Pulsar Timing Arrays and gravitational waves: a big step towards detection

Gilles Theureau

On behalf of PTA-France group and European Pulsar Timing Array collaboration

AGENCE NATIONALE DE LA RECHERCHE ANR
PNHE Programme national hautes énergies
PNCG Programme National de Cosmologie et Galaxies
LPC2E
SRN l'Observatoire de Paris | PSL Station de Radioastronomie de Nançay
APC, CNRS, FRANCE

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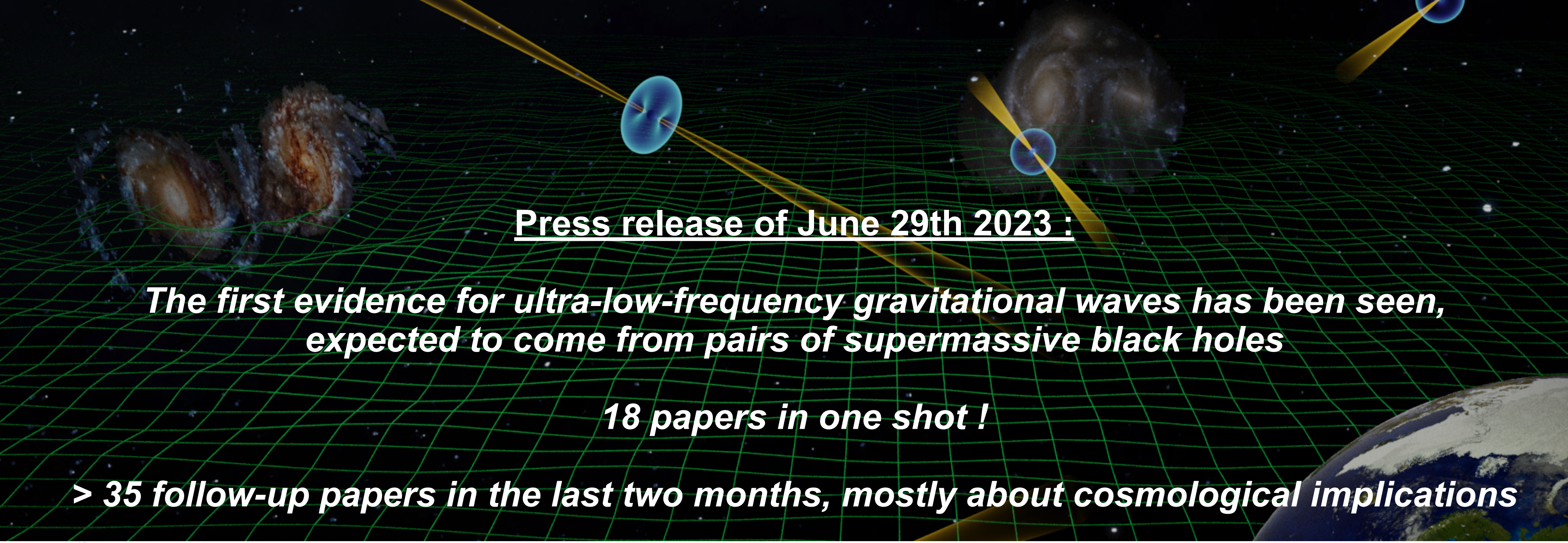
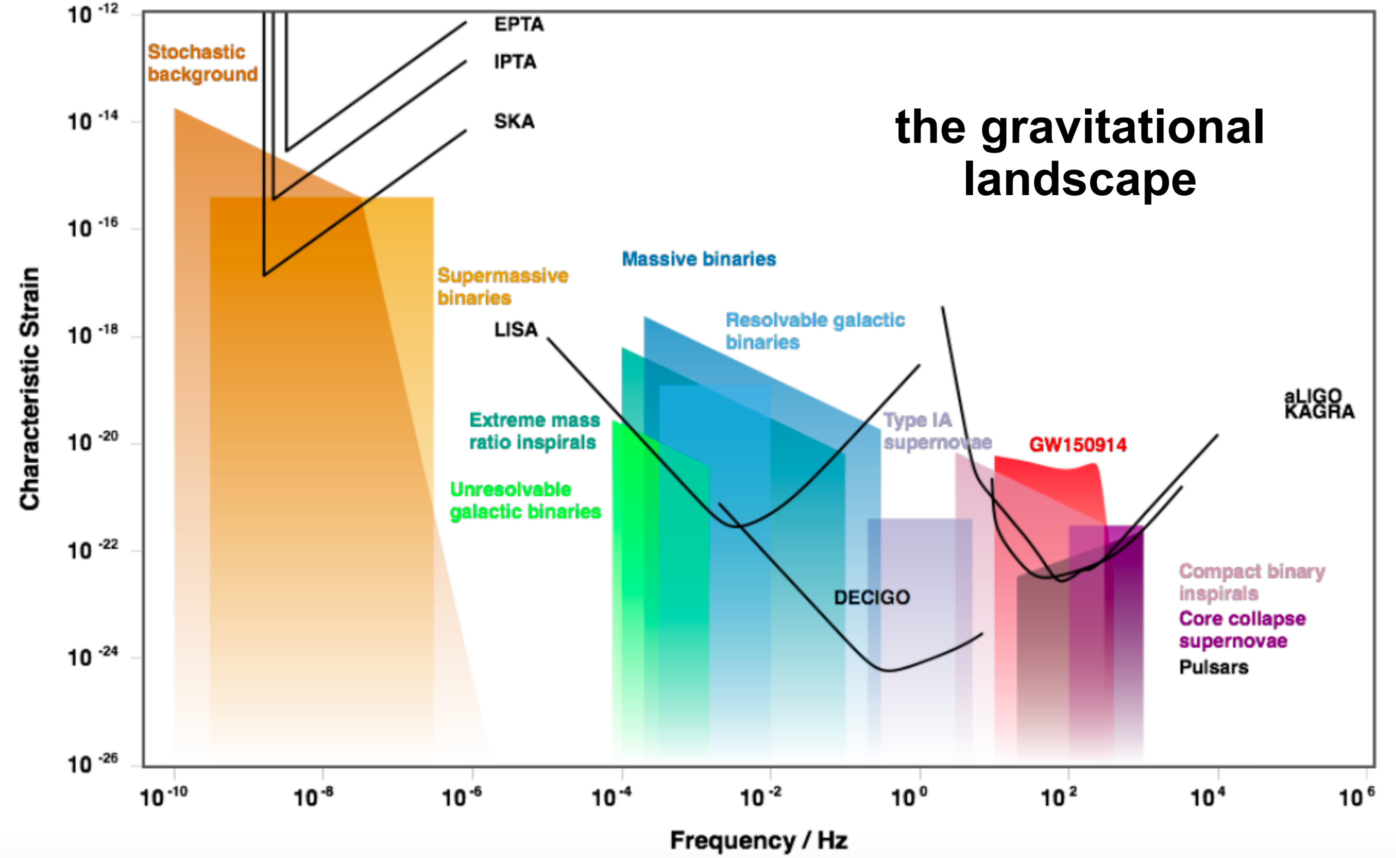


Press release of June 29th 2023 :

The first evidence for ultra-low-frequency gravitational waves has been seen, expected to come from pairs of supermassive black holes

18 papers in one shot !

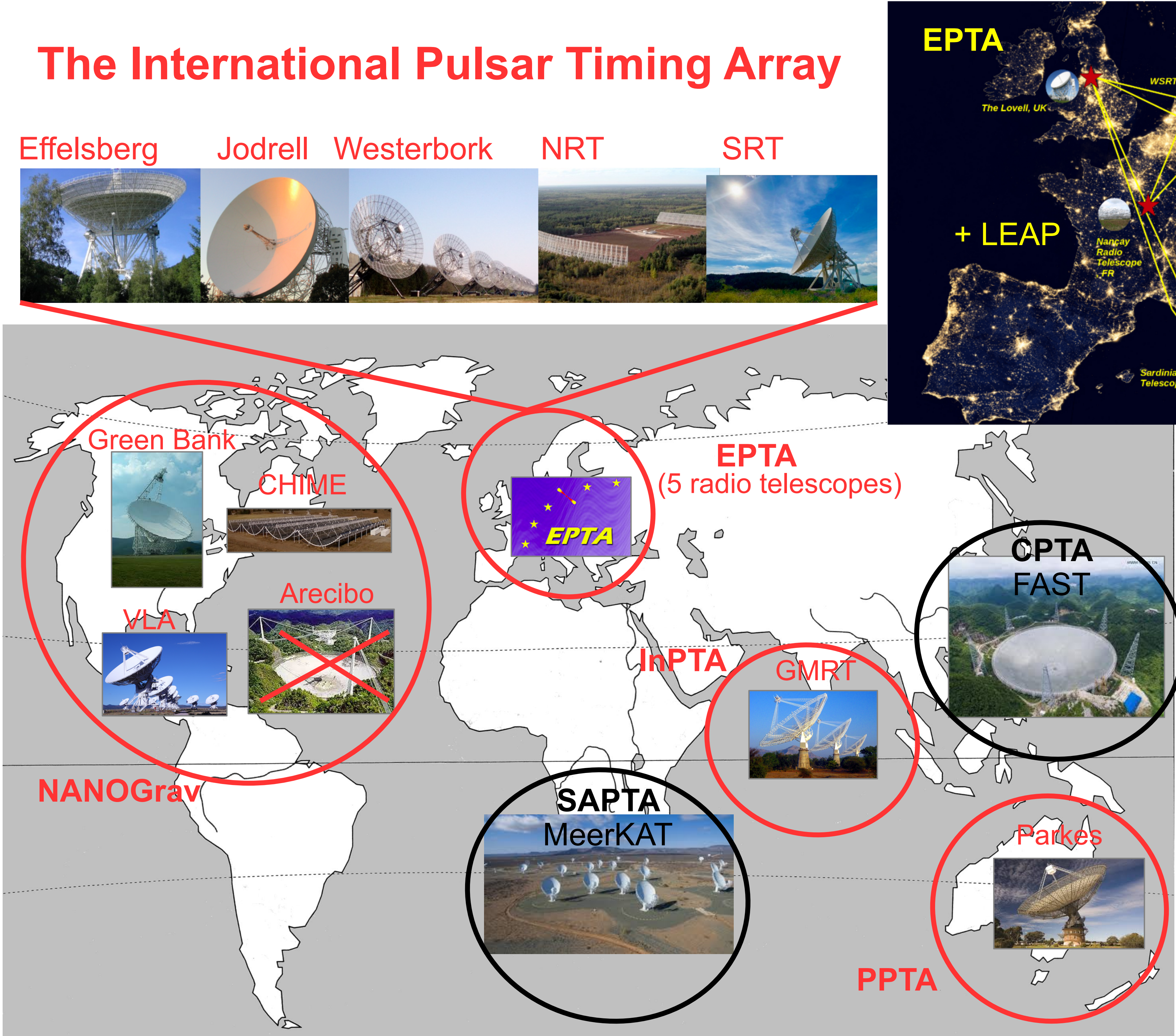
> 35 follow-up papers in the last two months, mostly about cosmological implications



The nanoHertz domain

- **Super Massive Black Hole Binaries (SMBHB)**
- **Cosmic string loops**
- **Relics of inflation**
- **First-order phase transition**
- **fuzzy dark matter**

The International Pulsar Timing Array

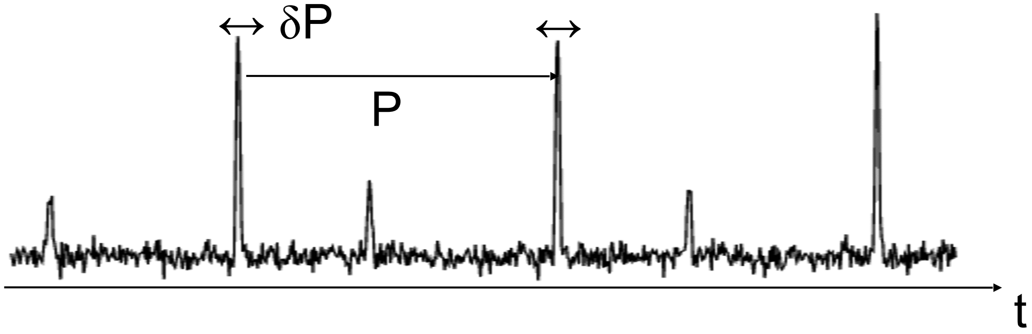


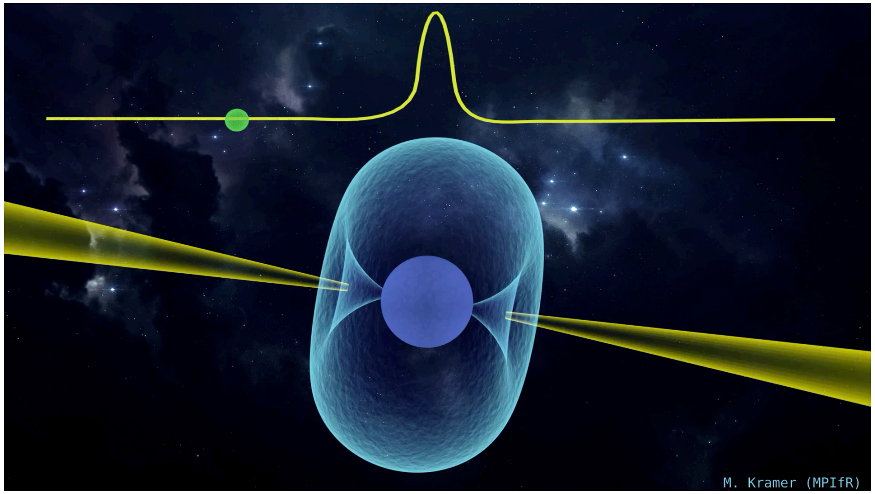
EPTA/InPTA, PPTA and NANOGrav

publish coherent results !

« a low-frequency quadrupolar signal common to all pulsars »

Pulsar Timing Arrays : principles

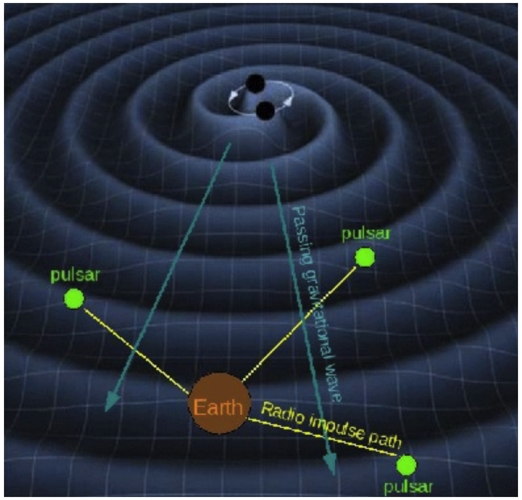




The Earth and the distant pulsar are considered as free masses whose position responds to changes in the metric of space-time

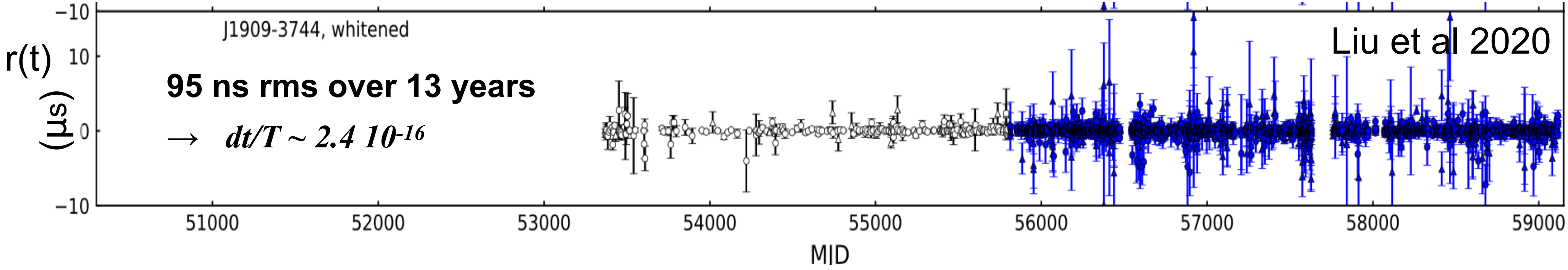
→ *The passage of a gravitational wave disturbs the metric and produces fluctuations in the arrival times of the pulses*

With timing uncertainties dt (~100 ns) and observation time spans T (~25 years)
→ PTA are sensitive to *amplitudes ~ dt/T and to frequencies f ~ 1/T*



Sensitivity ~ 100 10^{-9} / 25 x 3 10^{7} → A ~ 1.3 10^{-16}

Frequency domain (25 years - 1 week) → 10^{-9} – 10^{-6} Hz



95 ns rms over 13 years

→ ***dt/T ~ 2.4 10^{-16}***

Liu et al 2020

Pulsar Timing Arrays : principles

1) Describe the pulsar rotation in a reference frame co- moving with the pulsar

$$\nu(t) = \nu_0 + \dot{\nu}_0(t - t_0) + \frac{1}{2}\ddot{\nu}_0(t - t_0)^2 + \cdots$$

The observed parameters v and v˙ are associated
with the physical processes causing pulsars to spin down

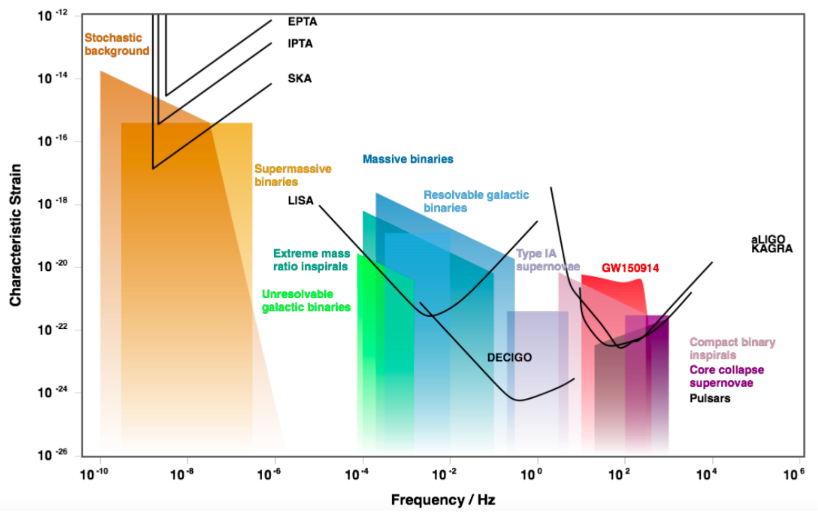
2) Timing model

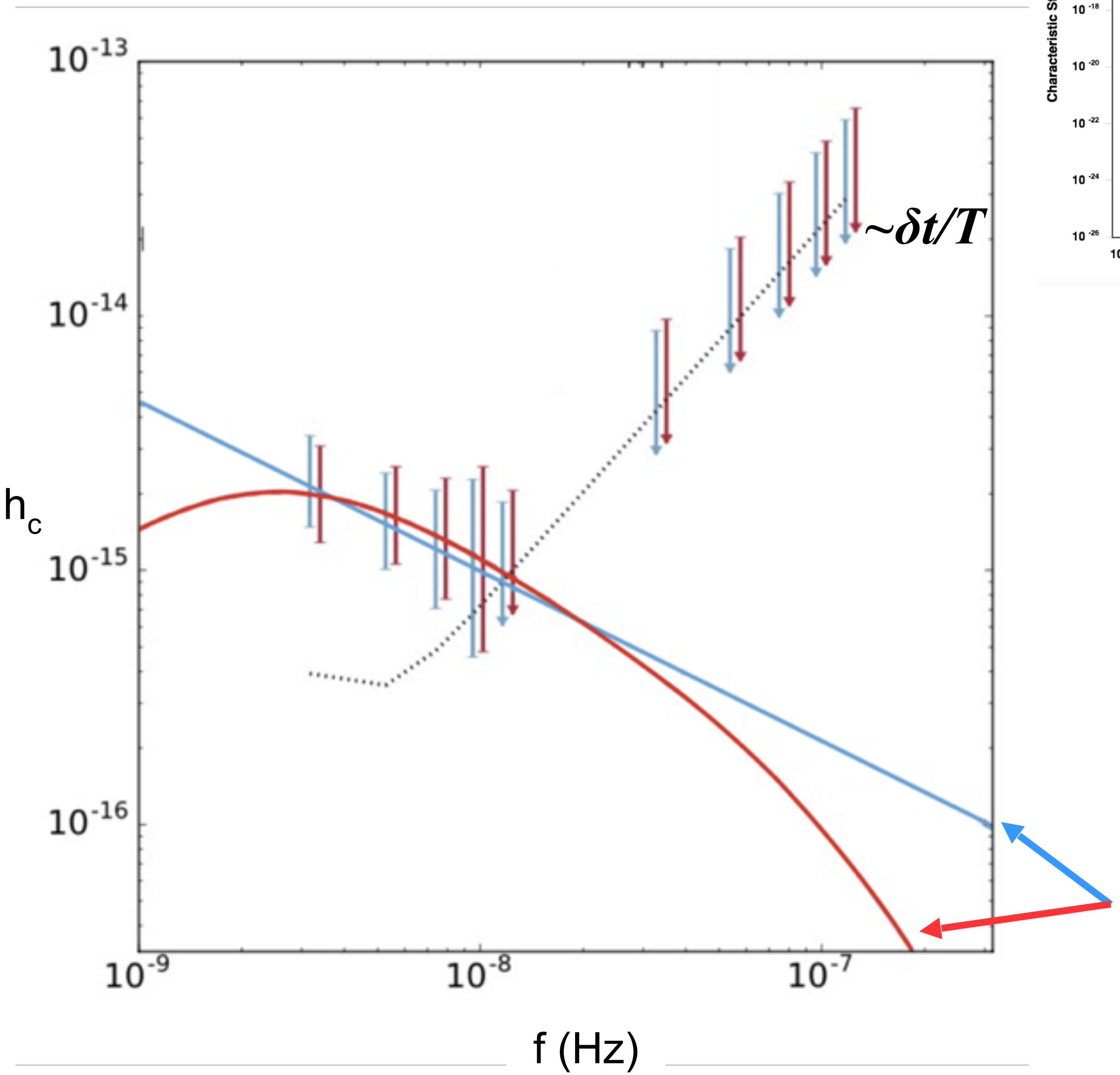
$$t_{SSB} = \overbrace{t_{topo} + \underbrace{t_{corr}}_{\text{clock}} - \underbrace{\delta D/f_{obs}^2}_{\text{dispersion}} + \underbrace{\Delta_{R\odot} + \Delta_{\pi} + \Delta_{S\odot} + \Delta_{E\odot}}_{\substack{\text{Solar System}\\ \text{Römer, parallax, Shapiro}\\ \text{and Einstein delays}}} + \underbrace{\Delta_{R} + \Delta_{S} + \Delta_{E} + \Delta_{A}}_{\substack{\text{binary system}\\ \text{Römer, Shapiro, Einstein}\\ \text{and Aberration delays}}}}^{\boldsymbol{\tau}^{\mathrm{TM}}}$$

3) Full noise model

$$\textbf{observed TOA} = \underset{\substack{\text{Timing}\\ \text{Model}\\ \text{(deterministic)}}}{\boldsymbol{\tau}^{\mathrm{TM}}} + \overbrace{\underset{\substack{\text{meas.}\\ \text{(white)}\\ \text{noise}}}{\boldsymbol{\tau}^{\mathrm{WN}}} + \underset{\substack{\text{pulsar}\\ \text{spin (red)}\\ \text{noise}}}{\boldsymbol{\tau}^{\mathrm{SN}}} + \underset{\substack{\text{DM}\\ +\\ \text{scatter}\\ \text{(red) noise}}}{\boldsymbol{\tau}^{\mathrm{DM}}} + \underset{\substack{\text{clock}\\ +\\ \text{ephem.}\\ \text{(red) noise}}}{\boldsymbol{\tau}^{\mathrm{CN}}}}^{\text{Noise model (stochastic)}} + \underset{\substack{\text{GWB}\\ \text{(red)}\\ \text{noise}}}{\boldsymbol{\tau}^{\mathrm{GW}}}$$

Pulsar Timing Arrays : principles





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

Expected spectrum for a population of super massive black hole binaries

Pulsar Timing Arrays : principles

we write the PTA likelihood as $$p(\boldsymbol{\delta t}|\boldsymbol{\eta}) = \frac{\exp\left(-\frac{1}{2}\boldsymbol{\delta t}^T C^{-1}\boldsymbol{\delta t}\right)}{\sqrt{\det(2\pi C)}}$$

The covariance matrix is decomposed into a sum of « noises » whose spectrum is described by a power law

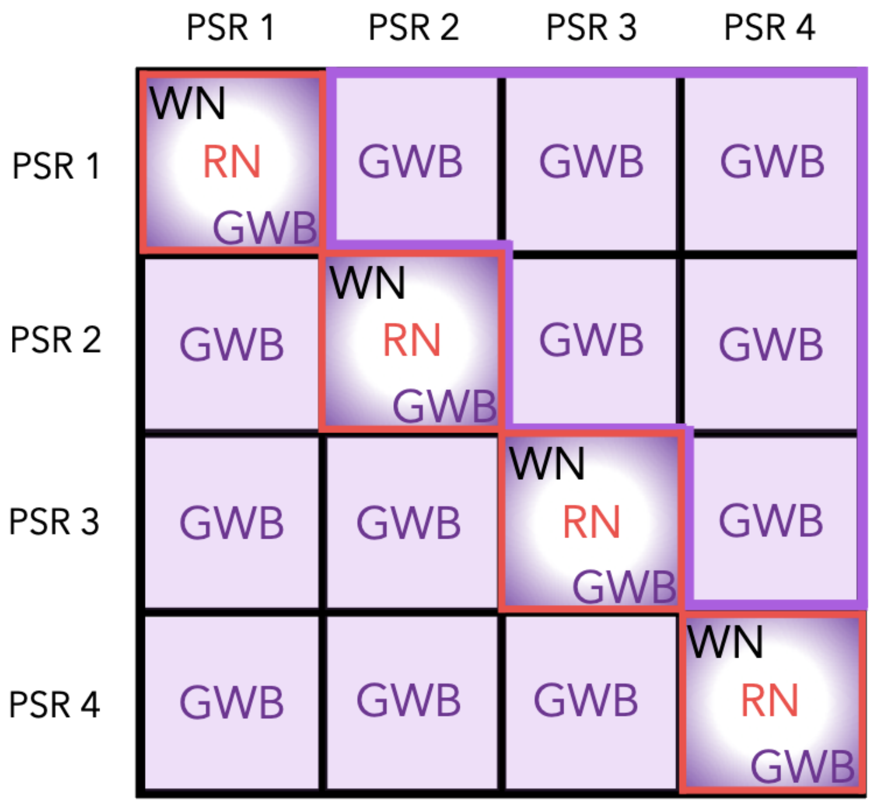
$$C \sim \underline{\Gamma_{ab}\rho_i\delta_{ij}} + \underline{\epsilon_i\delta_{ij}} + \underline{\eta_i\delta_{ab}\delta_{ij}} + \underline{\kappa_{ai}\delta_{ab}\delta_{ij}}$$

GW clock/eph. astroφ indiv. rot./disp.

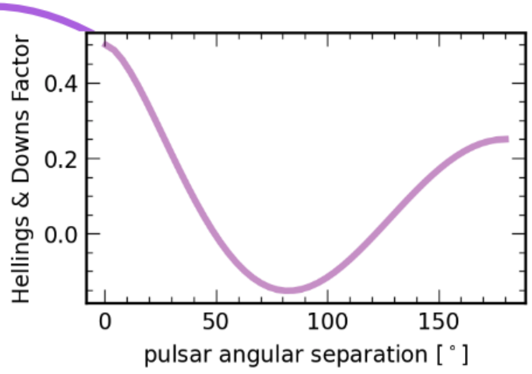
The GW term depends both on the amplitude of the signal as a function of its sky position and on the «antenna pattern »

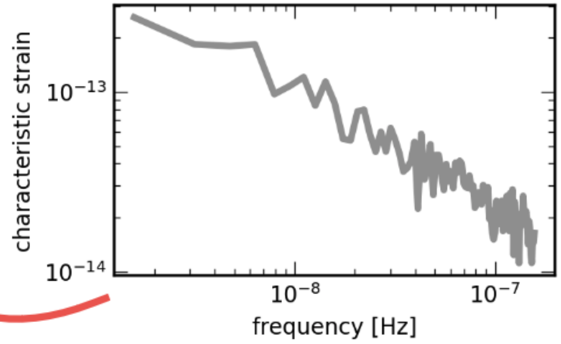
$$\boxed{\Gamma_{ab} = \frac{3}{8\pi}(1+\delta_{ab})\int_{S^2} d\hat{\Omega}\; P(\hat{\Omega}) \sum_q F_a^q(\hat{\Omega})F_b^q(\hat{\Omega})}$$

(overlap reduction function)



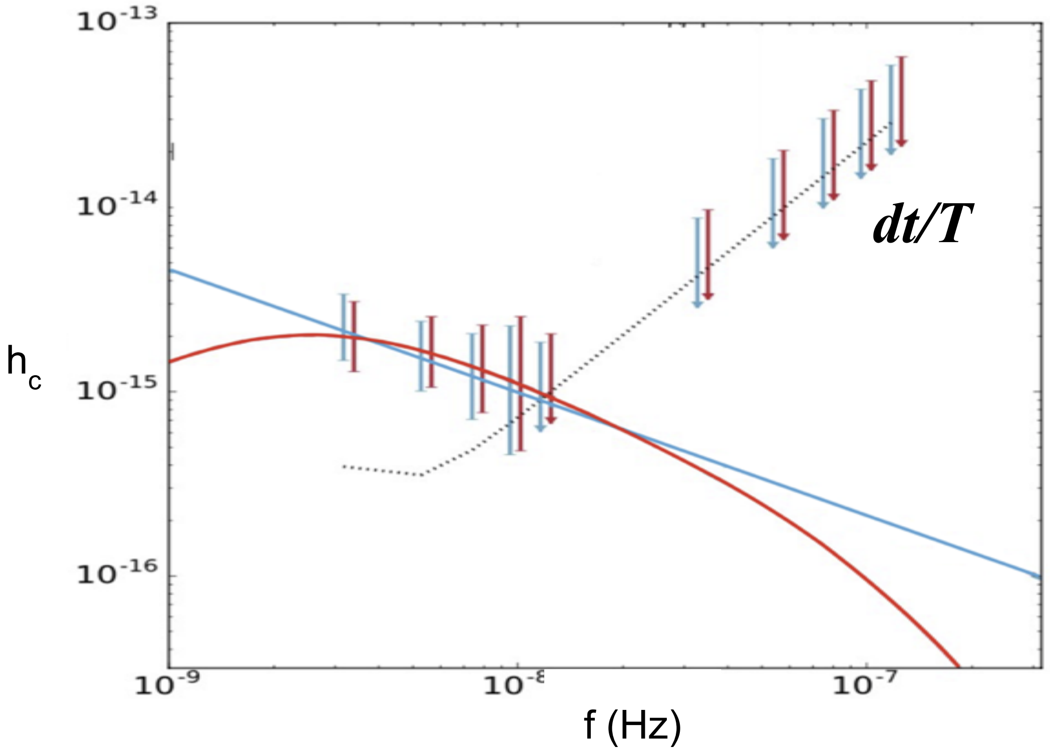
	PSR 1	PSR 2	PSR 3	PSR 4
PSR 1	WN RN GWB	GWB	GWB	GWB
PSR 2	GWB	WN RN GWB	GWB	GWB
PSR 3	GWB	GWB	WN RN GWB	GWB
PSR 4	GWB	GWB	GWB	WN RN GWB





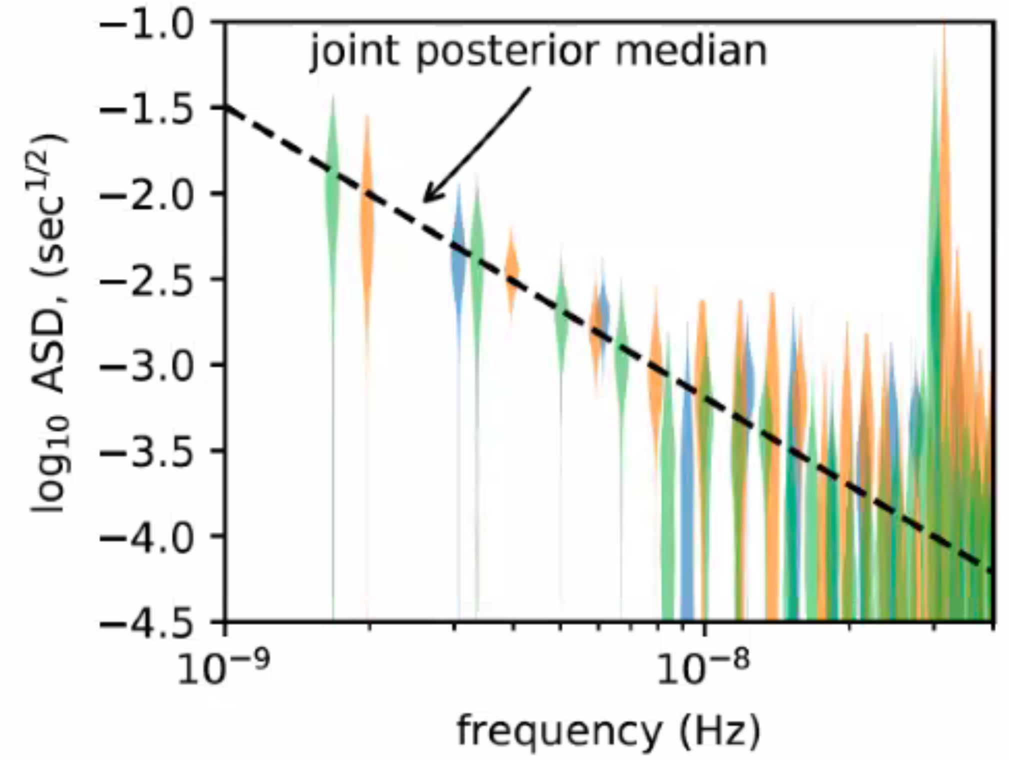
Taylor et al 2022

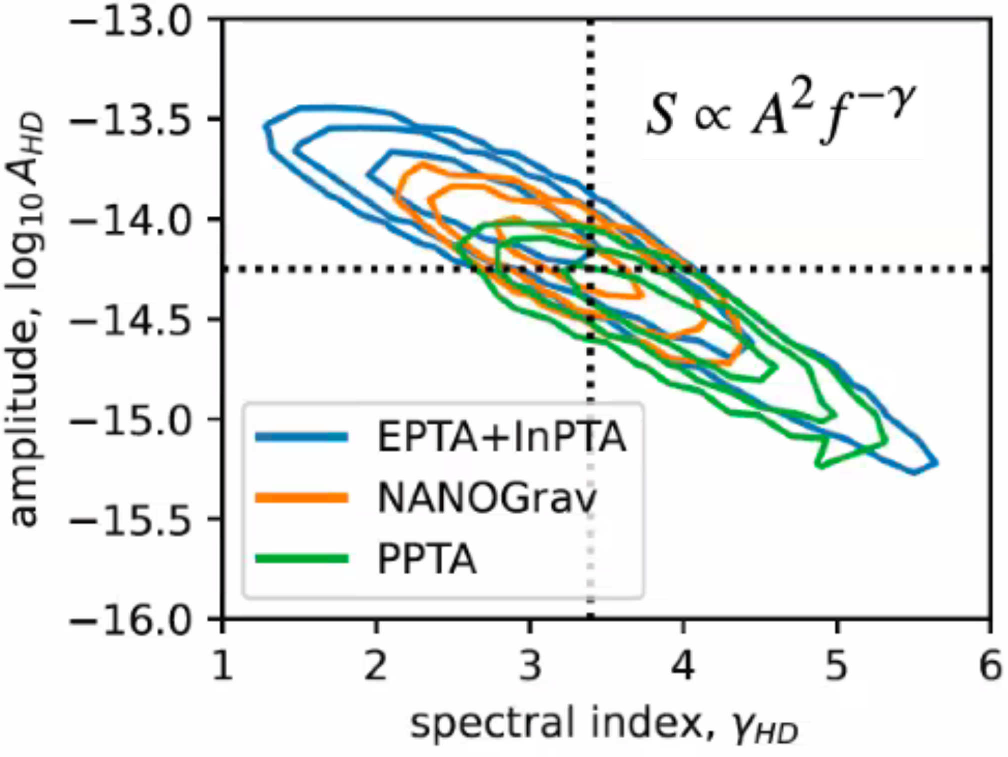
Observed spectrum



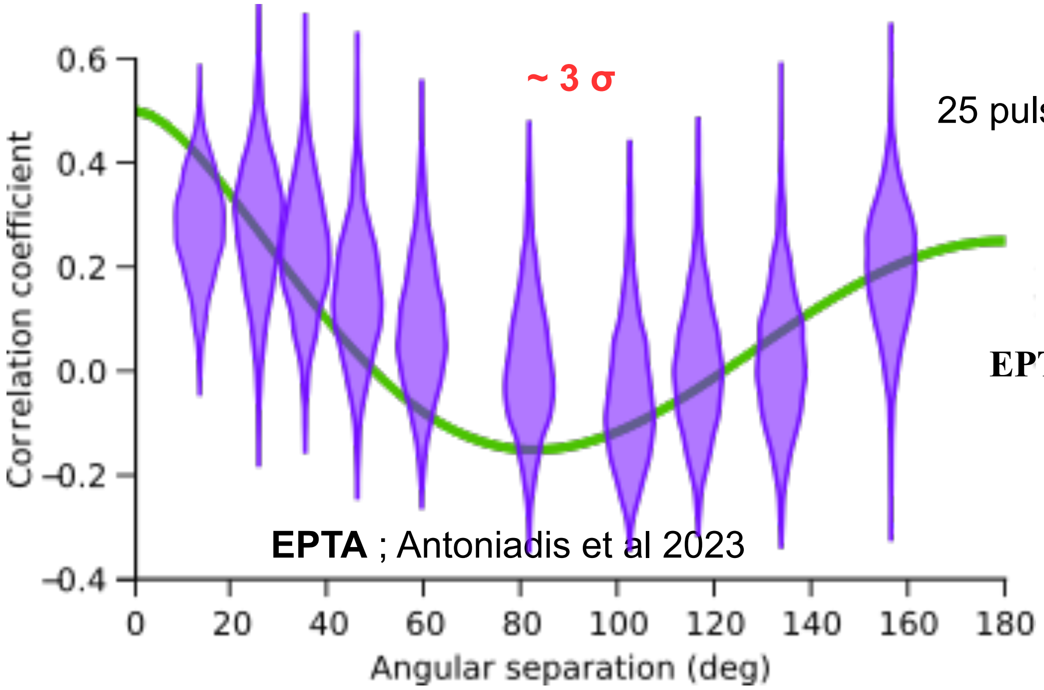
29th June 2023
EPTA, NANOGrav and PPTA
show coherent results

Courtesy of Paul Baker IPTA GWA WG





Spatial correlation of the signal



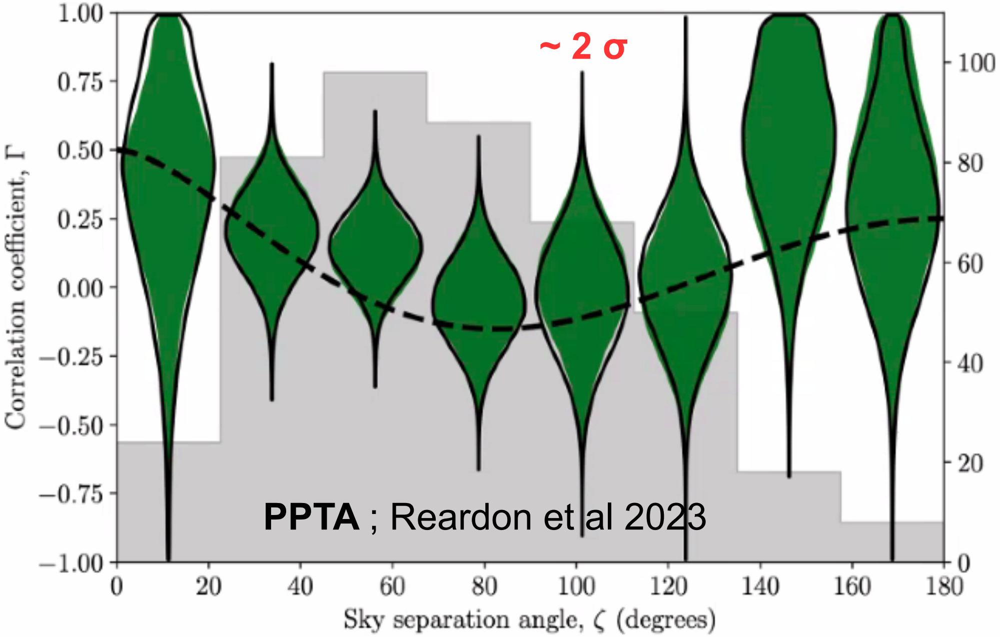
~ 3 σ

EPTA ; Antoniadis et al 2023

25 pulsars

29th June 2023
EPTA, NANOGrav and PPTA
show coherent results

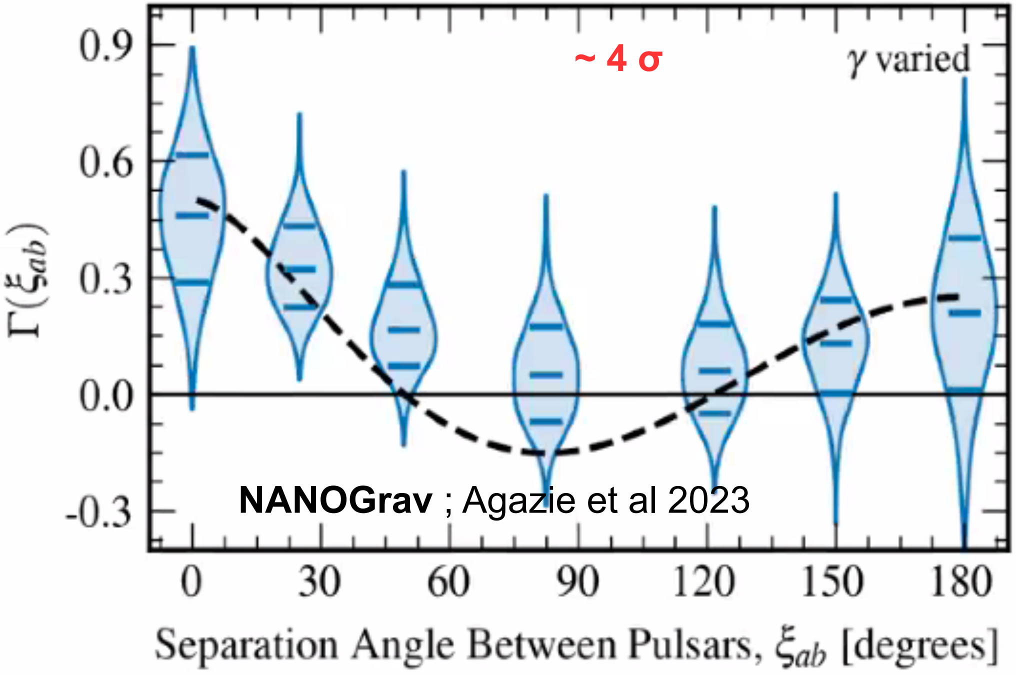
30 pulsars



~ 2 σ

PPTA ; Reardon et al 2023

67 pulsars

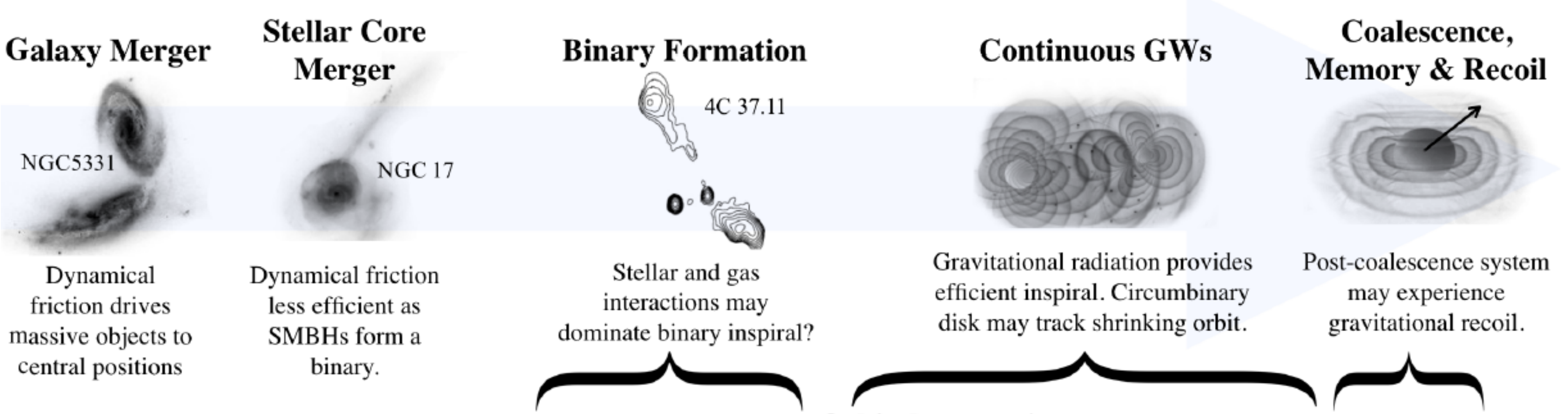


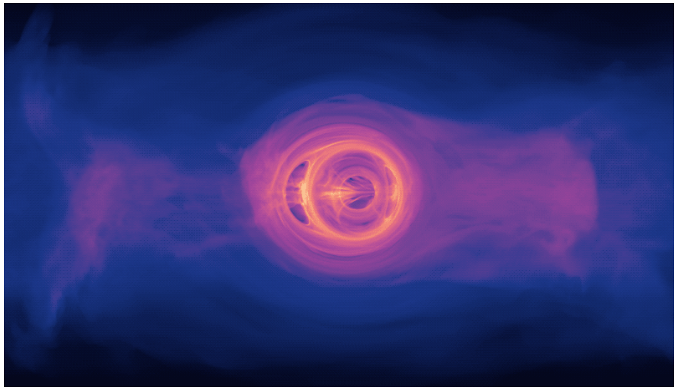
~ 4 σ

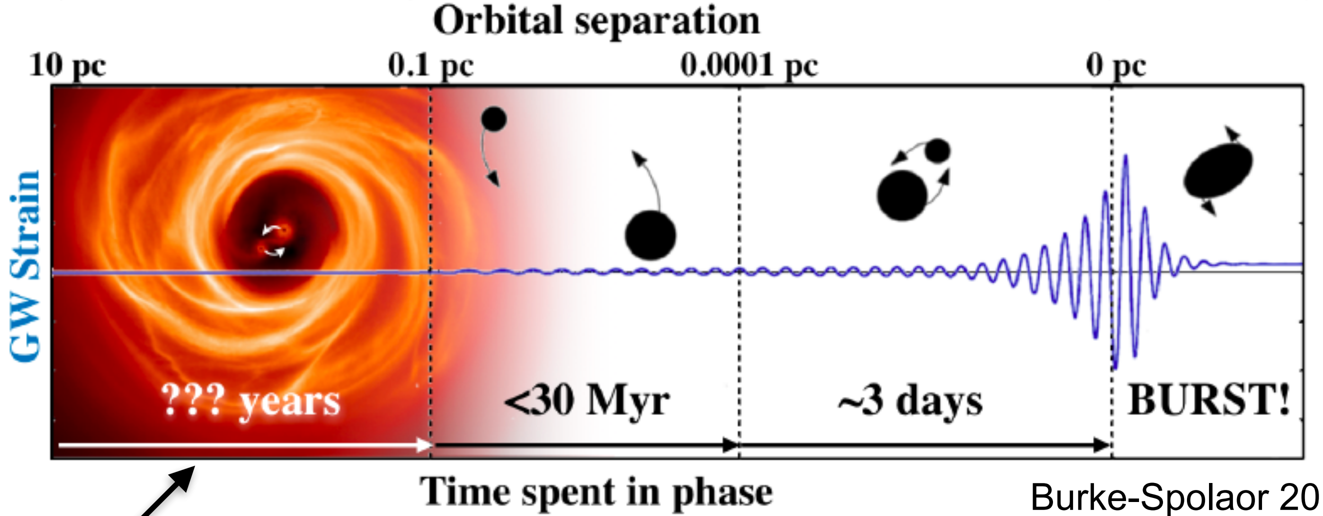
NANOGrav ; Agazie et al 2023

How interpreting such a common signal in terms of astrophysics ?

The life cycle of Super Massive Black Hole Binaries:







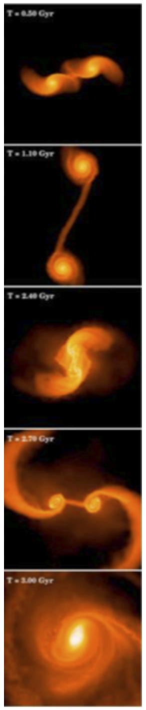
Burke-Spolaor 2018

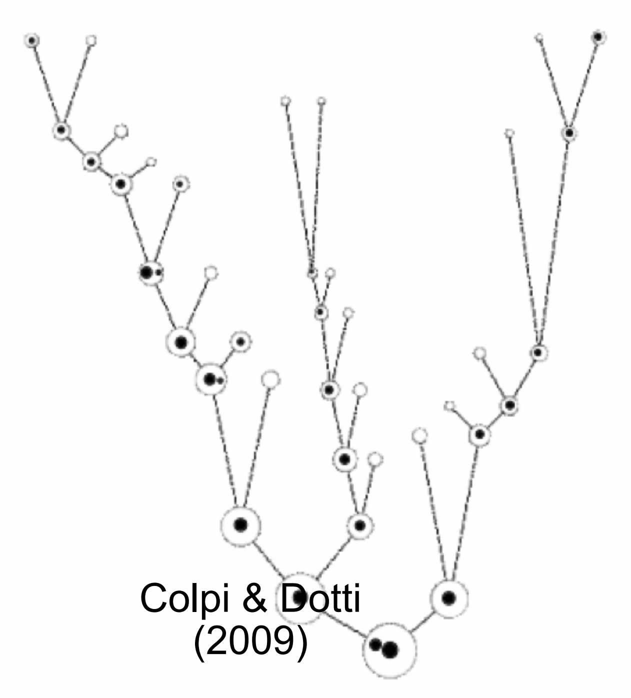
monochromatic
PTA regime

Last parsec problem

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

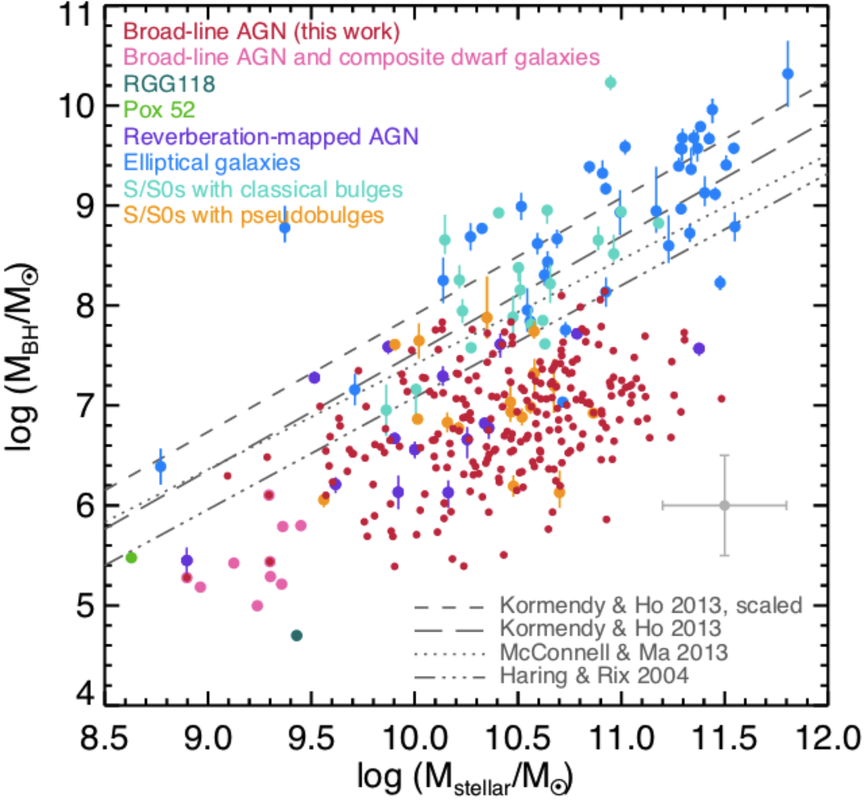
Population synthesis ingredients





Colpi & Dotti (2009)

Reines & Volonteri (2015)



Merger trees from cosmological N-body simulations (Illustris, TNG, EAGLE, Horizon-AGN, SIMBA ...)

Bulge to BH mass ratio from galaxies dynamical studies

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

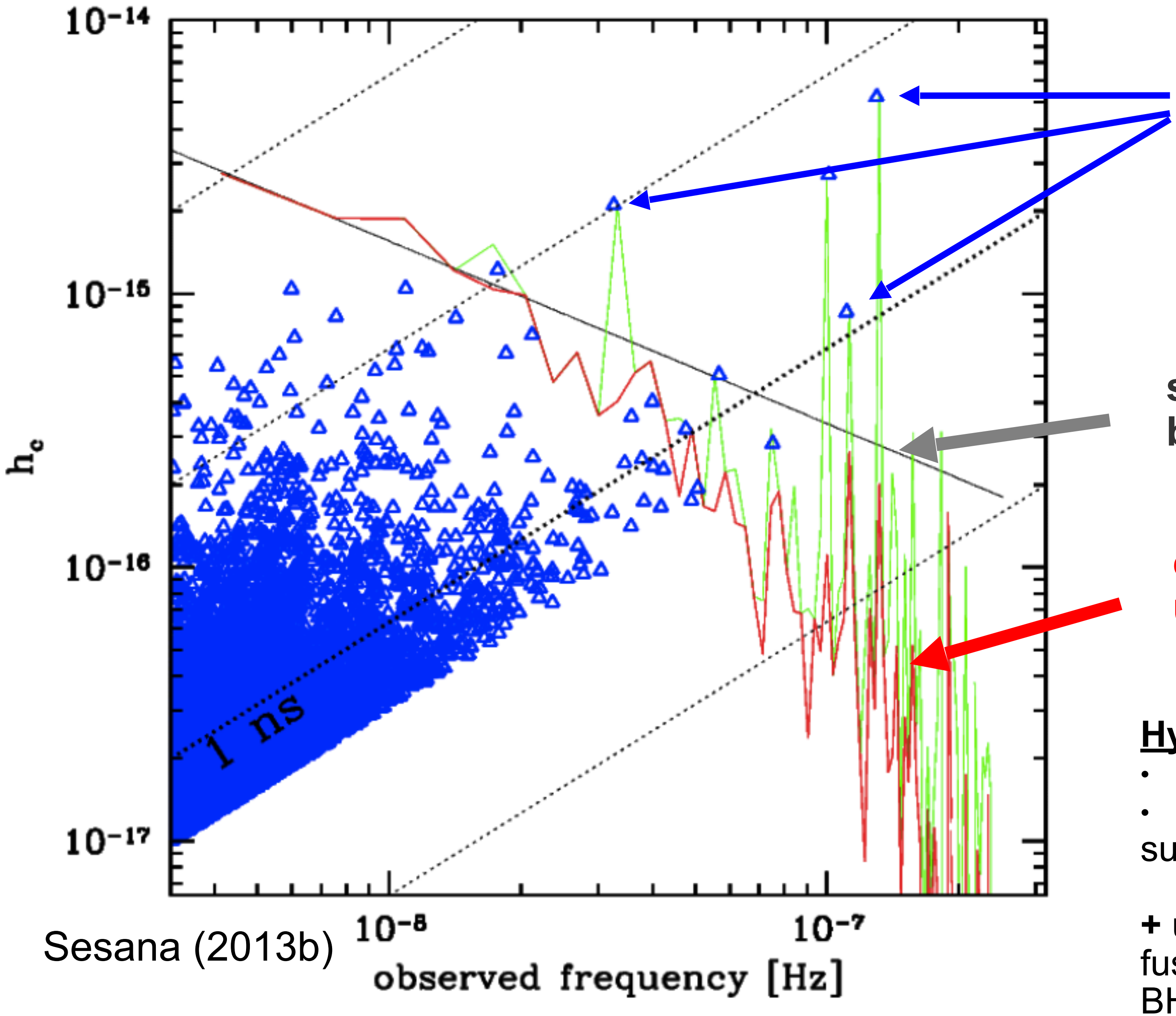
Three body interaction with stars from the loss cone region (when binary orbital velocity > stars)

GW emission

$$h_c^2(f) = \int_0^\infty dz \int_0^\infty d\mathcal{M}\, \frac{d^3N}{dz d\mathcal{M} d\ln f_r} h^2(f_r) \longrightarrow h_c(f) = A \left(\frac{f}{\mathrm{yr}^{-1}}\right)^{-2/3}$$

(Phinney 2001)

Population of SMBBH : contribution from background & individual sources



« resolvable » individual sources

stochastic background ~ f $^{-2/3}$

contribution from unresolved sources

Sesana (2013b)

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

GW emission

$$h_c^2(f) = \int_0^\infty dz \int_0^\infty d\mathcal{M} \, \frac{d^3N}{dz\,d\mathcal{M}\,d\ln f_r} h^2(f_r) \longrightarrow h_c(f) = A \left(\frac{f}{\mathrm{yr}^{-1}} \right)^{-2/3}$$

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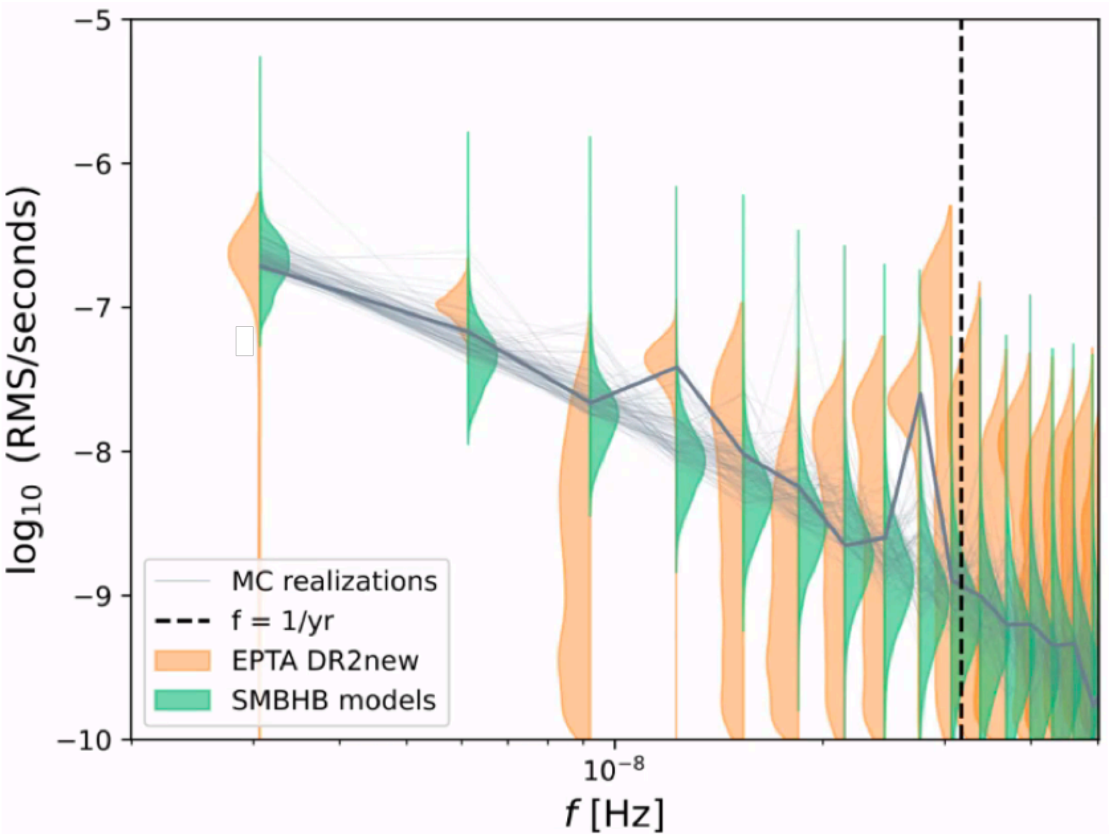
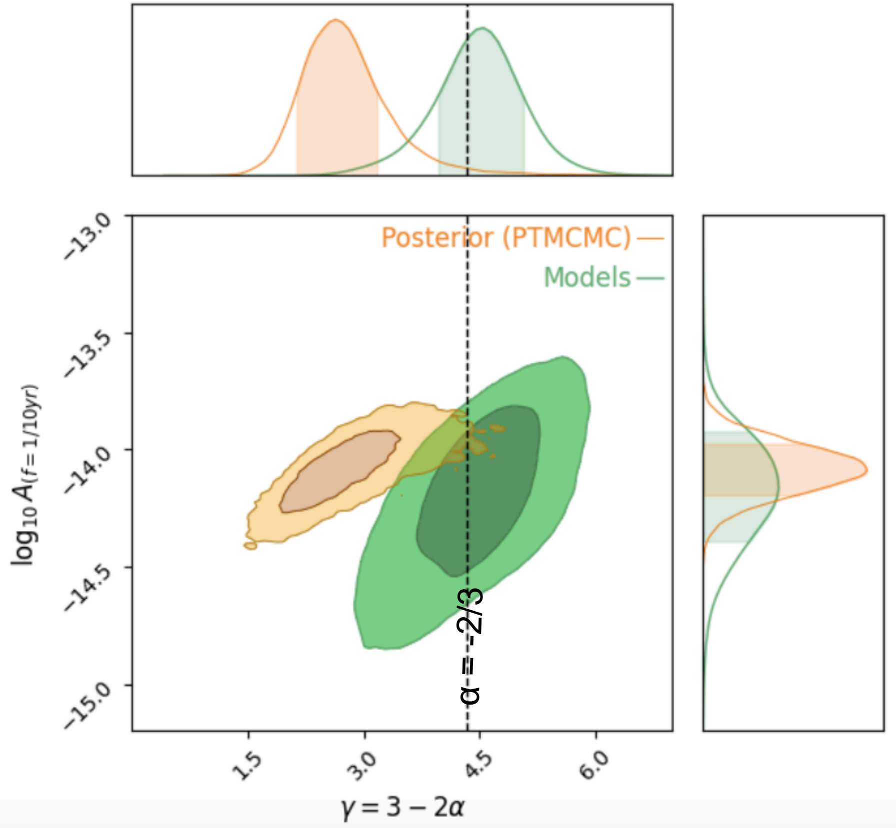
The PTA signal vs SMBHB population models





$$S \propto A^2 f^{-\gamma}$$

Comparing with the predictions of astrophysical models (paper V)

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

The PTA signal vs SMBHB population models

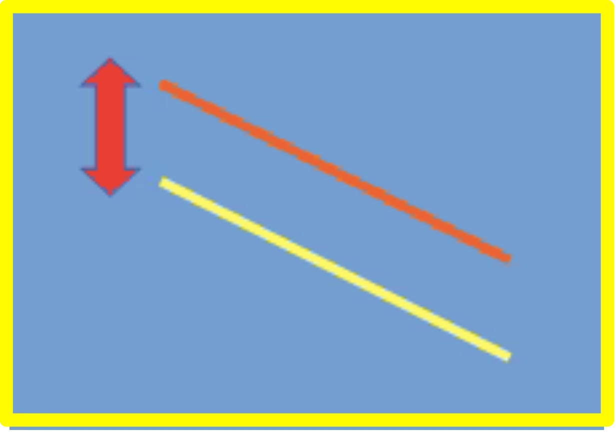
cosmic merger rate

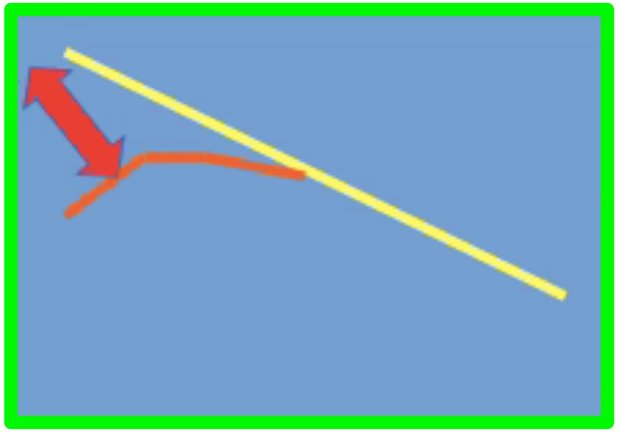
$$h_c^2(f) = \int_0^\infty dz \int_0^\infty dM_1 \int_0^1 dq \frac{d^4N}{dz\,dM_1\,dq\,dt_r} \frac{dt_r}{d\ln f_{\mathrm{K},r}} \times$$

$$h^2(f_{\mathrm{K},r}) \sum_{n=1}^{\infty} \frac{g[n, e(f_{\mathrm{K},r})]}{(n/2)^2} \delta\left[f - \frac{n f_{\mathrm{K},r}}{1+z}\right]$$

harmonics of gravitational wave signal from the various pairs

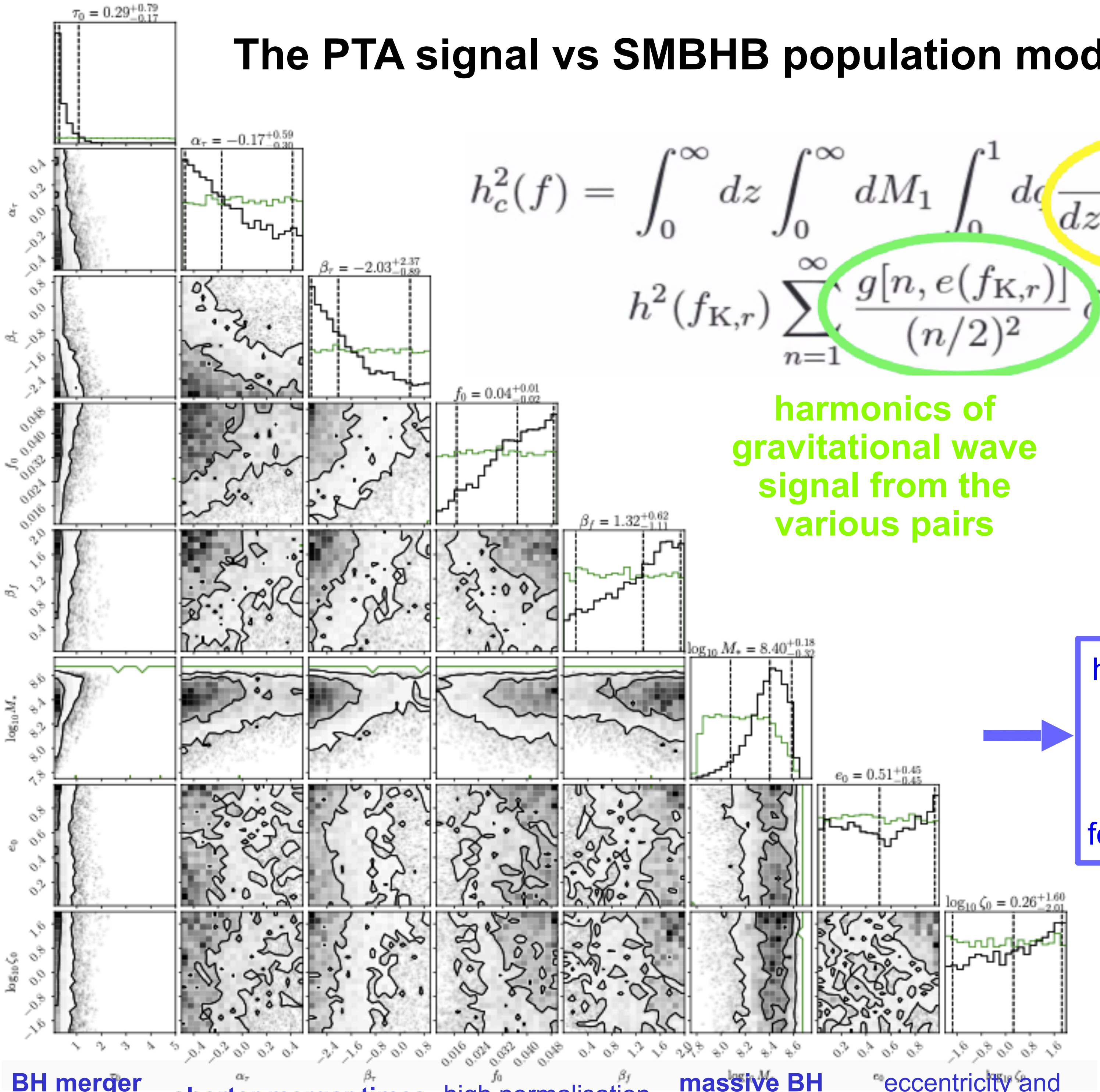
physical processes driving BH pair





Crédit: A.Sesana

The PTA signal vs SMBHB population models



cosmic merger rate

$$h_c^2(f) = \int_0^\infty dz \int_0^\infty dM_1 \int_0^1 dq \frac{d^4N}{dz\,dM_1\,dq\,dt_r} \frac{dt_r}{d\ln f_{\mathrm{K},r}} \times$$

$$h^2(f_{\mathrm{K},r}) \sum_{n=1}^{\infty} \frac{g[n, e(f_{\mathrm{K},r})]}{(n/2)^2} \delta\left[f - \frac{n f_{\mathrm{K},r}}{1+z}\right]$$

physical processes driving BH pair

harmonics of gravitational wave signal from the various pairs

high merger rate densities

short merger timescales

high normalization for BH-bulge mass relation

BH merger timescale < 1Gyr

shorter merger times for massive galaxies

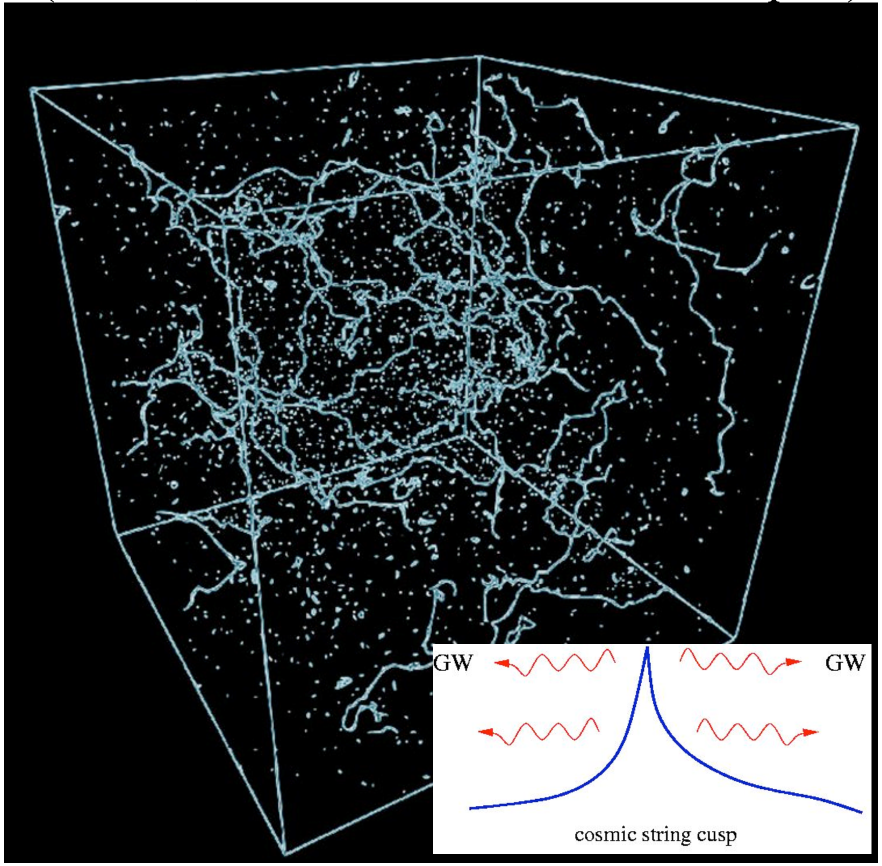
high normalisation of pair fraction

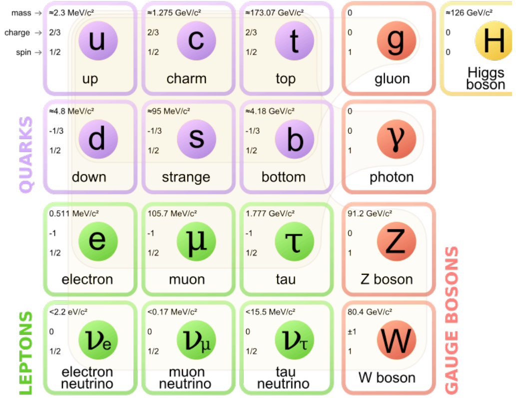
massive BH compared to bulge mass

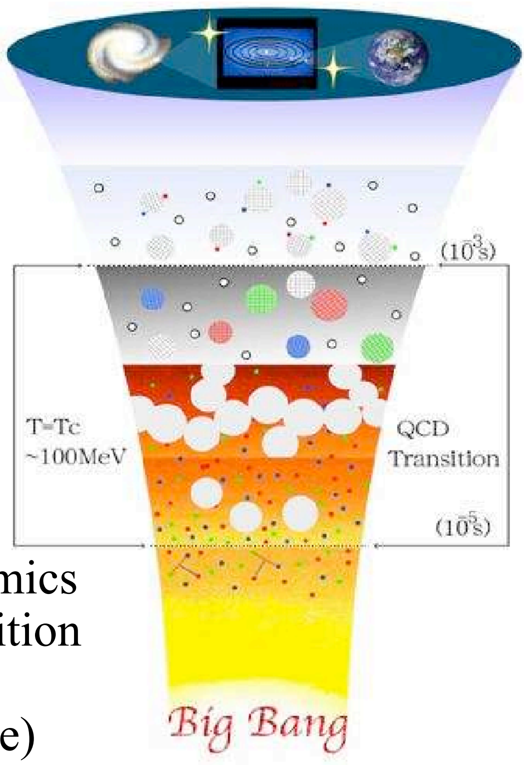
eccentricity and environment effects poorly constrained

But also, some constraints on the cosmology of the primordial Universe

The theory of cosmic strings
(tension, number of « kinks » or « cusps »)

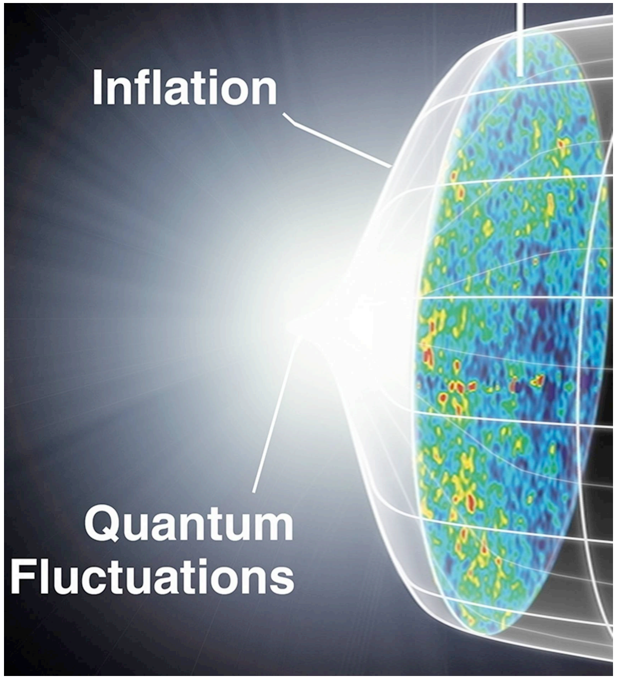




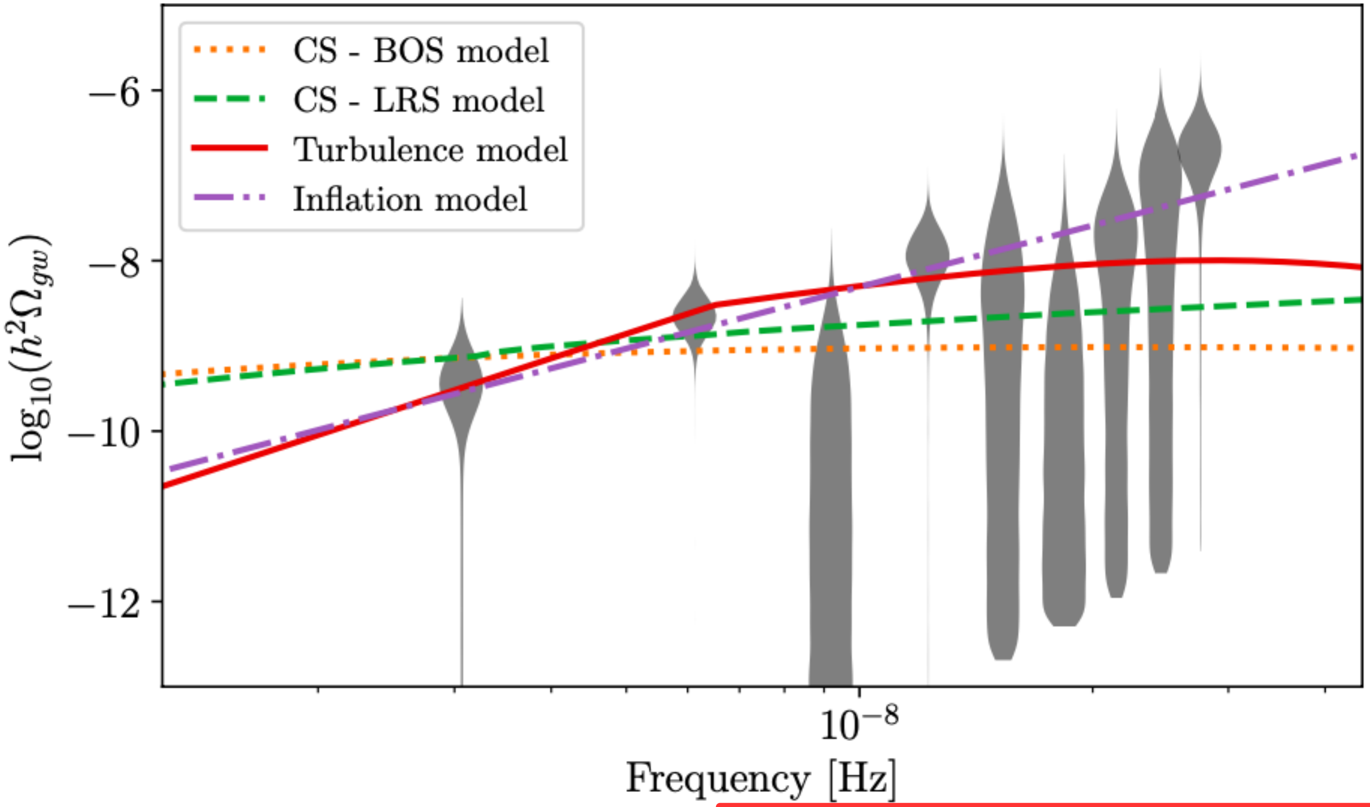


Quantum chromodynamics
= quarks-hadrons transition
(T° scale, size and
strength of turbulence)

The epoch of inflation
(tensor/scalar perturbation ratio,
spectral index of tensor perturbation)



Cosmological models (e.g. from EPTA - paperV)



Cosmic string background :

string tension → $\log_{10} G\mu = -10.1/-10.6$
features → Ncusp = 2 ; Nkinks = 0

GWB produced from vortical (M)HD turbulence around QCD energy scale:

temperature scale T* → 140 MeV
turbulence strenght Ω* → 0.3
turbulence characteristic length scale λ*H* → 1

Inflation model : i.e. tensor quantum fluctuation of metric amplified by accelerated expansion :

tensor/scalar perturbation ratio → $\log_{10} r = -13.1$
spectral index of tensor perturbation → $n_T = 2.4$

see you in a year with full IPTA data combination !

The second data release from the European Pulsar Timing Array

I. The Dataset

II. Customised Pulsar Noise Models for Spatially Correlated Gravitational Waves

III. Search for gravitational wave signals

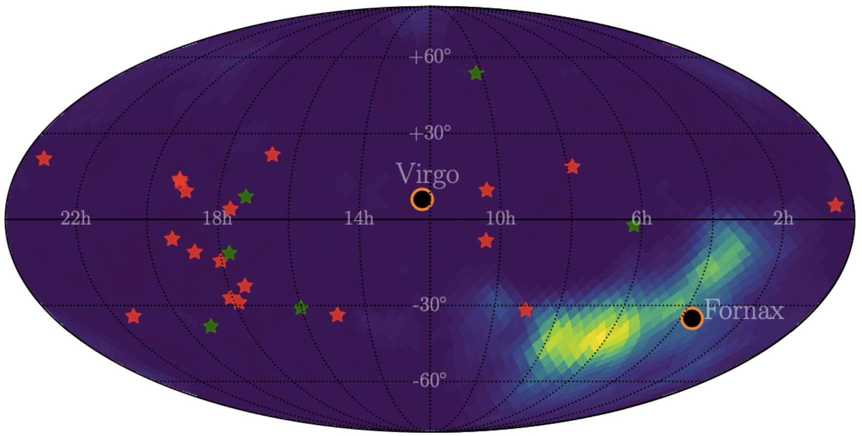
IV. Search for continuous gravitational wave signals

V. Implications for massive black holes, dark matter and the early Universe

VI. Narrowing down the abundance of ultralight scalar-field dark matter

Single continuous source search

A stochatic background
or
a unique source
or
both ?

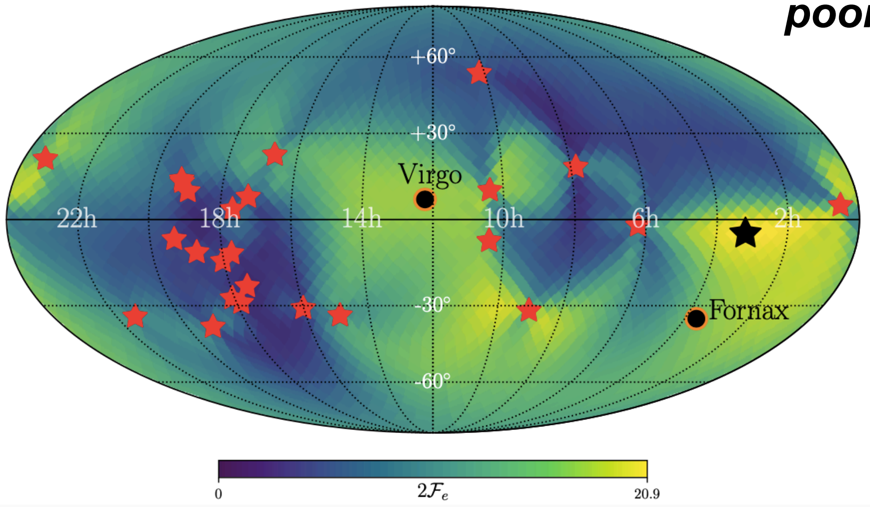


Bayesian

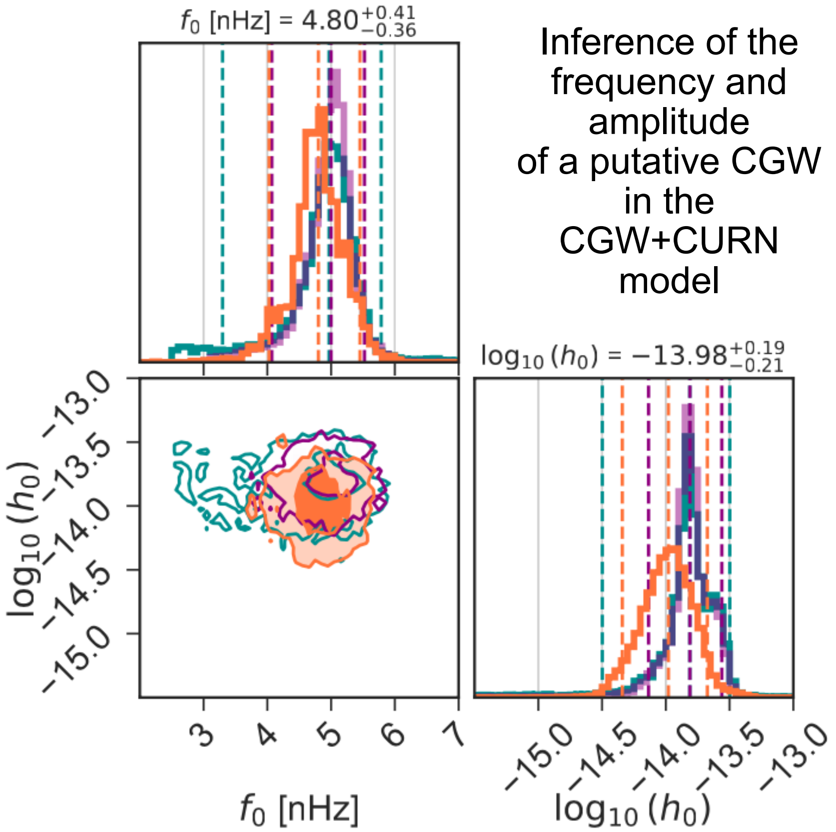
A signal at 4.6 nHz

poor sky position determination

very high Bayes factor

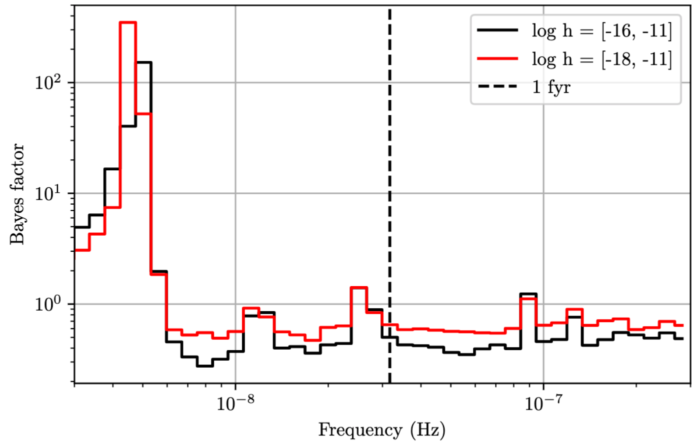


Frequentist



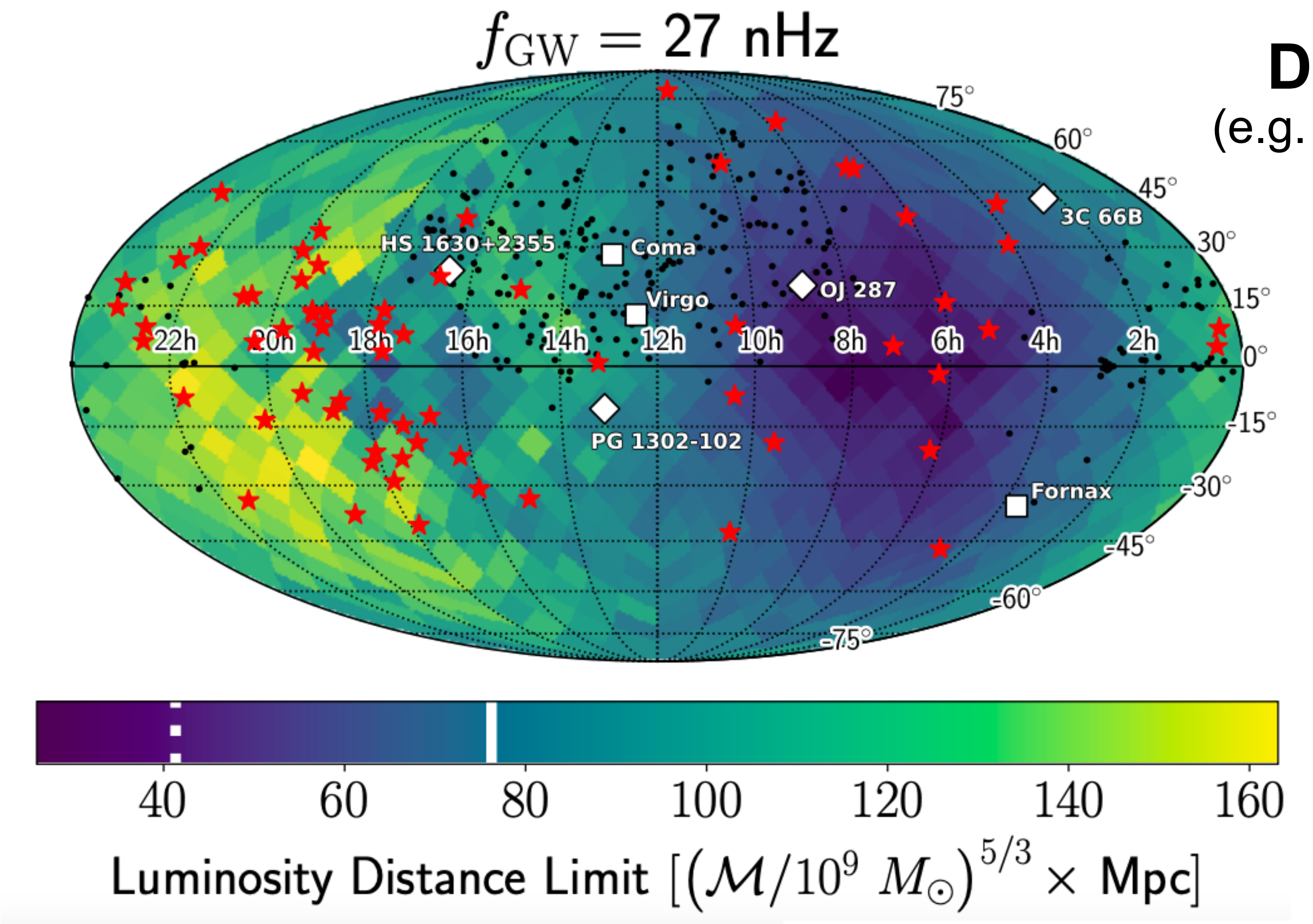
Inference of the frequency and amplitude of a putative CGW in the CGW+CURN model

Bayes Factor spectral distribution

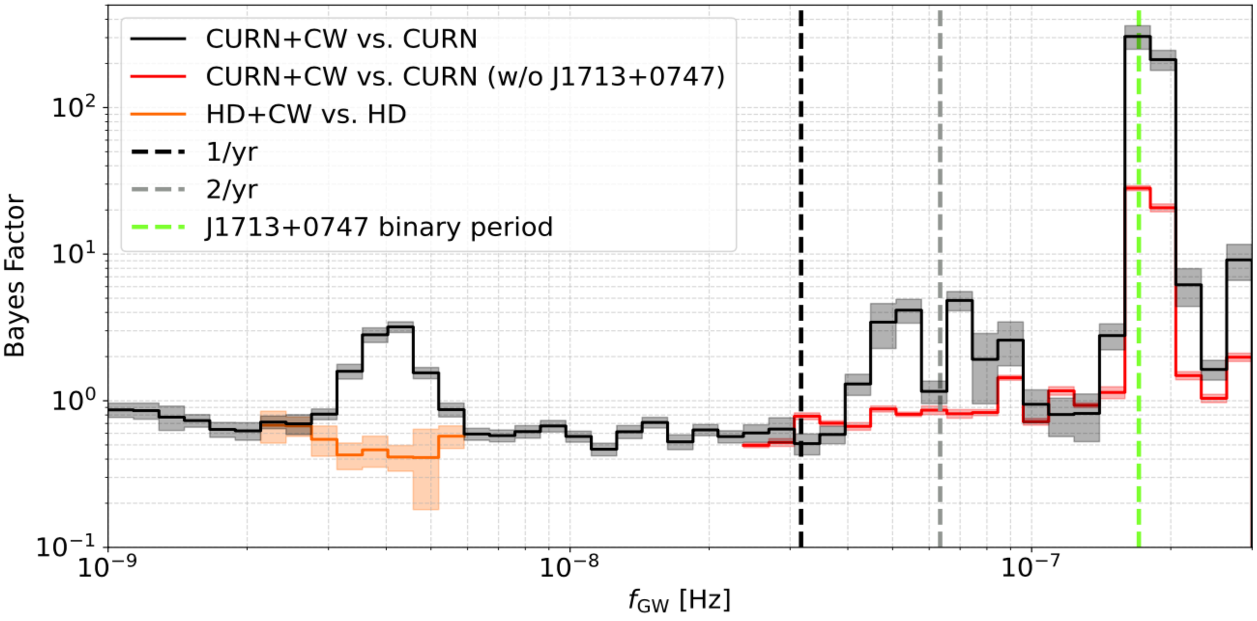


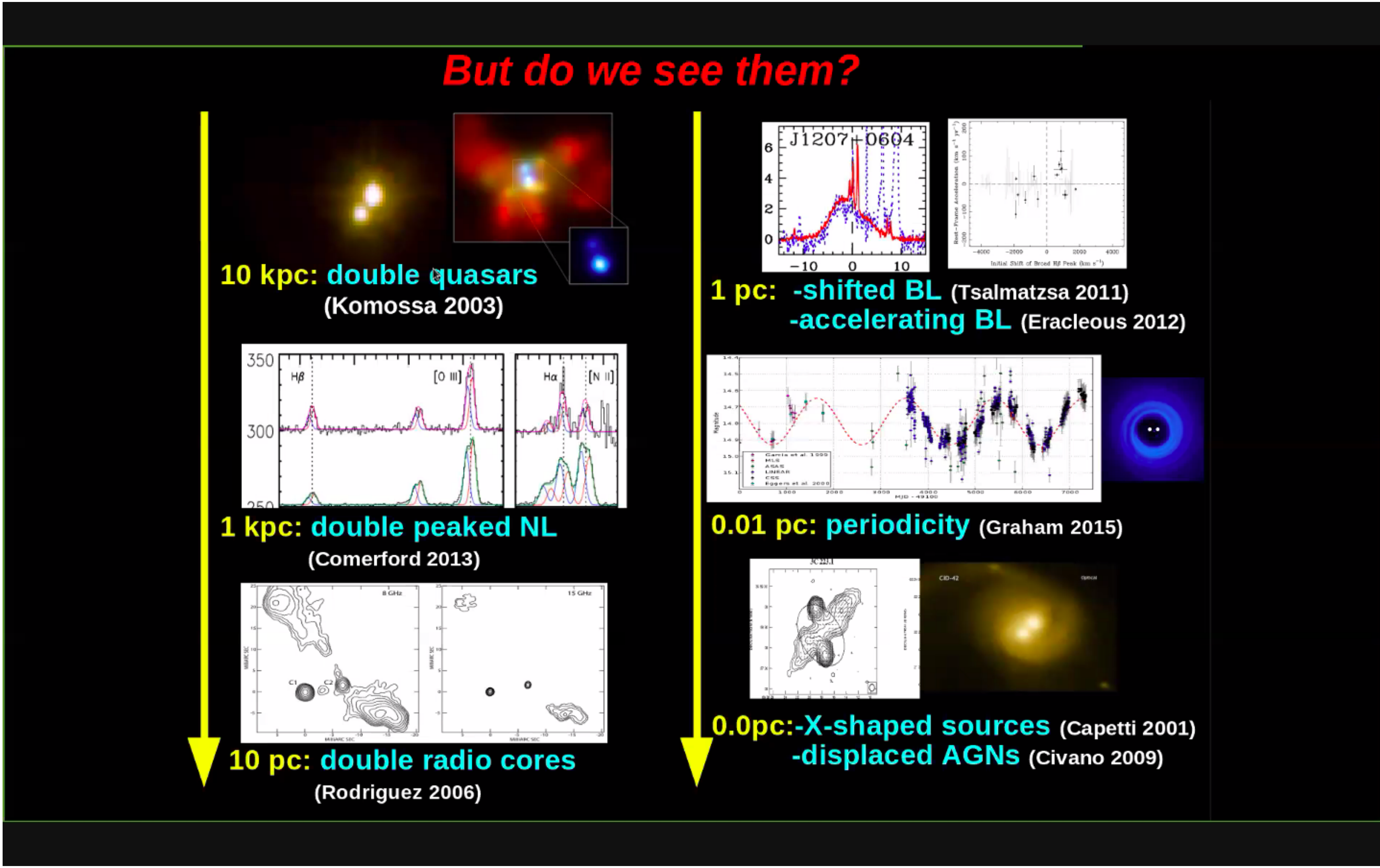
Distance limit skymap

(e.g. NANOGrav, Agazie et al 2023c)



continuous wave search,
single source candidates





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)

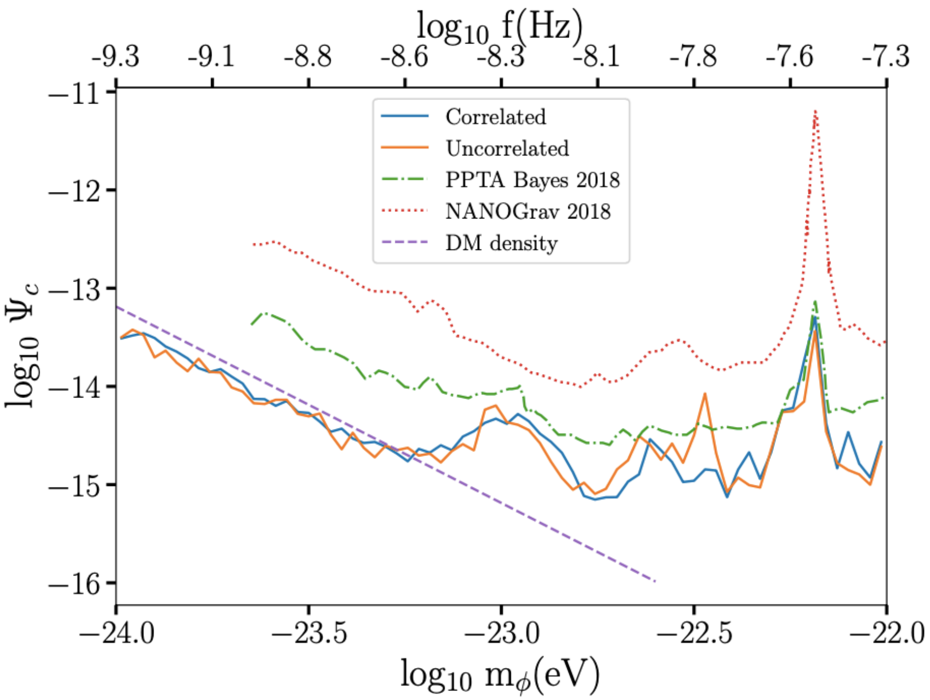
SESANA et al 2021 – GdR Ondes Gravitationnelles

Implications on fuzzy Dark Matter

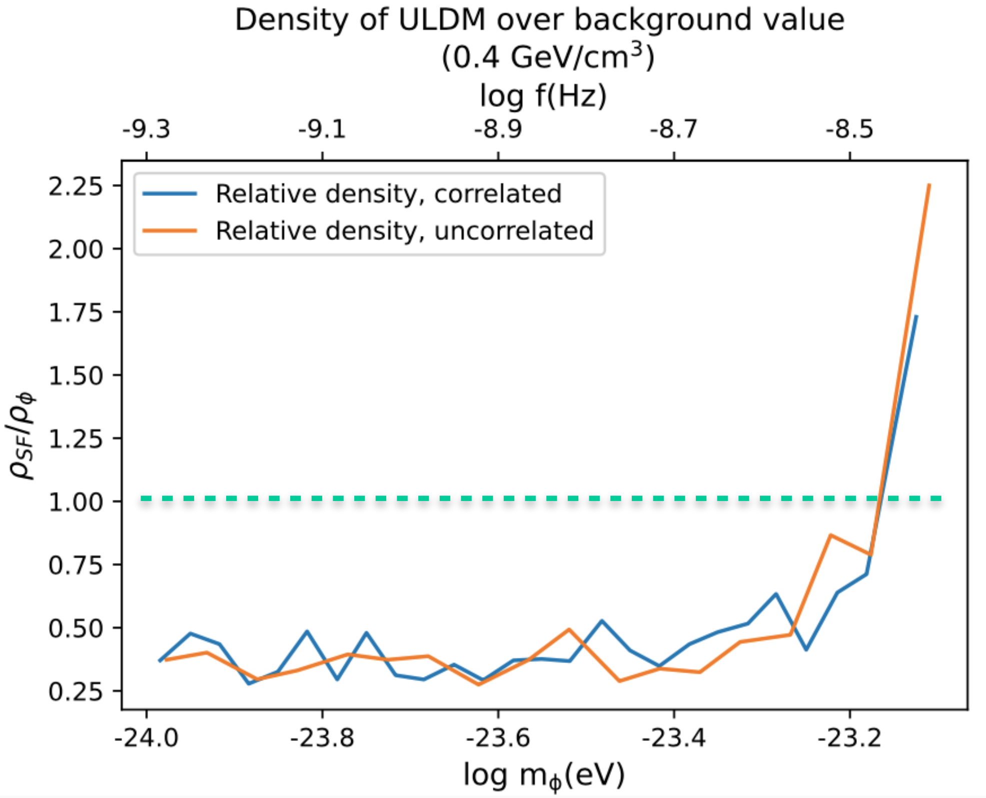
Implications on ultra light (scalar-field) dark matter content (ULDM)

Well known issue with CDM at kpc scales : core-cusp problem

Travel time of pulsar radio beam is affected by the gravitational potential from ULDM
—> periodic oscillations ~ prominent in a single frequency bin (like CGW)



Antoniadis et al 2023e

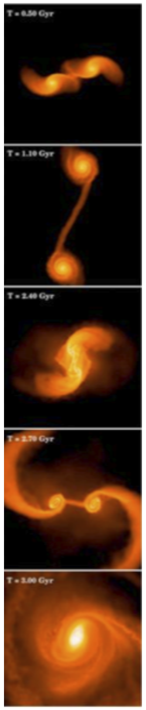

Density of ULDM over background value
(0.4 GeV/cm^3)

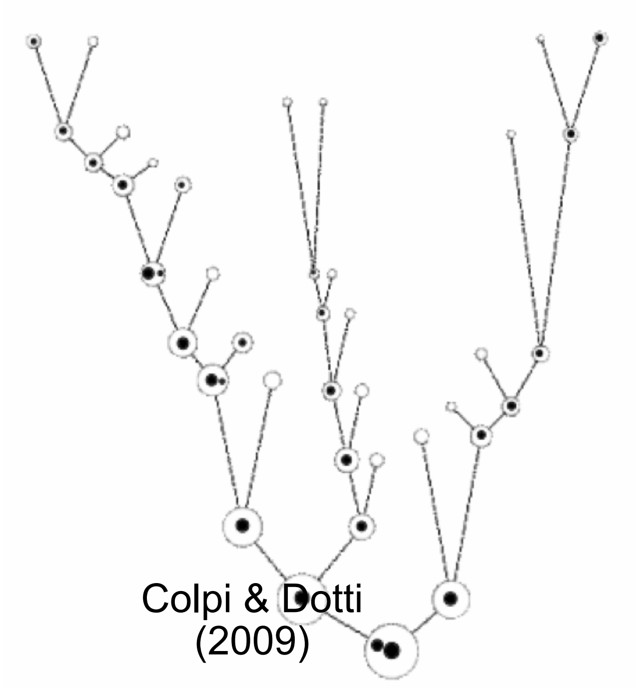
Smarra et al 2023

→ ULDM < 30% of DM in mass range log(m) ~ [-24, -23] (eV)

Last parsec problem,
Environmental effects

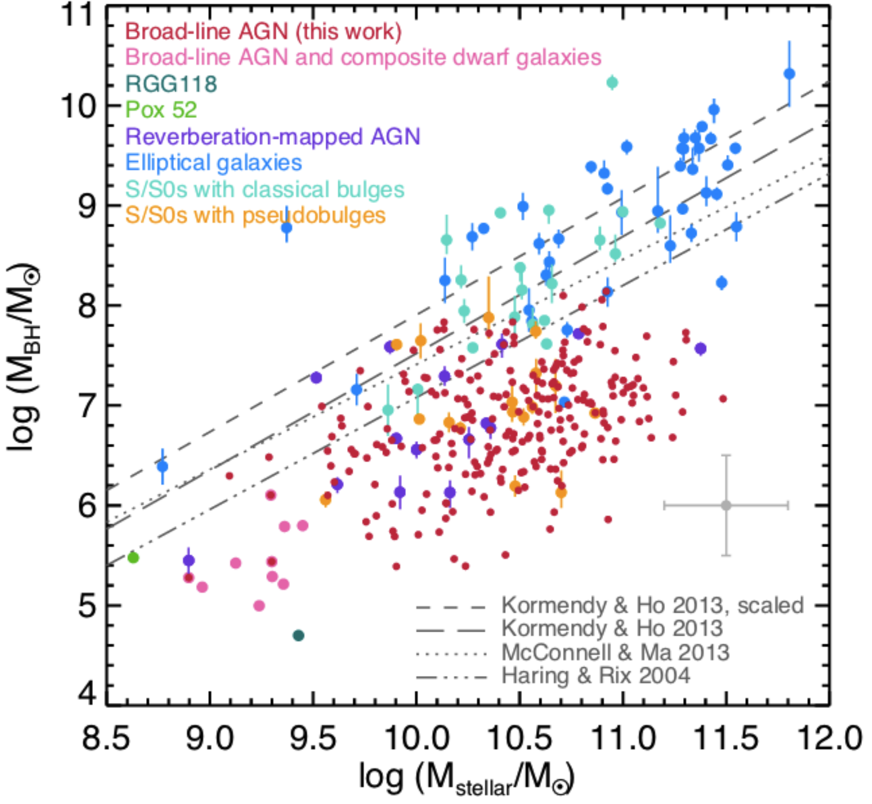
Population synthesis ingredients





Colpi & Dotti (2009)

Reines & Volonteri (2015)



Merger trees from cosmological N-body simulations (Illustris, TNG, EAG

Bulge to BH mass ratio from galaxies dynamical studies

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

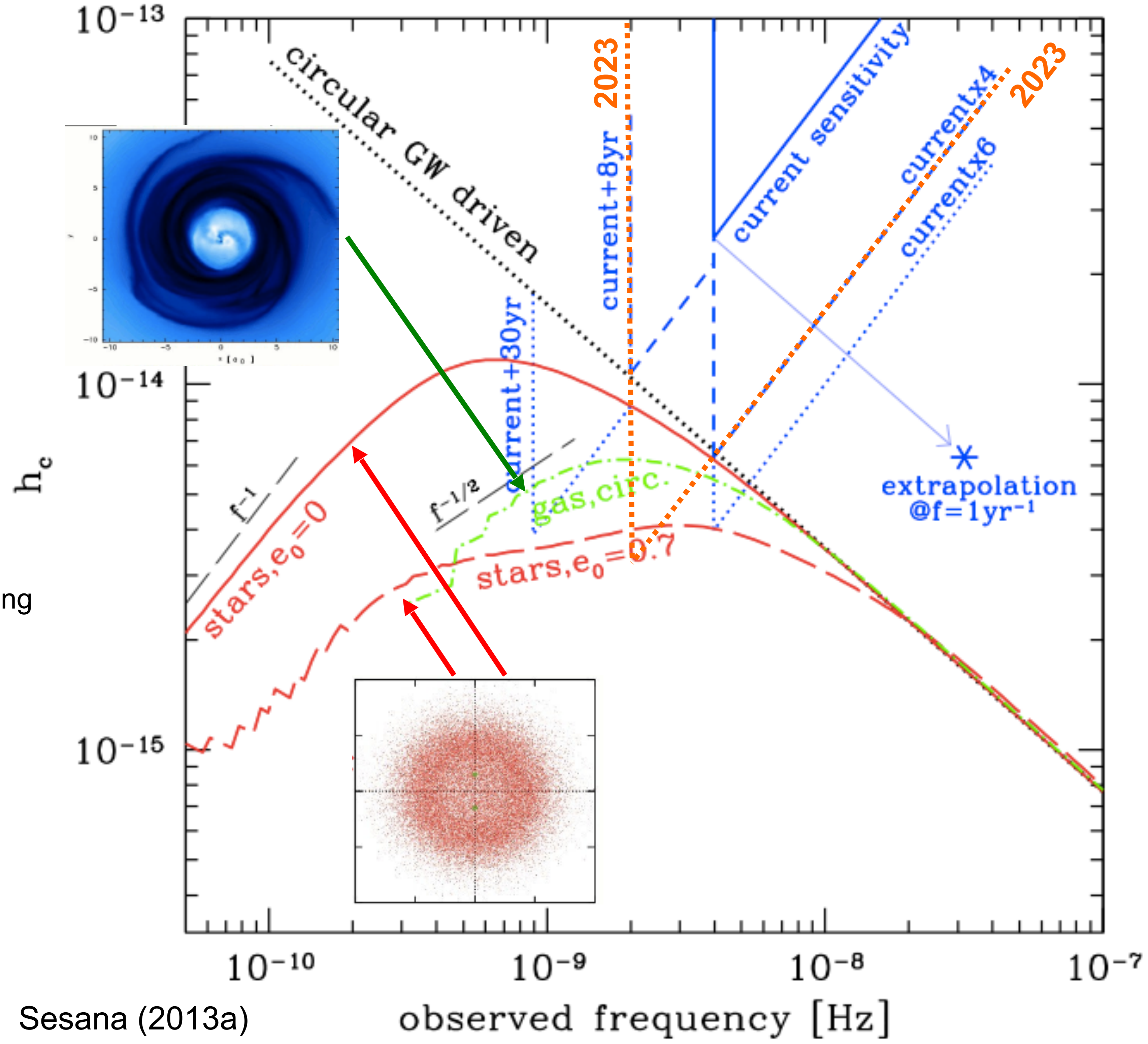
Three body interaction with stars from the loss cone region (when bina

Last parsec problem :
the BH pair empties its environment and stops losing energy.

- 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)

A more realistic scenario :

- + eccentricity
- + interactions with stars and gas
- + spin/orbite coupling



Sesana (2013a)

Timing and noise model

Pulsar Timing Arrays : principles

1) Describe the pulsar rotation in a reference frame co- moving with the pulsar

$$\nu(t) = \nu_0 + \dot{\nu}_0(t - t_0) + \frac{1}{2}\ddot{\nu}_0(t - t_0)^2 + \cdots$$

The observed parameters v and v˙ are associated
with the physical processes causing pulsars to spin down

2) Timing model

$$t_{SSB} = \overbrace{t_{topo} + \underbrace{t_{corr}}_{\text{clock}} - \underbrace{\delta D/f_{obs}^2}_{\text{dispersion}} + \underbrace{\Delta_{R\odot} + \Delta_{\pi} + \Delta_{S\odot} + \Delta_{E\odot}}_{\substack{\text{Solar System} \\ \text{Römer, parallax, Shapiro} \\ \text{and Einstein delays}}} + \underbrace{\Delta_R + \Delta_S + \Delta_E + \Delta_A}_{\substack{\text{binary system} \\ \text{Römer, Shapiro, Einstein} \\ \text{and Aberration delays}}}}^{\boldsymbol{\tau}^{\mathrm{TM}}}$$

3) Full noise model

$$\underset{\textbf{TOA}}{\textbf{observed}} = \underset{\substack{\text{Timing} \\ \text{Model} \\ \text{(deterministic)}}}{\boldsymbol{\tau}^{\mathrm{TM}}} + \overbrace{\underset{\substack{\text{meas.} \\ \text{(white)} \\ \text{noise}}}{\boldsymbol{\tau}^{\mathrm{WN}}} + \underset{\substack{\text{pulsar} \\ \text{spin (red)} \\ \text{noise}}}{\boldsymbol{\tau}^{\mathrm{SN}}} + \underset{\substack{\text{DM} \\ + \\ \text{scatter} \\ \text{(red) noise}}}{\boldsymbol{\tau}^{\mathrm{DM}}} + \underset{\substack{\text{clock} \\ + \\ \text{ephem.} \\ \text{(red) noise}}}{\boldsymbol{\tau}^{\mathrm{CN}}}}^{\text{Noise model}} + \underset{\substack{\text{GWB} \\ \text{(red)} \\ \text{noise}}}{\boldsymbol{\tau}^{\mathrm{GW}}}$$

Analysis of foregrounds: characterisation and separation of the noise components

« White noises » (un-correlated noise)

$$\hat{\sigma}^2 = (\sigma \cdot \mathrm{EFAC})^2 + \mathrm{EQUAD}^2$$

τ^{WN}

Instrumental → telescope gain stability, pass band, backend used

Astrophysical → 'pulse jitter' (pulse stochasticity, variations in pulsar magnetosphere)

« Red noises » (correlated noise)

$$S \propto A^2 f^{-\gamma}$$

τ^{DM} Variations in the Dispersion Measure → changes « e- » content along line of sight (chromatic : multi-frequency measurements)

τ^{Sv} Variations in the scattering → multi-path propagation

τ^{SN} Intrinsic rotation noise → perturbation from small bodies disc ?
Variations in radiated energy ? series of micro-glitches ?

τ^{CN} Clock variations → clock-telescope link → TAI → TT-BIPM

τ^{SSE} Solar System ephemerides → position of SS barycentre → links to INPOP, JPL

Galactic motion of the Sun → LSR

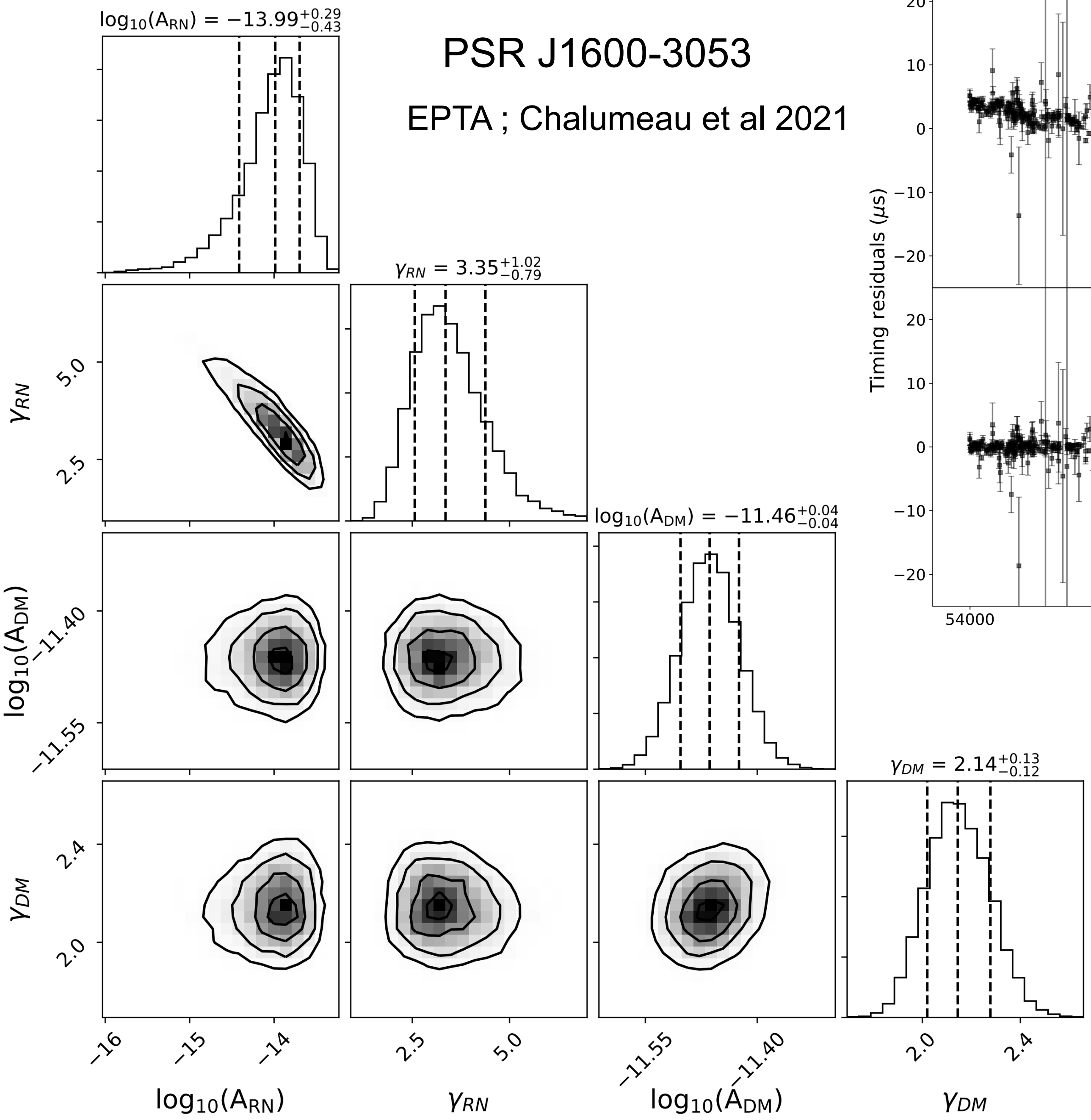
τ^{GW} Gravitational waves → indiv. sources, stochastic background, « bursts » events

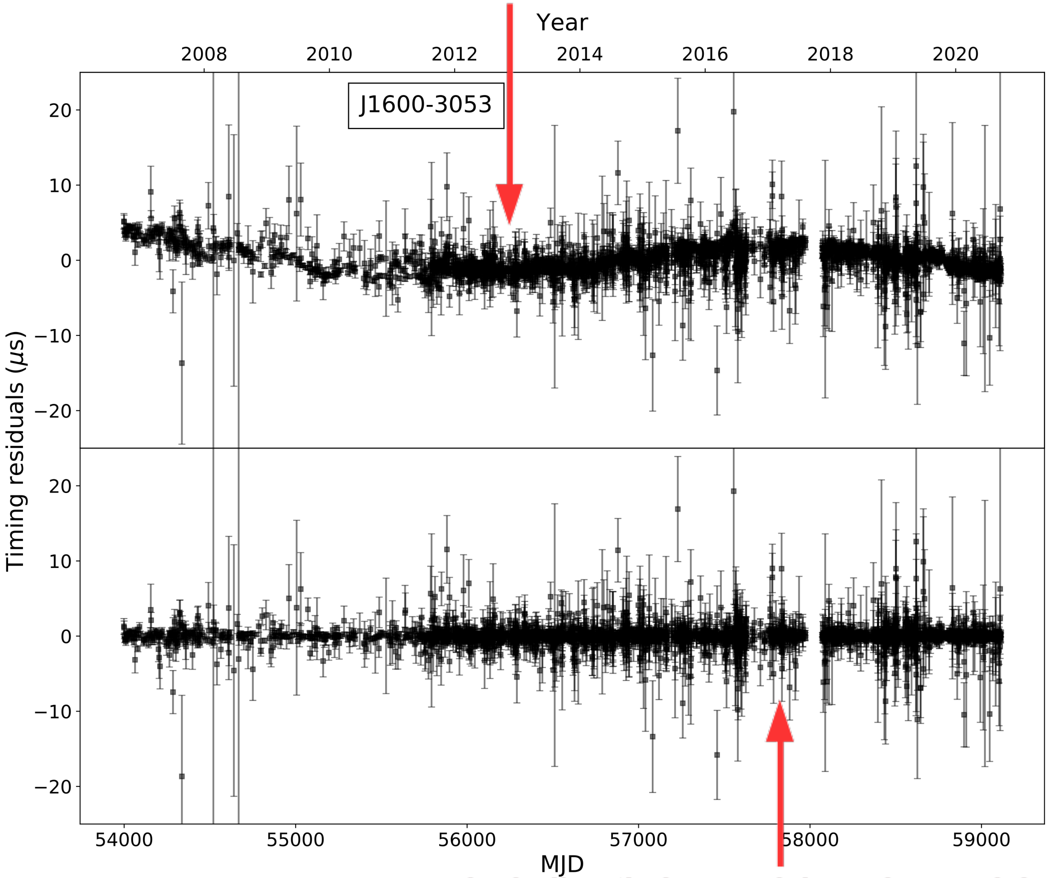
Red noise : individual pulsar models

(paper II)

PSR J1600-3053

EPTA ; Chalumeau et al 2021





including timing model

including timing model + noise model

- **Spin noise**
- **DM chromatic noise**
- Scaterring noise
- Band noise
- System noise

\+

Nb of freq bins
to characterise each

Single pulsar noise analysis

Pulsar Timing Arrays : principles

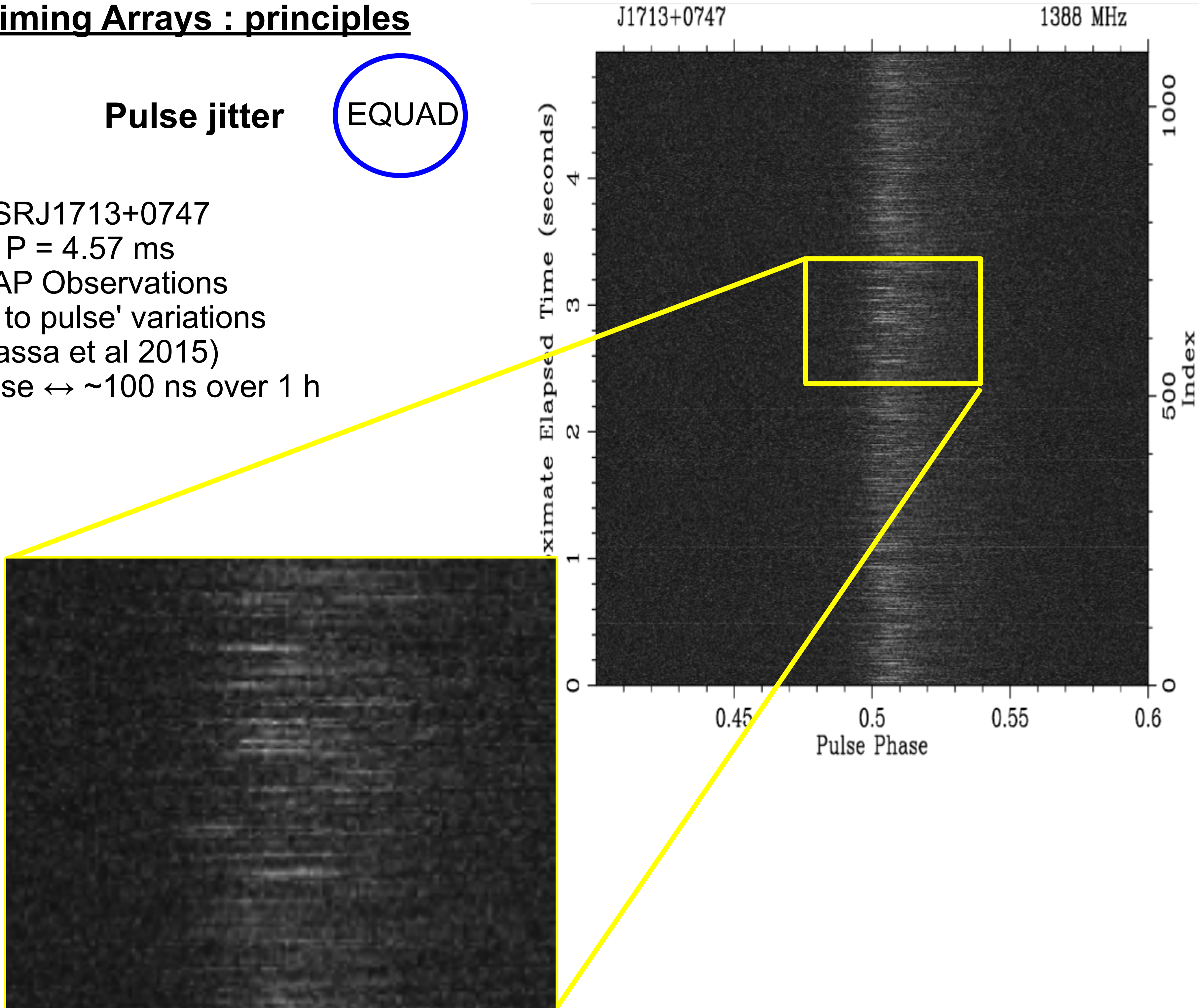
Pulse jitter EQUAD

PSR B1919+21
P = 1.3 s

Pulsar Timing Arrays : principles

Pulse jitter EQUAD

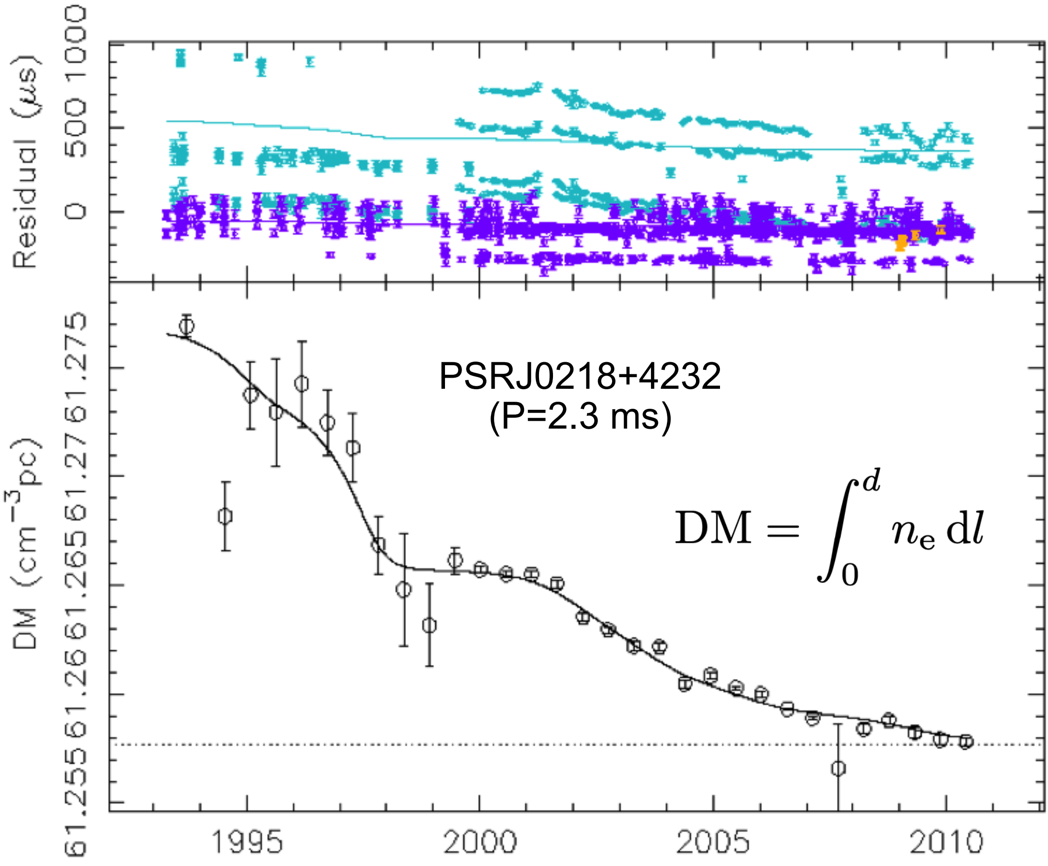
PSRJ1713+0747
P = 4.57 ms
LEAP Observations
'pulse to pulse' variations
(Bassa et al 2015)
1% in phase ↔ ~100 ns over 1 h



Red noise : dispersion noise or chromatic noise

= effects of interstellar medium

requires multi-wavelength observations
e.g. 500 MHz, 1400 MHz, 2.5 GHz



PSRJ0218+4232
(P=2.3 ms)

$$\mathrm{DM} = \int_0^d n_\mathrm{e}\,\mathrm{d}l$$

Janssen 2015

← Secular variation of the Dispersion Measure
(due to relative proper motion)

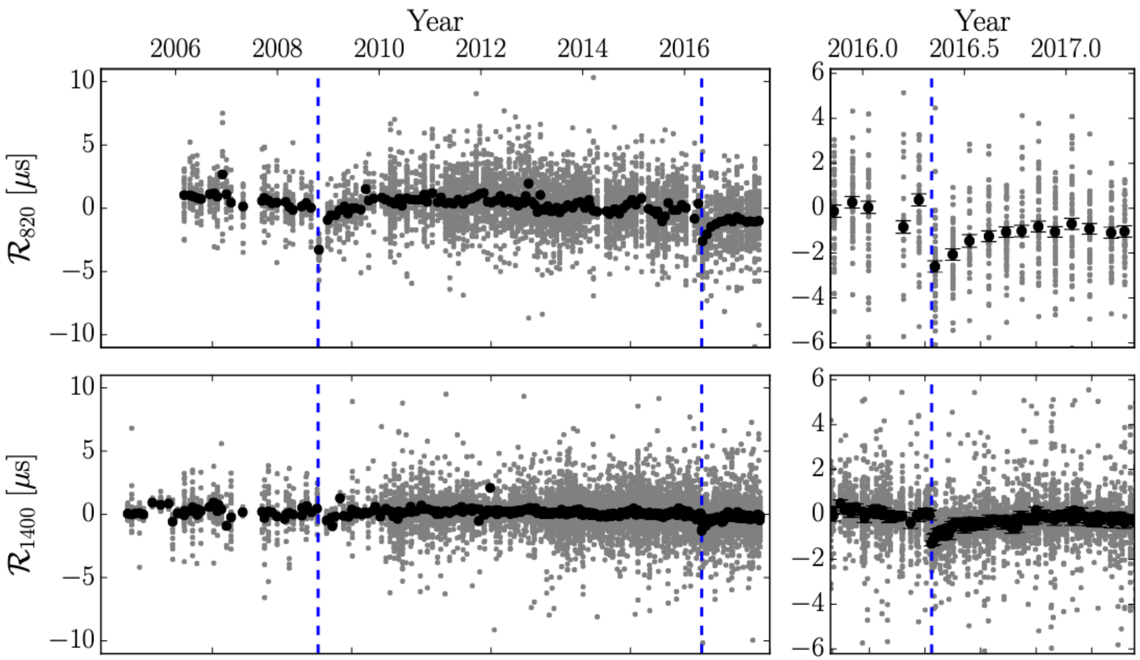
$$\tau^{\mathrm{DM}}$$

Red noise : dispersion noise or chromatic noise

= effects of interstellar medium

requires multi-wavelength observations
e.g. 500 MHz, 1400 MHz, 2.5 GHz

INTERSTELLAR MEDIUM EVENTS IN PSR J1713+0747



Lam et al 2018

DM events:

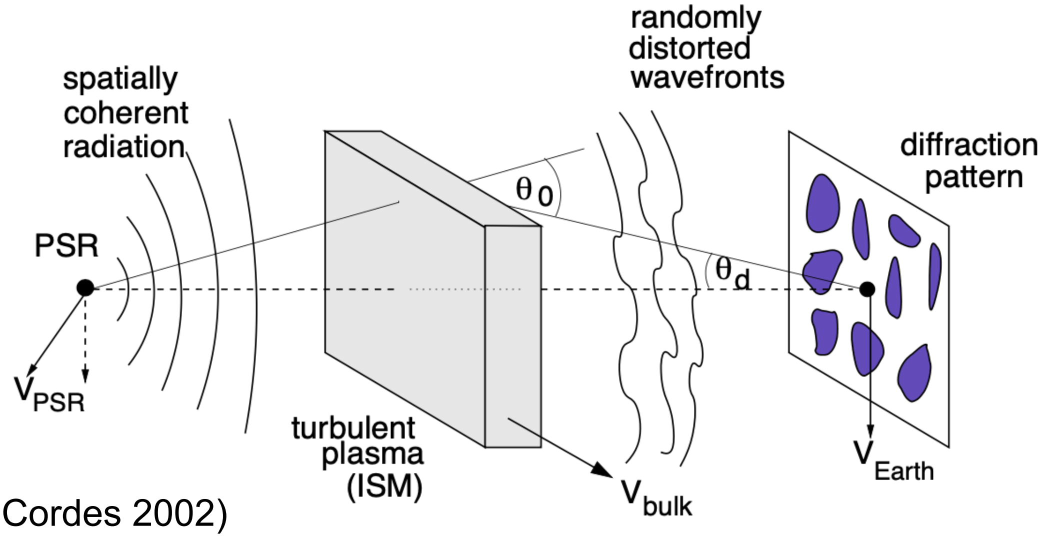
1) lense effect due to a plasma bubble along the line of sight

2) local process in the pulsar magnetosphere (pulse shape change)

Red noise : dispersion noise or chromatic noise

= effects of interstellar medium

requires multi-wavelength observations
e.g. 500 MHz, 1400 MHz, 2.5 GHz

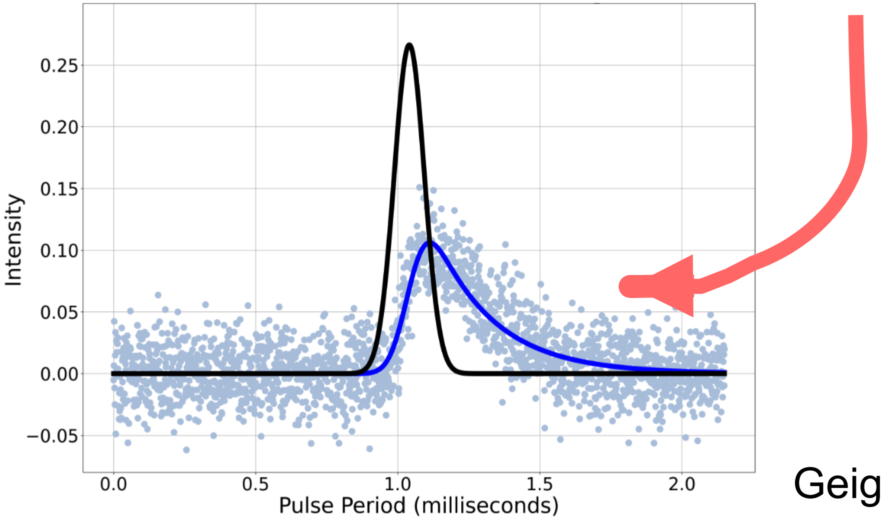


(Cordes 2002)

←

multi-path propagation
through turbulent plasma
+ scattering variations

τ^{Sv}



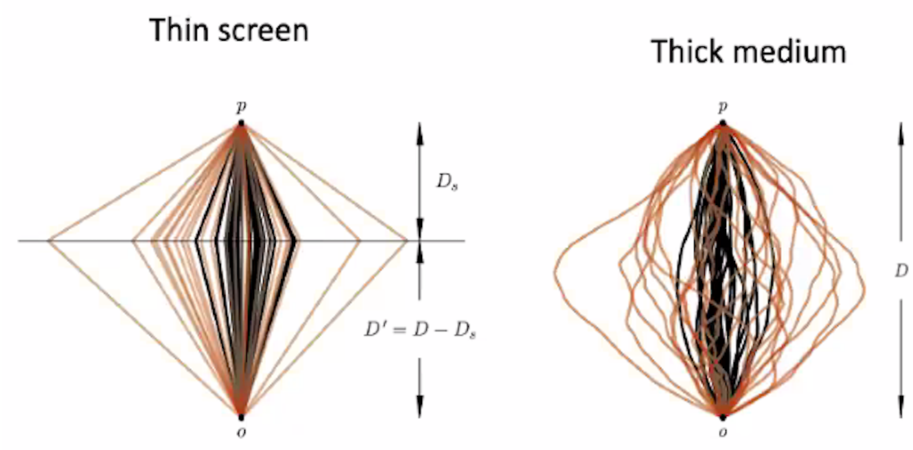
pulse
broadening

Geiger&Lam 2022

Red noise : dispersion noise or chromatic noise

= effects of interstellar medium

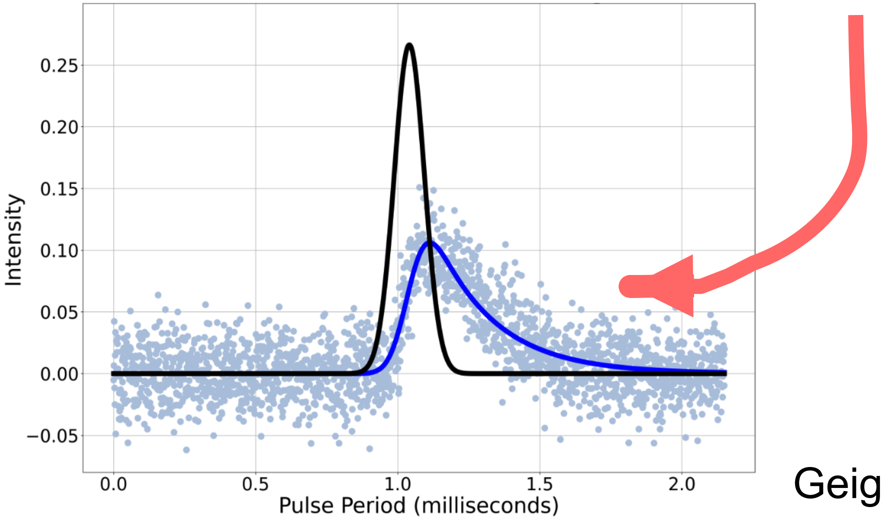
requires multi-wavelength observations
e.g. 500 MHz, 1400 MHz, 2.5 GHz



Cordes, Shannon & Stinebring (2016)
Orange: low frequency
Black: high frequency

multi-path propagation
through turbulent plasma
+ scattering variations

τ^{Sv}

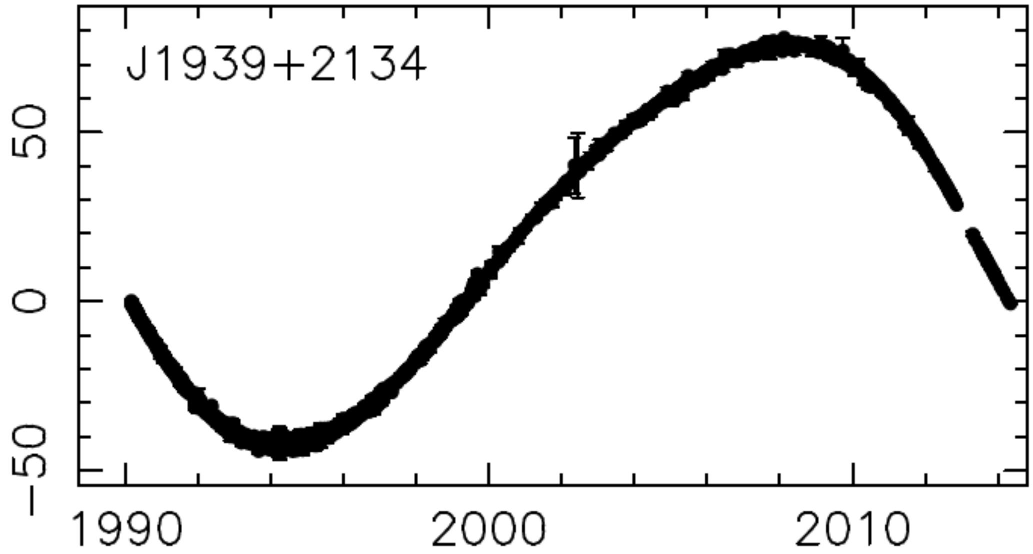


pulse
broadening

Geiger&Lam 2022

Red noise : spin noise

P=1.55 ms   rms ~ 34 .5 µs   <unc.> ~ 60 ns



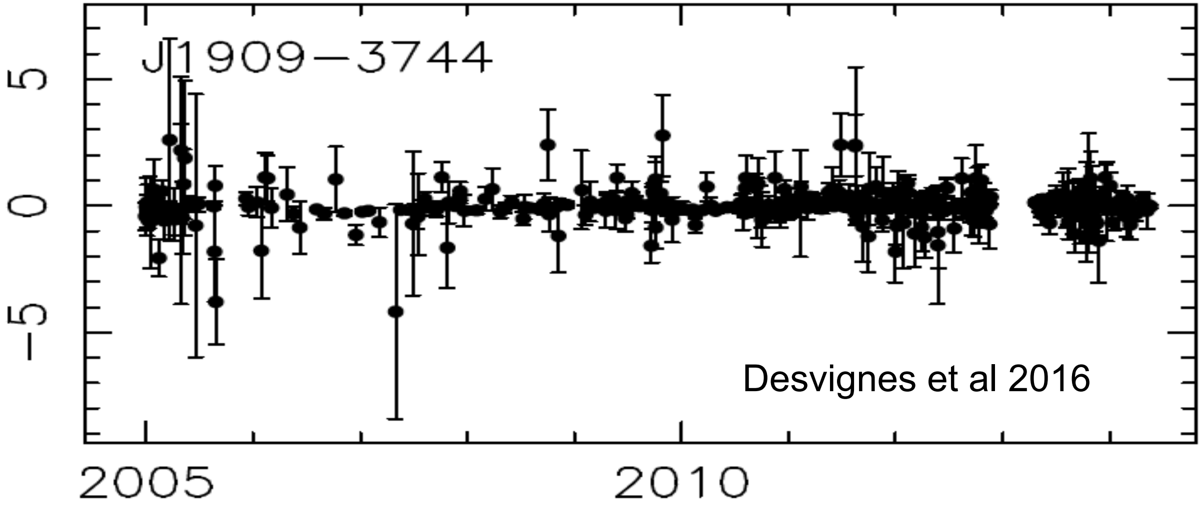
τ^{SN}

P=2.9 ms   rms ~ 0.092 µs   <unc.> ~ 60 ns

Small bodies disc perturbation ?

E_{dot} variations?

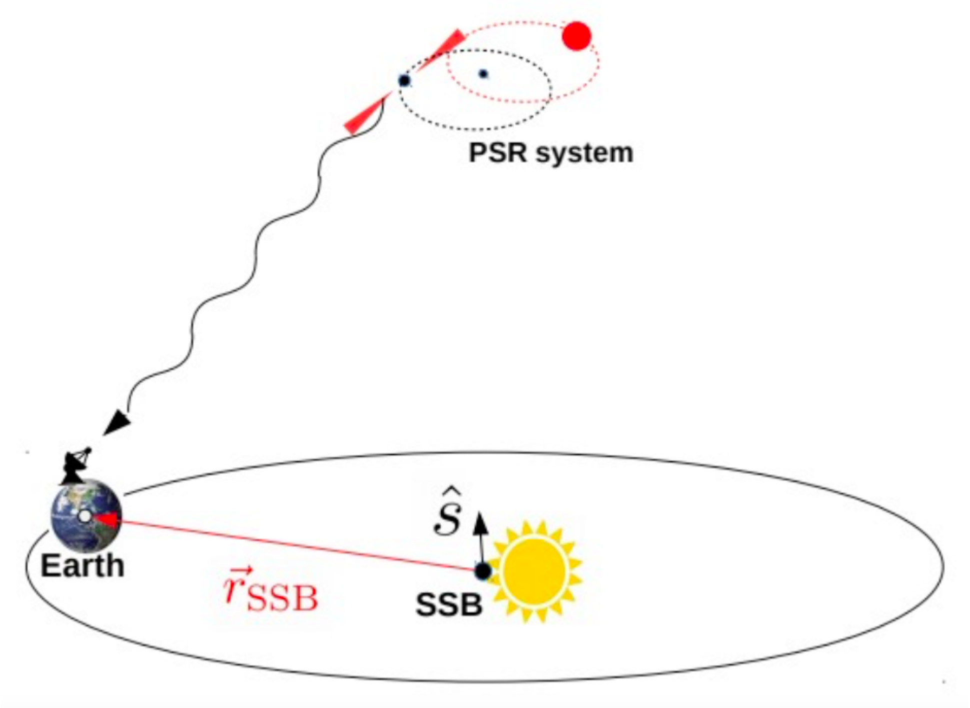
Series of micro-glitches ?



Desvignes et al 2016

Red noise : Impact of planetary ephemerides

τ^{SSE}

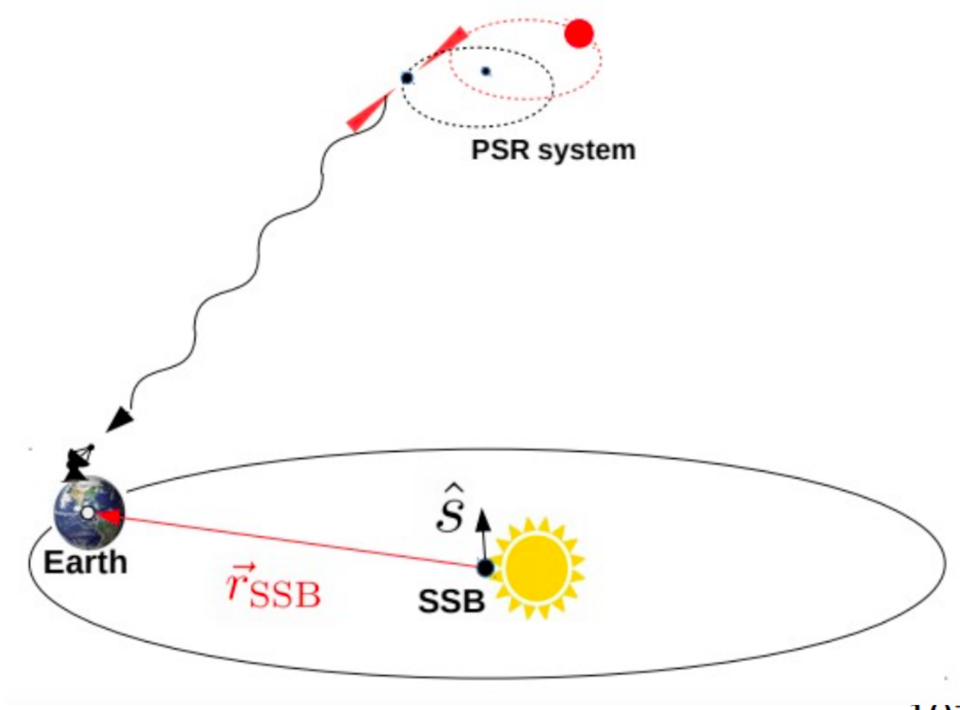


Uncertainties in the Römer delay when transposing to the Solar System barycentre induce a correlated signal with a dipole signature.

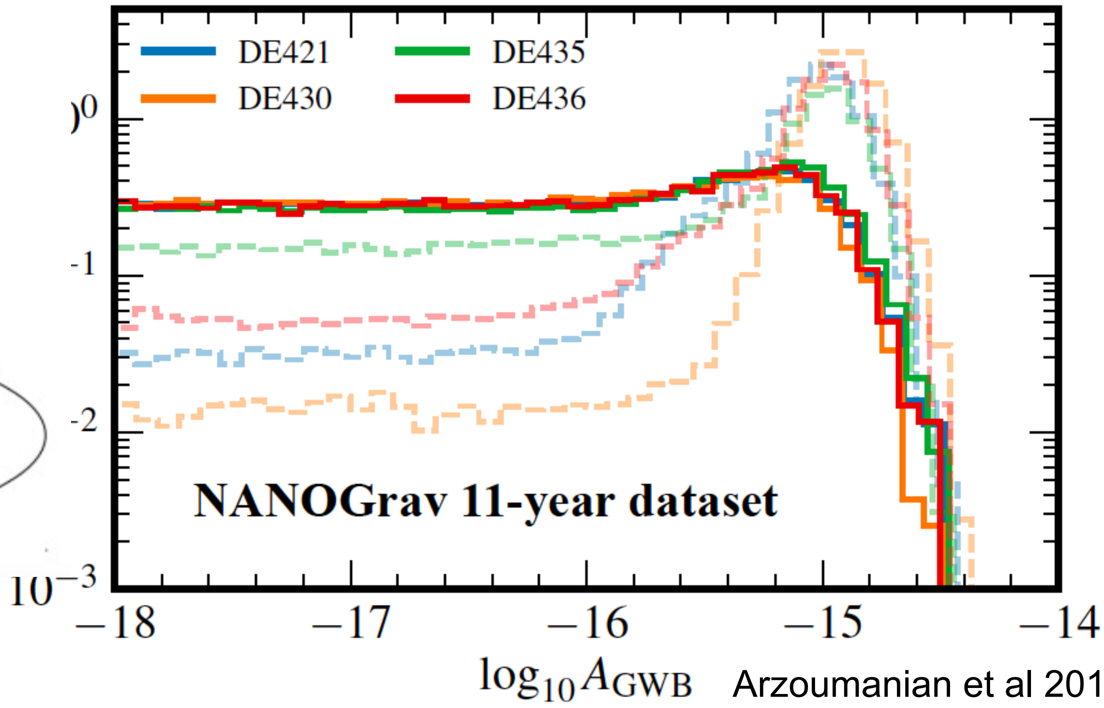
Conversely, we are sensitive to the orbital parameters of the planets!

Red noise : Impact of planetary ephemerides

τ^{SSE}



false detection of a common signal when uncertainties are not taken into account in the model



Arzoumanian et al 2018

Uncertainties in the Römer delay when transposing to the Solar System barycentre induce a correlated signal with a dipole signature.

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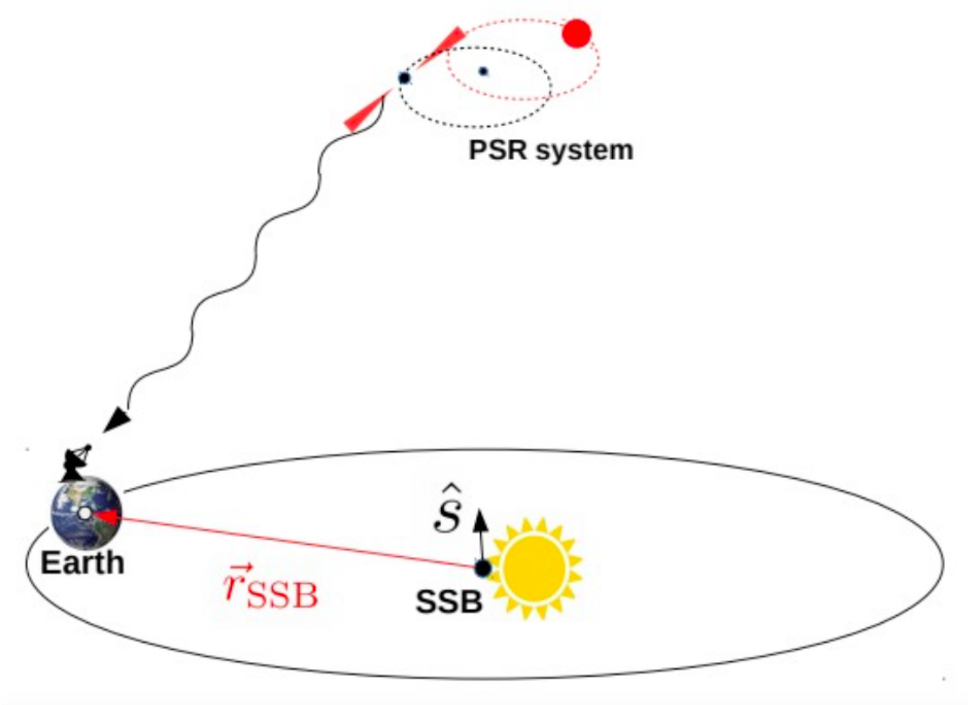
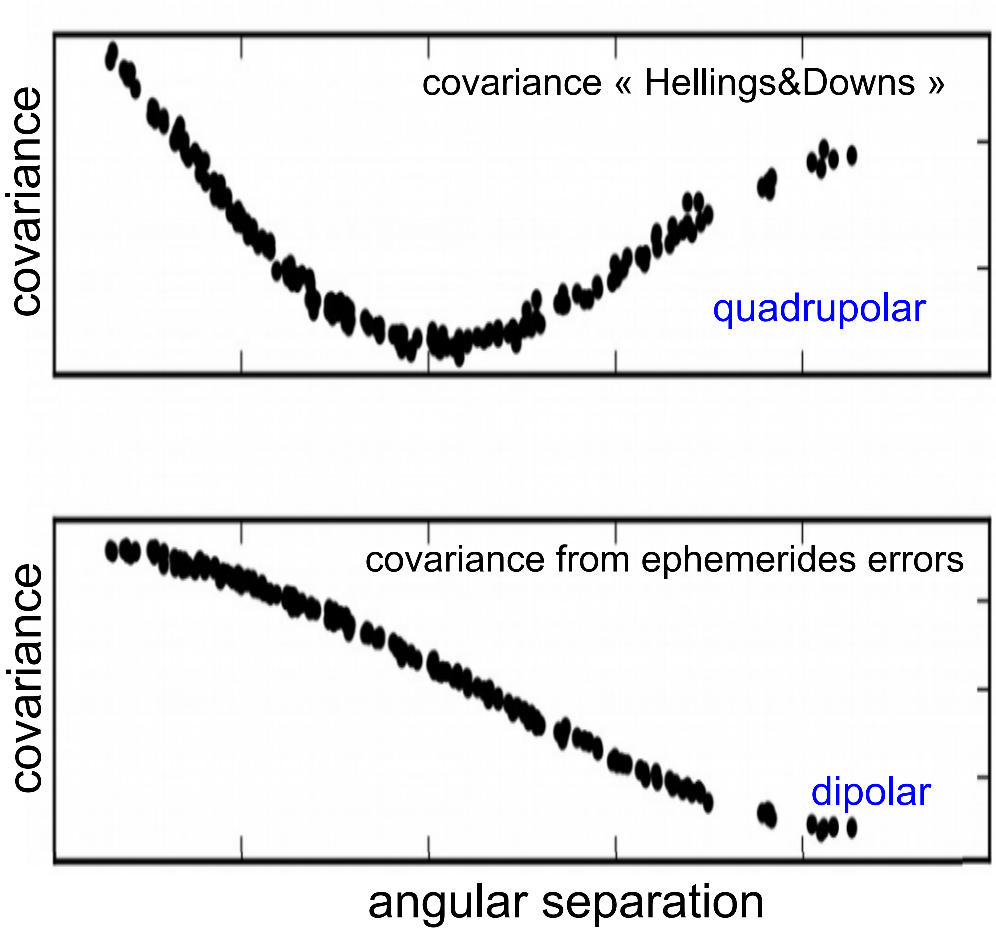
Red noise : Impact of planetary ephemerides

τ^{SSE}





Tiburzi et al 2016

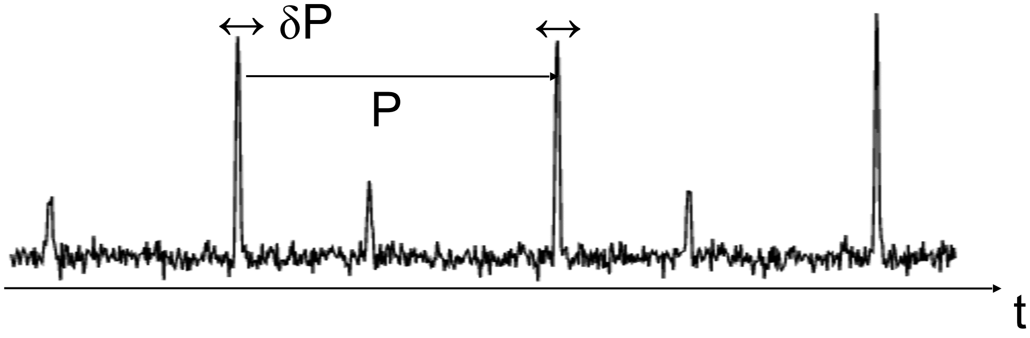
Uncertainties in the Römer delay when transposing to the Solar System barycentre induce a correlated signal with a dipole signature.

Conversely, we are sensitive to the orbital parameters of the planets!

Miscellaneous

Pulsar Timing Arrays : principles

$$r(t) = \int_0^t \frac{\nu(t') - \nu_0}{\nu_0} dt'$$



$$\frac{\nu(t) - \nu_0}{\nu_0} = \frac{1}{2} \frac{\hat{n}^i_\alpha \hat{n}^j_\alpha}{1 + \hat{n}_\alpha \cdot \hat{k}} \Delta h_{ij}$$

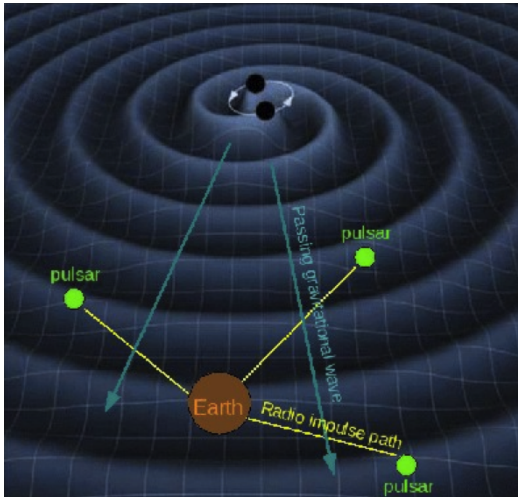
dir pulsar

dir GW source

The Earth and the distant pulsar are considered as free masses whose position responds to changes in the metric of space-time

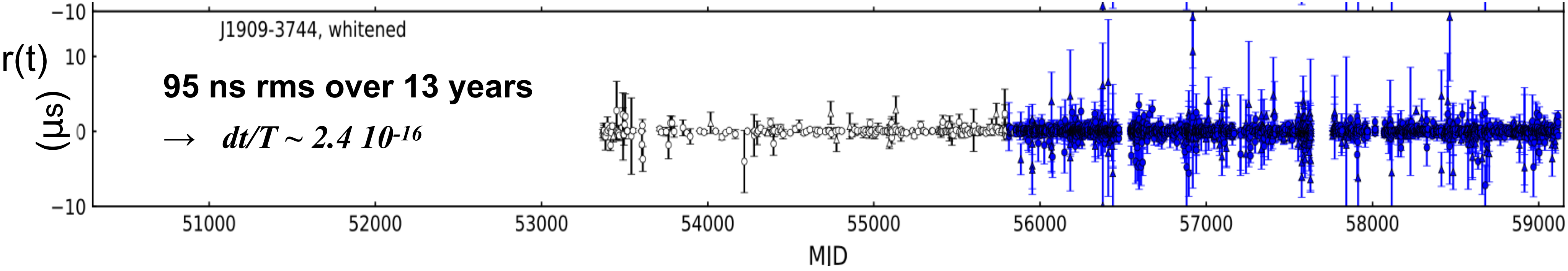
→ *The passage of a gravitational wave disturbs the metric and produces fluctuations in the arrival times of the pulses*

With timing uncertainties dt (~100 ns) and observation time spans T (~25 years)
→ PTA are sensitive to *amplitudes ~ dt/T and to frequencies f ~ 1/T*



Sensitivity ~ 100 10^{-9} / 25 x 3 10^{7} → A ~ 1.3 10^{-16}

Frequency domain (25 years - 1 week) → 10^{-9} – 10^{-6} Hz



95 ns rms over 13 years

→ ***dt/T ~ 2.4 10^{-16}***

Pulsar Timing Arrays : principles

we write the PTA likelihood as

$$p(\boldsymbol{\delta t}|\boldsymbol{\eta}) = \frac{\exp\left(-\frac{1}{2}\boldsymbol{\delta t}^T C^{-1}\boldsymbol{\delta t}\right)}{\sqrt{\det(2\pi C)}}$$

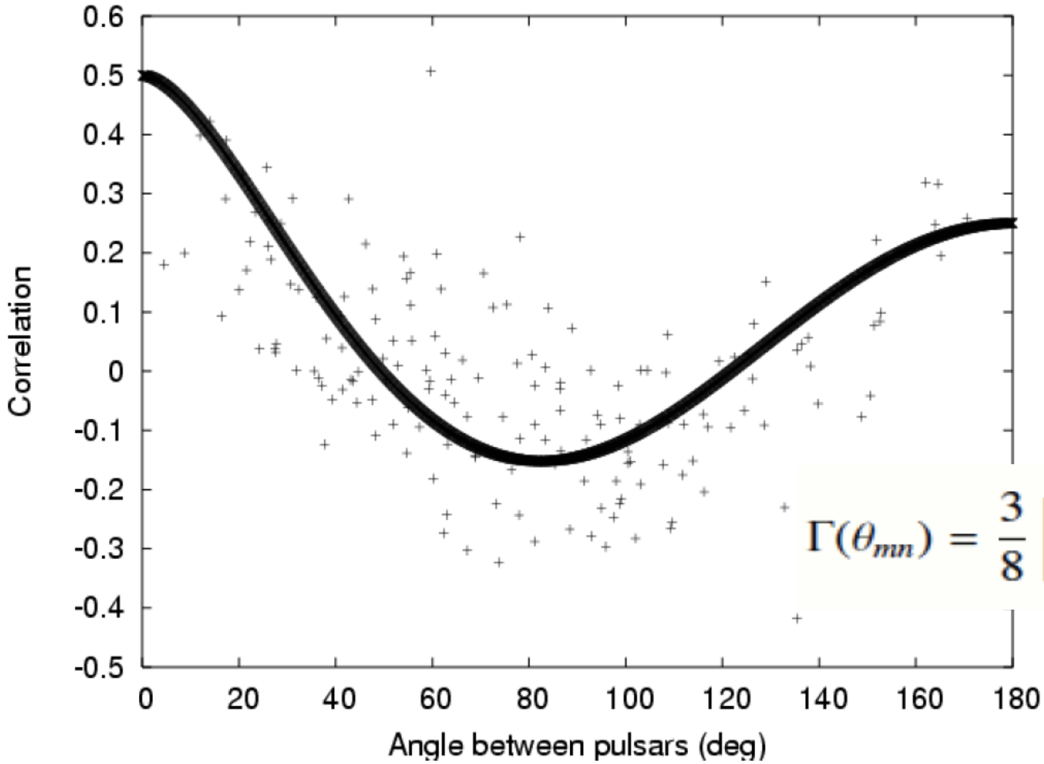
The covariance matrix is decomposed into a sum of « noises » whose spectrum is described by a power law

$$C \sim \underbrace{\Gamma_{ab}\rho_i\delta_{ij}}_{\text{GW}}+\underbrace{\epsilon_i\delta_{ij}}_{\text{clock/eph.}}+\underbrace{\eta_i\delta_{ab}\delta_{ij}}_{\text{astro}\phi}+\underbrace{\kappa_{ai}\delta_{ab}\delta_{ij}}_{\text{indiv. rot./disp.}}$$

the covariance matrix C depends both on the amplitude of the signal as a function of its sky position and on the «antenna pattern »

$$\boxed{\Gamma_{ab} = \frac{3}{8\pi}(1+\delta_{ab})\int_{S^2} d\hat{\Omega}\; P(\hat{\Omega})\sum_q F_a^q(\hat{\Omega})F_b^q(\hat{\Omega})}$$

→ **Earth term: the stochastic signal is spatially correlated between all pulsars as a function of their angular separation**

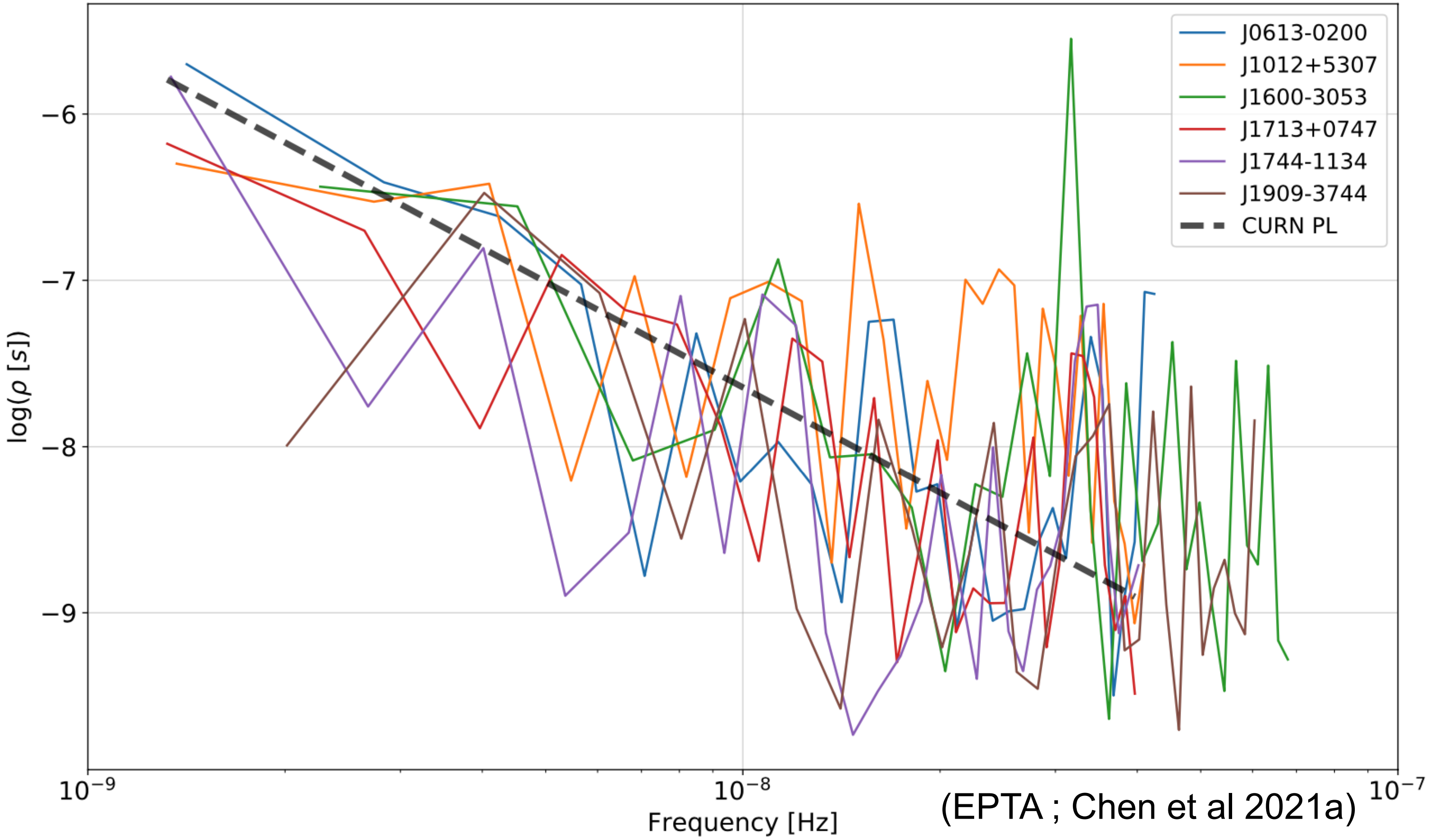


Cf Hellings & Downs 1983

solution for an isototropic background :

$$\Gamma(\theta_{mn}) = \frac{3}{8}\left[1+\frac{\cos\theta_{mn}}{3}+4(1-\cos\theta_{mn})\ln\left(\sin\frac{\theta_{mn}}{2}\right)\right](1+\delta_{mn}$$

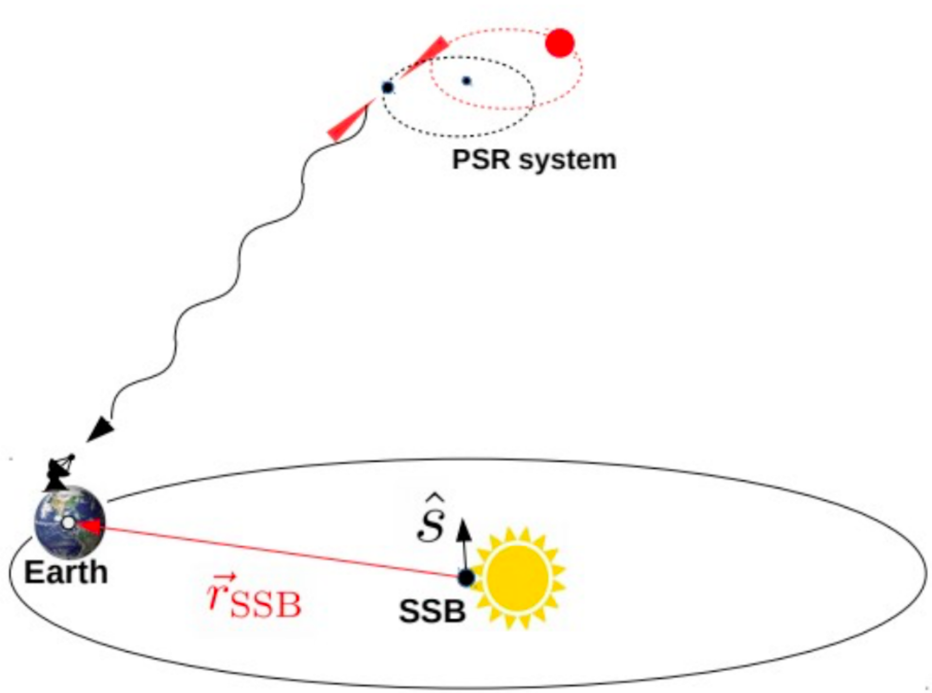
Red noise : individual pulsar models



(EPTA ; Chen et al 2021a)

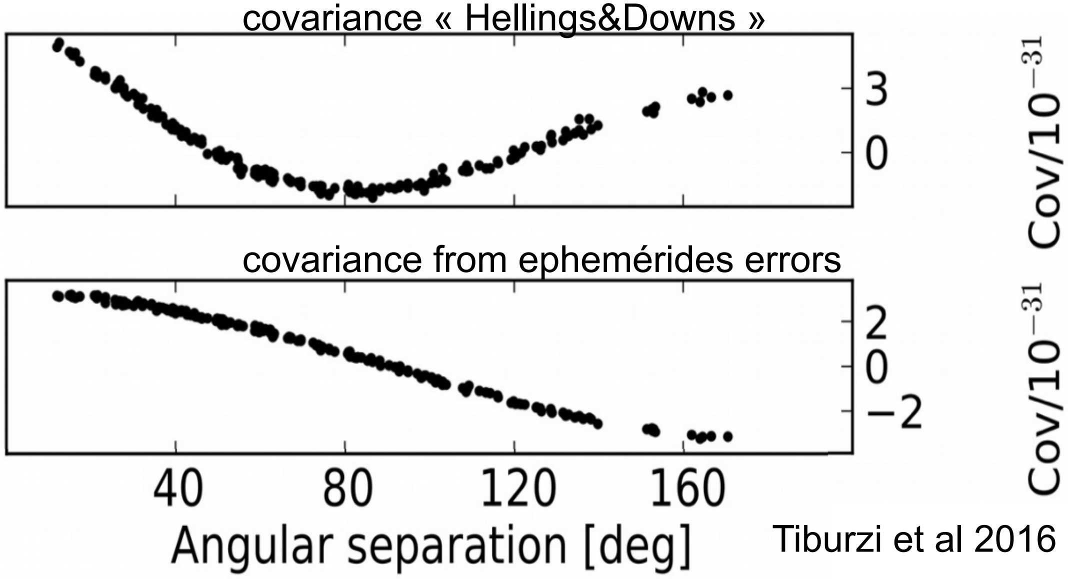
Compaparing **individual pulsar noise** models to inferred **Common Uncorrelated Red Noise**

Impact of planetary ephemerides



Uncertainties in the Römer delay when transposing to the Solar System barycentre induce a correlated signal with a dipole signature.

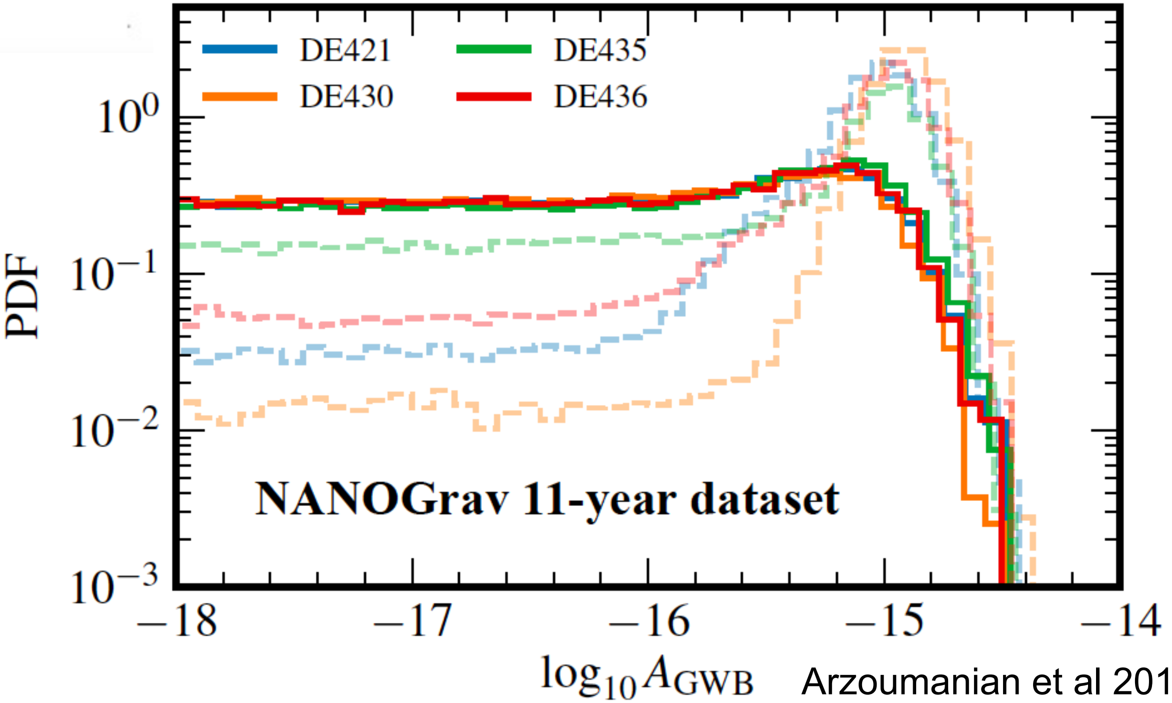
Conversely, we are sensitive to the orbital parameters of the planets!


covariance « Hellings&Downs »

covariance from ephemérides errors

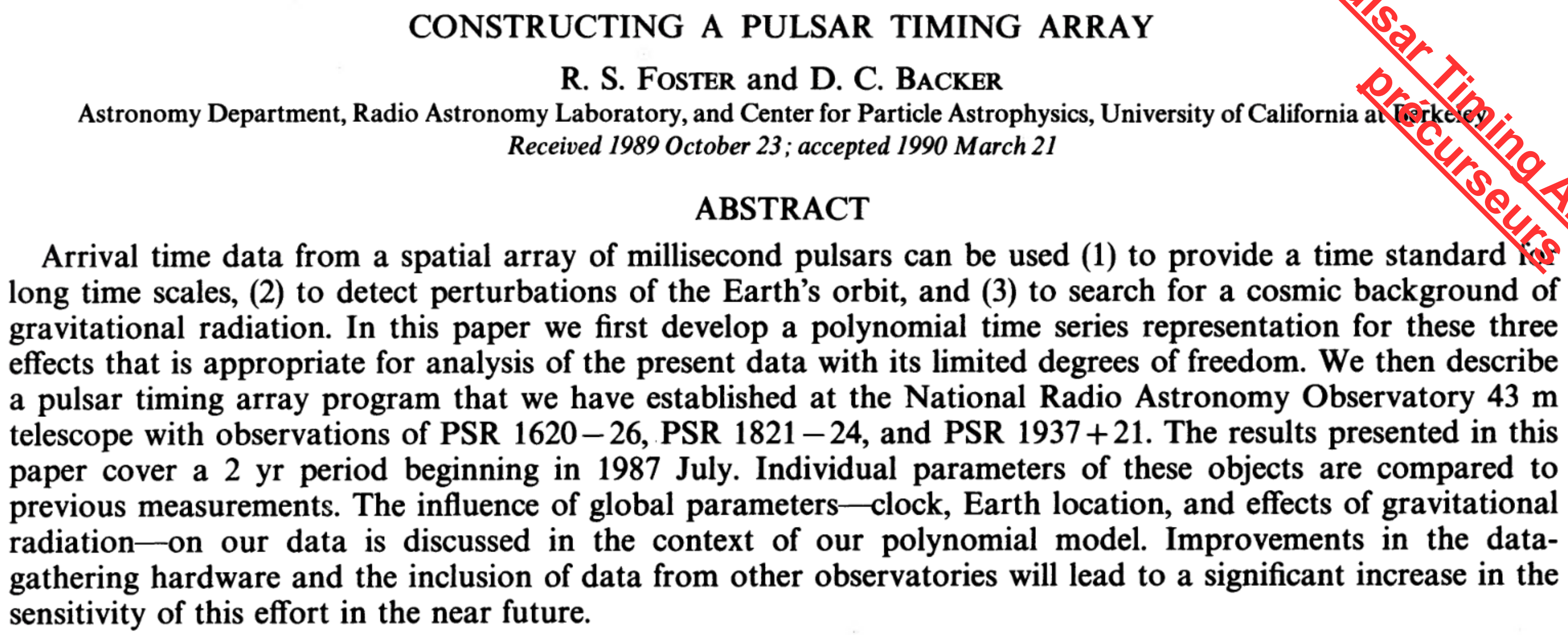
Tiburzi et al 2016

false detection of a common signal when uncertainties are not taken into account in the model



Arzoumanian et al 2018

Pulsar Timing Arrays : précurseurs



CONSTRUCTING A PULSAR TIMING ARRAY

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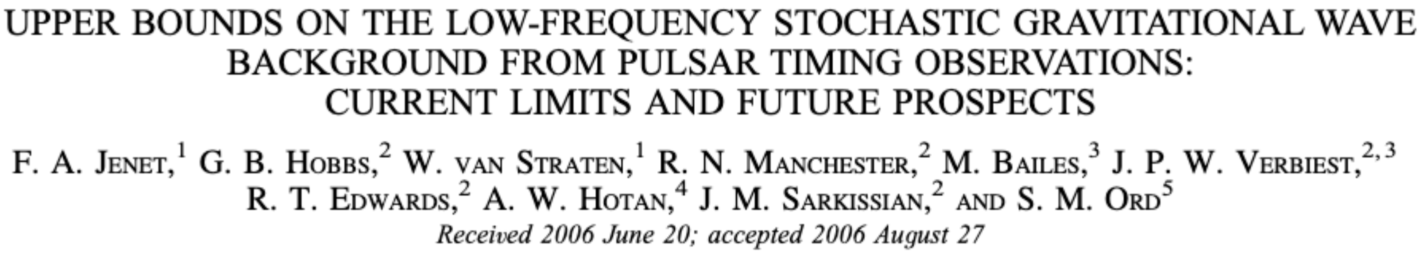
Received 1989 October 23; accepted 1990 March 21

ABSTRACT

Arrival time data from a spatial array of millisecond pulsars can be used (1) to provide a time standard for long time scales, (2) to detect perturbations of the Earth's orbit, and (3) to search for a cosmic background of gravitational radiation. In this paper we first develop a polynomial time series representation for these three effects that is appropriate for analysis of the present data with its limited degrees of freedom. We then describe a pulsar timing array program that we have established at the National Radio Astronomy Observatory 43 m telescope with observations of PSR 1620−26, PSR 1821−24, and PSR 1937+21. The results presented in this paper cover a 2 yr period beginning in 1987 July. Individual parameters of these objects are compared to previous measurements. The influence of global parameters—clock, Earth location, and effects of gravitational radiation—on our data is discussed in the context of our polynomial model. Improvements in the data-gathering hardware and the inclusion of data from other observatories will lead to a significant increase in the sensitivity of this effort in the near future.



UPPER BOUNDS ON THE LOW-FREQUENCY STOCHASTIC GRAVITATIONAL WAVE BACKGROUND FROM PULSAR TIMING OBSERVATIONS: CURRENT LIMITS AND FUTURE PROSPECTS

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R. T. Edwards,[2] A. W. Hotan,[4] J. M. Sarkissian,[2] and S. M. Ord[5]

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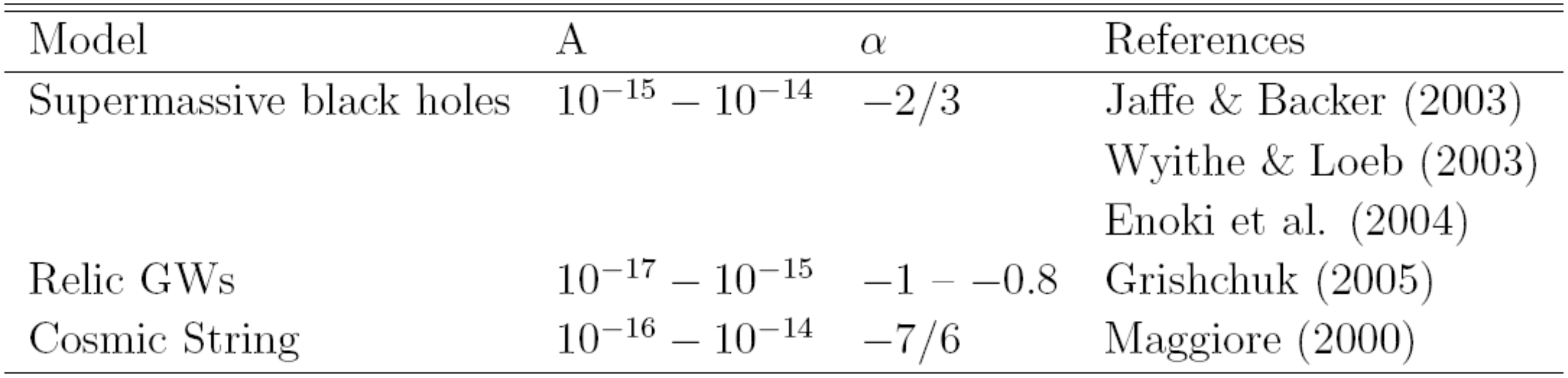
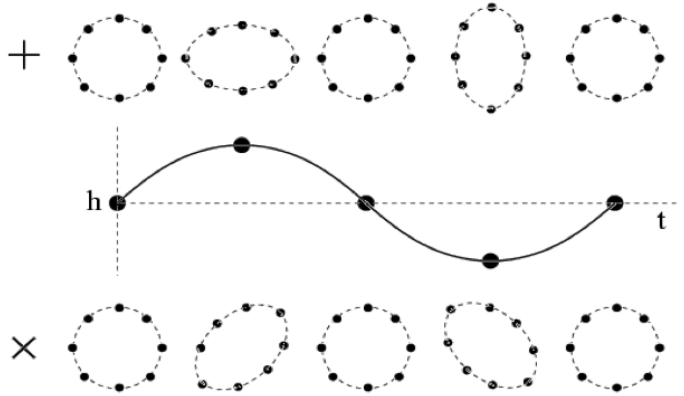


Model	A	α	References
Supermassive black holes	$10^{-15} - 10^{-14}$	$-2/3$	Jaffe & Backer (2003) Wyithe & Loeb (2003) Enoki et al. (2004)
Relic GWs	$10^{-17} - 10^{-15}$	$-1 - -0.8$	Grishchuk (2005)
Cosmic String	$10^{-16} - 10^{-14}$	$-7/6$	Maggiore (2000)

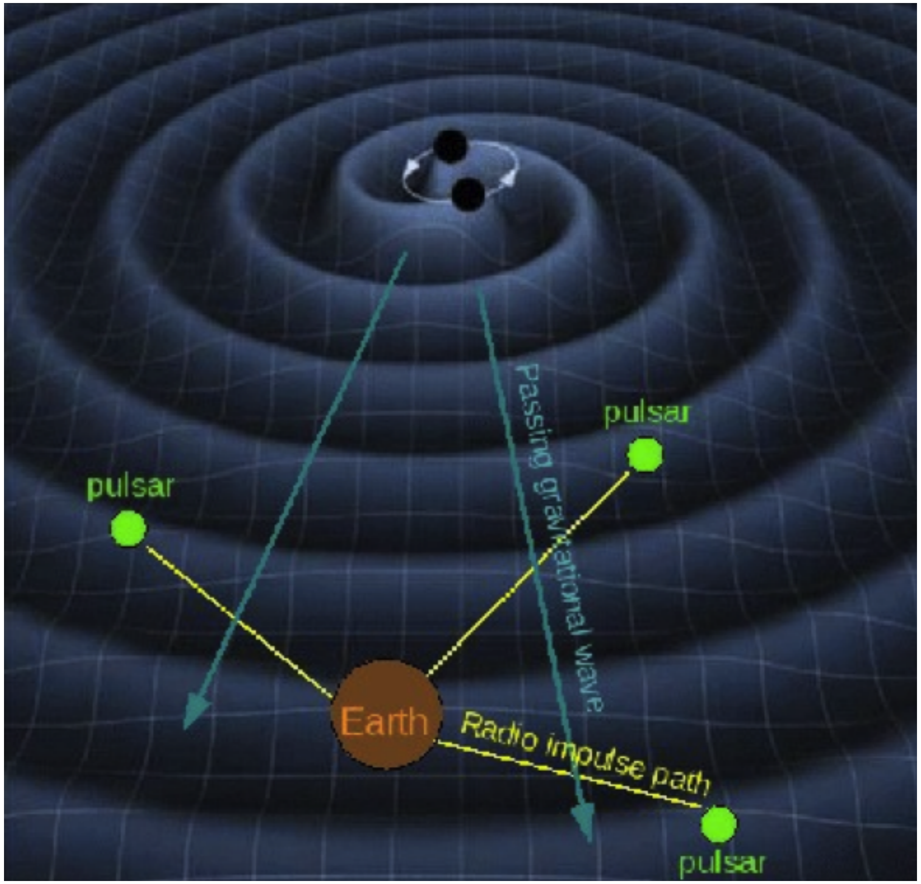
Caractérisation de l'onde gravitationnelle



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

Une onde gravitationnelle est une déformation de l'espace-temps

$$\begin{aligned} h_+(t) &= A(1+\cos^2 i)\cos(2\pi f t + \phi_0) \\ h_\times(t) &= -2A\cos i \sin(2\pi f t + \phi_0) \end{aligned}$$



avec $A = \frac{2\mathcal{M}_c^{5/3}}{D_L}(\pi f)^{2/3}$

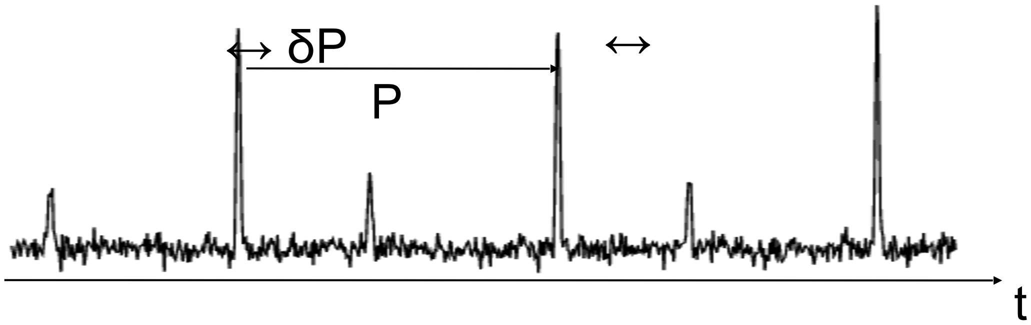
7 + 2 x N_{pulsars} paramètres

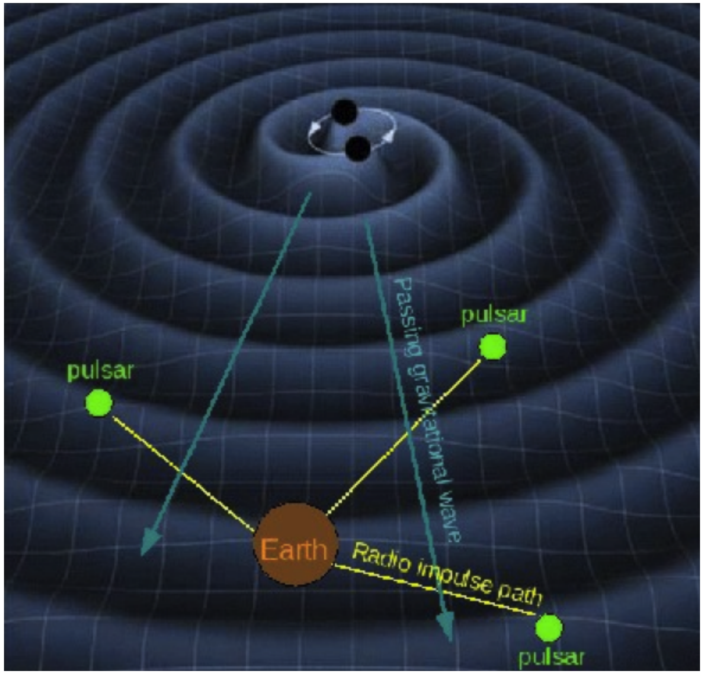
α, δ	position de la source
D_L	distance à la source
i	inclinaison
f_e	fréquence de l'onde à la Terre
Φ	phase
Ψ	orientation (polarisation)

\+

f_p	fréquence de l'onde au pulsar
Φ_p	décalage de phase dans le terme pulsar

Pulsar Timing Arrays : principles





Analysis of time residuals

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

$$\frac{\delta\nu}{\nu}(t) = \frac{1}{2}\frac{\hat{n}^i\hat{n}^j}{1+\underset{\text{dir pulsar}}{\hat{n}}.\underset{\text{dir GW source}}{\hat{k}}}\left(\underbrace{h_{ij}(t-\overbrace{L}^{\text{pulsar-Earth distance}}(1+\hat{k}.\hat{n}))}_{\text{wave amplitude at the pulsar}} - \underbrace{h_{ij}(t)}_{\text{wave amplitude at the Earth}}\right)$$

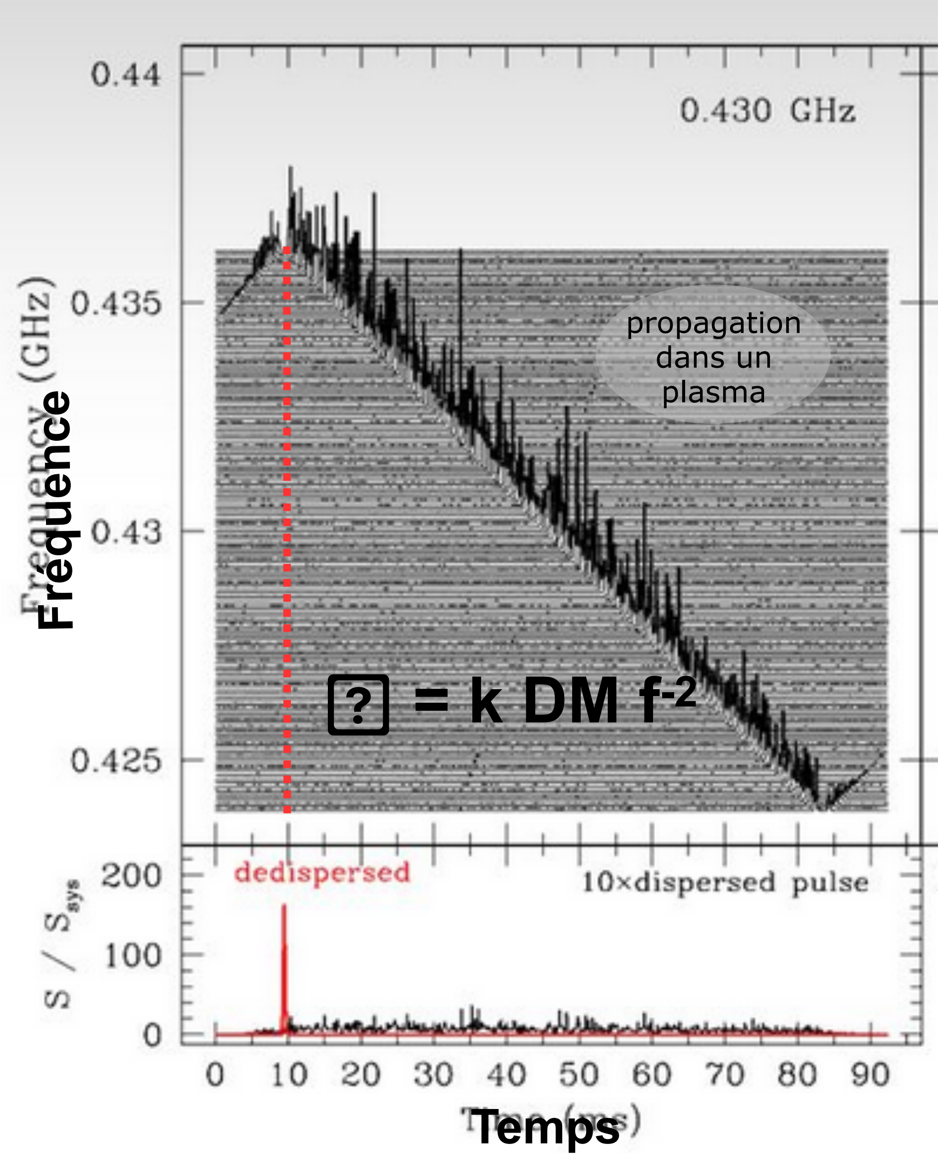
The Earth and the distant pulsar are considered as free masses whose position responds to changes in the metric of space-time

→ *The passage of a gravitational wave disturbs the metric and produces fluctuations in the arrival times of the pulses*

Mise en pratique : l'art de la chronométrie

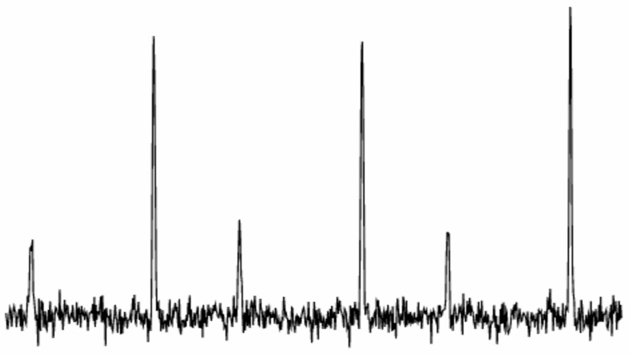
I - problème de la dispersion

Les fréquences les plus basses sont “retardées



$\boxed{?} = k\ DM\ f^{-2}$

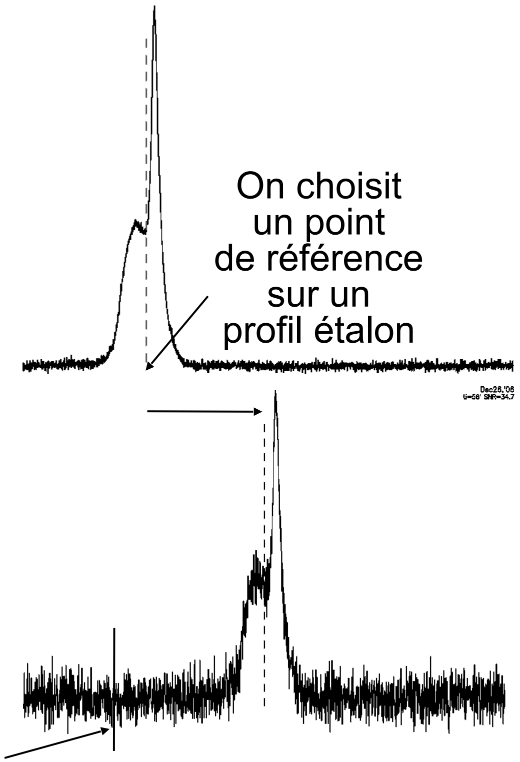
II- Empilement en phase avec la rotation



Selon un modèle :
ralentissement,
mvt orbital,
mvt propre
éph. planétaire

III – Datation
(calcul d'un temps d'arrivée)

« TOA »



On choisit un point de référence sur un profil étalon

Position du premier échantillon de données, correspondant au

Besoin d'une précision extrême

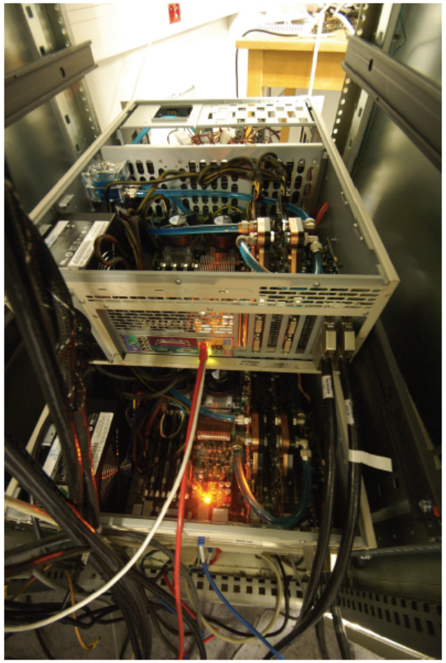
L'incertitude de datation peut descendre
à 10-20 ns pour quelques pulsars

$$\sigma_{\mathrm{TOA}} \propto \frac{w}{S_{\mathrm{PSR}}} \frac{T_{\mathrm{sys}}}{A} \frac{1}{\sqrt{BT}}$$

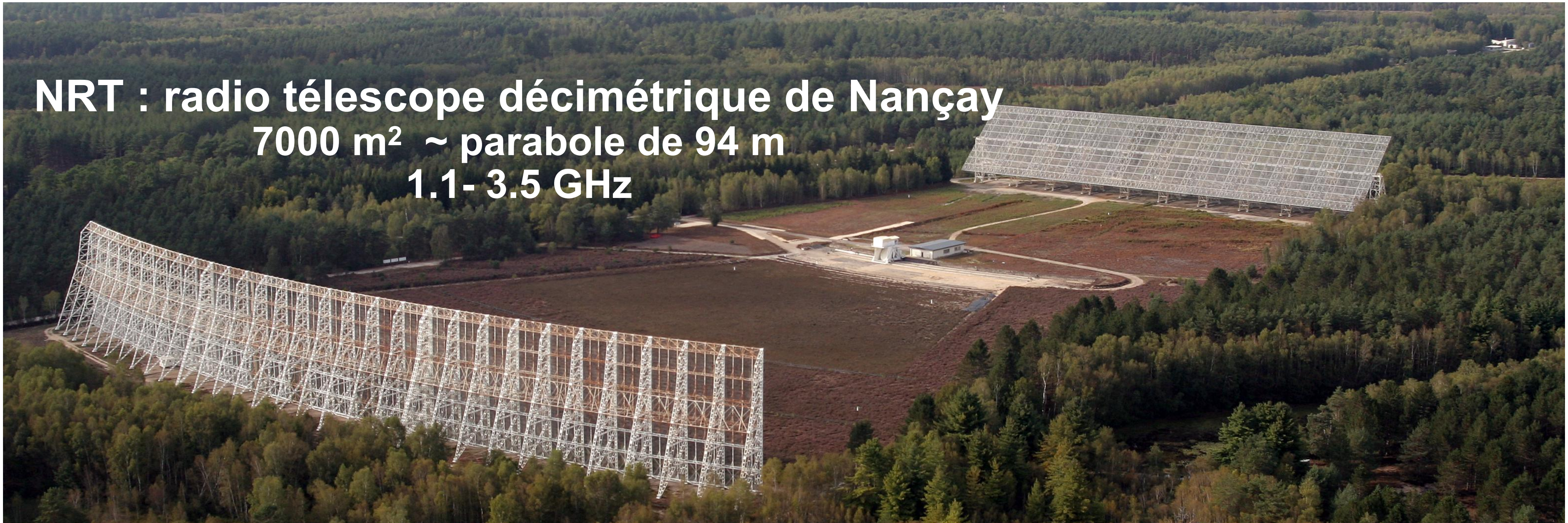
Des flux faibles ~mJy (1 Jy = 10^{-26} W/m^2)

→ besoin d'une large bande passante

→ besoin d'un grand radiotélescope



Instrumentation actuelle :
dédispersion cohérente sur 512 MHz
4 PCs / 8 GPUs (un flux de 16 Gb / s)



NRT : radio télescope décimétrique de Nançay
7000 m^2 ~ parabole de 94 m
1.1- 3.5 GHz