supermassive black hole astrophysics with pulsar timing arrays

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(University of Milano-Bicocca)

OUTLINE

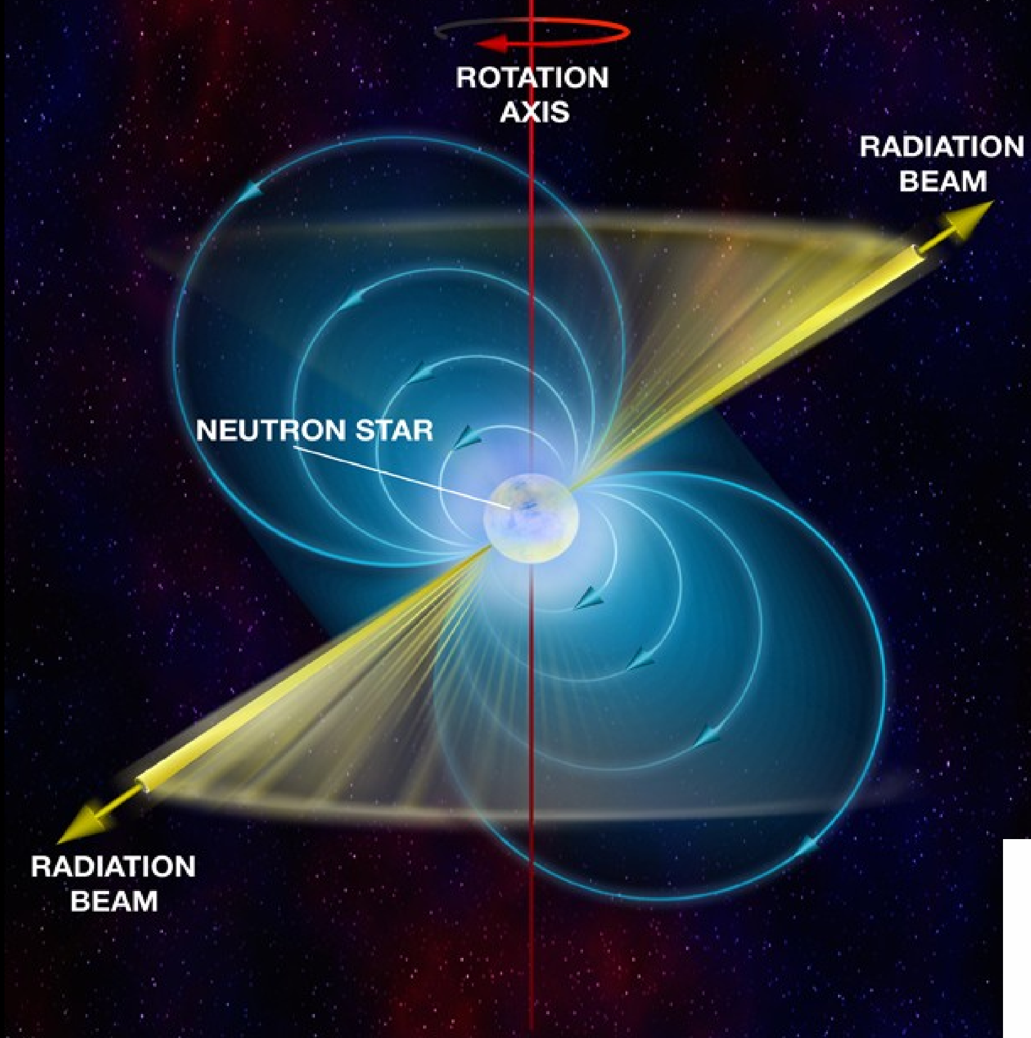
>Pulsars as ultra-precise clocks for GW detection

> (super)massive black hole binaries (MBHBs)

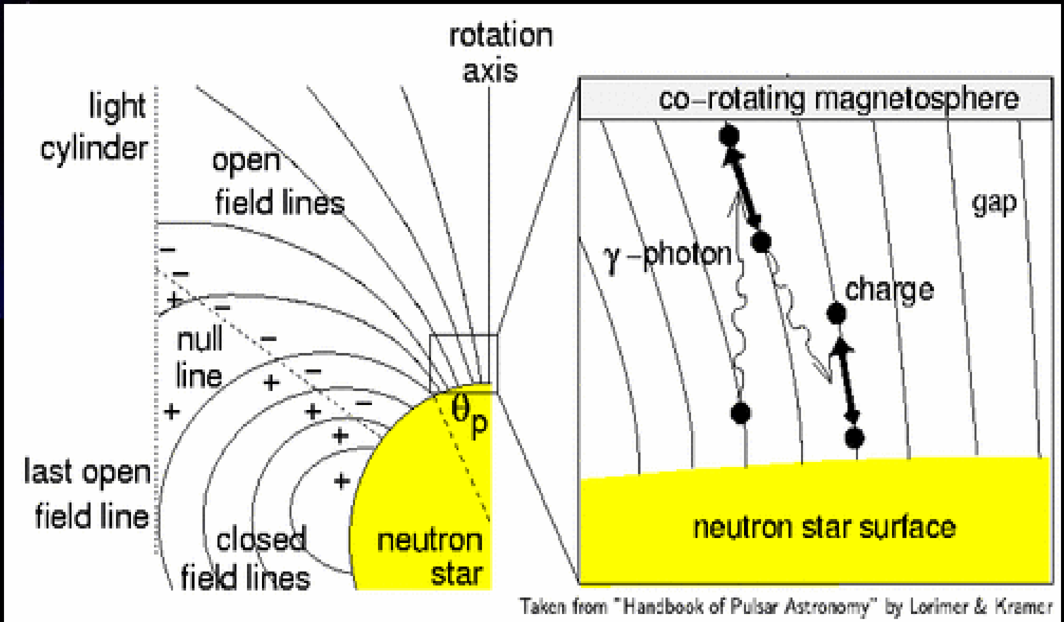
> Predictions & limits: state of the art

>The future

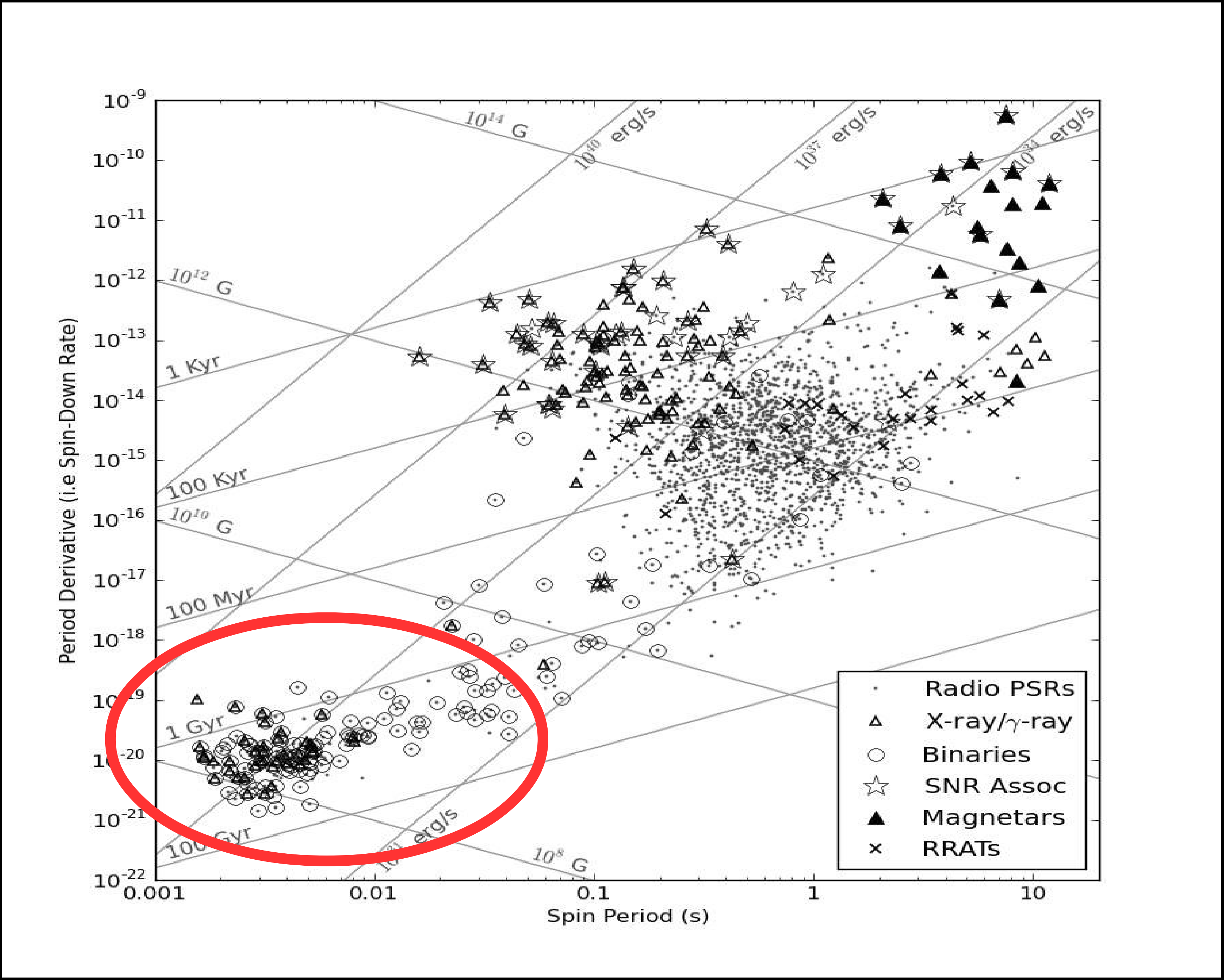
Pulsars



- -M ~1.4 solar mass
- -R~10 km
- -P~0.0014-10 s
- -B~10^{8} -10^{15} G



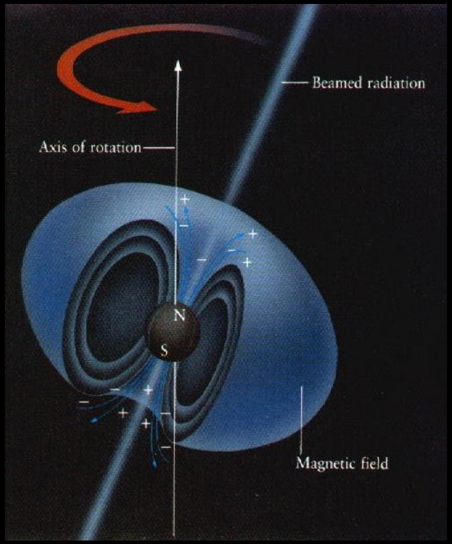
Millisecond pulsars



What is pulsar timing

Pulsars are neutron seen through their regular radio pulses

Pulsar timing is the art of measuring the time of arrival (ToA) of each pulse and then subtracting off the expected time of arrival given by a theoretical model for the system



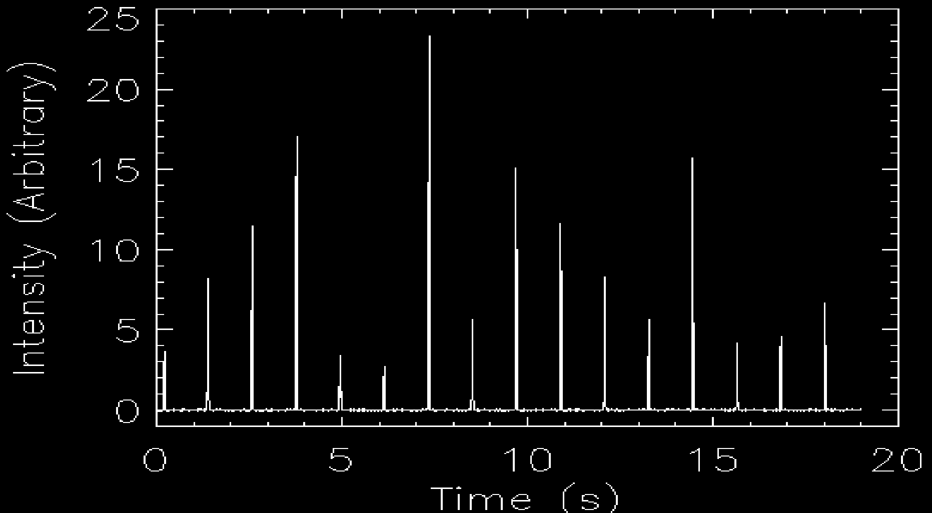
1-Observe a pulsar and measure the ToAs

2-Find the model which best fits the ToAs

3-Compute the timing residual R

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

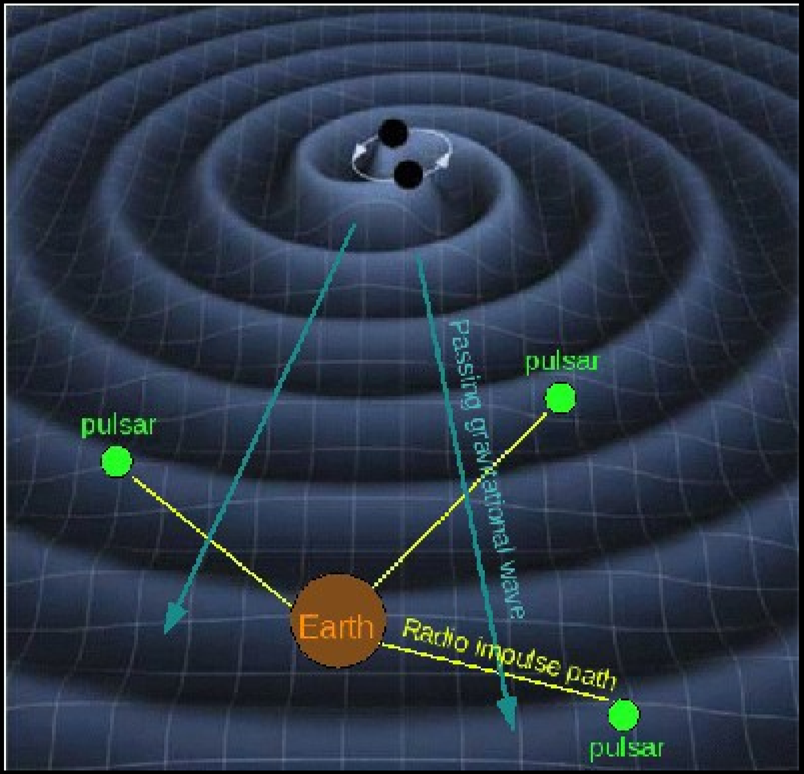
If the timing solution is perfect (and observations noiseless), then *R*=0. *R* contains all uncertainties related to the signal propagation and detection, plus the effect of unmodelled physics, like (possibly) *gravitational waves*



Effect of gravitational waves

The GW passage causes a modulation of the observed pulse frequency

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

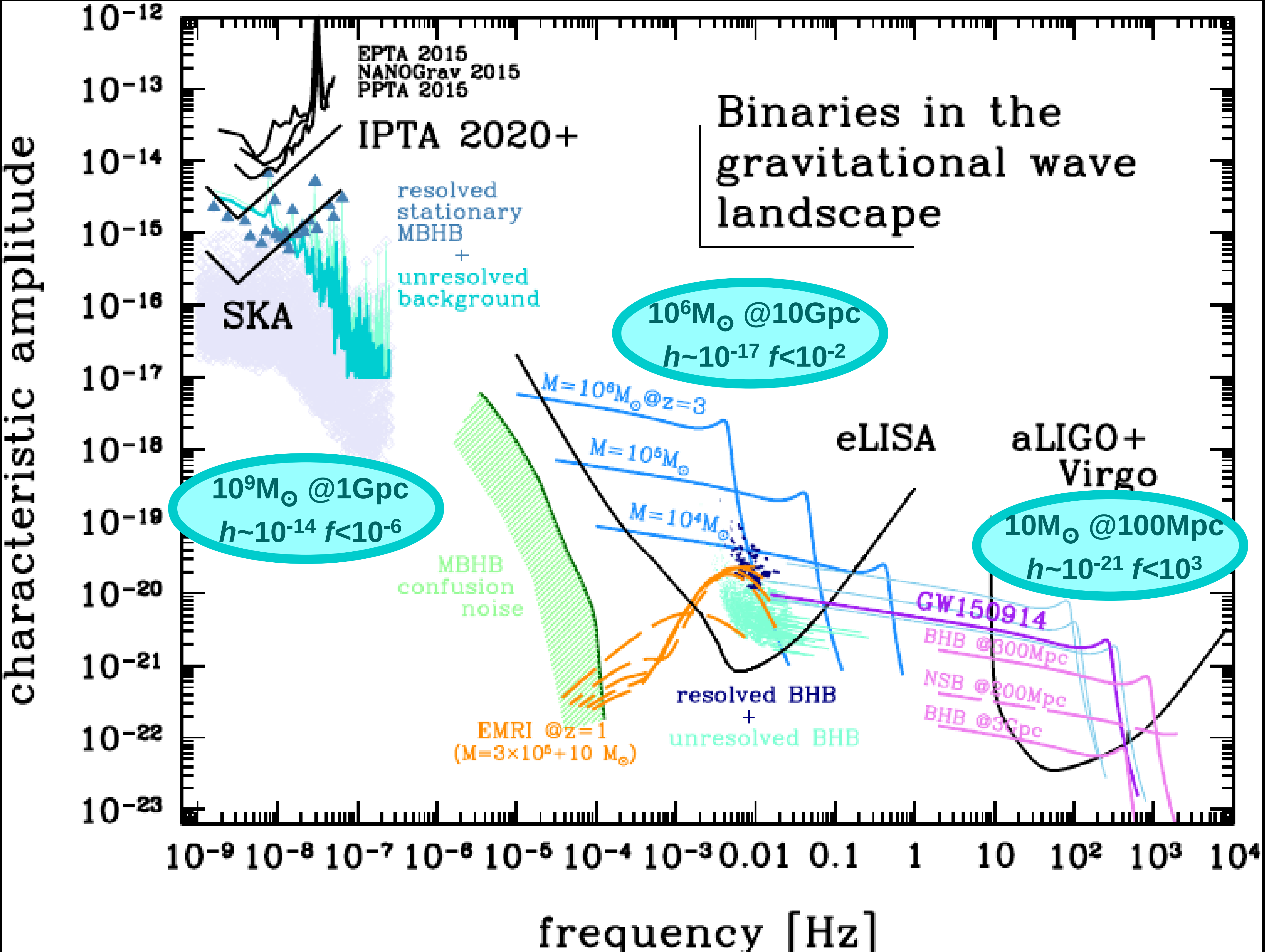


$$R(t) = \int_0^T \frac{\nu(t)-\nu_0}{\nu_0}dt$$

(Sazhin 1979, Hellings & Downs 1983, Jenet et al. 2005, AS et al. 2008, 2009)

R~h/(2πf)

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



characteristic amplitude
frequency [Hz]
EPTA 2015
NANOGrav 2015
PPTA 2015
IPTA 2020+
SKA
resolved stationary MBHB
+
unresolved background
Binaries in the gravitational wave landscape
10^6M⊙ @10Gpc
h~10^-17 f<10^-2
10^9M⊙ @1Gpc
h~10^-14 f<10^-6
10M⊙ @100Mpc
h~10^-21 f<10^3
M=10^6M⊙@z=3
M=10^5M⊙
M=10^4M⊙
eLISA
aLIGO+
Virgo
MBHB
confusion
noise
GW150914
BHB @300Mpc
NSB @200Mpc
BHB @3Gpc
EMRI @z=1
(M=3×10^5+10 M⊙)
resolved BHB
+
unresolved BHB

Observational facts

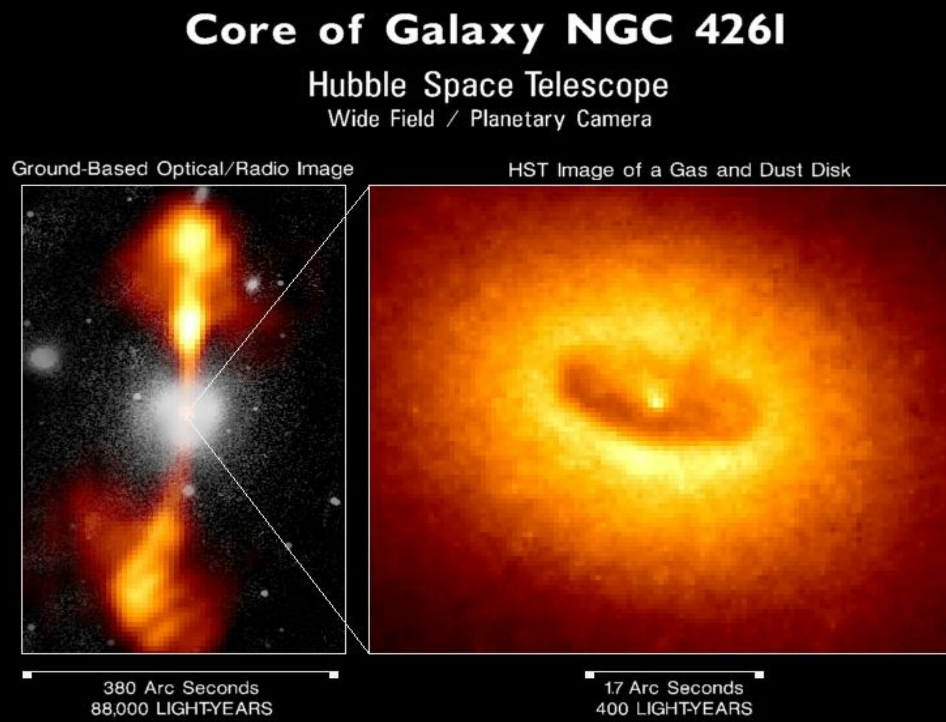
1- In all the cases where the inner core of a galaxy has been resolved (i.e. In nearby galaxies), a massive compact object (which I'll call Massive Black Hole, MBH for convenience) has been found in the centre.

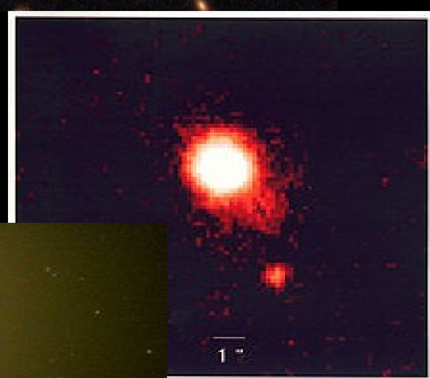
2- MBHs must be the central engines of Quasars: the only viable model to explain this cosmological objects is by means of gas accretion onto a MBH.

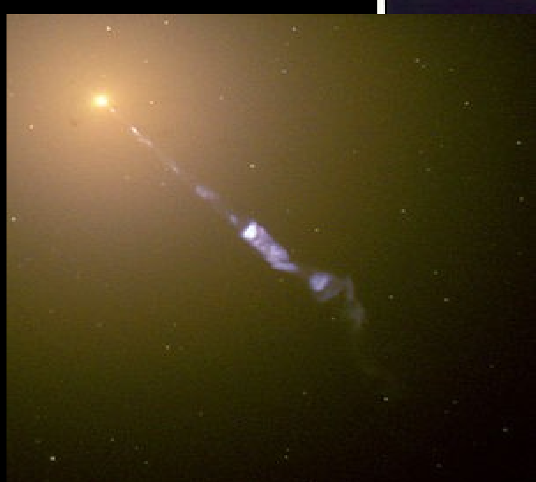
3- Quasars have been discovered at z~7, their inferred masses are ~10^9 solar masses!

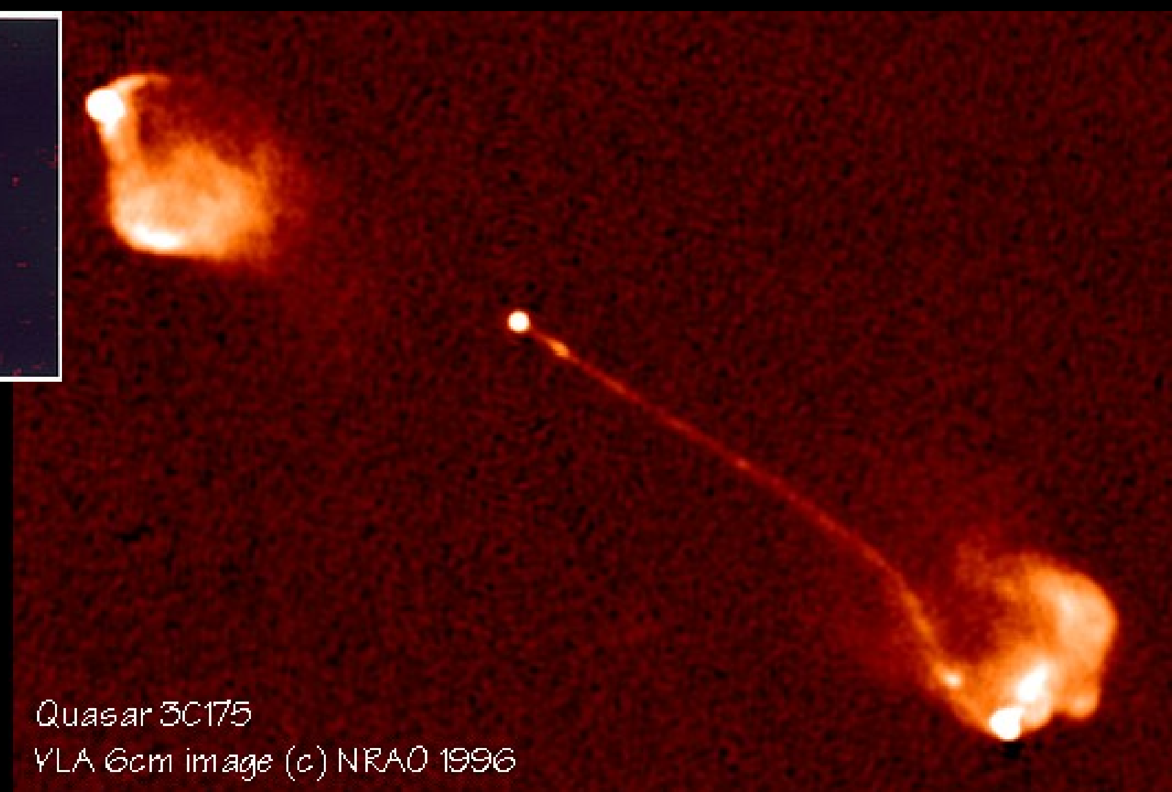
THERE WERE 10^9 SOLAR MASS BHs WHEN THE UNIVERSE WAS <1Gyr OLD!!!

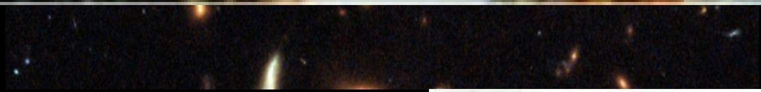
MBH formation and evolution have profound consequences for GW astronomy

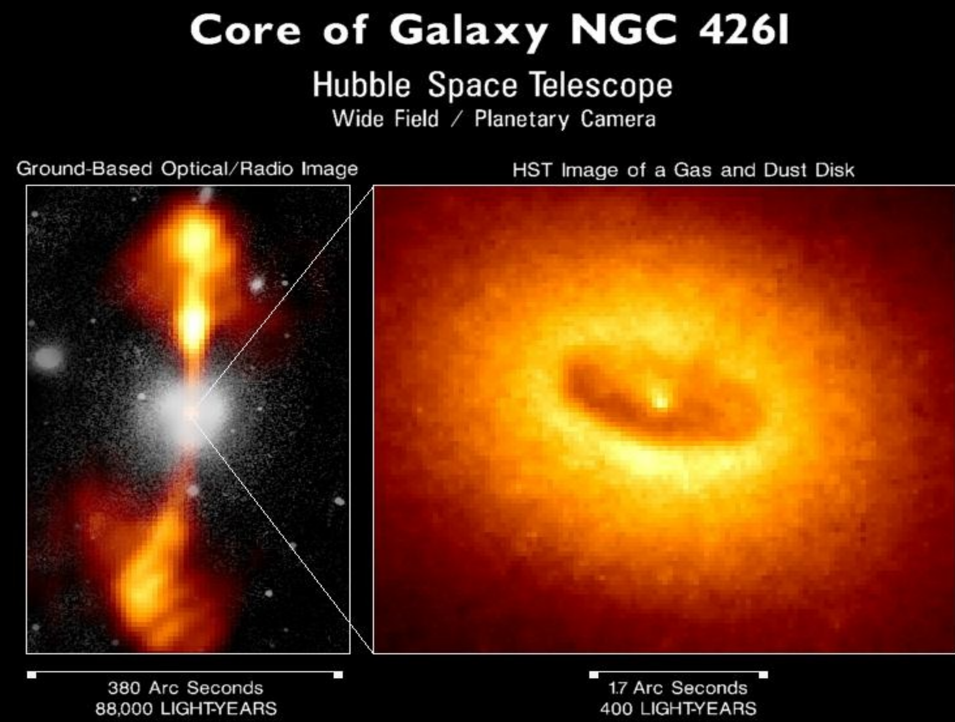

Core of Galaxy NGC 4261
Hubble Space Telescope
Wide Field / Planetary Camera
Ground-Based Optical/Radio Image
HST Image of a Gas and Dust Disk
380 Arc Seconds
88,000 LIGHT-YEARS
1.7 Arc Seconds
400 LIGHT-YEARS


1 "




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

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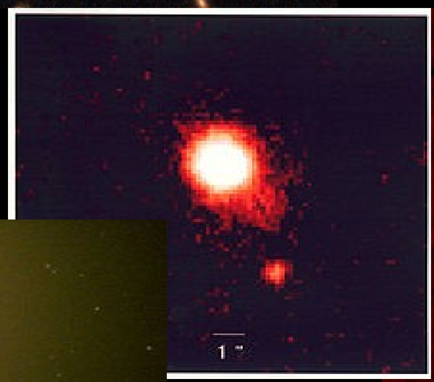
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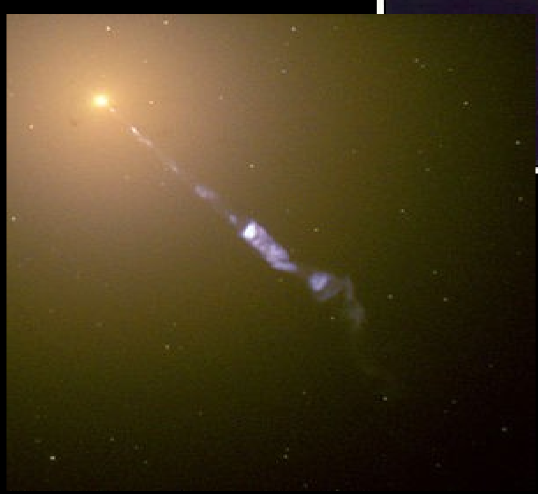

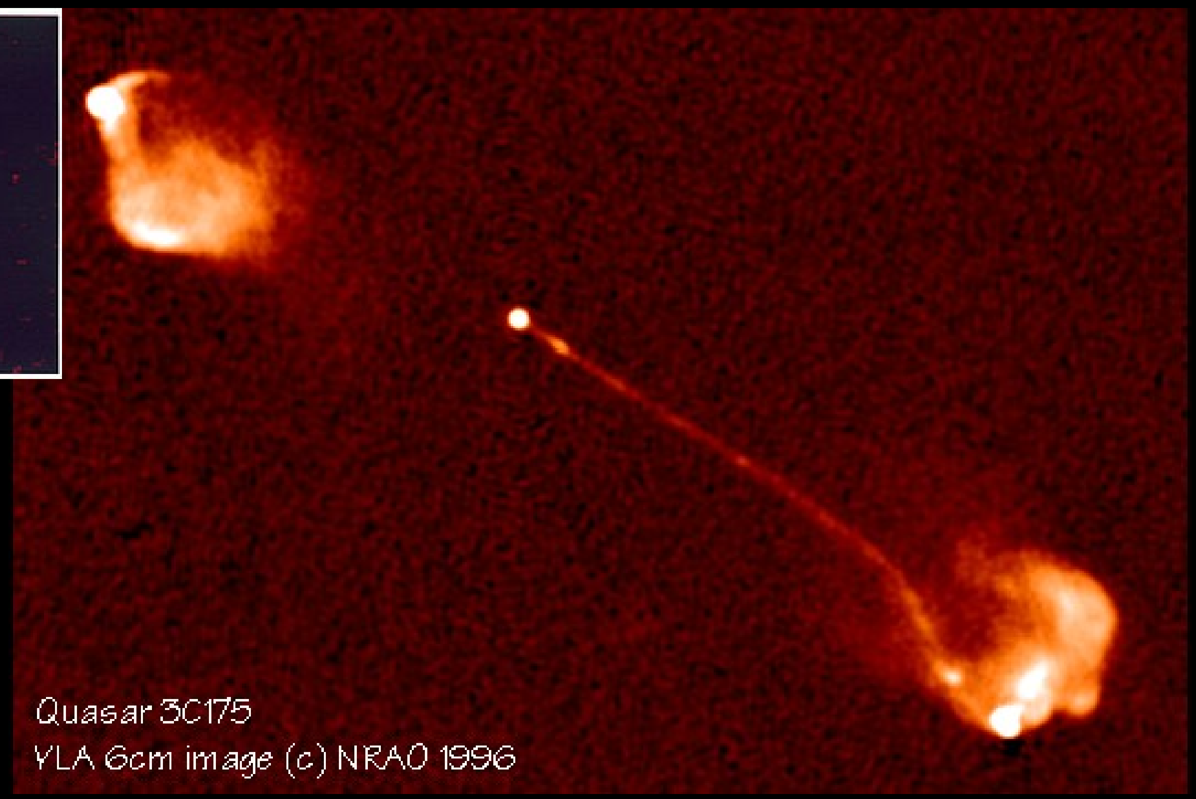
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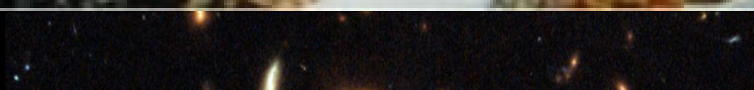
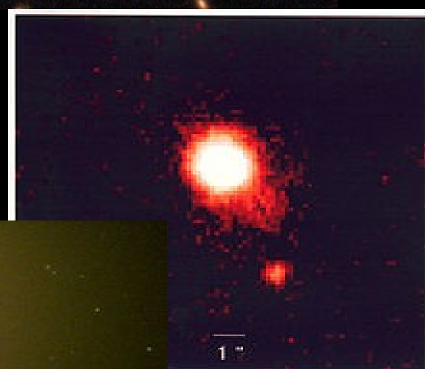
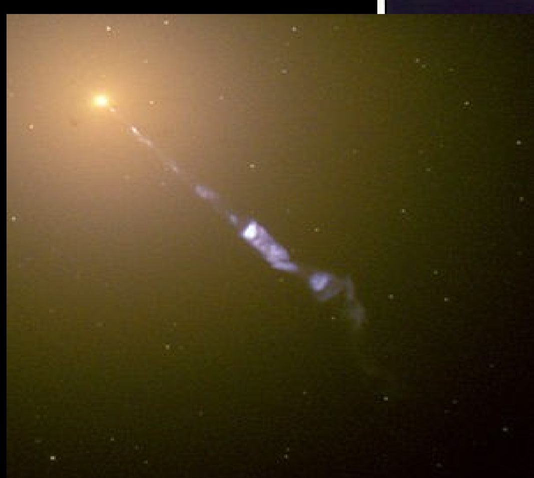
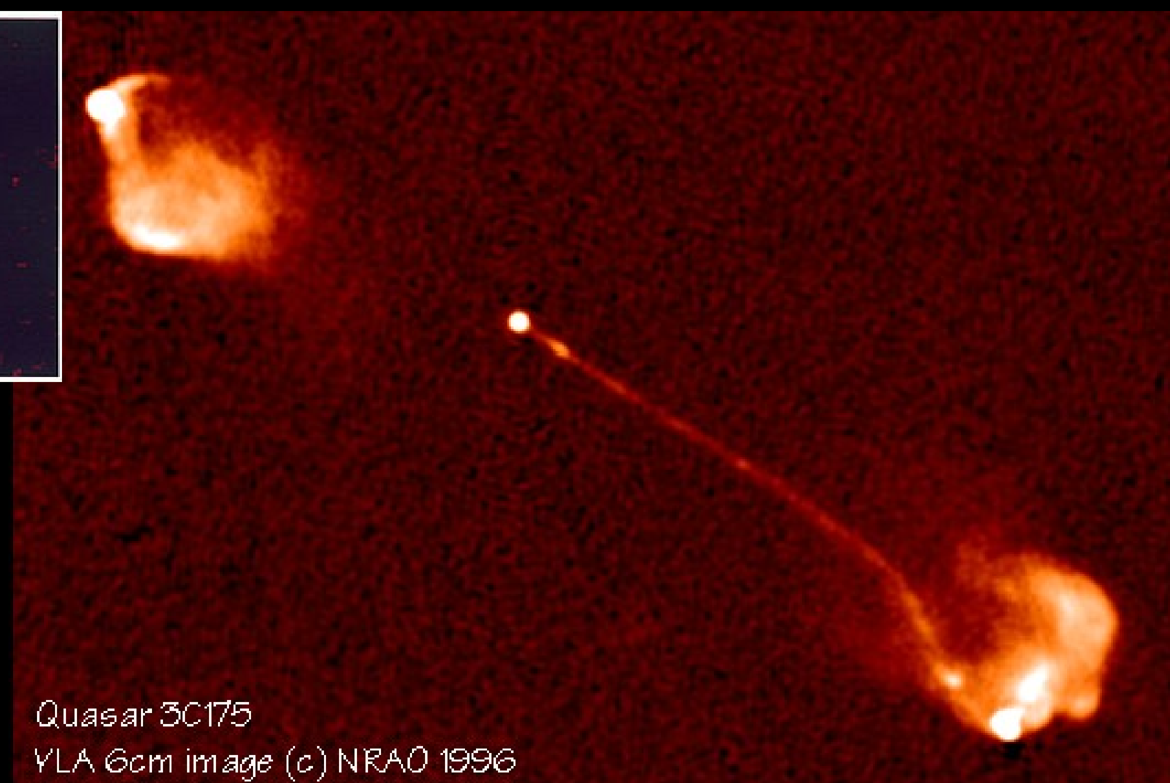
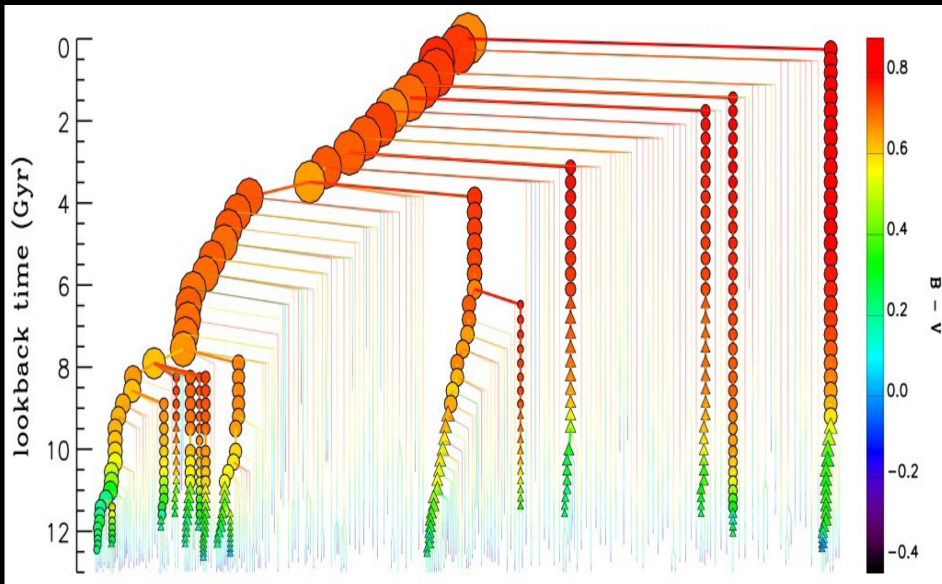




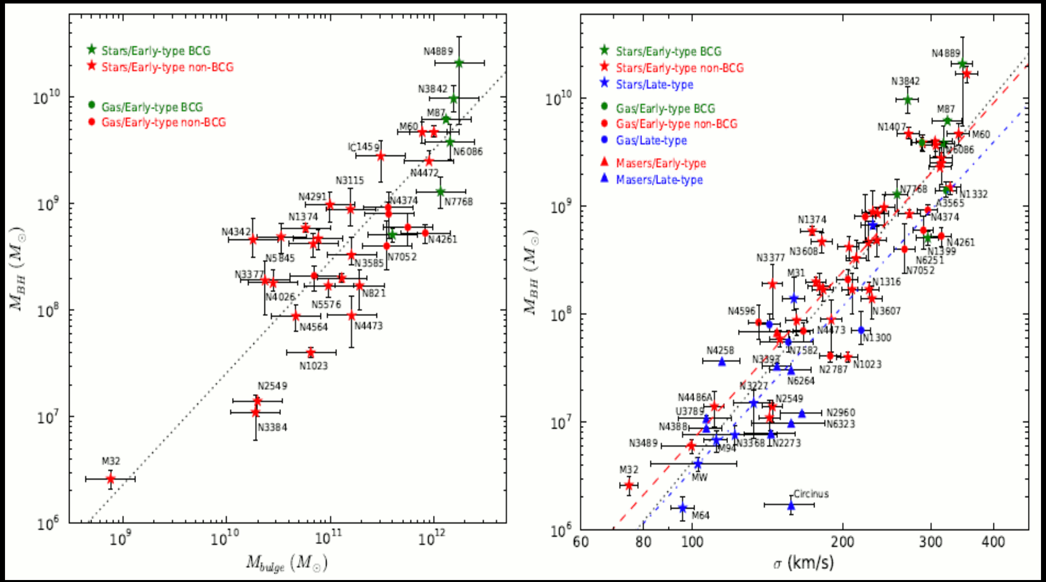



Quasar 3C175
VLA 6cm image (c) NRAO 1996

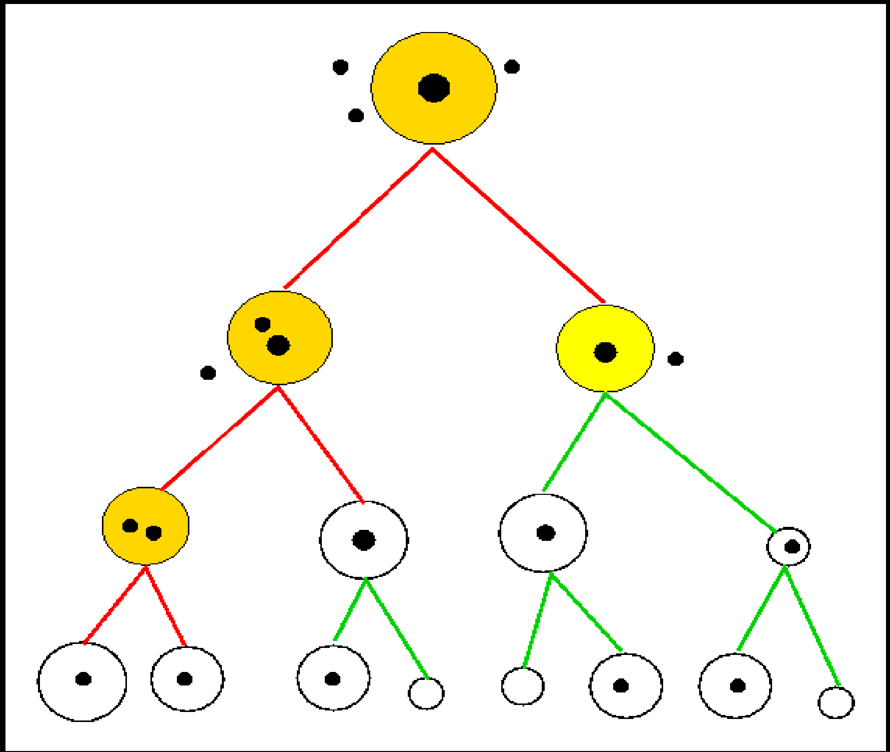
Structure formation in a nutshell



(From de Lucia et al. 2006)

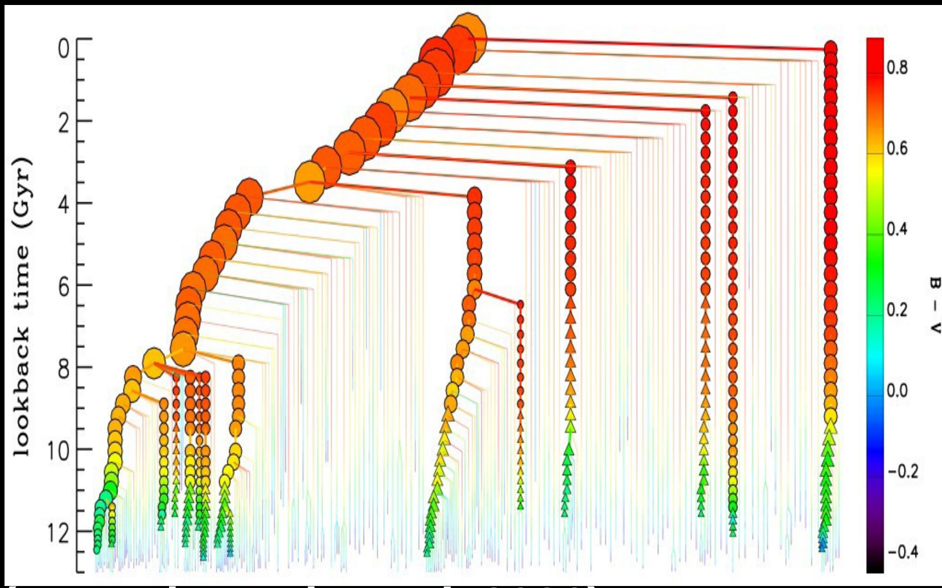


(Ferrarese & Merritt 2000, Gebhardt et al. 2000)



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

Structure formation in a nutshell



(From de Lucia et al. 2006)

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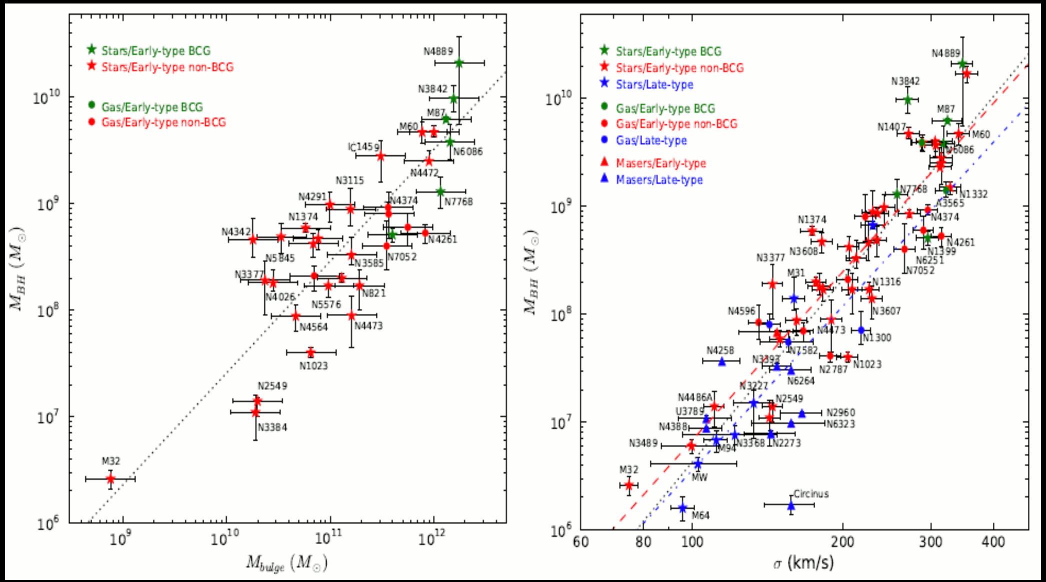

(Ferrarese & Merritt 2000, Gebhardt et al. 2000)

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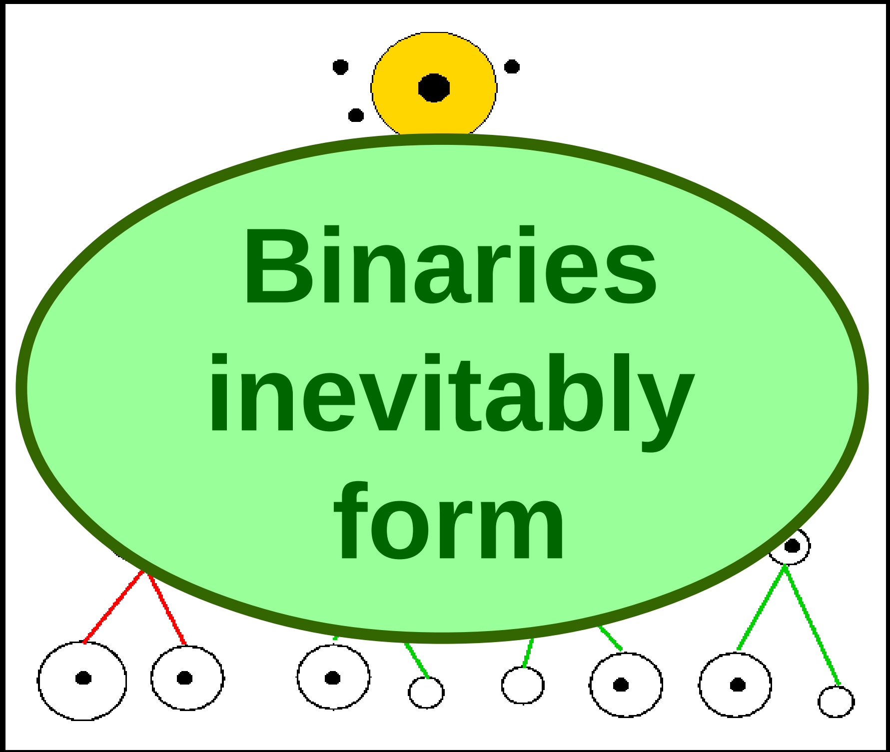
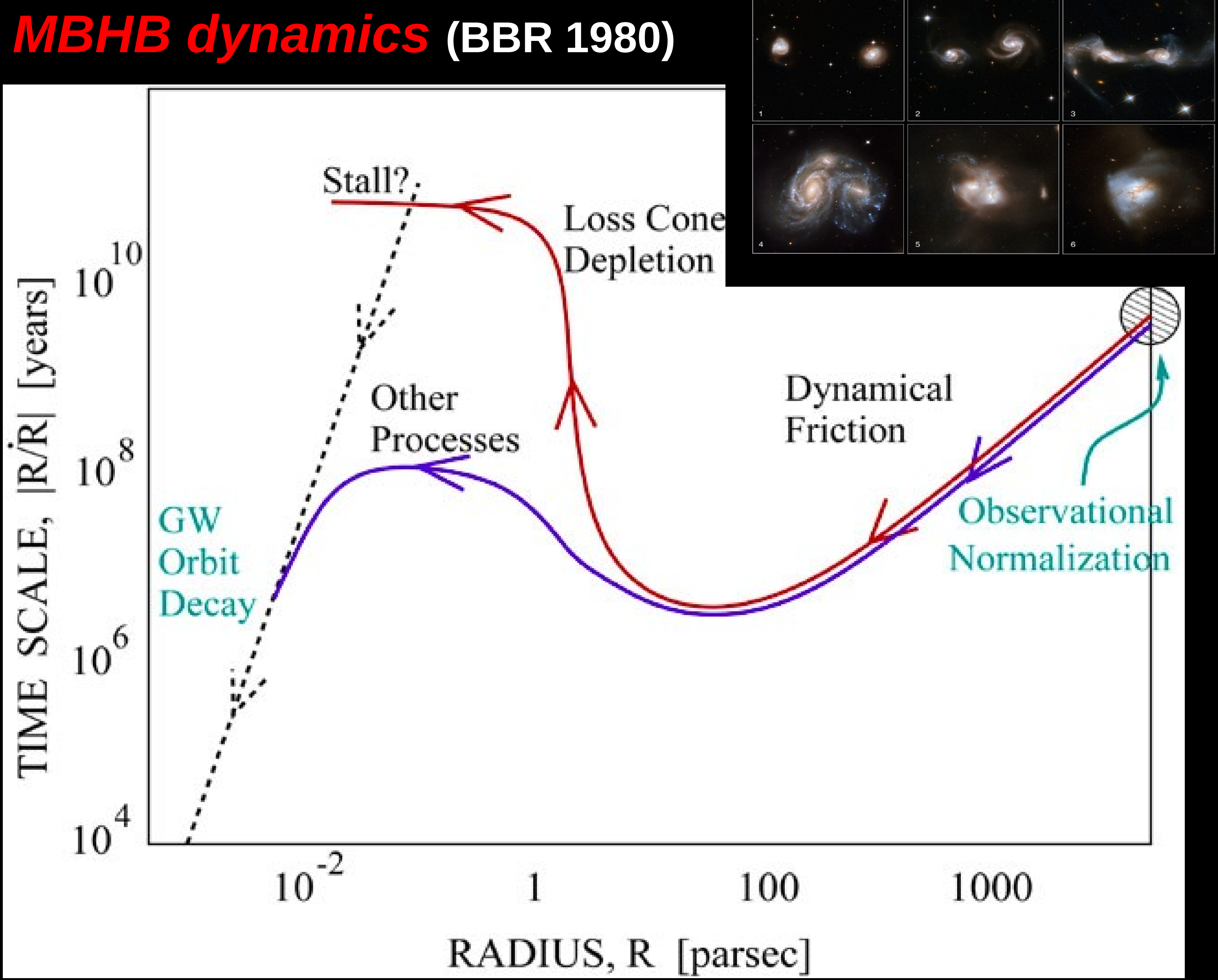


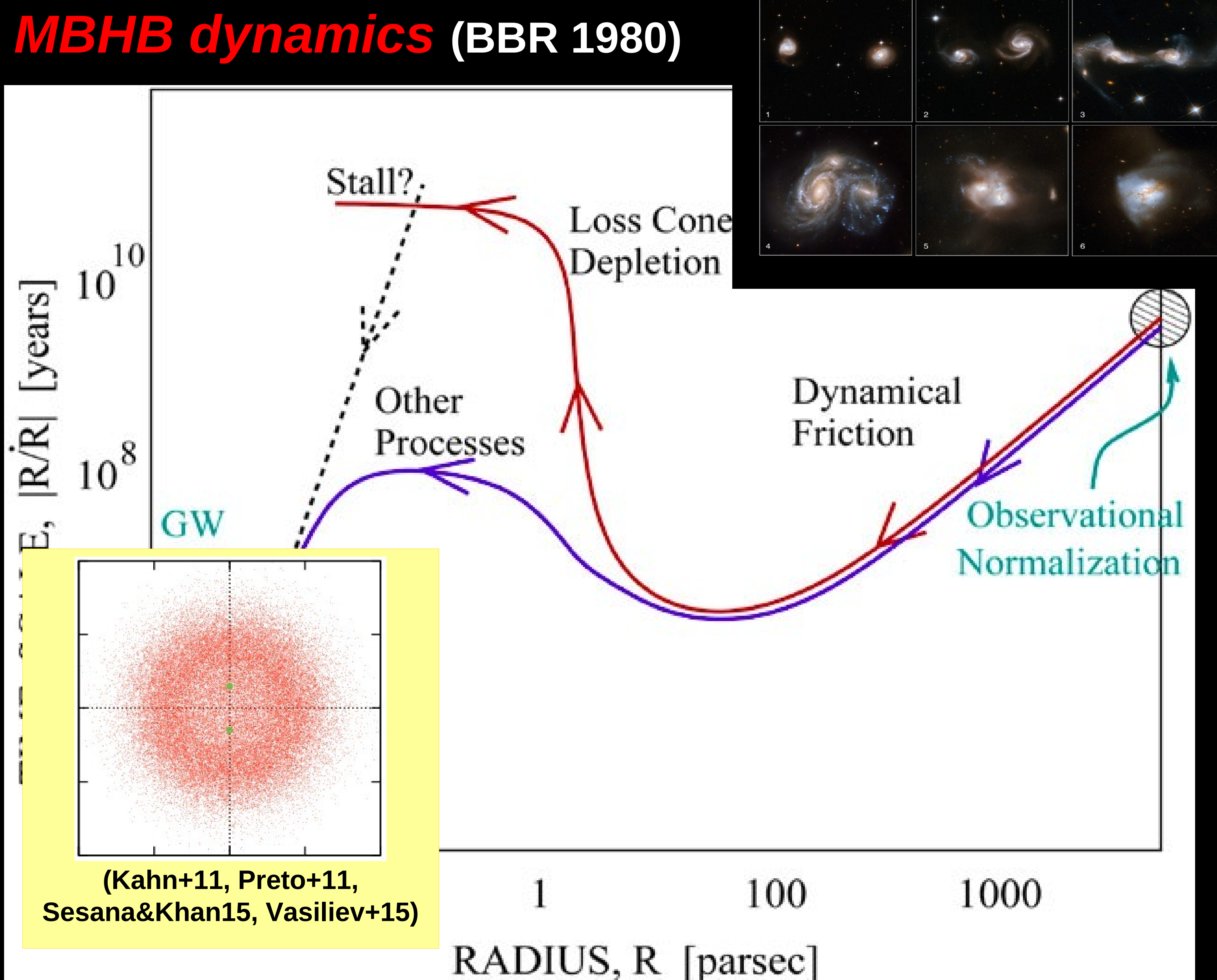
(Menou et al 2001, Volonteri et al. 2003)

*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?

MBHB dynamics (BBR 1980)

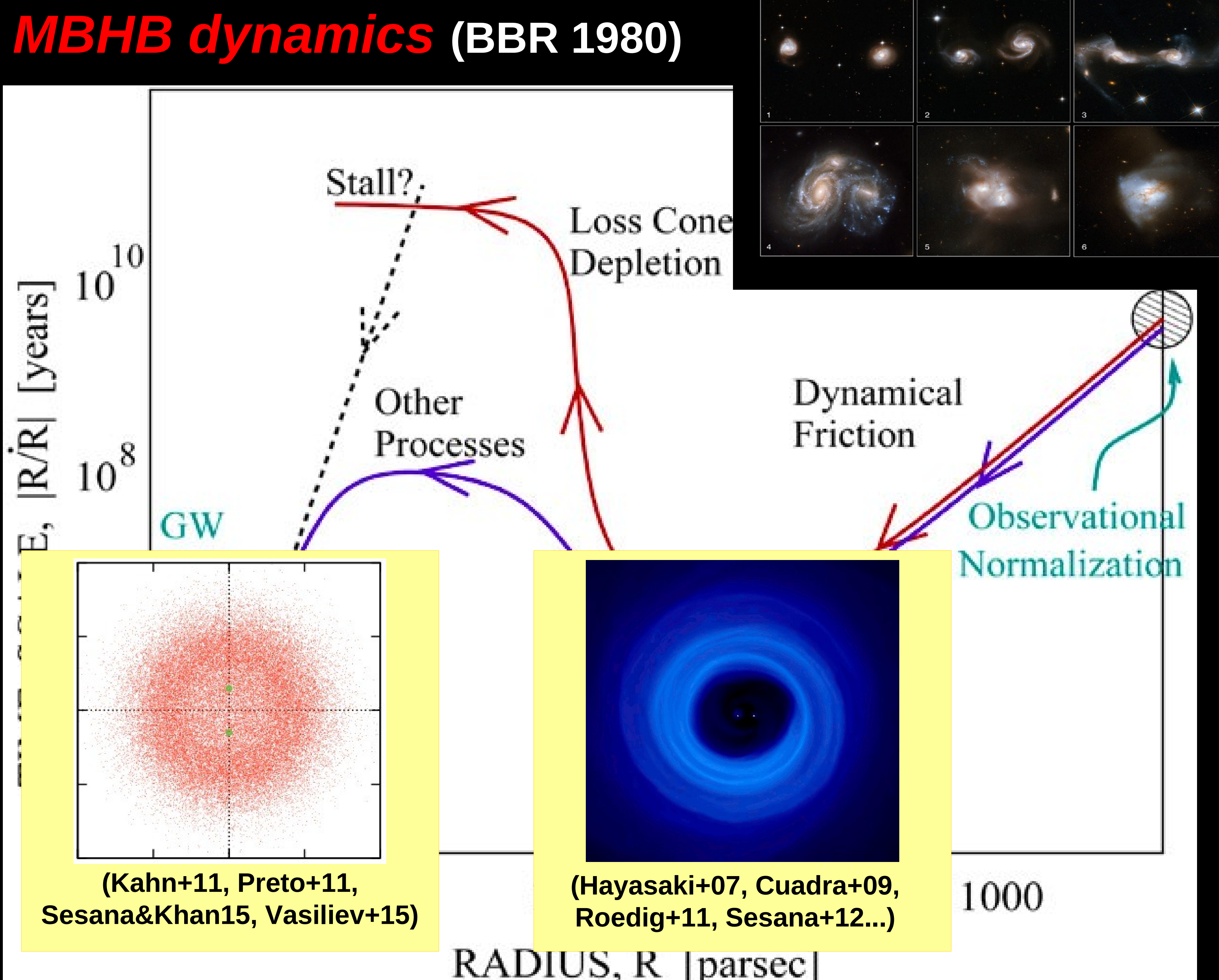


MBHB dynamics (BBR 1980)



(Kahn+11, Preto+11,
Sesana&Khan15, Vasiliev+15)

MBHB dynamics (BBR 1980)

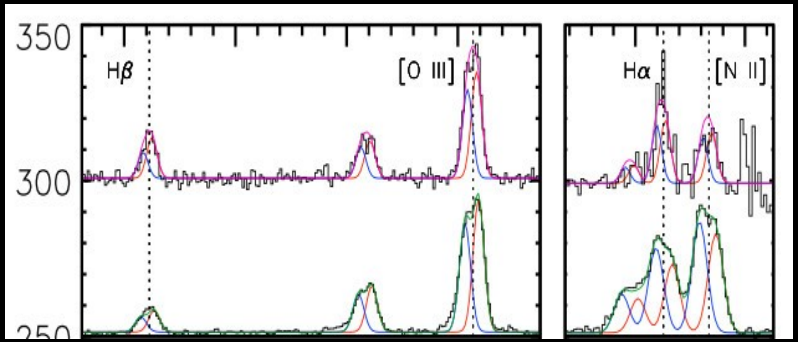


(Kahn+11, Preto+11, Sesana&Khan15, Vasiliev+15)

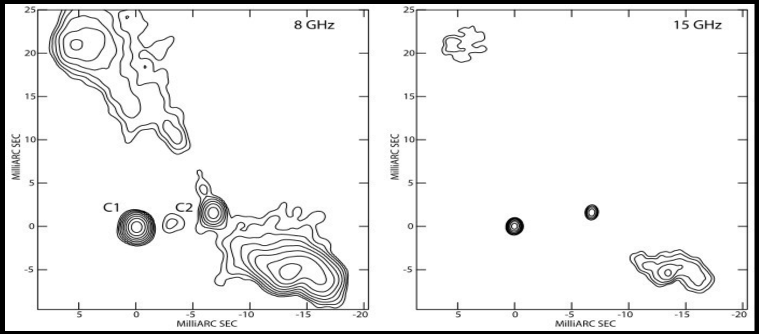
(Hayasaki+07, Cuadra+09, Roedig+11, Sesana+12...)

But do we see them?

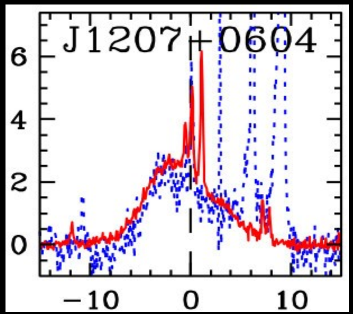
10 kpc: double quasars
(Komossa 2003)

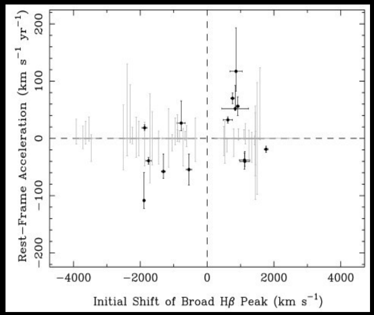


1 kpc: double peaked NL
(Comerford 2013)

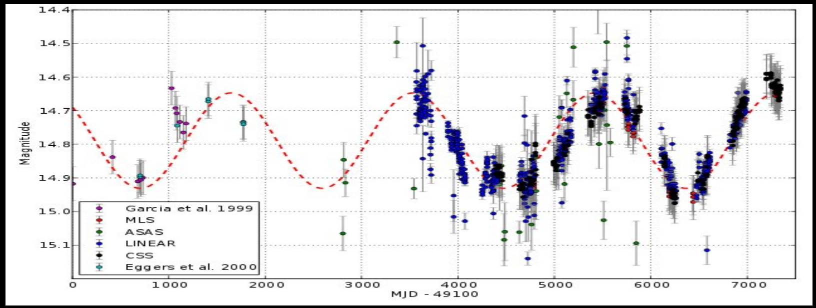


10 pc: double radio cores
(Rodriguez 2006)

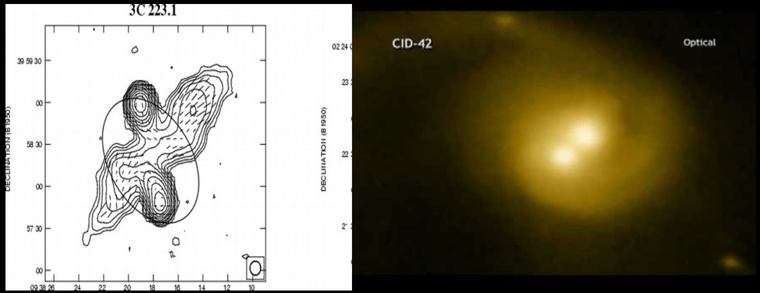




1 pc: -shifted BL (Tsalmatzsa 2011)
-accelerating BL (Eracleous 2012)



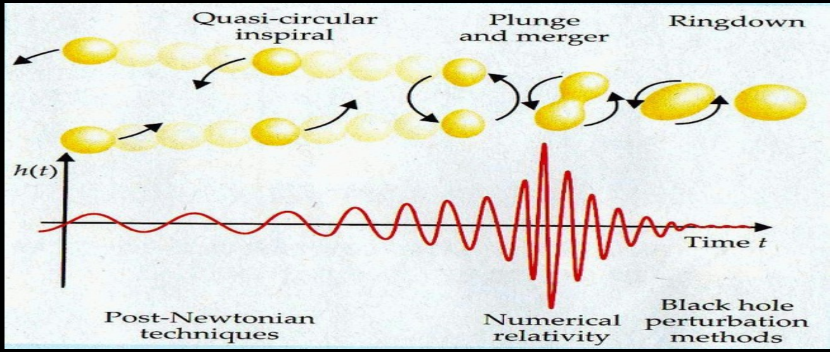
0.01 pc: periodicity (Graham 2015)

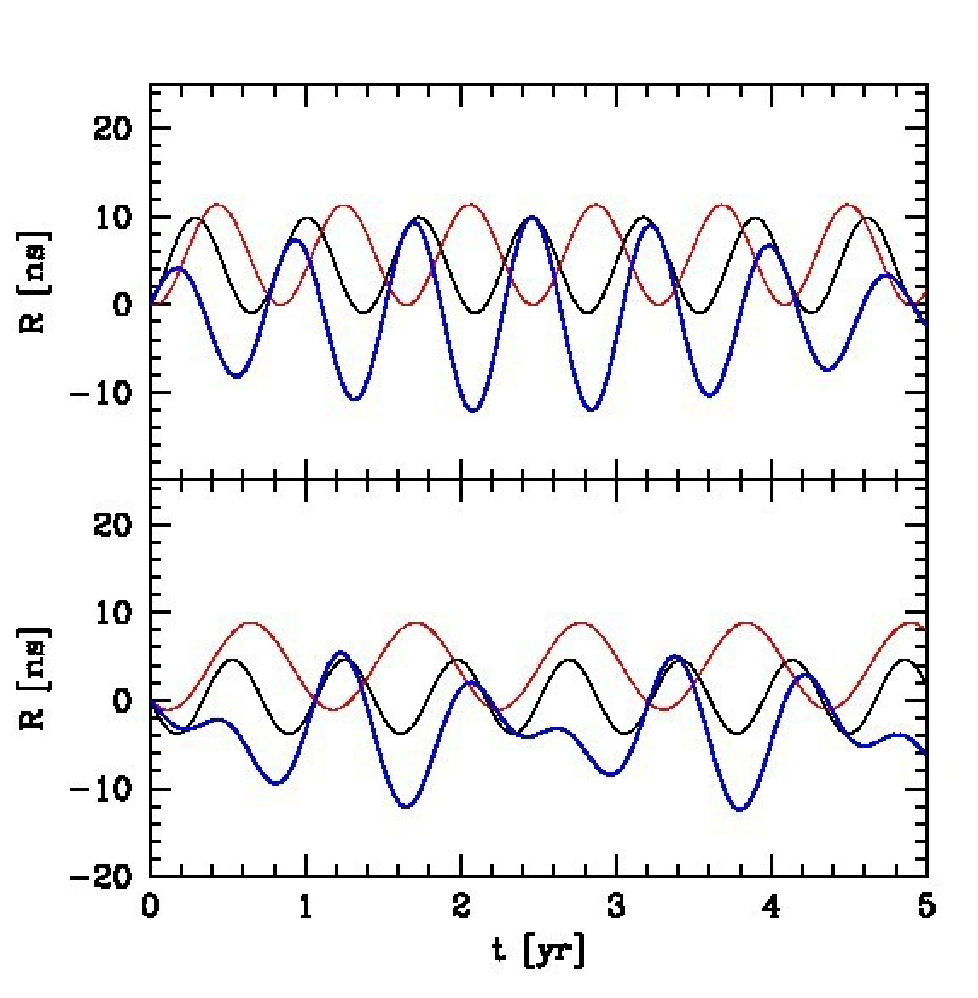


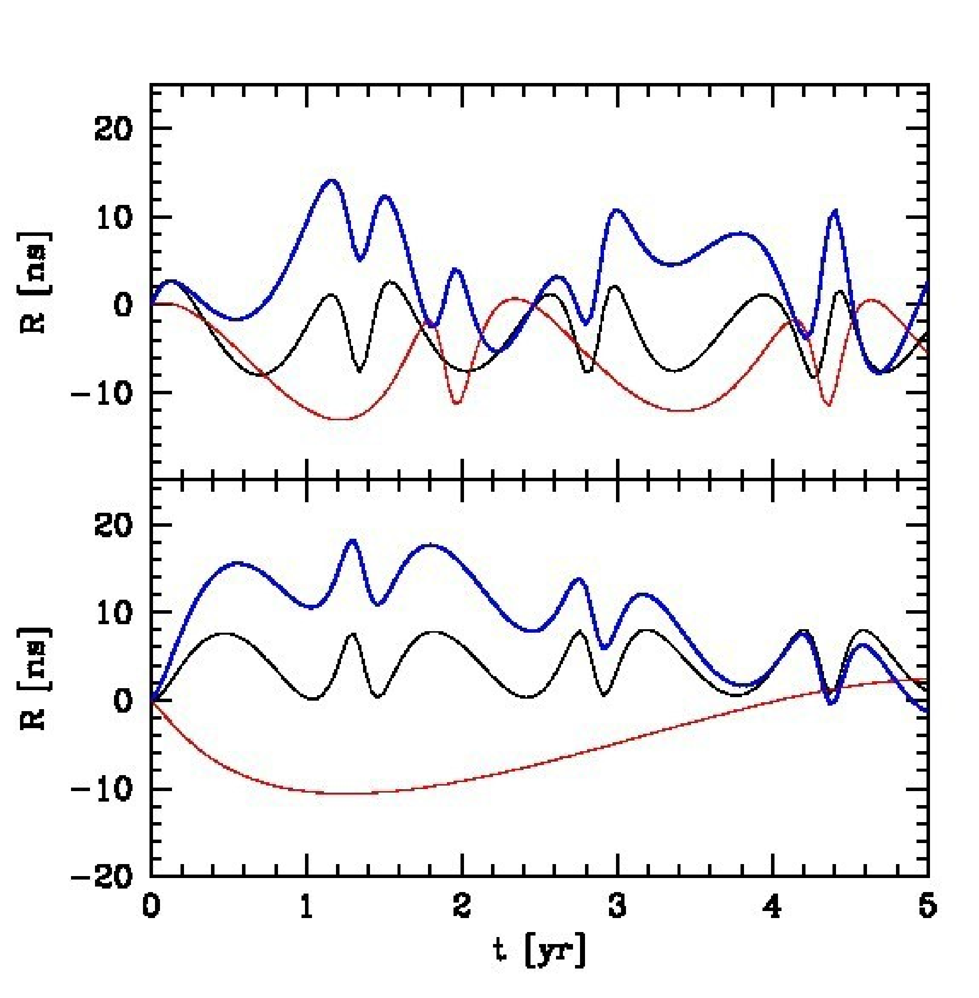
0.0pc:-X-shaped sources (Capetti 2001)
-displaced AGNs (Civano 2009)

Single MBHB timing residuals

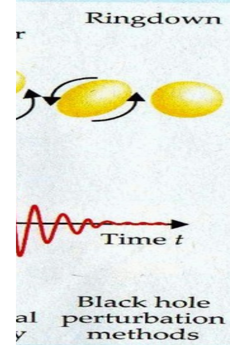
$$\frac{\nu(t)-\nu_0}{\nu_0} = \Delta h_{ab}(t) \equiv h_{ab}(t_{\rm p},\hat{\Omega}) - h_{ab}(t_{\rm ssb},\hat{\Omega})$$

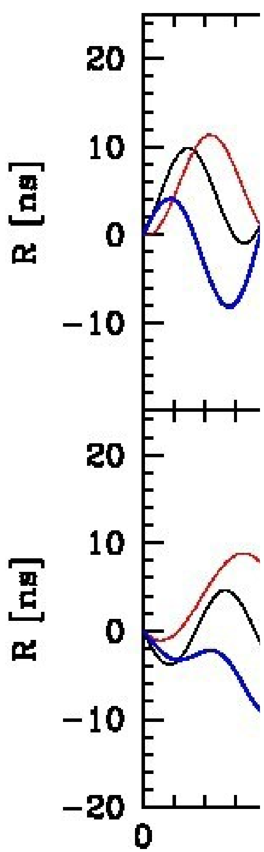


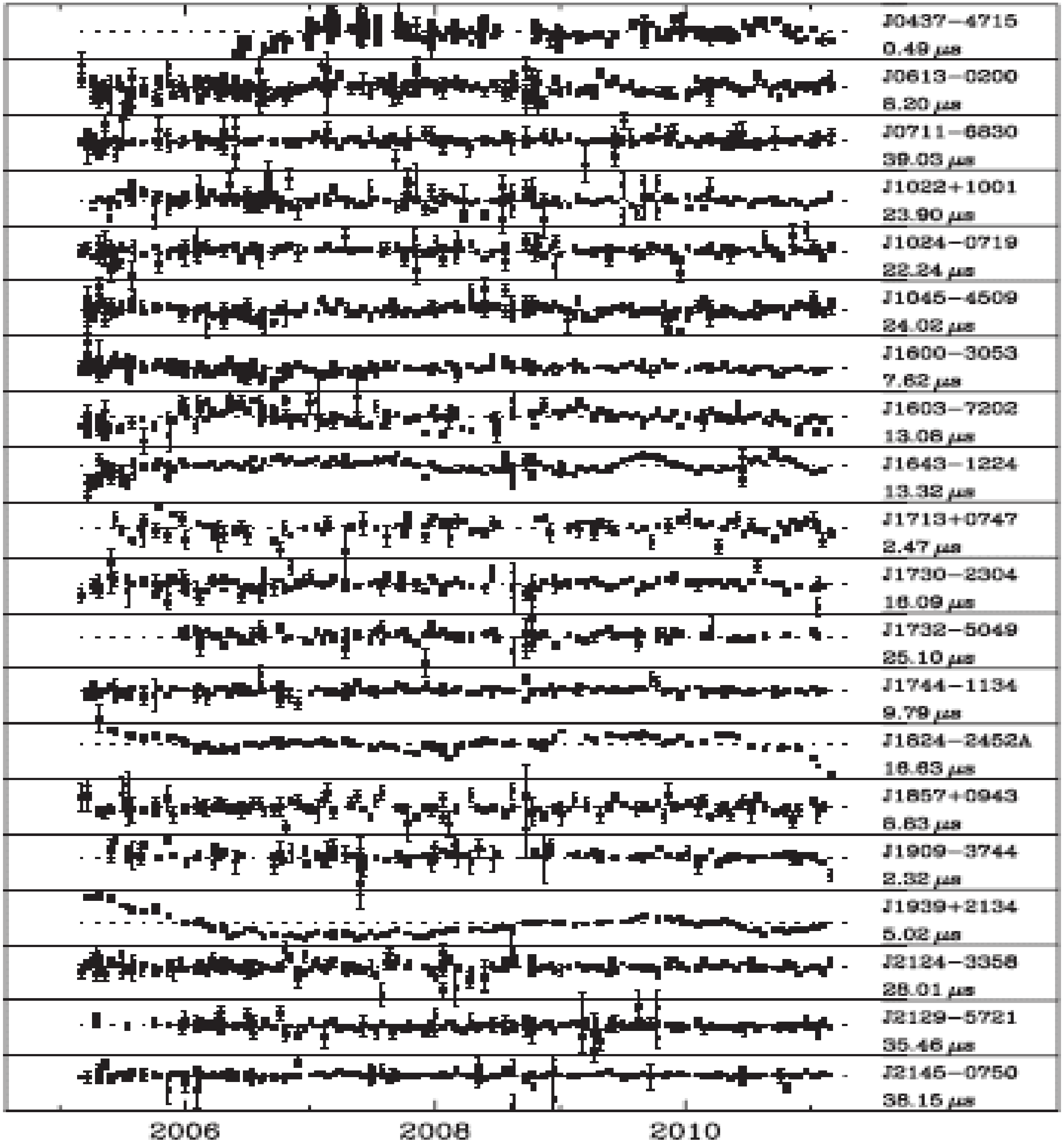


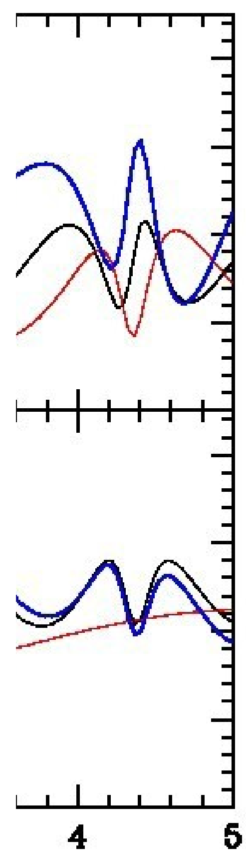


$$\frac{\nu(t) - \nu_0}{\nu_0} =$$

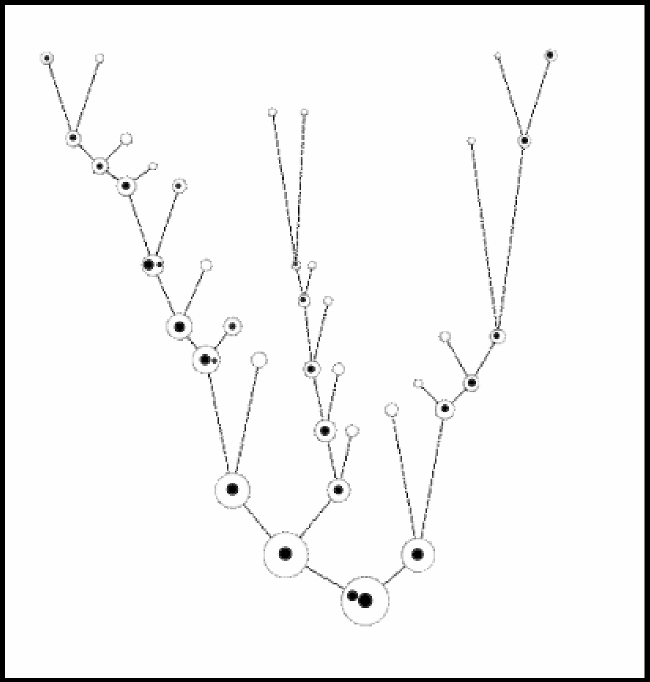








The expected GW signal in the PTA band



The GW characteristic amplitude coming from a population of circular MBH binaries

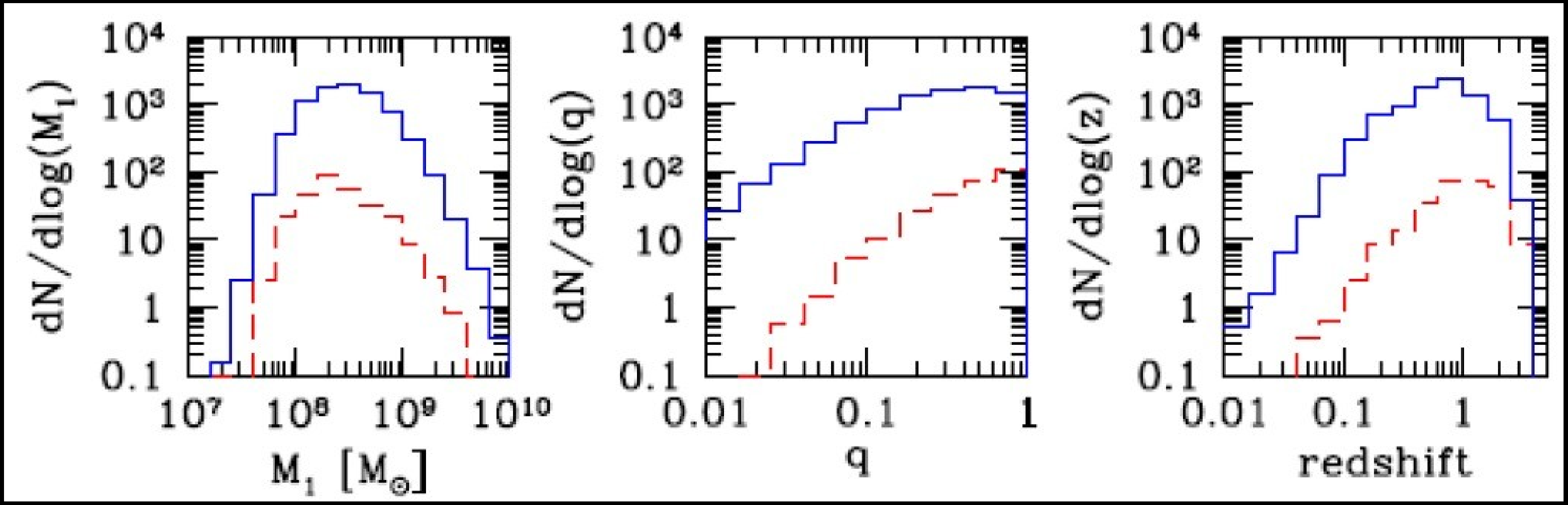
$$h_c^2(f) = \int_0^\infty dz \int_0^\infty d\mathcal{M}\, \frac{d^3N}{dz\,d\mathcal{M}\,d\ln f_r} h^2(f_r)$$

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

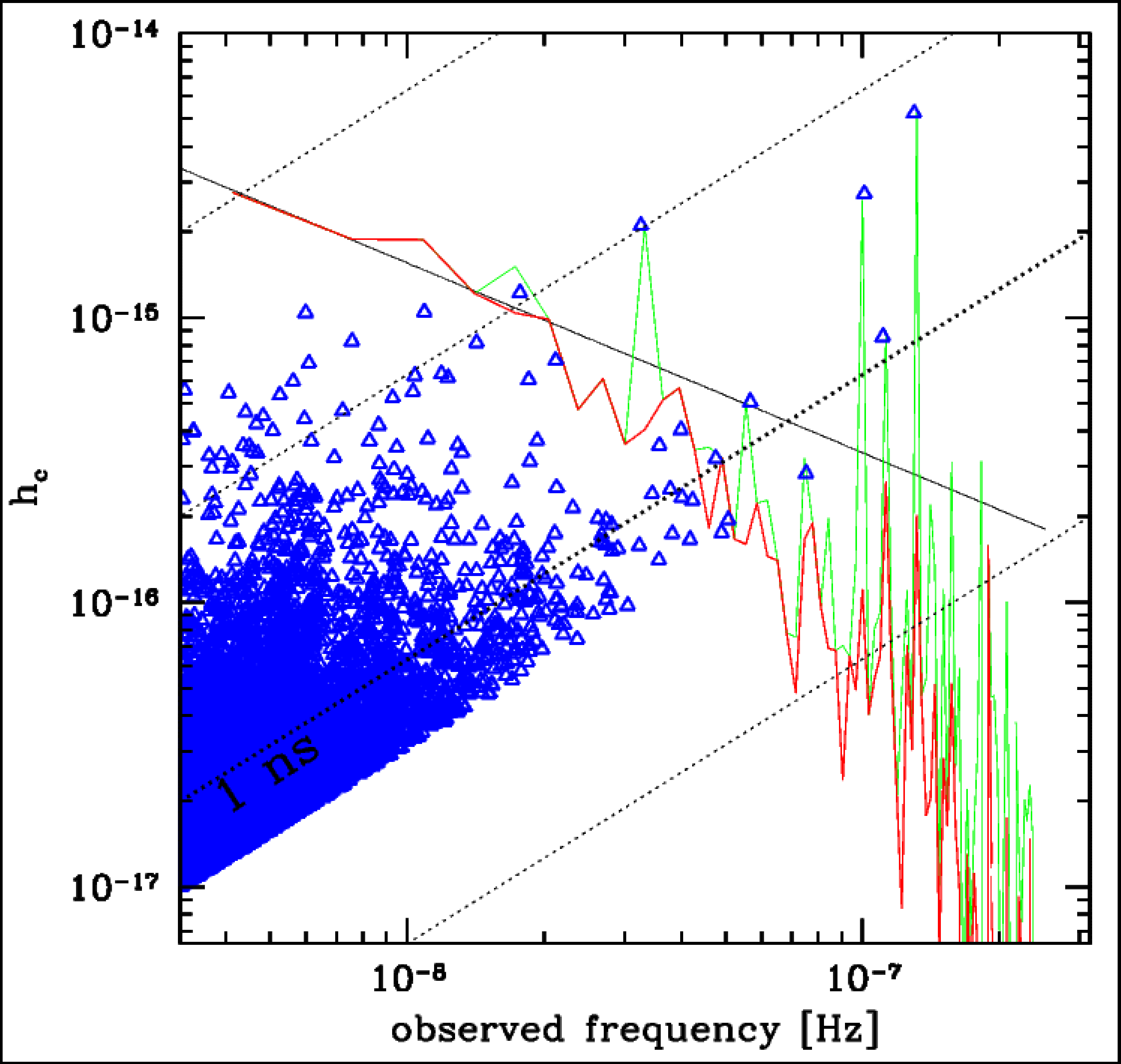
Theoretical spectrum: simple power law

(Phinney 2001)

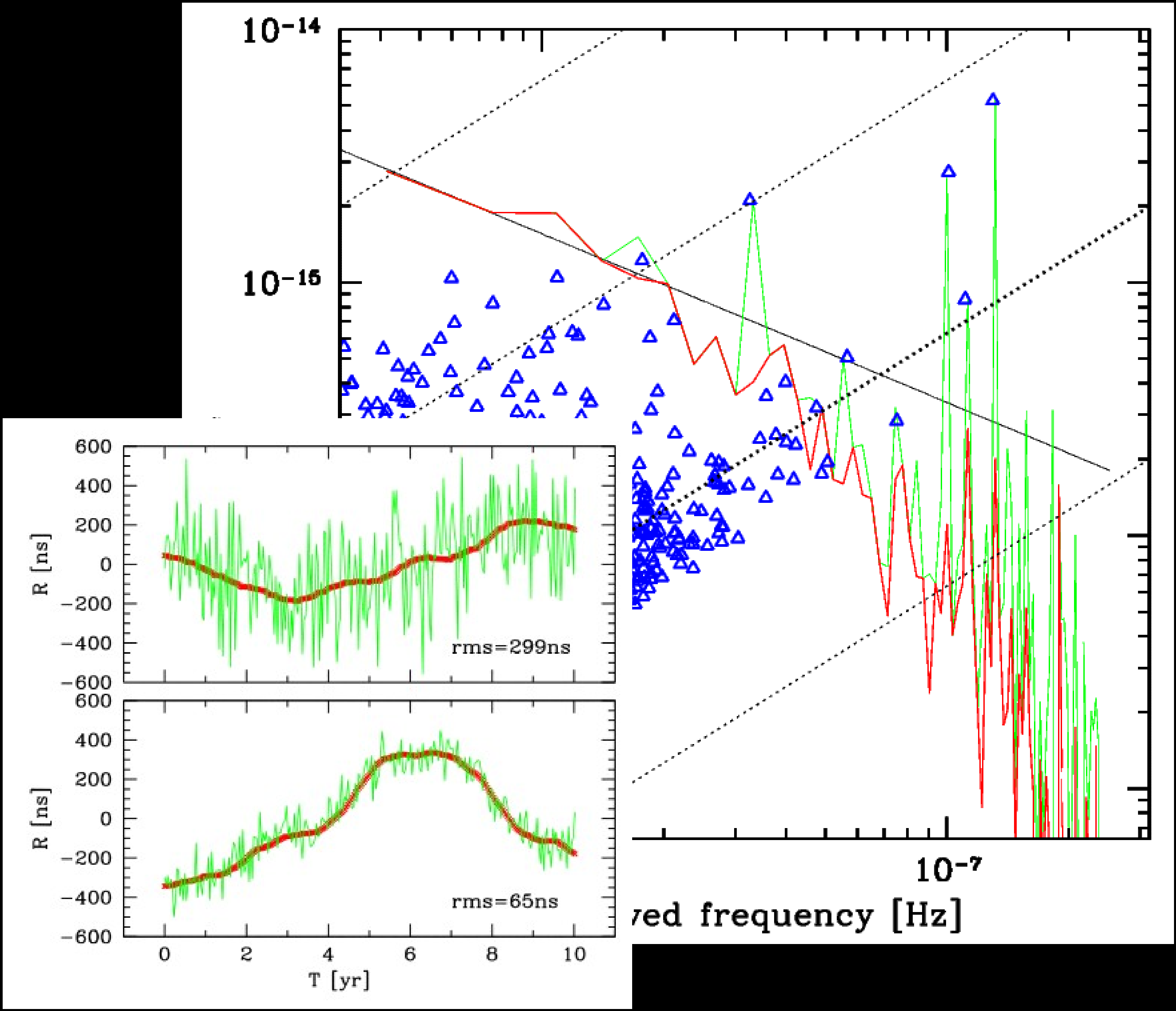
$$h_c(f) = A \left(\frac{f}{\mathrm{yr}^{-1}}\right)^{-2/3}$$



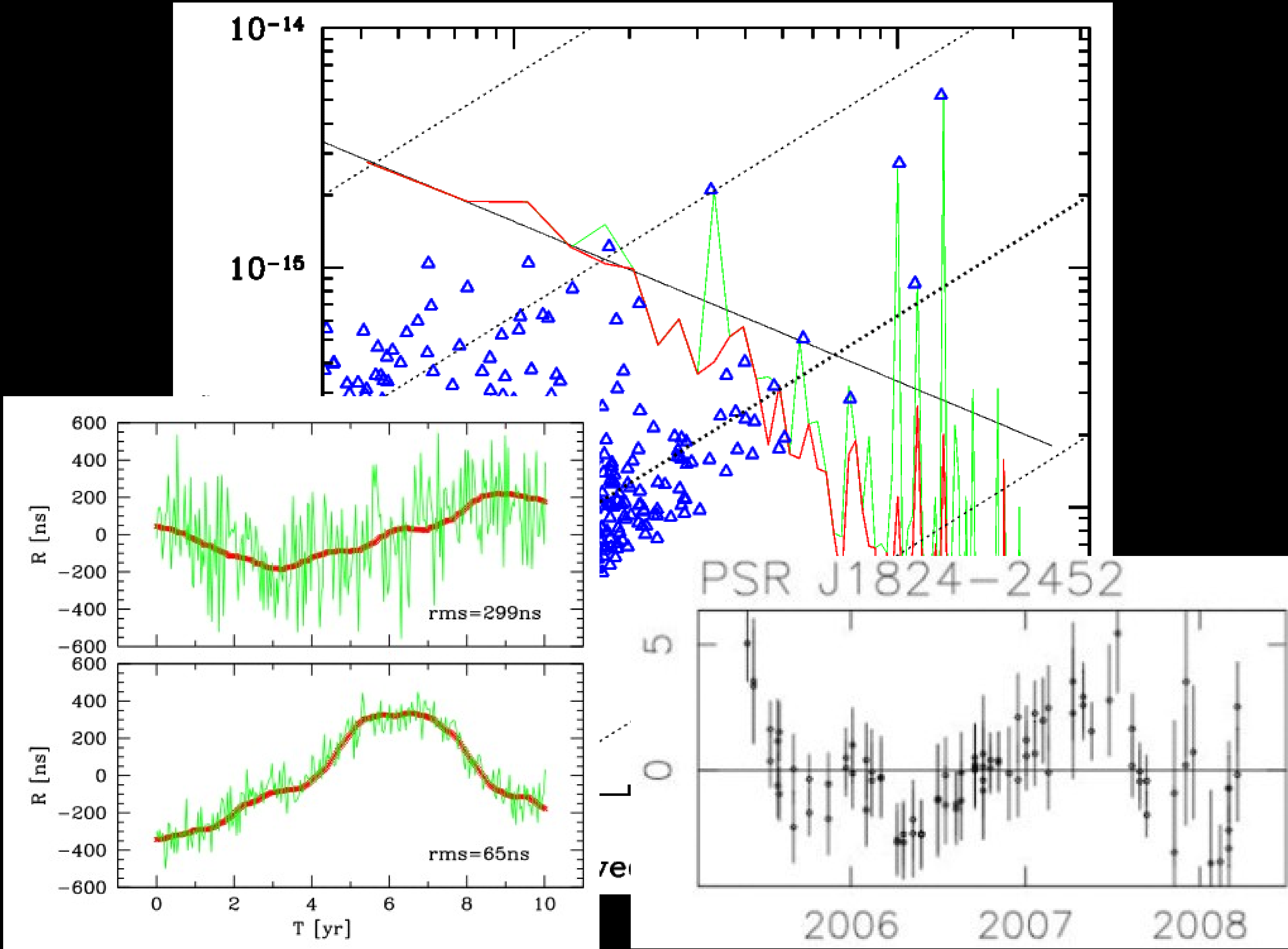
The signal is contributed by extremely massive (>$10^8 M_\odot$) relatively low redshift (z<1) MBH binaries **(AS et al. 2008, 2012)**



10^{-14}
10^{-15}
10^{-16}
10^{-17}
h_c
1 ns
10^{-8}
10^{-7}
observed frequency [Hz]

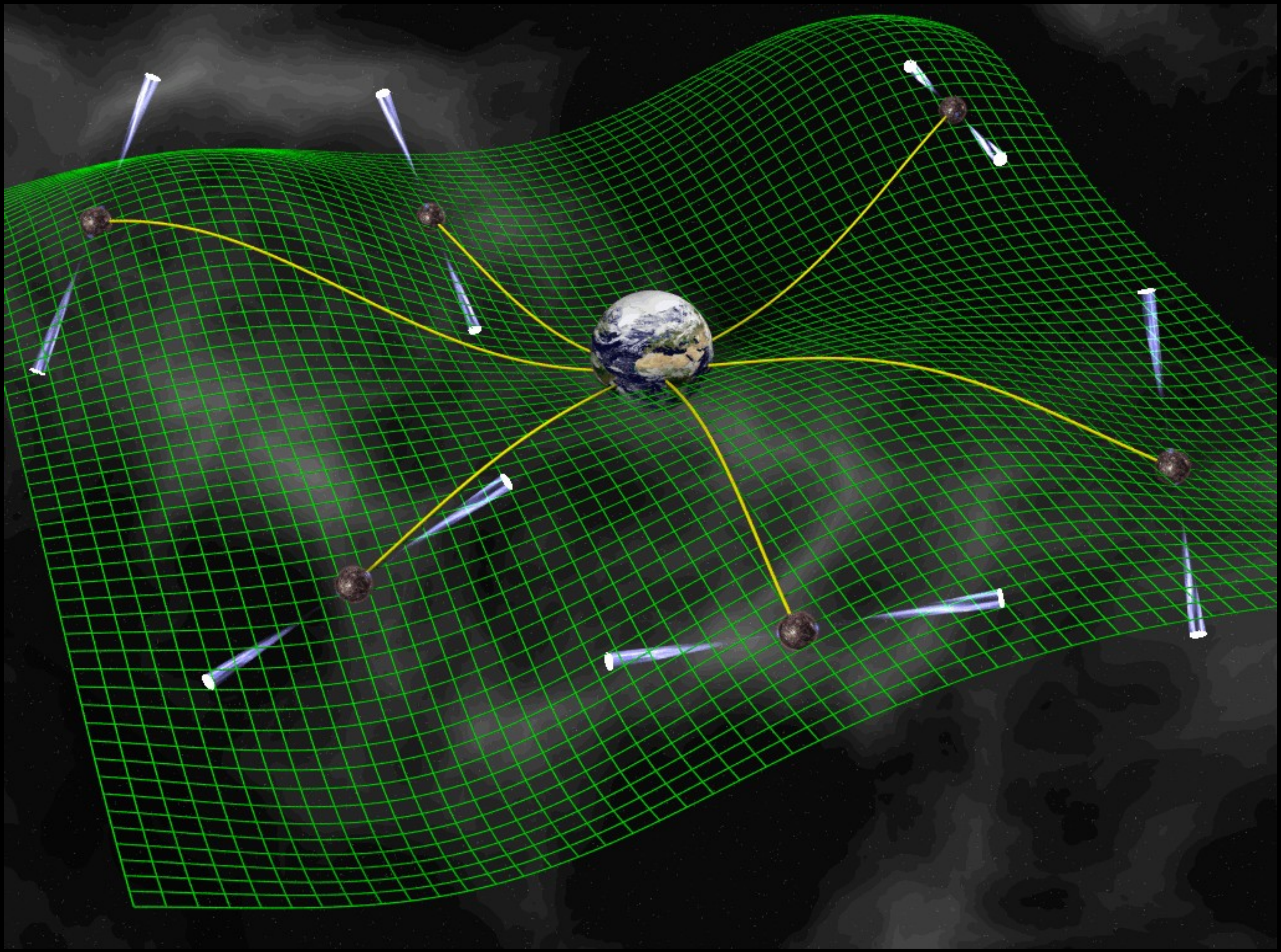


10^{-14}
10^{-15}
10^{-7}
ved frequency [Hz]
R [ns]
rms=299ns
rms=65ns
T [yr]



10⁻¹⁴
10⁻¹⁵
600
400
200
0
−200
−400
−600
R [ns]
rms=299ns
rms=65ns
T [yr]
0
2
4
6
8
10
PSR J1824−2452
5
0
2006
2007
2008

We are looking for a correlated signal



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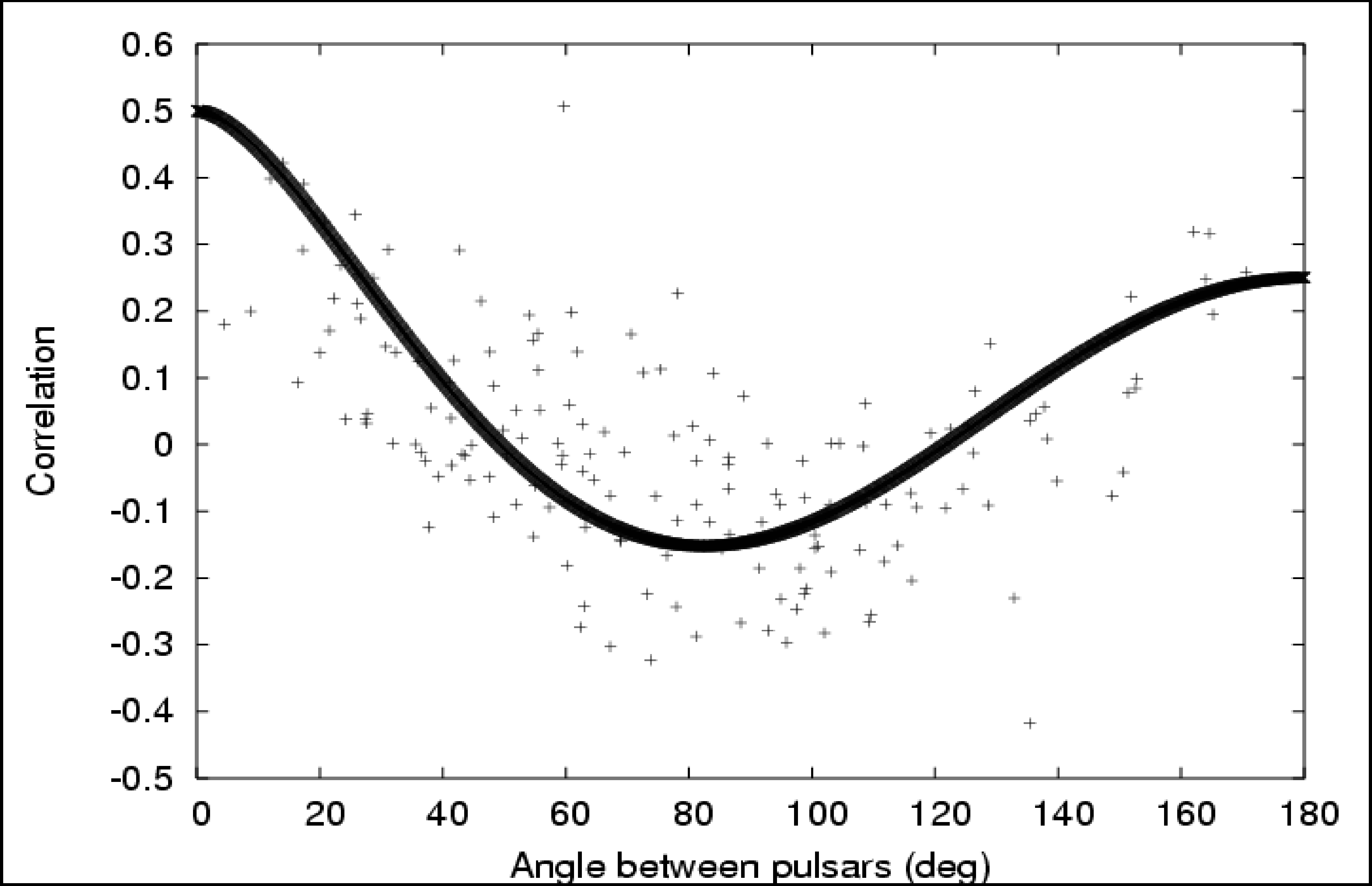
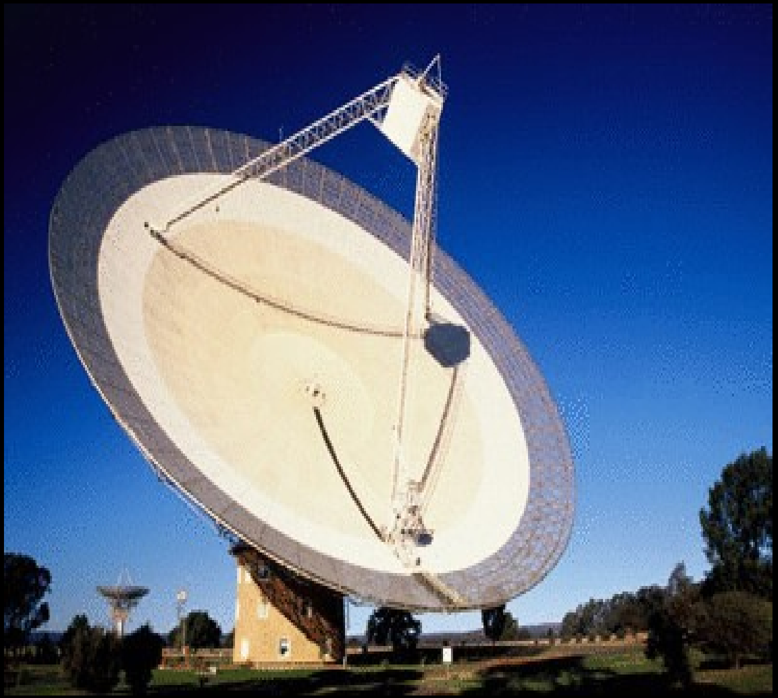


(Hellings & Downs 1983)

A worldwide observational effort

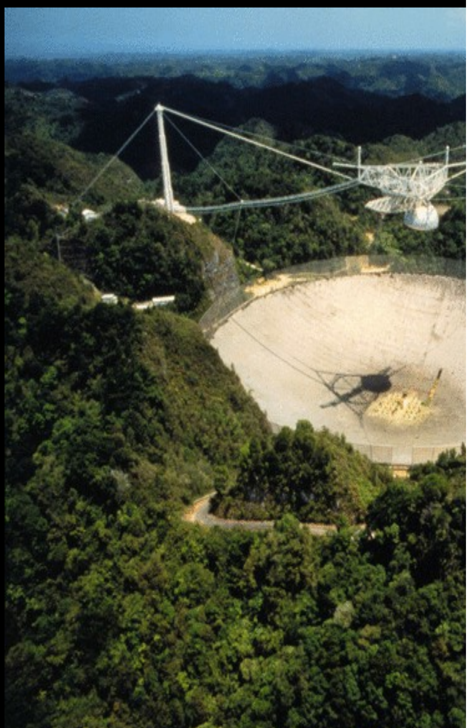
EPTA/LEAP **(Large European Array for Pulsars)**

NANOGrav **(North American nHz Observatory for Gravitational Waves)**



PPTA **(Parkes Pulsar Timing Array)**

A worldwide observational effort



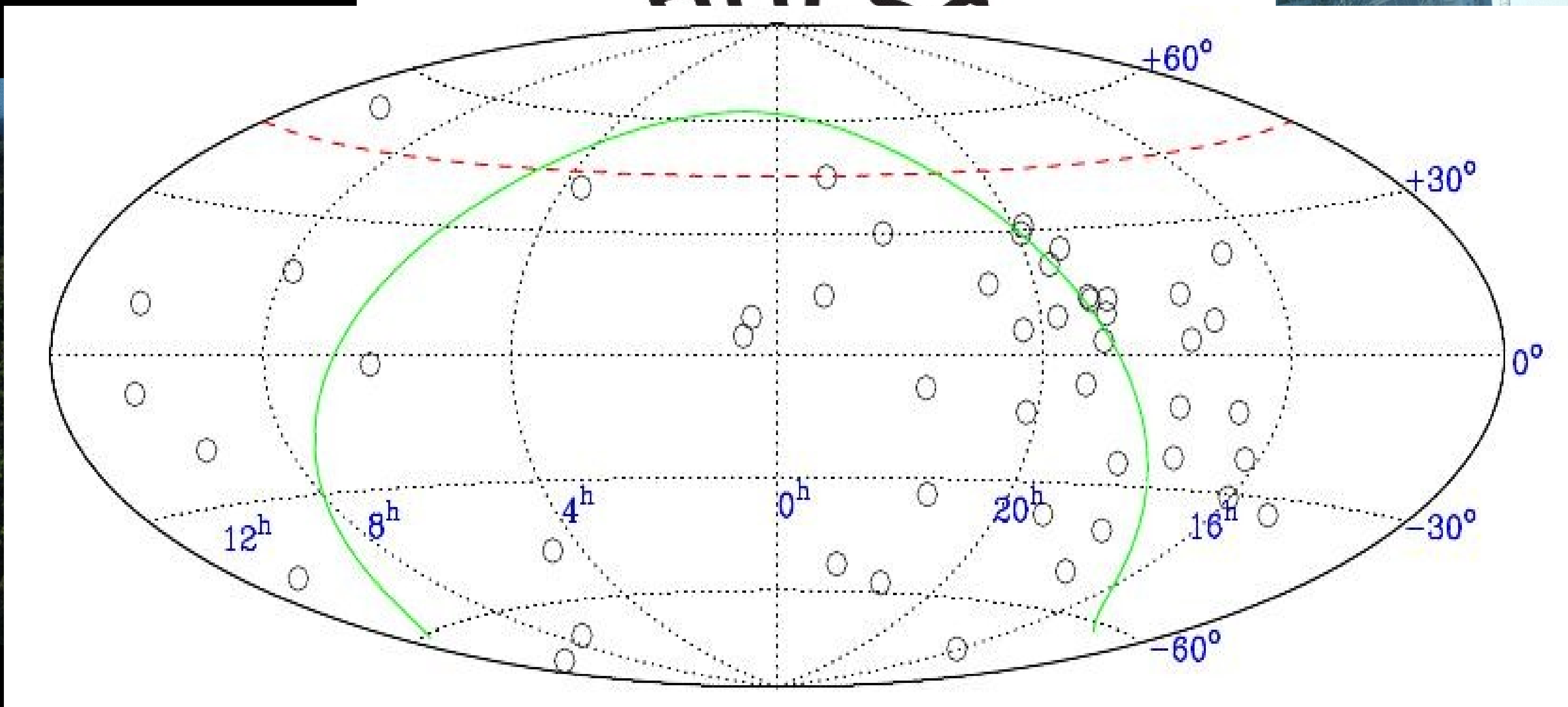
INTERNATIONAL PULSAR TIMING ARRAY

IPTA

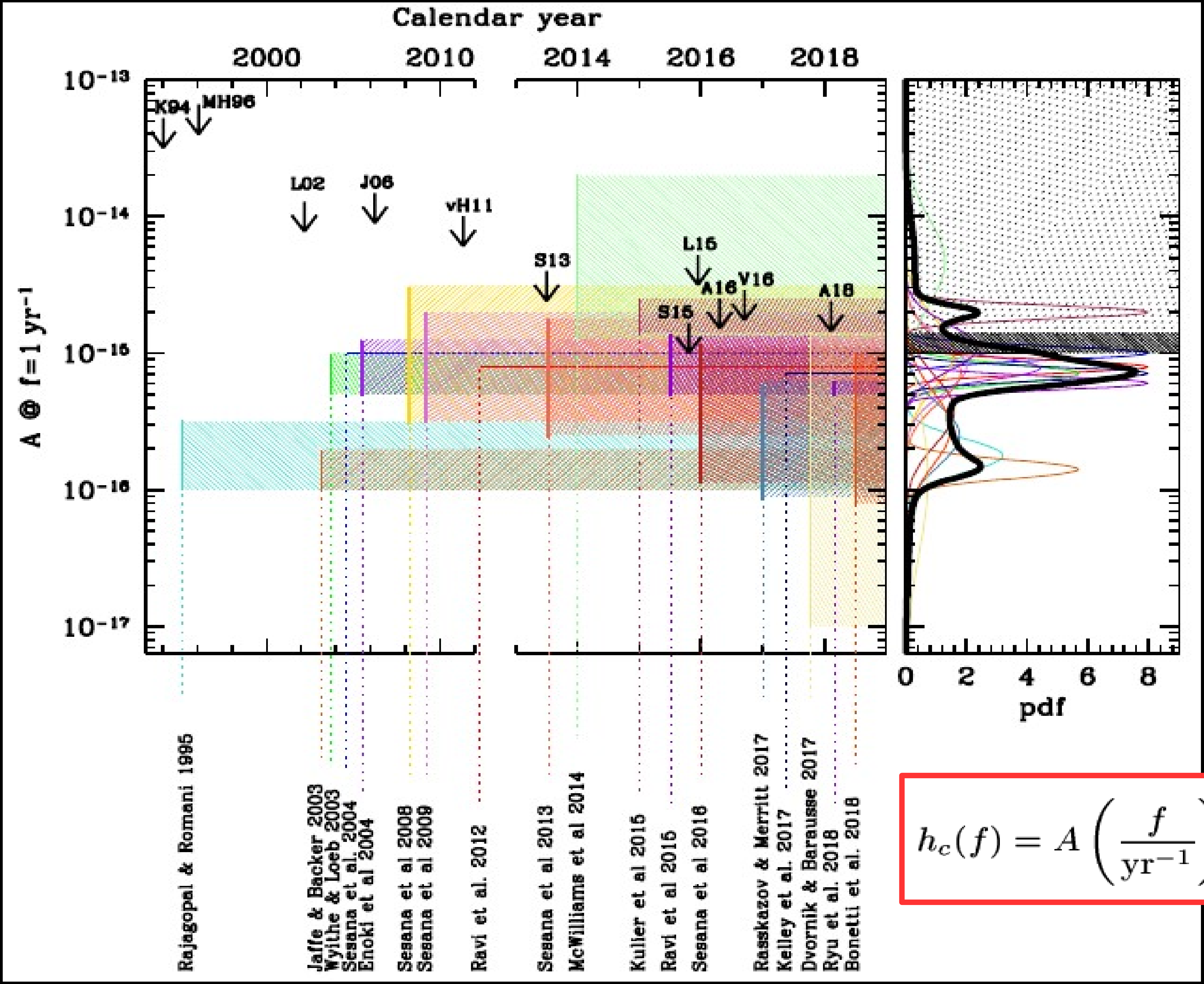
nHz
aves)

PPT

A worldwide observational effort

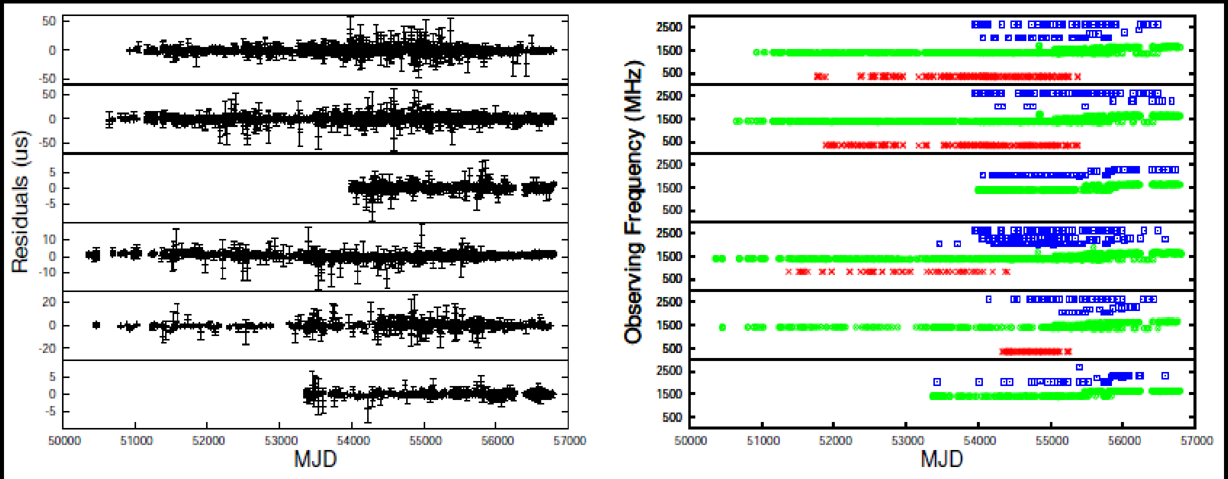


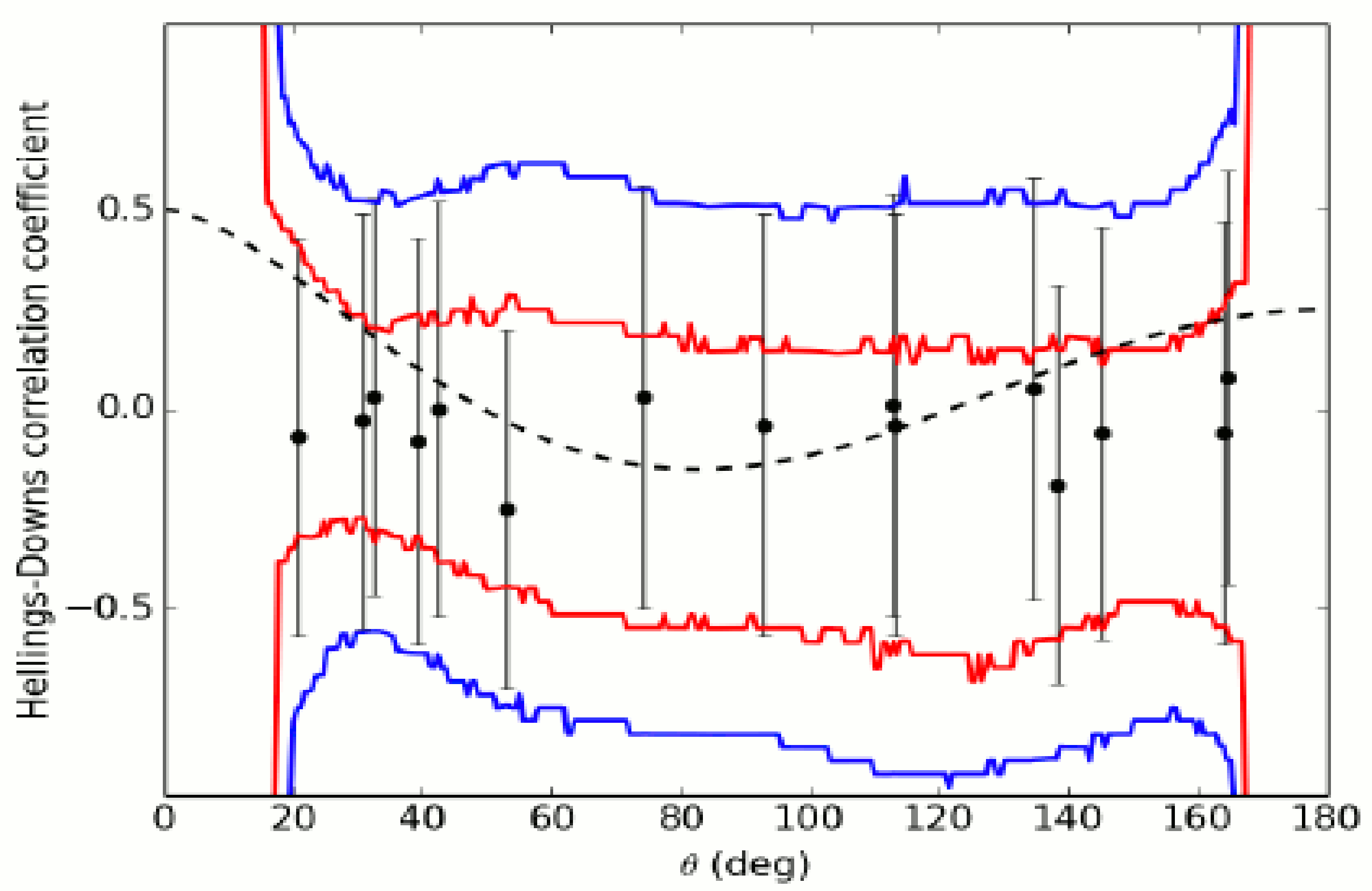
Theory and observations progression



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

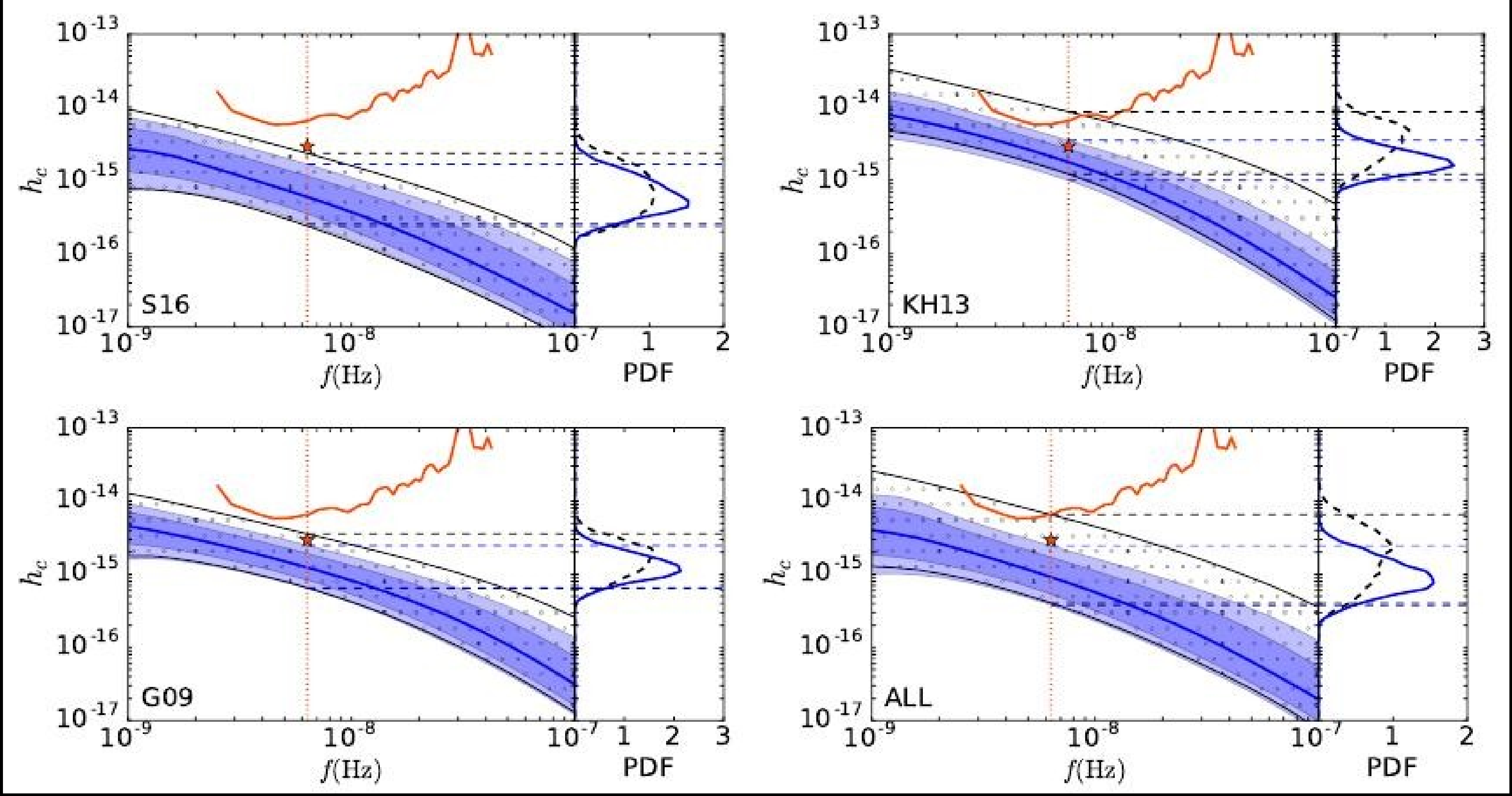
Example of non-detection (EPTA, Lentati et al. 2015)





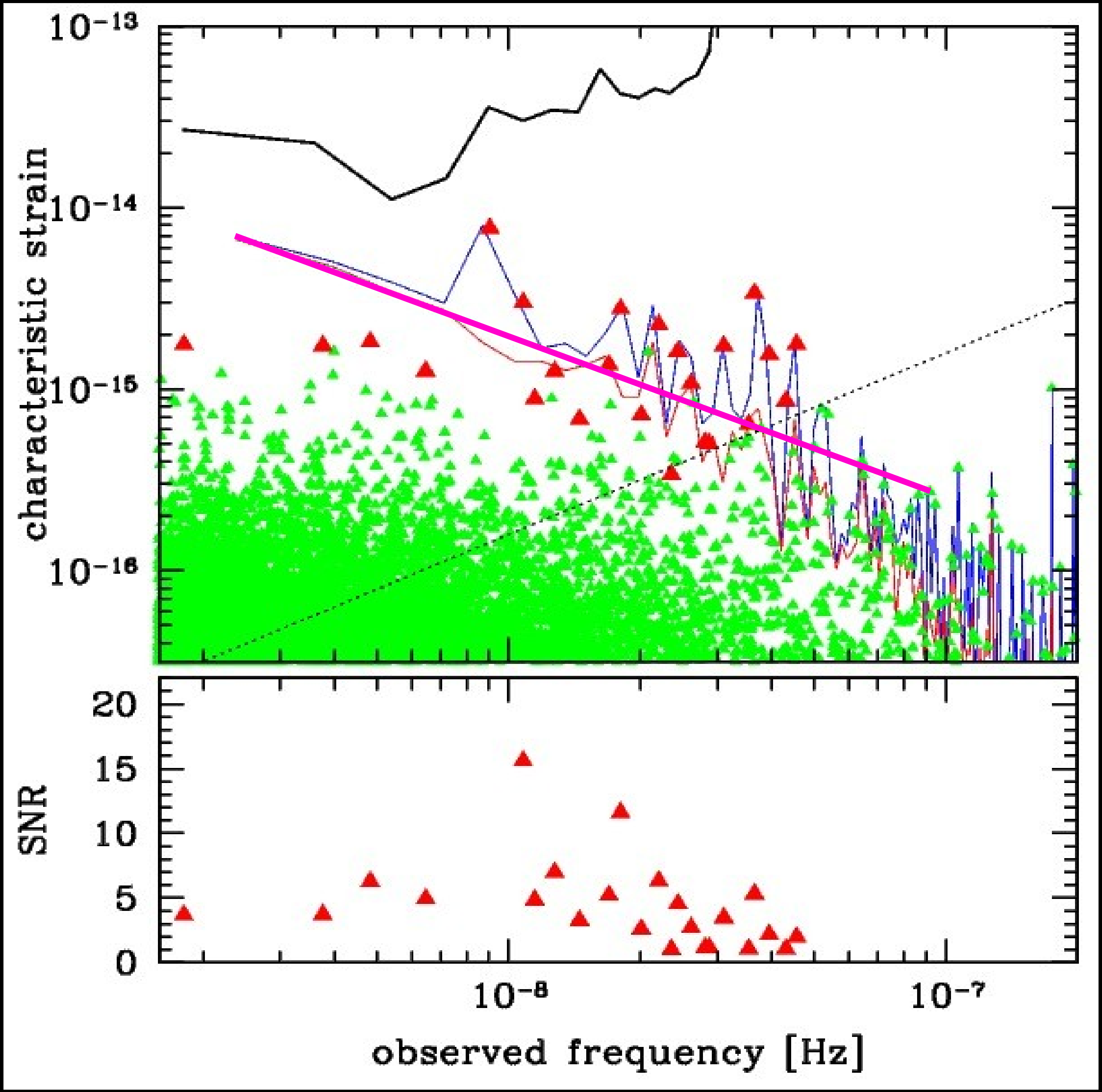
Current limits not quite constraining

- -Comprehensive set of semianalytic models anchored to observations of galaxy mass function and pair fractions (AS 2013, 2016)
- -Include different BH mass-galaxy relations
- -Include binary dynamics (coupling with the environment/eccentricity)



(Middleton et al., 2018)

The nature of the signal



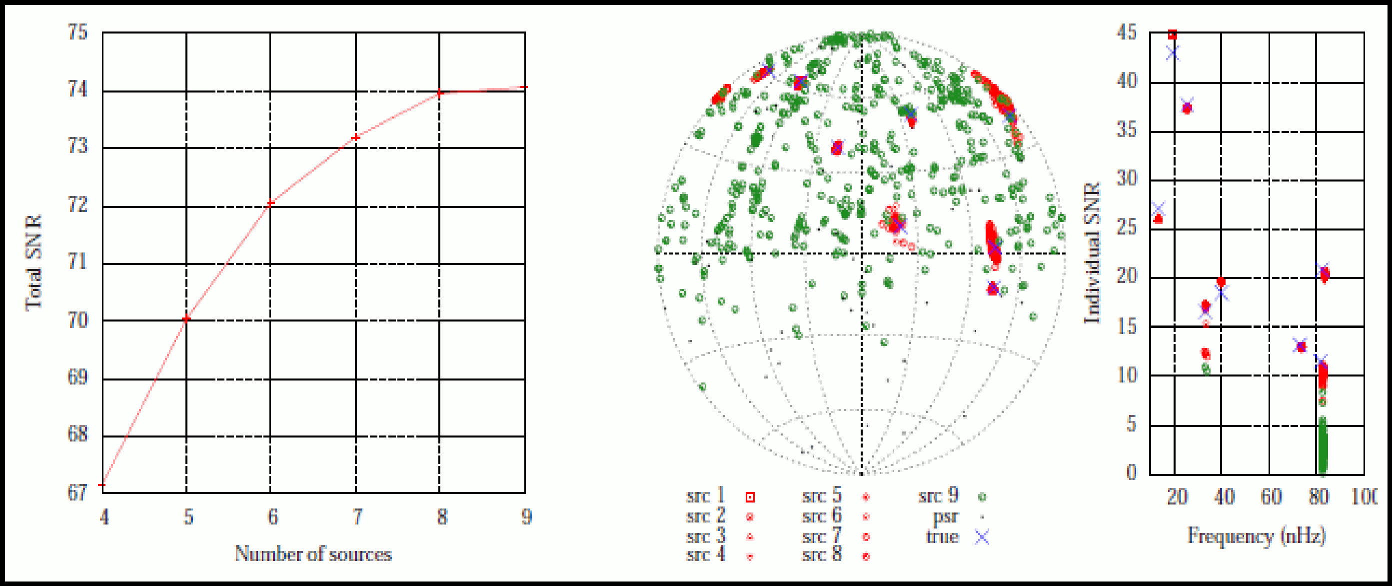
***It is not smooth**

***It is not Gaussian**

***Single sources might pop-up**

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

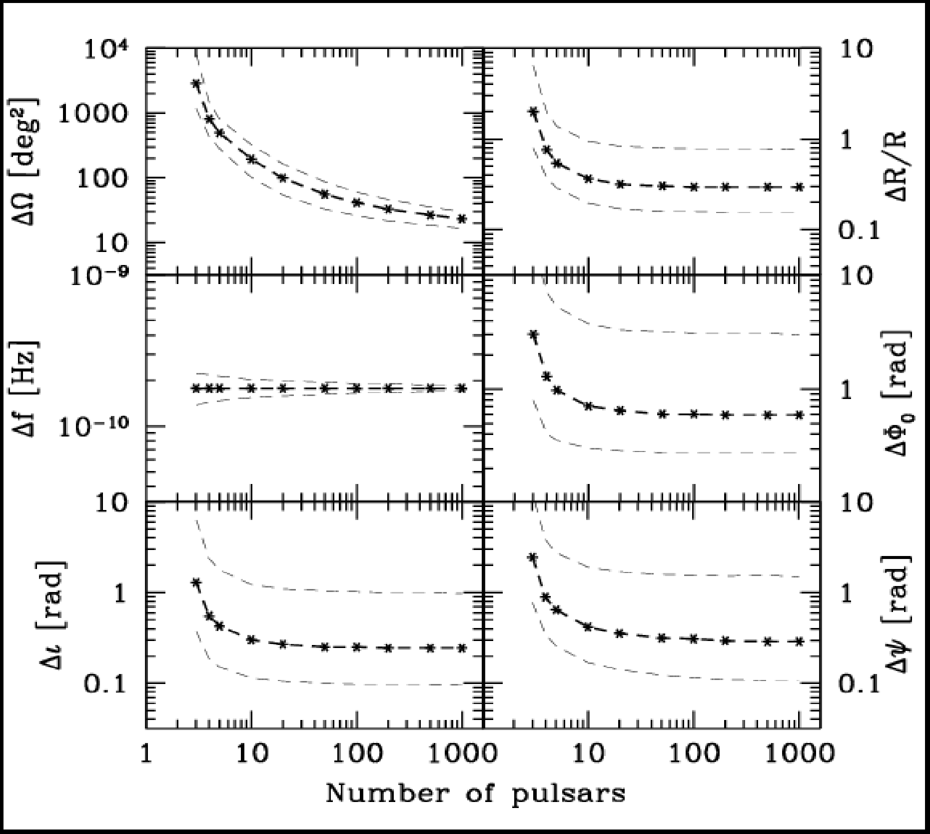
Identification and sky localization



We can recover multiple sources in PTA data
(Babak & AS 2012 Petiteau Babak AS Araujo 2013)

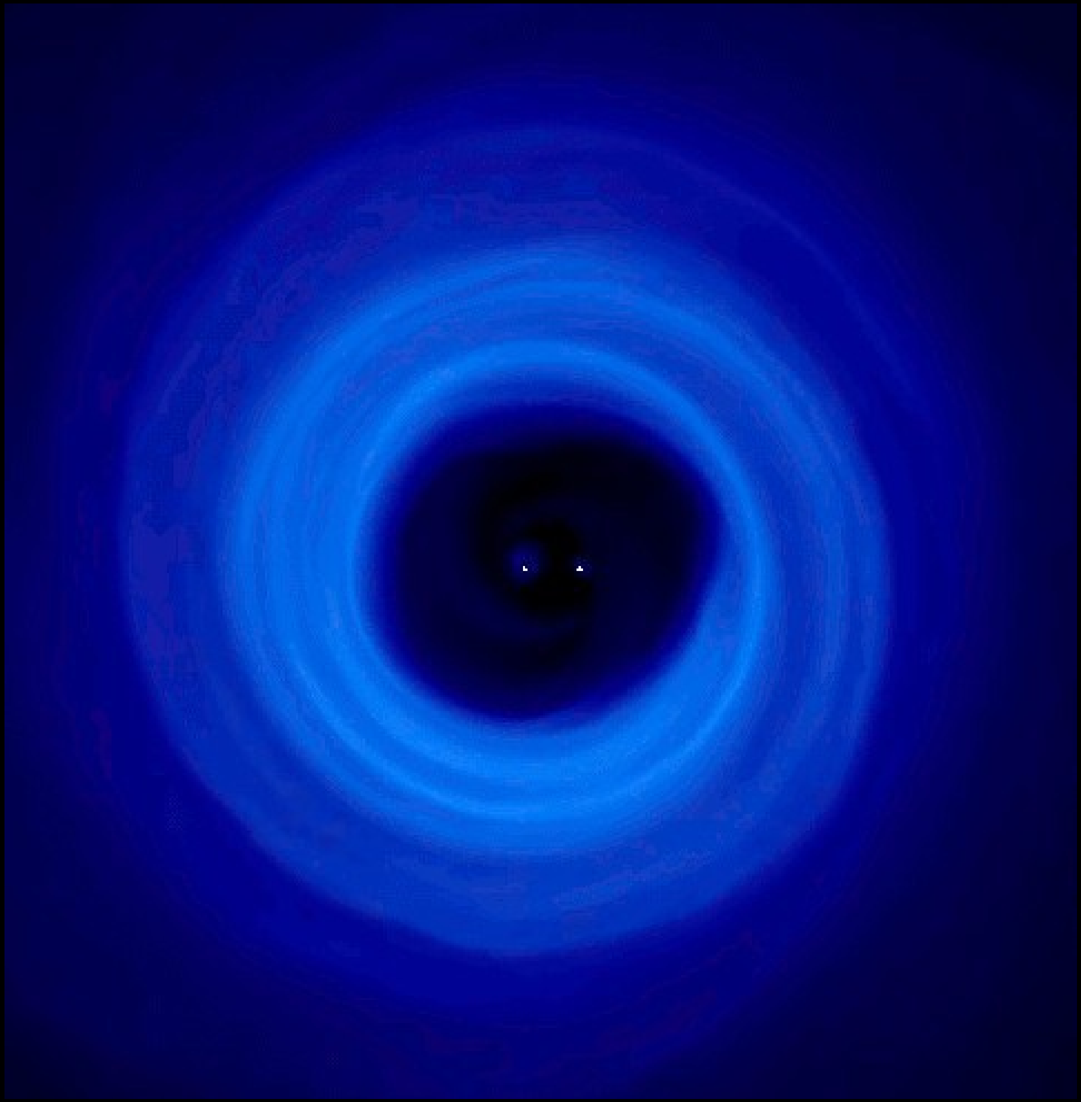
Sources can be localized in the sky (AS & Vecchio 2010, Ellis et al. 2012).

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



Associated electromagnetic signatures PTA

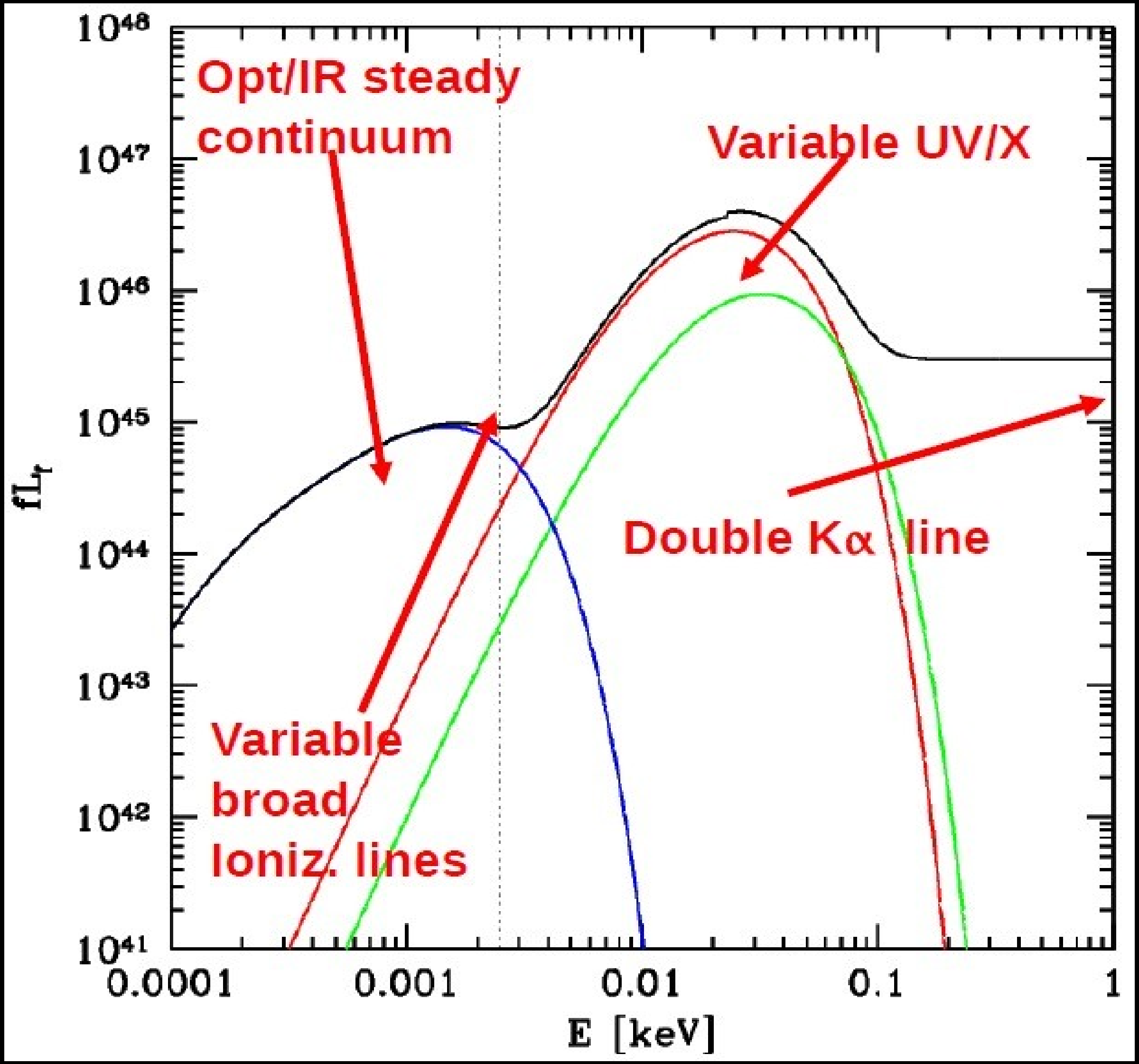
MBH binary + circumbinary disk



(Roedig et al. 2011, AS et al. 2012, Tanaka et al. 2012, Burke-Spolaor 2013)

Associated electromagnetic signatures PTA

MBH binary + circumbinary disk



(Roedig et al. 2011, AS et al. 2012, Tanaka et al. 2012, Burke-Spolaor 2013)

A variety of possibilities:

Optical/IR dominated by the outer disk: Steady/modulated?

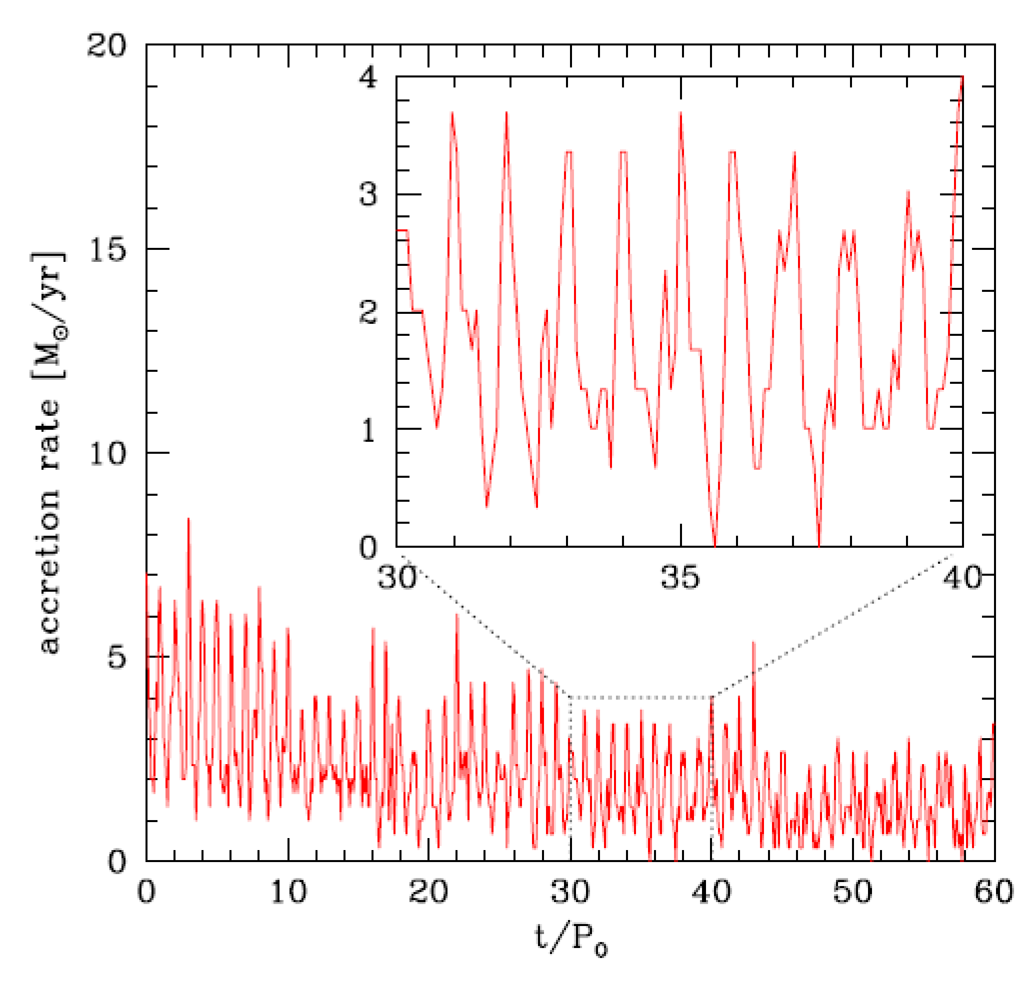
UV generated by inner streams/minidisk: periodic variability?

X rays variable from periodic shocks or intermittent corona?

Variable broad emission line in response to the varying ionizing continuum?

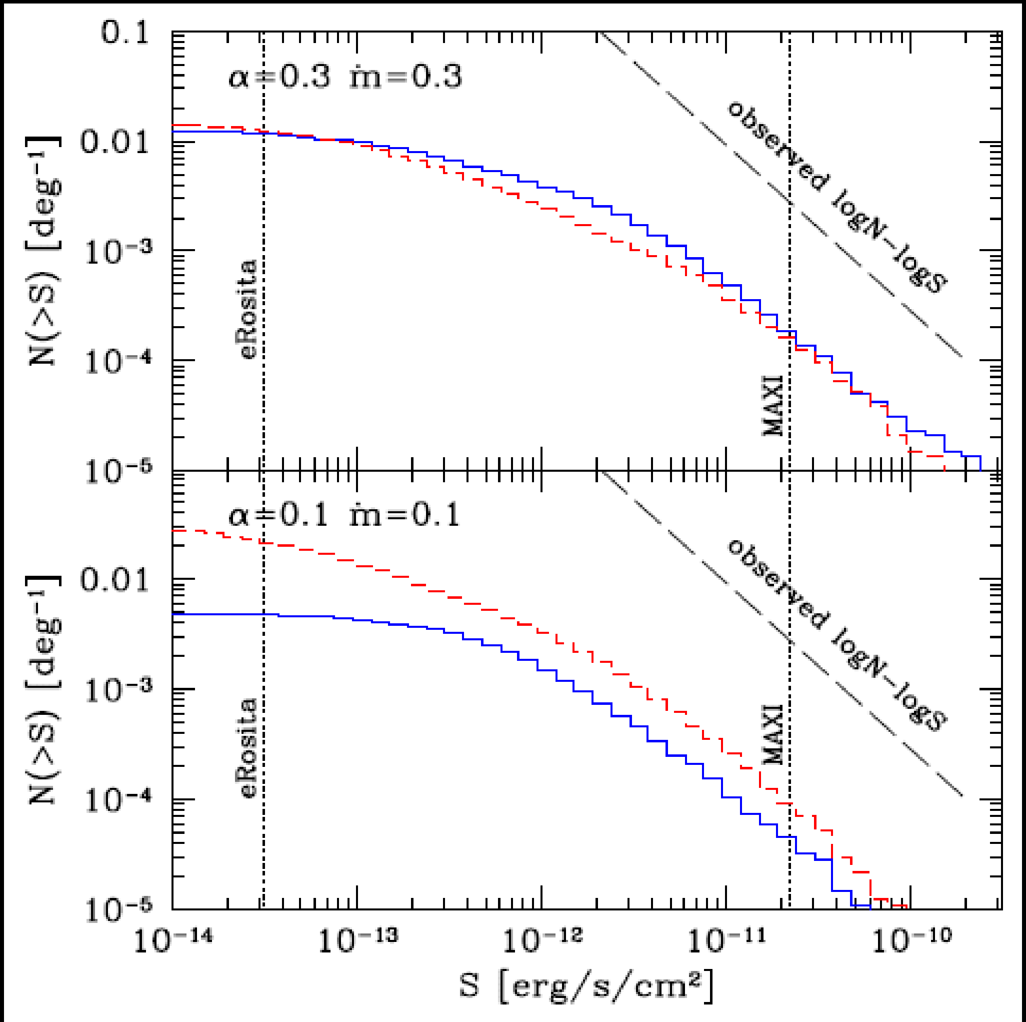
Double fluorescence lines?

Example: variability



Streams feed the inner minidisk extremely intermittent mass inflow.

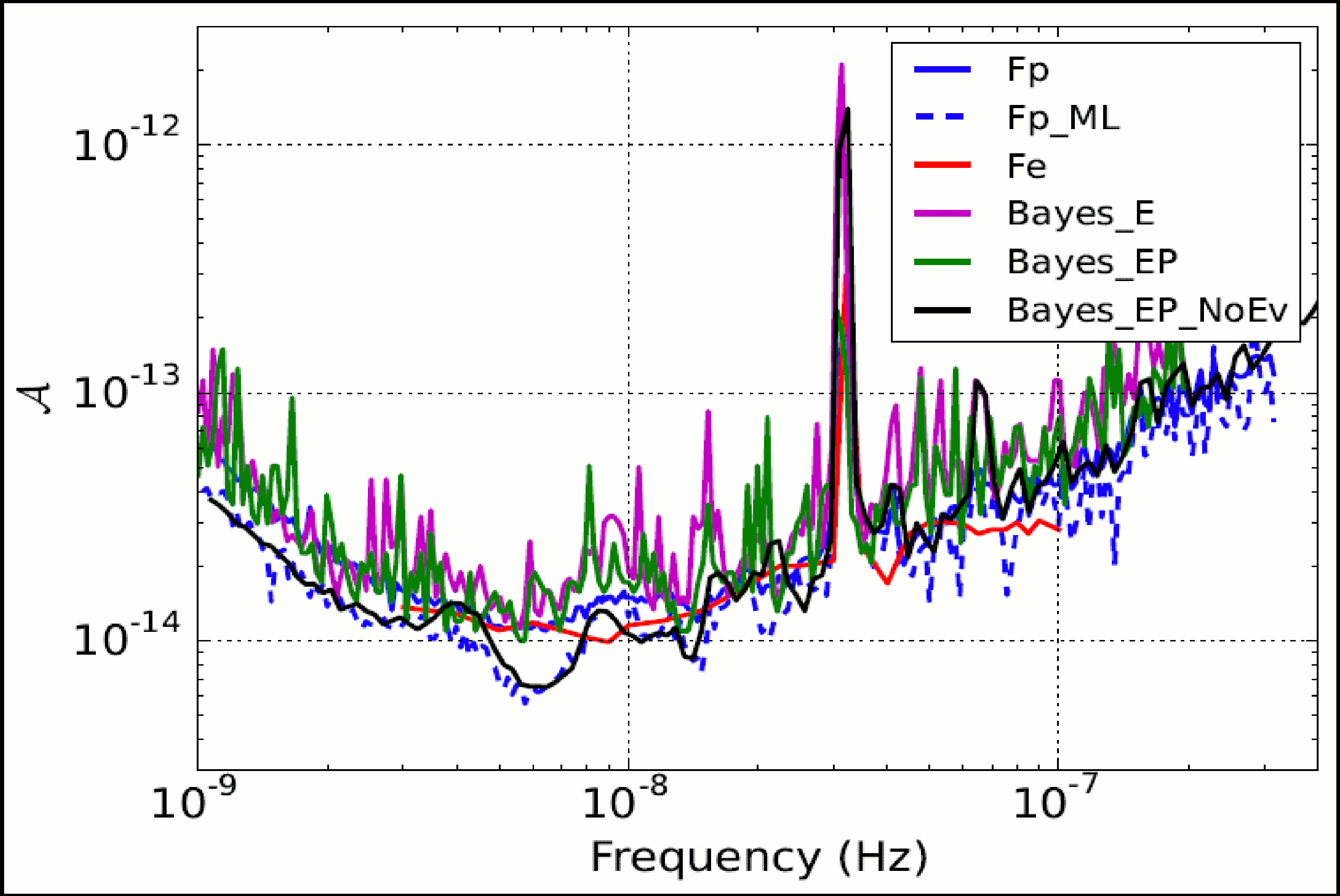
Applying this model to a tipical MBH binary population we get ~100 sources at the eRosita flux limit



Limits on continuous GWs

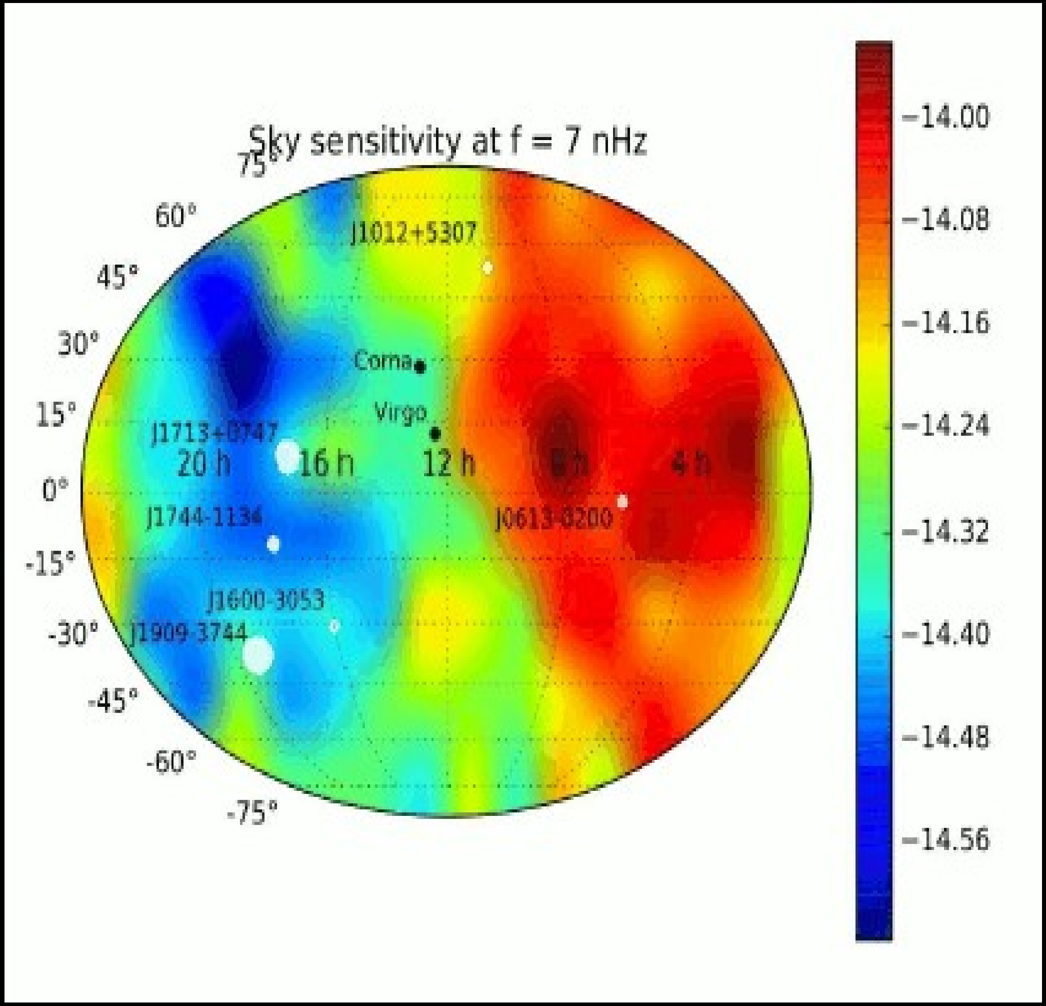
(EPTA, Babak et al. 2015)

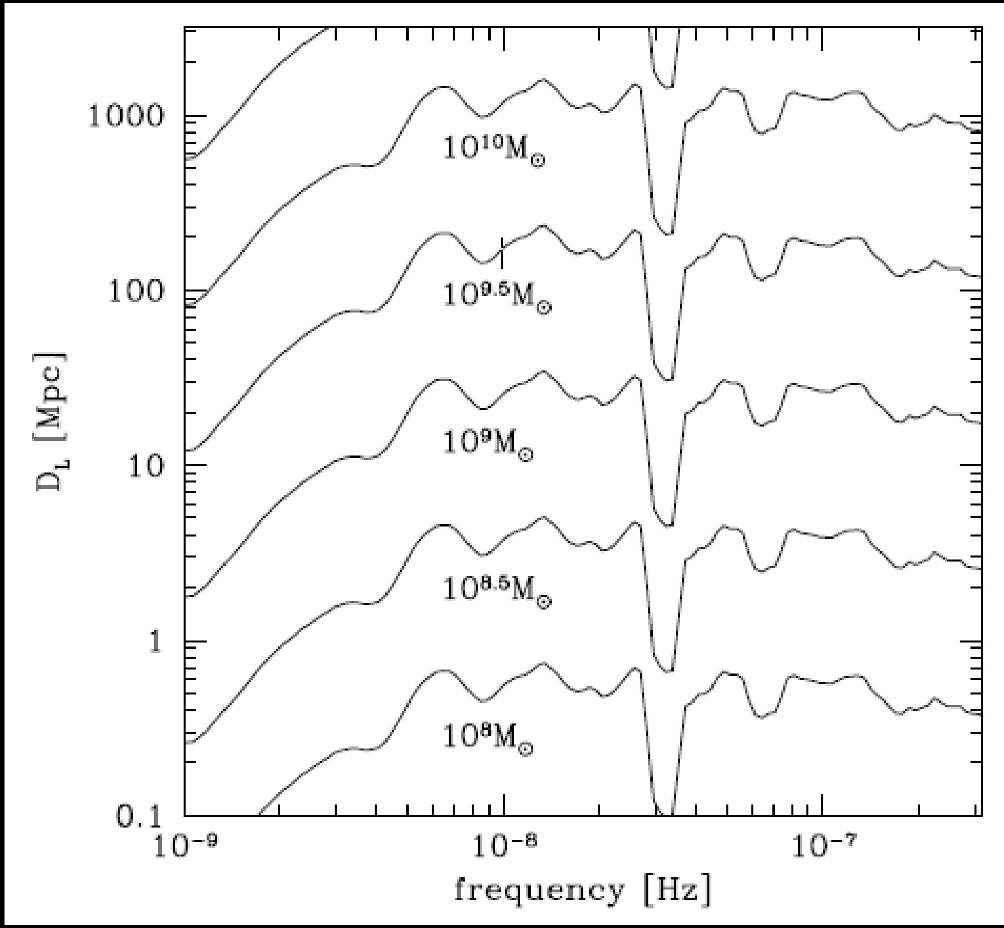
Search ID	Noise treatment	N pulsars	N parameters	Signal model	Likelihood
Fp_ML	Fixed ML	41	1	E+P NoEv	Maximized over 4 constant amplitudes plus pulsar phase
Fp	Sampling posterior	41	1	E+P NoEv	Maximized over 4 constant amplitudes plus pulsar phase
Fe	Fixed ML	41	3	E	Maximized over 4 constant amplitudes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

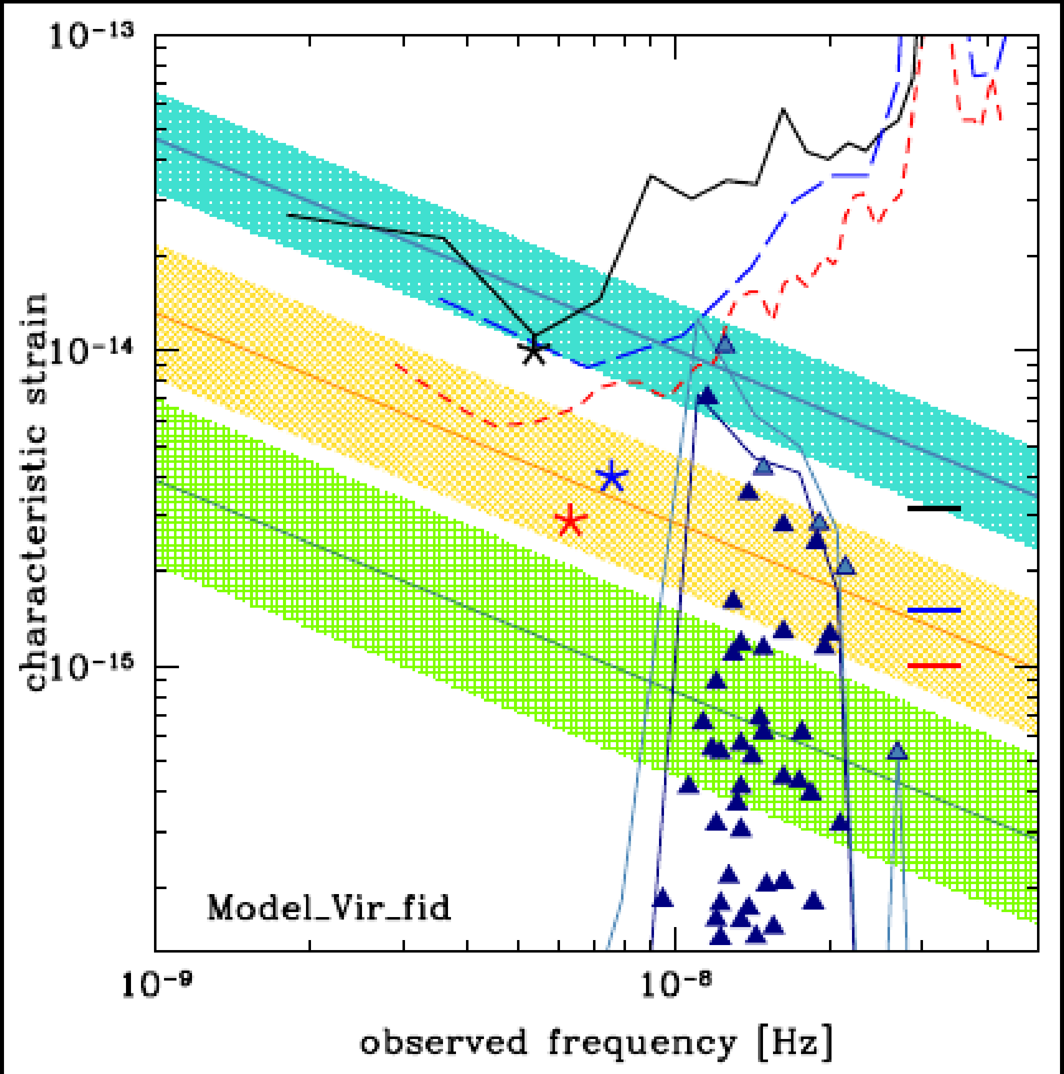


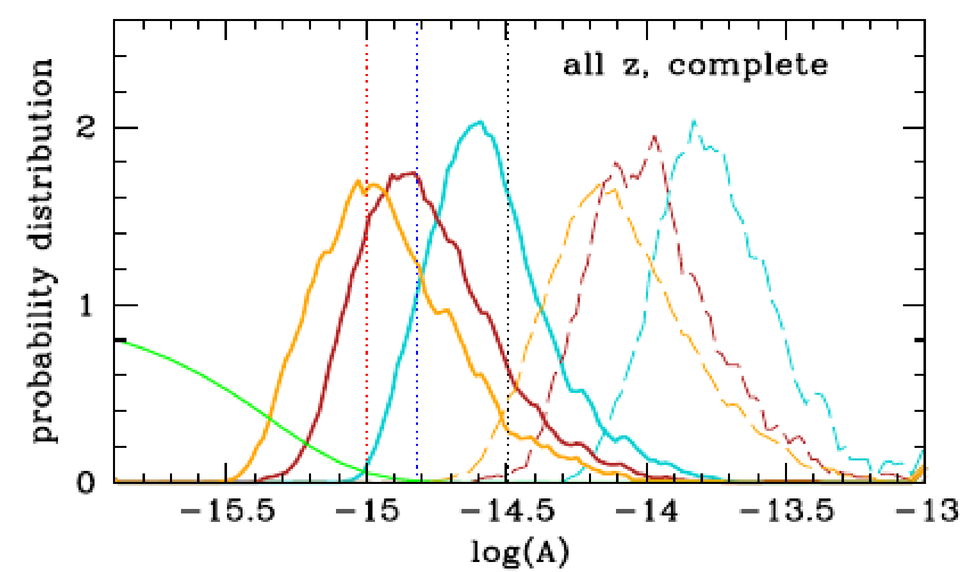


Data are not yet very constraining, we can rule out very massive systems to ~200Mpc, well beyond Coma

Constraining astrophysical candidates

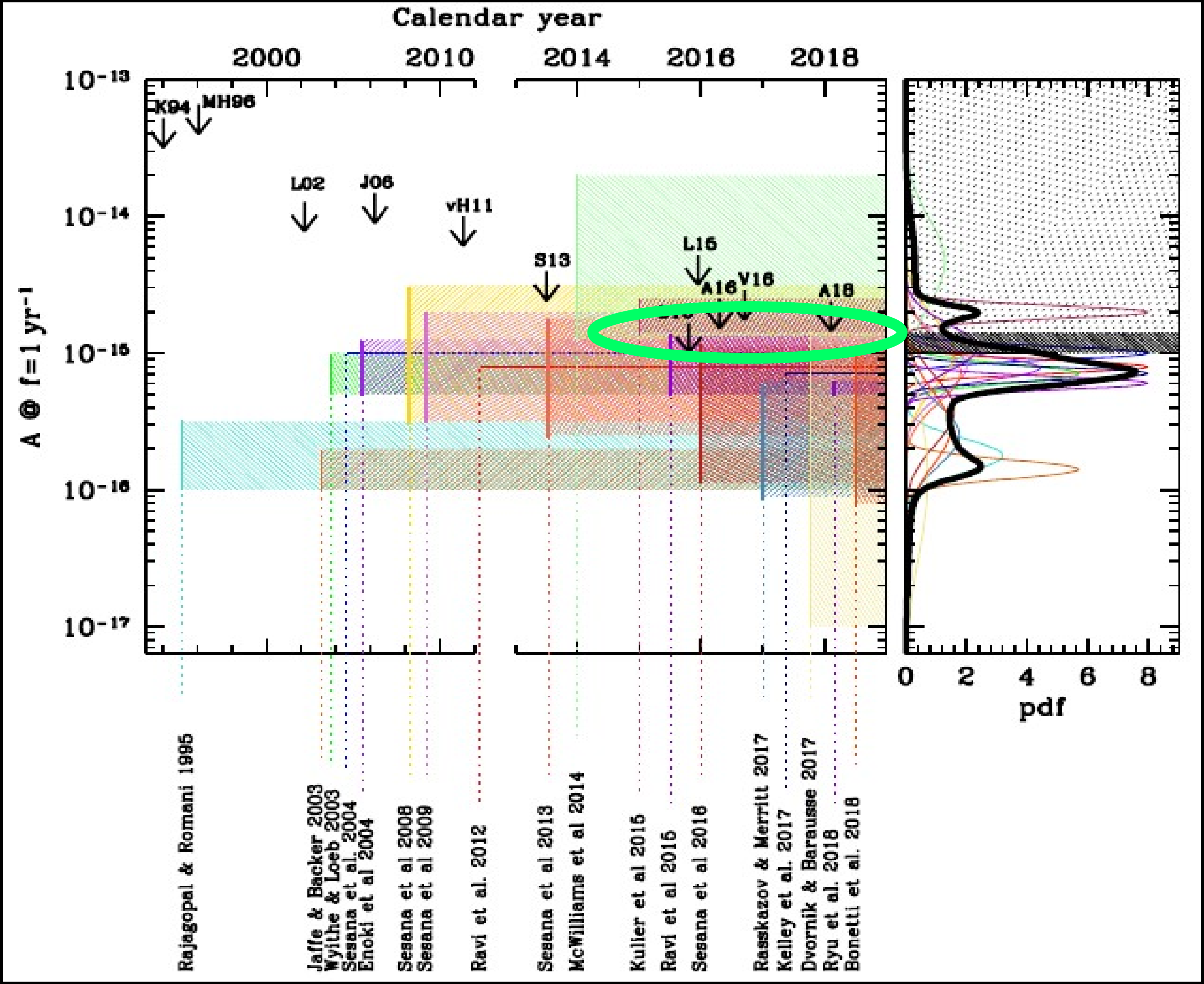
- -Graham et al. 2015: 111 candidates from CRTS
- -Charisi et al 2016: 33 candidates from PTF
- -All candidates are individually consistent with PTA limits
- -The implied total signal is in tension with PTA limits at 2 – 3 sigma level (Sesana et al. 2018)





model pair	odds ratio & probabilities		
	$\log\Lambda_{NB}$	p_N	p_B
N/True_hiq	2.61	0.9976	0.0024
N/True_fid	1.52	0.9709	0.0291
N/True_loq	1.10	0.9267	0.0733
N/Vir_hiq	11.1	> 0.9999	$< 10^{-11}$
N/Vir_fid	6.67	> 0.9999	$< 10^{-6}$
N/Vir_loq	5.22	> 0.9999	$< 10^{-5}$

...but...



Calendar year
2000
2010
2014
2016
2018
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
A @ f=1 yr^{-1}
K94
MH96
L02
J06
vH11
S13
L15
A16
V16
A18
0
2
4
6
8
pdf
Rajagopal & Romani 1995
Jaffe & Backer 2003
Wyithe & Loeb 2003
Sesana et al. 2004
Enoki et al 2004
Sesana et al 2008
Sesana et al 2009
Ravi et al. 2012
Sesana et al 2013
McWilliams et al 2014
Kulier et al 2015
Ravi et al 2015
Sesana et al 2016
Rasskazov & Merritt 2017
Kelley et al. 2017
Dvornik & Barausse 2017
Ryu et al. 2018
Bonetti et al. 2018

Limits published after 2015 might not be so solid

1- Shannon et al 2015 → essentially a single pulsar limit.
This might be a problem since you have to model the pulsar red noise and if your array is dominated by a single pulsar you can't really know whether its red noise is intrinsic. → 'over fitting risk'

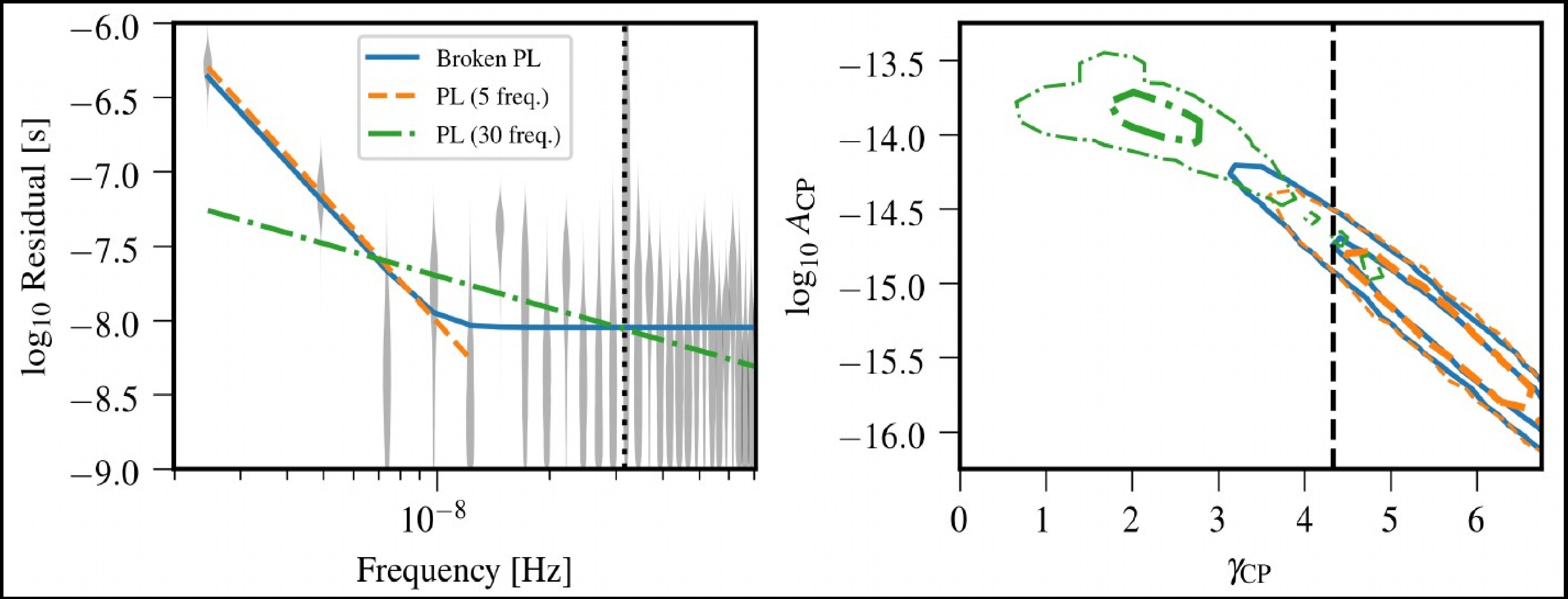
2- Arzoumanian 2016, 2018 → Issues with solar system Ephemeridis.
The data show some evidence of correlated red signal, but it can be absorbed in uncertanties in the SSE

NOTE:
The choice of the prior in your analysis matters. When you think you don't have a signal in the data, you use a log uniform prior in the amplitude to place an upper limit, which has the effect to likely push your UL down.

So it might be that by assuming there is no signal in the data, the recent UL have been overestimated.

NANOGrav 12.5 year analysis

Note of caution: not peer reviewed yet!



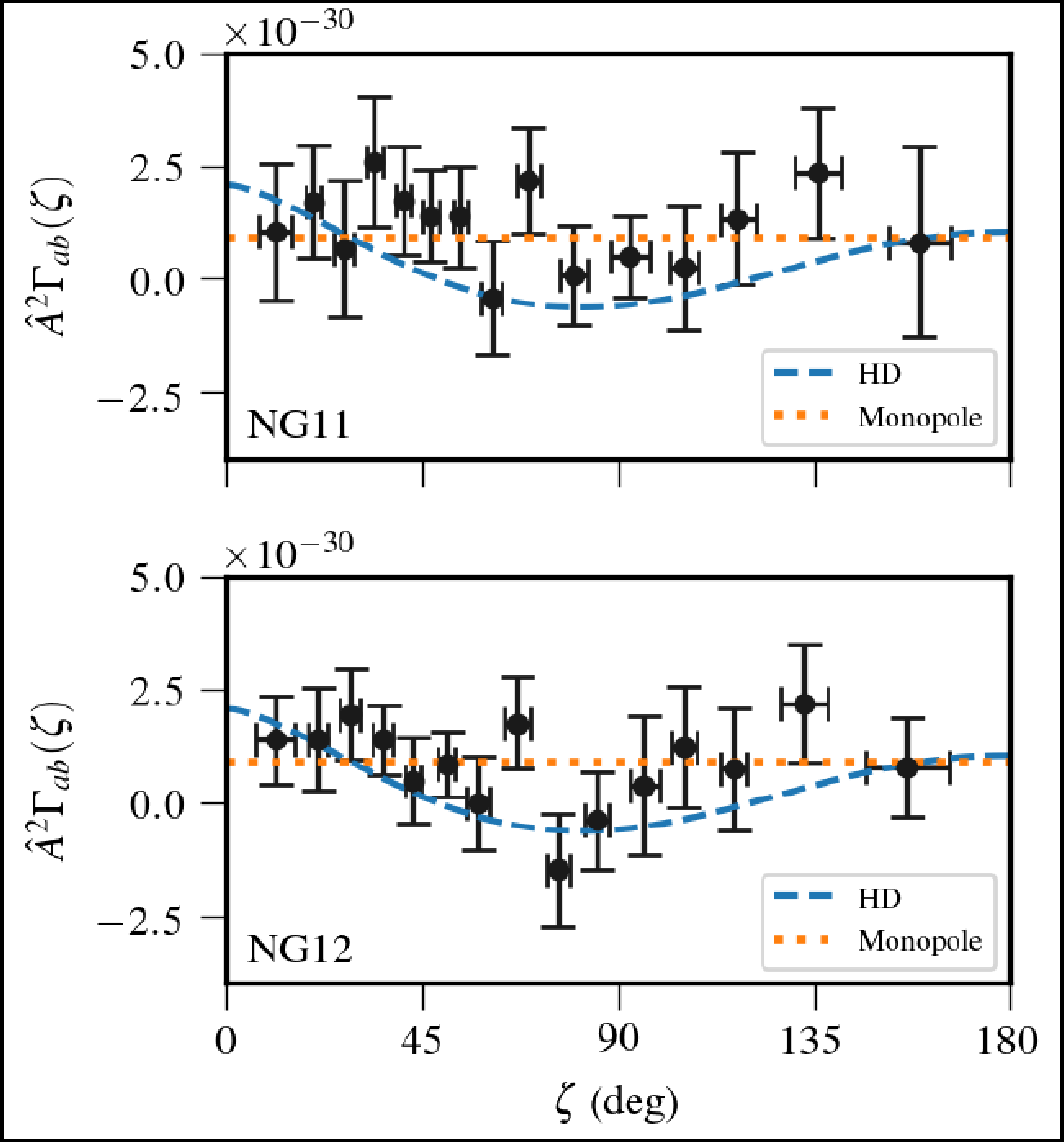
Full Bayesian analysis of 43 pulsars.
Schemes to account for SSE and other noises

Clear detection of a common red process.

Origin unknown at this point

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

If this was a GWB, then *A*~2x10^{-15}



Monopolar and Dipolar correlations seem disfavored.

However no evidence of HD correlation.

Extremely interesting, but systematics need further scrutiny.

All PTAs are carefully working on their data as we speak

MORE TO COME! Stay tuned!!

The future

MeerKAT, South Africa (2017)

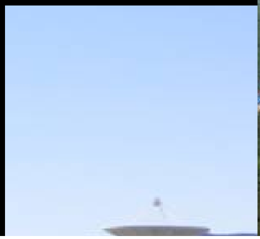
The future

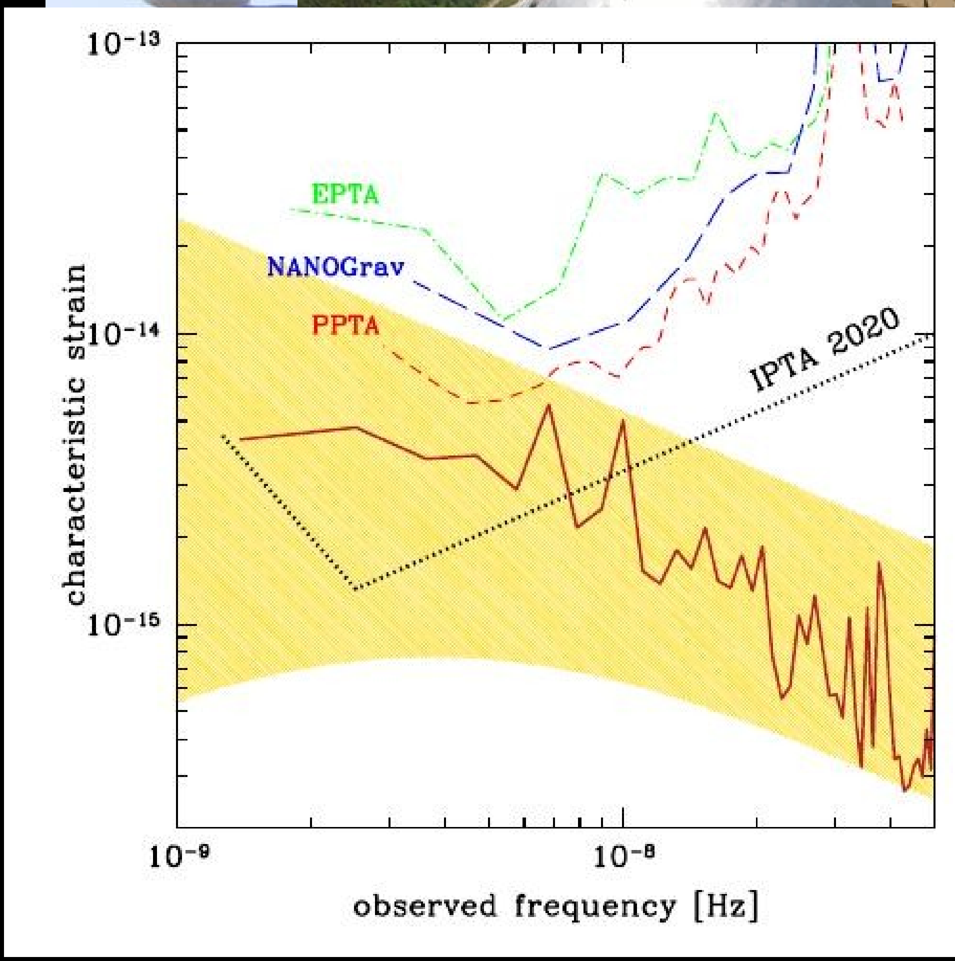

FAST, China (2017)

The future

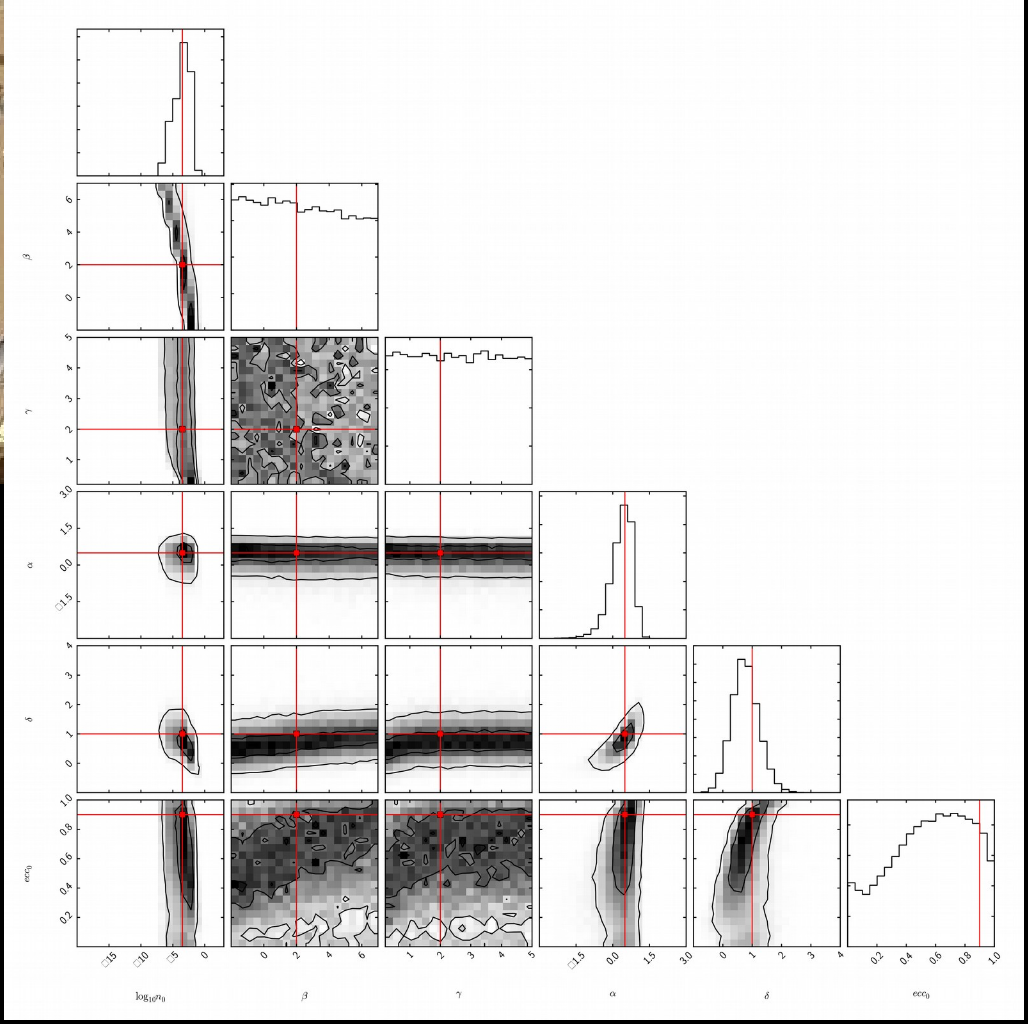
Square Kilometre Array (SKA, 2021+)

The future





10^{-13}
10^{-14}
10^{-15}
EPTA
NANOGrav
PPTA
IPTA 2020
characteristic strain
10^{-9}
10^{-8}
observed frequency [Hz]



Doggybag

Massive black hole binaries are expected to be the loudest gravitational wave sources in the Universe

Precise timing of ultra-stable millisecond pulsar in a Pulsar Timing Array provides an effective way to probe GWs from MBHBs in the nHz frequency window

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

Current limits are getting extremely interesting

However:

> recent limits are put into question

> tentative detection of a common red process of unknown nature

> need more work and checks for systematics, unmodeled noise etc.

STAY TUNED!!!