Observing the Universe with a Galactic scale detector: astrophysics of massive black holes with pulsar timing arrays

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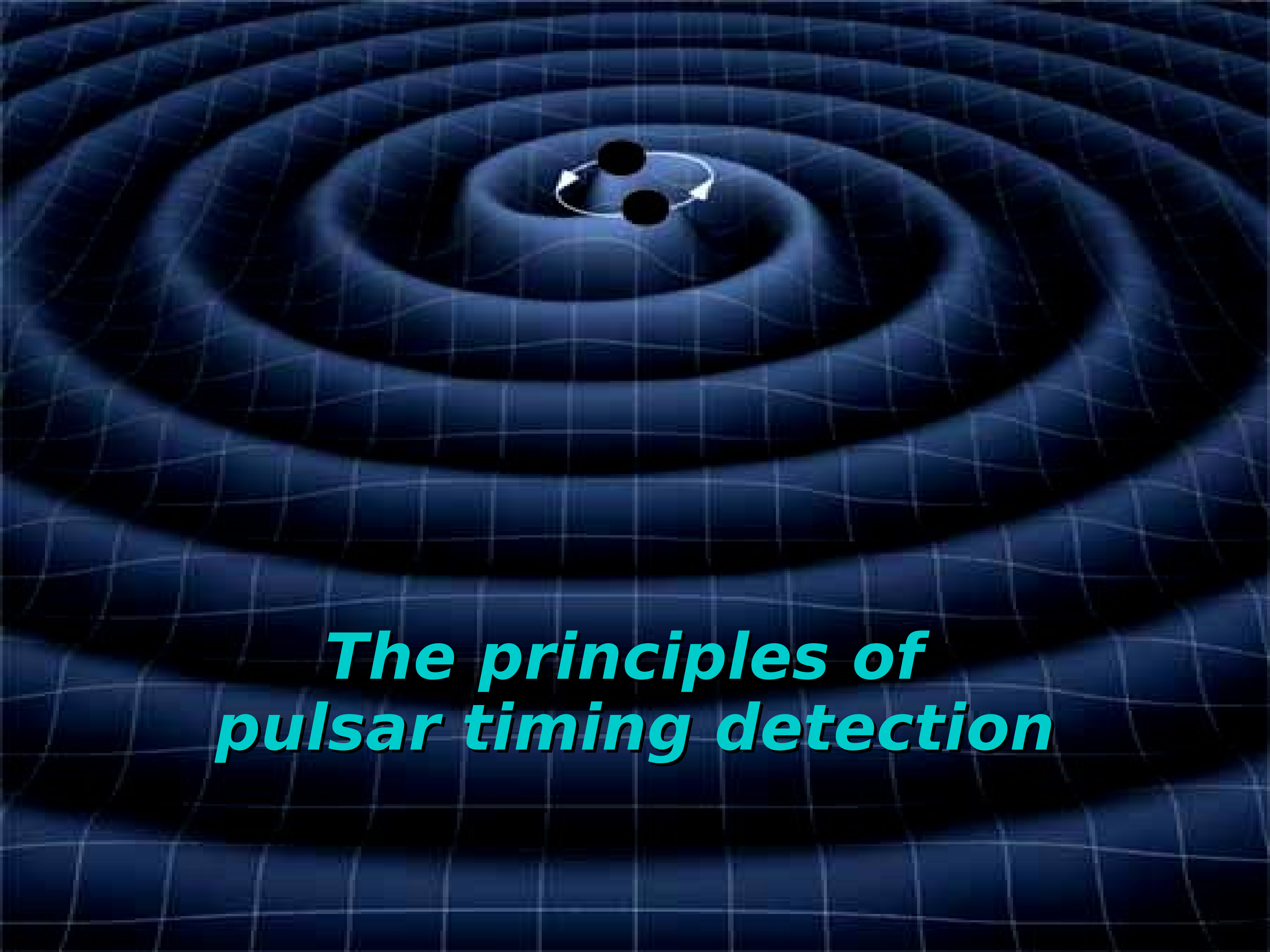
OUTLINE

> Gravitational wave detection with pulsar timing arrays: how does it work?

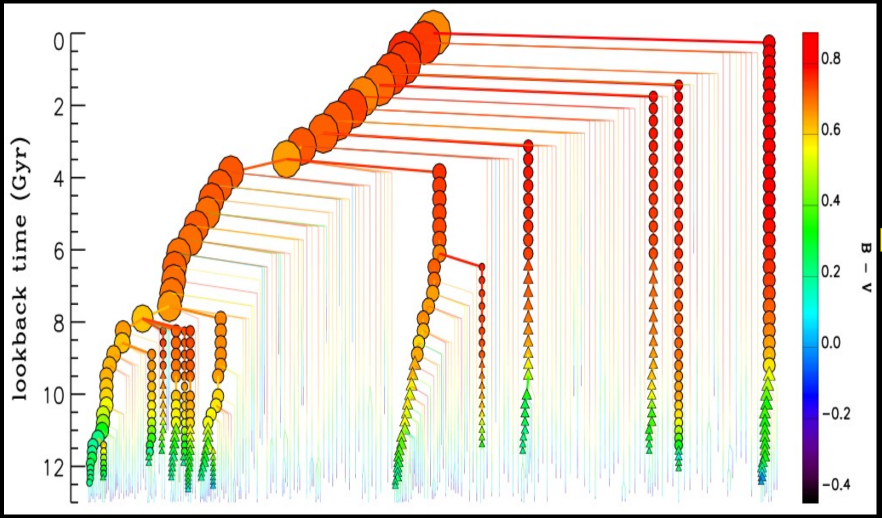
> Signal characterization: unresolved background and resolvable sources: what shapes the signal? What can be learned by observations

> Individual source detection: parameter estimation and search for electromagnetic counterparts

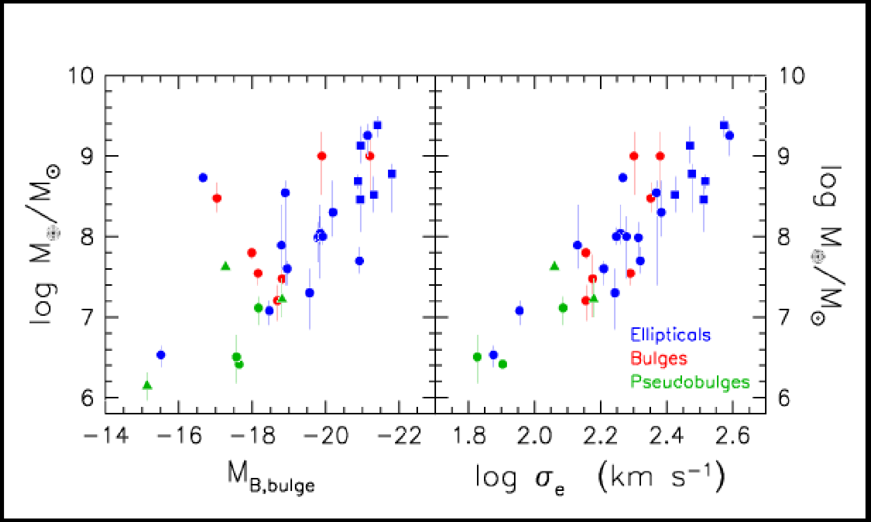


The principles of pulsar timing detection

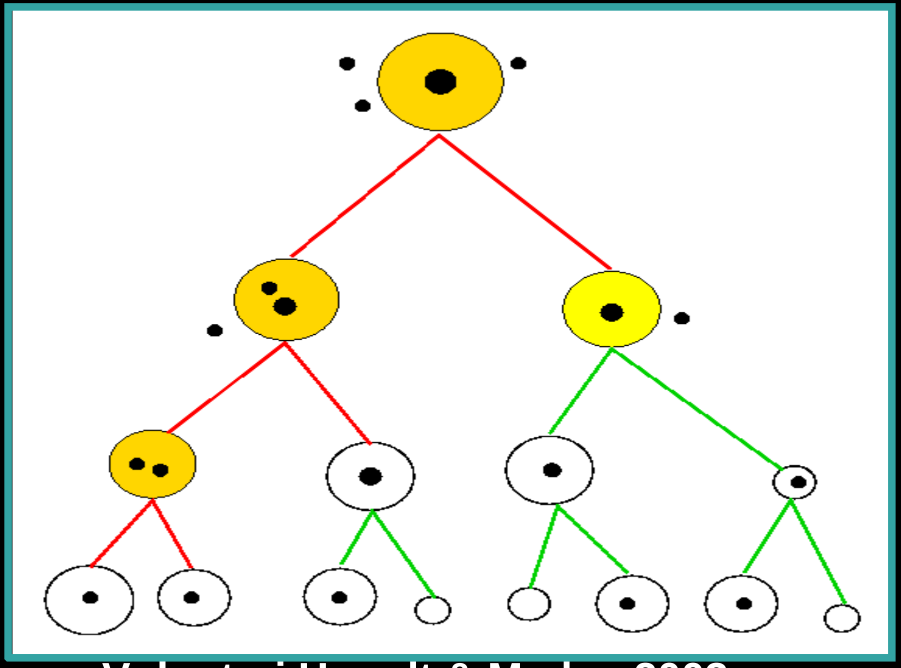
Structure formation in a nutshell



From De Lucia et al 2006

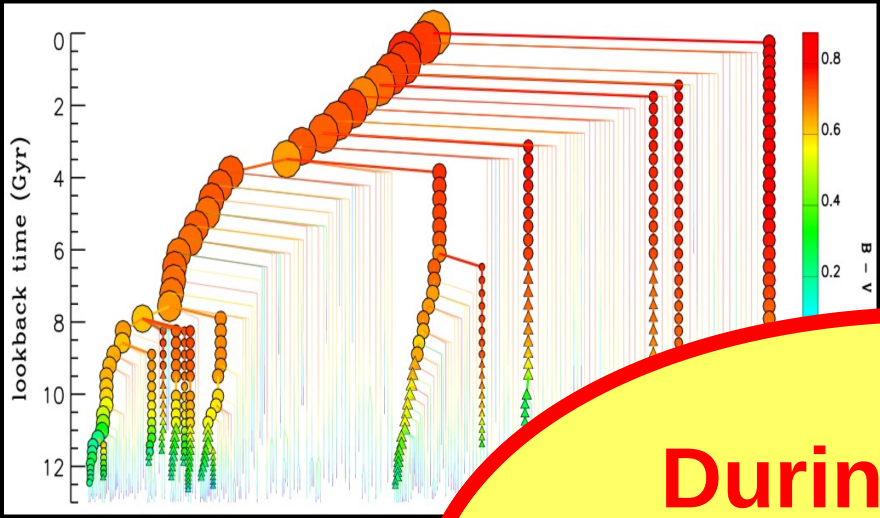


Ferrarese & Merritt 2000, Gebhardt et al. 2000



Volonteri Haardt & Madau 2003

Structure formation in a nutshell



From De Lucia et al 2

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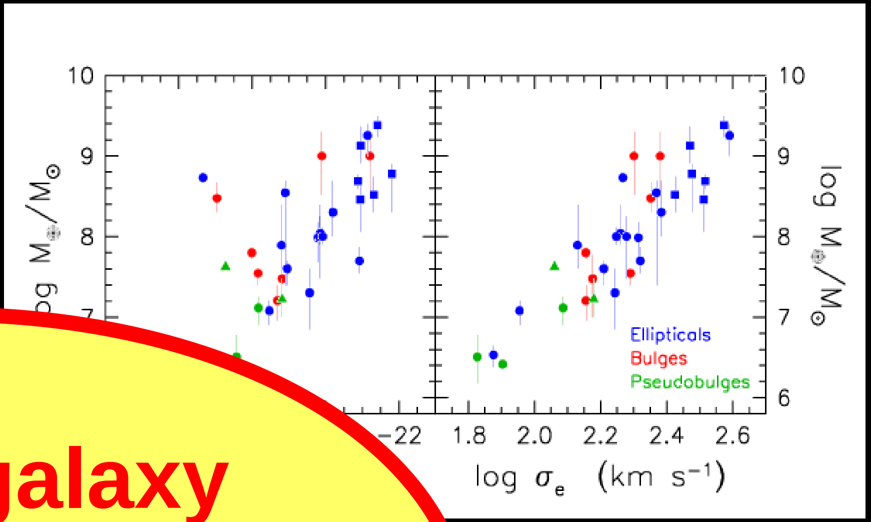

Gebhardt et al. 2000

During galaxy mergers, MBHBs will Inevitably form!

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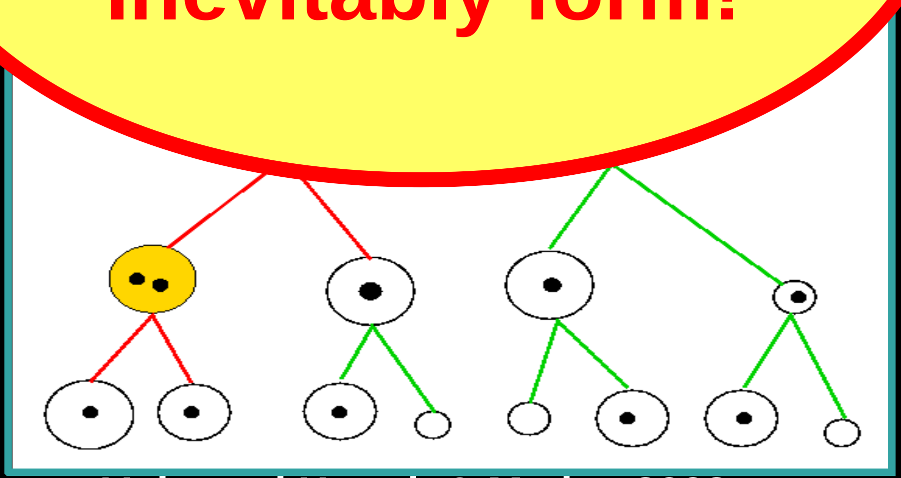


Volonteri Haardt & Madau 2003

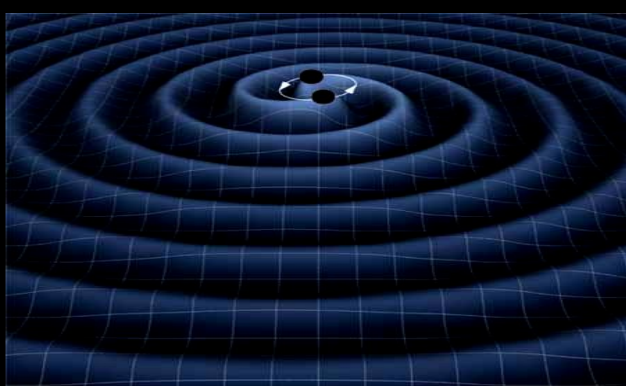
Directly from general relativity

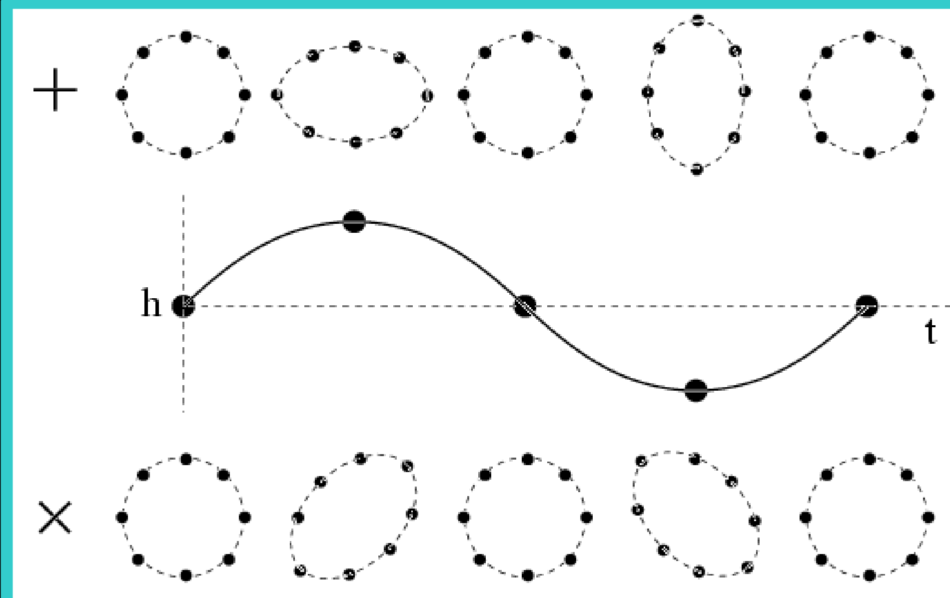
Every accelerating mass distribution with non-zero quadrupole momentum emits GWs!

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

Perturbed Minkowski metric tensor :

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

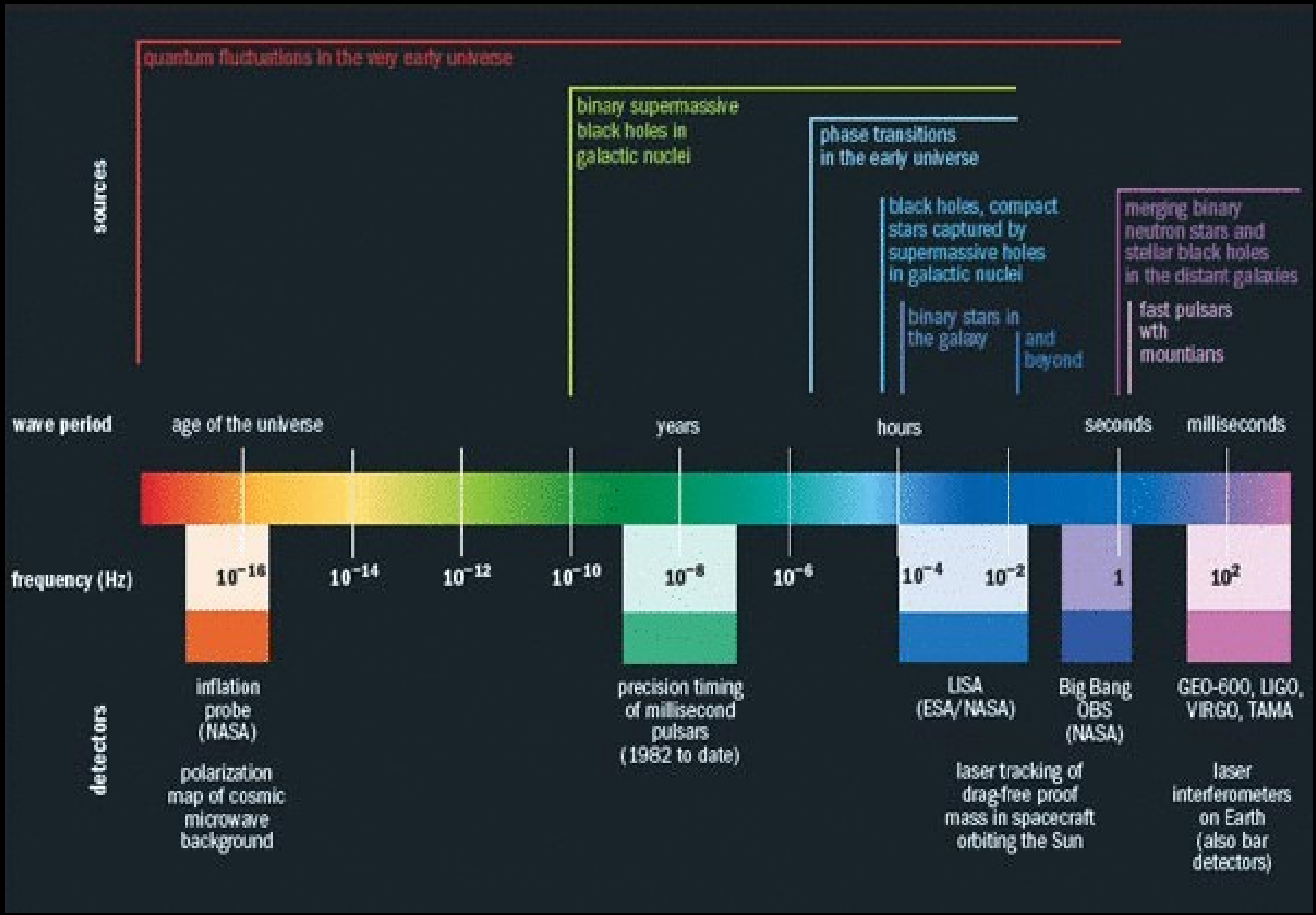




Perturbation perpendicular to the wave propagation direction

A MBHB is a perfect candidate for GW emission!

The gravitational wave spectrum

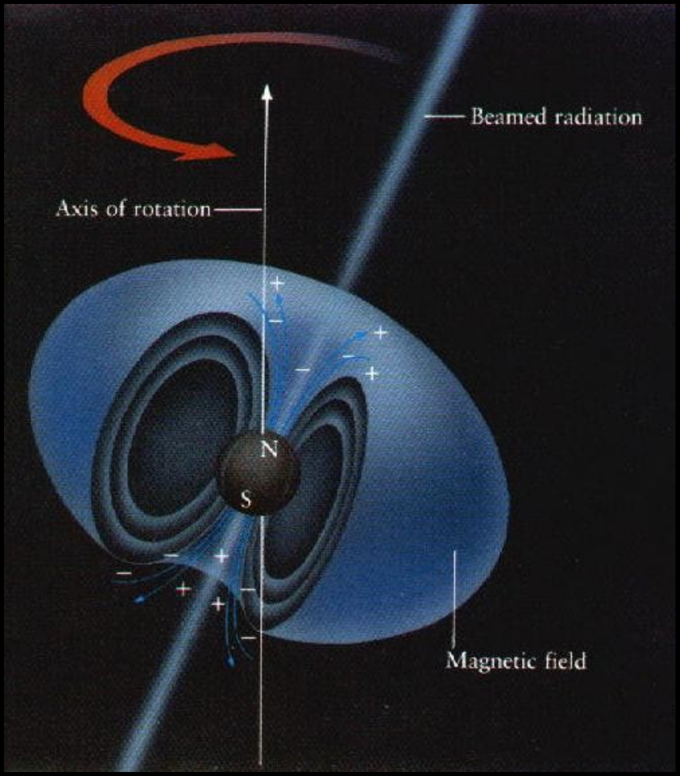


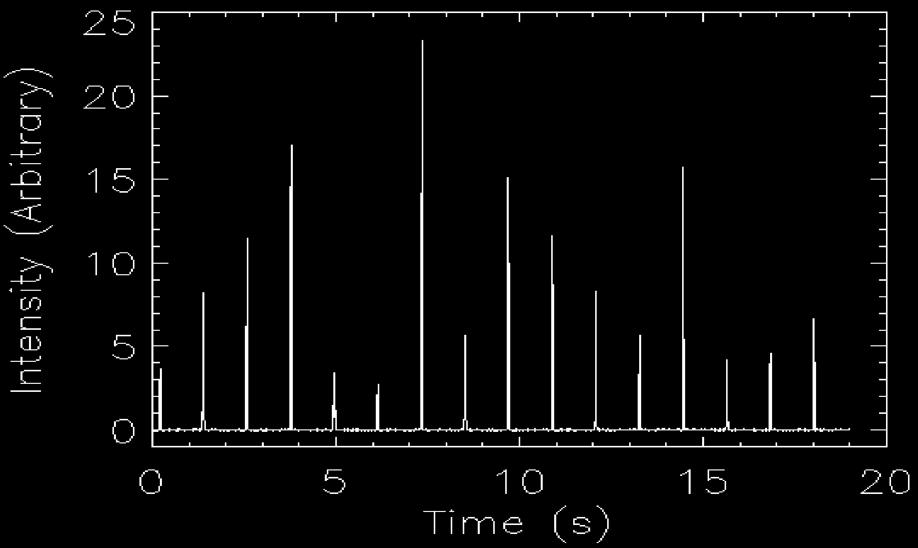
What is pulsar timing?

Pulsars are neutron stars that emit regular burst of radio radiation

Pulsar timing is the process of measuring the time of arrival (TOA) of each individual pulse and then subtracting off the expected time of arrival given a physical model for the system.

1- Observe a pulsar and measure the TOA of each pulse





2-Determine the model which best fits the TOA data

$$t_{\mathrm{e}}^{\mathrm{psr}} = t_{\mathrm{a}}^{\mathrm{obs}} - \Delta_{\odot} - \Delta_{\mathrm{IS}} - \Delta_{\mathrm{B}}.$$

The emission time at the pulsar is converted to the observed time at the Earth modelling several time delays due to:

- -coordinate transformations
- -GR effects (e.g. Shapiro delay, PN binary dynamics)
- -Propagation uncertainties (e.g. Atmospheric delay, ISM dispersion)

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3-Calculate the timing residual *R*

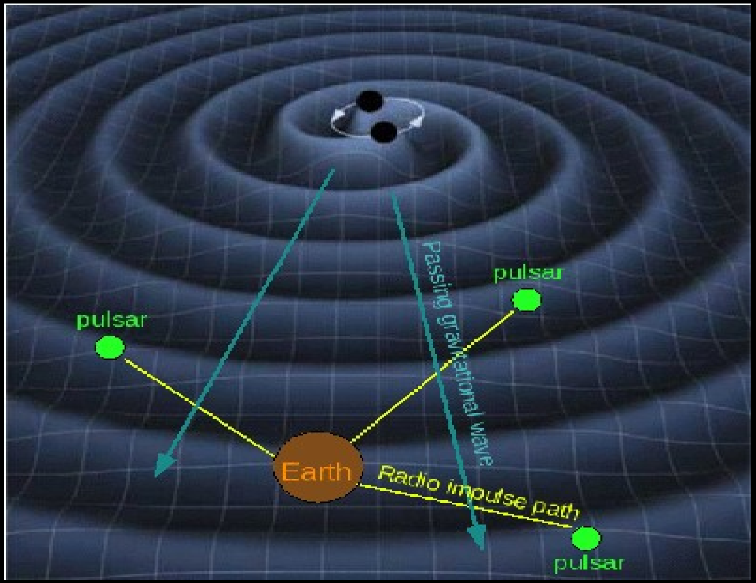
$$R = \mathrm{TOA} - \mathrm{TOA}_{\mathrm{m}}$$

If your model is perfect, then R=0. R contains all the uncertainties related to the signal propagation and detection plus the effect of unmodelled physics, like -possibly- ***gravitational waves***

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

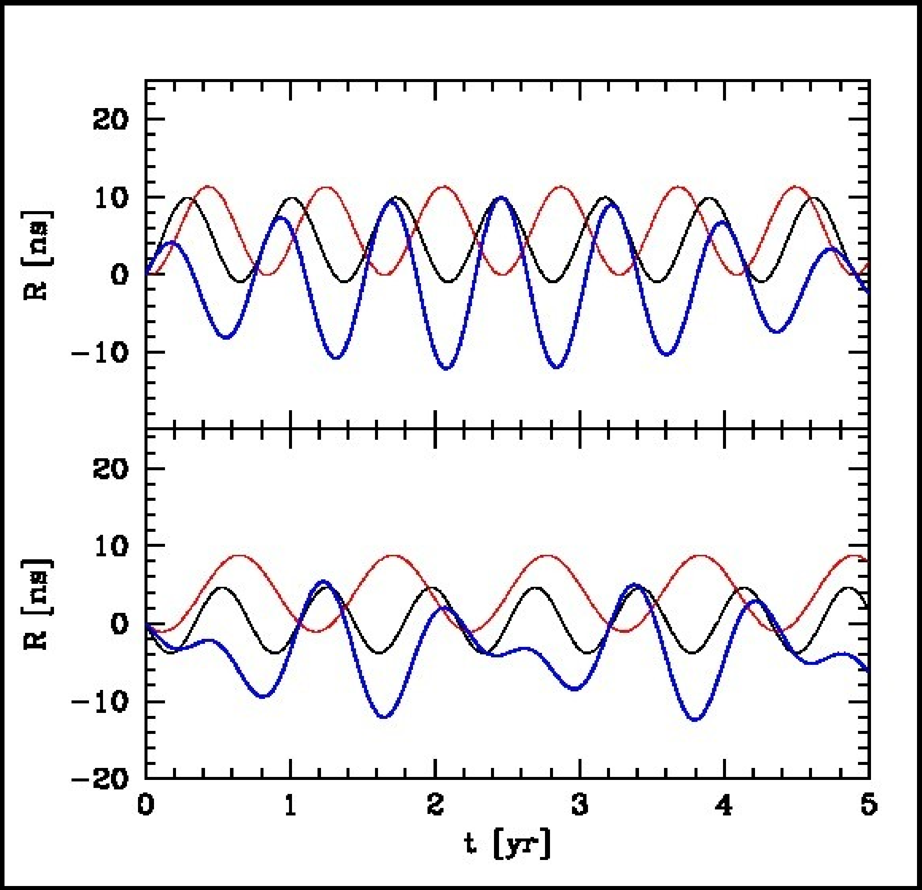
$$R(t) = \int_0^T \frac{\nu(t)-\nu_0}{\nu_0}\,dt$$

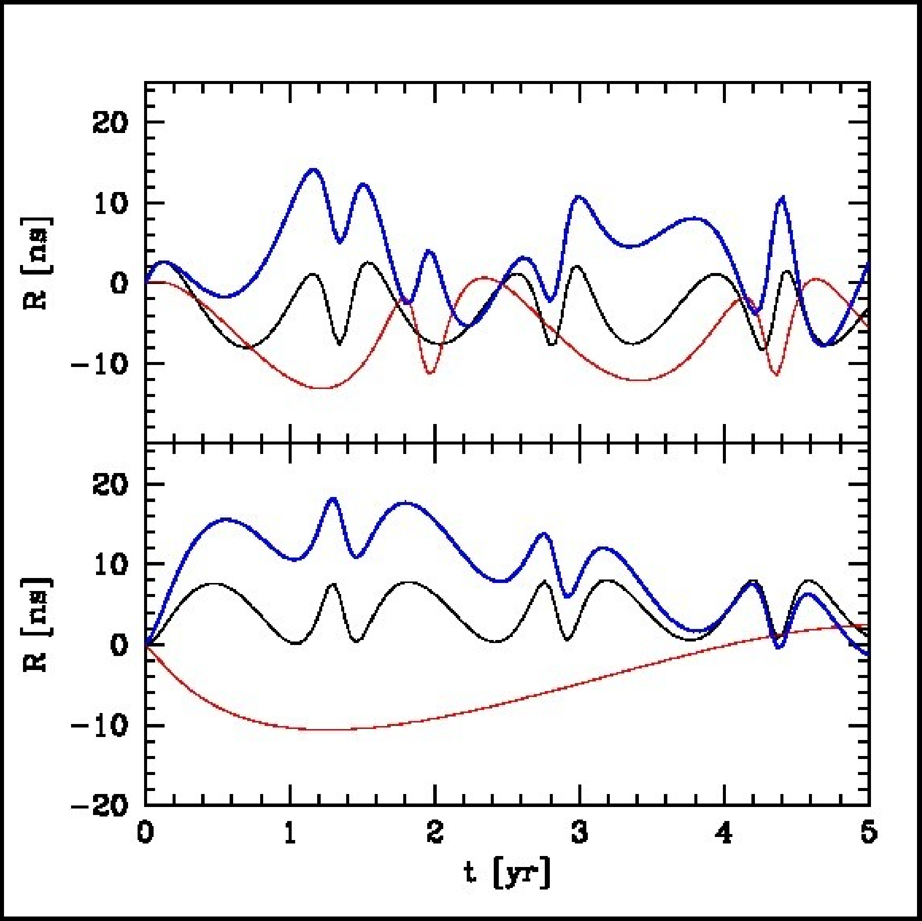
(Sazhin 1979, Helling & Downs 1983, Jenet et al. 2005, Sesana Vecchio & Volonteri 2009)

R~h/(2πf)

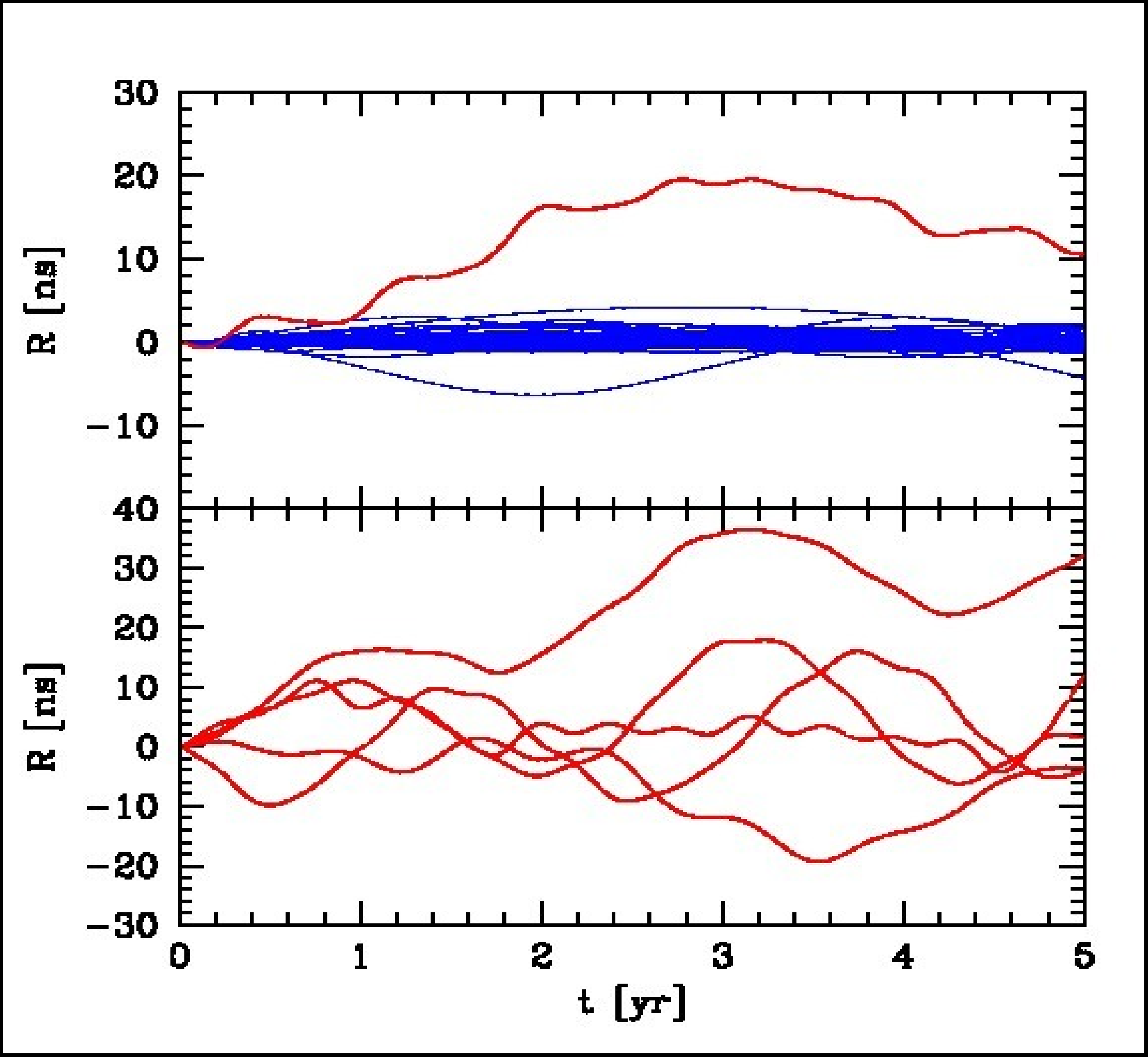
$$\begin{aligned} &= \frac{\mathcal{M}^{5/3}}{D}\,[\pi f(t)]^{-1/3} \\ &\simeq 25.7 \left(\frac{\mathcal{M}}{10^9\,M_\odot}\right)^{5/3} \left(\frac{D}{100\,\mathrm{Mpc}}\right)^{-1} \\ &\quad \times \left(\frac{f}{5\times 10^{-8}\,\mathrm{Hz}}\right)^{-1/3} \mathrm{ns} \end{aligned}$$

Examples of individual source signals





Global residuals from a population of MBHBs



Verbiest et al. 2009

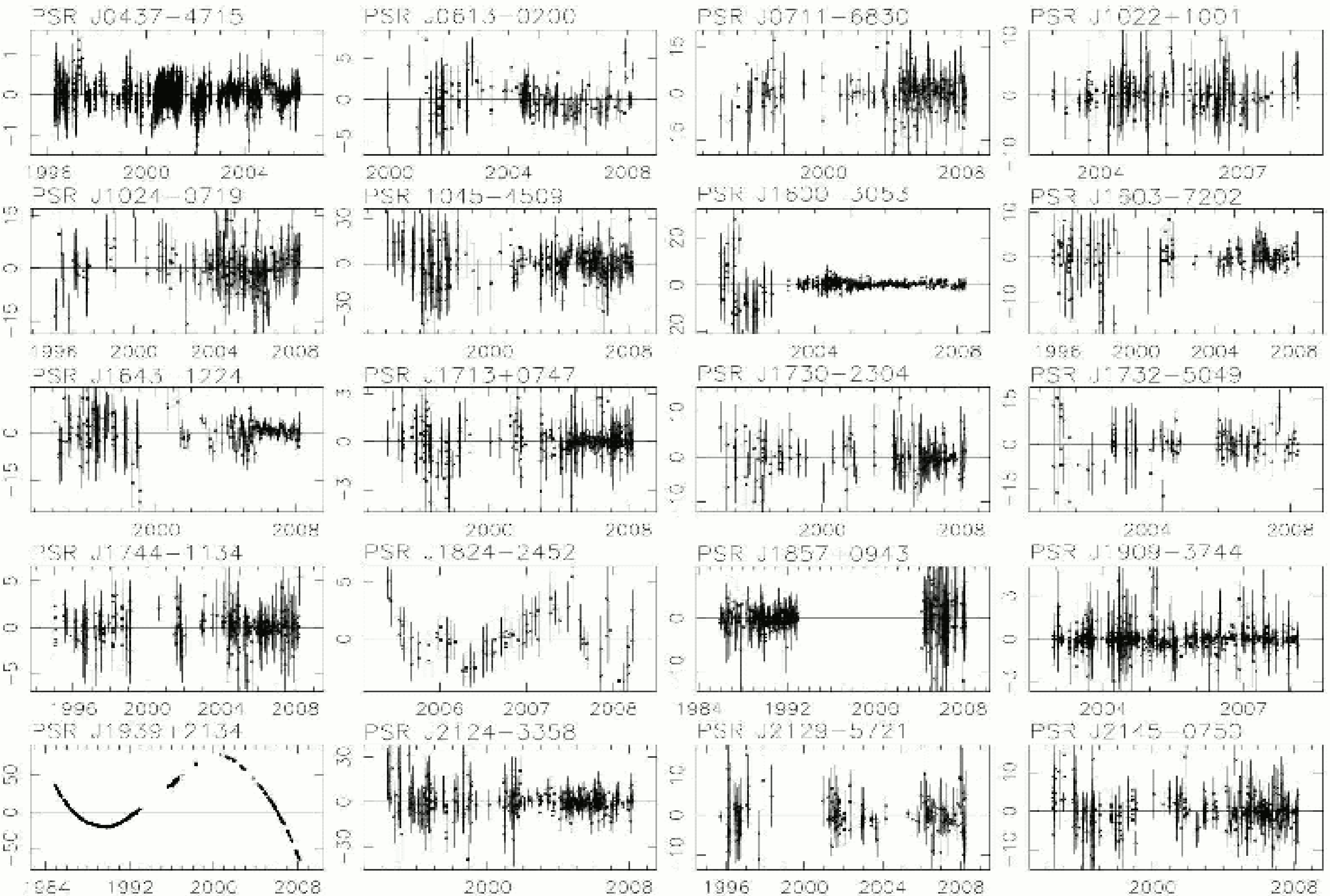


Figure 1. Timing residuals of the 20 pulsars in our sample. Scaling on the x-axis is in years and on the y-axis in μs. For PSRs J1857+0943 and J1939+2134, these plots include the Arecibo data made publically available by Kaspi et al. (1994); all other data are from the Parkes telescope, as described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

pulsar timing arrays

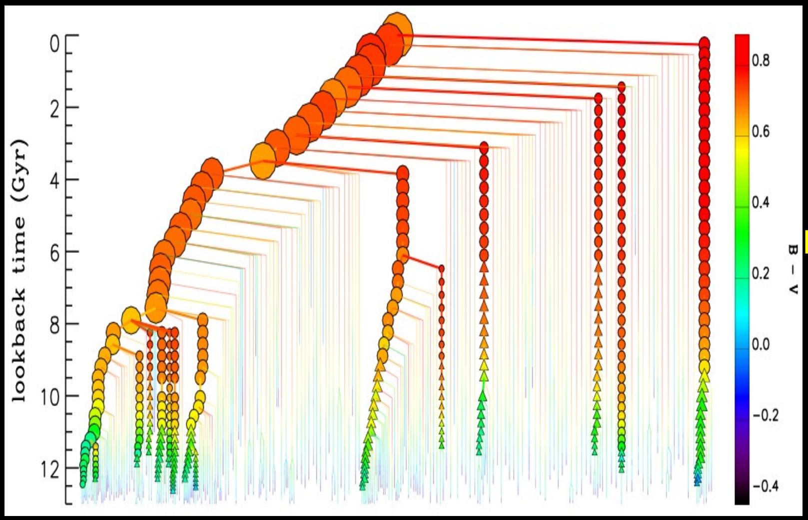
PPTA (Parkes pulsar timing array)

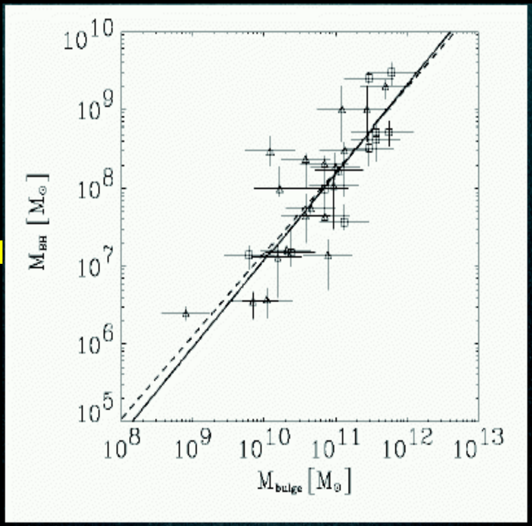
NanoGrav (north American nHz observatory for gravitational waves)

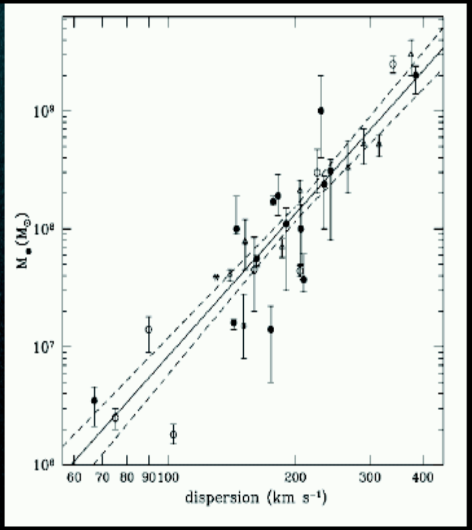
EPTA & LEAP
(large European array for pulsars)


What shapes the expected
signal? What can we learn?

Structure formation in a nutshell







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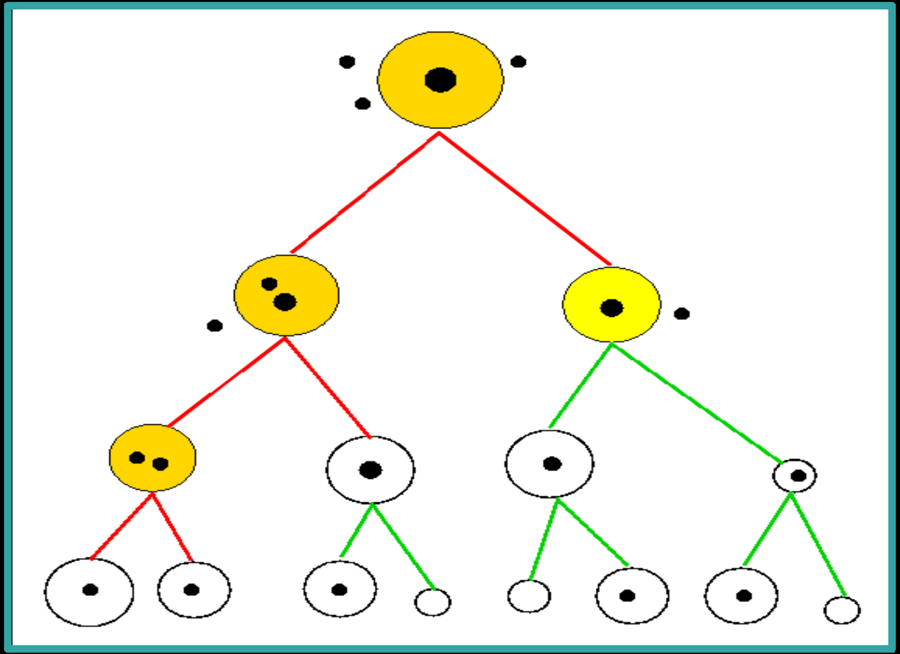


Volonteri Haardt & Madau 2003

GW signal from a MBHB population

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

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

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

For MBHBs *dN/d*ln*f*∝*f* $^{-8/3}$

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

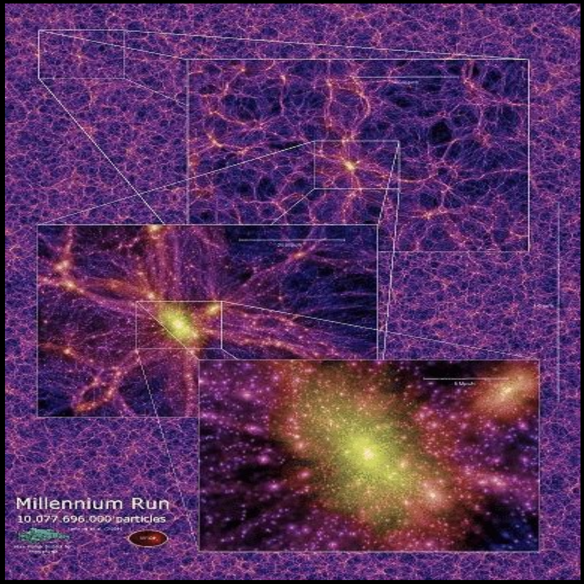
Phinney 2001, Jaffe & Backer 2003, Wyithe & Loeb 2003, AS et al. 2004, Enoki et al. 2004

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***



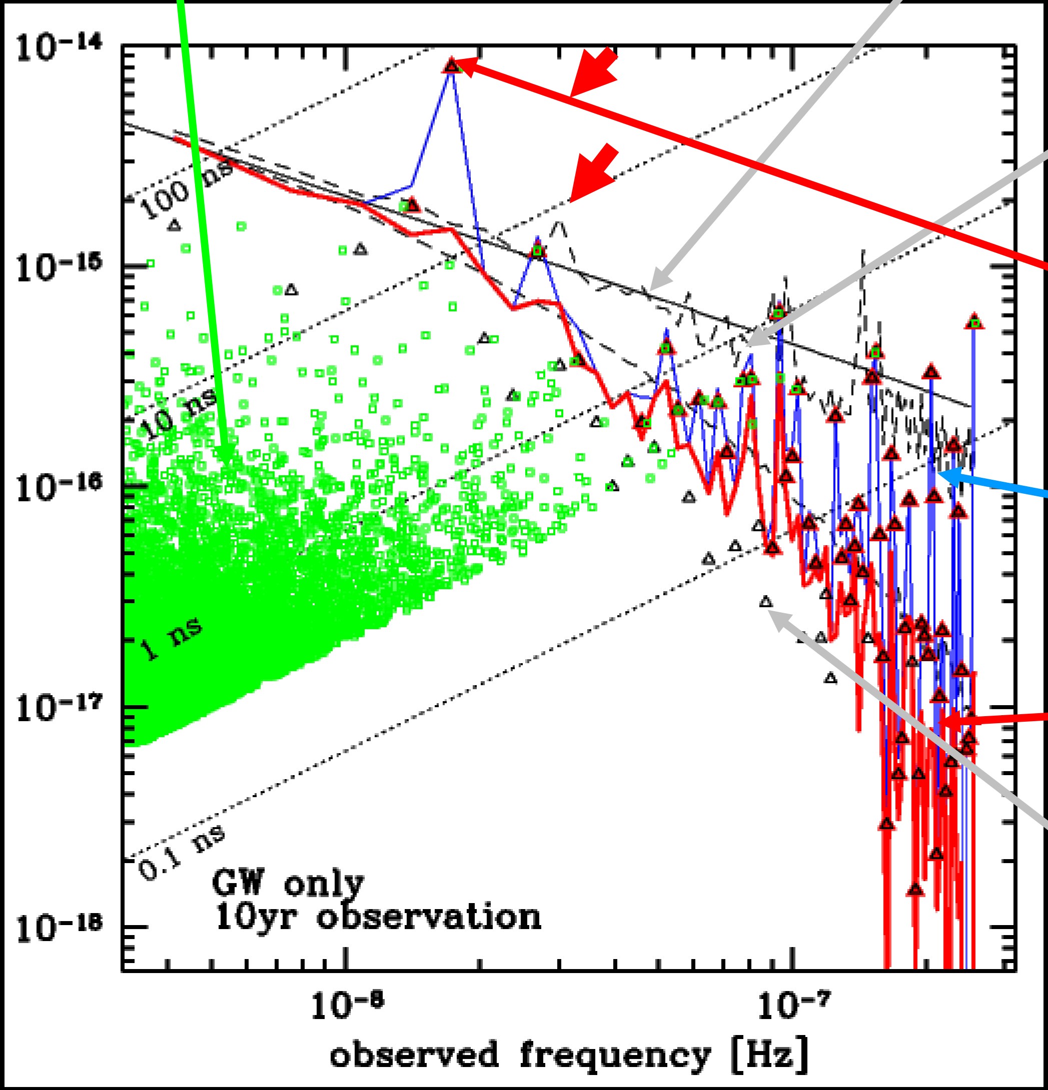
Typical signal

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*

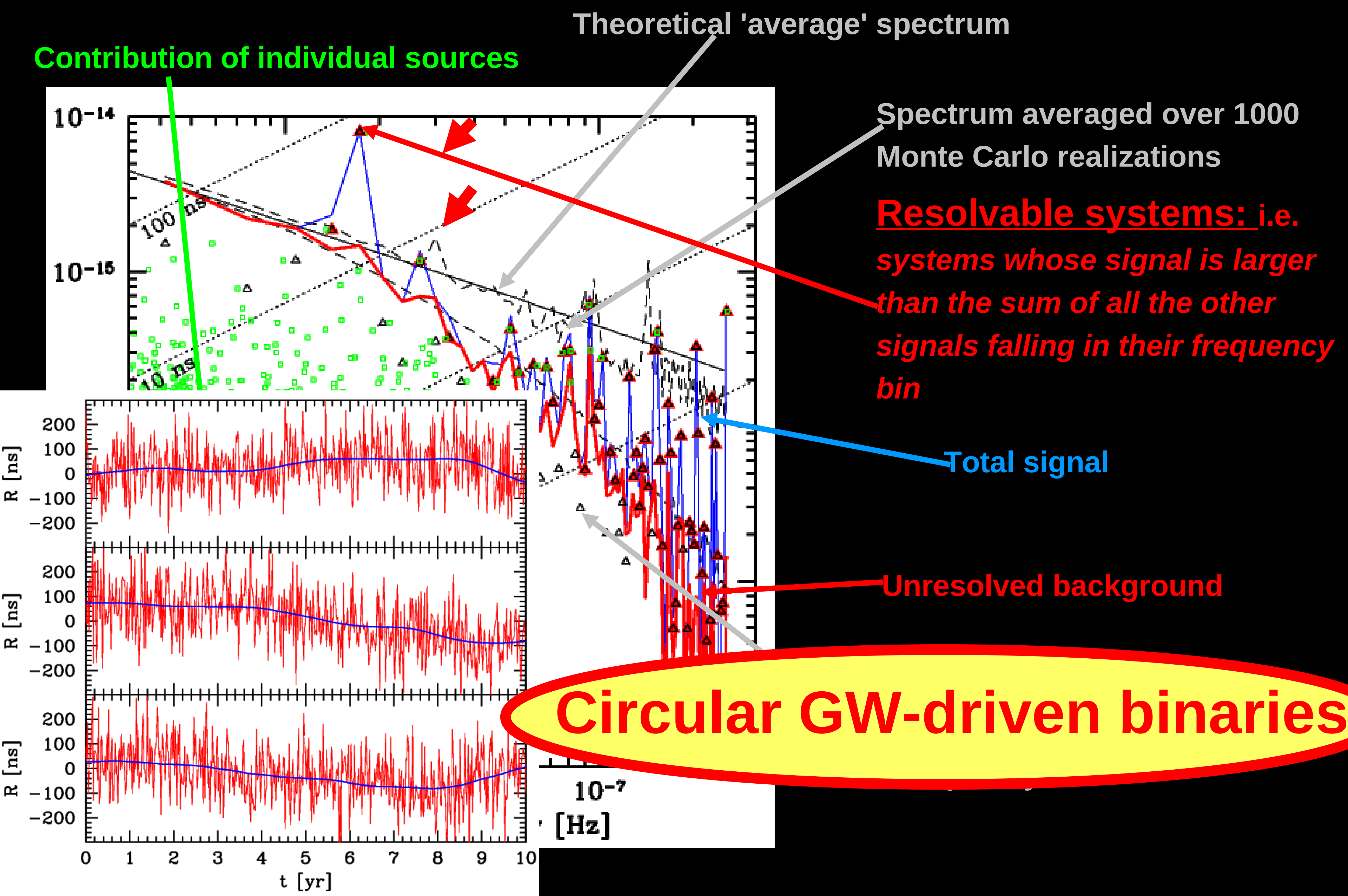


Total signal

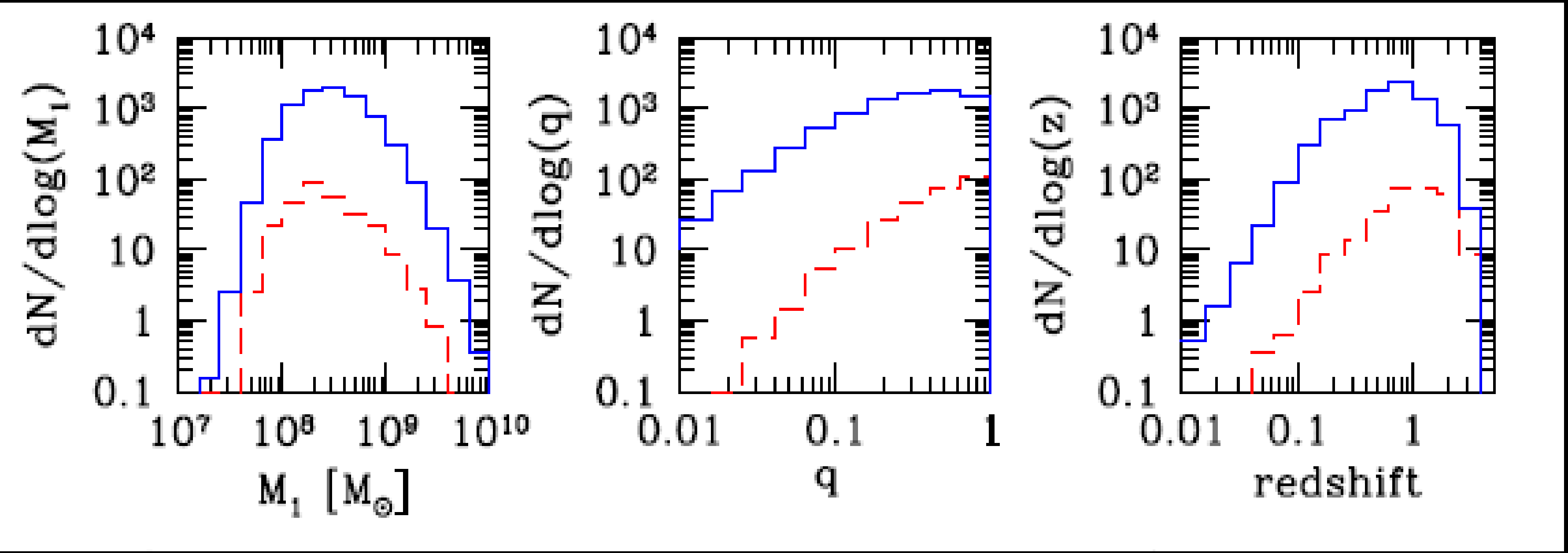
Unresolved background

Brightest sources in each frequency bin

Typical signal



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?

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

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

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

Galaxy merger rate

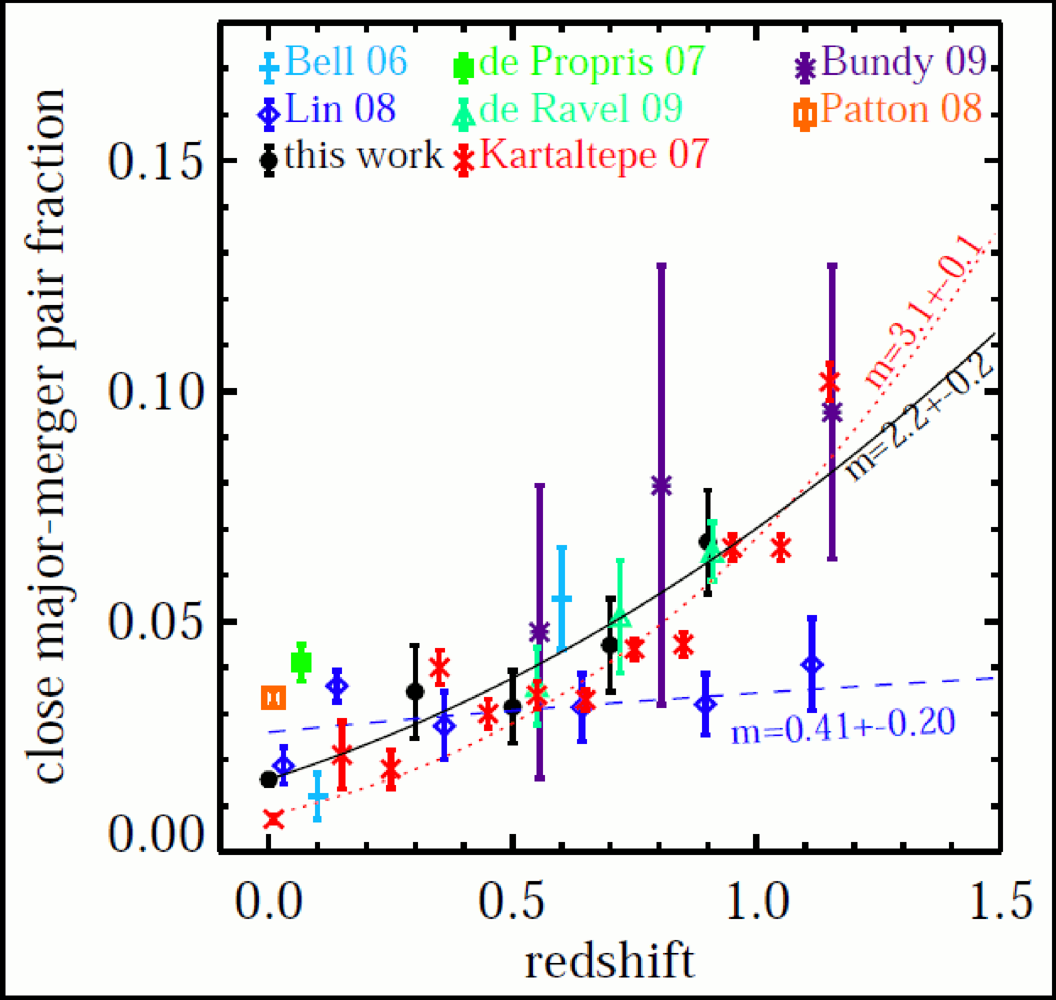
-The halo merger history is fixed both in merger trees and in the Millennium
-This can be compared with observed galaxy pairs but:
1-Huge uncertainties in the observations (bias, completeness)
2-Huge uncertainties in the merger timescale

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

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 $N^{1/2}$

Xu et al. 2012



MBHs-galaxy relation & accretion

Several proposed 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)

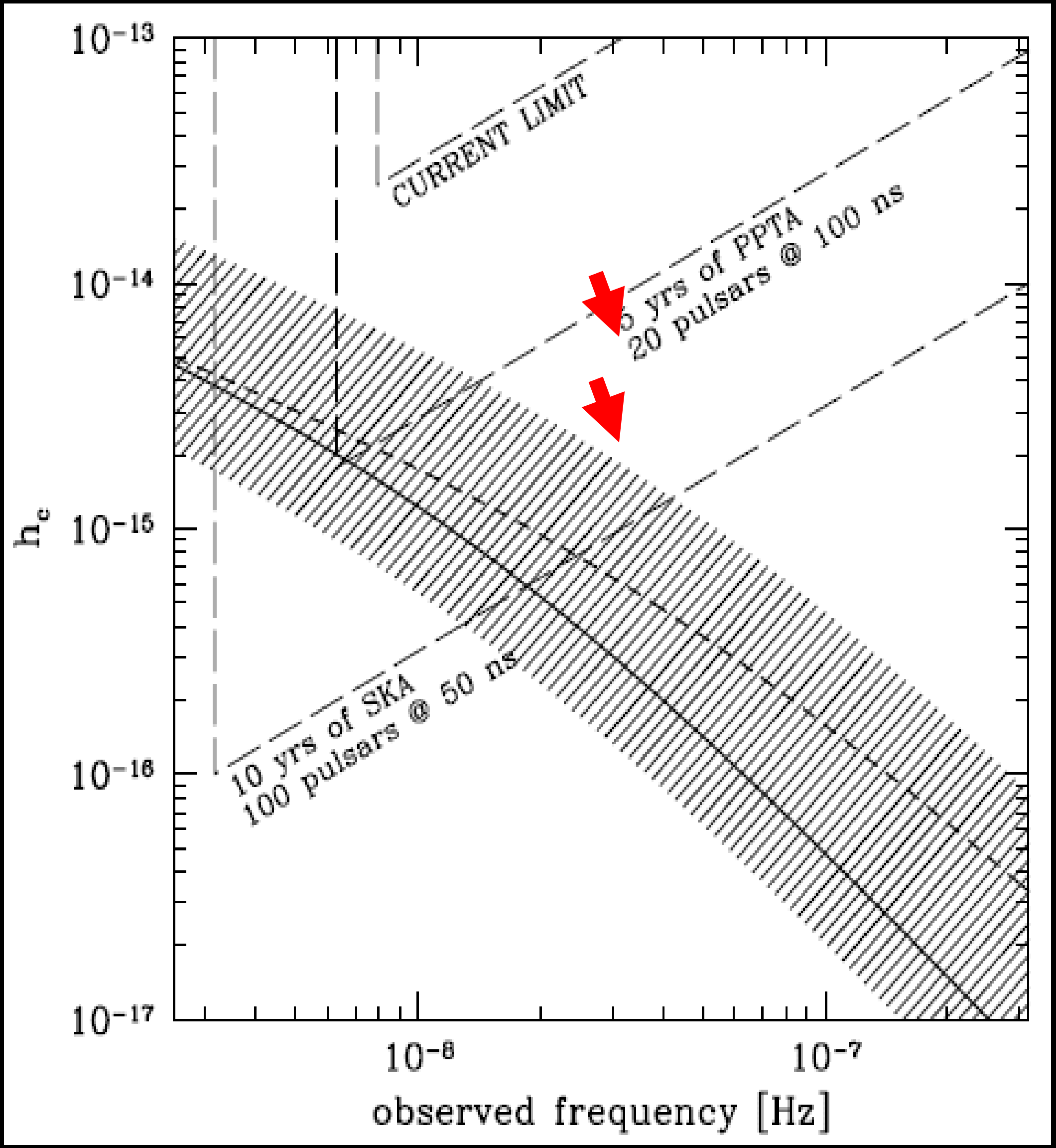
For any relation, several different possible accretion scenarios:

a- Accretion after merger

b- Accretion only onto M_1, before merger

c- Accretion on both MBHs before merger

Expected background level



AS Vecchio & Colacino 2008

Three parameter fit to the background

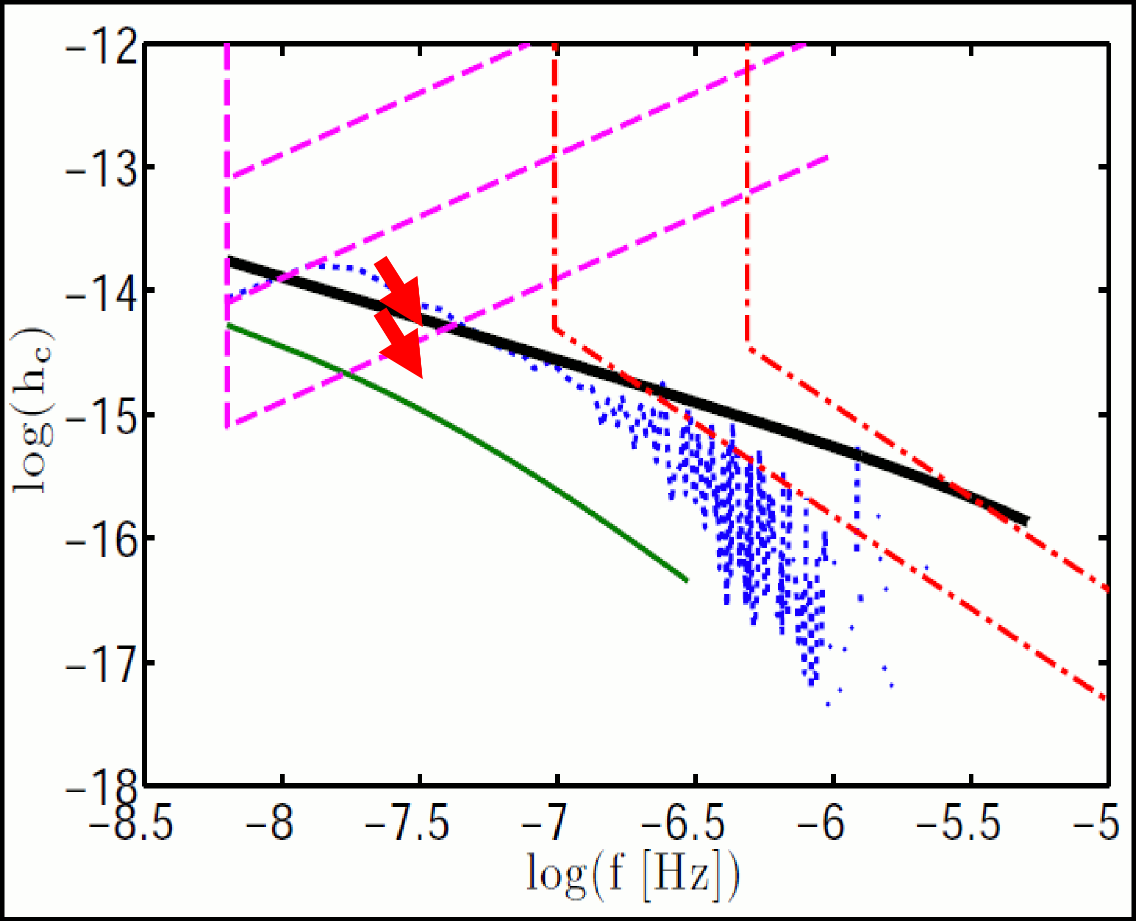
$$h_c(f) = h_0 \left(\frac{f}{f_0}\right)^{-2/3} \left(1 + \frac{f}{f_0}\right)^{\gamma}$$

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

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

First constrains on extreme models?

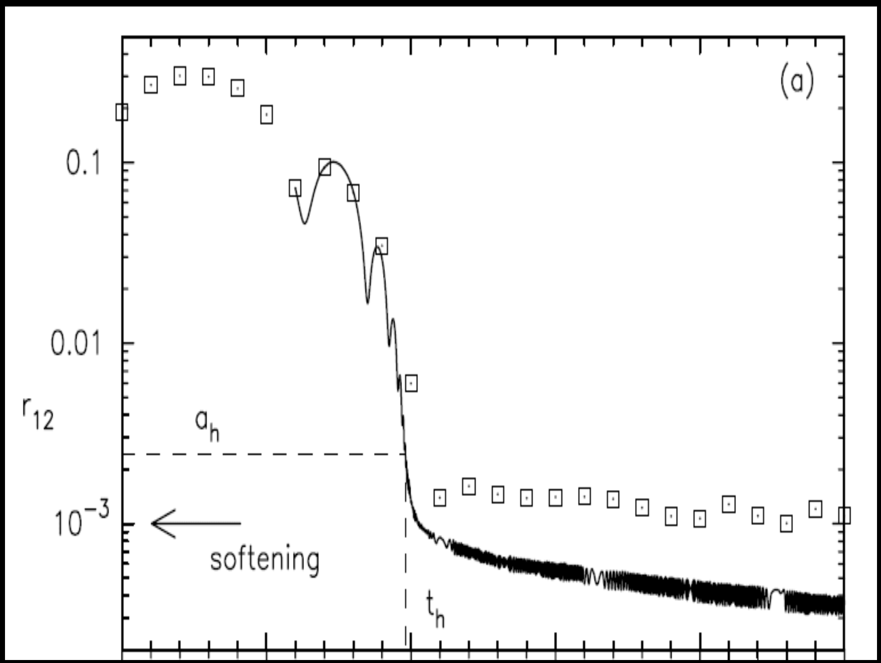
-Observations: SFRs of BCEs are too low to explain their mass build-up since z=1
-Come up with a model where all the mass is acquired through mergers
-Gives an 'upper limit' to the theoretical signal (depending on MBH--bulge relation adopted)



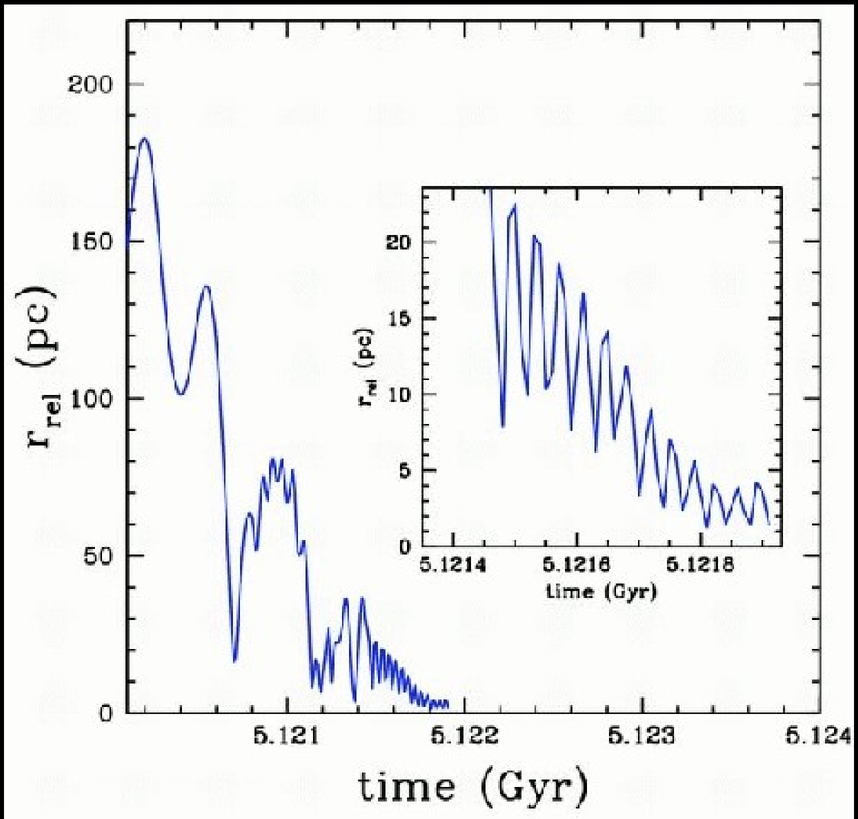
Borderline with NANOGrav and EPTA limits, may be ruled out already by upcoming PPTA limit!

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

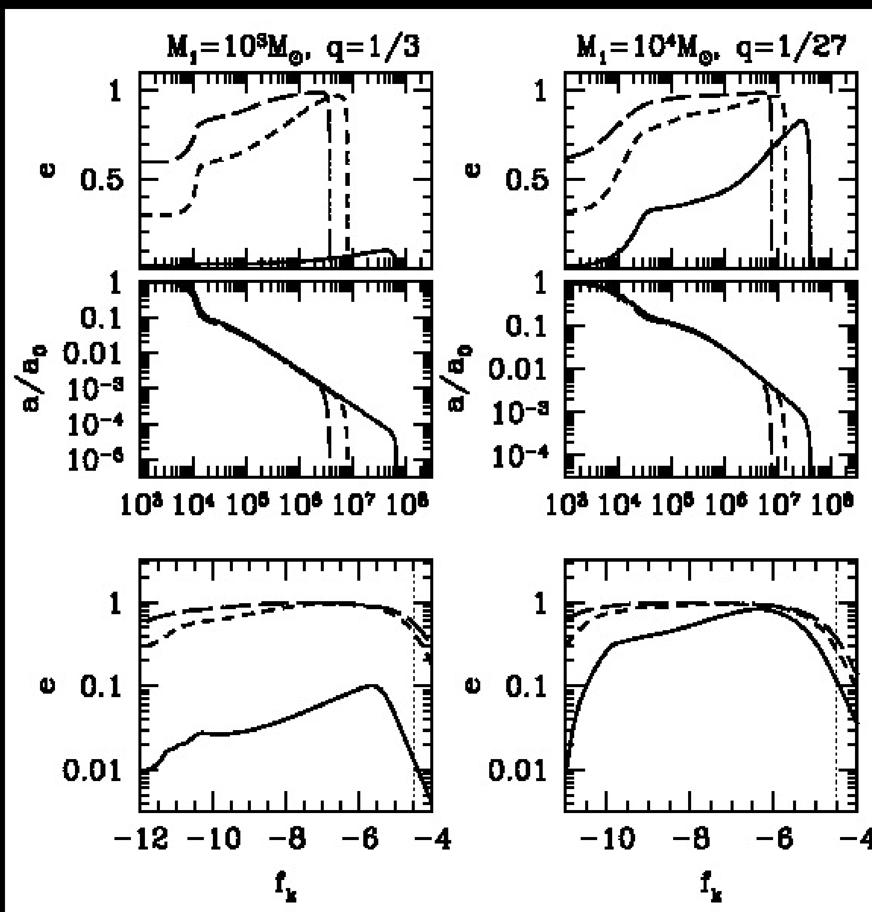
Dynamical friction is initially very efficient in shrinking the binary, but on parsec scales the mechanism is no longer efficient:

BINARY STALLING?

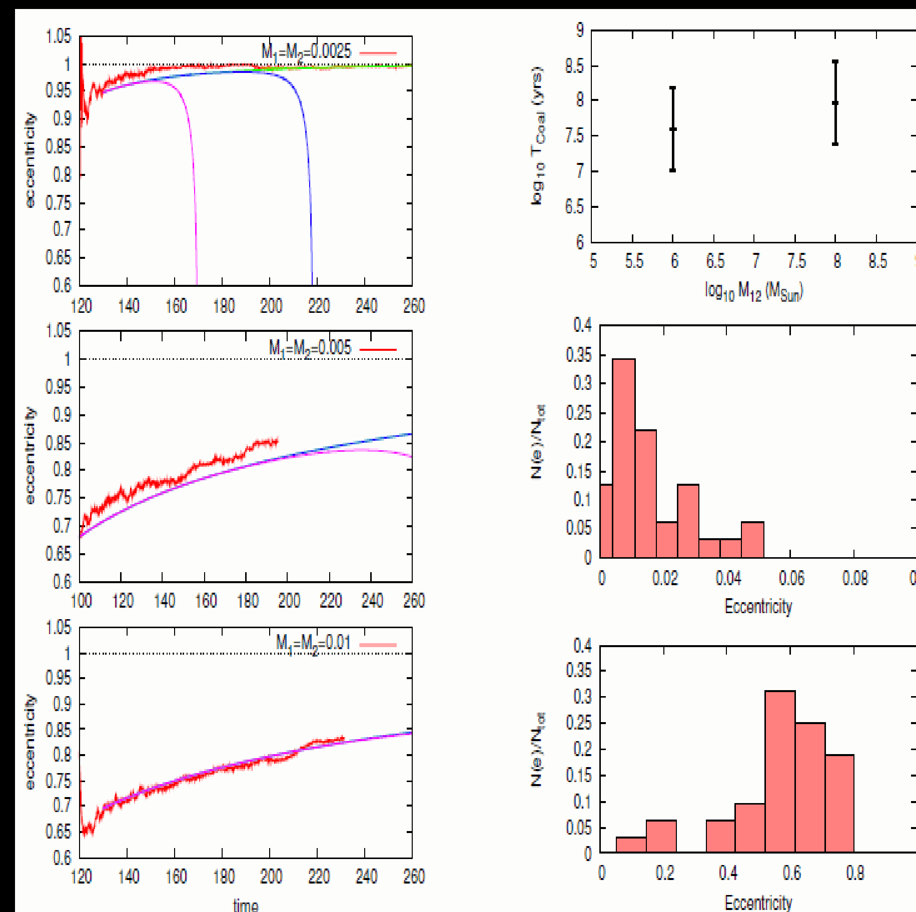
Binary evolution in stellar environments

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):**

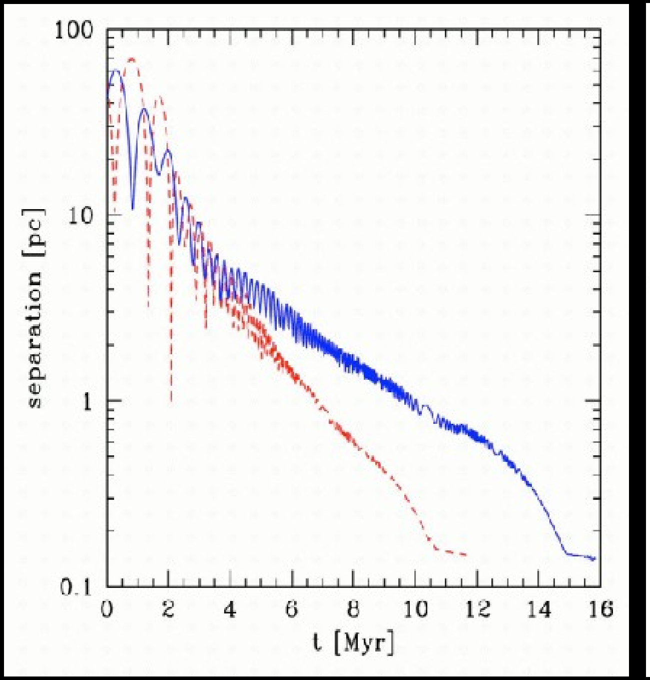
- **Coalescence in <1Gyr**
- **Eccentricity grows** (AS 2010)

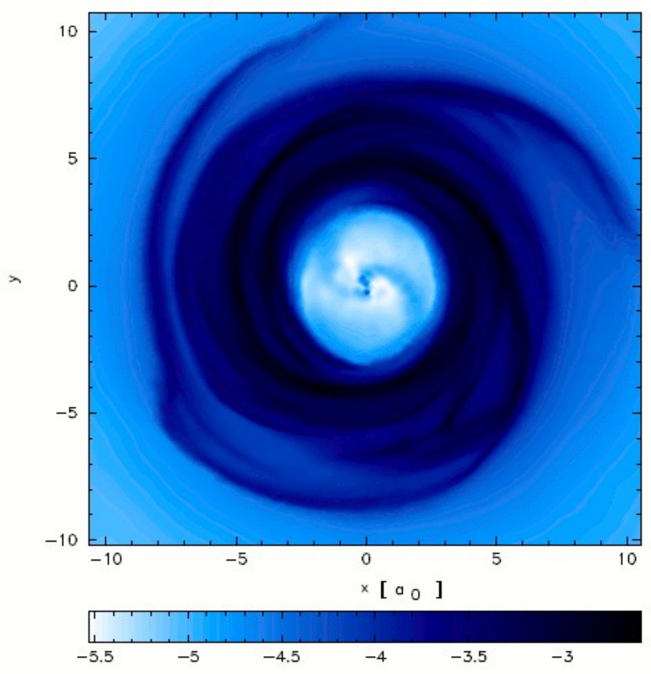


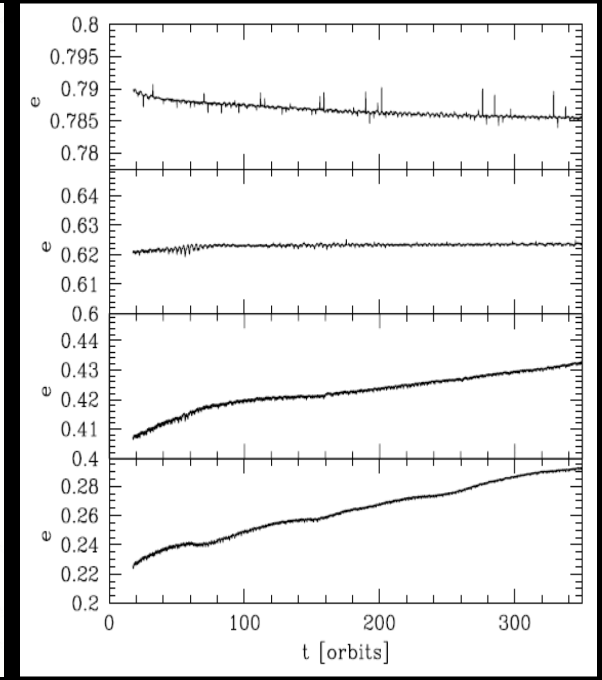
Preto et al. 2011



Binary evolution in gas rich environments





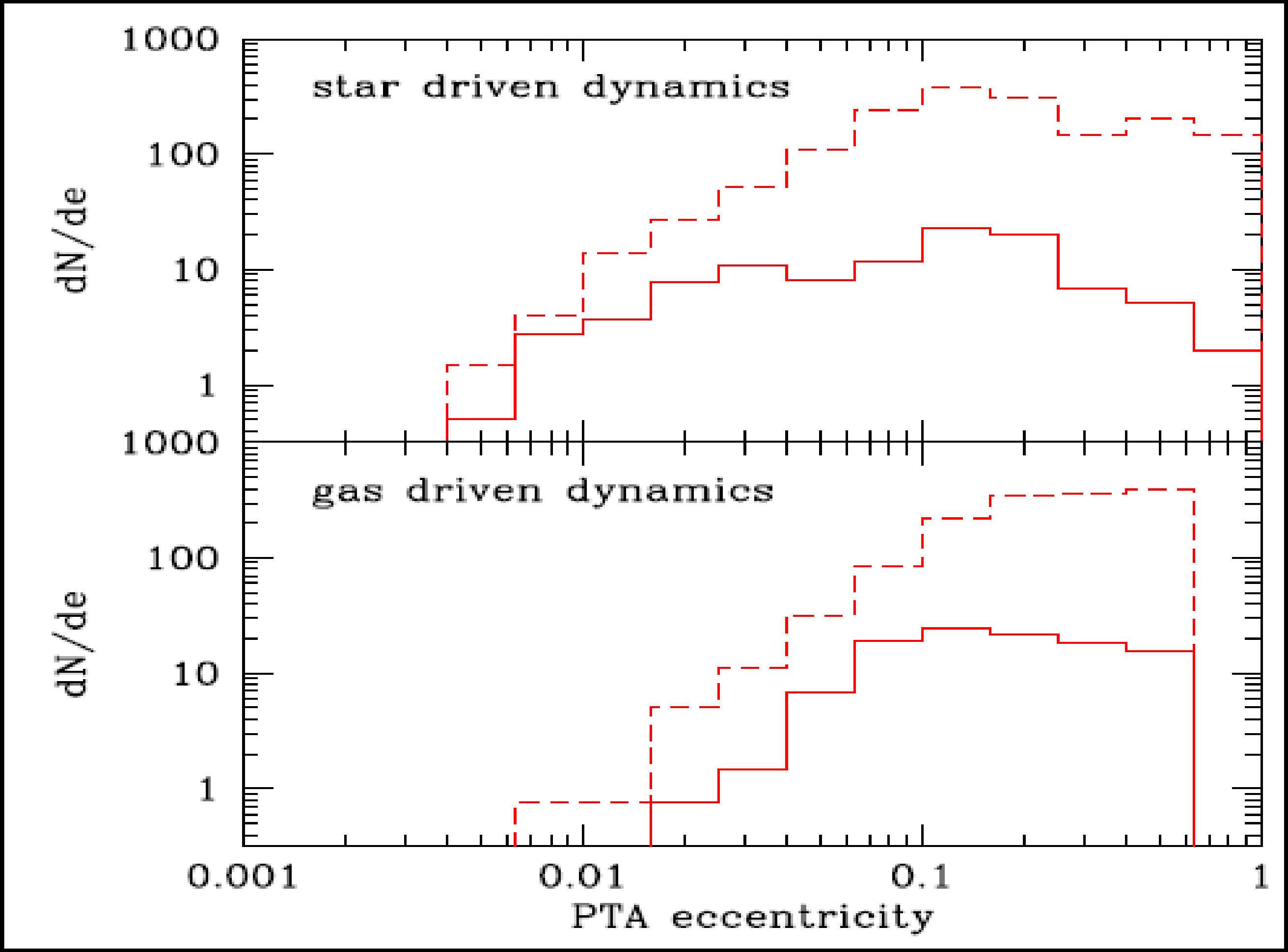


Simulation of binary hardening in a circumbinary massive disk (Escala et al. 2005, Dotti et al 2006, 2007) show that the *binary shrinks to the simulation resolution limit* without any apparent stalling problem.

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

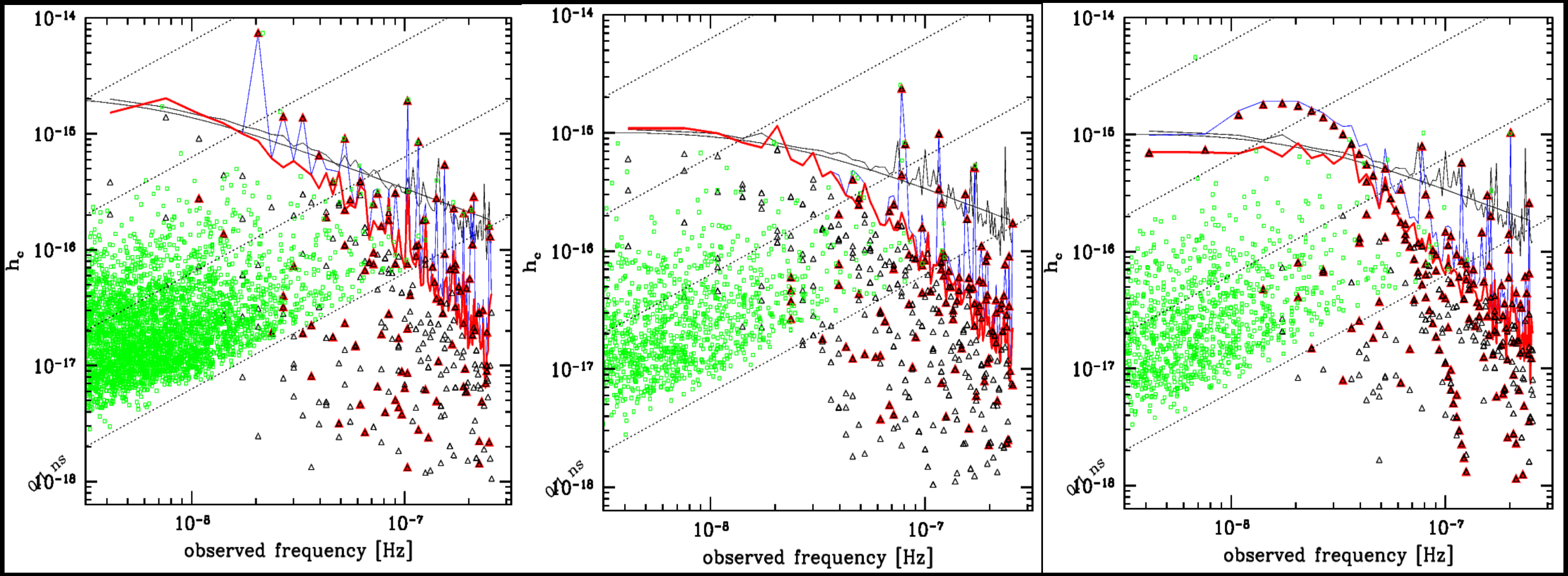
- **The binary migrates inward due to the effect of the disk torque (Cuadra 2009, Hayasaki 2009)**
- **Migration difficult to resolve**
- **Eccentricity seems to grow to a limit of the order 0.6-0.8 (Roedig et al. 2011)**
- **Periodic accretion (Hayasaki 2007, AS et al. 2011)**

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.

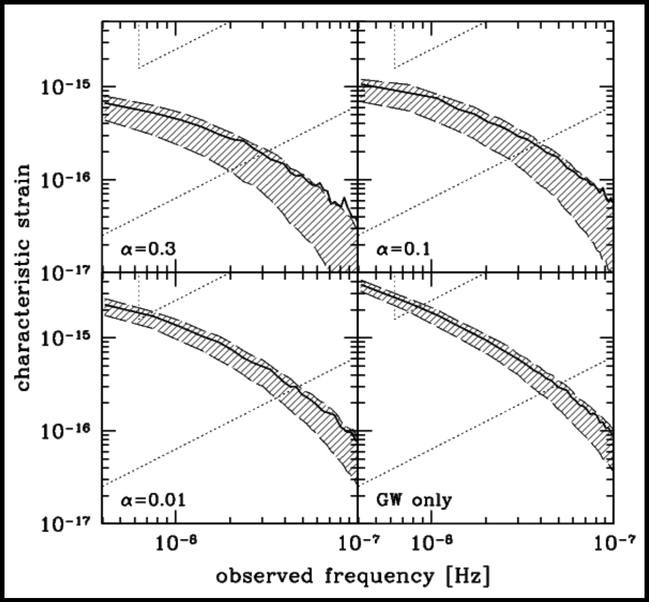
Gas driven binaries



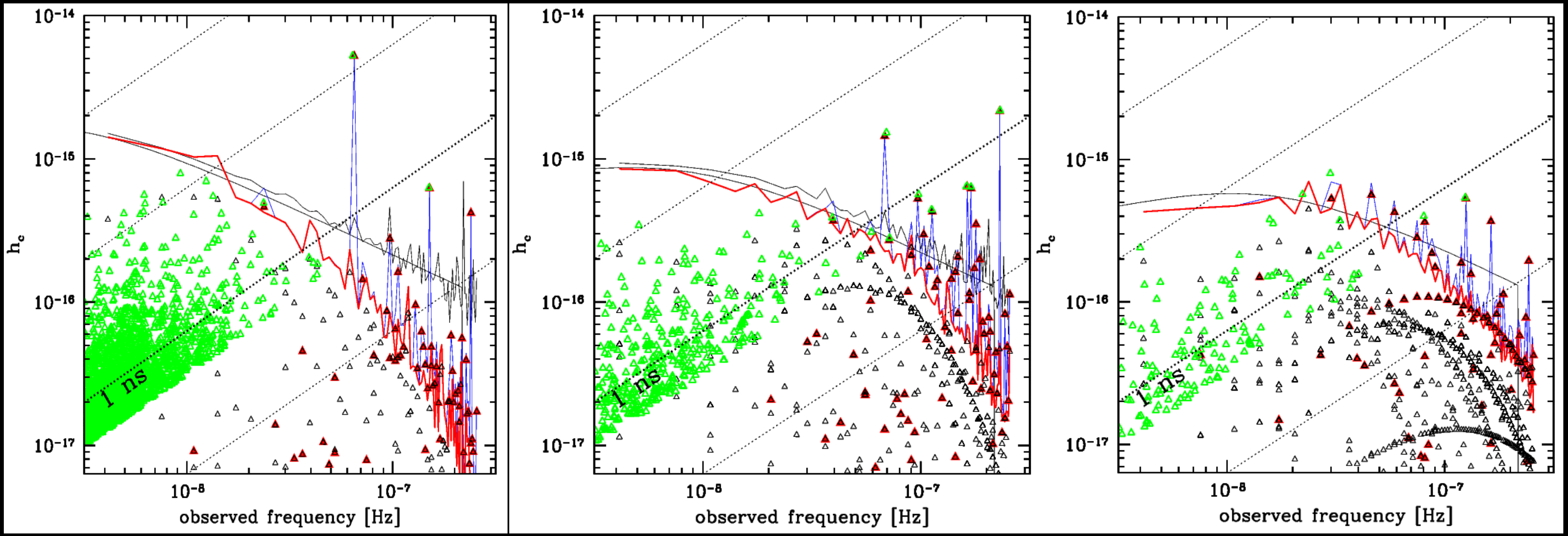
Critical physics:
- accretion disk nature (alpha disk vs beta disk)
- accretion rate and on viscosity
- eccentricity excitation

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

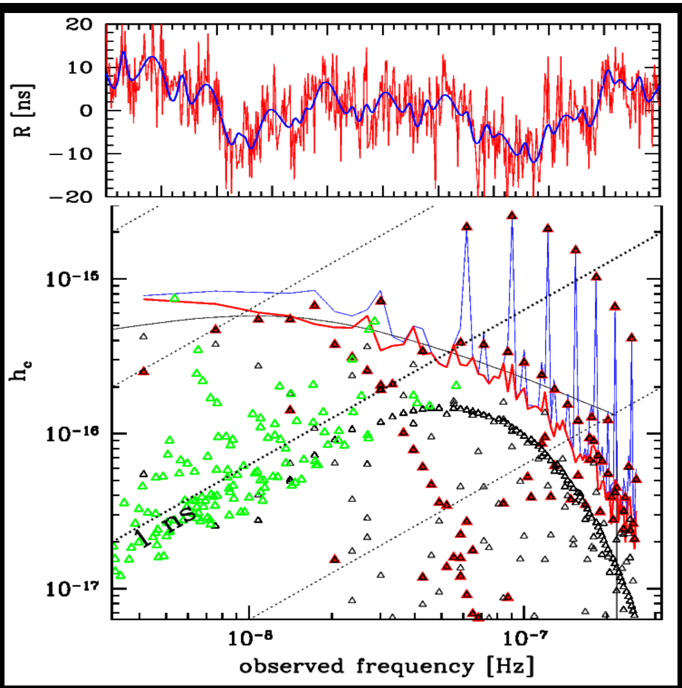
-efficiency of loss cone refilling

-rotation

Effects:

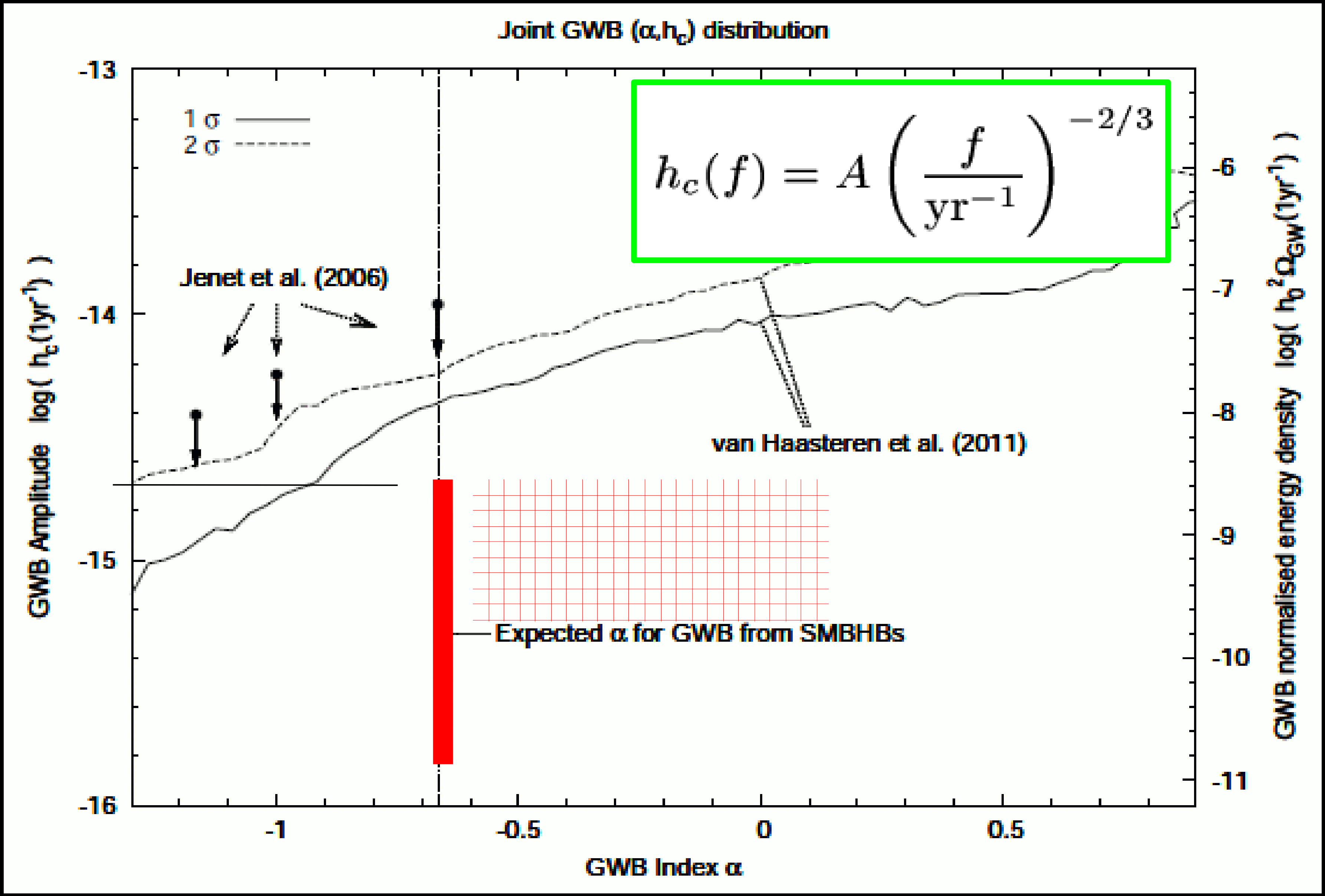
-lower signal, sparser, flatter

-likely many eccentric sources (broad bursts?)



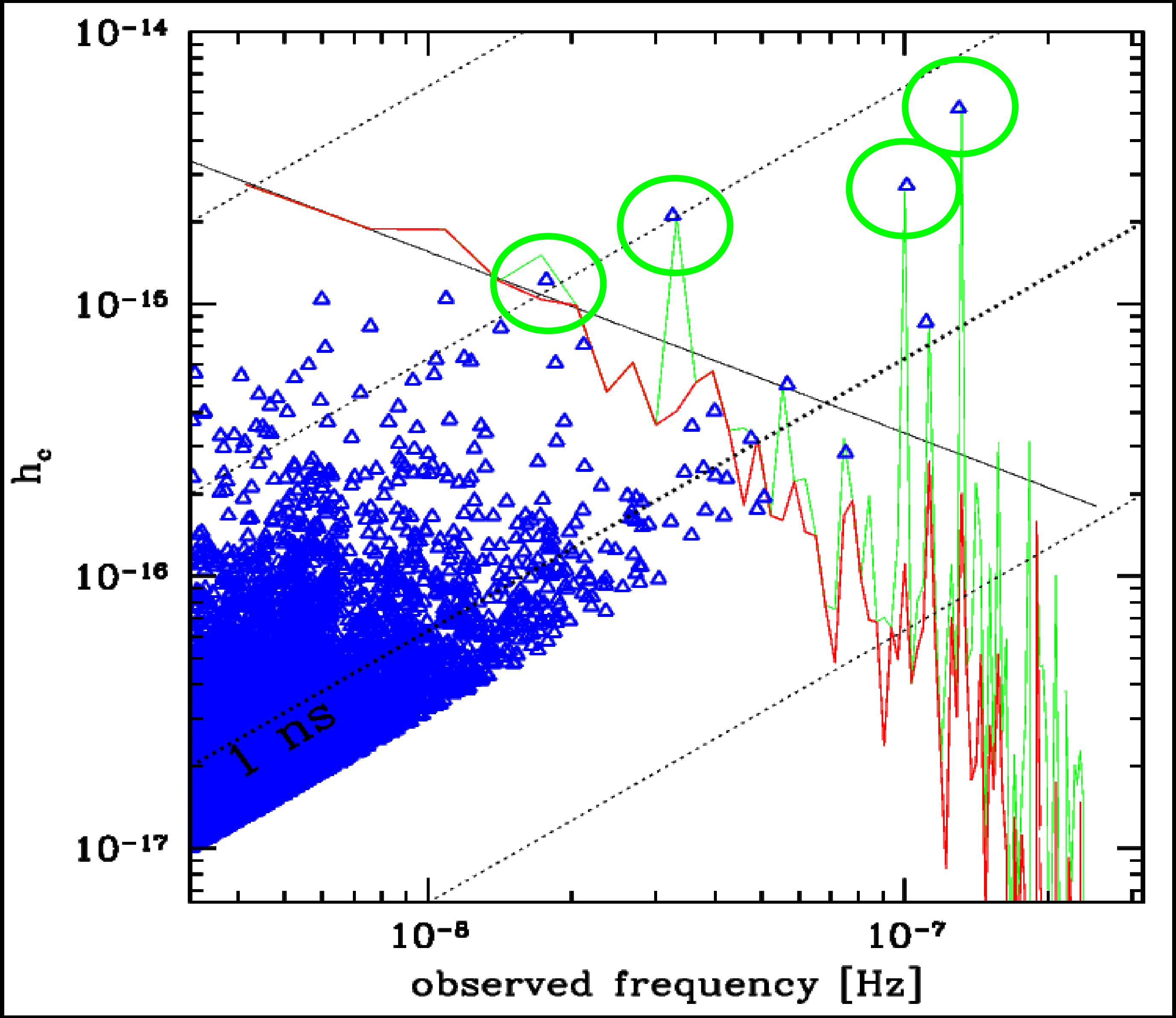
We don't have a good handle of any of this, but can be a *substantial effects*

What do current limits tell us?



Resolvable sources and Multimessenger astronomy

RESOLVABLE SOURCES



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

Such bright sources might be individually resolved:

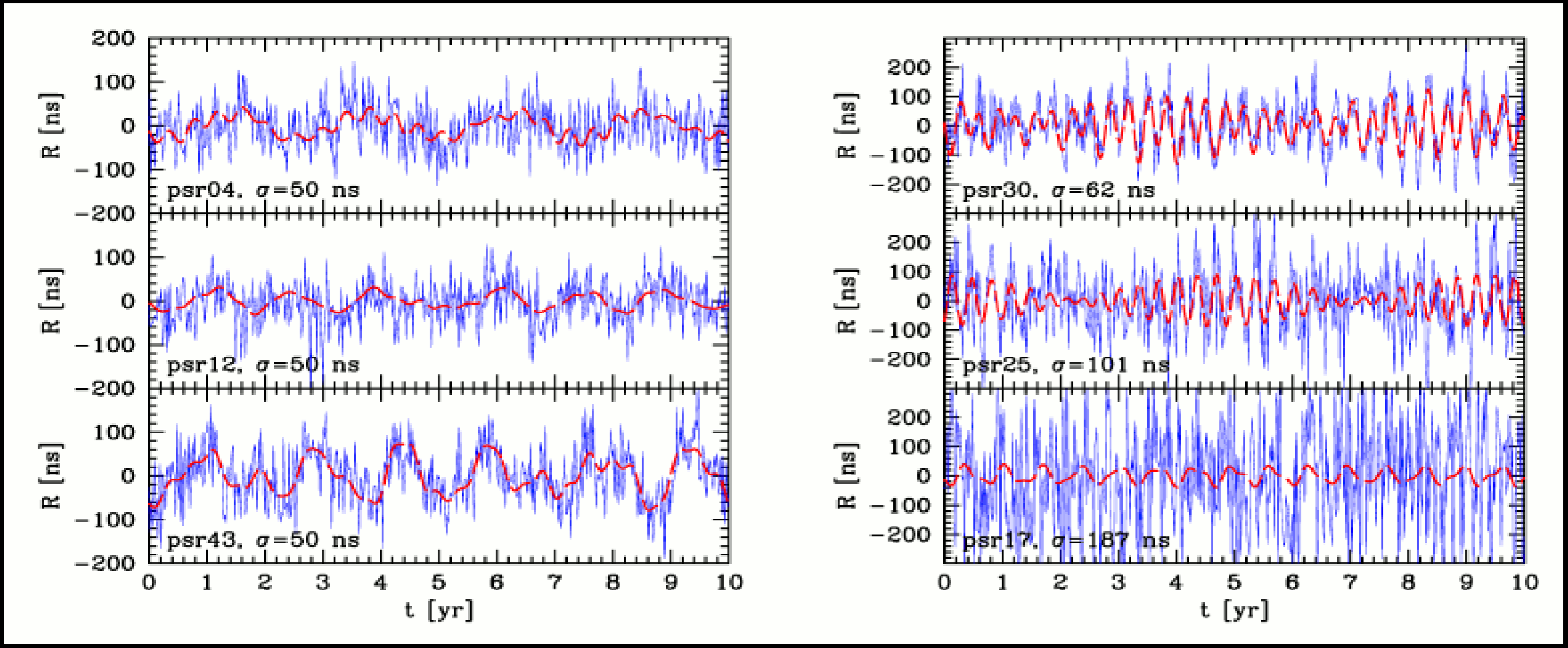
-can we infer their sky position?

-can we identify counterparts?

Such bright sources might be individually resolved:
-can we infer their sky position?
-can we identify counterparts?

We create several datasets

- -Unknown number of sources, random sky location, frequency, etc.
- -Circular non-spinning binaries evolved with PN equations of motion
- -Different number of pulsars in the array (30, 50), random sky location, random distance 1-3 kpc
- -Different noise levels, equal and unequal noise (white Gaussian)

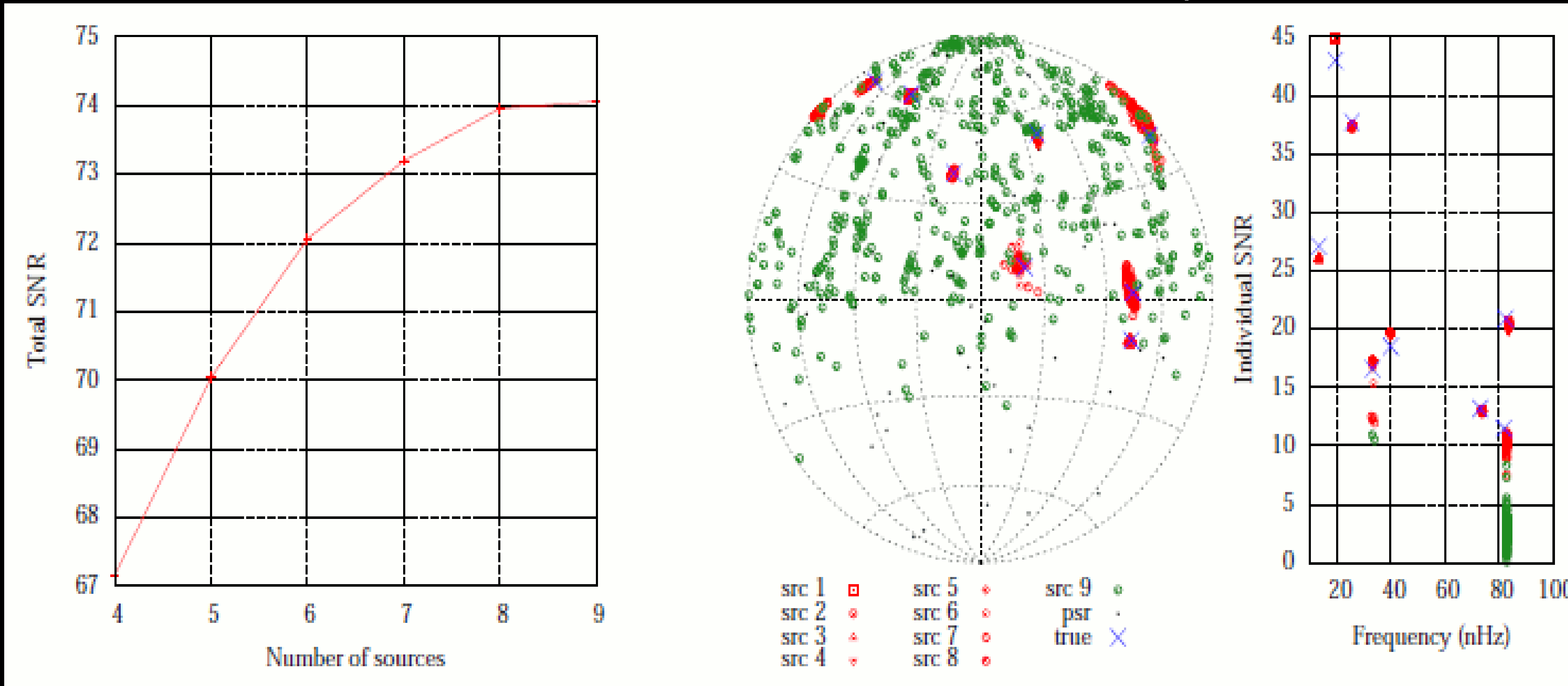


Search with Genetic Algorithm

-Common optimization technique based on natural selection
-Colony of organisms characterized by "fitness"-likelihood
-Each organism is described by a set of genes-parameters
(N sources, frequencies, sky locations)
-Strong organisms survive and proliferate

Genetic algorithm		GW search
organism	$\Longleftrightarrow$	template
gene (of an organism)	$\Longleftrightarrow$	parameter (of a template)
allele (of a gene)	$\Longleftrightarrow$	bits (of the value of the parameter)
quality Q	$\Longleftrightarrow$	Maximized Likelihood or A-statistic
colony of organisms	$\Longleftrightarrow$	evolving group of templates
n-th generation	$\Longleftrightarrow$	the state of colony at n-th step of evolution
(selection + breeding) + mutation	$\Longleftrightarrow$	way of exploring the parameter space

Babak & AS 2012; Petiteau et al. 2012



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

-We can determine the source parameters with high accuracy:

> SNR within few%

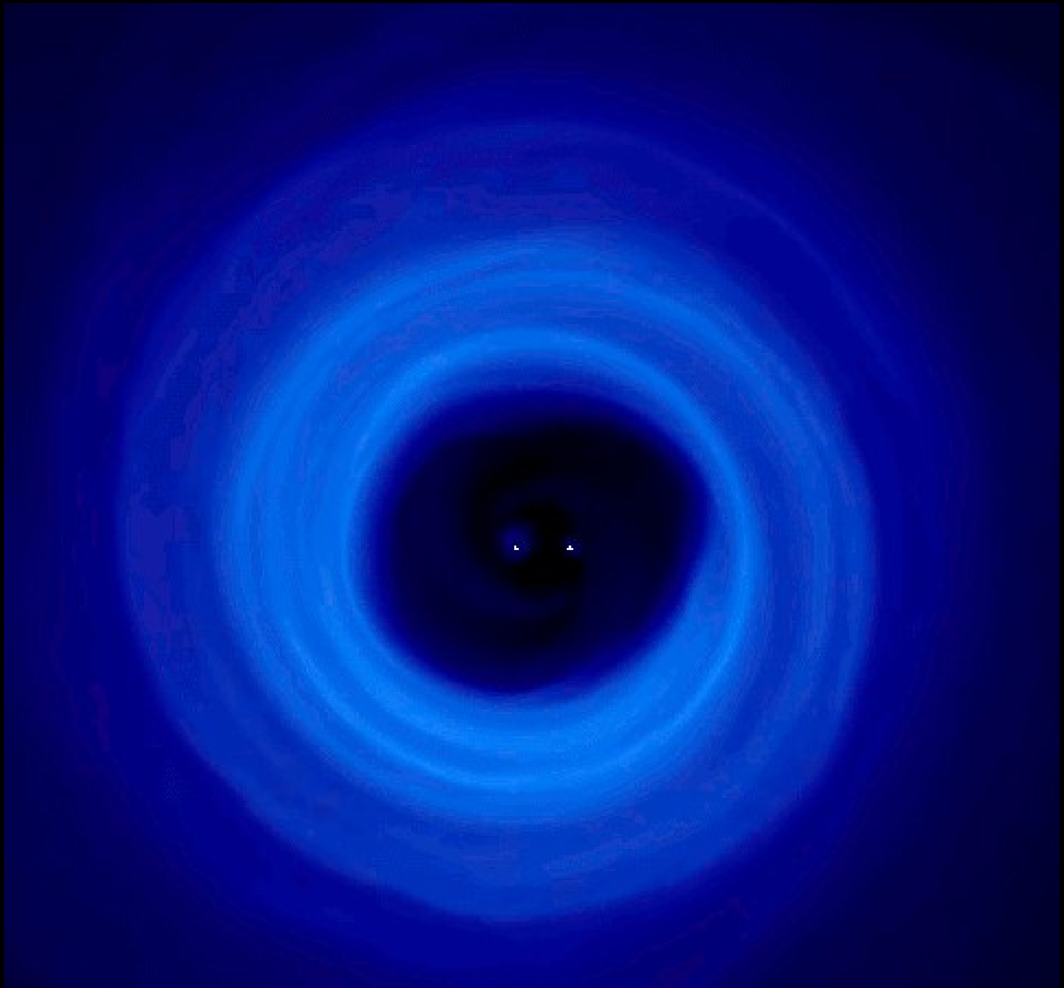
> sky location within few deg offset

> frequency at sub-bin level

-Extremely promising, needs test on more realistic situations

ELECTROMAGNETIC COUNTERPARTS

SPH simulation: MBHB+circumbinary disk



Roedig et al. 2011; AS et al. 2012

M_1~$3*10^8$ solar masses

M_2/M_1~1/3

a~0.01pc~300$R_{\rm Sch}$

P~6yr

e~0.6

$M_{\rm disk}/(M_1+M_2)$~0.03

$R_{\rm disk}$~3a-10a

Disk structure consistent with a thin alpha disk

Periodicity in binary feeding

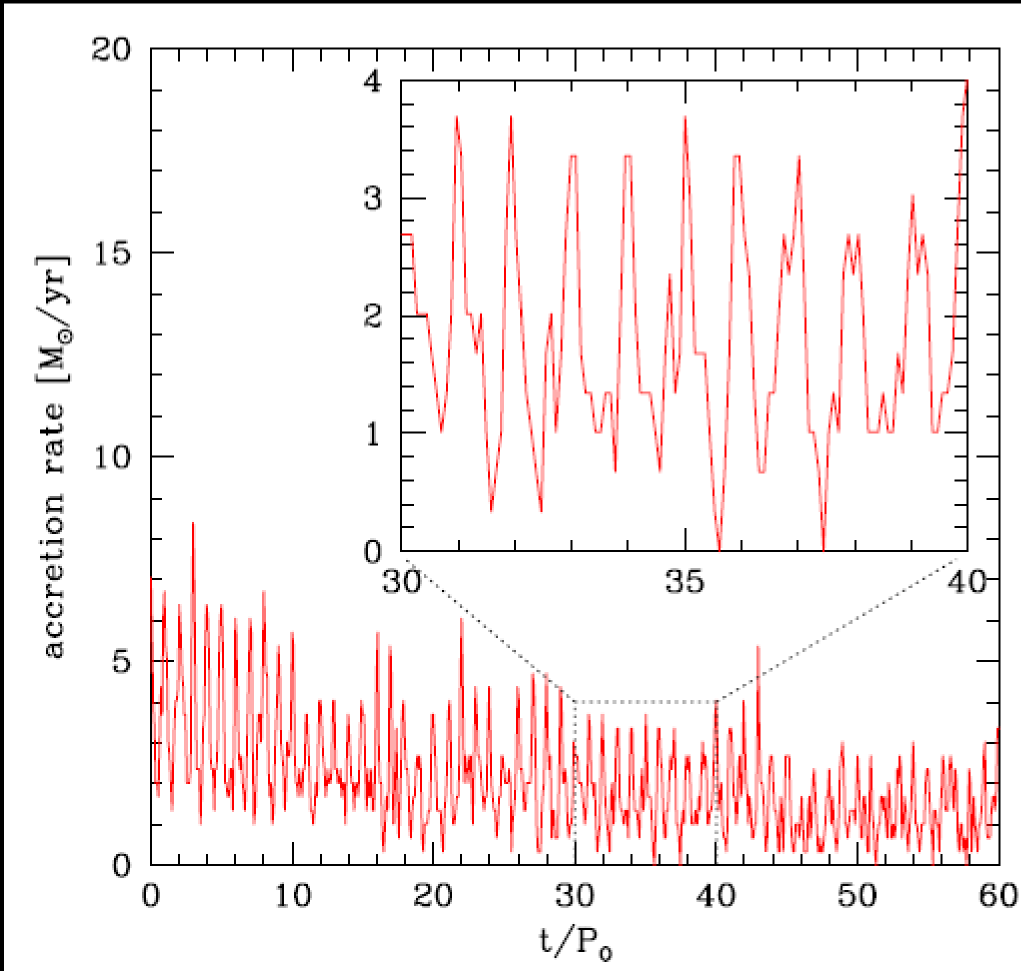
Observational campaigns will be obviously limited in time

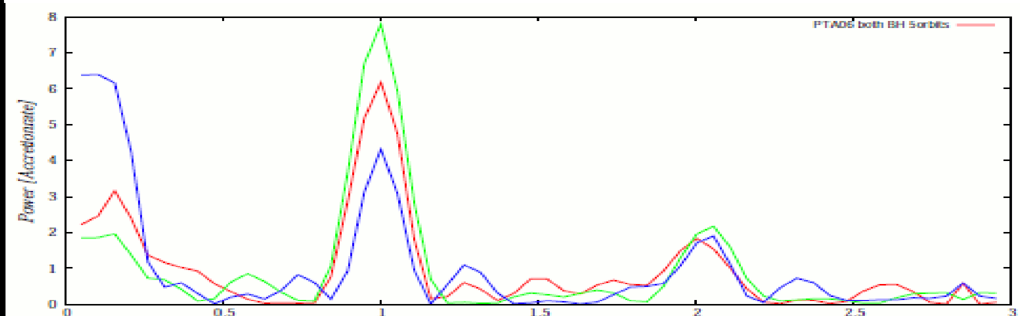
PTA sources have periods between few months to few years

We can observe the sources over few periods only

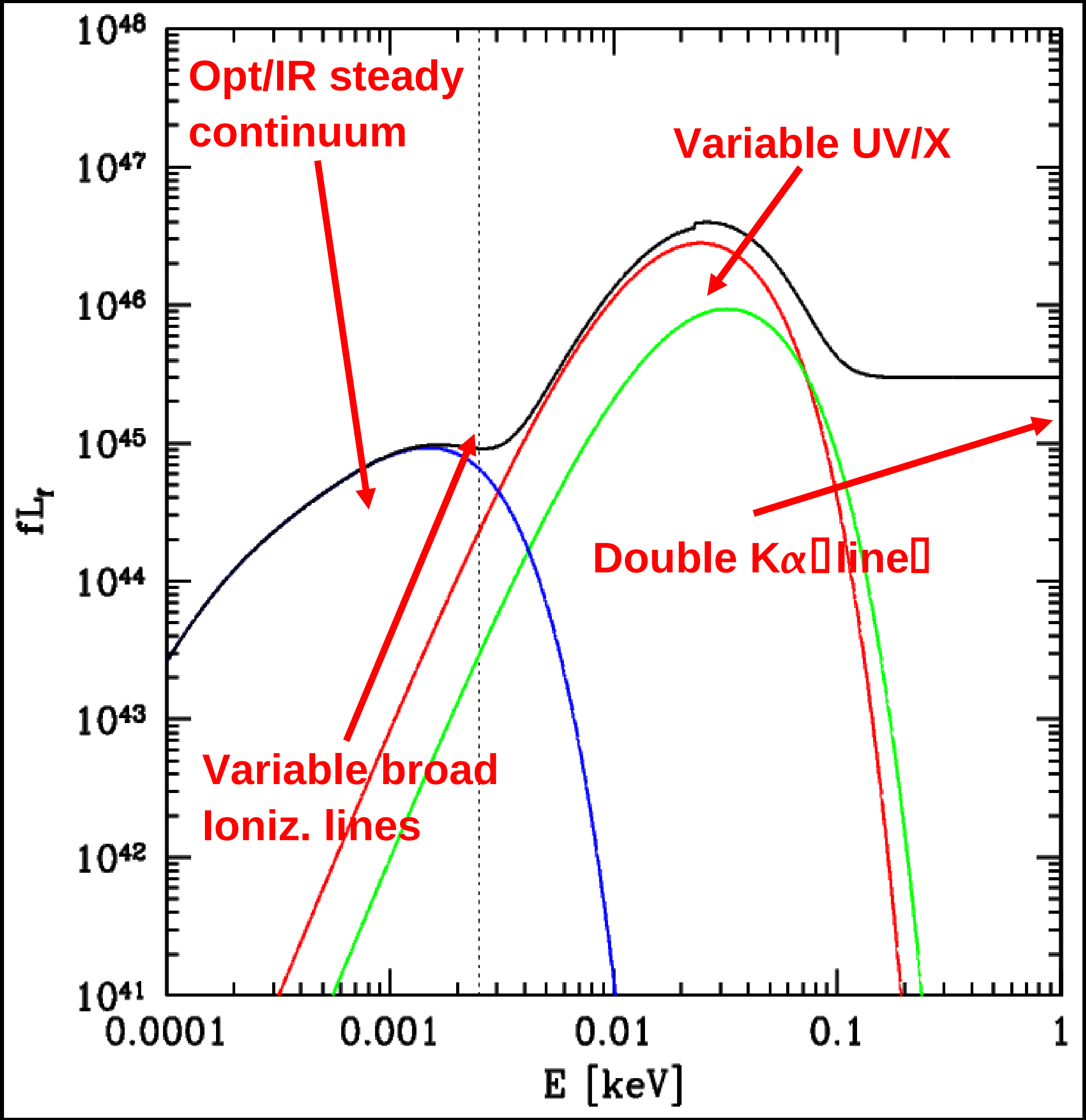
Fourier spectrum averaged over 3-5 orbital periods

Clear peak at the orbital frequency





Spectrum



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

-UV generated by the Inner disks. Periodic variability.

-X ray corona. Periodic variability

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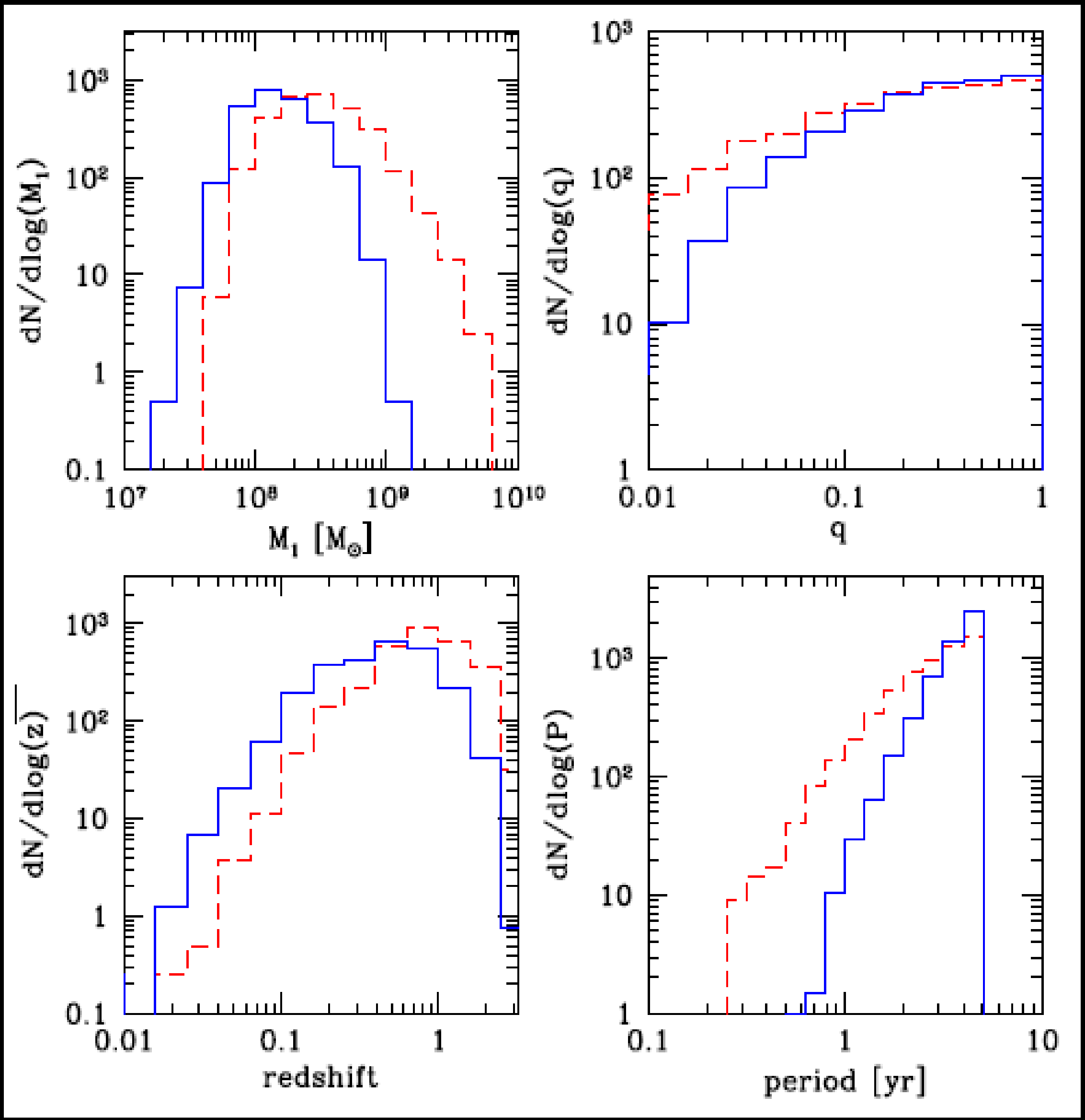
-Double fluorescence 6.4keV Kα iron lines

periodic sources: population statistics

L=0.3 L $_{Edd}$



Example: eRosita

-X-ray all sky monitor

-all sky every six months

-5yrs operation

-flux limit 3*10^{-14} erg/s/cm^2 per pointing

-to be launched in 2012

Model assumptions

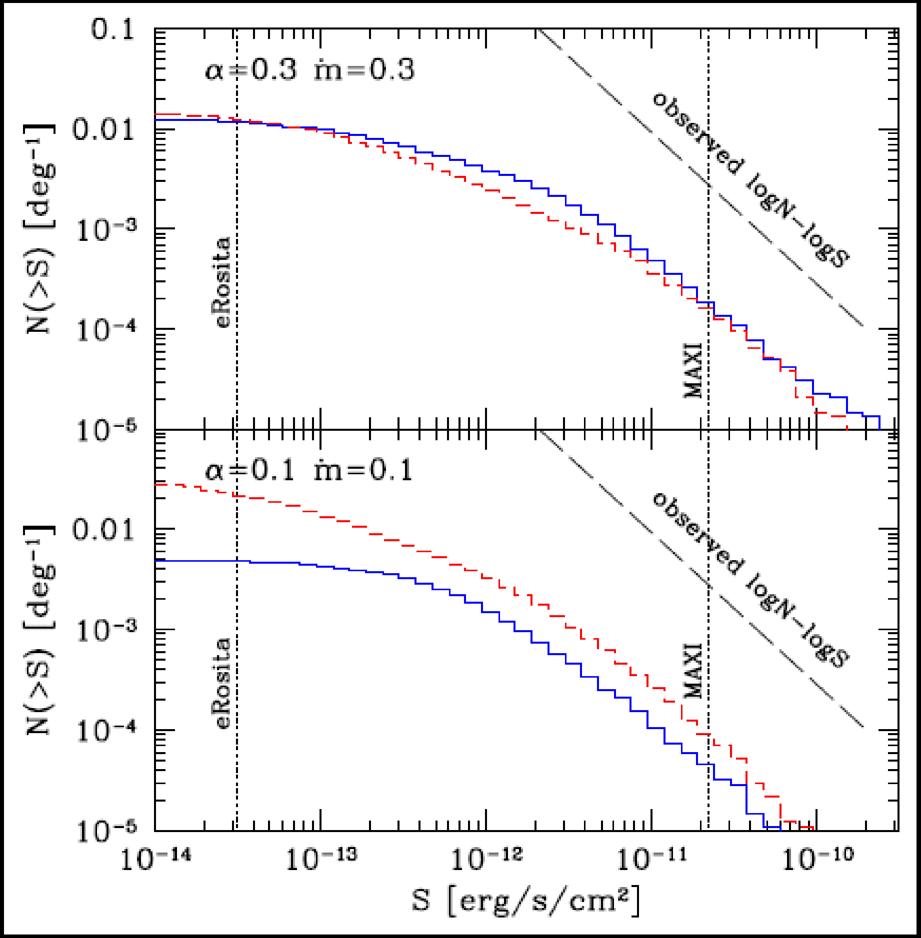
-L=0.3L$_{Edd}$

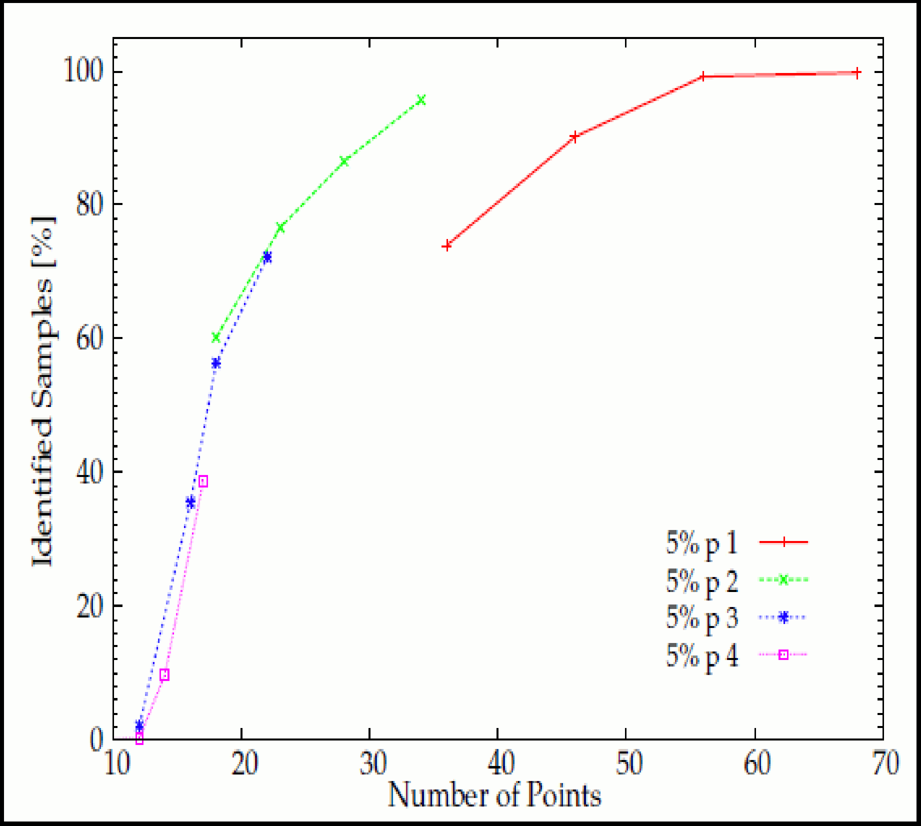
-L$_{0.5\text{-}2KeV}$=3%L$_{Bol}$

Can observe up to *~hundred sources with periodic variability* above five*flux limit

Useful to direct PTA observations?

However, *need better sampling* (other distinctive signatures?)





Sensitivity more than sufficient, *more than 100 sources* might be detected at the eROSITA senistivity limit!

In summary:

1-Pulsar timing arrays provide an effective method to detect low frequency (nHz) gravitational waves

2-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*

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

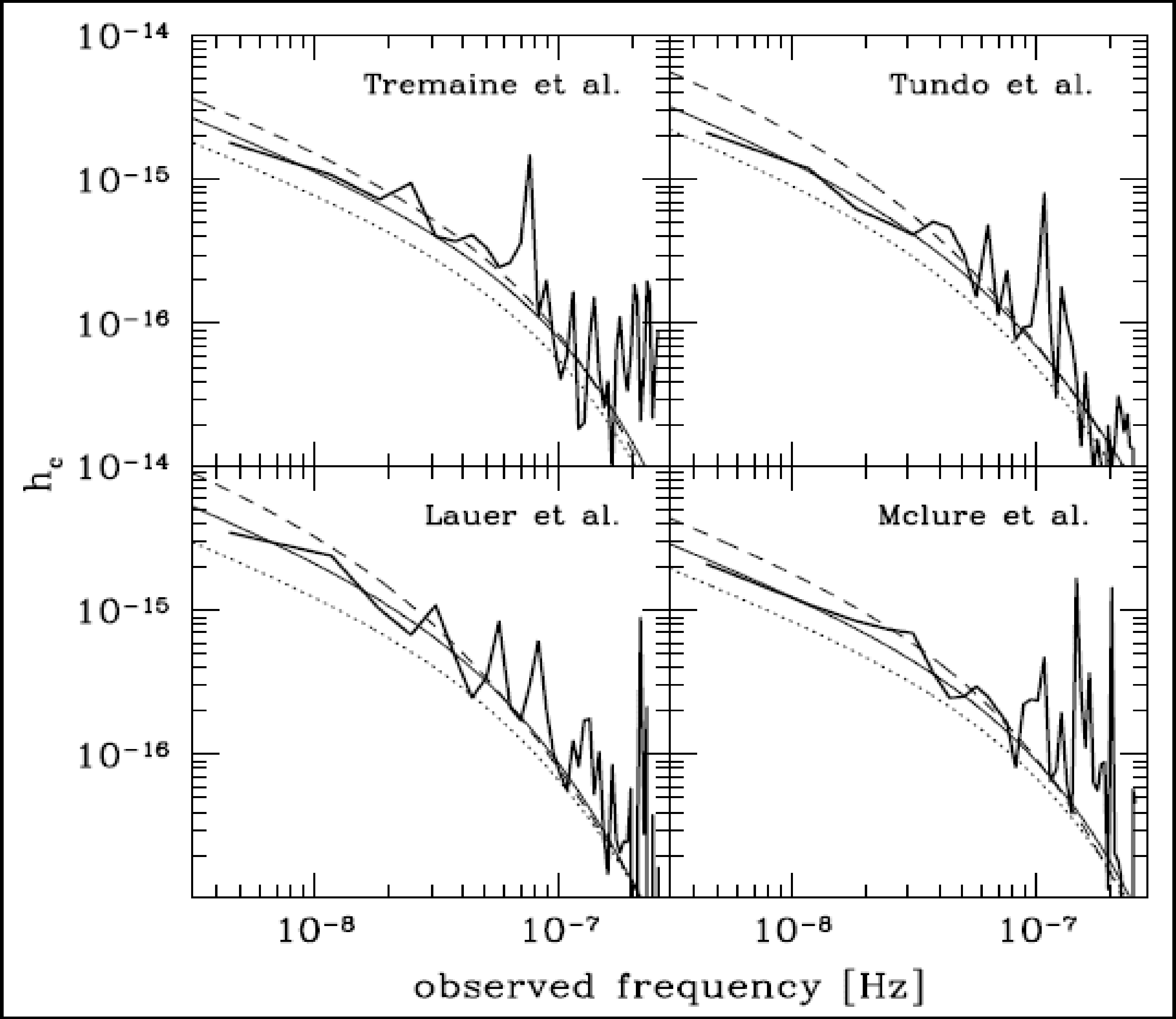
4-The signal shape, level and nature can be *SEVERELY affected by the dynamical processes* driving the binary:

- **-Shallower slope**
- **-Eccentric binaries**
- **-Earth-Pulsar term connection**

5-Bright sources might be individually resolved and located in the sky within *few deg^2* accuracy

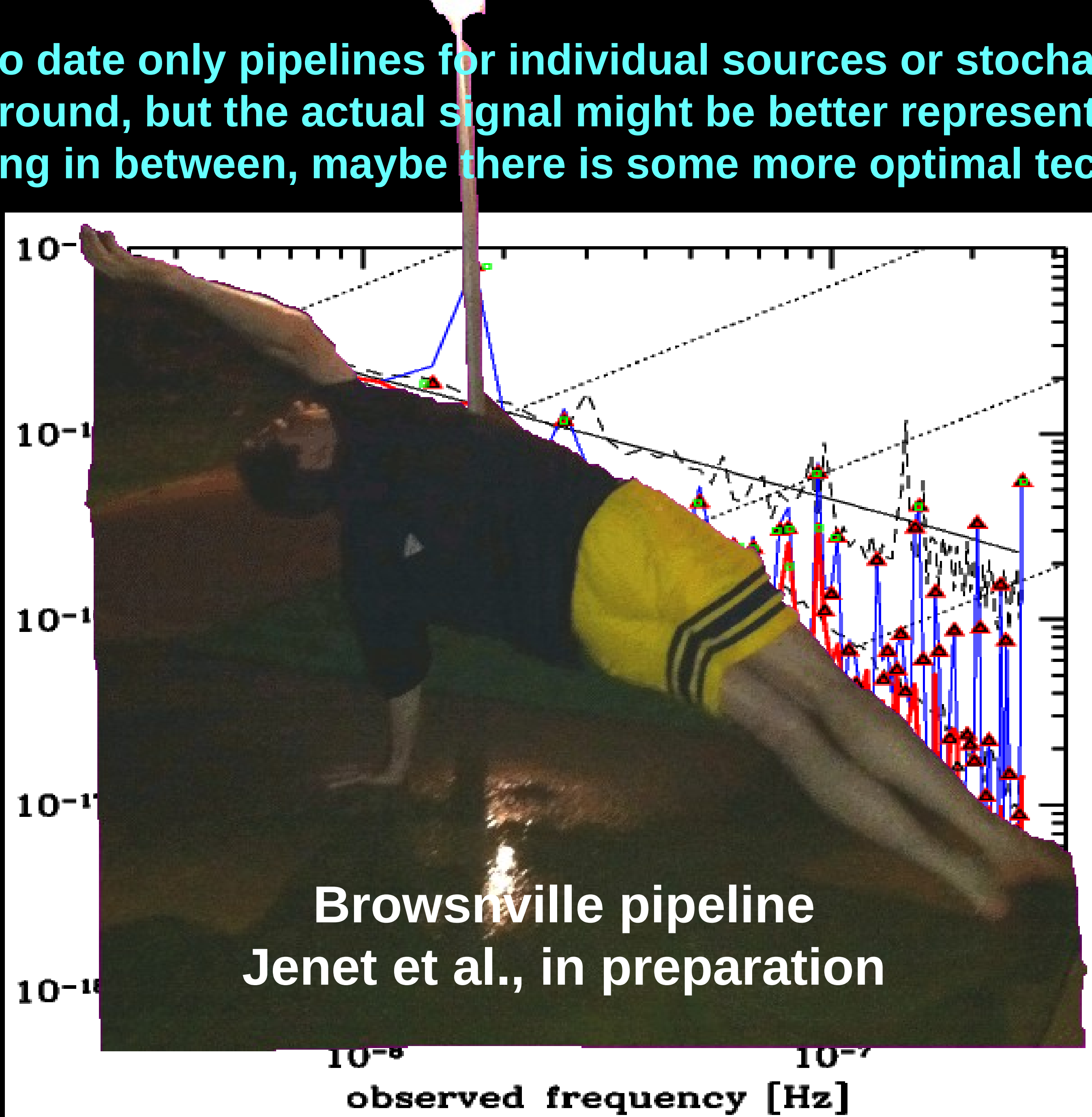
6-Peculiar signatures might be present (i.e., variability). Up to *several hundred* sources in the eROSITA range.

Signal examples

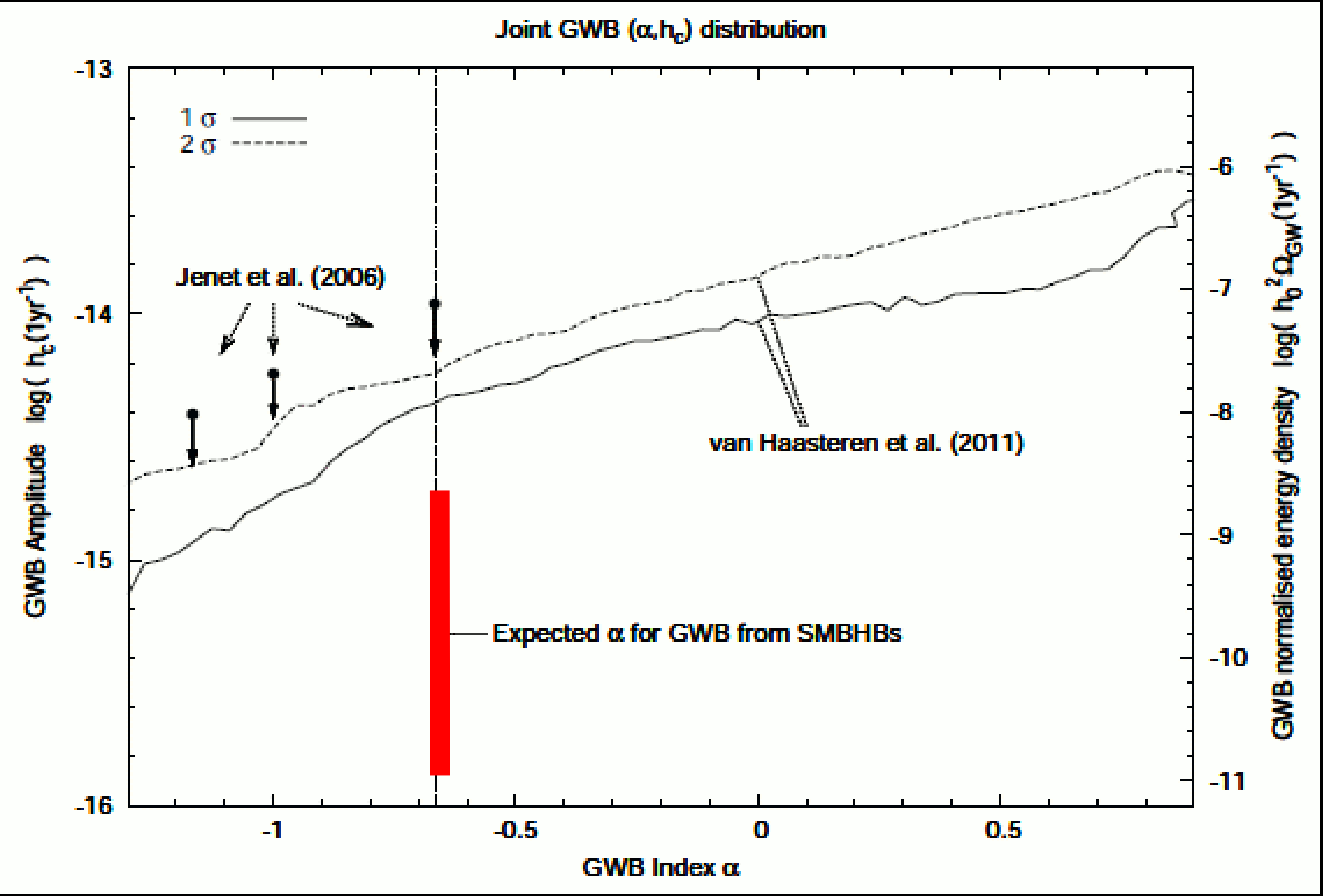


AS, Vecchio & Volonteri 2009

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.

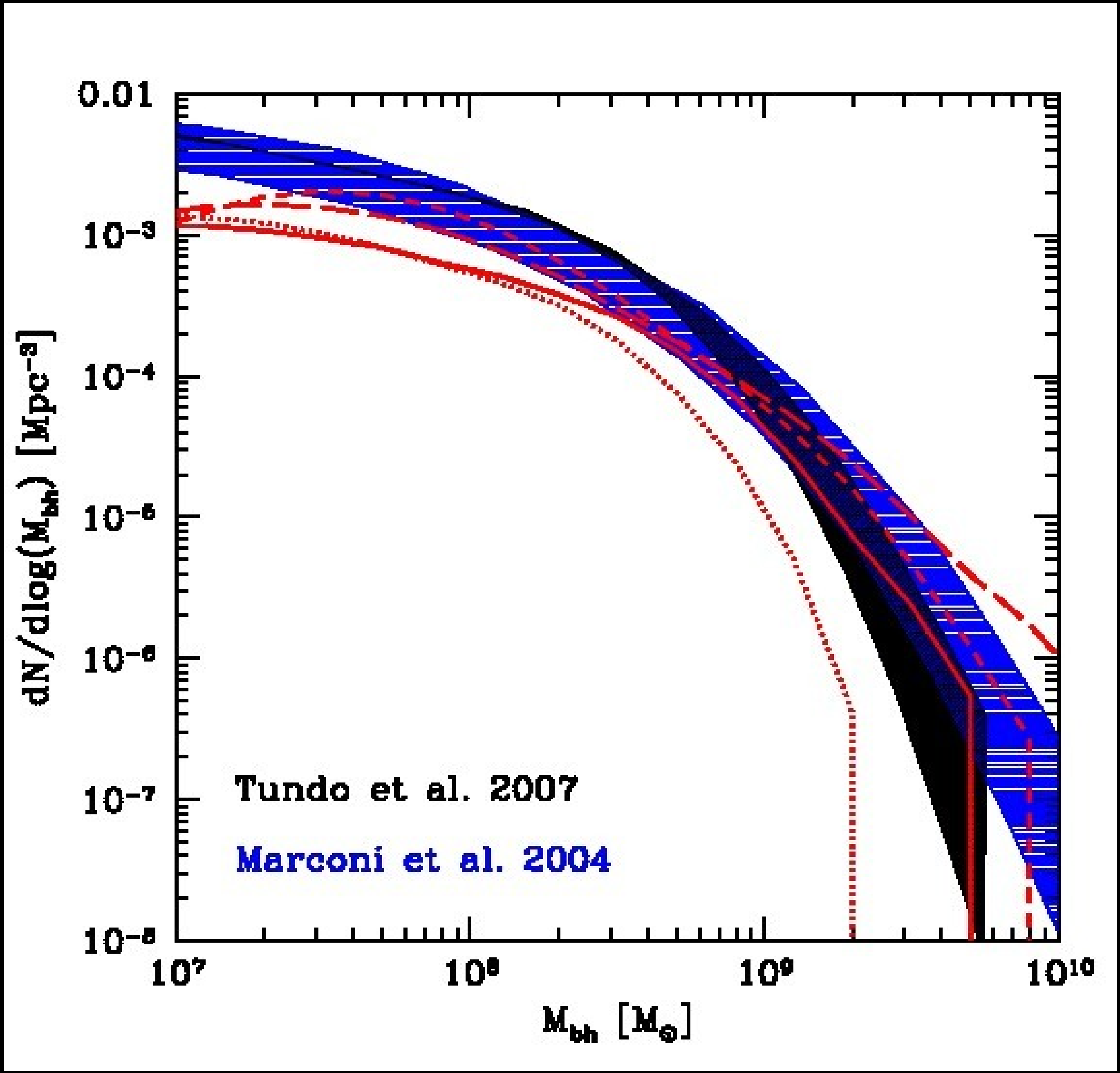


What do current limits tell us?

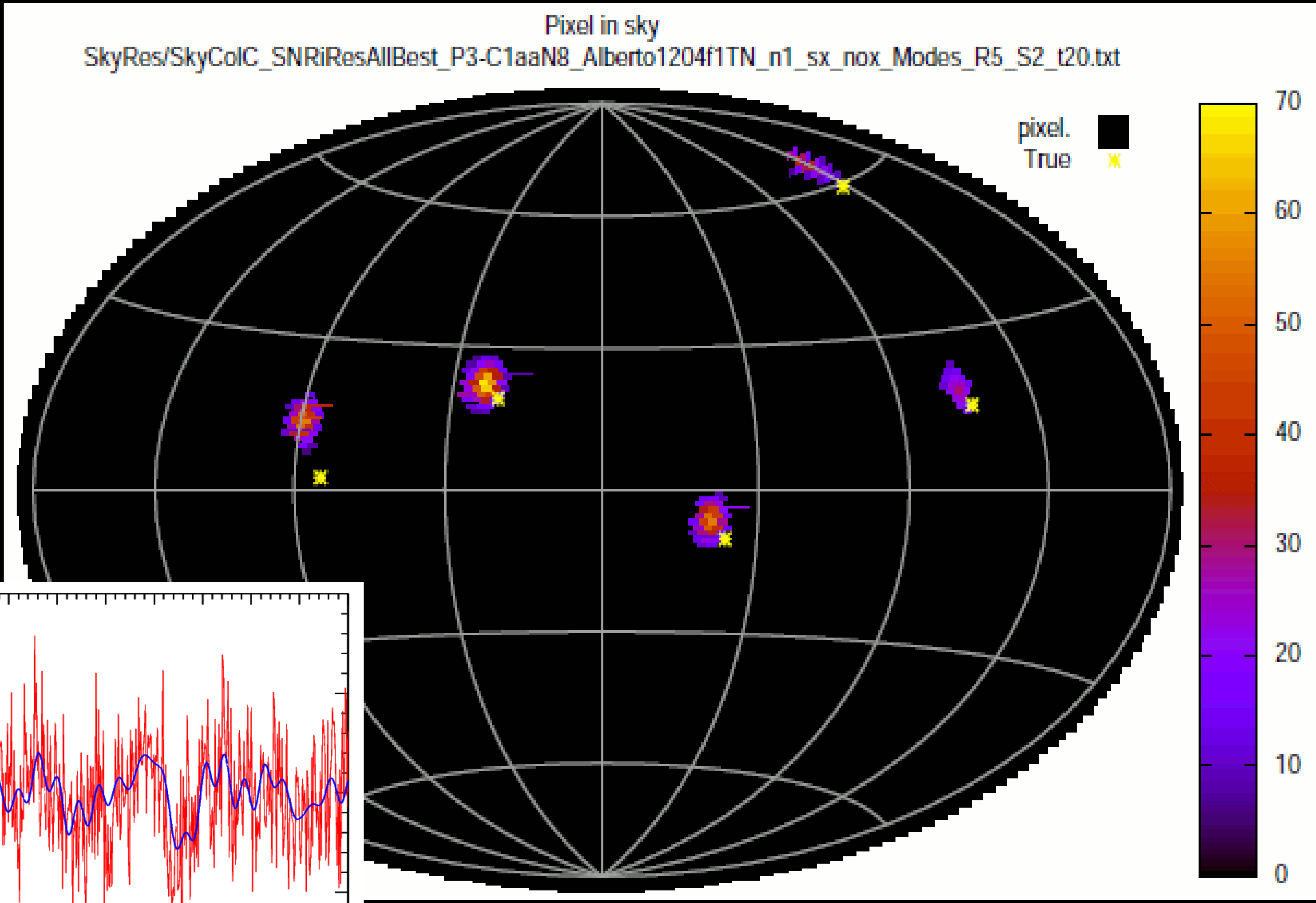


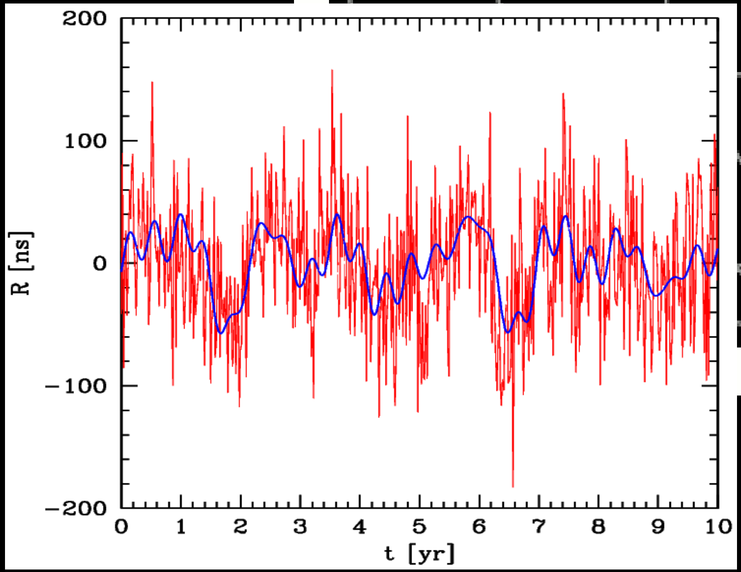
Van Haasteren et al. 2012

SMBH mass function



Can we resolve individual sources with PTAs?





Babak & Sesana 2012, Petiteau Babak & Sesana in prep.

Do we expect electromagnetic counterparts?

Observational facts:

-during galaxy mergers, a large amount of gas is funneled in the core

-we see MBHs shining: *MBH accreting* from a disk structure

-mean Quasars luminosity: $L \sim 0.3 L_{Edd}$

-poor knowledge of the disk properties

Theoretical facts:

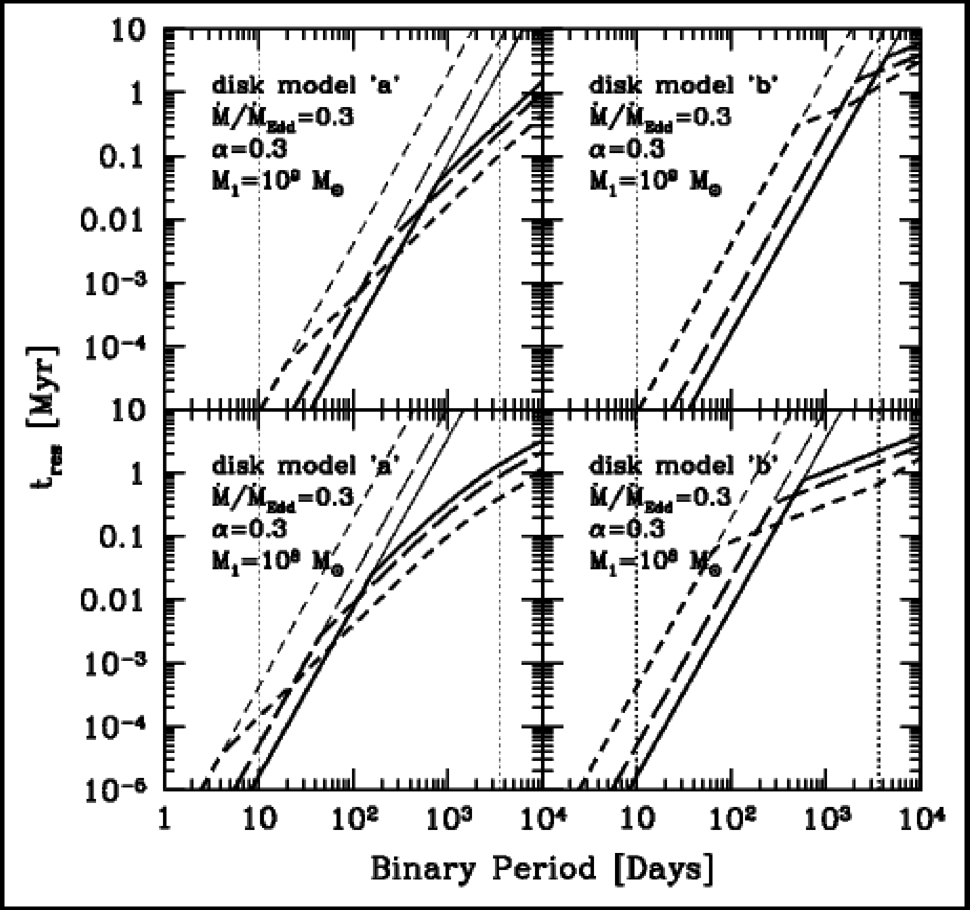
-gas driven binary evolution: the *eccentricity increases*

(-stellar driven evolution: the *eccentricity increases*)

Haiman Kocsis & Menou 2009:

-models for the binary migration in circumbinary disks

-*gas dynamics dominates* even during the late inspiral, *down to the PTA band*



Kocsis & Sesana 2010

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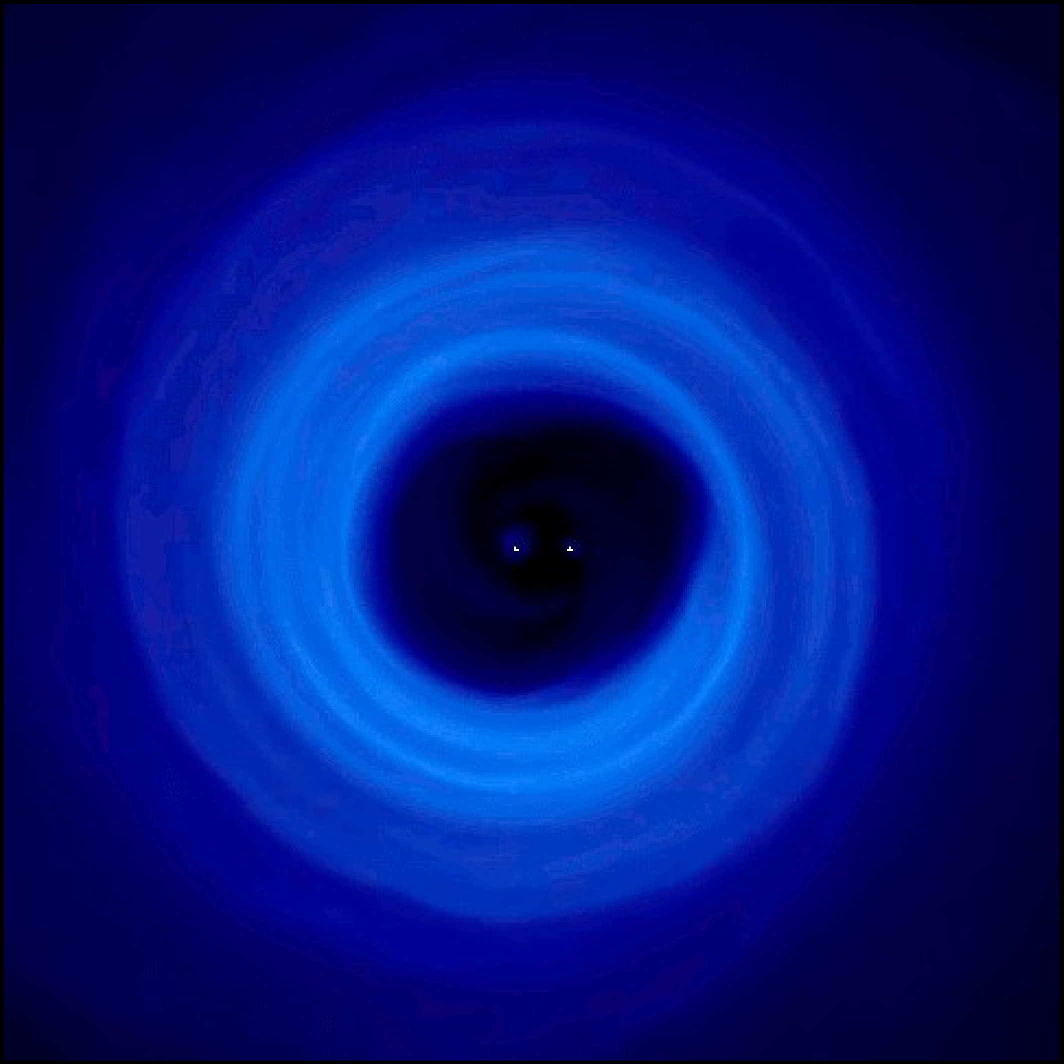

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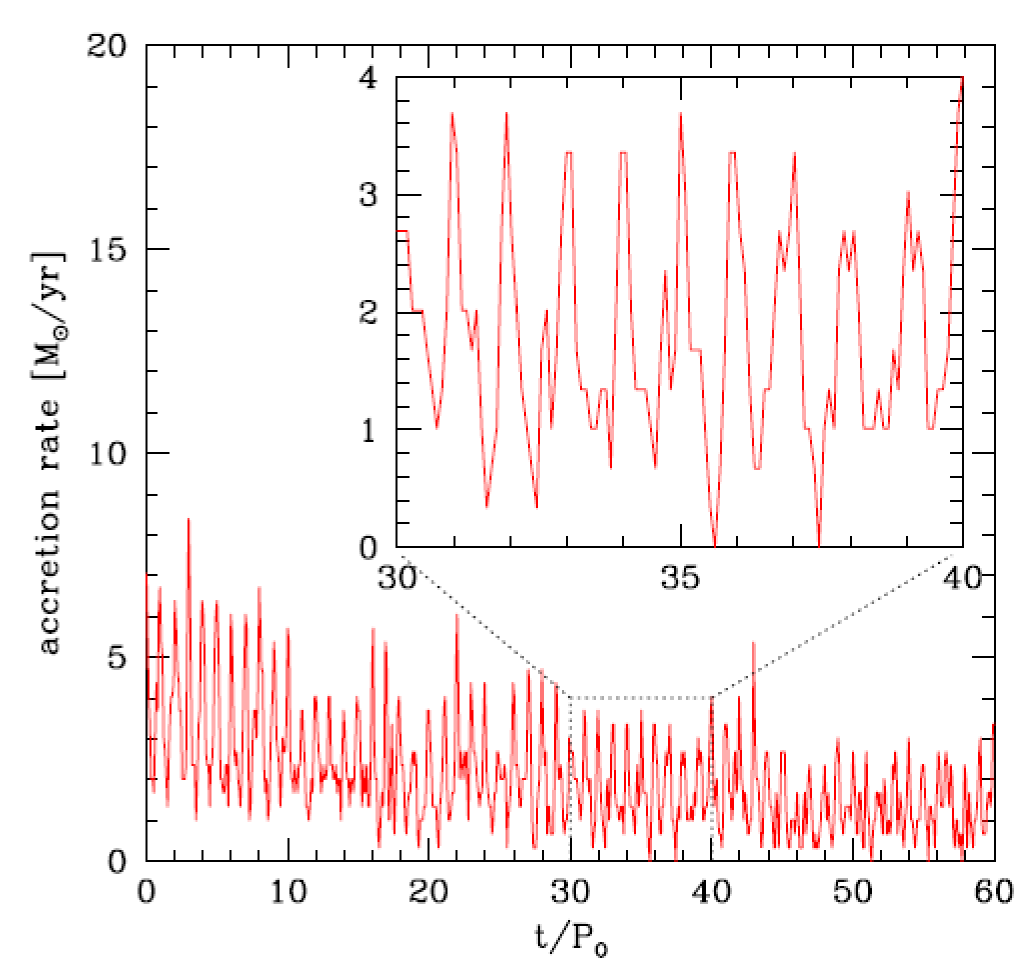
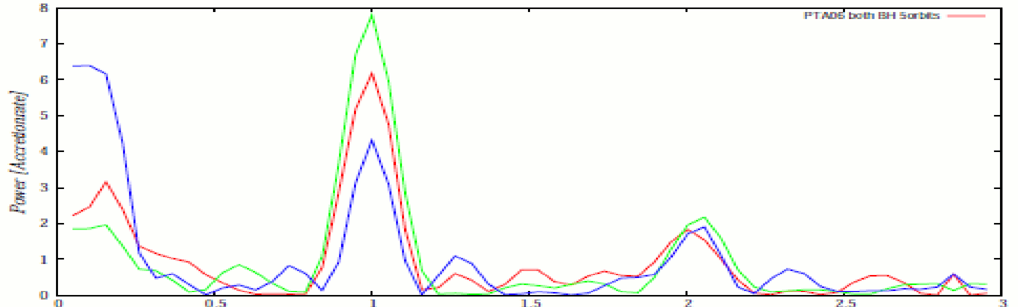
Clear peak at the orbital frequency

Good prospects for multimessenger astronomy (Sesana et al. 2011), needs more detailed investigations





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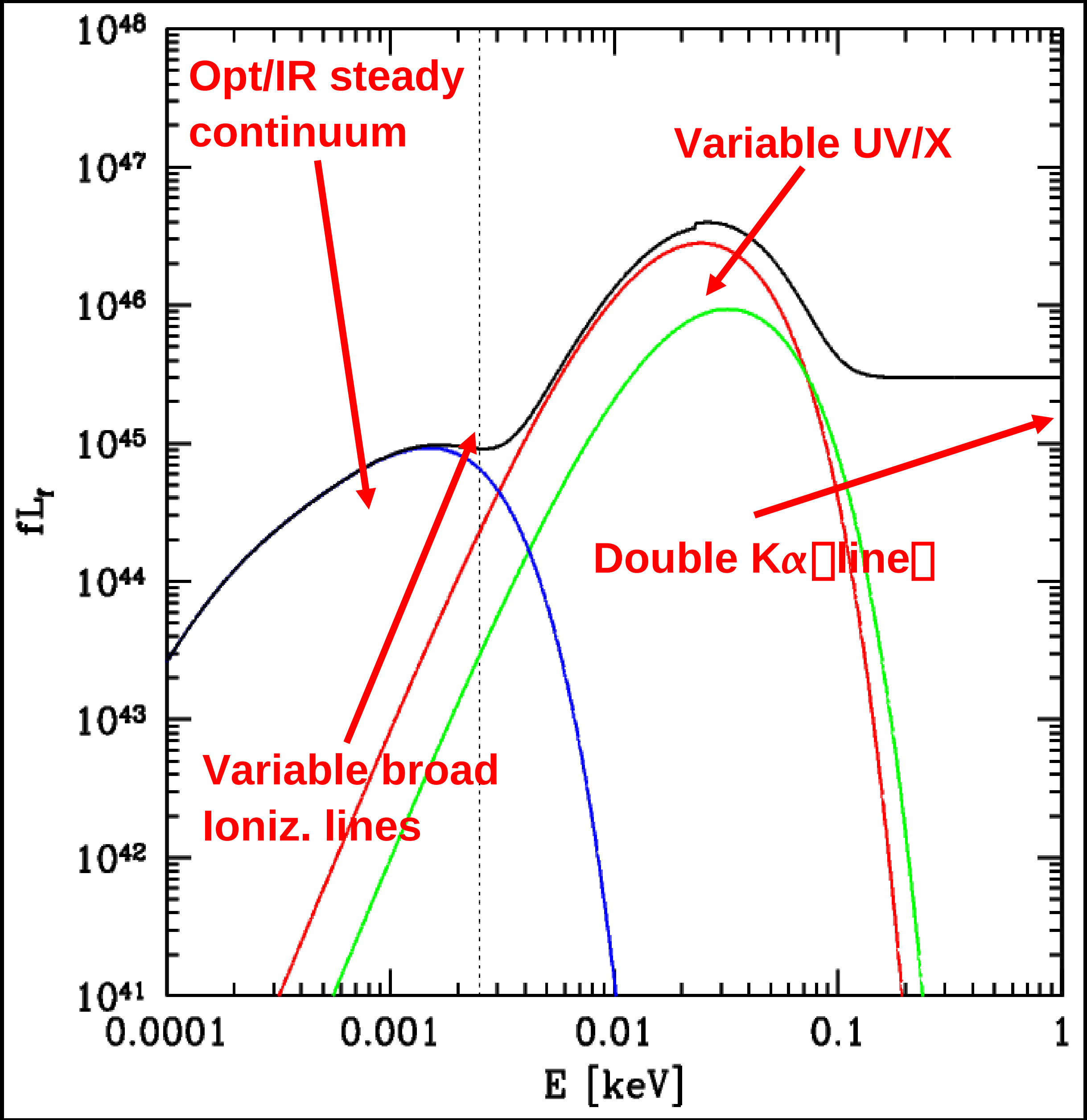

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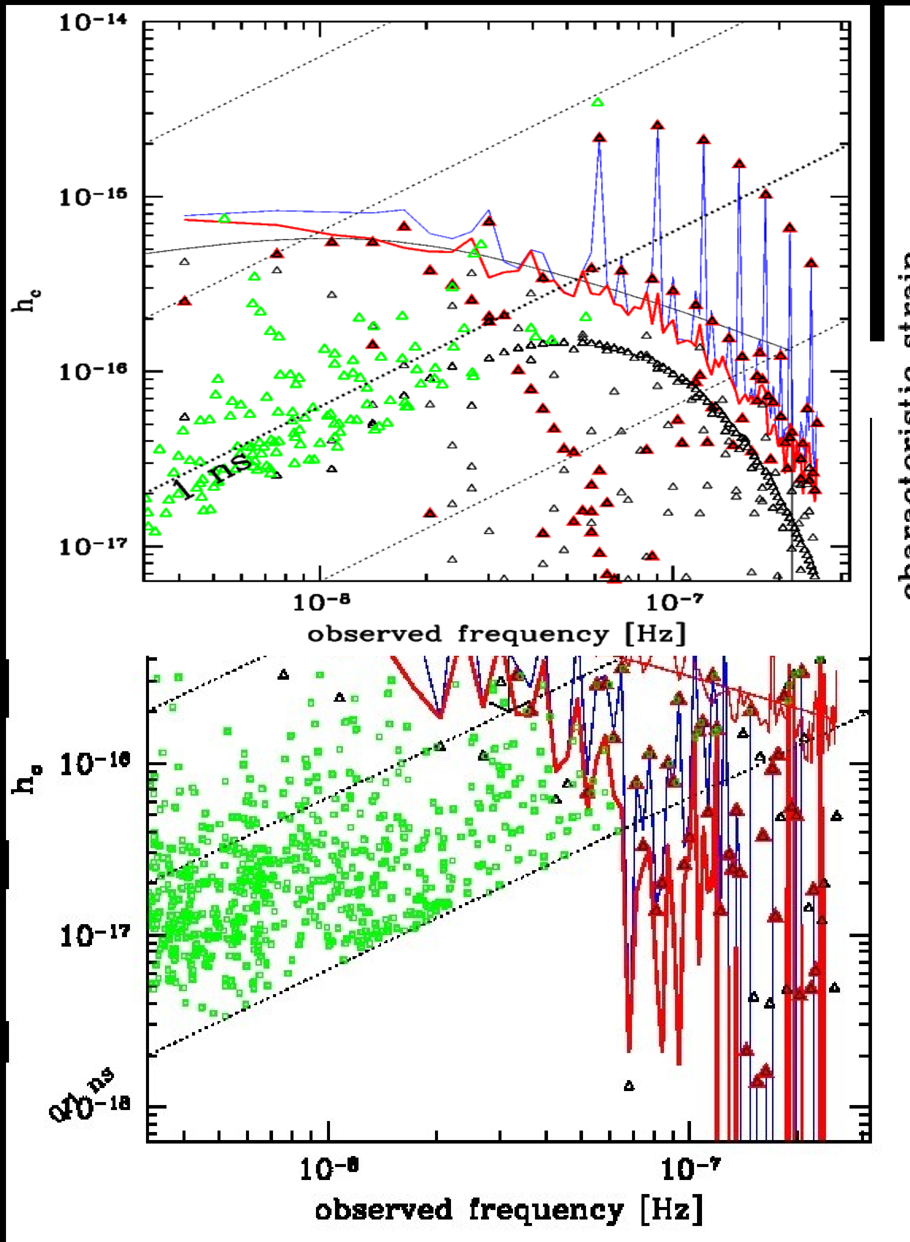
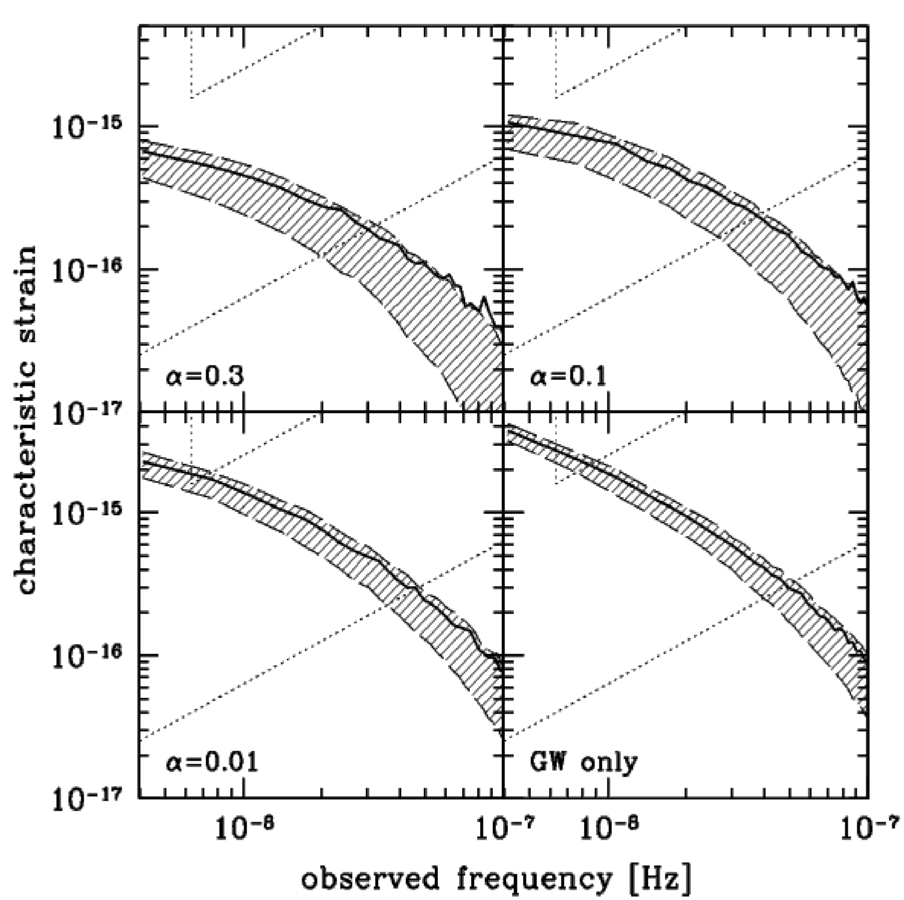
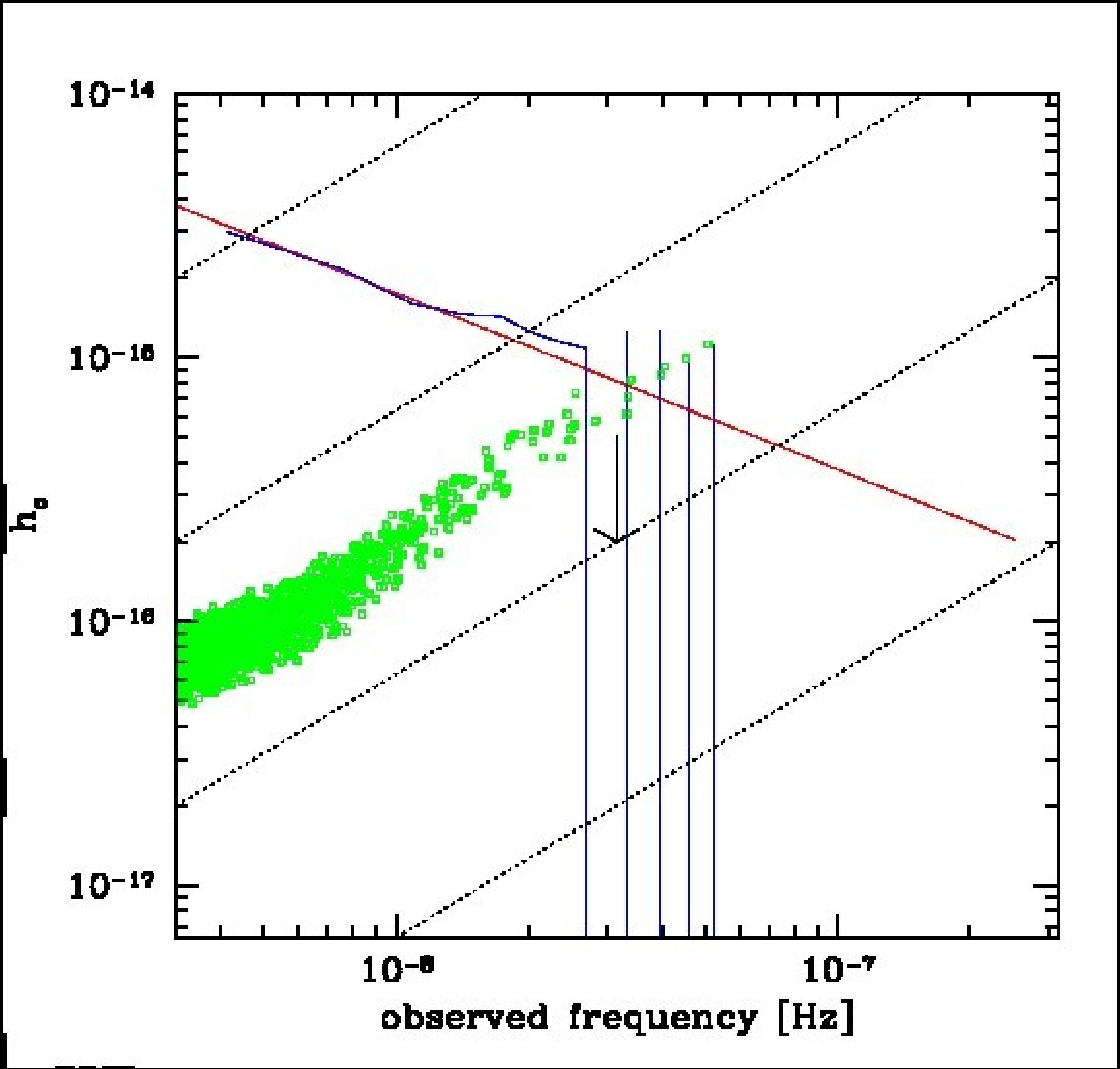
Gas driven binaries 2



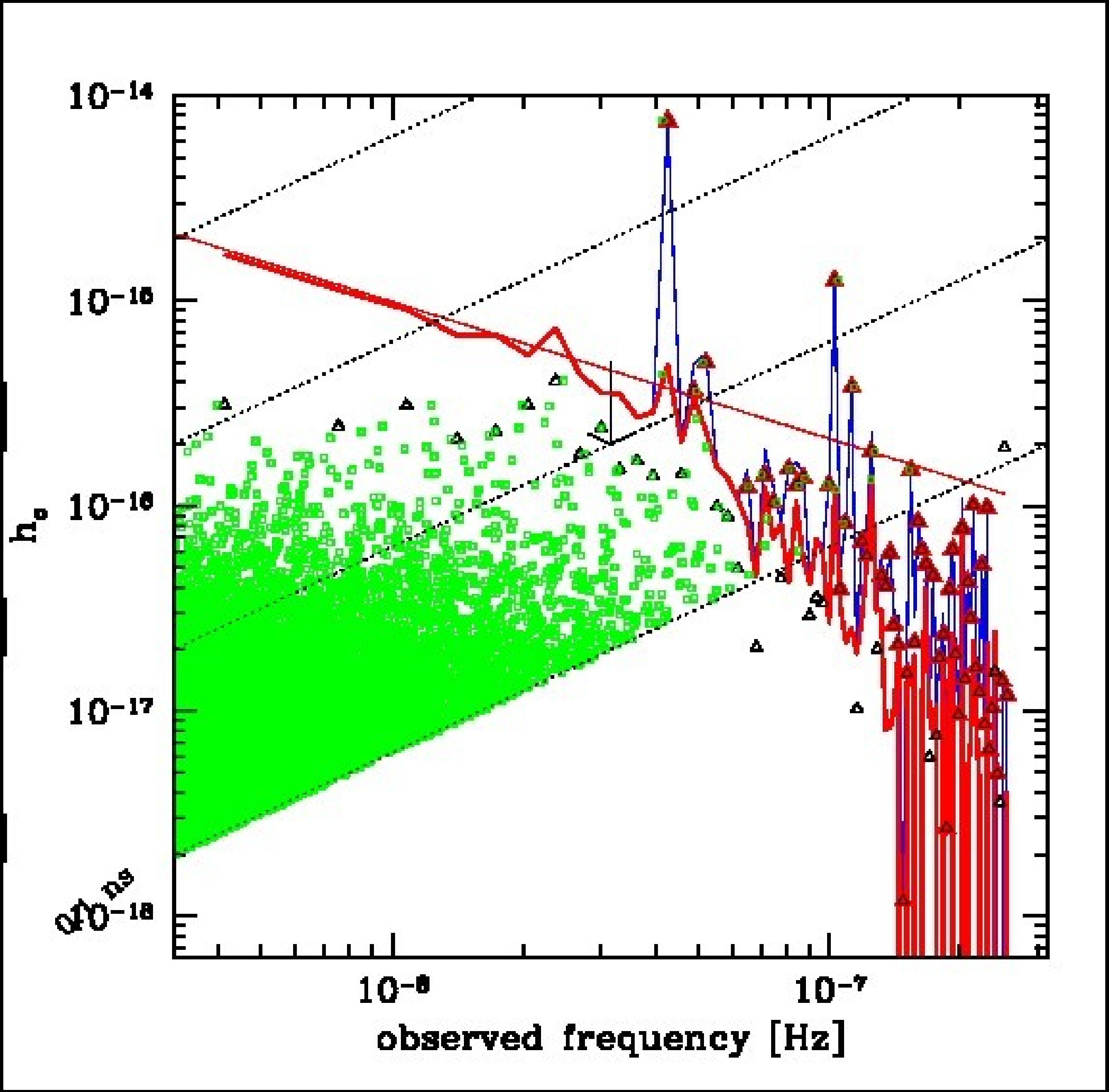


Signal lower and flatter at low *f*
Higher signal variance:
impossible to characterize the slope of the background a priori

The build-up of the signal

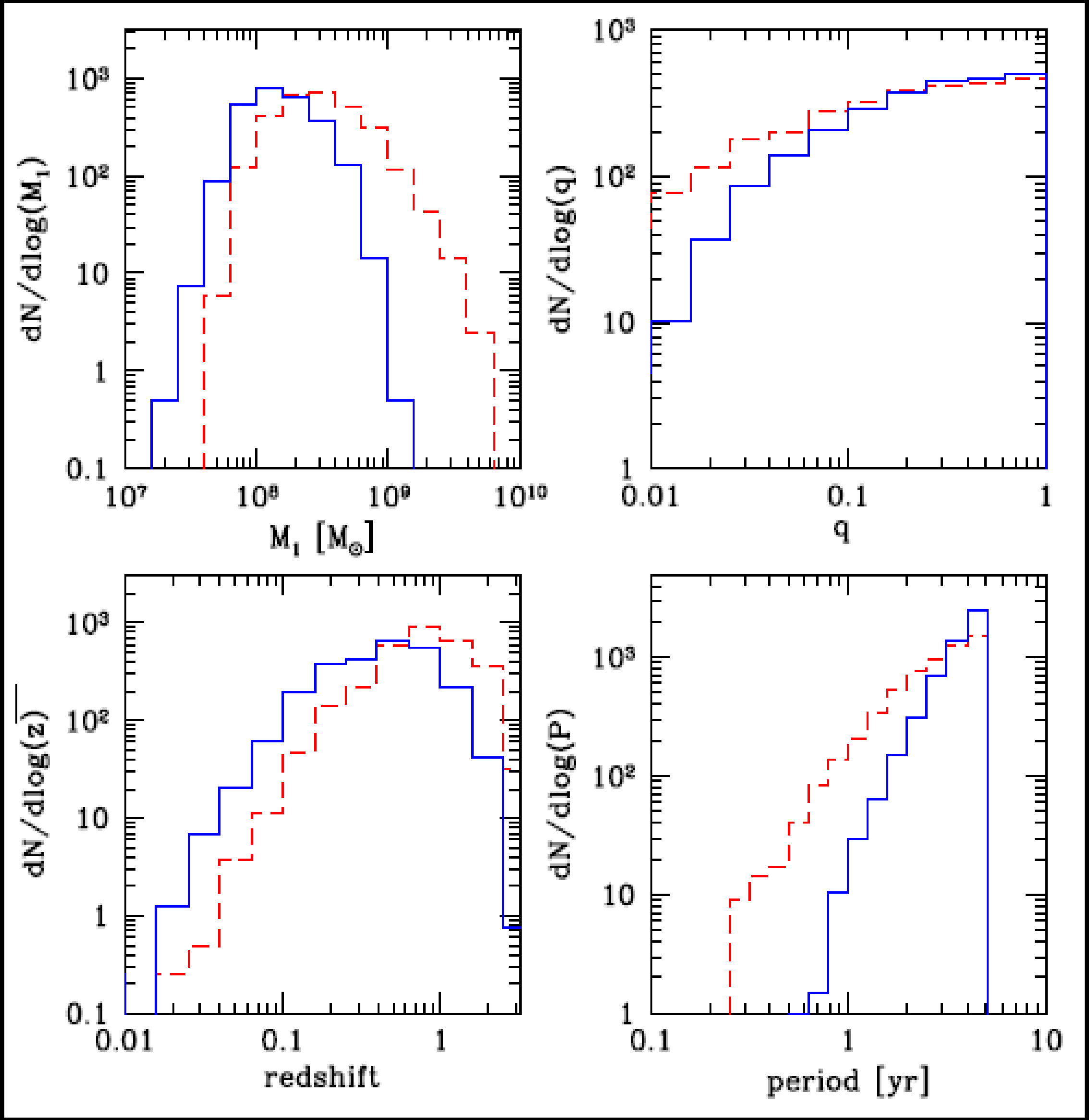


GW driven/circular binaries



periodic sources

L=0.3 L $_{Edd}$



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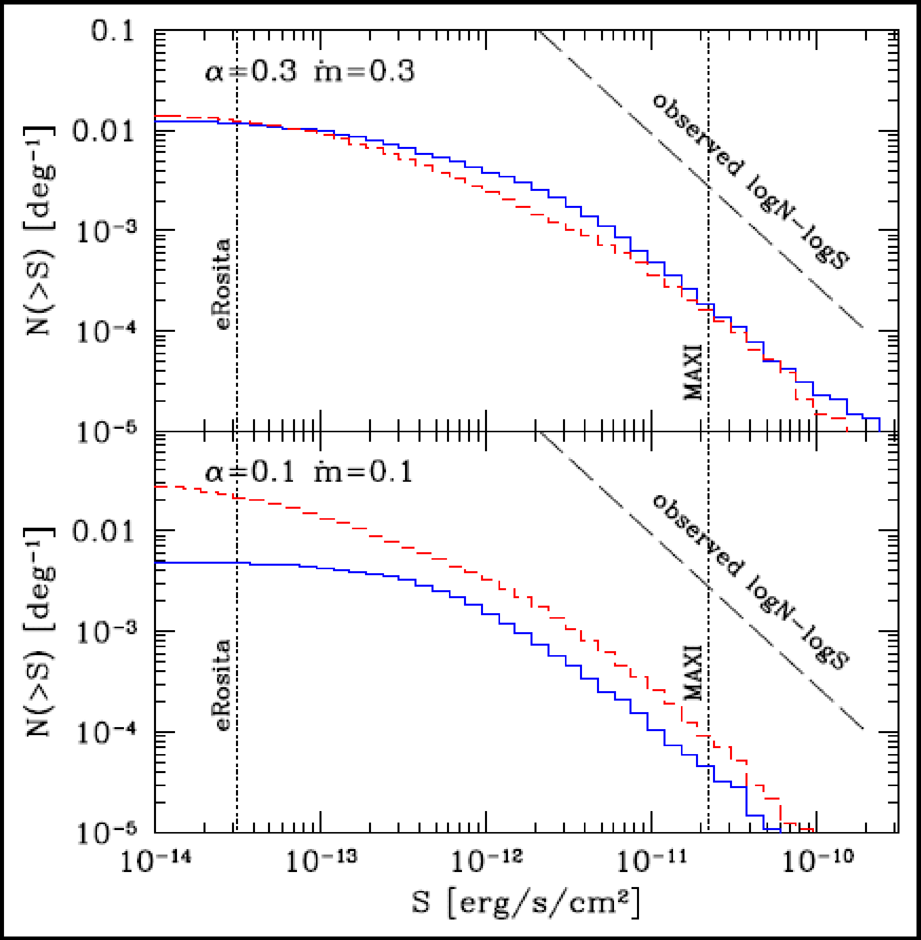

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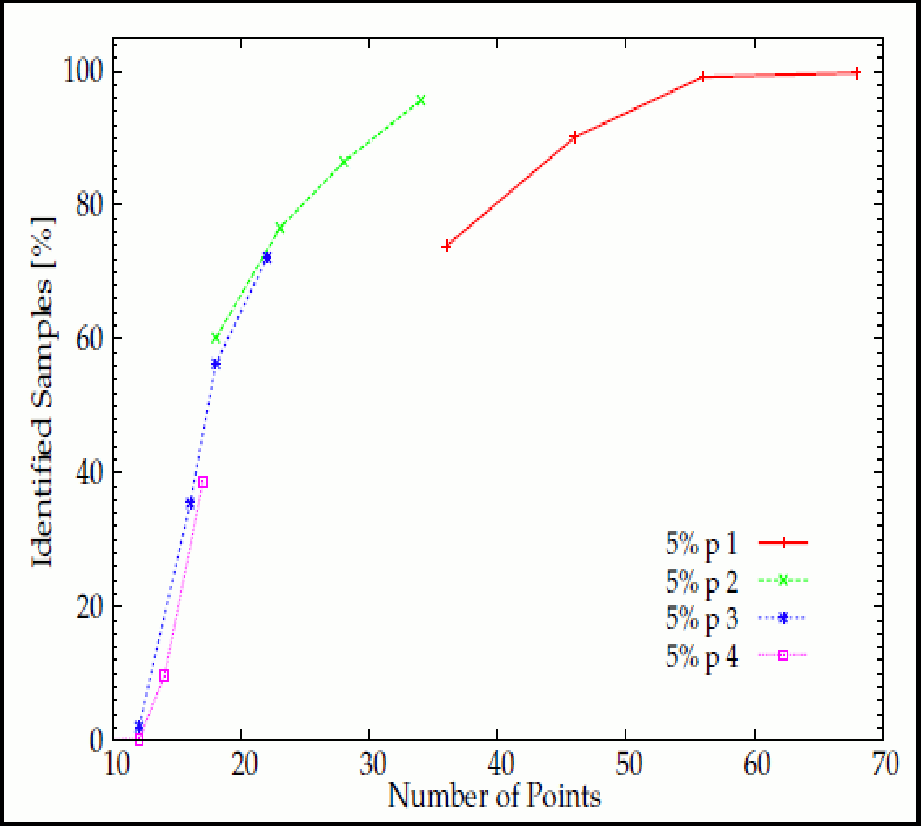
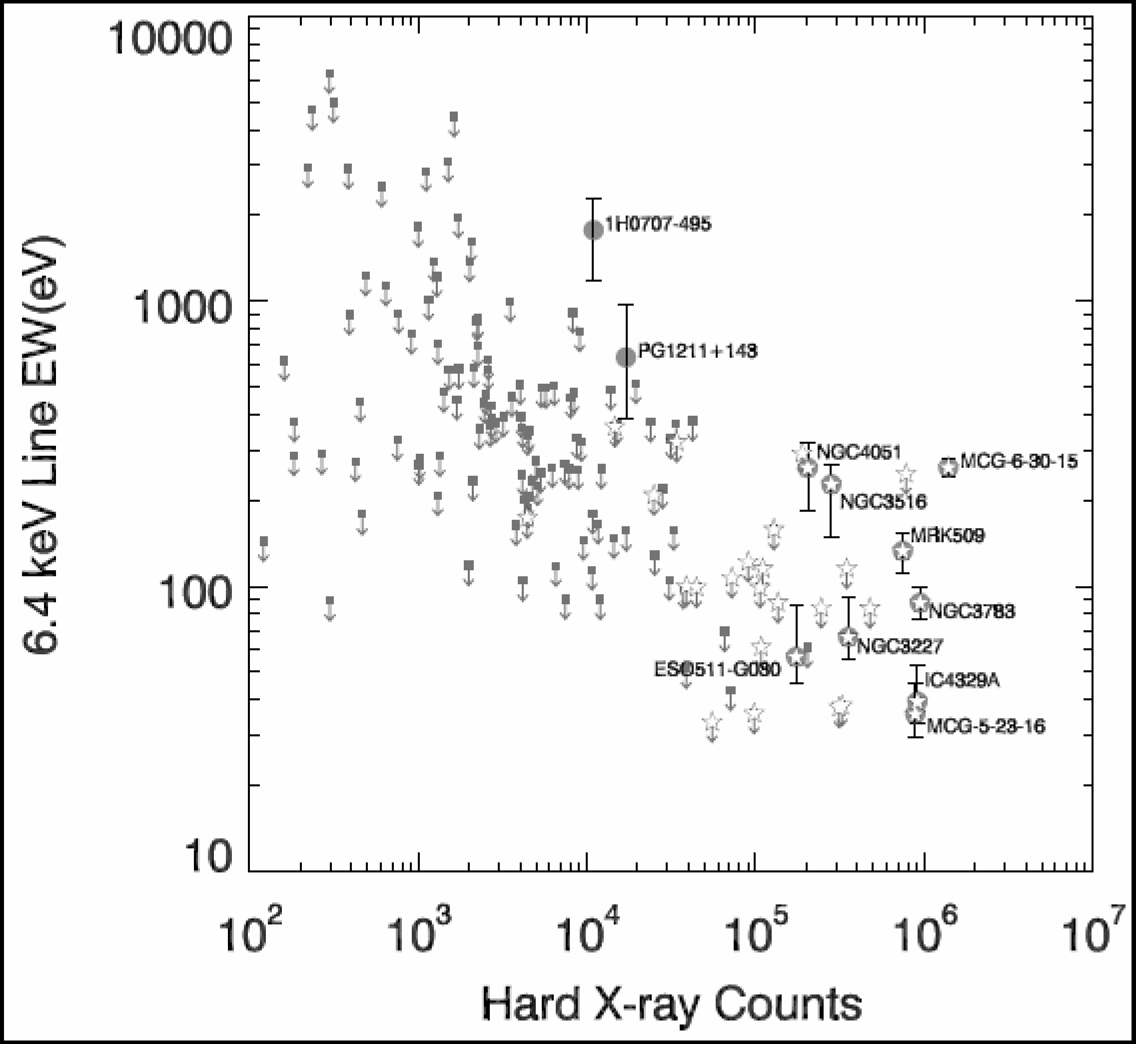


6.4keV Iron lines



Fluorescence emission line

Radiation emitted in the corona reprocessed by the inner parts of the accretion disk

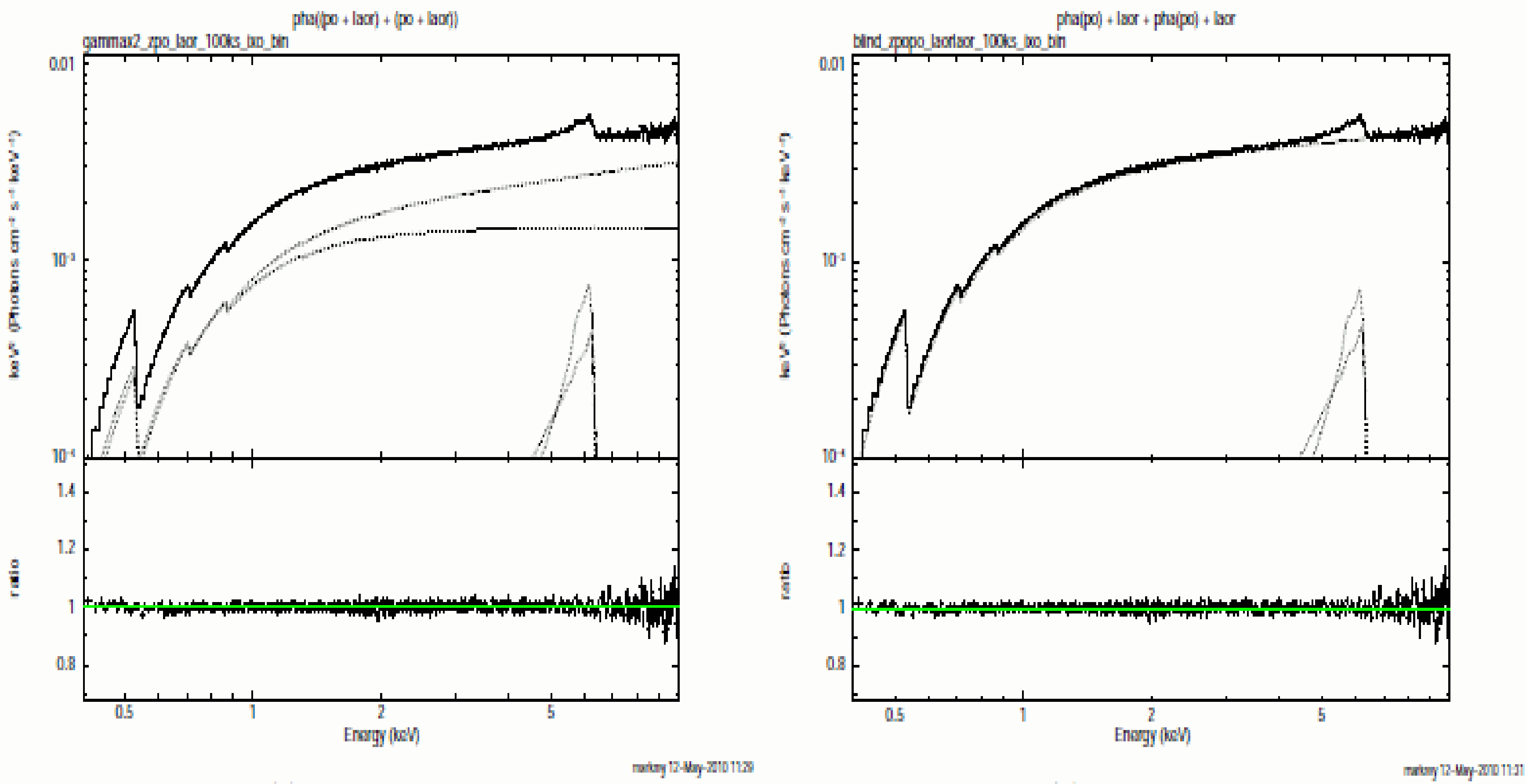
Potentially observable in all AGN with enough detected X-ray photons

Relativistic profile dependent on the line of sight and on the BH spin (but lots of unknowns)

Simulated next-generation X-ray spectra (Athena)

- -Two SMBHs, M_1=10^9 solar masses, q=1/3, spin parameters 0 and 0.9
- -Two-component X-ray continuum plus two 6.4keV iron lines
- -~100ks obsevation

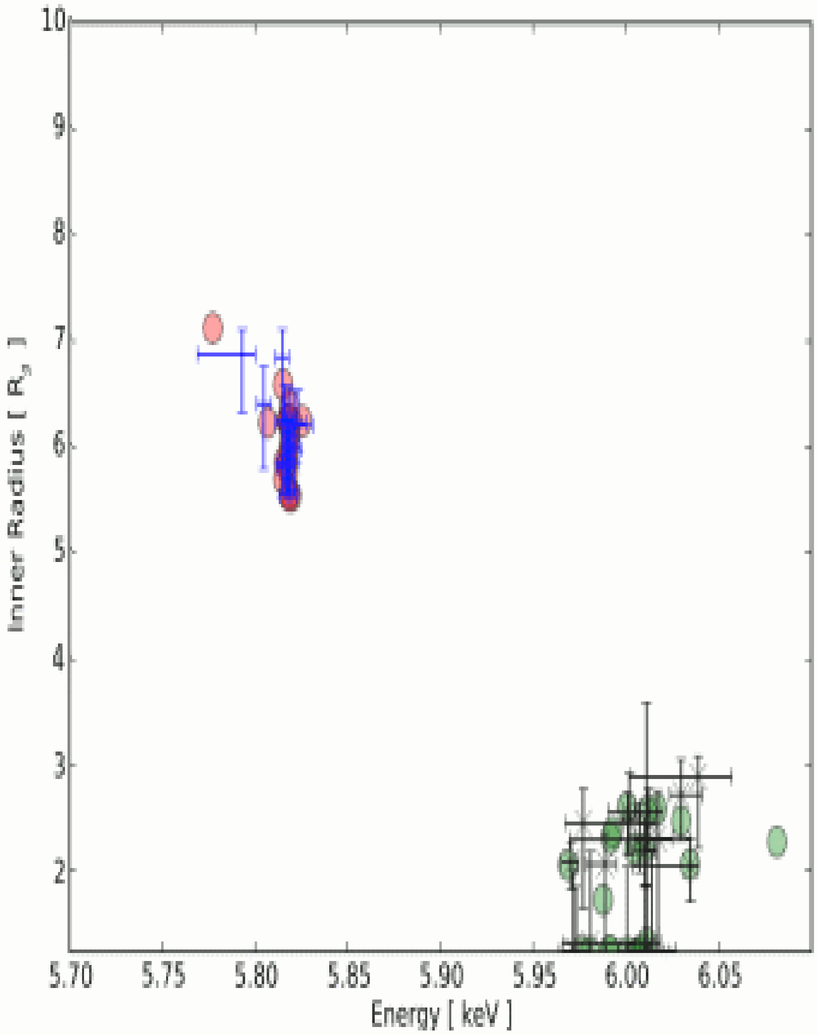
Almost face-on system z=0.1

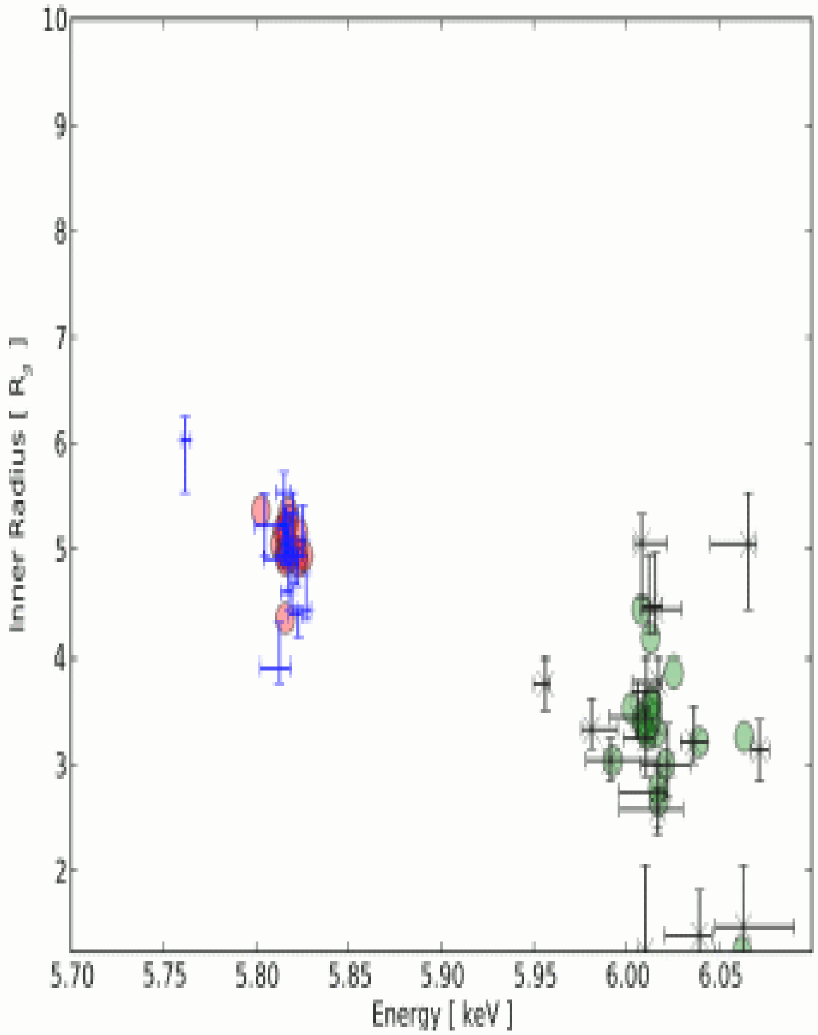


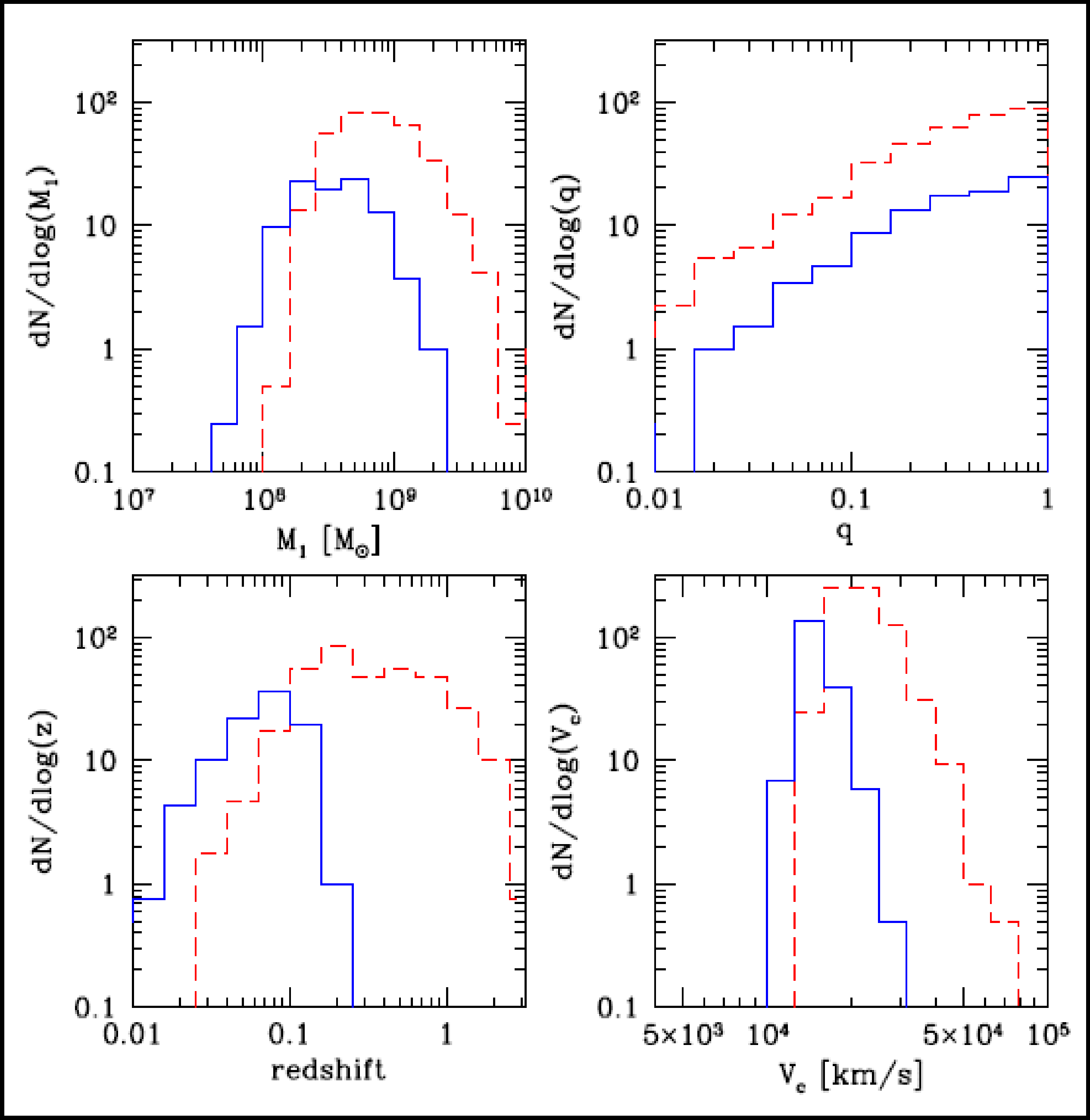
(a) Simulated data

(b) Best blind fit

Example of best fit parameters at z=0.1







-10-20 individually resolvable sources (still attached to their diks) with residual>1ns

-PTA sky location ~1-100 deg^2

-massive variable sources can help candidate selection

-follow-up X-ray spectroscopy

Summary

the formation and evolution of MBH(B)s is hierarchical and
We can investigate it with semianalytical and numerical tool

Following mergers MBHBs efficiently form and are driven to
coalescence by interacting with their stellar and/or gaseou
Environment

> MBHB eccentricity grows in the hardening process. Spin
evolution depends on the dynamical properties of the
accretion flow

e*LISA* will detect 10-1000 MBHBs over a 3 yrs
lifetime --> will provide information about seed BHs

> Future PTAs will detect the unresolved MBHB background
--> will probe MBH(B) population al low *z* and large masse
And will resolve at least few individual MBHBs

Future X-ray probe are promising for multimessenger
astronomy with PTA sources

3-Calculate the timing residual *R*

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

If your model is perfect, then R=0. R contains all the uncertainties related to the signal propagation and detection plus the effect of unmodelled physics, like -possibly- ***gravitational waves***

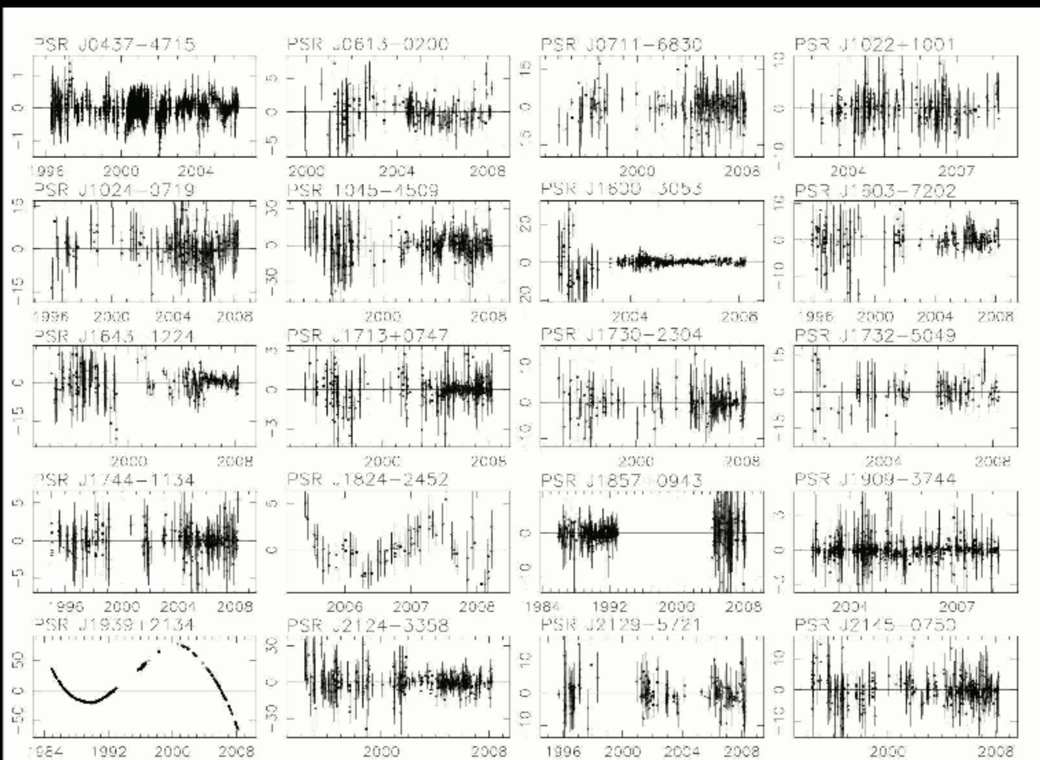
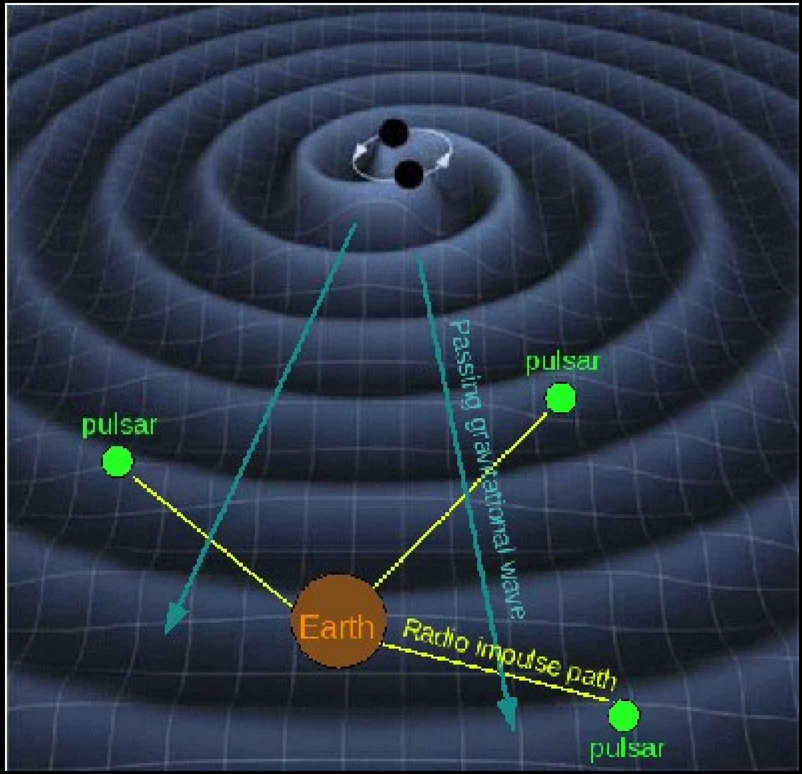


Figure 1. Timing residuals of the 20 pulsars in our sample. Scaling on the x-axis is in years and on the y-axis in μs. For PSRs J1857+0943 and J1939+2134, these plots include the Arecibo data made publically available by Kaspi et al. (1994); all other data are from the Parkes telescope, as described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



The GW passage cause a modulation of the MSP frequency

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

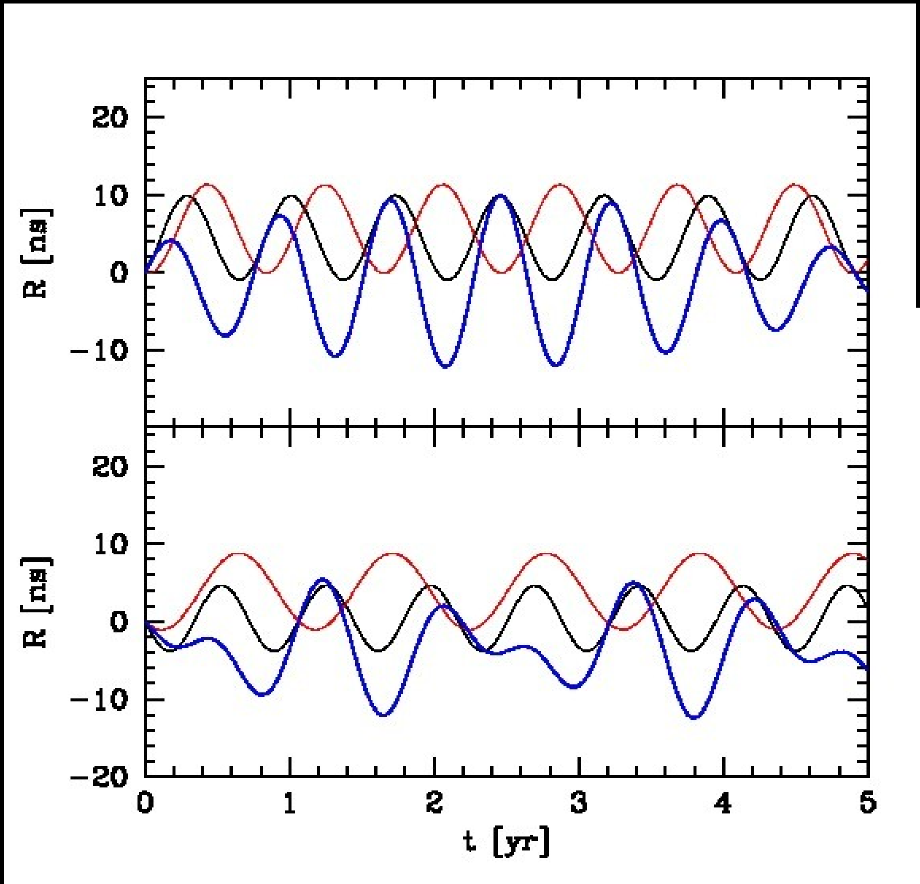
The ***residual*** in the time of arrival of the pulse is the integral of the frequency modulation over time

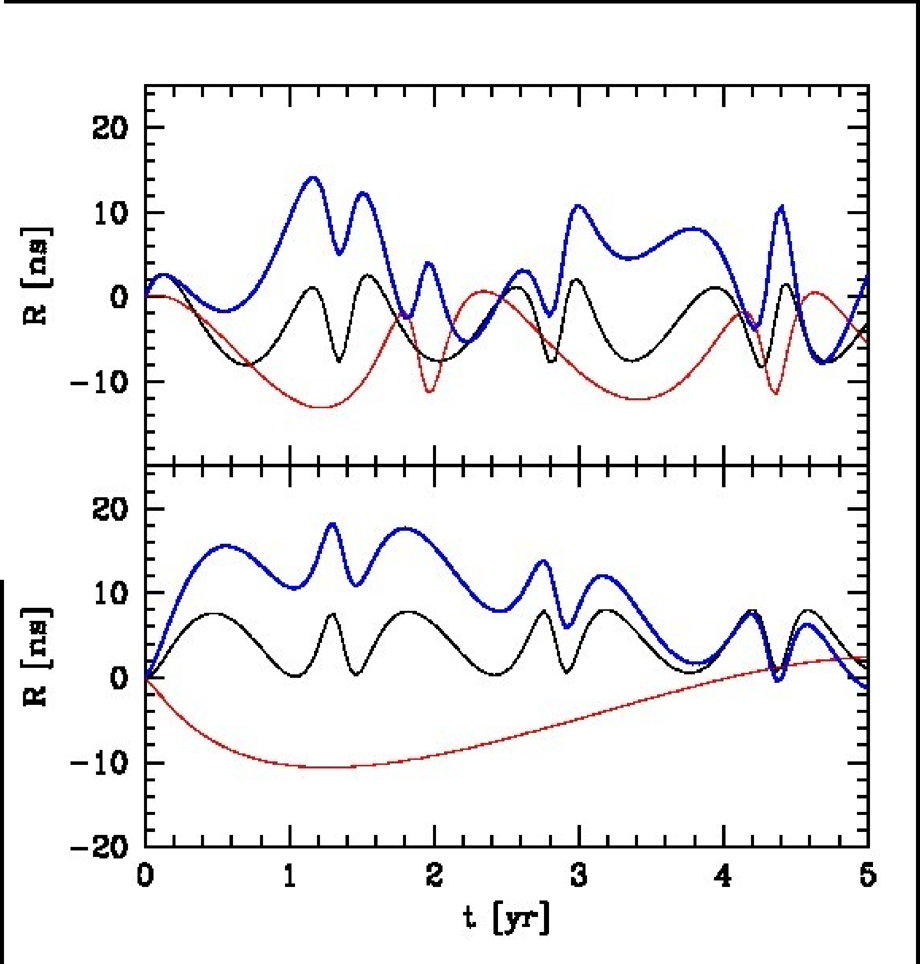
$$R(t) = \int_0^T \frac{\nu(t)-\nu_0}{\nu_0}\, dt$$

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

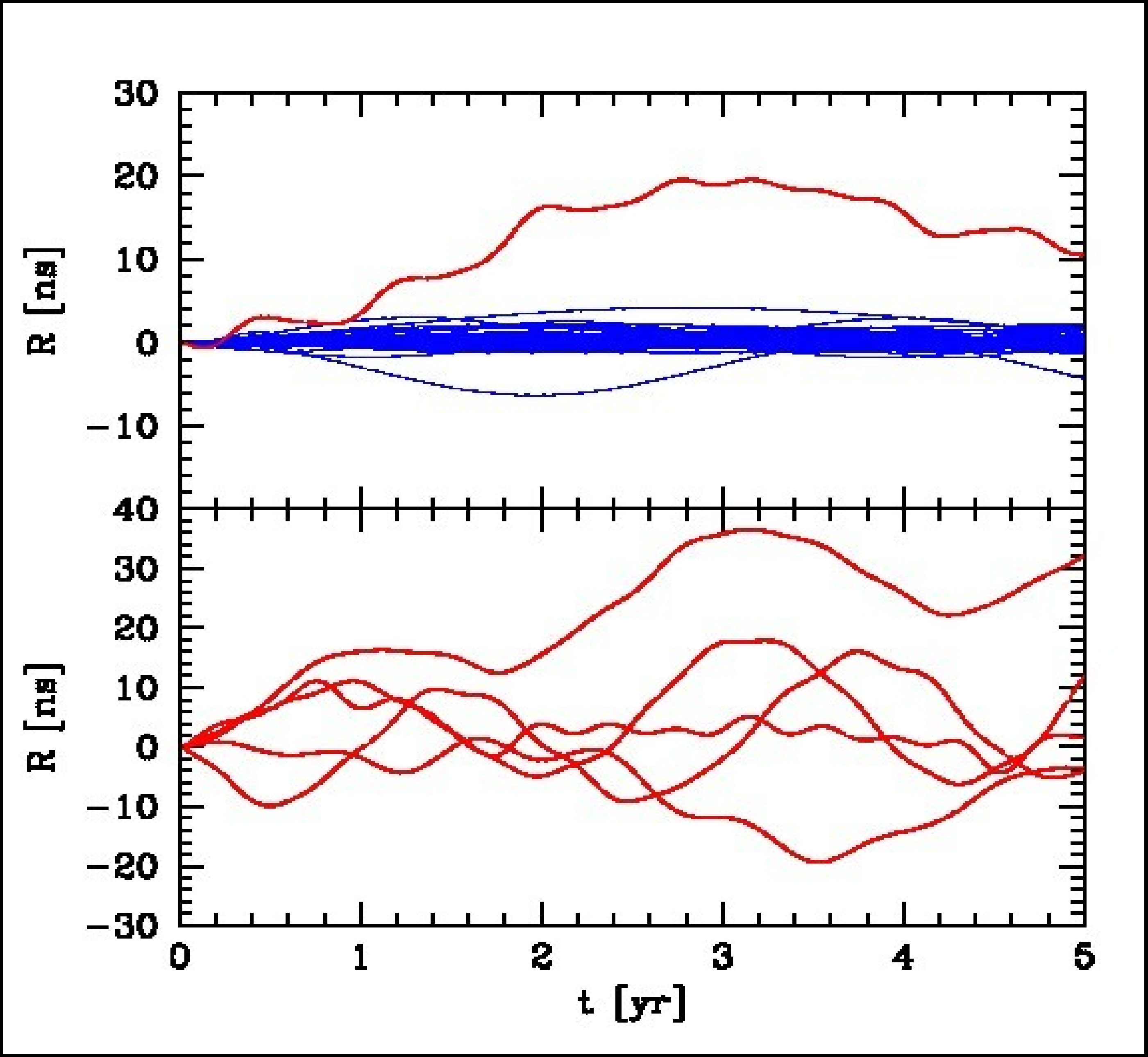
$$\begin{aligned} &= \quad \frac{\mathcal{M}^{5/3}}{D}\,[\pi f(t)]^{-1/3} \\ &\simeq \quad 25.7\left(\frac{\mathcal{M}}{10^9\,M_\odot}\right)^{5/3}\left(\frac{D}{100\,\mathrm{Mpc}}\right)^{-1} \\ &\quad\ \times\left(\frac{f}{5\times10^{-8}\,\mathrm{Hz}}\right)^{-1/3}\ \mathrm{ns} \end{aligned}$$

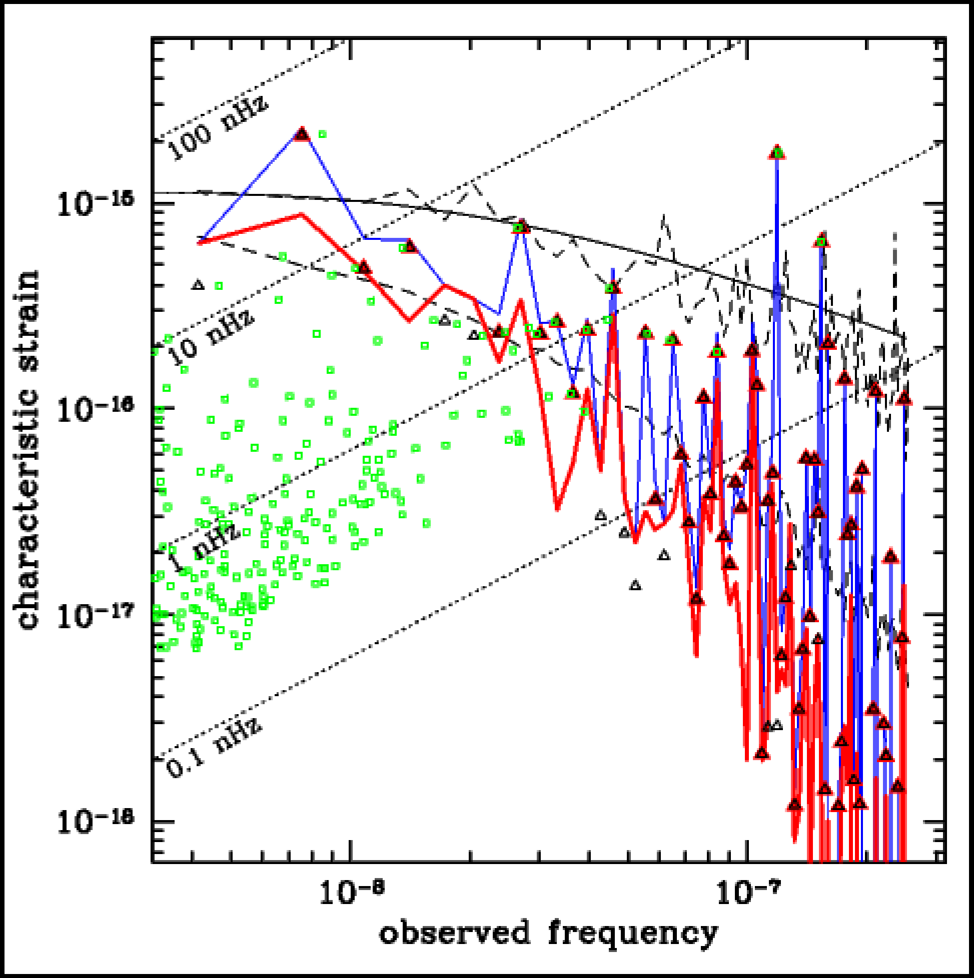
Single sources





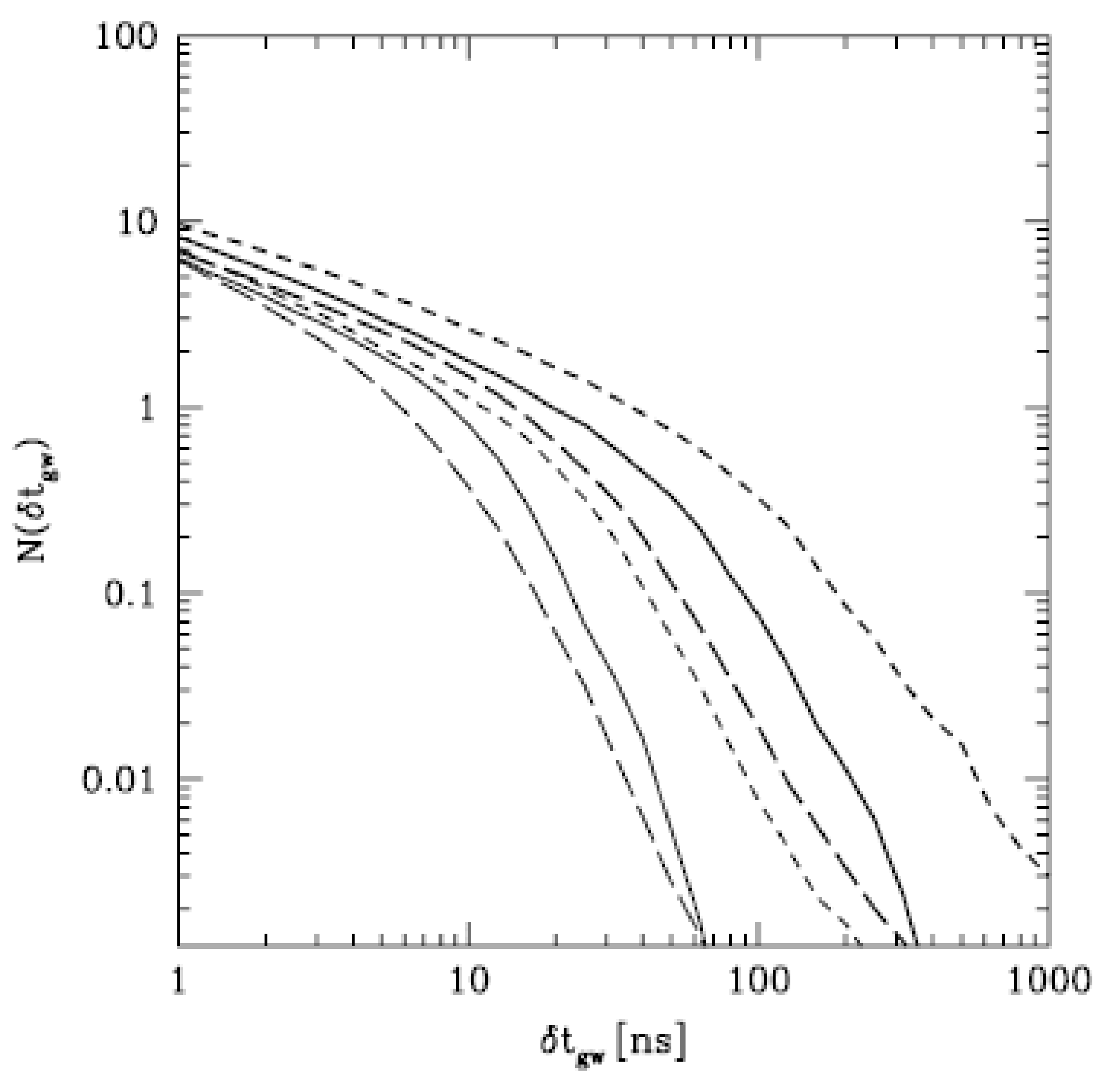
Generating global residuals





100 nHz
10 nHz
1 nHz
0.1 nHz
10^{-15}
10^{-16}
10^{-17}
10^{-18}
characteristic strain
10^{-8}
10^{-7}
observed frequency

Cumulative number of resolvable sources

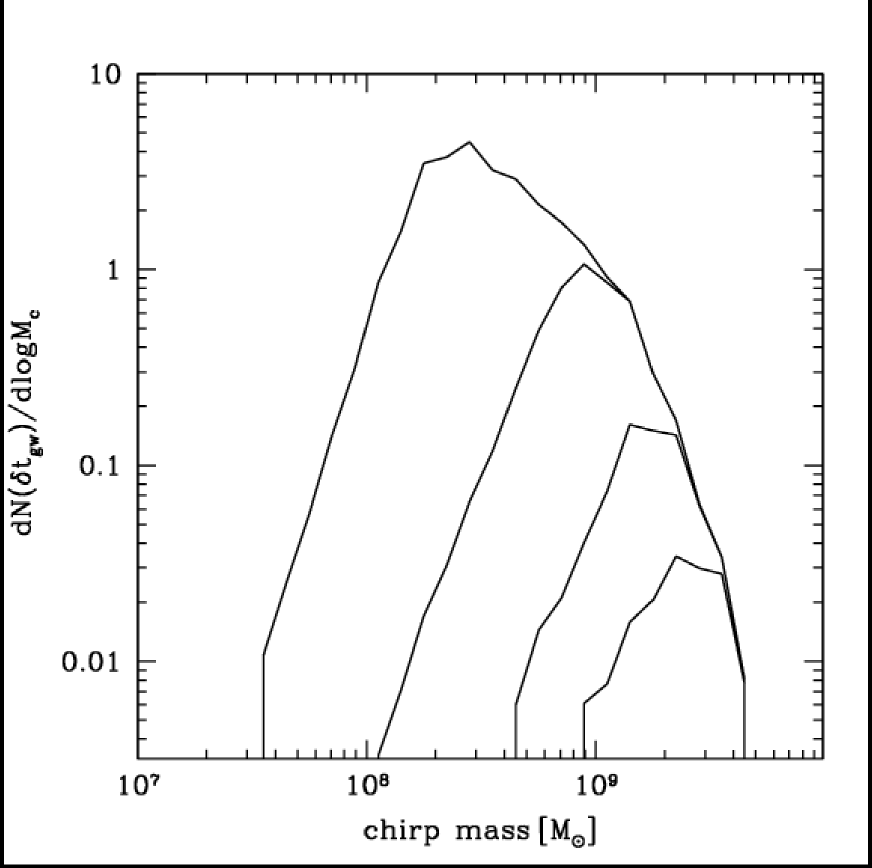


(Sesana Vecchio & Volonteri 2009)

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

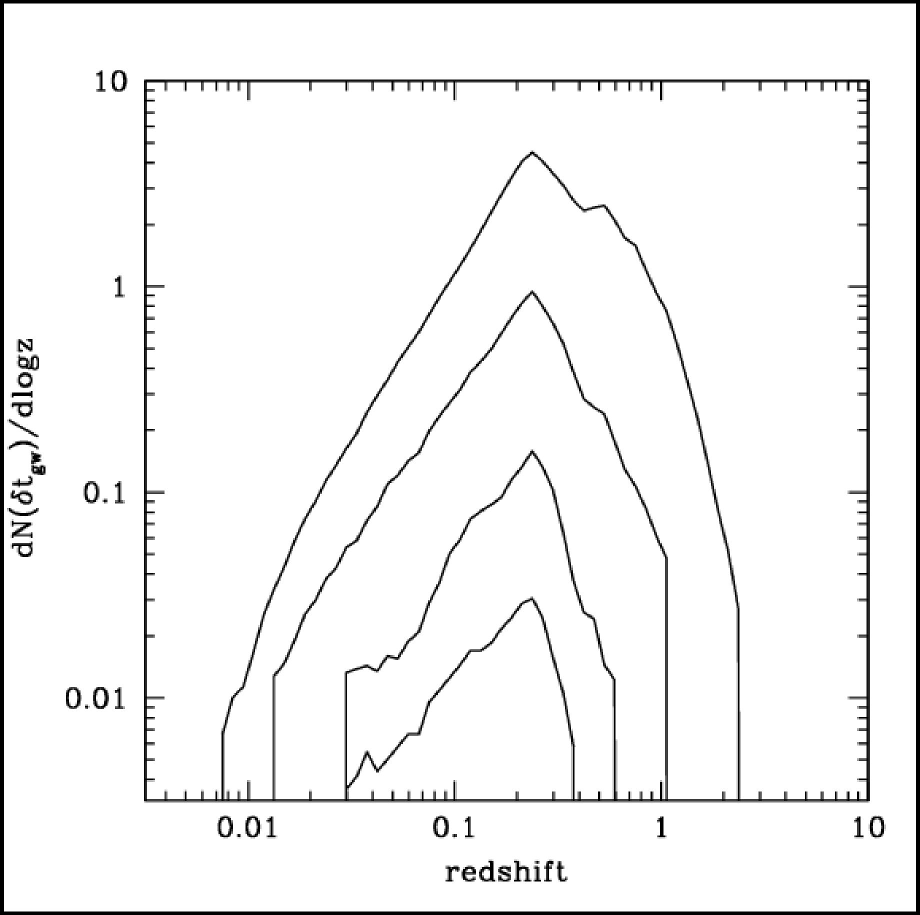
>Uncertainties depend on the ***MBH-host*** relation and MBH ***accretion route*** during mergers

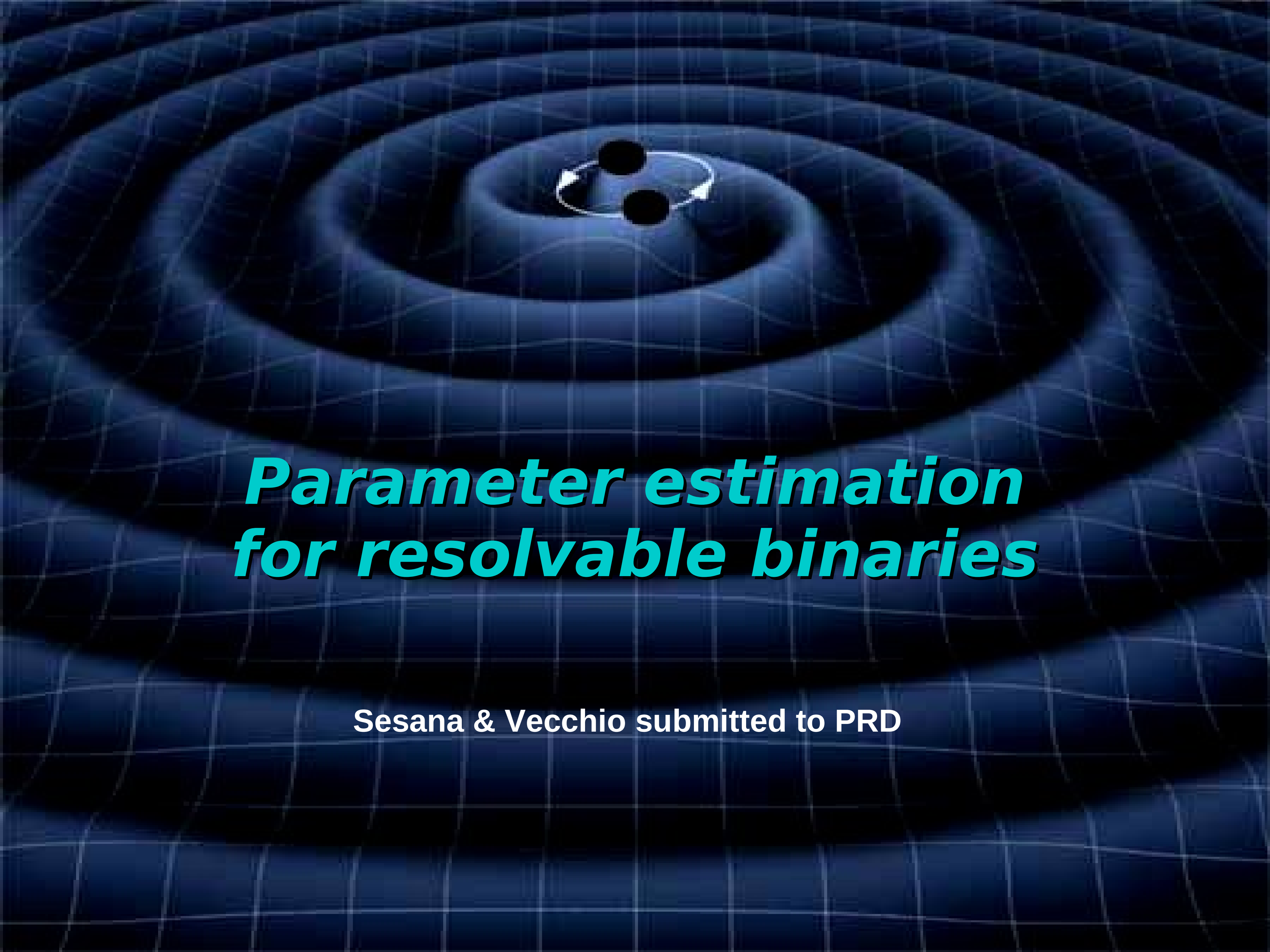
Source distributions



Probe very massive systems
mass > *10^8* solar masses

Probe MBHs at
low-to-medium redshift ***0.1<z<1.5***





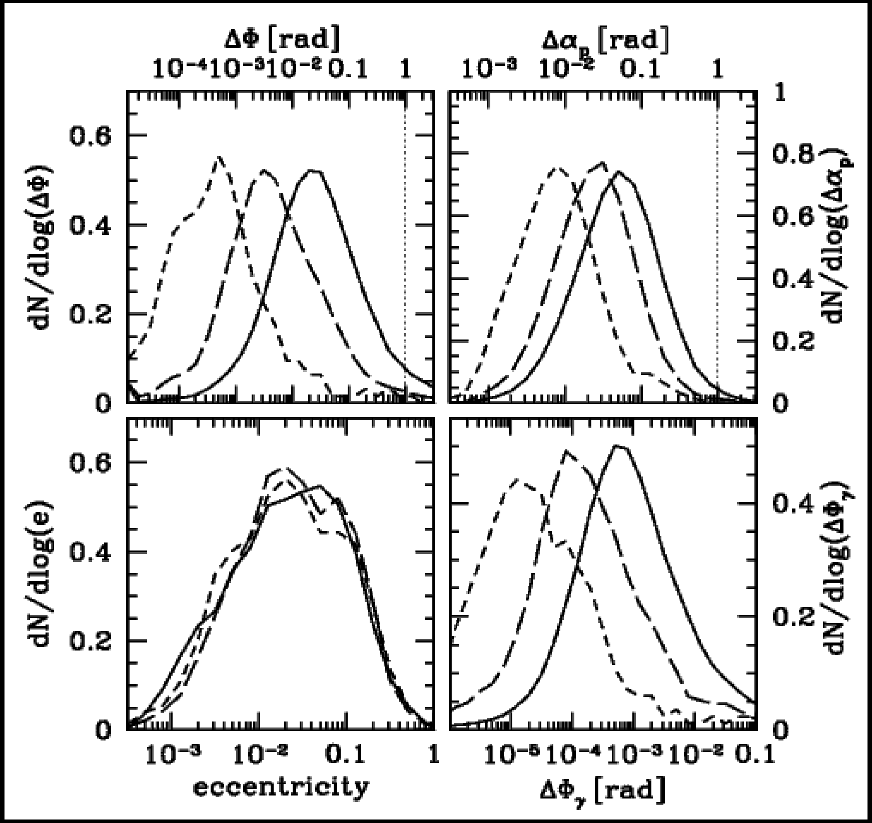
Parameter estimation for resolvable binaries

Sesana & Vecchio submitted to PRD

Why circular, non evolving binaries

>Dynamical models for MBHB evolution in stellar environments predict *mild eccentricities* in the PTA window, if binaries were circular at the moment of pairing (Sesana, private communication)

>Frequency drift, mild eccentricities and spin orbit coupling have a *negligible effect* on the orbital evolution and on the waveform



$$\Delta\Phi \approx \pi \dot{f} T^2 \approx 0.04\, \mathcal{M}_{8.5}^{5/3}\, f_{50}^{11/3}\, T_{10}^2 \;\; \mathrm{rad}$$

$$\Delta\Phi_\gamma \approx \frac{d^2\gamma}{dt^2} T^2 = \frac{96\pi^{13/3}}{(1-e^2)} M^{2/3} \mathcal{M}^{5/3} f^{13/3} T^2 \approx 2\times 10^{-3} \left(1-e^2\right)^{-1} M_9^{2/3} \mathcal{M}_{8.5}^{5/3}\, f_{50}^{13/3}\, T_{10}^2\,\mathrm{rad}$$

$$\Delta\alpha_p \approx 2\pi^{5/3}\left(1+\frac{3m_2}{4m_1}\right)\mu M^{-1/3} f^{5/3} T \approx 0.8\left(1+\frac{3m_2}{4m_1}\right)\left(\frac{\mu}{M}\right) M_9^{2/3} f_{50}^{5/3} T_{10}\,\mathrm{rad}$$

But binaries may as well be eccentric (Sesana Haardt & Amaro-Seoane, in prep.)
Eccentric waveform deferred to future work.

SMBHs DYNAMICS

1. **dynamical friction** (Lacey & Cole 1993, Colpi et al. 2000)

- from the interaction between the DM halos to the formation of the BH binary
- determined by the global distribution of matter
- efficient only for ***major mergers*** against mass stripping

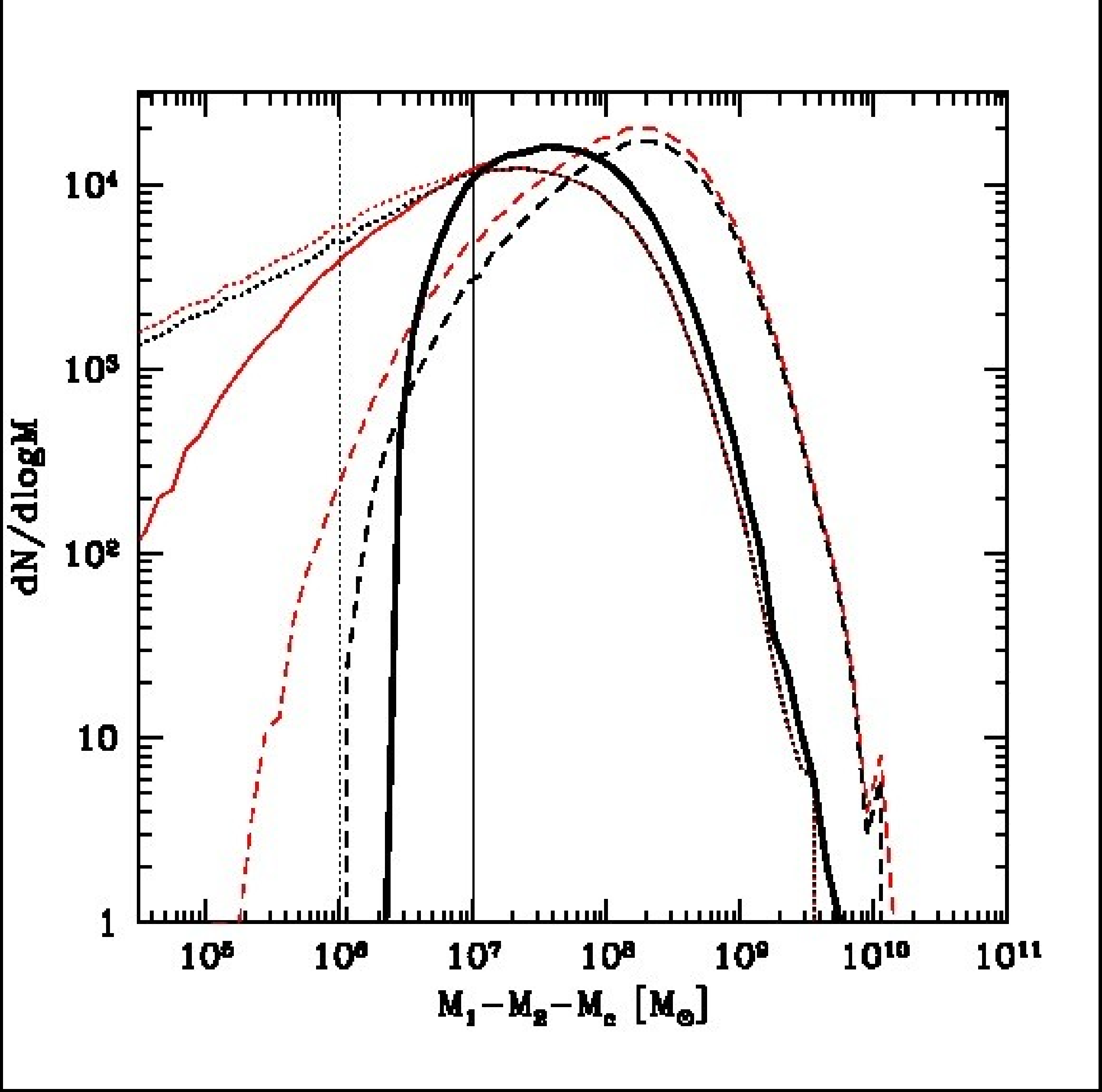
2. **binary hardening** (Quinlan 1996, Miloslavljevic & Merritt 2001, Sesana et al. 2007)

- ***3 bodies interactions*** between the binary and the surrounding stars
- the binding energy of the BHs is larger than the thermal energy of the stars
- the SMBHs create a ***stellar density core ejecting the background stars***

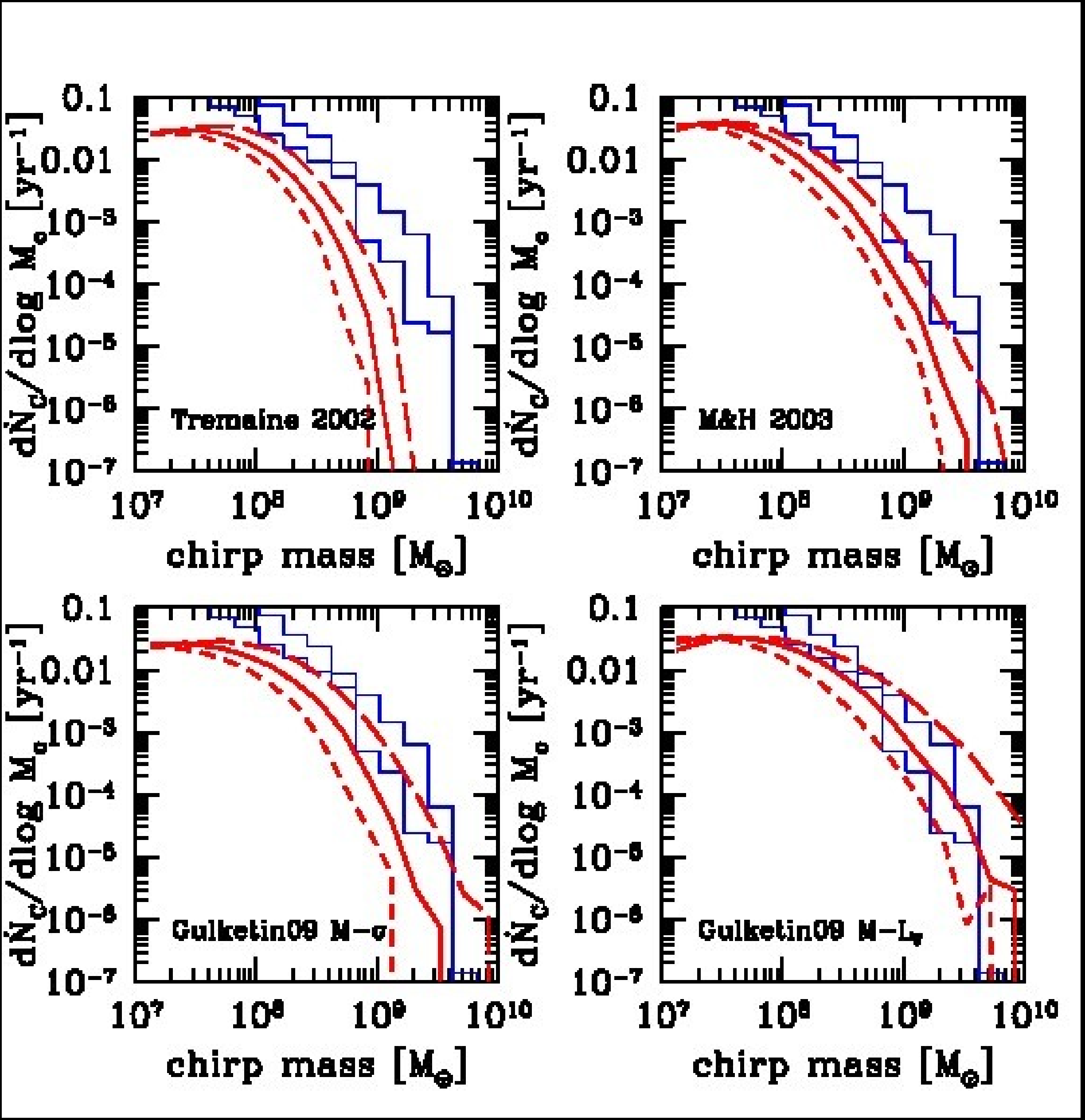
3. **emission of gravitational waves** (Peters 1964)

- takes over at subparsec scales
- leads the binary to coalescence

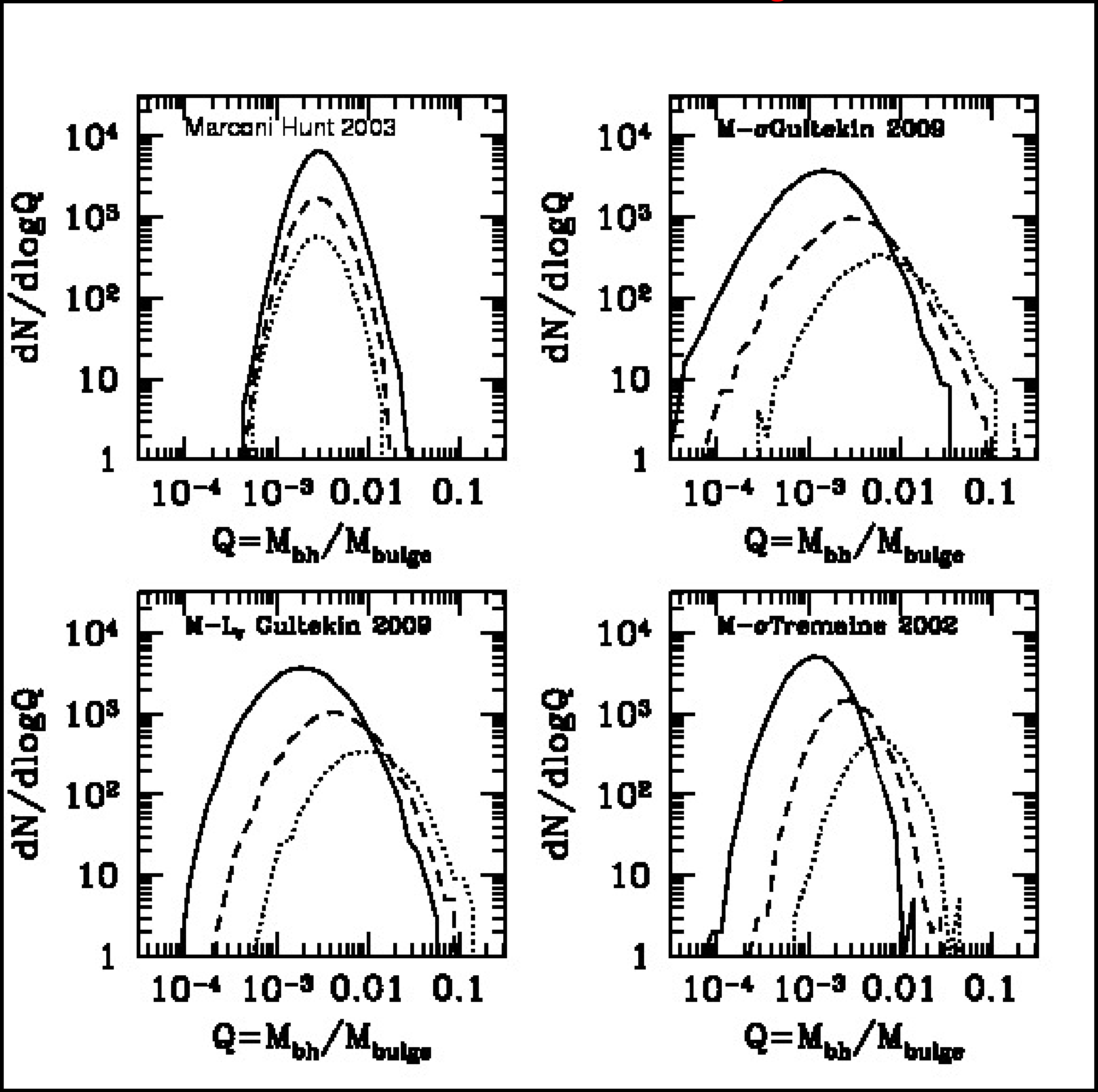
Selecting the MBHB population



Coalescing MBHB mass function



Evolution of the M_{BH}-M_{bulge} relation



The merging galaxy fraction