Supermassive black hole binary Mergers and Pulsar Timing Arrays

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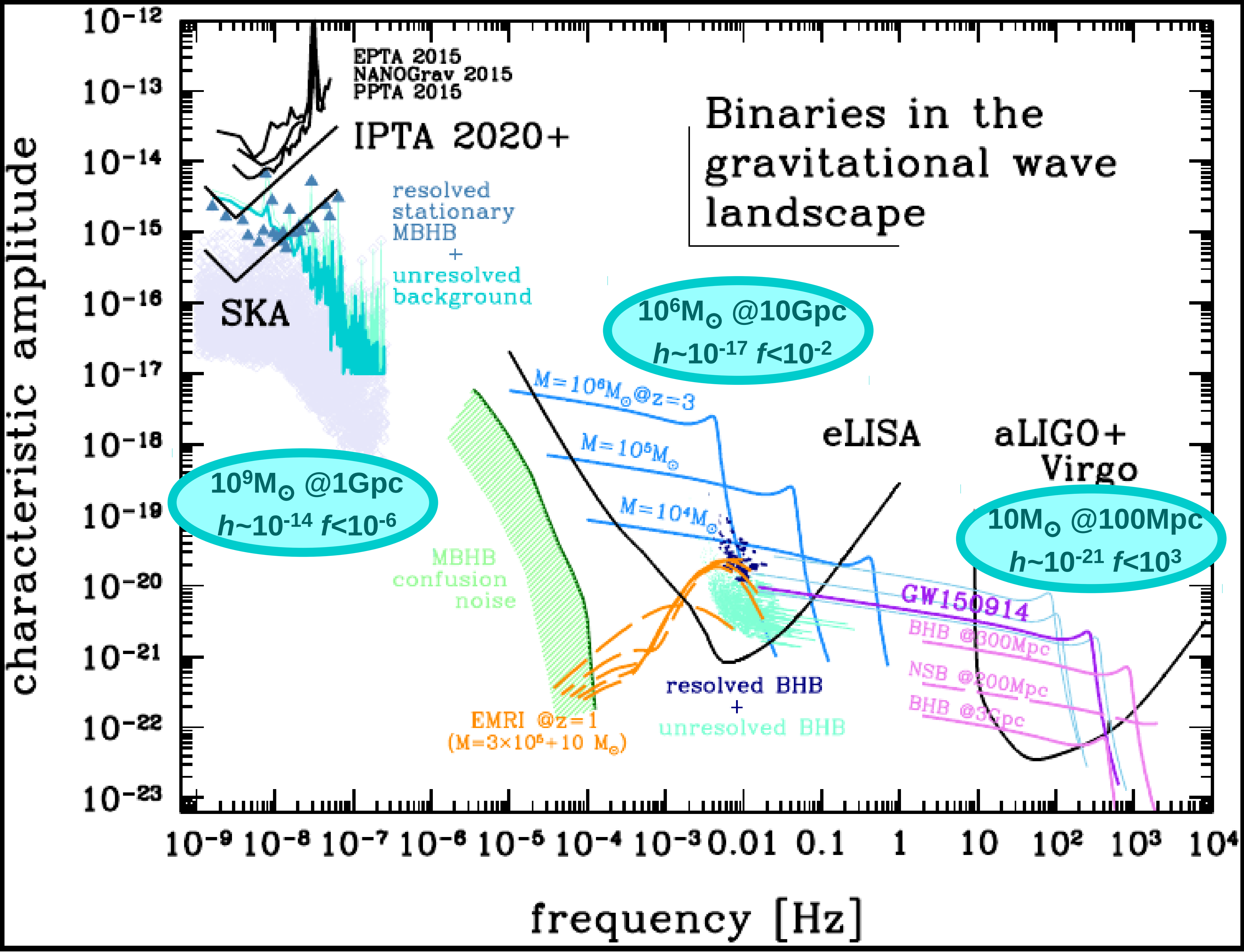
OUTLINE

>Pulsars as ultra-precise clocks for GW detection

> (super)massive black hole binaries (MBHBs)

>Constraining MBHB astrophysics with current
pulsar timing array observations

>The future

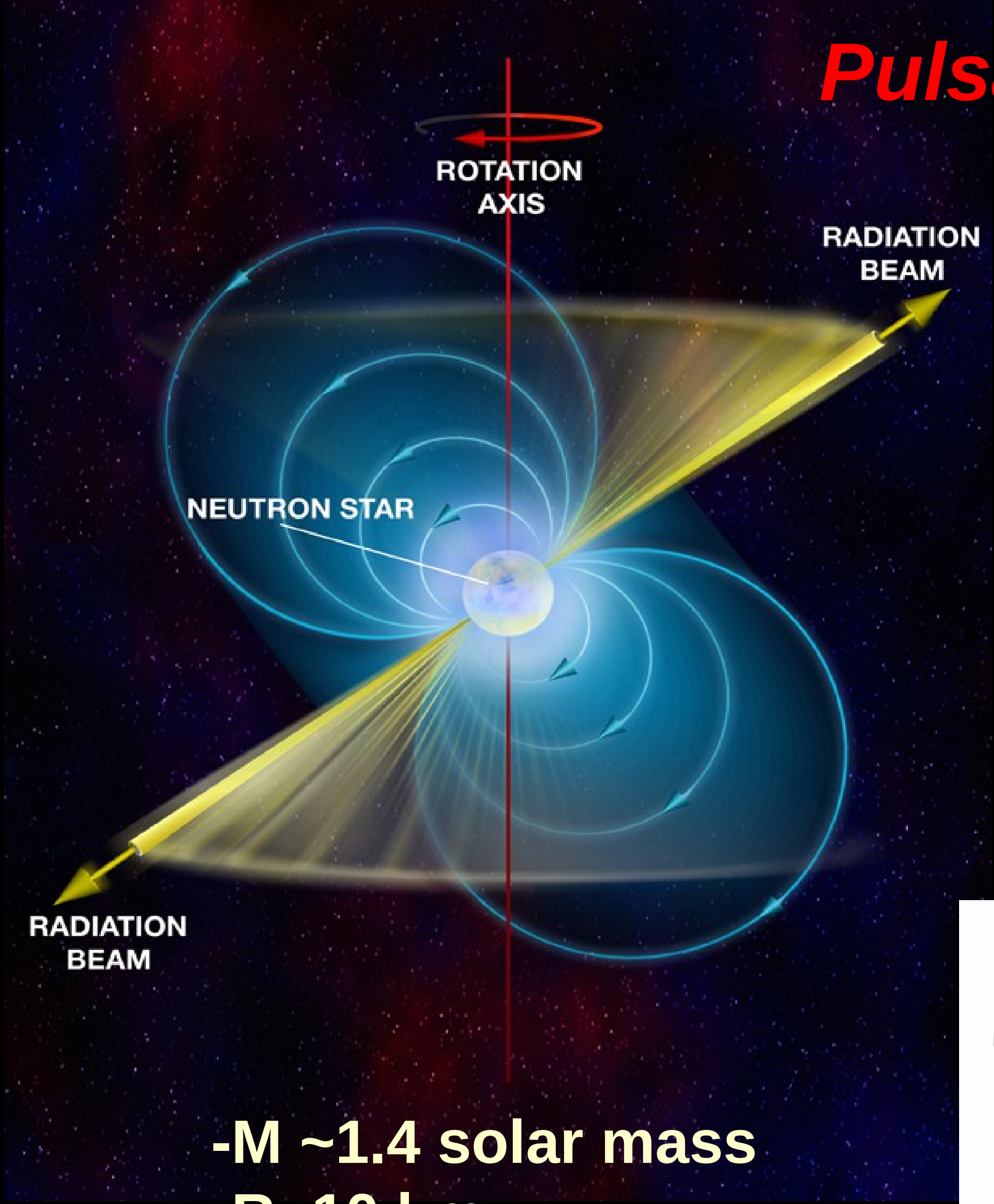


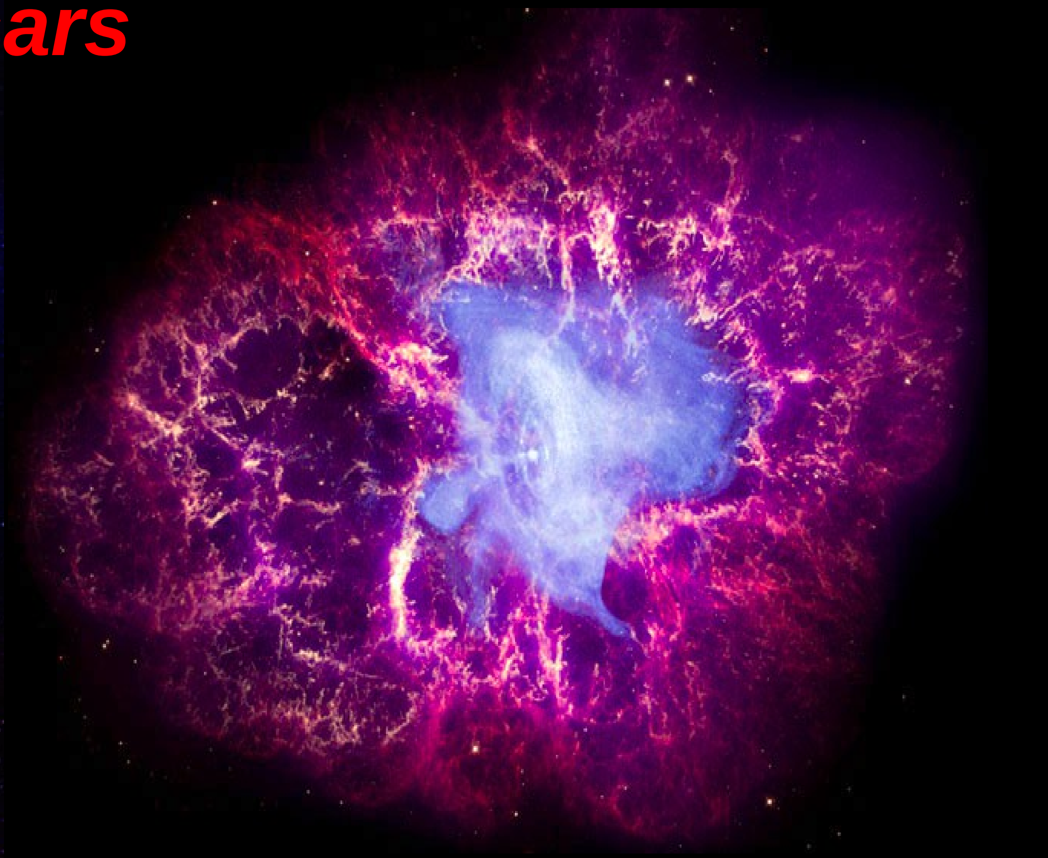
$10^{9}M_{\odot}$ @1Gpc
$h\sim10^{-14}$ $f<10^{-6}$

$10^{6}M_{\odot}$ @10Gpc
$h\sim10^{-17}$ $f<10^{-2}$

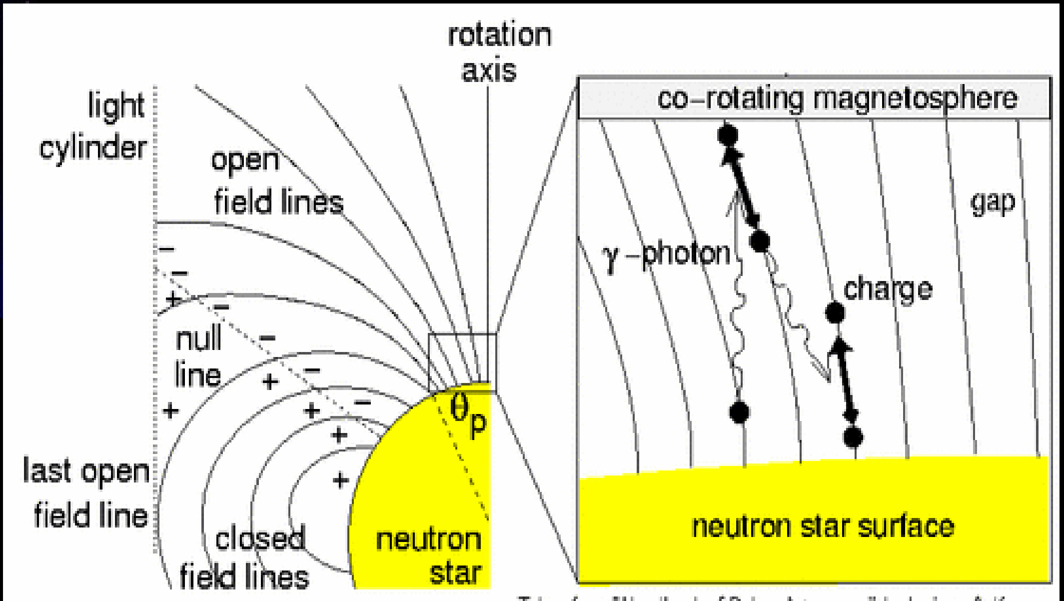
$10M_{\odot}$ @100Mpc
$h\sim10^{-21}$ $f<10^{3}$

Pulsars



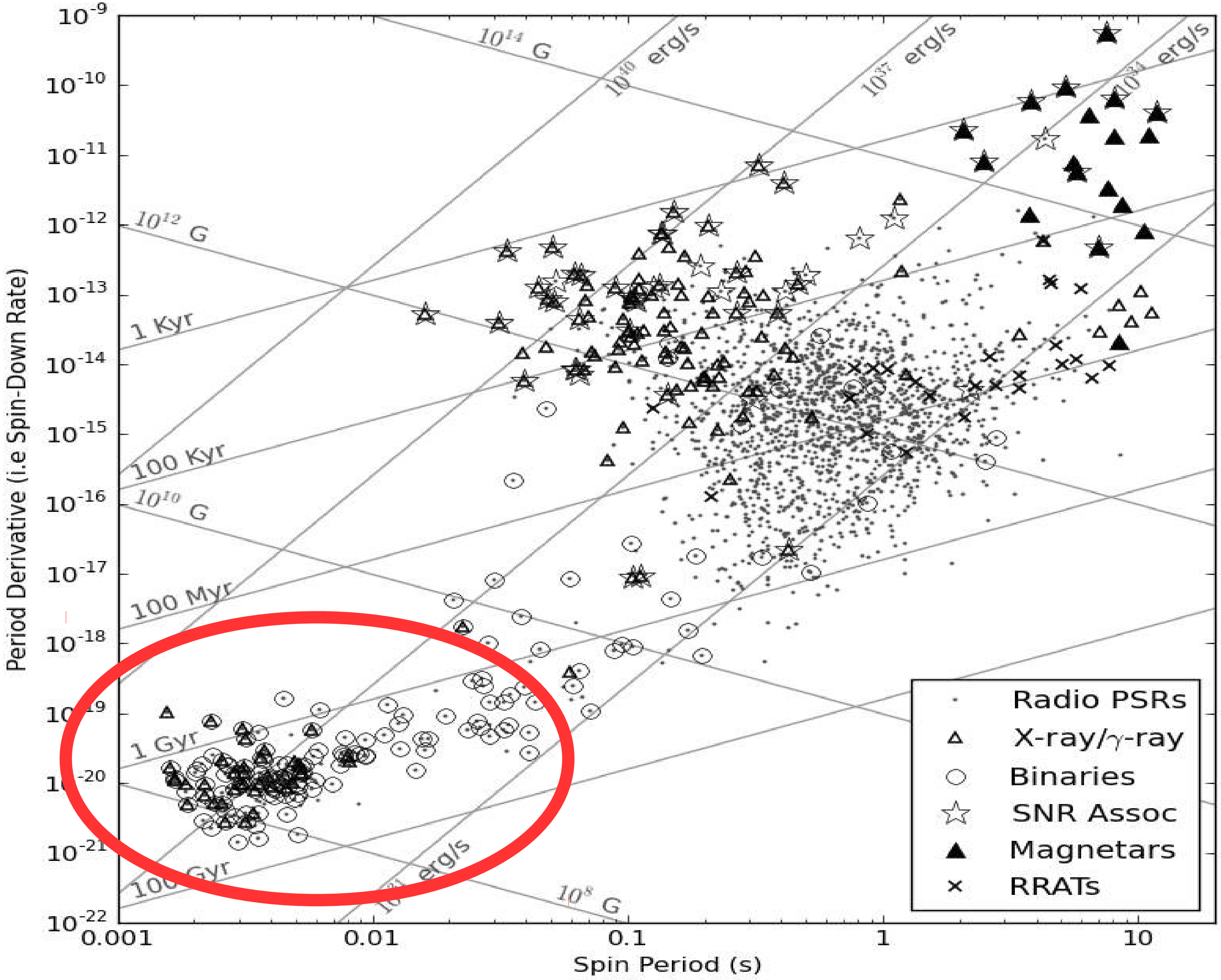


- -M ~1.4 solar mass
- -R~10 km
- -P~0.0014-10 s
- -B~10^8 -10^{15} G



Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

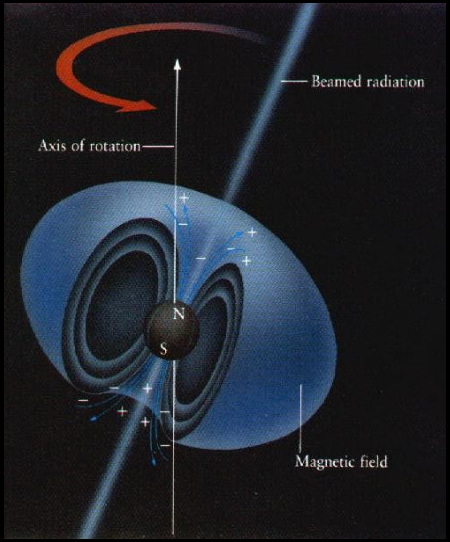
Millisecond pulsars



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



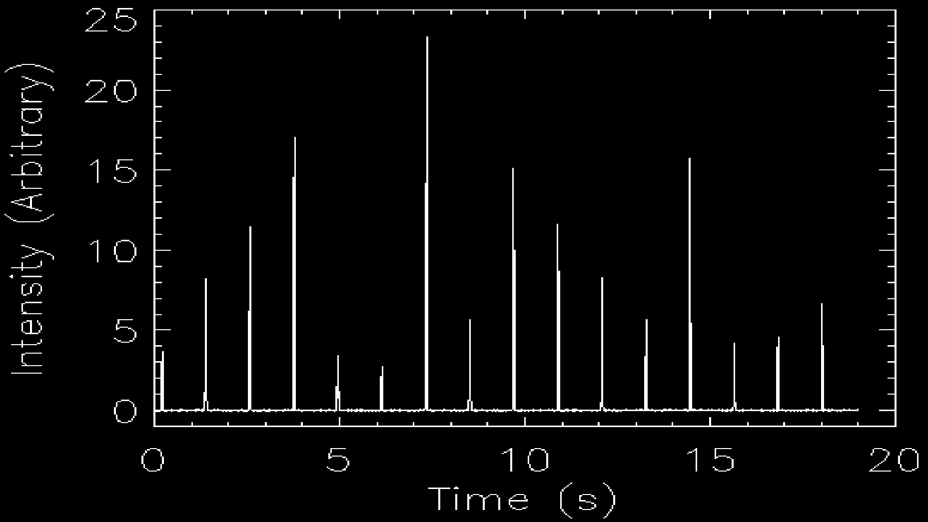
1-Observe a pulsar and measure the ToAs

2-Find the model which best fits the ToAs

3-Compute the timing residual R

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

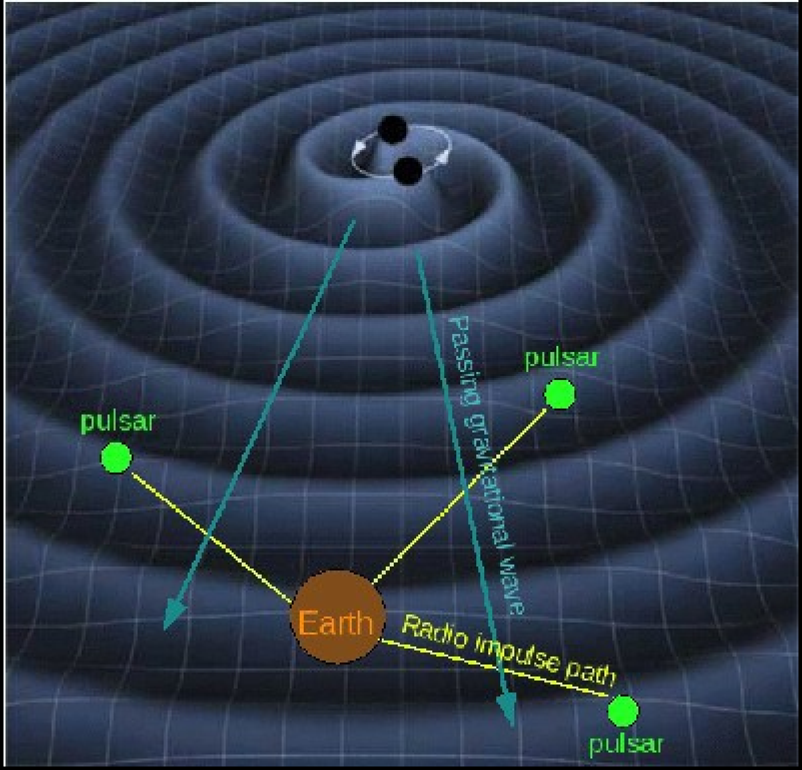
If the timing solution is perfect (and observations noiseless), then *R*=0. *R* contains all uncertainties related to the signal propagation and detection, plus the effect of unmodelled physics, like (possibly) *gravitational waves*



Effect of gravitational waves

The GW passage causes a modulation of the observed pulse frequency

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



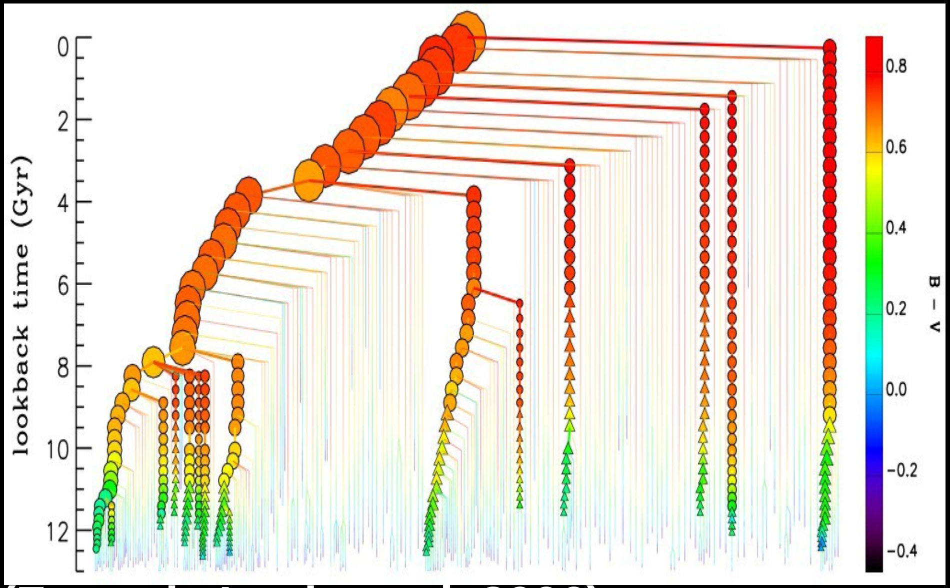
$$R(t) = \int_0^T \frac{\nu(t)-\nu_0}{\nu_0}\,dt$$

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

R~h/(2πf)

$$\begin{aligned} &= \frac{\mathcal{M}^{5/3}}{D}\,[\pi f(t)]^{-1/3} \\ &\simeq 25.7\left(\frac{\mathcal{M}}{10^9\,M_\odot}\right)^{5/3}\left(\frac{D}{100\,\mathrm{Mpc}}\right)^{-1} \\ &\quad\times\left(\frac{f}{5\times10^{-8}\,\mathrm{Hz}}\right)^{-1/3}\ \mathrm{ns} \end{aligned}$$

Structure formation in a nutshell



(From de Lucia et al. 2006)

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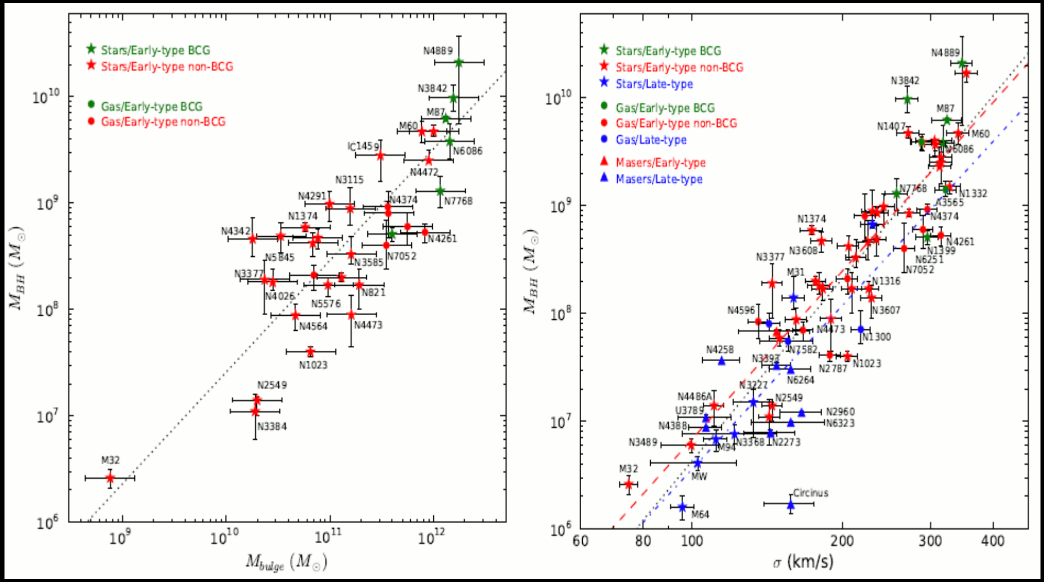

(Ferrarese & Merritt 2000, Gebhardt et al. 2000)

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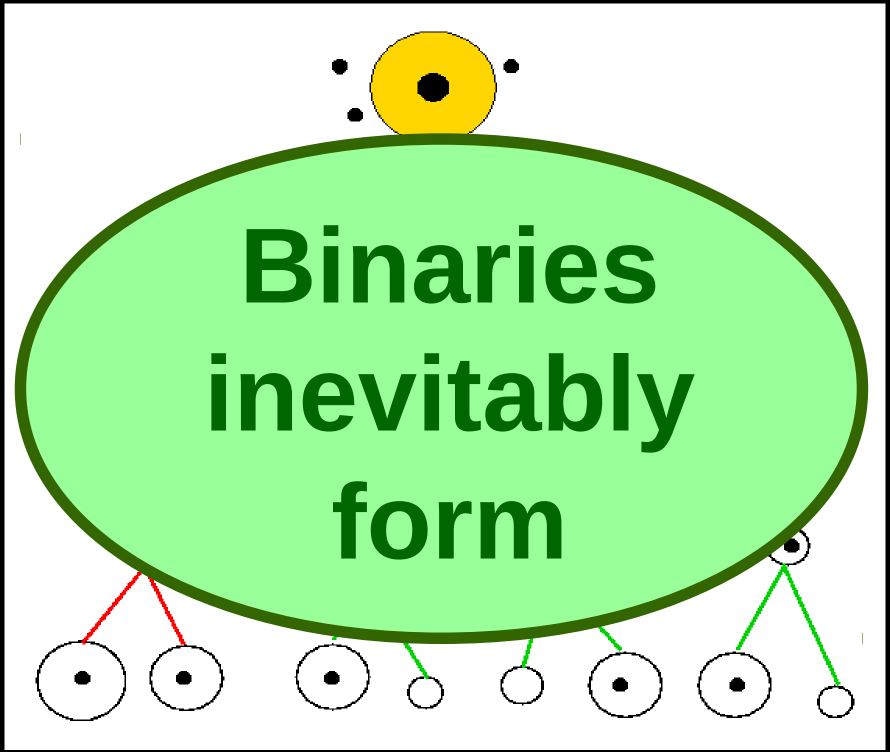


Binaries inevitably form

(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?

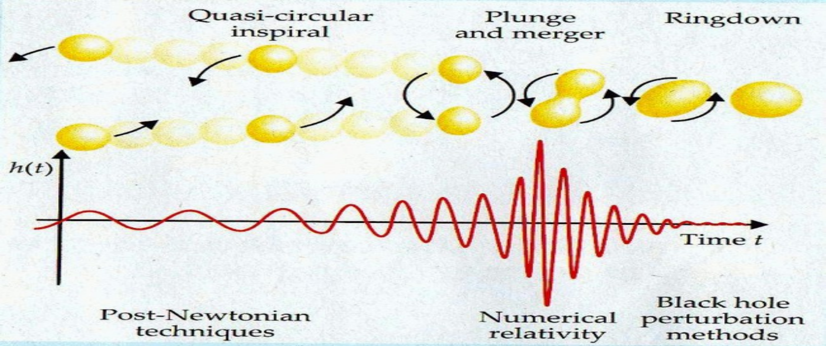
*What is their role in galaxy evolution?

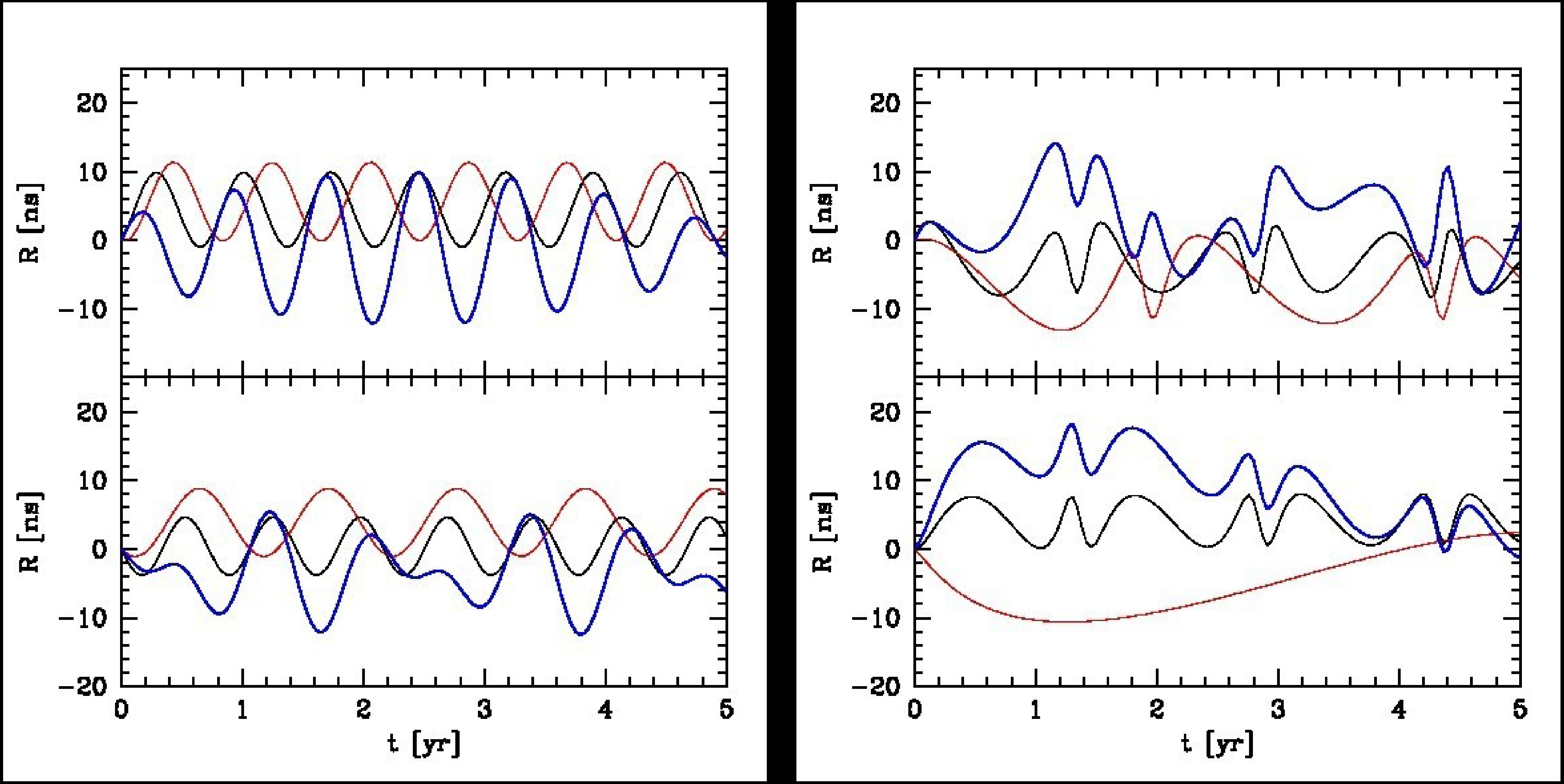
*What is their merger rate?

*How do they pair together and dynamically evolve?

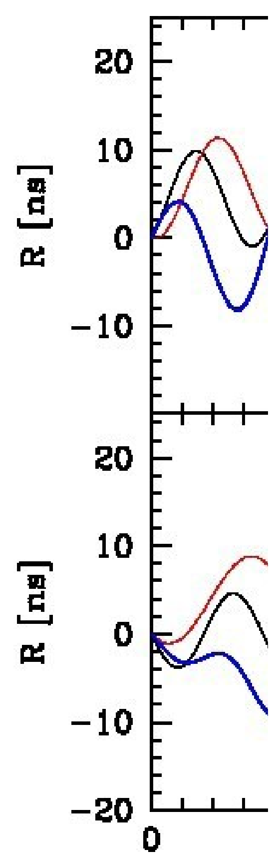
Single MBHB timing residuals

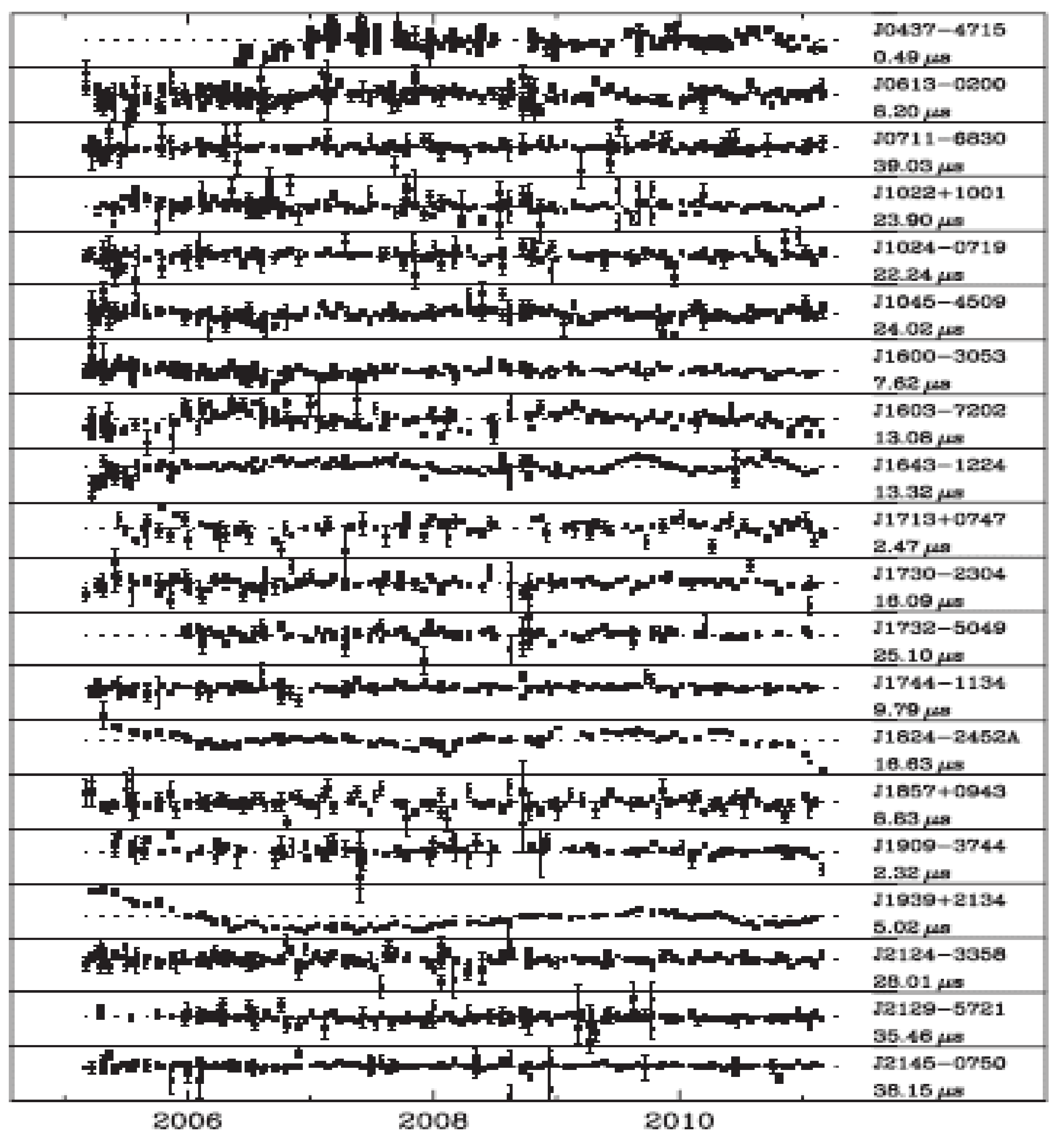
$$\frac{\nu(t)-\nu_0}{\nu_0} = \Delta h_{ab}(t) \equiv h_{ab}(t_{\rm p},\hat\Omega) - h_{ab}(t_{\rm ssb},\hat\Omega)$$

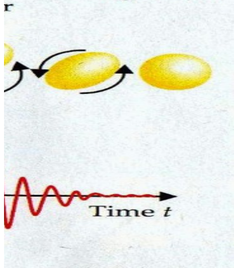


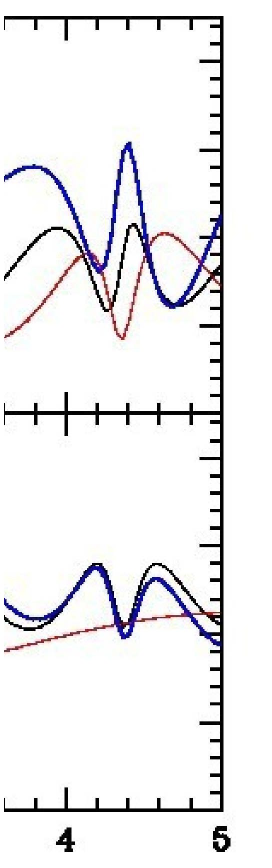


$$\frac{\nu(t)-\nu_0}{\nu_0} =$$

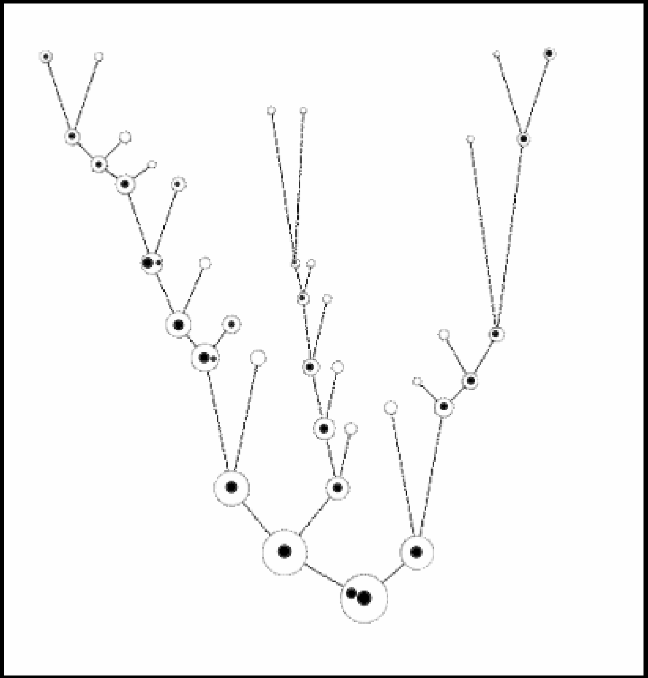








The expected GW signal in the PTA band



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

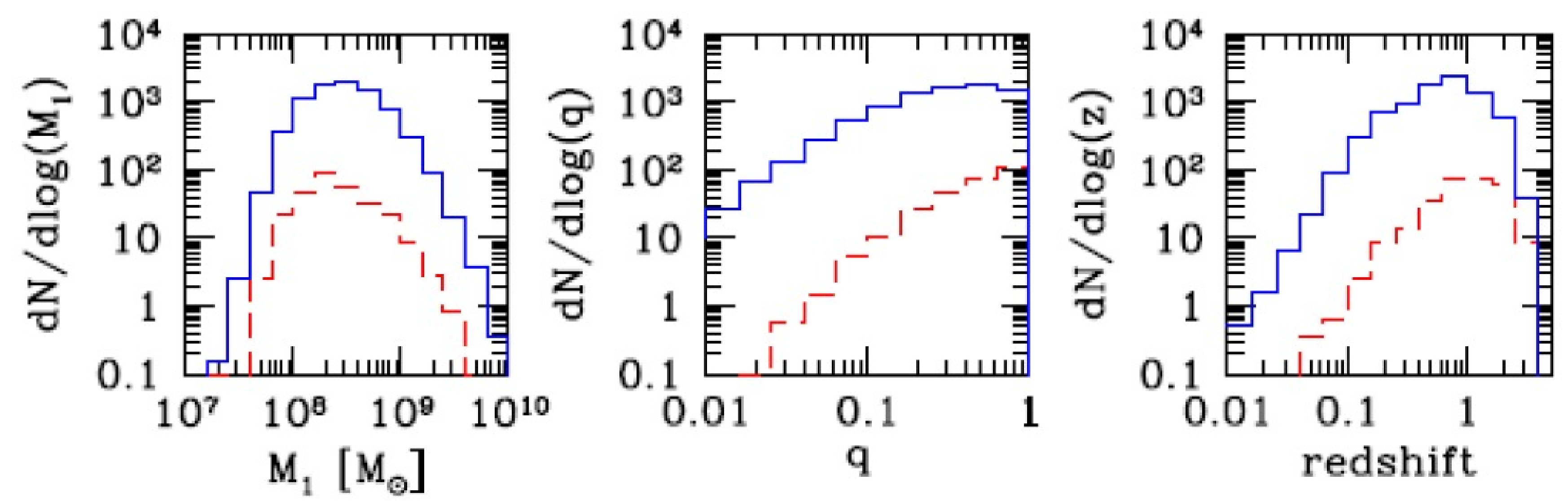
$$h_c^2(f) = \int_0^\infty dz \int_0^\infty d\mathcal{M}\, \frac{d^3N}{dz\,d\mathcal{M}\,d\ln f_r} h^2(f_r)$$

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

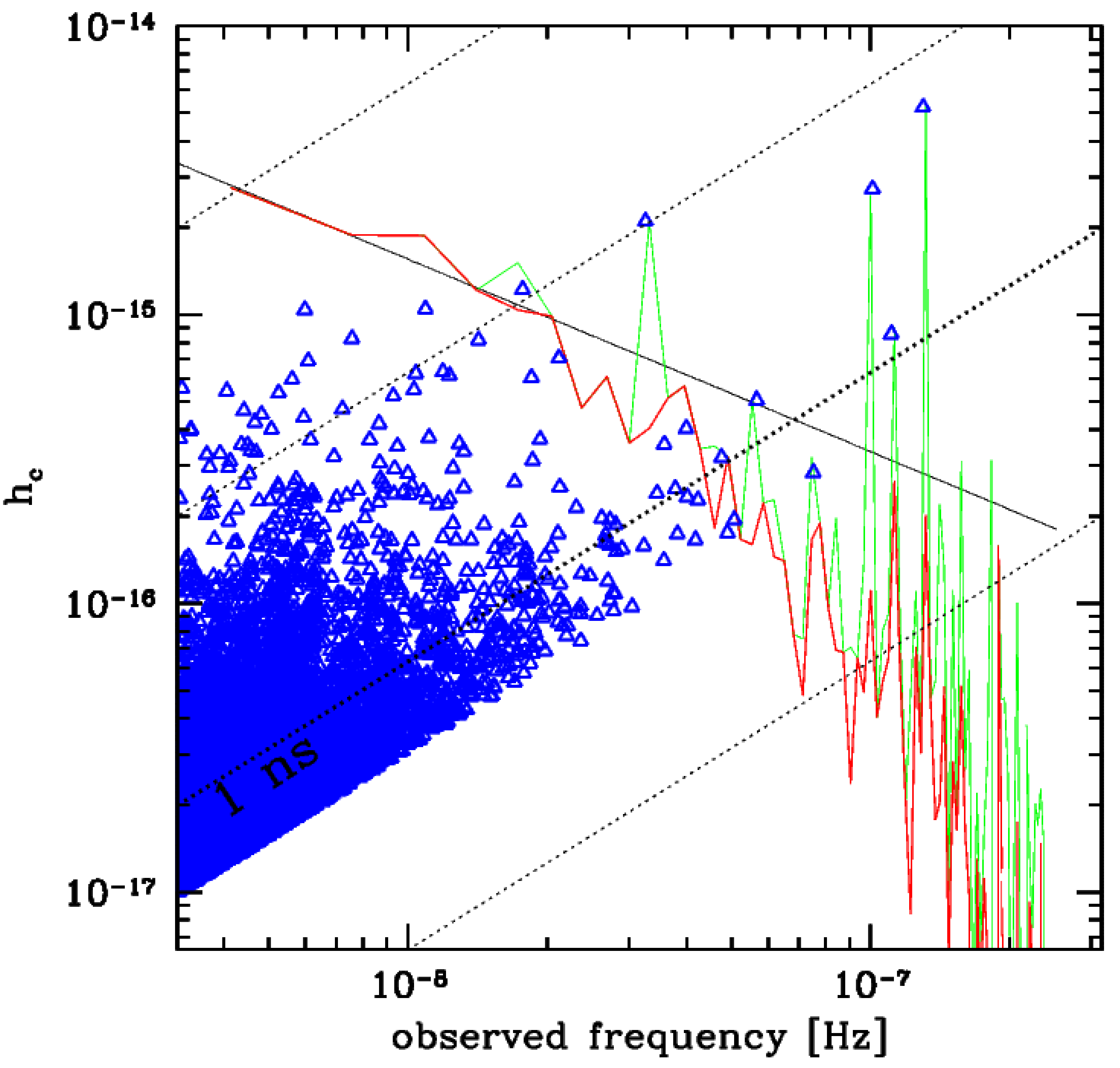
Theoretical spectrum: simple power law

(Phinney 2001)

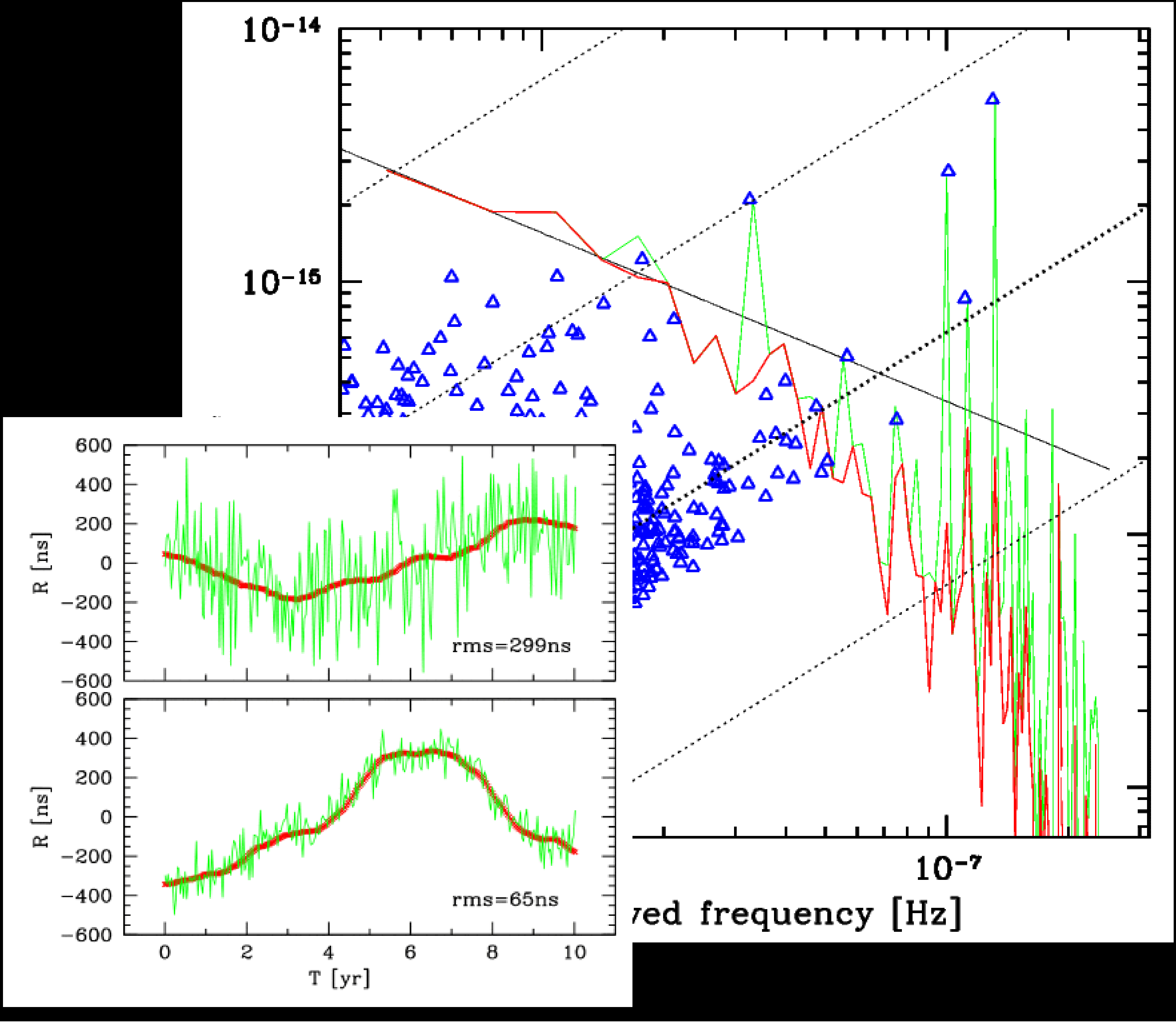
$$h_c(f) = A\left(\frac{f}{{\rm yr}^{-1}}\right)^{-2/3}$$

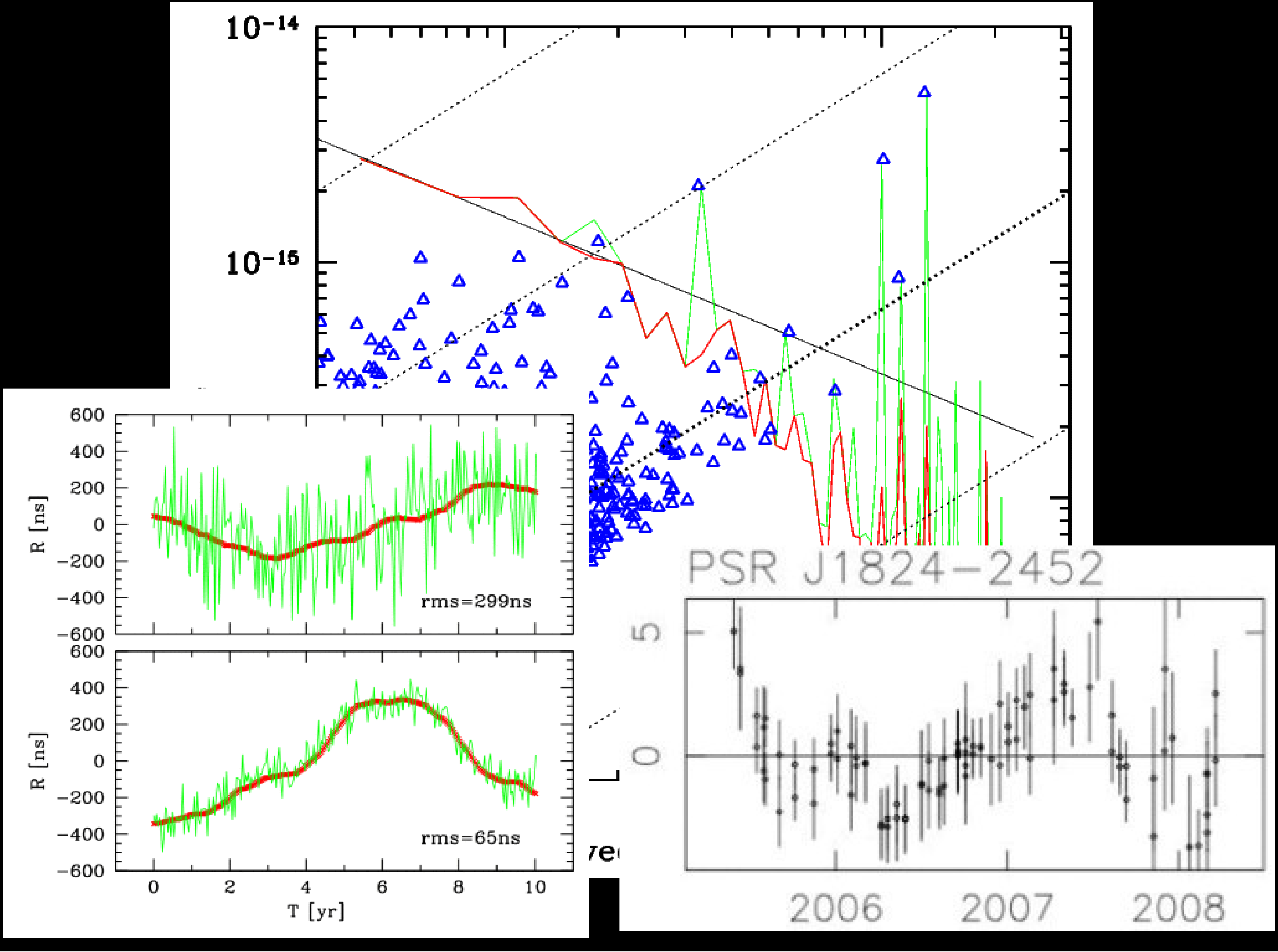


The signal is contributed by extremely massive ($>10^8 M_\odot$) relatively low redshift ($z<1$) MBH binaries (AS et al. 2008, 2012)

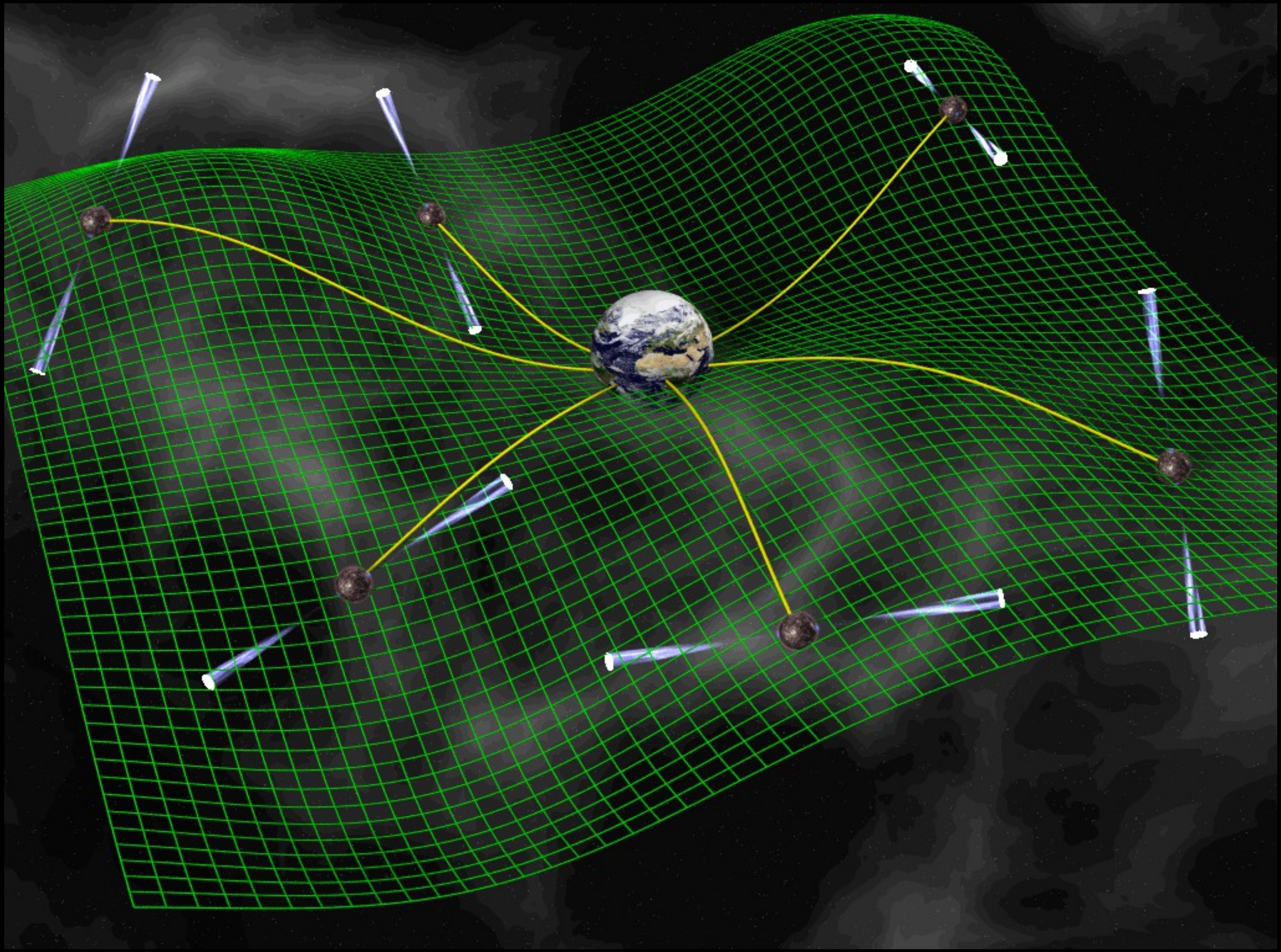


h_c
observed frequency [Hz]
10^-14
10^-15
10^-16
10^-17
10^-8
10^-7
1 ns

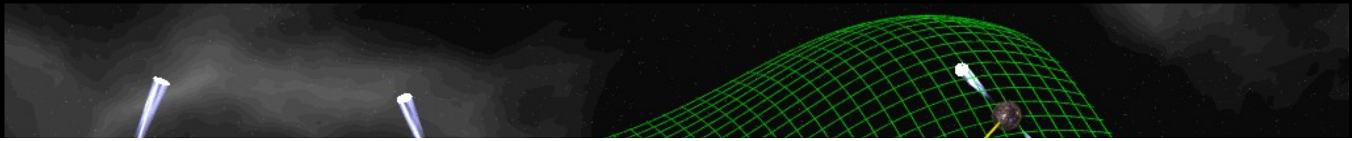

10^{-14}
10^{-15}
10^{-7}
ved frequency [Hz]
600
400
200
0
−200
−400
−600
R [ns]
rms=299ns
rms=65ns
0
2
4
6
8
10
T [yr]

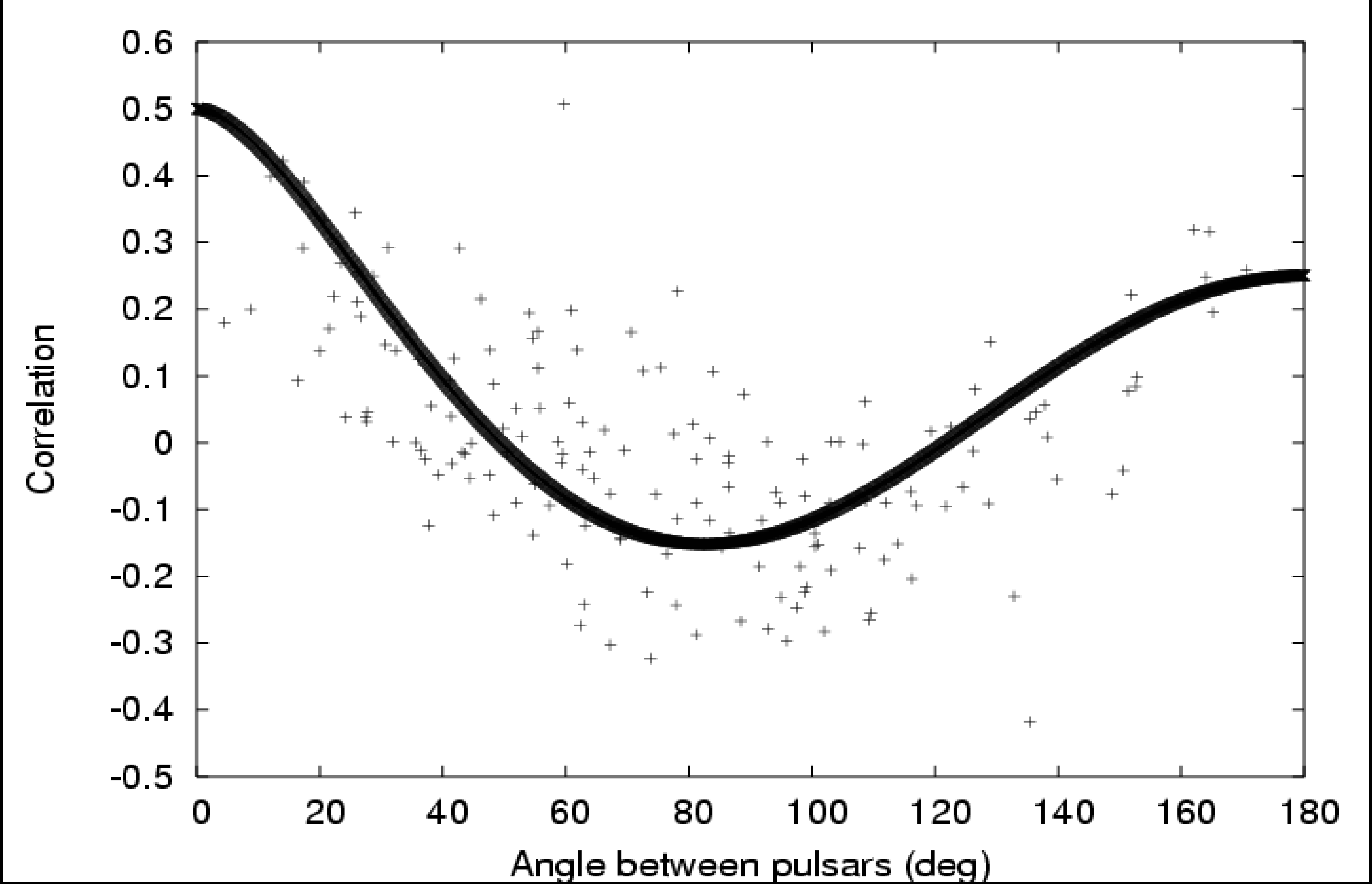

10^{-14}
10^{-16}
600
400
200
0
−200
−400
−600
R [ns]
rms=299ns
rms=65ns
0
2
4
6
8
10
T [yr]
PSR J1824−2452
5
0
2006
2007
2008

We are looking for a correlated signal



We are looking for a correlated signal



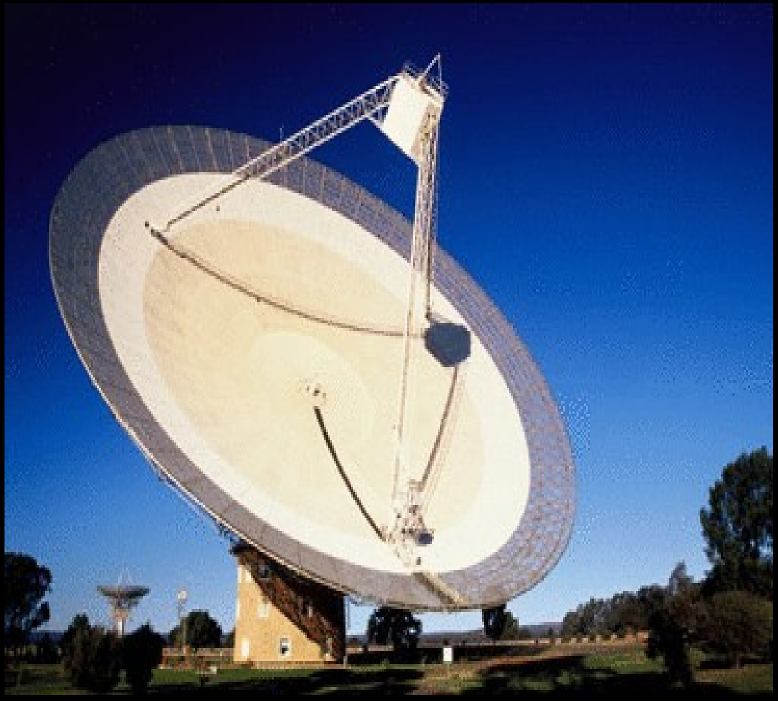


(Hellings & Downs 1983)

A worldwide observational effort

EPTA/LEAP (Large European Array for Pulsars)

NANOGrav (North American nHz Observatory for Gravitational Waves)

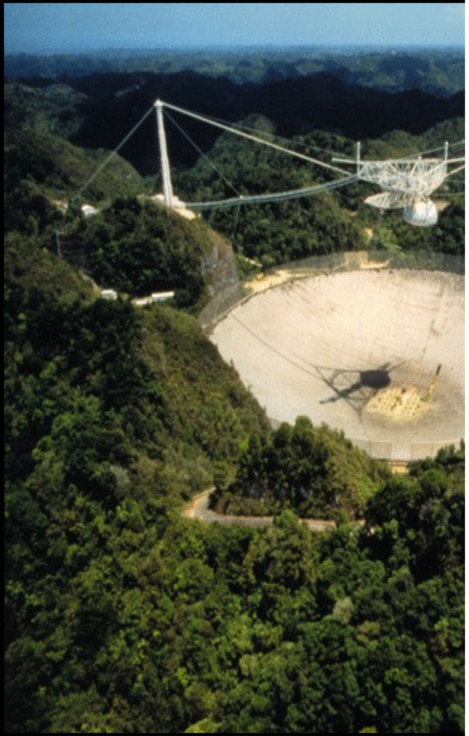


PPTA (Parkes Pulsar Timing Array)

A worldwide observational effort

nHz

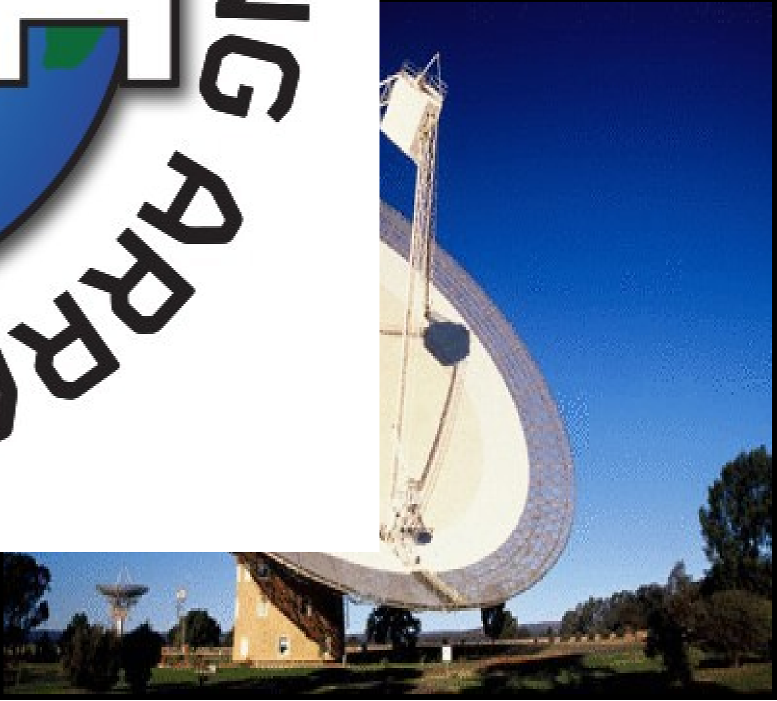
aves)



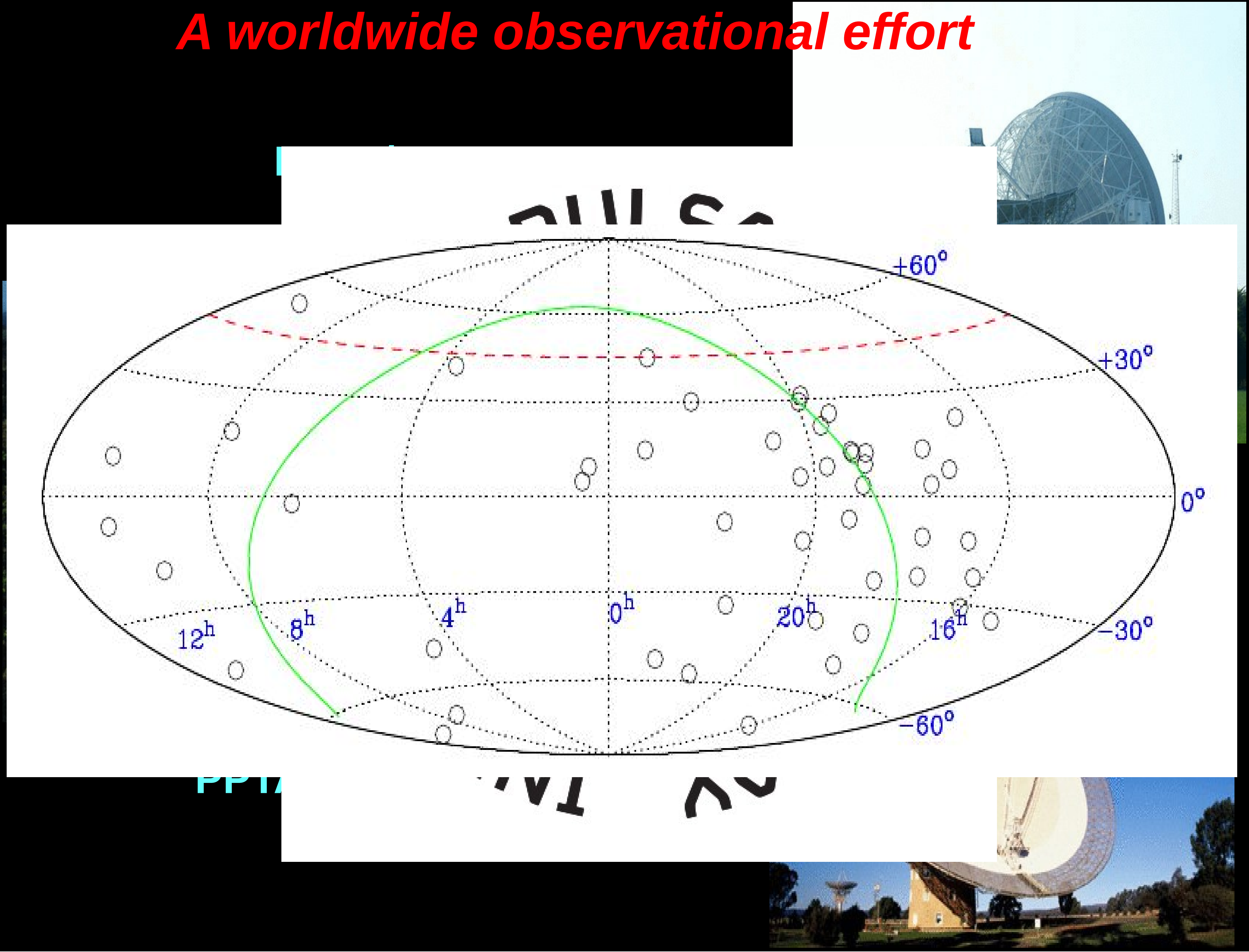
PPT

INTERNATIONAL PULSAR TIMING ARRAY

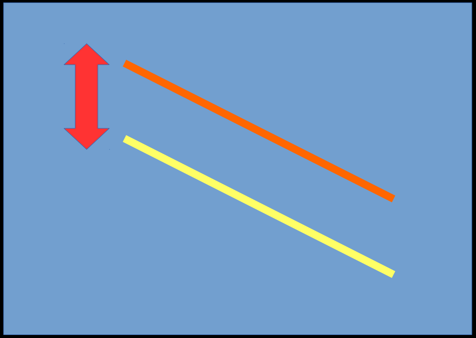
IPTA



A worldwide observational effort



The overall GW signal



Population parameters

1-Galaxy merger rate <-----> MBHB merger rate

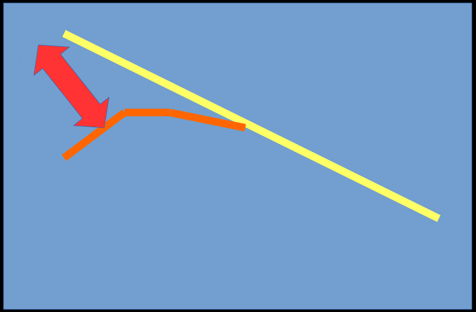
affects the number of sources at each frequency ---> N_0

2-MBH mass – merging galaxy relation

affects the mass of the sources ----> M_c

$$h_c^2(f) = \int_0^\infty dz \int_0^\infty dM_1 \int_0^1 dq \, \frac{d^4N}{dz\,dM_1\,dq\,dt_r} \frac{dt_r}{d\ln f_{\mathrm{K},r}} \times h^2(f_{\mathrm{K},r}) \sum_{n=1}^{\infty} \frac{g[n, e(f_{\mathrm{K},r})]}{(n/2)^2} \delta\left[f - \frac{n f_{\mathrm{K},r}}{1+z}\right].$$

$$h_c(f) \propto n_0^{1/2} f^{-\gamma} M_c^{5/6}$$



Local dynamics

1-Accretion (when? how?)

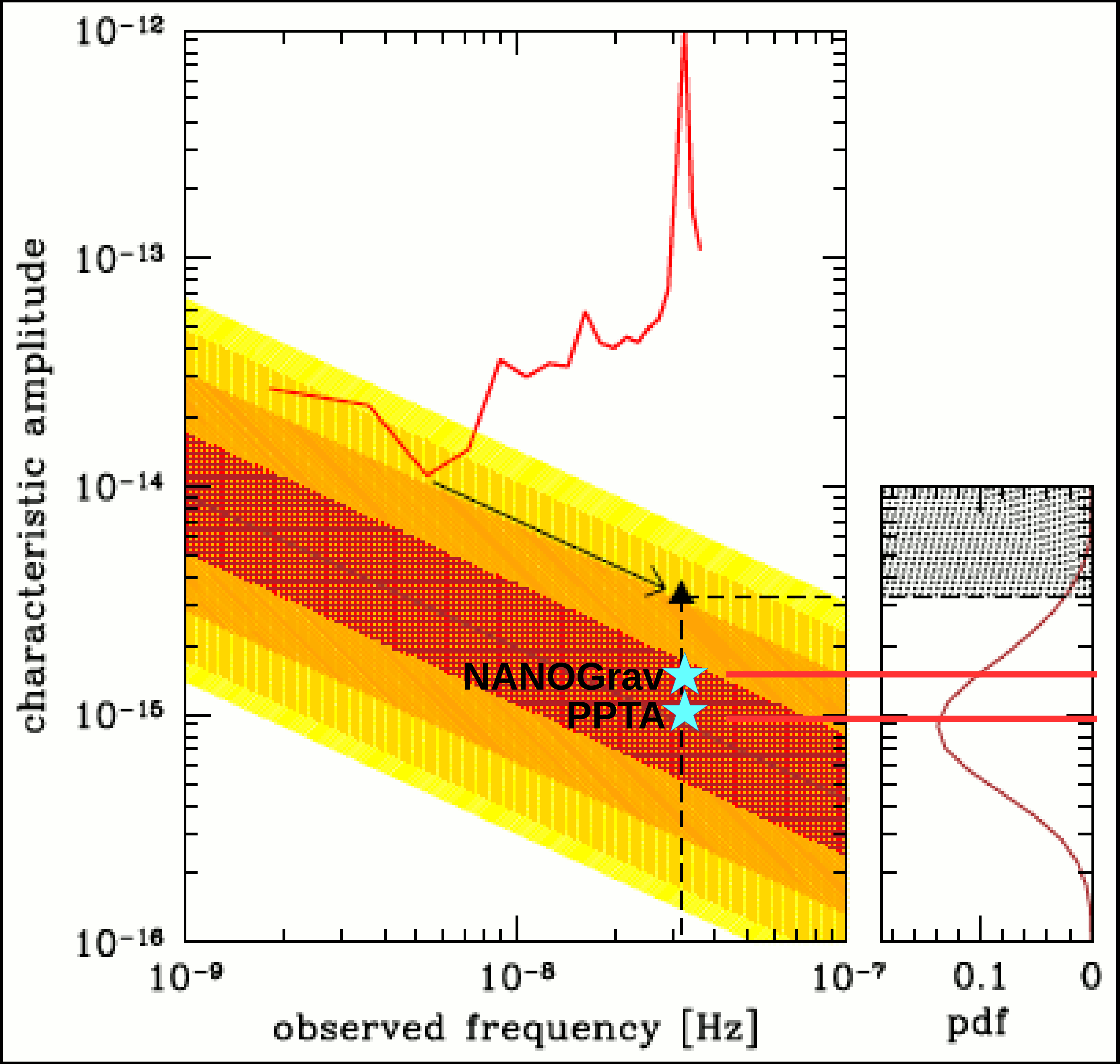
affects the mass of the sources ---> M_c

2-MBHB – environment coupling (gas & stars)

affects the chirping rate of the binaries ---> γ

affects the eccentricity ---> chirping rate ----> γ & single source detection

Uncertainty in the GW background level



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

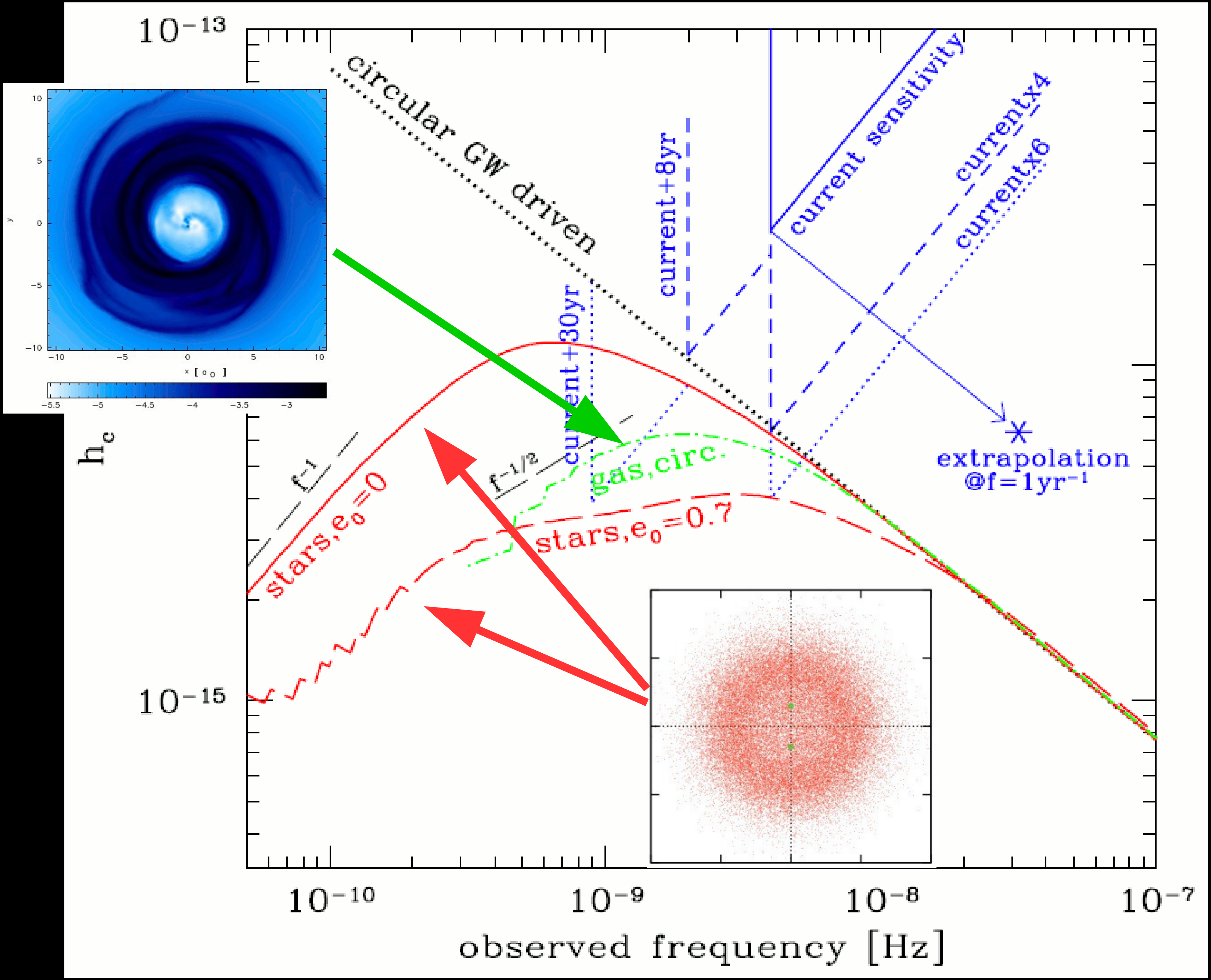
Predictions shown here (AS 2013):

>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)



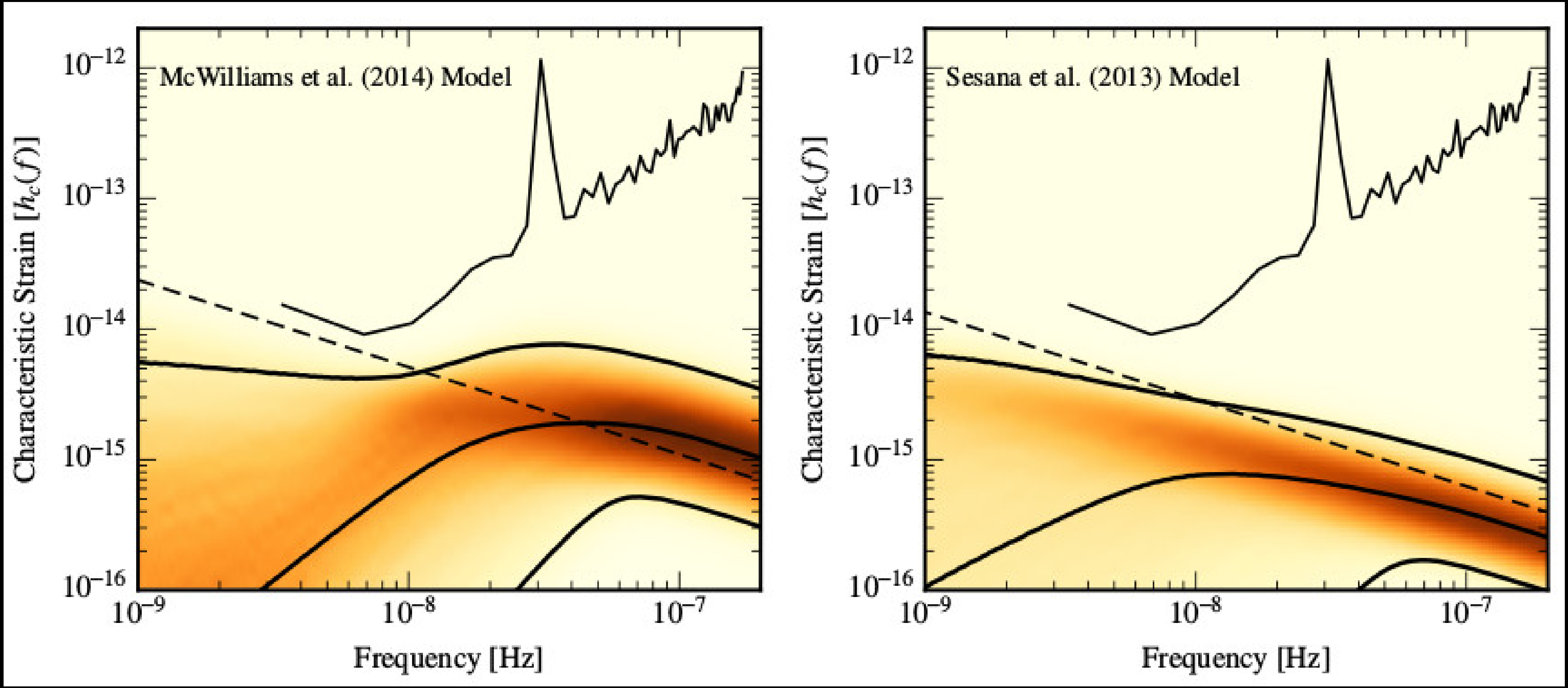
(Kocsis & AS 2011, AS 2013, Ravi et al. 2014, McWilliams et al. 2014)

Dynamical constraints from PTA

(NANOGrav, Arzoumanian et al. 2015)

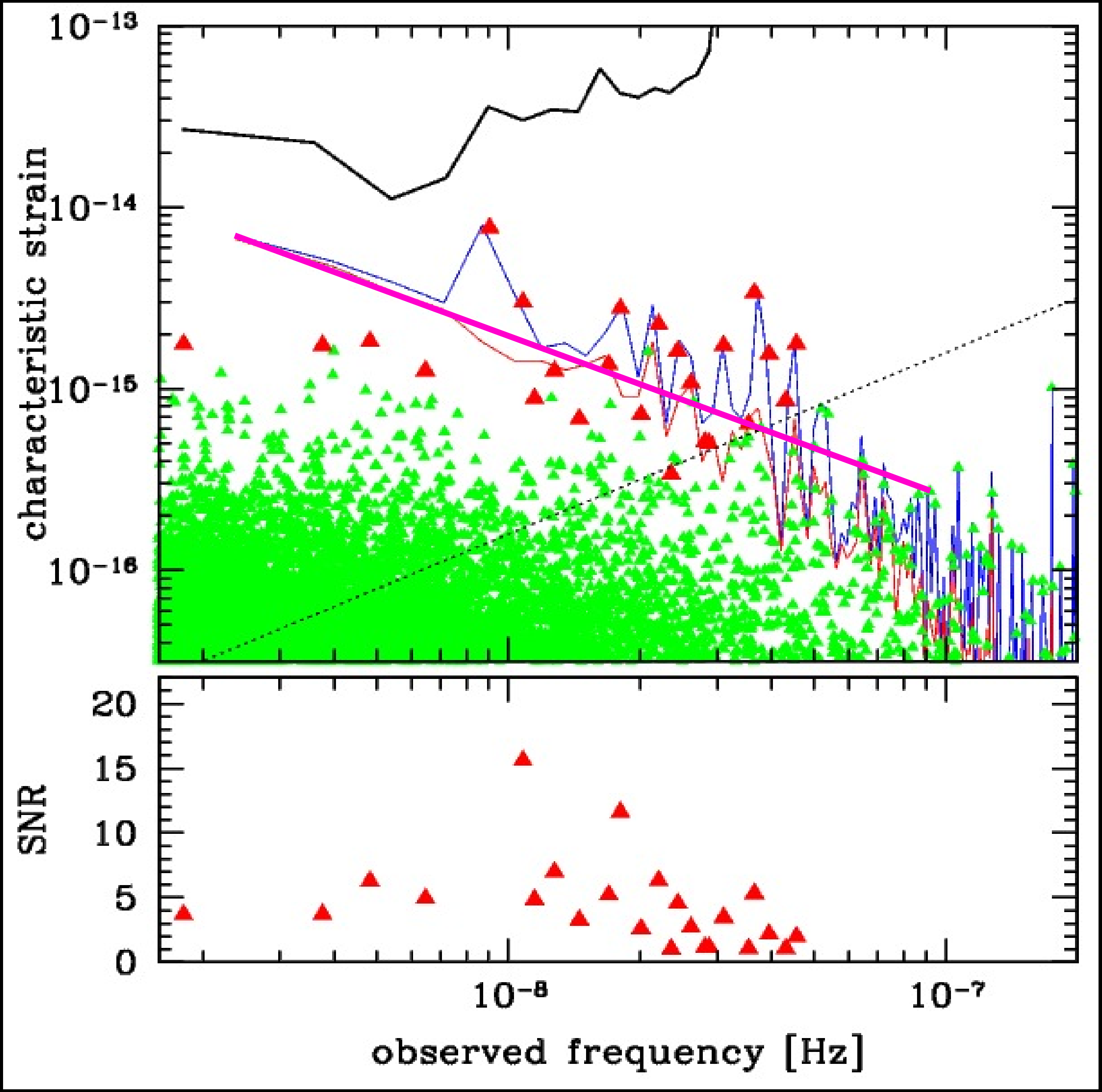
Simple broken-power law model mimicking possible environmental effects (Sampson et al. 2015)

$$h_c(f) = A\frac{(f/f_{\mathrm{year}})^{-2/3}}{(1+(f_b/f)^{\kappa})^{1/2}}$$



Depending on the prior on the amplitude, current non detection provide strong/little evidence of a background turnover

Resolvable sources



*It is not smooth

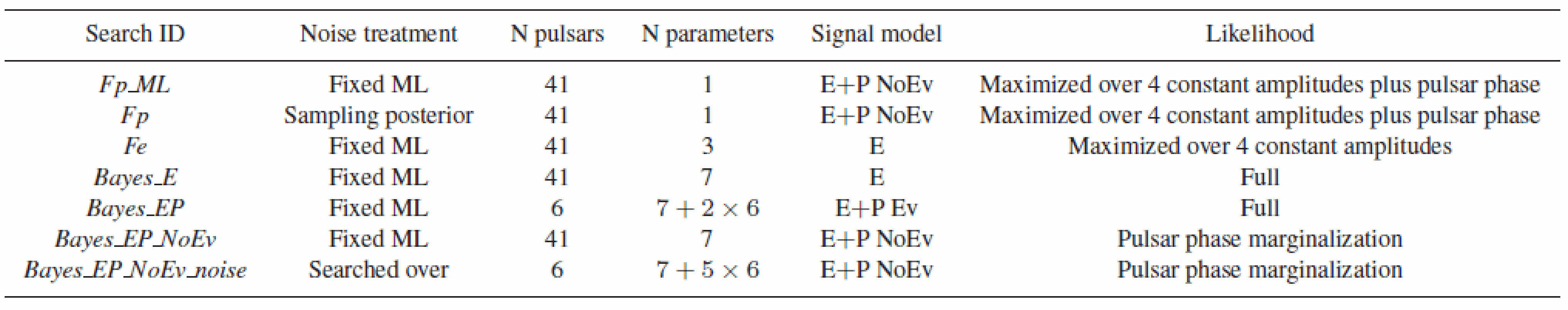
*It is not Gaussian

*Single sources might pop-up

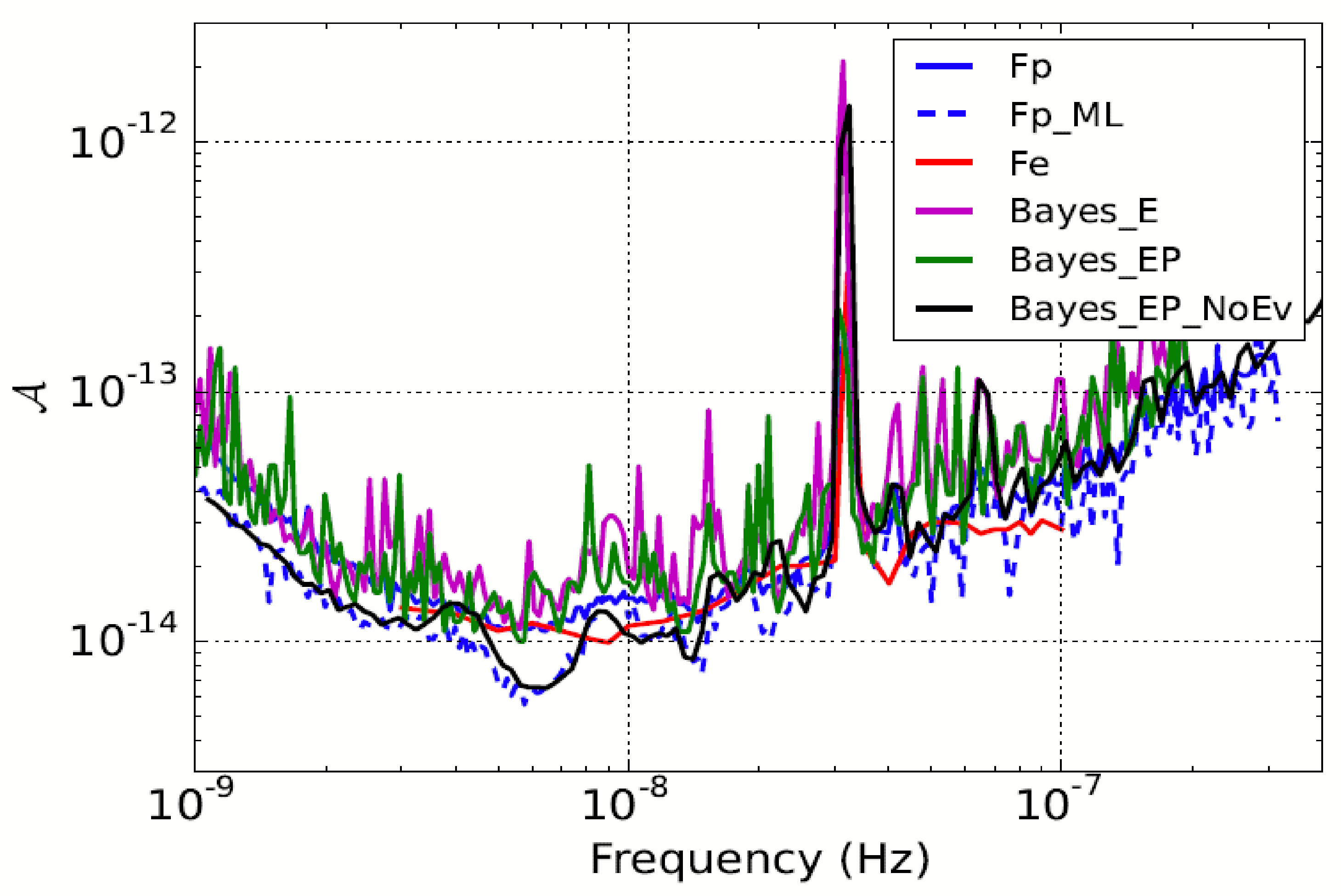
*The distribution of the brightest sources might well be anisotropic

Limits on continuous GWs

(EPTA, Babak et al. 2015)

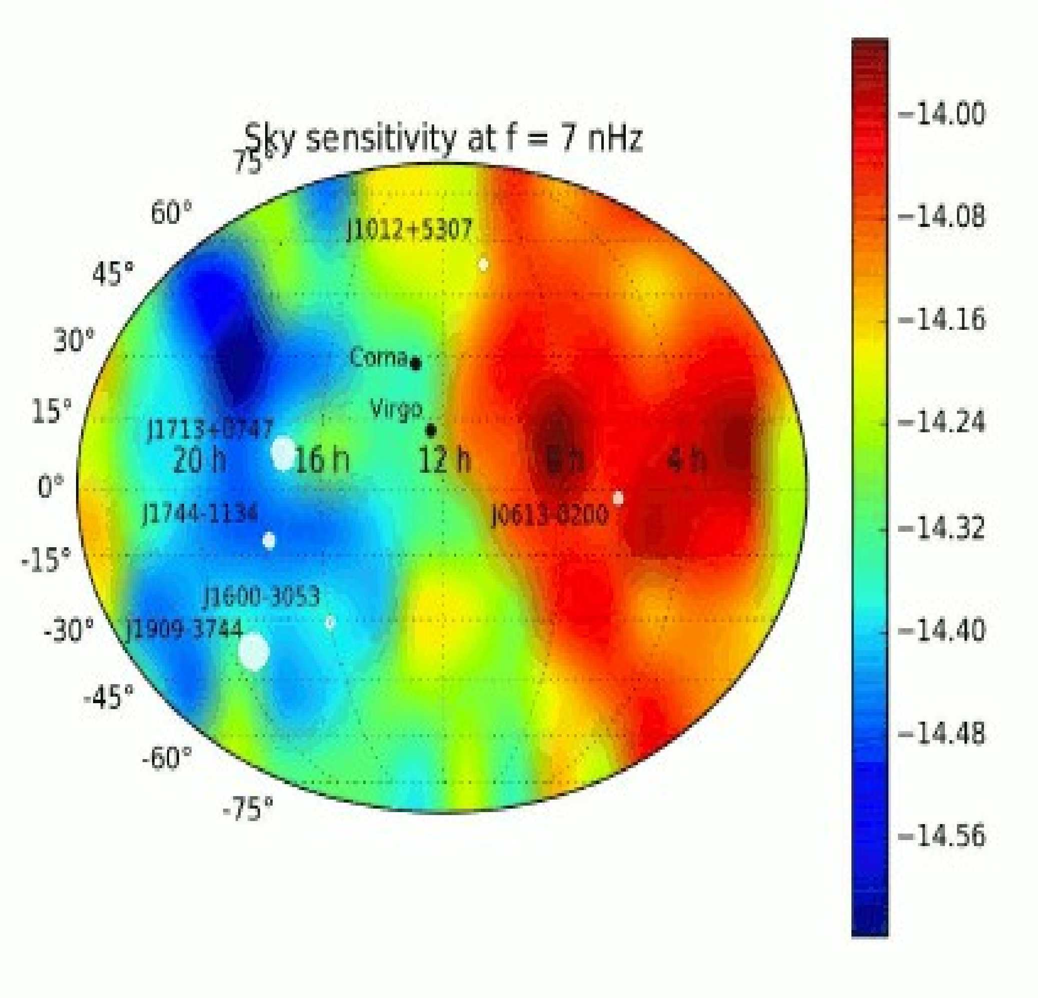


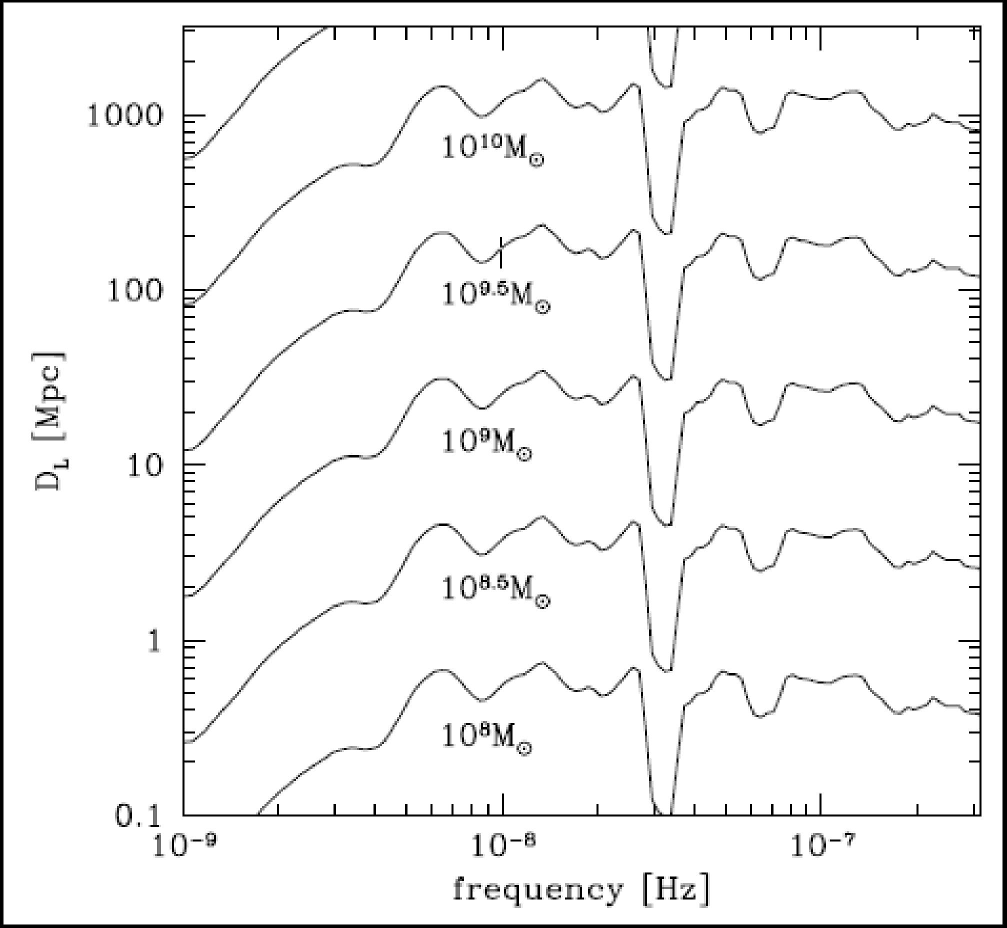
Search ID	Noise treatment	N pulsars	N parameters	Signal model	Likelihood
Fp_ML	Fixed ML	41	1	E+P NoEv	Maximized over 4 constant amplitudes plus pulsar phase
Fp	Sampling posterior	41	1	E+P NoEv	Maximized over 4 constant amplitudes plus pulsar phase
Fe	Fixed ML	41	3	E	Maximized over 4 constant amplitudes
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



Astrophysical implications

The array sensitivity is function of the sky location, we can build sensitivity skymaps





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

Doggybag

Massive black hole binaries are expected to be the loudest gravitational wave sources in the Universe

Precise timing of ultra-stable millisecond pulsar in a Pulsar Timing Array provides an effective way to probe GWs from MBHBs in the nHz frequency window

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

Current limits are getting extremely interesting, showing some tension with vanilla models for the cosmic SMBHB population.

However:

> considering current observational uncertainties, there might be tension, but even vanilla models cannot be confidently ruled out

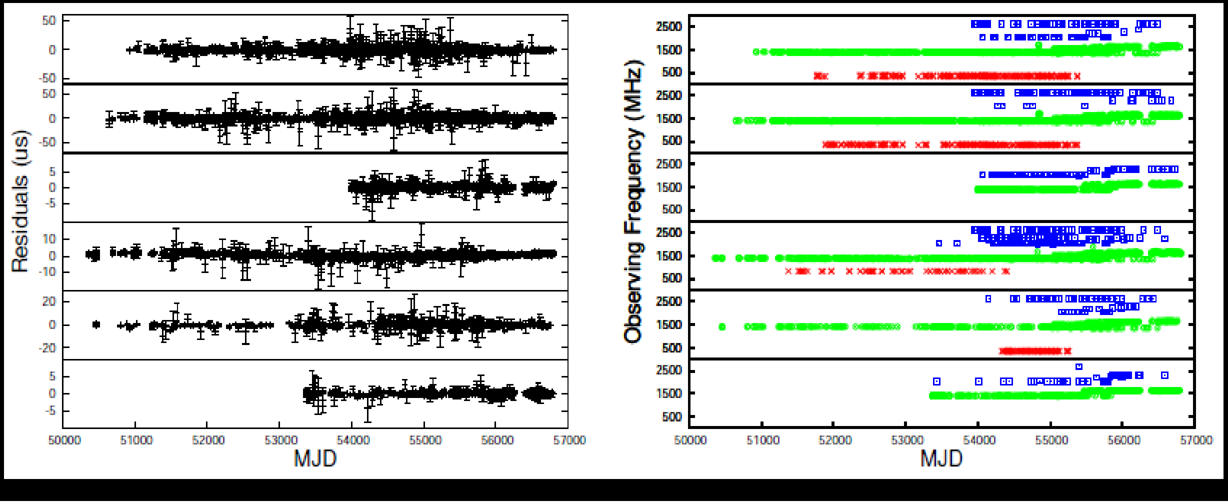
> detection statistics: is the signal stochastic?

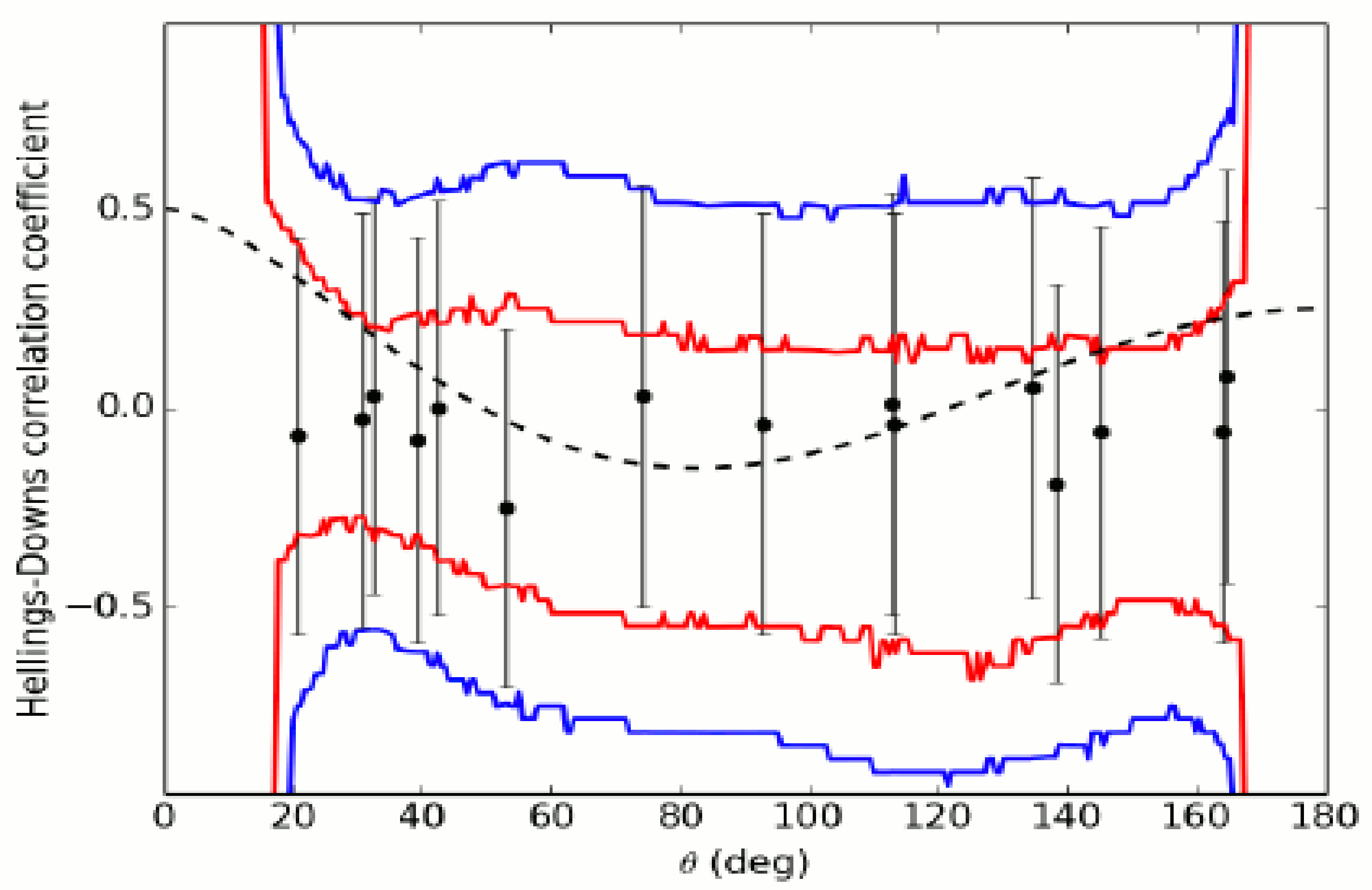
> basically any step towards a more realistic modelling tend to make the signal dimmer:

*coupling with the environment (but how efficient?)

*eccentricity (critical ingredient)

Pulsar correlations (EPTA, Lentati et al. 2015)

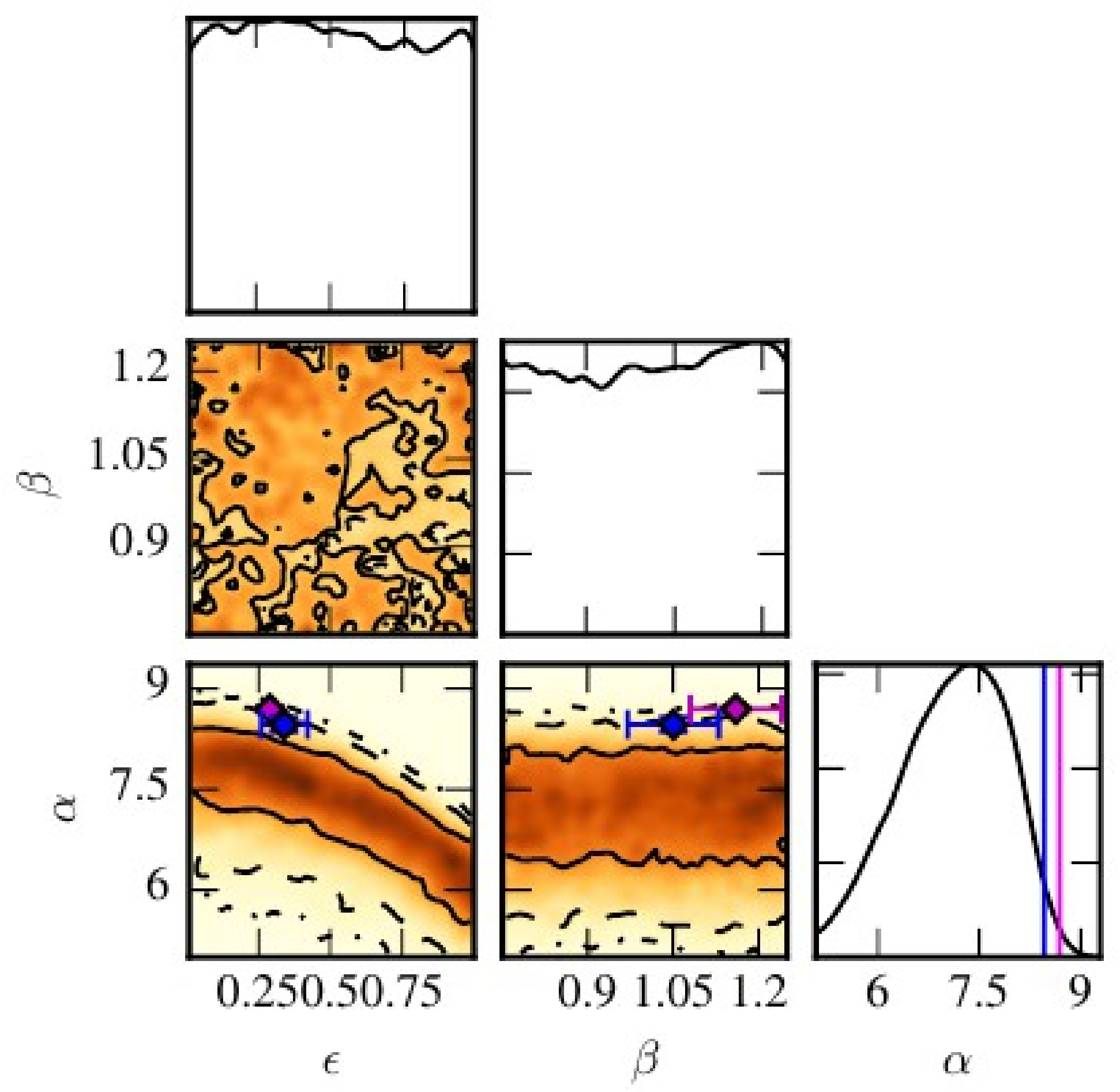




Constrains on the BH-galaxy relations

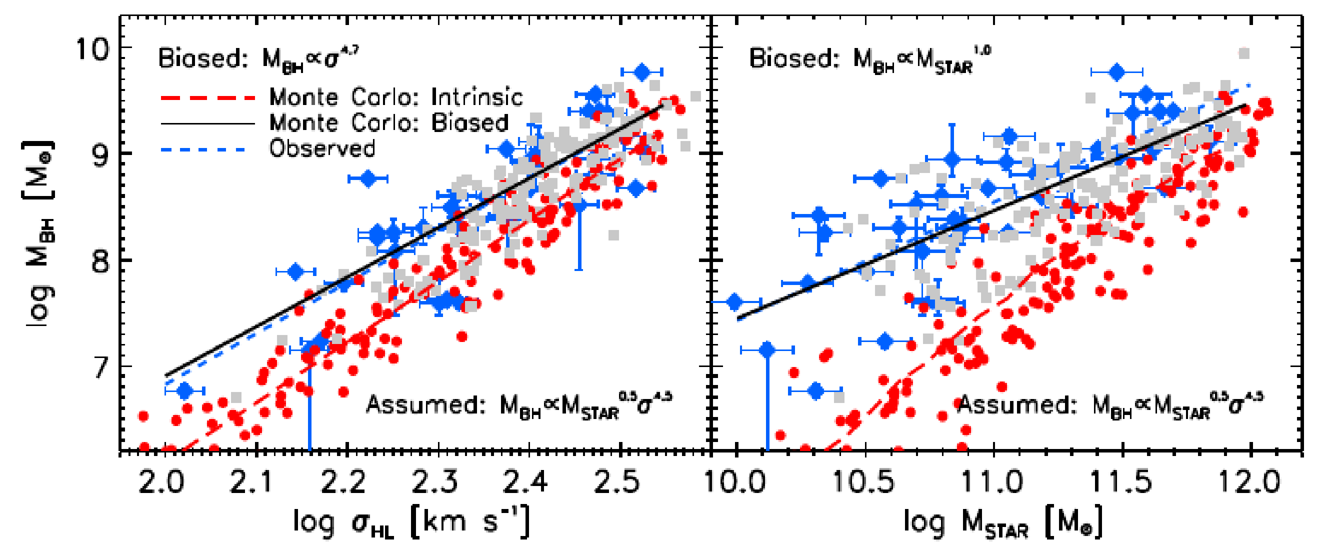
$$\log_{10} M_\bullet = \alpha + \beta \log_{10}\left(\frac{M_{\rm bulge}}{10^{11}{\rm M}_\odot}\right)$$

Parametric MBH-galaxy relation (plus a scatter ε)



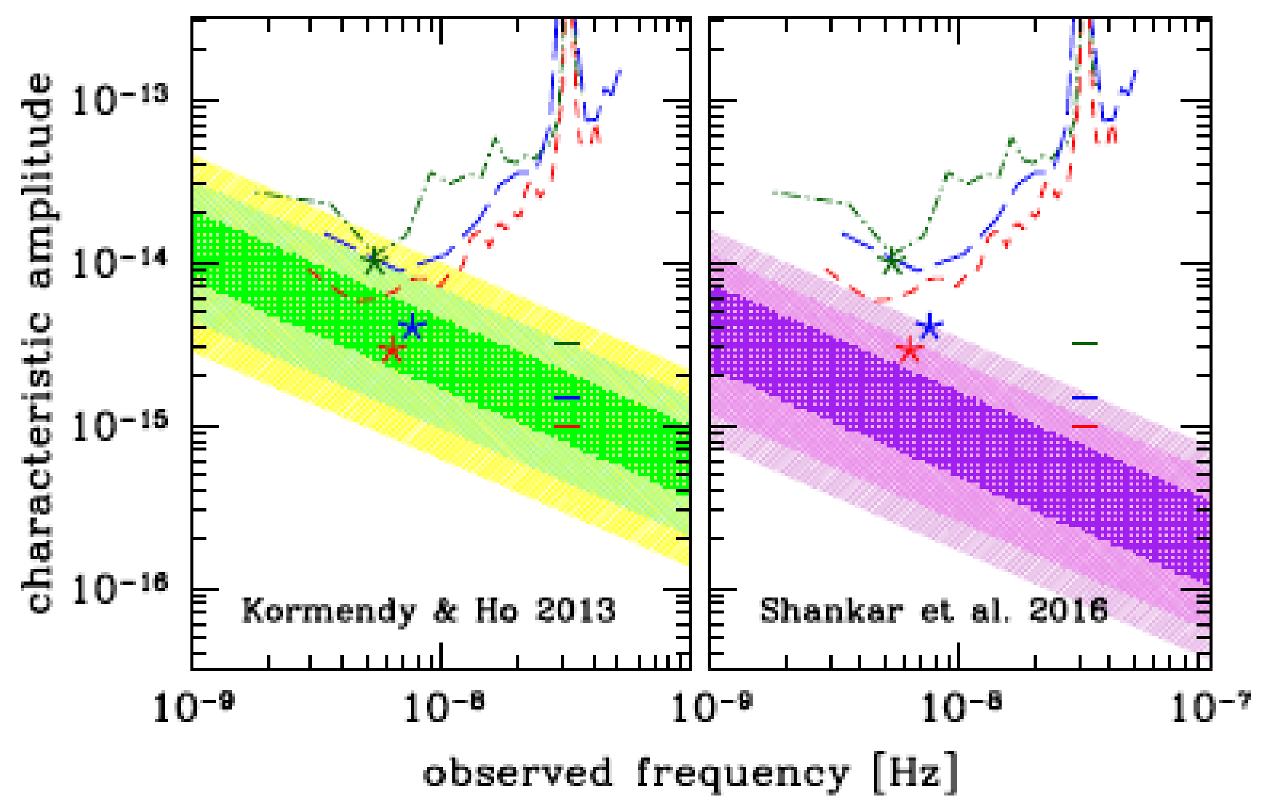
The meaured upper limit on the signal results in a posterior distribution on the parameters.

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



The BH-galaxy relations might be biased-high

(Shankar et al. 2016)



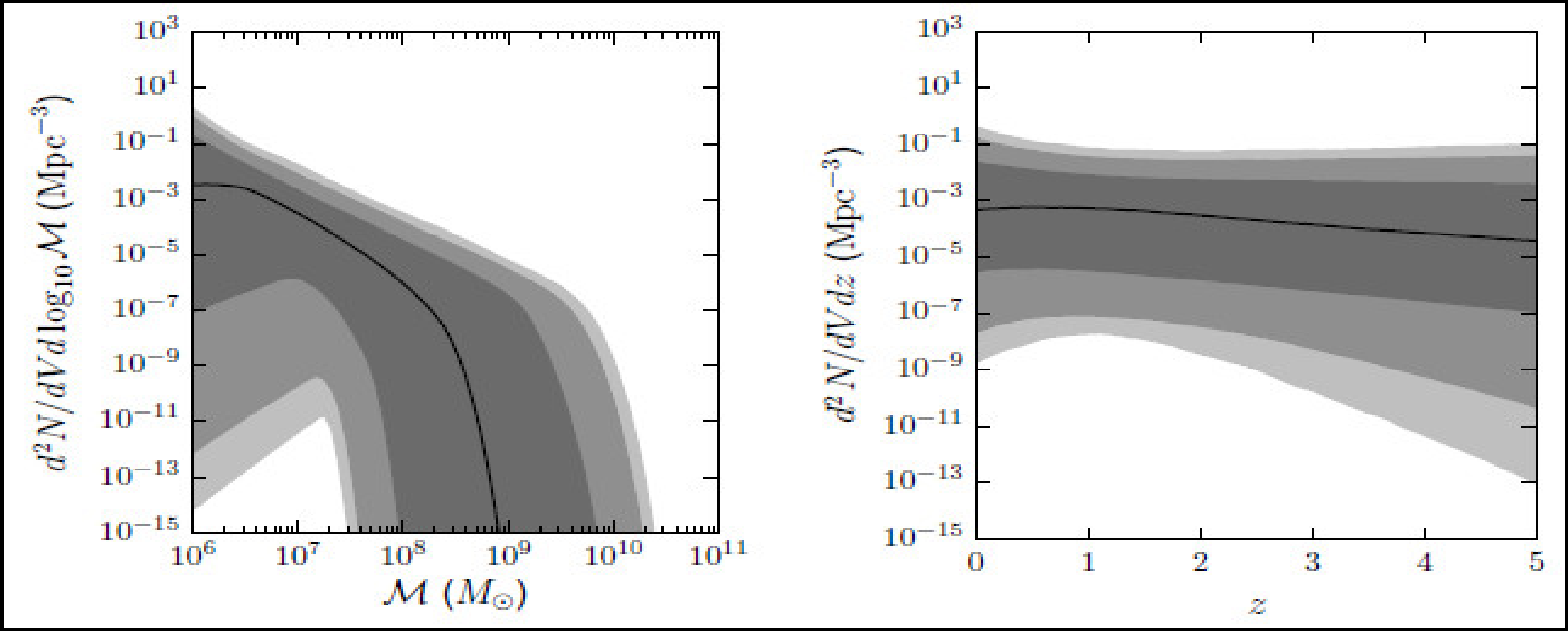
If this is in fact the case, the expected signal is a factor of ~3 lower.

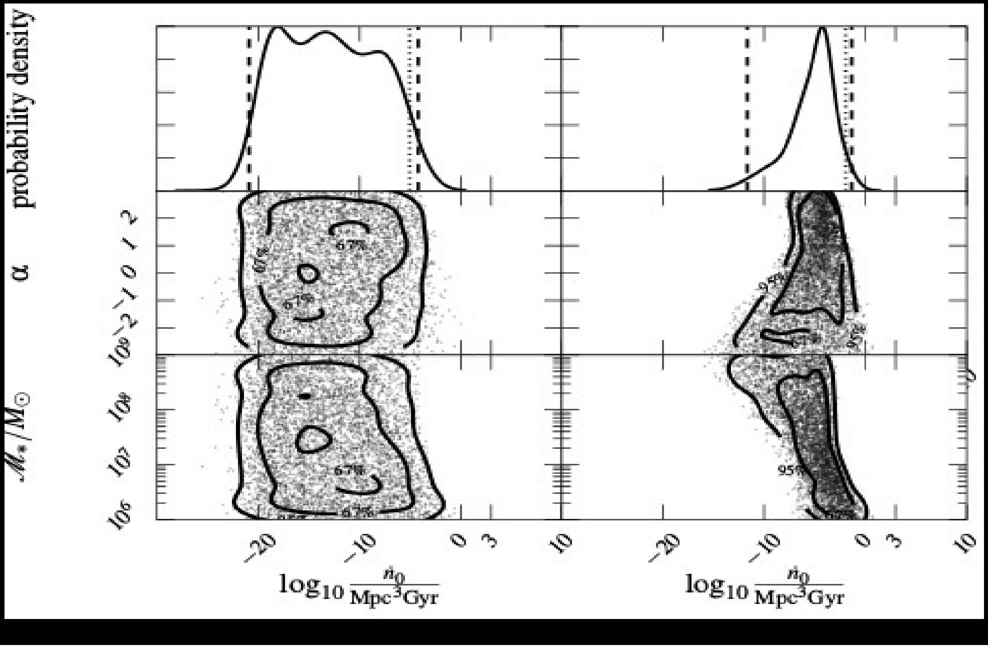
This will make GW detection with PTA more difficult, delaying detection by 5+ years

(AS et al. 2016)

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

(Middleton et al. 2015)





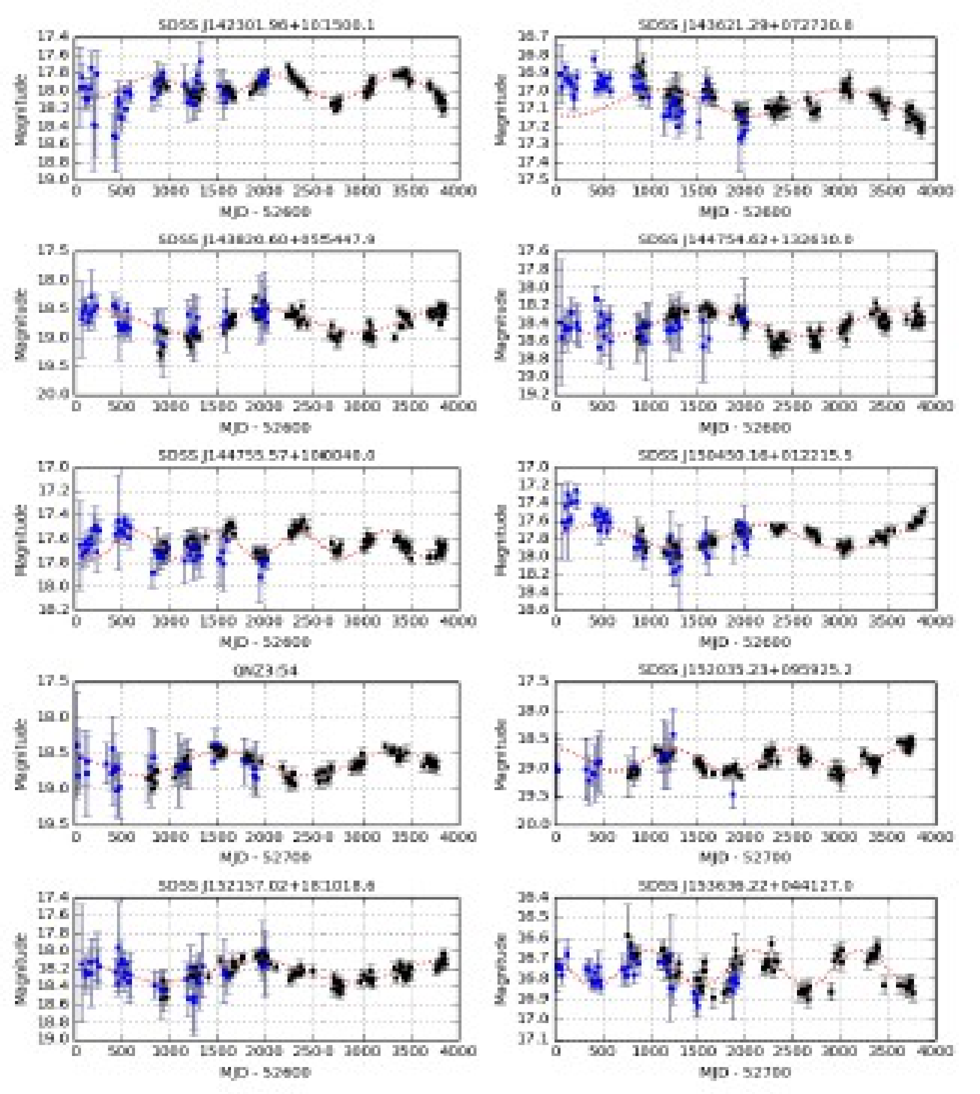
A PTA detection of a stochastic GWB will essentially *only constrain the overall MBHB merger rate*.

Need combination with other observation to be informative

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

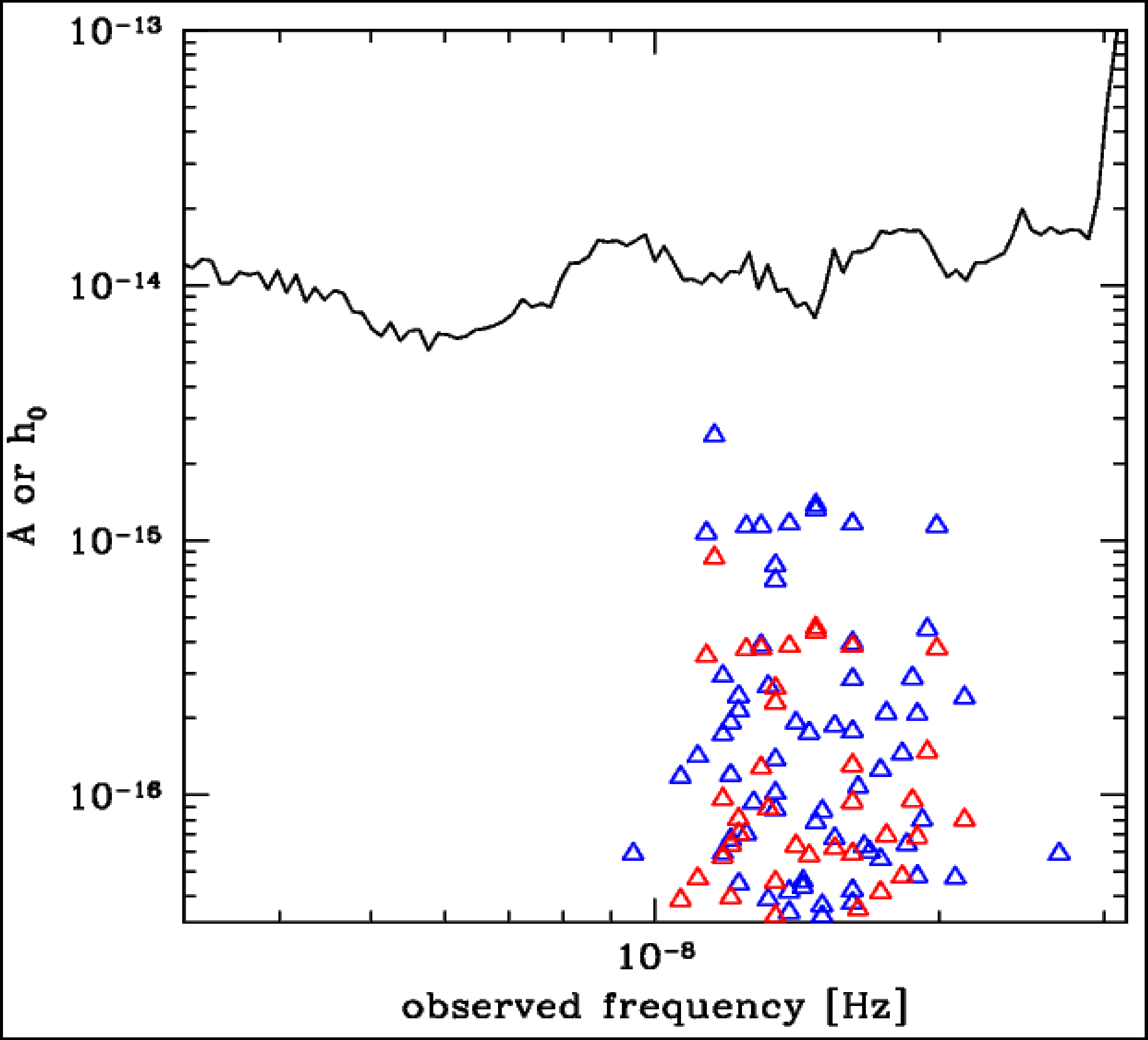
-required 1.5 cycles for periodicity identification.

-111 lightcurves showing periodic behaviour

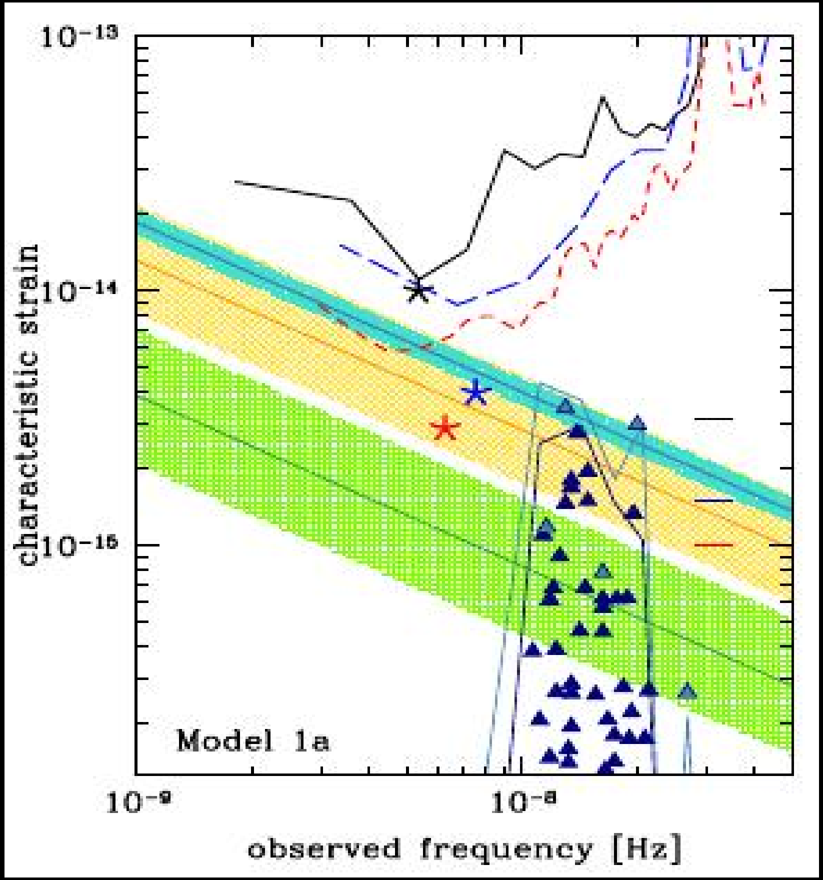
-For most of the systems we have: period, redshift, total mass, sky location, etc etc...

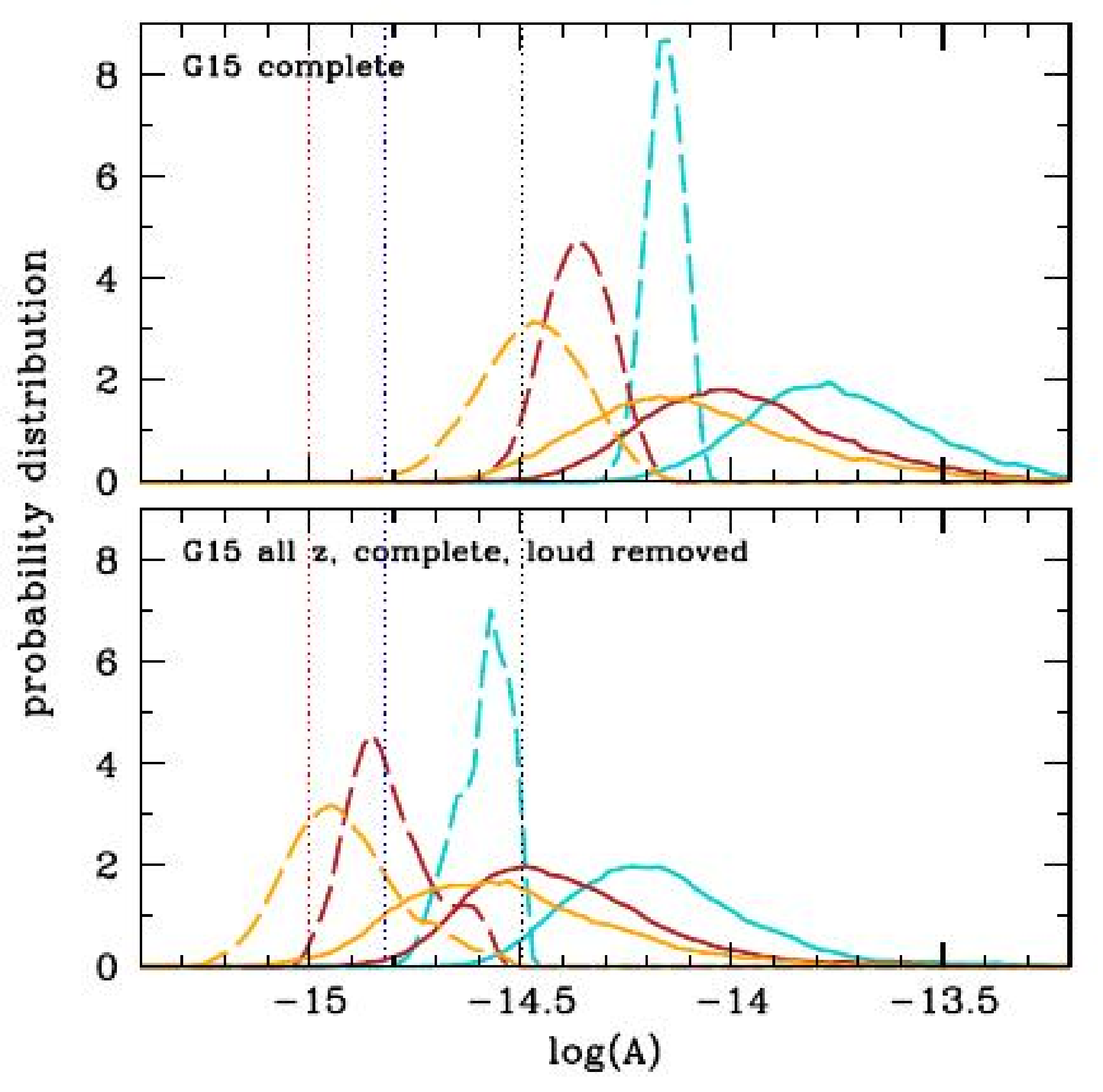
…not that I believe any of them, but...

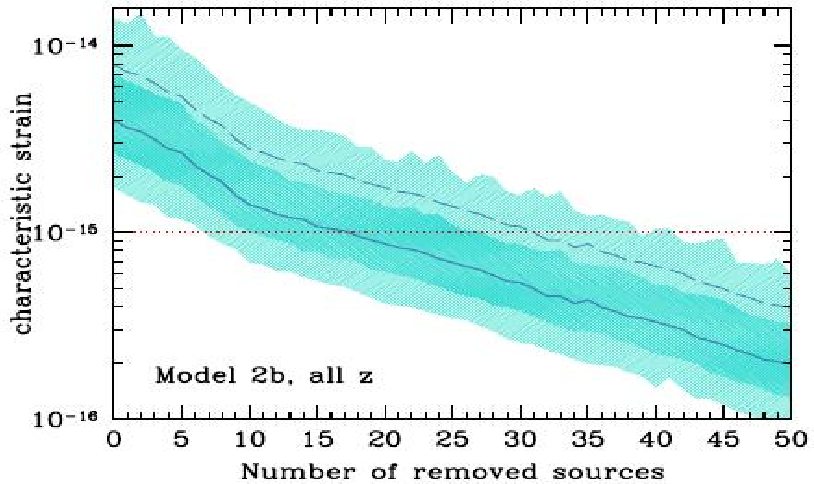
Strain amplitude of individual sources



Extrapolated GWB







GWB 3-to-15 times larger than PTA limits

Most of the candidates cannot be SMBHBs (check arXiv on Monday)

The future

MeerKAT, South Africa (2017)

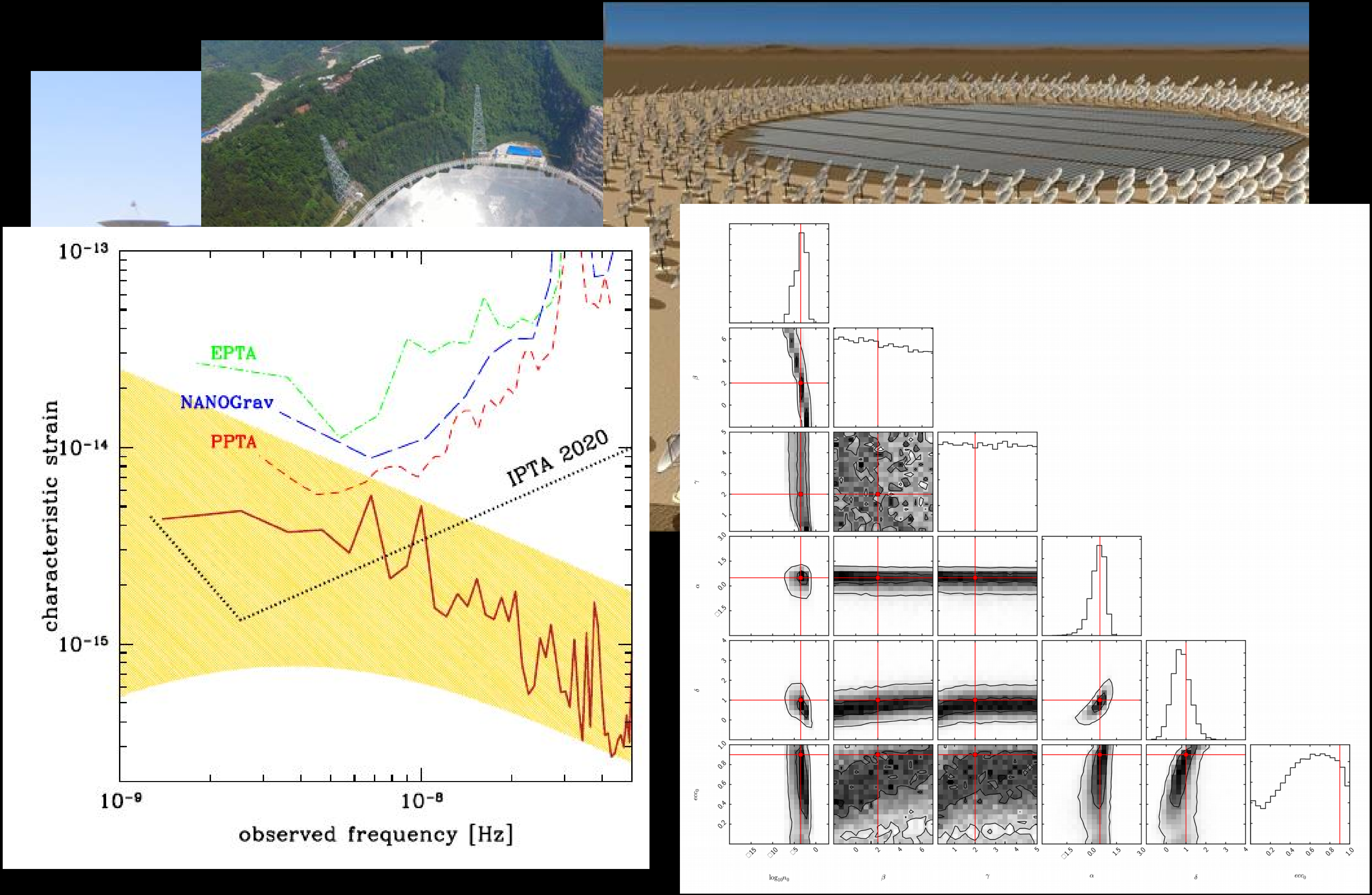
The future

FAST, China (2017)

The future

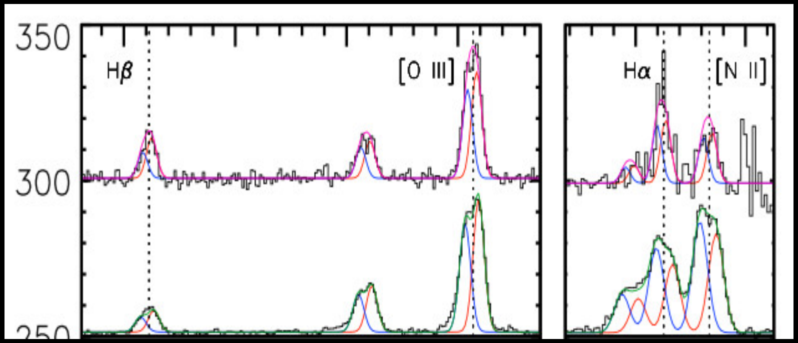
Square Kilometre Array (SKA, 2021+)

The future

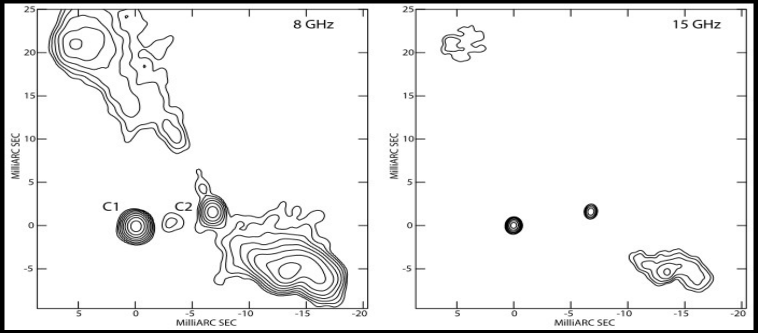

EPTA
NANOGrav
PPTA
IPTA 2020
characteristic strain
observed frequency [Hz]
10^{-13}
10^{-14}
10^{-15}
10^{-9}
10^{-8}
$\log_{10} n_0$
β
γ
α
δ
ecc_0

But do we see them?

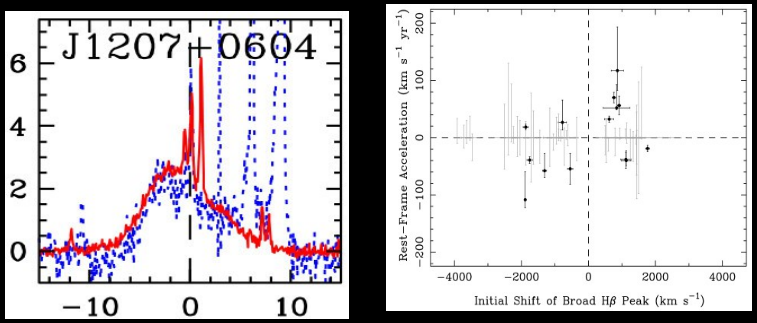
10 kpc: double quasars
(Komossa 2003)



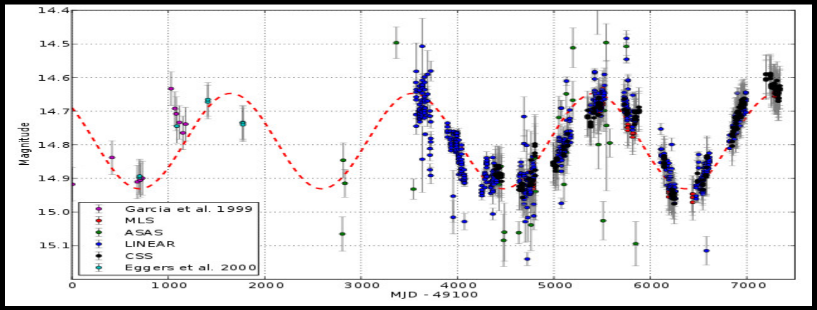
1 kpc: double peaked NL
(Comerford 2013)



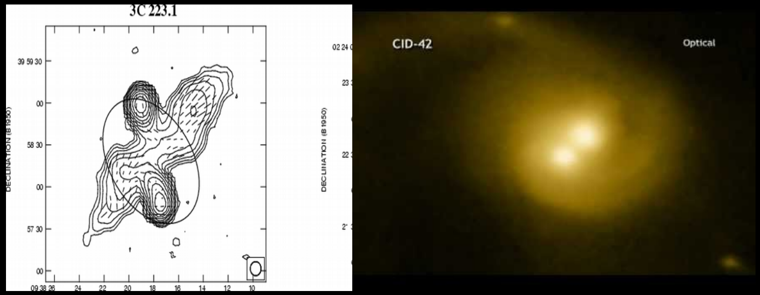
10 pc: double radio cores
(Rodriguez 2006)



1 pc: -shifted BL (Tsalmatzsa 2011)
-accelerating BL (Eracleous 2012)



0.01 pc: periodicity (Graham 2015)



0.0pc:-X-shaped sources (Capetti 2001)
-displaced AGNs (Civano 2009)