Gravitational wave science with pulsar timing arrays and the Square Kilometre Array

Alberto Sesana
Albert Einstein Institute, Golm

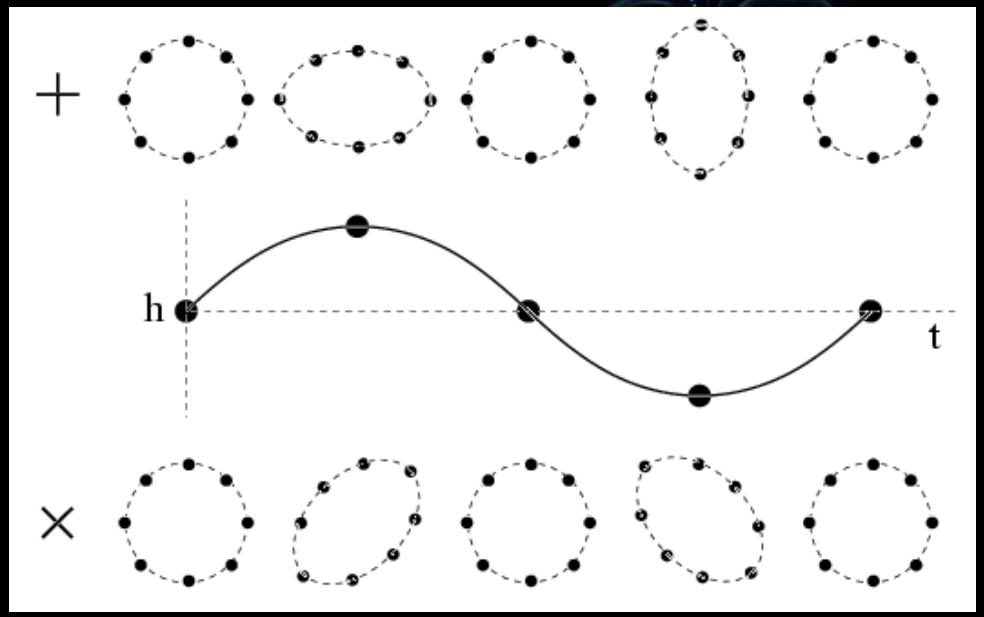
Gravitational waves (GWs)

Space-time perturbations **travelling at the speed of light in form of waves (like electromagnetic waves)**

Predicted by Einstein's General Relativity: fundamental prediction of the theory that *has not been directly tested*.

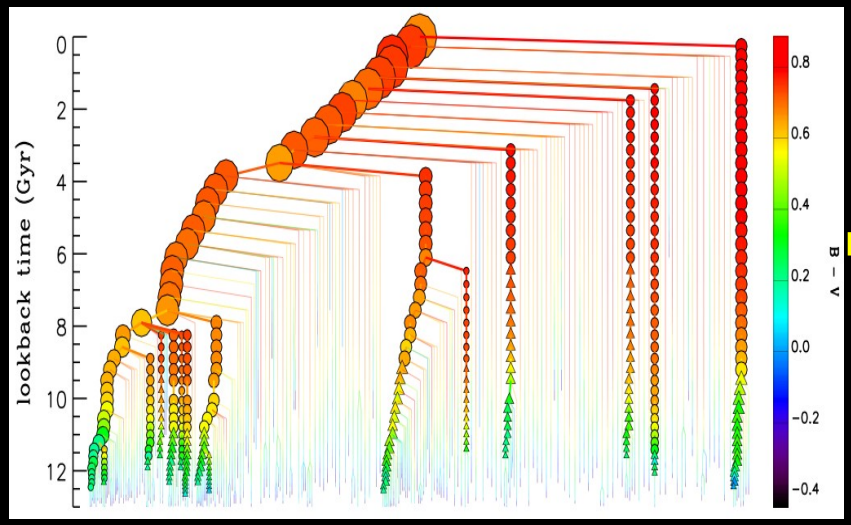
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, \qquad h_{\mu\nu} \ll 1$$

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



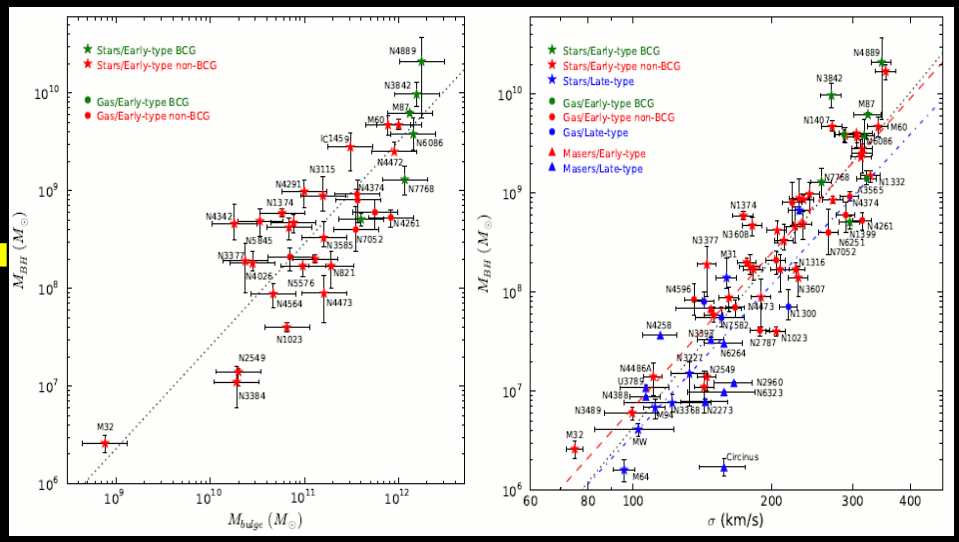
massive black hole binaries (MBHBs) forming following galaxy mergers are the loudest sources below micro-Hz frequencies

Structure formation in a nutshell



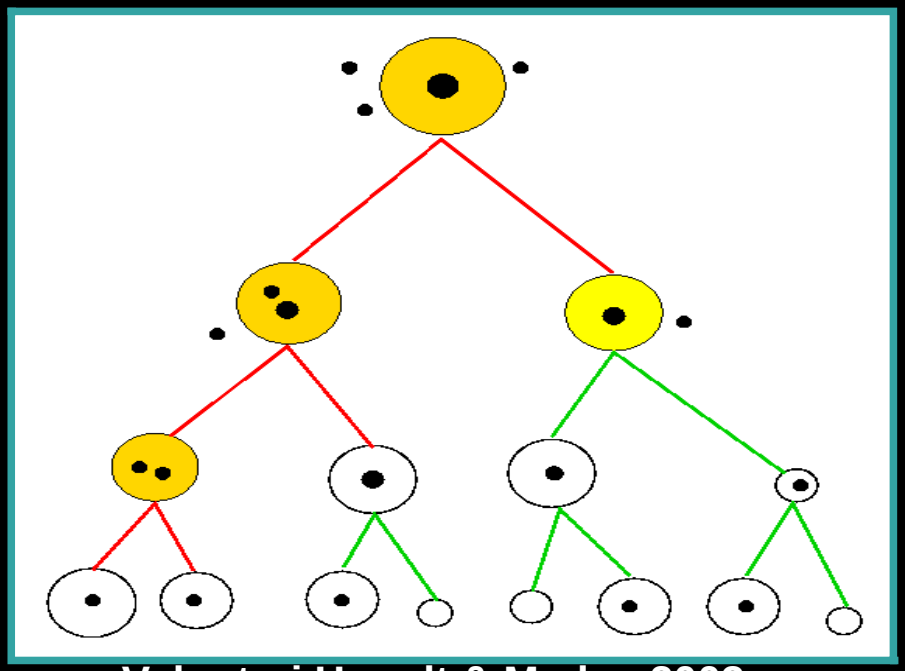
From De Lucia et al 2006

+



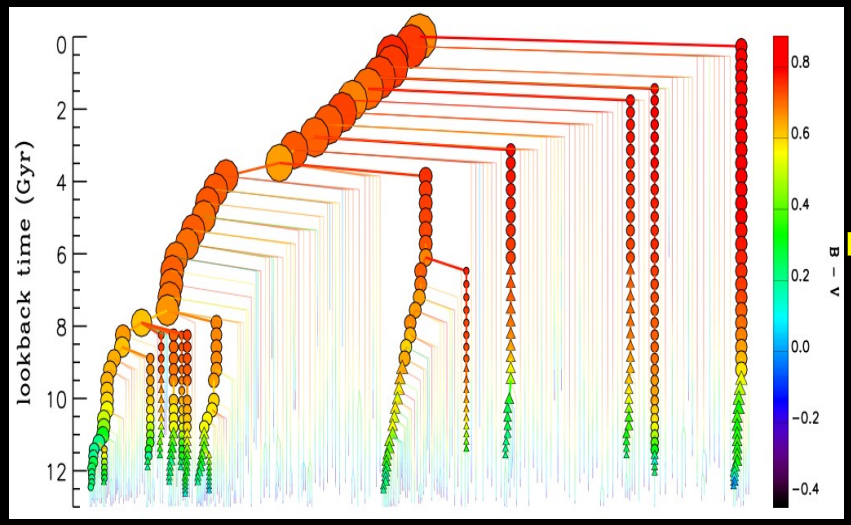
Ferrarese & Merritt 2000, Gebhardt et al. 2000

=

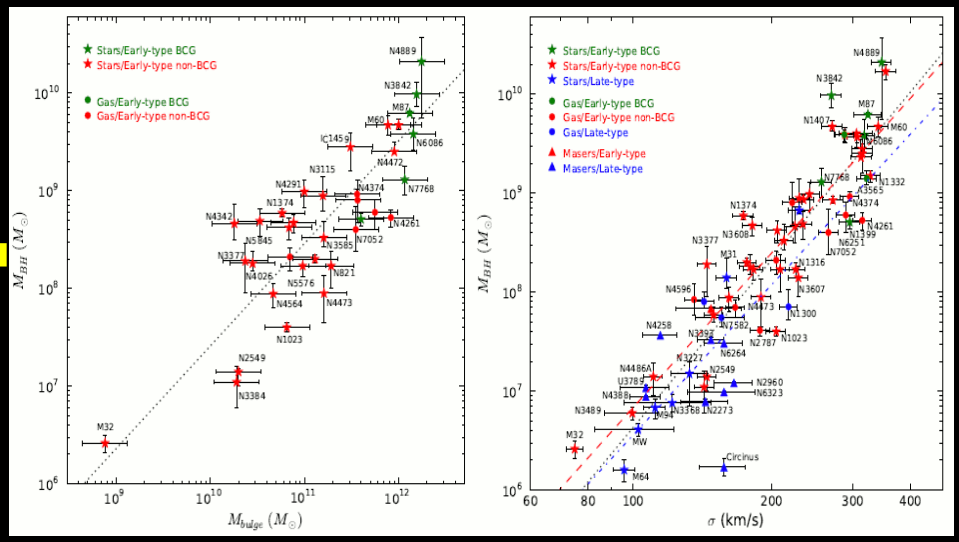


Volonteri Haardt & Madau 2003

Structure formation in a nutshell



From De Lucia et al 2006

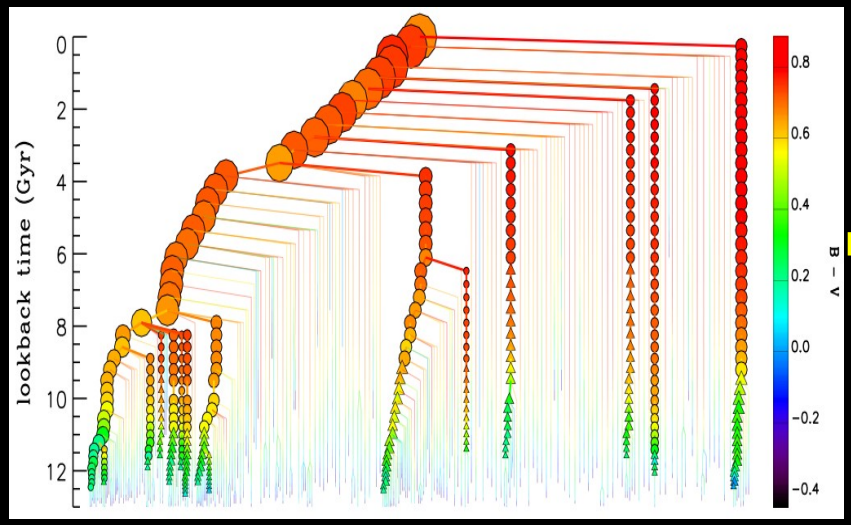


Ferrarese & Merritt 2000, Gebhardt et al. 2000

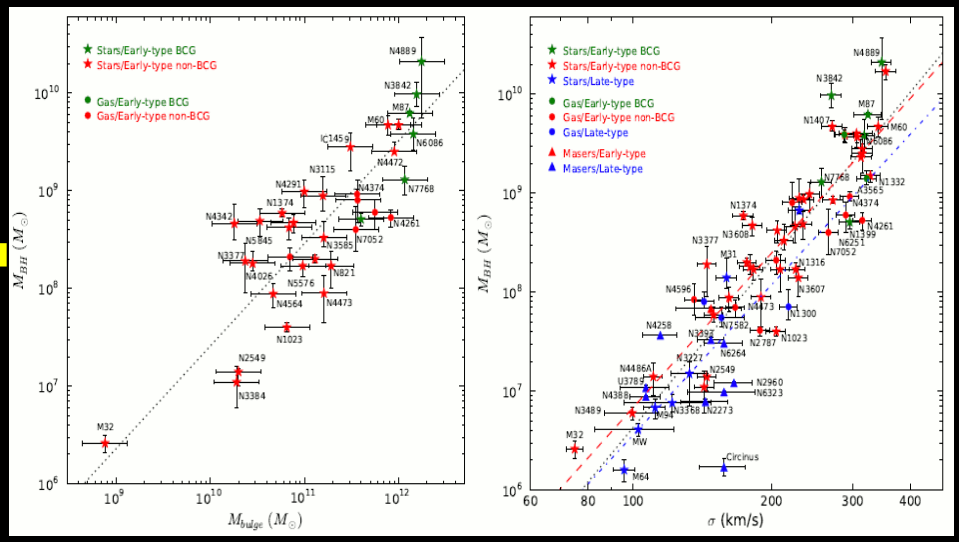
During galaxy mergers, MBHBs will inevitably form!

Volonteri Haardt & Madau 2003

Structure formation in a nutshell

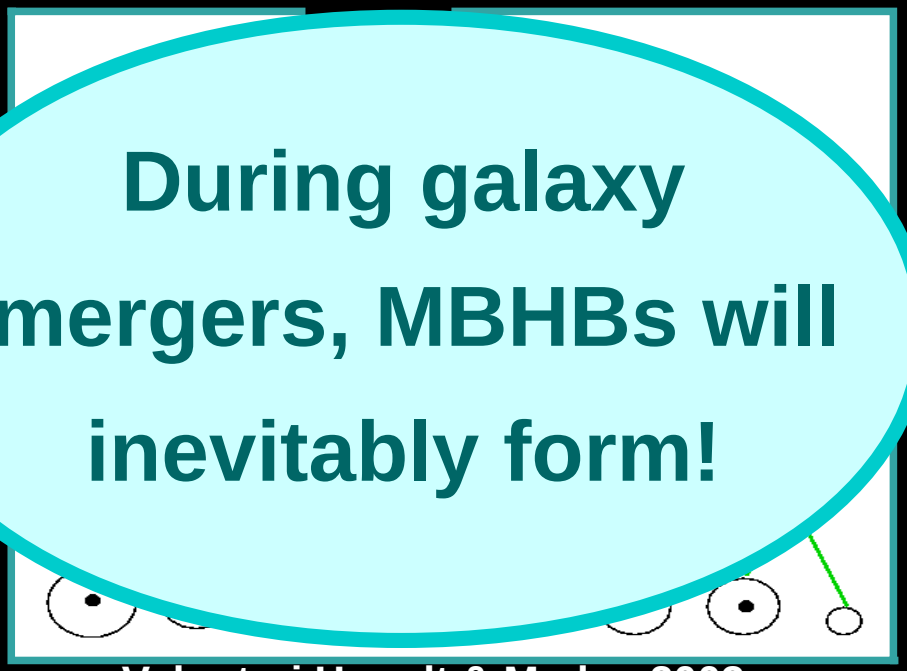


From De Lucia et al 2006



Ferrarese & Merritt 2000, Gebhardt et al. 2000

During galaxy mergers, MBHBs will inevitably form!



Volonteri Haardt & Madau 2003

QUESTIONS:

- *What is the role of MBHBs in structure formation?
- *What is the MBHB merger rate?
- *How do they pair together?
- *How do they interact with their environment?
- *How to they get to the GW regime?
- *Is there a last parsec problem?

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: $h \sim 10^{-18}$, $f < 10^{-2}$

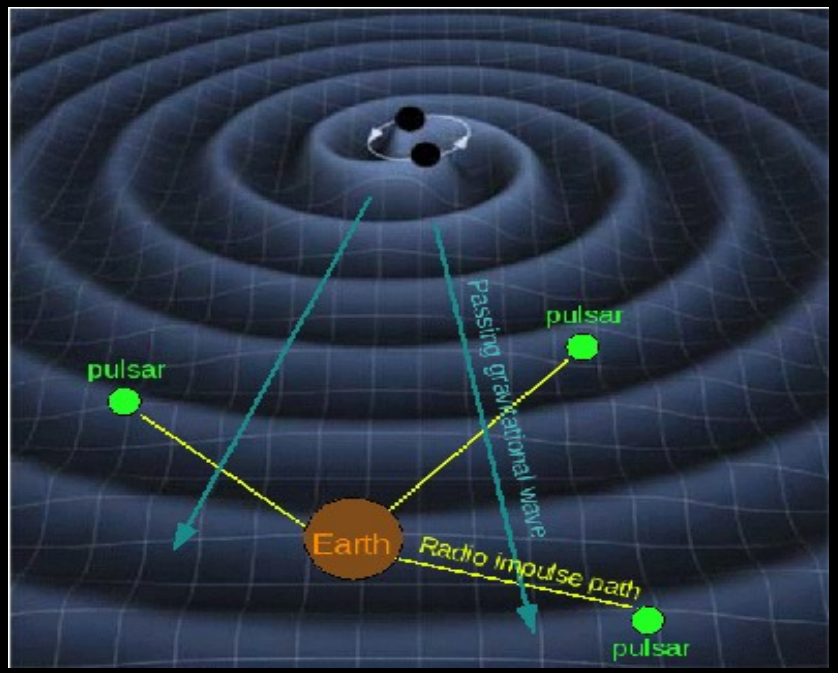
10^9 $M_\odot$ binary at 1Gpc: $h \sim 10^{-14}$, $f < 10^{-5}$

Timing residual from MBH binaries

GWs affect the arrival time of radio pulses (Sazhin 1979)

*** the delay is proportional to the wave amplitude *h***

*** when a timing model for the pulsar is fitted out, a *residual* of order *h/f* is left**

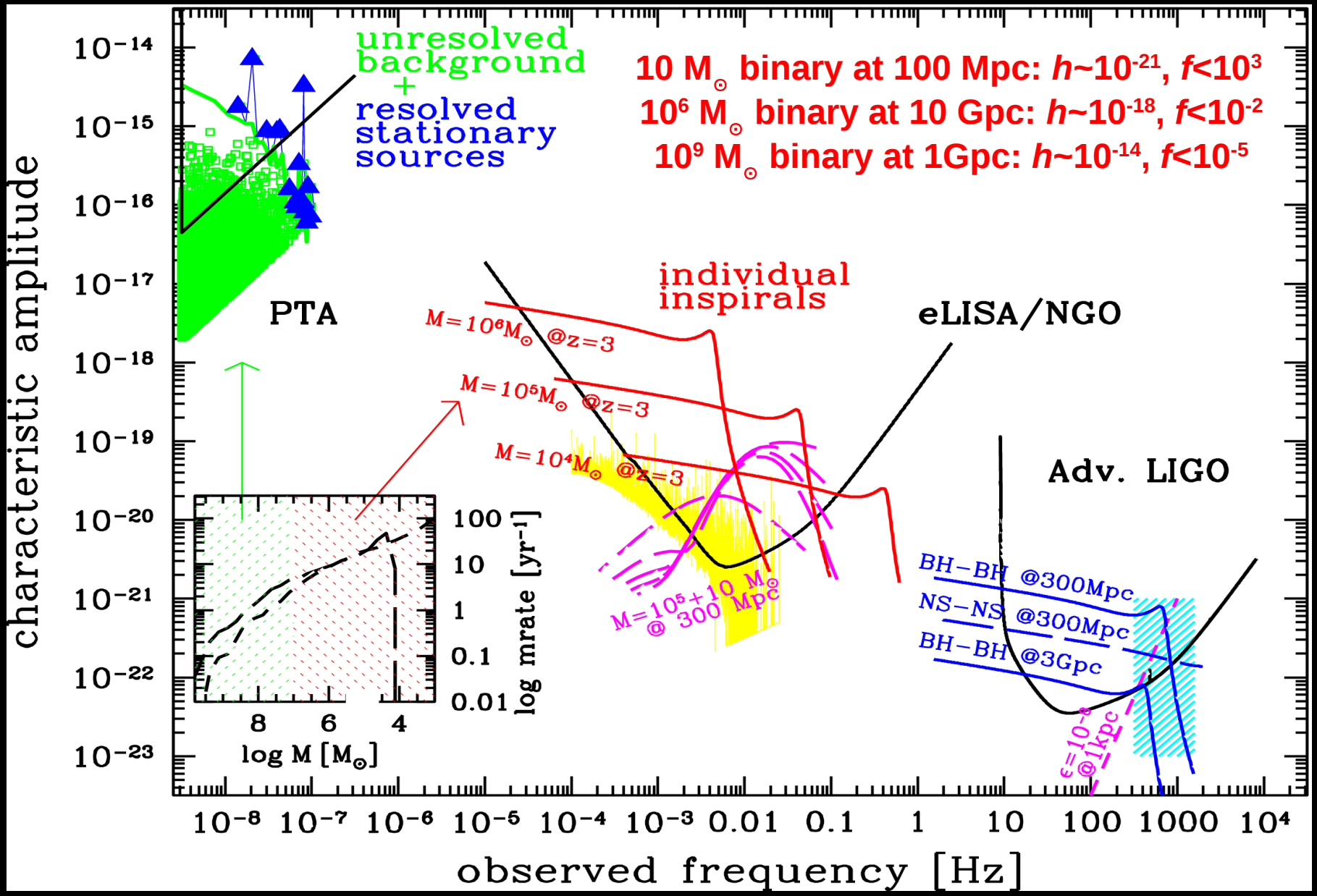


10^9 $M_\odot$ binary at 1Gpc: h~10^{-15}, f~10^{-8}

Implies a residual ~100ns

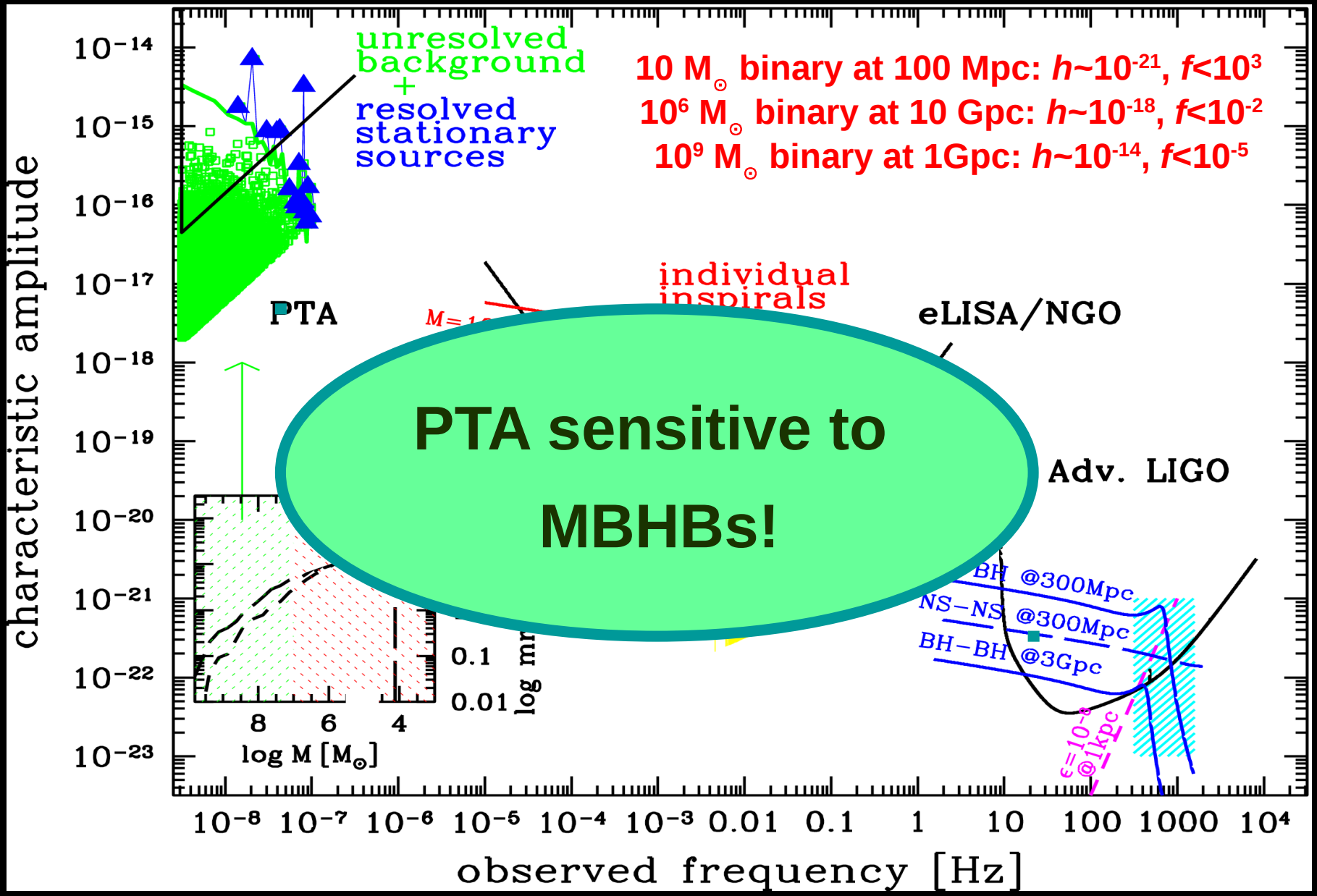
100ns is the accuracy at which we can time the most stable millisecond pulsars today!

The GW spectrum



AS 2013

The GW spectrum



PTA sensitive to MBHBs!

AS 2013

GW signal from a MBHB population

Characteristic amplitude of a GW signal coming from a certain source population

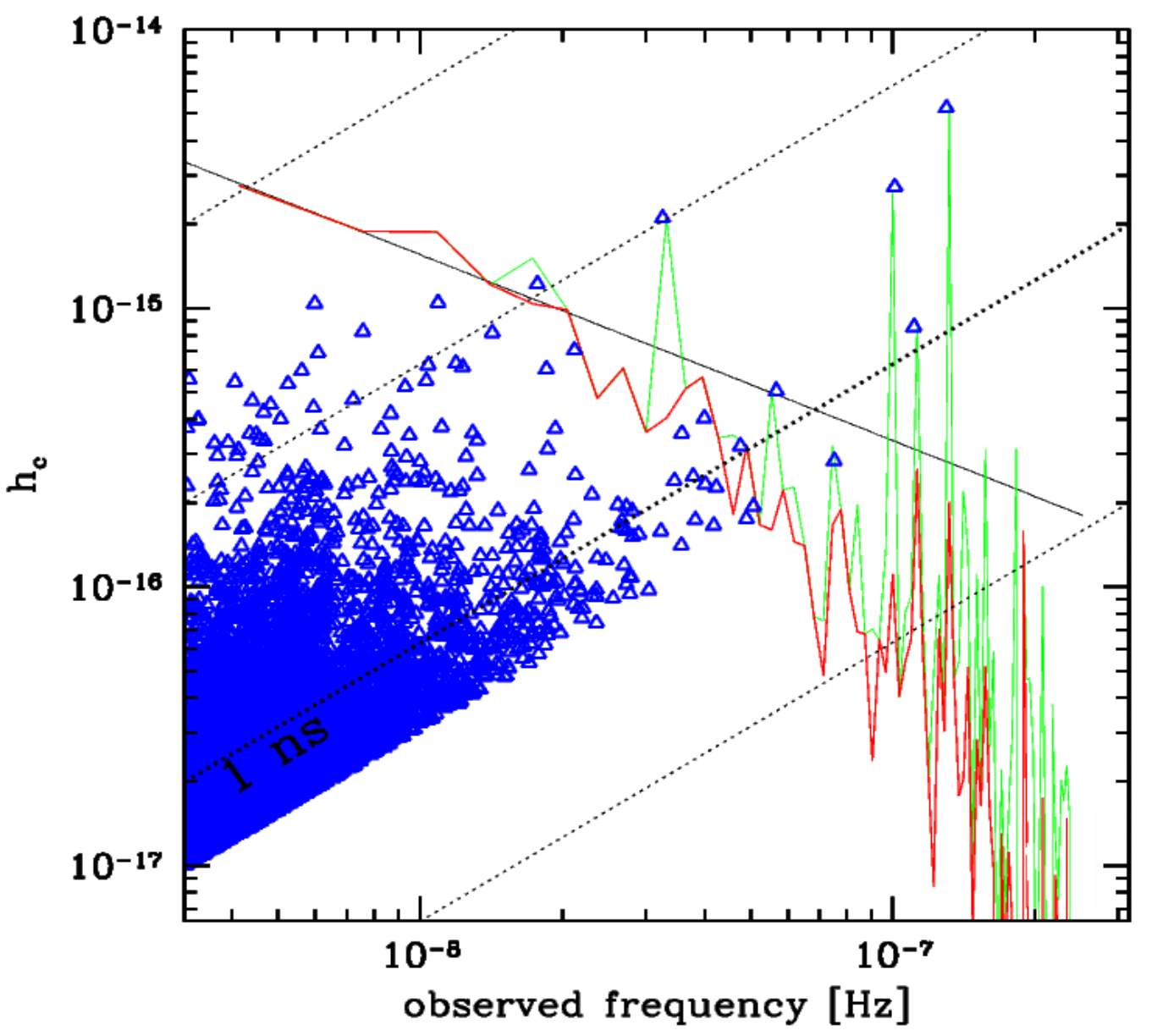
$$h_c^2(f) = \int_0^\infty dz \int_0^\infty d\mathcal{M} \frac{d^3N}{dz d\mathcal{M} d\ln f_r} h^2(f_r)$$

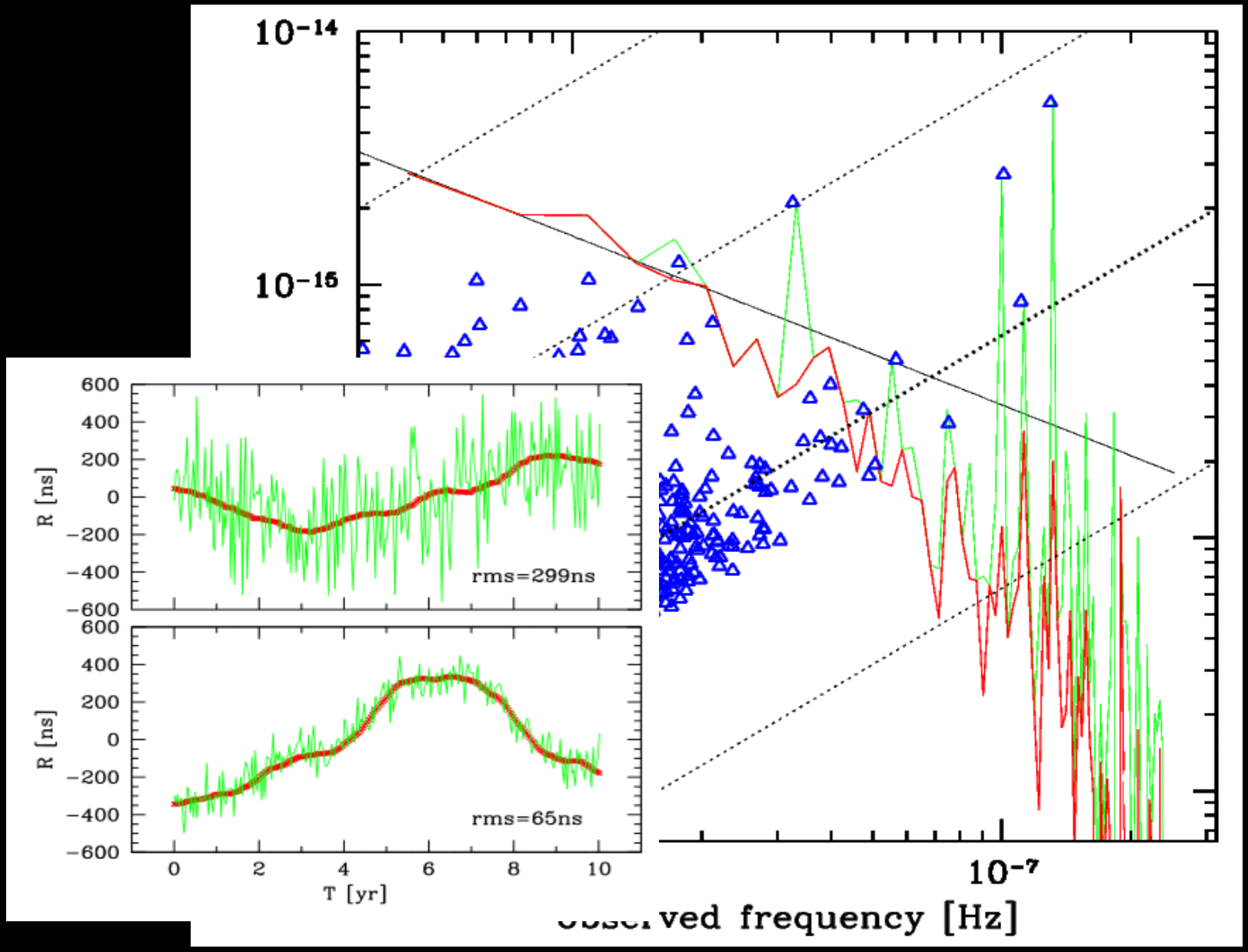
$$\delta t_{\rm bkg}(f) \approx h_c(f)/(2\pi f)$$

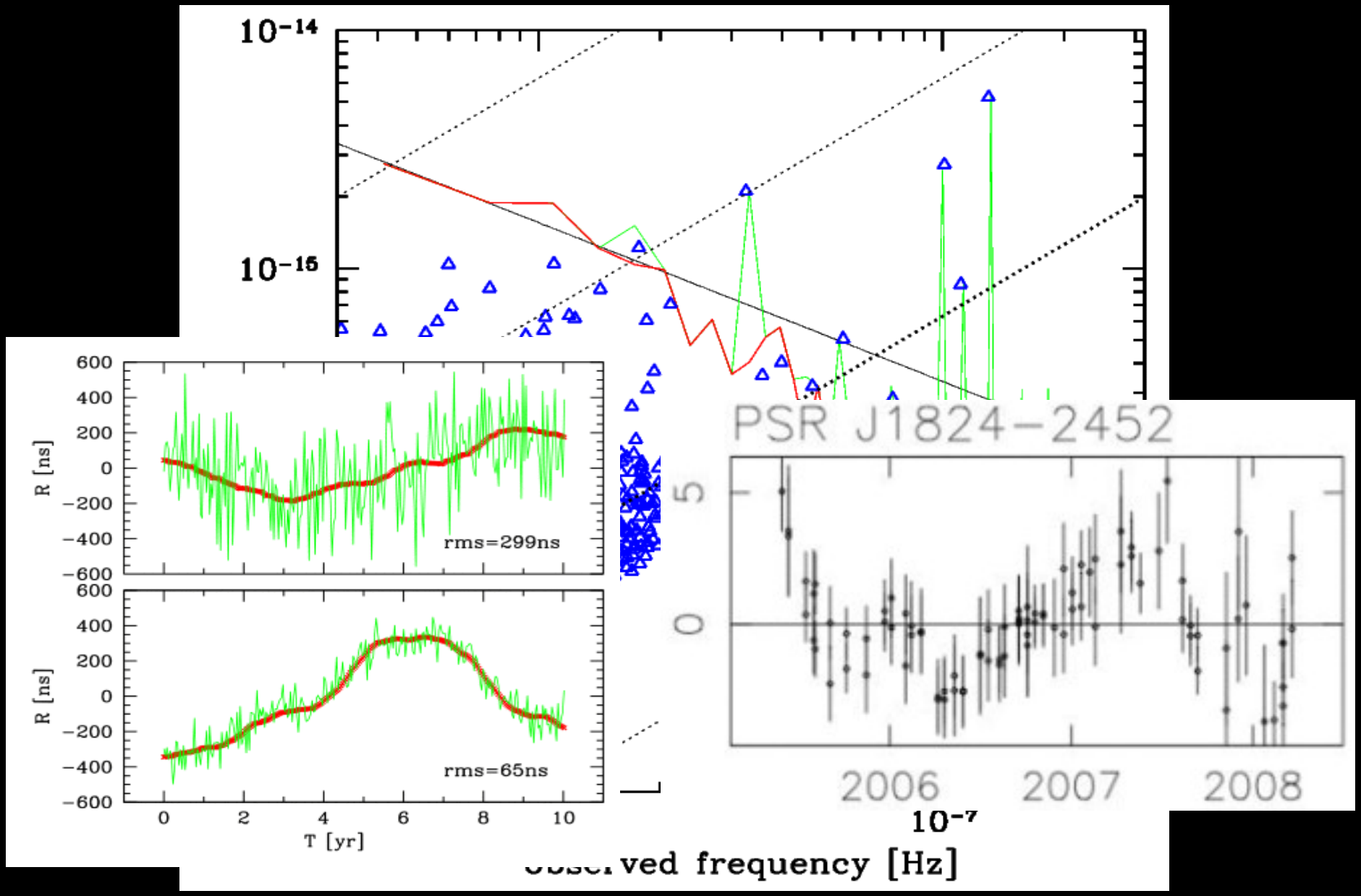
For circular GW driven MBHBs $dN/d\ln f \propto f^{-8/3}$

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

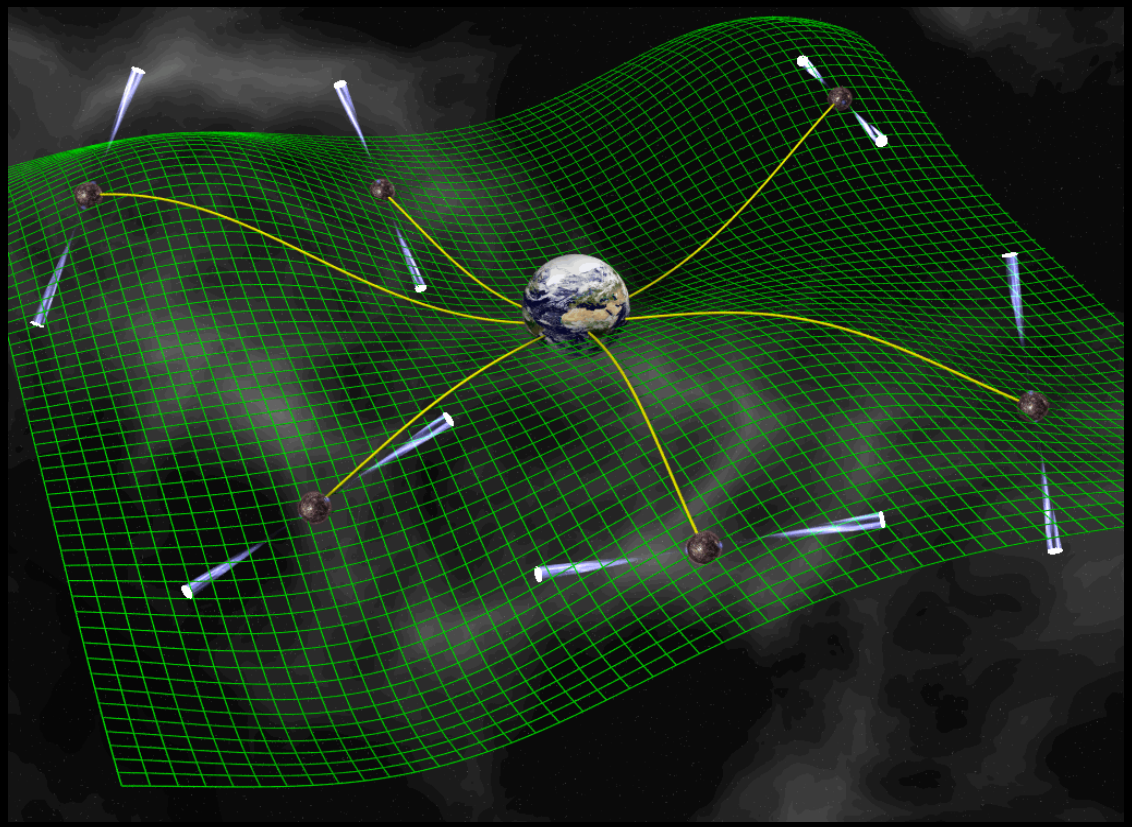
Phinney 2001, Jaffe & Backer 2003, Wyithe & Loeb 2003, AS et al. 2004, Enoki et al. 2004, Jenet et al 2005, 2006


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


10^-14
10^-15
10^-7
ved frequency [Hz]
R [ns]
rms=299ns
rms=65ns
T [yr]

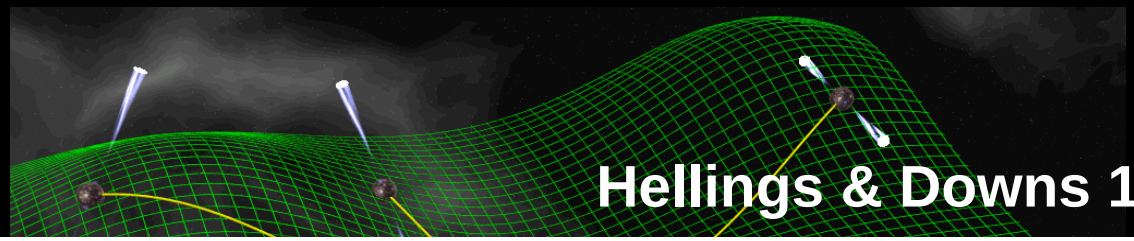


There are, however, many other sources of red noise in pulsar timing: intrinsic spin noise, DM effects, etc.

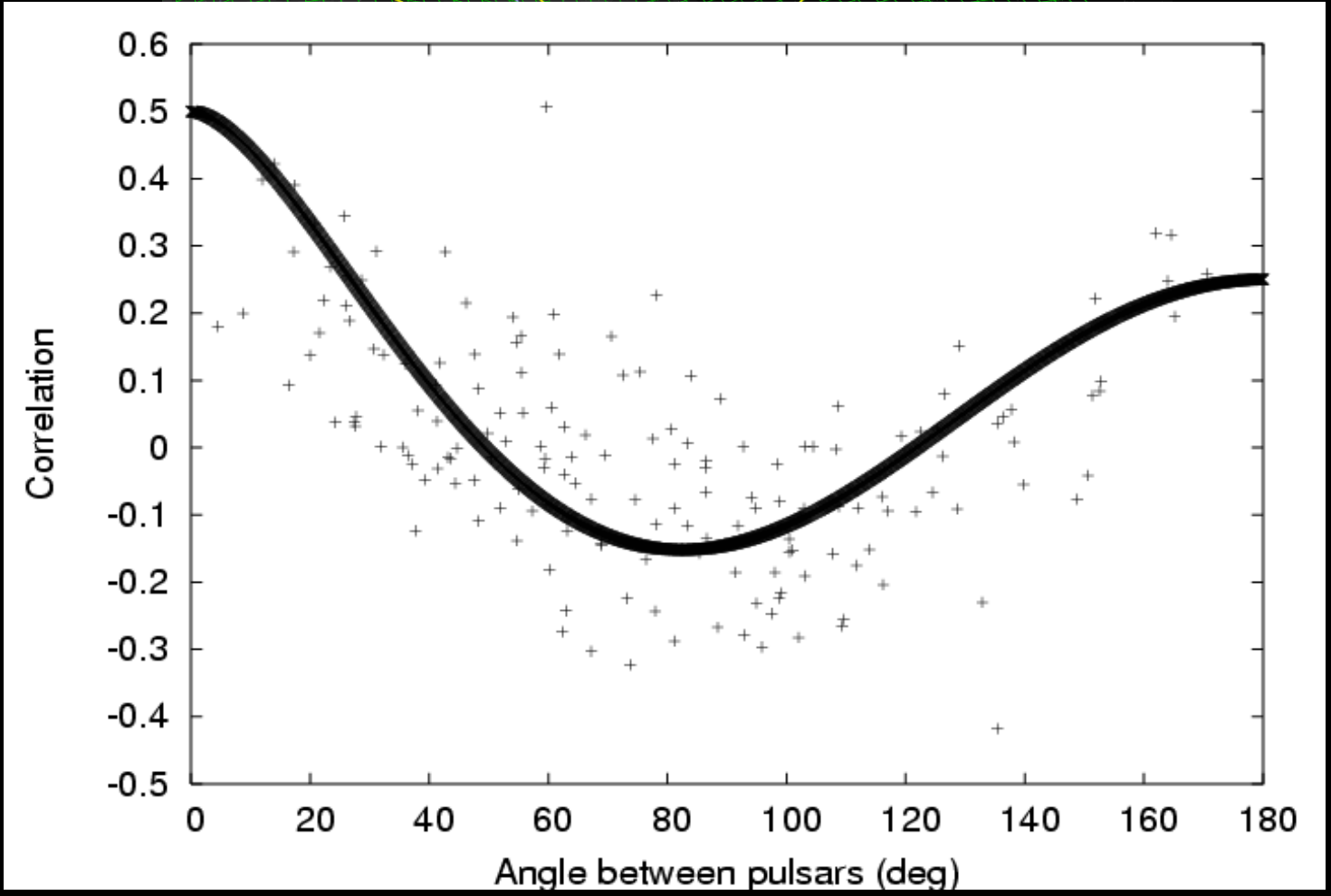


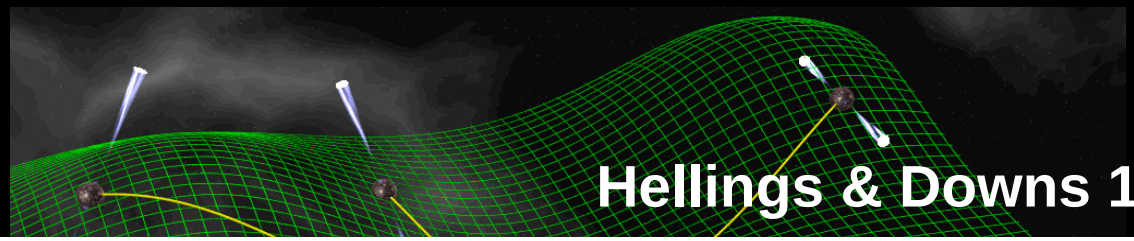
This very red signal has a peculiar correlation pattern among different pairs of pulsars, given by the quadrupolar nature of gravitational waves

Other sources of red noise are uncorrelated!

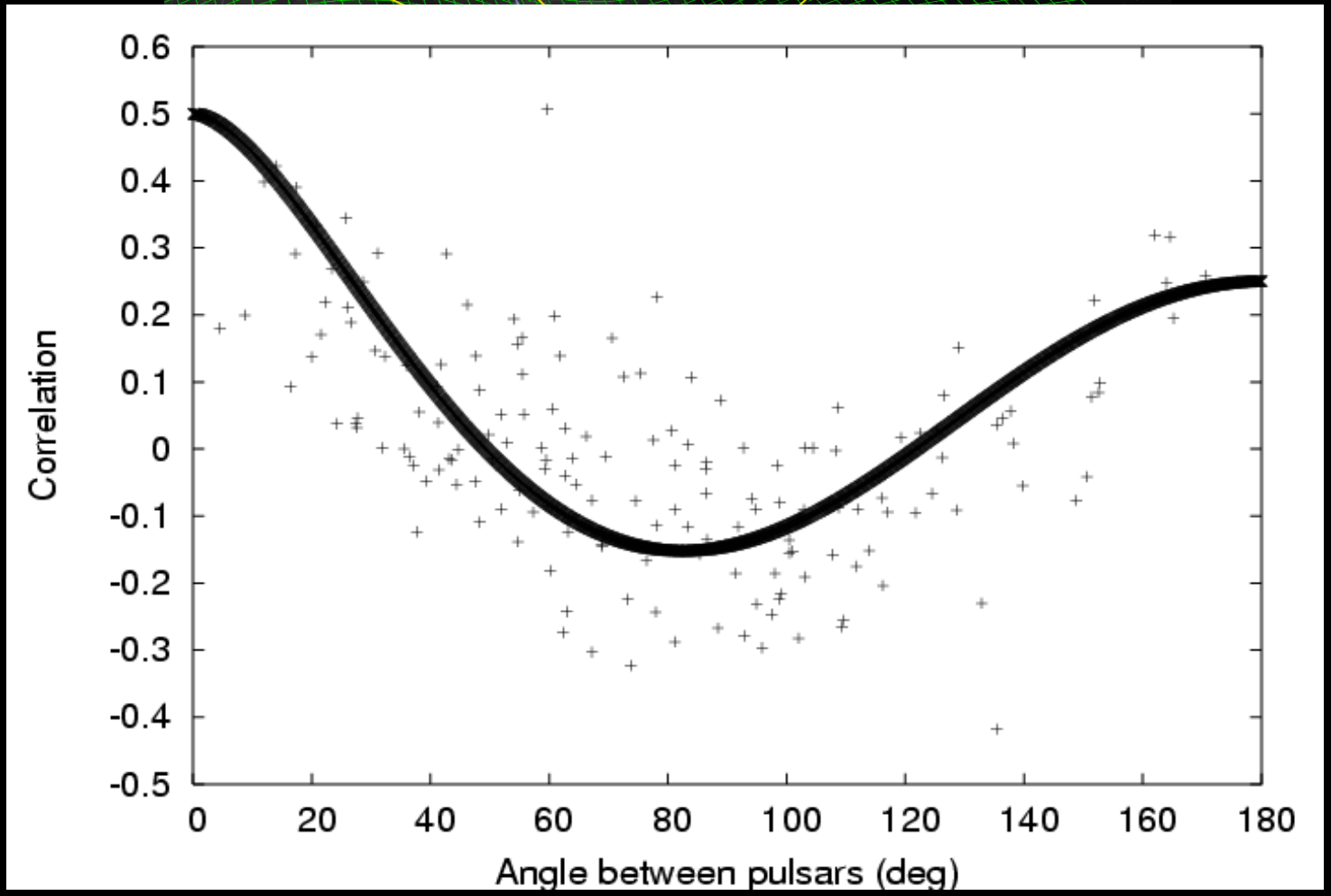


Hellings & Downs 1983





Hellings & Downs 1983



IT IS ESSENTIAL TO CORRELATE THE SIGNAL OF AS MANY PULSARS AS POSSIBLE

Pulsar Timing Arrays (PTAs)

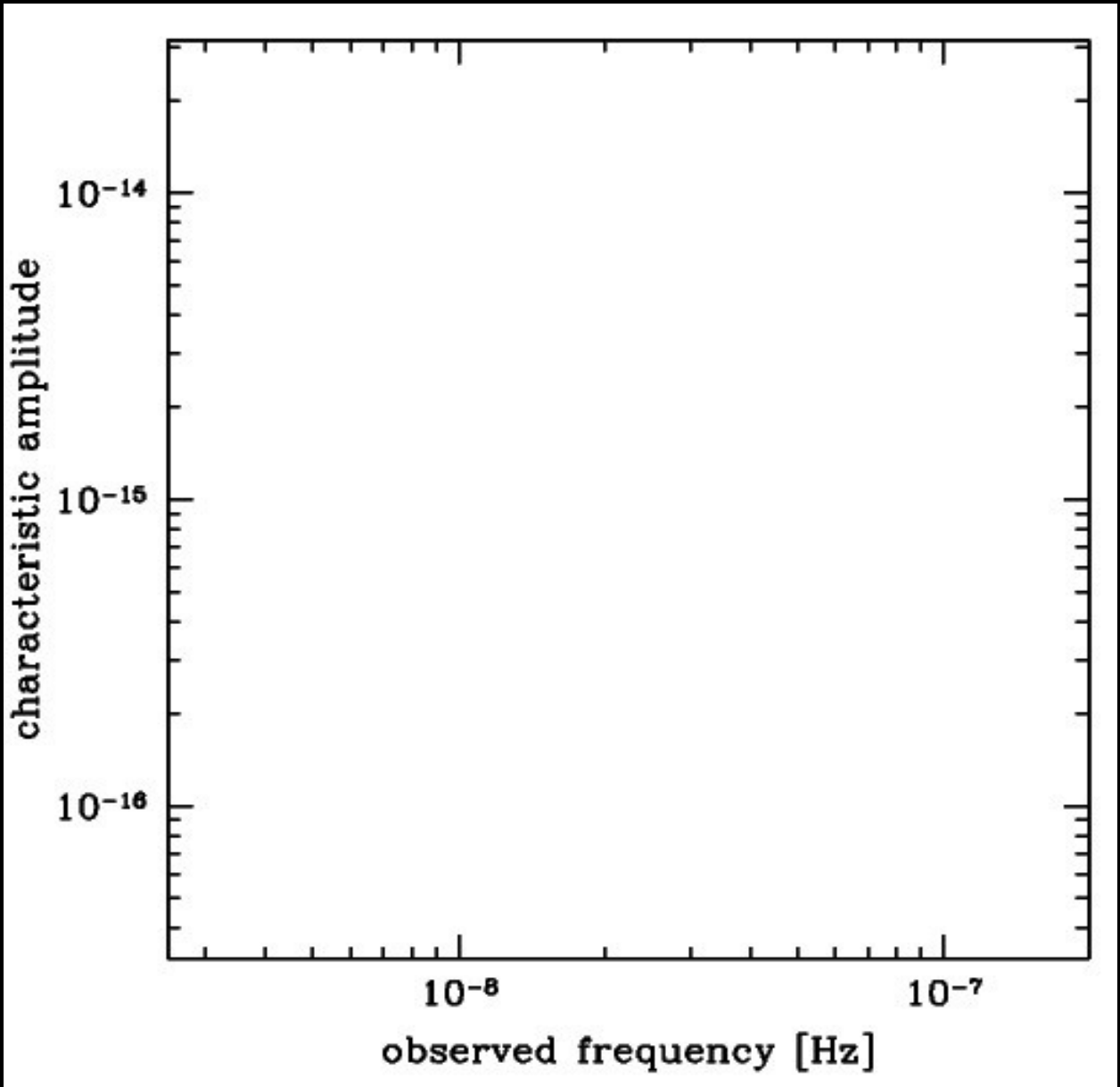
World-wide detection effort

EPTA: 9 institutes
5 telescopes
40 scientists

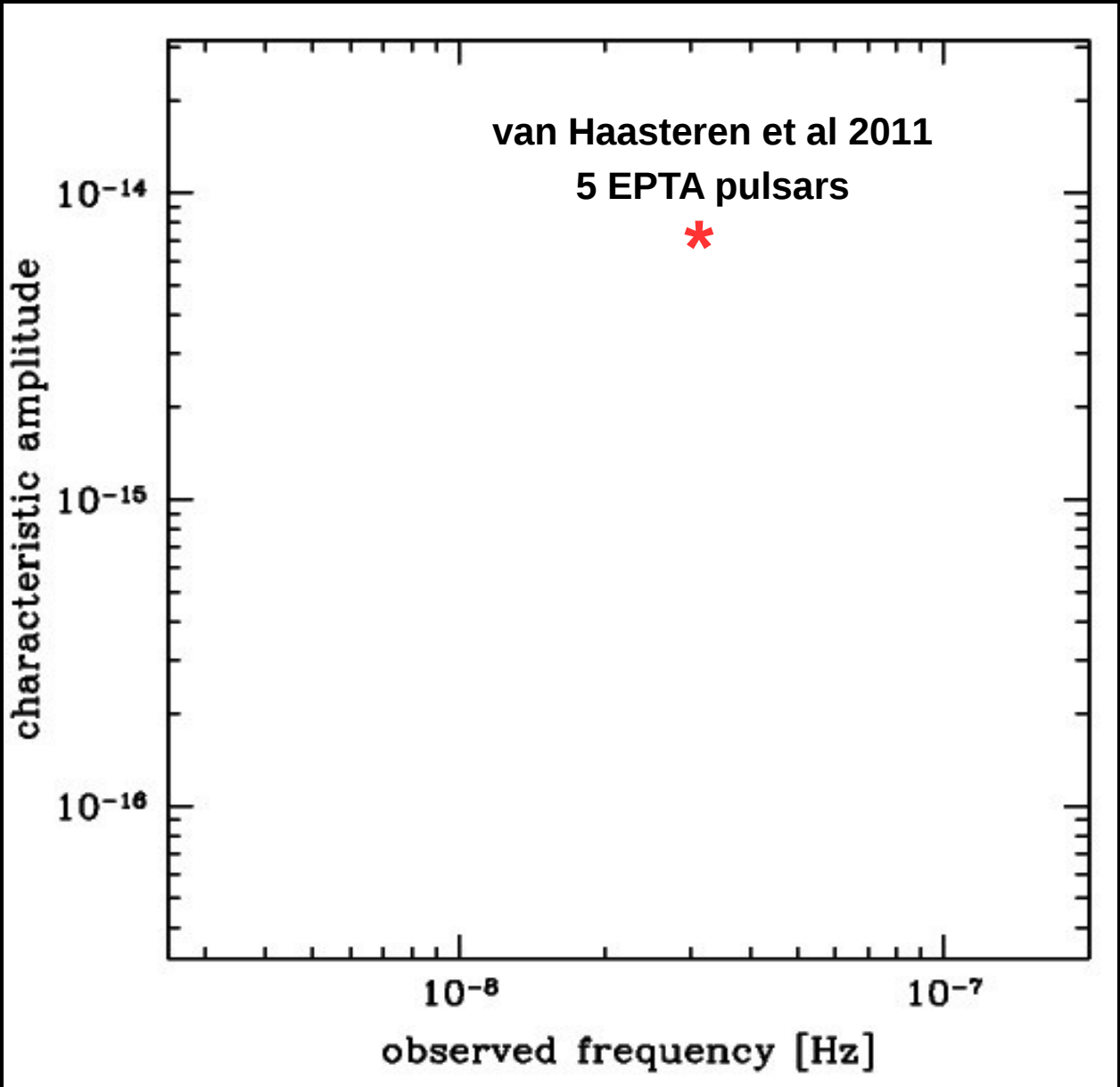
NANOGrav: 10 institutes
2 telescopes
40 scientists

PPTA: 4 institutes
1 telescope
20 scientists

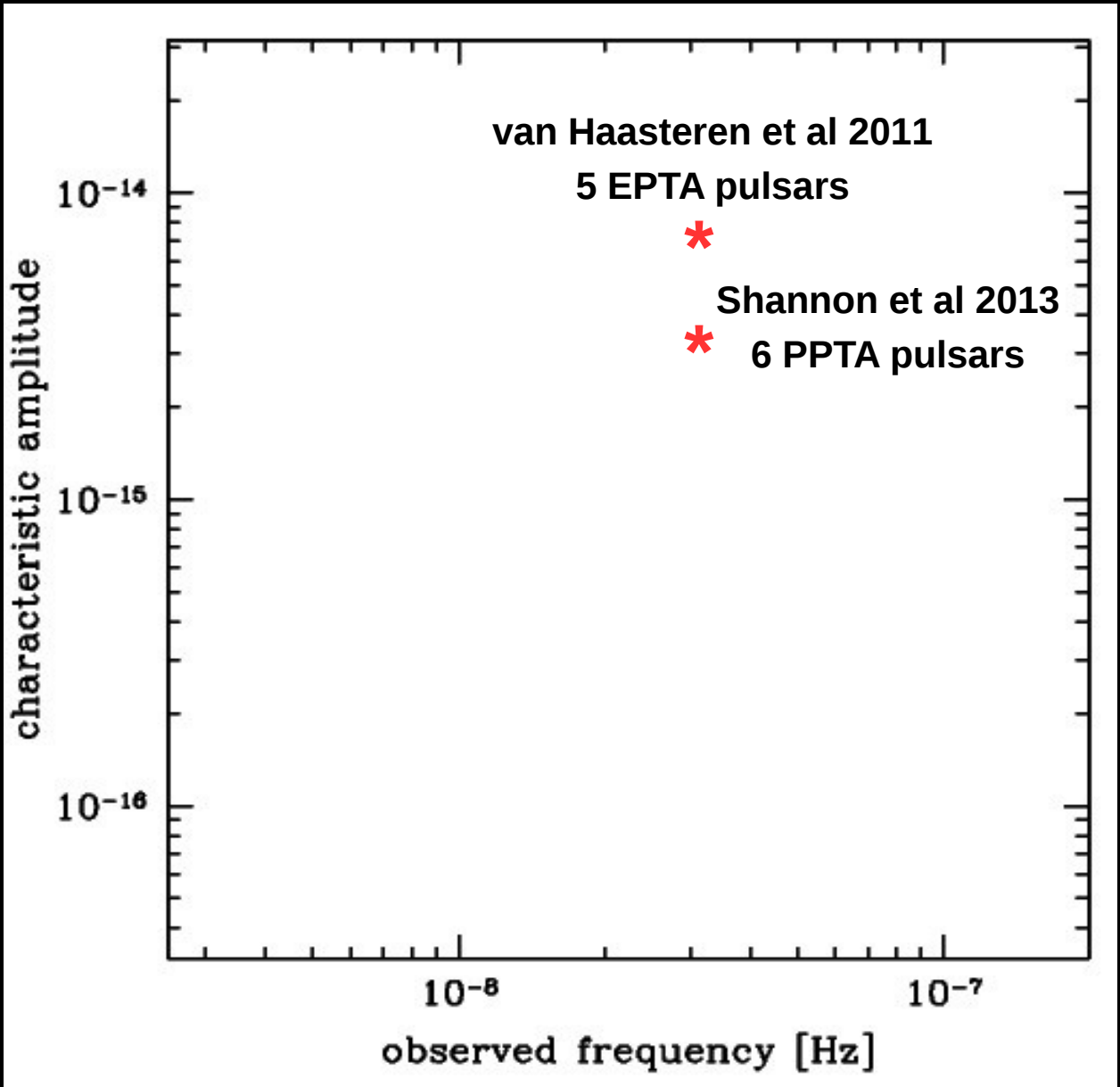
Where we stand: theory vs observations



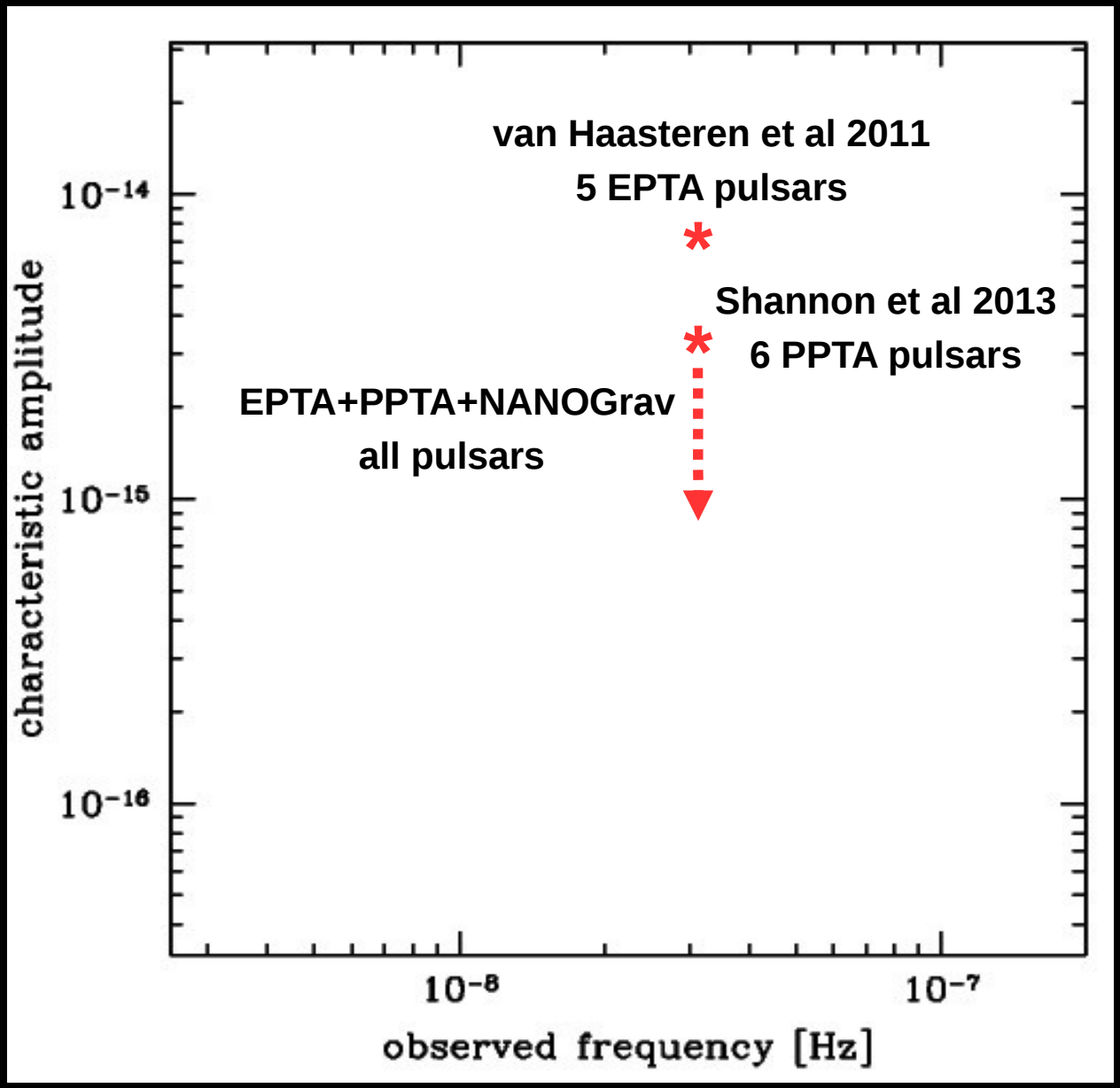
Where we stand: theory vs observations



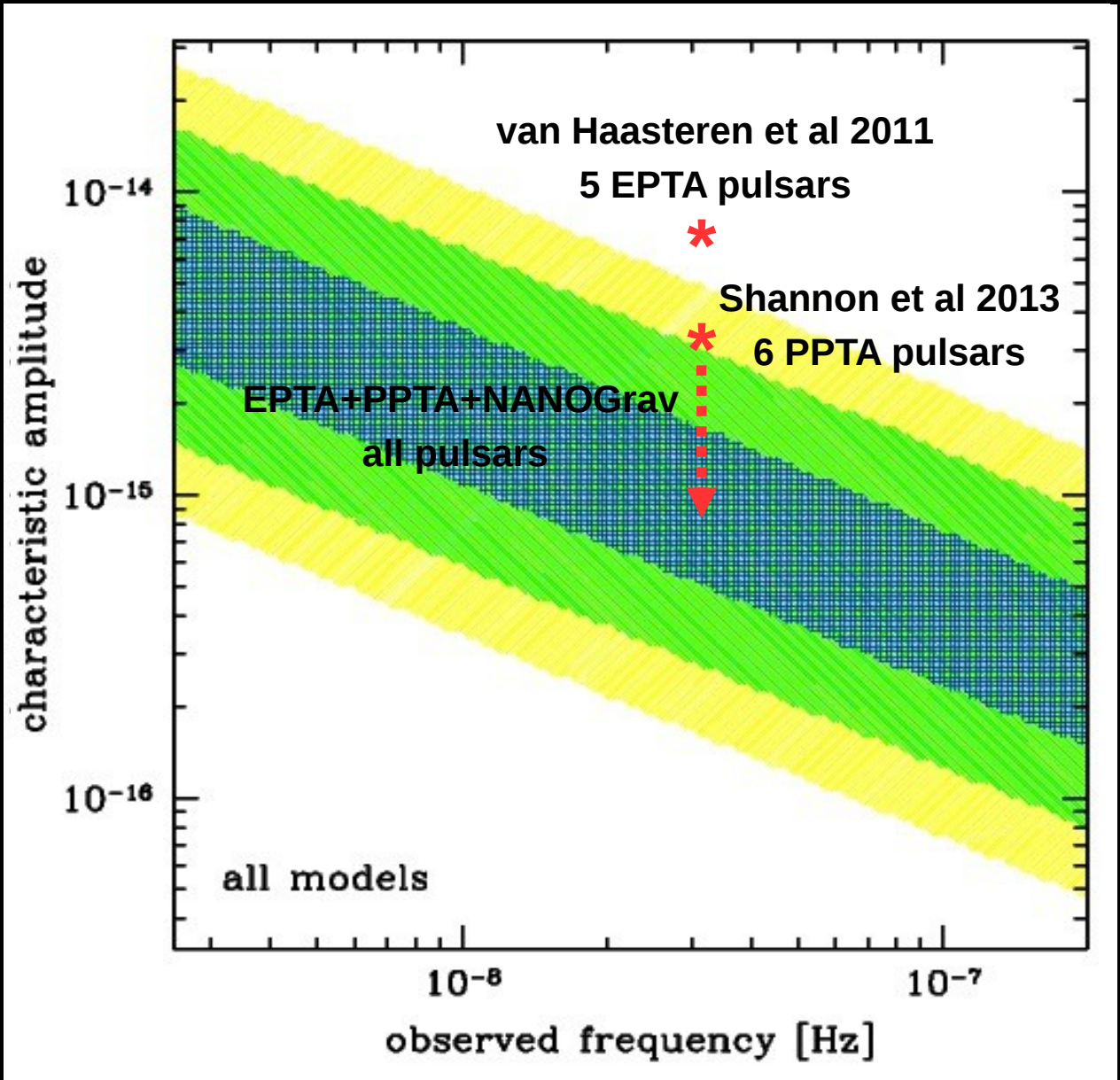
Where we stand: theory vs observations



Where we stand: theory vs observations

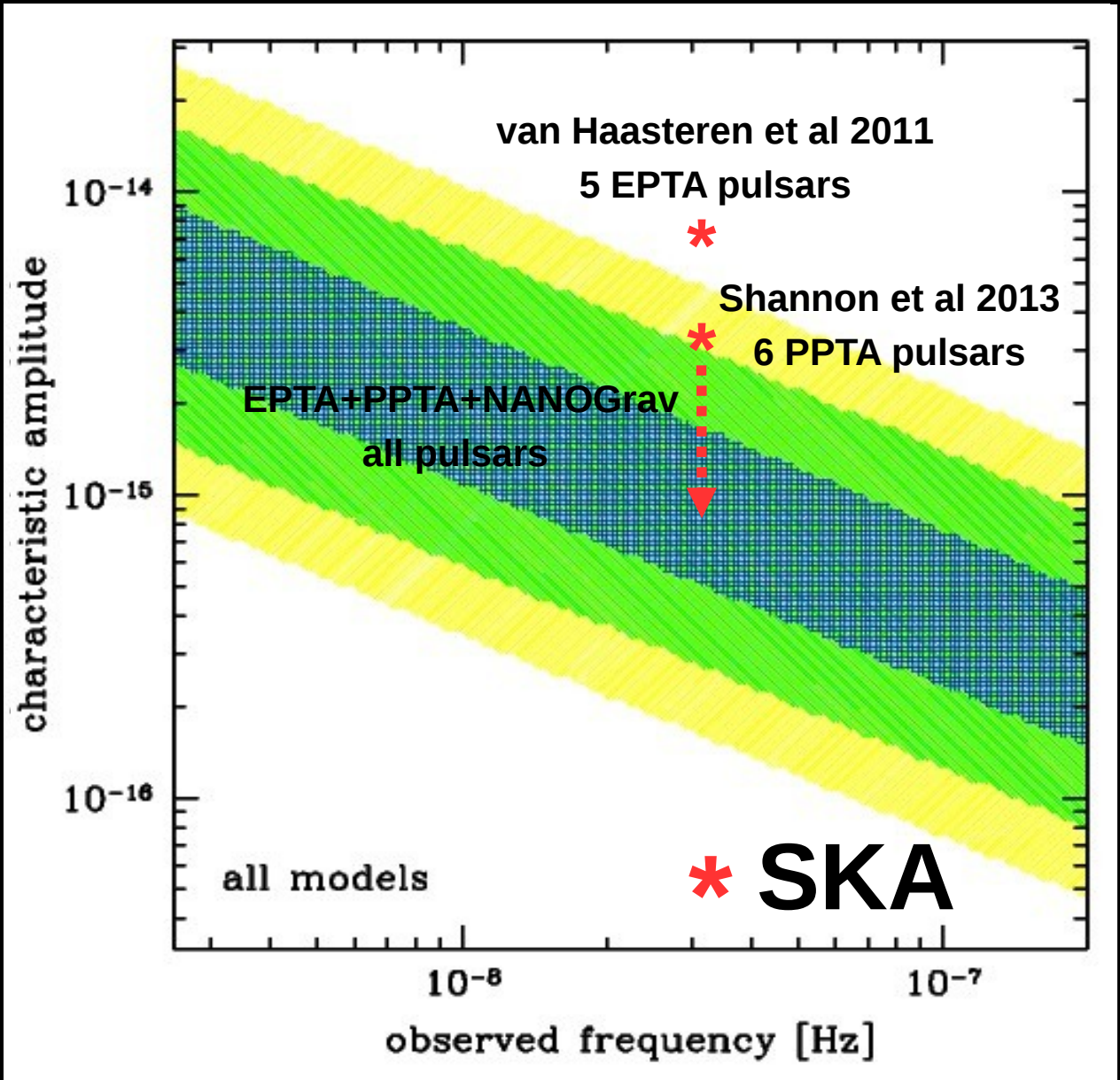


Where we stand: theory vs observations



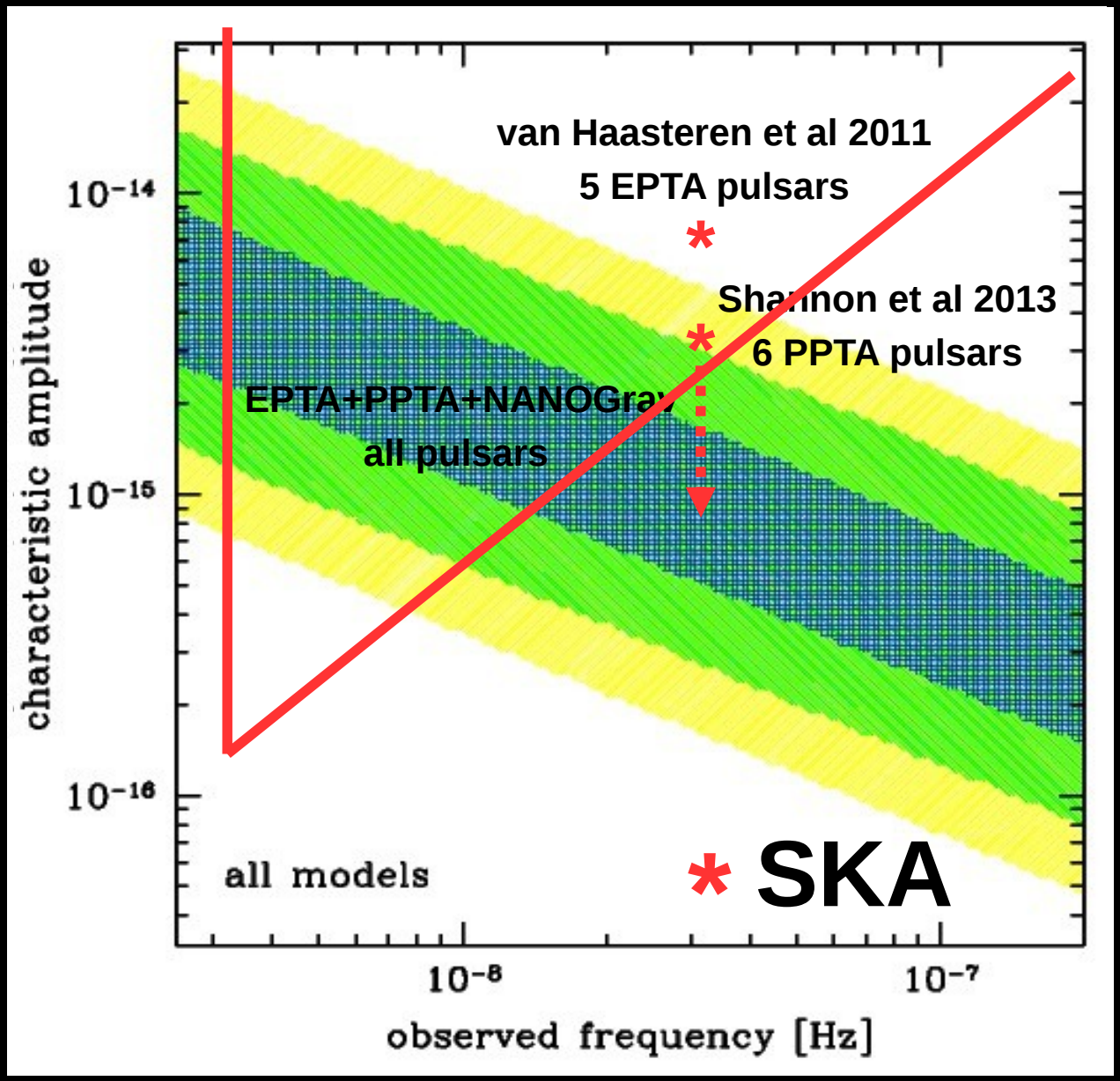
AS et al. 2008; AS et al. 2009; AS 2013

Where we stand: theory vs observations

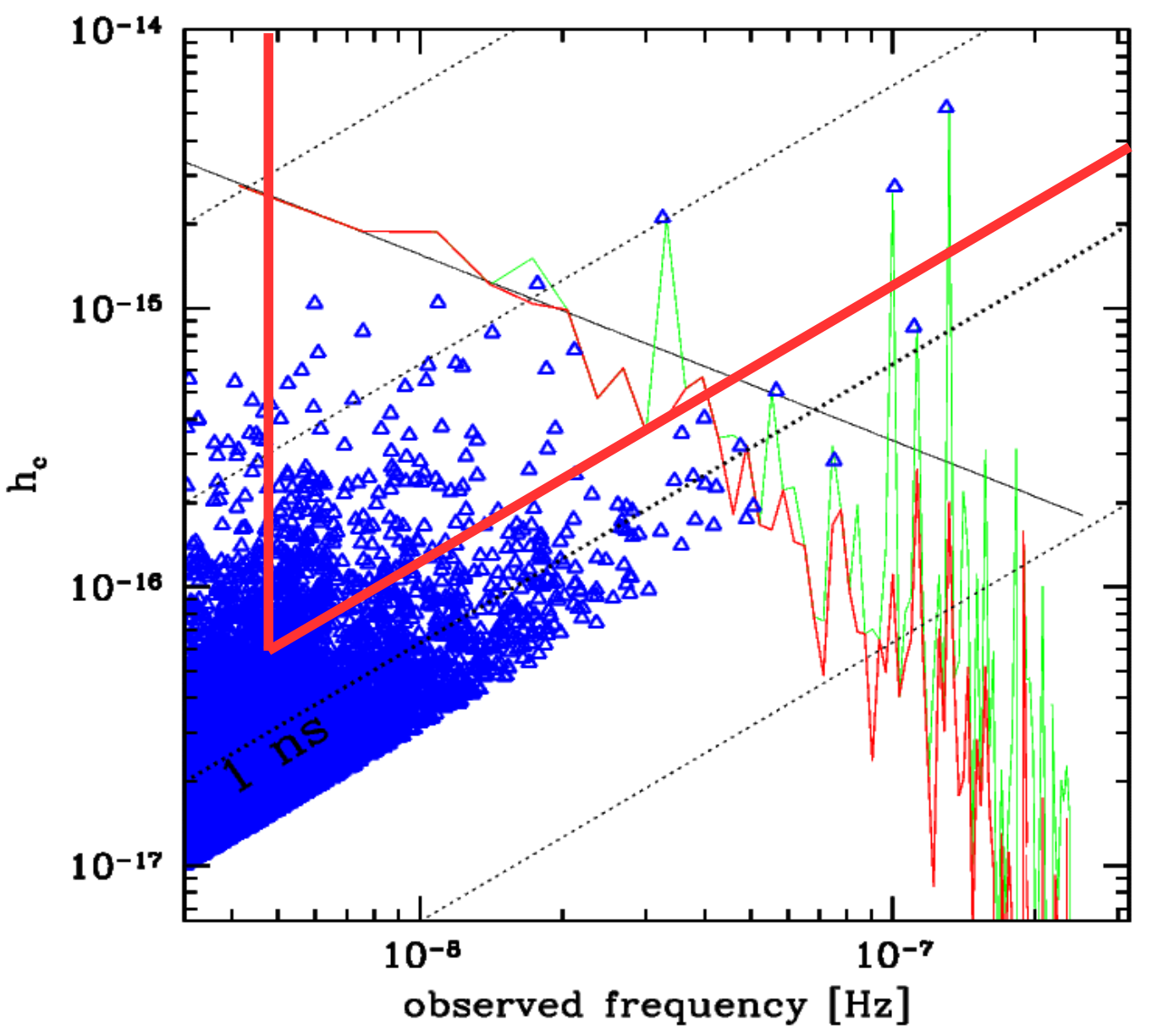


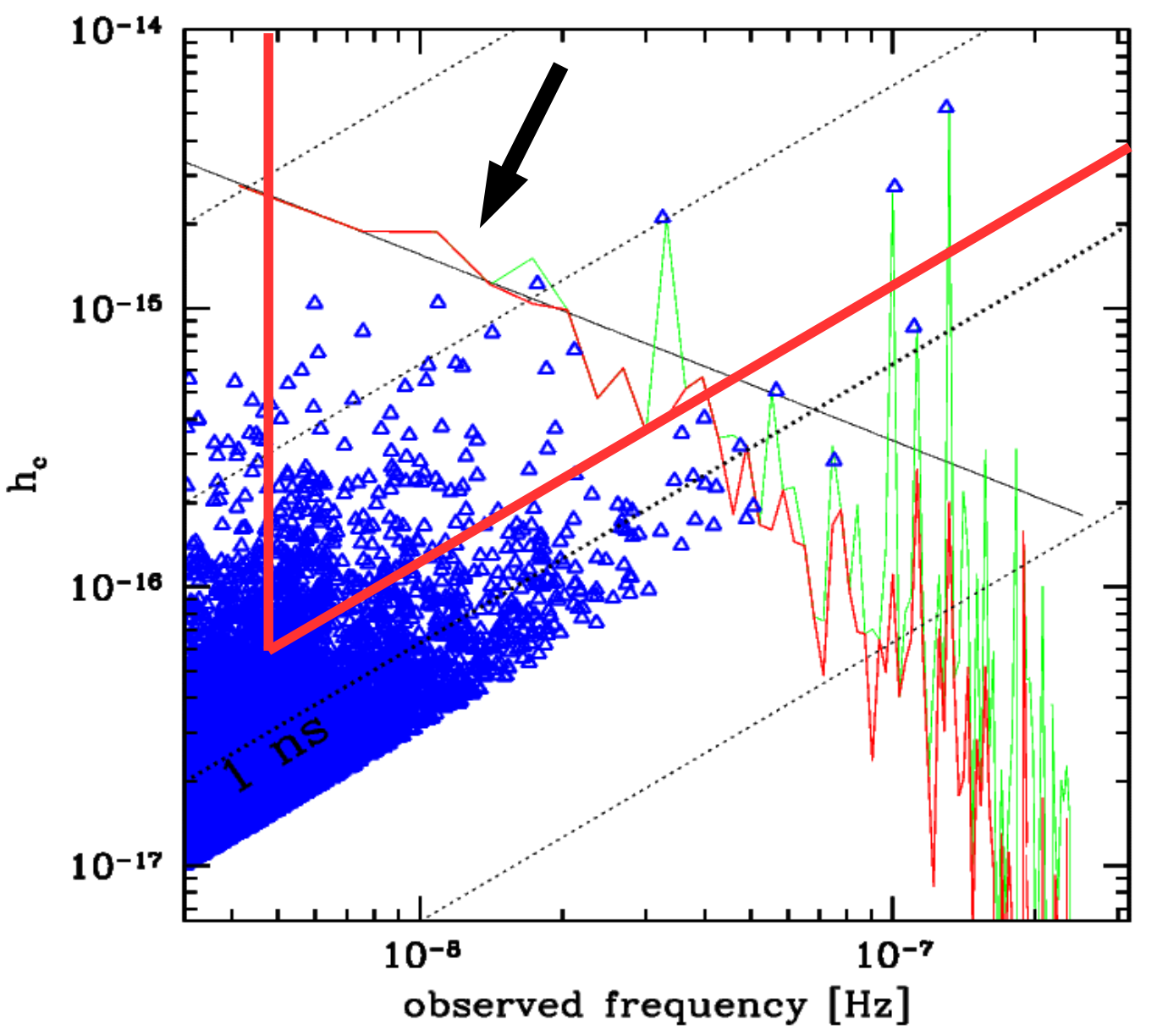
AS et al. 2008; AS et al. 2009; AS 2013

Where we stand: theory vs observations



AS et al. 2008; AS et al. 2009; AS 2013


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


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

*SKA will probe the overall amplitude and *shape* of the signal*

$$h_c(f) \propto N_0^{1/2} f^{-\gamma} M_c^{5/6}$$

Information about "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

Information about "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

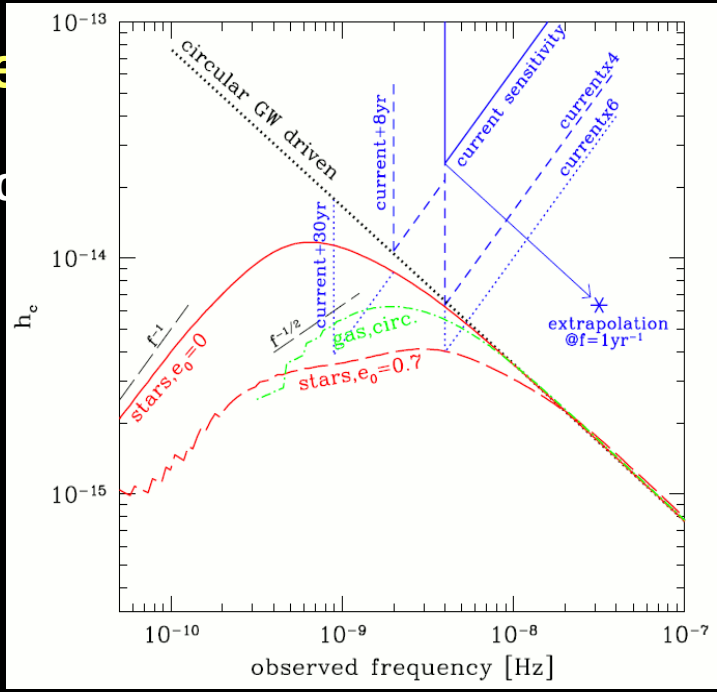
*SKA will probe the overall amplitude and *shape* of the signal*

$$h_c(f) \propto N_0^{1/2} f^{-\gamma} M_c^{5/6}$$

Information about "population paramete

1-Galaxy merger rate <-----> MBHB merger rate
affects the number of sources at each frequenc

2-MBH mass – merging galaxy relation
affects the mass of the sources ----> M_c

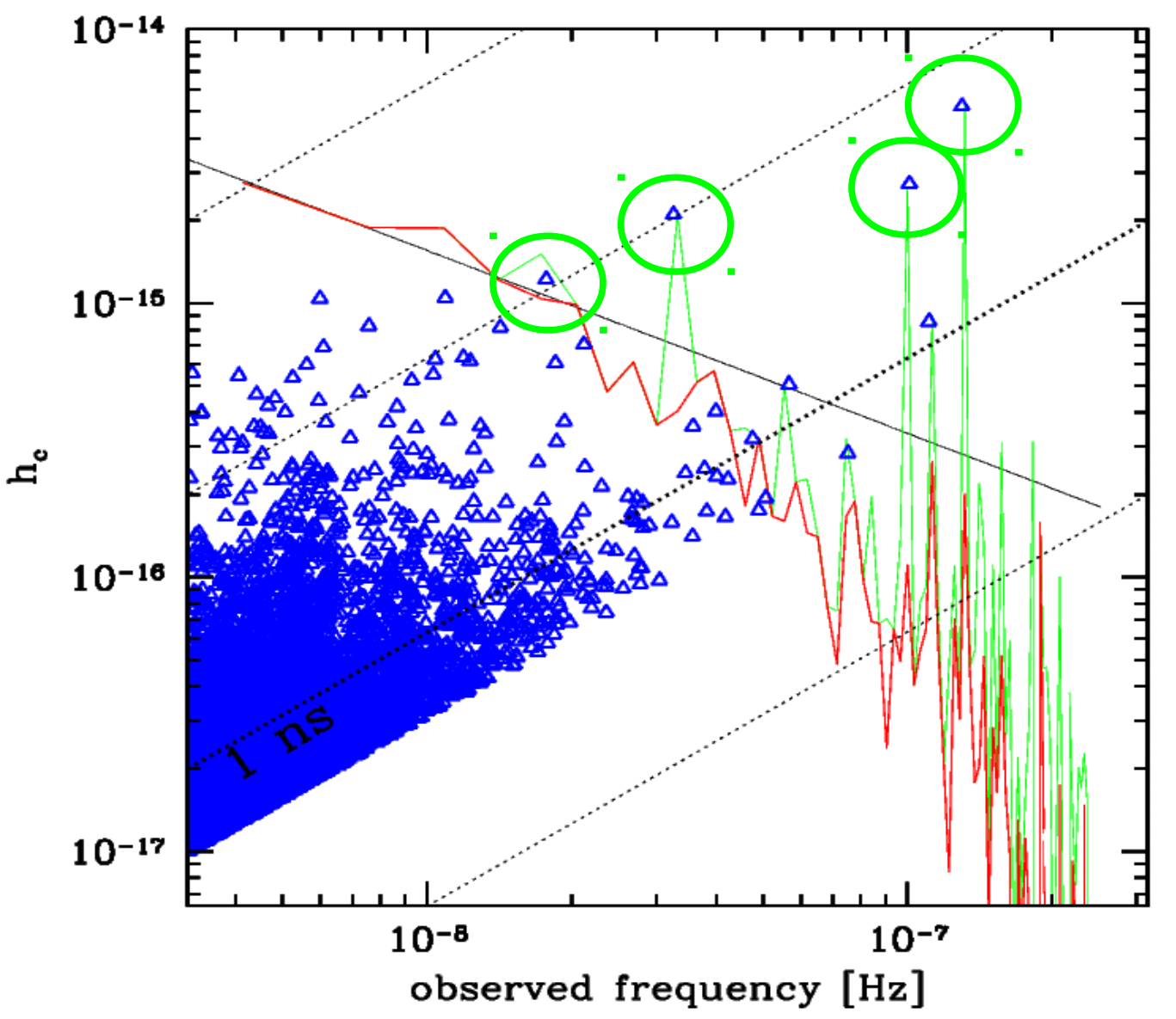


Information about "local dynamics"

1-Accretion (when? how?)
affects the mass of the sources ---> M_c

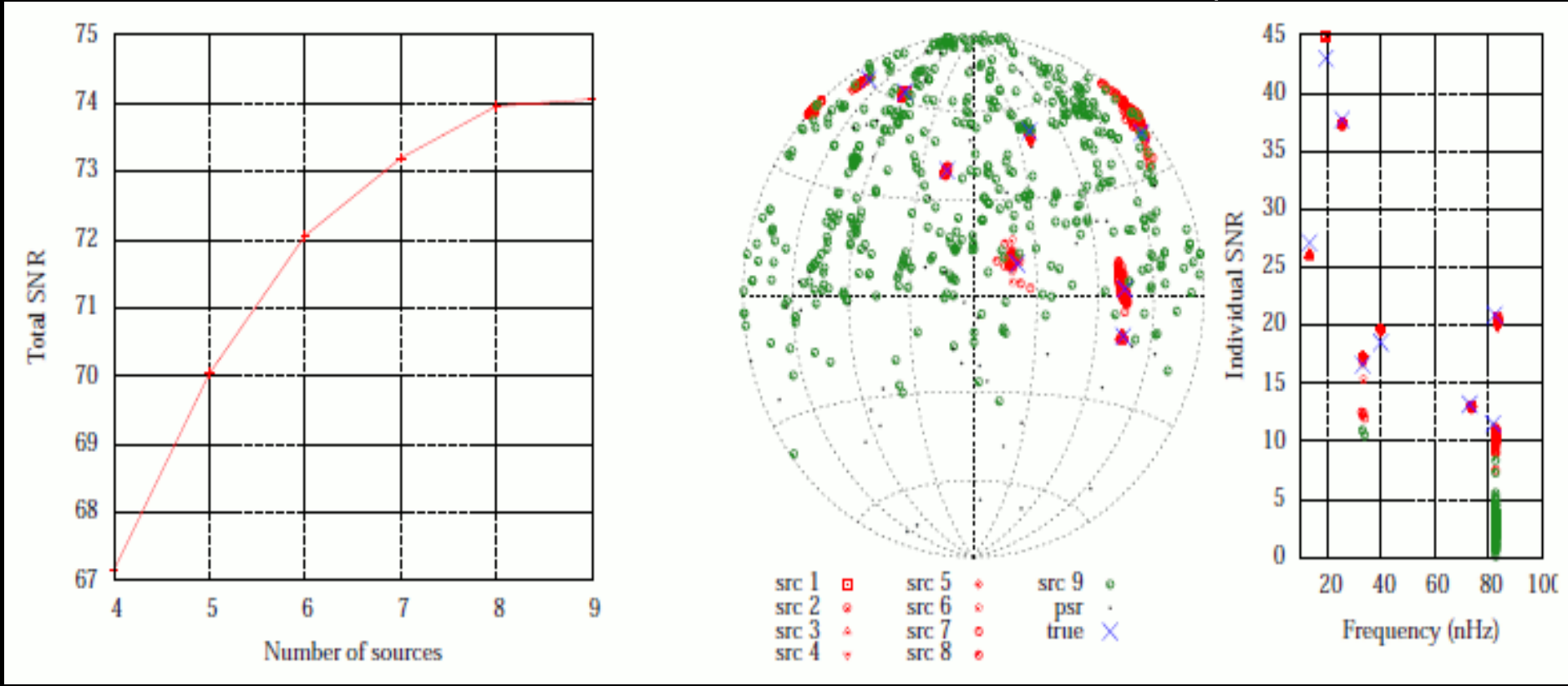
2-MBHB – environment coupling (gas & stars)
affects the chirping rate of the binaries ---> γ
affects the eccentricity ---> chirping rate ----> γ & single source detection

Resolvable sources



Particularly bright sources might stand above the 'confusion noise' level generated by other sources

Babak & AS 2012, Petiteau et al. 2013



-We recover the correct number of sources (no false positive)

-We can determine the source parameters with high accuracy:

> SNR within few%

> sky location within few deg offset

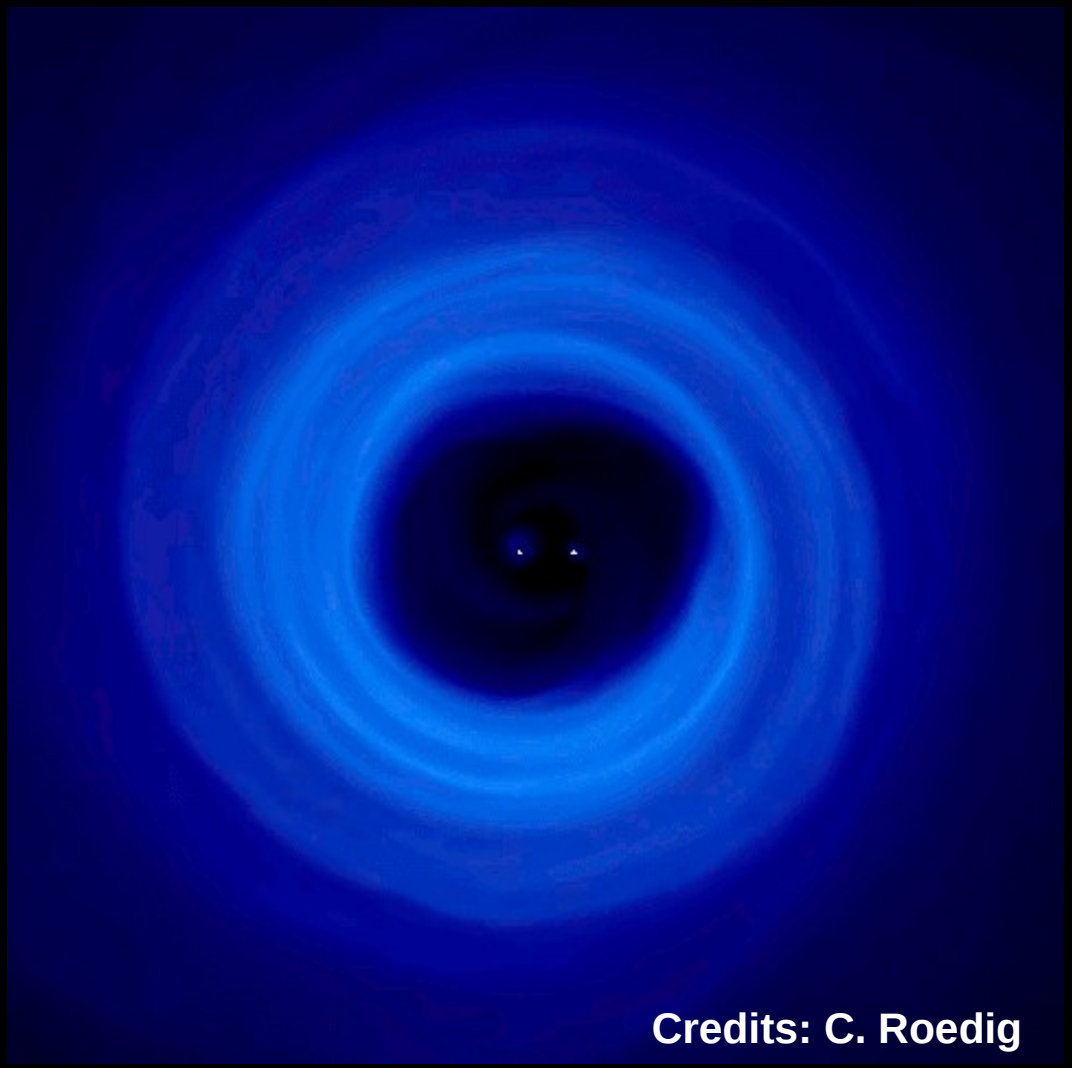
> frequency at sub-bin level

-Extremely promising, needs test on more realistic situations

ELECTROMAGNETIC COUNTERPARTS

Tanaka et al. 2012, AS et al. 2012

MBHB+circumbinary disk



-Opt/IR dominated by the outer disk. Steady?

-UV generated by the Inner disks. Periodic variability.

-X ray corona. Periodic variability

-Variable broad emission lines (in response to the UV/X ionizing continuum)

-Double fluorescence 6.4keV $K\alpha$ iron lines

In summary:

1-Pulsar timing arrays provide an effective method to detect low frequency (nHz) gravitational waves from massive black hole binaries

2-The signal level depends on the *MBH merger rate* and on the *MBH-host relations*. GW limits are becoming interesting in discarding 'optimistic' scenarios.

3-*IPTA might lead to a GW detection* in the near future

....but....

4-*Only with SKA* we will have a complete description of the '*stochastic background*' (amplitude, shape)

5-SKA will likely resolve several individual MBHBs opening the era of *low frequency multimessenger astronomy*