Constrain modified gravities with pulsar timing arrays

Zu-Cheng Chen (陈祖成)

Done with Yan-Chen Bi, Qing-Guo Huang, Jun Li, Lang Liu,
Zhu Yi, Chen Yuan, Yu-Mei Wu

Based on 2310.08366 (PRDL); 2401.09818 (PRDL); 2101.06869 (SCPMA);
2310.11238 (PRD); 2302.00229 (PRD); 2310.07469 (CQG)

Hunan Normal University (湖南师范大学)

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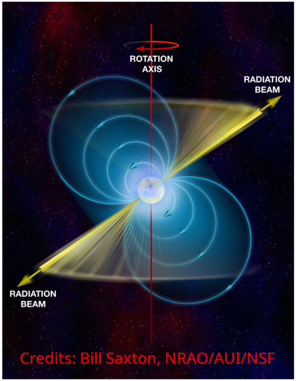
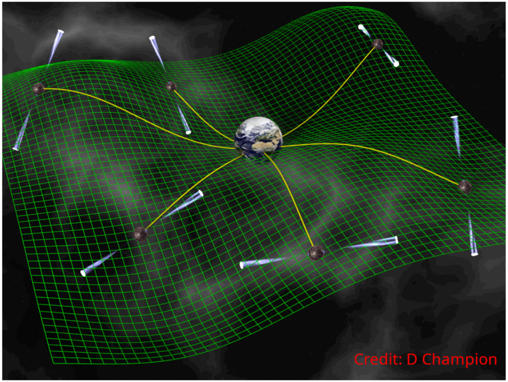
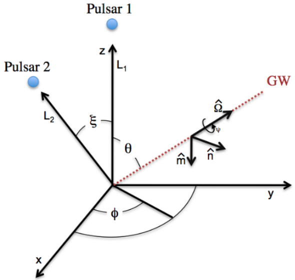
Pulsar and pulsar timing array (PTA)





- Pulsars are highly magnetized, rotating neutron stars that emit regular pulses of electromagnetic radiation.
- GWs can cause tiny distortion in spacetime inducing variations in the time of arrivals (ToAs).
- A PTA pursues to detect nHz GWs by regularly monitoring ToAs from an array of the ultra rotational stable millisecond pulsars.

Timing residual induced by a GWB



- Redshift

$$z(t,\hat{\Omega}) = \frac{\nu_e - \nu_p}{\nu_p}$$
$$= \frac{\hat{p}^i \hat{p}^j}{2(1+\hat{\Omega}\cdot\hat{p})}\left[h_{ij}\left(t_p,\hat{\Omega}\right) - h_{ij}\left(t_e,\hat{\Omega}\right)\right]$$
$$z(t) = \int_{S^2} d\hat{\Omega}\, z(t,\hat{\Omega})$$

- Timing residual in frequency-domain

$$\tilde{r}(f,\hat{\Omega}) = \frac{1}{2\pi i f}\left(1 - e^{-2\pi i f L(1+\hat{\Omega}\cdot\hat{p})}\right) \times \sum_A h_A(f,\hat{\Omega}) F^A(\hat{\Omega})$$

- Antenna pattern

$$F^A(\hat{\Omega}) = e^A_{ij}(\hat{\Omega}) \frac{\hat{p}^i \hat{p}^j}{2(1+\hat{\Omega}\cdot\hat{p})}$$

Detecting a GWB with PTA

- Assume the GWB is isotropic, unpolarized, and stationary

$$\left\langle h_A^*(f,\hat{\Omega})h_{A'}(f',\hat{\Omega}')\right\rangle = \frac{3H_0^2}{32\pi^3 f^3}\delta^2(\hat{\Omega},\hat{\Omega}')\delta_{AA'}\delta(f-f')\Omega_{\rm gw}(f)$$

- Spectrum of GWB

$$\Omega_{\rm gw}(f) \equiv \frac{1}{\rho_{\rm crit}}\frac{d\rho_{\rm gw}}{d\ln f}, \qquad \rho_{\rm crit} = \frac{3H_0^2}{8\pi}, \quad \rho_{\rm gw} = \frac{1}{32\pi}\left\langle \dot{h}_{ij}(t,\vec{x})\dot{h}^{ij}(t,\vec{x})\right\rangle,$$

- Cross-power spectral density

$$S_{IJ} = \langle \tilde{r}_I^*(f)\tilde{r}_J(f')\rangle = \frac{1}{\gamma}\frac{H_0^2}{16\pi^4 f^5}\delta\left(f-f'\right)\Gamma_{IJ}(f,L_I,L_J,\xi)\,\Omega_{\rm gw}(f)$$

- Overlap reduction function (ORF) is function of f, L_I, L_J, ξ

$$\Gamma_{IJ} = \gamma\sum_A\int d\hat{\Omega}\left(e^{2\pi i f L_I(1+\hat{\Omega}\cdot\hat{p}_I)}-1\right)\times\left(e^{-2\pi i f L_J(1+\hat{\Omega}\cdot\hat{p}_J)}-1\right)F_I^A(\hat{\Omega})F_J^A(\hat{\Omega})$$

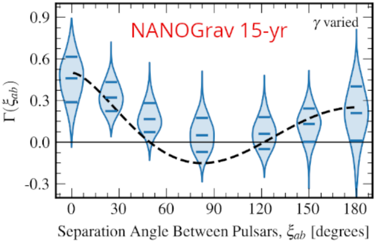
- Hellings & Downs correlations for $fL \gg 1$ (short-wavelength approximation)

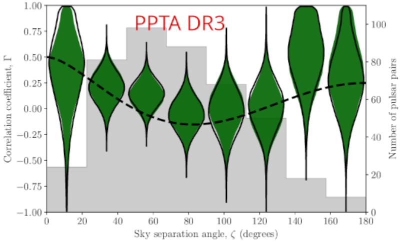
$$\Gamma_{IJ} = \frac{3}{2}\left(\frac{1-\cos\xi}{2}\right)\ln\frac{1-\cos\xi}{2} - \frac{1-\cos\xi}{8} + \frac{1}{2}$$

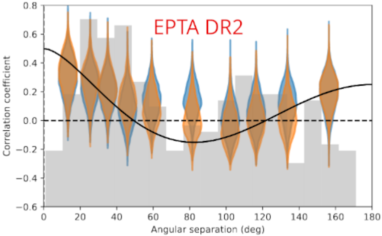
PTAs in operation

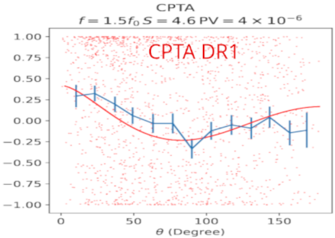
IPTA: PPTA + EPTA + NANOGrav + InPTA
Observers: CPTA, MPTA

The stochastic signal in PTAs (2023-06-29)









NANOGrav, 2306.16213 (ApJL); PPTA, 2306.16215 (ApJL)

EPTA+InPTA, 2306.16214 (A&A); CPTA, 2306.16216 (RAA)

SIGWs can explain the PTA signal.

NANOGRAV 15-YEAR NEW-PHYSICS SIGNALS 9

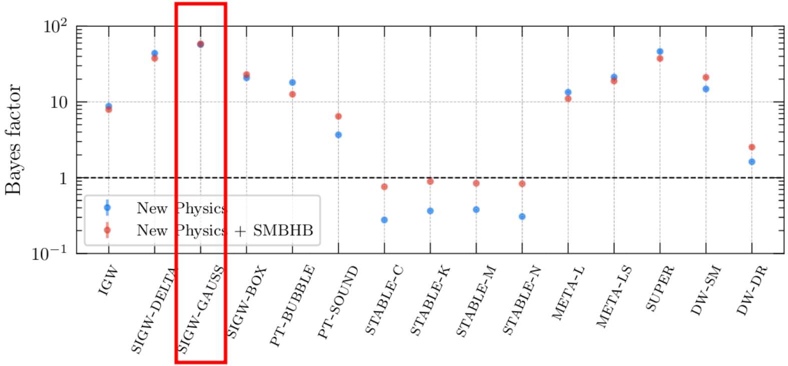


Figure 2. Bayes factors for the model comparisons between the new-physics interpretations of the signal considered in this work and the interpretation in terms of SMBHBs alone. Blue points are for the new physics alone, and red points are for the new physics in combination with the SMBHB signal. We also plot the error bars of all Bayes factors, which we obtain following the bootstrapping method outlined in Section 3.2. In most cases, however, these error bars are small and not visible.

NANOGrav Collaboration, 2306.16219 (ApJL)

Scalar-Induced Gravitational Waves (SIGWs)

- Primordial perturbations can be generated by quantum fluctuations during inflation.

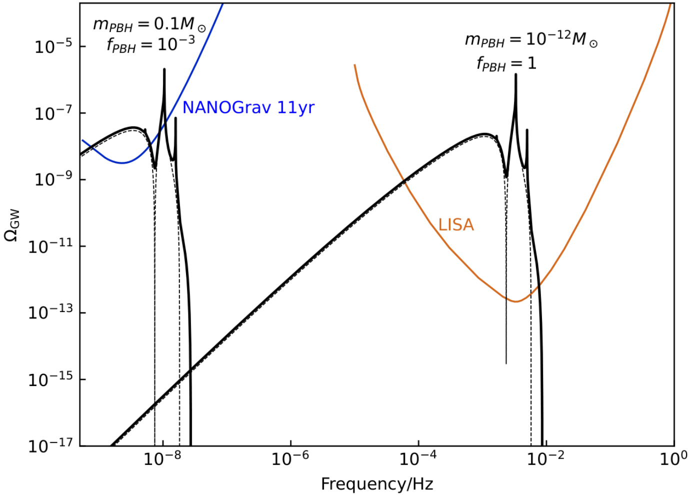
- Metric perturbation in Newtonian gauge

$$\mathrm{d}s^2 = a^2\left\{-(1+2\phi)\mathrm{d}\eta^2 + \left[(1-2\phi)\delta_{ij} + \frac{h_{ij}}{2}\right]\mathrm{d}x^i\mathrm{d}x^j\right\}, \tag{1}$$

where $\phi \equiv \phi^{(1)}$ and $h_{ij} \equiv h_{ij}^{(2)}$ are the scalar and tensor perturbations, respectively.

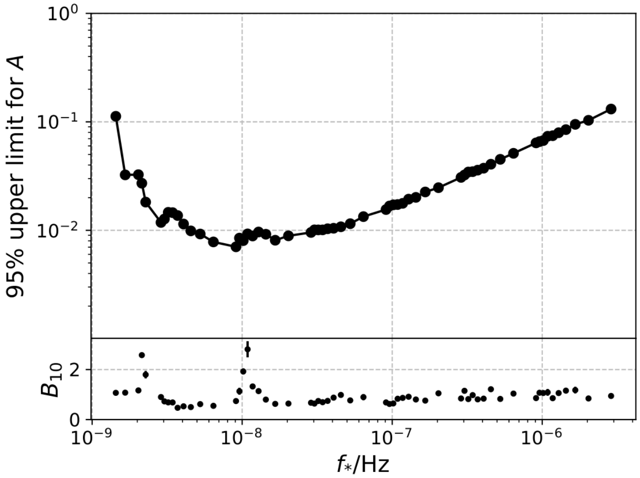
- Primordial scalar perturbation can be the source of SIGWs, as well as primordial black holes (PBHs).

Detecting SIGW with PTA



*Chen Yuan, **ZCC**, Qing-Guo Huang, 1906.11549 (PRD Rapid Communications)*

Constrain SIGWs with NANOGrav 11-yr data set



ZCC, Chen Yuan, Qing-Guo Huang, 1910.12239 (PRL)

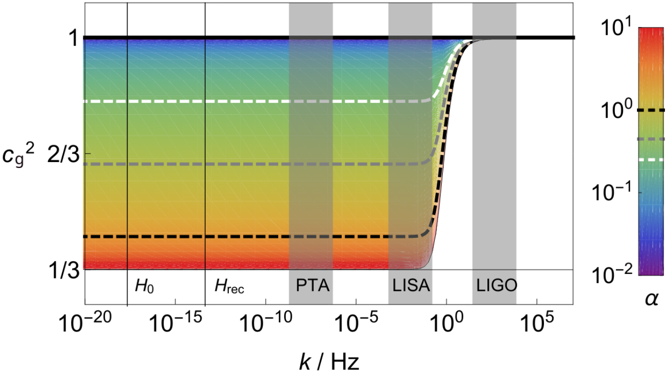
Can we test gravity if the PTA signal is indeed from SIGW?

Speed of GW

- GW170817: $-3 \times 10^{-15} \leq c_g - 1 \leq 7 \times 10^{-16}$

LVK, 1710.05832 (PRL)

- c_g can be frequency dependent



Claudia de Rham, Scott Melville, 1806.09417 (PRL)

Speed of SIGW

- EoM

$$h_{\mathbf{k}}''(\eta) + 2\mathcal{H}h_{\mathbf{k}}'(\eta) + c_g^2 k^2 h_{\mathbf{k}}(\eta) = 4S_{\mathbf{k}}(\eta). \quad (2)$$

- SIGW spectrum

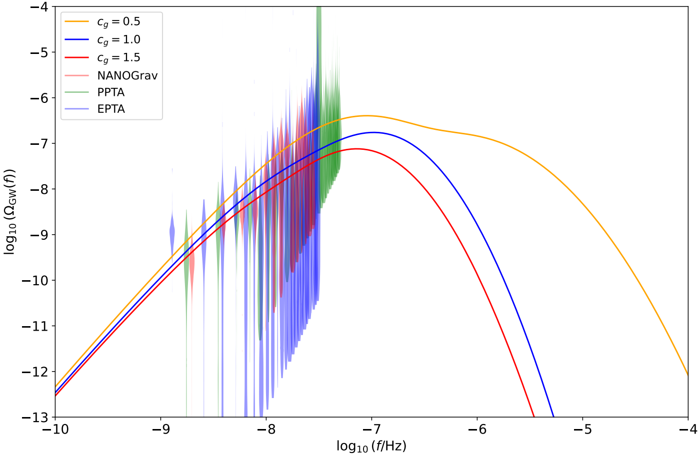
$$\Omega_{\mathrm{GW}}(k) = \int_0^\infty \mathrm{d}v \int_{|1-v|}^{1+v} \mathrm{d}u \mathcal{T}(u, v, c_g) P_\zeta(vk) P_\zeta(uk). \quad (3)$$

- Transfer function

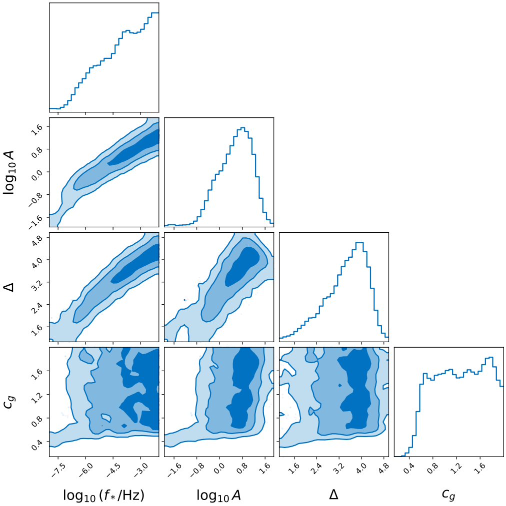
$$\mathcal{T}(u, v, c_g) = \frac{3\left[4v^2 - (v^2 - u^2 + 1)^2\right]^2 (v^2 + u^2 - 3c_g^2)^2}{1024 v^8 u^8} \times \left\{ \left[(v^2 + u^2 - 3c_g^2) \ln\left(\left| \frac{3c_g^2 - (v+u)^2}{3c_g^2 - (v-u)^2} \right| \right) - 4vu \right]^2 + \pi^2 (v^2 + u^2 - 3c_g^2)^2 \Theta(v + u - \sqrt{3}c_g) \right\}. \quad (4)$$

Jun Li, Guang-Hai Guo, 2312.04589

PE with NANOGrav 15-yr data set + PPTA DR3 + EPTA DR2



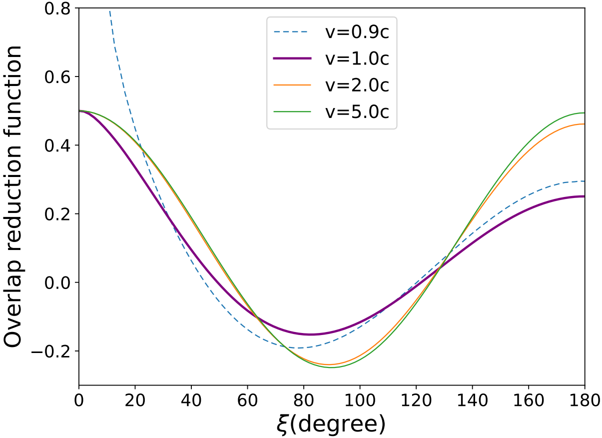
ZCC, Jun Li, Lang Liu, Zhu Yi, 2401.09818 (PRDL)



- $c_g \gtrsim 0.61$ at a 95% CI.
- Consistent with $c_g = 1$.

ZCC, Jun Li, Lang Liu, Zhu Yi, 2401.09818 (PRDL)

ORF

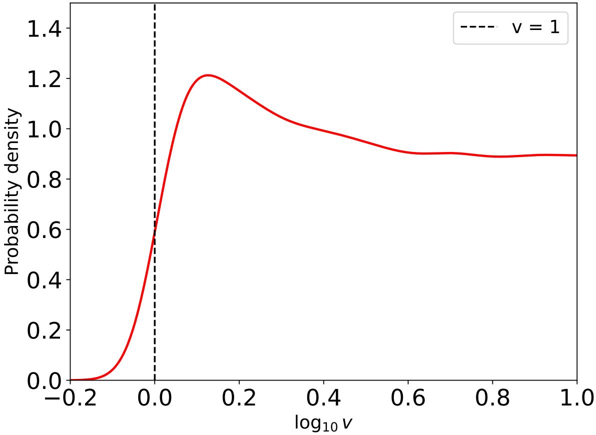


Reginald Christian Bernardo, Kin-Wang Ng, 2208.12538, (PRD)

Reginald Christian Bernardo, Kin-Wang Ng, 2302.11796, (PRDL)

*Yan-Chen Bi, Yu-Mei Wu, **ZCC**, Qing-Guo Huang, 2310.08366 (PRDL)*

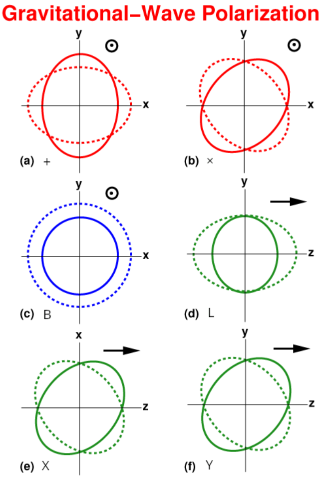
PE with NANOGrav 15-yr data set



- $c_g \gtrsim 0.85$
- Still consistent with $c_g = 1$.

*Yan-Chen Bi, Yu-Mei Wu, **ZCC**, Qing-Guo Huang, 2310.08366 (PRDL)*

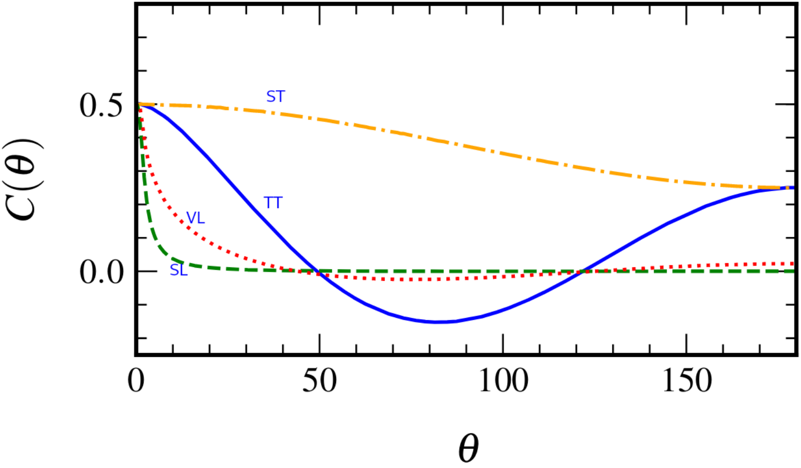
Alternative Polarizations



- A general metric gravity theory in 4D spacetime can have 6 polarization modes.
- polarization tensors

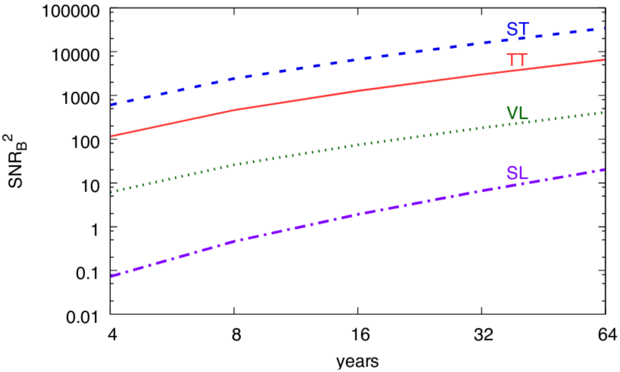
$$
\begin{aligned}
\epsilon^{+}_{ij} &= \hat{m}\otimes\hat{m} - \hat{n}\otimes\hat{n}, \\
\epsilon^{\times}_{ij} &= \hat{m}\otimes\hat{n} + \hat{n}\otimes\hat{m}, \\
\epsilon^{B}_{ij} &= \hat{m}\otimes\hat{m} + \hat{n}\otimes\hat{n}, \\
\epsilon^{L}_{ij} &= \hat{\Omega}\otimes\hat{\Omega}, \\
\epsilon^{X}_{ij} &= \hat{m}\otimes\hat{\Omega} + \hat{\Omega}\otimes\hat{m}, \\
\epsilon^{Y}_{ij} &= \hat{n}\otimes\hat{\Omega} + \hat{\Omega}\otimes\hat{n}
\end{aligned}
$$

ORF



$$|\Gamma_{ST}| > |\Gamma_{TT}| > |\Gamma_{VL}| > |\Gamma_{SL}|$$

$$\mathrm{SNR}_B^2 = 2\sum_f \sum_a^{N_p} \sum_{b>a}^{N_p} \frac{\Gamma_{ab}^{I\,2}(f)}{\Gamma_{aa}^I(f)\Gamma_{bb}^I(f) + \Gamma_{ab}^I(f)}.$$



ST is the easiest to detect among the four polarization modes.

Neil J. Cornish, Logan O'Beirne, Stephen R. Taylor, Nicolás Yunes, 1712.07132 (PRL)

Evidence for the ST correlations in NANOGrav 12.5-yr data set

- Bayes factor ***ZCC**, Chen Yuan, Qing-Guo Huang, 2101.06869 (SCPMA)*

	TT	ST	VL	SL	ST+TT
DE438	4.96(9)	107(7)	1.94(3)	0.373(5)	96(3)

- Our results were reproduced ~ 8 months later by *NANOGrav, 2109.14706 (ApJL)*

> As shown in Fig. 10, the most favored Bayesian model is a GWB with GW-like monopolar correlations of Eq. (25) with a Bayes factor greater than 100. Additionally, as a cross-check, we have reproduced the results of Chen et al. (2021), where a model with ST correlations with a spectral index of 5, [ST]M3A[5], was compared to a model without correlations and a spectral index of 13/3, M2A[13/3]. We obtain a Bayes factor of

- The significance of ST signal is reduced when removing pulsar J0030+0451.

Search for alternative polarizations in NANOGrav 15-yr data set

- Our paper appeared on arXiv one day prior to NANOGrav's. Both sets of results are broadly consistent with each other.
- Bayes factor *ZCC, Yu-Mei Wu, Yan-Chen Bi, Qing-Guo Huang, 2310.11238 (PRD)*

Model	ST	VL	SL	GTb	TT + ST
BF	0.40(3)	0.12(2)	0.002(1)	3.9(3)	0.943(5)

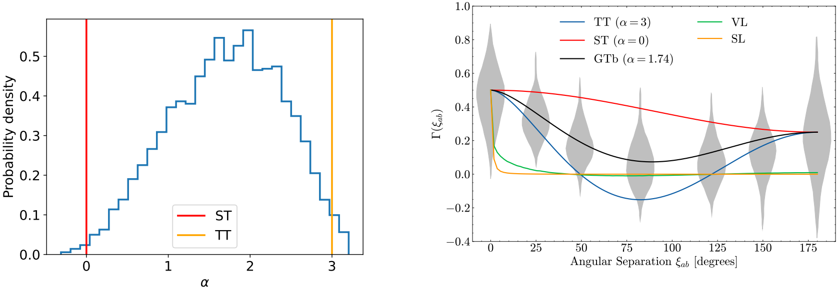
- Official NANOGrav *NANOGrav, 2310.12138 (ApJL)*

Our Bayesian analyses show the Bayes factor for HD over ST is ∼2, and the Bayes factor for a model with both correlations compared to a model with just HD is ∼1. These results are largely consistent with a similar study by Chen et al. (2023), in which they searched NANOGrav's 15 yr data set for nontensorial GWBs on a similar timescale to the work presented here. Taking the spectral parameter recovery into account, as in Figure 3, we found each correlation, when fit for individually, is in agreement with CURN. We also found more informative $\log_{10} A_g$ and γ_g recovery for HD than ST, and HD parameters show better agreement with CURN spectral parameters when correlations are included together. The analyses in this Letter, as well as those in Bernardo & Ng (2023c) and Chen et al. (2023), do not rule out the possibility of ST correlations in our data. However, our analysis also shows no statistical need for an additional stochastic process with ST correlations.

We also consider a parameterized transverse ORF as

$$\Gamma_{ab}(f) = \frac{1}{8}\left(3 + 4\delta_{ab} + \cos\xi_{ab}\right) + \frac{\alpha}{2} k_{ab} \ln k_{ab}. \quad (5)$$

ST: $\alpha = 0$ TT: $\alpha = 3$ prior of α: Uniform(-10, 10)



- Our analysis yields $\alpha = 1.74^{+1.18}_{-1.41}$, thus excluding both the TT and ST models at the 90% CL.

ZCC, Yu-Mei Wu, Yan-Chen Bi, Qing-Guo Huang, 2310.11238 (PRD)

Summary

PTAs are promising tools for testing modified gravity theories, including:

- Speed of GW: $c_g \gtrsim 0.85$

  *Yan-Chen Bi, Yu-Mei Wu, **ZCC**, Qing-Guo Huang, 2310.08366 (PRDL)*

  ***ZCC**, Jun Li, Lang Liu, Zhu Yi, 2401.09818 (PRDL)*

- Alternative polarizations: TT and ST both seem to be disfavored

  ***ZCC**, Chen Yuan, Qing-Guo Huang, 2101.06869 (SCPMA)*

  *Yu-Mei Wu, **ZCC**, Qing-Guo Huang, 2108.10518 (ApJ)*

  ***ZCC**, Yu-Mei Wu, Qing-Guo Huang, 2109.00296 (CTP)*

  ***ZCC**, Yu-Mei Wu, Yan-Chen Bi, Qing-Guo Huang, 2310.11238 (PRD)*

- Massive gravity: $m_g \lesssim 8.2 \times 10^{-24}\,\mathrm{eV}$

  *Yu-Mei Wu, **ZCC**, Qing-Guo Huang, 2302.00229 (PRD)*

  *Yu-Mei Wu, **ZCC**, Yan-Chen Bi, Qing-Guo Huang, 2310.07469 (CQG)*

- $\cdots$

Outlook

- IPTA DR3 will contain the timing data from approximately 115 pulsars spaning more than 35 years of observations.
- Testing modified gravity theories with the IPTA DR3 is underway.

The talk reflects my personal opinions and does not represent the official views of PPTA or IPTA.

Thank you for your attention!