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Erratum: "The NANOGrav 15 yr Data Set: Search for Signals from New Physics" (2023, ApJL 951 L11)

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In Afzal et al. (2023), we used the NANOGrav 15 yr pulsar timing array data to search for signals from new physics. In particular, we considered various sources of gravitational waves (GWs) in the early Universe as an explanation of the signal contained in the data, including cosmological first-order phase transitions. In this Erratum, we report on a minor mistake in the phase-transition analysis: in our numerical implementation of the GW signal from a phase transition, we had erroneously included a normalization factor $\mathcal{N}$ in the spectral-shape function $\mathcal{S}$, even though the correct normalization factor is of the form $1/\mathcal{N}$. As we discuss in this Erratum, correcting the normalization factor leads to qualitatively nearly identical results as in Afzal et al. (2023) and only mild quantitative changes.

In Afzal et al. (2023), we considered two models of GW production during a first-order phase transition in the early Universe: (i) GWs from the collision of vacuum bubbles (PT-BUBBLE) and (ii) GWs from sound waves in the thermal plasma (PT-SOUND). In both

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Table 1
Old and New Credible Intervals for the Parameters of PT-BUBBLE and PT-SOUND Models

Parameter	68% Credible Interval		95% Credible Interval	
	NP	NP+SMBHB	NP	NP+SMBHB
Cosmological Phase Transition (PT-BUBBLE)				
T_*/MeV (old)	[47, 410]	[46, 460]	[23, 1750]	[17, 3270]
T_*/MeV (new)	[79, 349]	[71, 392]	[41, 752]	$<2.01 \times 10^5$
α_* (old)	>1.1	>1.0	>0.29	>0.23
α_* (new)	>1.7	>1.5	>0.56	>0.25
H_*R_* (old)	>0.28	>0.26	>0.14	>0.11
H_*R_* (new)	>0.44	>0.39	>0.26	>0.013
Cosmological Phase Transition (PT-SOUND)				
T_*/MeV (old)	[4.7, 33]	[4.9, 50]	[2.7, 93]	$[0.8, 2 \times 10^6]$
T_*/MeV (new)	[8.8, 50]	[8.4, 67]	[4.6, 107]	no bound
α_* (old)	>0.42	[0.46, 5.4]	>0.37	>0.16
α_* (new)	[0.66, 5.0]	[0.72, 6.5]	>0.53	no bound
H_*R_* (old)	[0.053, 0.27]	[0.054, 0.35]	[0.046, 0.89]	>0.0015
H_*R_* (new)	[0.098, 0.40]	[0.097, 0.50]	[0.086, 0.97]	>0.015

Note. The old intervals are taken from Afzal et al. (2023); they are now outdated and need to be replaced by the new intervals obtained in this Erratum.

cases, we modeled the shape of the GW energy density spectrum $h^2\Omega$ in terms of a broken power law,

$$\mathcal{S}(x) = \frac{1}{\mathcal{N}} \frac{(a+b)^c}{(b\, x^{-a/c} + a\, x^{b/c})^c}. \tag{1}$$

Here, x stands for the GW frequency in units of the frequency at which the GW spectrum reaches its peak,[81]

$$x = \begin{cases} f/f_b, & \text{PT-BUBBLE} \\ f/f_s, & \text{PT-SOUND} \end{cases}; \tag{2}$$

a and $-b$ denote the spectral indices at frequencies much smaller and larger than the peak frequency, respectively, and c characterizes the width of the peak in the spectrum, where the f^a power law valid at low frequencies smoothly transitions to the f^{-b} power law valid at high frequencies. The values of a, b, and c are model-dependent; but in typical phase-transition scenarios, they are of $\mathcal{O}(1)$ (see the prior choices for a, b, and c below). The overall factor $\mathcal{N}$, finally, ensures the proper normalization of the spectral shape function $\mathcal{S}$,

$$\int_{-\infty}^{+\infty} \frac{dx}{x}\, \mathcal{S}(x) = 1. \tag{3}$$

Solving this condition for $\mathcal{N}$ yields, with $n = (a+b)/c$,

$$\mathcal{N}(a, b, c) = \left(\frac{b}{a}\right)^{a/n} \left(\frac{nc}{b}\right)^c \frac{\Gamma(a/n)\Gamma(b/n)}{n\,\Gamma(c)}. \tag{4}$$

While the expression in Equation (1) contains a factor $1/\mathcal{N}$, we had erroneously included a factor $\mathcal{N}$ in our numerical implementation of the GW signal from a cosmological phase transition in our analysis in Afzal et al. (2023). The purpose of this Erratum is therefore to correct this mistake and update our numerical results for the PT-BUBBLE, PT-SOUND, PT-BUBBLE+SMBHB, and PT-SOUND+SMBHB models in Afzal et al. (2023).

First, we observe that $\mathcal{N}$ is typically of $\mathcal{O}(1)$. Before rerunning any numerical analysis, it is thus clear that we should expect only minor changes in our results. Indeed, in the case of the PT-BUBBLE model, the parameters a, b, and c are drawn from the uniform prior distributions $a \in [1, 3]$, $b \in [1, 3]$, and $c \in [1, 3]$, such that

$$\mathcal{N}_{\min} = \mathcal{N}(3, 3, 1) = \frac{\pi}{3} \simeq 1.05, \tag{5}$$

$$\mathcal{N}_{\max} = \mathcal{N}(1, 1, 3) = \frac{3\pi}{2} \simeq 4.71\,. \tag{6}$$

[81] See Afzal et al. (2023) for the precise definition of f_b and f_s.

Table 2
Old and New Bayes Factors for the Model Comparison with the SMBHB Reference Model

	Bayes Factor	
	NP	NP+SMBHB
Cosmological Phase Transition (PT-BUBBLE)		
$\mathcal{B}$ (old)	18.1 ± 0.6	12.6 ± 0.5
$\mathcal{B}$ (new)	8.4 ± 0.3	8.5 ± 0.3
Cosmological Phase Transition (PT-SOUND)		
$\mathcal{B}$ (old)	3.7 ± 0.1	6.5 ± 0.3
$\mathcal{B}$ (new)	4.8 ± 0.1	5.7 ± 0.2

Note. The old Bayes factors are taken from Afzal et al. (2023); they are now outdated and need to be replaced by the new Bayes factors obtained in this Erratum.

Similarly, in the case of the PT-SOUND model, the parameters a, b, and c are drawn from the uniform prior distributions $a \in [3, 5]$, $b \in [2, 4]$, and $c \in [3, 5]$, such that

$$\mathcal{N}_{\rm min} = \mathcal{N}(5, 4, 3) = \frac{243}{40}\frac{\Gamma\left(\frac{4}{3}\right)\Gamma\left(\frac{5}{3}\right)}{10^{\frac{2}{3}}} \simeq 1.06, \tag{7}$$

$$\mathcal{N}_{\rm max} = \mathcal{N}(3, 2, 5) = \frac{3125}{1296} \simeq 2.41. \tag{8}$$

Based on these values, we conclude that replacing $\mathcal{N}$ by $1/\mathcal{N}$ in our code effectively amounts to a decrease in the peak value of $\mathcal{S}$ by a factor $\mathcal{N}^2$, which ranges between $\mathcal{N}^2_{\rm min} \simeq 1.10$ and $\mathcal{N}^2_{\rm max} \simeq 22.21$ in the case of PT-BUBBLE and between $\mathcal{N}^2_{\rm min} \simeq 1.11$ and $\mathcal{N}^2_{\rm max} \simeq 5.81$ in the case of PT-SOUND. Consequently, the replacement $\mathcal{N} \to 1/\mathcal{N}$ will affect the posteriors of the PT-BUBBLE model more severely than those of the PT-SOUND model.

Having corrected the normalization of the spectral shape function in our code, we rerun the Bayesian Markov Chain Monte Carlo analyses for the PT-BUBBLE, PT-SOUND, PT-BUBBLE+SMBHB, and PT-SOUND+SMBHB models. In doing so, all other aspects of our runs remain unchanged (see Afzal et al. 2023 for more details); the only change in our code is indeed nothing but the corrected normalization of the spectral shape function $\mathcal{S}$. We summarize the results of our reruns in Tables 1 and 2 and in Figure 8. In Figure 8, which now supersedes Figure 8 in Afzal et al. (2023), we present the corner plots for all four models of interest, which show the marginalized 2D posterior distributions for pairs of model parameters as well as marginalized 1D posterior distributions for individual model parameters. From the marginalized 1D posterior distributions, we are able to read off 68% and 95% credible intervals, i.e., highest-posterior density intervals that, respectively, contain 68% or 95% of the total integrated posterior probability. These intervals are summarized in Table 1, where, for convenience, we list not only our new results obtained in this Erratum but also our old results that we had obtained in Afzal et al. (2023).

For some parameters, our marginalized 1D posteriors do not result in credible intervals bounded from both sides. This is, e.g., the case for α_* in the PT-BUBBLE model and happens whenever the upper boundary of a highest-posterior density interval that one intends to construct coincides with the upper boundary of the prior range for the parameter under consideration. In these cases, we refrain from stating the upper boundary of the prior range as the upper boundary of the credible interval and simply quote the lower boundary of the credible interval as a lower limit instead. Furthermore, in two cases, we are not able to construct a 95% credible interval or limit, namely, for the parameters T_* and α_* in the PT-SOUND+SMBHB model. In these two cases, there is no threshold value of the posterior density that would result in a 95% highest-posterior density interval. The reason for this is the extended plateaus in the marginalized 1D posterior distributions for T_* and α_* in the PT-SOUND+SMBHB model. In both cases, setting the threshold value in the construction of the highest-posterior density interval to the height of the plateau returns an integrated probability of less than 95%. However, slightly decreasing the threshold value below the height of the plateau results in a sudden jump in the integrated probability to a value larger than 95%.

Comparing our new parameter intervals summarized in Table 1 to the old intervals reported in Afzal et al. (2023), we observe a tendency (with exceptions) toward slightly larger values of T_*, α_*, and H_*R_*. This observation is explained by the fact that larger values of α_* and H_*R_* increase the strength of the GW signal and thus allow to compensate for the decrease in signal strength caused by the change in the normalization of the spectral shape function $\mathcal{S}$. At the same time, larger values of H_*R_* result in smaller peak frequencies f_b and f_s in Equation (2). This effect can be compensated for by larger values of T_*, which partially explains the shift in the credible intervals for T_* in Table 1. Overall, however, all changes in the reconstructed parameter intervals remain rather mild, which means that most of our physical conclusions in Afzal et al. (2023) remain valid.

A noticeable difference between the results in Afzal et al. (2023) and those presented in this Erratum consists in the fact that the marginalized 2D posterior distributions of the PT-BUBBLE+SMBHB model now cover larger regions in the parameter space spanned by T_*, α_*, and H_*R_*; see the red 95% credible regions in the left panel of Figure 1. The appearance of these red 95% credible

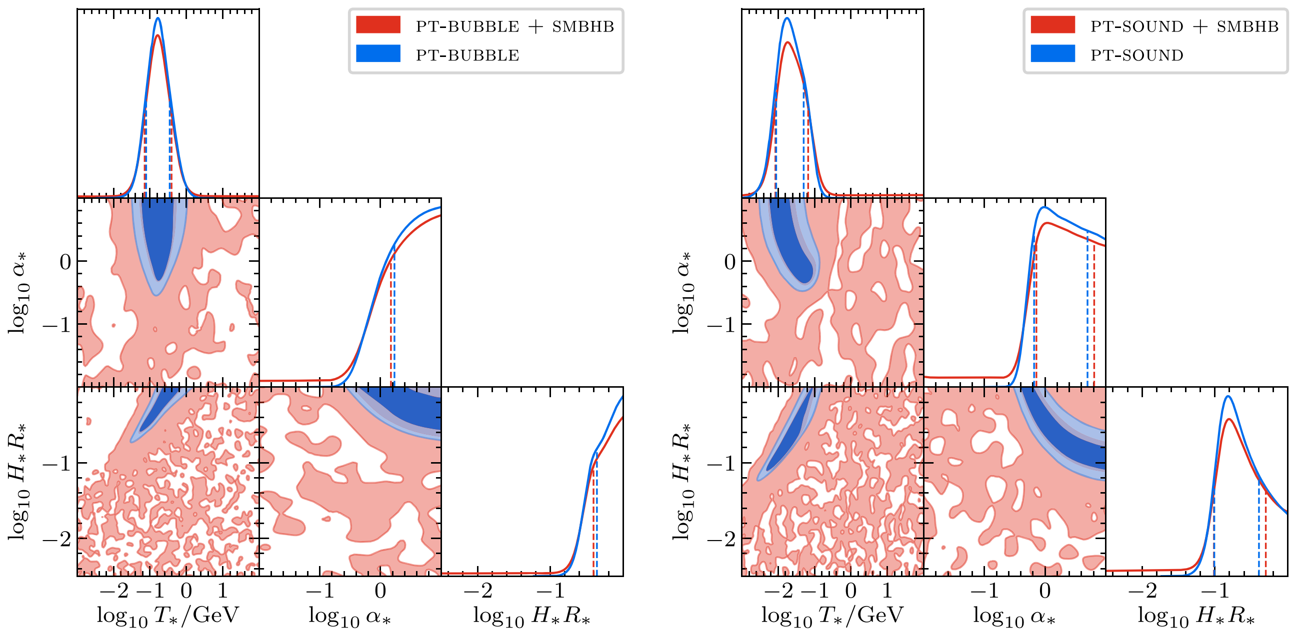

Figure 8. Updated contour plots for the PT-BUBBLE and PT-SOUND models, superseding Figure 8 in Afzal et al. (2023).

regions is now more similar to those in the PT-SOUND+SMBHB model, for which we had already found similar results in Afzal et al. (2023). The conclusion from this observation is that, similarly to the PT-SOUND+SMBHB model, the PT-BUBBLE+SMBHB model also accommodates fits of the data, at the 95% credible level, that are dominated by the contribution from supermassive black hole binaries (SMBHBs) to the total GW spectrum, with the phase-transition contribution to the spectrum playing a subdominant role.

Finally, we comment on our new results for the Bayes factors, which are listed in Table 2. Compared to the Bayes factors reported in Afzal et al. (2023), we notice a decrease in the Bayes factors for the PT-BUBBLE and PT-BUBBLE+SMBHB models, an increase in the Bayes factor for the PT-SOUND model, and a more or less unchanged Bayes factor (in view of the standard deviations quoted in Table 2) for the PT-SOUND+SMBHB model. Besides, we observe that adding the GW signal from SMBHBs to the GW signal of the PT-BUBBLE model no longer results in a decrease in the Bayes factor, which we had attributed to a prior volume effect in Afzal et al. (2023). Instead, adding SMBHBs to the phase-transition model leaves the Bayes factor nearly unchanged. From this, we conclude that fits of the data in terms of the phase-transition signal cannot be improved by an additional SMBHB contribution. On the other hand, in the case of the PT-SOUND model, adding SMBHBs to the phase-transition model still results in a small increase in the Bayes factor, which we had already observed in Afzal et al. (2023). As discussed in Afzal et al. (2023), the PT-SOUND model benefits from the additional SMBHB contribution because the GW signal from SMBHBs can add power to the low-frequency bins that the PT-SOUND model alone struggles to fit well on its own.

In summary, we conclude that GWs from a cosmological first-order phase transition still represent an attractive explanation of the signal in the NANOGrav 15 yr data. The updated contour plots, credible intervals, and Bayes factors presented in this Erratum will hopefully provide some guidance in the further phenomenological and theoretical exploration of this exciting scenario. More results derived from the rerun of our Bayesian analysis (e.g., updates of the results presented in the Appendix of Afzal et al. 2023) can be requested by email (comments@nanograv.org). Furthermore, in order to facilitate fitting the phase-transition models discussed in this Erratum to future pulsar timing array (PTA) data sets, we also updated the relevant model files for our analysis software package `PTArcade` (Mitridate et al. 2023). The normalization of the spectral shape function $\mathcal{S}$ has been corrected, such that the latest version of the `PTArcade` model files can be readily used to fit the GW signal from a first-order phase transition to PTA data.

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