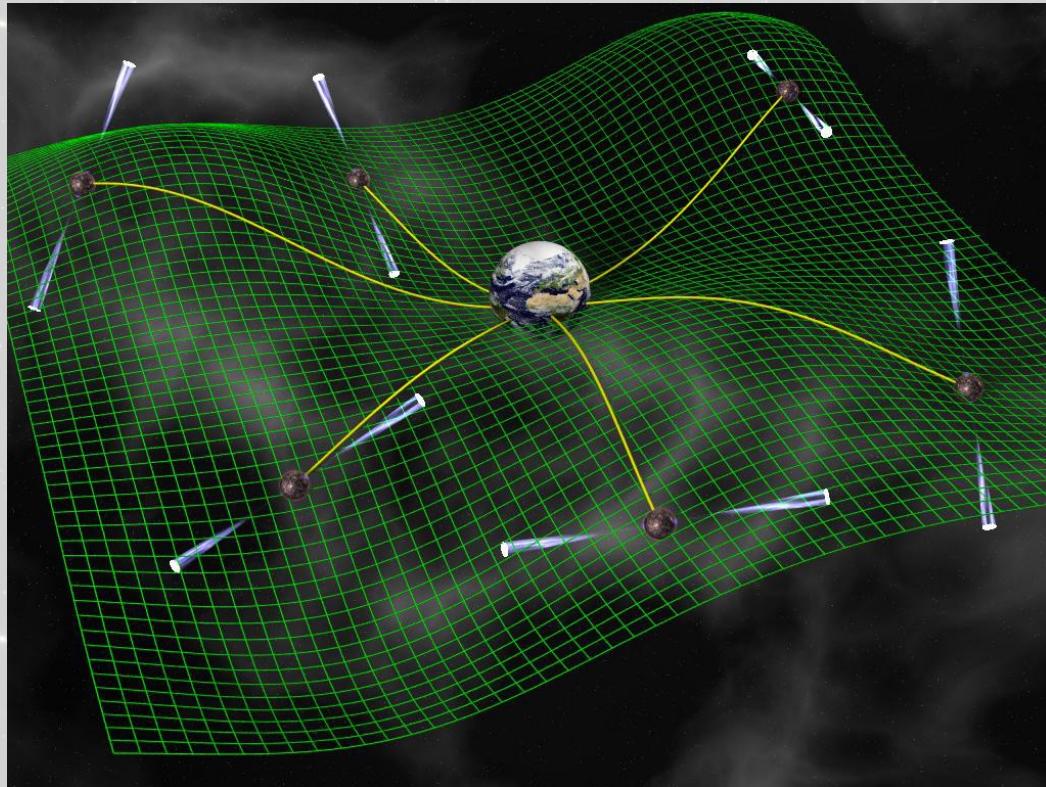


Pulsar Timing Arrays Sources



Rencontres du GdR Ondes Gravitationnelles, 18-19 octobre 2018
G.Theureau (LPC2E-Orléans et Observatoire de Paris)

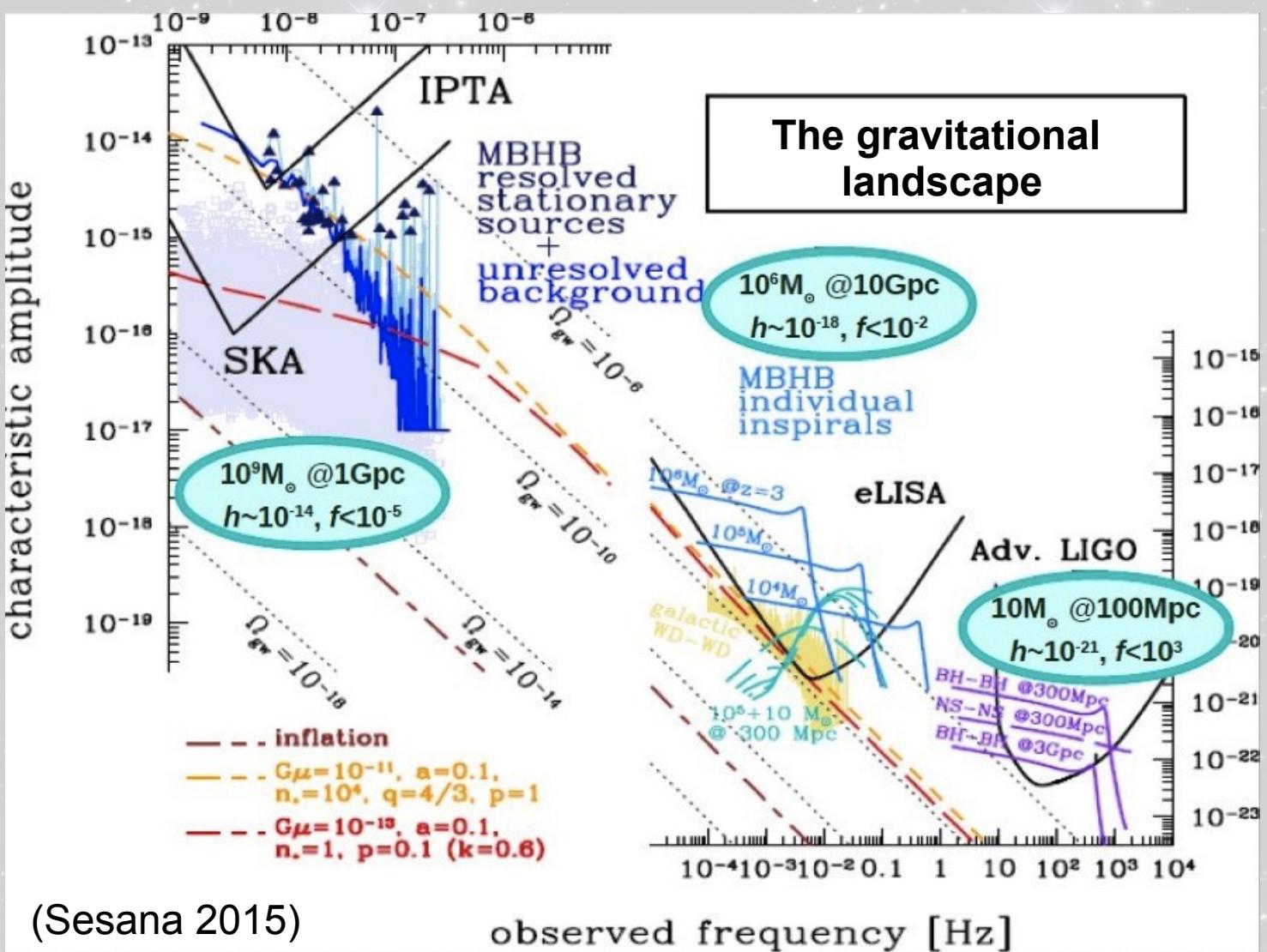
+ I.Cognard, L.Guillemot, A.Chalumeau, S.Chen (LPC2E/USN), A.Petiteau, S.Babak (APC)

The gravitational wave background :

nHz-mHz domain

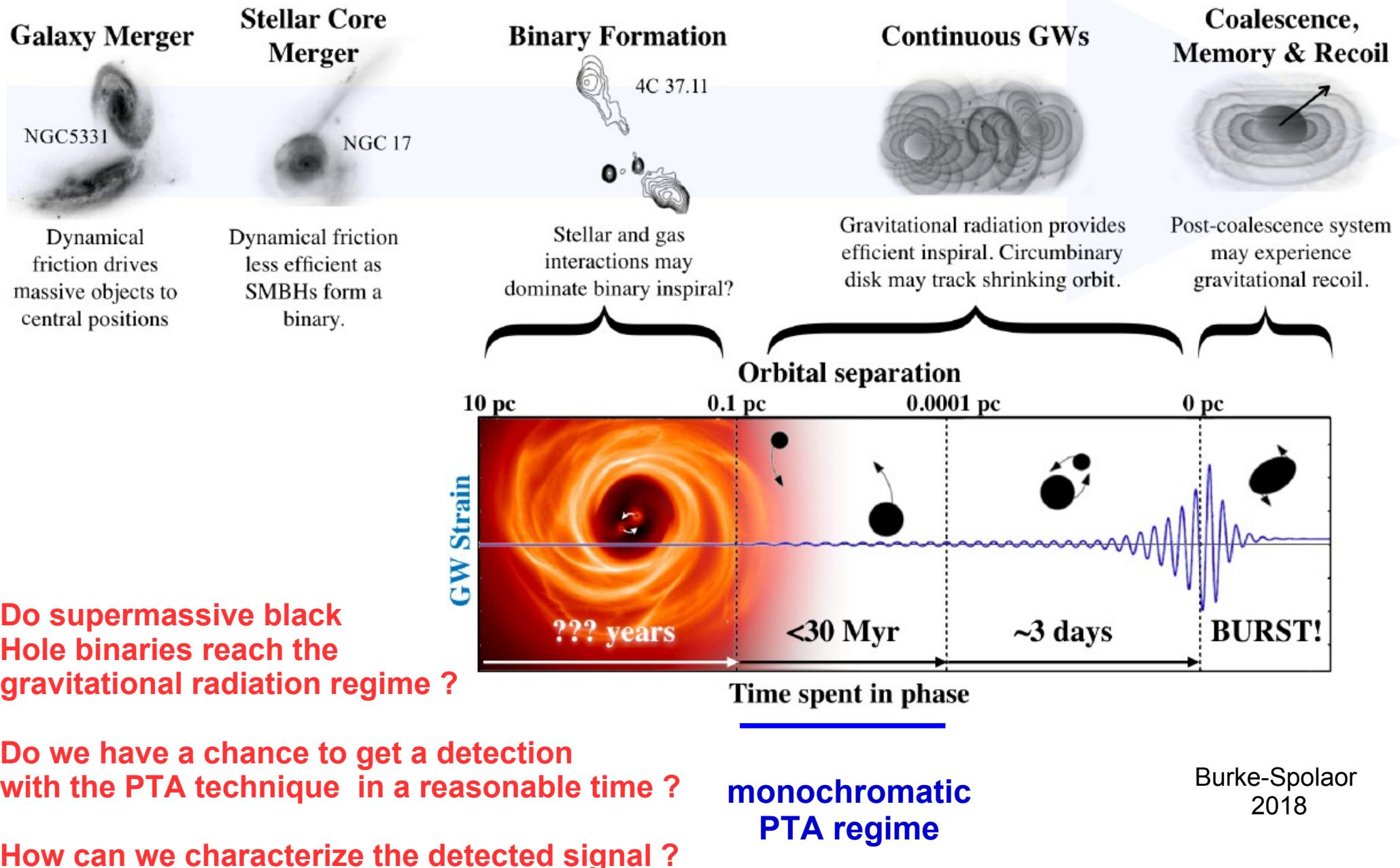
- Super massive black hole binaries (SMBHB)
 - Cosmic string loops
 - Relics of inflation

$$h_c(f) = A \left(\frac{f}{\text{yr}^{-1}} \right)^\alpha$$

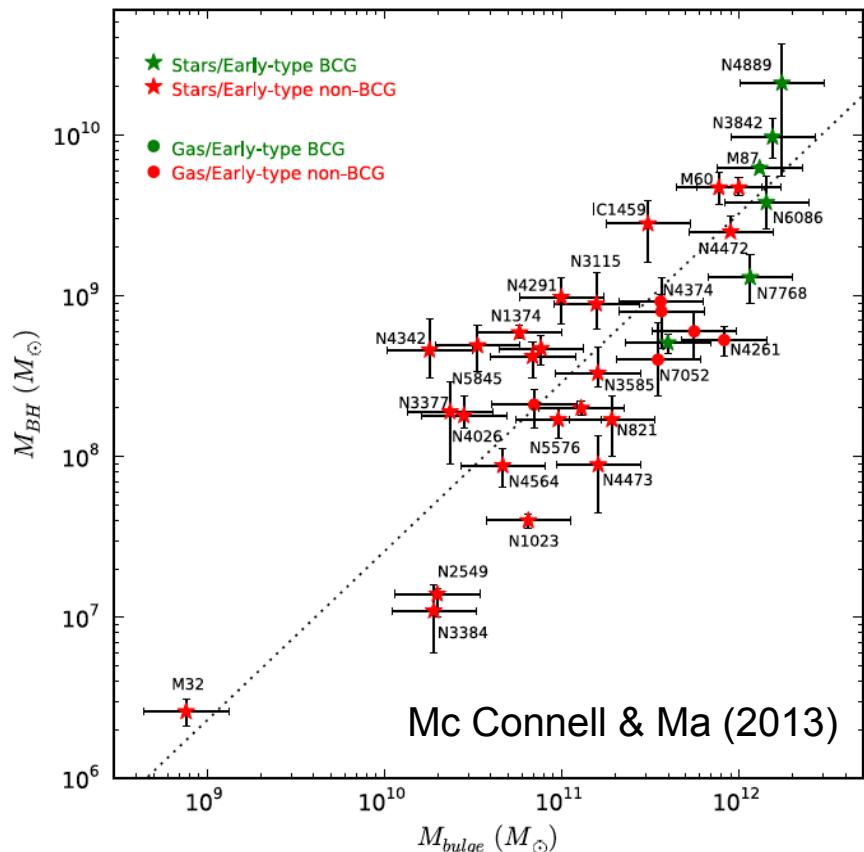
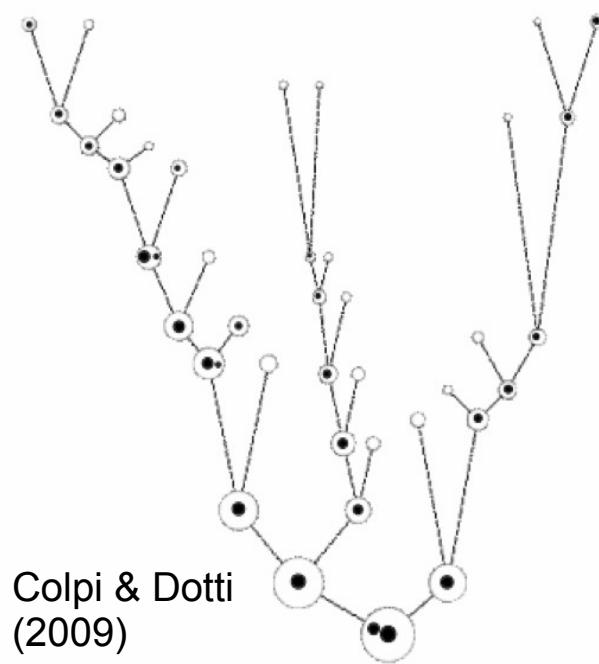


| Model | A | α | References |
|--------------------------|-----------------------|------------|-----------------------|
| Supermassive black holes | $10^{-15} - 10^{-14}$ | -2/3 | Jaffe & Backer (2003) |
| | | | Wyithe & Loeb (2003) |
| | | | Enoki et al. (2004) |
| Relic GWs | $10^{-17} - 10^{-15}$ | -1 -- -0.8 | Grishchuk (2005) |
| Cosmic String | $10^{-16} - 10^{-14}$ | -7/6 | Maggiore (2000) |

The life cycle of supermassive binary black holes



Populations synthesis ingredients



Merger trees from cosmological N-body simulations

Bulge to BH mass ratio from galaxies dynamical studies

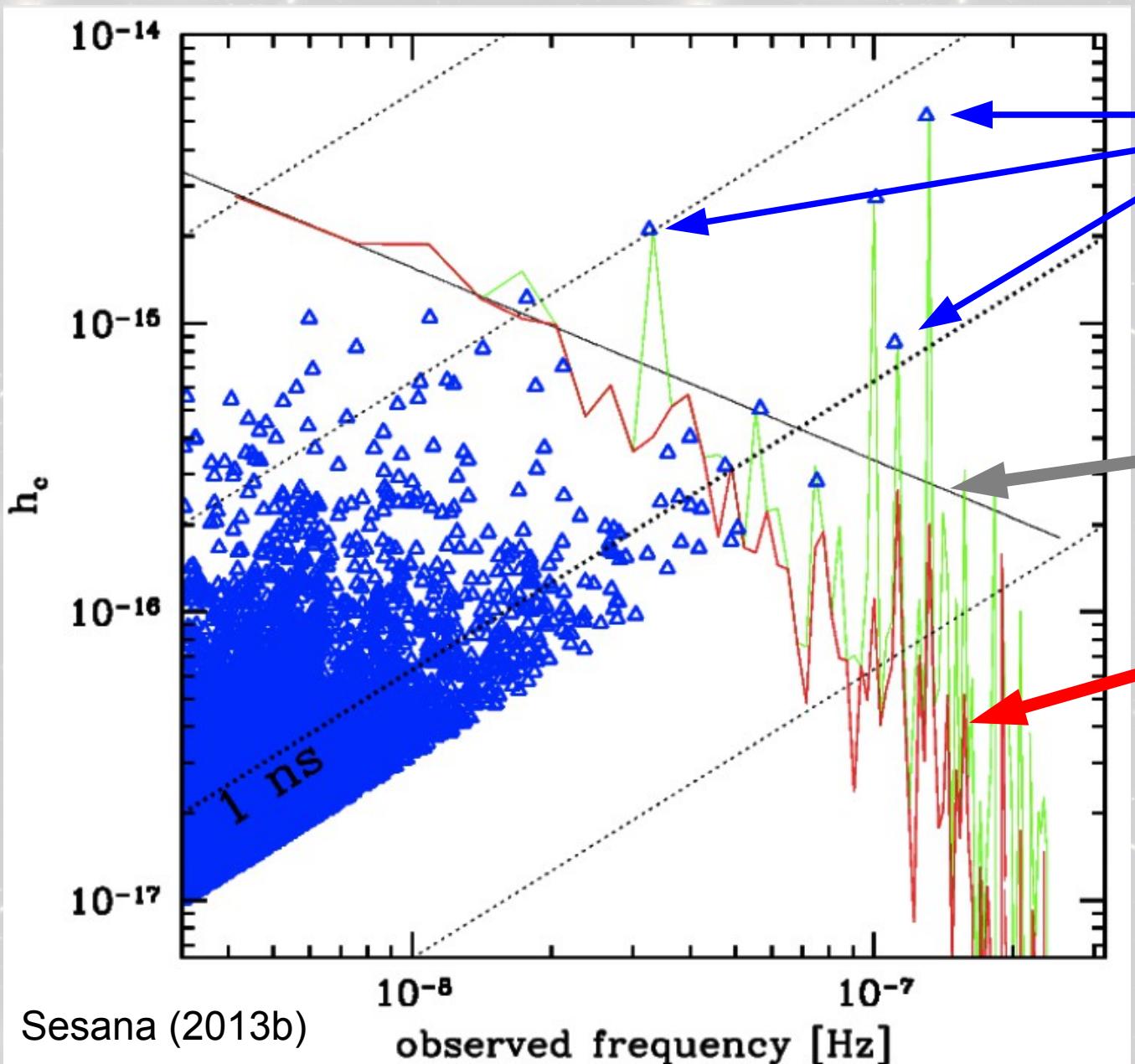
Add dynamical friction with stars and gas to migrate the BHs towards the center

Three body interaction with stars from the loss cone region (when binary orbital velocity > stars)

Find mechanisms to solve the last parsec problem

- massive BH triplets (Bonetti et al 2018),
- triaxial potential/density of the nuclei refilling the loss-cone (Vasiliev et al 2015),
- circumbinary accretion disk (Tang et al 2017)
- accretion of clumpy cold gas (Goicovic et al 2018),
- a large population of stalled binaries at low frequencies (Dvorkin&Barausse 2017)

Population of SMBH : contribution from background & individual sources



« resolvable »
individual sources

stochastic
background $\sim f^{-2/3}$

Contribution from
unresolved sources

Hypothesis :

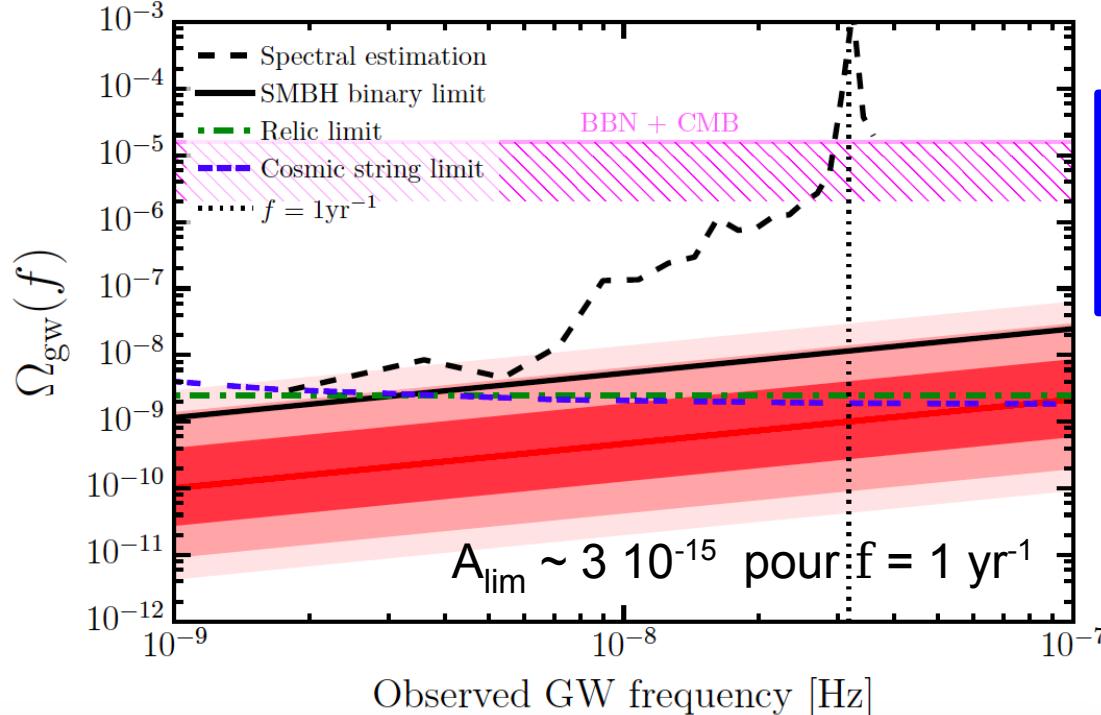
- circular orbits
- all the population reaches the sub-pc GW emission regime

+ uncertainties about :

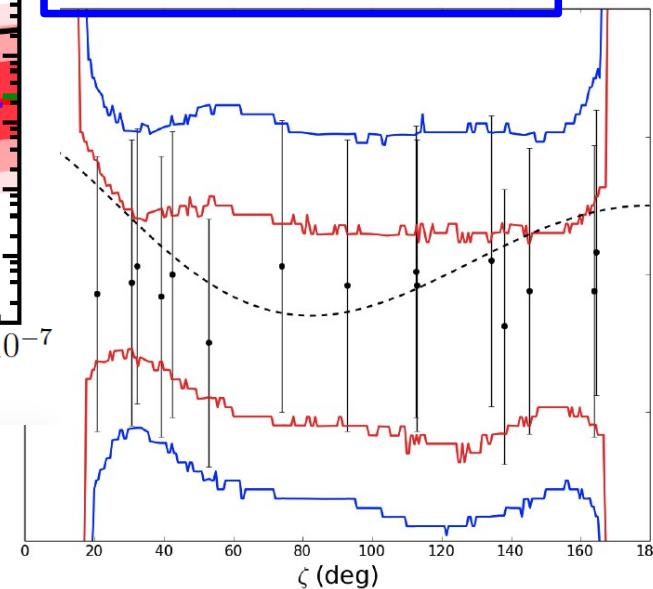
fusion rate

BH – host galaxy mass relation
time to coalescence

First European results in 2015



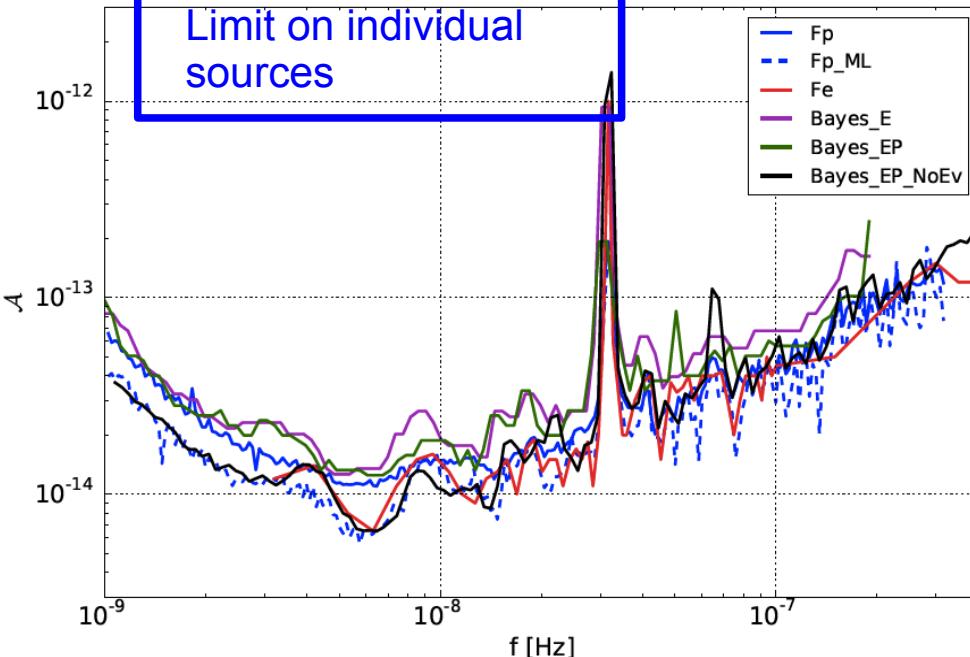
EPTA – 6 « best »
Lentati et al 2015
 Limit on the isotropic stochastic background



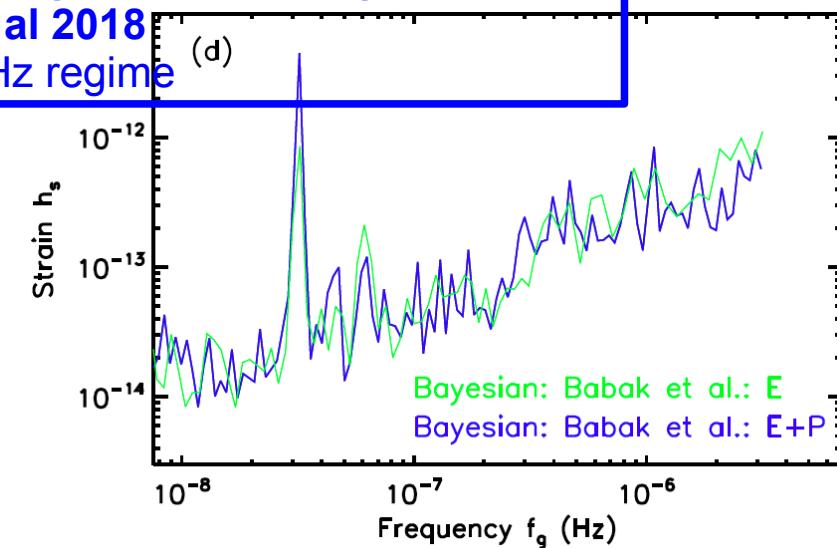
« Hellings&Downs » correlation curve
 → no detection

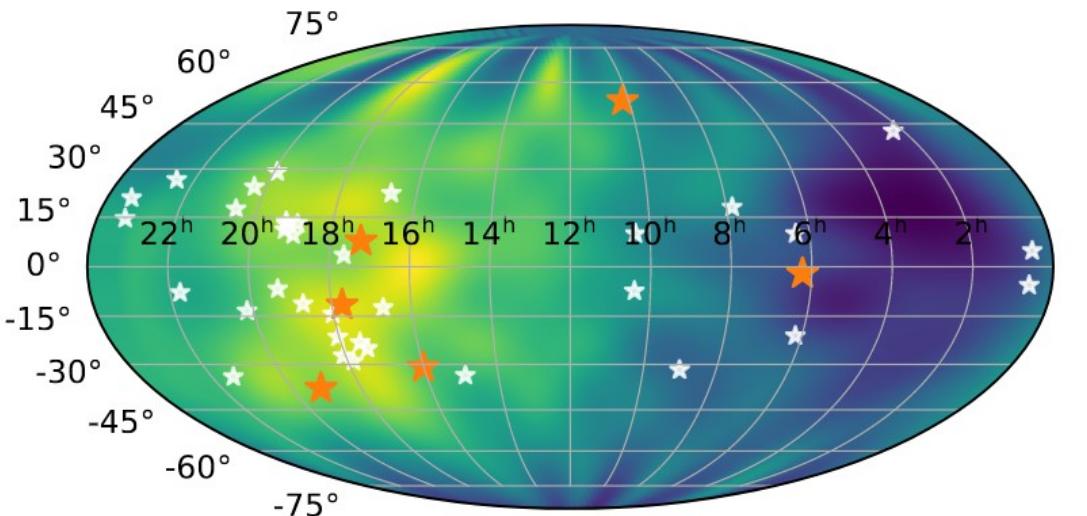
EPTA – 6 « best »
Babak et al 2016

Limit on individual sources



EPTA – « high cadence single pulsar »
Perera et al 2018
 Limit in μHz regime

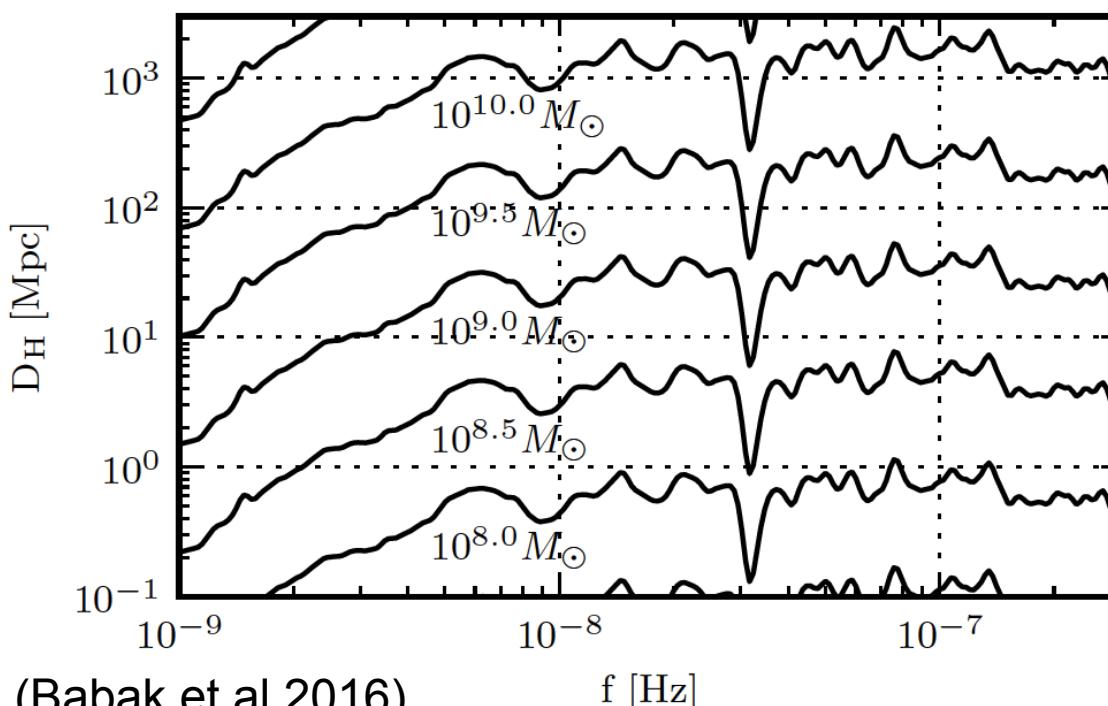




$\log_{10}(h)$, GW sky at $f = 3.79 \text{e-}09 \text{ Hz}$

Mingarelli et al 2017
Sky sensitivity map
from EPTA-2015 at 3.8 nHz

The sensitivity of the pulsar array depends on the position on the celestial sphere and on the distribution of pulsar pair angular separations



Current astrophysical models predict a detection probability of **1% with EPTA 2015 sensitivity**

One can exclude the presence of a SMBHB with a « chirp mass »

$M_c > 10^9 M_\odot$ up to 25 Mpc

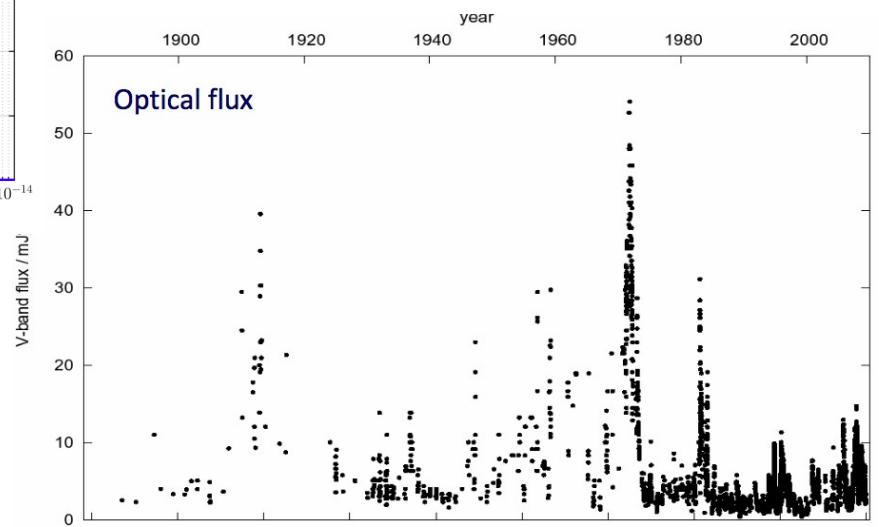
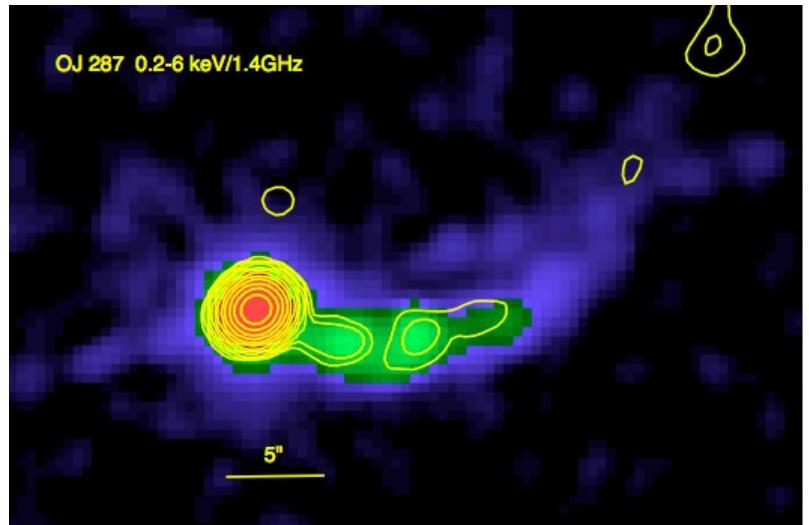
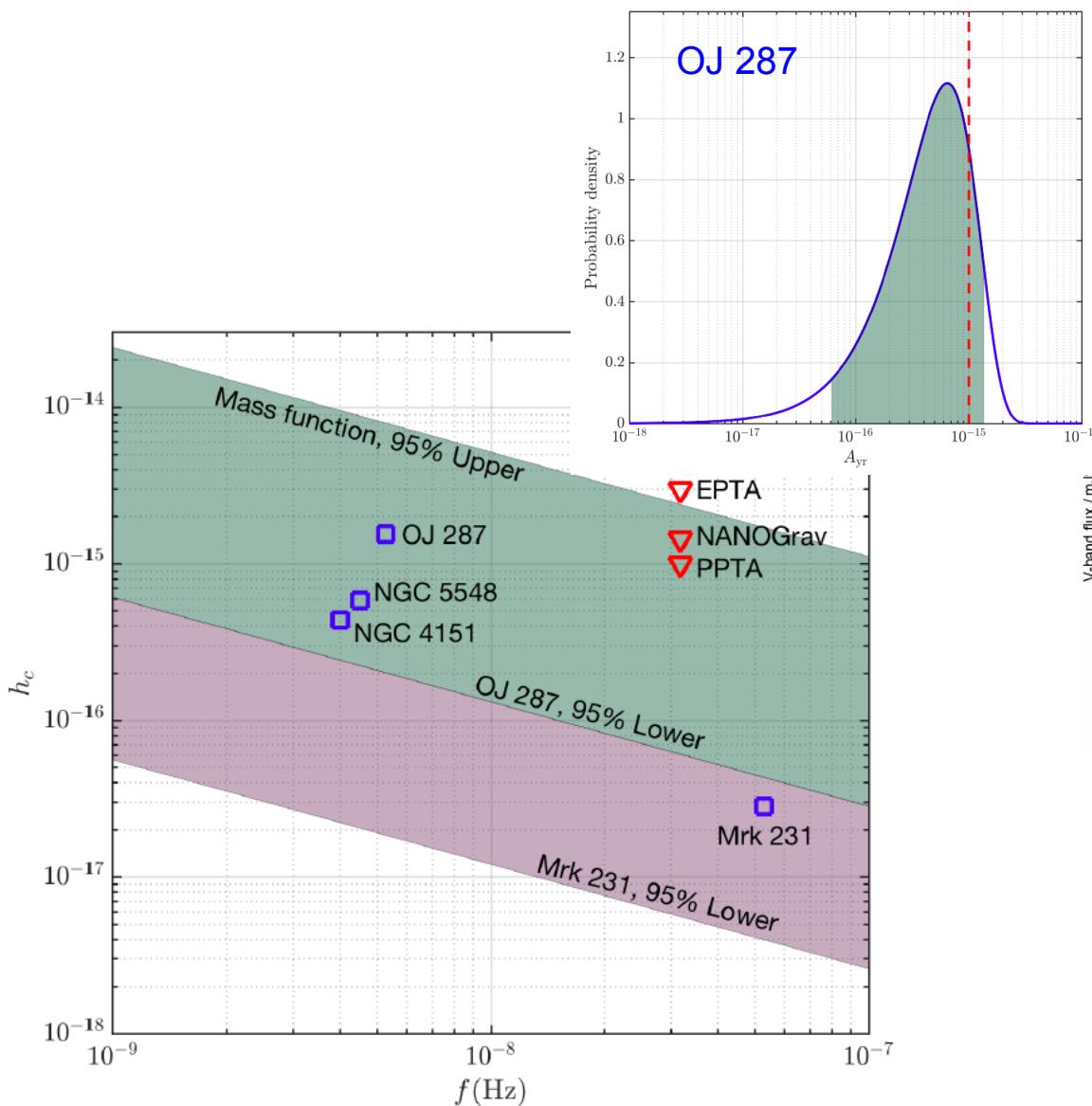
$M_c > 3 \cdot 10^9 M_\odot$ up to 200 Mpc

OJ 287 as a SMBH binary candidate

(discovered in 1988 by Sillanpää et al)

also NGC5548, NGC4151, Mrk231

Zhu et al 2018 computed the probability distribution of the gravitational wave background amplitude



OJ 287
~12 yrs period
 18×10^9 solar masses
0.663 eccentricity
 $z = 0.3$

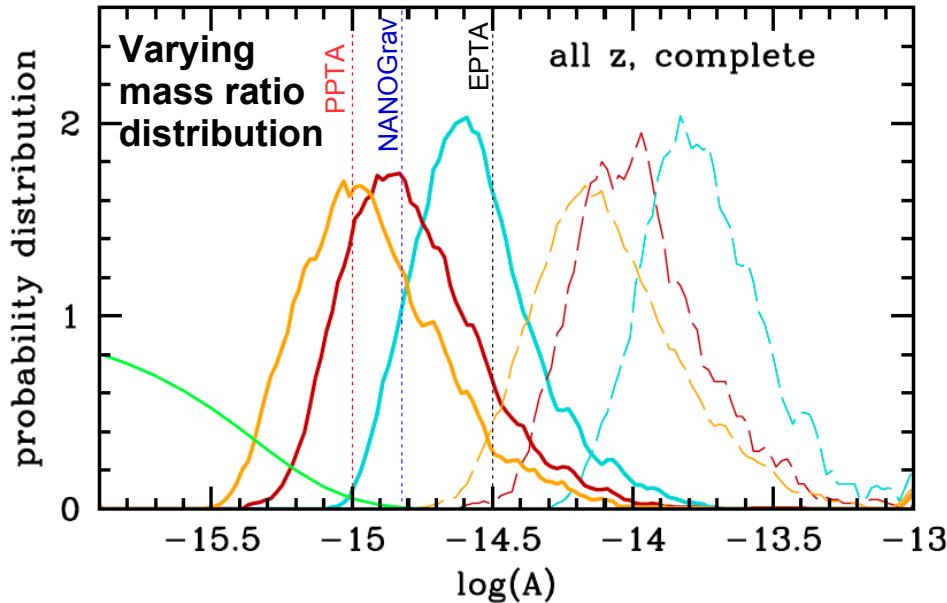
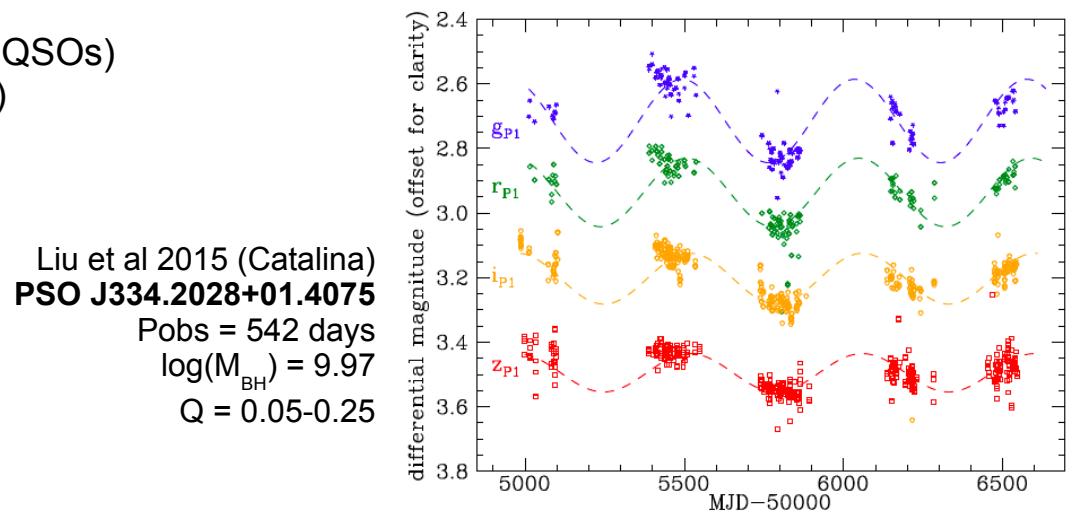
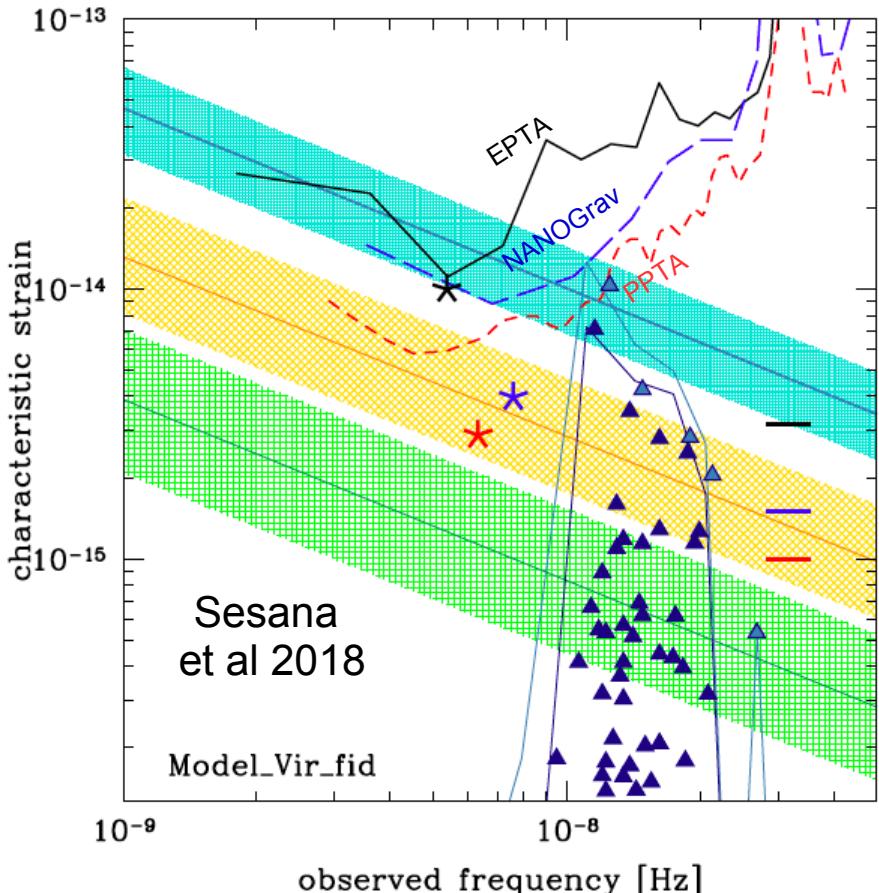
Ciprini et al 2016
Valtonen et al 2008

Periodic variability of quasars and AGNs (Graham et al 2015, Sesana et al 2018)

Binarity induces periodic material streaming from the cavity edge onto the binary, and hence luminosity periodicity, better detected in X-ray and UV

Catalina Real-time Transient Survey (CRTS – 250,000 QSOs)
 → 111 periodic sources ($P < 6$ yrs ; Graham et al 2015)

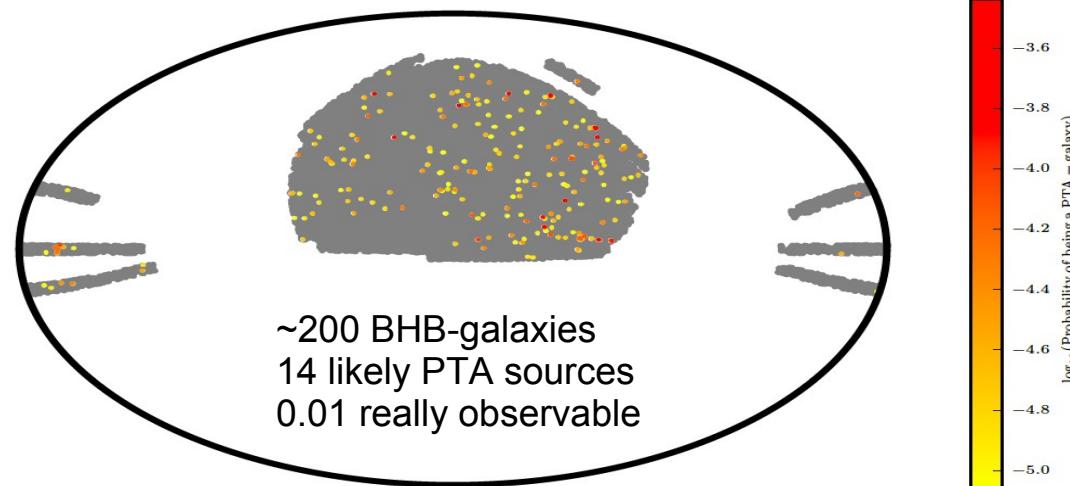
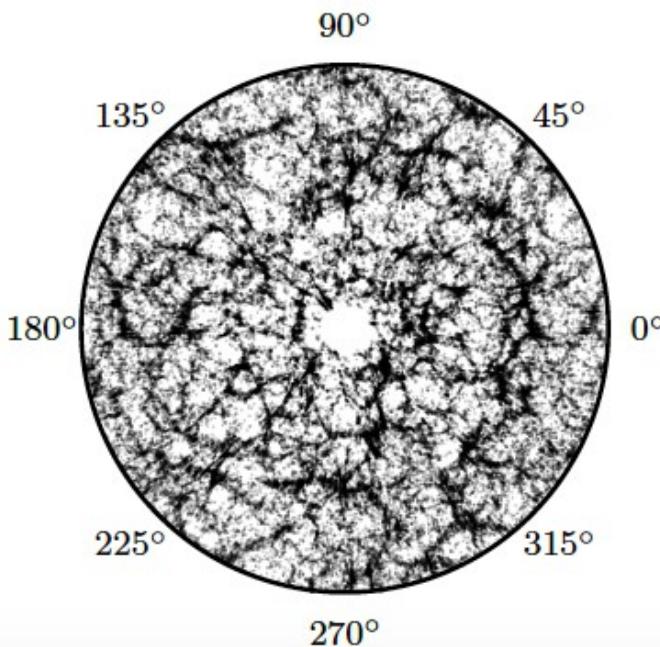
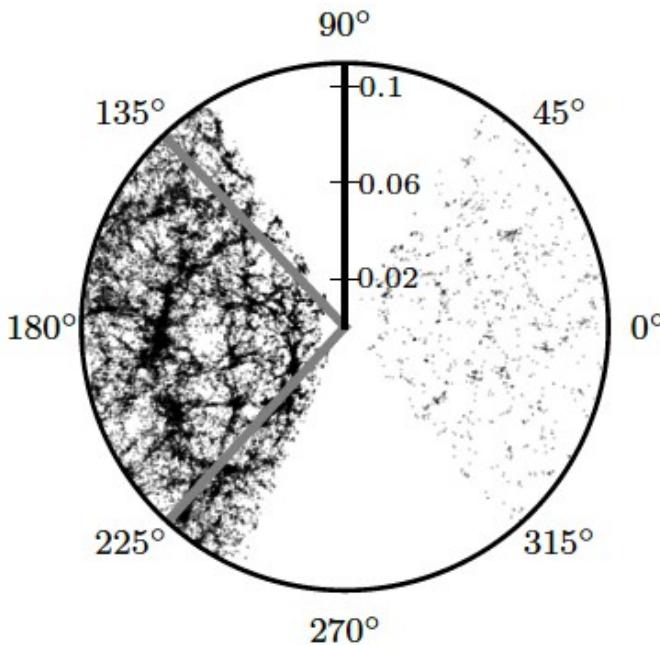
Palomar Transient Factory (OTF – 35,000 QSOs)
 → 33 periodic sources (Charisi et al 2016)



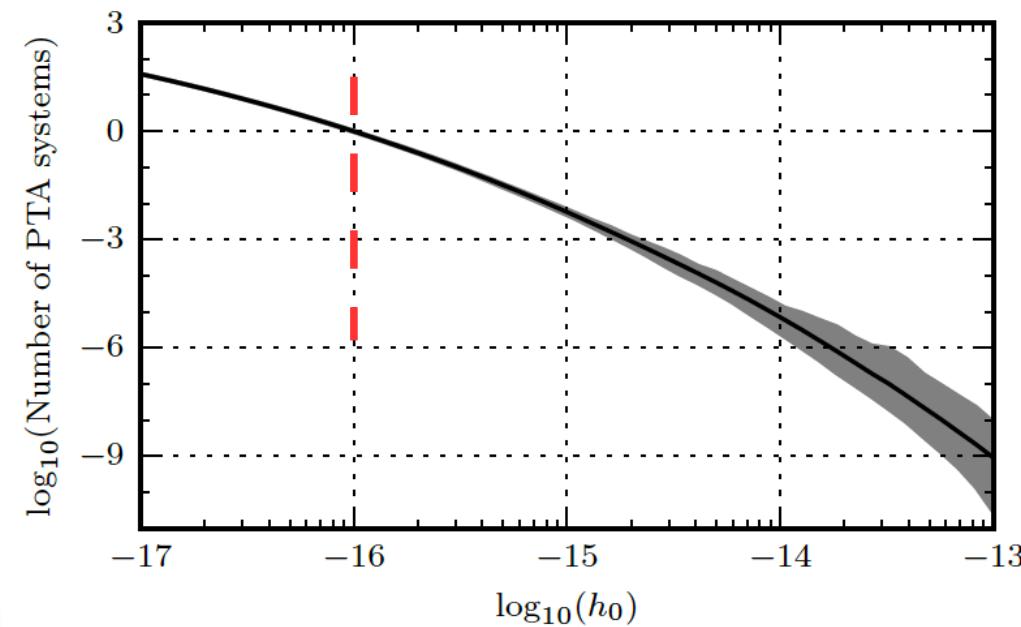
Periodic QSO candidates in tension with PTA results and population models (mainly high $z > 1.3$)

Massive cluster galaxies from SDSS

Rosado&Sesana 2014 used SDSS (25% of the sky) to produce a map of the sky in which each galaxy is assigned a probability to have suffered a recent merger and hosting a SMBHB emitting GW in the PTA band



Compare simulation (Springel et al 2005) with real catalog
→ high mass galaxies ($\geq 10^{11} M_{\odot}$) and cluster members are favored



Massive elliptical galaxies from 2MASS

Mingarelli et al 2017

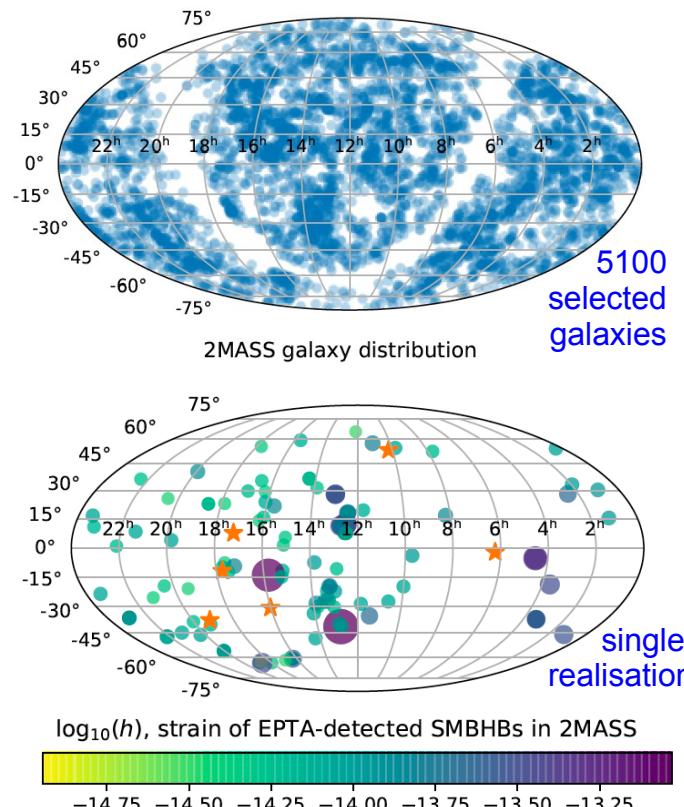
Use merger tree from Illustris simulation :

- probability of hosting a SMBHB,
- time spent in stellar hardening and dynamical friction phases

Use 2MASS redshift survey galaxies (Huchra et al 2012):

- mainly massive ($M^* \geq 10^{11} M_\odot$, $K < -25$), nearby (< 225 Mpc), early type galaxies
- + 33 direct SMBH dynamical mass measurements (Schutz&Ma 2016)
- total mass (from M^* and BH-bulge relation) and mass ratio (random)
- time to coalescence and probability that the SMBHB emits in PTA band

+ MonteCarlo realisations



Results

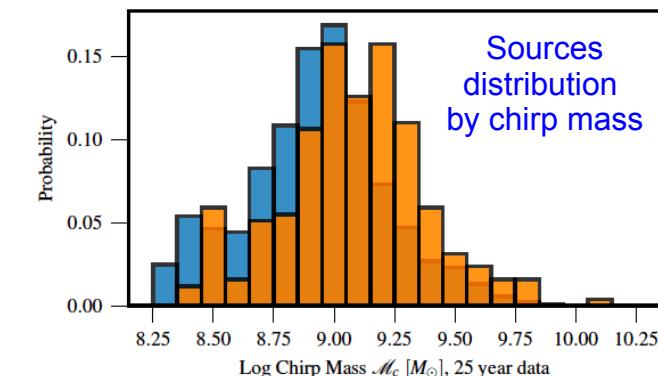
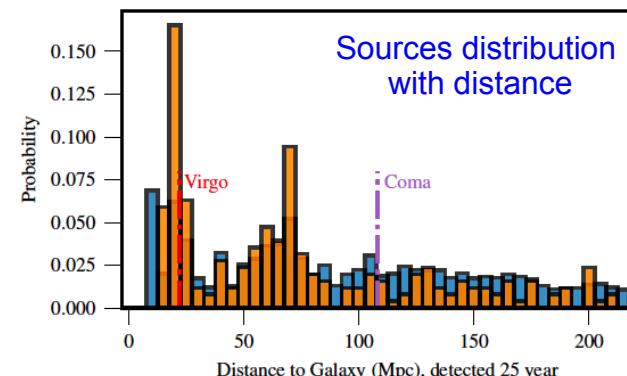
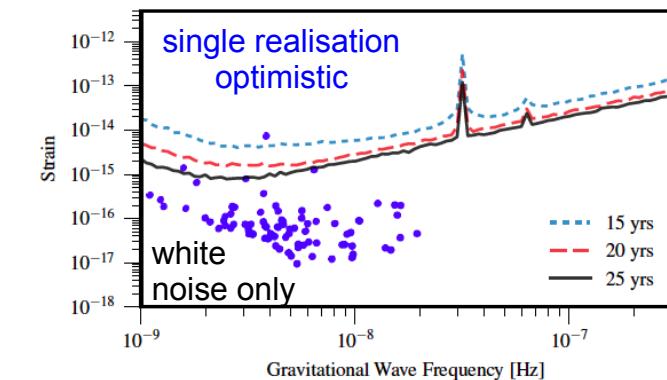
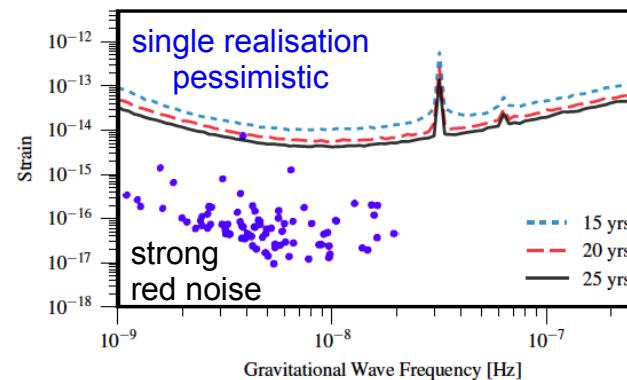
on average 91 ± 7 galaxies hosting SMBHB in PTA band

1% of sky hosting a detectable GW source

best probability for $M_c \sim 10^9 M_\odot$

favors $q <$ few % in dynamically selected nearby galaxies

+ IPTA projections



Role of :

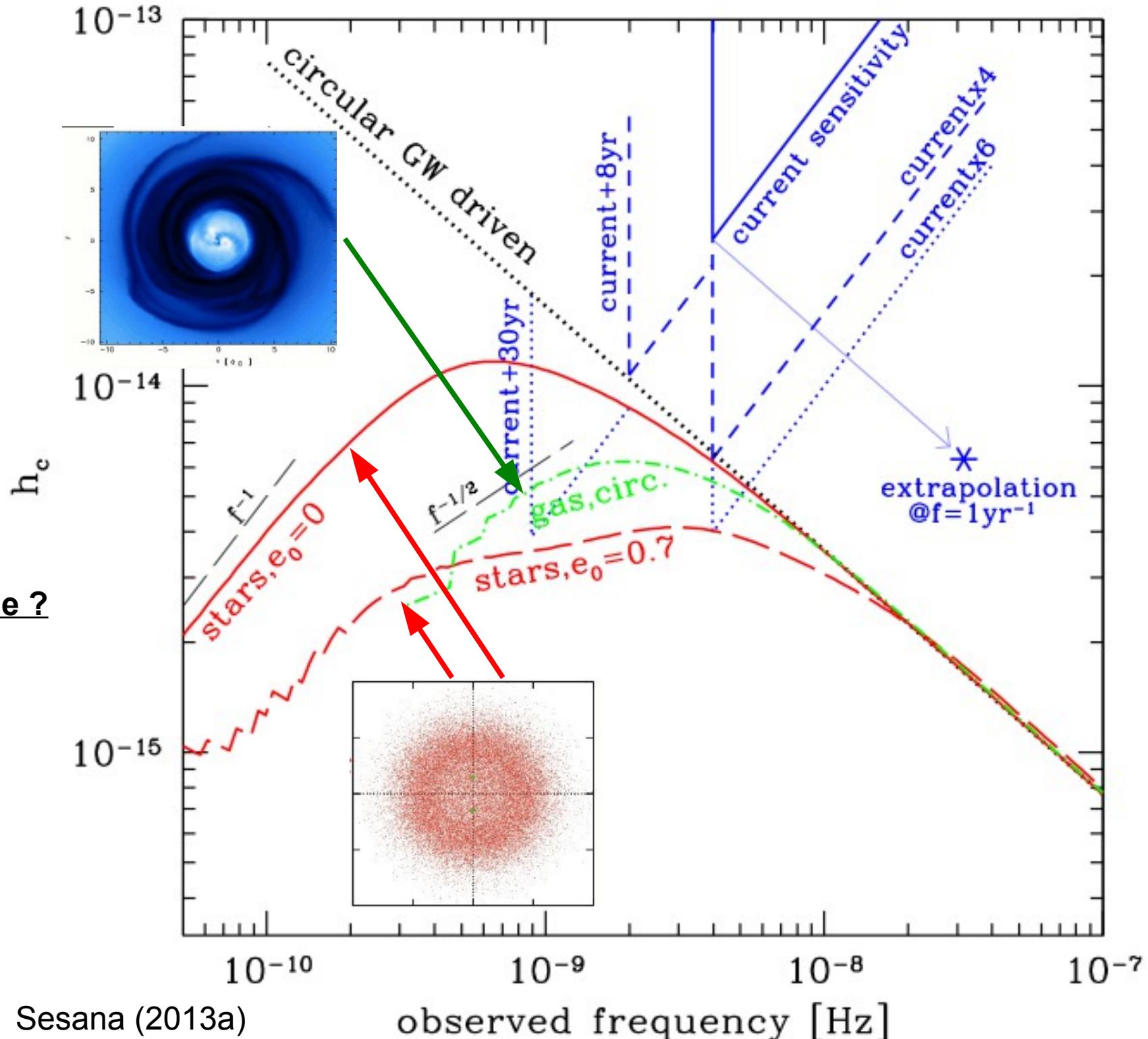
Accretion disk

Nucleus stars

Spin orientation

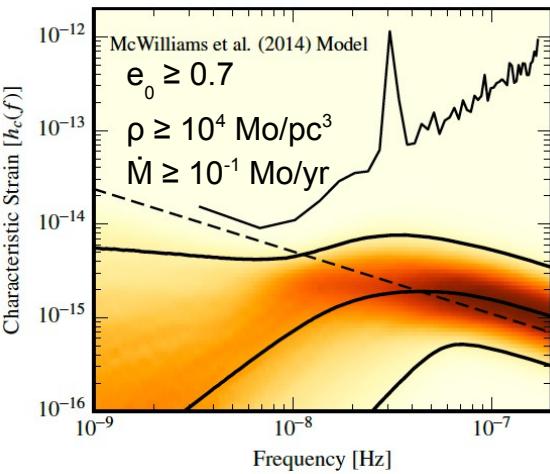
Eccentricity

Which time scale ?



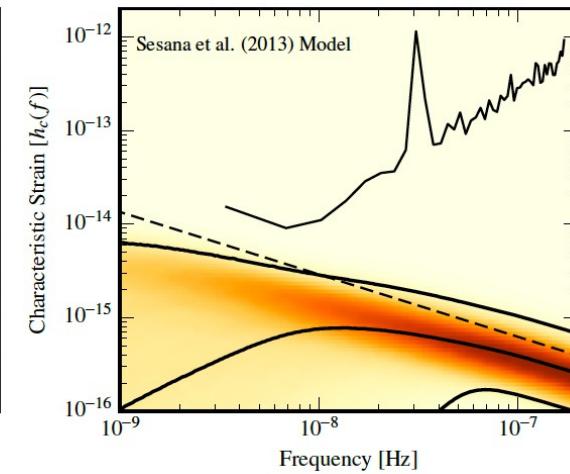
Tests of Astrophysical models

Arzoumanian et al 2016
NanoGRAV 9 years



$$h_c(f) = A \frac{(f/f_{\text{yr}})^{\alpha}}{(1 + (f_{\text{bend}}/f)^{\kappa})^{1/2}}$$

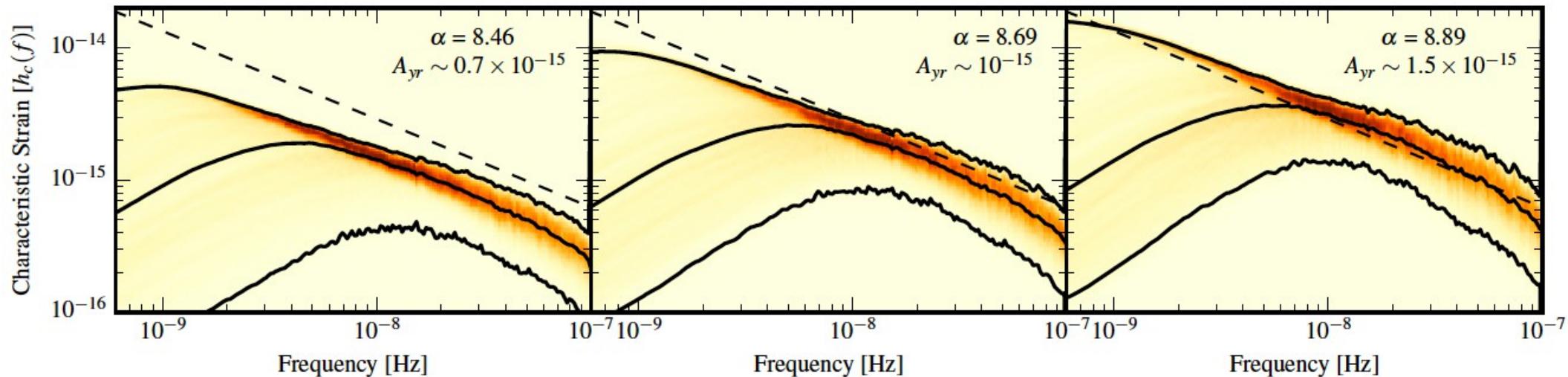
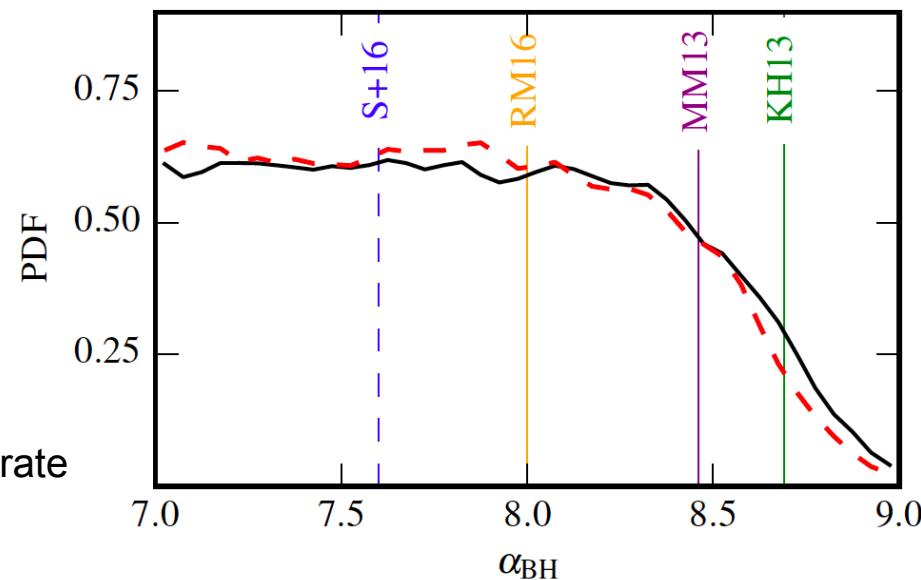
f_{bend} related to either excentricity, star core density or accretion rate



a turnover frequency f_{bend}
a shape parameter κ

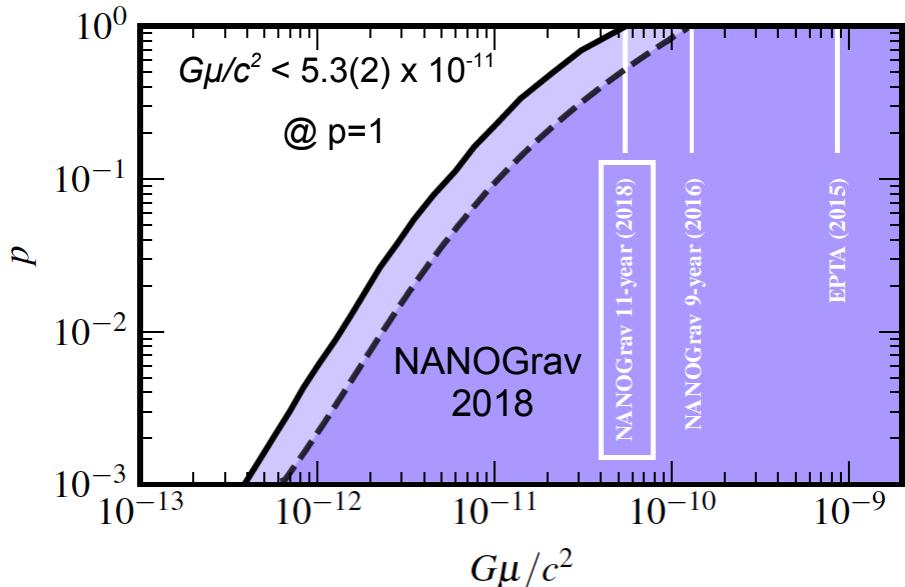
Arzoumanian et al 2018
NanoGRAV 11 years

α_{BH} y-intercept of $M_{\text{BH}} - M_{\text{bulge}}$ relation
 ρ_{stars} mass density of galactic-core stars
 e_0 binary eccentricity at formation



Limits on cosmic strings tension

one-dimensional topological defects,
relics of some spontaneous symmetry breaking
during various phase transitions in the early Universe



Parameter space of cosmic strings :

dimension less tension $G\mu/c^2$
birth scale relative to horizon α_{cs}
reconnection probability p

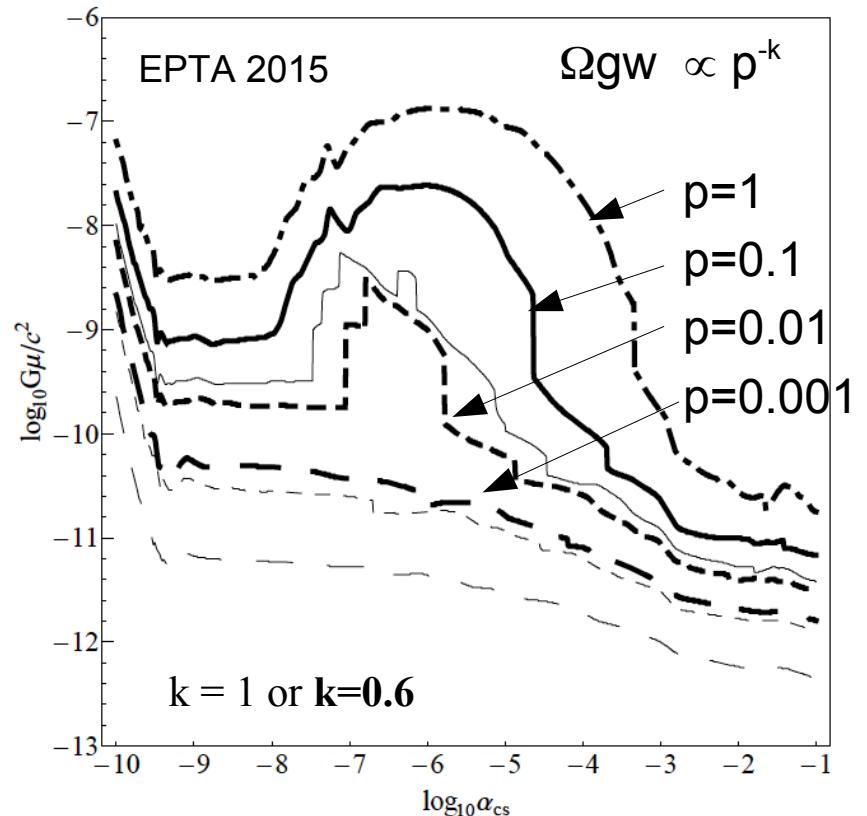
Simulations : e.g. <http://cosmos.phy.tufts.edu/cosmic-string-spectra/>

→ output = GW energy density spectra at a range of string tension values
+ conversion into a characteristic strain (a value in each PTA frequency bin)

→ $G\mu/c^2 < 5.3(2) \times 10^{-11}$ @ $p=1$

→ not detectable through either CMB measurement nor gravitational lensing

Rem : CMB more robust since relies on large scale properties of infinite strings, and not on the complex mechanisms of emission or on the actual cosmic string loop population



Relics of primordial gravitational waves

Quantum fluctuations of the gravitational field in the early Universe, amplified by an inflationary phase, are expected to produce a stochastic relic GWB observable in the PTA band

and at longer wavelength, anisotropies and characteristic signature in the polarization of the CMB

The spectral index of the primordial GWB is determined by the equation-of-state parameter w during inflation and by the tensor index n_t , which depends on the detailed dynamics of inflation (Grishchuck 2005)

$$S_{ab}(f) = \Gamma_{ab} \frac{A_{\text{GWB}}^2}{12\pi^2} \left(\frac{f}{\text{yr}^{-1}} \right)^{-\gamma} \text{yr}^3 \quad \gamma = \frac{4}{3w+1} + 3 - n_t$$

Radiation-dominated ($w = 1/3$),

Matter-dominated ($w = 0$)

Kinetic-energy-dominated ($w = 1$)

$n_t=0$ (i.e. scale-invariant primordial spectral index – Zhao et al 2011)

Results

$w=1/3$

$$\Omega_{\text{gw}}^{\text{relic}}(f) h^2 < 1.2 \times 10^{-9}$$

EPTA 2015 (Lentati et al 2015)

$n_t \sim 0$

$$\Omega_{\text{GWB}}(f_{\text{yr}}) h^2 \leq 3.4(1) \times 10^{-10}$$

NANOGrav 11-yr (Arzoumanian et al 2018)

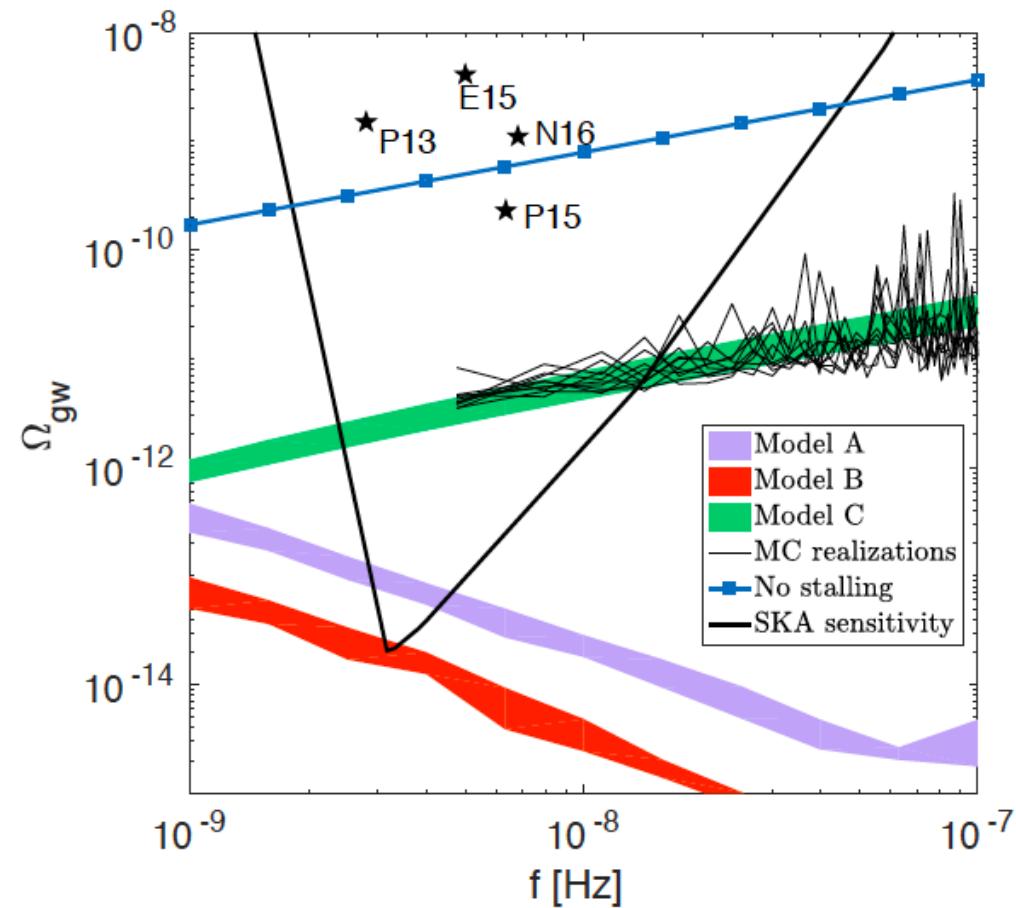
Conclusion

PTA technique produces interesting limits

We start constraining models

Detection is not so far

Thank you !



The nightmare scenario :
all the population stalled

Dvorkin&Barausse (2017)

A : all MBH binaries stalling at agw

B : all MBH binaries stalling at $\max(ah, agw)$

C : all MBH binaries form at ah
and are let free to evolve from there under GW emission

ah = hardening radius

agw = GW regime radius

De l'onde gravitationnelle au résidu de temps d'arrivée :

$$r(t) = \int_0^t \frac{\delta\nu}{\nu}(t') dt'$$

$$\frac{\delta\nu}{\nu}(t) = \frac{1}{2} \frac{\hat{n}^i \hat{n}^j}{1 + \hat{n} \cdot \hat{k}} (h_{ij}(t - L(1 + \hat{k} \cdot \hat{n})) - h_{ij}(t))$$

Amplitude de l'onde au pulsar

Amplitude de l'onde à la Terre

- n : direction du pulsar
- L : distance Terre – pulsar
- h_{ij} : amplitude de l'onde
- k : direction de propagation

De l'onde gravitationnelle au résidu de temps d'arrivée :

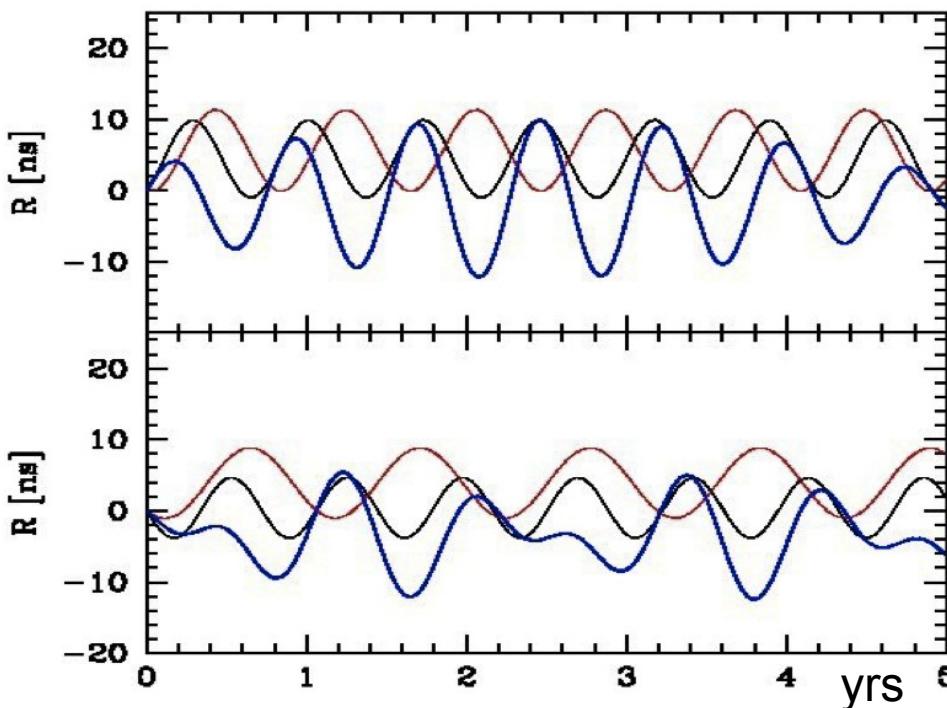
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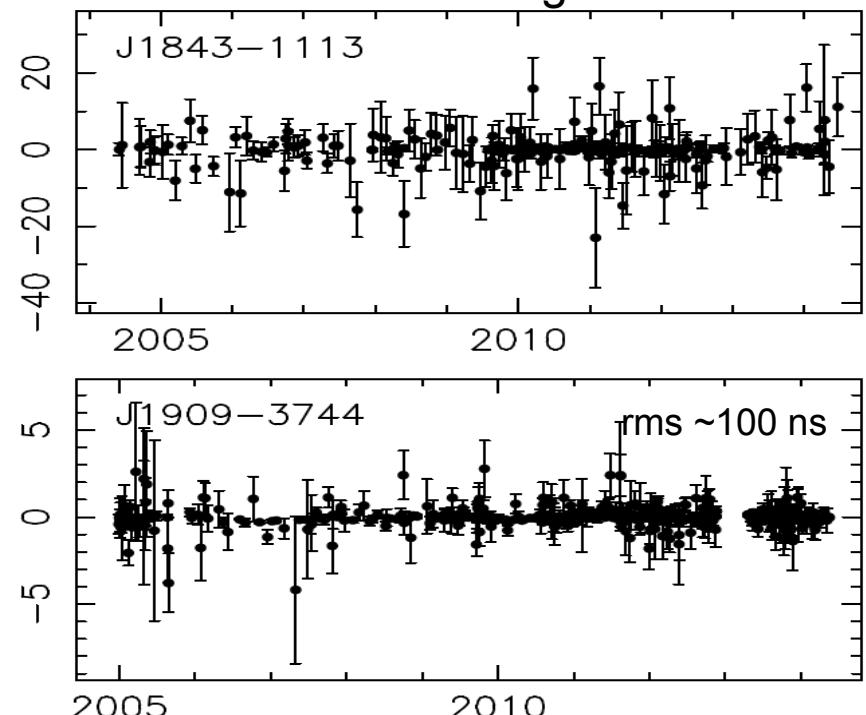
Amplitude de l'onde au pulsar

Amplitude de l'onde à la Terre

Sesana 2015



Desvignes et al 2015



- n : direction du pulsar
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De l'onde gravitationnelle au résidu de temps d'arrivée :

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- h_{ij} : amplitude de l'onde
- k : direction de propagation

Amplitude de l'onde au pulsar

Amplitude de l'onde à la Terre

L'amplitude caractéristique des ondes gravitationnelles pour une population de trous noirs binaires circulaires :

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

Fond
stochastique

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

Phinney 2001