Groupement de recherche
Ondes gravitationnelles

October 17th 2023

(Alternative) Interpretations of the Data Release 2 of the EPTA

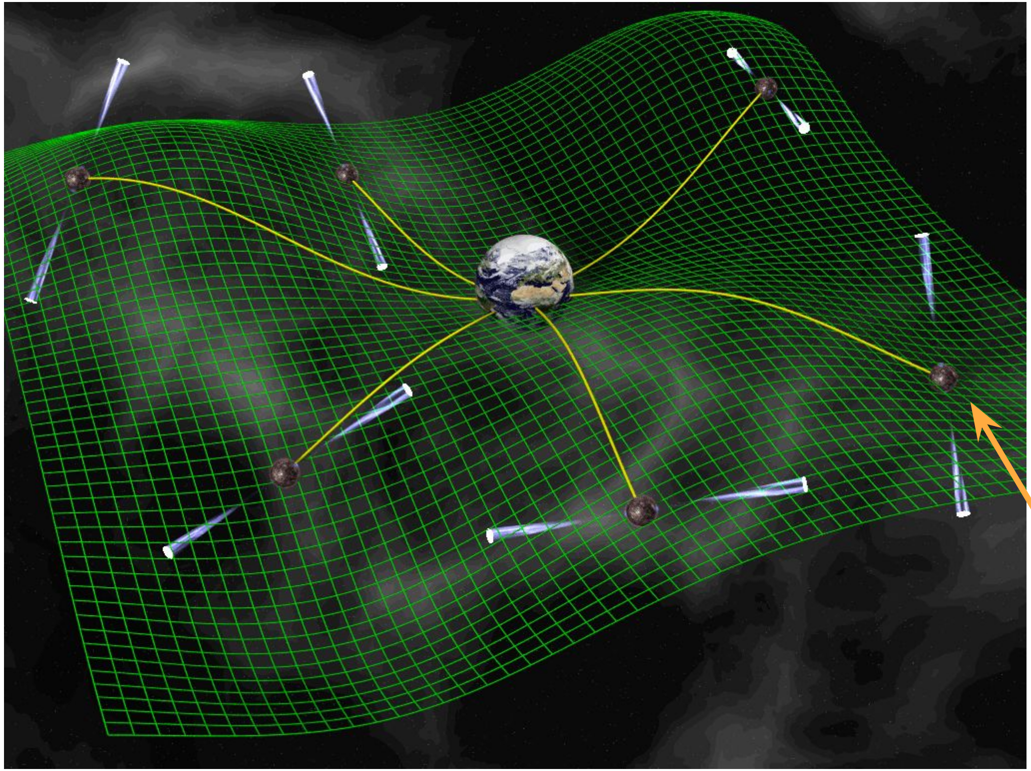
Université Paris Cité

EPTA

Hippolyte QUELQUEJAY - PhD Student (2nd year)

European Pulsar Timing Array Collaboration

What are Pulsar Timing Arrays ?



credits: David Champion

Data : Time series of **residuals** for each pulsar

$$\delta t^i = t^i_{obs} - t^i_{TM}$$

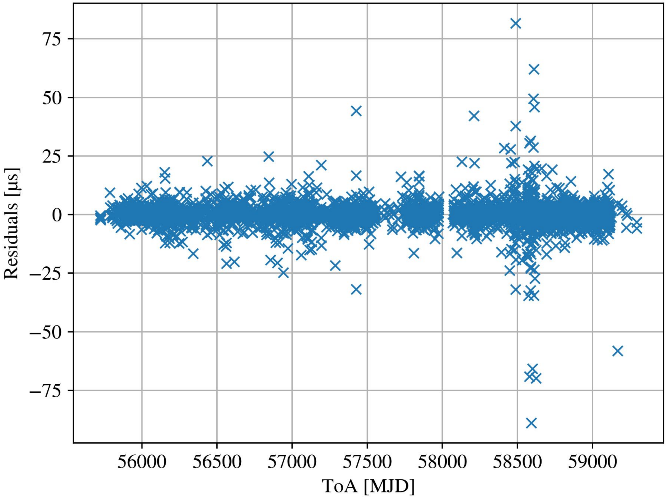
Residual

Time of Arrival observed

ToA predicted by a Timing Model

Millisecond pulsar with their radio jet

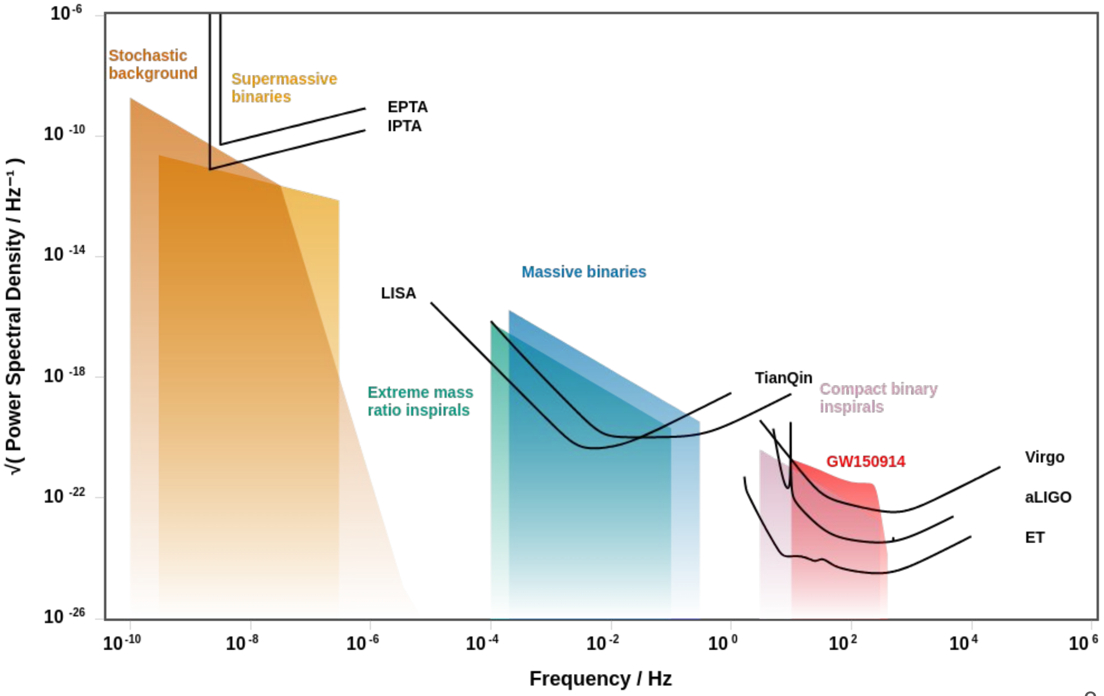
PSR J0030+0451



× 25 MSPs

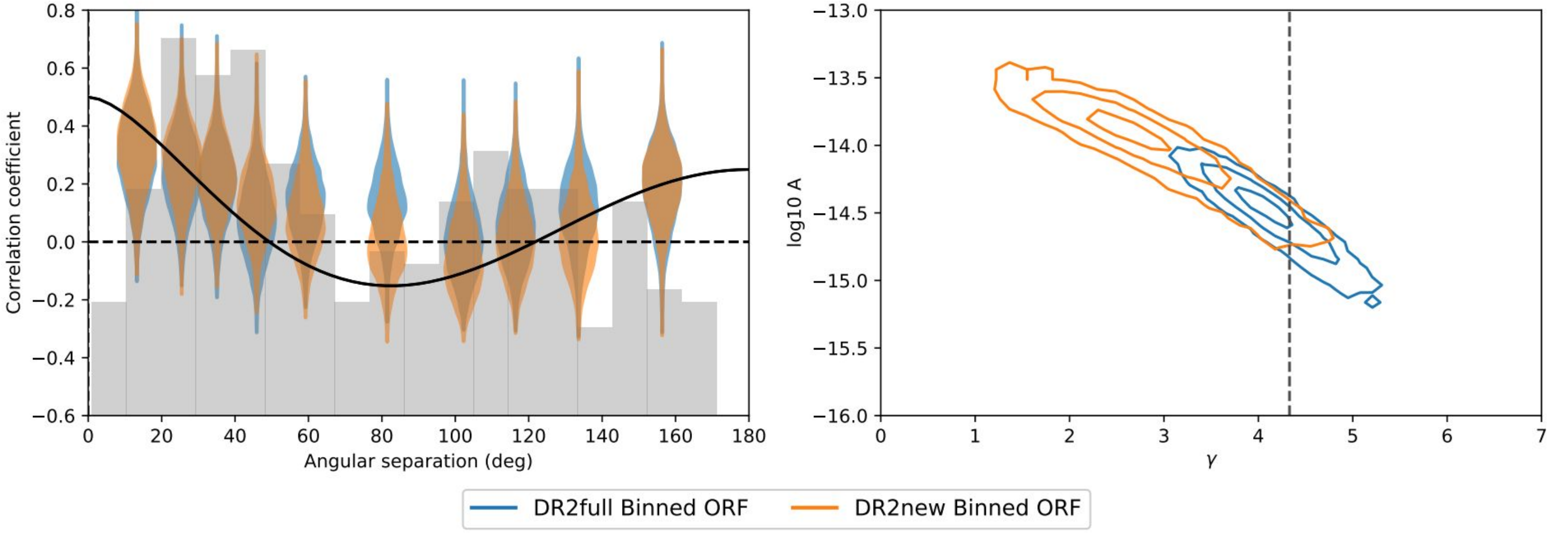
~ 10 years of data

Sensitivity of PTA



The results of the EPTA DR2new

arXiv : 2306.16214



Strong evidence for Hellings&Downs (HD) correlations (GW-induced) in the common red noise (CRN)

Bayes Factor 60

Significance 3.5σ

HD/CURN

↑

uncorrelated

What could produce such signal ?

Astrophysical Sources

- GWB produced by a population of SMBHB
- Individual SMBH Binary Source
- …

Cosmological Sources

- Inflation
- Cosmic Strings
- Phase Transitions
- …

SMBHB : Super Massive Black Hole Binary

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Astrophysical Sources

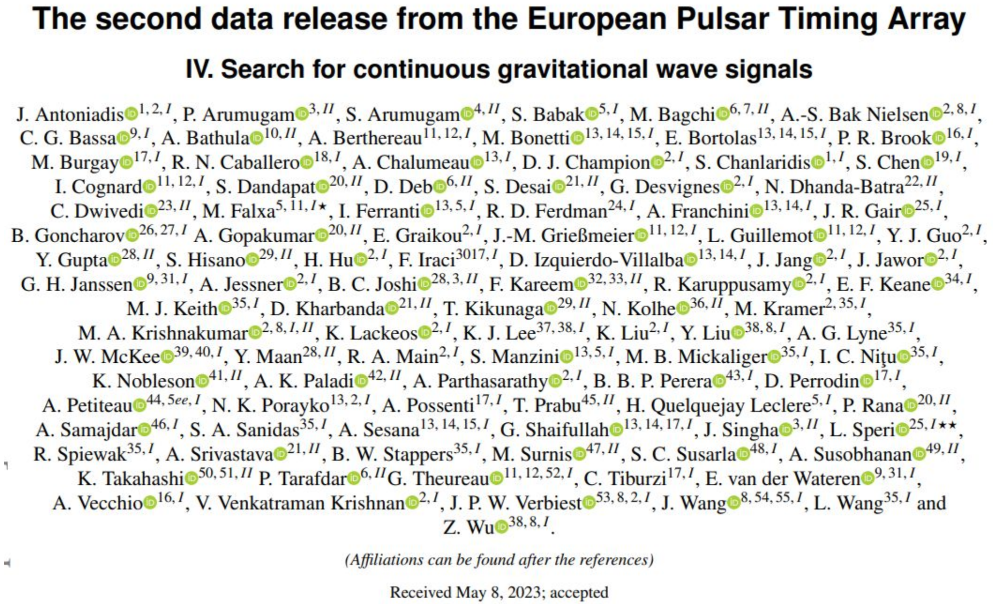
- GWB produced by a population of SMBHB
- Individual SMBH Binary Source
- …

Cosmological Sources

- Inflation
- Cosmic Strings
- Phase Transitions
- …

SMBHB : Super Massive Black Hole Binary

What if the signal we observe is (partially) produced by a <u>single</u> SMBHB ?



The second data release from the European Pulsar Timing Array

IV. Search for continuous gravitational wave signals

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C. G. Bassa[9,I], A. Bathula[10,II], A. Berthereau[11,12,I], M. Bonetti[13,14,15,I], E. Bortolas[13,14,15,I], P. R. Brook[16,I],
M. Burgay[17,I], R. N. Caballero[18,I], A. Chalumeau[13,I], D. J. Champion[2,I], S. Chanlaridis[1,I], S. Chen[19,I],
I. Cognard[11,12,I], S. Dandapat[20,II], D. Deb[6,II], S. Desai[21,II], G. Desvignes[2,I], N. Dhanda-Batra[22,II],
C. Dwivedi[23,II], M. Falxa[5,11,I★], I. Ferranti[13,5,I], R. D. Ferdman[24,I], A. Franchini[13,14,I], J. R. Gair[25,I],
B. Goncharov[26,27,I] A. Gopakumar[20,II], E. Graikou[2,I], J.-M. Grießmeier[11,12,I], L. Guillemot[11,12,I], Y. J. Guo[2,I],
Y. Gupta[28,II], S. Hisano[29,II], H. Hu[2,I], F. Iraci[3017,I], D. Izquierdo-Villalba[13,14,I], J. Jang[2,I], J. Jawor[2,I],
G. H. Janssen[9,31,I], A. Jessner[2,I], B. C. Joshi[28,3,II], F. Kareem[32,33,II], R. Karuppusamy[2,I], E. F. Keane[34,I],
M. J. Keith[35,I], D. Kharbanda[21,II], T. Kikunaga[29,II], N. Kolhe[36,II], M. Kramer[2,35,I],
M. A. Krishnakumar[2,8,I,II], K. Lackeos[2,I], K. J. Lee[37,38,I], K. Liu[2,I], Y. Liu[38,8,I], A. G. Lyne[35,I],
J. W. McKee[39,40,I], Y. Maan[28,II], R. A. Main[2,I], S. Manzini[13,5,I], M. B. Mickaliger[35,I], I. C. Niţu[35,I],
K. Nobleson[41,II], A. K. Paladi[42,II], A. Parthasarathy[2,I], B. B. P. Perera[43,I], D. Perrodin[17,I],
A. Petiteau[44,5ee,I], N. K. Porayko[13,2,I], A. Possenti[17,I], T. Prabu[45,II], H. Quelquejay Leclere[5,I], P. Rana[20,II],
A. Samajdar[46,I], S. A. Sanidas[35,I], A. Sesana[13,14,15,I], G. Shaifullah[13,14,17,I], J. Singha[3,II], L. Speri[25,I★★],
R. Spiewak[35,I], A. Srivastava[21,II], B. W. Stappers[35,I], M. Surnis[47,II], S. C. Susarla[48,I], A. Susobhanan[49,II],
K. Takahashi[50,51,II] P. Tarafdar[6,II]G. Theureau[11,12,52,I], C. Tiburzi[17,I], E. van der Wateren[9,31,I],
A. Vecchio[16,I], V. Venkatraman Krishnan[2,I], J. P. W. Verbiest[53,8,2,I], J. Wang[8,54,55,I], L. Wang[35,I] and
Z. Wu[38,8,I].

(Affiliations can be found after the references)

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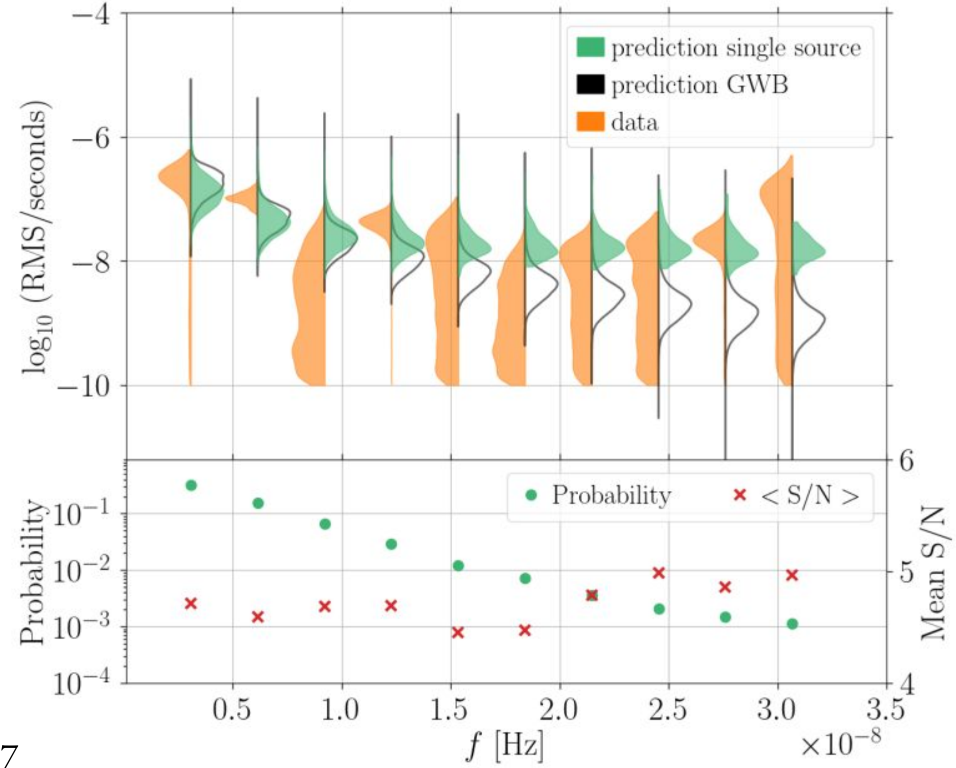
Is this possibility physically well motivated ?

→ Would be the outcome of a massive and nearby SMBHB emerging above the background noise

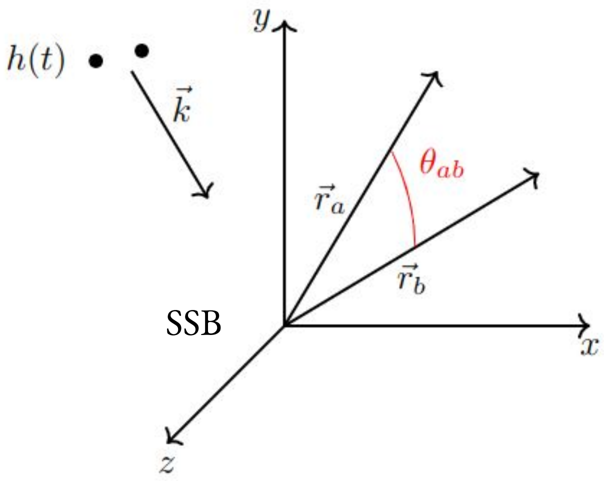


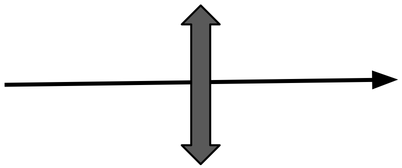
Reasonable chance of having an individual source with SNR > 3 at low frequencies

See: 2306.16227

Problem : It is hard to distinguish a signal produced by a single source from an isotropic background noise

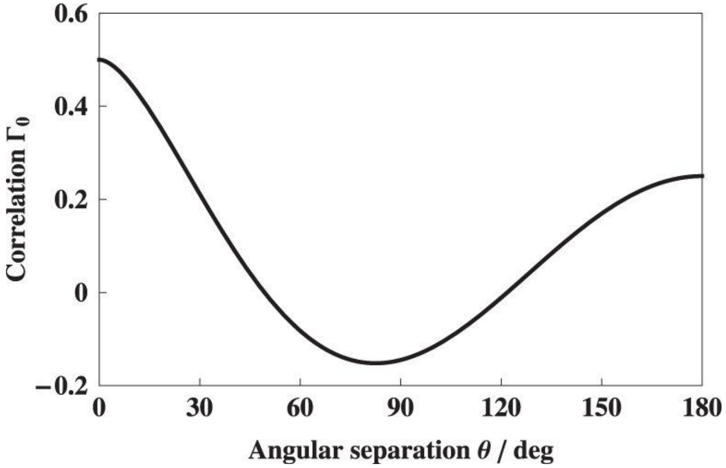
Indeed, HD correlations are also expected from a single source





Averaging over *k*

Averaging over pulsar pairs



Residuals induced by an individual SMBHB

→ Plane wave approximation

→ Residuals are composed of two terms

1. **Pulsar term** : time delay caused by the GW at the radio pulse emission at the pulsar (pulsar dependent)
2. **Earth term** : time delay caused by the GW at the radio pulse reception on Earth (common to all pulsars at a given time)

$$r_{CW}(t) = r(t_e) - r(t_p), \text{ with } t_e = t_p + \tau$$

→ Frequency evolution of the binary

1. During observation time : very small
   a. $r(t)$ → simple sine wave
2. Between Earth and Pulsar term : can be significant!

$$\omega(t) = \omega_0 \left[1 - \frac{256}{5}\mathcal{M}^{5/3}\omega_0^{8/3}(t - t_0)\right]^{-3/8}$$

Principle of the Bayesian analysis

Deterministic signal from the SMBHB

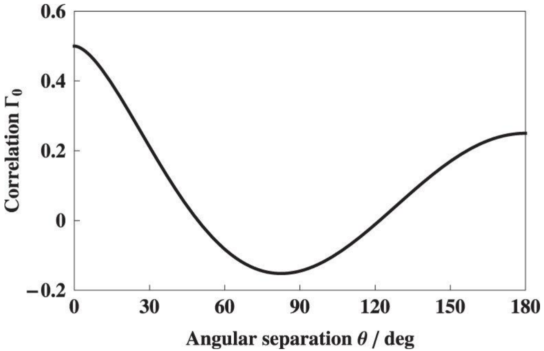
$$\log \mathcal{L} = (\delta t - r_{CW})_a^T C_{ab}^{-1} (\delta t - r_{CW})_b + \dots$$

Pulsar indices

$$C_{(ai)(bj)} = \underbrace{\mathcal{N}_{a,(ij)}}_{\text{Radiometer White Noise (fixed)}} \delta_{ab} + \underbrace{C^{\mathrm{PSR}}_{a,(ij)}}_{\text{Pulsar Red Noises}} \delta_{ab} + \underbrace{\Gamma_{ab}}_{\text{Overlap Reduction Function}} C^{\mathrm{CRN}}_{(ij)}$$

Frequency domain

$$S(f;\vec{\eta}) = \frac{H_0^2}{8\pi^4 f^5}\Omega_{\mathrm{SGWB}}(f;\vec{\eta})$$

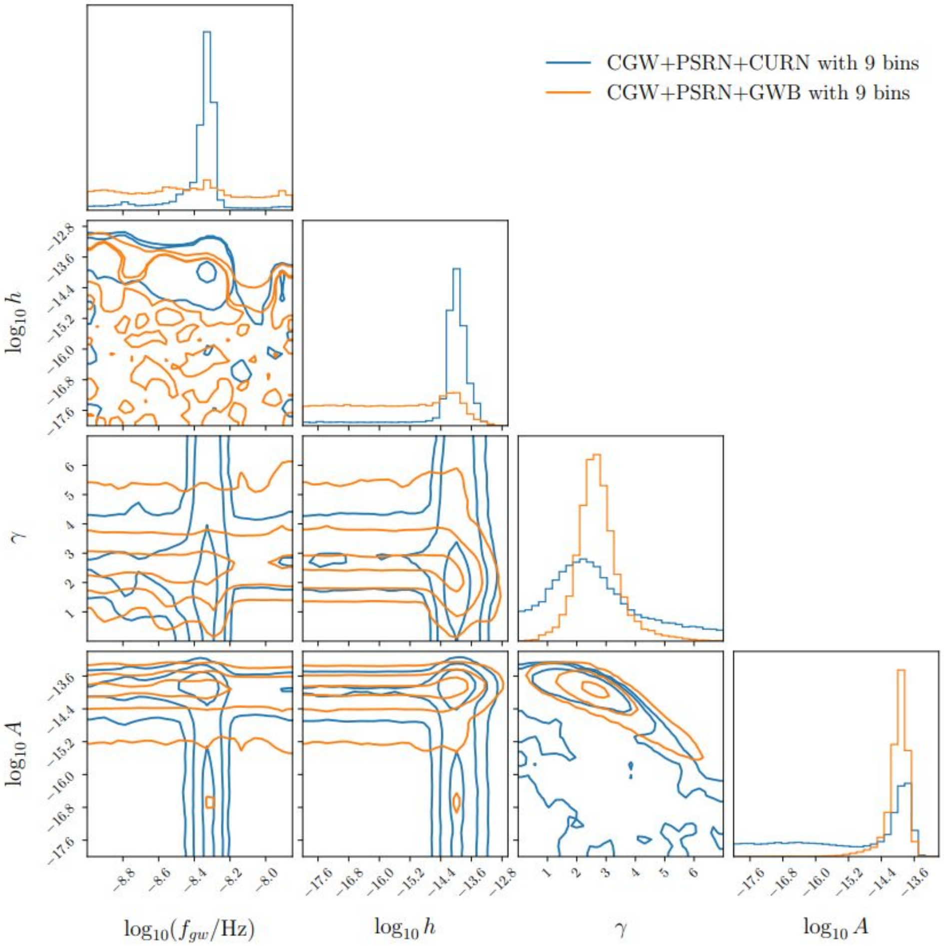


For pulsar red noises

$$S(f;A,\gamma) = \frac{A^2}{12\pi^2}\left(\frac{f}{\mathrm{yr}^{-1}}\right)^{-\gamma}\mathrm{yr}^3$$

Results for circular SMBHB search

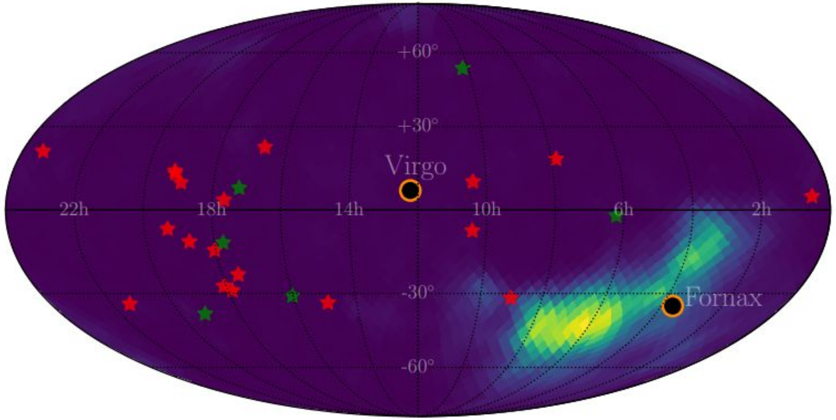
PSRN : PulSar Red Noise



→ CGW candidate around 5 nHz

→ Chirp mass is loosely constrained

→ Adding HD correlations to the background noise **absorbs** the CGW candidate



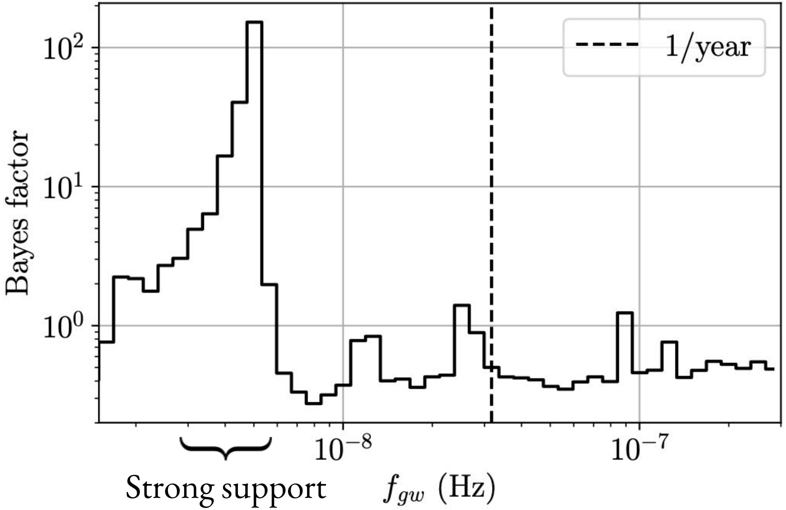
PSRN : PulSar Red Noise
CRN : Common Red Noise

What about statistical significance ?

Model comparison	Bayes factor
CGW+PSRN vs PSRN	4000
CGW+PSRN+CURN vs PSRN+CURN, 3 bins	12
CGW+PSRN+CURN vs PSRN+CURN, 9 bins	4
CGW+PSRN+GWB vs PSRN+GWB, 3 bins	1
CGW+PSRN+GWB vs PSRN+GWB, 9 bins	0.7

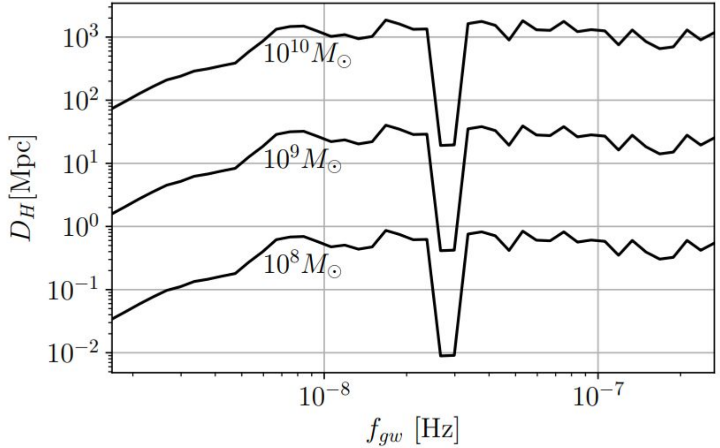
→ Very strong support if no CRN is included in the noise model

The inclusion of the CGW (in addition to a CURN) is not really favoured **with wide frequency prior range** (model complexity penalty)



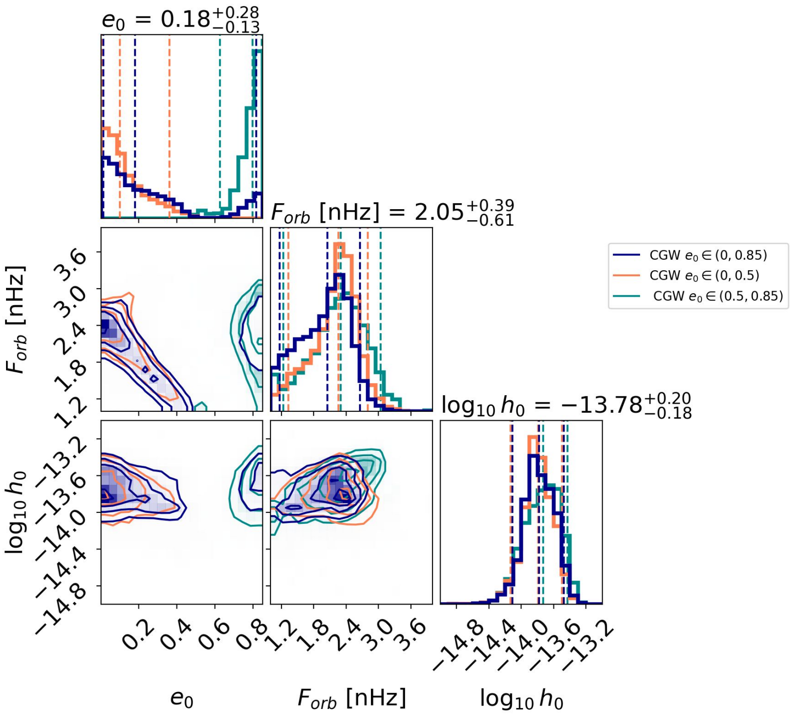
Strong support

Upper limit determination



Results for eccentric SMBH binary

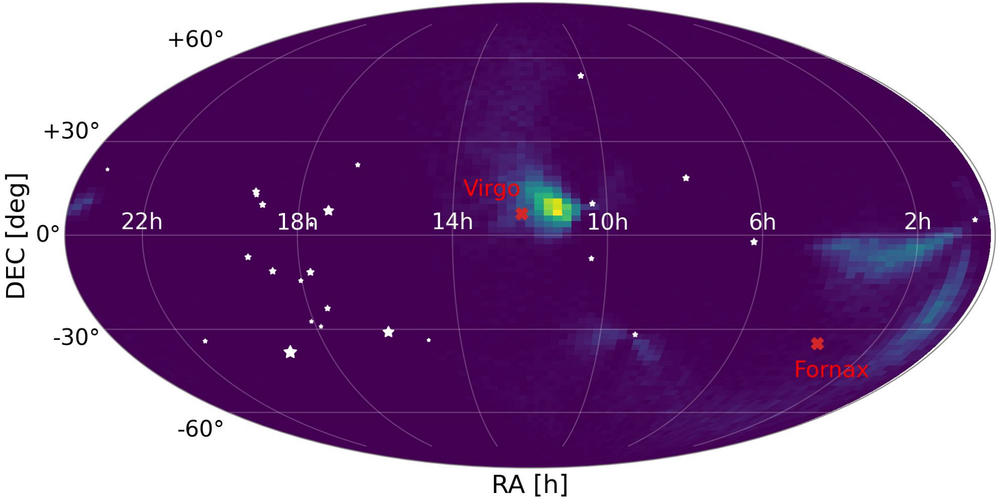
Preliminary Results from Sara Manzini



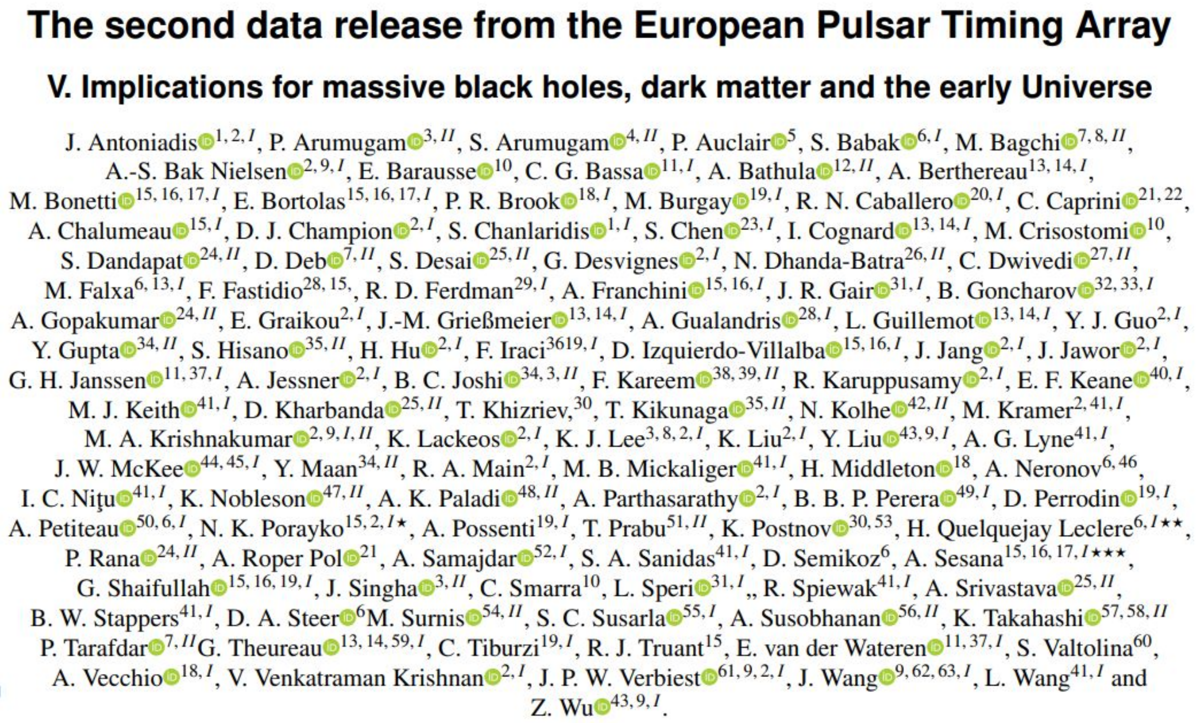
$\underbrace{}_{}$
eccentricity

→ Search using Earth Term only

→ Two modes found : low and high eccentricity



How much can we constrain the early Universe with the EPTA DR2new ?



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

J. Antoniadis[1,2,I], P. Arumugam[3,II], S. Arumugam[4,II], P. Auclair[5], S. Babak[6,I], M. Bagchi[7,8,II],
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A. Gopakumar[24,II], E. Graikou[2,I], J.-M. Grießmeier[13,14,I], A. Gualandris[28,I], L. Guillemot[13,14,I], Y. J. Guo[2,I],
Y. Gupta[34,II], S. Hisano[35,II], H. Hu[2,I], F. Iraci[3619,I], D. Izquierdo-Villalba[15,16,I], J. Jang[2,I], J. Jawor[2,I],
G. H. Janssen[11,37,I], A. Jessner[2,I], B. C. Joshi[34,3,II], F. Kareem[38,39,II], R. Karuppusamy[2,I], E. F. Keane[40,I],
M. J. Keith[41,I], D. Kharbanda[25,II], T. Khizriev,[30], T. Kikunaga[35,II], N. Kolhe[42,II], M. Kramer[2,41,I],
M. A. Krishnakumar[2,9,I,II], K. Lackeos[2,I], K. J. Lee[3,8,2,I], K. Liu[2,I], Y. Liu[43,9,I], A. G. Lyne[41,I],
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P. Rana[24,II], A. Roper Pol[21], A. Samajdar[52,I], S. A. Sanidas[41,I], D. Semikoz[6], A. Sesana[15,16,17,I★★★],
G. Shaifullah[15,16,19,I], J. Singha[3,II], C. Smarra[10], L. Speri[31,I],, R. Spiewak[41,I], A. Srivastava[25,II],
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P. Tarafdar[7,II]G. Theureau[13,14,59,I], C. Tiburzi[19,I], R. J. Truant[15], E. van der Wateren[11,37,I], S. Valtolina[60],
A. Vecchio[18,I], V. Venkatraman Krishnan[2,I], J. P. W. Verbiest[61,9,2,I], J. Wang[9,62,63,I], L. Wang[41,I] and
Z. Wu[43,9,I].

See Caprini, Figueroa [1801.04268] for review

Primordial GWs | SGWB from inflation

→ very simple modelisation : **power law** to link the large CMB scales to small PTA scales

Tensor spectral index

Tensor to scalar ratio

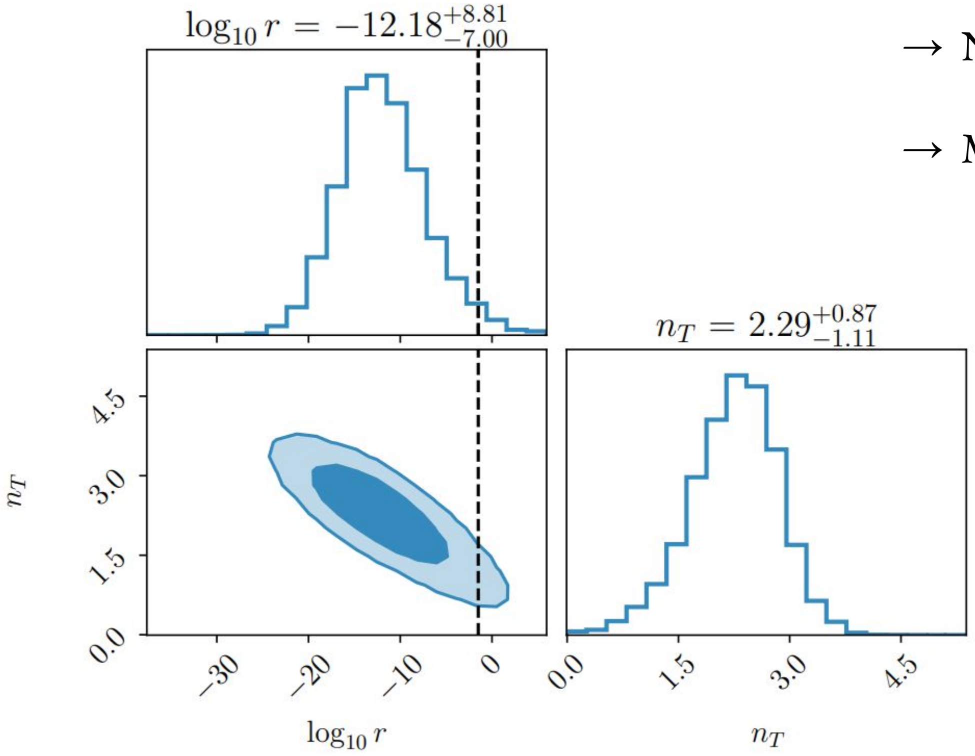
$$\Omega_{\mathrm{GW}}(f) \approx 1.5 \times 10^{-16}\left(\frac{r}{0.032}\right)\left(\frac{f}{f_*}\right)^{n_T}$$

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

→ 2 model parameters, for **slow roll** inflation: $n_T \simeq 0$

→ Constraints from CMB (Planck collaboration) : $r < 0.076$ and $-0.55 < n_T < 2.54$ at 95%

Explaining all the PTA CRN with inflation



→ Not compatible with classic slow roll inflation

→ Must be a blue tilted spectrum

Obtaining upper limit
including simple circular
SMBHB background

$$n_T = a \log_{10}\left(\frac{r}{0.032}\right) + b$$

$$a = -0.16, b = 0.70$$

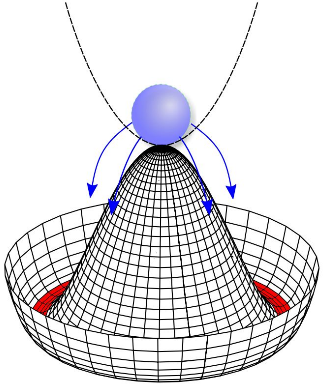
How cosmic strings produce GWs ?

Some **assumptions** used

→ stable cosmic strings associated to a local symmetry

→ intercommutation probability of 1

→ GW emission is dominant (Nambu-Goto strings)

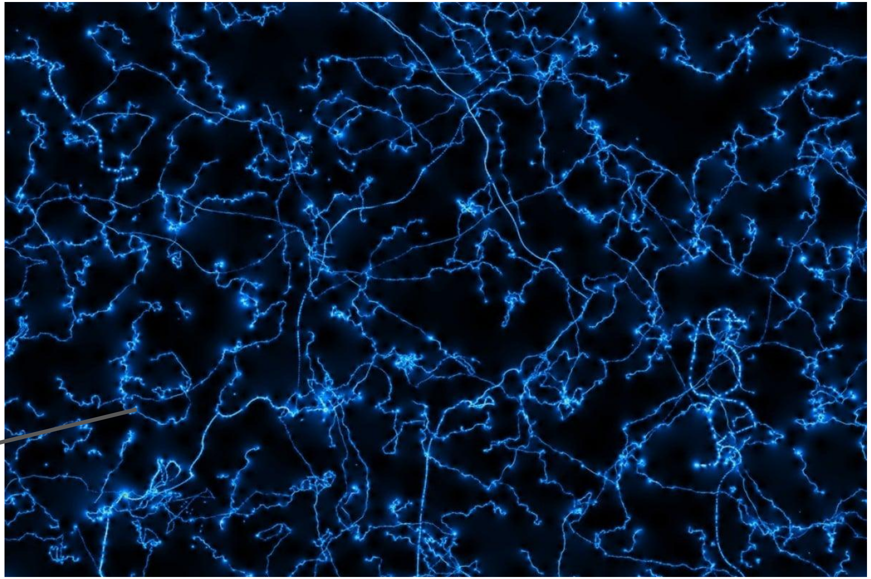


credits: Pierre Auclair

spontaneous
symmetry breaking

$$\xrightarrow{\hspace{4em}}$$

at $\eta \propto \sqrt{G\mu}$



credits: freeastroscience

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

$$f_n = \frac{2n}{\ell}$$

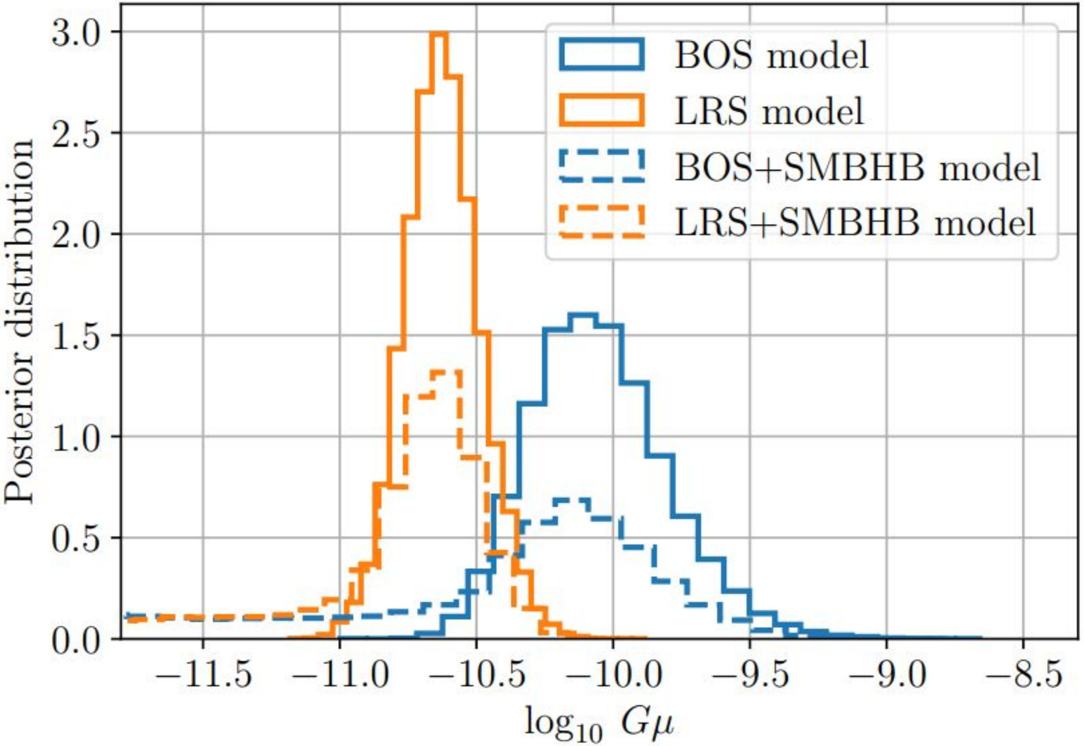
Constraints for smooth loops network

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

summing over cosmic time

Loop number density

(two models used: BOS, LRS)



→ 90% symmetric credible intervals

BOS model $\log_{10} G\mu = -10.06^{+0.48}_{-0.36}$

LRS model $\log_{10} G\mu = -10.63^{+0.24}_{-0.22}$

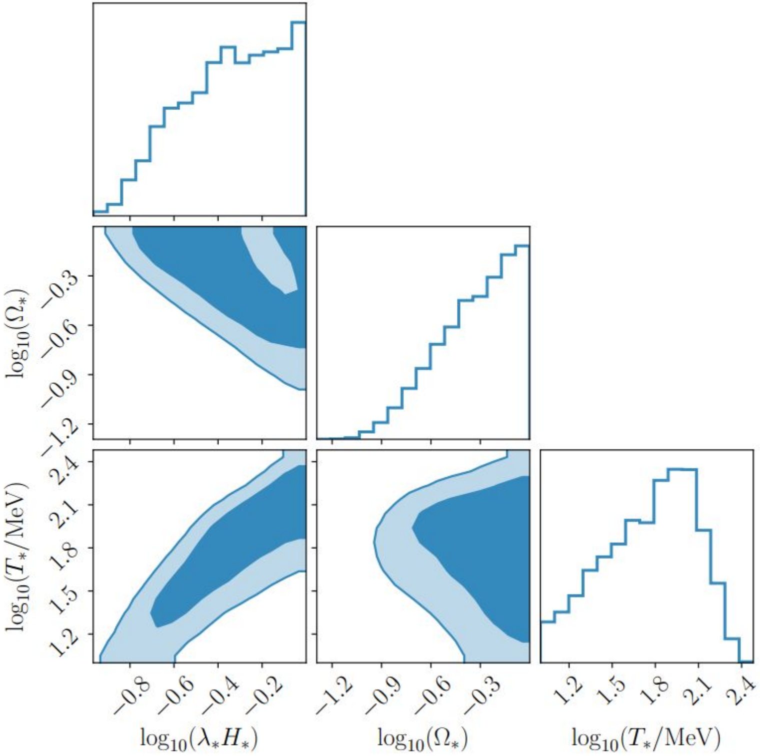
→ 95% confidence upper limit extracted from a **two component SGWB** analysis

BOS+SMBHB model $\log_{10} G\mu < -9.75$

LRS+SMBHB model $\log_{10} G\mu < -10.44$

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

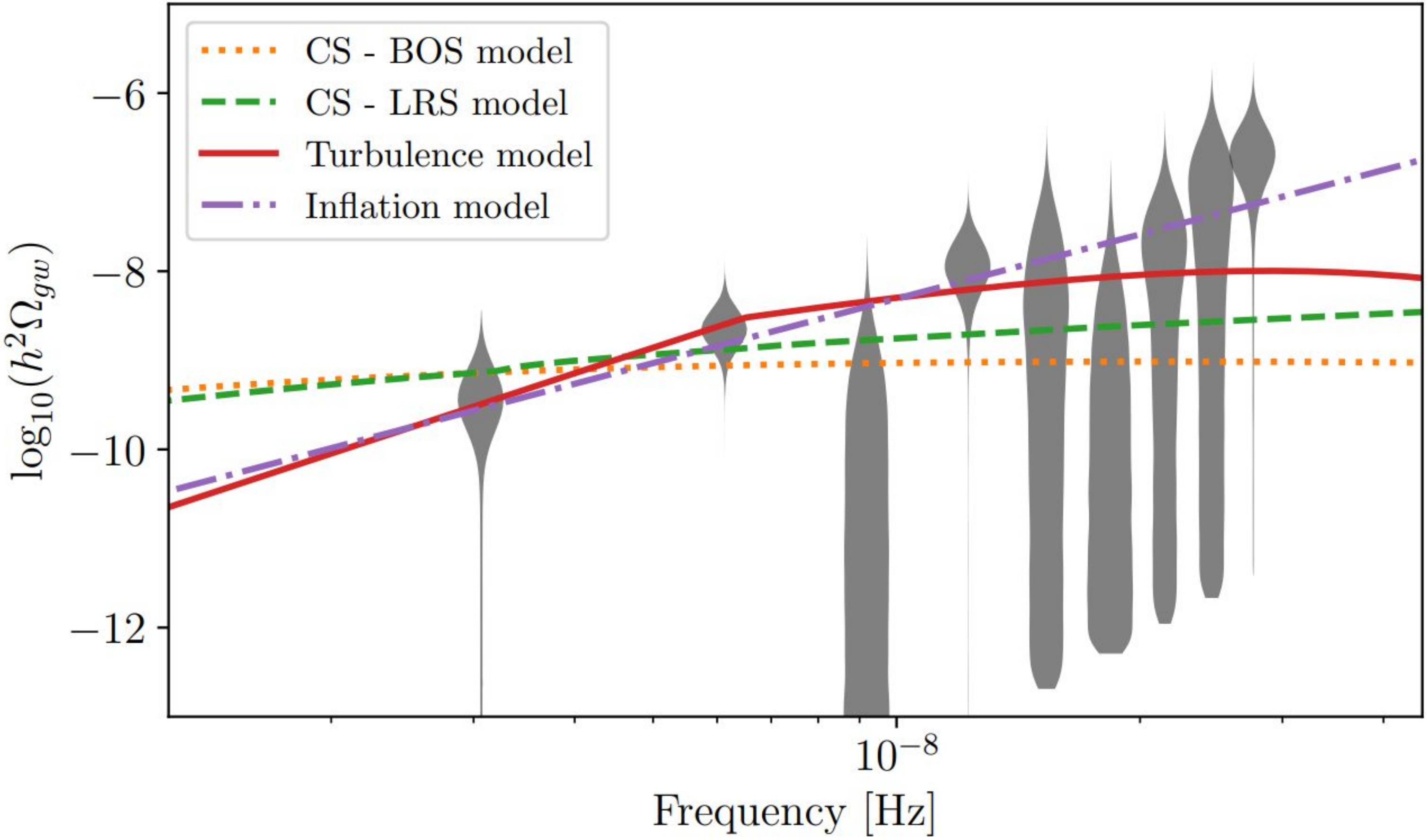
SGWB sourced by turbulence after QCD phase transition



λ_*	Characteristic scale of the turbulence
Ω_*	Ratio of the turbulent energy density to the radiation one
T_*	Temperature scale of the phase transition

→ The preferred set of parameters require a lot of turbulent energy density but can fit also fit the data with smaller values of Ω_*

See Roper Pol et al [2201.05630] for model description


CS - BOS model
CS - LRS model
Turbulence model
Inflation model
-6
-8
-10
-12
$\log_{10}(h^2\Omega_{gw})$
10^{-8}
Frequency [Hz]

Summary

→ The correlated signal that is detected in EPTA DR2new could have several origin

→ The presence of a SMBHB at ~2.5 nHz (orbital frequency) could explain very well the correlated power we see at low frequency (strong interaction with the GWB modelisation)

→ The statistical significance of this candidate is hard to assess due to the difference in model complexity

→ We constrained many early universe models that predict a SGWB : can all (partially) fit the signal we see

1. Slow roll inflation alone is quite incompatible with the data
   → must be blue tilted to reach PTA sensitivity
2. Cosmic strings can only fit the lowest frequency bins (not blue tilted enough spectrum)
   → place stringent constraints on the string tension
3. Turbulence from QCD PT can fit the data at low frequency

Backup slides

NANOGrav also sees something at this frequency