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

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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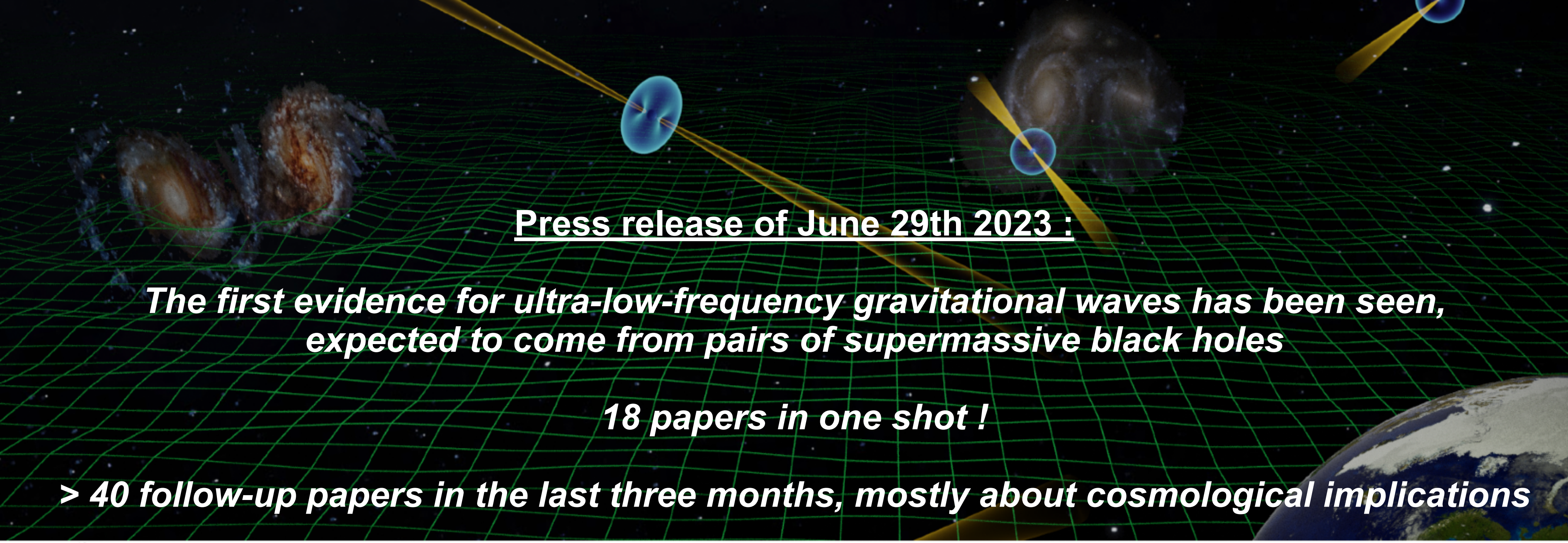
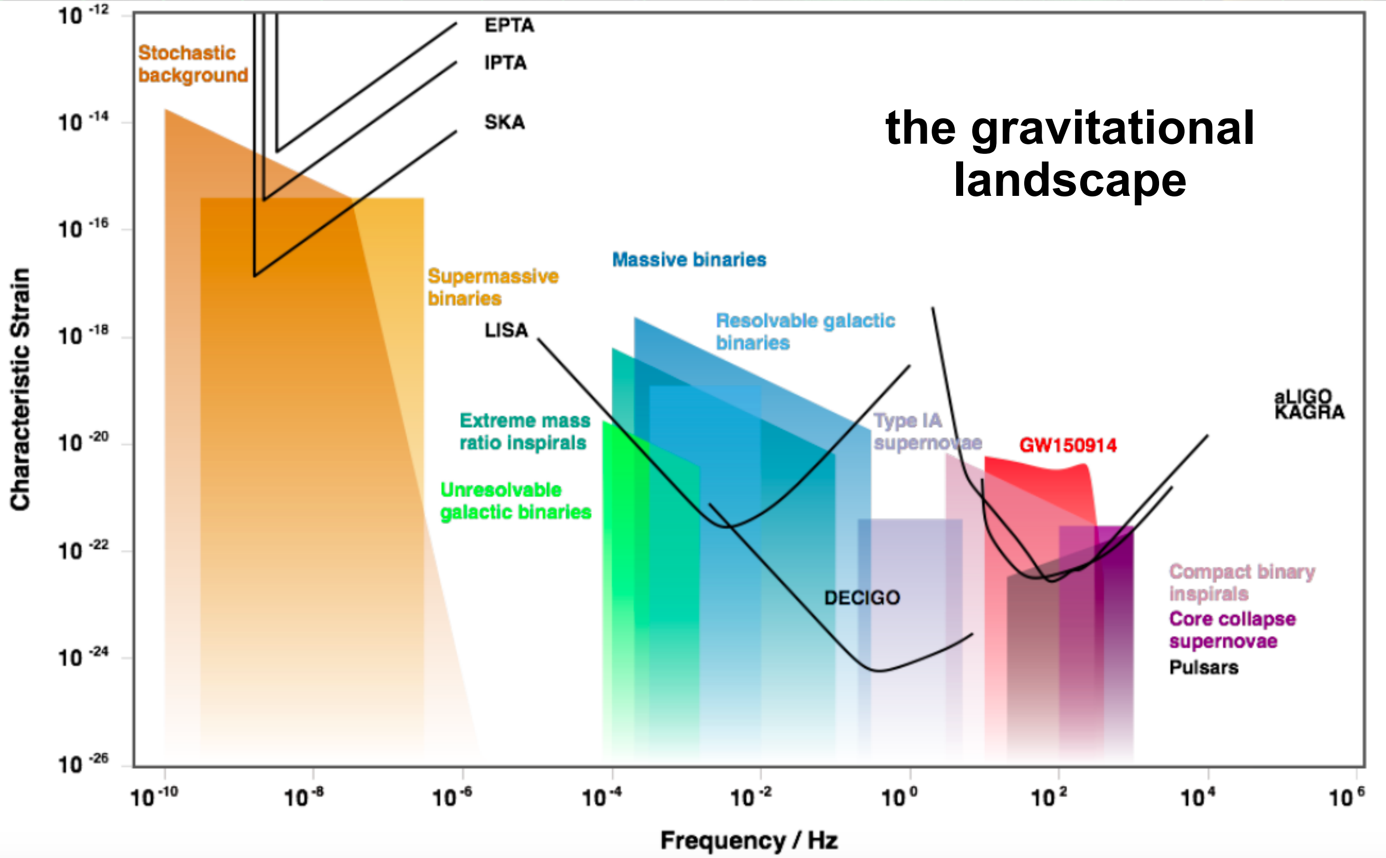


Press release of June 29th 2023 :

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 !

> 40 follow-up papers in the last three months, mostly about cosmological implications

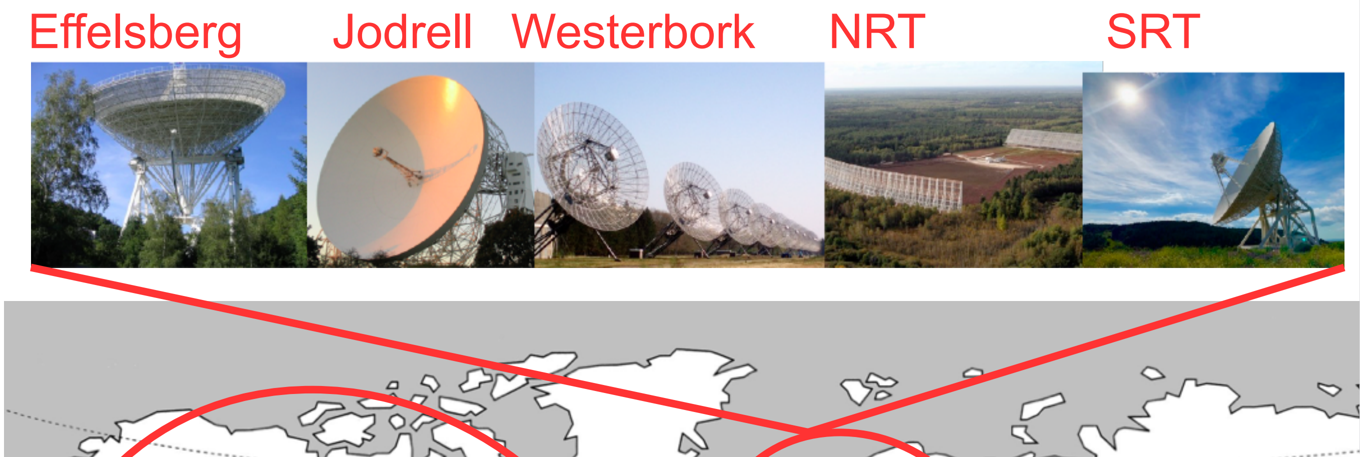


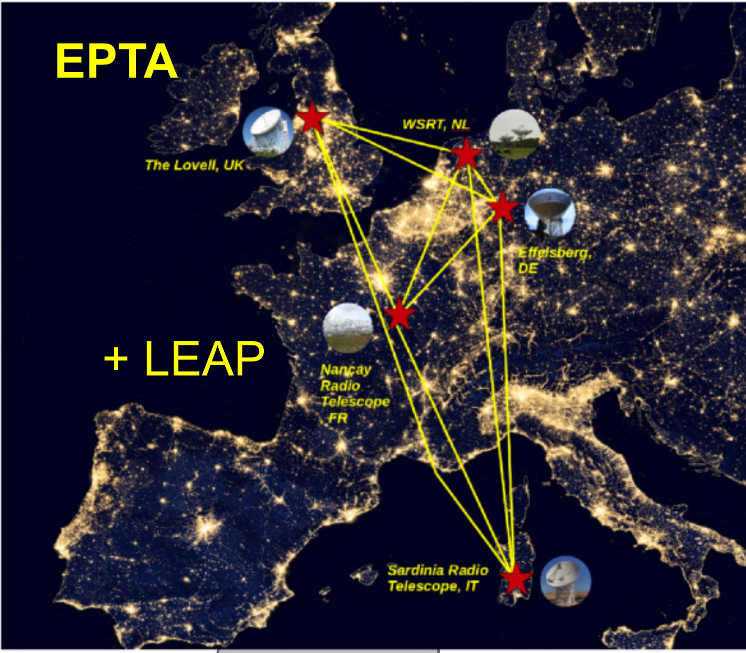
the gravitational landscape

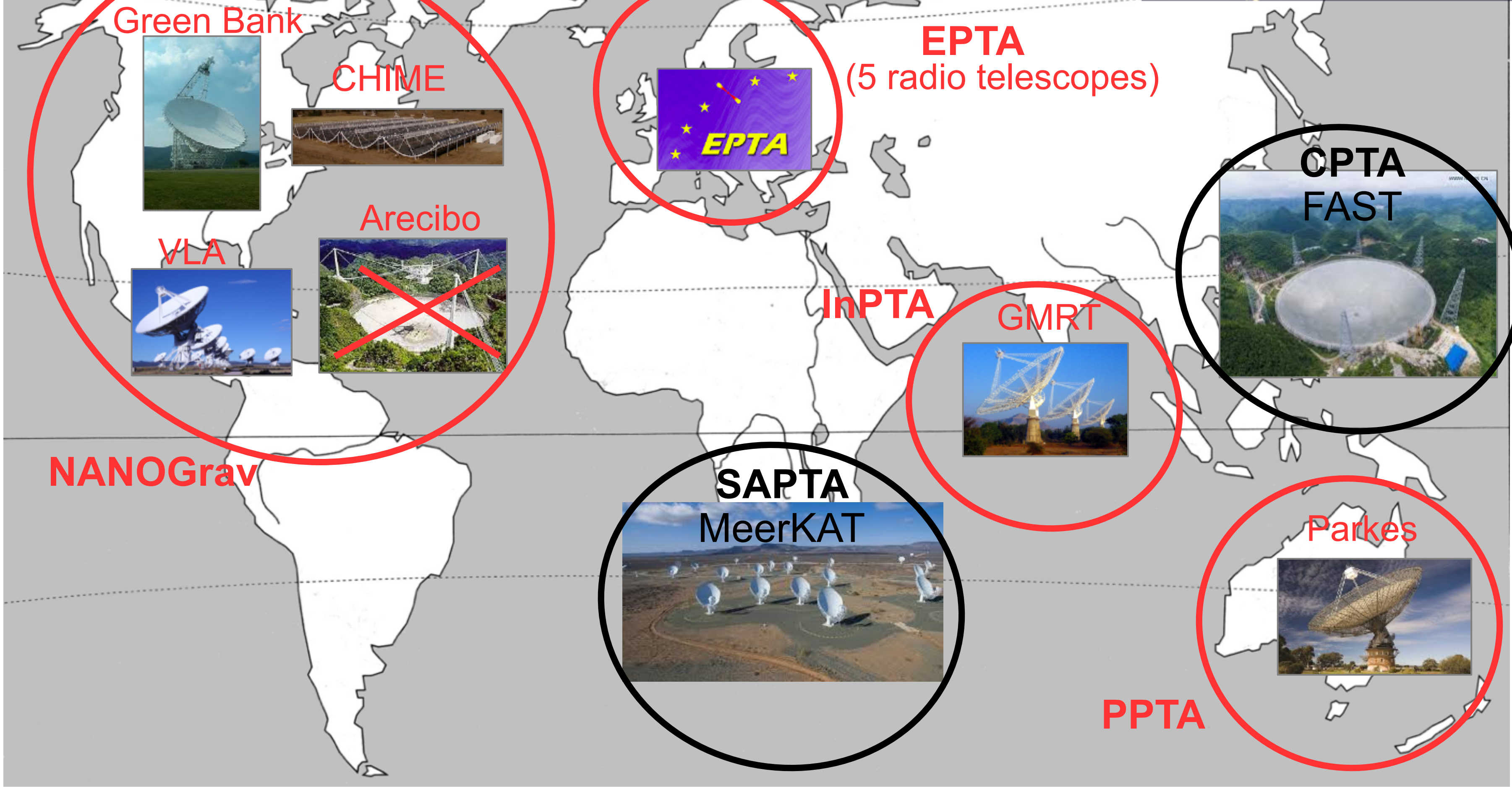
The nanoHertz domain

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

The International Pulsar Timing Array





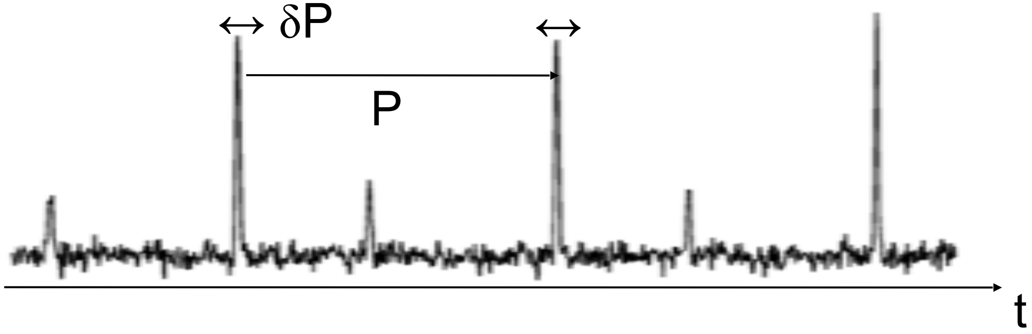


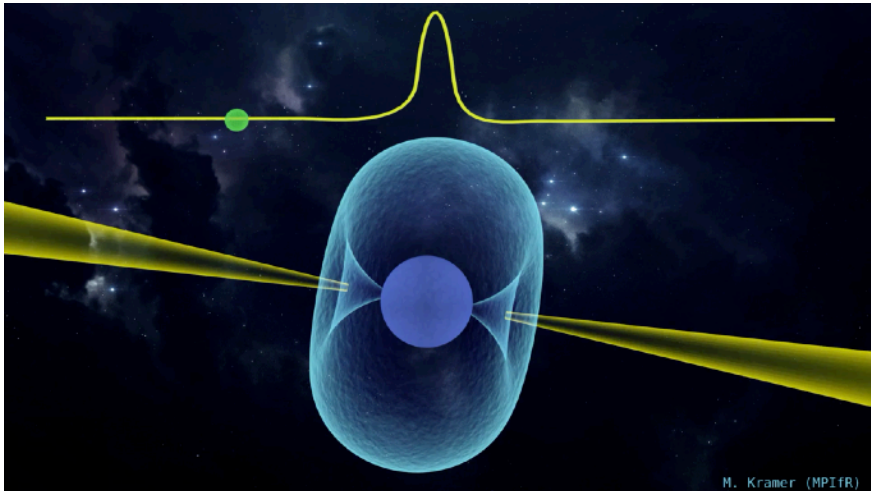
EPTA/InPTA, PPTA and NANOGrav

publish coherent results !

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

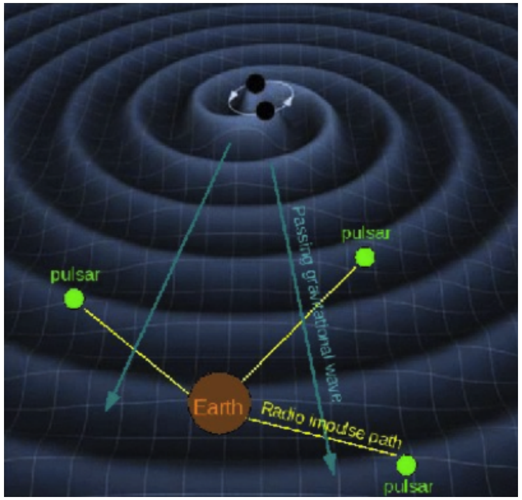
Pulsar Timing Arrays : principles





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

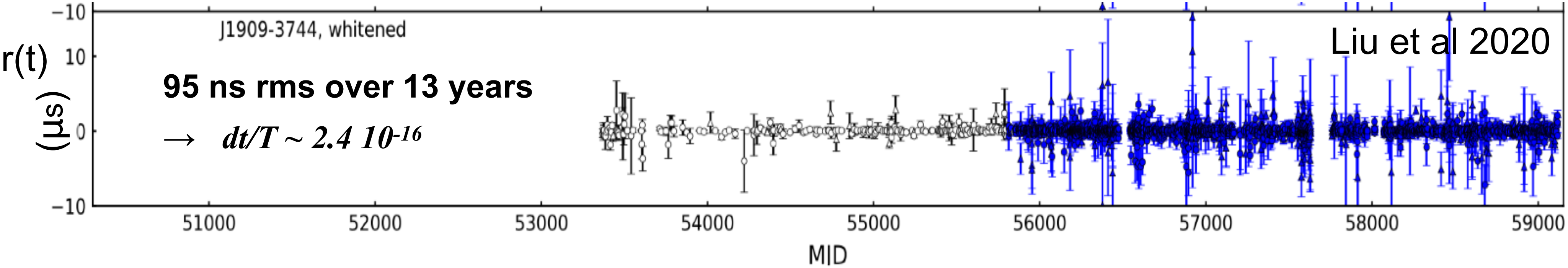
→ *The passage of a gravitational wave disturbs the metric and produces fluctuations in the arrival times of the pulses*



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

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

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

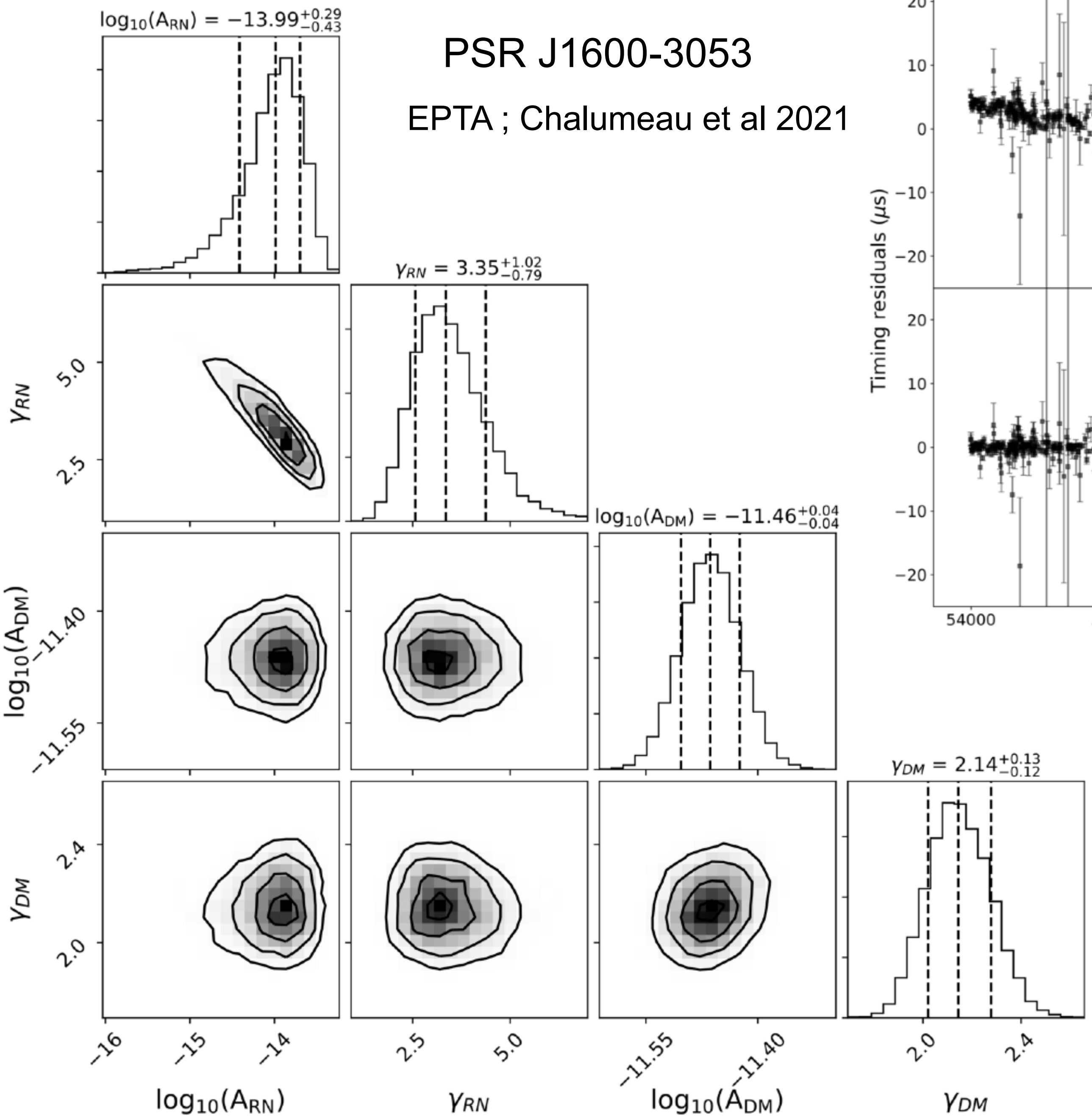
τ^{GW} Gravitational waves → indiv. sources, stochastic background, « bursts » events

Red noise : individual pulsar models

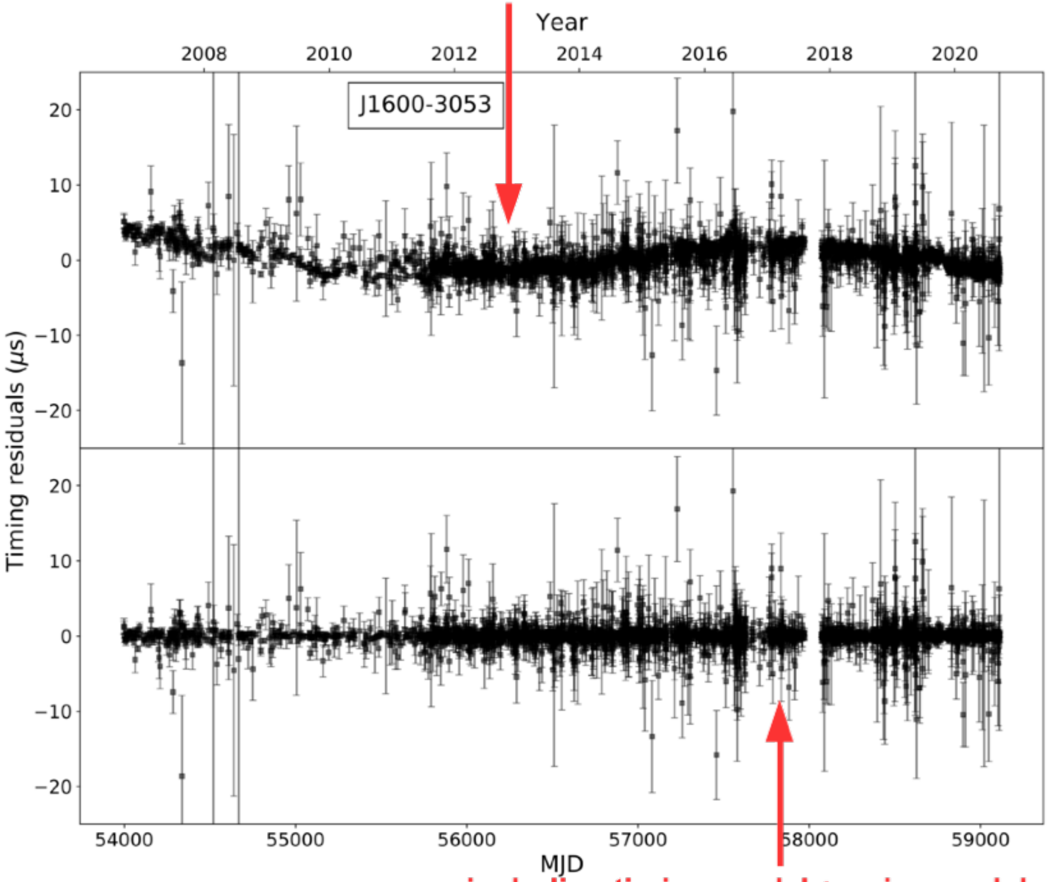
(paper II)

PSR J1600-3053

EPTA ; Chalumeau et al 2021



including timing model



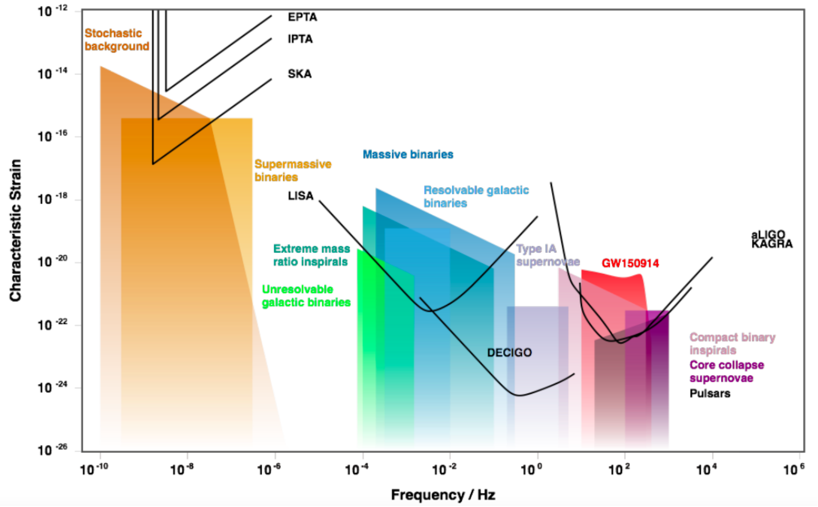
including timing model + noise model

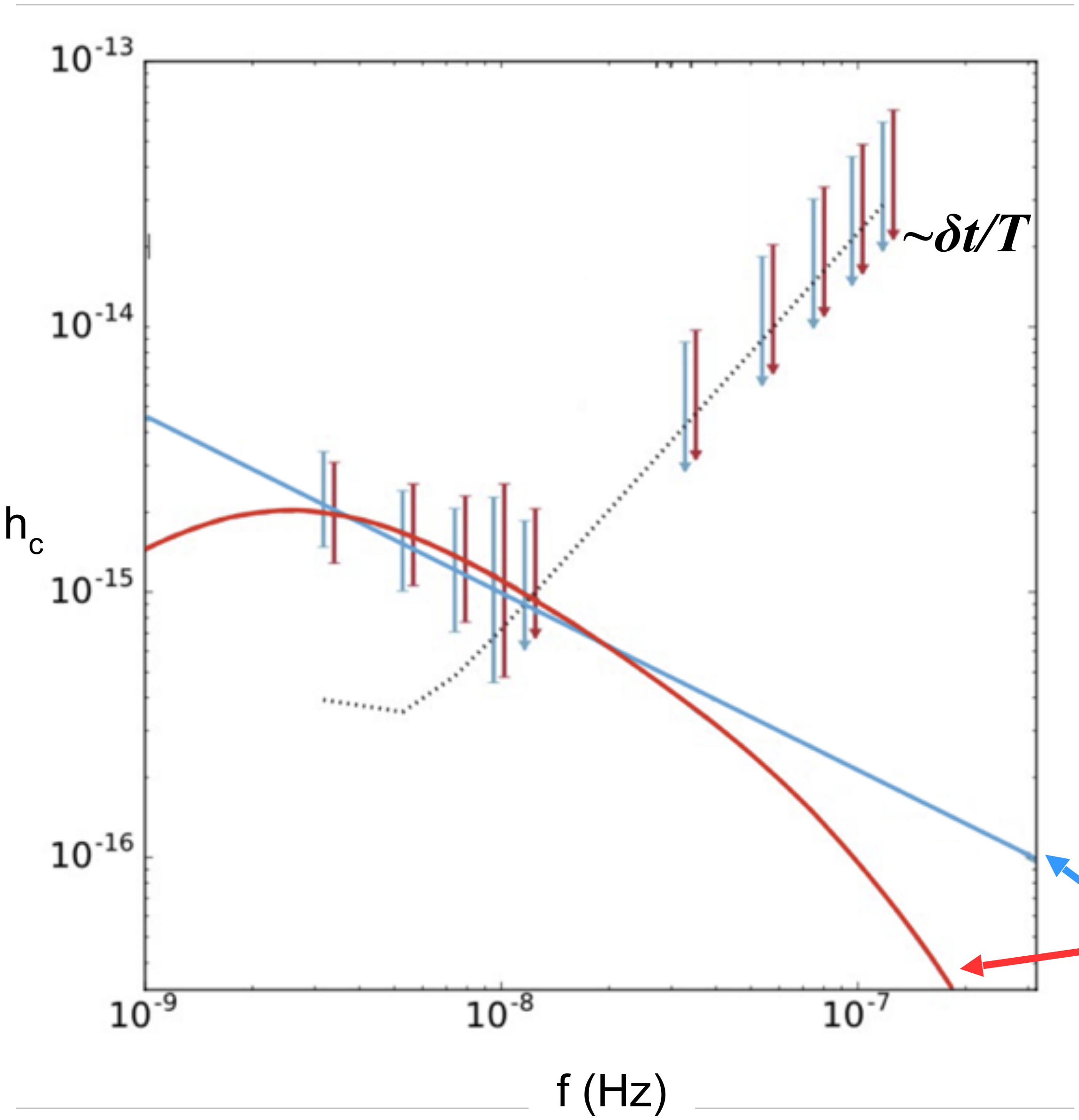
- **Spin noise**
- **DM chromatic noise**
- Scaterring noise
- Band noise
- System noise

+

Nb of freq bins
to characterise each

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

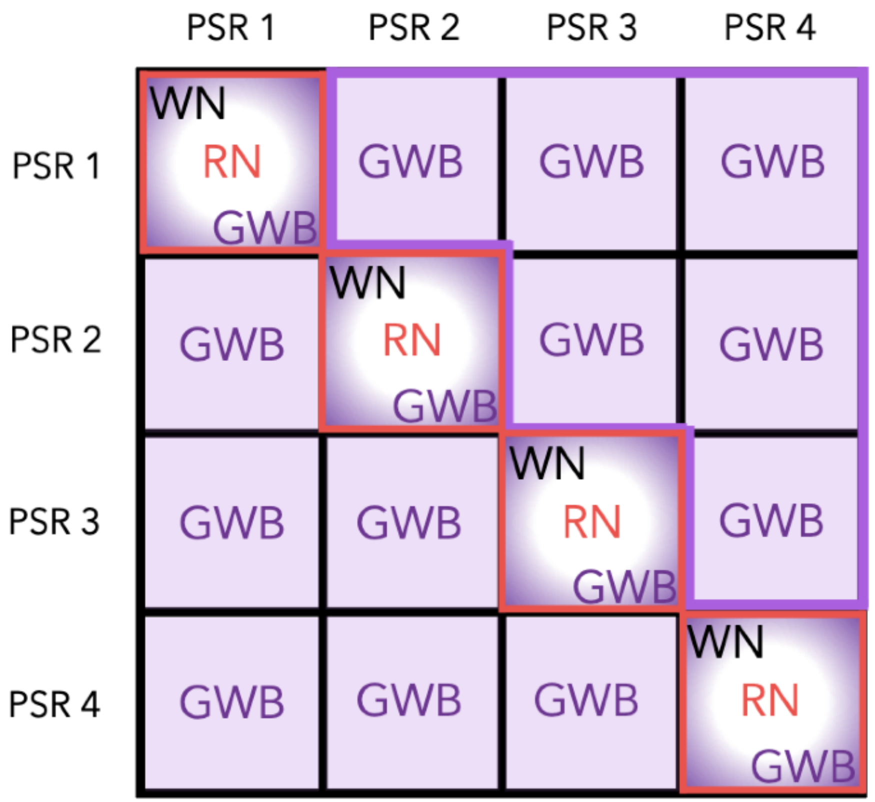
The covariance matrix is decomposed into a sum of « noises » whose spectrum is described by a power law

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

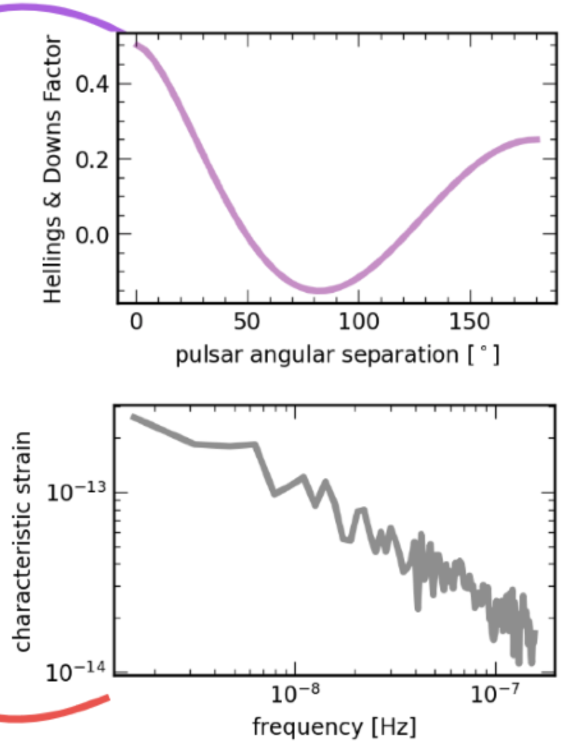
The GW term depends both on the amplitude of the signal as a function of its sky position and on the «antenna pattern »

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

(overlap reduction function)

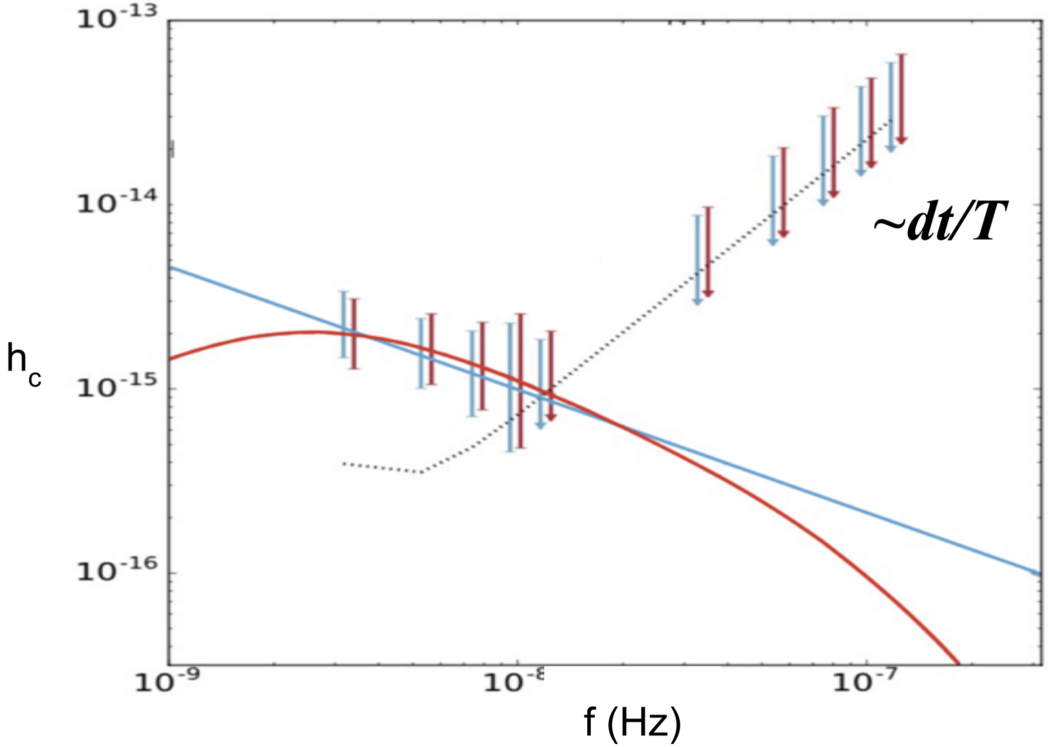


	PSR 1	PSR 2	PSR 3	PSR 4
PSR 1	WN RN GWB	GWB	GWB	GWB
PSR 2	GWB	WN RN GWB	GWB	GWB
PSR 3	GWB	GWB	WN RN GWB	GWB
PSR 4	GWB	GWB	GWB	WN RN GWB

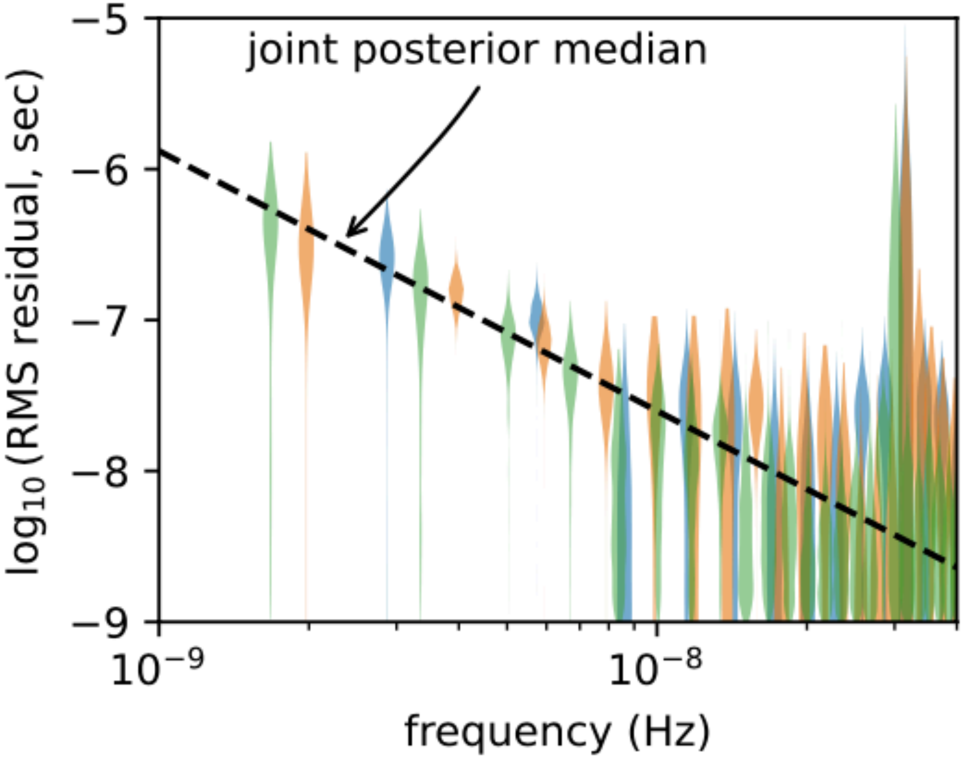


Taylor et al 2022

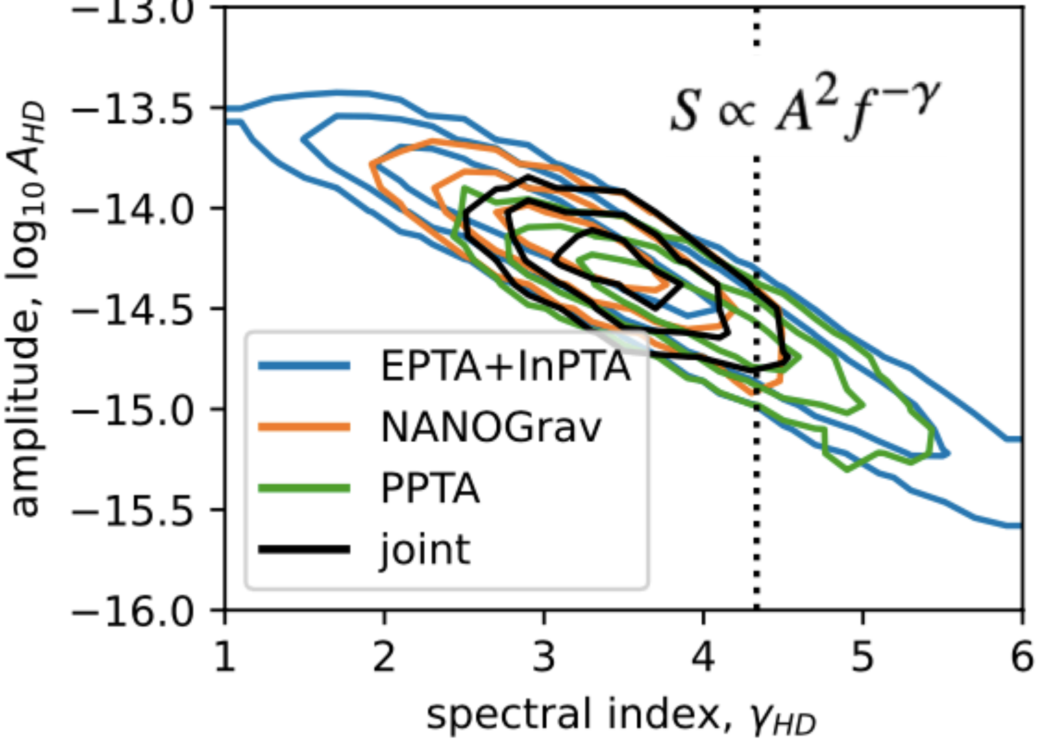
Observed spectrum



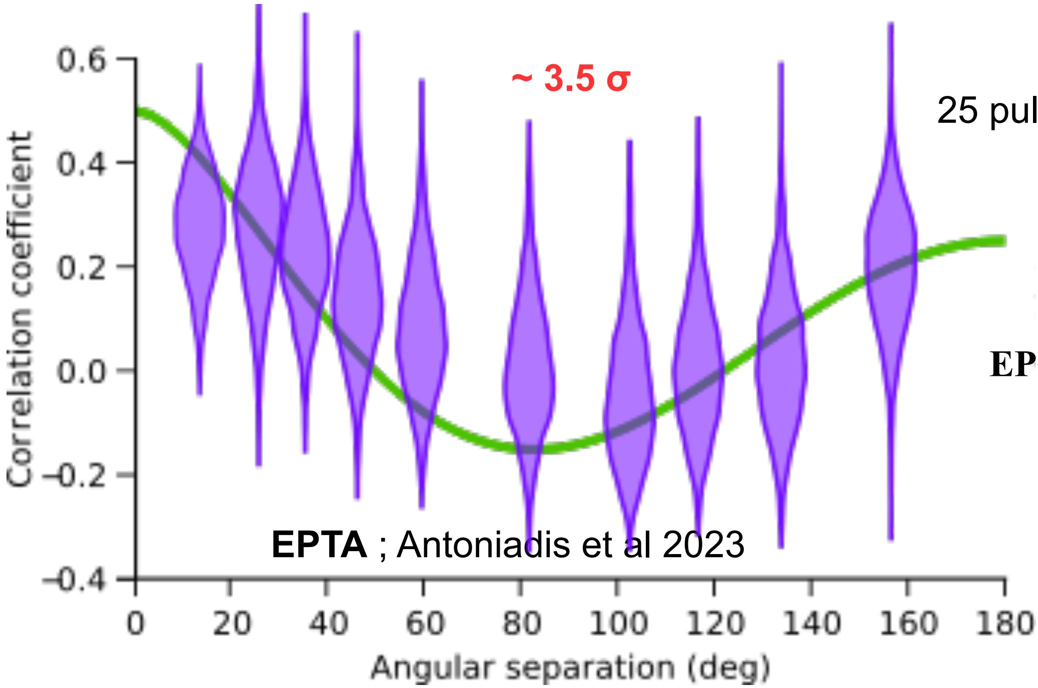
29^{th} June 2023
EPTA, NANOGrav and PPTA
show coherent results



Courtesy of Paul Baker IPTA GWA WG



Spatial correlation of the signal



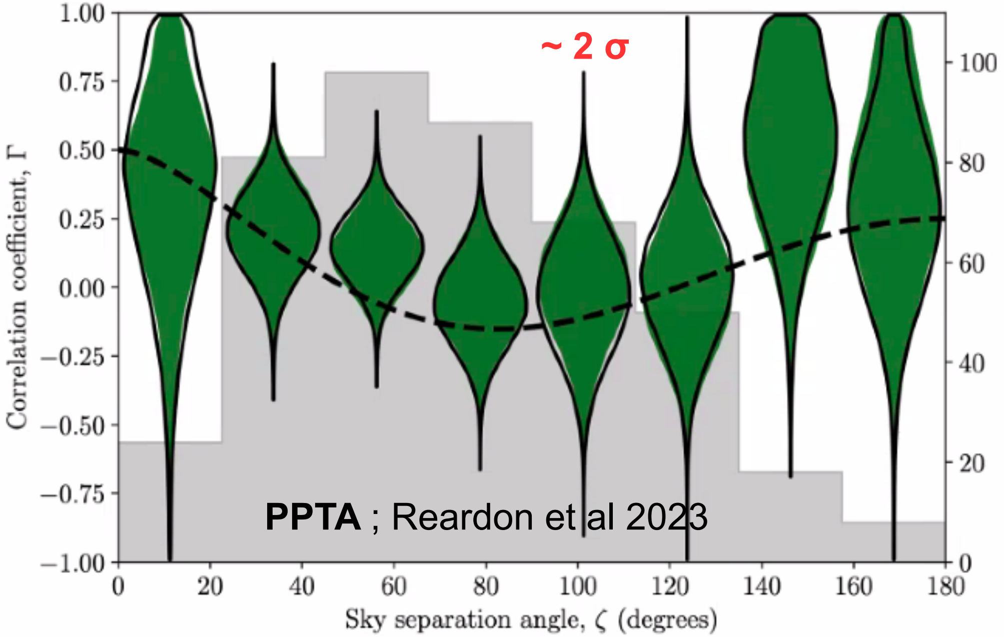
~ 3.5 σ

25 pulsars

EPTA ; Antoniadis et al 2023

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

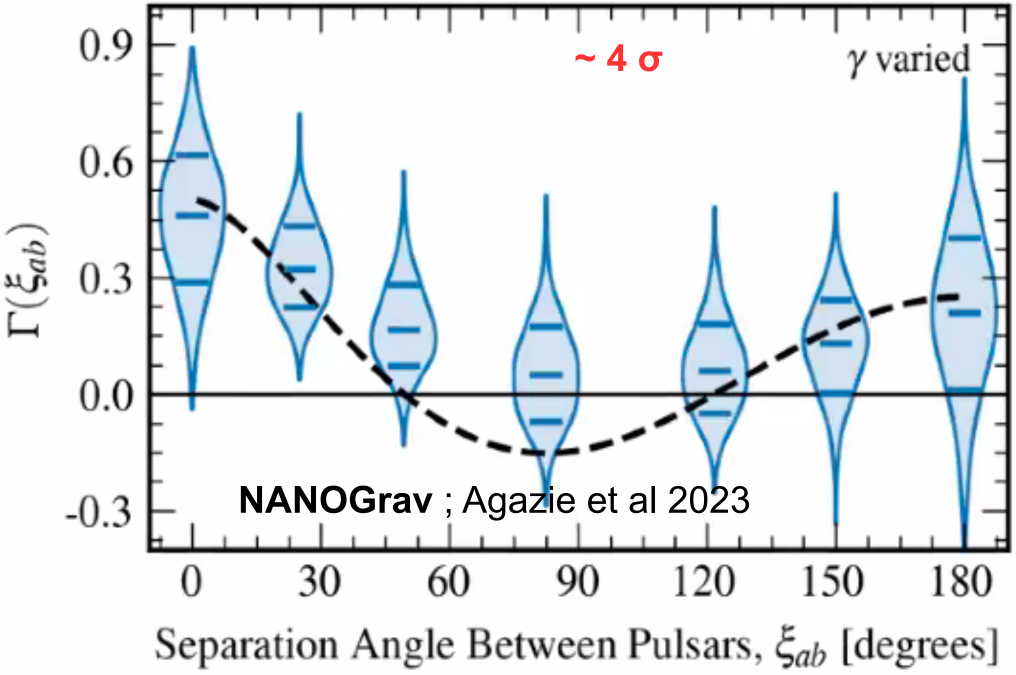
30 pulsars



~ 2 σ

PPTA ; Reardon et al 2023

67 pulsars

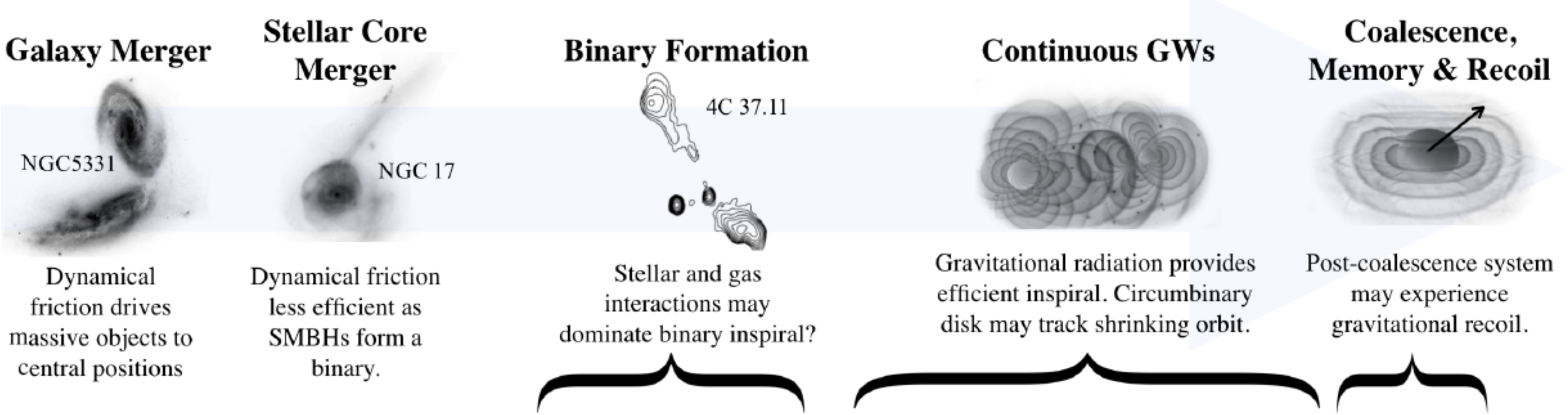


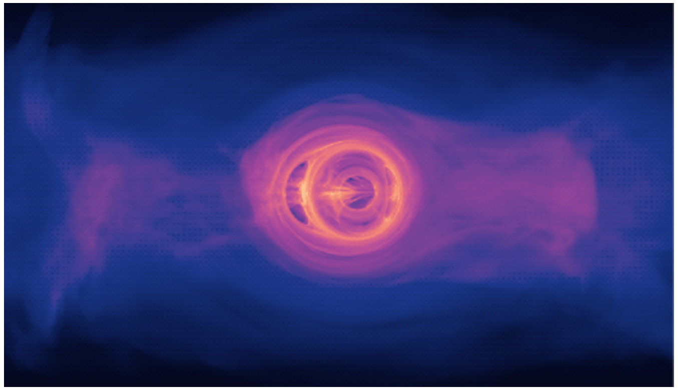
~ 4 σ

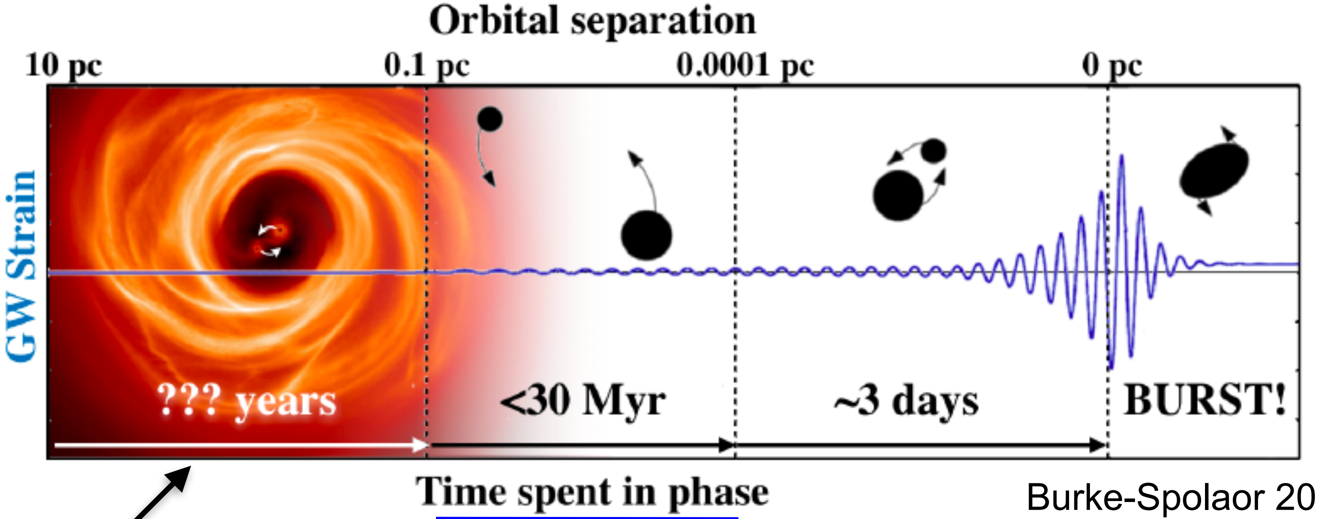
NANOGrav ; Agazie et al 2023

How interpreting such a common signal in terms of astrophysics ?

The life cycle of Super Massive Black Hole Binaries:







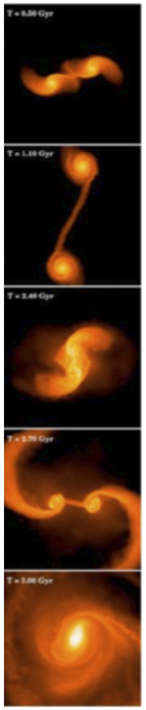
Burke-Spolaor 2018

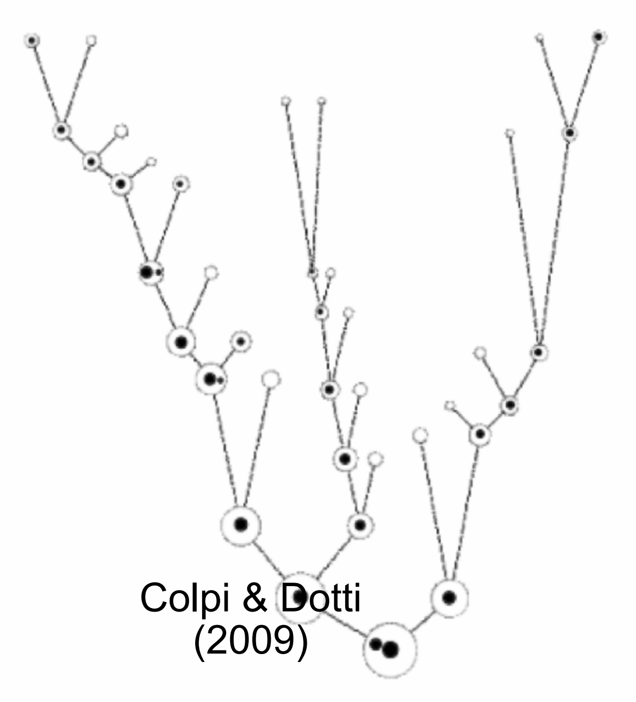
monochromatic PTA regime

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)

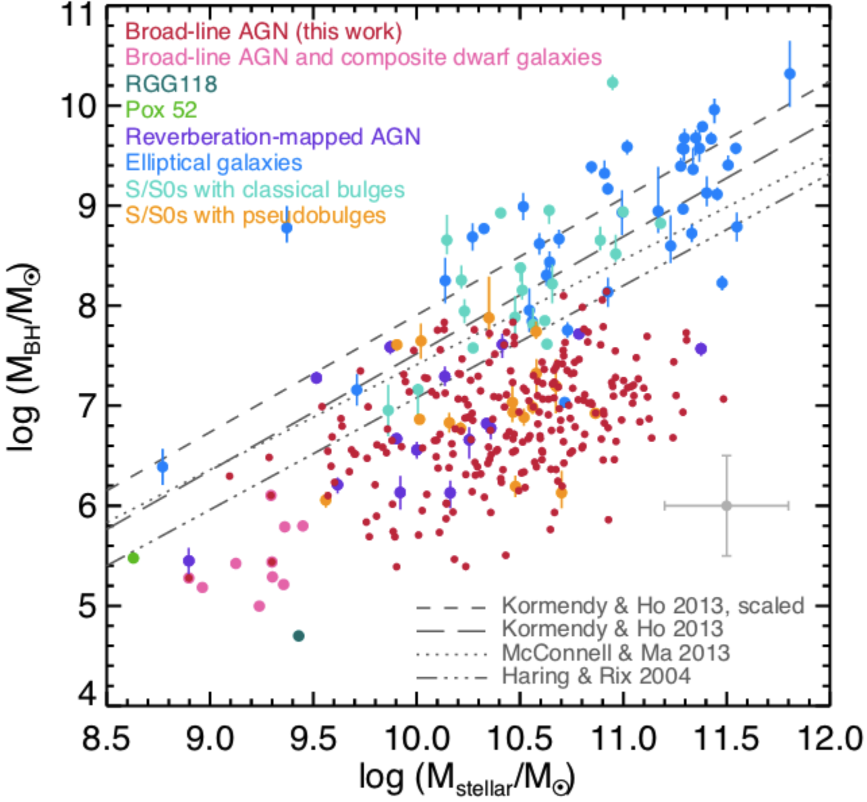
Population synthesis ingredients





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

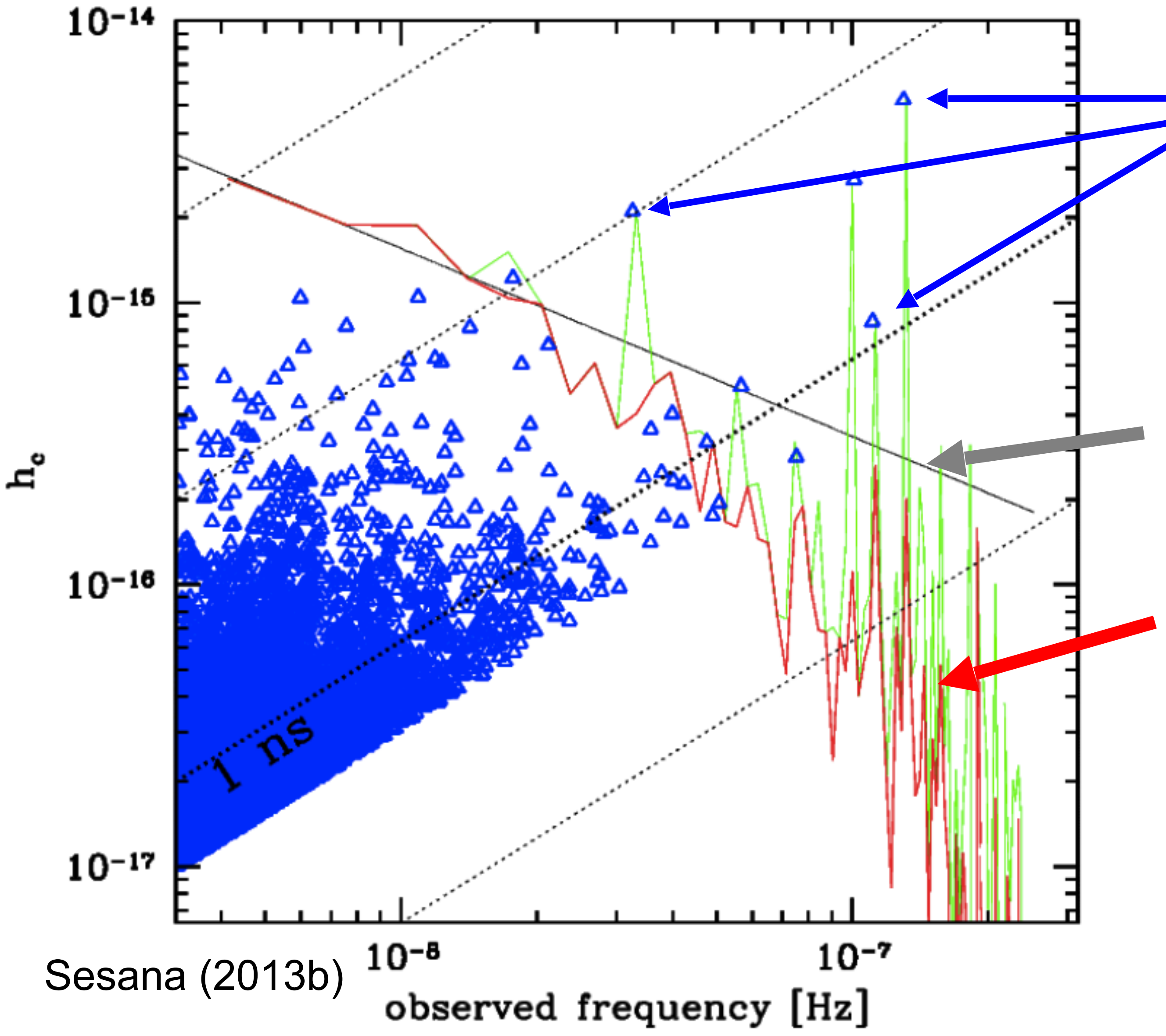
Three body interaction with stars from the loss cone region (when binary orbital velocity > stars)

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



Sesana (2013b)

« resolvable » individual sources

stochastic background ~ 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

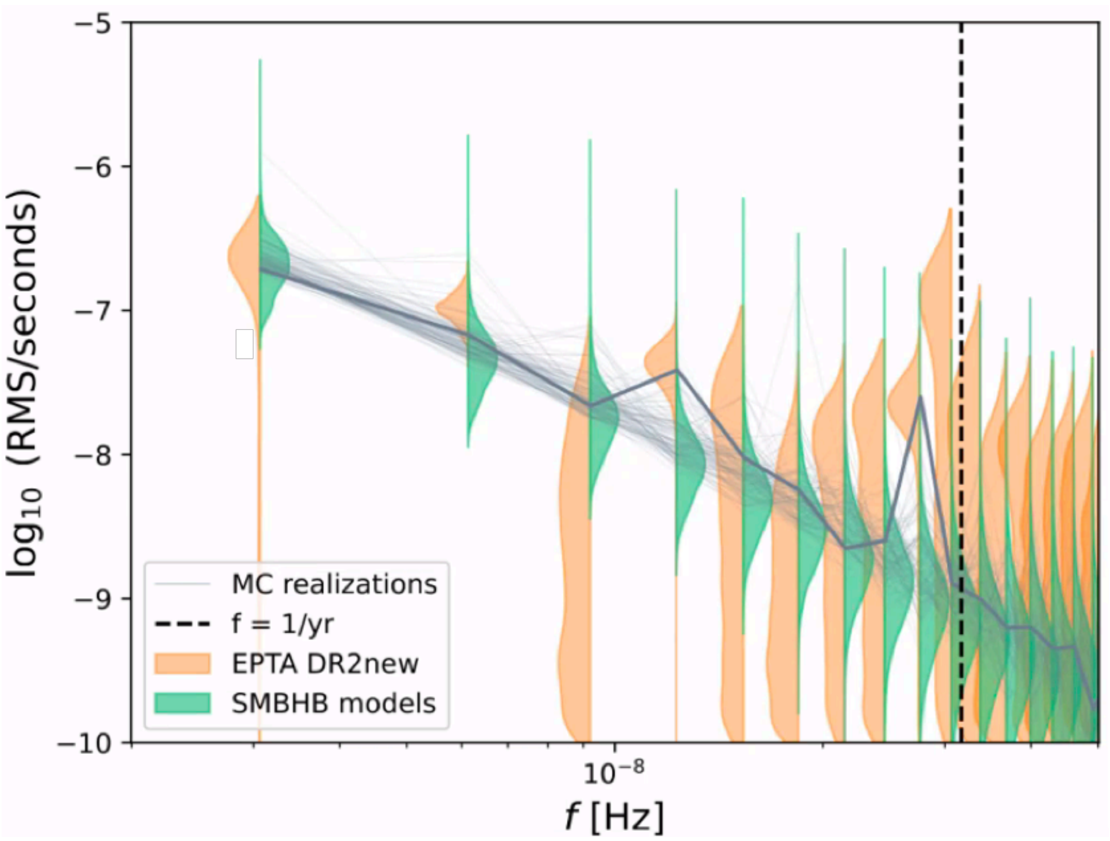
time to coalescence

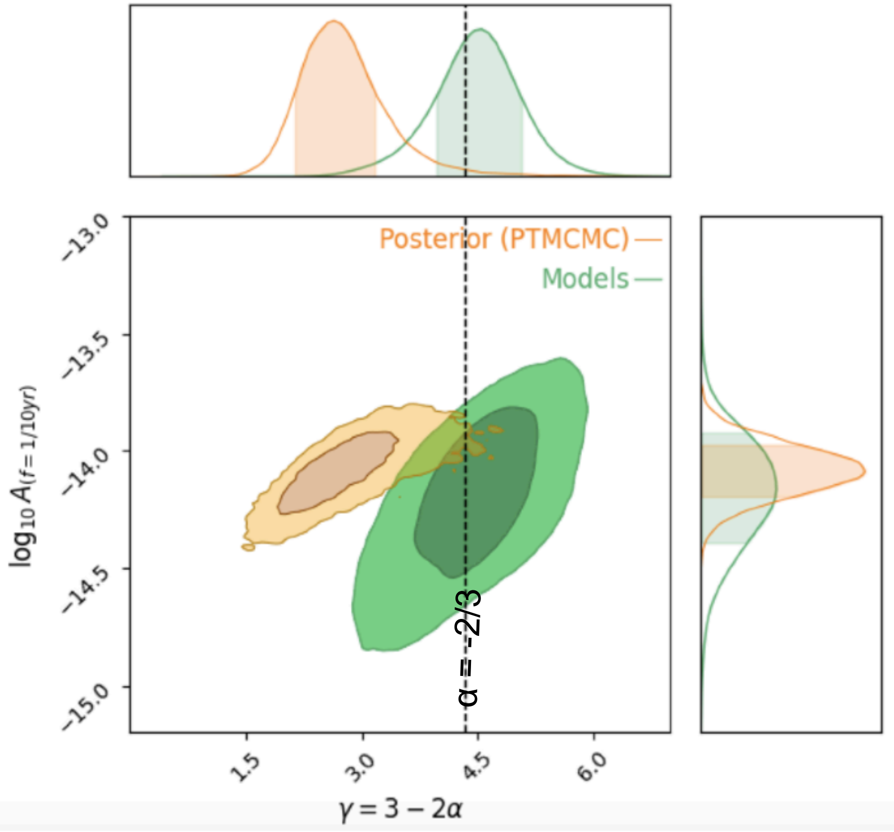
GW emission

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

(Phinney 2001)

The PTA signal vs SMBHB population models





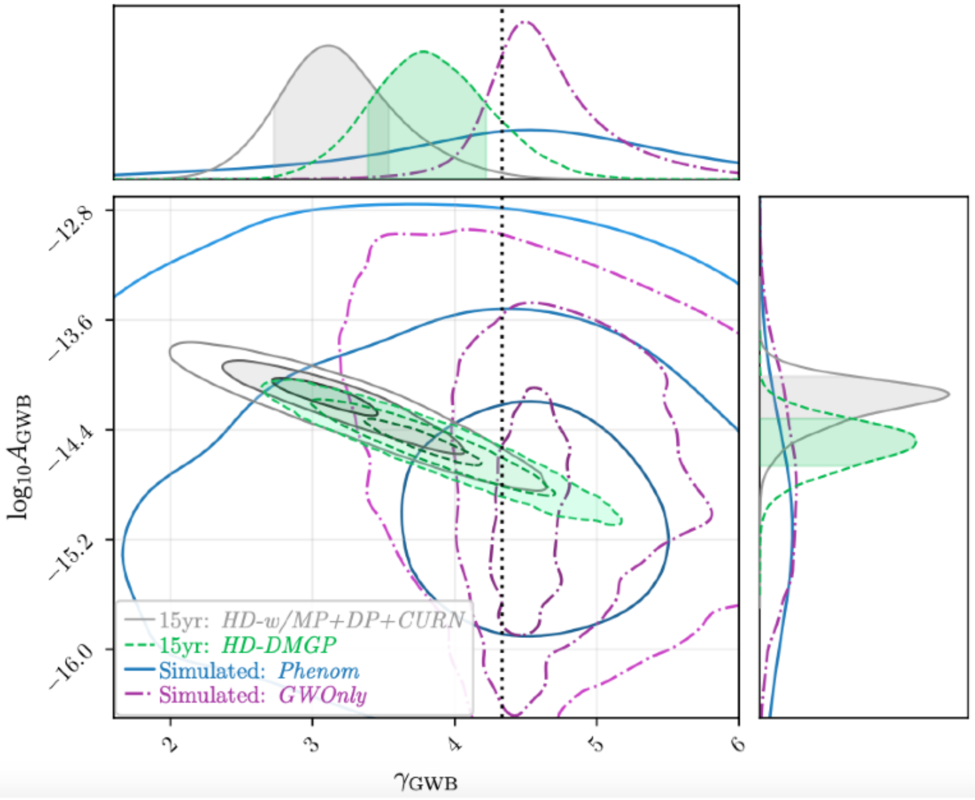
$$S \propto A^2 f^{-\gamma}$$

Comparing with the predictions of astrophysical models (paper V)

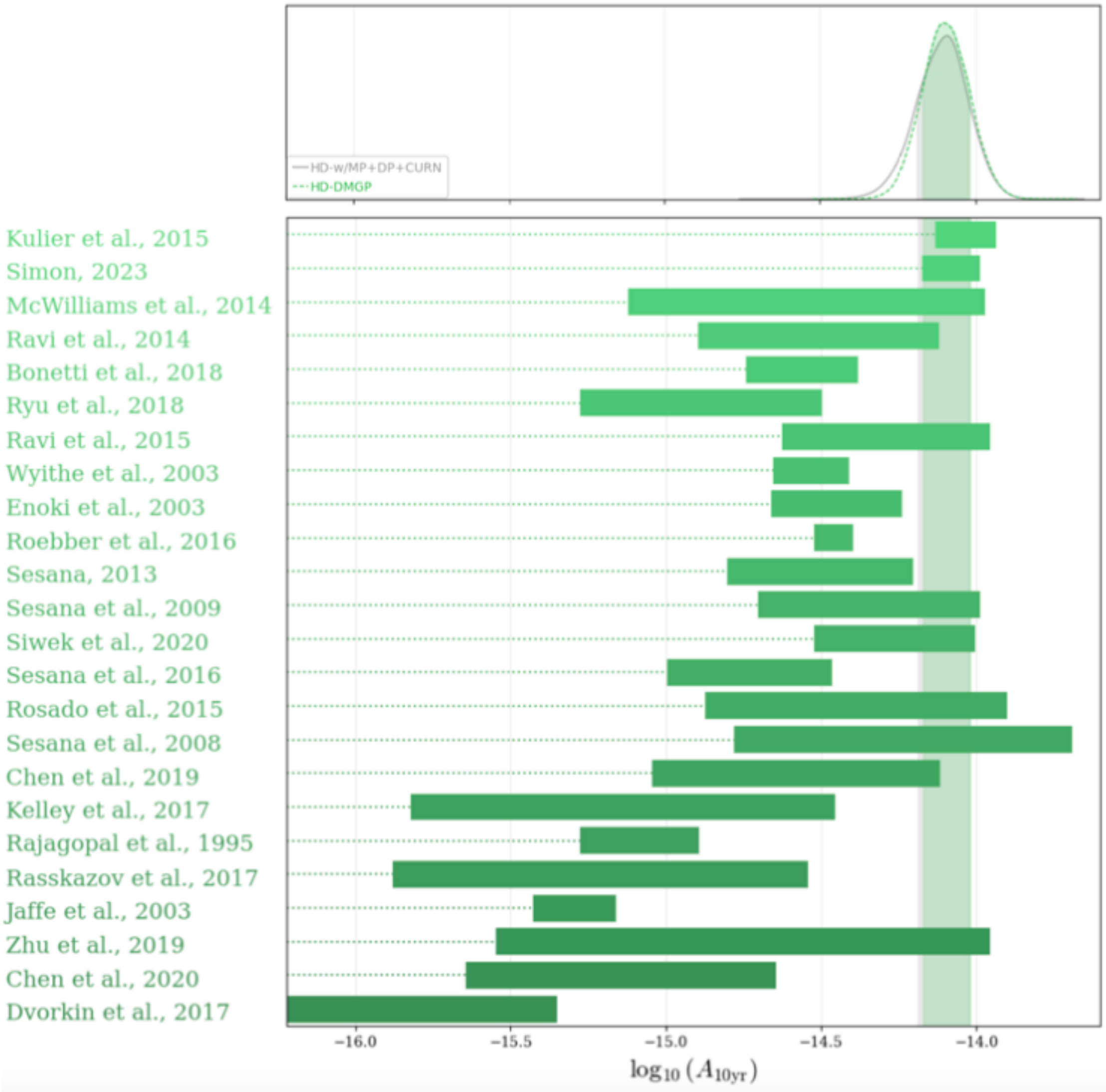
$$h_c(f) = A\left(\frac{f}{\mathrm{yr}^{-1}}\right)^{-2/3}$$

Antoniadis et al 2023e
(EPTA paper V)

The PTA signal vs SMBHB population models



NANOGrav 15-yrs
Agazie et al 2023e



The PTA signal vs SMBHB population models

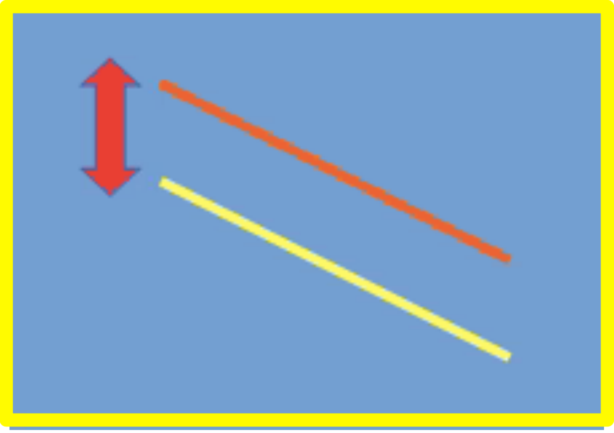
$$h_c^2(f) = \int_0^\infty \mathrm{d}z \int_0^\infty \mathrm{d}m_1 \int_0^1 \mathrm{d}q \frac{\mathrm{d}^5 N}{\mathrm{d}z\mathrm{d}m_1\mathrm{d}q\mathrm{d}e\mathrm{d}t_r} \frac{\mathrm{d}t_r}{\mathrm{d}\ln f_{\mathrm{K},r}} \times$$

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

The PTA signal vs SMBHB population models

cosmic merger rate

$$h_c^2(f) = \int_0^\infty \mathrm{d}z \int_0^\infty \mathrm{d}m_1 \int_0^1 \mathrm{d}q \frac{\mathrm{d}^5N}{\mathrm{d}z\,\mathrm{d}m_1\,\mathrm{d}q\,\mathrm{d}e\,\mathrm{d}t_r}\frac{\mathrm{d}t_r}{\mathrm{d}\ln f_{\mathrm{K},r}} \times h^2(f_{\mathrm{K},r}) \sum_{n=1}^{\infty} \frac{g[n, e(f_{\mathrm{K},r})]}{(n/2)^2}\Bigg|_{f_{\mathrm{K},r}=f(1+z)/n}$$



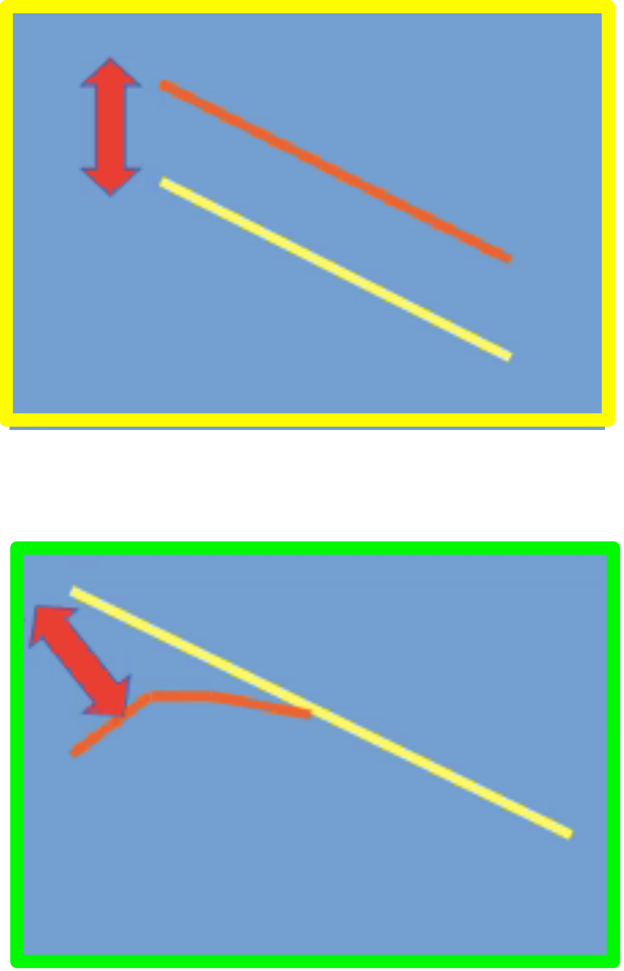
The PTA signal vs SMBHB population models

cosmic merger rate

$$h_c^2(f) = \int_0^\infty \mathrm{d}z \int_0^\infty \mathrm{d}m_1 \int_0^1 \mathrm{d}q \, \frac{\mathrm{d}^5 N}{\mathrm{d}z\,\mathrm{d}m_1\,\mathrm{d}q\,\mathrm{d}e\,\mathrm{d}t} \frac{\mathrm{d}t_r}{\mathrm{d}\ln f_{K,r}} \times h^2(f_{K,r}) \sum_{n=1}^{\infty} \frac{g[n, e(f_{K,r})]}{(n/2)^2} \Bigg|_{f_{K,r}=f(1+z)/n}$$

harmonics of gravitational wave signal from the various pairs

physical processes driving BH pair



Crédit: A.Sesana

The PTA signal vs SMBHB population models

$$h_c^2(f) = \int_0^\infty \mathrm{d}z \int_0^\infty \mathrm{d}m_1 \int_0^1 \mathrm{d}q \, \frac{\mathrm{d}^5 N}{\mathrm{d}z\,\mathrm{d}m_1\,\mathrm{d}q\,\mathrm{d}e\,\mathrm{d}t_r} \frac{\mathrm{d}t_r}{\mathrm{d}\ln f_{\mathrm{K},r}} \times h^2(f_{\mathrm{K},r}) \sum_{n=1}^{\infty} \frac{g[n, e(f_{\mathrm{K},r})]}{(n/2)^2} \Bigg|_{f_{\mathrm{K},r}=f(1+z)/n}$$

cosmic merger rate

harmonics of gravitational wave signal from the various pairs

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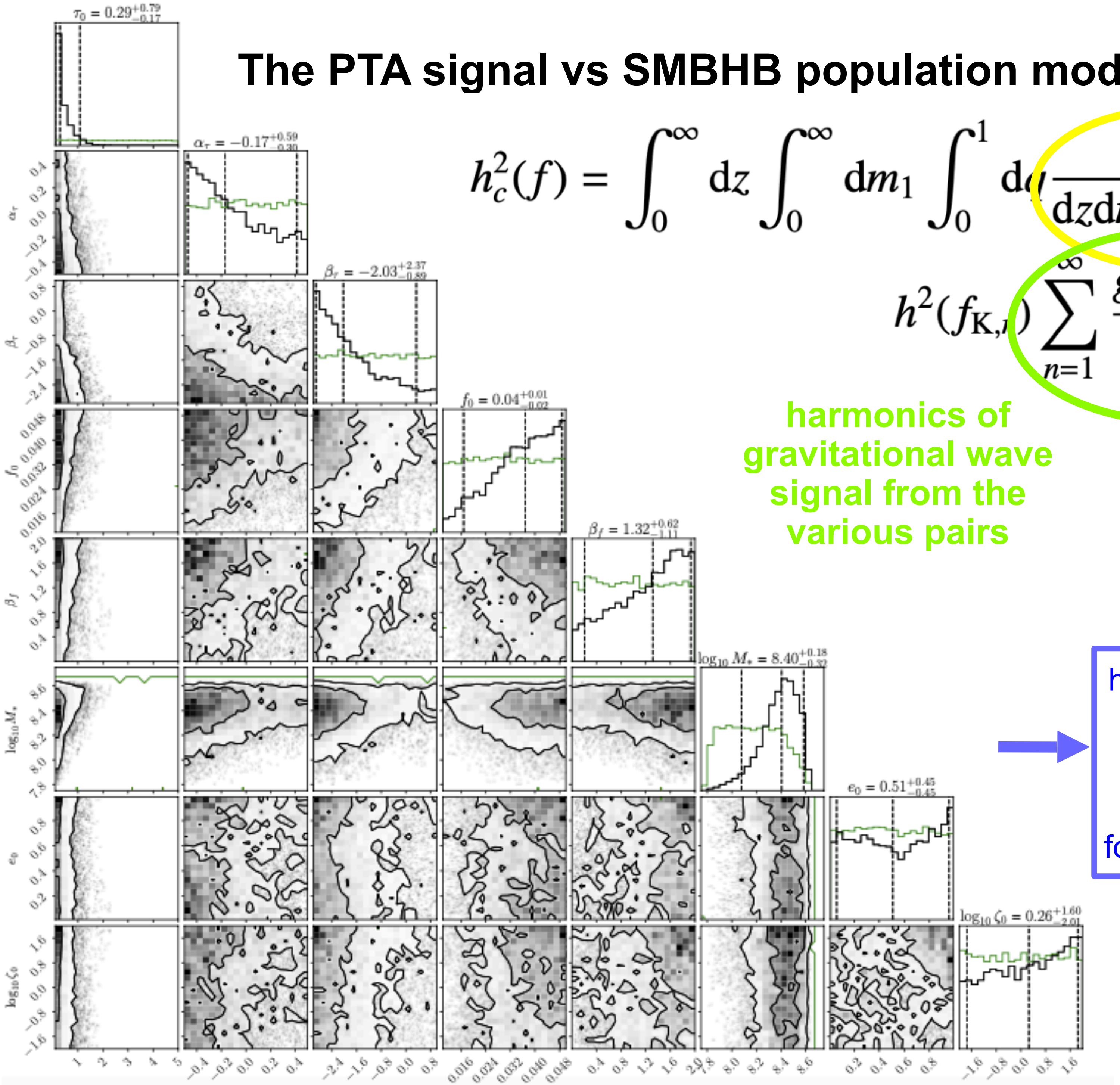


high merger rate densities

short merger timescales

high normalization for BH-bulge mass relation

Antoniadis et al 2023e
(EPTA paper V)

BH merger timescale < 1Gyr

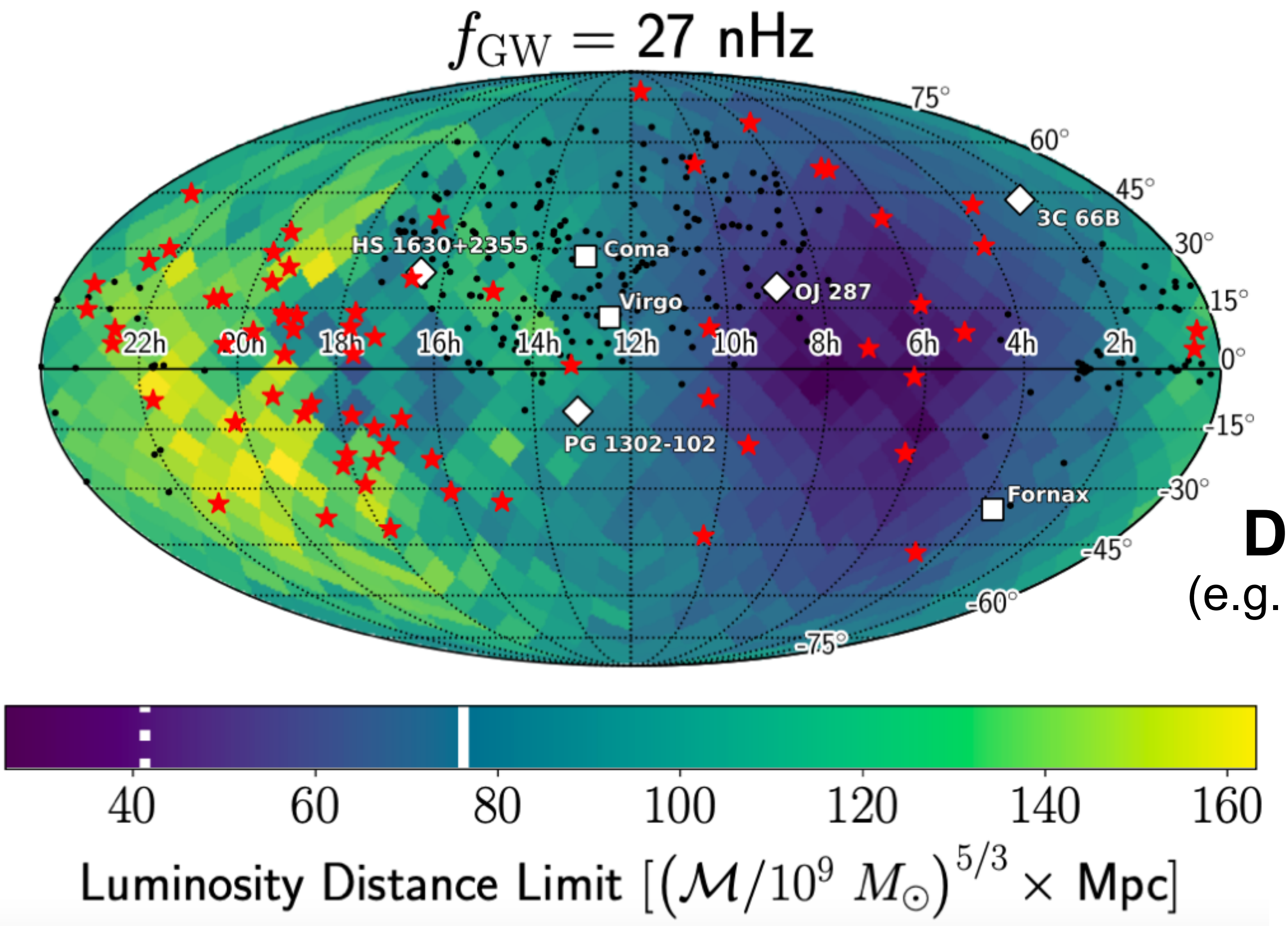
shorter merger times for massive galaxies

high normalisation of pair fraction

massive BH compared to bulge mass

eccentricity and environment effects poorly constrained

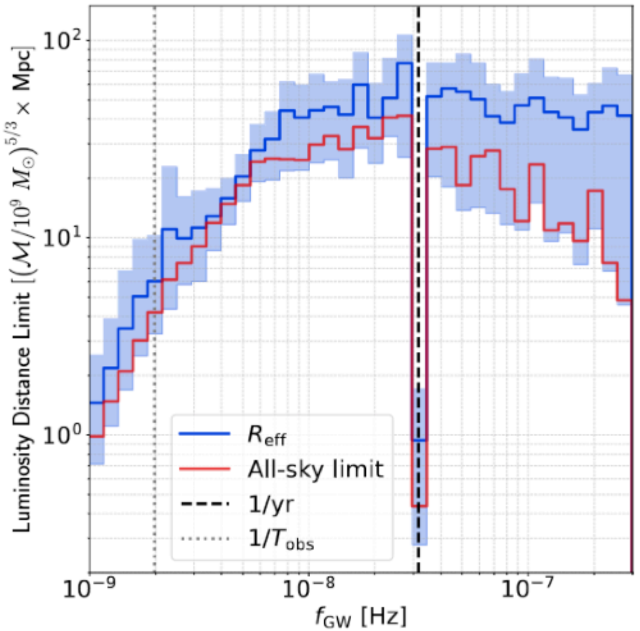
A stochatic background
or
a unique source
or
both ?

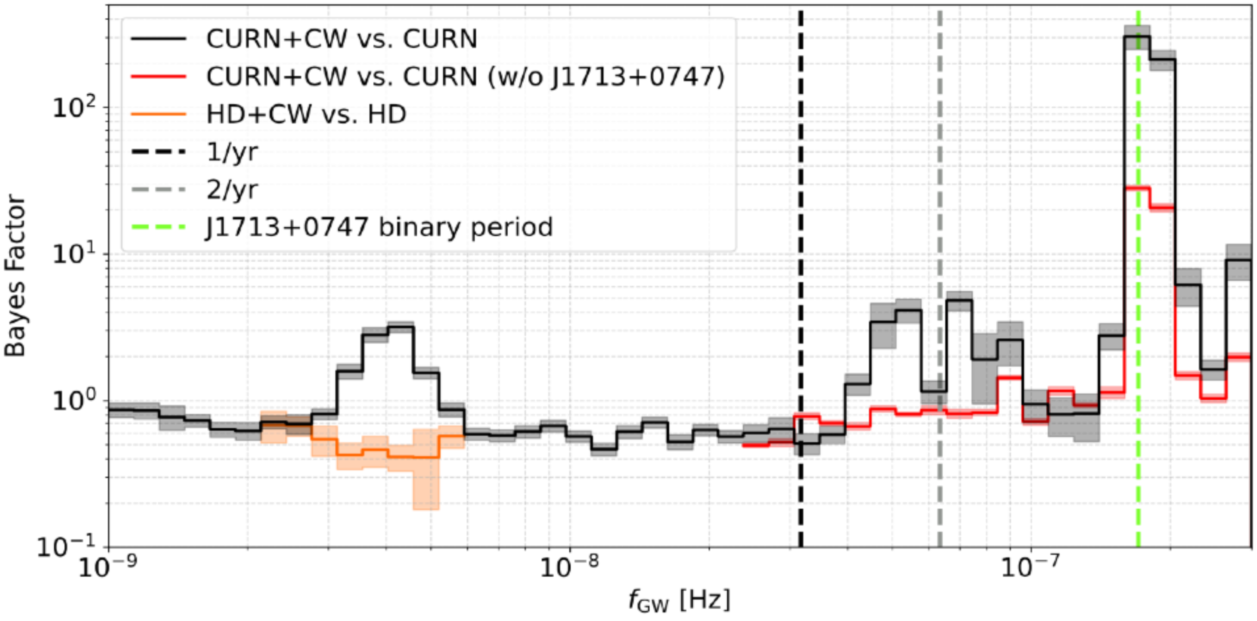


Distance limit skymap

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

continuous wave search,
single source candidates





A stochatic background
or
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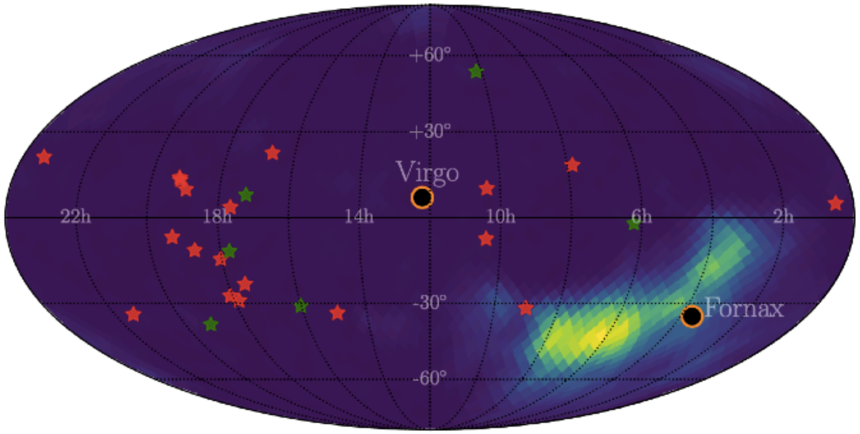


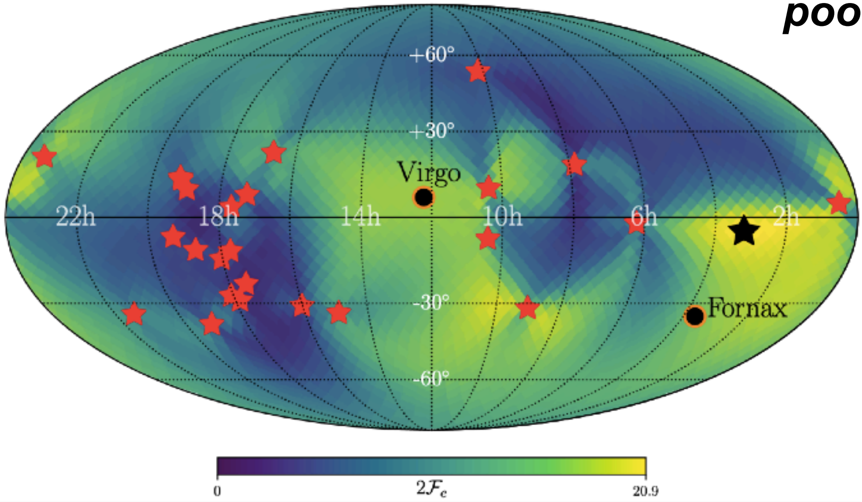
Bayesian

A signal at 4.6 nHz

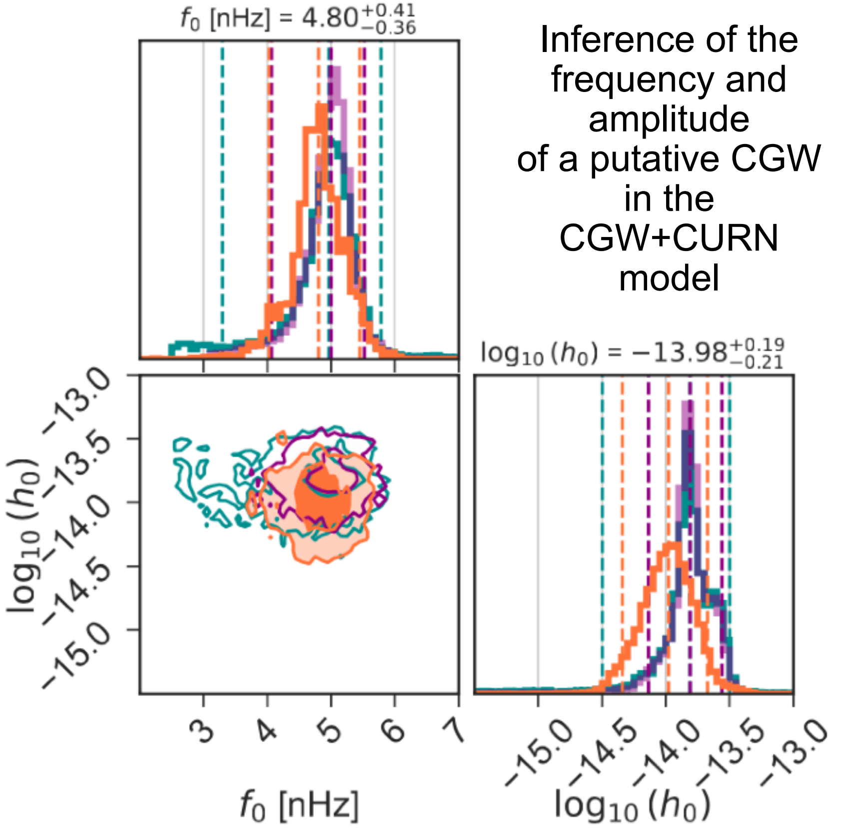
poor sky position determination

very high Bayes factor

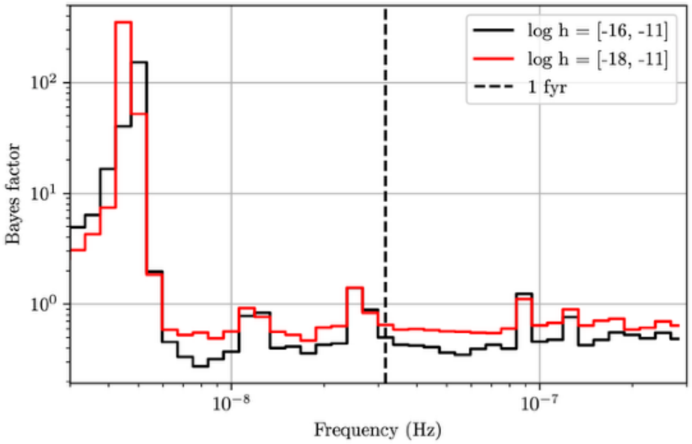
Antoniadis et al 2023e
(EPTA)



Frequentist



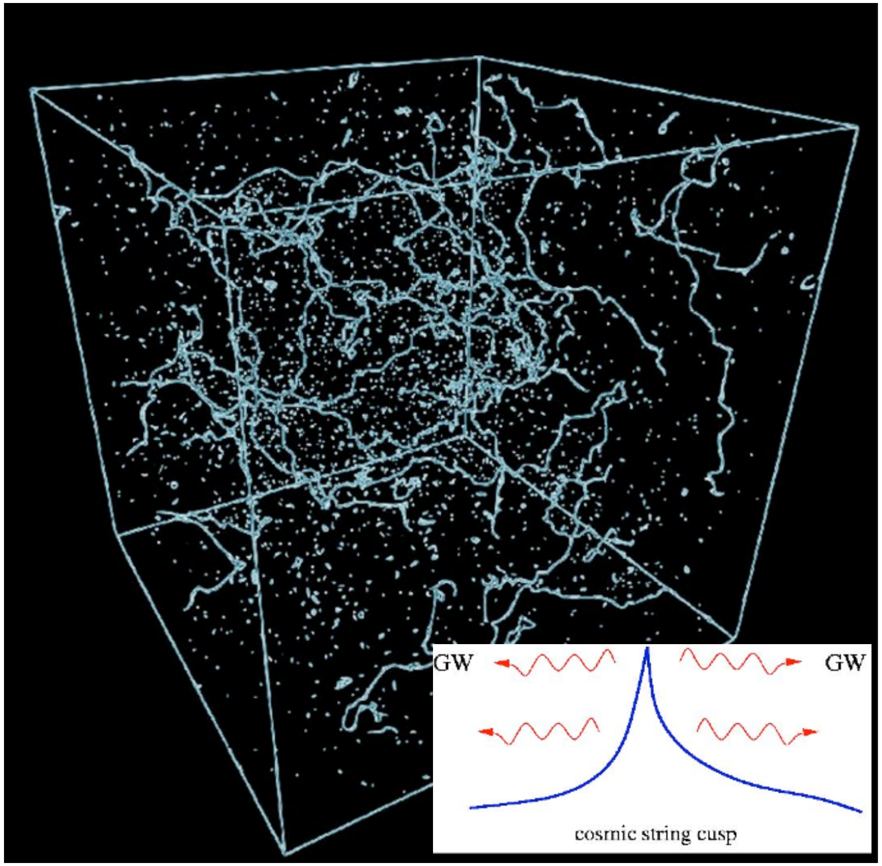
Inference of the
frequency and
amplitude
of a putative CGW
in the
CGW+CURN
model

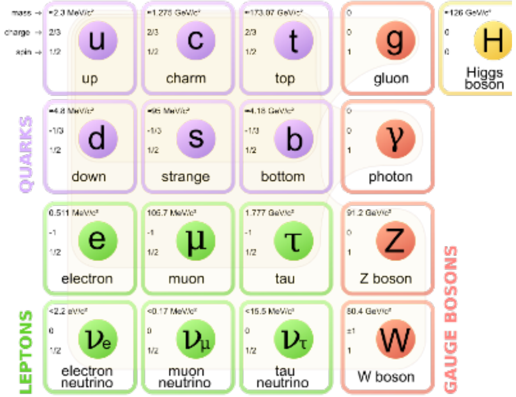


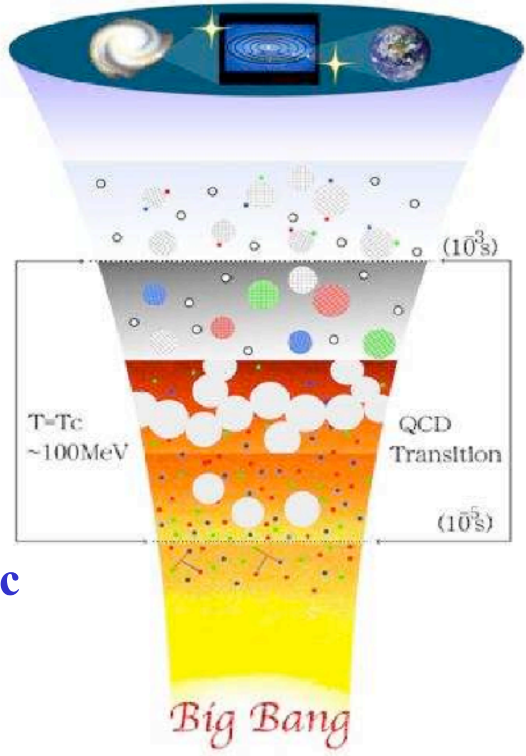
Bayes Factor
spectral distribution

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

Cosmic strings emission

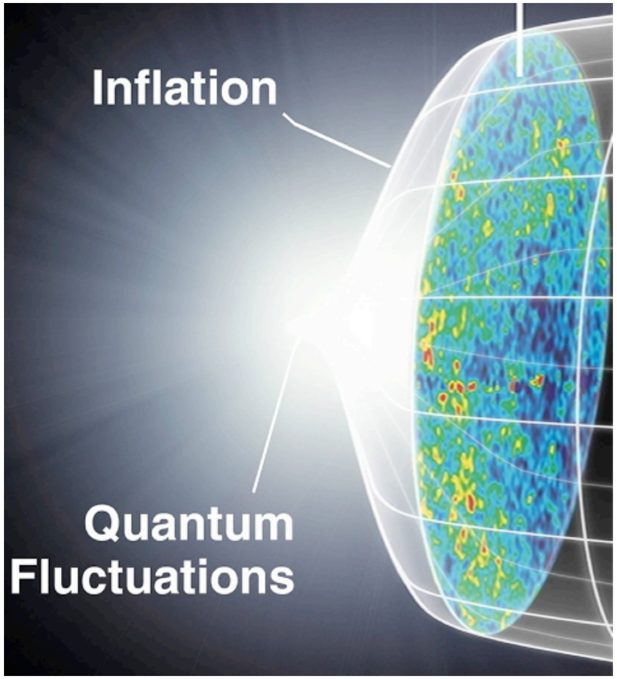






(Magneto)-hydrodynamic turbulence during QCD

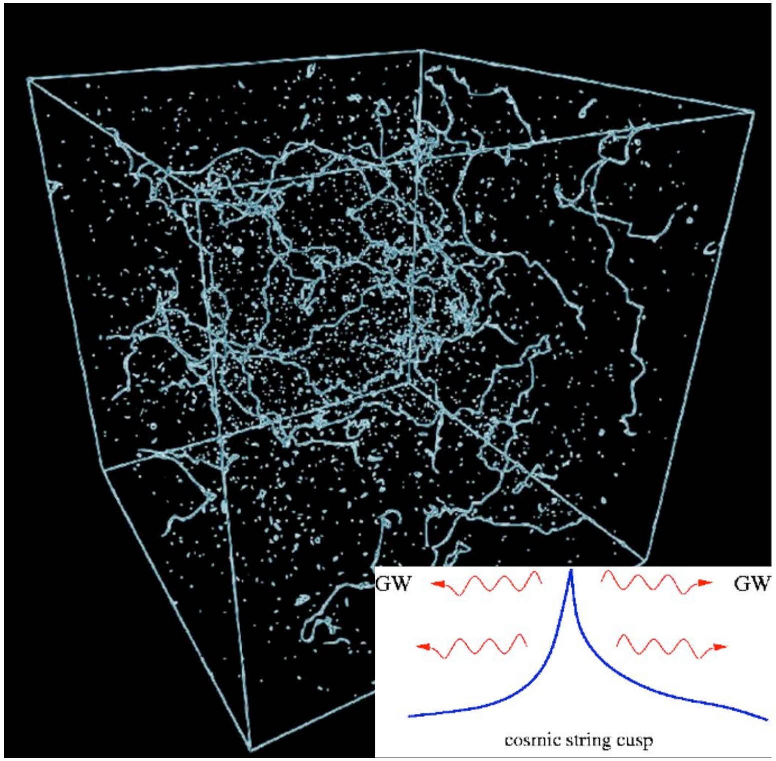
Quantum fluctuation of the metric during inflation



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

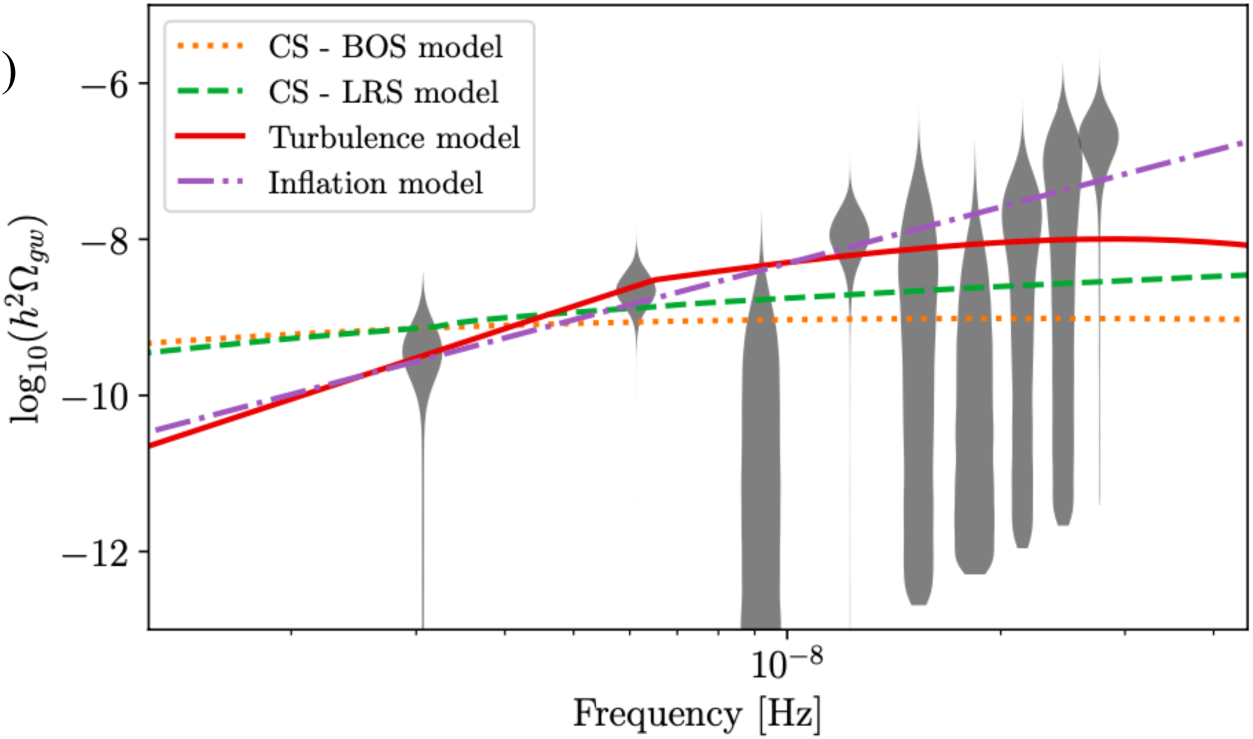
The theory of cosmic strings

(tension, number of « kinks » or « cusps »)



→ Loops are produced and emit GWs via oscillation and burst emission (cusp, kink, kink-kink collision)

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

$$\frac{\mathrm{d}\rho_{gw}}{\mathrm{d}f} = \frac{2G\mu^2}{f}\sum_b \frac{N_b\Gamma^{(b)}}{\zeta(q_b)} \times \sum_{n=1}^{+\infty}\int \frac{n^{1-q_b}\,\mathrm{d}z}{(1+z)^5 H(z)}\,\mathbf{n}\left[\frac{2n}{(1+z)f}, t(z)\right]$$

summing over cosmic time

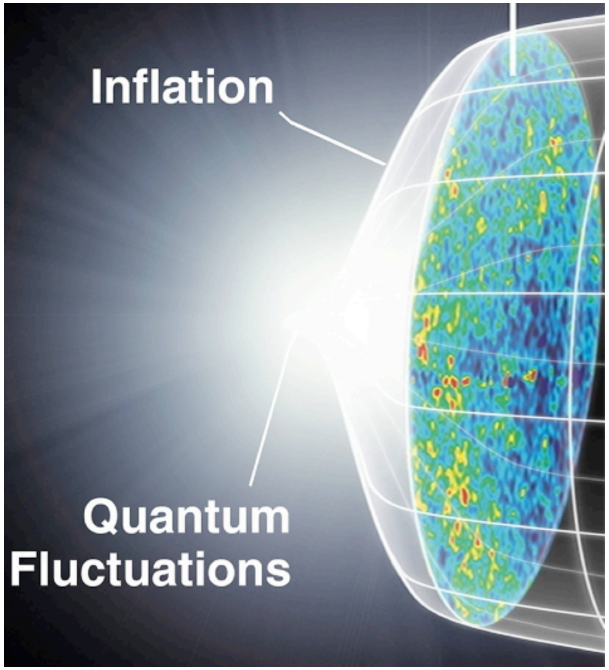
Loop number density
(two models used: BOS, LRS)

(Courtesy H.Quelquejay)

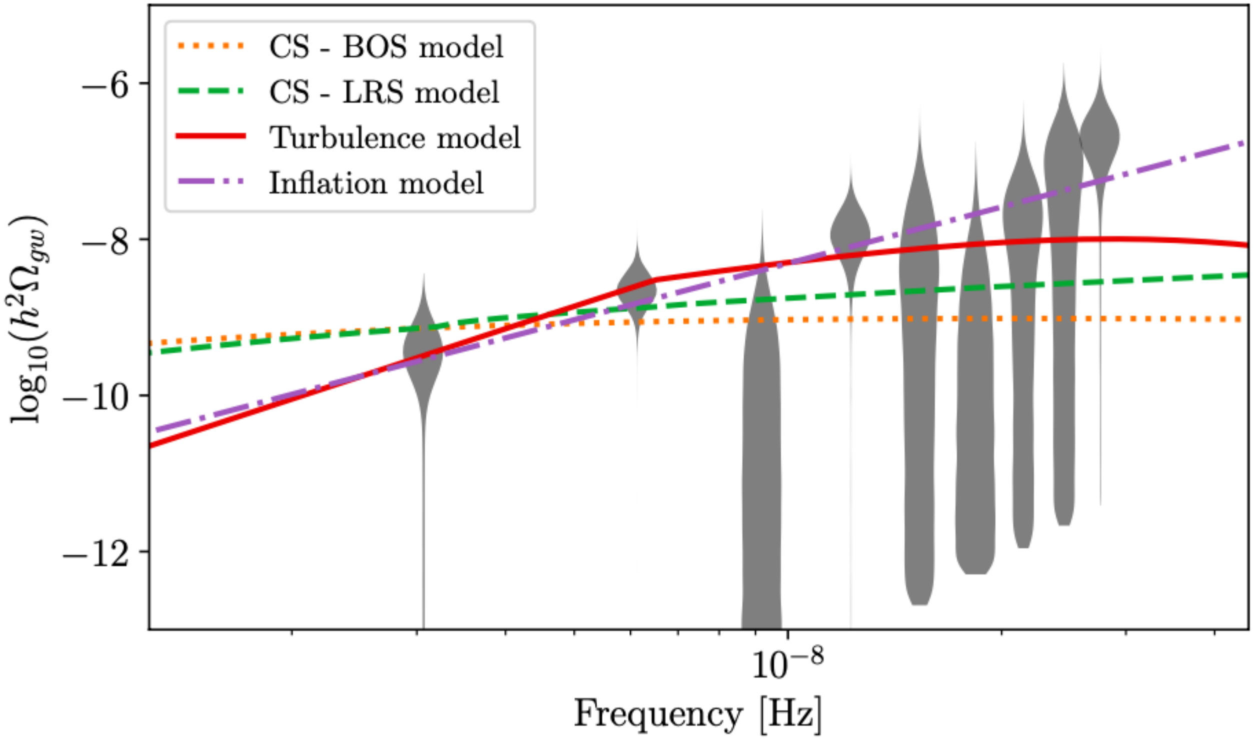
But also, some constraints on the cosmology of the primordial Universe

The epoch of inflation

(tensor/scalar perturbation ratio, spectral index of tensor perturbation)



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



Tensor to scalar perturbation ratio

Tensor spectral index

$$\Omega_{\rm GW}(f) \approx 1.5 \times 10^{-16} \left(\frac{r}{0.032}\right)\left(\frac{f}{f_*}\right)^{n_T}$$

CMB scale (~ 0.05 Mpc^{-1})

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

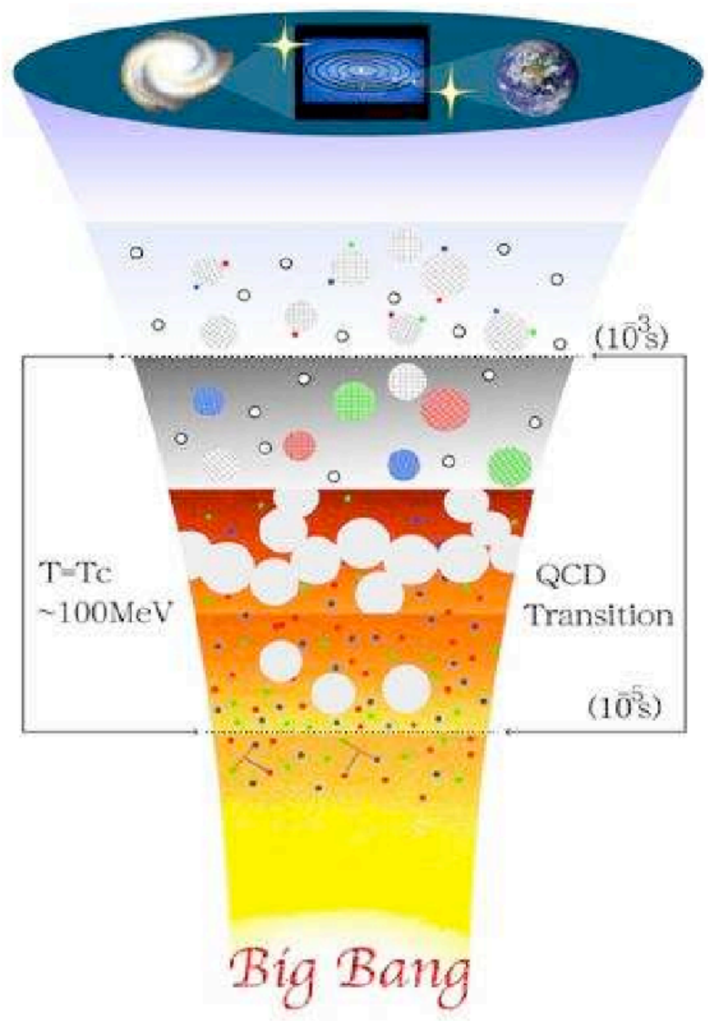
tensor/scalar perturbation ratio → $\log_{10}$ r = -13.1

spectral index of tensor perturbation → n_T = 2.4

not compatible with slow roll inflation $n_T \simeq 0$

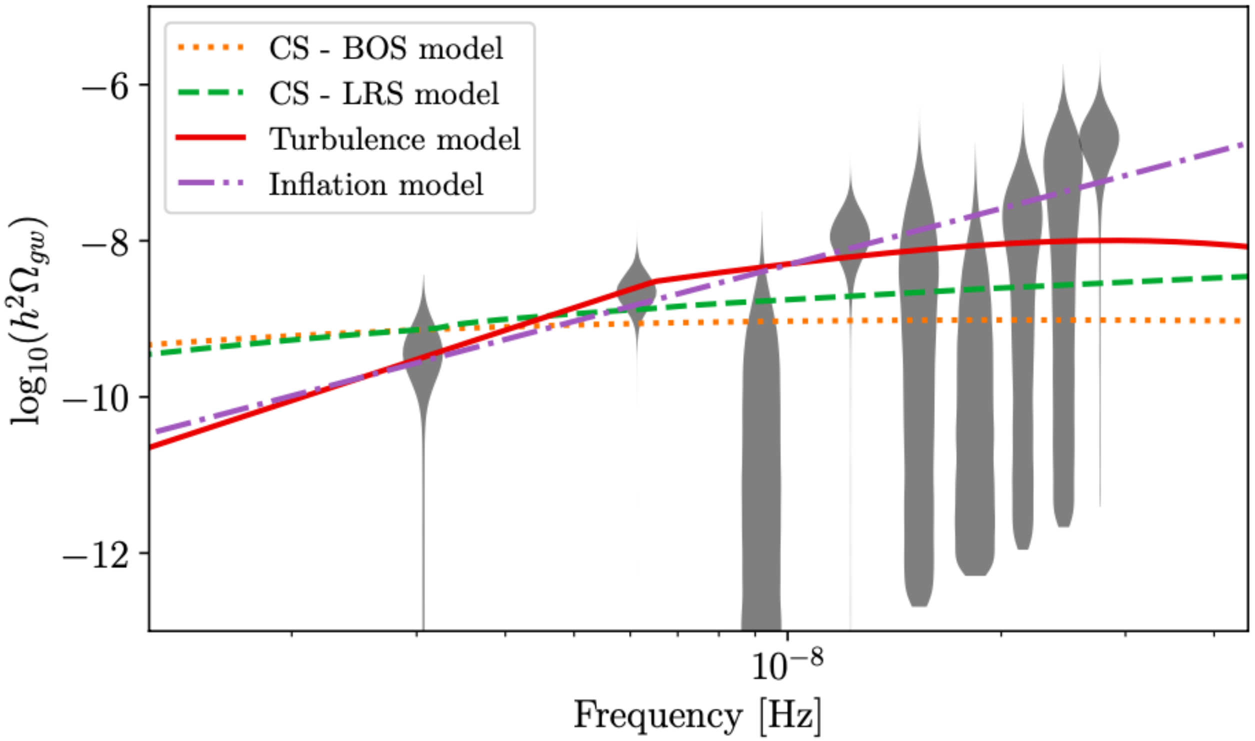
But also, some constraints on the cosmology of the primordial Universe

Quantum chromodynamics
= quarks-hadrons transition



$$\Omega_{\rm GW}(f) = 3\,\mathcal{A}\,\Omega_*^2\,(\lambda_*\mathcal{H}_*)^2\,F_{\rm GW,0}\,S_{\rm turb}(\lambda_* f)$$

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



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

temperature scale T* → 140 MeV

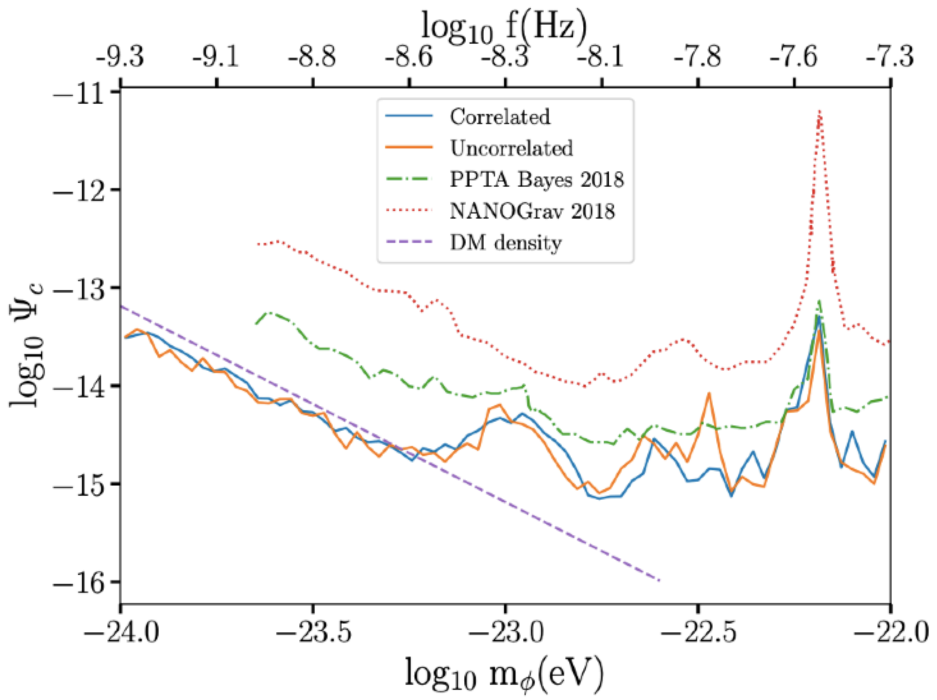
ratio of the turbulent energy density to the radiation one Ω* → 0.3

turbulence characteristic length scale λ*H* → 1

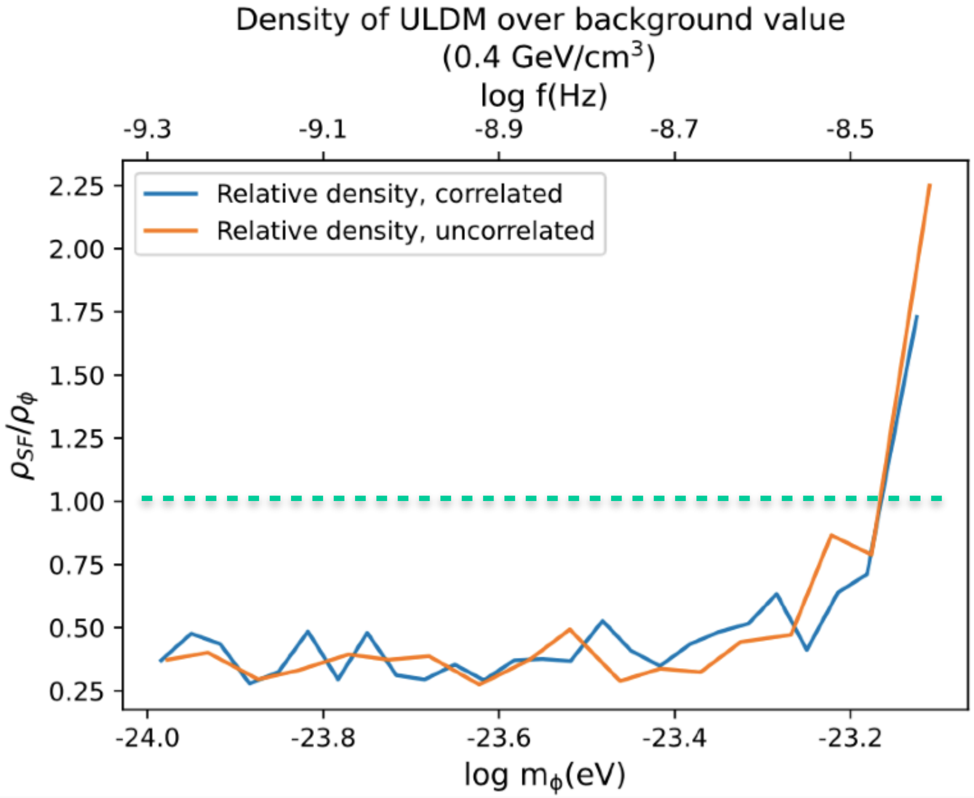
Implications on ultra light (scalar-field) dark matter content

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



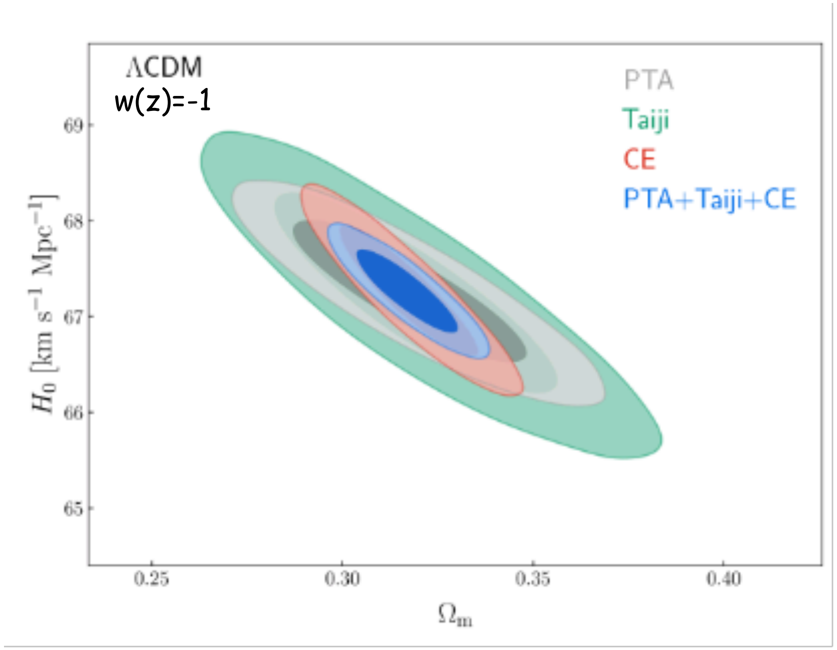
Smarra et al 2023

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

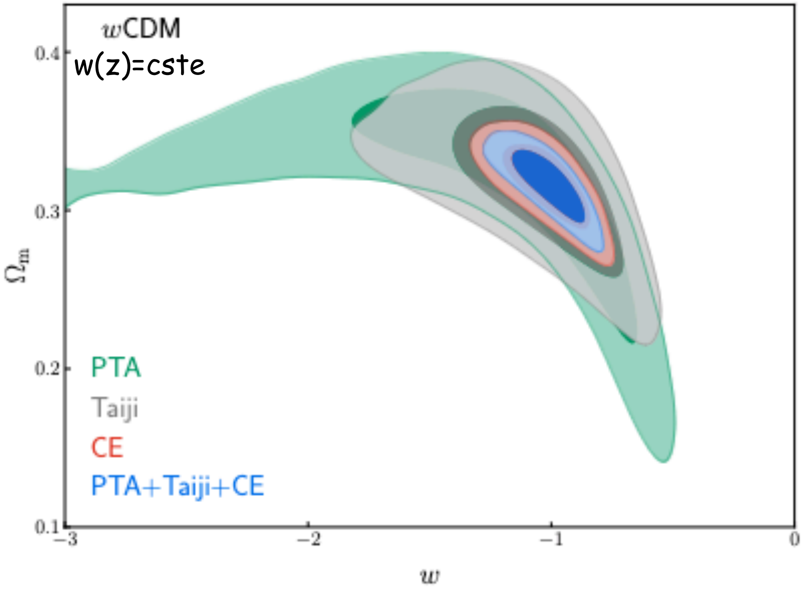
Prospects…

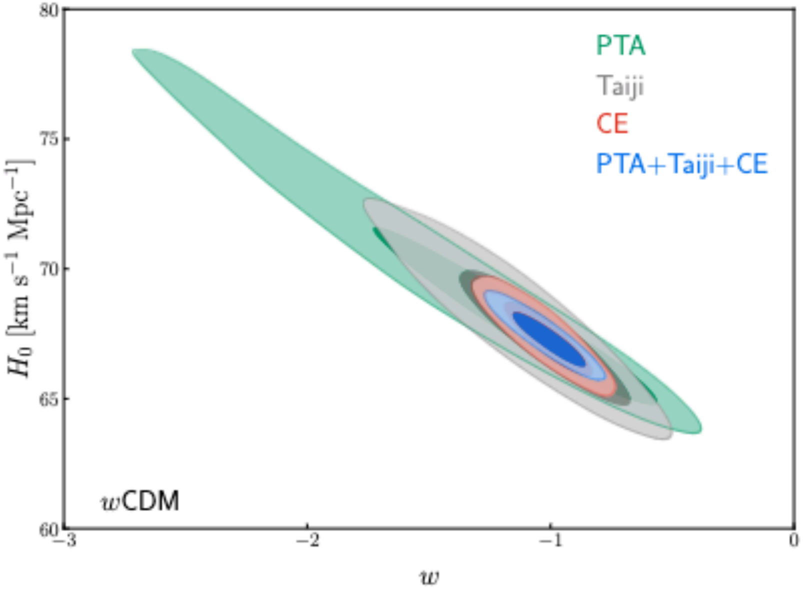
Gravitational waves as standard sirens

Luminosity distances from GW
Redshifts from EM counterpart



Jin et al 2023
Compare CE, Taiji and PTA/SKA
Simulate 200 pulsars @ 20 ns precision (10 years)
Simulate 35 bright SMBHB's in PTA band
(28 sources x 5 years for Taiji)
(1000 sources x 10 years for CE)





Prospects…

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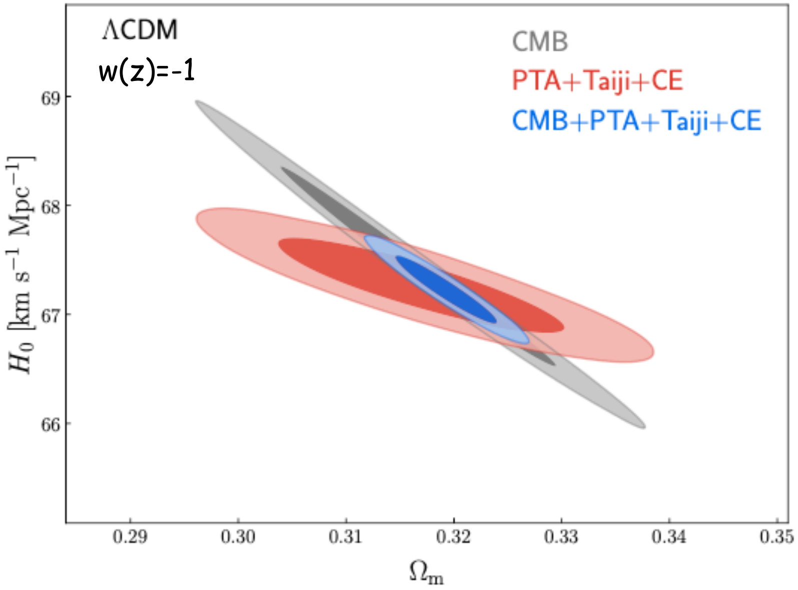

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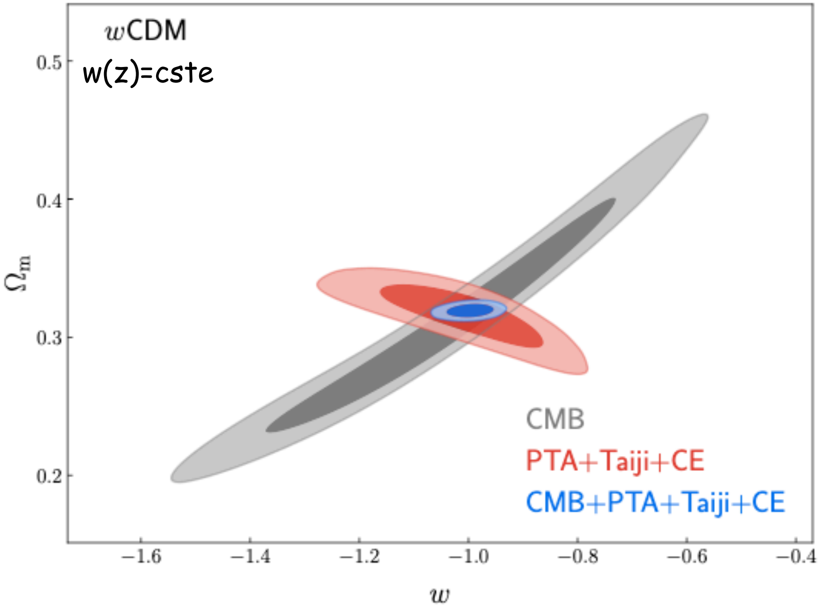

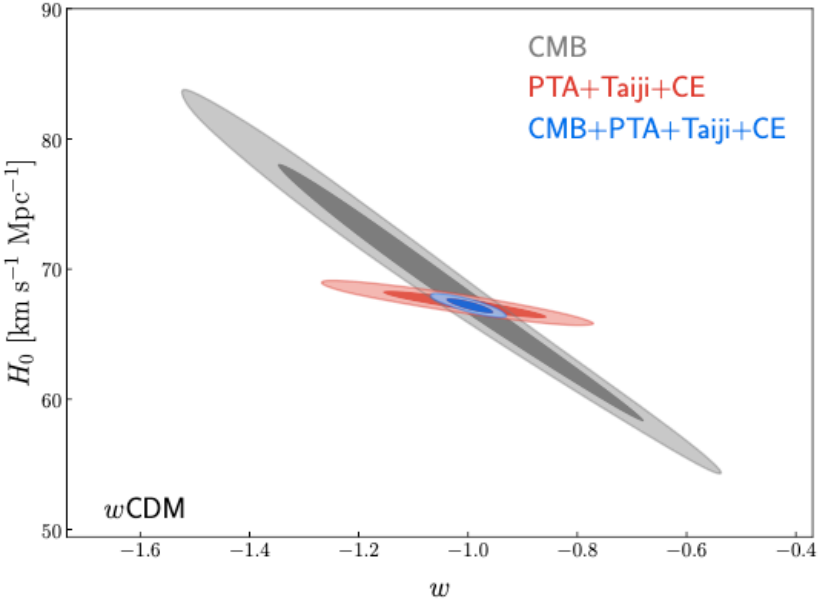

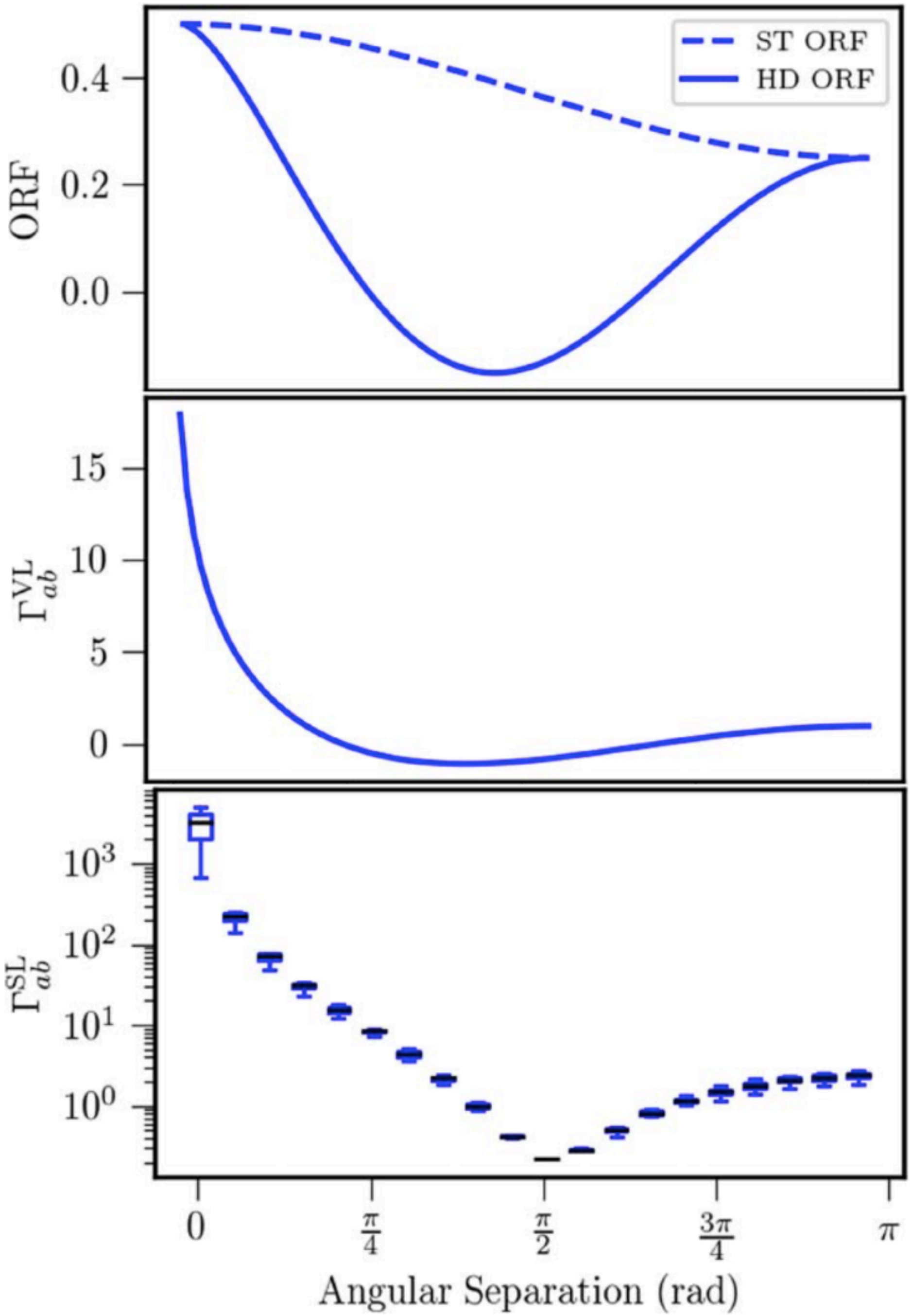

Arzoumanian et al 2021

Prospects…

Testing Gravity theories

GR predicts two (tensor-)transverse polarisations

general metric theories have up to six GW polarization modes

Tensor-Transverse (+ , x)
Scalar-Transverse (1)
Vector-Longitudinal (x-vector , y-vector)
Scalar-Longitudinal (1)

each produces a different ORF

→ PTA can probe many independent projections of GW polarisation, with better response to longitudinal modes

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