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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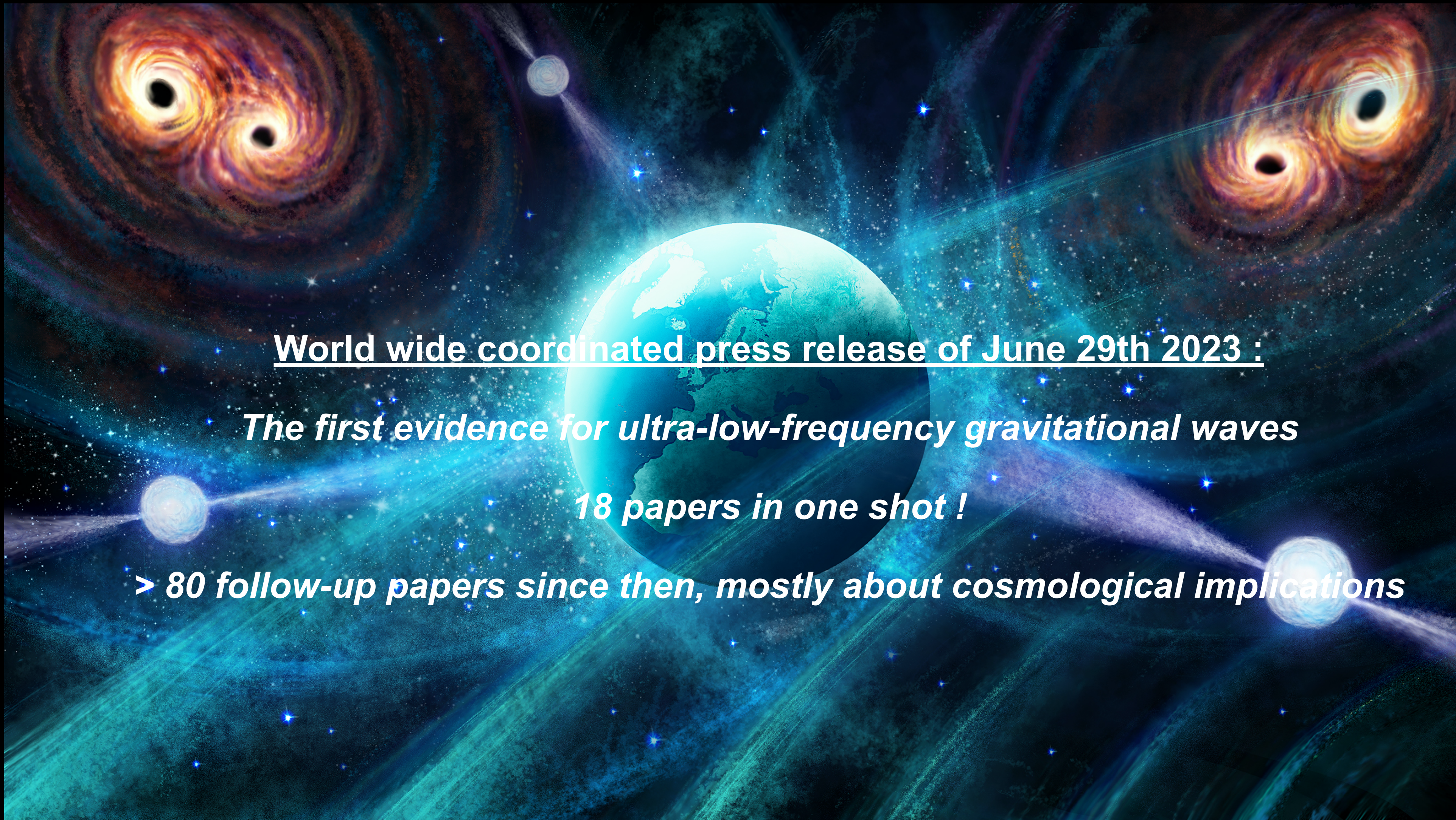

World wide coordinated press release of June 29th 2023 :

The first evidence for ultra-low-frequency gravitational waves

18 papers in one shot !

> 80 follow-up papers since then, mostly about cosmological implications

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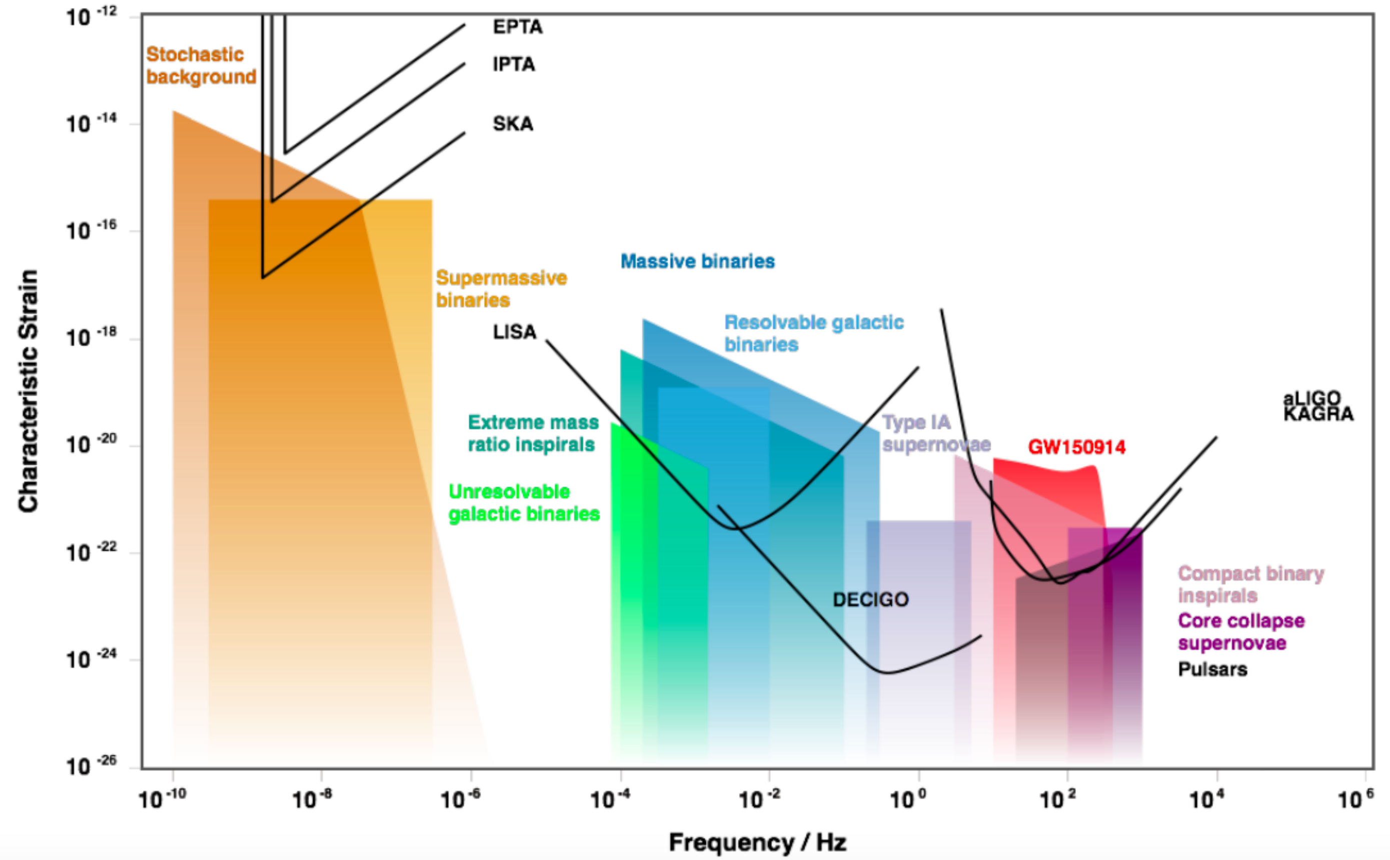
the gravitational landscape



nanoHz — microHz

The nanoHertz domain

Super Massive Black Hole Binaries (SMBHB)

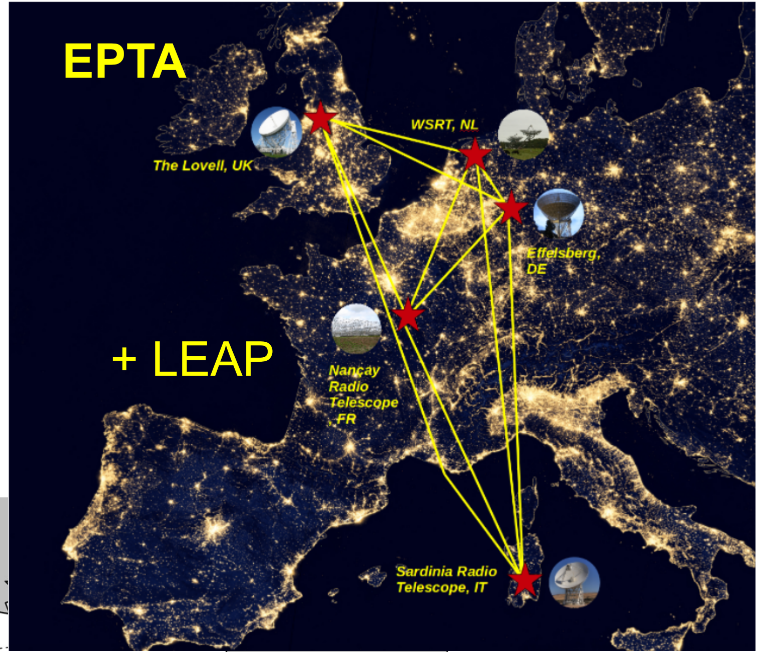
Cosmic string loops

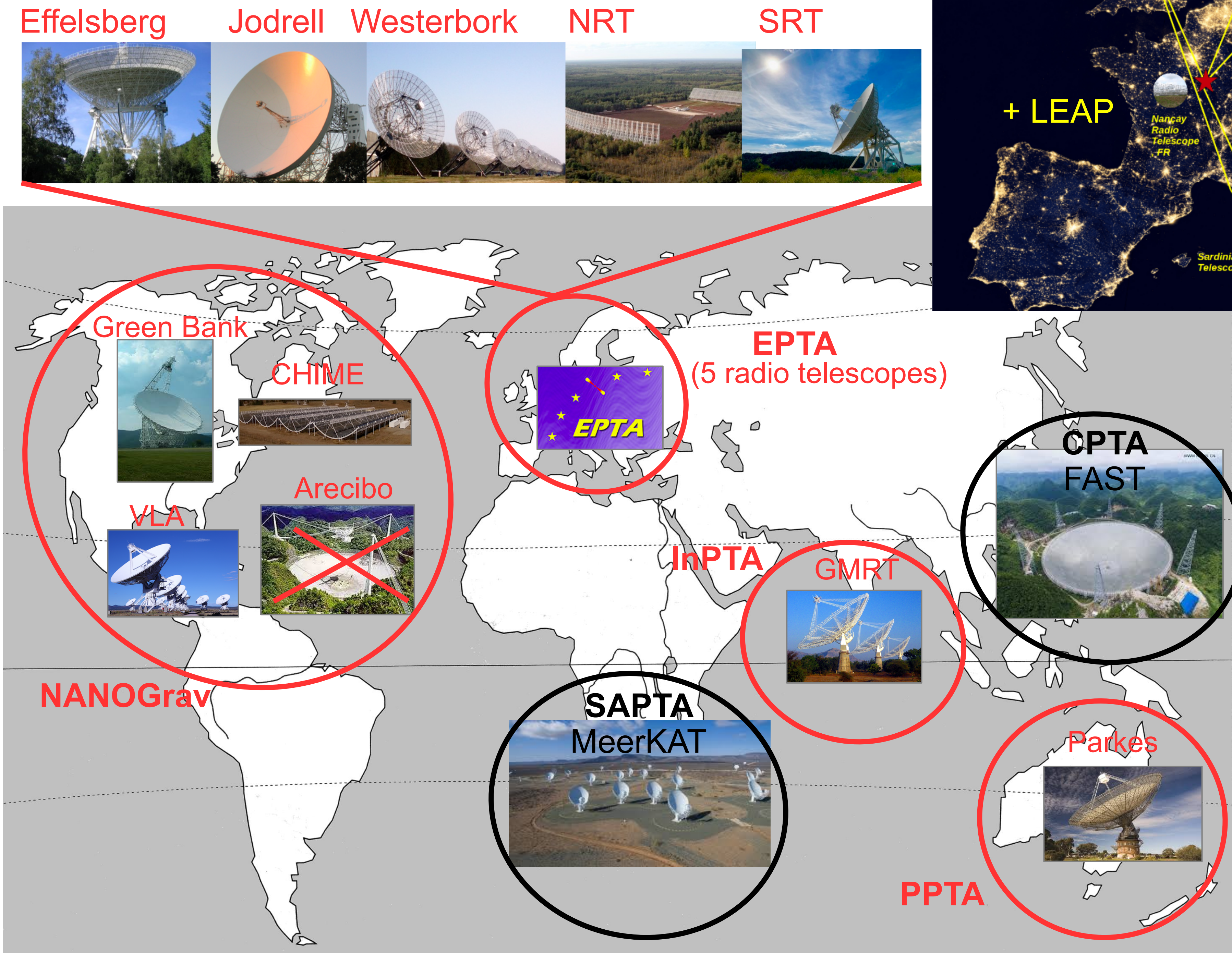
Relics of inflation

First-order phase transition

+ fuzzy dark matter

The International Pulsar Timing Array



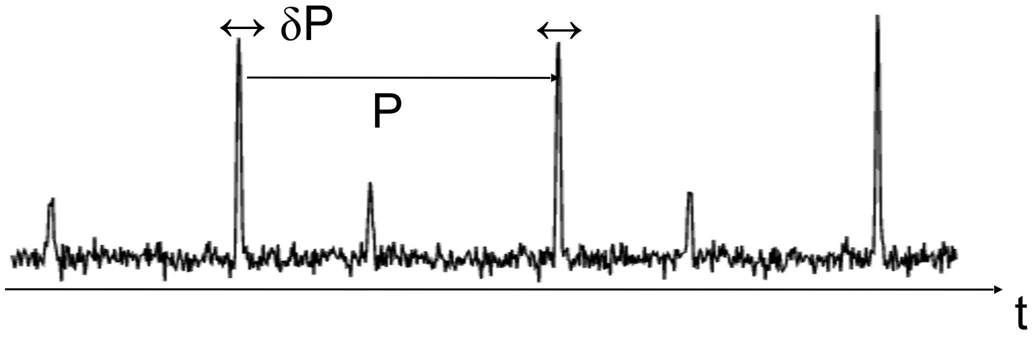


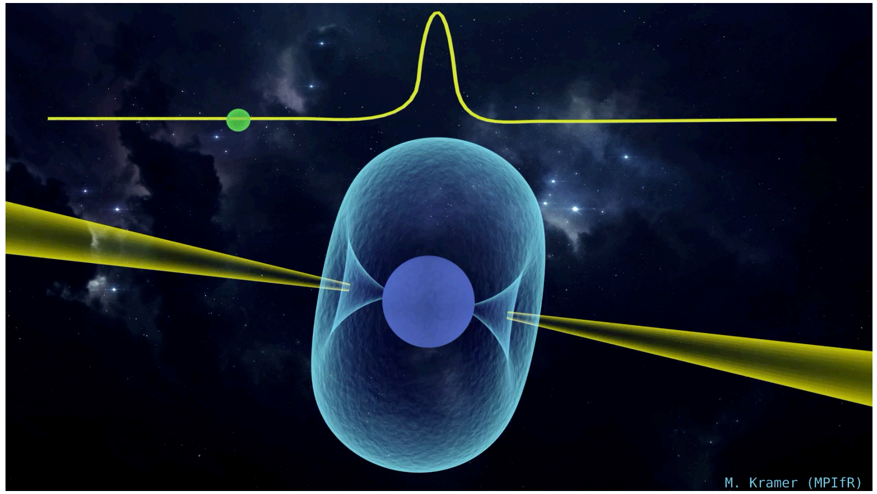
EPTA/InPTA, PPTA and NANOGrav

publish coherent results !

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

Pulsar Timing Arrays : principles

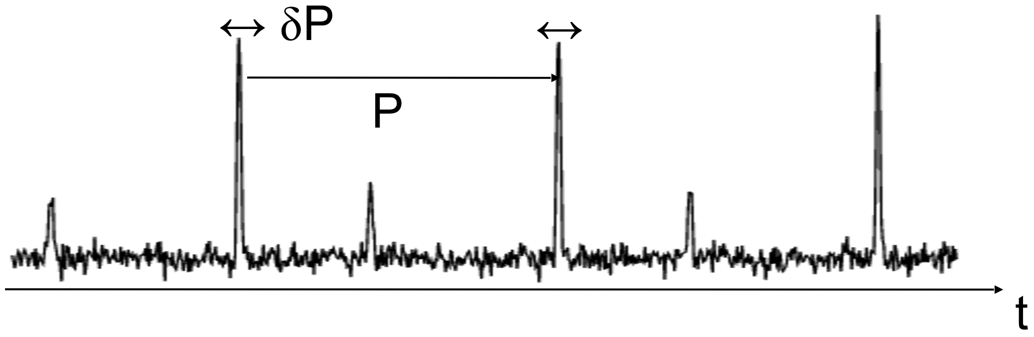


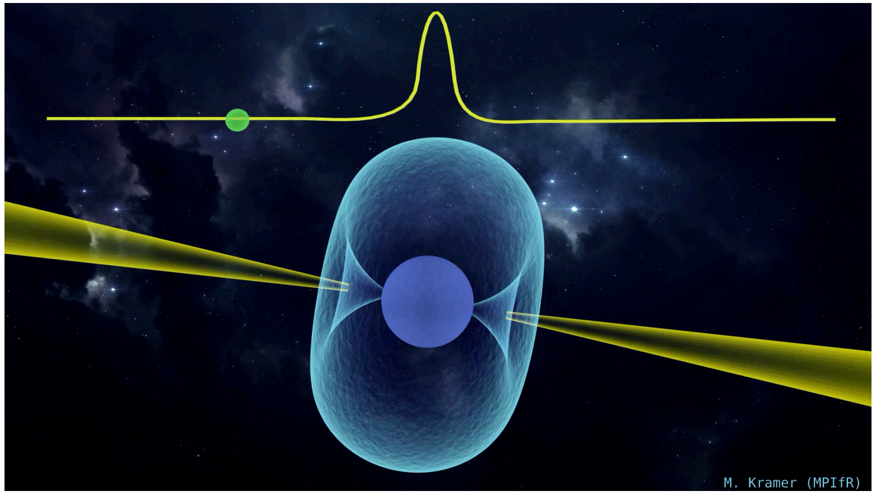


a highly magnetized neutron star
rapidly rotating (few ms to few s)
a radiation beam aligned with magnetic axis
lighthouse behaviour
observed from radio to gamma rays

60 are very stable → natural clocks

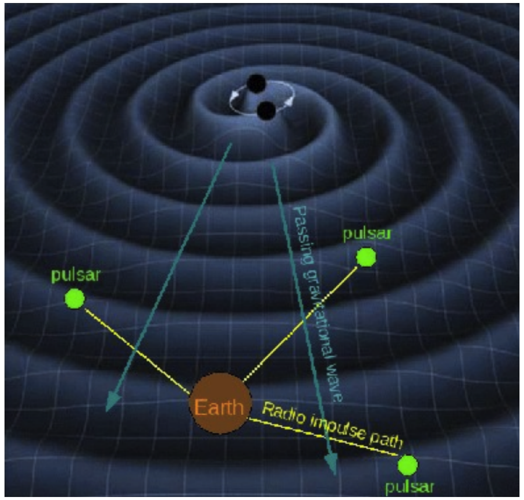
Pulsar Timing Arrays : principles





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*

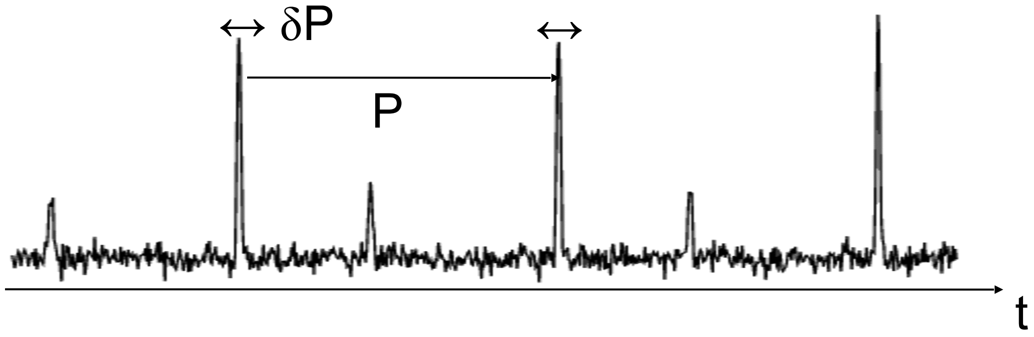


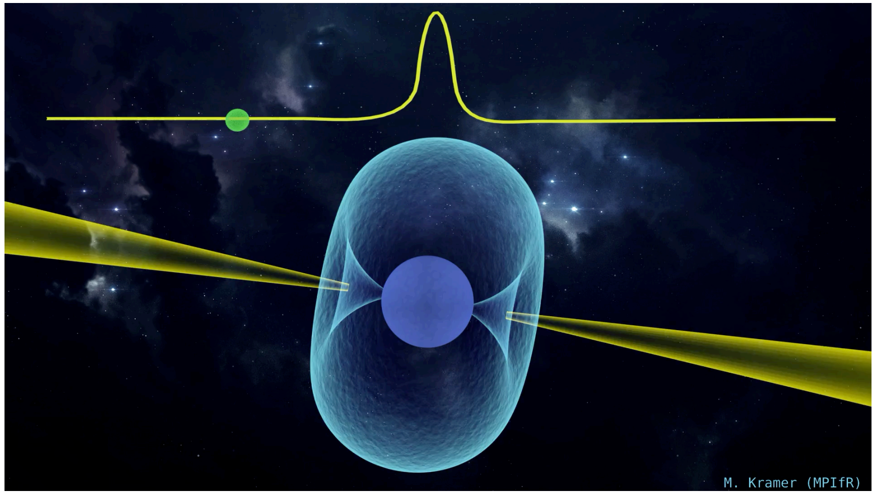
With timing uncertainties dt (~100 ns) and observation time spans T (~25 years)
→ PTA are sensitive to *amplitudes ~ dt/T and to frequencies f ~ 1/T*

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

Pulsar Timing Arrays : principles





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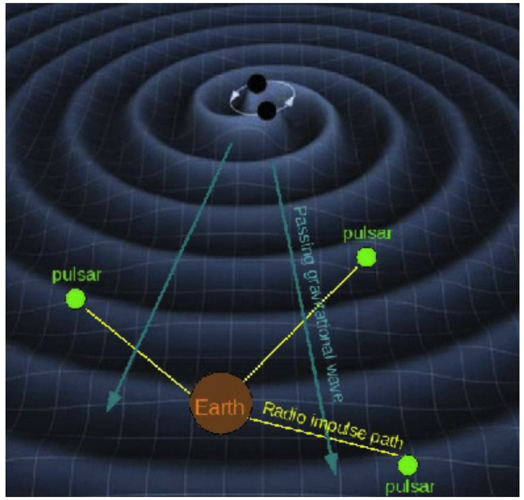

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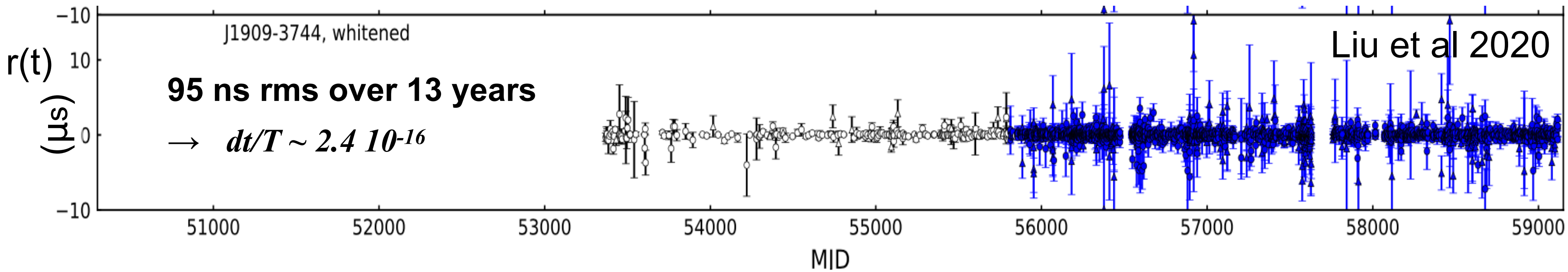

Pulsar Timing Arrays : principles

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 ν and $\dot{\nu}$ are associated with the physical processes causing pulsars to spin down

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2) Timing model

$$t_{SSB} = \overbrace{t_{topo} + t_{corr} - \delta D/f_{obs}^2 + \Delta_{R\odot} + \Delta_\pi + \Delta_{S\odot} + \Delta_{E\odot} + \Delta_R + \Delta_S + \Delta_E + \Delta_A}^{\boldsymbol{\tau}^{\mathrm{TM}}}$$

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- t_{corr}: clock
- $\delta D/f_{obs}^2$: dispersion
- $\Delta_{R\odot} + \Delta_{\pi} + \Delta_{S\odot} + \Delta_{E\odot}$: Solar System Römer, parallax, Shapiro and Einstein delays
- $\Delta_R + \Delta_S + \Delta_E + \Delta_A$: binary system Römer, Shapiro, Einstein and Aberration delays

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clock

dispersion

Solar System
Römer, parallax, Shapiro
and Einstein delays

binary system
Römer, Shapiro, Einstein
and Aberration delays

3) Full noise model

Noise model (stochastic)

observed TOA $= \boldsymbol{\tau}^{\mathrm{TM}} + \overbrace{\boldsymbol{\tau}^{\mathrm{WN}} + \boldsymbol{\tau}^{\mathrm{SN}} + \boldsymbol{\tau}^{\mathrm{DM}} + \boldsymbol{\tau}^{\mathrm{CN}}} + \boldsymbol{\tau}^{\mathrm{GW}}$

- $\boldsymbol{\tau}^{\mathrm{TM}}$: Timing Model (deterministic)
- $\boldsymbol{\tau}^{\mathrm{WN}}$: meas. (white) noise
- $\boldsymbol{\tau}^{\mathrm{SN}}$: pulsar spin (red) noise
- $\boldsymbol{\tau}^{\mathrm{DM}}$: DM + scatter (red) noise
- $\boldsymbol{\tau}^{\mathrm{CN}}$: clock + SS ephem. (red) noise
- $\boldsymbol{\tau}^{\mathrm{GW}}$: GWB (red) noise

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

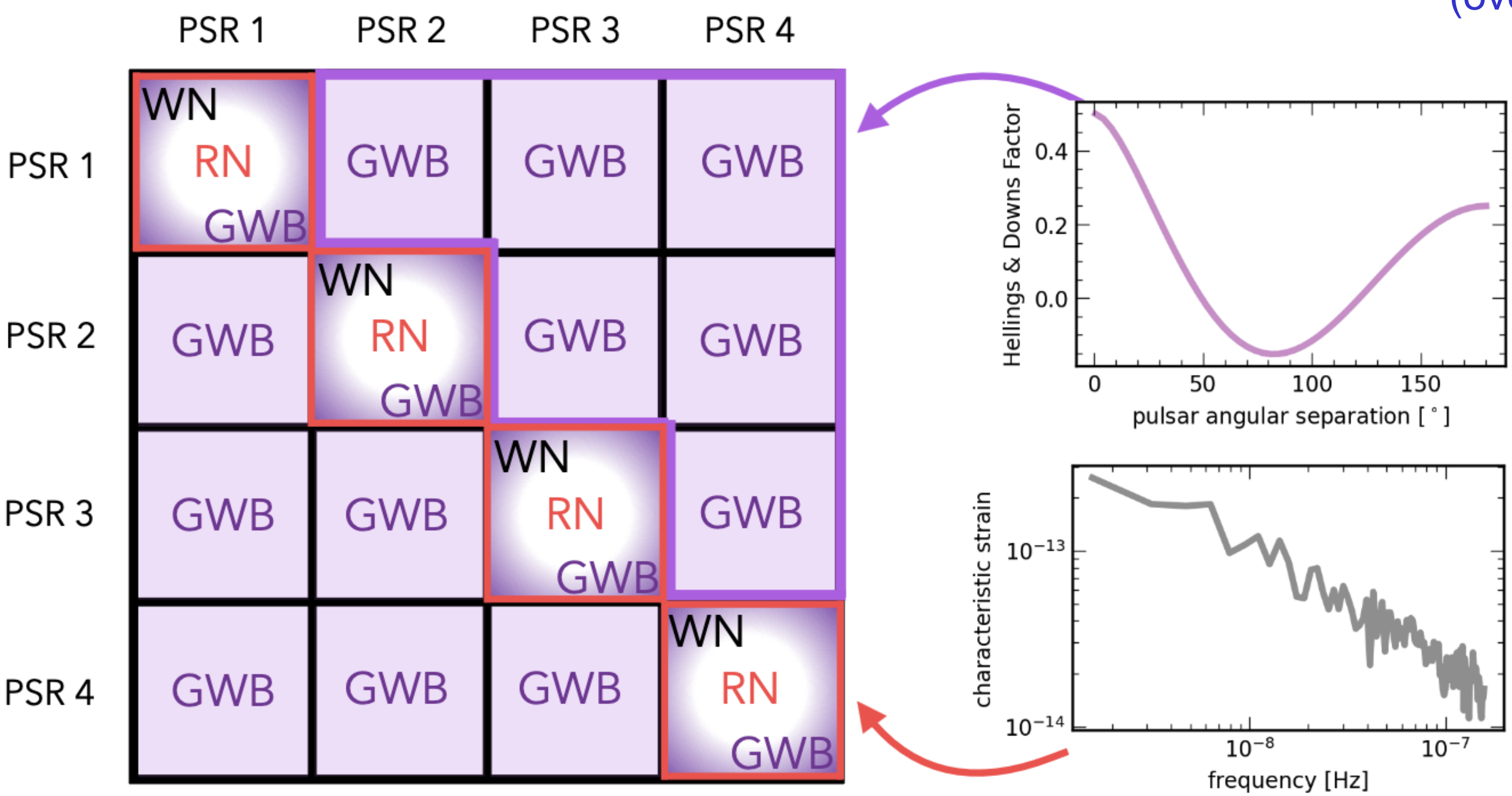
$$C \sim \underbrace{\Gamma_{ab}\rho_i\delta_{ij}}_{\text{GW}} + \underbrace{\epsilon_i\delta_{ij}}_{\text{clock/eph.}} + \underbrace{\eta_i\delta_{ab}\delta_{ij}}_{\text{astro}\phi} + \underbrace{\kappa_{ai}\delta_{ab}\delta_{ij}}_{\text{indiv. rot./disp.}}$$

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

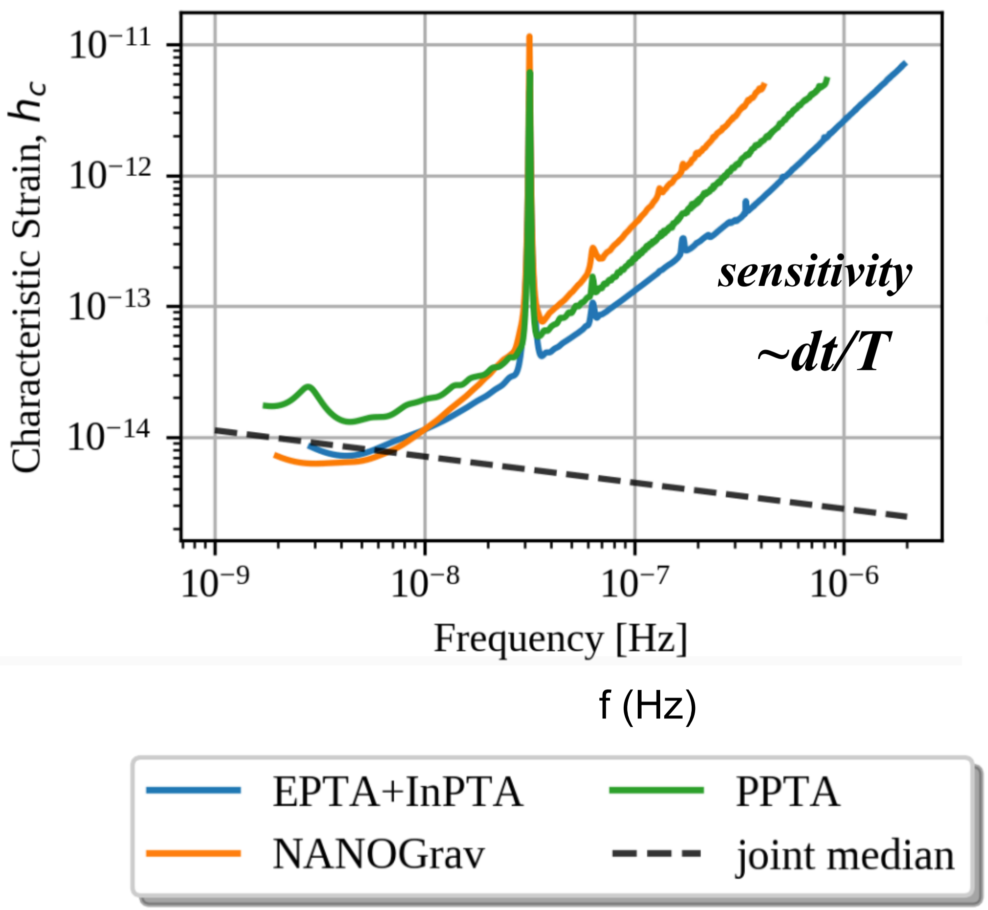
The GW term depends both on the amplitude of the signal as a function of its sky position and on the «antenna pattern »

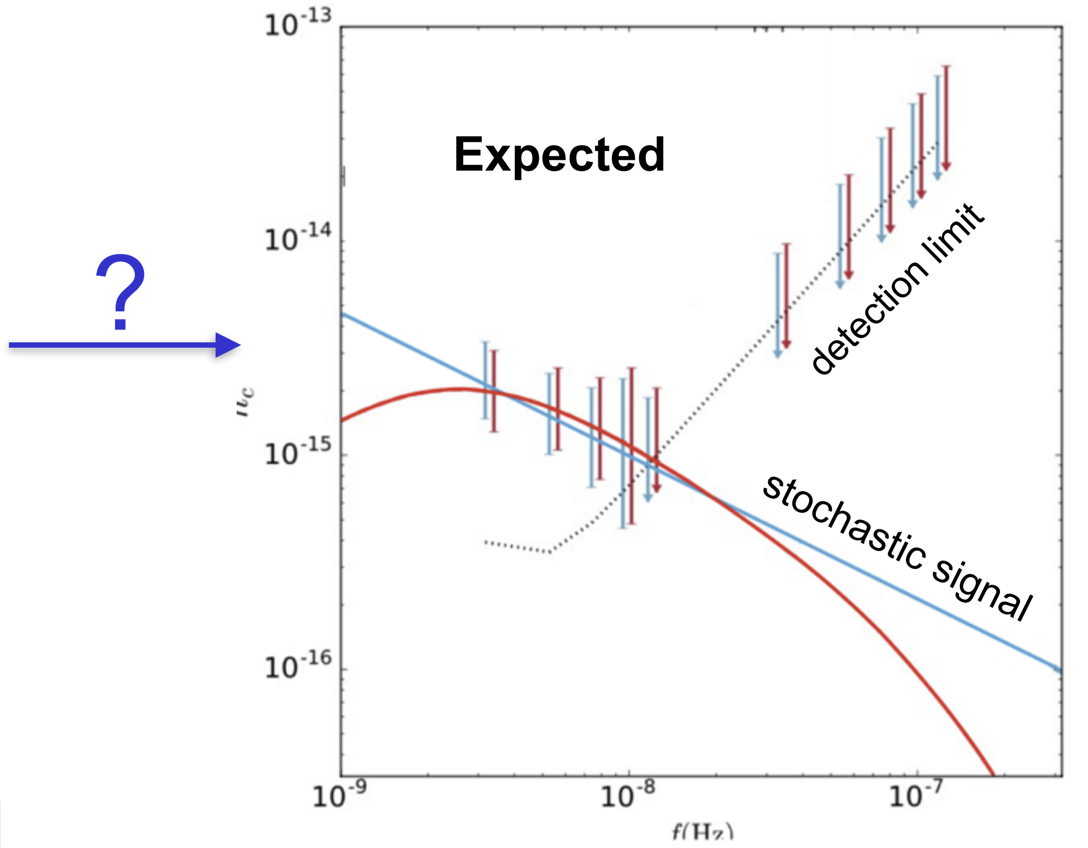
$$\Gamma_{ab} = \frac{3}{8\pi}(1+\delta_{ab})\int_{S^2} d\hat{\Omega}\ P(\hat{\Omega}) \sum_q F_a^q(\hat{\Omega})F_b^q(\hat{\Omega})$$

(overlap reduction function)



Taylor et al 2022



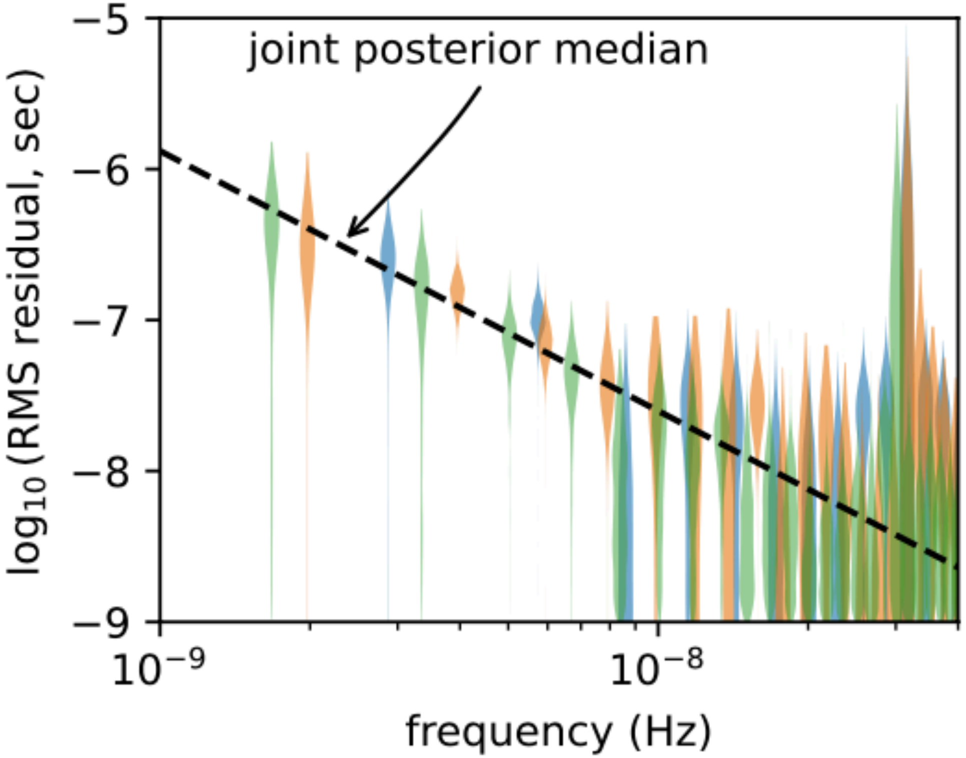


$h_c(f) \ = \ A_{\rm yr}(f/f_{\rm yr})^{\alpha}$ (characteristic strain)

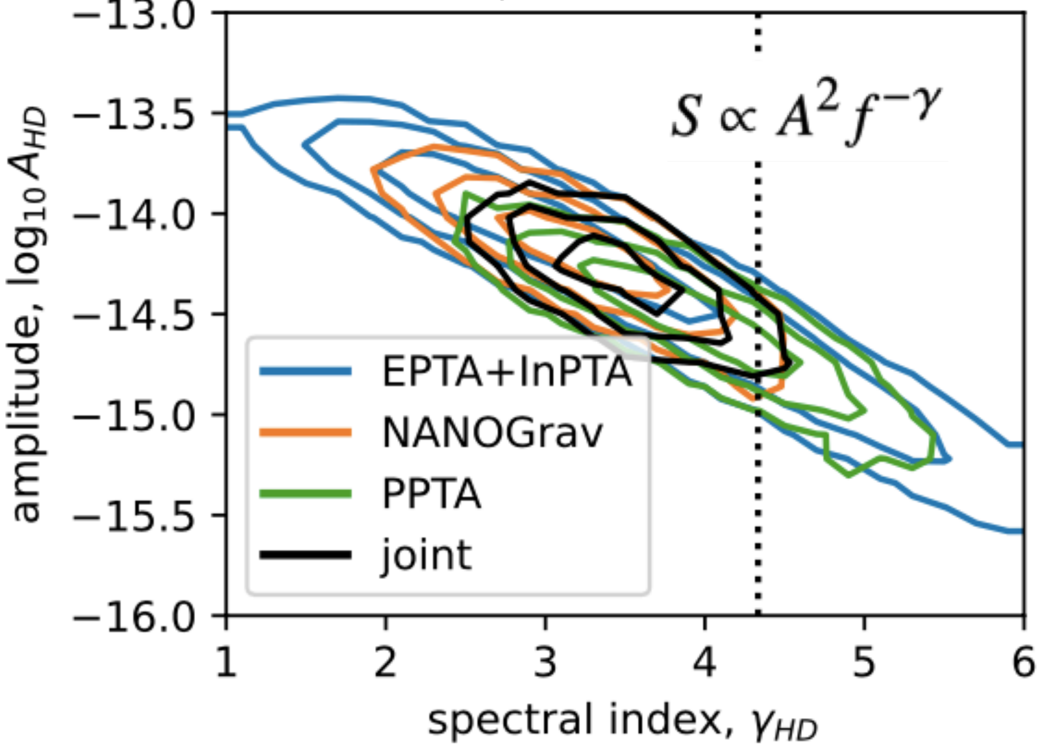
Observed spectrum

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

h_c



Agazie et al 2024

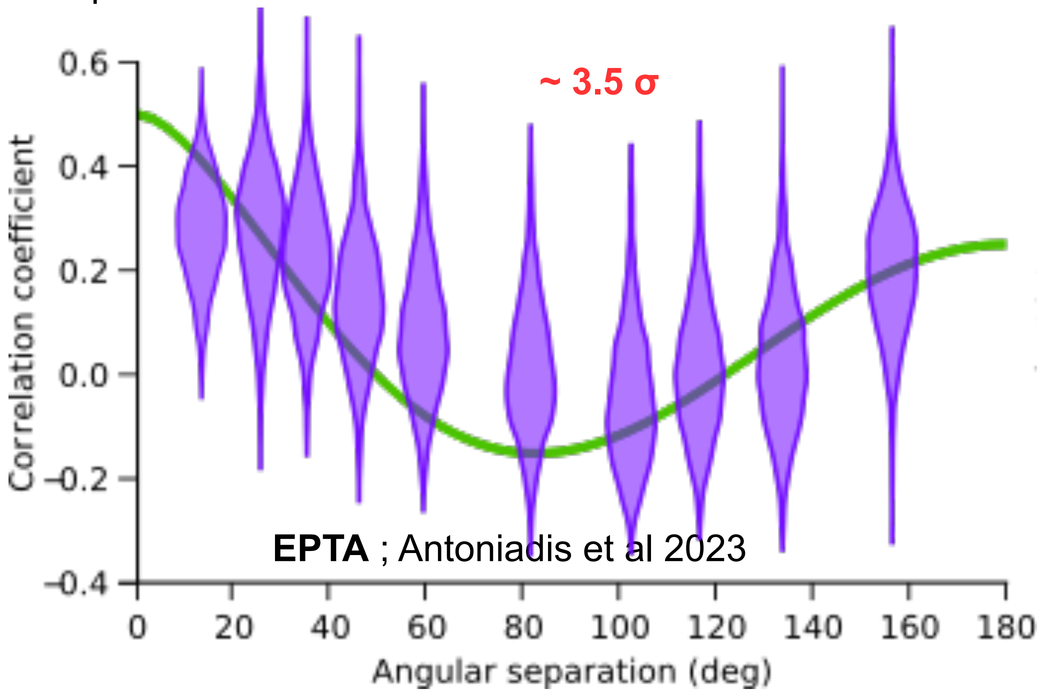


$h_c(f)^2/(12\pi^2 f^3) \;=\; A_{\rm yr}^2/(12\pi^2)(f/f_{\rm yr})^{-\gamma}\,{\rm yr}^{-3}$ (residual power spectral density)

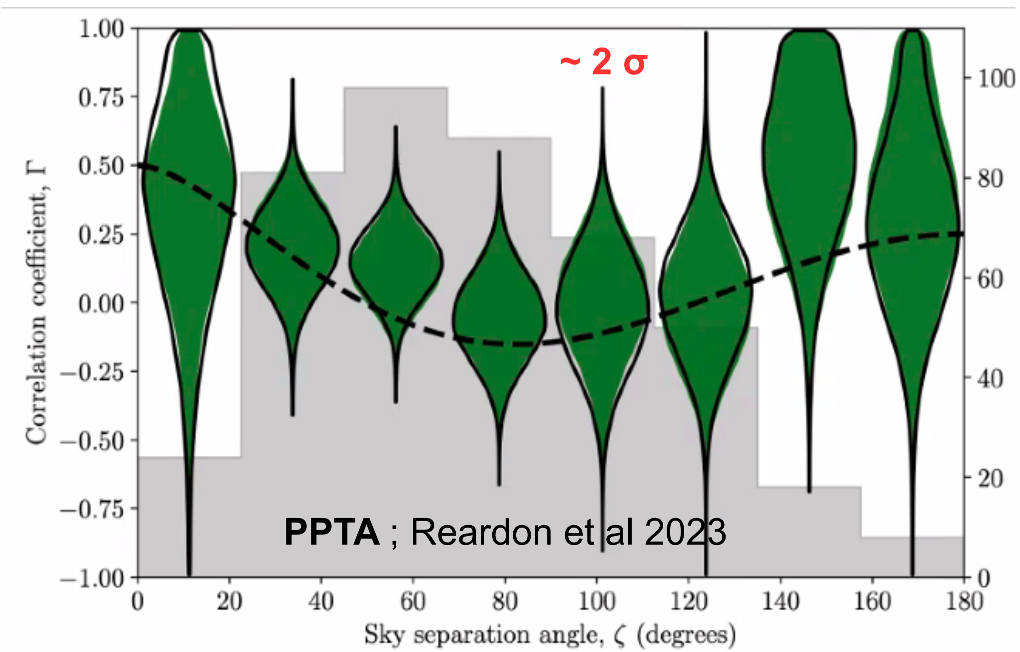
Spatial correlation of the signal

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

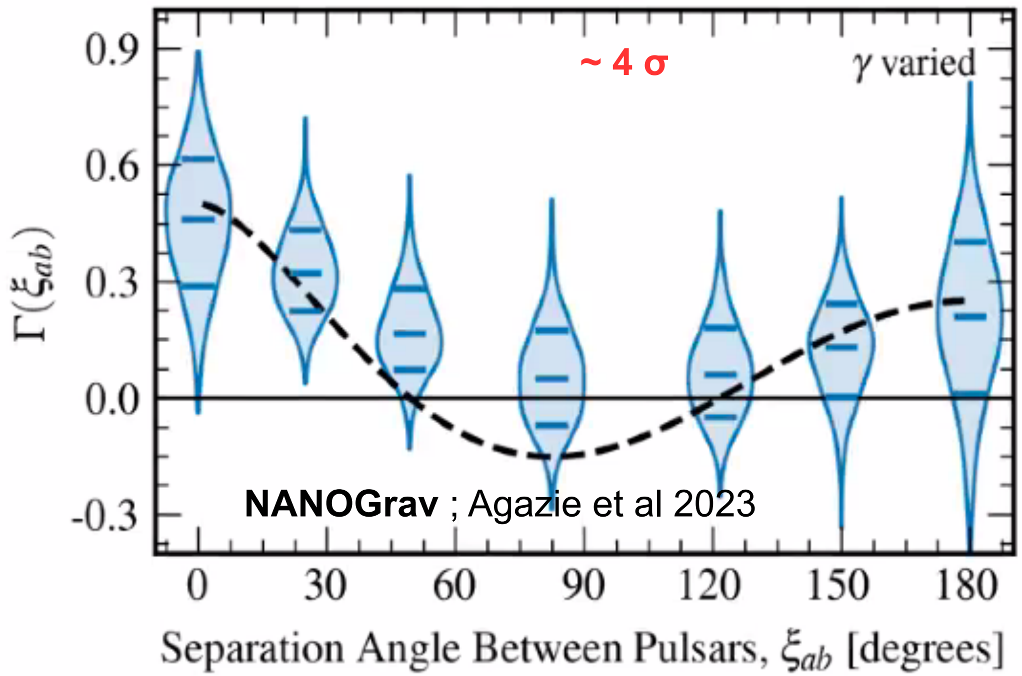
25 pulsars



30 pulsars

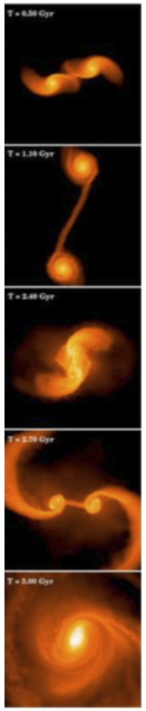


67 pulsars

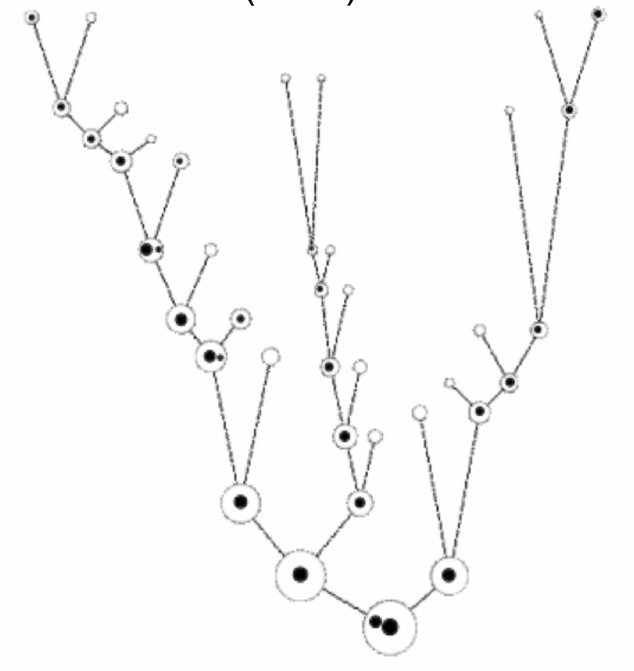


How interpreting such a common signal in terms of astrophysics ?

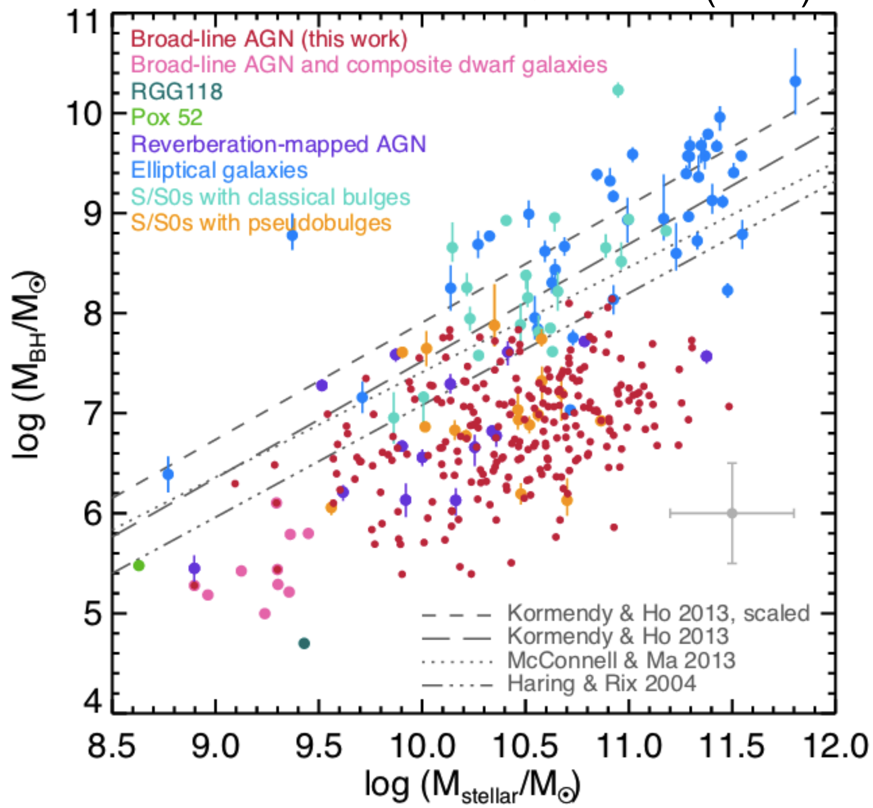
Population synthesis ingredients



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

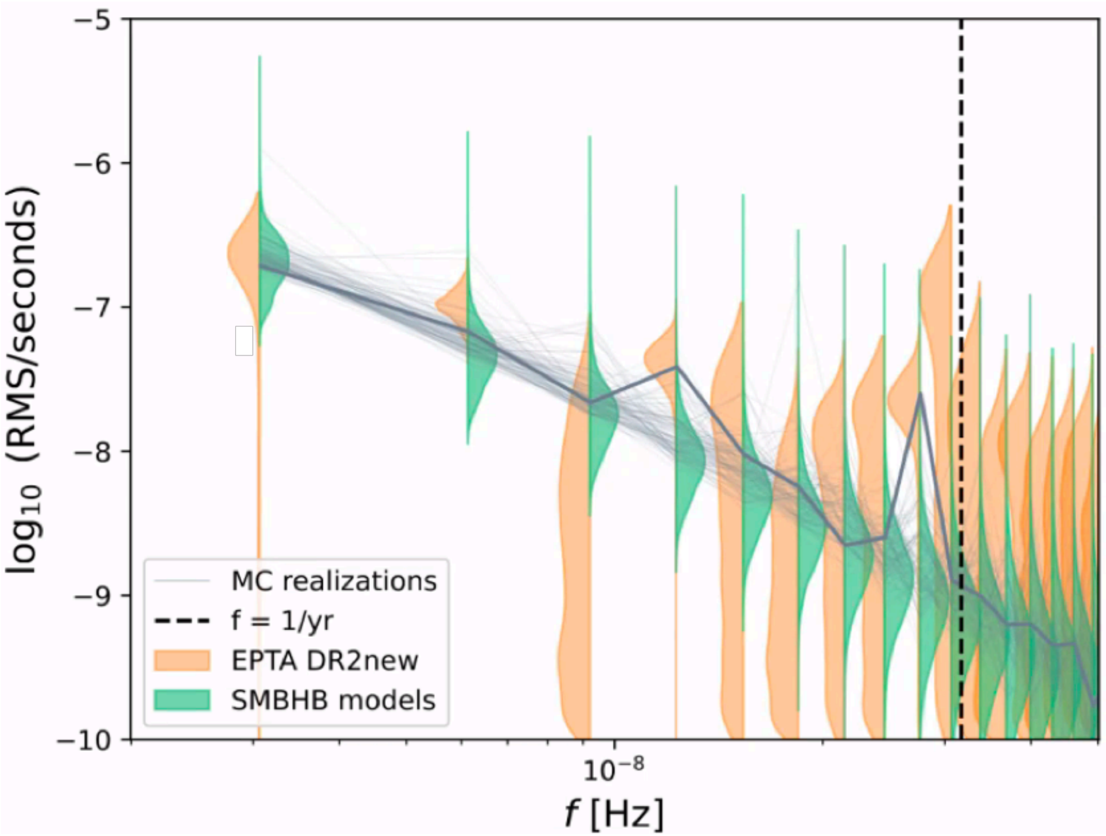
Three body interaction with stars from the loss cone region (when binary orbital velocity > stars)

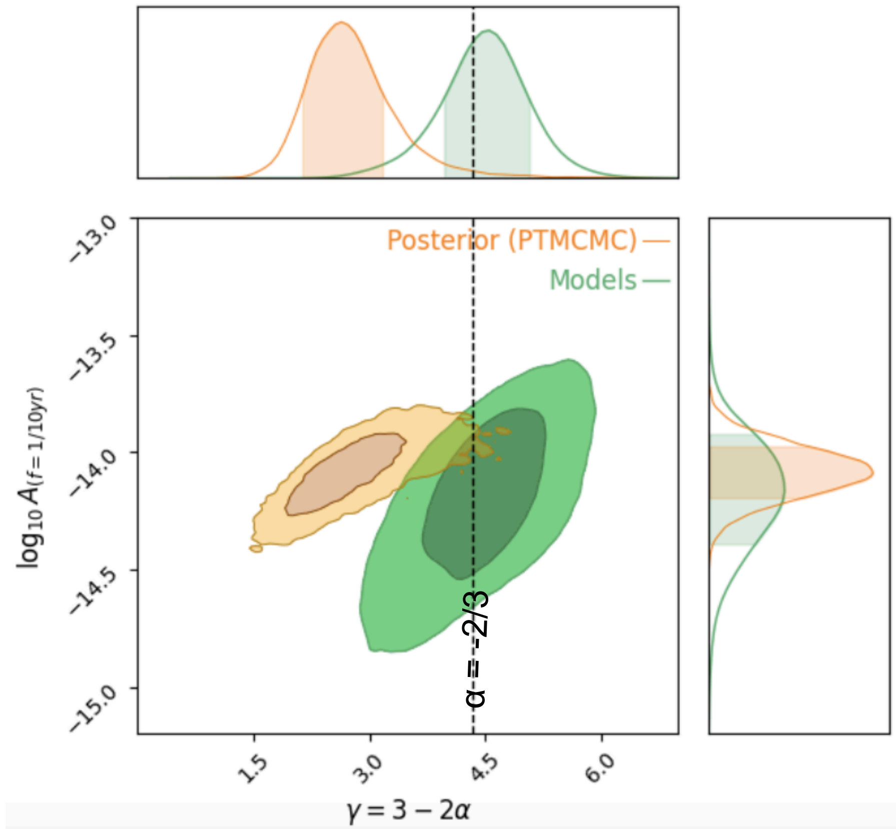
GW emission

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

(Phinney 2001)

The PTA signal vs SMBHB population models





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

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

Comparing with the predictions of astrophysical models (Antoniadis et al 2024 / EPTA - paperIV)

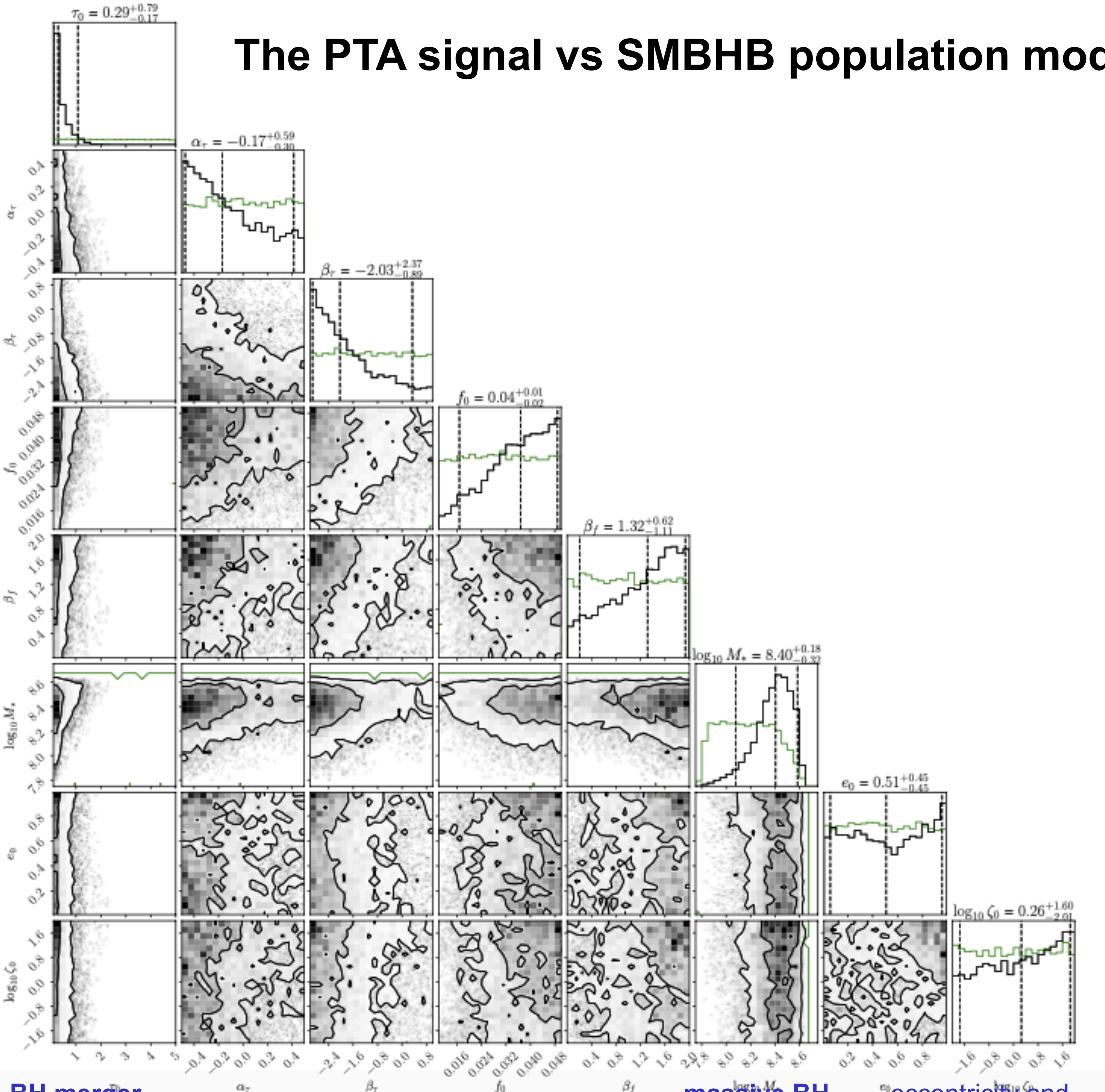
$$h_c^2(f) = \int_0^\infty \mathrm{d}z \int_0^\infty \mathrm{d}m_1 \int_0^1 \mathrm{d}q \frac{\mathrm{d}^5 N}{\mathrm{d}z\mathrm{d}m_1\mathrm{d}q\mathrm{d}e\mathrm{d}t_r} \frac{\mathrm{d}t_r}{\mathrm{d}\ln f_{\mathrm{K},r}} \times h^2(f_{\mathrm{K},r}) \sum_{n=1}^{\infty} \frac{g[n, e(f_{\mathrm{K},r})]}{(n/2)^2}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

cosmic merger rate

physical processes driving BH pair

Eccentricity (harmonics)

The PTA signal vs SMBHB population models



BH merger timescale < 1Gyr

shorter merger times for massive galaxies

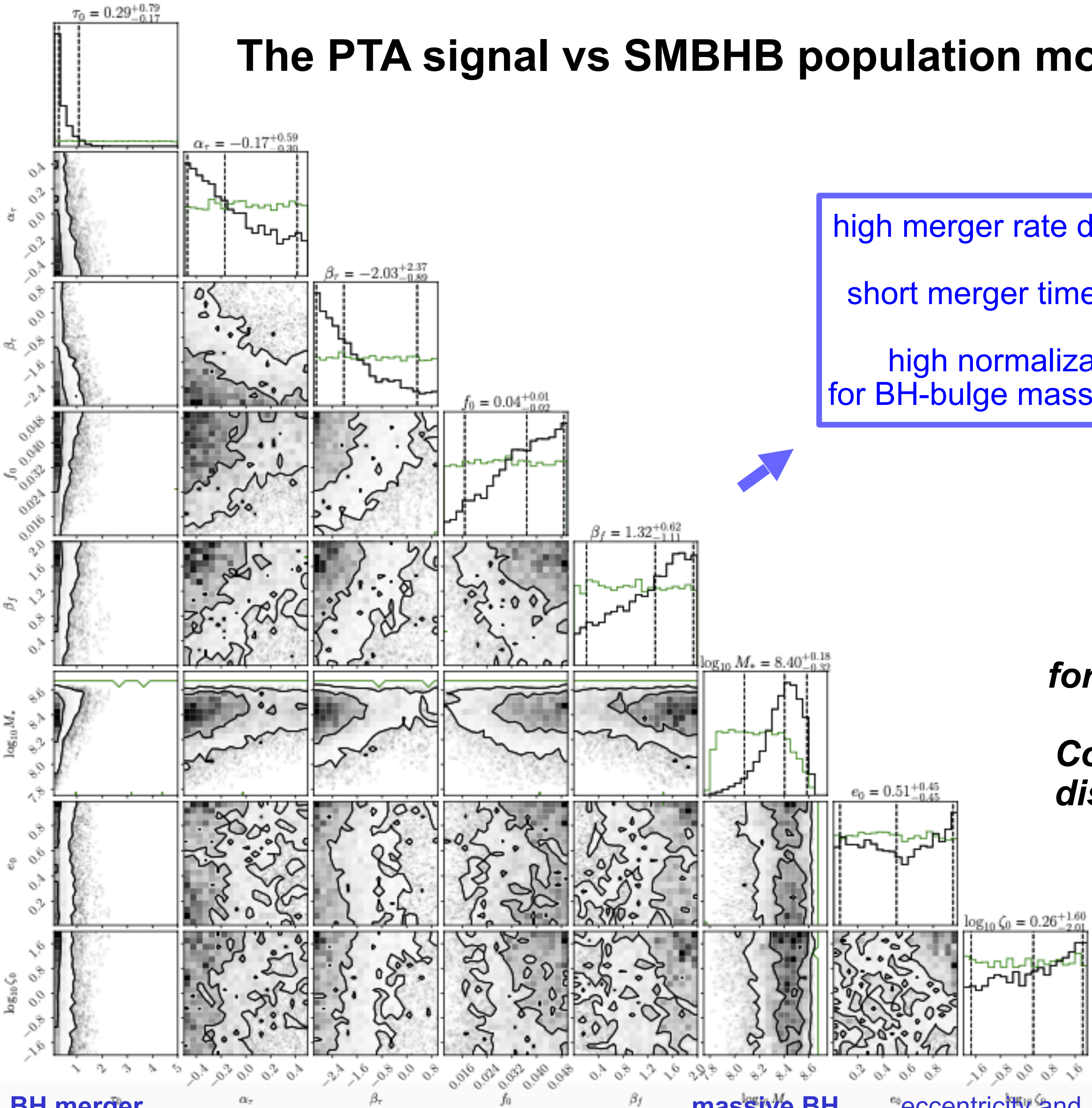
high normalisation of pair fraction

massive BH compared to bulge mass

eccentricity and environment effects poorly constrained

Results
from Antoniadis et al 2024
EPTA - paperIV

The PTA signal vs SMBHB population models



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massive BH compared to bulge mass

eccentricity and environment effects poorly constrained

high merger rate densities

short merger timescales

high normalization for BH-bulge mass relation

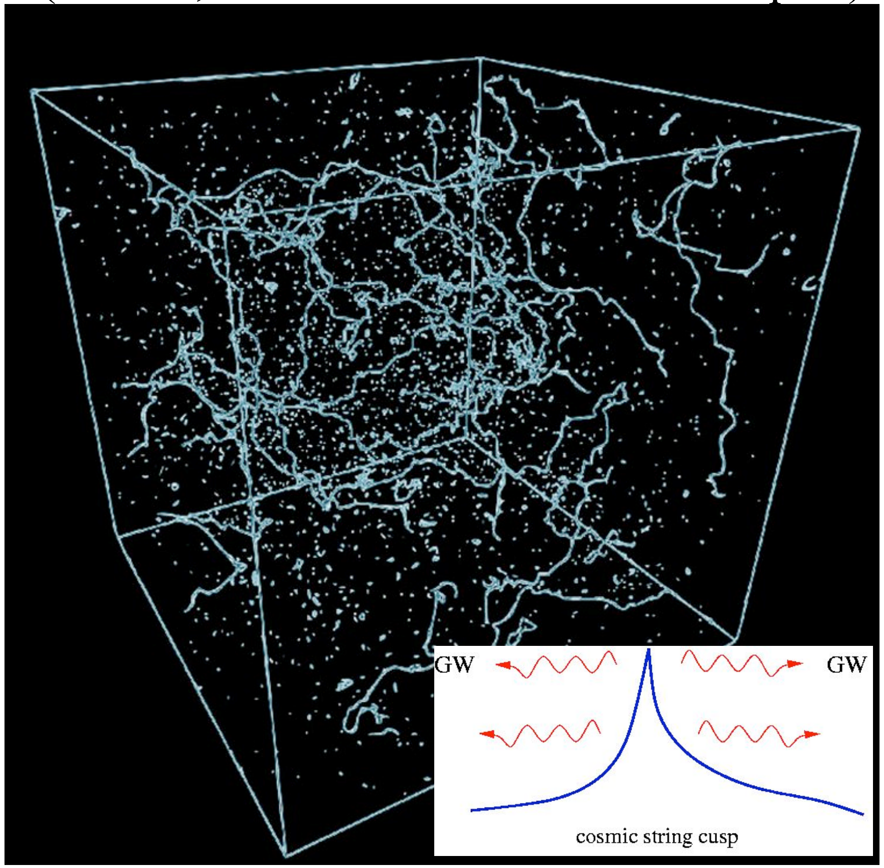
Massive galaxies and massive black holes form earlier than expected ?

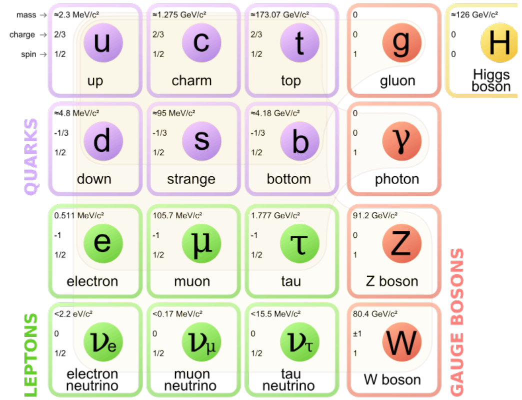
Coherent with JWST recent discoveries at high redshift

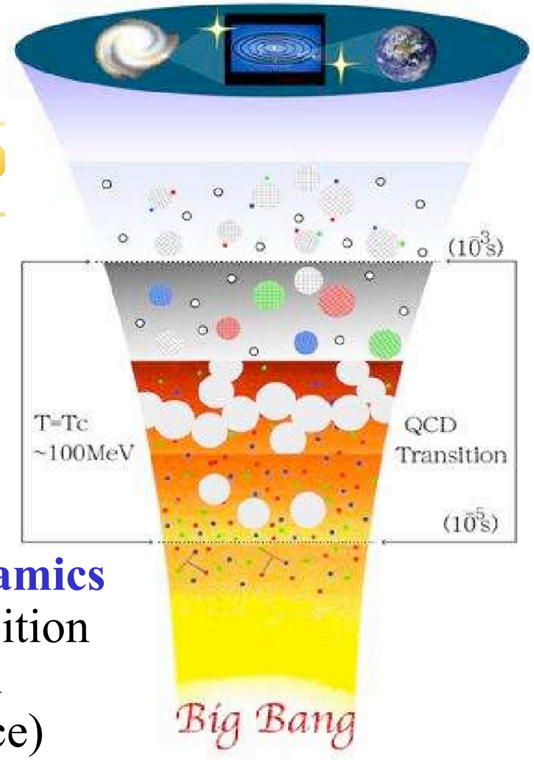
Results from Antoniadis et al 2024 EPTA - paperIV

Constraints on the cosmology of the primordial Universe

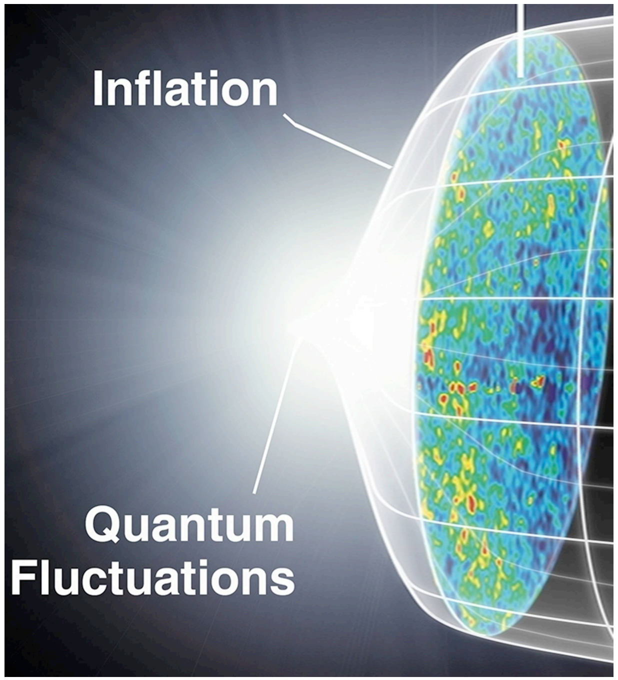
The theory of cosmic strings
(tension, number of « kinks » or « cusps »)





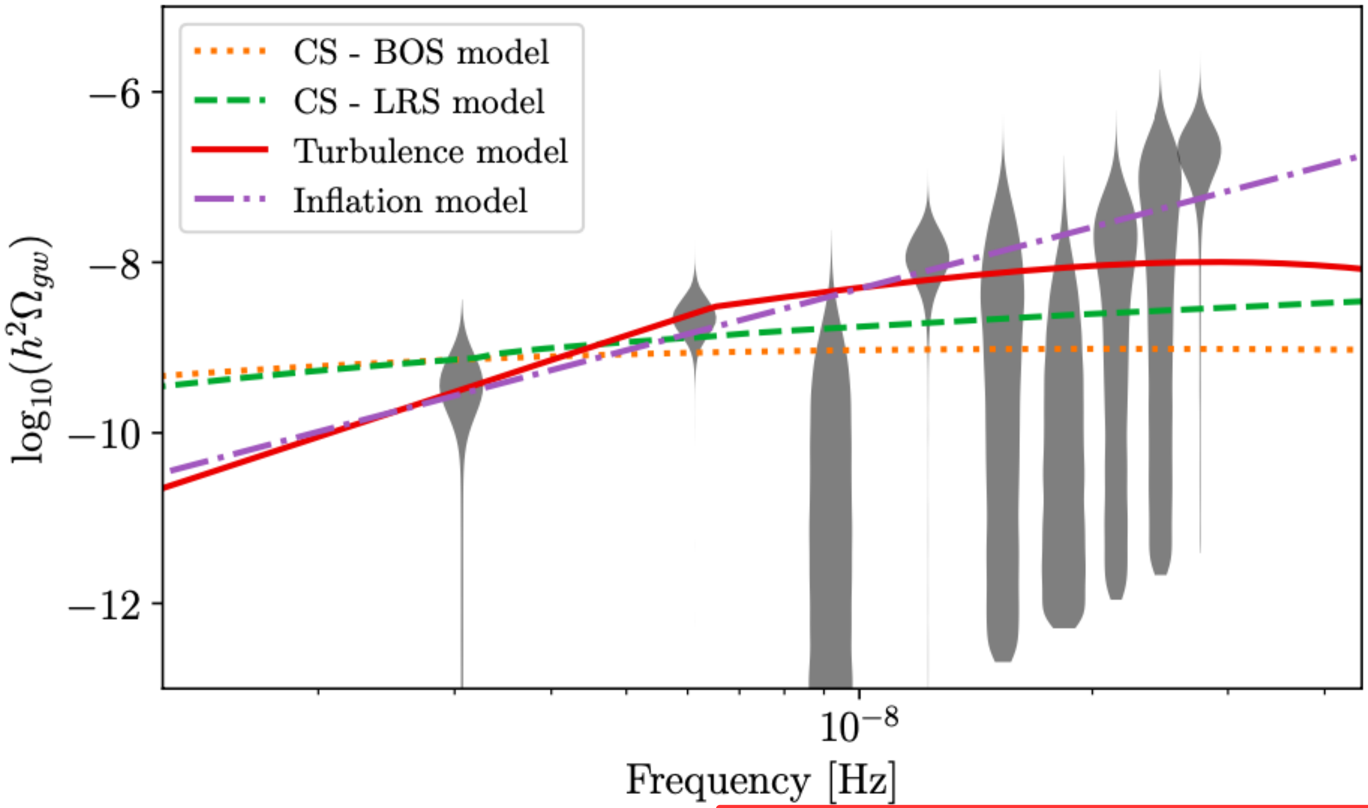


Quantum chromodynamics
= quarks-hadrons transition
(T° scale, size and
strength of turbulence)



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

Constraints on the cosmology of the primordial Universe



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 strength Ω* → 0.3
turbulence characteristic length scale λ*H* → 1

Inflation model :

tensor/scalar perturbation ratio → $\log_{10} r = -12.18^{+8.81}_{-7.00}$

spectral index of tensor perturbation → $n_T = 2.29^{+0.87}_{-1.11}$

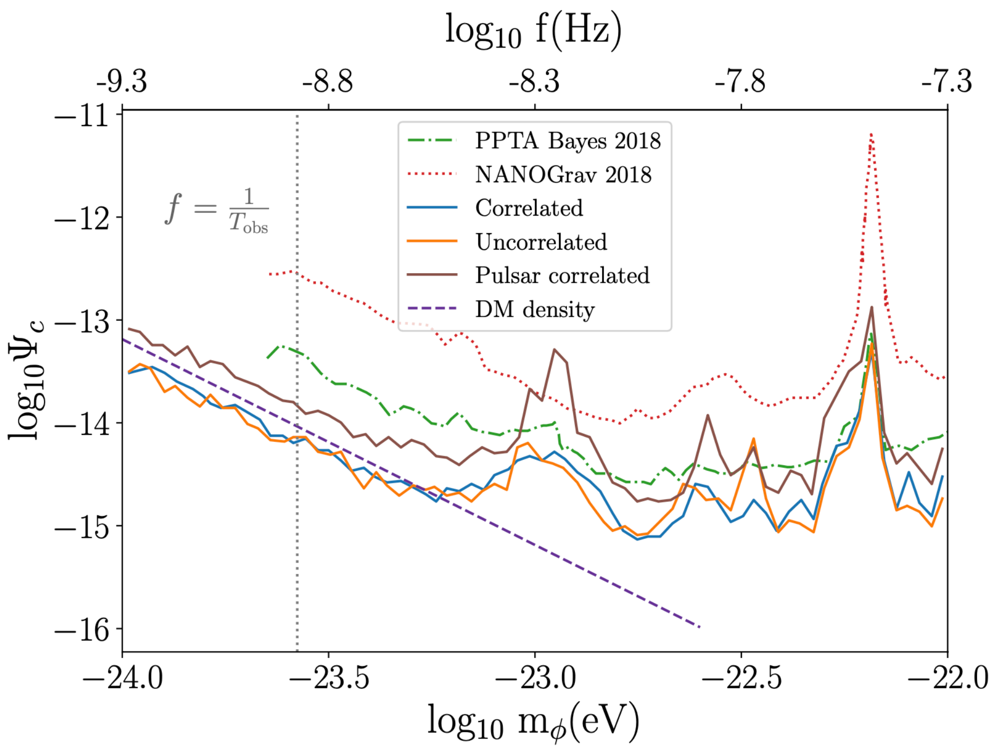
Results
from Antoniadis et al 2024
EPTA - paperIV

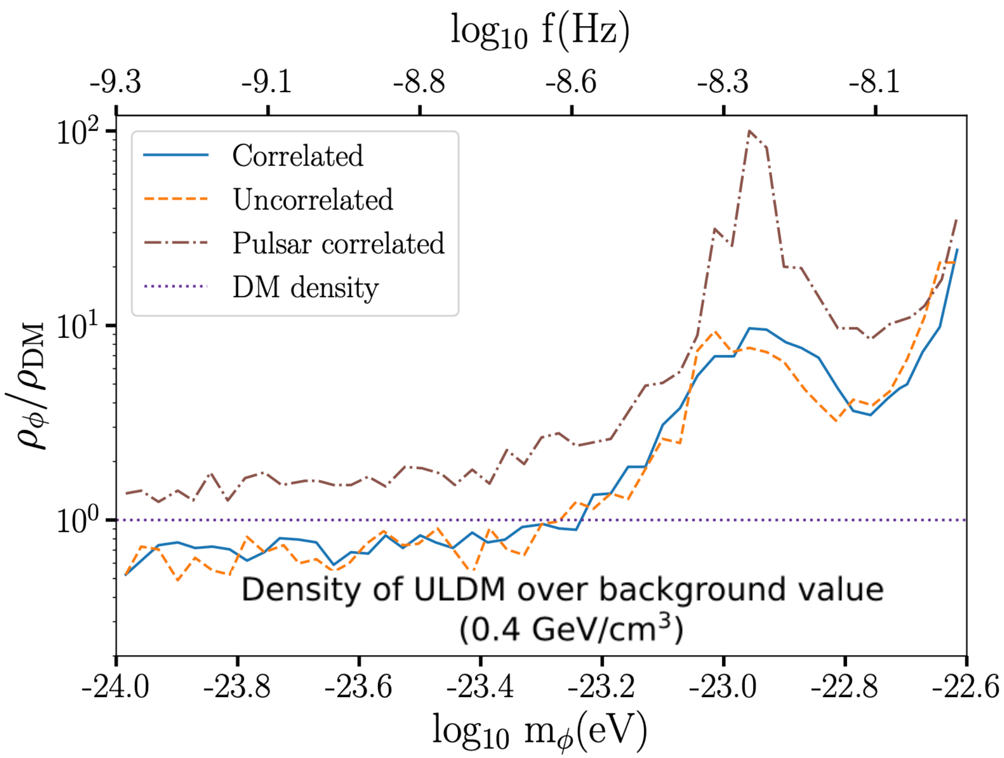
Implications on ultra light dark matter content
(scalar-field, axion-like field)

Well known issue with CDM (WIMPS or QCD axions) 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 (Khmelnitsky&Rubakov 2014)

(amplitude Ψ_c translates into a density)



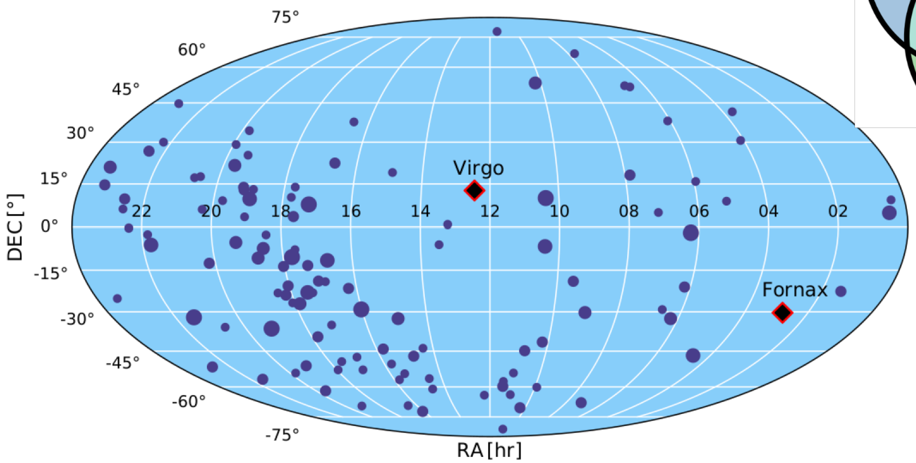


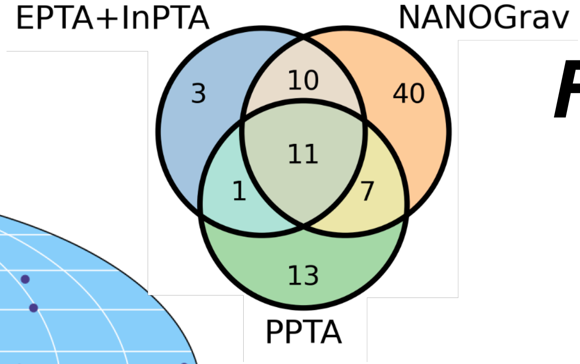
Results
from Antoniadis et al 2024
EPTA - paperIV

From PTA's to IPTA

Full IPTA DR3 = 125 pulsars

Current IPTA





(Verbiest et al 2024)

$$S/N \propto N_{psr} \sqrt{T} \left(\frac{A\sqrt{C}}{\sigma} \right)^{3/13}$$

GW signal amplitude

number of pulsars

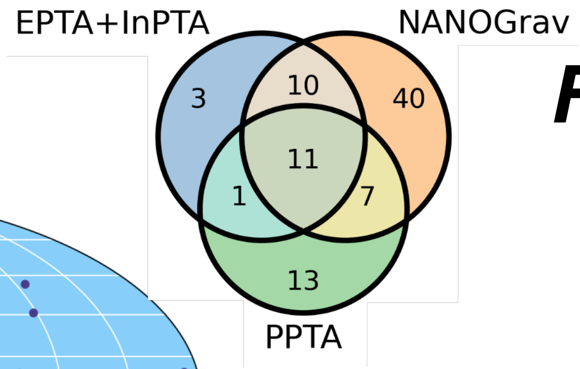
time span

timing precision

cadence

From PTA's to IPTA

Full IPTA DR3 = 125 pulsars



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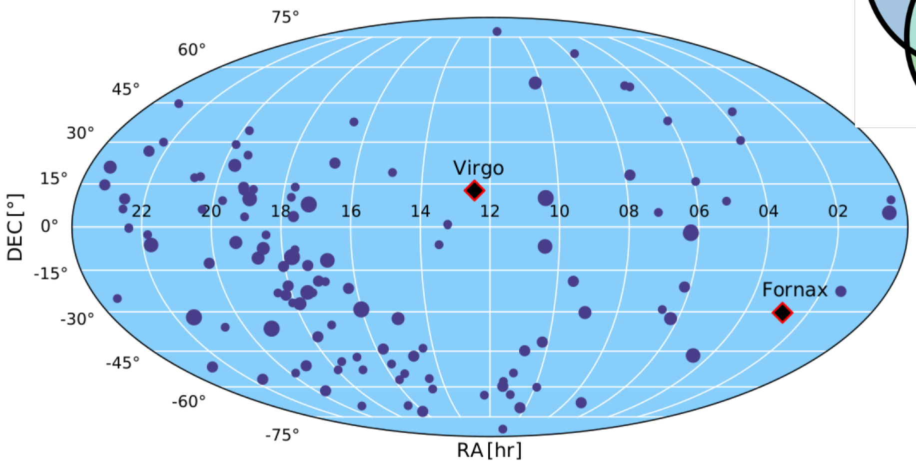

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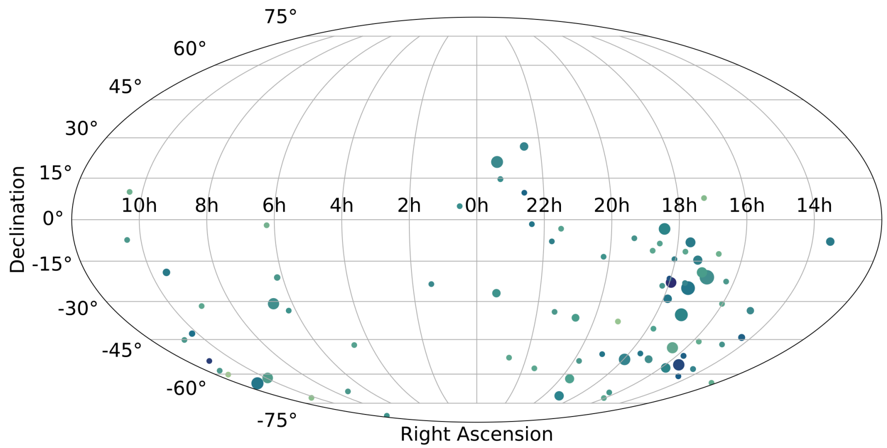
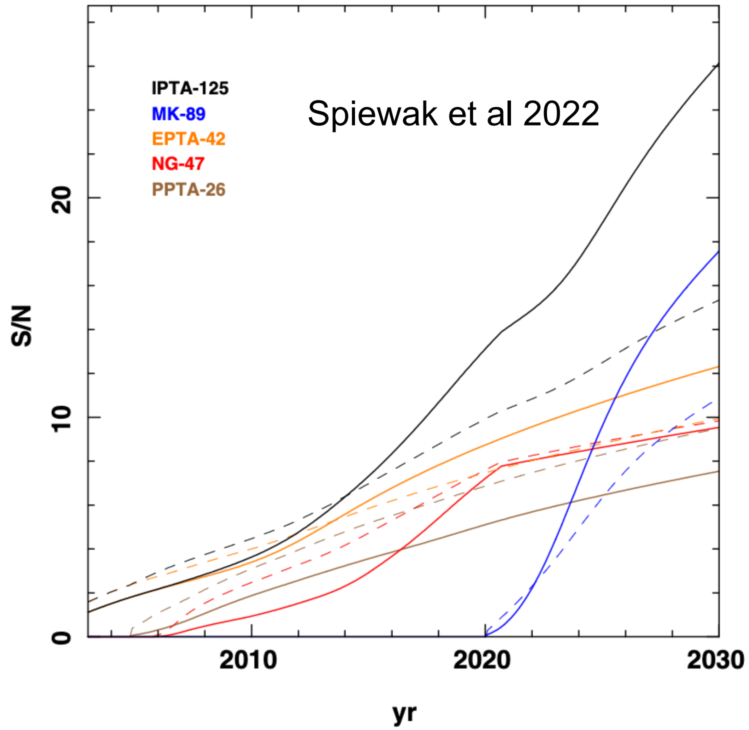
MeerKAT MSP's



Miles et al 2023



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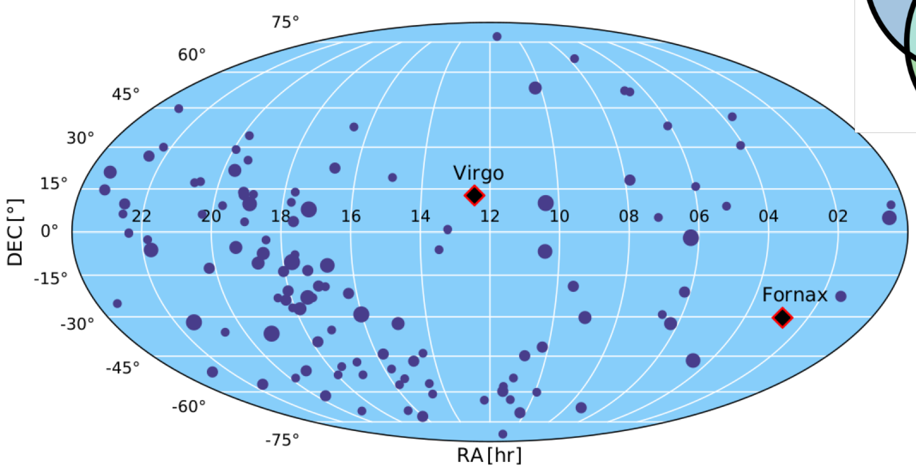
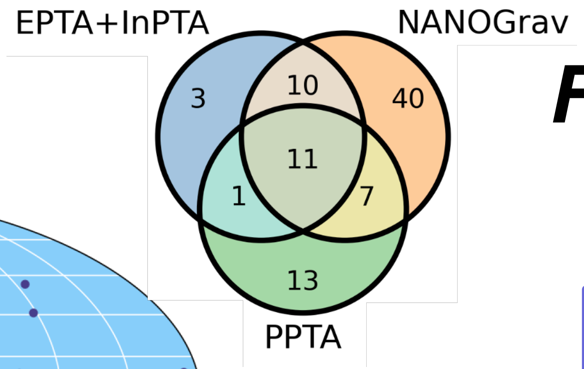




From PTA's to IPTA

GW signal amplitude

(Verbiest et al 2024)

$$S/N \propto N_{psr} \sqrt{T} \left(\frac{A\sqrt{C}}{\sigma} \right)^{3/13}$$

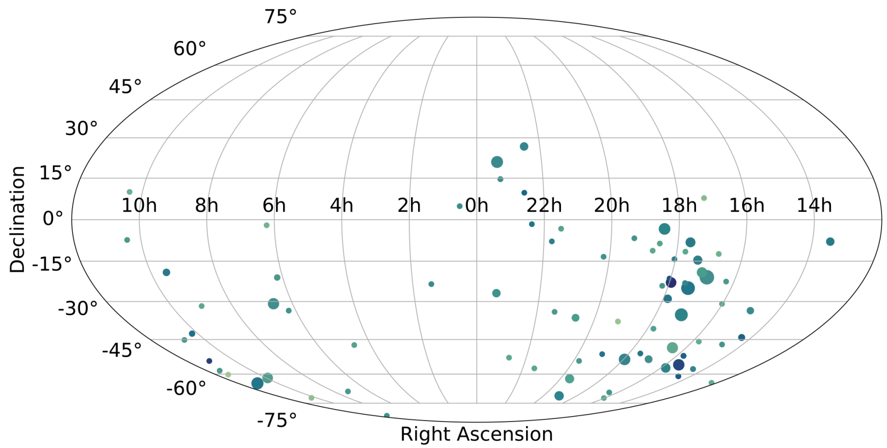
number of pulsars

time span

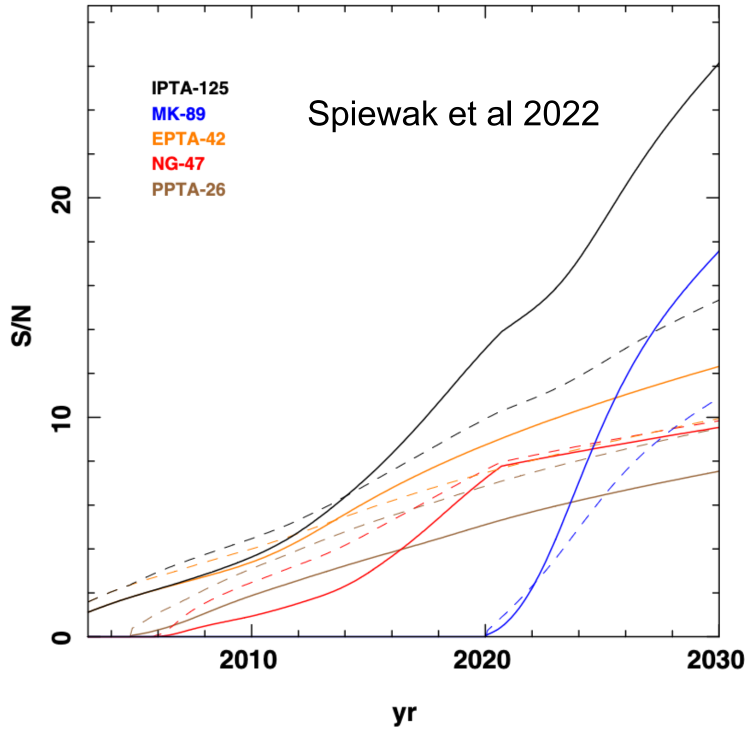
timing precision

cadence

MeerKAT MSP's



Miles et al 2023



reach the 5-σ level by summer 2025?

On going work

Checking anisotropy (e.g. Bécsy et al 2023)
(a way to separate foreground astrophysical signal from cosmological ones)

Checking stationarity (e.g. Falxa et al 2024)
(signature of an eccentric binary dominating the signal)

Checking signal template mismatch (e.g. Valtolina 2024)
(≠ single power law, Gaussian, isotropic and stationary)

Develop multi-sources population inference models
(SMBHB background + individual BH pairs + various cosmological source populations)

Combine recent data releases under IPTA umbrella
(acquire sensitivity and cross-checks of systematics)

Include low frequency data from LOFAR and NenuFAR
(better constrain DM noise and scattering noise)

Address the impact of variable Solar Wind
(ecliptic latitude, time variation)

Improve SS ephemerides model
(collaboration with INPOP people)


Thank you