Searching For Gravitational Waves From Cosmological Phase Transitions With The NANOGrav 12.5-year dataset

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We search for a first-order phase transition gravitational wave signal in 45 pulsars from the NANOGrav 12.5 year dataset. We find that the data can be explained in terms of a strong first order phase transition taking place at temperatures below the electroweak scale. In our search, we find that the signal from a first order phase transition is degenerate with that generated by Supermassive Black Hole Binary mergers. An interesting open question is how well gravitational wave observatories could separate such signals.

Introduction — The search for gravitational waves (GWs) spans many orders of magnitude and encapsulates a plethora of source phenomena. At very-low frequencies ($\sim 1 - 100$ nHz), pulsar-timing arrays (PTAs; [4–6]) aim to detect GWs through the presence of correlated deviations to radio-pulse arrival times across an ensemble of precisely-timed Milky Way millisecond pulsars. There are three PTA collaborations that currently have decadal-length timing data from an ensemble of pulsars: The North American Nanohertz Observatory for Gravitational Waves (NANOGrav; [7]), the European Pulsar Timing Array (EPTA; [8]), and the Parkes Pulsar Timing Array (PPTA; [9]). These three, in addition to the Indian PTA (InPTA; [10]), are synthesized into the International Pulsar Timing Array (IPTA; Perera *et al.* 11). There are also emerging efforts in China (CPTA; [12]), as well as some telescope-centered timing programs (MeerKAT; [13]; CHIME; [14]).

The dominant GW signals at such low frequencies frequencies are expected to be from a cosmic population of tightly-bound inspiralling supermassive binary black holes (SMBHBs; [15, 16]), producing an aggregate incoherent signal that we search for as a stochastic GW background (GWB), and also individual binary signals that we attempt to resolve out of this stochastic confusion background. However, other more speculative GW sources in the PTA frequency range include cosmic strings [17, 18], a primordial GWB produced by quantum fluctuations of the gravitational field in the early universe, amplified by inflation [19, 20], and cosmological phase transitions [21, 22], the latter of which is the subject this study.

The most recent PTA results are from NANOGrav's analysis of 12.5 years of precision timing data from 47 pulsars [23, hereafter NG12], of which 45 exceeded a timing baseline of 3 years and were analysed in a search for a stochastic GWB [24, hereafter NG12gwb]. NANOGrav reported strong evidence for a common-spectrum low-frequency stochastic process in its array of 45 analyzed pulsars, where ~ 10 of those pulsars are strongly supportive, most are ambivalent, and a few seem to disfavor the process (although not significantly). No evidence for the characteristic inter-pulsar correlation signature imparted by GWs was found. At low frequencies the shape of the characteristic strain spectrum was well matched to a power-law, with an amplitude and slope consistent with theoretical models of SMBHB populations. Under a model that assumes the origin of the GWB is a population of SMBHBs, the median characteristic strain amplitude at a frequency of 1/year is 1.92×10^{-15}. Interpretations of this common-spectrum process as a GWB from SMBHBs have since appeared in the literature, showing that, if it is indeed so, robust evidence of the distinctive inter-pulsar correlations should accrue within the next several years, followed by characterization of the strain spectrum and astrophysical probes of the underlying population [25, 26]. However, the Bayesian posterior probability distributions of the strain-spectrum amplitude and slope are broad enough to entertain a variety of different source interpretations, many of which have

	Bubble Walls collisions [1]	Sound Waves collisions [2]	Turbulence [3]
$\Delta(v_w)$	$\dfrac{0.48v_w^3}{1+5.3v_w^2+5v_w^4}$	$0.513\,v_w$	$20.2\,v_w$
κ	κ_ϕ	$\kappa_{\rm sw}$	$\sim 0.1\times\kappa_{\rm sw}$
p	2	2	3/2
q	2	1	1
$\mathcal{S}(x)$	$\dfrac{(a+b)^c}{[bx^{-a/c}+ax^{b/c}]^c}$	$x^3\left(\dfrac{7}{4+3x^2}\right)^{7/2}$	$\dfrac{x^3}{(1+x)^{11/3}(1+8\pi x f_*^0/\widetilde{H}_*)}$
f_*/β	$\dfrac{0.35}{1+0.07v_w+0.69v_w^4}$	$\dfrac{0.536}{v_w}$	$\dfrac{1.63}{v_w}$

TABLE I. Parameters for the gravitational wave spectrum of eq. (5). The values of the parameters (a,b,c) in the spectral shape of the bubble contribution are reported in Table II, and the value of the Hubble parameter redshifted today $\widetilde{H}_*$ is given by $\widetilde{H}_*=1.1\times10^{-9}(T_*/\,\mathrm{MeV})(g_*/10)^{1/6}$.

since appeared in the literature [e.g. 27–30].

In this Letter we consider gravitational waves produced by first-order cosmological phase transitions, both as an alternative origin of the common process measured in the NANOGrav 12.5 year Dataset [31–38], and as a subdominant signal to that produced by SMBHBs. The frequency range to which NANOGrav is sensitive corresponds to phase transitions at temperatures below the electroweak phase transitions of the Standard Model (*i.e.* $T\lesssim 100\,\mathrm{GeV}$). This has led many to consider higher frequency GW observatories, such as LISA and LIGO, as the dominant instruments to search for phase transitions. However, phase transitions may occur at much lower temperatures in particular in *hidden sectors* [39–41]. Hidden sectors/valleys feature rich dynamics, with multiple matter fields and forces, independent of the dynamics of the Standard Model. They appear generically in top-down constructions like string theory, and in some solutions to the so-called hierarchy problem. In many cases, they may be difficult to detect via their particle interactions with the Standard Model, but gravity is an irreducible messenger. In this regard, PTAs provide a powerful complementary probe to the dynamics of hidden sectors already being explored through many terrestrial, astrophysical and cosmological probes (see Ref. [42] for a recent summary).

Previous studies on cosmological first order phase transition in the context of the NANOGrav results were carried out in [36, 43, 44]. Our analysis presents two main novelties compared to these works: first, we properly include the relevant noise sources and discuss the impact of backgrounds (like the one generated by SMBHBs); second, we discuss how the results are affected by the theoretical uncertainties on the GW spectrum produced by first order phase transitions.

The outline of this Letter is as follows. In the next section we briefly summarize the signature of GWs from the dominant background of SMBH mergers. We then dive into the main subject of this Letter, GWs from a first-order phase transition, where we discuss the relevant parameters characterizing the signal. We then carry out an analysis with the NANOGrav 12.5 year dataset, finding that the data are well-fit by a strong phase transition with a transition temperature around 10 MeV. The dataset and data model for these analyses are exactly as described in NG12 and NG12gwb, respectively. All common processes (whether interpreted as being of SMBHB or phase-transition origin) are modeled within the five lowest sampling frequencies of the array time series, corresponding to $\sim 2.5-12$ nHz. Finally, we discuss theoretical uncertainties, and the need to disentangle the phase-transition signal from the SMBHB GW background.

GW from SMBHBs mergers — Regardless of origin, the energy density of GWs as a fraction of closure density is related to the GW characteristic strain spectrum by [45]

$$\Omega_{\rm GW}(f)=\frac{2\pi^2}{3H_0^2}f^2h_c^2(f), \tag{1}$$

where H_0 is the Hubble constant (set here to be $67\,\mathrm{km/s/Mpc}$ [46]), and the GWB characteristic strain spectrum $h_c(f)$ is often described by a power-law function for astrophysical and cosmological sources:

$$h_c(f)=A_{\rm GWB}\left(\frac{f}{\mathrm{yr}^{-1}}\right)^{\alpha}, \tag{2}$$

where $A_{\rm GWB}$ is the amplitude at a reference frequency of 1/year, and α is an exponent that depends on the origin of the GWB. For a population of inspiraling SMBHBs, this is $\alpha=-2/3$ [47]. The cross-power spectral density of GW-induced timing deviations between two pulsars a

	Envelope	Semi-analytic	Numerical
a	3	$1-2.2$	$1.6-0.7$
b	1	$2.6-2.9$	$1.4-2.3$
c	1.5	$1.5-3.5$	1
f_*/β	$\dfrac{0.35}{1+0.07v_w+0.69v_w^2}$	0.1	0.2

TABLE II. Comparison of the bubble spectral shape parameters derived using the envelope and thin wall approximation [49] (left column), the semi-analytic approach of reference [50] (middle column), and lattice simulations [51] (right column). For numerical and semi-analytic results the values of the parameters depend on the choice of the scalar field potential, we report the range of values obtained for the different scalar field potentials considered in the above mentioned works.

and b can be written as

$$S_{ab}(f) = \Gamma_{ab}\frac{A_{\rm GWB}^2}{12\pi^2}\left(\frac{f}{\rm yr^{-1}}\right)^{-\gamma}\,{\rm yr}^3\,, \tag{3}$$

where $\gamma \equiv 3-2\alpha = 13/3$ for SMBHBs, and Γ_{ab} is the Hellings-Downs [48] correlation coefficient between pulsar a and pulsar b.

GWs from first-order phase transition — A first-order phase transition (PT) occurs when the true minimum of a potential is separated from a false minimum by a barrier through which a field must locally tunnel. This can occur in either weakly coupled (where a scalar field tunnels) or strongly coupled (where a vacuum condensate corresponds to the scalar field) theory. Such transitions are known to proceed through nucleation of bubbles of true vacuum which, if sufficiently large, expand in the background plasma (still in the false vacuum). Collisions of these bubbles, as well as interactions between the expanding bubble walls and the surrounding plasma, can be efficient sources of GWs.

We characterize the phase transition in terms of four parameters:

- T_* – the Universe temperature at which the phase transition takes place.
- α_* – the strength of the phase transition, defined as the ratio of the vacuum and relativistic energy density at the time of the phase transition.
- β/H_* – the bubble nucleation rate in units of the Hubble rate at the time of the phase transition, H_*.
- η – the friction coefficient, which parametrizes the strength of the interactions between the bubble walls and the plasma.

The three main sources of GWs associated with a first-order phase transition are: (i) collisions of bubble walls, (ii) collisions of the sound waves generated in the background plasma by the bubbles expansion, and (iii) turbulence in the plasma generated by expansion and collisions of the sound-wave. These three contributions approximately sum together to give the total gravitational wave power spectrum:

$$\Omega_{\rm GW}(f) = \Omega_\phi(f) + \Omega_{\rm sw}(f) + \Omega_{\rm turb}(f)\,, \tag{4}$$

where, in general, each contribution has a different amplitude and peak frequency. (See Refs. [52, 53] for a summary of the individual contributions). A suitable parametrization for the GW spectrum today, valid for all three contributions, is given by [1–3]

$$h^2\Omega(f) = \mathcal{R}\,\Delta(v_w)\left(\frac{\kappa\,\alpha_*}{1+\alpha_*}\right)^p\left(\frac{H_*}{\beta}\right)^q\mathcal{S}\left(f/f_*^0\right)\,, \tag{5}$$

where the prefactor $\mathcal{R}\simeq 7.69\times10^{-5}g_*^{-1/3}$ accounts for the redshift of the GW energy density, $\mathcal{S}(\cdot)$ parametrizes the spectral shape, and $\Delta(v_w)$ is a normalization factor which depends on the bubble wall velocity, v_w. The value of the peak frequency today, f_*^0, is related to the value of the peak frequency at emission, f_*, by:

$$f_*^0 \simeq 1.13\times10^{-10}\,{\rm Hz}\left(\frac{f_*}{\beta}\right)\left(\frac{\beta}{H_*}\right)\left(\frac{T_*}{\rm MeV}\right)\left(\frac{g_*}{10}\right)^{1/6}\,, \tag{6}$$

where g_* denotes the number of relativistic degrees of freedom at the time of the phase transition. The values of the peak frequency at emission, the spectral shape, the normalization factor, and the exponents p and q are reported in Table I for all the three production mechanisms. Finally, we relate the bubble wall velocity, v_w, and the efficiency factor, κ, to the parameters α_* and η following the results of Ref. [54].

We conclude this section emphasizing that, despite recent progress [2, 50, 51, 55, 56], large theoretical uncertainties still affect the prediction of the GW signal from cosmological phase transitions. The largest of these uncertainties is associated with the spectral shape of the bubble contribution. Assuming that the stress energy density of the expanding bubbles is localized in an infinitesimally thin shell near the bubble wall (thin shell approximation), and that it instantaneously decays to zero after two bubbles collide (envelope approximation), the bubble spectral shape can be derived analytically [1]. The spectral shape parameters obtained in this way are reported in the left column of Table II. To go beyond these approximations, 3D lattice simulations are needed. These simulations are extremely expensive given the hierarchy between the large simulation volume needed to include multiple bubbles, and the small lattice spacing needed to resolve the thin walls. Because of the relativistic contraction of the wall width, this separation of scales becomes increasingly large for increasing wall velocities, making it impossible to simulate ultra-relativistic walls.

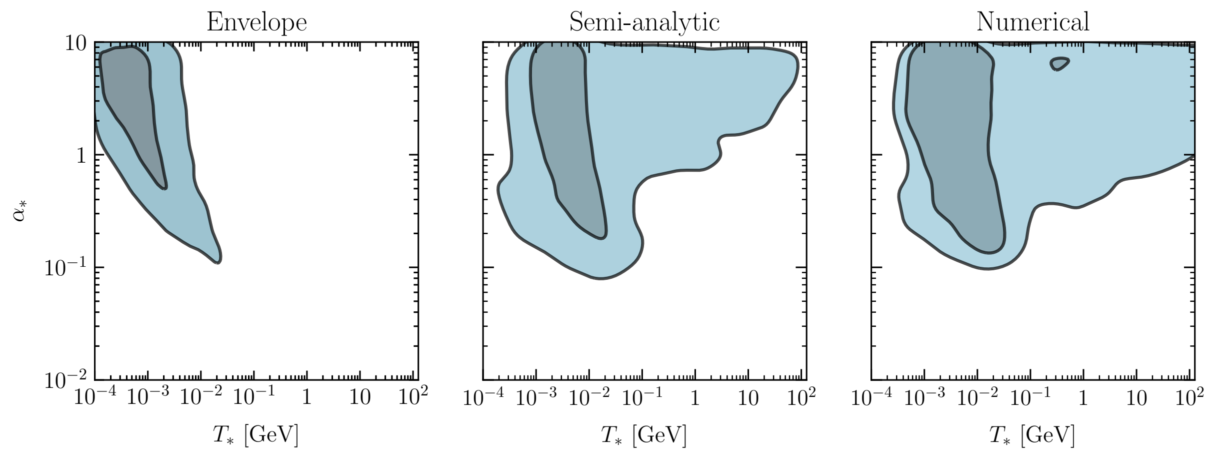

FIG. 1. 1-σ (68% posterior credible level), and 2-σ (95% posterior credible level) contours for the two dimensional posterior distributions in the (T_*, α_*) plane obtained using the bubble spectral shape computed by using the envelope approximation (left panel), semi-analytic results (central panel), and numerical results (right panel). Specifically, we use $(a, b, c) = (1, 2.61, 1.5)$ for the semi-analytic results, and $(a, b, c) = (0.7, 2.3, 1)$ for the numerical results.

However, the GW spectrum can be simulated at lower velocities and the results extrapolated to larger values. This is the approach taken in Refs. [51, 55], where the authors show that at high frequencies the GW spectrum is much steeper than predicted by the envelope approximation ($b \sim 1.4 - 2.3$ depending on the form of the scalar field potential). An alternative approach to the problem has been taken by the authors of Refs. [50, 56]. In these works a parametric form for the evolution of the scalar field during bubble collisions is found by using two-bubble simulations. This parametric form is then used in many-bubble simulations to derive the GW spectrum. They also find a steeper high frequency slope ($b \sim 2.6 - 2.9$) compared to the prediction of the envelope approximation. Similar discrepancies are found at low frequencies, where both the numerical and semi-analytic results find a shallower spectrum compared to the envelope approximation (see Tab. II). To probe the theoretical uncertainty associated with each of these approximations, we will carry out a separate analysis utilizing each approach and compare the constraint on the phase transition temperature and strength.

Results — We now report our results for two separate analyses. In the first we search for a GWB spectrum produced by a cosmological phase transition, while in the second we search for the GWB given by the superposition of the SMBHB background and the contribution from a phase transition. This latter analysis will give an indication of how difficult it will be to disentangle a signal from a phase transition from the SMBHB background. As described previously, the first type of search has four model parameters, while the second type of search has five model parameters (four from phase transition and one from the SMBHB amplitude, fixing the spectral index from the latter). The prior distributions for all of these parameters, in addition to other noise characterization parameters, are listed in Table III.

The two parameters that we can constrain the most are the transition temperature, T_*, and the phase transition strength, α_*. Their 2D posterior distributions for the PT-only search are shown in Fig. 1. To assess the impact of theoretical uncertainties, we report the results obtained by using the three different estimates of the GW spectrum described in the previous section (envelope, semi-analytic, and numercal). We can see that at the 1-σ (68% posterior credible) level all the searches prefer a strong PT, $\alpha_* \gtrsim 0.1$, with low transition temperature, $T_* \lesssim 10\,\text{MeV}$. At 2-$\sigma$ (95% posterior credible) level the posteriors for the semi-analytical and numerical results have support at much higher temperatures, while the envelope results still prefer relatively low values. The preference for small values of T_* at the 1-σ level can be understood by noticing (see Fig. 2) that the data prefer GW spectra that are peaked at frequencies below the NANOGrav sensitivity window (*i.e.* $f_*^0 \lesssim 10^{-9}\,\text{Hz}$). And, by setting $\beta/H_* = 1$ in (6), we see that this requirement corresponds to $T_* \lesssim 10\,\text{MeV}$. The low-frequency part of the numerical and semi-analytical GW spectra is shallow enough that, at the 2-σ level, the data can be fitted also by spectra with peak frequencies above the NANOGrav sensitivity window. The same is not true for the envelope results, which have a much steeper low-frequency spectrum; this is the reason why the 2-σ levels of the envelope results deviate substantially from the other two.

In Fig. 2 we show the GWB spectrum predicted for the maximum likelihood parameters of PT-only searches. To better illustrate our results, and how the different parameters and theoretical uncertainties affect the GWB spectrum, we release an interactive version of Fig. 2 at

Parameter	Description	Prior	Comments
		White Noise	
E_k	EFAC per backend/receiver system	Uniform $[0, 10]$	single-pulsar analysis only
Q_k [s]	EQUAD per backend/receiver system	log-Uniform $[-8.5, -5]$	single-pulsar analysis only
J_k [s]	ECORR per backend/receiver system	log-Uniform $[-8.5, -5]$	single-pulsar analysis only
		Red Noise	
$A_{\rm red}$	red-noise power-law amplitude	log-Uniform $[-20, -11]$	one parameter per pulsar
$\gamma_{\rm red}$	red-noise power-law spectral index	Uniform $[0, 7]$	one parameter per pulsar
		Phase Transition	
T_* [GeV]	phase transition temperature	log-Uniform $[-4, 3]$	one parameter for PTA
α_*	phase transition strength	log-Uniform $[-2, 1]$	one parameter for PTA
H_*/β	bubble nucleation rate	log-Uniform $[-2, 0]$	one parameter for PTA
η	friction coefficient	log-Uniform $[-2, 1]$	one parameter for PTA
		Supermassive Black Bole Binaries (SMBHB)	
$A_{\rm GWB}$	common process strain amplitude	log-Uniform $[-18, -14]$	one parameter for PTA
$\gamma_{\rm GWB}$	common process power-law spectral index	delta function ($\gamma_{\rm GWB} = 13/3$)	fixed

TABLE III. Priors distributions for the parameters used in all the analyses in this work.

this link.

To understand how the inclusion of the SMBHB background affects our results, in Fig. 3 we show the posterior for the parameters α_* and $A_{\rm GWB}$ obtained in the PT+SMBHB search. As expected, with the inclusion of the SMBHB background, the posteriors for α_* stretch to lower values where most of the signal is provided by the SMBHB contribution. The Bayesian Information Criterion (BIC) [57], defined to be $\text{BIC} = k \ln n - 2 \ln \hat{\mathcal{L}}$ where $n = 5$ is the number of data points in the frequency space, k is the number of parameters in the model and $\hat{\mathcal{L}}$ is the maximum likelihood, is also computed. The differences in BIC between the PT+SMBHB and SMBHB only searches are found to be -1.64, 2.10 and 0.34 for the envelope, semi-analytic and numerical results respectively; similarly the BIC differences between the PT-only and SMBHB-only searches are 0.27, -2.19, -0.04. We can then conclude that that the PT+SMBHB and PT-only models were neither strongly favored nor disfavored compared to the SMBHB only model [58].

A complete set of posteriors for the parameters of the PT-only search (derived by using the semi-analytic spectrum) are shown in Fig. 4. As noted previously, at 1-σ level the data prefer a strongly first-order phase transition ($\alpha_* \gtrsim 0.1$) taking place at temperature $T_* \lesssim 10\,\text{MeV}$; while no strong constraints on η or H_*/β is observed. We can also notice that the higher values of T_* allowed in the 2-σ region are accompanied by slower nucleation rates (large H_*/β). Given the low value of T_*, and the strong constraints on new physics at such low scales, we expect the phase transition to take place in a dark sector with only feeble interactions with the Standard Model (SM). In order to be consistent with the Hubble parameter constraints during the era of Big Bang Nucleosynthesis (BBN) [59], the energy of this dark sector must be transferred to the SM before the onset of BBN at $T \sim 1\,\text{MeV}$. This leaves an allowed range of values for the transition temperature given by $T_* \sim 1\,\text{MeV} - 100\,\text{GeV}$. The next data release, which adds multiple years of observations and extends the the sensitivity window to lower frequency, should begin to resolve the peak of the spectrum or additionally shrink the range of allowed values for T_*.

Conclusions — We performed a search for a stochastic gravitational wave background from first-order phase transitions in the 12.5 year NANOGrav dataset. While previous NANOGrav analysis found no evidence yet for the inter-pulsar correlation signature of a GWB, the evidence for a common-spectrum process was significant. Here we have interpreted this process as being a GWB of phase-transition origin. We found that the data are well modeled by a strong ($\alpha_* > 0.1$) phase transition taking place at temperatures below the electroweak scale. The data do not show any strong preference between an SMBHB and a PT generated signal, but we expect to gain additional discriminating power with future datasets, improving the signal to noise ratio and extending the sensitivity window to lower frequencies. In particular, data from the International Pulsar Timing Array will allow the baseline of observations to be significantly extended, and the number of monitored pulsars to be greatly expanded. The present quality of the data is such that our results are not strongly affected by theoretical uncertainties on the GW spectral shape. However, methodological improve-

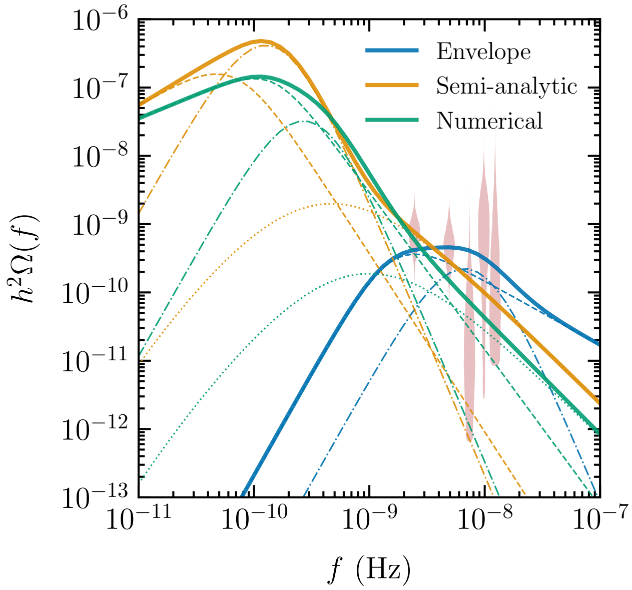

FIG. 2. Maximum likelihood GWB fractional energy-density spectrum compared with the marginalized posterior for the free power spectrum (independent per-frequency characterization; red violin plot) derived in NG12gwb. The blue, oranage, and green lines represent the maximum likelihood spectra derived using the envelope, semi-analytical, and numerical results for the bubble contribution. We also show the breakdown of the spectrum in the three contributions: bubble (dashed lines), sound waves (dash-doted lines), and turbulence (dotted lines). The values of (α_*, T_*) for these maximum likelihood spectra are $(2.3, 2.8\,\mathrm{MeV})$ for the envelope results, $(2.3, 1.7\,\mathrm{MeV})$ for the semi-analytic results, and $(2.1, 2.5\,\mathrm{MeV})$ for the numerical results.

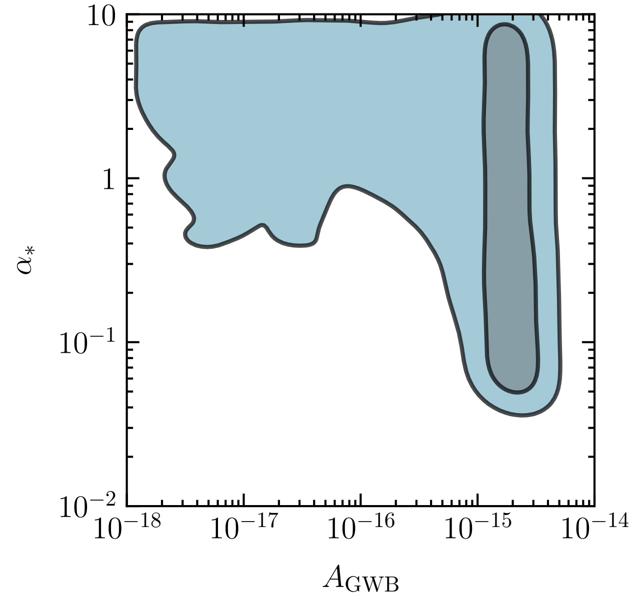

FIG. 3. 1-σ (68% posterior credible level), and 2-σ (95% posterior credible level) contours for the parameters $A_{\rm GWB}$ and α_* in the PT+SMBHB search.

ments on determining the origin of the GWB spectrum will be needed for future datasets in order to separate the signal from a first-order PT from the SMBHB background, as well as to constrain the microscopic origins of the PT.

Author contributions — An alphabetical-order author list was used for this paper in recognition of the fact that a large, decade timescale project such as NANOGrav is necessarily the result of the work of many people. All authors contributed to the activities of the NANOGrav collaboration leading to the work presented here, and reviewed the manuscript, text, and figures prior to the paper's submission. Additional specific contributions to this paper are as follows. ZA, HB, PRB, HTC, MED, PBD, TD, JAE, RDF, ECF, EF, NG-D, PAG, DCG, MLJ, MTL, DRL, RSL, JL, MAM, CN, DJN, TTP, NSP, SMR, KS, IHS, RS, JKS, RS and SJV developed the 12.5-year dataset through a combination of observations, arrival time calculations, data checks and refinements, and timing model development and analysis; additional specific contributions to the dataset are summarized in NG12. KZ and SRT coordinated the writing of the paper. VL and AM performed all analyses presented in this paper. KZ, SRT, AM, and VL wrote the paper and collected the bibliography.

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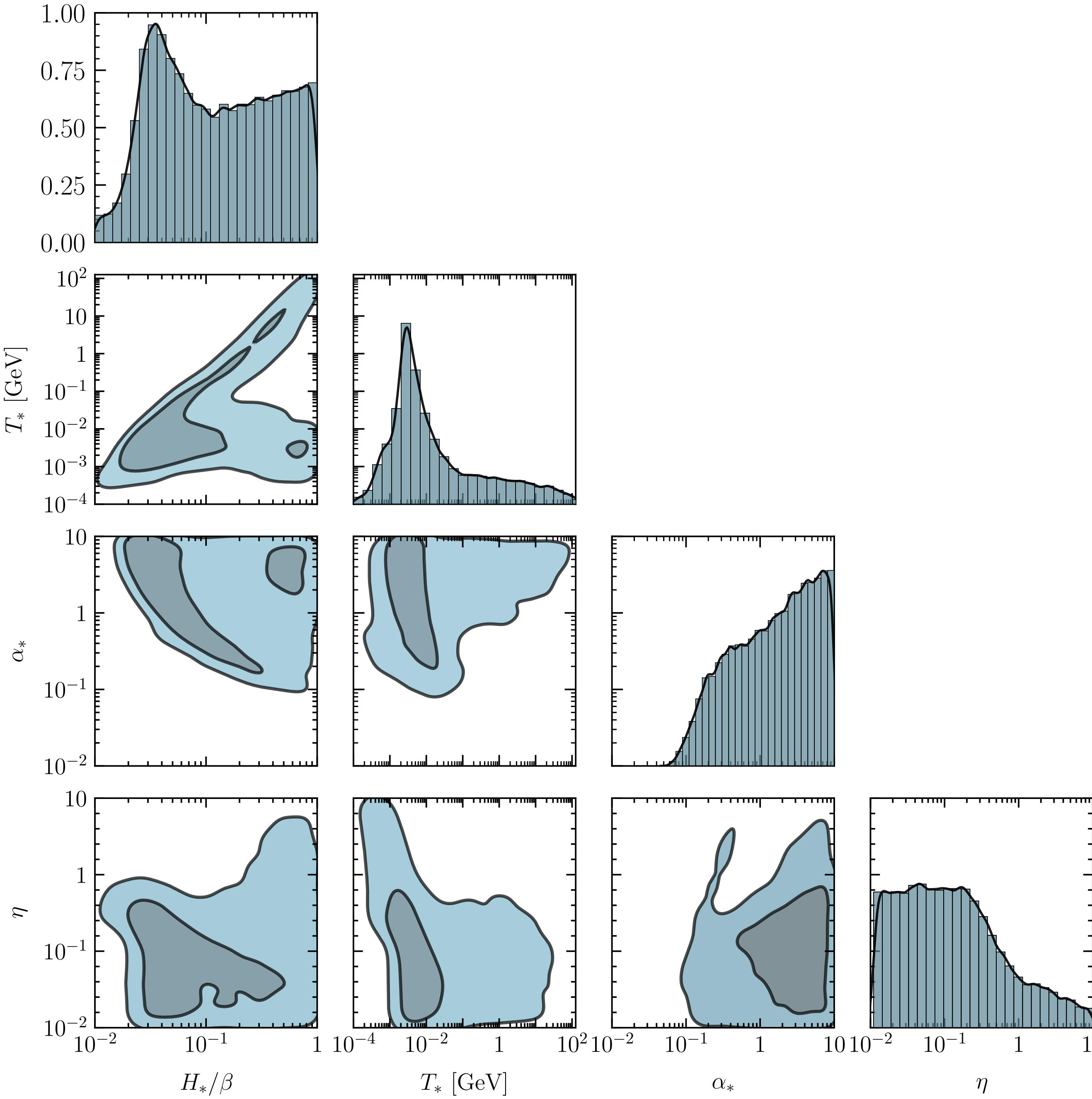

FIG. 4. Corner plot showing the 1D and 2D posterior distributions for the parameters of the PT-only search. In deriving these results we have used the semi-analytic bubble spectral shape with $(a, b, c) = (1, 2.61, 1.5)$.

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