Massive black hole binaries as gravitational wave sources for pulsar timing arrays

Alberto Sesana

AEI Golm

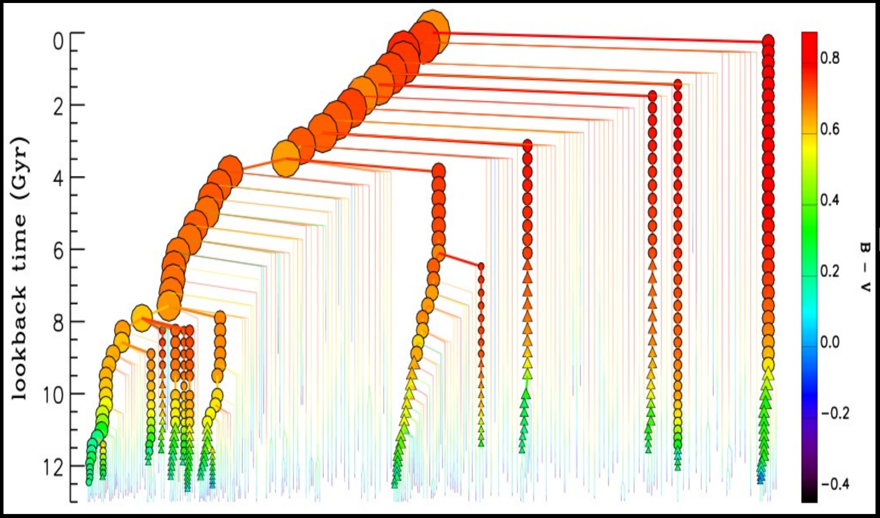
Heidelberg, 21/09/2011

OUTLINE

> Gravitational wave astronomy with pulsar timing arrays: sources and detection

> Signal characterization: unresolved background and resolvable sources

Structure formation in a nutshell



From De Lucia et al 2006

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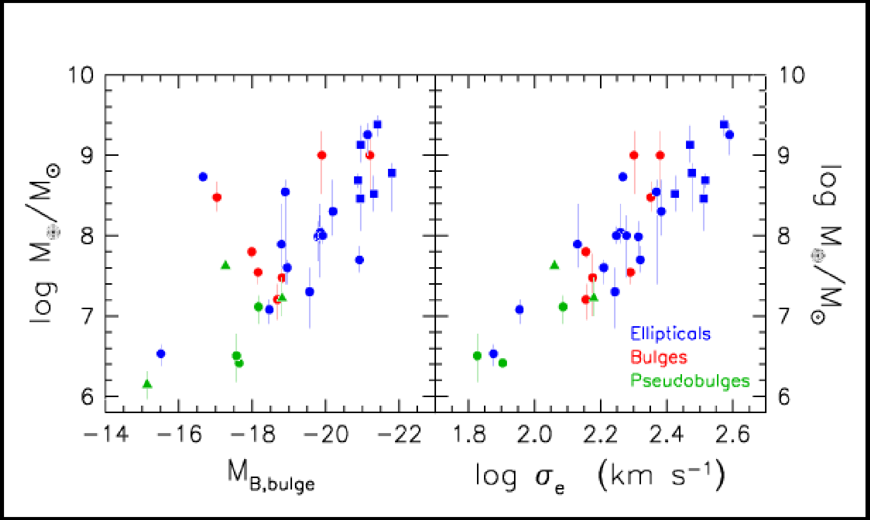

Ferrarese & Merritt 2000, Gebhardt et al. 2000

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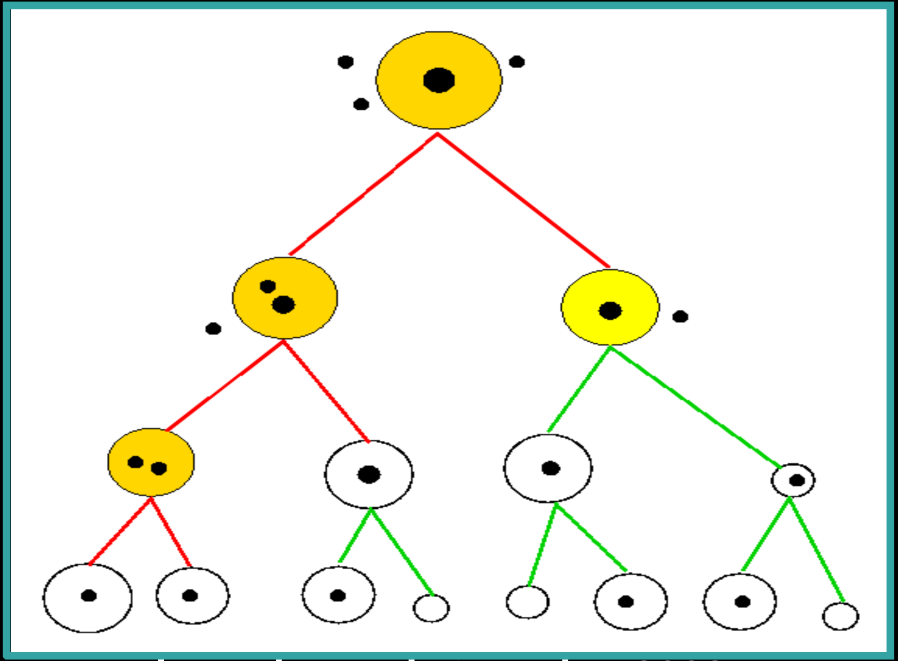
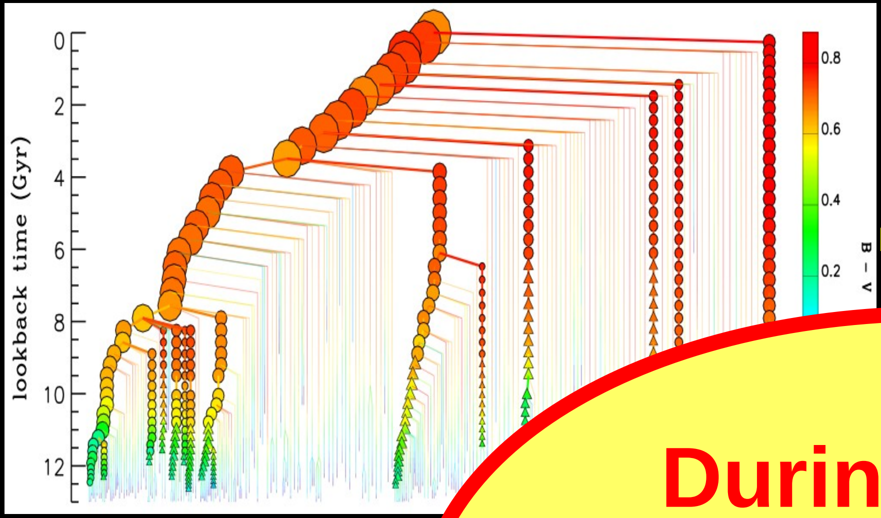


Volonteri Haardt & Madau 2003

Structure formation in a nutshell



From De Lucia et al 2

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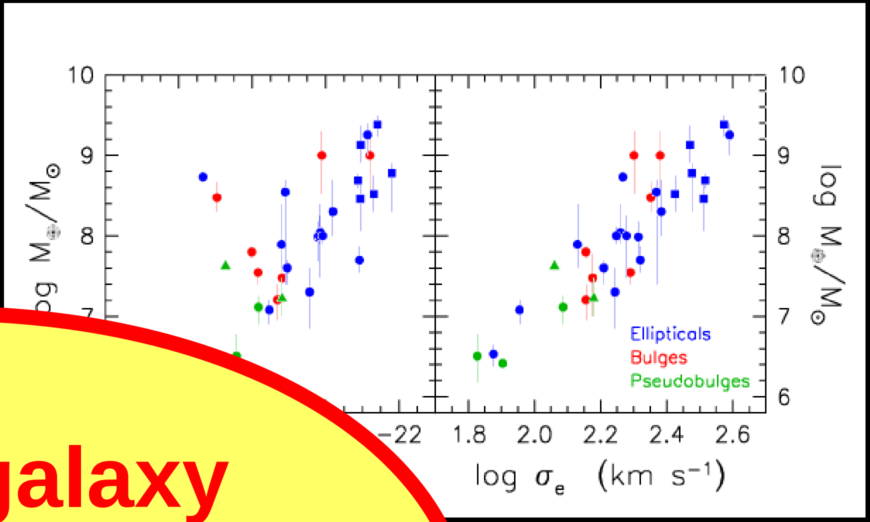

Gebhardt et al. 2000

During galaxy mergers, MBHBs will Inevitably form!

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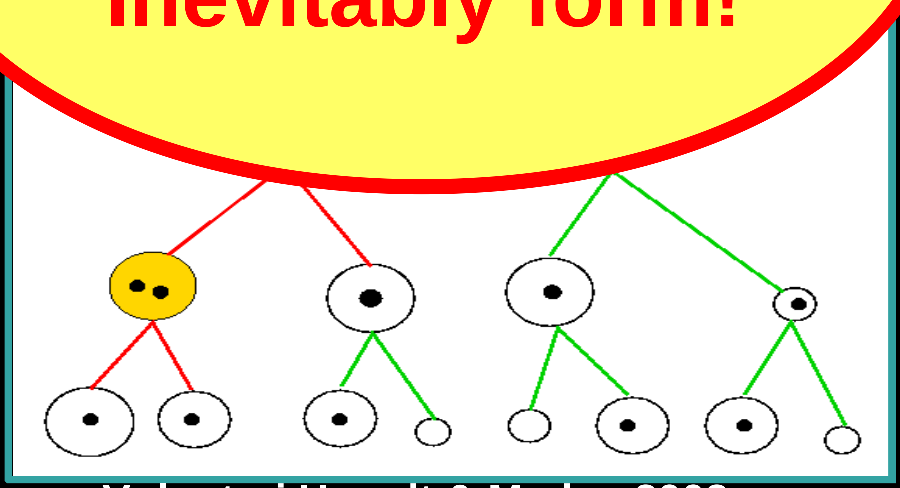
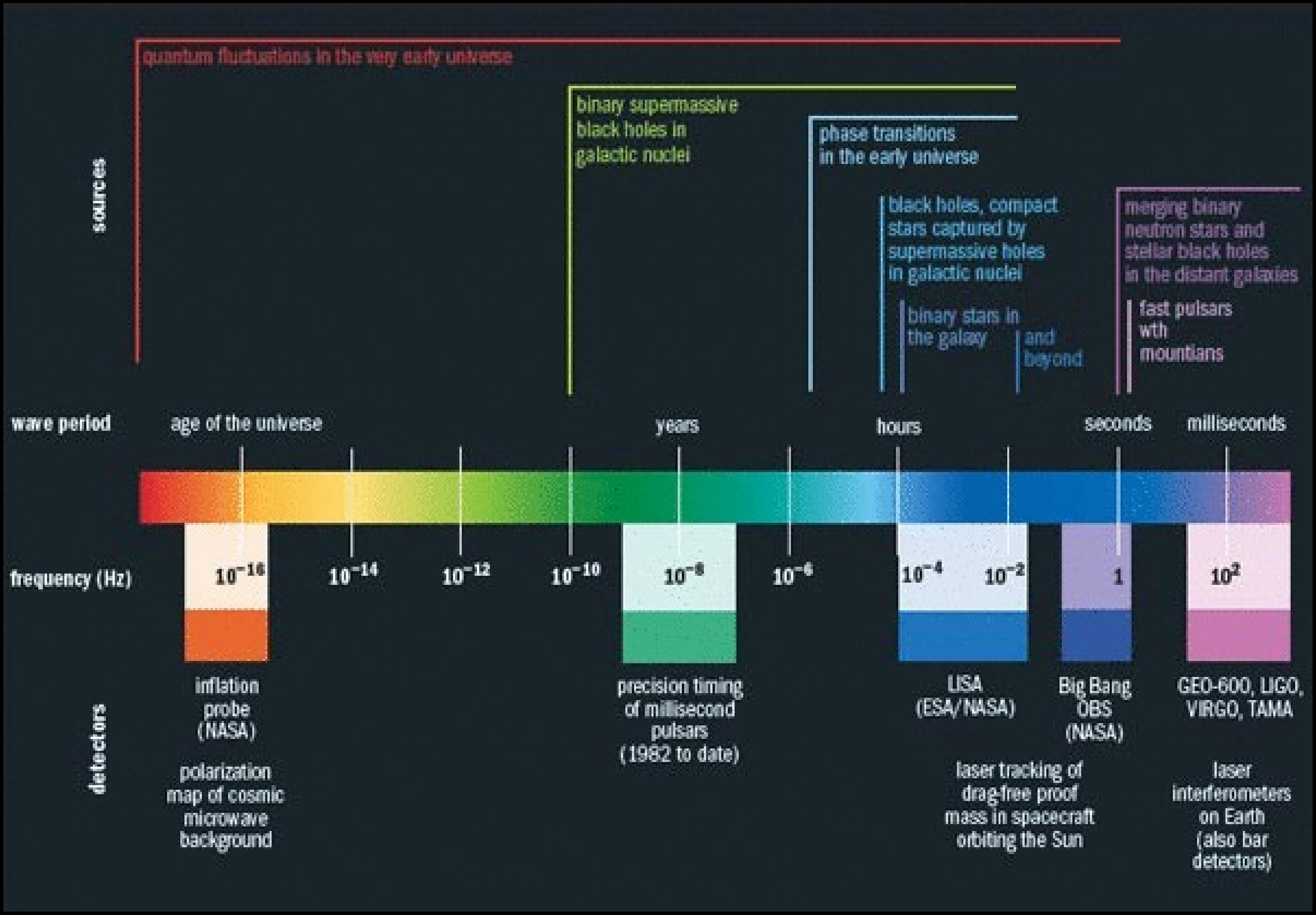
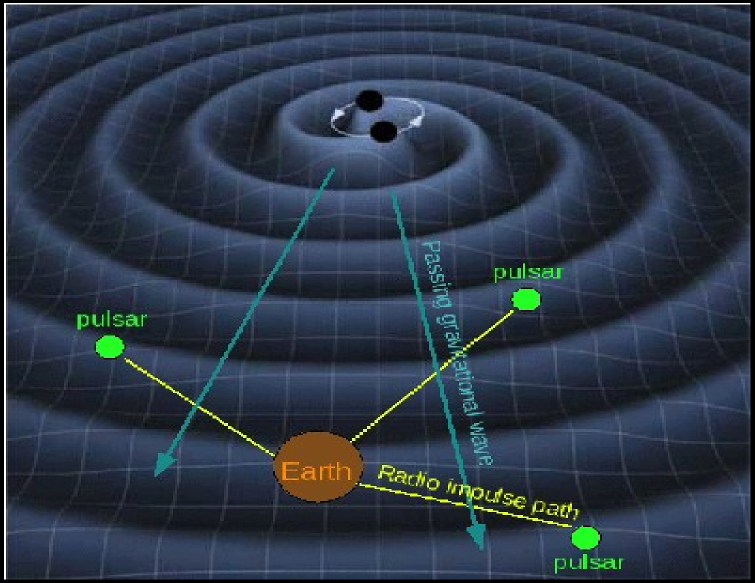


Volonteri Haardt & Madau 2003

The gravitational wave spectrum



The timing residual R



The GW passage cause a modulation of the MSP 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* in the time of arrival of the pulse is the integral of the frequency modulation over time

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

(Sazhin 1979, Helling & Downs 1983, Jenet et al. 2005, Sesana Vecchio & Volonteri 2009)

$R \sim h/(2\pi f)$

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

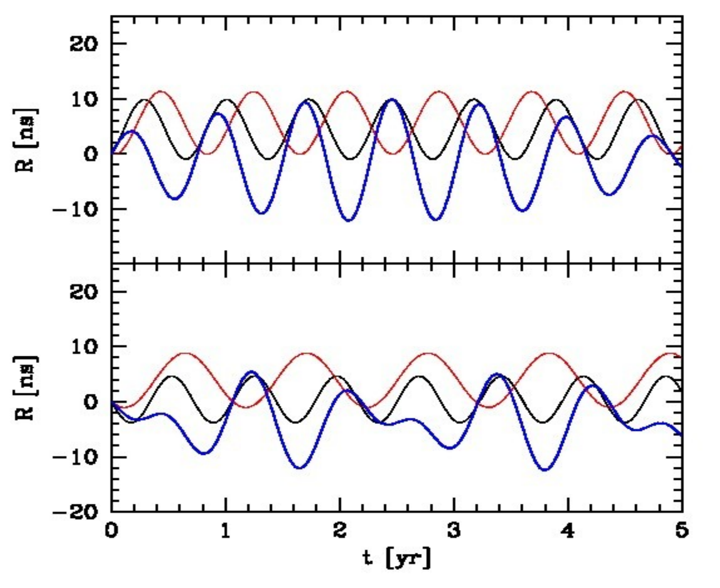
pulsar timing arrays

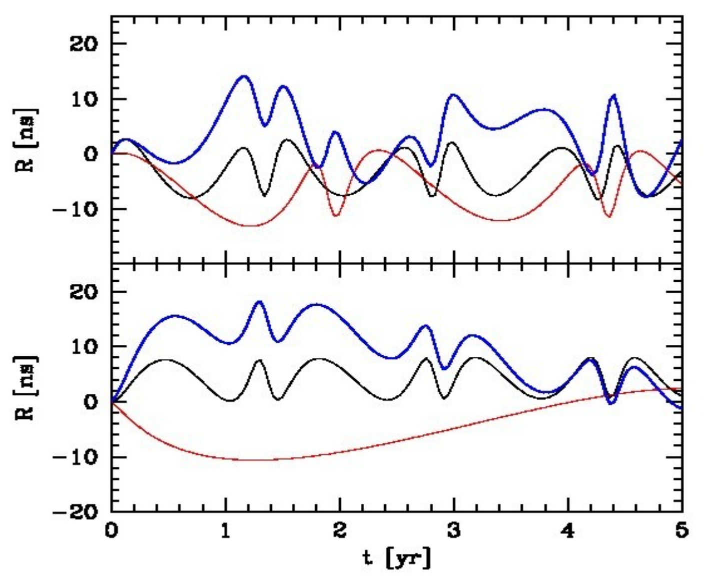
PPTA (Parkes pulsar timing array)

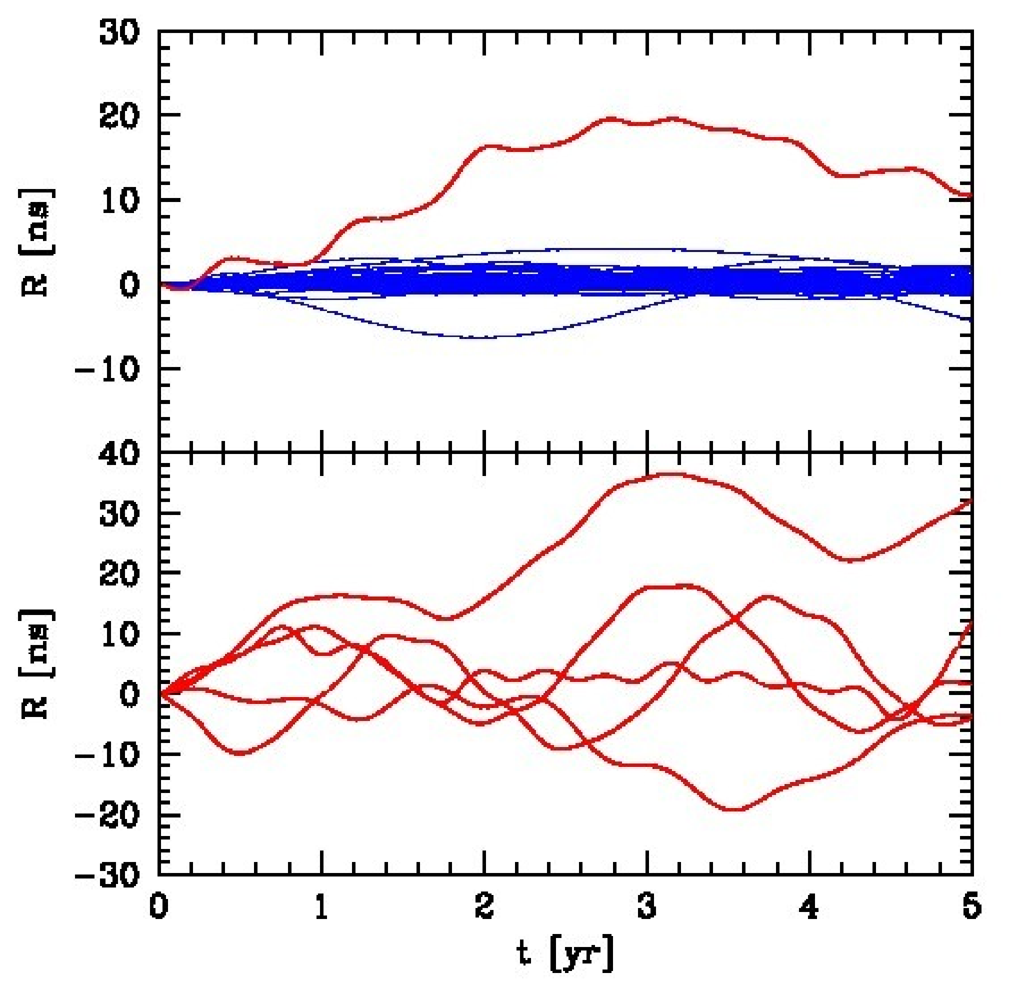
NanoGrav (north American nHz observatory for gravitational waves)

LEAP (large European array for pulsars)

Examples of signals







Verbiest et al. 2009

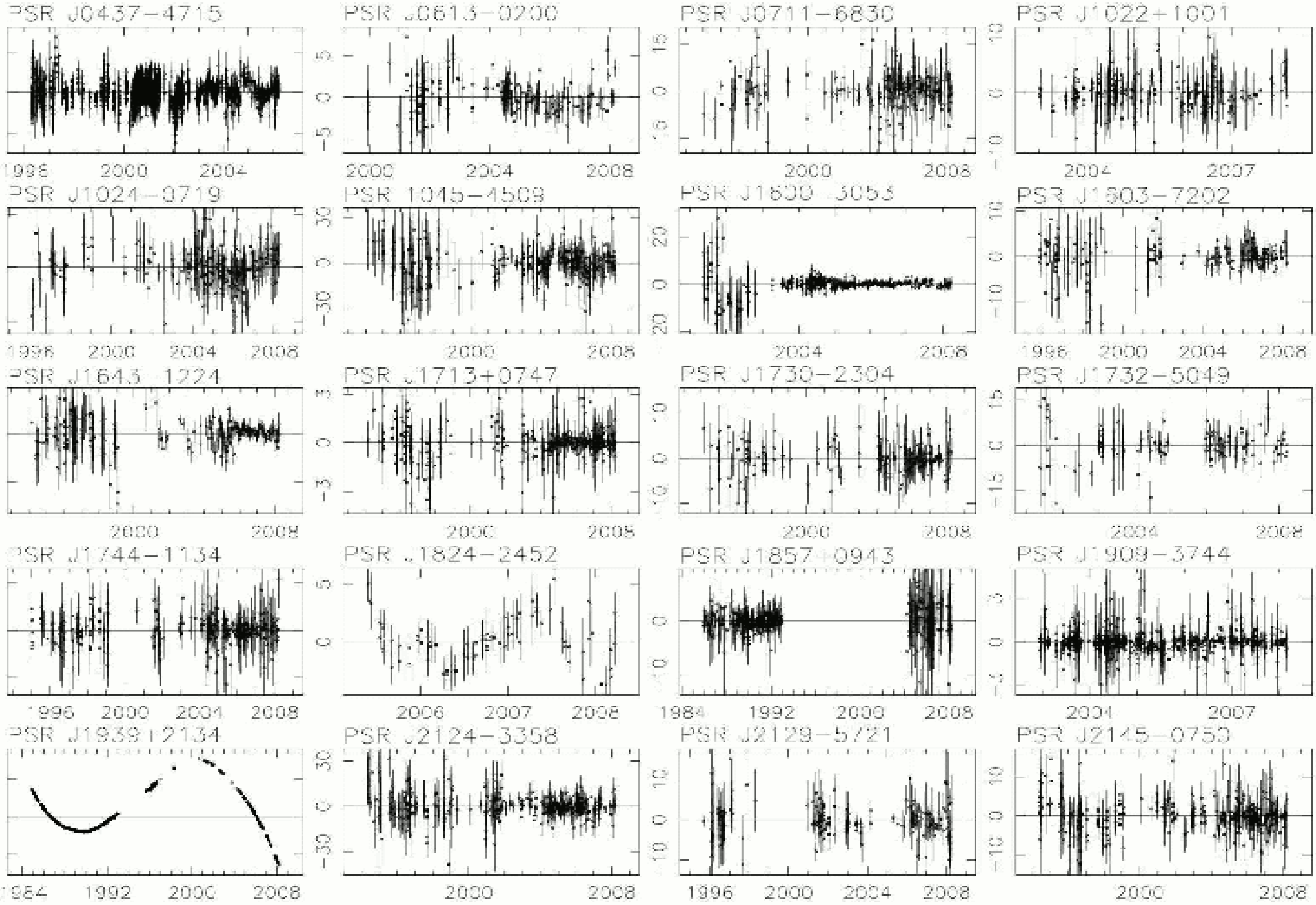


Figure 1. Timing residuals of the 20 pulsars in our sample. Scaling on the x-axis is in years and on the y-axis in μs. For PSRs J1857+0943 and J1939+2134, these plots include the Arecibo data made publically available by Kaspi et al. (1994); all other data are from the Parkes telescope, as described in §2. Sudden changes in white noise levels are due to changes in pulsar backend set-up - see §2 for more details.

GW signal from a SMBH binary population

Consider a class of sources with differential number density $d^2n/dzdM$
emitting an energy spectrum $dE/d\ln f$

$$h_c^2(f) = \frac{4G}{\pi c^2 f^2} \int_0^\infty dz \int_0^\infty d\mathcal{M} \, \frac{d^2 n}{dz d\mathcal{M}} \frac{1}{1+z} \frac{dE_{\mathrm{gw}}}{d\ln f_r}$$

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

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

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

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

(Phinney 2001, Jaffe & Backer 2003, Wyithe & Loeb 2003, Sesana et al. 2004, Enoki et al. 2004)

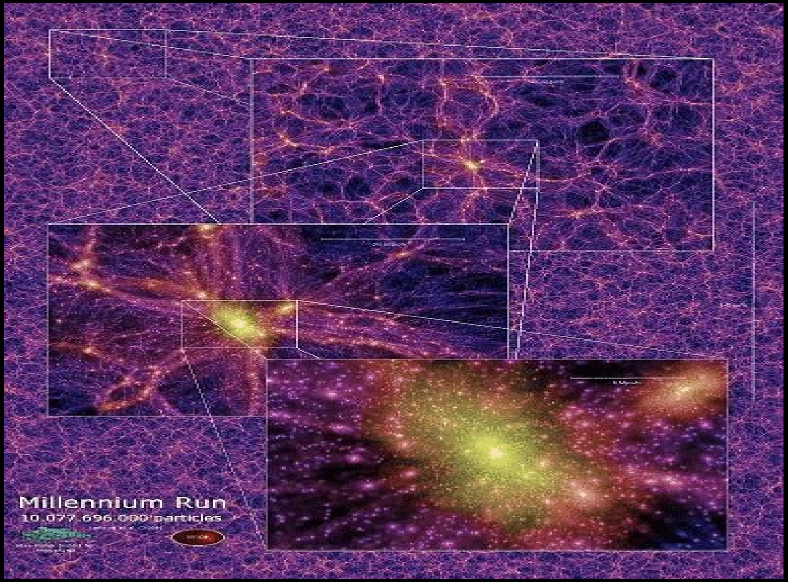
Modelling the SMBH population

MILLENNIUM RUN (Springel et al 2005)**:**

> *N-body numerical simulations of the halo hierarchy*

> *Semi-analytical models for galaxy formation and evolution*

> *We extract catalogues of merging galaxies and we populate them with sensible MBH prescriptions*



We consider several BH-host relations:

1- **M_{BH}-sigma** (Gultekin et al. 2009)
2- **M_{BH}-M_{bulge}** (Gultekin et al. 2009)
3- **M_{BH}-M_{bulge} z dep.** (Mclure et al. 2006)
4- **M_{BH}-L_{bulge}** (Lauer et al. 2007)

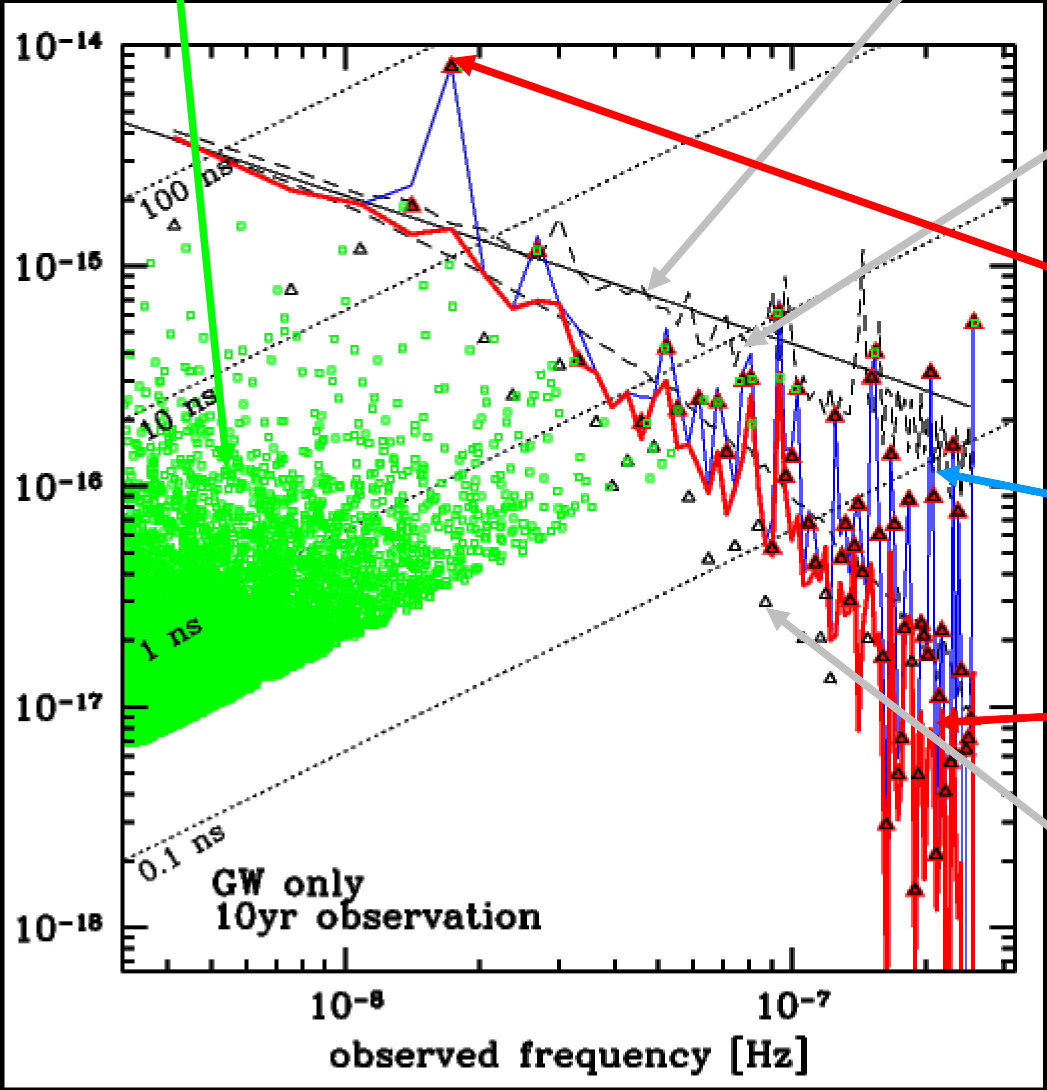
For any relation we employ three different accretion prescriptions:

a- Accretion after merger
b- Accretion only onto M_1, before merger
c- Accretion on both MBHs before merger

We further assume:

- Circular orbits
- GW driven merger ($N(f)\ \alpha\ f^{-8/3}$)

Signal from a MBHB population



Contribution of individual sources

Theoretical 'average' spectrum

Spectrum averaged over 1000 Monte Carlo realizations

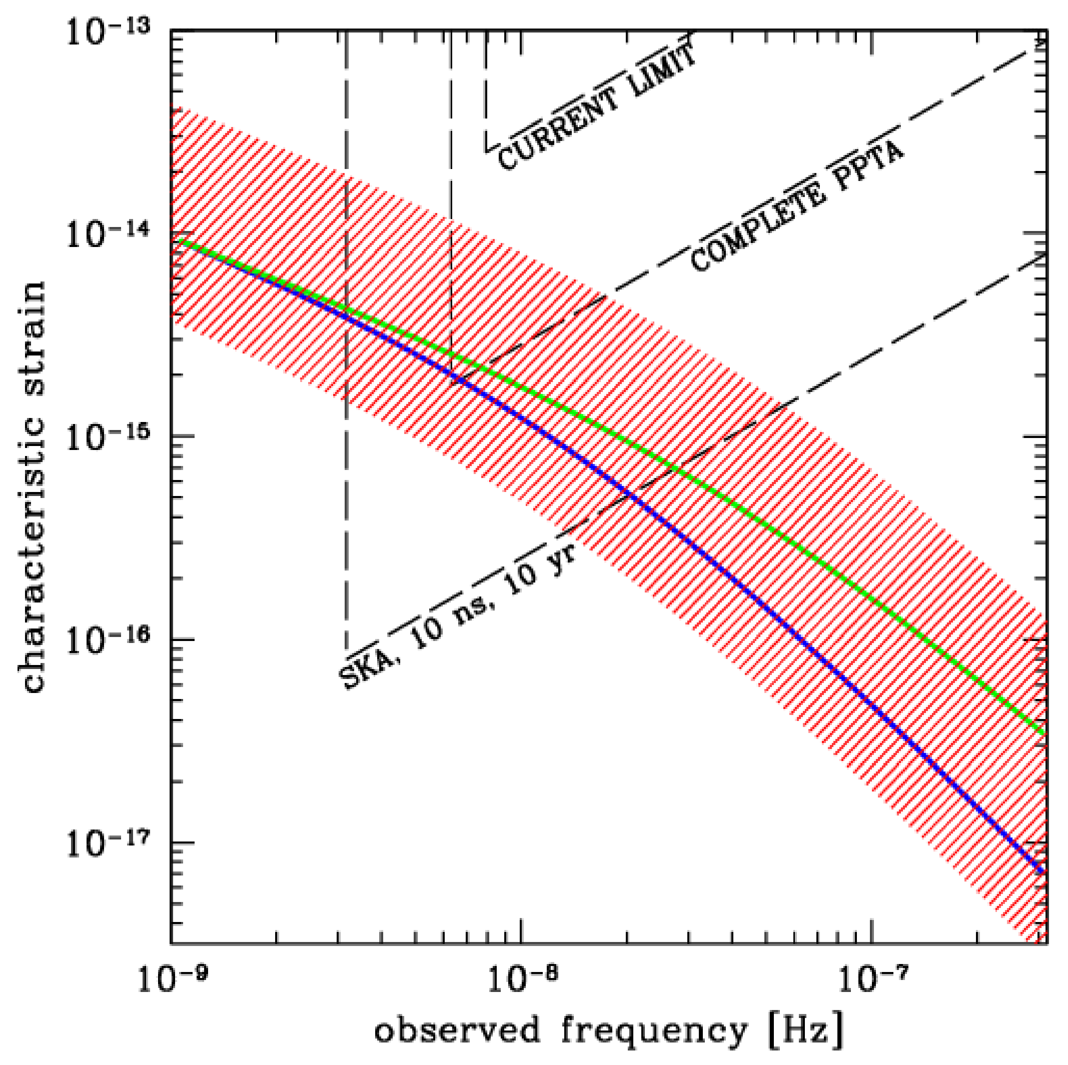
Resolvable systems: **i.e.** ***systems whose signal is larger than the sum of all the other signals falling in their frequency bin***

Total signal

Unresolved background

Brightest sources in each frequency bin

Expected background level



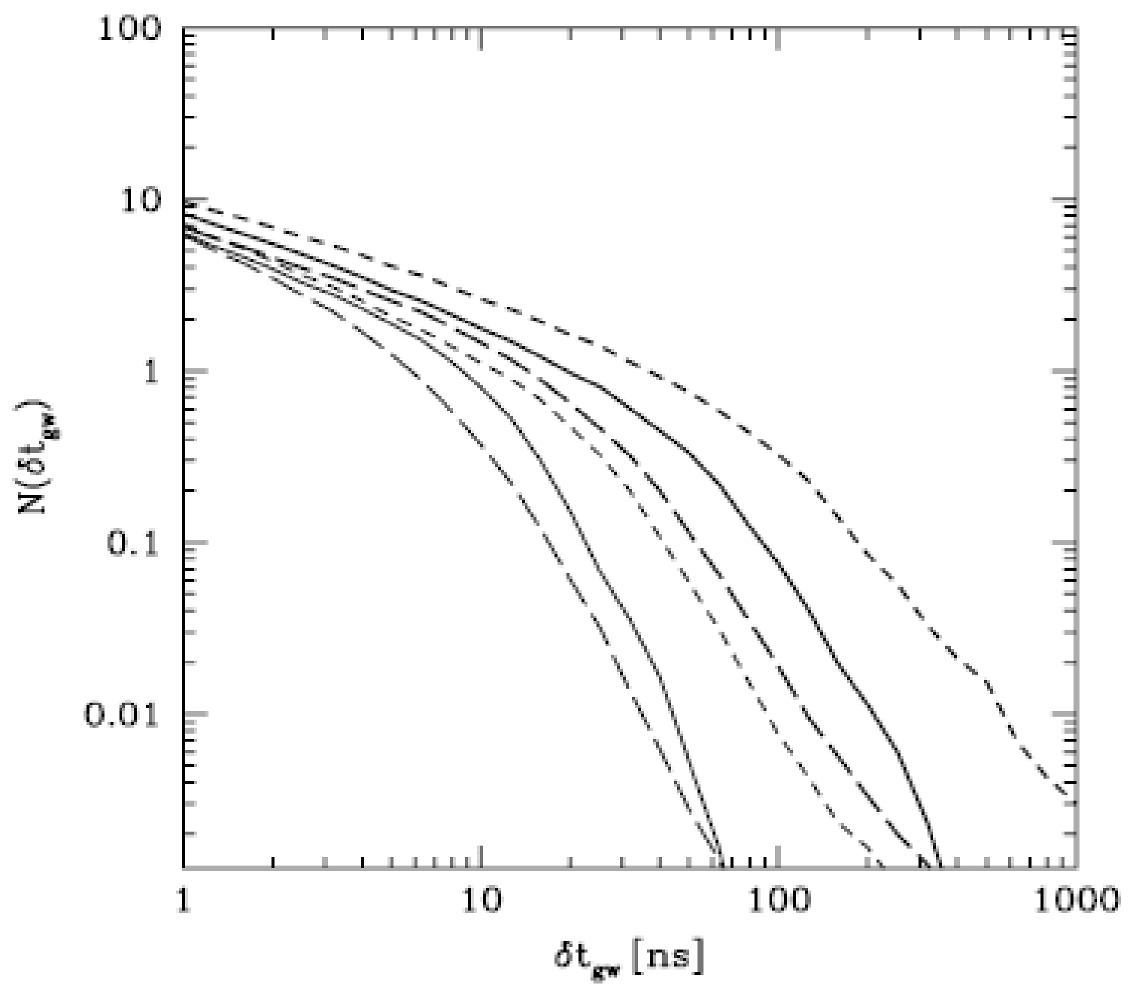
Sesana, Vecchio & Colacino 2008

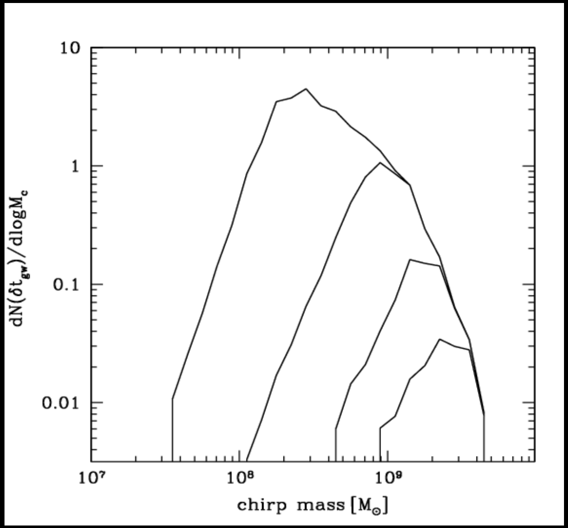
Three parameter fit to the background

$$h_c(f) = h_0 \left(\frac{f}{f_0}\right)^{-2/3} \left(1 + \frac{f}{f_0}\right)^{\gamma}$$

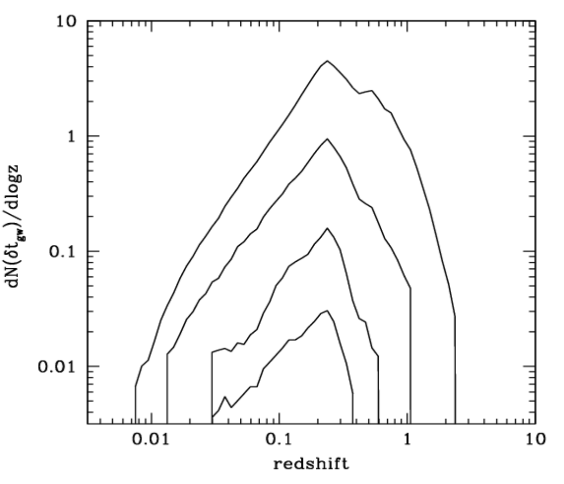
$$\begin{aligned} h_0 &= (1.93 \pm 1.25) \times 10^{-15}\,, \\ f_0 &= 3.72^{+1.52}_{-1.30} \times 10^{-8}\,\mathrm{Hz}\,, \\ \gamma &= -1.08^{+0.03}_{-0.04}\,; \end{aligned}$$

Resolvable sources





Probe systems with mass $>10^8 M_\odot$ at $z<1$

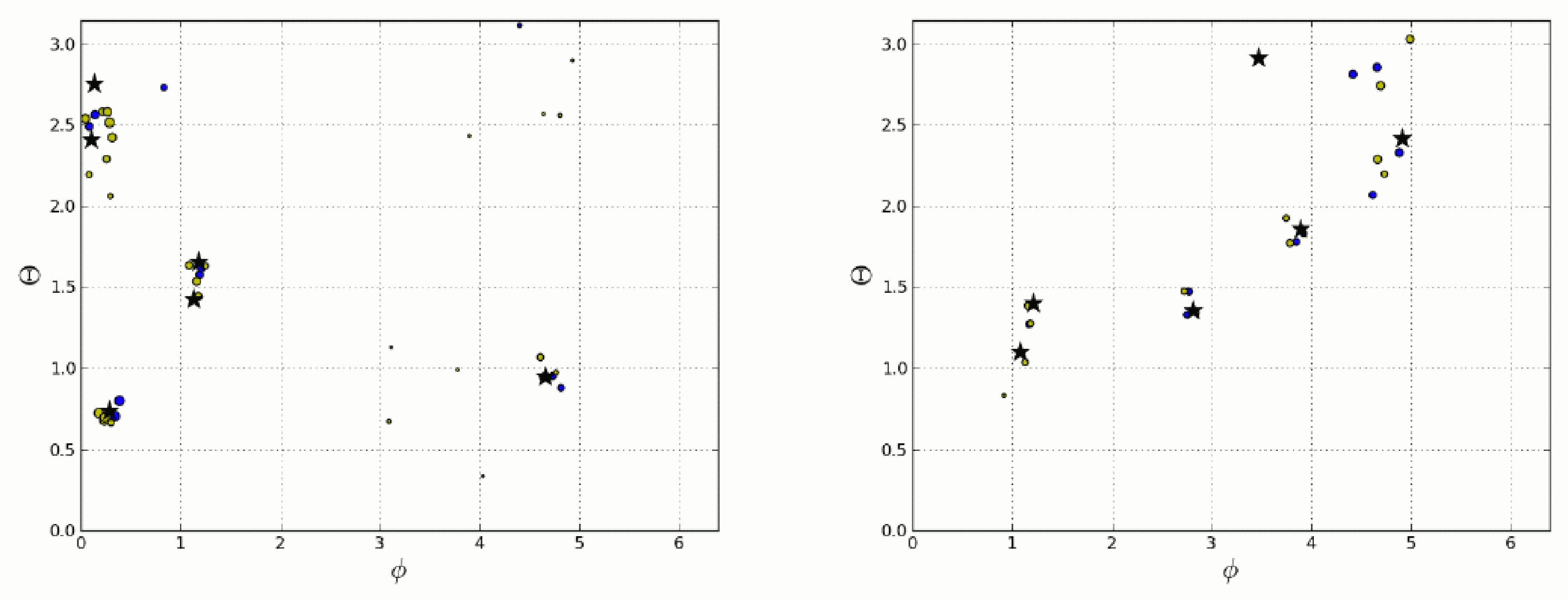


Sesana, Vecchio & Volonteri 2009

>a total timing precision of *5-50 ns* is required to detect an individual resolvable MBHB

>Uncertainties depend on the *MBH-host* relation and MBH *accretion route* during mergers

Individual source resolvability

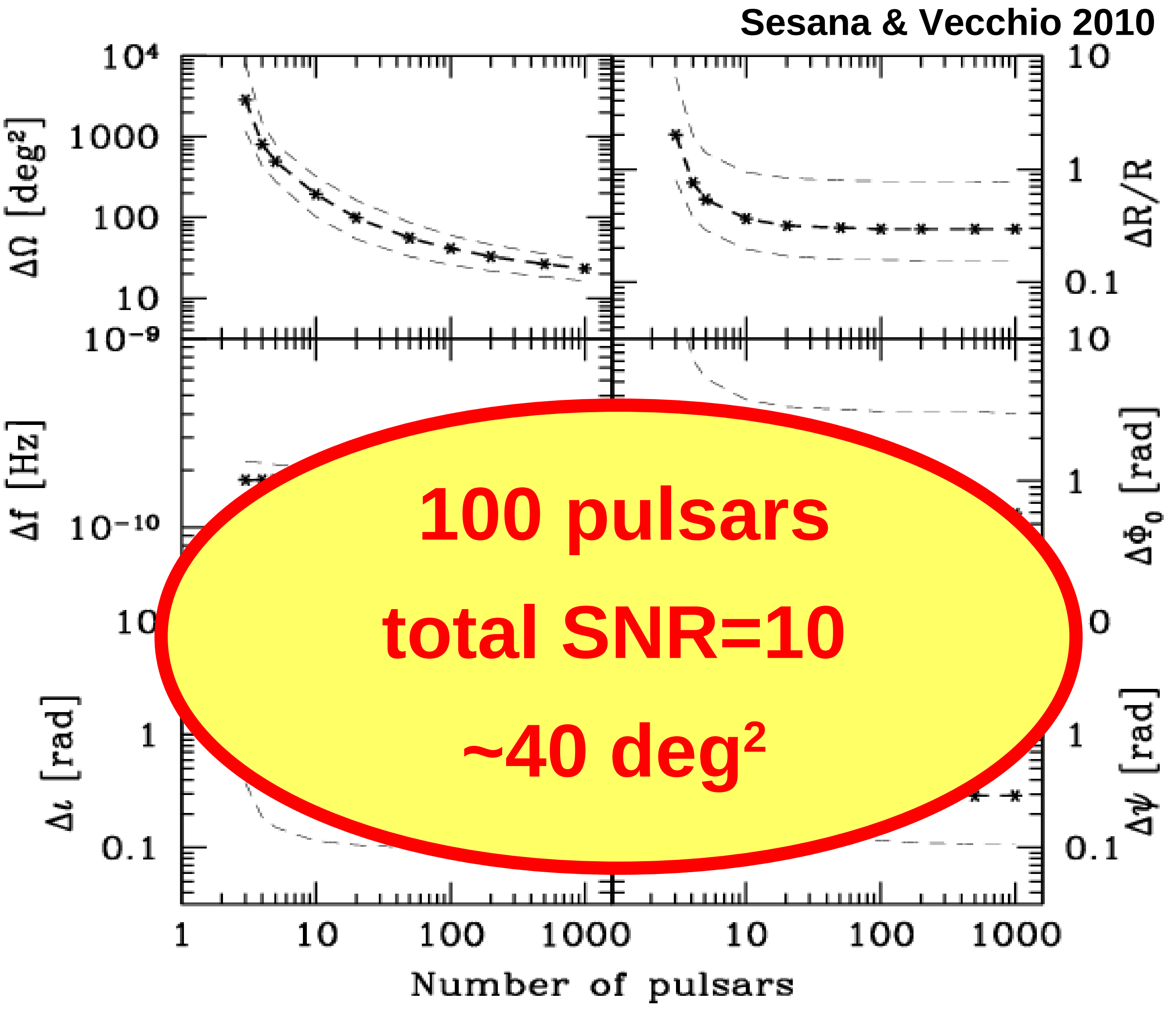


Babak Sesana & Petiteau, in preparation

In general, given an array of *N* pulsars, we can pin down up to *N*/3 individual sources (consistent with analytical estimates of Boyle & Pen 2010).

Still work in progress (monochromatic sources, earth term only, no noise, non-optimal search algorithm). Looks promising .

Median statistical errors



Sesana & Vecchio 2010

100 pulsars

total SNR=10

~40 deg^2

With pulsar term: **-few times better sky location**

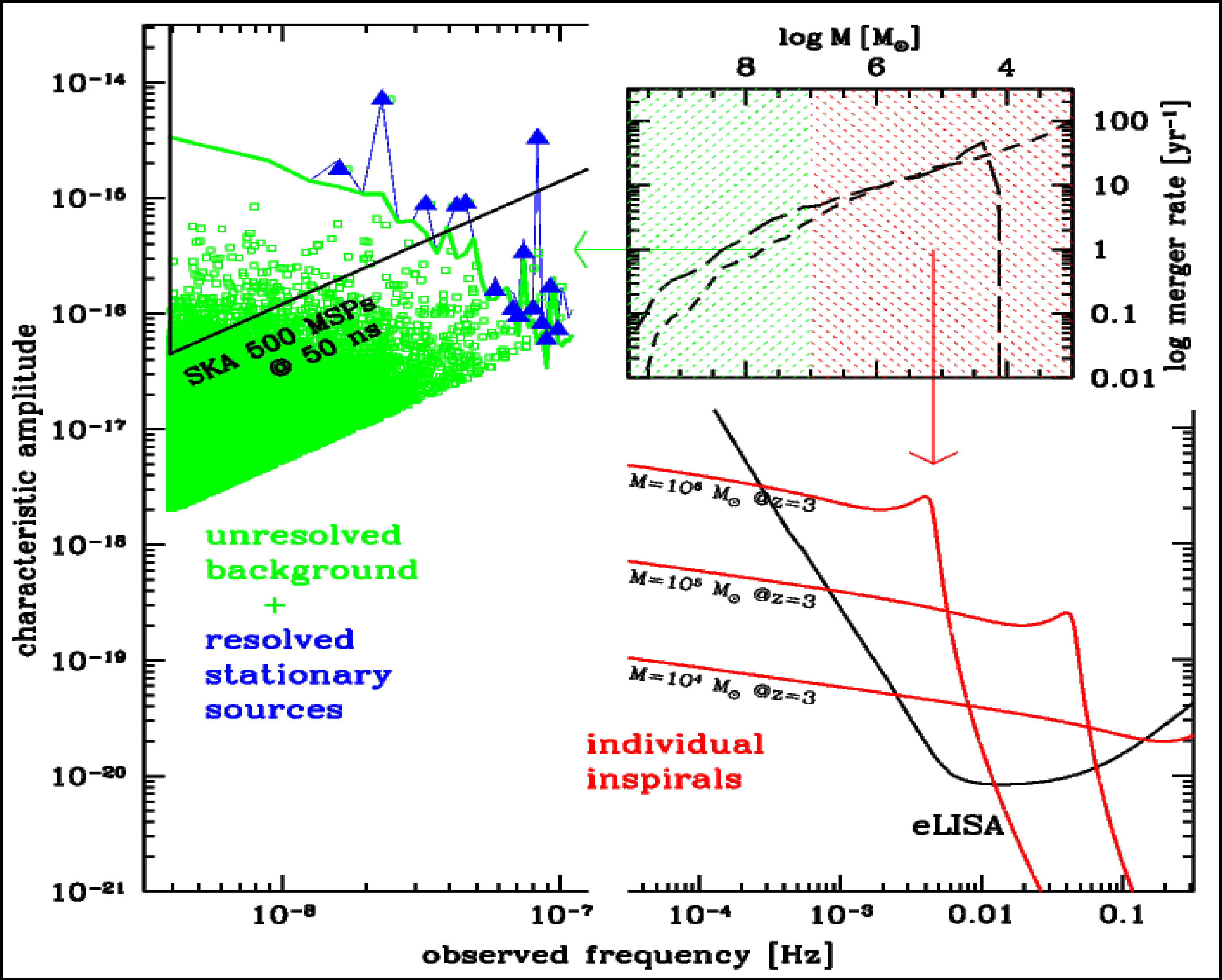
(Corbin & Cornish 2010) **-10% error in luminosity distance**

Summary

> Future PTAs will detect the unresolved MBHB GW background

> At least a dozen (but likely many more) sources may be individually resolved.

> Error box in the sky not so promising, but resolved sources are massive and cosmologically nearby. Good prospects for identifying a counterpart.


log M [M$_\odot$]
8
6
4
100
10
1
0.1
0.01
log merger rate [yr^{-1}]
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
characteristic amplitude
SKA 500 MSPs @ 50 ns
unresolved background
+
resolved stationary sources
$M=10^6$ M$_\odot$ @z=3
$M=10^5$ M$_\odot$ @z=3
$M=10^4$ M$_\odot$ @z=3
individual inspirals
eLISA
10^{-8}
10^{-7}
10^{-4}
10^{-3}
0.01
0.1
observed frequency [Hz]