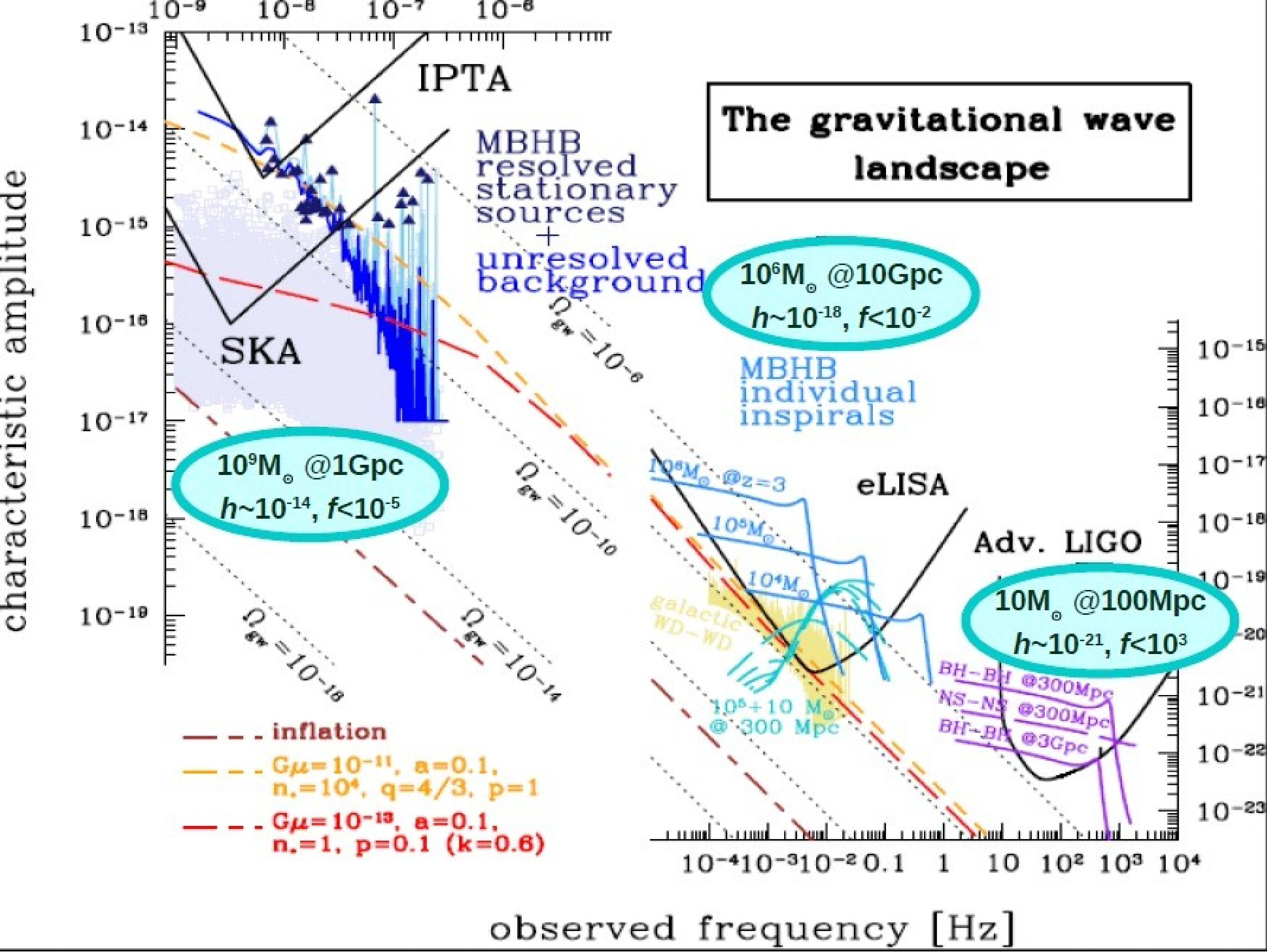
Lessons on Supermassive Black Hole Binaries from Pulsar Timing Arrays

Alberto Sesana

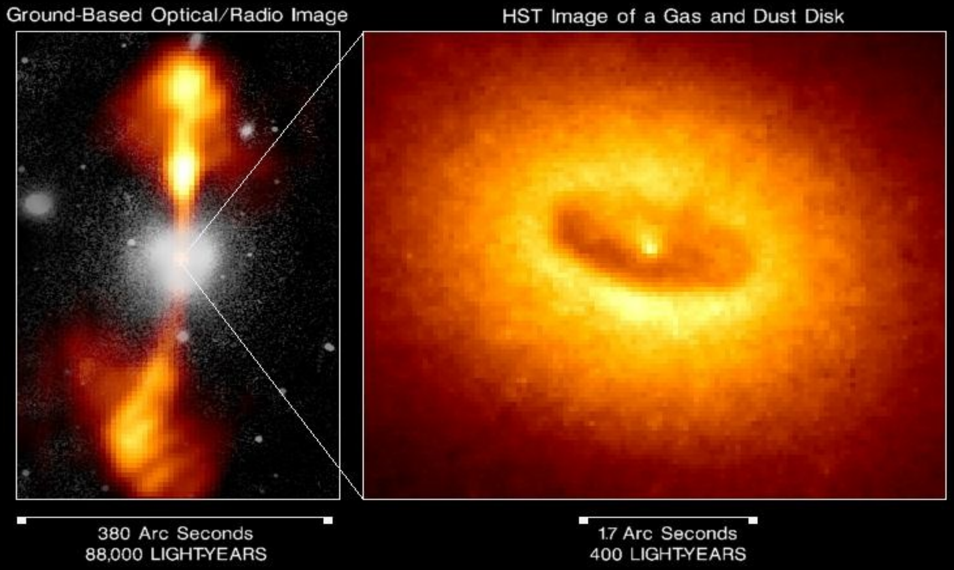
(Univeristy of Birmingham)

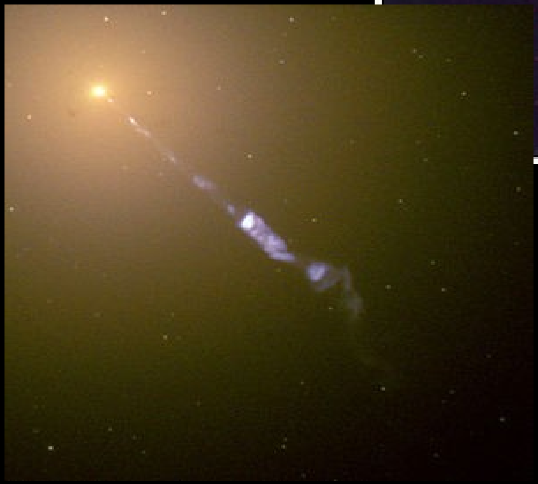
The gravitational wave landscape

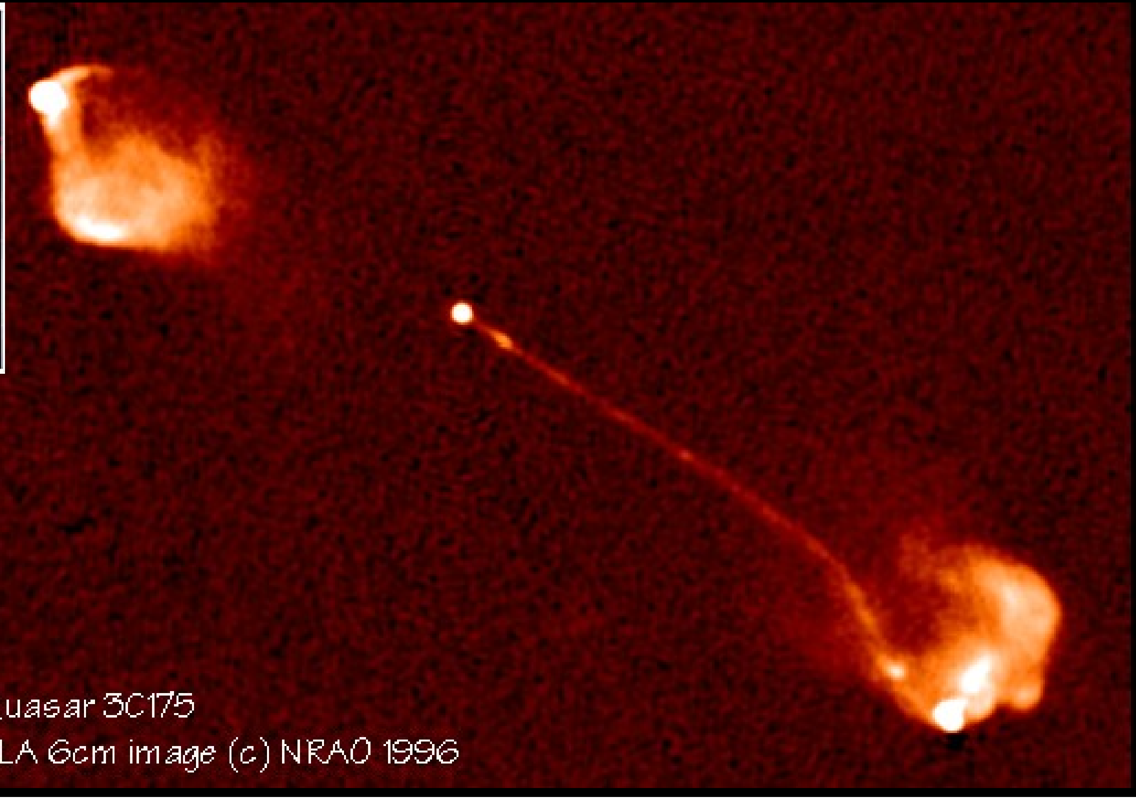


Core of Galaxy NGC 4261

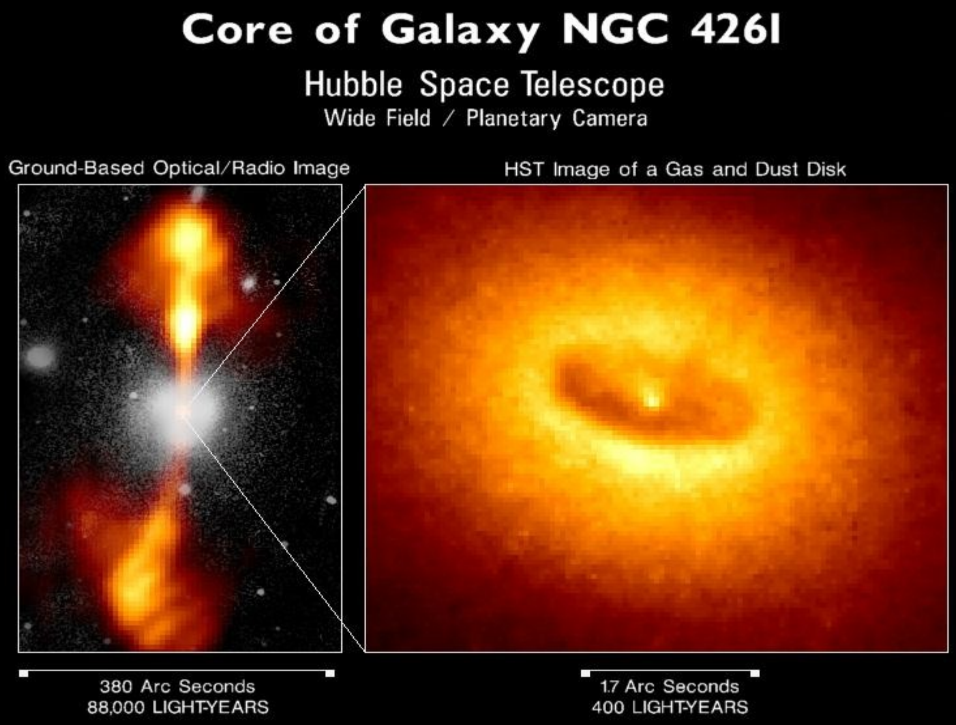
Hubble Space Telescope
Wide Field / Planetary Camera





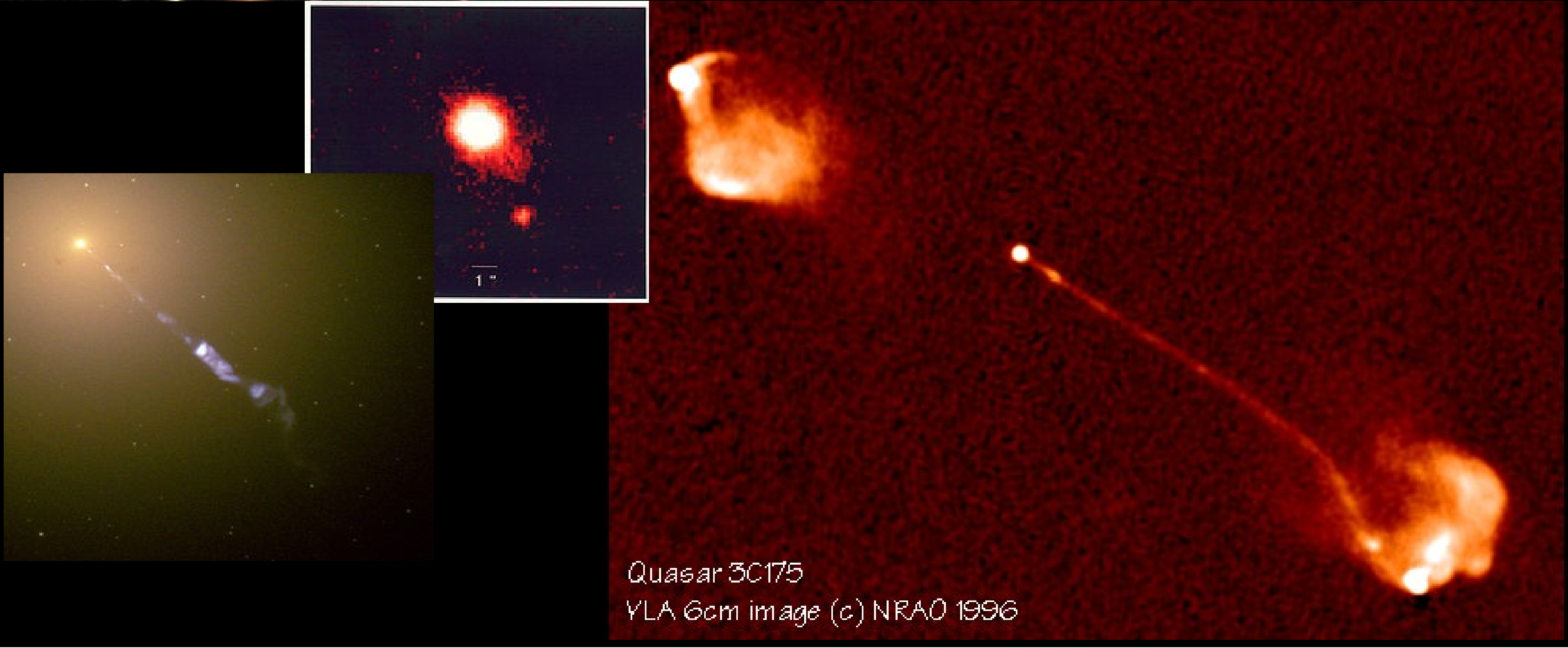


Quasar 3C175
VLA 6cm image (c) NRAO 1996

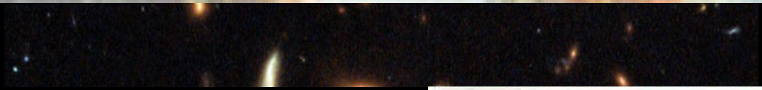


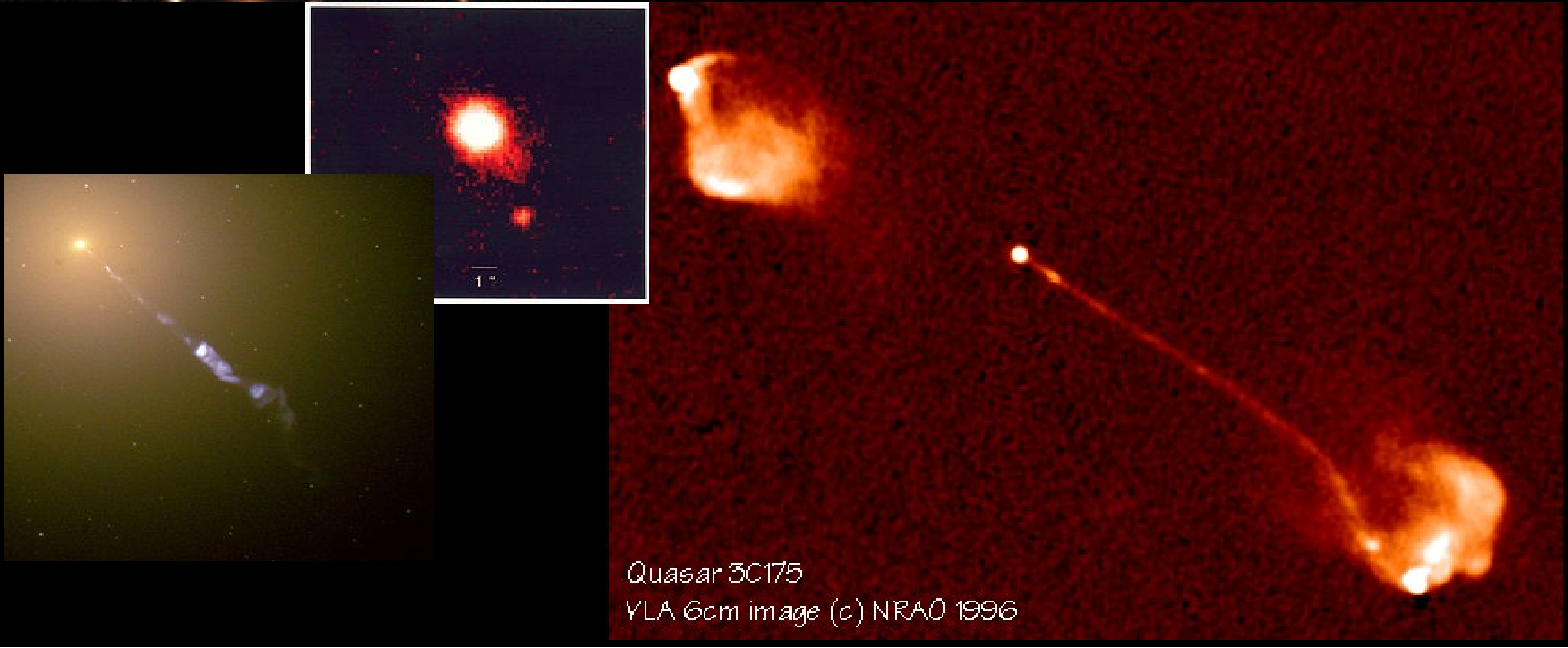
Core of Galaxy NGC 4261

Hubble Space Telescope
Wide Field / Planetary Camera



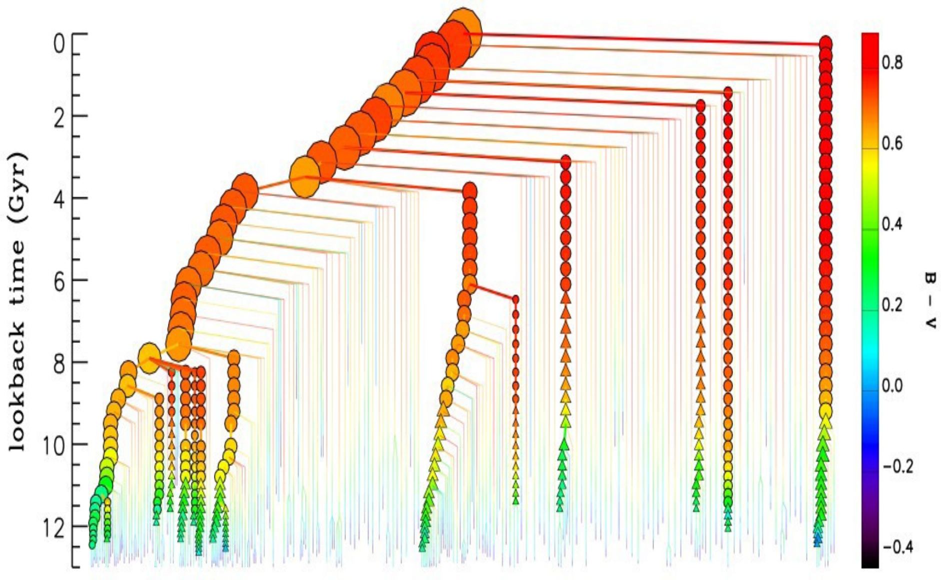
Quasar 3C175
VLA 6cm image (c) NRAO 1996





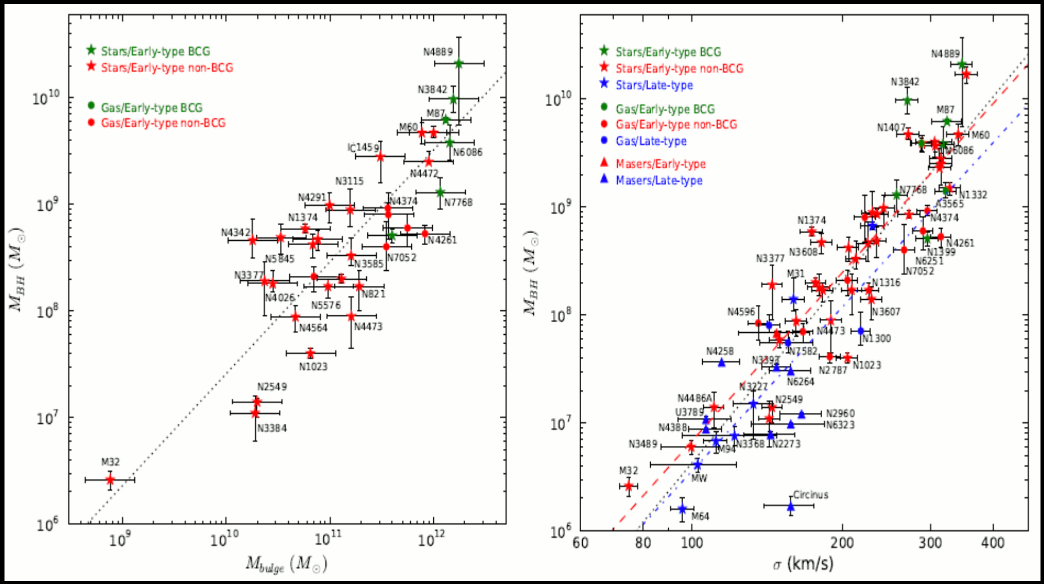
Quasar 3C175
VLA 6cm image (c) NRAO 1996

Structure formation in a nutshell



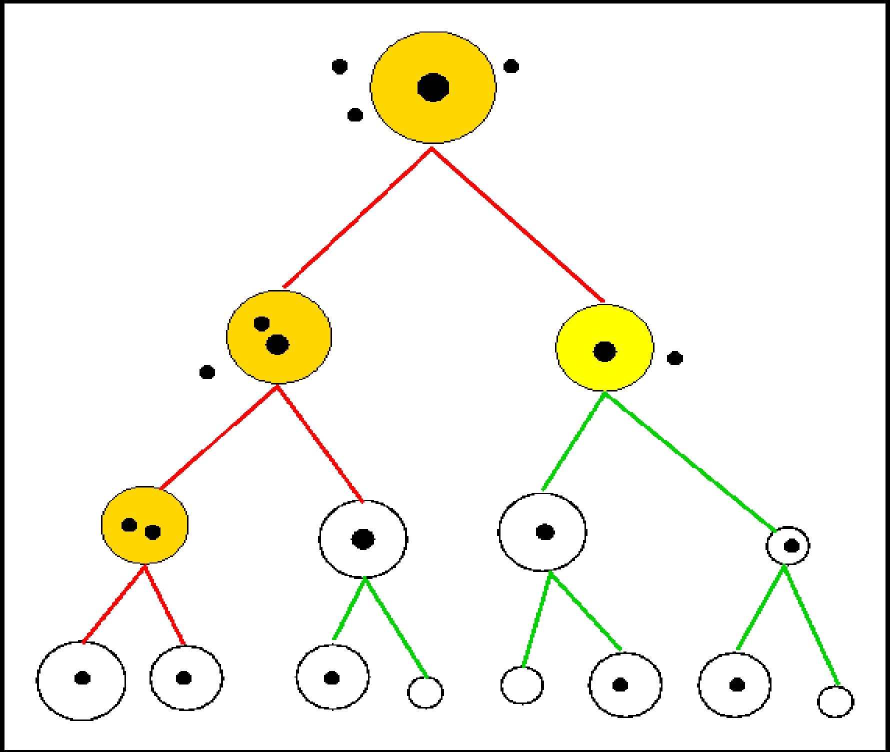
(From de Lucia et al. 2006)

+



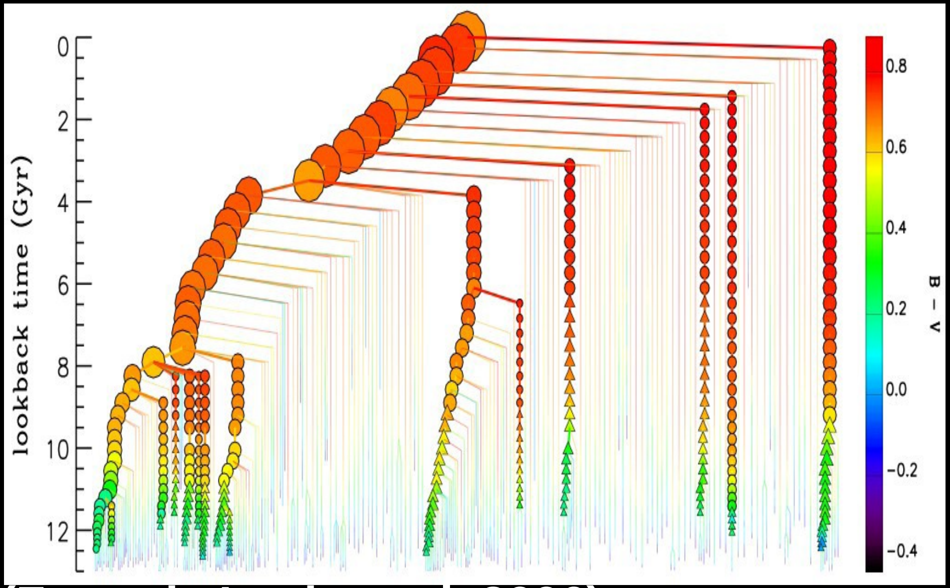
(Ferrarese & Merritt 2000, Gebhardt et al. 2000)

=



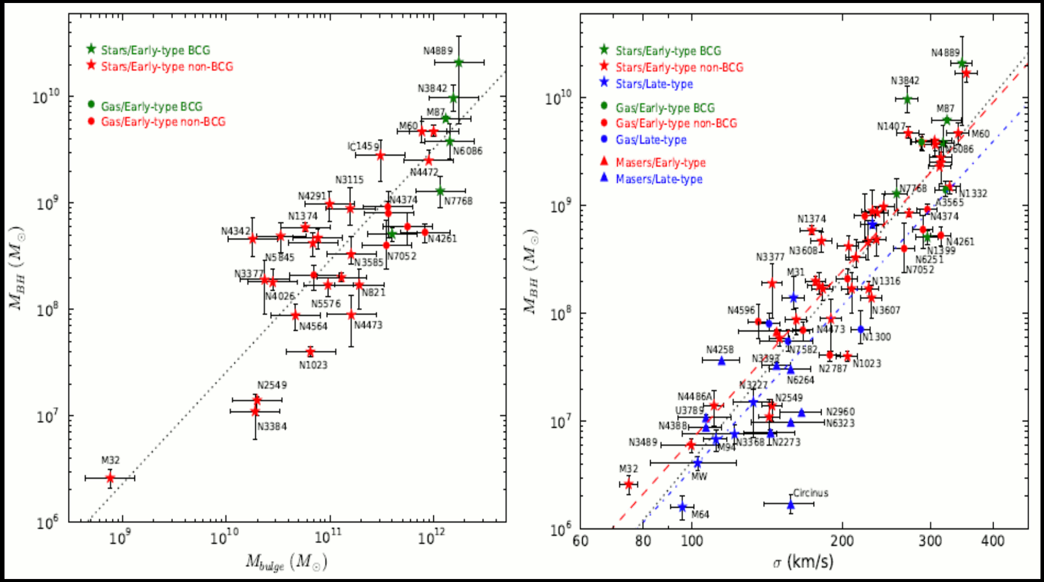
(Menou et al 2001, Volonteri et al. 2003)

Structure formation in a nutshell



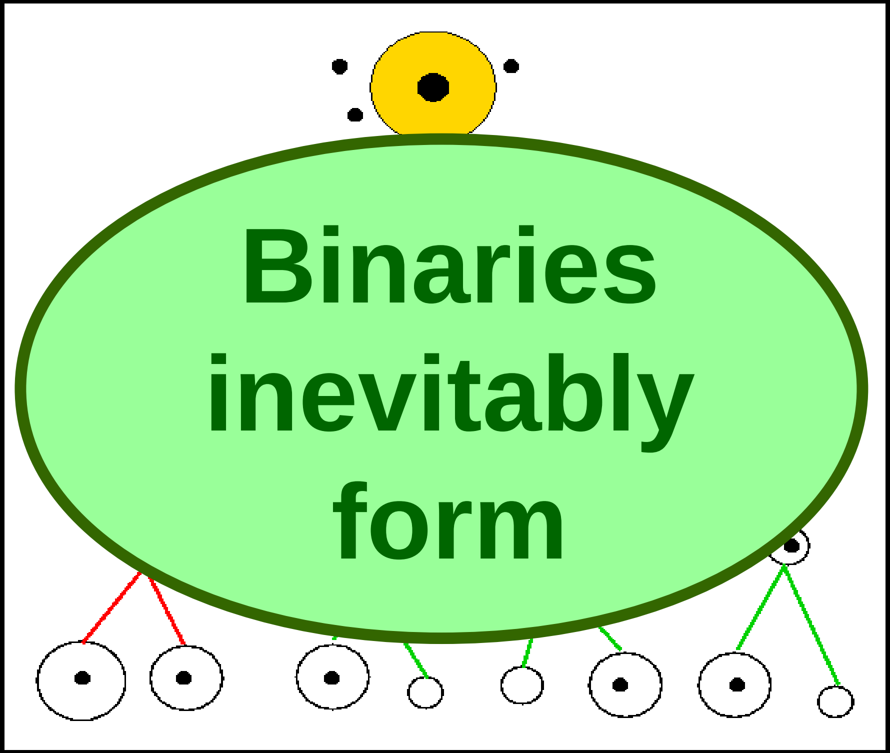
(From de Lucia et al. 2006)

+



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

=



Binaries inevitably form

(Menou et al 2001, Volonteri et al. 2003)

***Where and when do the first MBH seeds form?**

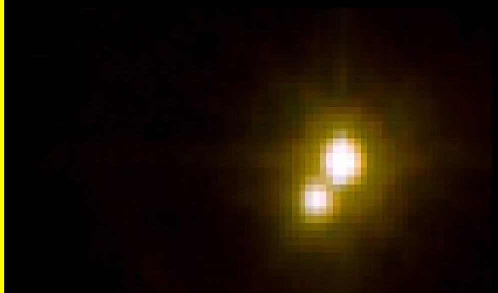
***How do they grow along the cosmic history?**

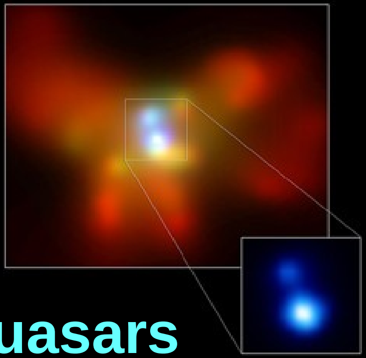
***What is their role in galaxy evolution?**

***What is their merger rate?**

***How do they pair together and dynamically evolve?**

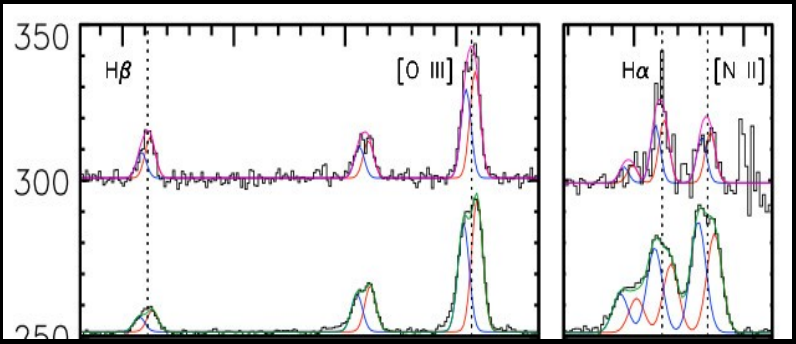
But do we see them?





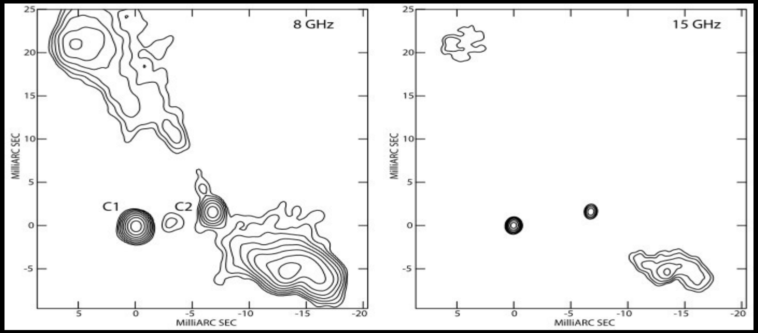
10 kpc: **double quasars**

(Komossa 2003)



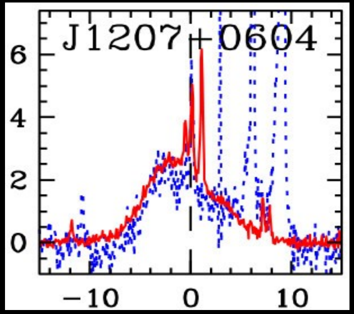
1 kpc: **double peaked NL**

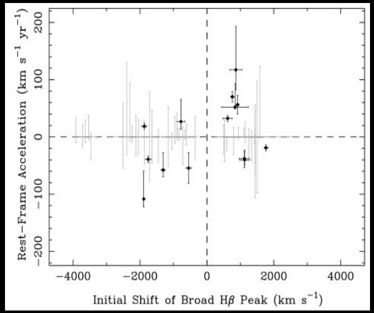
(Comerford 2013)



10 pc: **double radio cores**

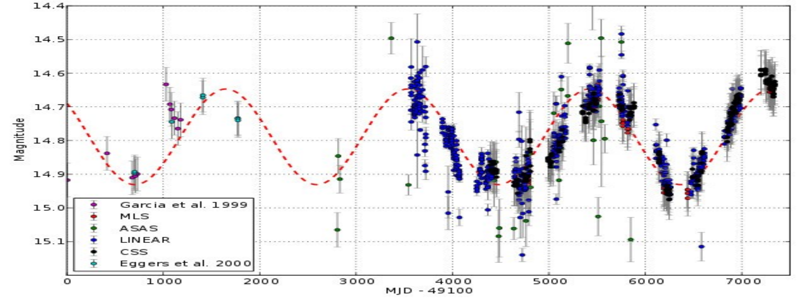
(Rodriguez 2006)



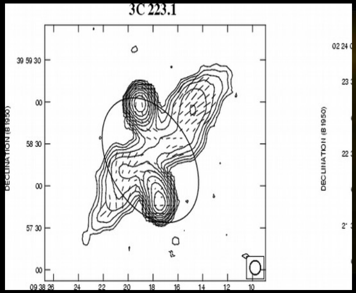


1 pc: **-shifted BL** (Tsalmatzsa 2011)

-accelerating BL (Eracleous 2012)



0.01 pc: **periodicity** (Graham 2015)



0.0pc:-X-shaped sources (Capetti 2001)

-displaced AGNs (Civano 2009)

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

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

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

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

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

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

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

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

The overall GW signal

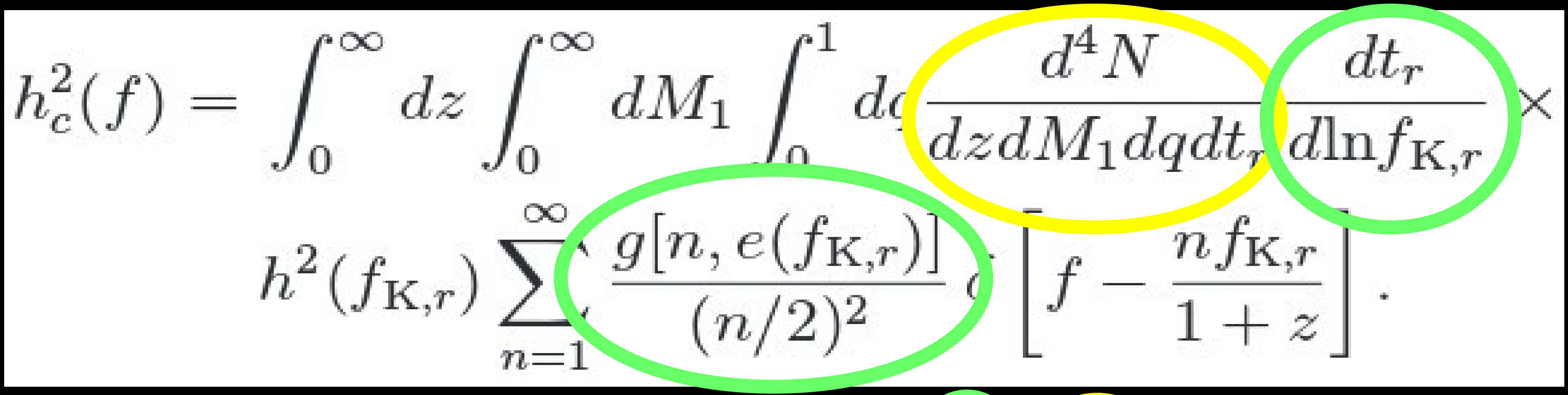
Population parameters

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



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

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

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

1-Population parameters

Minimal assumptions:

-Whenever there is a galaxy merger there is a SMBHB merger (pending a DF timescale that does not affect major mergers)

-SMBH are connected through the properties of galaxies through scaling relations

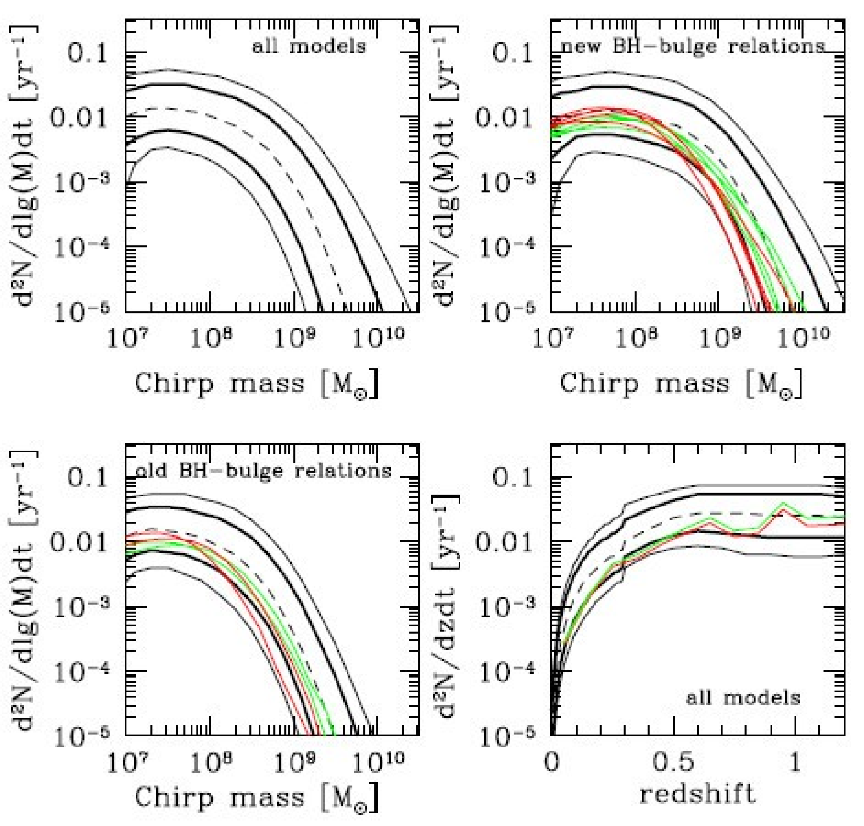
-SMBHB are circular GW driven in the PTA band

Even so....

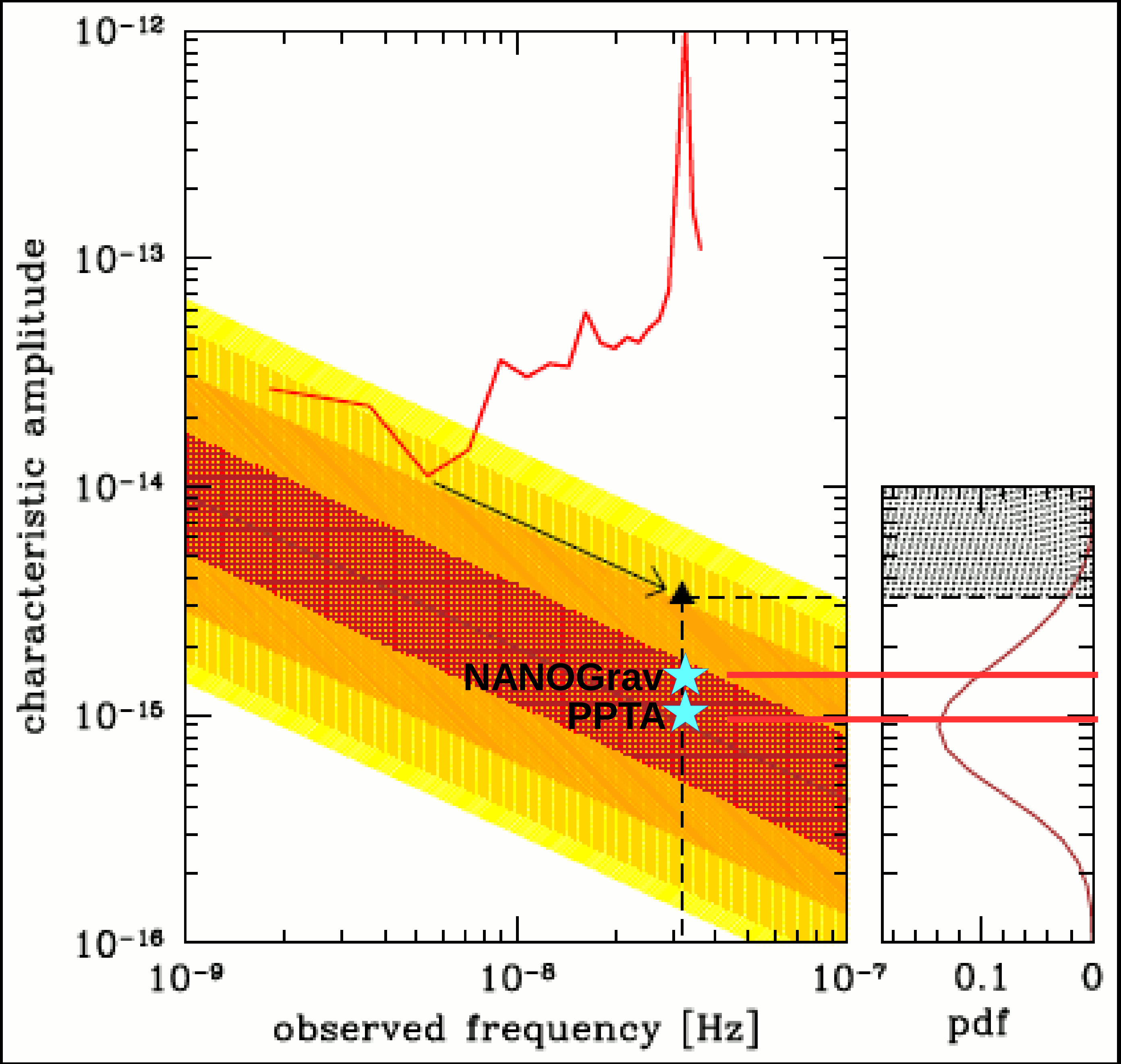
The MBHB merger rate is poorly determined:

-The galaxy merger rate is not know very well observationally

-The MBH-galaxy scaling relations has uncertainties and scatter (MBH measurements are hard)



Uncertainty in the GW background level



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

Predictions shown here (AS 2013):

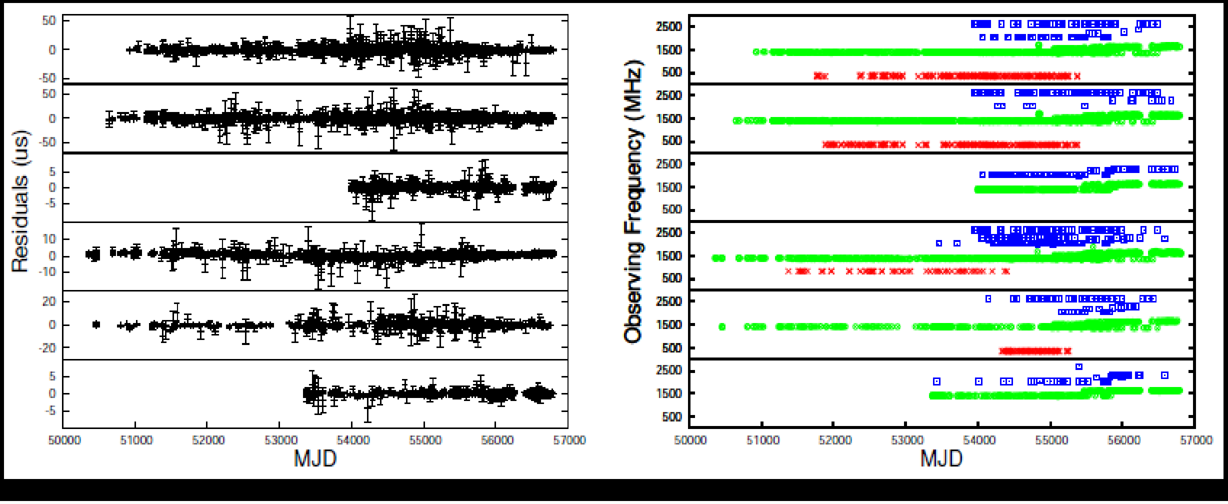
>Assume circular GW driven binaries

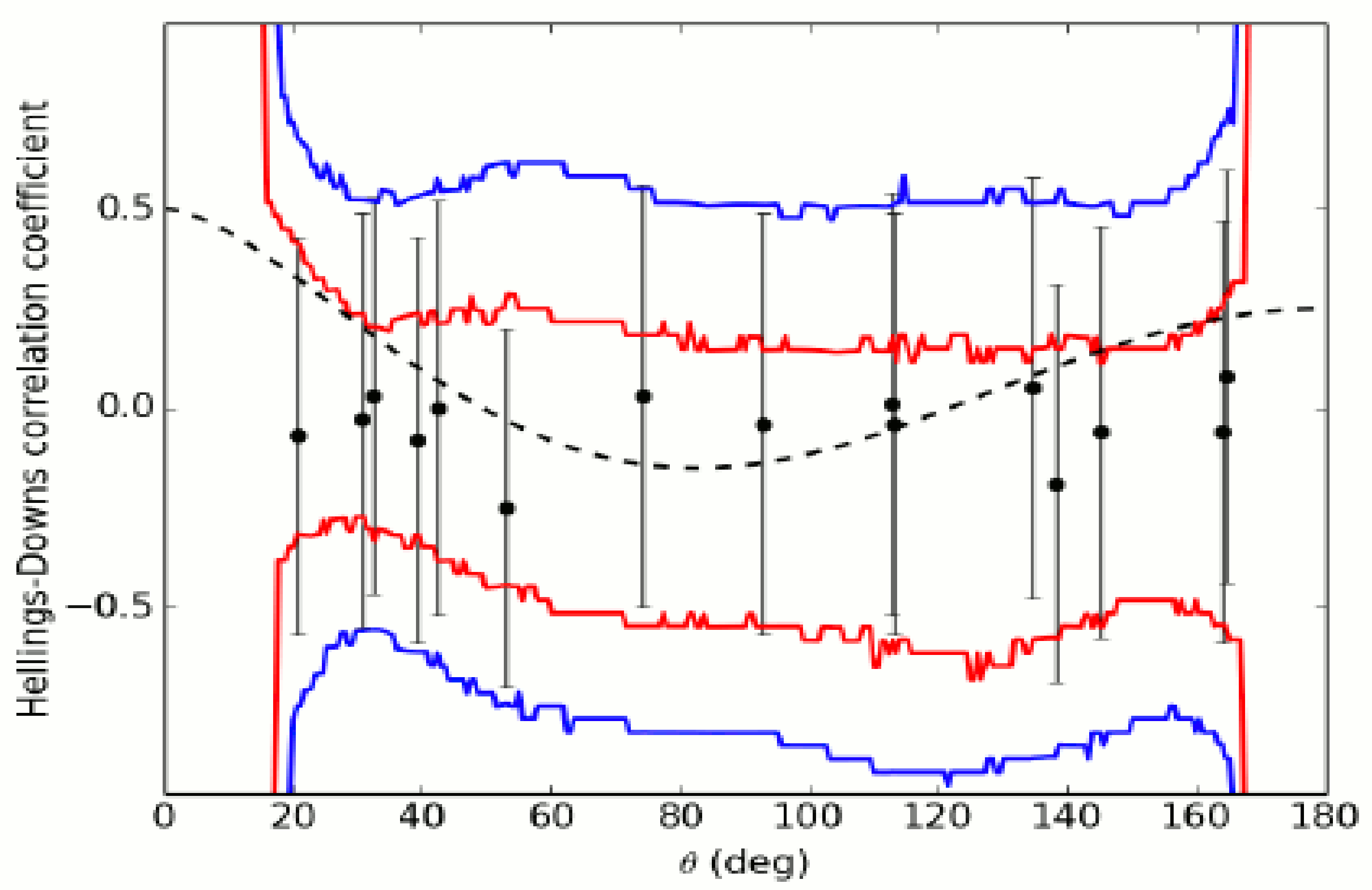
>Efficient MBH binary merger following galaxy mergers

>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)

Pulsar correlations (EPTA, Lentati et al. 2015)





2-Local Dynamics:Coupling with the environment

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, driven by stars and/or gas
- efficient only for ***major mergers*** against mass stripping

2. **hardening of the binary** (Quinlan 1996, Miloslavljevic & Merritt 2001, Sesana et al. 2007, Escala et al. 2004, Dotti et al. 2007)

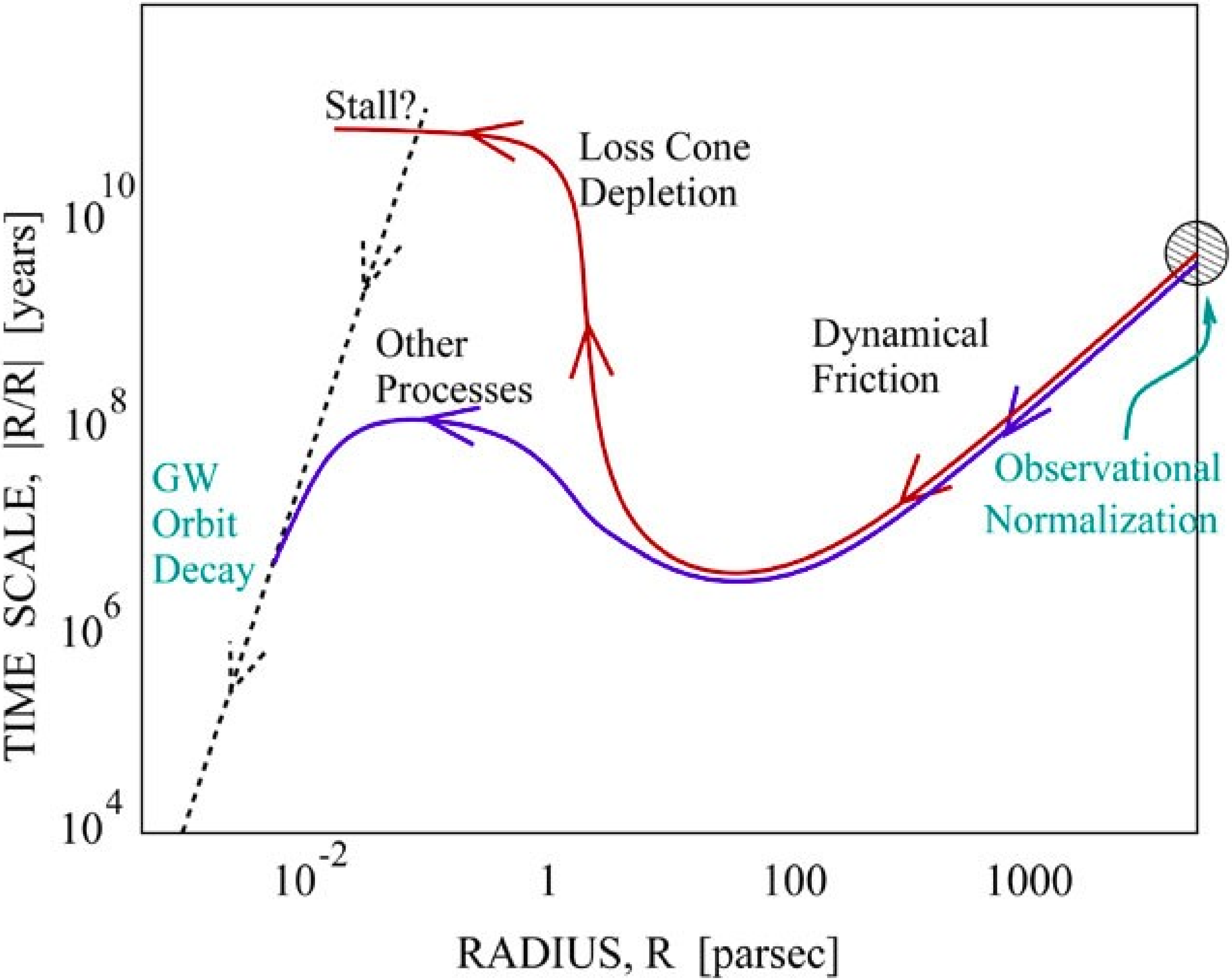
- ***3 bodies interactions*** between the binary and the surrounding stars
- the binding energy of the BHs is larger than the thermal energy of the stars
- the SMBHs create a ***stellar density core ejecting the background stars***
- ***Dynamical drag*** caused by a thick ***circumbinary disk***

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

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

The two MBH separation has to decay from 10 kpc to 10^{-6}pc

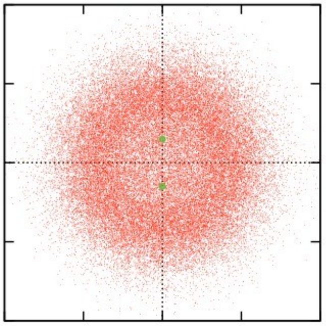
DYNAMICAL RANGE OF TEN ORDER OF MAGNITUDE!!!!!



Stall?
Loss Cone
Depletion
Other
Processes
Dynamical
Friction
GW
Orbit
Decay
Observational
Normalization
TIME SCALE, |R/Ṙ| [years]
10^{10}
10^8
10^6
10^4
10^{-2}
1
100
1000
RADIUS, R [parsec]

STELLAR DRIVEN BINARIES

assuming stars are supplied to the binary loss cone at a constant rate:



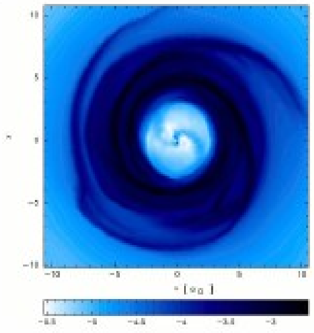
$$\frac{da}{dt} = \frac{a^2 G\rho}{\sigma} H$$

$$dt/d\ln f \propto f^{2/3} M_1^{2/3}$$

$$h_c \propto M_1^2 q f.$$

GAS DRIVEN BINARIES

self-consistent solution for the binary-disk interaction with no leakage in the cavity:



$$\frac{da}{dt} = \frac{2\dot{M}}{\mu}(aa_0)^{1/2}$$

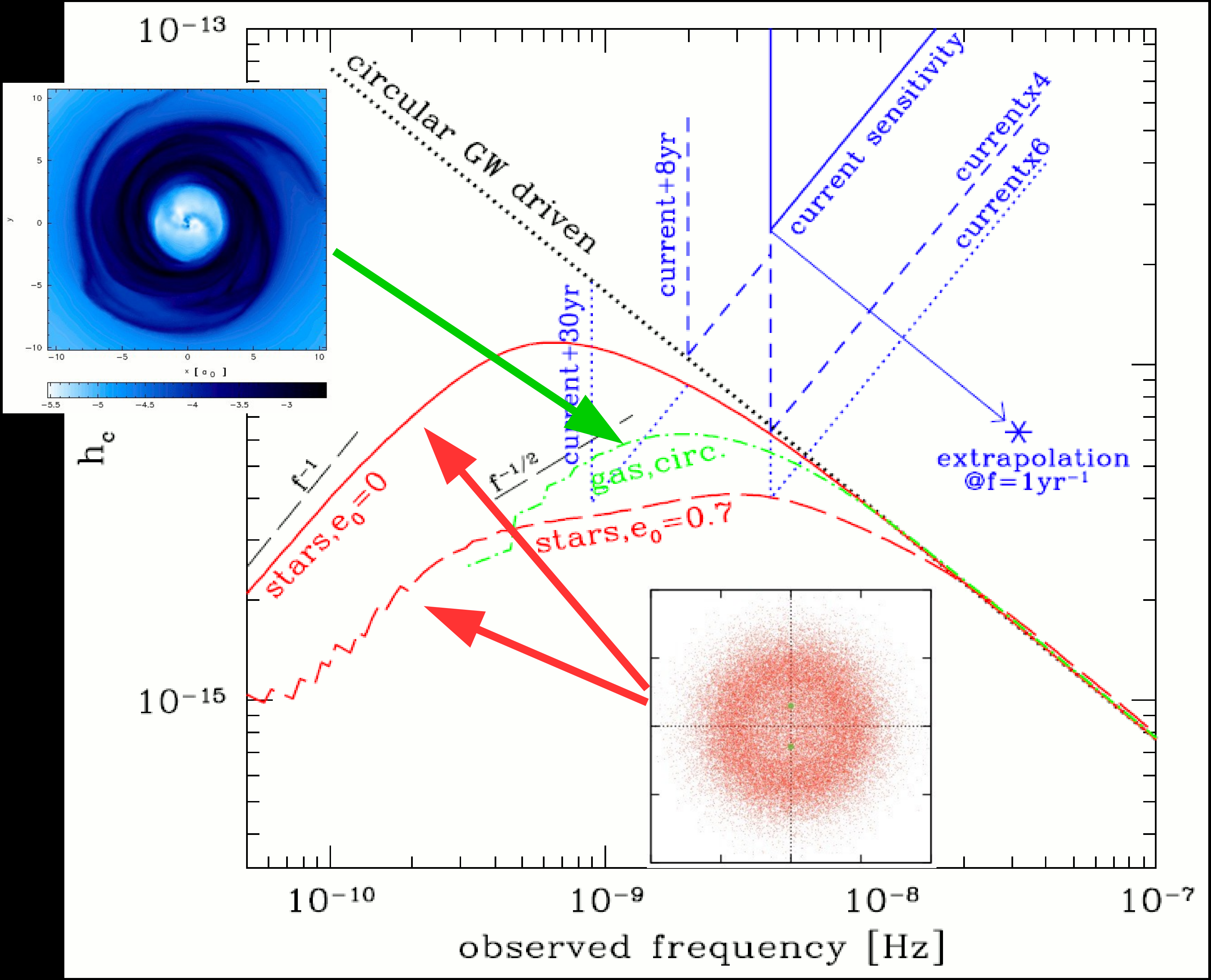
$$dt/d\ln f \propto f^{-1/3} M_1^{1/6}$$

$$h_c \propto M_1^{7/4} q^{3/2} f^{1/2}$$

Transition frequency

$$f_{\rm star/GW} \approx 5 \times 10^{-9} M_8^{-7/10} q^{-3/10}$$

$$f_{\rm gas/GW} \approx 5 \times 10^{-9} M_8^{-37/49} q^{-69/98}$$

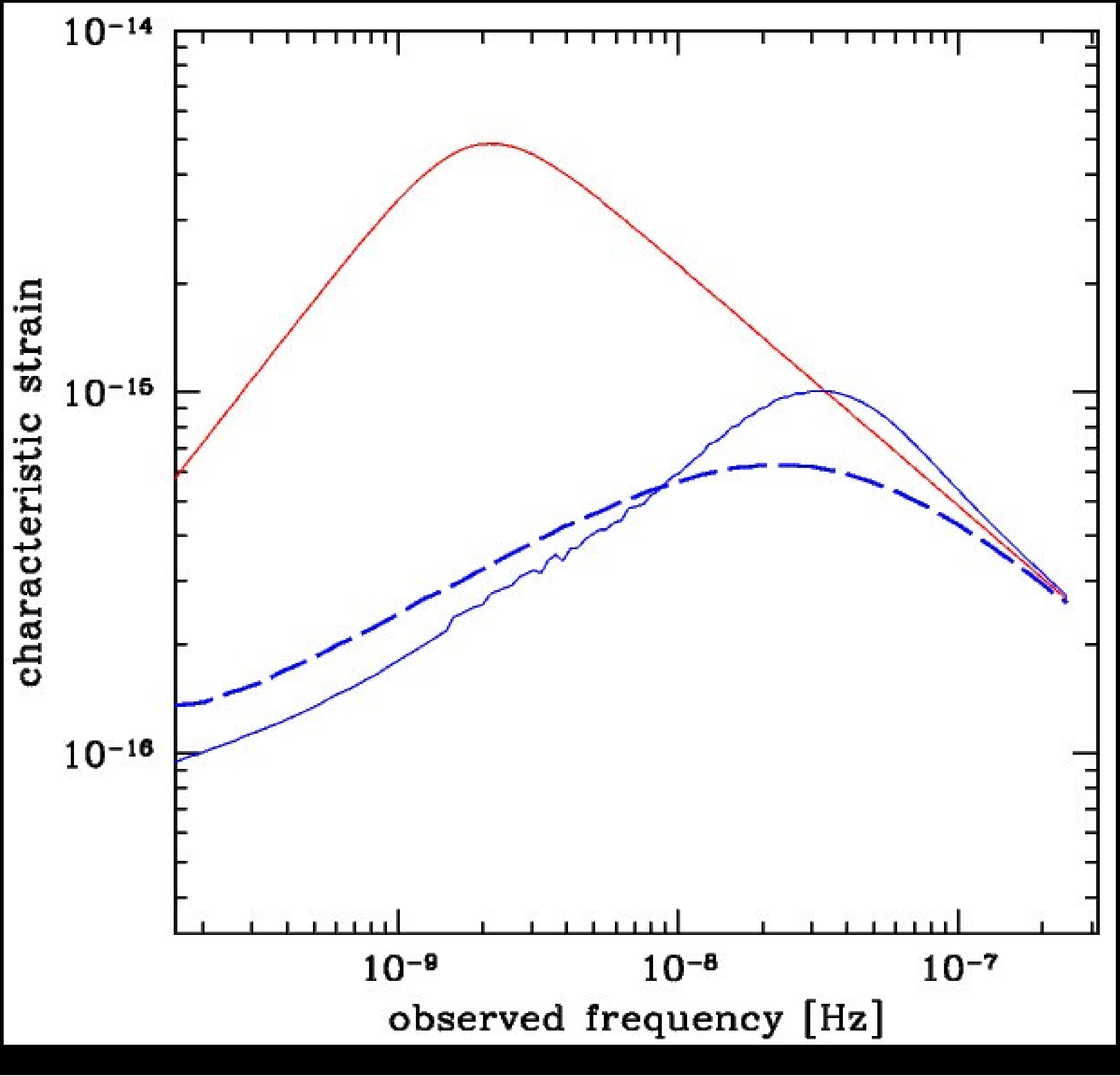


(Kocsis & AS 2011, AS 2013, Ravi et al. 2014, McWilliams et al. 2014)

Eccentricity

Eccentric binaries emit a whole spectrum of harmonics (Peters & Mathews 1963) with the consequence that:

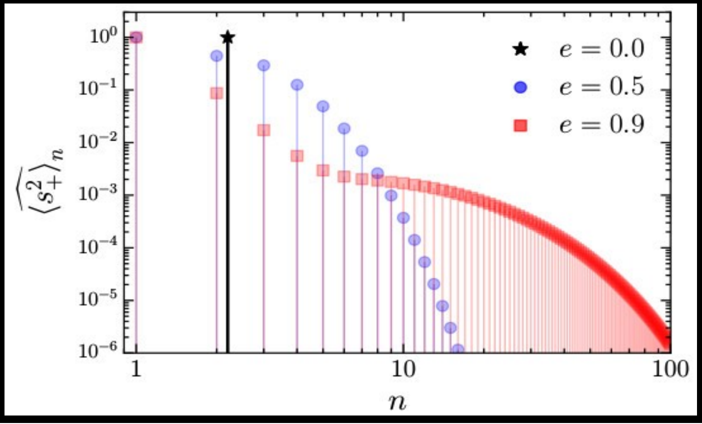
1) **they evolve faster (their dE/dt Is proportional to $(1-e^2)^{-7/2}$**
2) **their emission moves toward higher frequency.**



Point 1) causes a drop in the number of sources emitting at each frequency (analogue to environmental coupling)

Point 2) modifies the spectrum of the individual system

Both effects contribute to the shaping of the spectrum, but 1) is the dominant

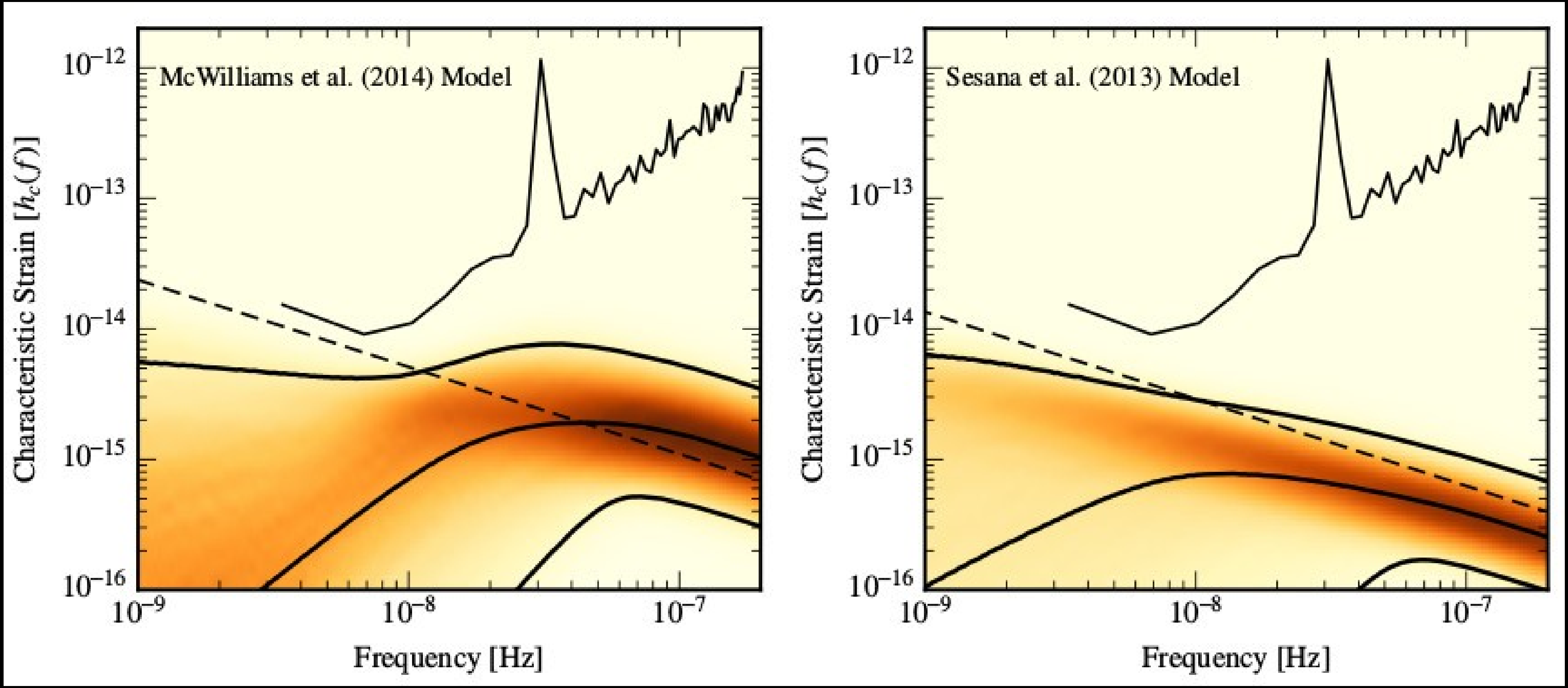


Dynamical constraints from PTA

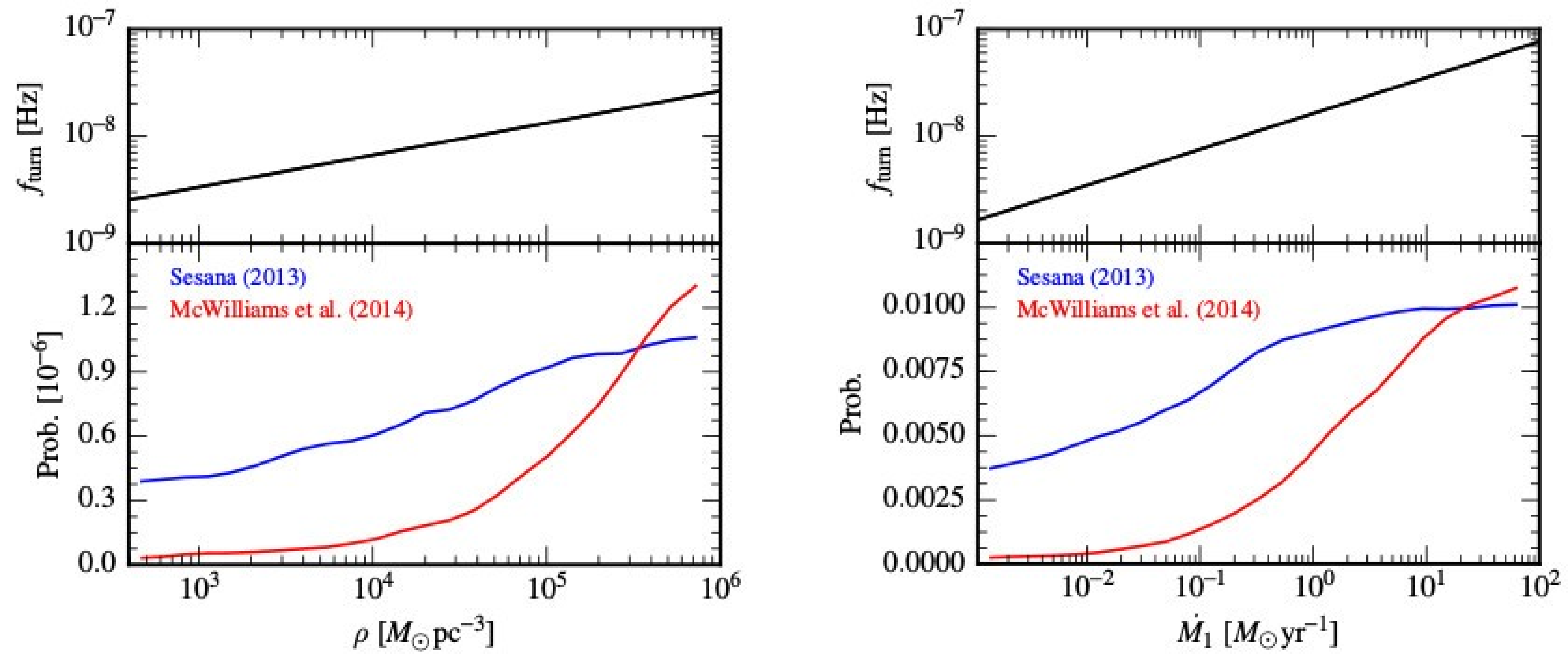
(NANOGrav, Arzoumanian et al. 2015)

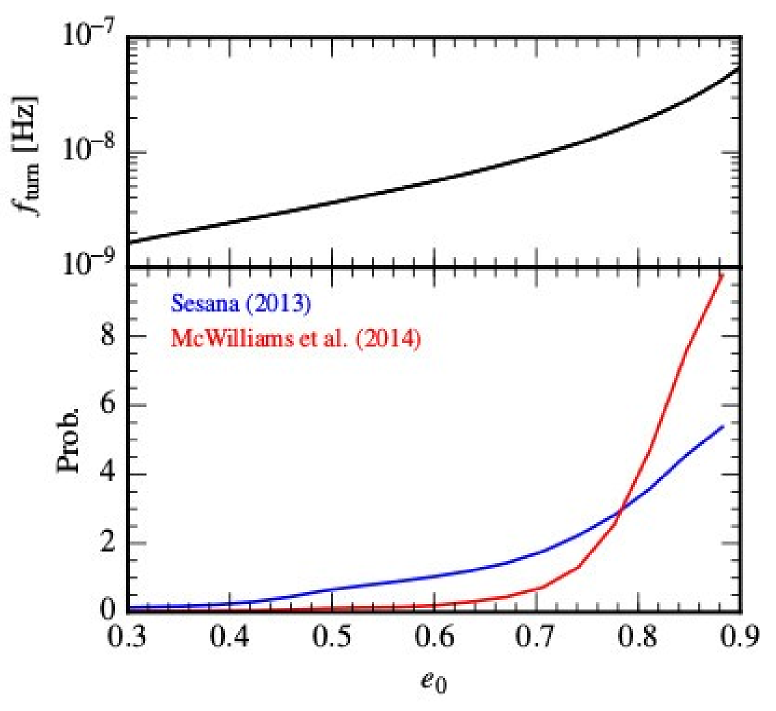
Simple broken-power law model mimicking possible environmental effects (Sampson et al. 2015)

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



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





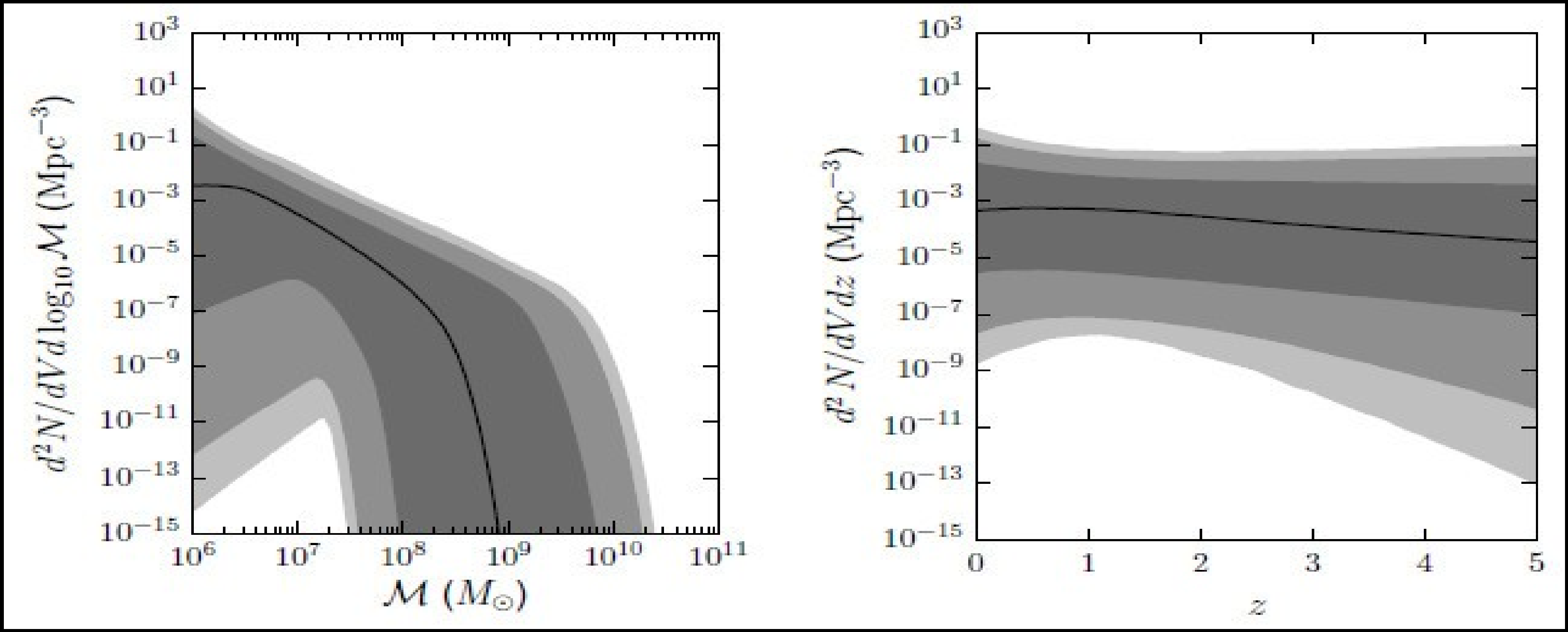
Similarly one can play the game of placing constraints on specific parameters *by keeping everything else fixed*:

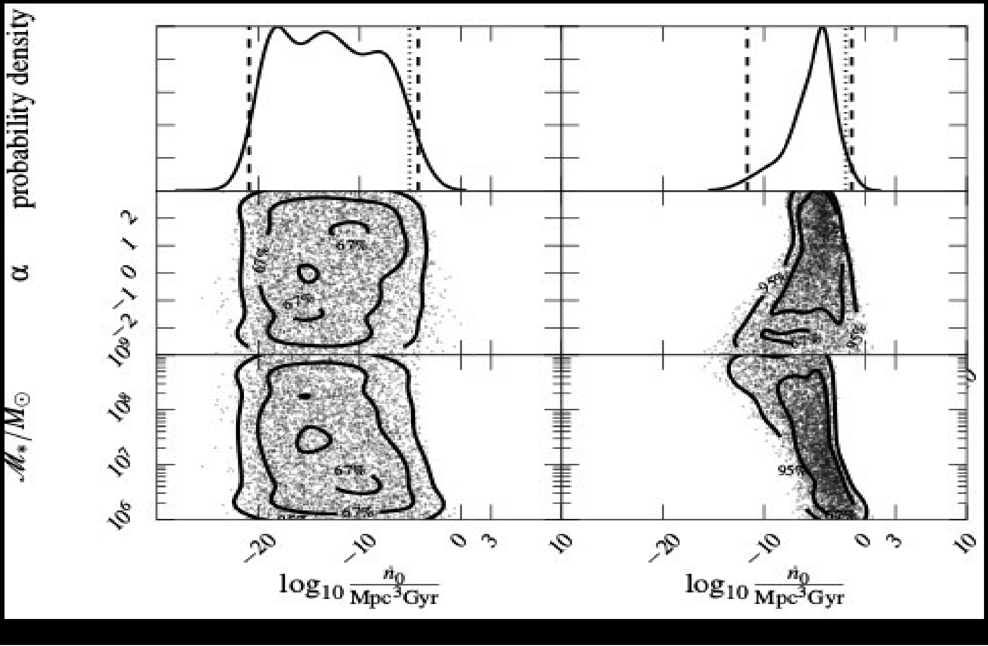
-density of the MBHB environment
-eccentricity

STILL AT THE LEVEL OF TOY MODELLING

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

(Middleton et al. 2015)

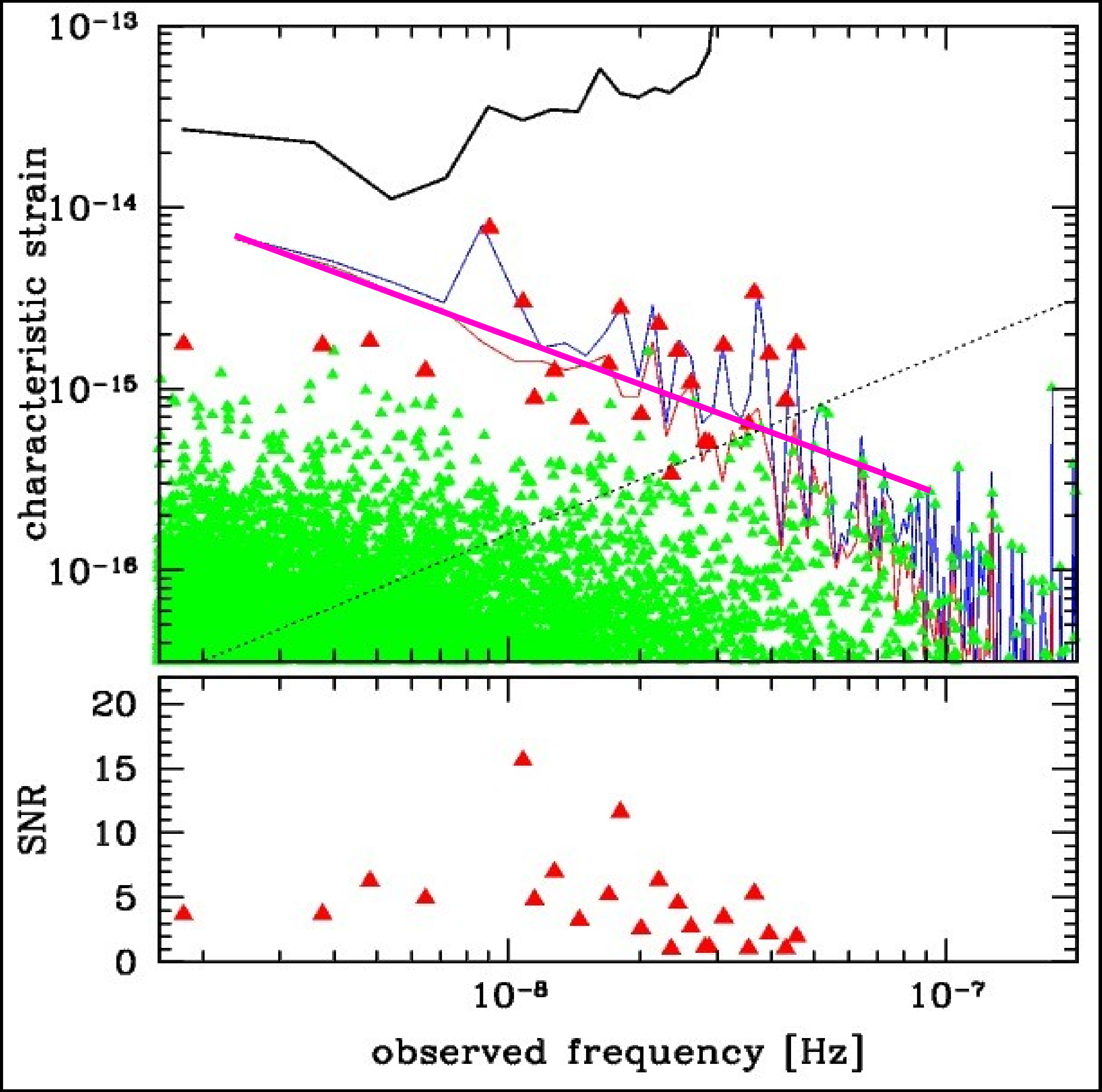




A PTA detection of a stochastic GWB will essentially *only constrain the overall MBHB merger rate*.

Need combination with other observation to be informative

The nature of the signal



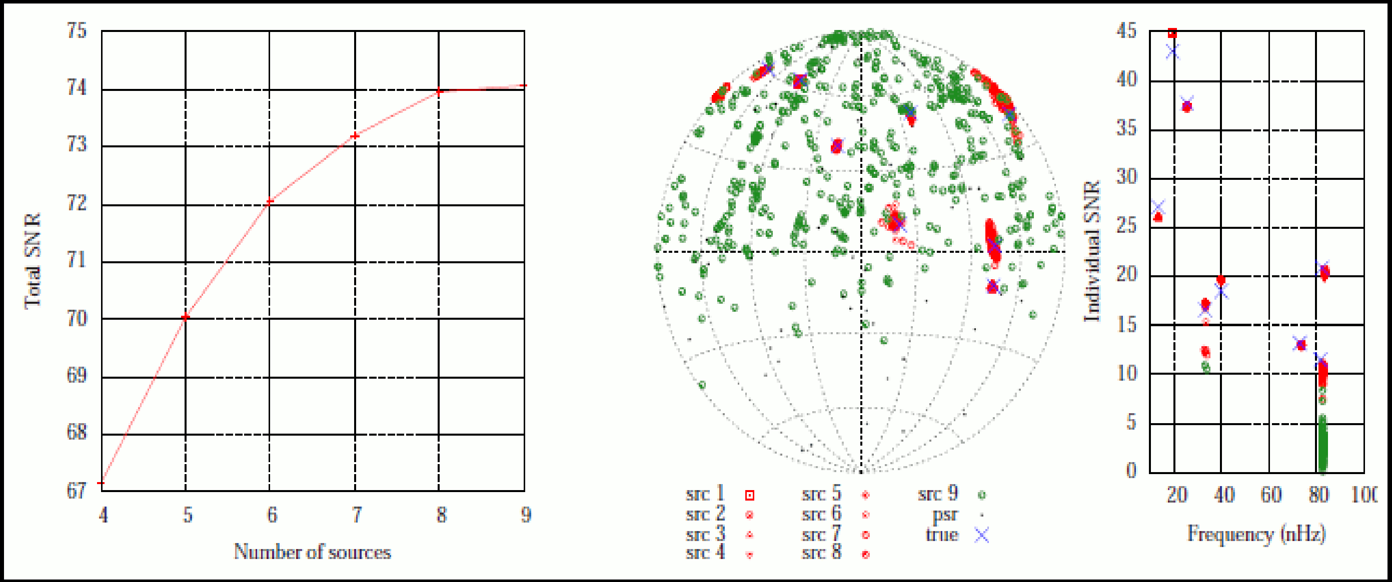
***It is not smooth**

***It is not Gaussian**

***Single sources might pop-up**

***The distribution of the brightest sources might well be anisotropic**

Identification and sky localization

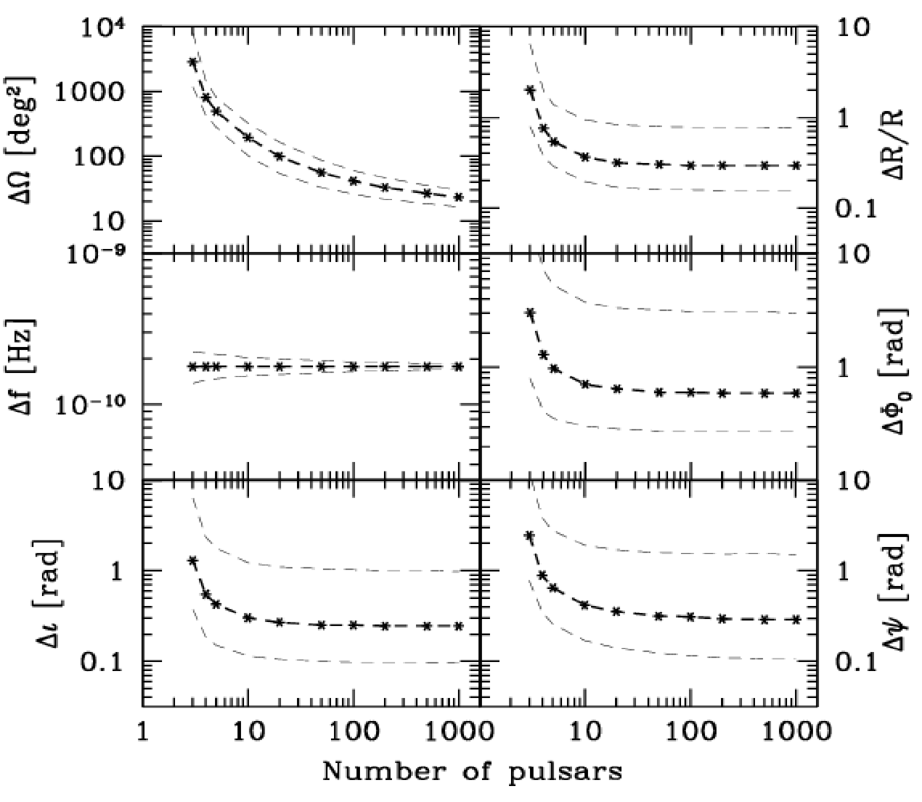


We can recover multiple sources in PTA data

(Babak & AS 2012
Petiteau et al. 2013)

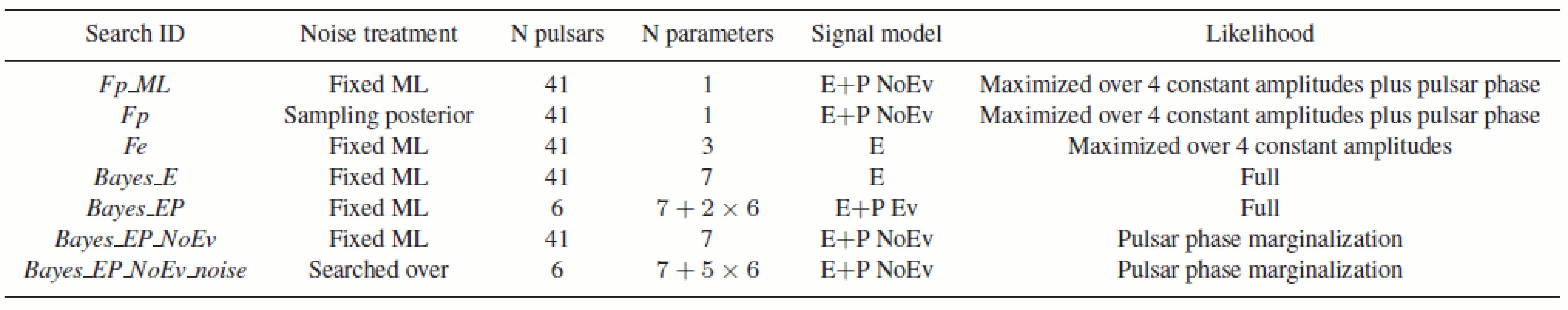
Sources can be localized in the sky (AS & Vecchio 2010, Ellis et al. 2012).

For example, the largest SNR source shown in the previous slide can be located by SKA in the sky with a sky accuracy <10deg^2

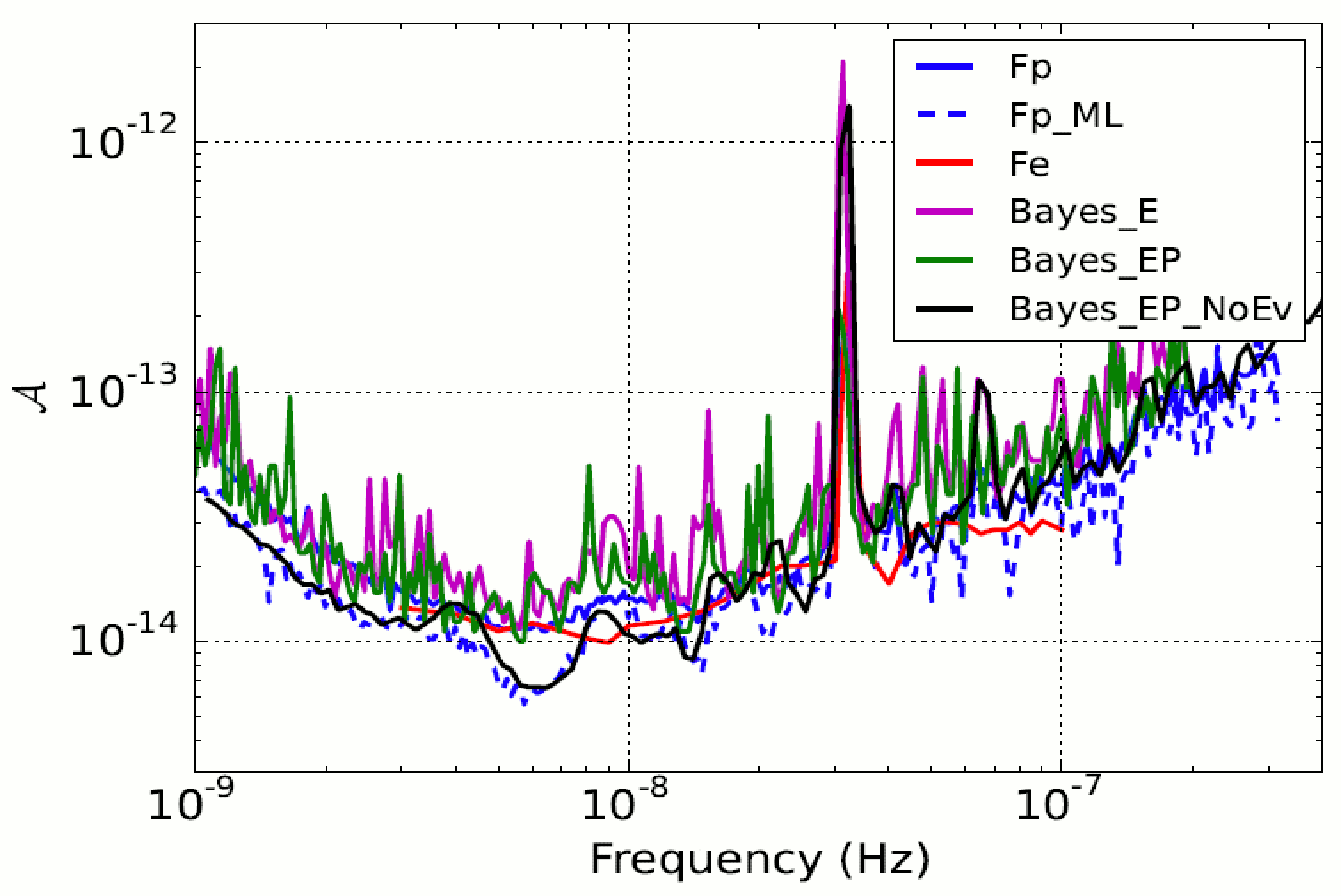


Limits on continuous GWs

(EPTA, Babak et al. 2015)

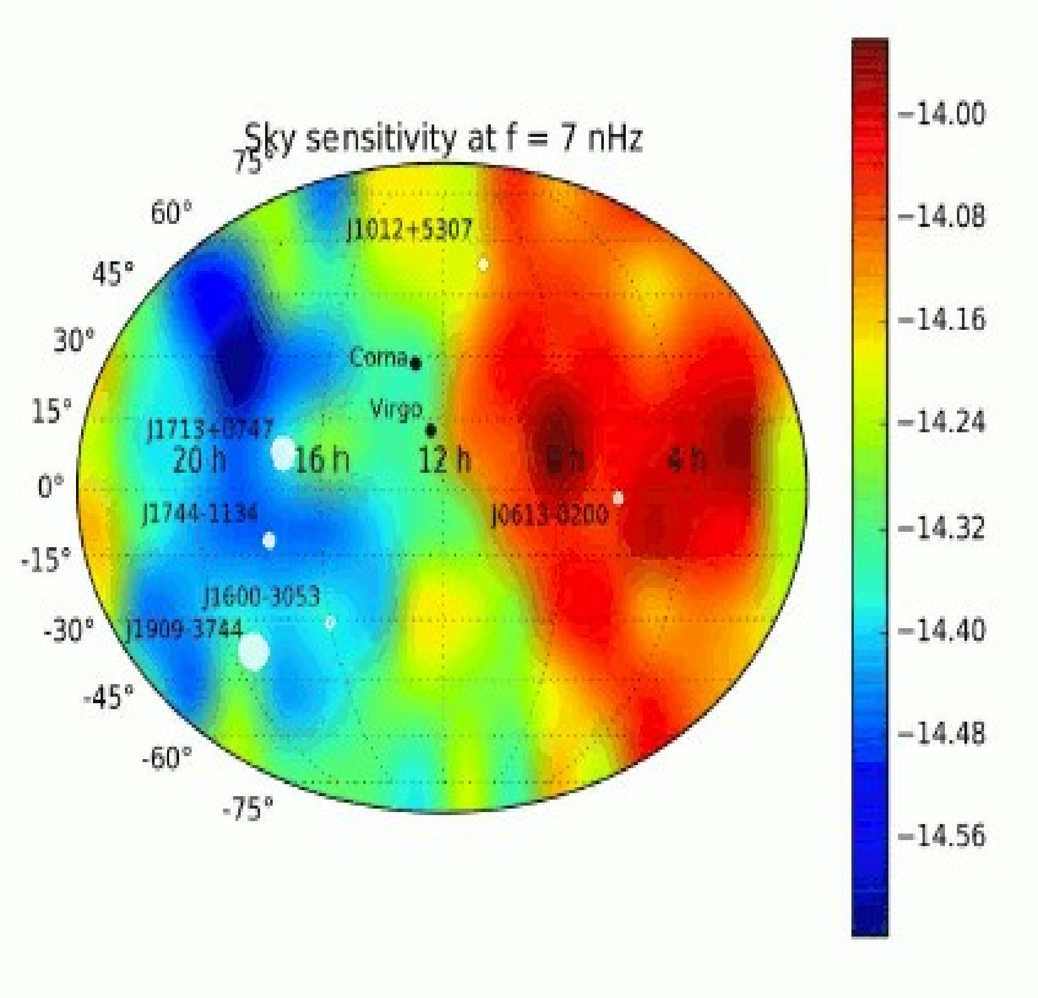


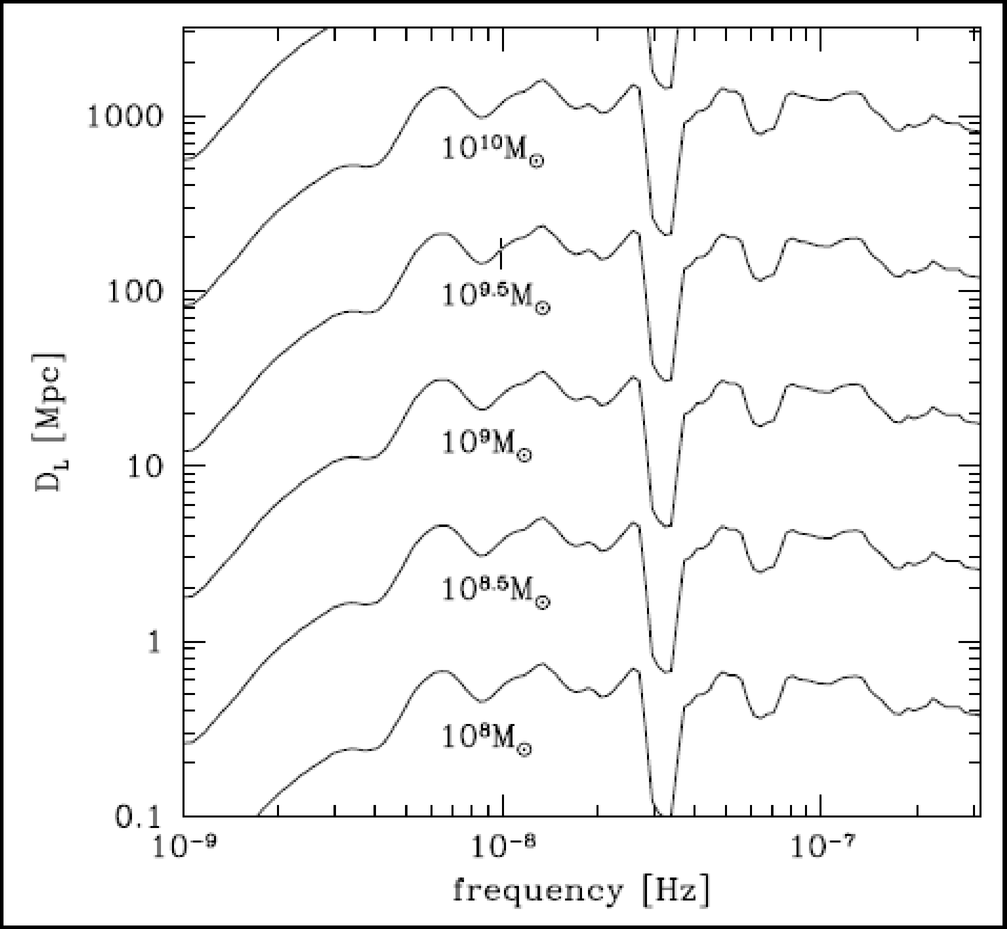
Search ID	Noise treatment	N pulsars	N parameters	Signal model	Likelihood
Fp_ML	Fixed ML	41	1	E+P NoEv	Maximized over 4 constant amplitudes plus pulsar phase
Fp	Sampling posterior	41	1	E+P NoEv	Maximized over 4 constant amplitudes plus pulsar phase
Fe	Fixed ML	41	3	E	Maximized over 4 constant amplitudes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

Current limits are getting extremely interesting, probing the predicted range of vanilla models for the cosmic SMBHB population

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

However:

> considering current observational uncertainties,
> 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 (maybe a critical ingredient)

> stalling might be an issue in the
> most massive low density ellipticals
> * time delays?
> * triple interactions common?