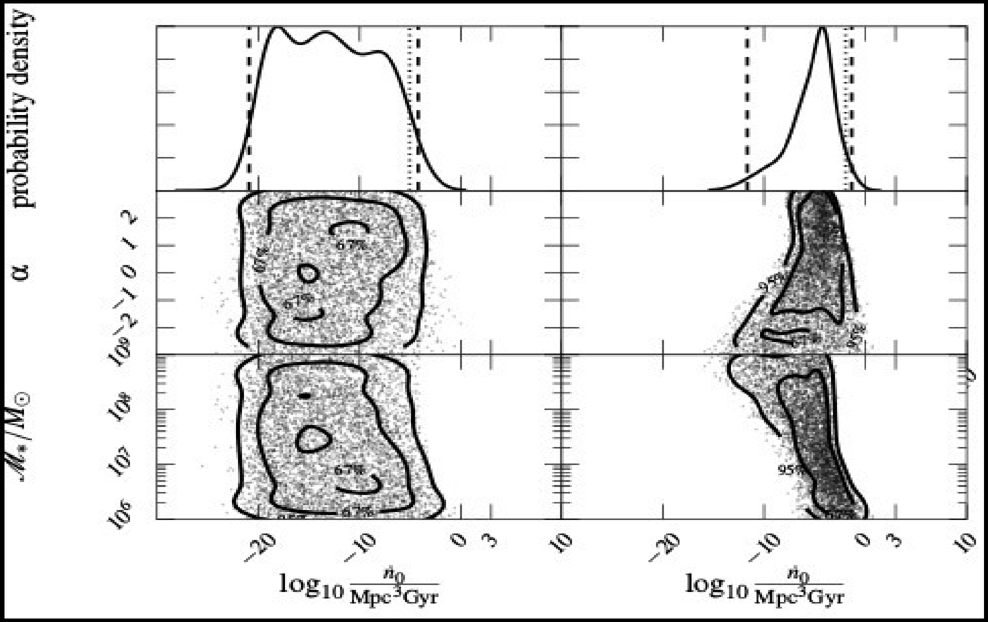
If this is in fact the case, the expected signal is a factor of ~3 lower.

This will make GW detection with PTA more difficult, delaying detection by 5+ years
(AS et al. 2016)

What if we don't assume any merger rate prior?

(Middleton et al. 2015)

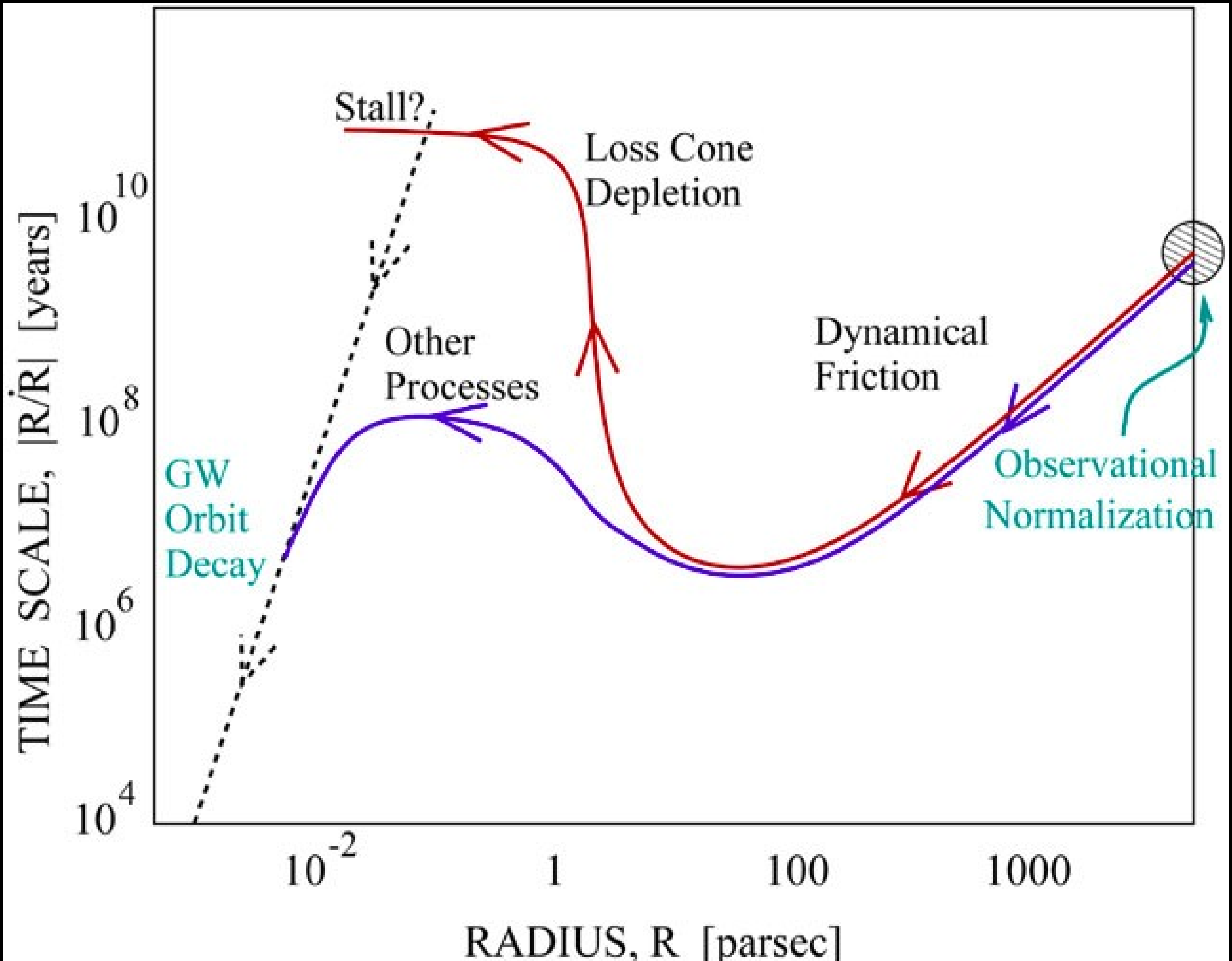


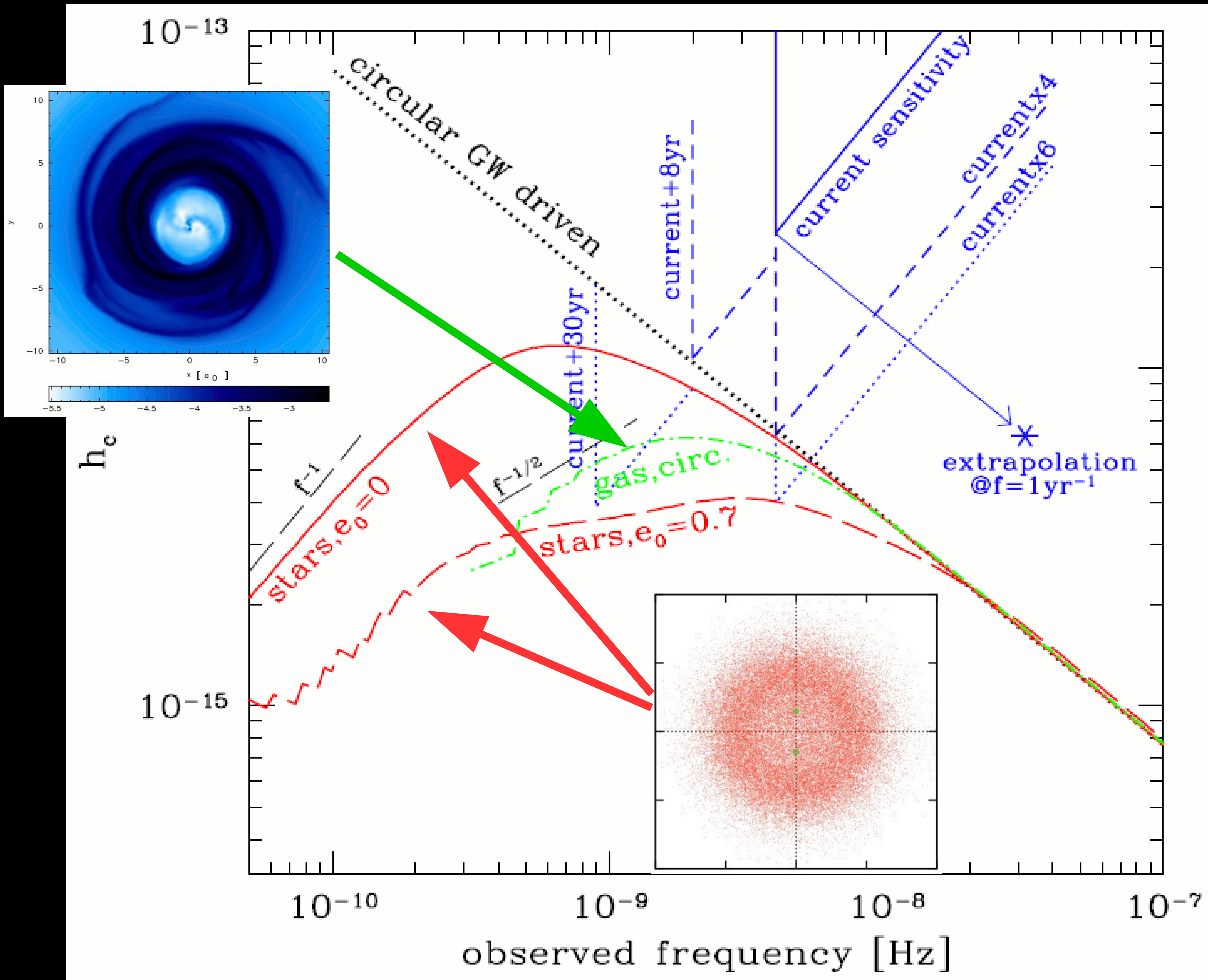


A PTA detection of a stochastic GWB will essentially *only constrain the overall MBHB merger rate*.

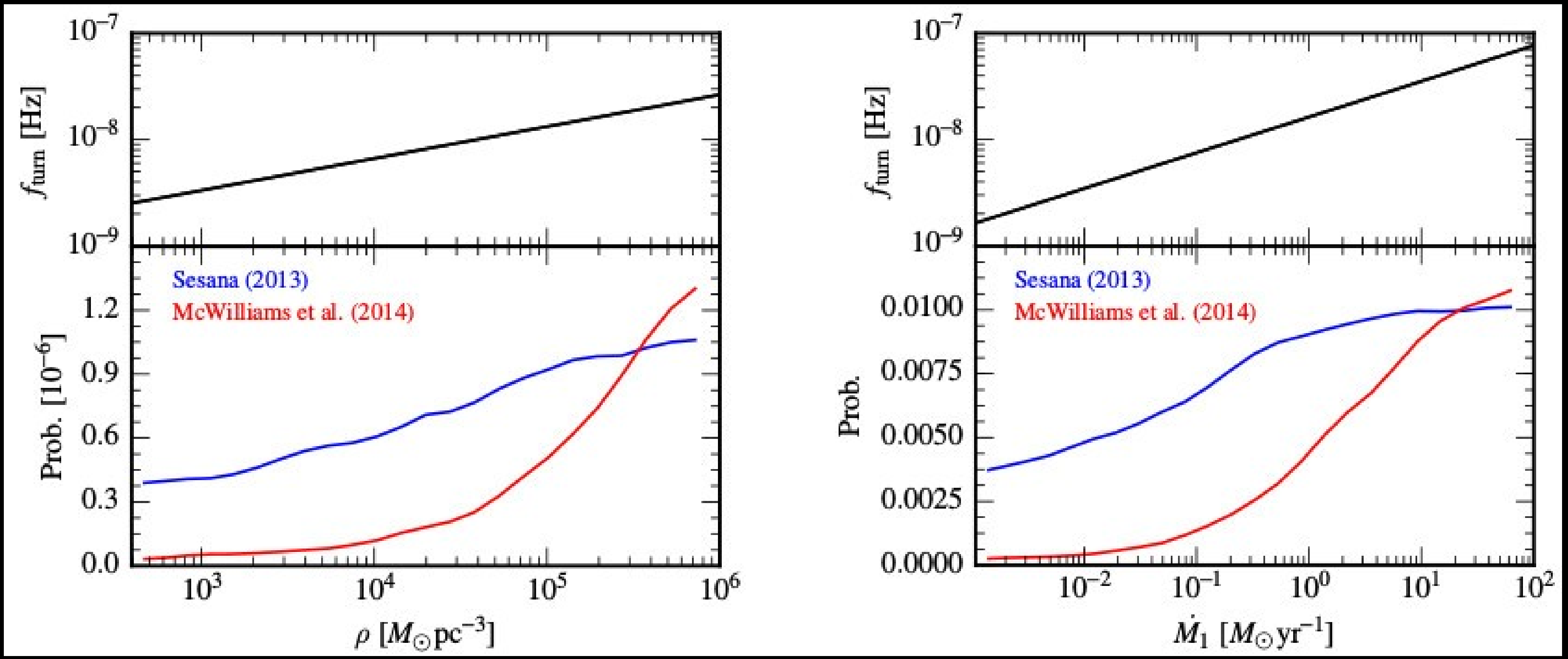
Need combination with other observation to be informative

Uncertainty in the GW background shape

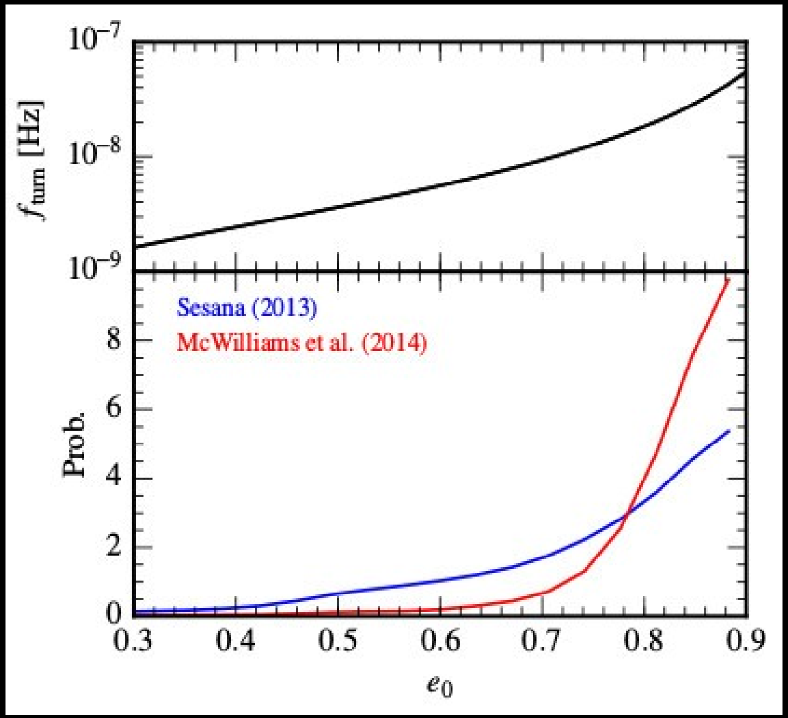




(Kocsis & AS 2011, AS 2013, Ravi et al. 2014, McWilliams et al. 2014)



(NANOGrav, Arzoumanian et al. 2015)



One can play the game of placing constraints on specific parameters *by keeping everything else fixed*:

-density of the MBHB environment
-eccentricity

STILL AT THE LEVEL OF TOY MODELLING

Doggybag

On September 14 2015, aLIGO officially opened the era of GW astronomy

The event involved two fairly massive Bhs at a distance of z~0.1

The signal is (still) a spectacular confirmation of general relativity.

GW150914 is the prototype of cross-band GW binaries.

Multi-band GW sources will open a new era in the quest of multimessenger astronomy

Massive black holes are ubiquitous in the centre of galaxies and exist already at high redshift

eLISA will also probe the whole MBHB cosmic history

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 of cosmic MBHB populations, but nothing can be ruled out yet