What PTA limits/detection tell us about the astrophysics of GW sources?

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OUTLINE

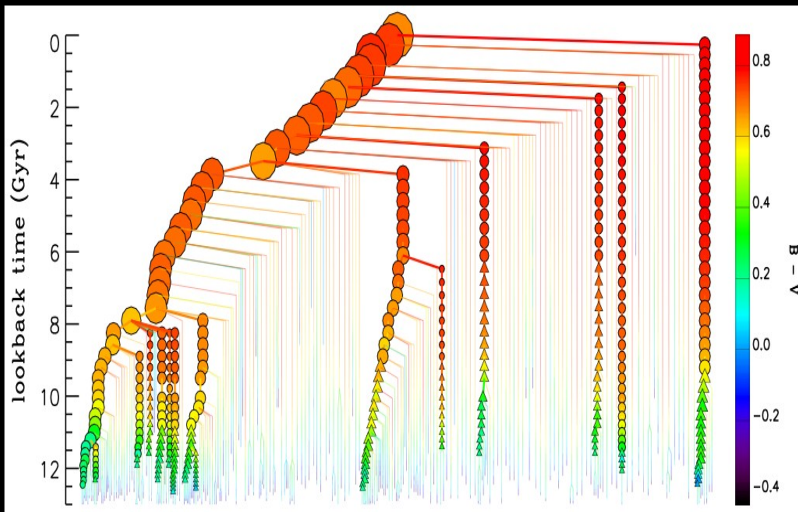
1 - Build-up of the typical PTA GW signal

2 - Impact of the collective MBH population

3 - Impact of individual MBHB dynamics

4 - General thoughts

Structure formation in a nutshell



From De Lucia et al 2006

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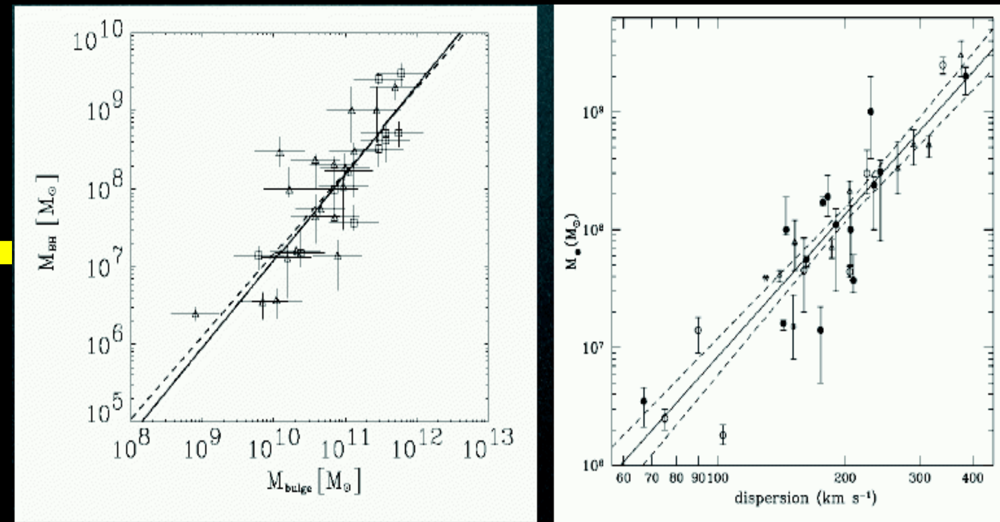

Ferrarese & Merritt 2000, Gebhardt et al. 2000

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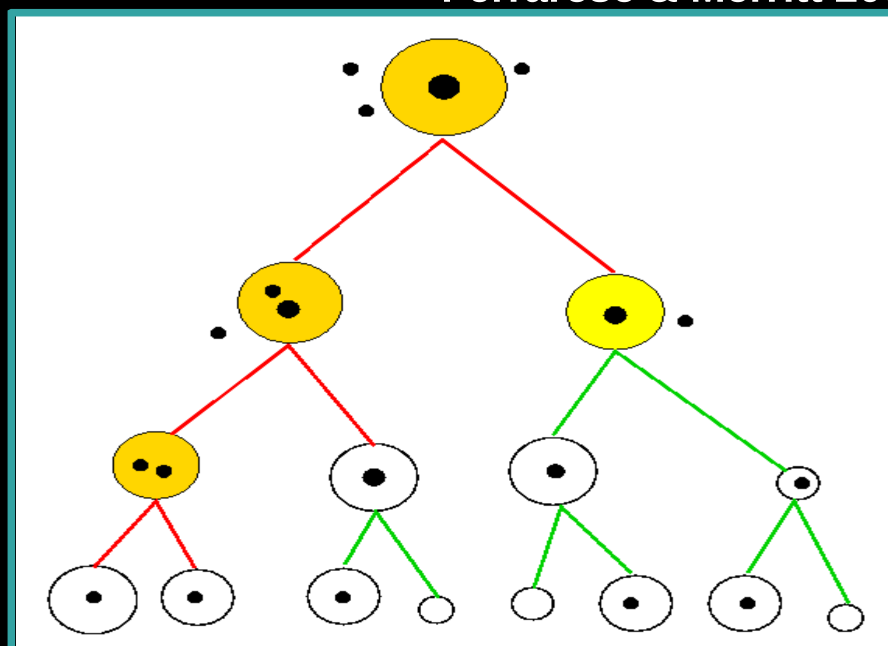


Volonteri Haardt & Madau 2003

GW signal from a MBHB population

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

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

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

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

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

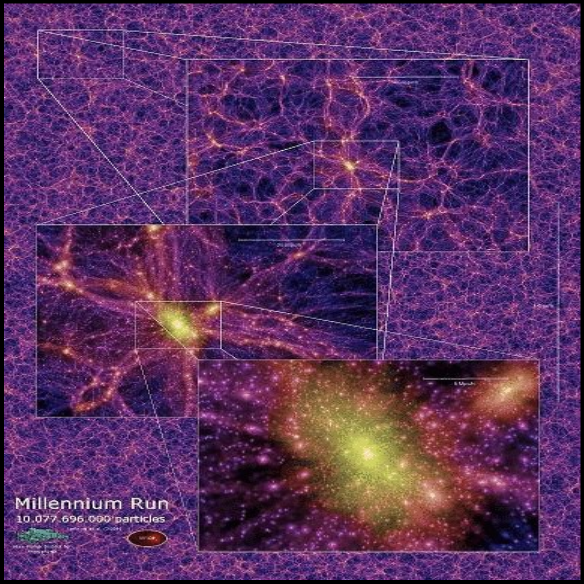
Phinney 2001, Jaffe & Backer 2003, Wyithe & Loeb 2003, AS et al. 2004, Enoki et al. 2004

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*



Typical signal

Theoretical 'average' spectrum

Contribution of individual sources

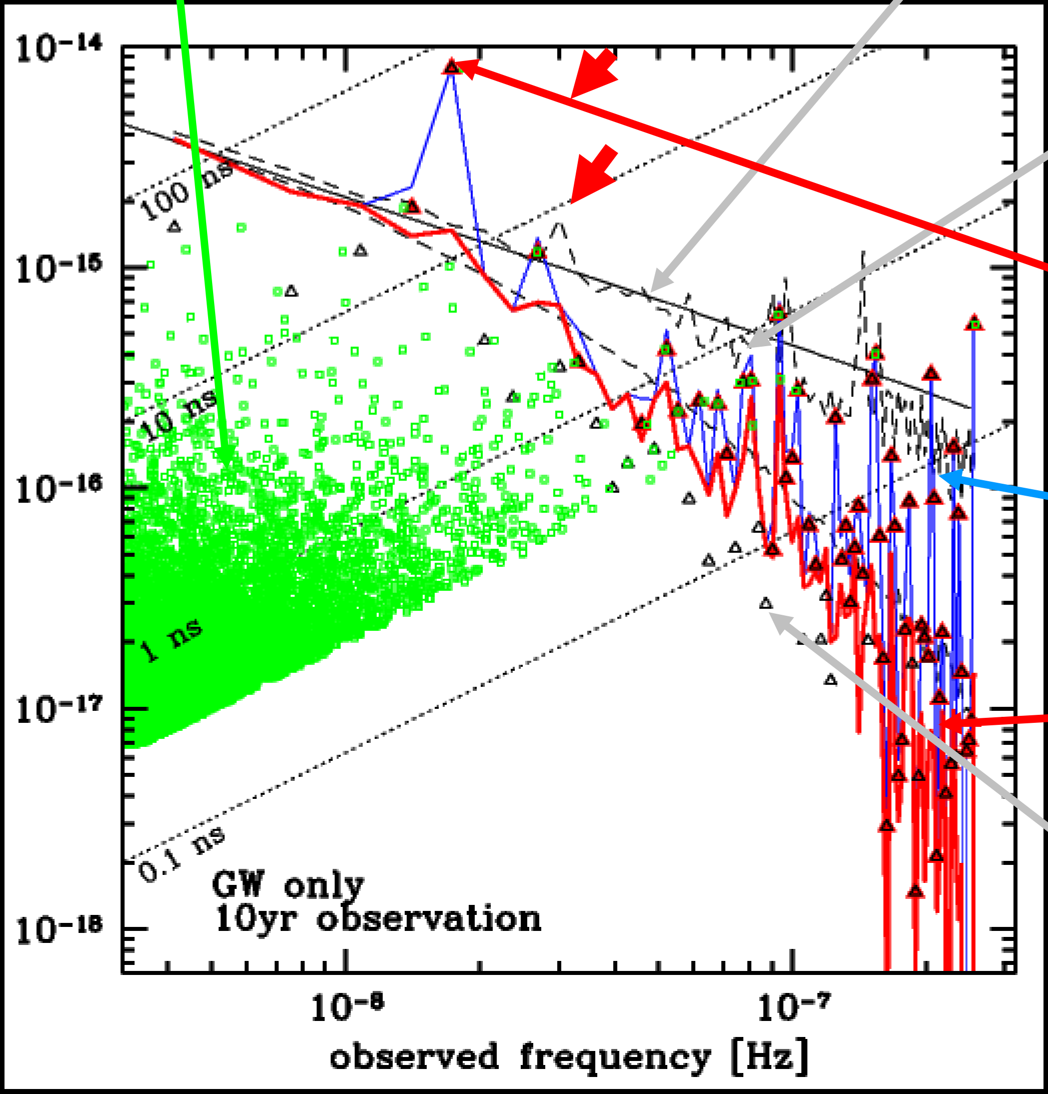
Spectrum averaged over 1000 Monte Carlo realizations

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



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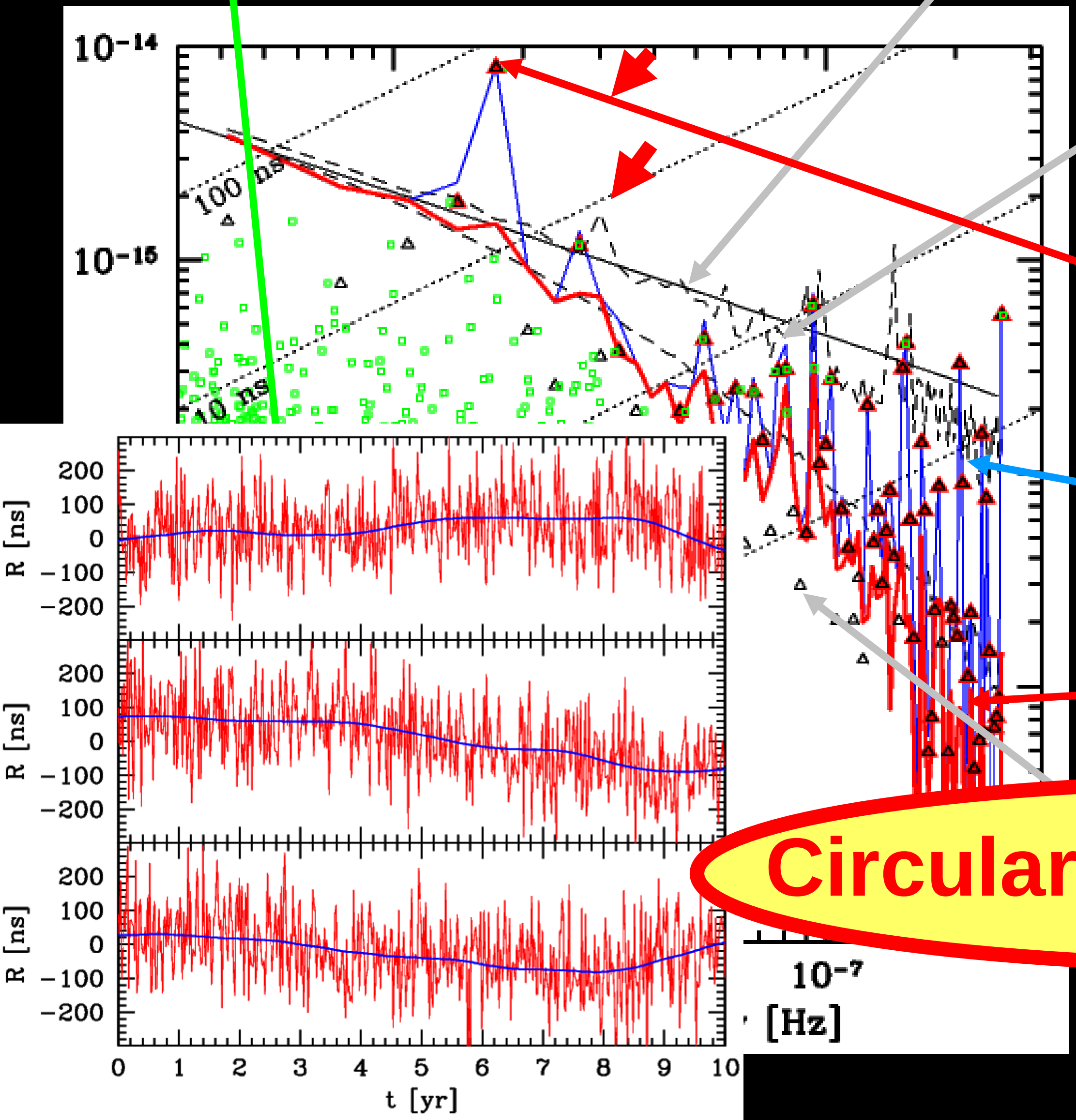

Spectrum averaged over 1000 Monte Carlo realizations

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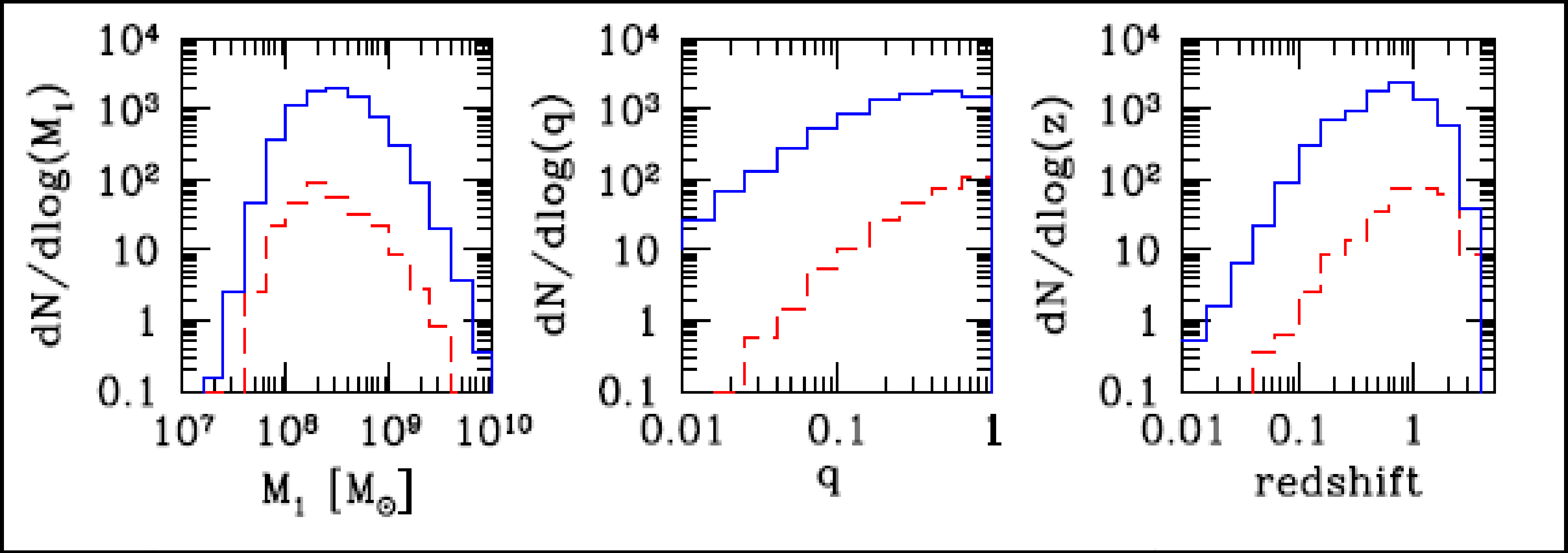
Circular GW-driven binaries

Detail of the contributing population



-sensitive to massive (>$10^8 M_\odot$), cosmologically nearby (z<2) binaries: complementary to the LISA range (AS et al. 2008, 2009, 2012).

-if a source can be individually resolved, its sky position can be pinned down to high accuracy (AS & Vecchio 2010, Corbin & Cornish 2010, Ellis et al. 2012 ....). Promising prospects for multimessenger astronomy (massive+nearby---> bright counterparts)

What shapes the expected signals?

$h_c \propto N(f)^{1/2} M_c^{5/6}$; $N(f)=Af^{-\gamma}$

Population parameters

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

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

2-MBH mass – merging galaxy relation

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

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

3-Eccentricity

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

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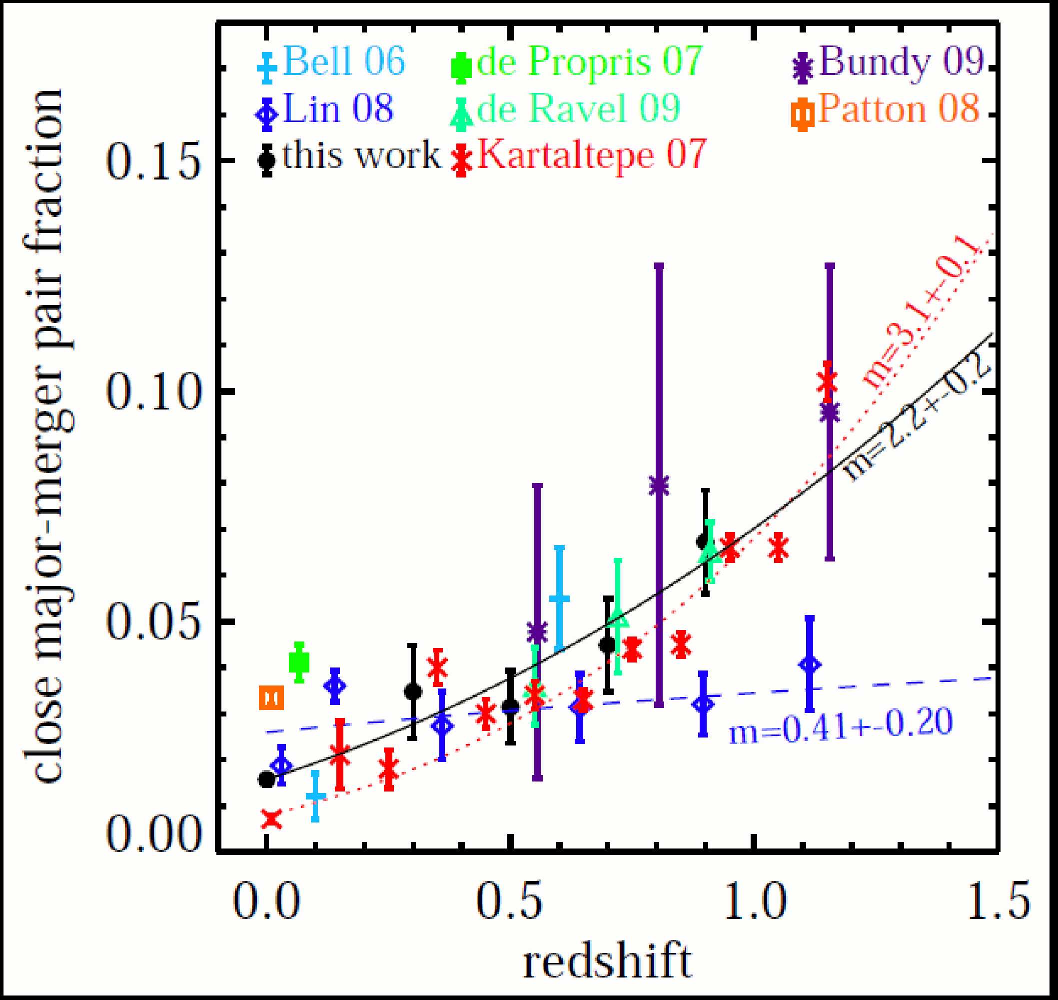
1-Galaxy merger rate

-The halo merger history is fixed both in merger trees and in the Millennium
-This can be compared with observed galaxy pairs but:
1-Huge uncertainties in the observations (bias, completeness)
2-Huge uncertainties in the merger timescale

Xu et al. 2012

$$\dot{N}_{\mathrm{M}} = \frac{\phi}{2\mathcal{T}_{\mathrm{M}}} \int n_{\mathrm{G}}\, dV_c$$



AS et al. 2008: Comparisons between merger trees and Combo survey merger rates (Bell et al. 2006) agreed within a factor of a few. But much more to explore!

Signal not extremely sensitive to this, as amplitude goes only with $N^{1/2}$

2-MBHs-galaxy relation & accretion

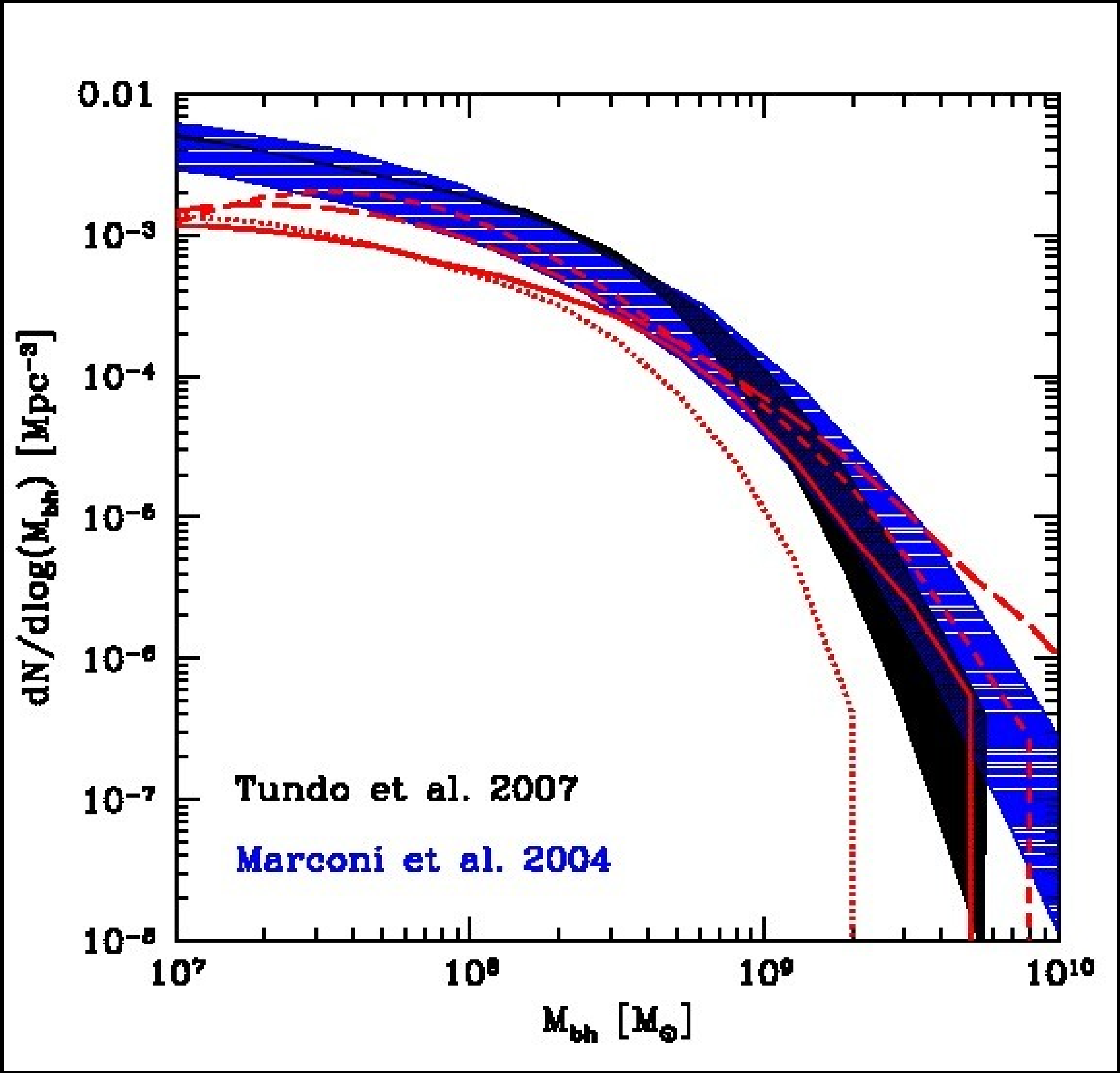
We consider several BH-host relations:

1- M_{BH}-sigma (Tremaine et al. 2002, Gulketin et. al 2009)
2- M_{BH}-M_{bulge} (Tundo et al. 2007, Gulketin et. al 2009)
3- M_{BH}-M_{bulge} z dependent (Mclure et al. 2006)
4- M_{BH}-L_{bulge} (Lauer et al. 2007)

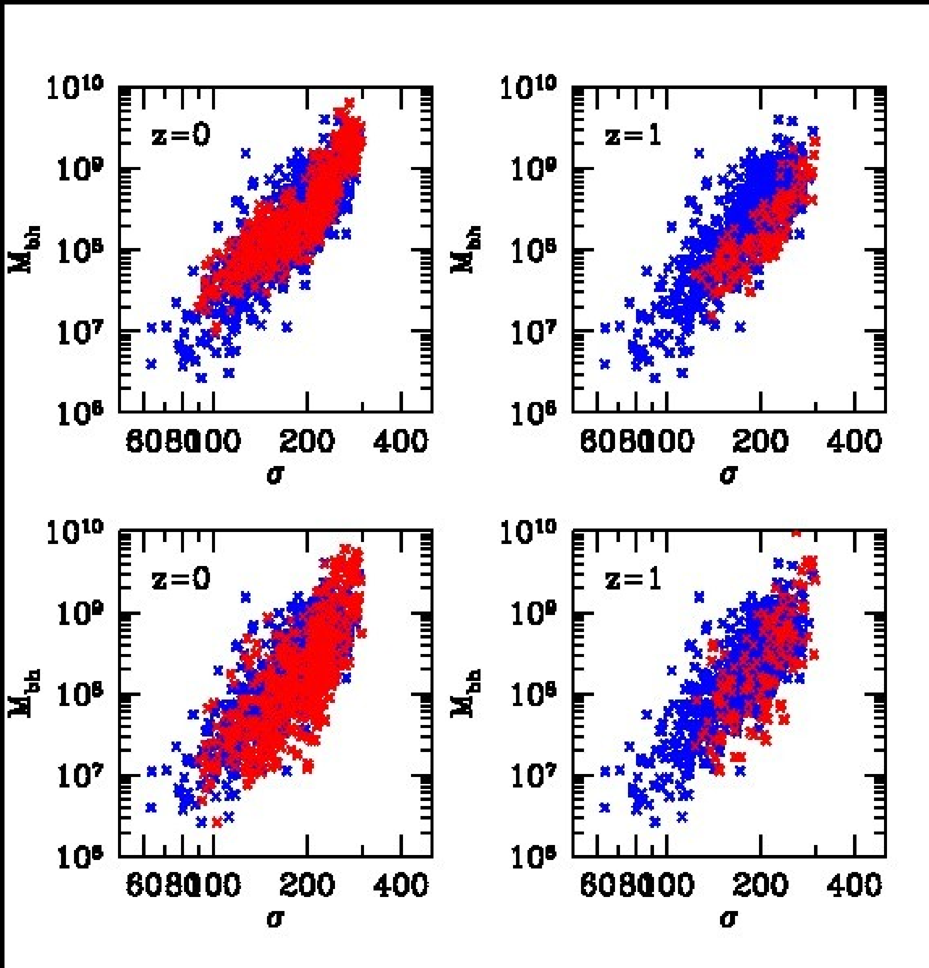
For any relation we employ three different accretion prescriptions:

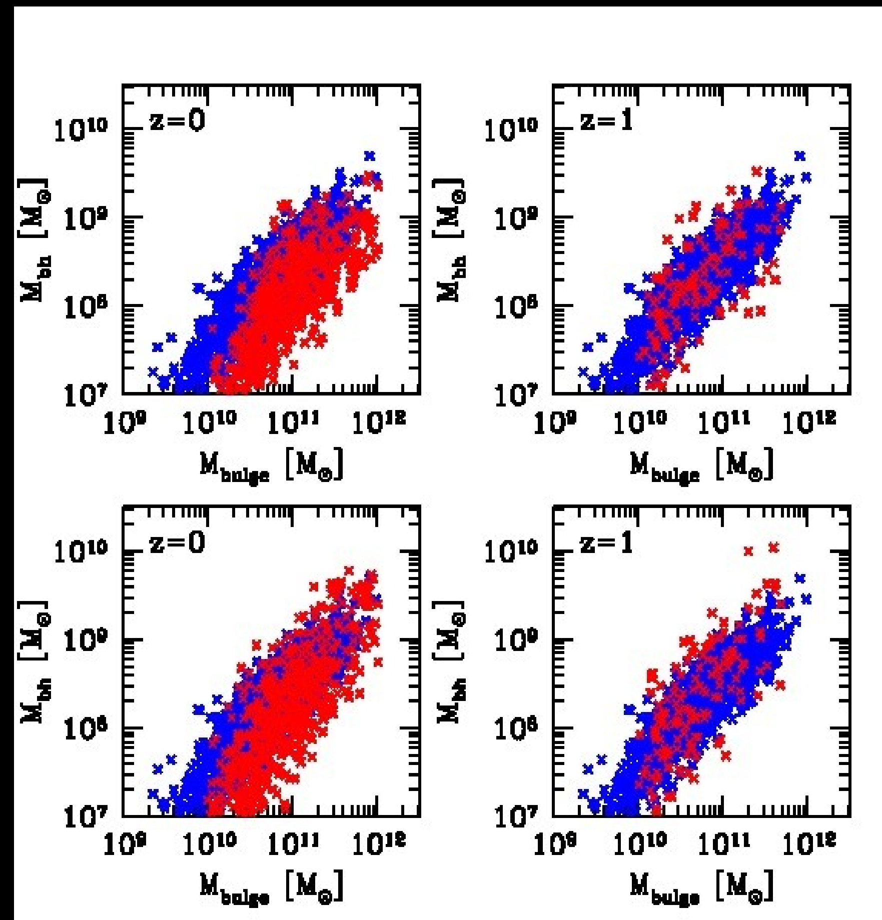
a- Accretion after merger
b- Accretion only onto M_1, before merger
c- Accretion on both MBHs before merger

SMBH mass function

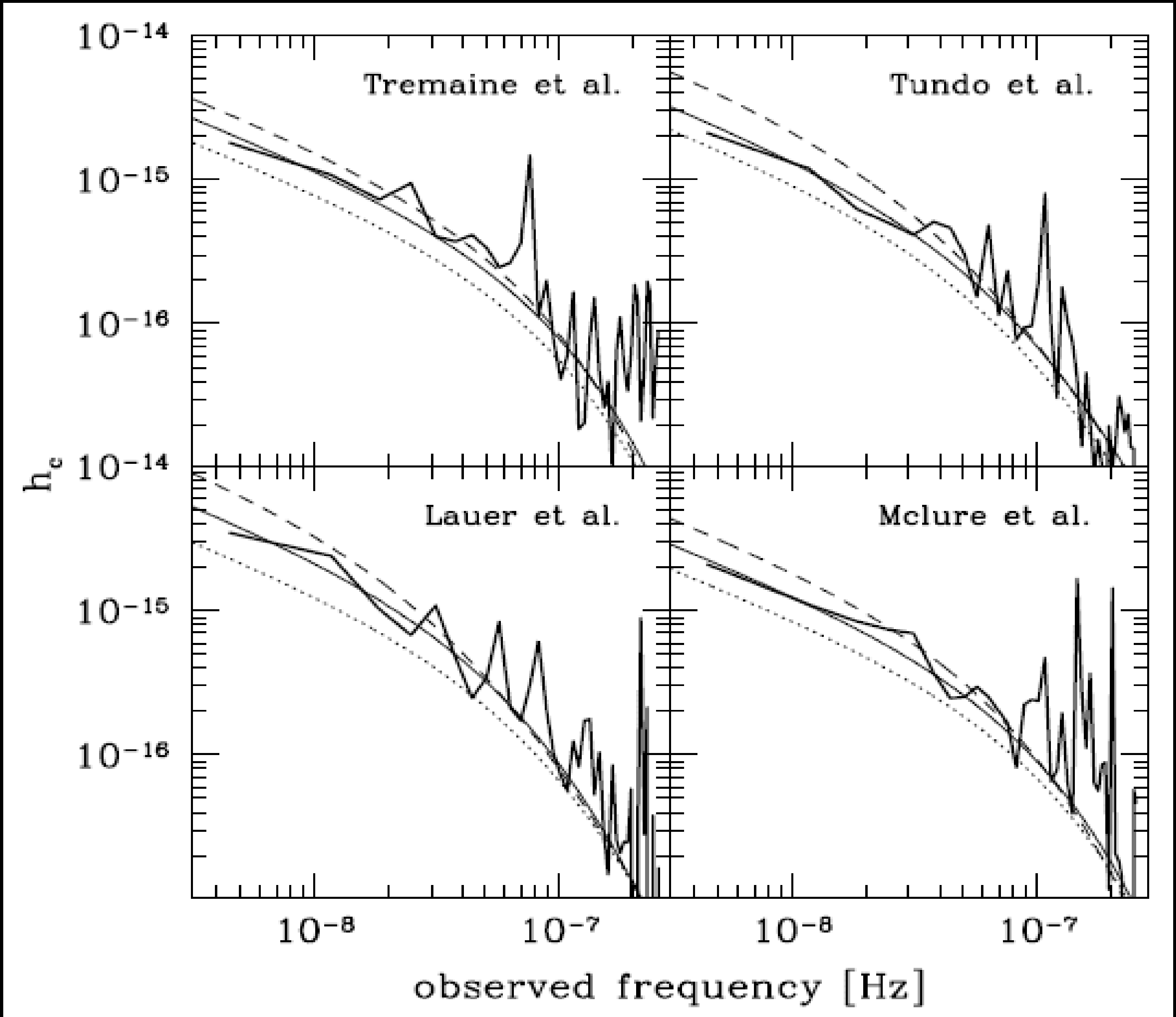


Scaling relations



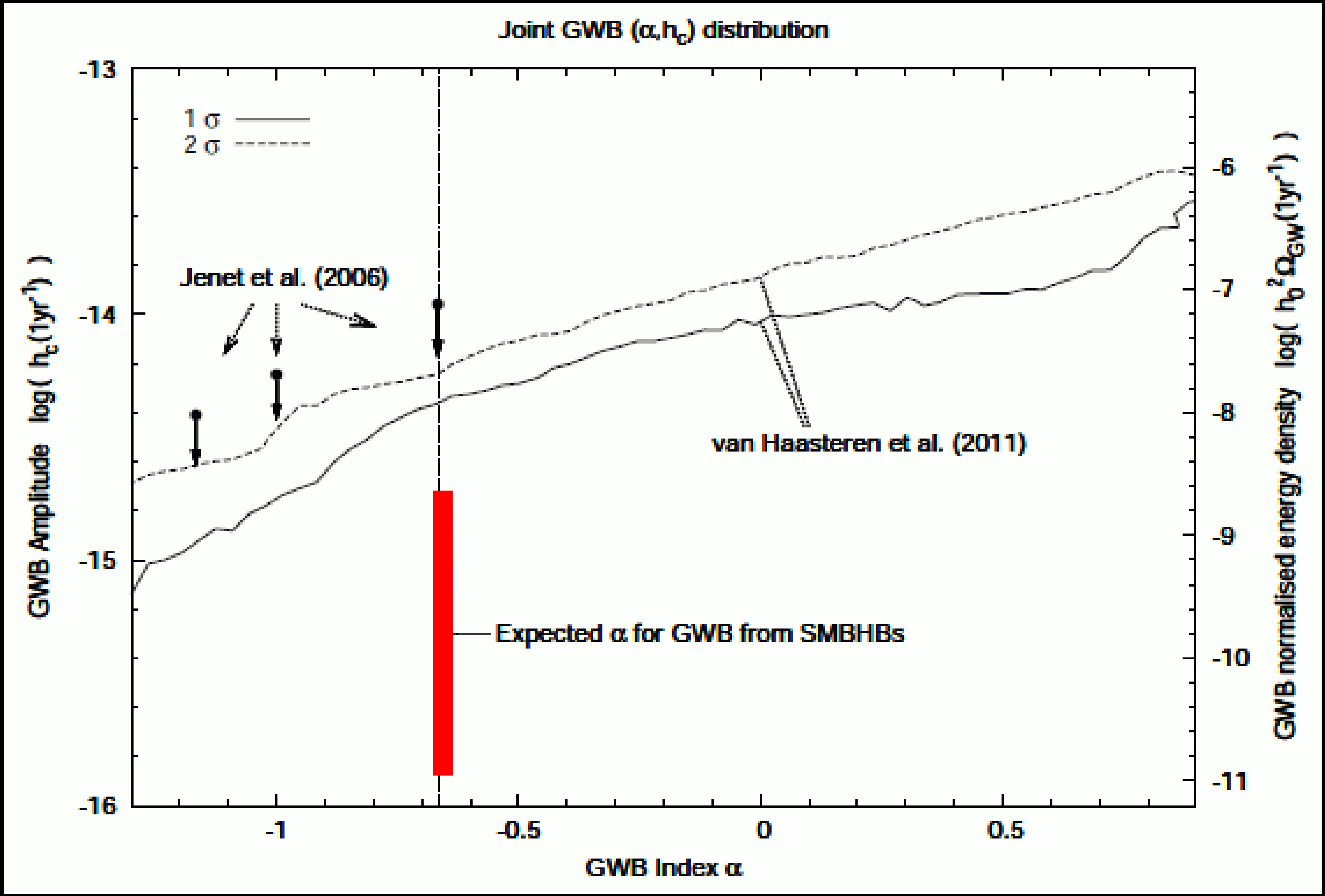


Signal examples



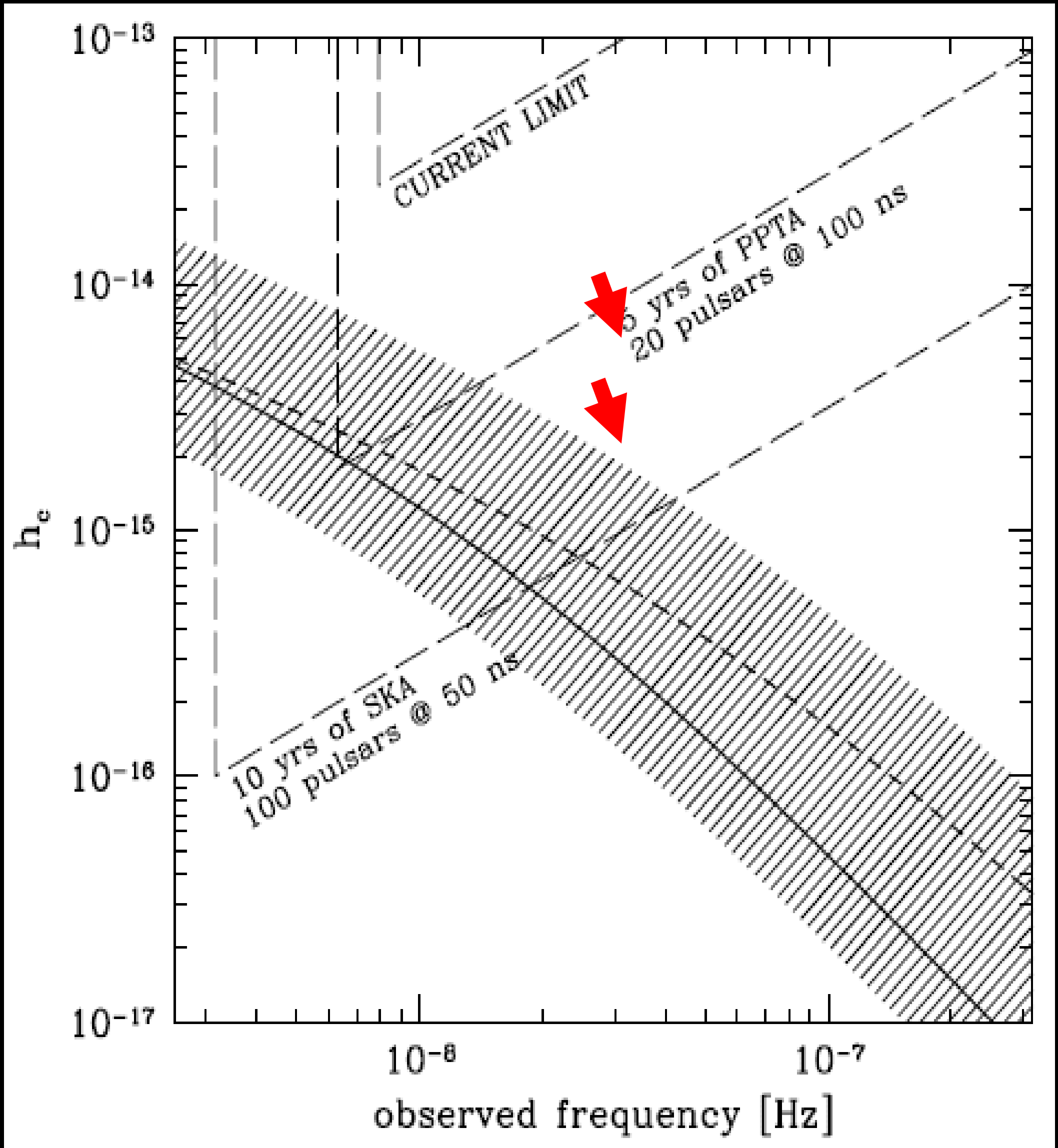
AS, Vecchio & Volonteri 2009

What do current limits tell us?



Van Haasteren et al. 2012

Expected background level



AS Vecchio & Colacino 2008

Three parameter fit to the background

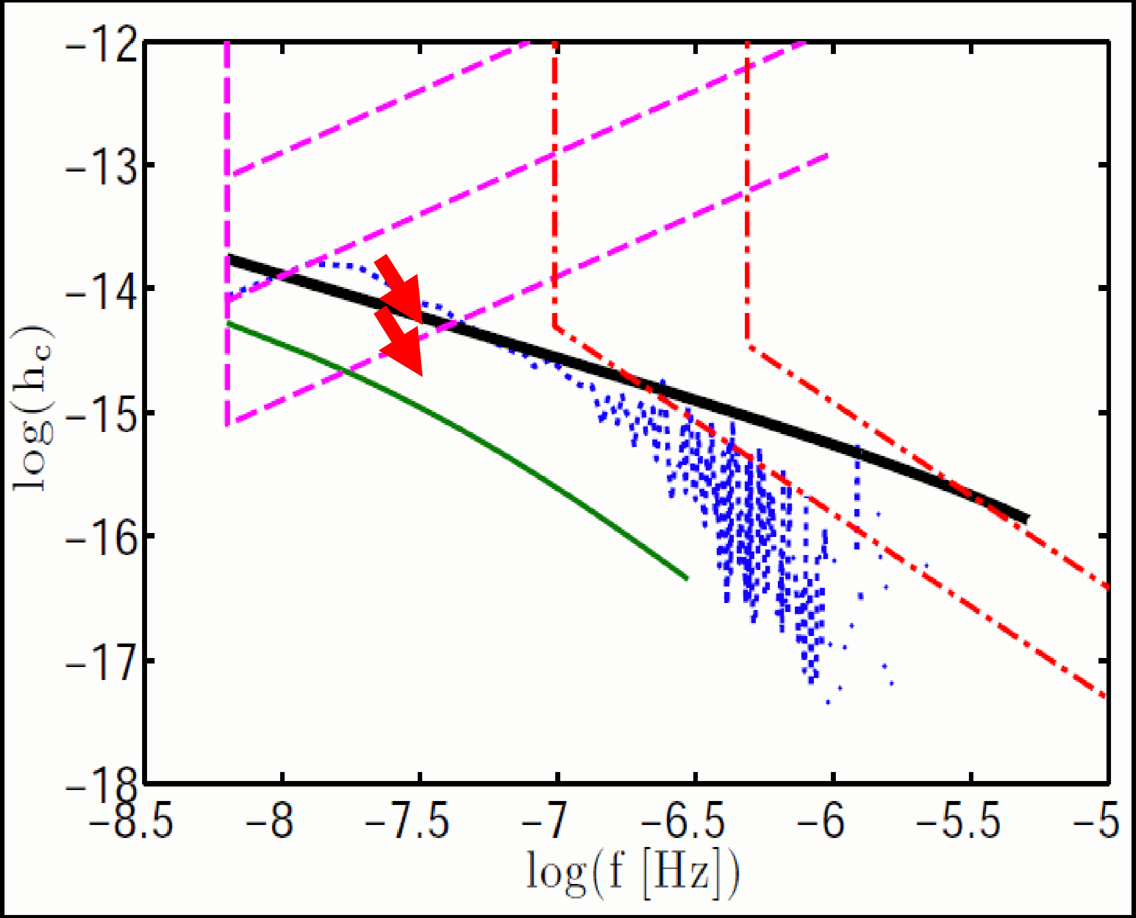
$$h_c(f) = h_0 \left(\frac{f}{f_0}\right)^{-2/3} \left(1 + \frac{f}{f_0}\right)^{\gamma}$$

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

>This correspond to a background level of *~10-100 ns at 10^{-8} Hz*

First constrains on extreme models?

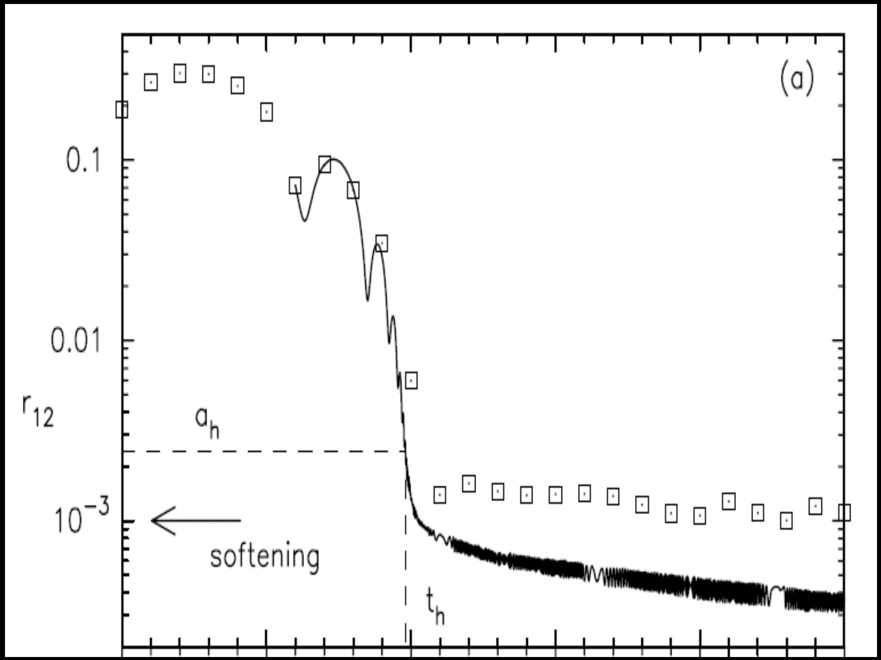
-Observations: SFRs of BCEs are too low to explain their mass build-up since z=1
-Come up with a model where all the mass is acquired through mergers
-Gives some sort of 'upper limit' to the theoretical signal (depending on MBH--bulge relation adopted)



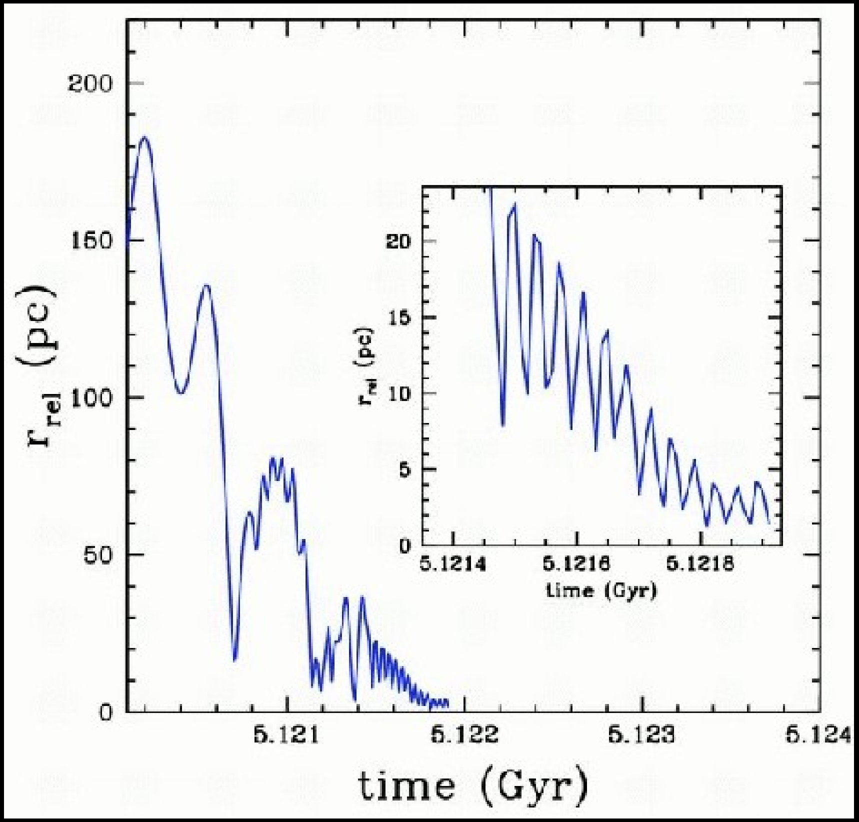
Borderline with NANOGrav and EPTA limits, ruled out already by PPTA limit!

Most massive mergers involve at least one cold gas-rich galaxy --> All mass acquired through mergers with negligible star formation might be a too extreme assumption

Binary dynamics: environmental coupling



From Milosavljevic & Merritt 2001



From Colpi & Dotti 2009

Dynamical friction is initially very efficient in shrinking the binary,
but on parsec scales the mechanism is no longer efficient:

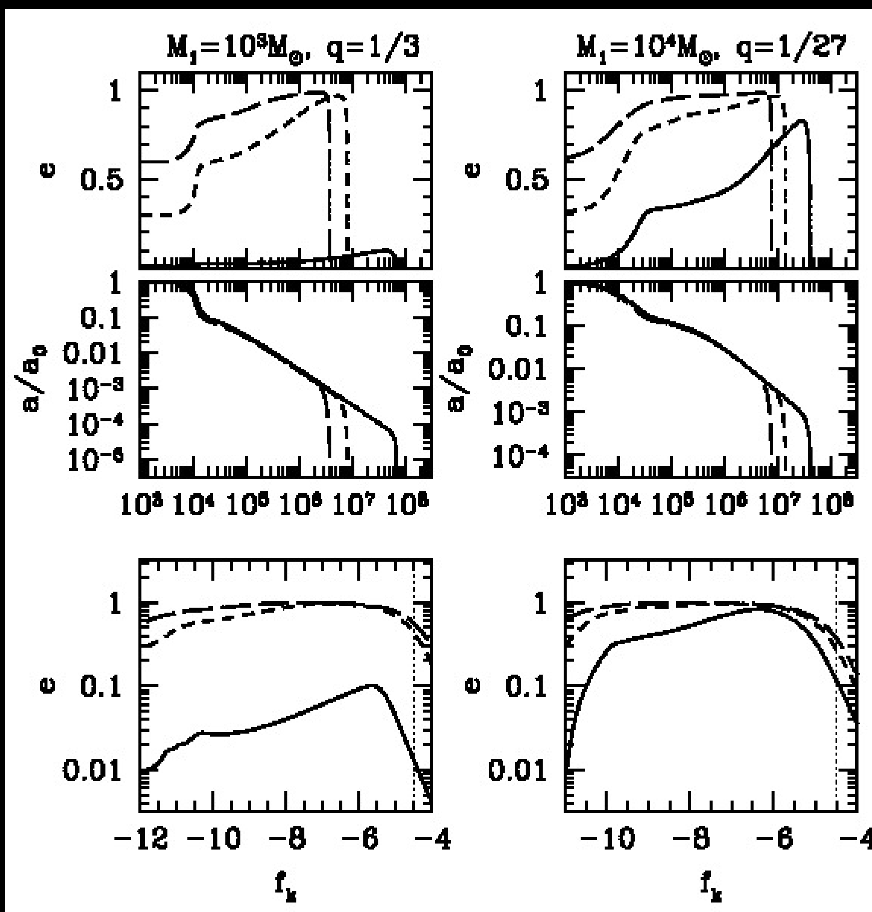
BINARY STALLING?

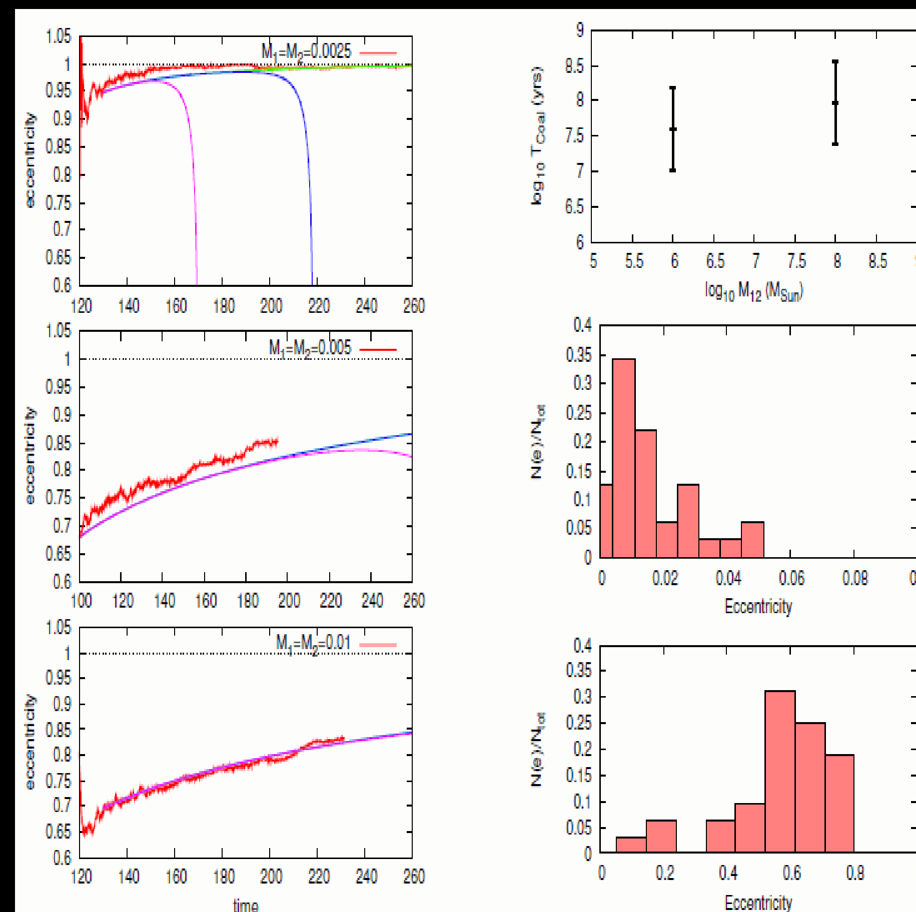
Binary evolution in stellar environments

Recent N-bodies (Berczik et al. 2006, Preto et al. 2011, Khan et al. 2011, Gualandris & Merritt 2011) suggest that *stalling does not occur in realistic merging bulges* (contrary to spherically symmetric systems):

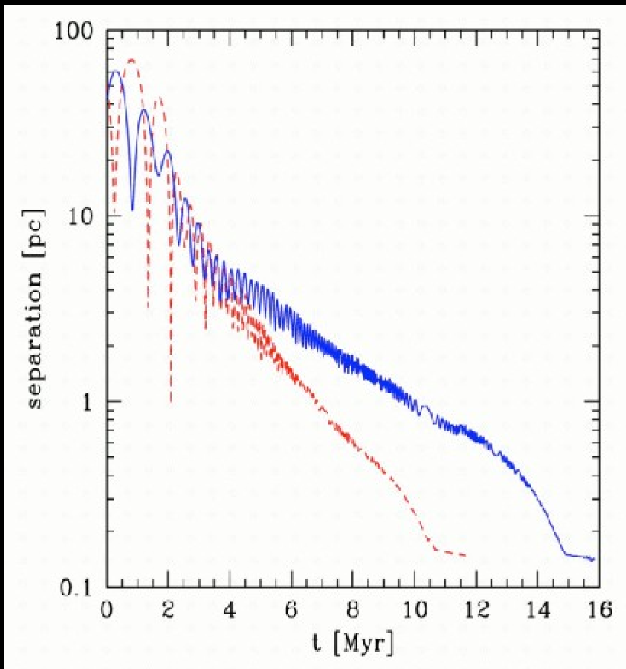
- **Coalescence in <1Gyr**
- **Eccentricity grows (AS 2010)**

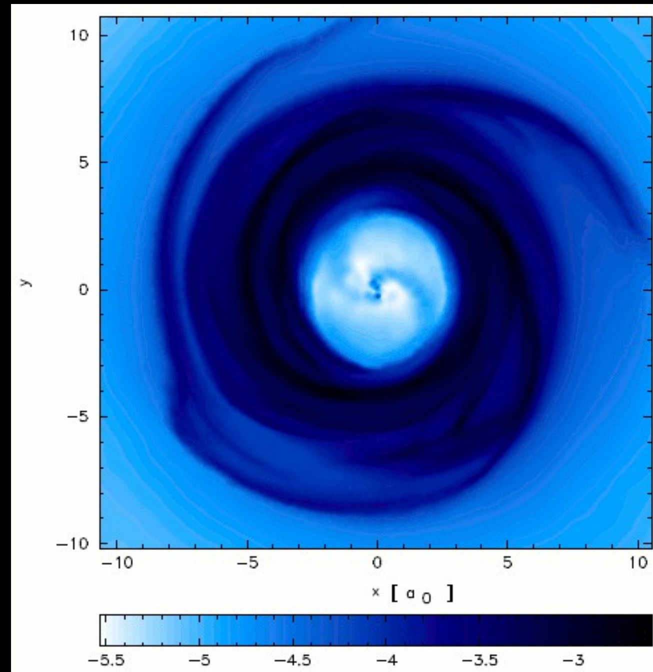
Preto et al. 2011

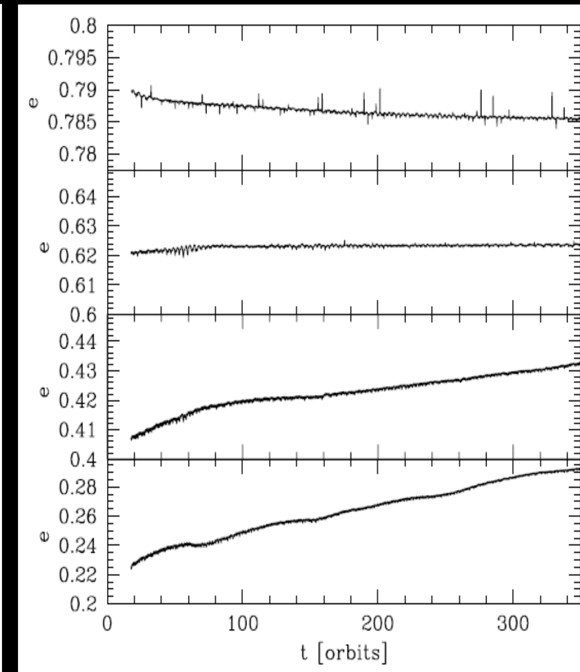




Binary evolution in gas rich environments





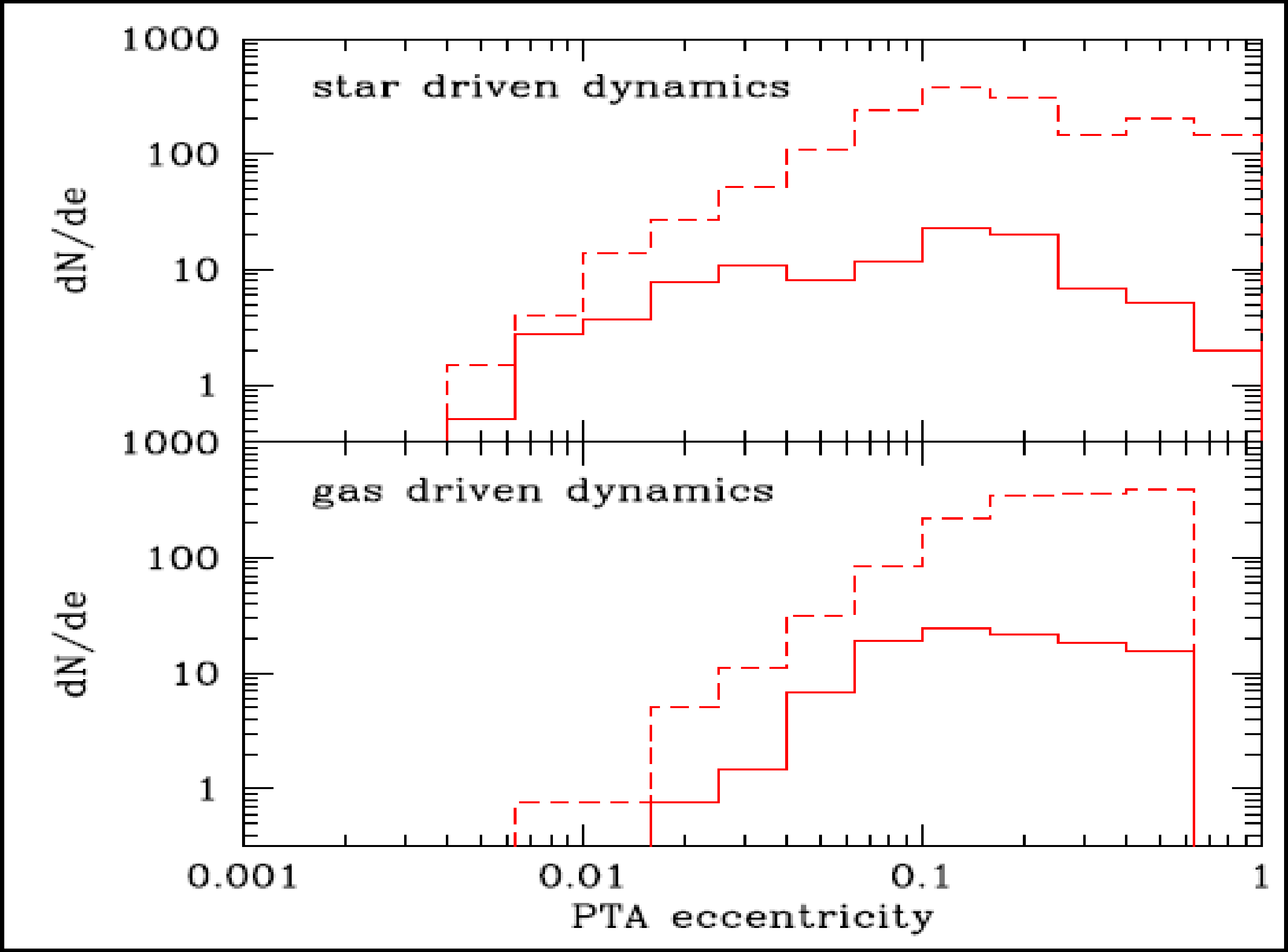


Simulation of binary hardening in a circumbinary massive disk (Escala et al. 2005, Dotti et al 2006, 2007) show that the *binary shrinks to the simulation resolution limit* without any apparent stalling problem.

When $M_{disk} \sim M_2$ a *gap opens* in the gas distribution.

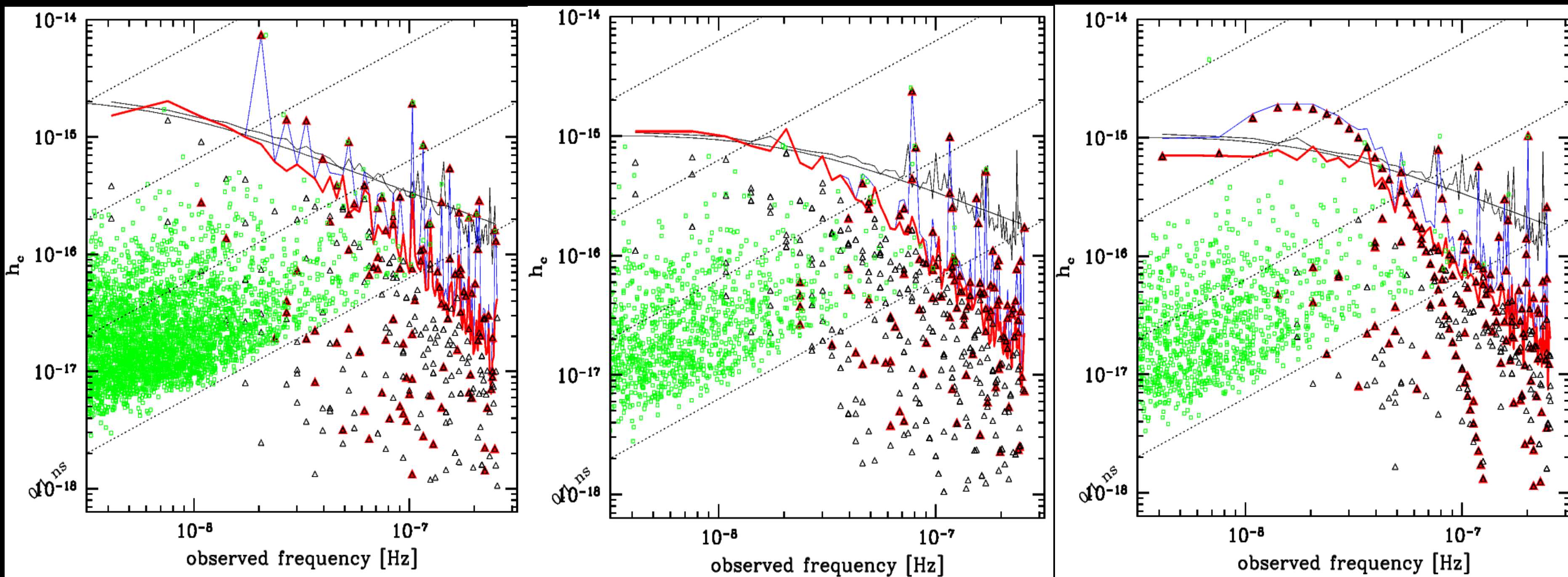
- The binary migrates inward due to the effect of the disk torque (Cuadra 2009, Hayasaki 2009)
- Migration difficult to resolve
- Eccentricity seems to grow to a limit of the order 0.6-0.8 (Roedig et al. 2011)
- Periodic accretion (Hayasaki 2007, AS et al. 2011)

Eccentricity distributions in the PTA band



GW sources are *in general eccentric* (Roedig & AS 2012)
-Eccentricity can be an important factor in the PTA band....BUT...it's pretty much stochastic and very sensitive to many factors.

Gas driven binaries

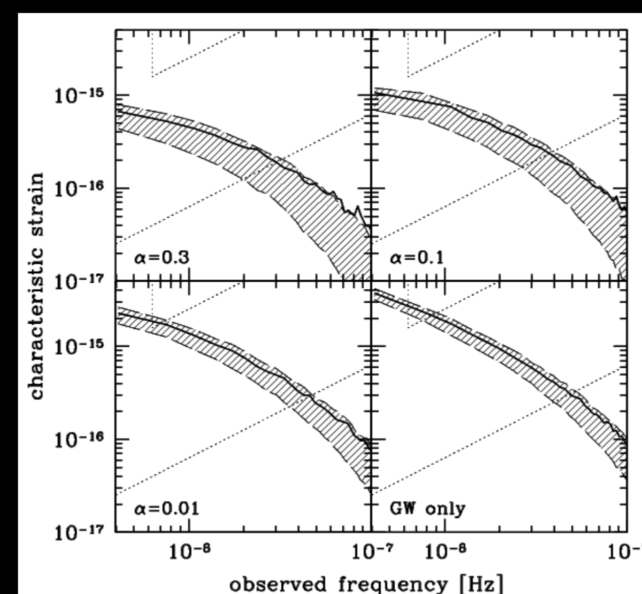


Critical physics:

-accretion disk nature (alpha disk vs beta disk)

-accretion rate and on viscosity

-eccentricity excitation

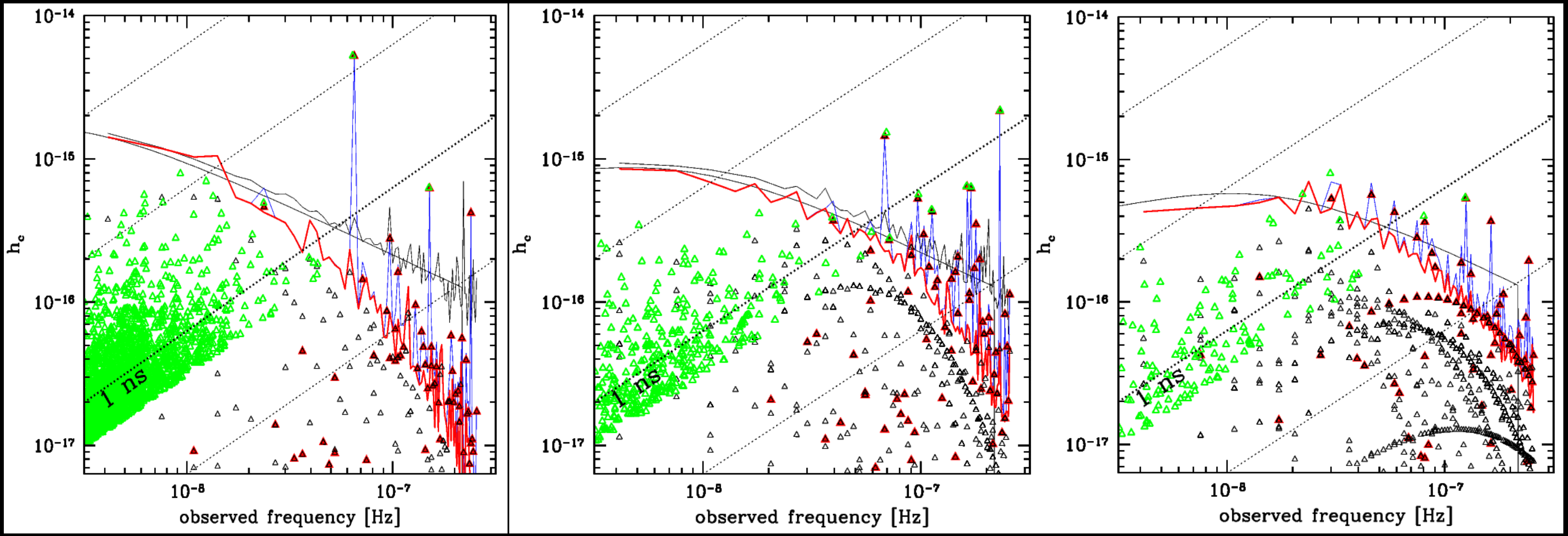


Effects:

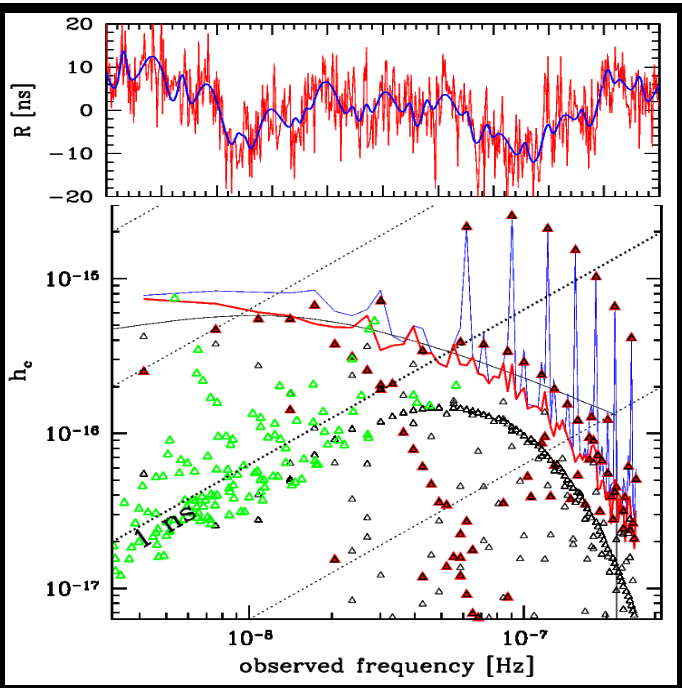
-less sources: lower signal, sparser, flatter

We don't have a good handle of any of this,
but *likely small effect*

Stellar driven binaries



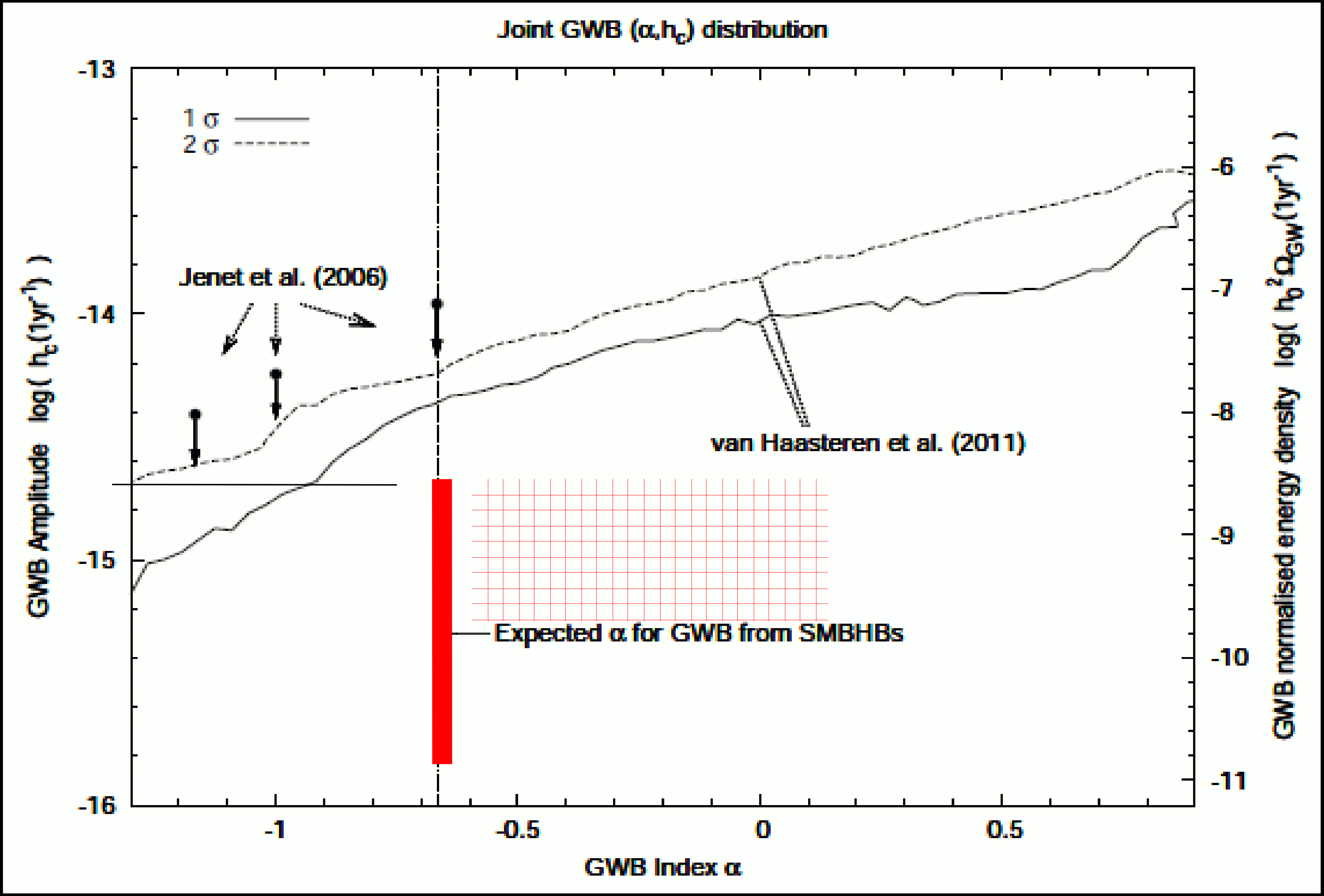
Critical physics:
-initial eccentricity at pairing
-efficiency of loss cone refilling
-rotation



Effects:
-lower signal, sparser, flatter
-likely many eccentric sources (broad bursts?)

We don't have a good handle of any of this,
but I suspect *substantial effects*

What do current limits tell us?



In summary:

1-The GW signal from MBHB is an *incoherent superposition* of a large number of signals but it is likely *dominated* at each frequency *by few sources* (See Vikram talk).

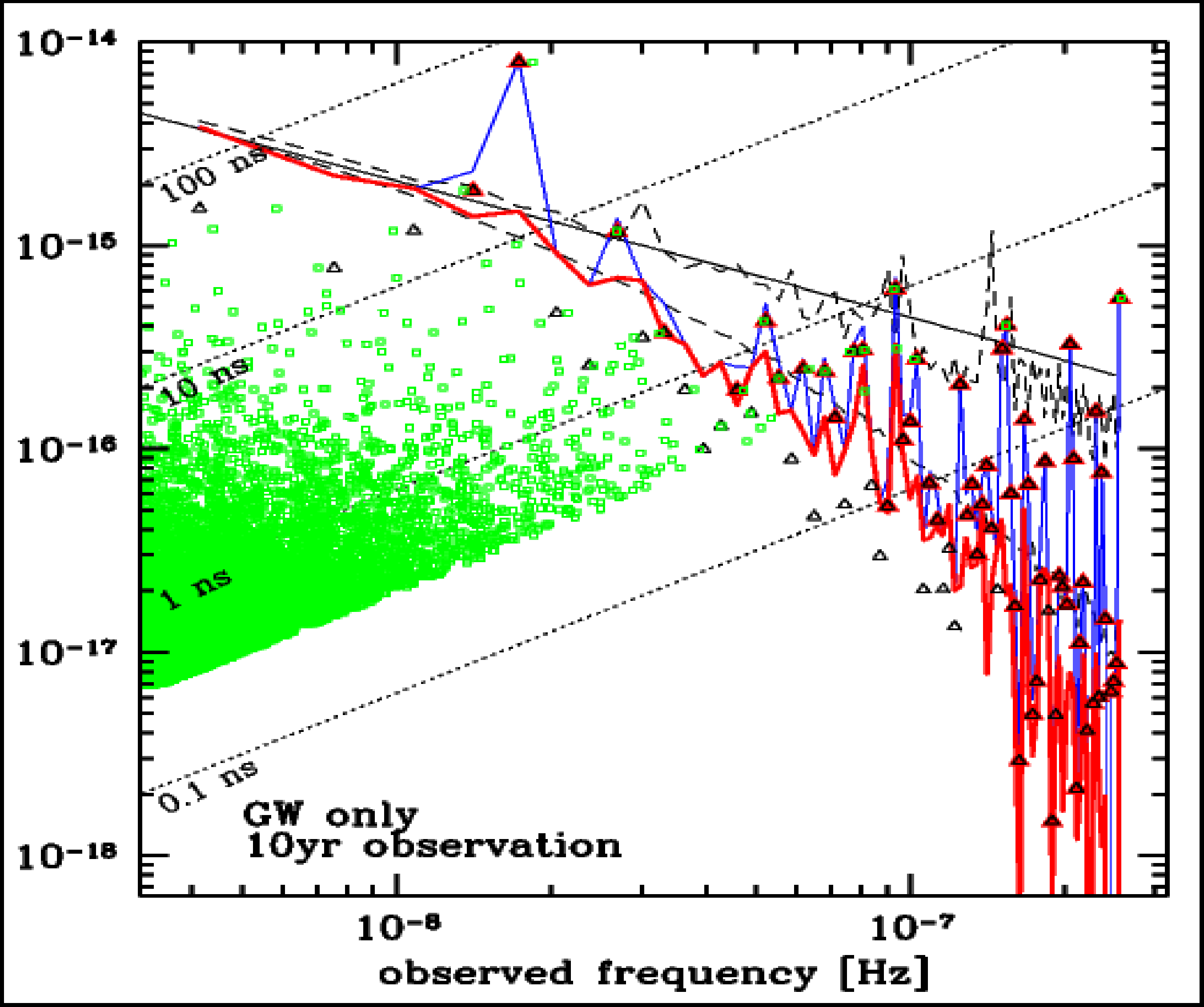
2-The signal level depends on the *MBH merger rate* and on the *MBH-host relations*.
GW limits are becoming interesting in discarding 'extreme' scenarios.
Estimation of the signal level from OBSERVED merger rates.

3-The signal shape, level and nature can be *SEVERELY affected by the dynamical processes* driving the binary:
- -Shallower slope
- -Eccentric binaries
- -Earth-Pulsar term connection

4-What we will detect first? GW 'background'? Individual source?

5-What is the optimal detection technique? (bunch of individual sources vs background)

Up to date only pipelines for individual sources or stochastic background, but the actual signal might be better represented by something in between, maybe there is some more optimal technique.



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