12th Iberian Gravitational Waves Meeting

Implications for first-order cosmological phase transitions and the formation of primordial black holes from the third LIGO-Virgo observing run

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6^{th}–8^{th} June 2022 - University of Minho, Campus Gualtar

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Stochastic gravitational wave background (SGWB)

The SGWB is a superposition of gravitational wave (GW) sources [1] that can be either:

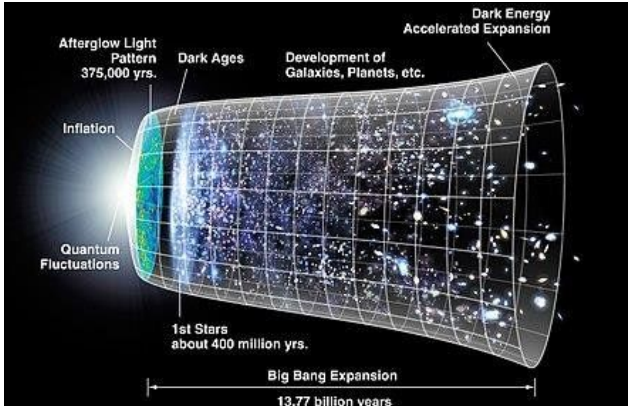
- Astrophysical: distant compact binary coalescences (CBCs), core collapse supernovae, rotating neutron stars, stellar core collapses.
- Cosmological: cosmic strings, primordial black holes, superradiance of axion clouds around black holes, phase transitions in the early universe, inflation.

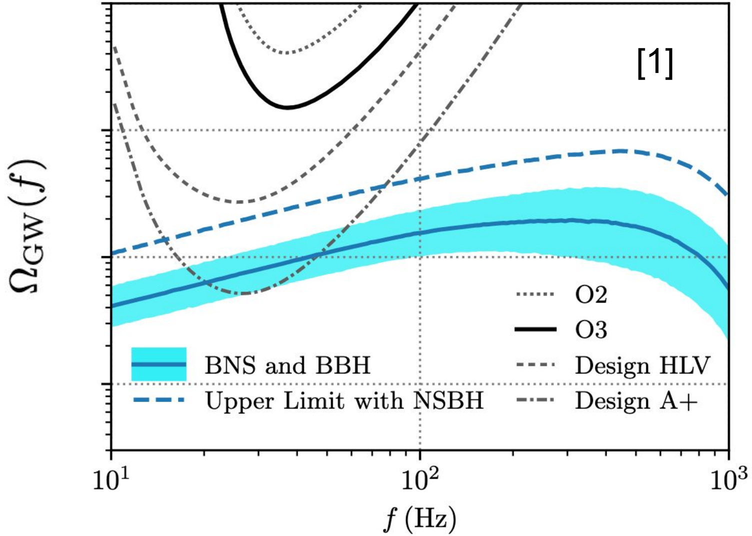
The SGWB is characterized by the energy density in gravitational waves spectrum:

$$\Omega_{\rm GW}(f) = \frac{f}{\rho_c}\frac{{\rm d}\rho_{\rm GW}}{{\rm d}f}$$

GW energy density

$$\rho_c = 3H_0^2c^2/(8\pi G)$$





[1] R. Abbott et al. (LIGO Scientific, Virgo, KAGRA) (2021), Phys. Rev. D 104, 022004 – Published 23 July 2021.

SGWB detection method - Cross correlation technique

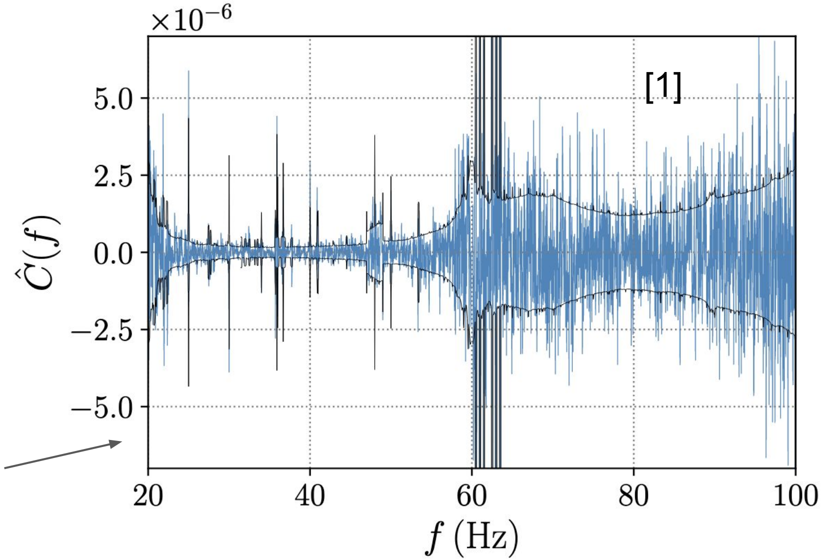
The search for a SGWB is done by cross correlating the data from two detectors I ($s_I(t)$) and J ($s_J(t)$) via the cross-correlation statistic for the pair IJ :

$$\hat{C}^{IJ}(f) = \frac{2}{T}\frac{\mathrm{Re}[\tilde{s}_I^\star(f)\tilde{s}_J(f)]}{\gamma_{IJ}(f)S_0(f)}$$

Observation time (T)

Overlap reduction function ($\gamma_{IJ}(f)$)

$S_0(f) = (3H_0^2)/(10\pi^2 f^3)$



From the O1+O2+O3 isotropic search no correlation was found, i.e.: **no detection of a GWB was claimed.**

Still, we set bounds on the parameters of the spectrum describing the GWB.

[1] R. Abbott et al. (LIGO Scientific, Virgo, KAGRA) (2021), Phys. Rev. D 104, 022004 – Published 23 July 2021.

Upper limits on the parameters of the GWB

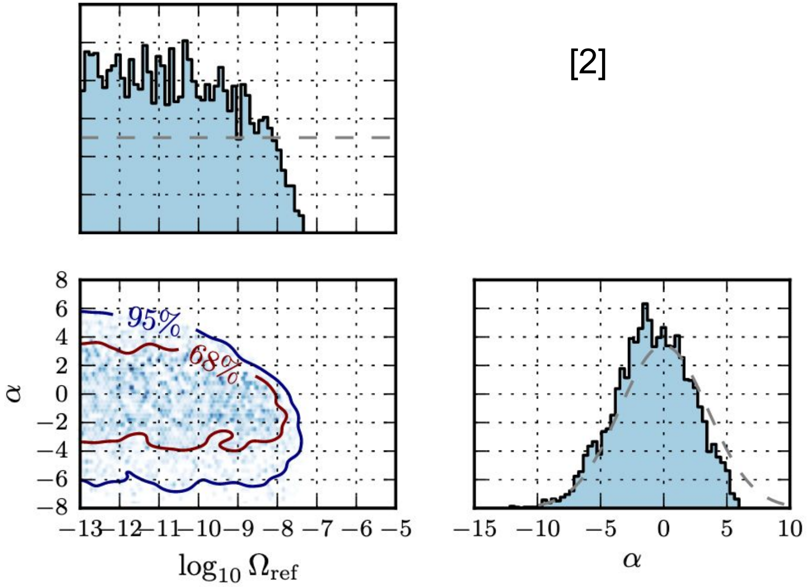
We obtained upper limits from a hybrid frequentist-Bayesian formalism [1]. The likelihood for the pair IJ:

$$p(\hat{C}_k^{IJ}|\boldsymbol{\Theta}) \propto \exp\left[-\frac{1}{2}\sum_{IJ}\sum_{k}\left(\frac{\hat{C}_k^{IJ} - \Omega_{\mathrm{M}}(f_k|\boldsymbol{\Theta})}{\sigma_{IJ}^2(f_k)}\right)^2\right]$$

Cross-correlation statistic for the pair IJ with variance $\sigma_{IJ}^2(f_k)$

model for the GWB, with parameters $\boldsymbol{\Theta}$

[2]



As mentioned in the previous slide, we set bounds on the parameters of the spectrum describing the GWB. The spectrum chosen is model independent:

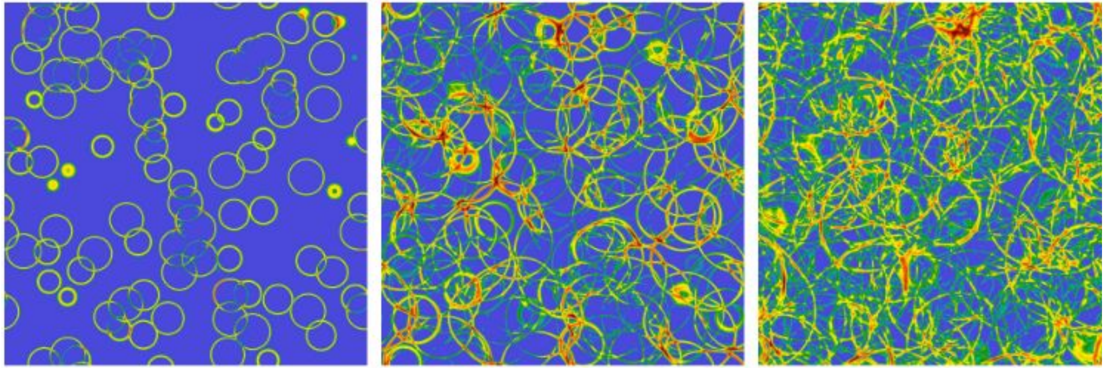
$$\Omega_{\mathrm{GW}}(f) = \Omega_{\mathrm{ref}}\left(\frac{f}{f_{\mathrm{ref}}}\right)^{\alpha}$$

$f_{\mathrm{ref}} = 25$ Hz → corresponds to the start of the most sensitive frequency band for the isotropic search

[1] V. Mandic, E. Thrane, S. Giampanis, and T. Regimbau, PRL. 109, 171102 – 24 Oct. 2012.
[2] R. Abbott et al. (LIGO Scientific, Virgo, KAGRA) (2021), Phys. Rev. D 104, 022004 – Published 23 July 2021.

Reinterpretations: Early Universe Physics

- We recast the results from the isotropic SGWB search [1] shown in previous slides in terms of constraints to First Order Phase Transitions (FOPTs) and Primordial Black Holes (PBH) inspired models.
- We focus on these sources for the following reasons:
  - Models Beyond the Standard Model (BSM) predict **First Order Phase Transitions (FOPTs)** in the early Universe. Energies >> energy scale of Big Bang Nucleosynthesis and the CMB. The production of GWs in FOPTs is then an alternative probe.
  - **Primordial Black Holes (PBHs)** have gained interest as the particle dark matter candidates have become more tightly constrained.



[2]

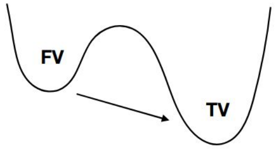
[1] R. Abbott et al. (LIGO Scientific, Virgo, KAGRA) (2021), Phys. Rev. D 104, 022004 – Published 23 July 2021.

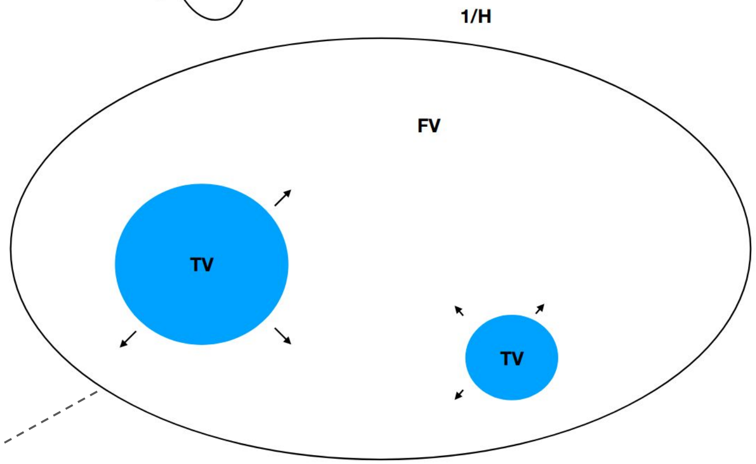
[2] Mark Hindmarsh, Stephan J. Huber, Kari Rummukainen, and David J. Weir Phys. Rev. D **92**, 123009 (2015).

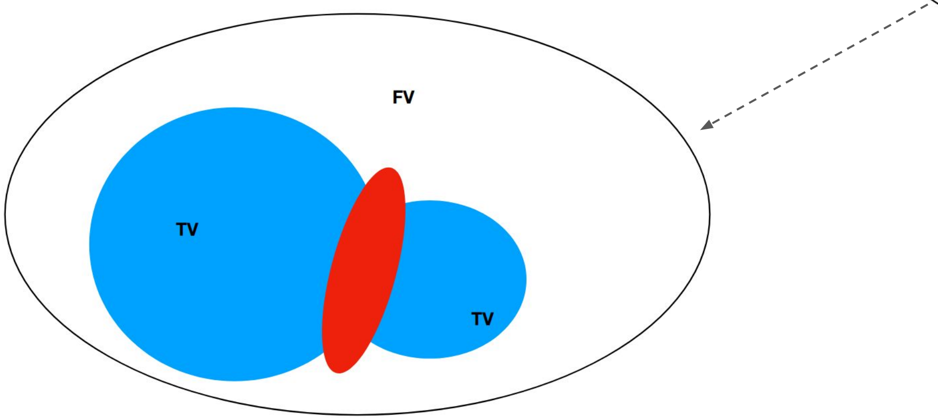
First Order Phase Transitions (FOPTs)

Sources of GWs

- In a cosmological FOPT the Universe goes from a metastable high energy (symmetric) phase (FV) to a stable lower energy (broken) phase (TV).
- The TV bubbles expand, collide and eventually coalesce, generating shear stresses which source GWs → three sources of GWs:
  - Bubble collisions (BC): $\Omega_{\rm coll}$.
  - Sound waves (SW): Ω_{sw} These are the dominant GW production mechanism.
  - Turbulence: Ω_t We will consider it negligible.



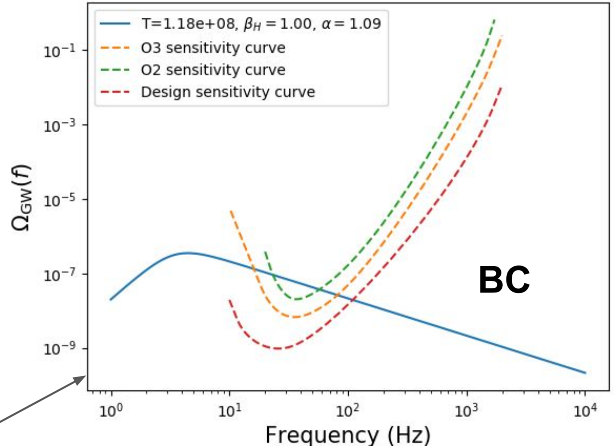




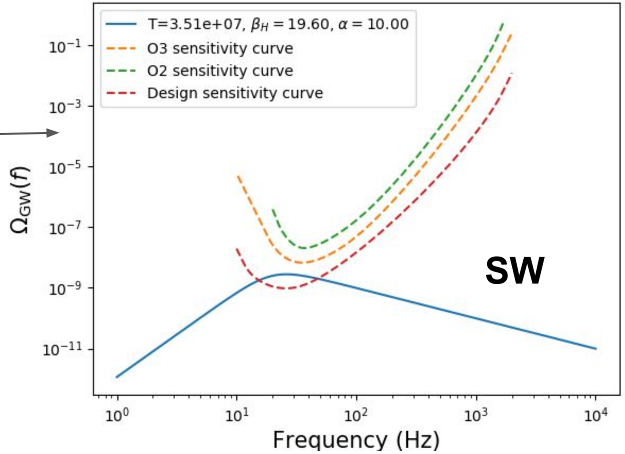
Phenomenological model parameters for BC and SW

The parameters to consider are the following:

- T_{pt}: temperature after the GW generation (GeV).
- v_w: bubble wall 'terminal' velocity (units of speed of light).
- α : strength of the transition.
- $\frac{\beta}{H_{\mathrm{pt}}}$, with β the inverse duration of the FOPT (H_{pt}=hubble rate at the time of the transition).
- $\kappa_t, \kappa_\phi, \kappa_{sw}$: 'efficiencies' of each type of signal.



The orange curve is the O3 sensitivity (that with respect to which we have compared the models). The red curve is the sensitivity expected for Ad-LIGO +.



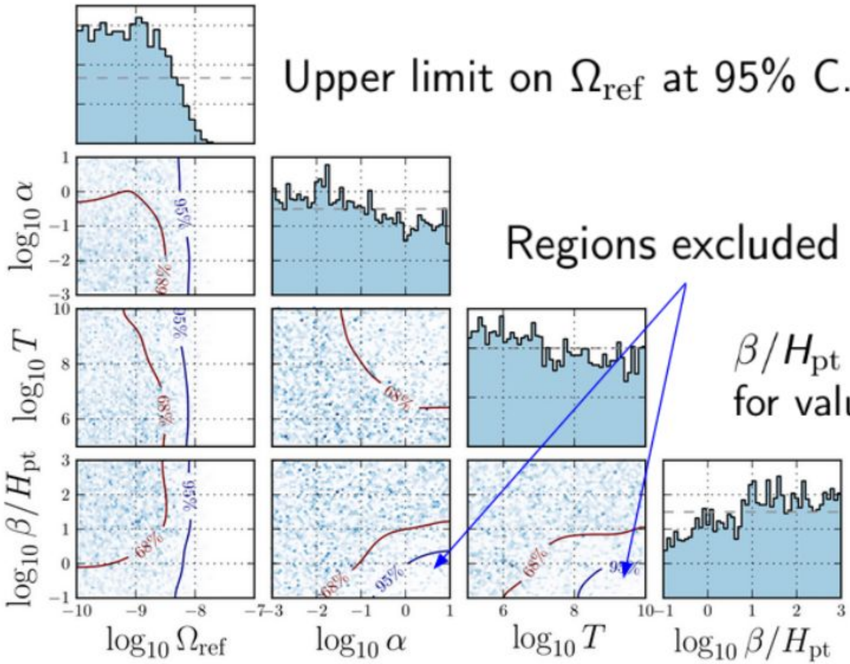
Priors and results from the CBC+phenomenological model for FOPTs (BC) search

We use the energy density spectrum given by Eqs. (1) and (3) from [Phys. Rev. Lett. 126, 151301 – Published 16 April 2021](#).

The contribution from CBCs is a non-negligible component of the SGWB signal: $$\Omega_{\rm cbc} = \Omega_{\rm ref}(f/f_{\rm ref})^{2/3}$$

consistent with expectations for CBCs (contributions from the inspiral dominate)

Phenomenological model	
Parameter	Prior
$\Omega_{\rm ref}$	LogUniform$(10^{-10}, 10^{-7})$
α	LogUniform $(10^{-3}, 10)$
$\beta/H_{\rm pt}$	LogUniform $(10^{-1}, 10^{3})$
$T_{\rm pt}$	LogUniform $(10^{5}, 10^{10}$ GeV$)$
$v_{\rm w}$	1
κ_ϕ	1
$\kappa_{\rm sw}$	$f(\alpha, v_{\rm w}) \in [0.1 - 0.9]$



Upper limit on $\Omega_{\rm ref}$ at 95% C.L.:5.91×10^{-9}

Regions excluded at 95% C.L.

$\beta/H_{\rm pt}$ shows preference for values above 10

Exclusion of very high temperatures not accessible at colliders.

For SW sourcing the generation of GWs, we cannot make exclusions in parameter space except for the amplitude of the CBC background (UL at 95% CL of 5.86×10^{-9}).

Primordial Black Holes (PBHs)

PBHs formation, generation of GWs and curvature power spectrum

- PBHs formed in the early radiation dominated era due to the collapse of large inhomogeneities.
- The PBH formation is accompanied by a GWB generated at 2nd order in the cosmological perturbation theory due to scalar perturbations. The spectrum of the generated GWB is given in terms of the curvature power spectrum → log-normal shape (choice of parametrisation).

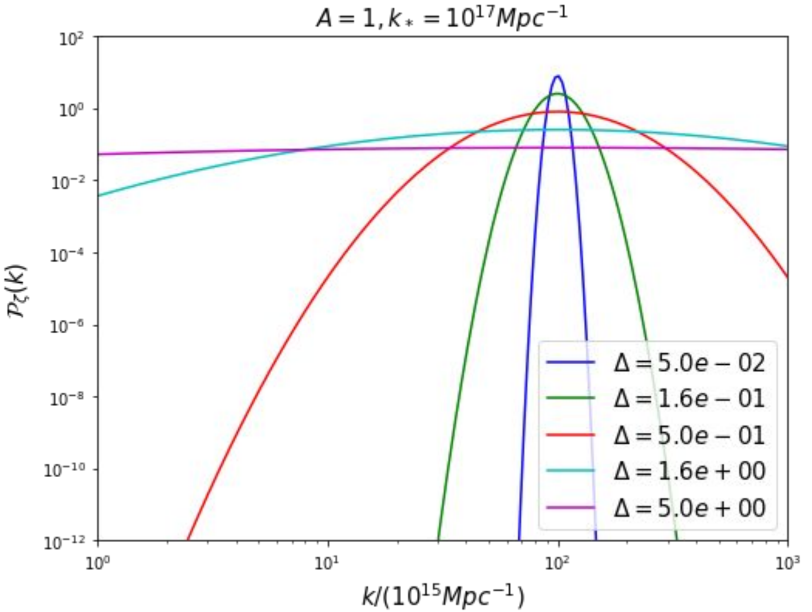
$$\mathcal{P}_\zeta(k) = \frac{A}{\sqrt{2\pi}\Delta}\exp\left[-\frac{\ln^2(k/k_*)}{2\Delta^2}\right]$$

Integrated power of the peak

Width of the peak

Position of the peak. It is more common to use k than f, and they are related by:

$$f_*/\text{Hz} = 1.6\times10^{-15}k_*/\text{Mpc}^{-1}$$



The SIGW spectrum

Spectrum for scalar induced gravitational waves (SIGW): [1]

$$\Omega_{GW}(f) = 0.387 \cdot \Omega_R \left(\frac{g_{*,s}^4 g_*^{-3}}{106.75}\right)^{-1/3} \frac{1}{6} \int_{-1}^{1} dx \int_{1}^{\infty} dy \mathcal{P}\left(\frac{y-x}{2} f\right) \mathcal{P}\left(\frac{x+y}{2} f\right) F(x,y)$$

5.38e-5

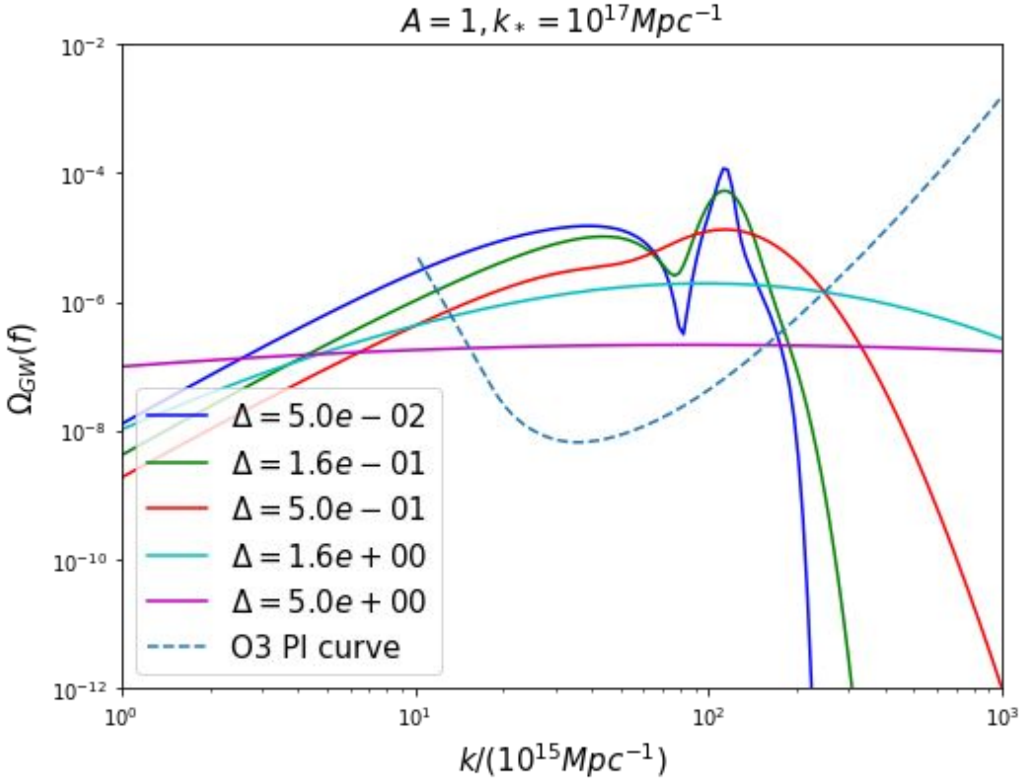
~100 (scales larger than 10^{15} Mpc^{-1} reentered the horizon at T>10^{8} GeV)

- At Δ<<1 the amplitude of the induced GWs as well as the generated PBH abundance are independent on Δ, whereas for Δ>1 they are determined by $\mathcal{P}_\zeta(k_*) = A/(\sqrt{2\pi}\Delta)$.
- This spectrum is peaked around the same wavenumber as the curvature power spectrum and its peak amplitude is $\Omega_{\rm GW} = \mathcal{O}(10^{-5})A^2$ for $\Delta \ll 1$.

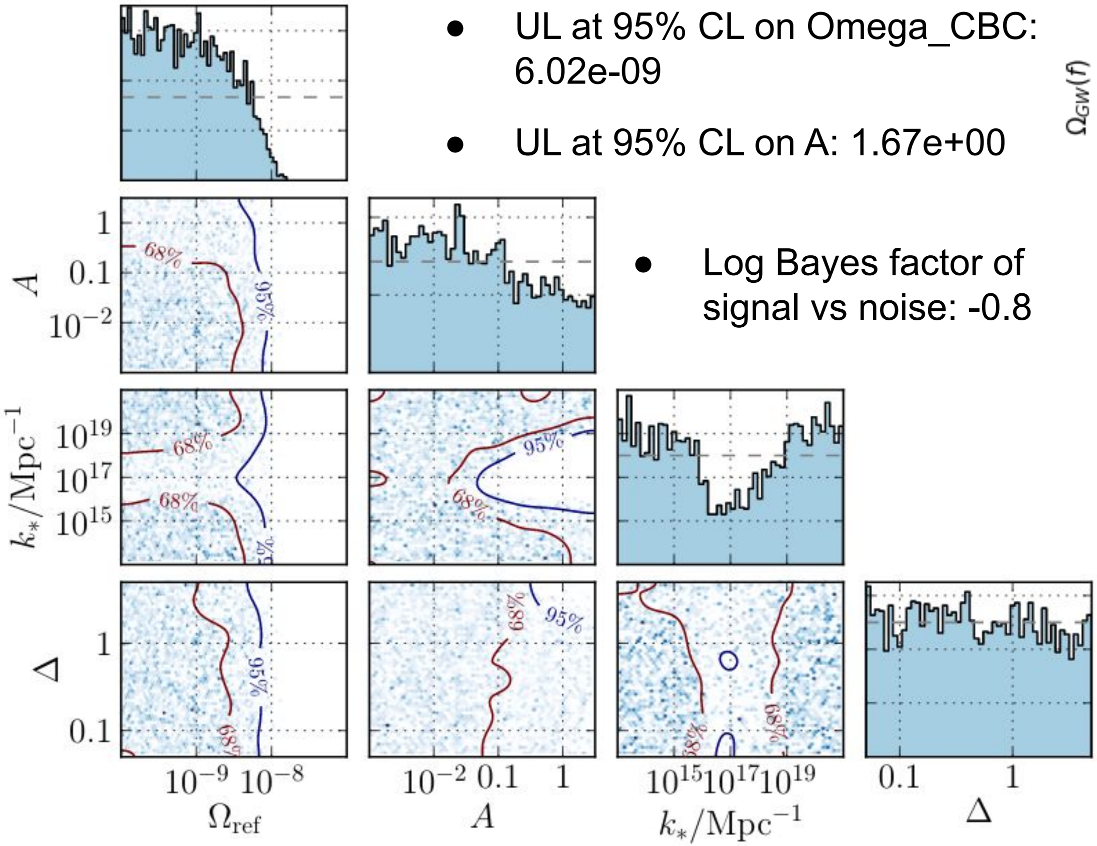
[1] K. Kohri and T. Terada, Phys. Rev. D97, 123532(2018), 1804.08577

The SIGW spectrum

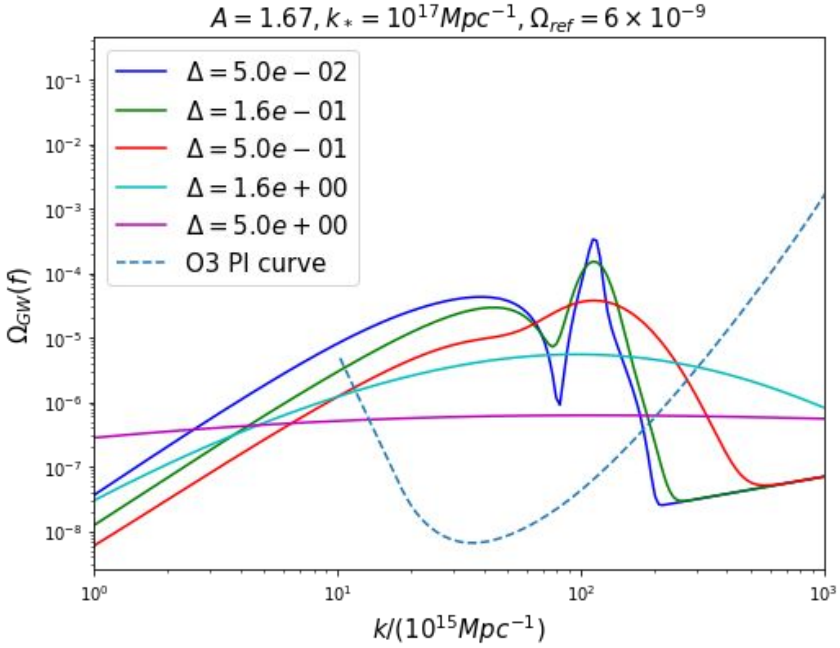
- The LIGO-Virgo detectors, being sensitive to frequencies between 10-500Hz, can potentially probe peaks in the curvature power spectrum at scales (k) larger than 10^{15} Mpc^{-1} and smaller than 10^{18} Mpc^{-1}.
- CMB observations show that at large scales the amplitude of the curvature power spectrum is of the order of 10^{-9} → SIGW cannot be probed.
- For PBHs to form, the curvature power spectrum amplitude needs to be of the order of 0.01 at small scales → SIGW within the reach of GW observatories.



Results from the Bayesian search



- UL at 95% CL on Omega_CBC: 6.02e-09
- UL at 95% CL on A: 1.67e+00
- Log Bayes factor of signal vs noise: -0.8



Parameter	Prior
$\Omega_{\rm ref}$	$\mathrm{LogUniform}(10^{-10},\ 10^{-7})$
A	$\mathrm{LogUniform}(10^{-3},\ 10^{0.5})$
k_*/Mpc^{-1}	$\mathrm{LogUniform}(10^{13},\ 10^{21})$
Δ	$\mathrm{LogUniform}(0.05,\ 5)$

Implications for PBHs

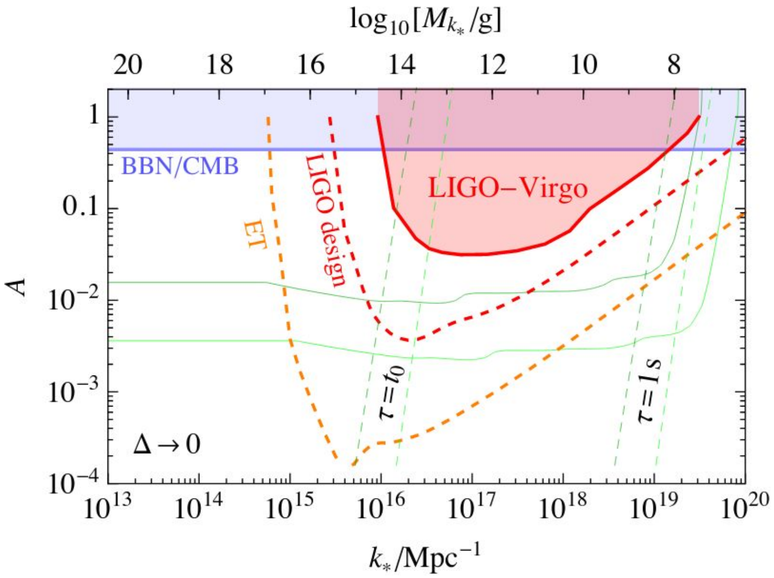
- We compare constraints arising from BBN/CMB and PBH formation with the 95% CL LIGO-Virgo bound for A as a function of k_* obtained from our Bayesian analysis.
- We show the LIGO-Virgo bounds from running two searches with these curvature power spectrum:
  - Dirac delta function peak ($\Delta \to 0$)
  - Log-normal peak with $\Delta = 1$
- We calculate the PBH abundance generated from the peak in the curvature power spectrum shown earlier,

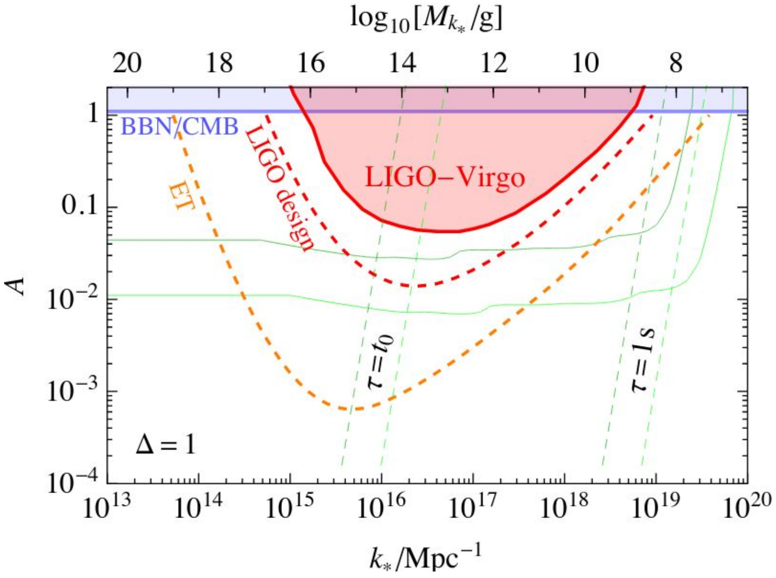
$$\mathcal{P}_\zeta(k) = \frac{A}{\sqrt{2\pi}\Delta} \exp\left[-\frac{\ln^2(k/k_*)}{2\Delta^2}\right]$$

following the procedure in [5]. We also use: $M_{\rm PBH} \sim M_k$ to show the PBH mass associated to certain k.

[5] S. Young, I. Musco, and C. T. Byrnes, JCAP 11, 012 (2019), 1904.00984.

- In the range of k_* from 10^{15}-10^{18} Mpc^{-1} the LIGO-Virgo bound is stronger than the indirect bounds on the abundance of GWs arising from BBN, $\Omega_{GW} < 3.7 \times 10^{-6}$ and the CMB observations, $\Omega_{GW} < 3.5 \times 10^{-6}$.
- The relevant PBH masses for our sensitivity band are $M_{\rm PBH} \lesssim 10^{16}\,{\rm g}$.
- Our current LIGO-Virgo sensitivity is not enough to constrain the PBH formation.





The dashed red and orange curves show the projected sensitivities of LIGO in its final phase and ET. The green dashed curves indicate the evaporation timescales of the PBHs.

Conclusions

- We recast the results from the isotropic SGWB searches in terms of constraints to FOPT and PBH inspired models.
- We used the LIGO-Virgo O1+O2+O3 correlated data and were able to place upper limits over the parameters of our models with a hybrid frequentist-Bayesian formalism.
- In the case that the SGWB is sourced by CBCs+FOPTs, we exclude very high temperatures not accessible at colliders. Our work is published in PRL: Phys. Rev. Lett. 126, 151301 – Published 16 April 2021.
- In the case that the SGWB is sourced by CBCs+PBHs, we cannot constrain the PBH formation as well as the PBH abundance. The future Einstein Telescope will reach the required sensitivity to set stringer ULs. This work has been recently published in PRL: Phys. Rev. Lett. 128, 051301 – Published 1 February 2022 (editor’s suggestion).

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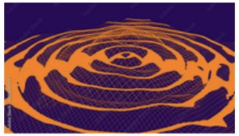


Search for a scalar induced stochastic gravitational wave background in the third LIGO-Virgo observing run

Alba Romero-Rodriguez *et al.*
Phys. Rev. Lett. **128**, 051301 (2022)

Published 1 February 2022

has been highlighted by the editors as an Editors’ Suggestion. Publication of a Letter is

Backup slides

Searches performed

We have performed a series of searches including a CBC background, since it is a non-negligible component of any SGWB signal. We model it as:

$$\Omega_{\mathrm{CBC}} = \Omega_{\mathrm{ref}}\left(\frac{f}{f_{\mathrm{ref}}}\right)^{2/3}, \text{ where } f_{\mathrm{ref}} = 25\mathrm{Hz}$$

We take two different approaches in constraining the SGWB due to FOPTs. Approximated broken power law (BPL)

- BPL
- CBC + BPL

Analytical theory-based models

- CBC + BC
- CBC + SW

Smooth broken power law

We simplify and model the phase transition contribution as a smooth BPL function,

$$\Omega_{\rm BPL}(f) = \Omega_* \left(\frac{f}{f_*}\right)^{n_1} \left[1 + \left(\frac{f}{f_*}\right)^{\Delta}\right]^{(n_2-n_1)/\Delta} .$$

Where we fix $n_1 = 3$ by causality, $\Delta = 2$, and depending on the source of the GWs, n_2 takes the values:

- $n_2 = -1 \rightarrow$ corresponding to assuming GW sourced by BC
- $n_2 = -4 \rightarrow$ corresponding to assuming GW sourced by SW

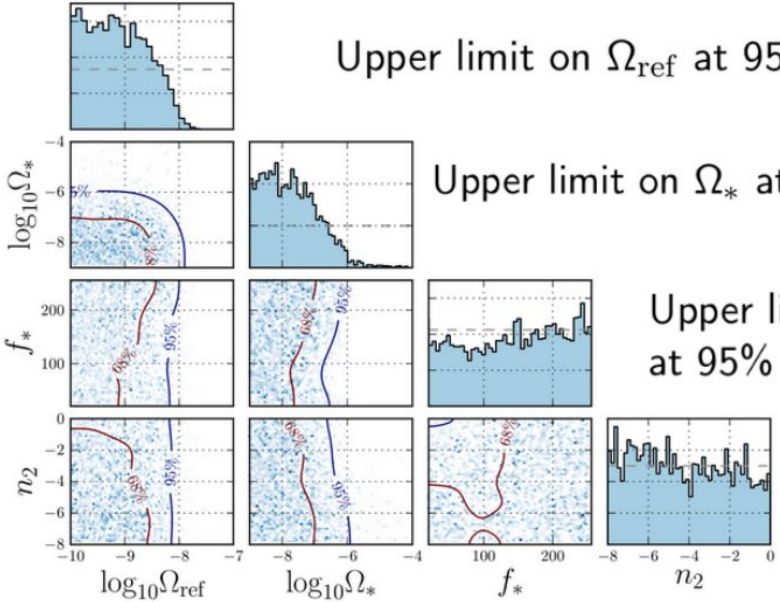
With this, we present results for $\Omega_{\rm BPL}$ considering as parameters: $\boldsymbol{\theta}_{\rm gw} = (\Omega_{\rm ref}, f_*, \Omega_*)$.

Priors and results from the CBC+BPL search

$$\Omega_{\mathrm{BPL}}(f) = \Omega_* \left(\frac{f}{f_*}\right)^{n_1} \left[1 + \left(\frac{f}{f_*}\right)^{\Delta}\right]^{(n_2-n_1)/\Delta}$$

Broken power law model	
Parameter	Prior
Ω_{ref}	LogUniform(10^{-10}, 10^{-7})
Ω_*	LogUniform(10^{-9}, 10^{-4})
f_*	Uniform(0, 256 Hz)
n_1	3
n_2	Uniform(-8,0)
Δ	2

The narrow, informative prior on Ω_{ref} stems from the estimate of the CBC background (arXiv:2111.03634). The peak frequency prior is uniform across the frequency range considered since we have no information about it.



Upper limit on Ω_{ref} at 95% C.L.: 6.1×10^{-9}

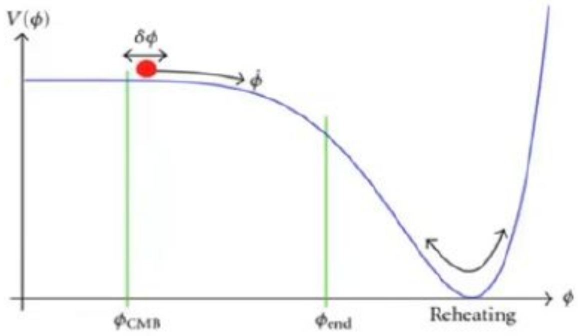
Upper limit on Ω_* at 95% C.L.: 5.6×10^{-7}

Upper limit on Ω_{BPL}(25Hz) at 95% C.L.: 4.4×10^{-9}

Posterior distributions for the parameters of this model. In all of these searches, the UL at 95% CL on Ω_{ref} is in agreement with the UL obtained in the O3 isotropic search.

PBHs formation

- PBHs were formed in the early radiation-dominated era.
- Source: highly over-dense region that would gravitationally collapse into a black hole, known as primordial (PBH). Said otherwise, PBHs are the product of the collapse of large density perturbations ($\delta \sim 0.01$, where δ denotes the density contrast of the patch).



- These density perturbations could have been formed during inflation (due to quantum fluctuations of ϕ).
- In the case of "slow roll" inflation, the production would be from ϕ_{CMB} to ϕ_{end}.
- The collapse takes place when the large fluctuations re-enter horizon.

Production of GWs

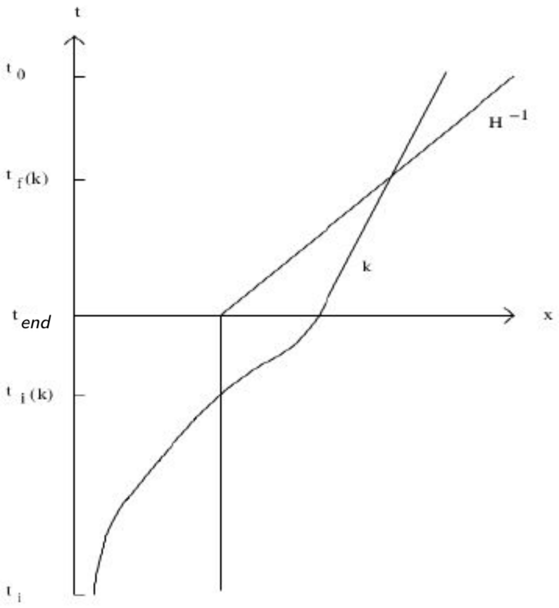


Figure 1: Scale re-entering the horizon

- Inflationary period $t \in [t_i, t_{end}]$.
- During inflation, the Hubble radius H^{-1} is constant in spatial coordinates, whereas it increases linearly in time after t_{end}.
- The physical length corresponding to a fixed comoving length scale (k) increases exponentially during inflation but increases less fast than the Hubble radius after t_{end}.
- This leads k to re-enter the horizon, which is when GWs are generated (at the same epoch as the PBH formation).

UL at 95% CL on A

We run 12 more searches where we set delta priors over k_* and Δ to obtain upper limits at 95 % CL on the integrated power A of the peak in the curvature power spectrum:

	$k_* = 10^{15}\ \mathrm{Mpc}^{-1}$	$k_* = 10^{17}\ \mathrm{Mpc}^{-1}$	$k_* = 10^{19}\ \mathrm{Mpc}^{-1}$
$\Delta = 0.05$	2.1	0.02	1.4
$\Delta = 0.2$	2.2	0.03	1.6
$\Delta = 1$	1.6	0.05	1.8
$\Delta = 5$	0.2	0.2	0.3

In all of these searches, the UL at 95% CL on Ω_{ref} is between 5.5e-9 to 6.6e-9, which is in agreement with the UL obtained in the O3 isotropic search.