Implications for first-order cosmological phase transitions from the third LIGO-Virgo observing run

Alba Romero,1 Katarina Martinovic,2 Thomas A. Callister,3 Huai-Ke Guo,4 Mario Martínez,1,5 Mairi Sakellaridou,2,6 Feng-Wei Yang,7 and Yue Zhao7

1Institut de Física d’Altes Energies (IFAE), Barcelona Institute of Science and Technology, E-08193 Barcelona, Spain
2Theoretical Particle Physics and Cosmology Group, Physics Department, King’s College London, University of London, Strand, London WC2R 2LS, UK
3Center for Computational Astrophysics, Flatiron Institute, New York, NY 10010, USA
4Department of Physics and Astronomy, University of Oklahoma, Norman, OK 73019, USA
5Catalan Institution for Research and Advanced Studies (ICREA), E-08010 Barcelona, Spain
6Theoretical Physics Department, CERN, Geneva, Switzerland
7Department of Physics and Astronomy, University of Utah, Salt Lake City, UT 84112, USA

(Dated: February 4, 2021)

We place constraints on the normalised energy density in gravitational waves from first-order strong phase transitions using data from Advanced LIGO and Virgo’s first, second and third observing runs. First, adopting a broken power law model, we place 95% confidence level upper limits simultaneously on the gravitational-wave energy density at 25 Hz from unresolved compact binary mergers, $\Omega_{\text{GW}} < 5.9 \times 10^{-9}$, and strong first-order phase transitions, $\Omega_{\text{pt}} < 2.8 \times 10^{-9}$. We then consider two more complex phenomenological models, limiting at 25 Hz the gravitational-wave background due to bubble collisions to $\Omega_{\text{pt}} < 5.0 \times 10^{-9}$ and the background due to sound waves to $\Omega_{\text{pt}} < 5.8 \times 10^{-9}$ at 95% confidence level for temperatures above $10^8$ GeV.

PACS numbers: 95.85Sz, 04.80.Nn, 95.55Ym, 04.30-w

Introduction.— The Advanced LIGO [1] and Advanced Virgo [2] detection of gravitational waves (GW) from compact binary coalescences (CBCs) [3] offers a novel and powerful tool in understanding our universe and its evolution. We have detected compact binary coalescences (CBCs), and before the detectors reach their designed sensitivity we may detect a stochastic gravitational-wave background (SGWB) produced by many weak, independent and unresolved sources of cosmological or astrophysical origin [4,5]. Among the former, phase transitions occurring in the early universe, is one of the plausible mechanisms leading to a SGWB.

The universe might have undergone a series of phase transitions (see, e.g. [7,8]. In the case of a first-order phase transition (FOPT), once the temperature drops below a critical value, the universe transitions from a meta-stable phase to a stable one, through a sequence of bubble nucleation, growth and merger. During this process, a SGWB is expected to be generated [9,10].

Many compelling extensions of the Standard Model predict strong FOPTs, e.g., grand unification models [11,12], supersymmetric models [13,14], extra dimensions [15,16], composite Higgs models [17,18] and models with an extended Higgs sector (see, e.g. [19,20]). Generally there might exist symmetries beyond the ones of the Standard Model, which are spontaneously broken through a FOPT: for example the Peccei-Quinn symmetry [21,22], the $B-L$ symmetry [23,24], or the left-right symmetry [25]. The nature of cosmological phase transitions depends strongly on the particle physics model at high energy scales.

The SGWB sourced by a FOPT spans a wide frequency range. The peak frequency is mainly determined by the temperature $T_{\text{pt}}$ at which the FOPT occurs. Interestingly, if $T_{\text{pt}} \sim (10^7 - 10^9) \text{ GeV}$ – an energy scale not accessible by any existing terrestrial accelerators – the produced SGWB is within the frequency range of Advanced LIGO and Advanced Virgo [39,40]. Such an energy scale is well-supported by either the Peccei-Quinn axion model [41], which solves the strong CP problem and provides a dark matter candidate, or high-scale supersymmetry models [42,43], among others.

During the third observing run (O3) of the LIGO/Virgo/KAGRA Collaboration (LVKC) – started on 1st April 2019 and ended on 27th March 2020 – no SGWB signal was detected [45]. Nevertheless, one can use the O3 data to constrain the energy density of gravitational waves, and consequently the underlying particle physics models. This is the aim of this Letter.

SGWB from Phase Transitions.— In a FOPT, it is well established that GW can be produced by mainly three sources: bubble collisions, sound waves, and magnetohydrodynamic turbulence (see, e.g. [8] for recent reviews). The GW thus produced is a SGWB, described by the energy density spectrum: $\Omega_{\text{GW}}(f) = d\rho_{\text{GW}}/(\rho_c d\ln f)$ with $\rho_c$ the present critical energy density $\rho_c = 3c^2H_0^2/(8\pi G)$. Each spectrum can be well approximated by a broken power law, with its peak frequency determined by the typical length scale at the transition, the mean bubble separation $R_{\text{pt}}$ which is related to the inverse time duration of the transition $\beta$, and also by the amount of redshifting determined by $T_{\text{pt}}$ and the cosmic
history. The amplitude of each contribution is largely determined by the energy released normalized by the radiation energy density $\alpha$, its fraction going into the corresponding source and the bubble wall velocity $v_w$. Here we do not consider the contribution from magnetohydrodynamic turbulence as it always happens together with sound waves and is subdominant. Also because its spectrum is the least understood and might witness significant changes in the future [46, 49, 54].

The dominant source for GW production in a thermal transition, as most commonly encountered in the early universe, is the sound waves in the plasma induced by the coupling between the scalar field and the thermal bath [55, 57]. A good analytical understanding of this spectrum has been achieved through the sound shell model [58–60], though it still does not capture all the physics [8, 57, 61] to match perfectly the result from numerical simulations [46, 55]:

$$\Omega_{sw}(f) h^2 = 2.65 \times 10^{-6} \left( \frac{H_{pt}}{\beta} \right) \left( \frac{\kappa_{sw} \alpha}{1 + \alpha} \right)^2 \left( \frac{100}{g_*} \right)^{1/3} v_w \left( \frac{f}{f_{sw}} \right)^3 \left( \frac{7}{4 + 3(f/f_{sw})^2} \right)^7 \Upsilon(\tau_{sw}), \quad (1)$$

where $\kappa_{sw}$ is the fraction of vacuum energy converted into the kinetic energy of the bulk flow, a function of $v_w$ and $\alpha$ [62, 63]; $H_{pt}$ is the Hubble parameter at $T_{pt}$; $g_*$ is the number of relativistic degrees of freedom; $h$ is the dimensionless Hubble parameter; $f_{sw}$ is the present peak frequency,

$$f_{sw} = 19 \frac{1}{v_w} \left( \frac{\beta}{H_{pt}} \right) \left( \frac{T_{pt}}{100 \text{GeV}} \right) \left( \frac{g_*}{100} \right)^{1/3} \mu\text{Hz}, \quad (2)$$

and $\Upsilon = 1 - (1 + 2\tau_{sw} H_{pt})^{-1/2}$ [66] which is a suppression factor due to the finite lifetime [60, 64], $\tau_{sw}$, of sound waves. $\tau_{sw}$ is typically smaller than a Hubble time unit [65, 66] and is usually chosen to be the timescale for the onset of turbulence [48], $\tau_{sw} \approx R_{pt}/U_f$, with $R_{pt} = (8\pi)^{1/3} v_w/\beta$ for an exponential nucleation of bubbles [59, 60], and $U_f^2 = 3\kappa_{sw} \alpha/[4(1 + \alpha)]$ [48].

When sound waves, and thus also magnetohydrodynamic turbulence, is highly suppressed or absent, bubble collisions can become dominant, e.g., for a FOPT in vacuum of a dark sector which has no or very weak interactions with the standard plasma. The resulting GW spectrum can be well modelled with the envelope approximation [67, 69], which assumes infinitely thin bubble wall and neglects the contribution from overlapping bubble segments. In the low-frequency regime, $\Omega_{gw} \propto f^3$ from causality [70], and for high-frequencies $\Omega_{gw} \propto f^{-1}$ [71] due to the dominant single bubble contribution as revealed by the analytical calculation [69]. The spectrum is [48, 69, 71]:

$$\Omega_{\text{coll}}(f) h^2 = 1.67 \times 10^{-5} \Delta \left( \frac{H_{pt}}{\beta} \right)^2 \left( \frac{\kappa_{\phi} \alpha}{1 + \alpha} \right)^2 \times \left( \frac{100}{g_*} \right)^{1/3} S_{\text{env}}(f), \quad (3)$$

where $\kappa_{\phi} = \rho_{\phi}/\rho_{\text{vac}}$ denotes the fraction of vacuum energy converted into gradient energy of the scalar field. The amplitude $\Delta$ is $\Delta(v_w) = 0.48 v_w^3/(1 + 5.3 v_w^2 + 5 n_{w})$ and the spectral shape is $S_{\text{env}} = 1/(c_l f^{-3} + (1 - c_l - c_b) f^{-3} + c_b f)$ where $c_l = 0.064$, $c_b = 0.48$ and $f = f/f_{\text{env}}$ with $f_{\text{env}}$ the present peak frequency

$$f_{\text{env}} = 16.5 \left( \frac{f_{bc}}{\beta} \right) \left( \frac{\beta}{H_{pt}} \right) \left( \frac{T_{pt}}{100 \text{GeV}} \right) \left( \frac{g_*}{100} \right)^{1/3} \mu\text{Hz}, \quad (4)$$

and $f_{bc}$ the peak frequency right after the transition $f_{bc} = 0.35\beta/(1 + 0.069 v_w + 0.69 v_w^2)$. More recent simulations going beyond the envelope approximation shows a steeper shape $f^{-1.5}$ for high-frequencies [72], and it also varies from $f^{-1.4}$ to $f^{-2.3}$ as the wall thickness increases [73].

Data Analysis.— Here we take two analysis approaches. First, we consider an approximated broken power law including main features of the shape and its peak. We then consider the phenomenological models (Eqs. [3] and [4]), for contributions from bubble collisions and sound waves.

I. Broken power law model. The spectrum can be approximated by a broken power law (bpl) as

$$\Omega_{\text{bpl}}(f) = \Omega_\ast \left( \frac{f}{f_\ast} \right)^{n_1} \left[ 1 + \left( \frac{f}{f_\ast} \right)^\Delta \right]^{(n_2-n_1)/\Delta}. \quad (5)$$

Here $n_1 = 3$, from causality, and $n_2$ takes the values $-4$ and $-1$, for sound waves and bubble collisions, respectively. $\Delta$ is set to 2 for sound waves and 4 for approximating bubble collisions. We run a Bayesian search for both values, but present results only for $\Delta = 2$, since it gives more conservative upper limits. Besides the fixed values for $n_1$ and $\Delta$, we remain agnostic about the value of $n_2$.

We follow [74, 76] to perform a Bayesian search and model selection. In addition to a search for the broken power law, we undertake a study on simultaneous estimation of a CBC background and a broken power law background, because current estimates of the CBC background [43, 77] shows it as a non-negligible component of any SGWB signal. The CBC background is very well-approximated by an $f^{2/3}$ power law [83]. The challenge then is to search for a broken power law in the presence of a CBC background.

The log-likelihood for a single detector pair is Gaus-
\[ \log p(\hat{C}_{IJ}(f)|\theta_{gw}, \lambda) \propto -\frac{1}{2} \sum_f \left[ \hat{C}_{IJ}(f) - \lambda \Omega_{gw}(f, \theta_{gw}) \right]^2 \]

(6)

where \( \hat{C}_{IJ}(f) \) and \( \sigma_{IJ}^2(f) \) are data products of the O3 analysis; \( \hat{C}_{IJ}(f) \) is the cross-correlation estimator of the SGWB calculated using data from detectors I and J, and \( \sigma_{IJ}^2(f) \) is its variance [79]. The O3 search for an isotropic stochastic signal shows no evidence of correlated magnetic noise, and a pure Gaussian noise model is still preferred by the data [85]. Therefore, here, a contribution from Schumann resonances is neglected. The model we fit to the data is \( \Omega_{gw}(f, \theta_{gw}) \), with parameters \( \theta_{gw} \). The parameter \( \lambda \) captures calibration uncertainties of the detectors [80] and is marginalized over [81]. For a multi-baseline study, we add all log-likelihoods of individual baselines. The set of GW parameters depends on the type of search we perform.

We consider three separate scenarios: contributions from unresolved CBC sources, with \( \theta_{gw} = (\Omega_{ref}) \); broken power law contributions, with \( \theta_{gw} = (\Omega_s, f_s, n_2) \); and the combination of CBC and broken power law contributions, for which \( \theta_{gw} = (\Omega_{ref}, \Omega_s, f_s, n_2) \).

The CBC spectrum is modelled as

\[ \Omega_{cbc} = \Omega_{ref}(f/f_{ref})^{2/3}, \]

(7)

with \( f_{ref} = 25 \text{ Hz} \). The priors used are summarised in Table I. To compare GW models and assess which provides a better fit, we use ratios of evidences, otherwise known as Bayes factors. In particular, we consider \( \log B_{\text{noise}}^{\text{cbc}+\text{bpl}} \) and \( \log B_{\text{cbc}}^{\text{cbc}+\text{bpl}} \) as indicative detection statistics.

| Parameter          | Prior              |
|--------------------|--------------------|
| \( \Omega_{ref} \) | \( \text{LogUniform}(10^{-10}, 10^{-2}) \) |
| \( \Omega_s \)     | \( \text{LogUniform}(10^{-9}, 10^{-4}) \) |
| \( f_s \)          | \( \text{Uniform}(20, 256 \text{ Hz}) \) |
| \( n_1 \)          | 3                  |
| \( n_2 \)          | \( \text{Uniform}(-8,0) \) |
| \( \Delta \)        | 2                  |

TABLE I: List of prior distributions used for all parameters in the various searches. The narrow, informative prior on \( \Omega_{ref} \) stems from the estimate of the CBC background [77]. The peak frequency prior is uniform across the frequency range considered since we have no information about it.

II. Phenomenological model. Two scenarios are considered, corresponding to dominant contributions from bubble collisions or sound waves, respectively, following an approach similar to [31]. The analysis procedure follows closely that of the broken power law search, with \( \theta_{gw} = (\Omega_{ref}, \alpha, \beta/H_{pt}, T_{pt}) \) including CBC background \( \Omega_{cbc} \), and \( \Omega_{gw} \) from bubble collisions and sound waves described by Eqs. (3) and (1), respectively.

For bubble collisions, \( v_w \) and \( \kappa_\phi \) are set to unity. The remaining model parameters are varied in the ranges in Table I. We note that the GW spectra in Eqs. (3) and (1) may not be applicable when \( \alpha \geq 10 \), and also a large \( \alpha \) does not translate into a significant increase in the GW amplitude. Moreover, \( \beta/H_{pt} \) is related to the mean bubble separation, and one should be cautious when it is smaller than 1 [65 82].

For sound waves, we initially set \( v_w = 1 \), and then explore different values for \( v_w \) in the range (0.7 - 1.0), corresponding to various detonation and hybrid modes of fluid velocity profile [61 62]. Here \( \kappa_{gw} \) is a function of \( \alpha \) and \( v_w \), e.g., for \( v_w = 1, \kappa_{gw} \) increases from 0.1 to 0.9 as \( \alpha \) increases from 0.1 to 10. The rest of the parameters are varied as in the case of bubble collisions.

Results. — I. Broken power law model. In Fig. 1 we present posterior distributions of parameters in the combined CBC and BPL search. The Bayes factor is \( \log B_{\text{bc}+\text{pl}} = -1.4 \), demonstrating no evidence of such a signal in the O3 data. The 2-d posterior of \( \Omega_{ref} \) and \( \Omega_s \) allows us to place simultaneous estimates on the amplitudes of the two spectra. The 95% confidence level (CL) upper limits are \( \Omega_{ref} = 5.9 \times 10^{-9} \) and \( \Omega_s = 2.7 \times 10^{-7} \), respectively. If we take individual posterior samples

FIG. 1: Posterior distributions for the combined CBC and broken power law search as a function \( \log \Omega_{ref} \) and the different parameters of the model. The 68% and 95% CL exclusion contours are shown. The horizontal dashed line in the posteriors indicate the flat priors used in the analysis.

TABLE I: List of prior distributions used for all parameters in the various searches. The narrow, informative prior on \( \Omega_{ref} \) stems from the estimate of the CBC background [77]. The peak frequency prior is uniform across the frequency range considered since we have no information about it.
of $\Omega_*$, $f_*$ and $n_2$ from Fig. 1 and combine them to construct a posterior of $\Omega_{bpl}^\ast$. We estimate at 95% CL $\Omega_{bpl}^\ast (25 \text{ Hz}) = 2.8 \times 10^{-9}$. The width of the $n_2$ posterior suggests no preference for a particular value by the data, and we are unable to rule out any part of the parameter space at this time. Other searches give Bayes factors $\log B_{\text{noise}}^{\text{bpl}} = -0.78$ and $\log B_{\text{cbc} + \text{bpl}}^{\text{gen}} = -0.81$, once again giving no evidence for a BPL signal, with or without CBCs considered.

To demonstrate the dependence of GW amplitude constraints on other parameters, we present 95% CL upper limits on $\Omega_*$ for a set of $n_2$ and $f_*$ in Table II. We choose representative values of $n_2$, for bubble collisions, $n_2 = -1$ and -2, and for sound waves, $n_2 = -4$. The $f_*$ values are chosen to represent broken power laws that peak before, at, and after the most sensitive part of the LIGO-Virgo band, $f_* = 25 \text{ Hz}$. As expected, the most constraining upper limits are obtained for a signal that peaks at 25 Hz. For the signal in the first column that peaks at 1 Hz, the faster it decays, the weaker it is at 25 Hz. Therefore, the more negative $n_2$ values give less constraining upper limits on the amplitude. Finally, the signal that peaks at 200 Hz gives similar $\Omega_*$ upper limits for all values of $n_2$ since it resembles a simple $n_1 = 3$ power law in the range with largest SNR. Note the upper limits in Table II are fundamentally different from results in Fig. 1. In the former case we fix $f_*$ and $n_2$ and find $\Omega_*^{0.95}$, while in the latter we marginalise over all parameters to obtain $\Omega_*^{0.95}$.

| $f_*$ (Hz) | $n_2 = -1$ | $n_2 = -2$ | $n_2 = -4$ |
|-----------|-------------|-------------|-------------|
| 1         | $3.3 \times 10^{-6}$ | $4.5 \times 10^{-8}$ | $2.8 \times 10^{-7}$ |
| 25        | $6.0 \times 10^{-8}$ | $1.8 \times 10^{-7}$ |
| 200       | $3.7 \times 10^{-7}$ |

TABLE II: Upper limits for the energy density amplitude, $\Omega_*^{0.95}$, in the broken power law model for fixed values of the peak frequency, $f_*$, and negative power law index, $n_2$.

II. Phenomenological model. We now estimate 95% CL upper limits on $\Omega_{\text{coll}}$ and $\Omega_{\text{sw}}$ from bubble collisions and sound waves respectively. First, a simplified Bayesian search is performed considering contributions from unresolved CBC sources plus an unmodelled generic term with a log-uniform prior in the range $10^{17} - 10^{5}$. This leads to a Bayes factor of $\log B_{\text{cbc} + \text{gen}}^{\text{noise}} = -0.64$, indicating again no signal for new phenomena. Values for $\Omega_{\text{ref}}$ above $6.6 \times 10^{-9}$ are excluded at 95% CL, and additional contributions to the normalised energy density above $3.3 \times 10^{-9}$ are also excluded. The Bayesian analysis is then repeated separately for $\Omega_{\text{coll}}$ and $\Omega_{\text{sw}}$ contributions, with priors in Table I leading to very similar Bayes factors and 95% CL upper limits on $\Omega_{\text{ref}}$.

In Fig. 2 we present exclusion regions as a function of the different parameters of the CBC+FOPT model, now under the assumption that contributions from bubble collisions dominate, with $v_w = 1$ and $\kappa_\phi = 1$. In general, with the chosen prior, the data can exclude part of the parameter space at 95% CL, especially when $T_{\text{pt}} > 10^8 \text{ GeV}$, $\alpha > 1$, or $\beta/H_{\text{pt}} < 1$.

Table III presents 95% CL upper limits on $\Omega_{\text{coll}} (25 \text{ Hz})$ for several $\beta/H_{\text{pt}}$ and $T_{\text{pt}}$, where $\alpha$ is left as a free parameter to be inferred from the data. We consider three values for $\beta/H_{\text{pt}}$, namely 0.1, 1, and 10, and three for $T_{\text{pt}}$: $10^7$, $10^8$, and $10^9 \text{ GeV}$. Our constraints on $\Omega_{\text{coll}} (25 \text{ Hz})$, as computed at the reference frequency of 25 Hz, vary in the range $4.0 \times 10^{-9} - 1.0 \times 10^{-8}$, with more stringent limits at large $\beta/H_{\text{pt}}$ or large $T_{\text{pt}}$. At the largest values of $\beta/H_{\text{pt}}$ and $T_{\text{pt}}$ there is not enough sensitivity to place constraints to the model. In all cases, the inferred upper limits on the CBC background are fairly constant, and range between $\Omega_{\text{ref}} = 5.3 \times 10^{-9}$ and $6.1 \times 10^{-9}$.

| Phenomenological model (bubble collisions) | $\Omega_{\text{coll}}^{0.95}$ (25 Hz) |
|------------------------------------------|-----------------------------------|
| $\beta/H_{\text{pt}}$, $T_{\text{pt}} = 10^7 \text{ GeV}$ | $7.8 \times 10^{-8}$ |
| 0.1                                      | $9.2 \times 10^{-8}$ |
| 1                                        | $1.0 \times 10^{-8}$ |
| 10                                       | $4.0 \times 10^{-9}$ |

TABLE III: The 95% CL upper limits on $\Omega_{\text{coll}}^{0.95} (25 \text{ Hz})$ for fixed values of $\beta/H_{\text{pt}}$ and $T_{\text{pt}}$, and $v_w = \kappa_\phi = 1$. The dashed line denotes no sensitivity for exclusion.

Similarly, in Fig. 3 we present the results for the CBC+FOPT hypothesis in which the sound waves dominate with $v_w = 1$ and $\kappa_\phi$ a function of $v_w$ and $\alpha$. 

The Bayesian analysis shows sensitivity at large values of $\alpha$ and $T_{\text{pt}}$, but does not exclude regions in the parameter space at 95% CL. The analysis is then performed for given values of $\beta/H_{\text{pt}}$ and $T_{\text{pt}}$, leaving $\alpha$ as a free parameter. As a result, a 95% CL upper limit on $\Omega_{\text{sw}}(25\text{Hz})$ of $5.9 \times 10^{-9}$ is obtained for $\beta/H_{\text{pt}} < 1$ and $T_{\text{pt}} > 10^8$ GeV. The analysis is repeated for models with reduced velocities of $v_w = 0.9$, $v_w = 0.8$, and $v_w = 0.7$, with Bayes factor $\log L_{\text{Bayes}} = -6.60$ and upper limit $\Omega_{\text{ref}} \approx 5.9 \times 10^{-9}$, with no significant $v_w$ dependence. In all studied cases, the models with reduced $v_w$ lead to significantly lower sound waves predicted energy densities, and with no 95% CL exclusions in the considered parameter space.

Conclusions.—We have searched for signals from FOPTs in the early universe, potentially leading to a SGWB in the Advanced LIGO/Advanced Virgo frequency band. The analysis is based on the data from the O3 observation period, for which no generic stochastic signals above the detector noise has been observed.

We use the results to deduce implications for models describing SGWB. We first consider a generic broken power law spectrum, describing its main features in terms of the shape and the peak amplitude. We place 95% CL upper limits simultaneously on the normalised energy density contribution from unresolved CBCs and a FOPT, $\Omega_{\text{cbc}}(25\text{Hz}) = 5.9 \times 10^{-9}$ and $\Omega_{\text{bpl}}(25\text{Hz}) = 2.8 \times 10^{-9}$, respectively.

The results are then interpreted in terms of a phenomenological model describing contributions from bubble collisions or sound waves, showing that the data can exclude a part of the parameter space at large temperatures. Contributions from unresolved CBC sources with normalised energy density in gravitational waves larger than $\Omega_{\text{cbc}}(25\text{Hz}) = 6.6 \times 10^{-9}$ are excluded. In a scenario in which bubble collision contributions dominate, with $v_w = 1$ and $\kappa_0 = 1$, part of the phase space with $T_{\text{pt}} > 10^8$ GeV, $\alpha > 1$, and $\beta/H_{\text{pt}} < 1$ is excluded at 95% CL. For fixed values of $\beta/H_{\text{pt}} = 0.1$, 1 or 10 and $T_{\text{pt}} = 10^7, 10^8$ or $10^9$ GeV, the 95% CL upper limits on $\Omega_{\text{coll}}(25\text{Hz})$ vary in the range between $4.0 \times 10^{-9}$ and $1.0 \times 10^{-8}$ which depends on the $\beta/H_{\text{pt}}$ and $T_{\text{pt}}$ values considered. In the case where sound waves dominate, several scenarios are explored considering different $v_w$. The data only shows a limited sensitivity, and a 95% CL upper limit on $\Omega_{\text{sw}}(25\text{Hz})$ of $5.9 \times 10^{-9}$ is placed in the case of $v_w = 1$, for $\beta/H_{\text{pt}} < 0.1$ and $T_{\text{pt}} > 10^8$ GeV. Altogether, the results indicate the importance of using LIGO-Virgo GW data to place constraints on new phenomena related to strong FOPTs in the early universe.

Acknowledgements.—The authors would like to thank the LIGO-Virgo stochastic background group for helpful comments and discussions. In particular, the authors thank Patrick M. Meyers on his contributions to the parameter estimation analysis code. We thank AlbertoMariotti on his useful feedback on the draft. The authors are grateful for computational resources provided by the LIGO Laboratory and supported by National Science Foundation Grants PHY-075708 and PHY-0823459. This paper has been given LIGO DCC number LIGO-P2000518.

A.R and M.M would like to thank O. Pujolàs for the motivation and the fruitful discussions. This work was partially supported by the Spanish MINECO under the grants SEV-2016-0588 and PGC2018-101858-B-I00, some of which include ERDF funds from the European Union. IFAE is partially funded by the CERCA program of the Generalitat de Catalunya. K.M. is supported by King’s College London through a Postgraduate International Scholarship. M.S. is supported in part by the Science and Technology Facilities Council (STFC), United Kingdom, under the research grant ST/P000258/1. H.G. is supported by the U.S. Department of Energy grant No. DE-SC0009956. F.W.Y. and Y.Z. are supported by the U.S. Department of Energy under Award No. DE-SC0009959. Numerous software packages were used in this paper. These include matplotlib [83], numpy [84], scipy [85], bilby [85], dynesty [87], PyMultiNest [88].

[1] J. Aasi, B. P. Abbott, R. Abbott, T. Abbott, M. R. Abernathy, K. Ackley, C. Adams, T. Adams, P. Addesso, and R. X. A. et. al., Class. Quant. Grav. 32, 074001 (2015), URL https://doi.org/10.1088/0264-9381/32/7/074001
...and Cosmology (Oxford University Press, 2018). ISBN 978-0-19-857089-9.

[71] S. J. Huber and T. Konstandin, JCAP 0809, 022 (2008), 0806.1828.

[72] D. Cutting, M. Hindmarsh, and D. J. Weir, Phys. Rev. D 97, 123513 (2018), 1802.05712.

[73] D. Cutting, E. G. Escartin, M. Hindmarsh, and D. J. Weir (2020), 2005.13537.

[74] V. Mandic, E. Thrane, S. Giampanis, and T. Regimbau, Phys. Rev. Lett. 109, 171102 (2012), URL https://link.aps.org/doi/10.1103/PhysRevLett.109.171102.

[75] T. Callister, A. S. Biscoveanu, N. Christensen, M. Isi, A. Matas, O. Minazzoli, T. Regimbau, M. Sakellariadou, J. Tasson, and E. Thrane, Phys. Rev. X 7, 041058 (2017), URL https://link.aps.org/doi/10.1103/PhysRevX.7.041058.

[76] P. M. Meyers, K. Martinovic, N. Christensen, and M. Sakellariadou, Phys. Rev. D 102, 102005 (2020), URL https://link.aps.org/doi/10.1103/PhysRevD.102.102005.

[77] B. P. Abbott et al. (LIGO Scientific, Virgo), Phys. Rev. Lett. 120, 091101 (2018), 1710.05837.

[78] T. Callister, L. Sammut, S. Qiu, I. Mandel, and E. Thrane, Phys. Rev. X 6, 031018 (2016), URL https://link.aps.org/doi/10.1103/PhysRevX.6.031018.

[79] B. Allen and J. D. Romano, Phys. Rev. D 59, 102001 (1999), URL https://link.aps.org/doi/10.1103/PhysRevD.59.102001.

[80] L. Sun et al., Class. Quant. Grav. 37, 225008 (2020), 2005.02531.

[81] J. T. Whelan, E. L. Robinson, J. D. Romano, and E. H. Thrane, J. Phys. Conf. Ser. 484, 012027 (2014), 1205.3112.

[82] J. Ellis, M. Lewicki, and J. M. No, JCAP 04, 003 (2019), 1809.08242.

[83] J. D. Hunter, Computing in Science & Engineering 9, 90 (2007).

[84] S. van der Walt, S. C. Colbert, and G. Varoquaux, Computing in Science Engineering 13, 22 (2011).

[85] P. Virtanen, R. Gommers, T. E. Oliphant, M. Haberland, T. Reddy, D. Cournapeau, E. Burovski, P. Peterson, W. Weckesser, J. Bright, et al., Nature Methods 17, 261 (2020).

[86] G. Ashton et al., Astrophys. J. Suppl. 241, 27 (2019), 1811.02042.

[87] J. S. Speagle, Mon. Not. Roy. Astron. Soc. 493, 3132 (2020), 1904.02180.

[88] Buchner, J., Georgakakis, A., Nandra, K., Hsu, L., Rangel, C., Brightman, M., Merloni, A., Salvato, M., Donley, J., and Kocevski, D., A&A 564, A125 (2014), URL https://doi.org/10.1051/0004-6361/201322971.