The latest updates from the PTA community: 29th of June announcement

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UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

DFG

INTERNATIONAL PULSAR TIMING ARRAY IPTA

InPTA Indian Pulsar Timing Array

erc

EPTA + InPTA: more telescopes the better

Partner telescopes:

- Effelsberg
- Lovell
- Nancay Radio Telescope
- Sardinia Radio Telescope
- Westerbork Synthesis Radio Telescope

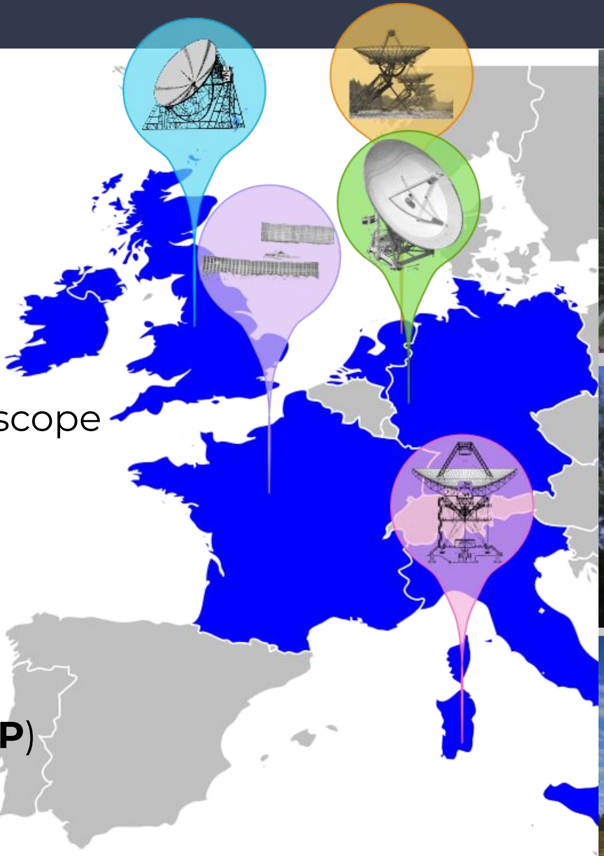
+

GMRT in India

+

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

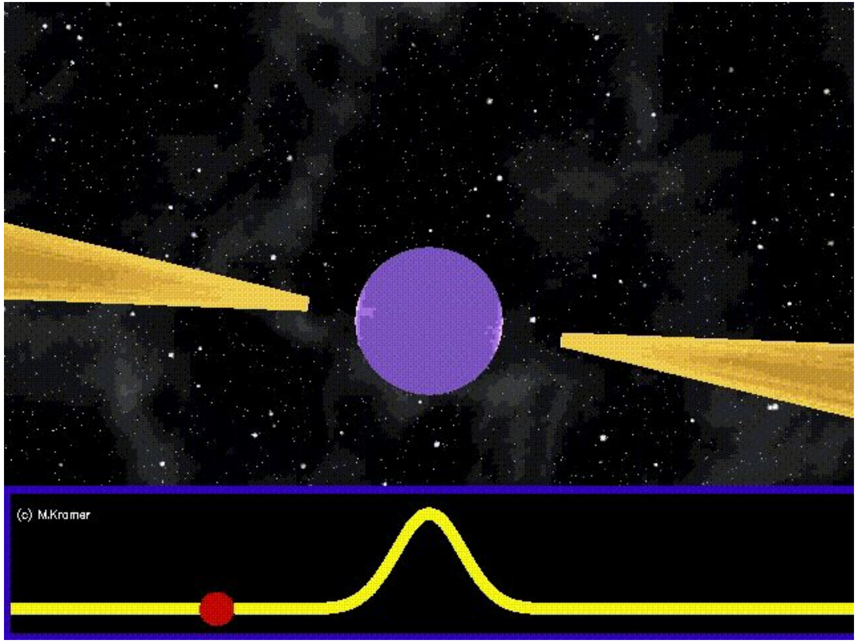
Low Frequency Array (**LOFAR**)



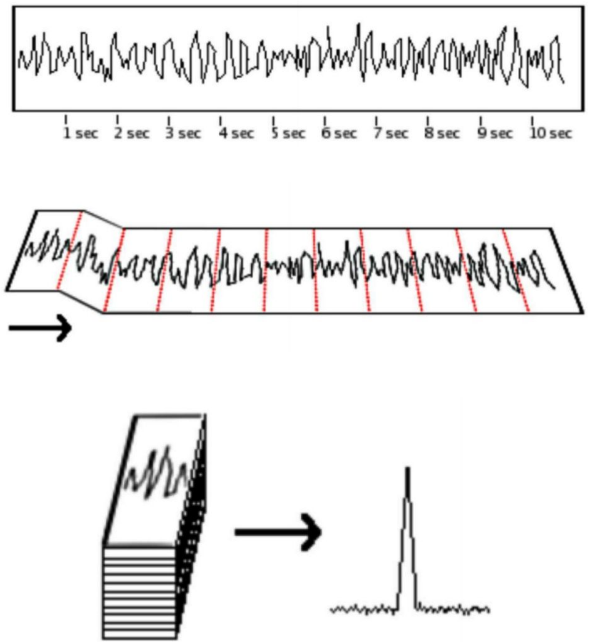
Pulsars in a nutshell

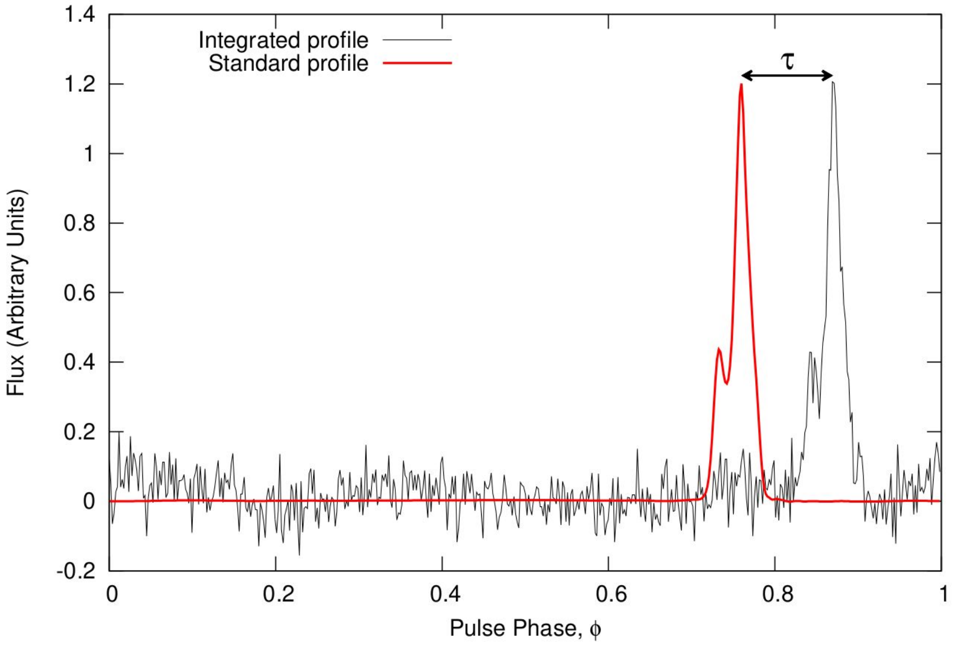
Pulsars are neutron stars, which are:

- Rapidly spinning. Periods: from few ms to several seconds
- Highly magnetised $\sim 10^8 - 10^{15}\mathrm{G}$
- Extremely dense: $\rho > 10^{14}\mathrm{g/cm^3}$
- **Stable rotators (“Galactic clocks”)**



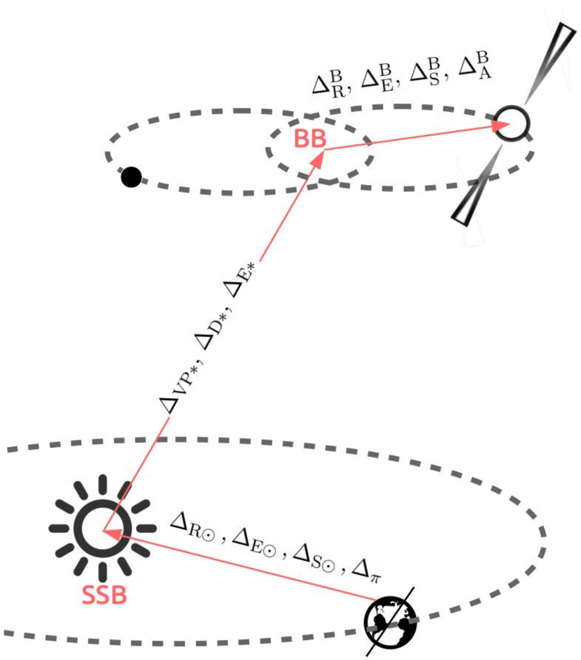
Pulsar timing





Credit: Ridolfi, PhD thesis

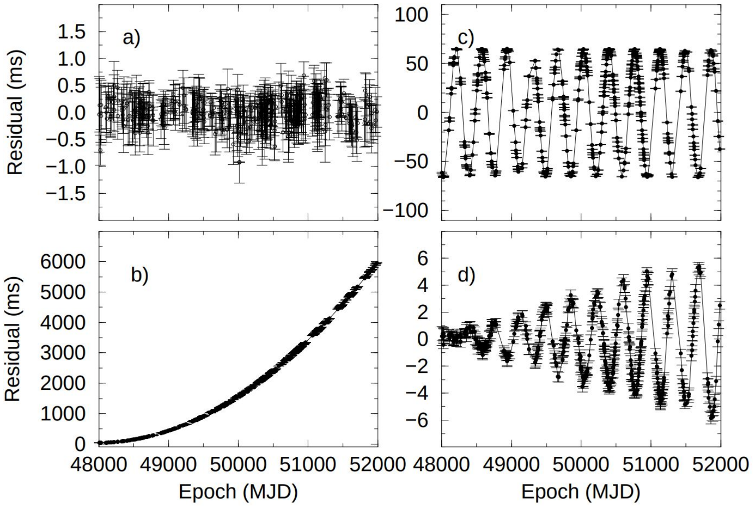
Pulsar timing



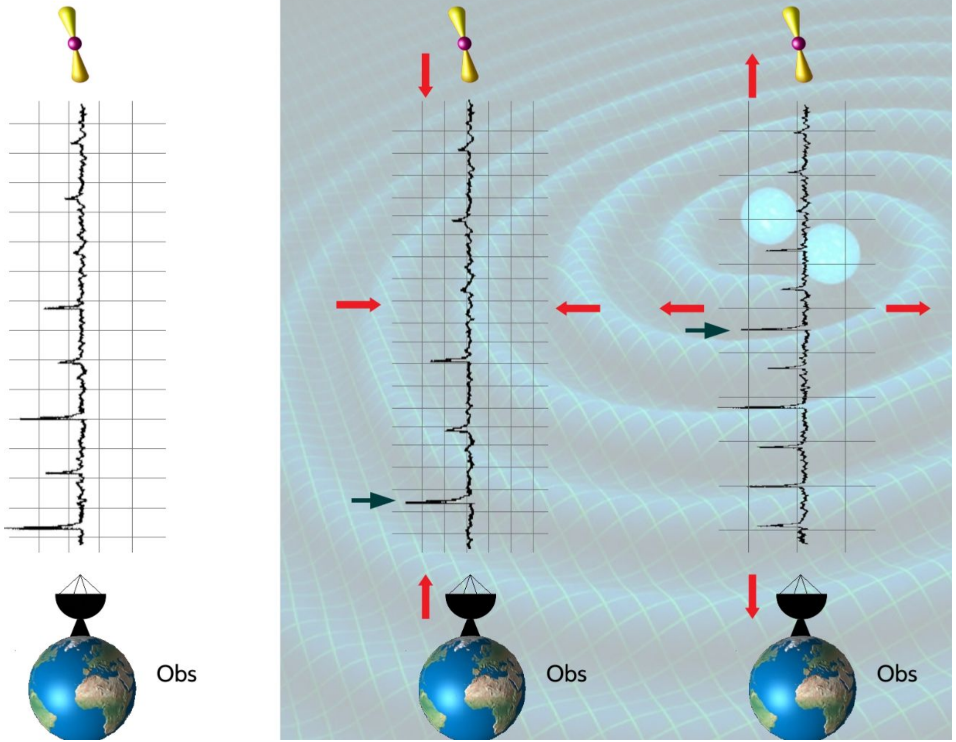
Solar system terms (pulsar binary terms)

$$t_{SSB} = t_{topo} + t_{corr} - \frac{\Delta D}{f^2} + \Delta_{R\odot} + \Delta_{S\odot} + \Delta_{E\odot} + \Delta_{RB} + \Delta_{SB} + \Delta_{EB}$$

Conversion to topocentric (time at observatory) | Clock corrections | Dispersion measure | Römer delay | Shapiro delay | Einstein delay



PTA response on CGW

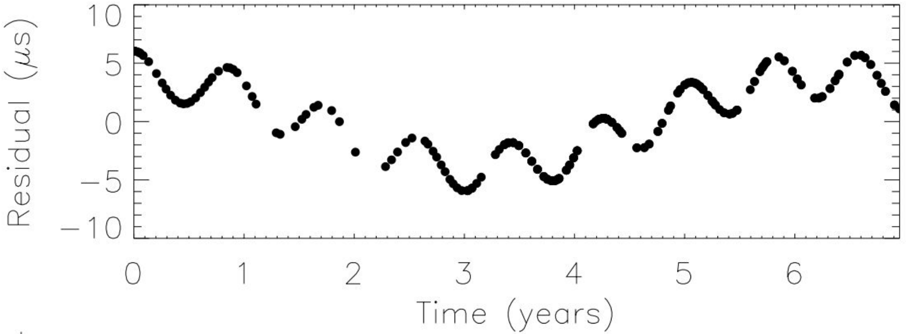


Credit: C. Tiburzi slide

$$R(t) = \frac{1}{2}(1 + \cos\mu) \times [r_+(t)\cos 2\Psi + r_\times(t)\sin 2\Psi]$$

$$\sim e^{i\omega t}, \quad \omega = 2\omega_{orb}$$

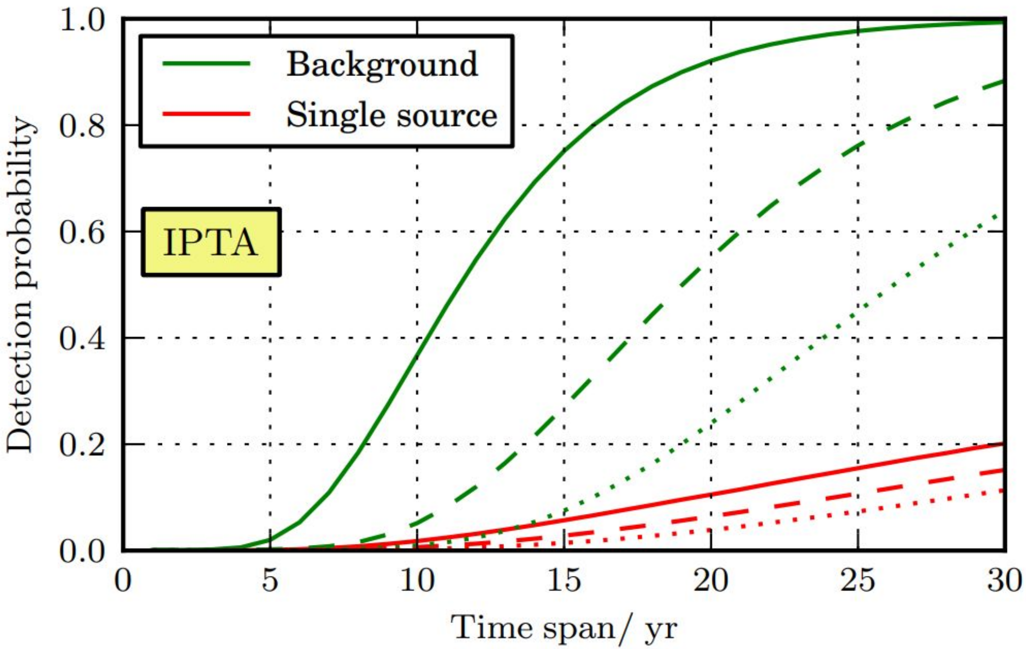
$$r_{+,\times}(t) = r^E_{+,\times}(t) - r^P_{+,\times}(t)$$

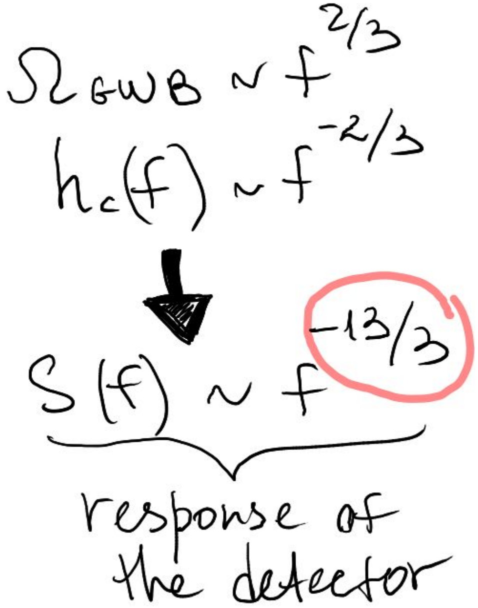


Credit: Jenet et al 2004

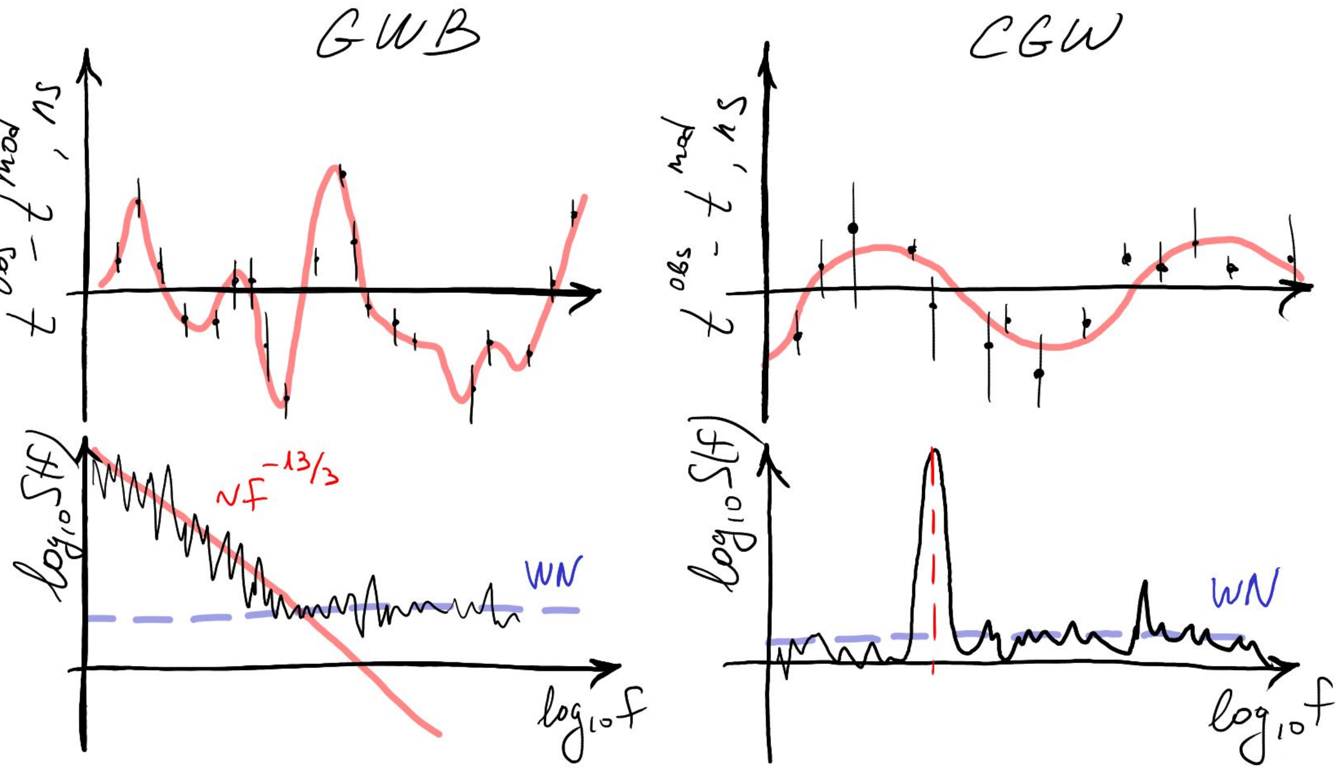
PTA response on GW background

Credit: Rosado, Sesana, Gair 2015





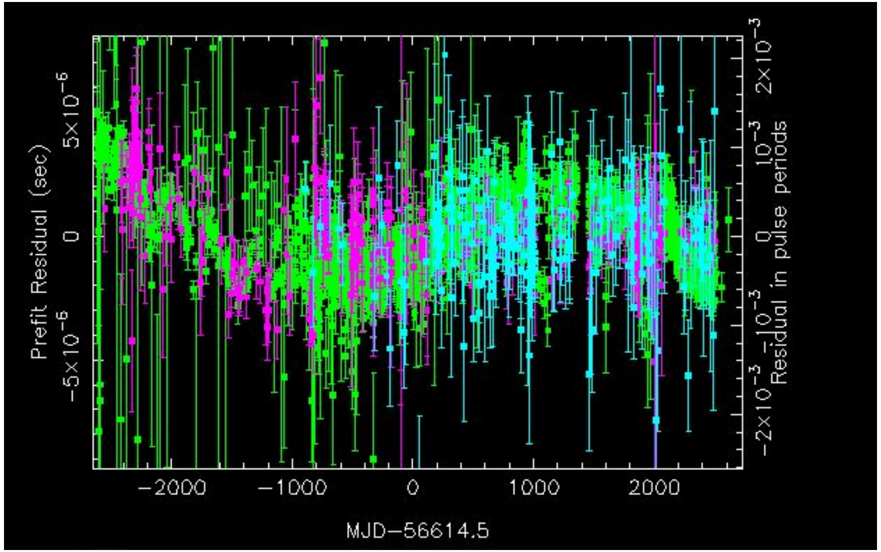
GWB vs CGW



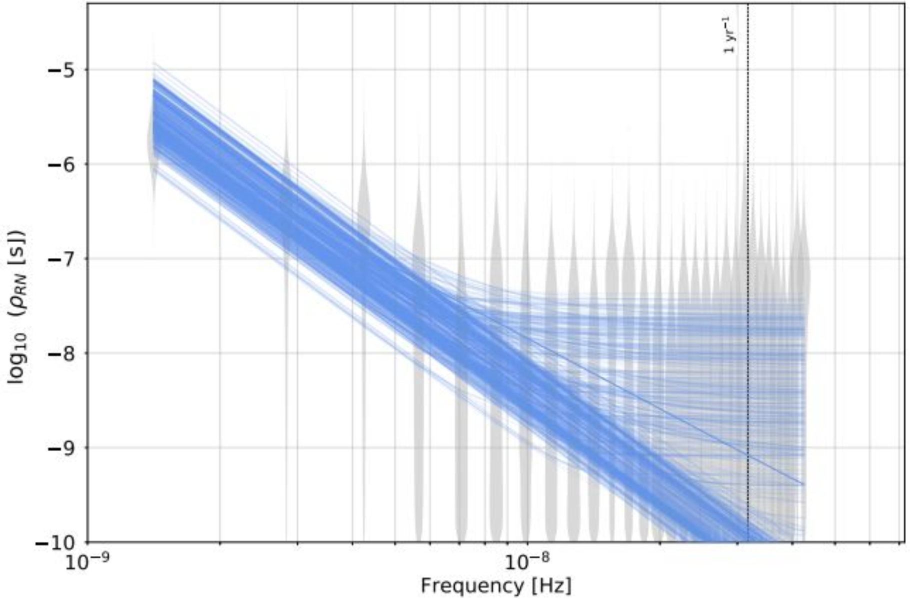
GWB
CGW
$t^{obs} - t^{mod}$, ns
$t^{obs} - t^{mod}$, ns
$\log_{10} S(f)$
$\sim f^{-13/3}$
WN
$\log_{10} f$
$\log_{10} S(f)$
WN
$\log_{10} f$

Pulsar timing: obstacles

Timing residuals …



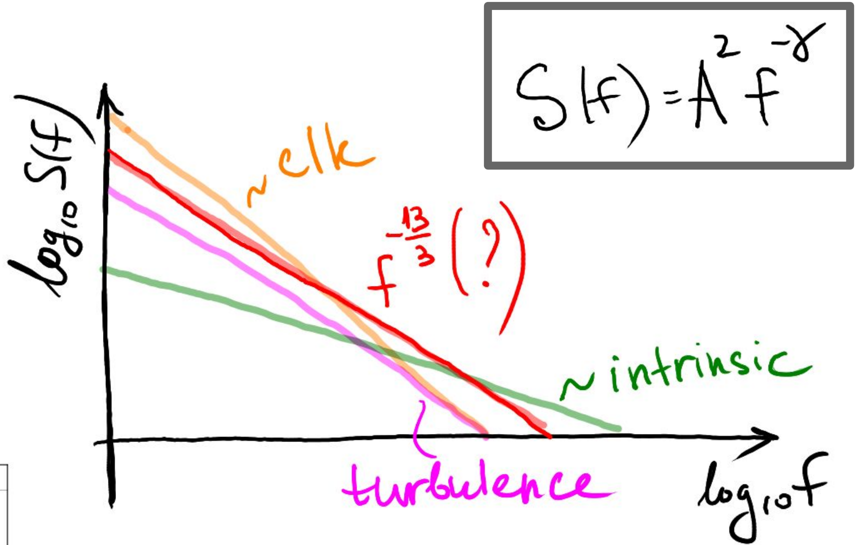
and power spectrum of PSR J0613-0200

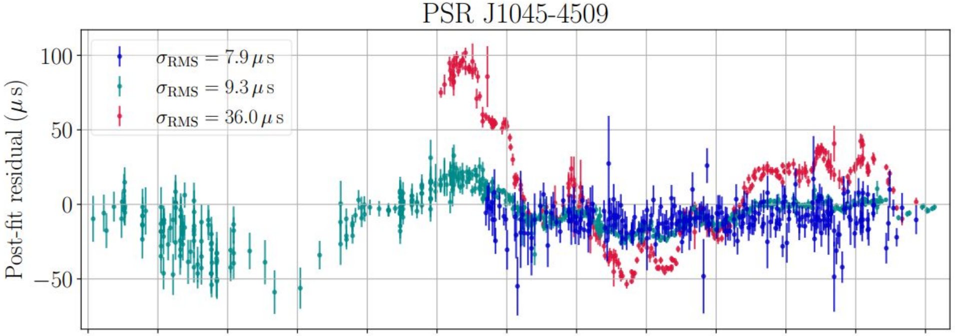


Credit: Chalumeau et al 2021

Sources of noise in pulsar timing

- Intrinsic pulsar noise (red)
- IISM related chromatic noise (red)
- Instrumental noise (usually assumed to be white)
- Clock noise (red)
- Ephemerid noise (red)



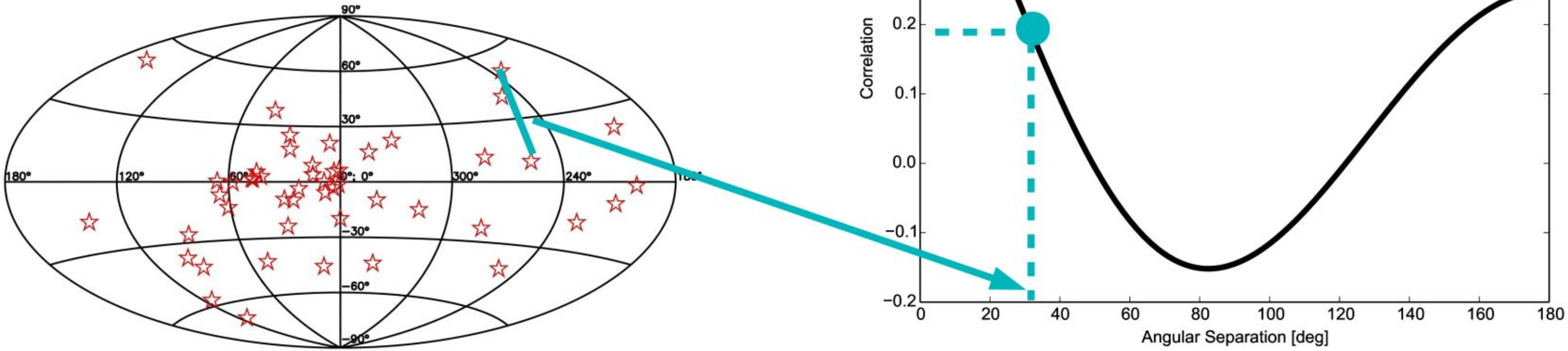


Credit: Reardon et al 2021

Hellings and Downs curve

$$\zeta(\theta_{ij}) = \frac{3}{2} x \log(x) - \frac{x}{4} + \frac{1}{2}$$

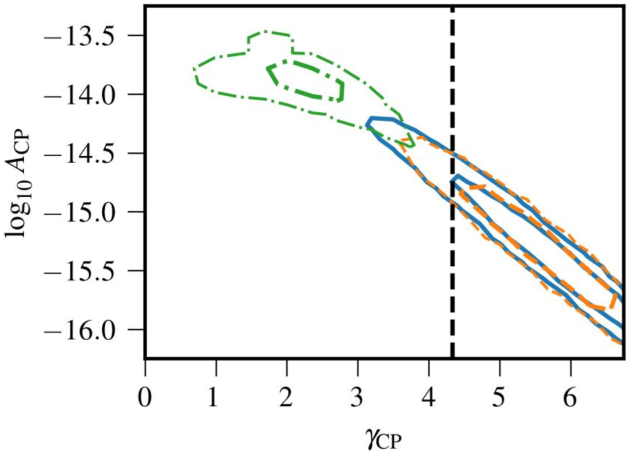
$$x = [1 - \cos(\theta_{ij})]$$



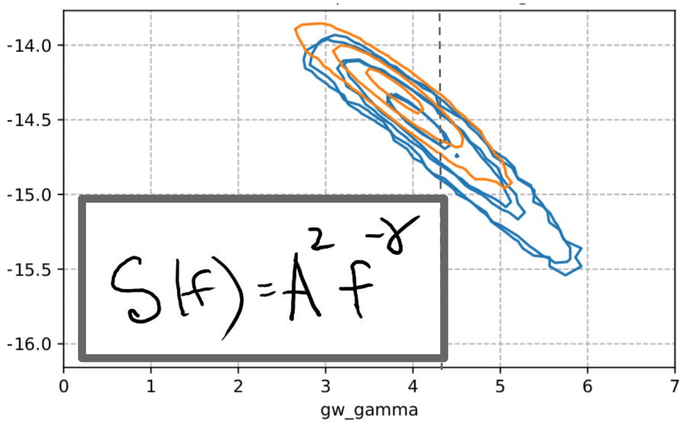
Verbiest+2016

Pulsar Timing Arrays ~~today~~ yesterday: common signal

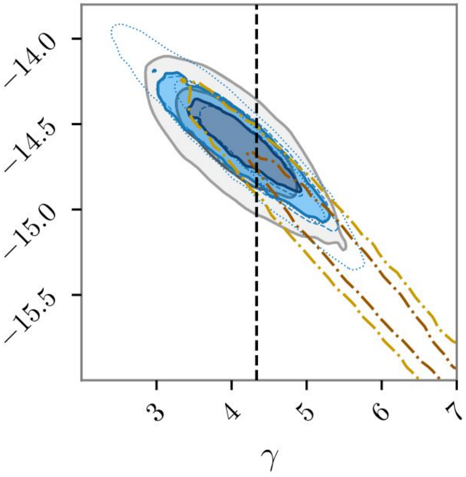
NANOGrav, 2021
12.5 years, 47 PSRs



EPTA, 2021
24 years, 6 PSRs

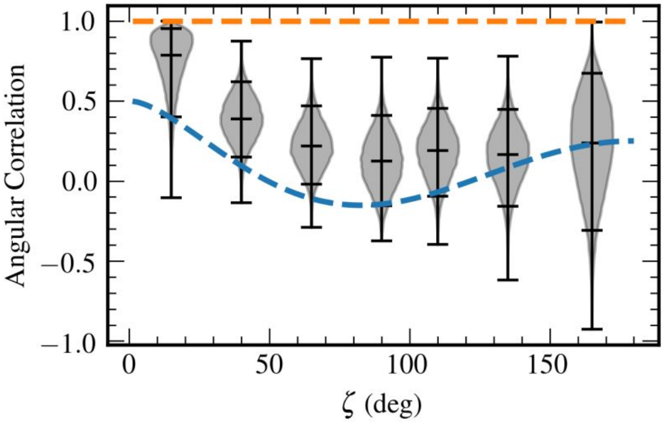


PPTA, 2021
14 years, 26 PSRs

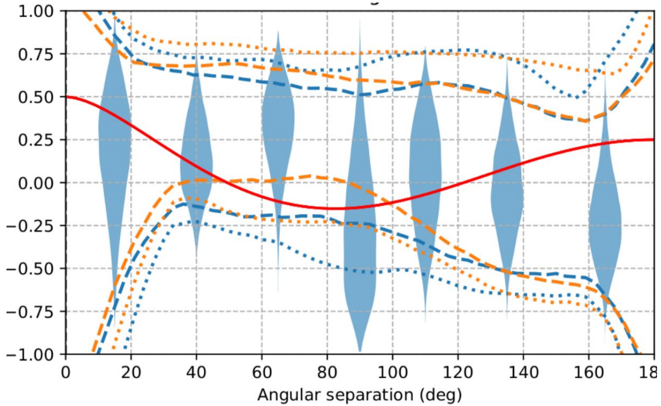


Pulsar Timing Arrays ~~today~~ yesterday: correlation curves

NANOGrav, 2021
12.5 years, 47 PSRs



EPTA, 2021
24 years, 6 PSRs



PPTA, 2021
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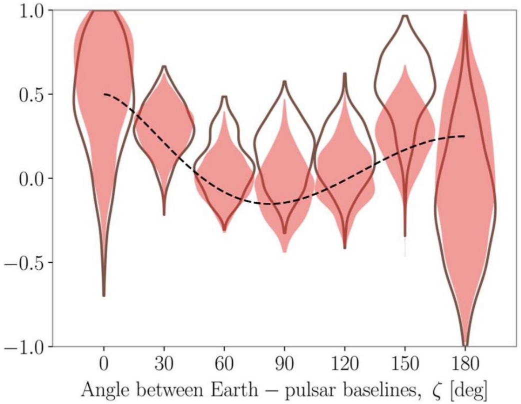
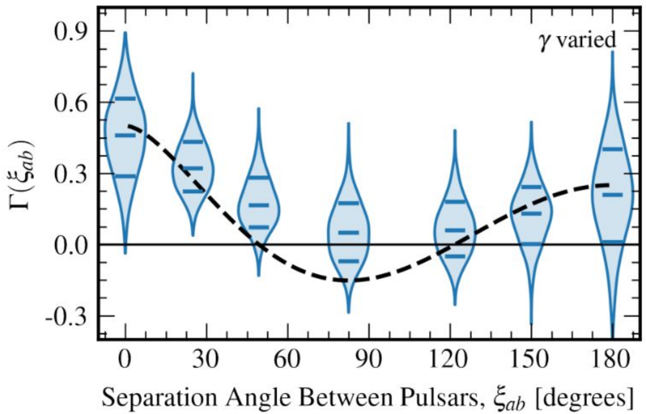


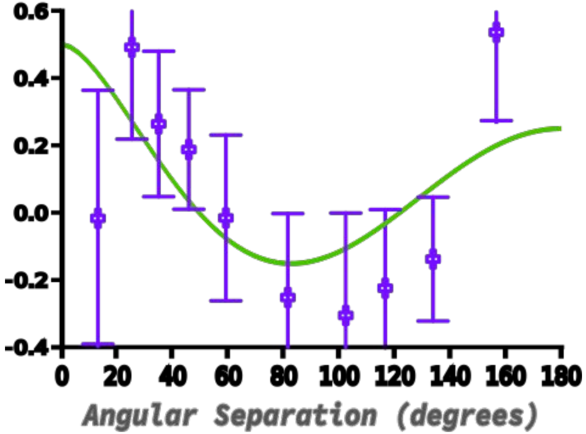
Pulsar Timing Arrays today: 29th of June, 2023

NANOGrav, 2023
15 years, 70 PSRs
3σ-4σ



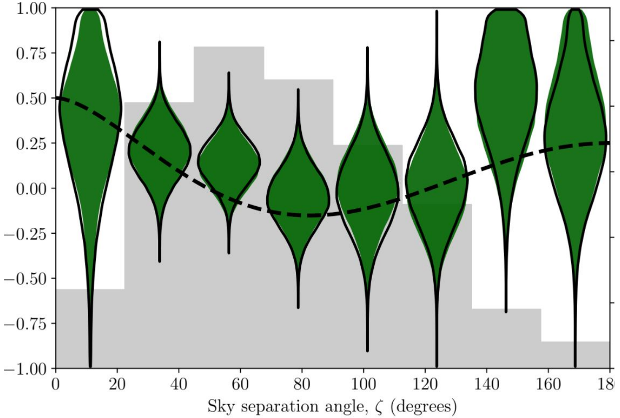
arXiv: 2306.16213

EPTA+InPTA, 2023
10.3 years, 25 PSRs,
3σ



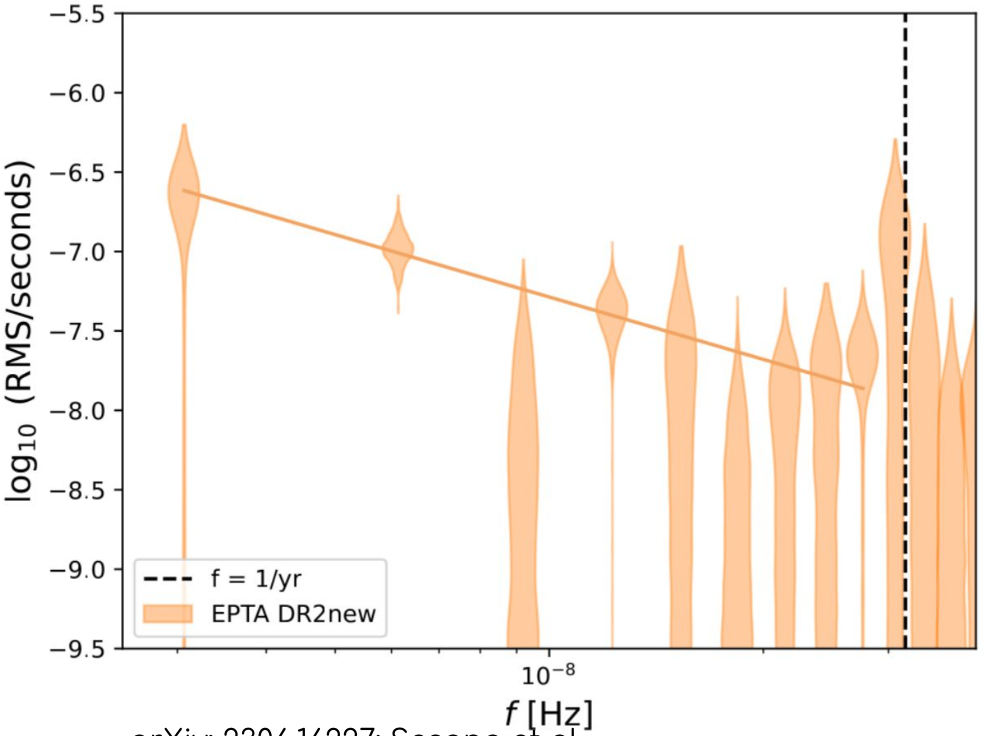
arXiv: 2306.16214

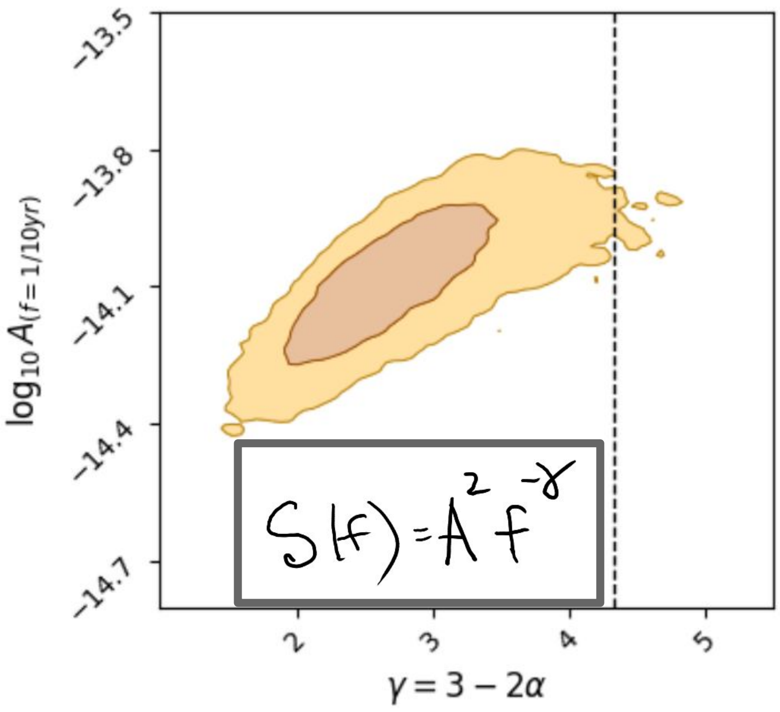
PPTA, 2023
18 years, 32 PSRs
2σ



arXiv: 2306.16215

EPTA+InPTA power spectrum

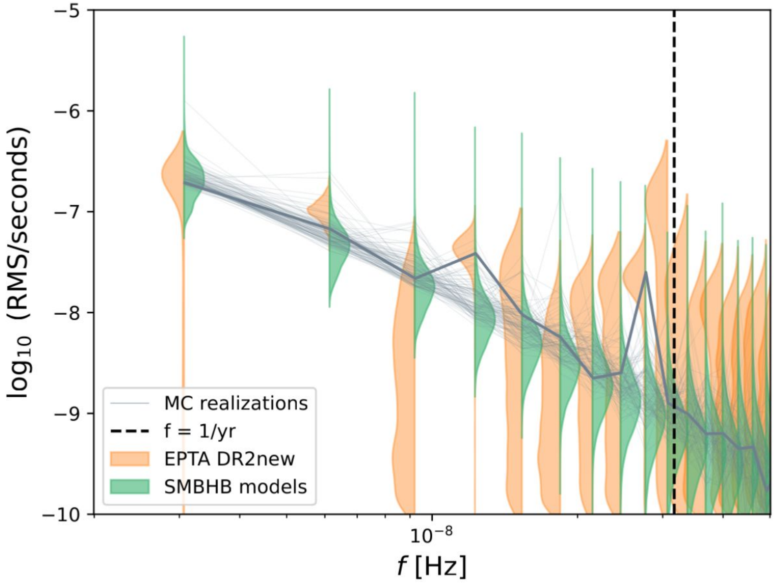




arXiv: 2306.16227: Sesana et al

EPTA+InPTA power spectrum: GWB

$$h_c^2(f) = \frac{4}{\pi f^2} \int\int\int dz dM_{\bullet,1} dq_{\bullet} \frac{d^3 n}{dz dM_{\bullet,1} dq_{\bullet}} \frac{1}{1+z} \frac{dE_{\rm gw}(\mathcal{M})}{d \ln f_r}$$



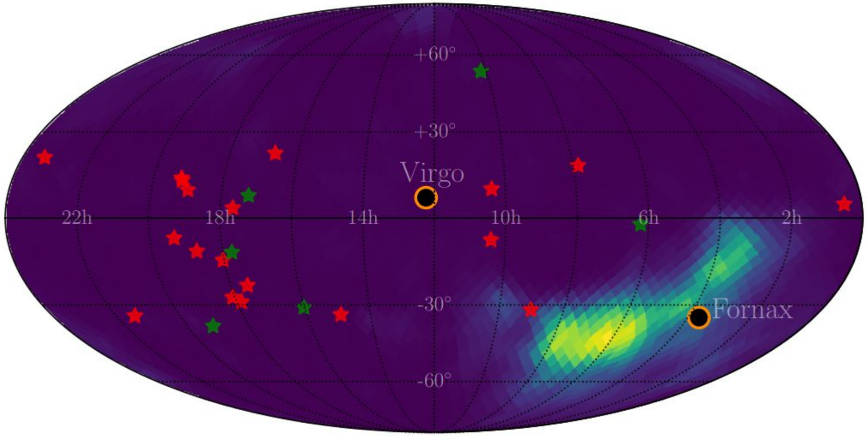
arXiv: 2306.16227: Sesana et al

Defines the amplitude: number of mergers per comoving volume (per redshift, mass, mass ration)

Defines the slope: the energy emitted per log frequency interval; ⅔ in pure GTR with circular binaries, can be modified by accreation and eccentricity

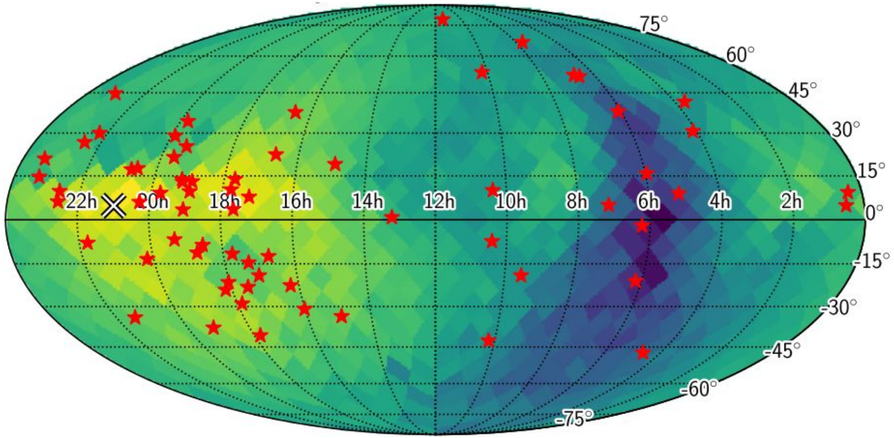
Continuous GW search

EPTA+InPTA



arXiv: 2306.16226 (Falxa, Babak, Speri et al)

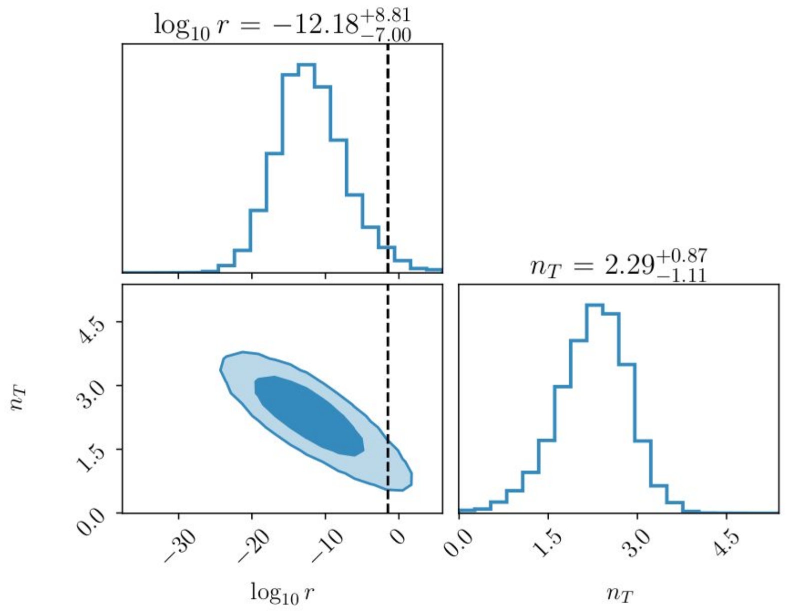
NANOGrav



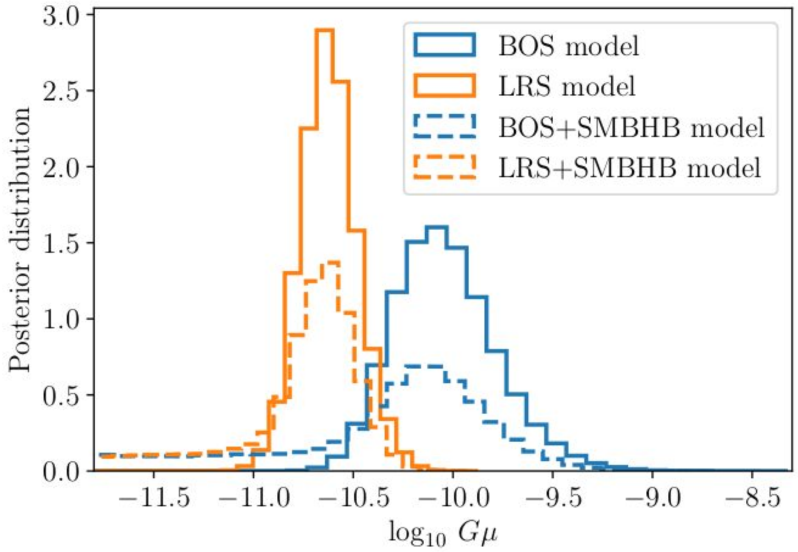
arXiv: 2306.16222

Alternative explanations: early Universe

Inflationary GWB



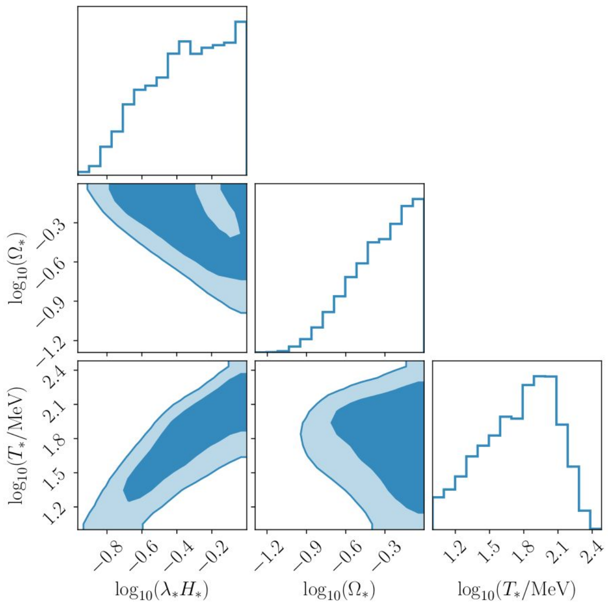
Cosmic strings



arXiv: 2306.16227: Quelquejay Leclere et al

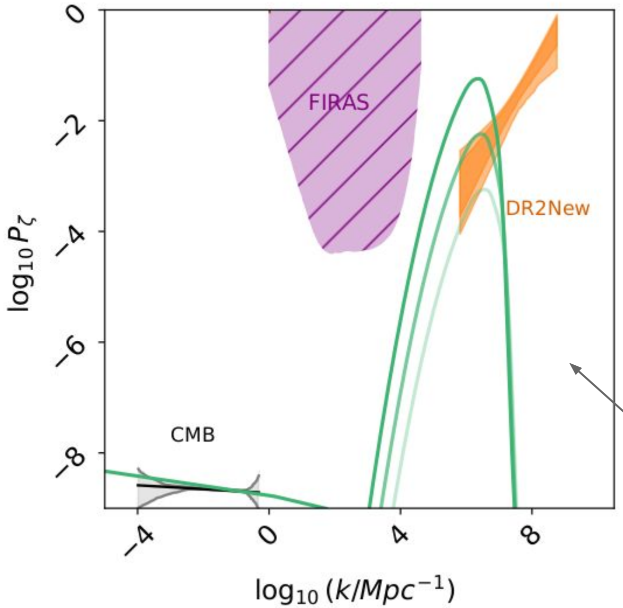
Alternative explanations: early Universe

Cosmic turbulence



arXiv: 2306.16227

2nd order scalar induced GWB



$$P_\zeta = A_\zeta^{10\mathrm{yr}} \left(\frac{k}{k_{10\mathrm{yr}}} \right)^{(n_s - 1)}$$

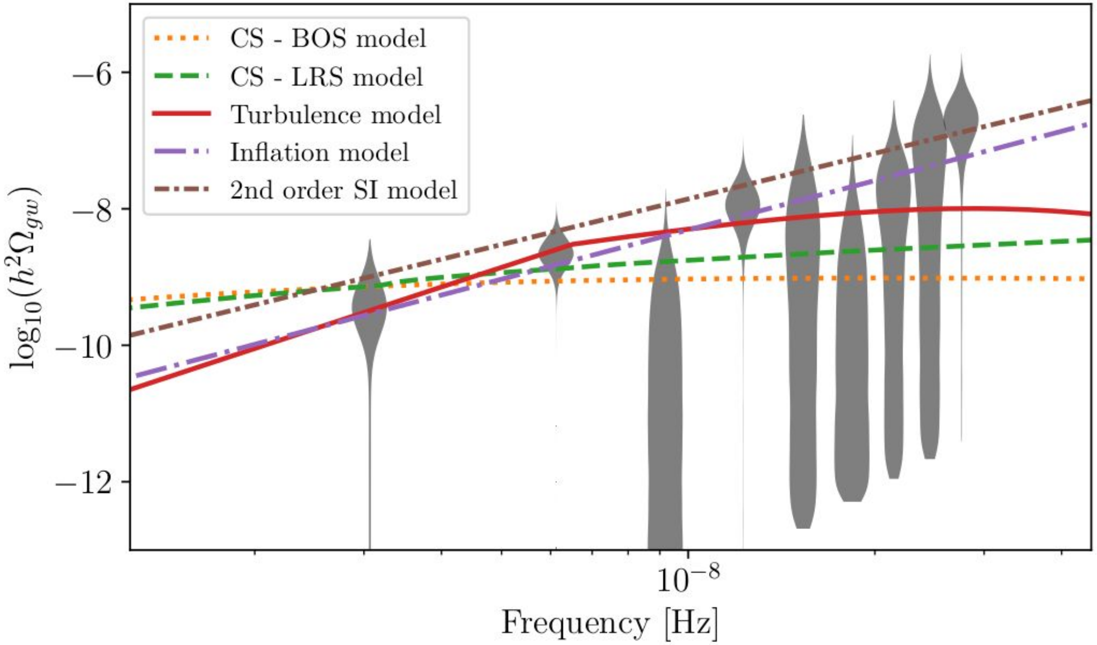
$$\Omega_{\mathrm{GW}} \left(f = \frac{kc}{2\pi} \right) = Q(n_s) A_\zeta^{10\mathrm{yr}} \left(\frac{k}{k_{10\mathrm{yr}}} \right)^{2(n_s - 1)}$$

$$\Omega_{\mathrm{GW}}^0 = 2\Omega_r^0 \left(\frac{g_*(T)}{g_*(T_{\mathrm{eq}})} \right) \left(\frac{g_{*s}(T)}{g_{*s}(T_{\mathrm{eq}})} \right)^{-\frac{4}{3}} \Omega_{\mathrm{GW}}$$

Kohri, Terada 2018

Braglia et al 2020

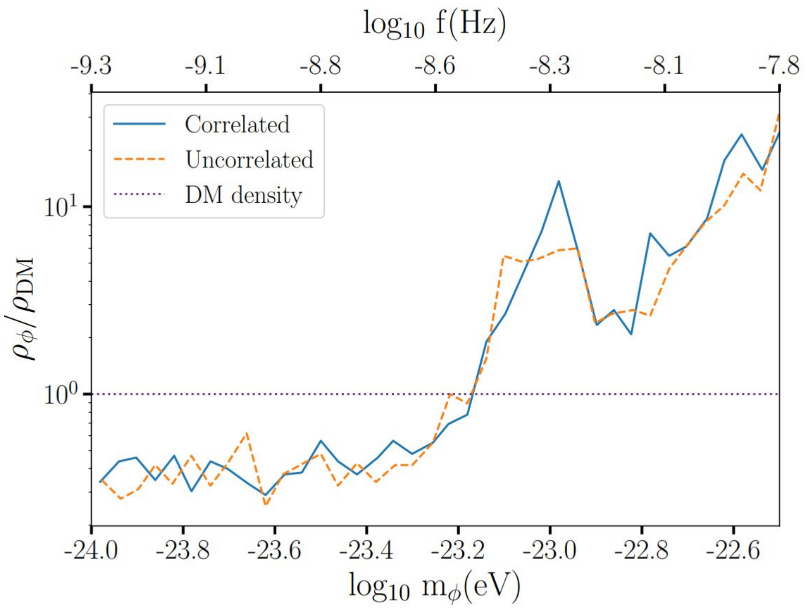
Alternative explanations: early Universe



arXiv: 2306.16227: Quelquejay Leclere et al

Alternative explanations: scalar field dark matter

Upper limits on the FDM using 25-yr EPTA dataset



Scalar field of the form: (boson mass)

$$\varphi(x,t) = A(x)\cos(mt + \alpha(x))$$

Energy-momentum tensor:

$$T_{\mu\nu} = \partial_\mu\varphi\,\partial_\nu\varphi - \tfrac{1}{2}g_{\mu\nu}\left((\partial\varphi)^2 - m^2\varphi^2\right)$$

To the first order v/c

$$T_{\mu\nu} = \begin{pmatrix} \rho = \tfrac{1}{2}m^2A^2 & & & 0 \\ & p & & \\ & & p & \\ 0 & & & p \sim \cos(2mt) \end{pmatrix} \xrightarrow{8\pi G T_{\mu\nu} = G_{\mu\nu}} g_{\mu\nu}(t) = \begin{pmatrix} 2\Phi(t) & & & 0 \\ & -2\Psi(t) \sim \cos(2mt) & & \\ & & -2\Psi(t) & \\ 0 & & & -2\Psi(t) \end{pmatrix}$$

The final expression for the perturbed timing residuals

$$R(t) = \frac{\Psi(x_e)}{2\pi f}\sin(2\pi f t + \alpha(x_e)) - \frac{\Psi(x_p)}{2\pi f}\sin\left(2\pi f\left(t - \frac{D}{c}\right) + \alpha(x_p)\right)$$

$\Psi \sim \rho_{DM}$; $f = \frac{2mc^2}{h} = 5\cdot 10^{-8}\left(\frac{m}{10^{-22}eV}\right)$ Hz

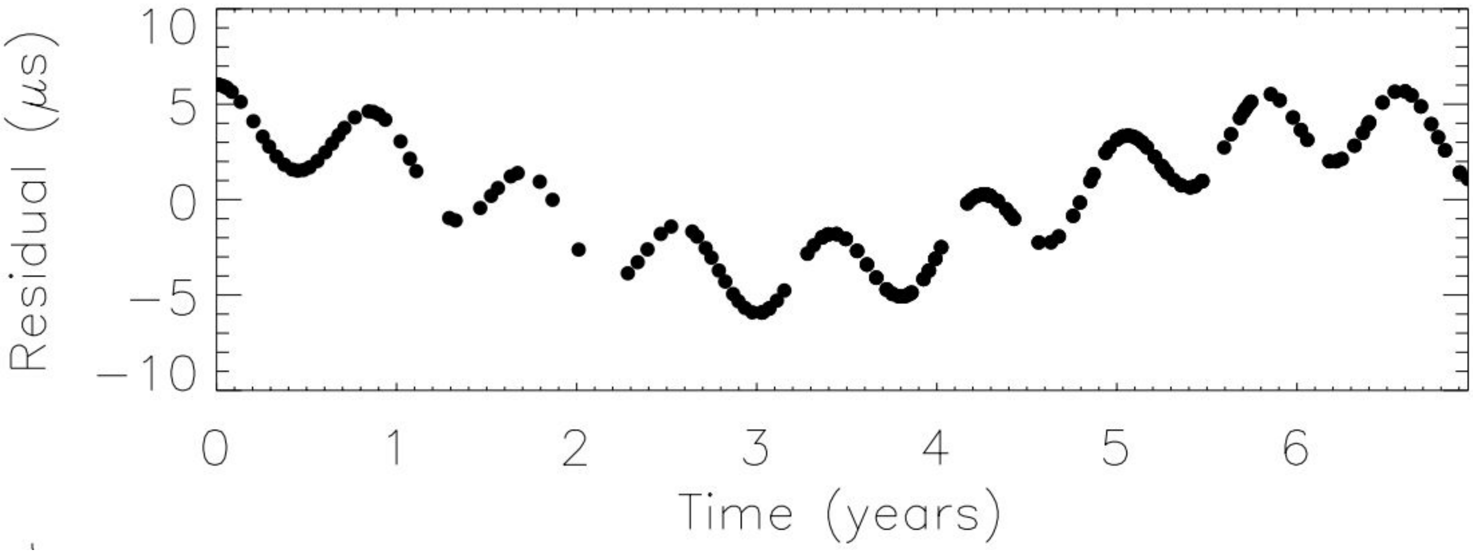
Earth term — Pulsar term

arXiv: 2306.16227: Smarra, Goncharov, Barausse et al


Thank you
Credit: AnastasiaPavlovaArt

Pulsar timing: GW response

Simulated residuals of PSR B1855+09 from the alleged SMBHB in 3C66B



Credit: Jenet et al 2004

EPTA results