# A Stochastic Gravitational Wave Background Coming from a Double Peak Domain Wall Model

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# Outline

- Introduction to Stochastic Gravitational Waves Backgrounds
- Motivation for the Domain Walls Search
- Parametrization
- Search Results
- Discussion

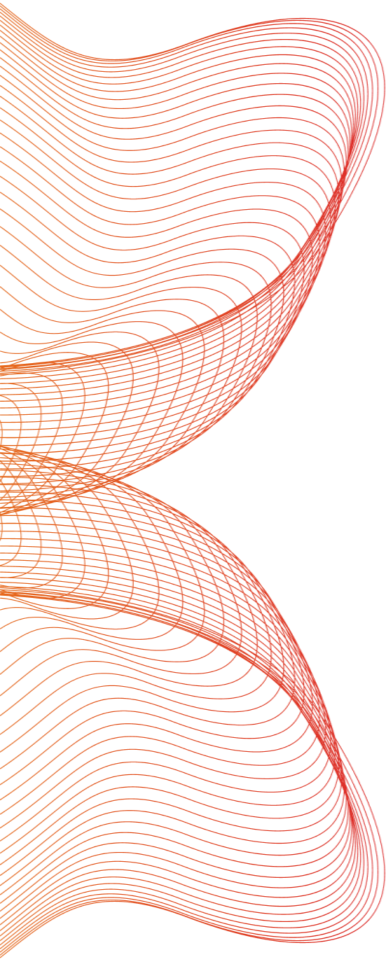
# Introduction to Stochastic Gravitational Wave Backgrounds

A stochastic gravitational wave background (SGWB) is a superposition of gravitational waves with a broad range of frequencies and amplitudes.

It appears as a seemingly random or "stochastic" pattern.

SGWBs can have astrophysical or cosmological sources.

# Sources of Stochastic Gravitational Wave Backgrounds



**01** Cosmological sources: inflation, phase transitions, cosmic strings, topological defects in the early universe;

**02** Astrophysical sources: superposition of independent, unresolved compact binary coalescence signals (CBCs).

# Observations and Detection

Image from www.virgo-gw.eu

- ☐ The Pulsar Timing Array project (Agazie, G. et al. 2023) has observed SGWB in the nanohertz frequency range;

- ☐ **No detection** has been achieved so far with groundbased interferometers (LIGO, VIRGO, KAGRA), but constraints can be placed on various models using the gathered data.

Image from www.ligo.org

# Motivation for the Domain Walls Search

Cosmic domain walls (DW) are two-dimensional topological defects predicted by theories beyond the standard model.

They arise from the spontaneous breaking of a discrete symmetry in the early universe.

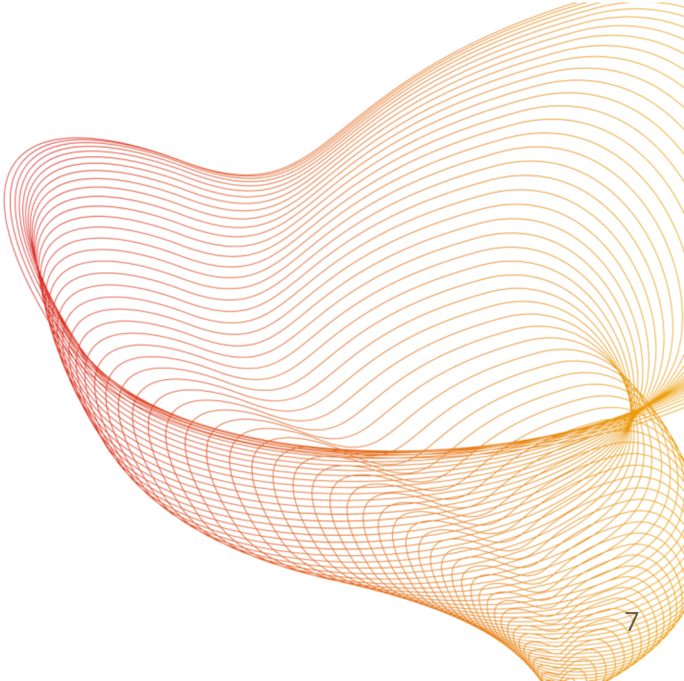
After formation, their energy density would soon dominate the total energy density of the universe, which contradicts current observations. Thus, an annihilation mechanism for domain walls is needed.

# Oscillons and Gravitational Waves

- Hindmarsh, M. and Salmi, P. 2008, Vaquero, A. et al. 2019, Kitajima, N. et al. 2022 argue that the collapse of domain walls could give rise to long-lived, non-perturbative oscillating energy concentrations – oscillons.

- Both the DW network annihilation and the resulting oscillons radiate gravitational waves, and a stochastic gravitational wave background power spectrum can be derived.

- While the DW GW spectrum has been modelled and searched for before in the O1+O2+O3 LVK data (Jiang, Y. and Huang, Q.-G. 2022), we now add a second feature due to the presence of oscillons.



# Parametrization of the SGWB Power Spectrum

The total SGWB is the sum of the compact binary coalescence signals (CBCs), the domain wall contribution (DW) and the oscillon feature, which we will call the second peak (SP):

$$\Omega(\mathrm{f}) = \Omega_{CBC} + \Omega_{DW} + \Omega_{SP}$$

We will use the parametrization from Ferreira, R. Z. et al. 2023 to describe both the peak corresponding to DW annihilation and the second peak, while the CBC will take the usual power law form.

$$\Omega(\mathrm{f}) = \Omega_{ref}\left(\frac{f}{f_{ref}}\right)^{\alpha} + \Omega_{*1}S_1\left(\frac{f}{f_{*1}}\right) + \Omega_{*2}S_2\left(\frac{f}{f_{*2}}\right)$$

$$S_{1,2}\left(\frac{f}{f_{*1,2}}\right) = \frac{(\gamma_{1,2}+\beta_{1,2})^{\delta_{1,2}}}{\left(\beta_{1,2}\left(\frac{f}{f_{*1,2}}\right)^{\frac{-\gamma_{1,2}}{\delta_{1,2}}} + \gamma_{1,2}\left(\frac{f}{f_{*1,2}}\right)^{\frac{\beta_{1,2}}{\delta_{1,2}}}\right)^{\delta_{1,2}}}$$

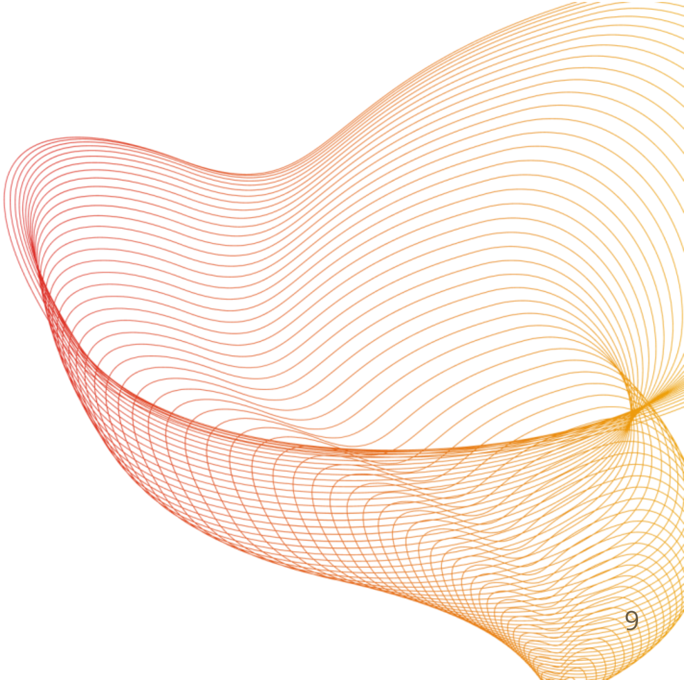
Here, $\gamma$ describes the behaviour of the function at low frequencies, while $\beta$ describes the behaviour at high frequencies, and $\delta$ is the width around the maximum.

# Power Spectrum Modelling

- Some parameters can be fixed due to physical constraints ( $\gamma_1 = 3$ due to causality), while others have been determined from numerical simulations for a single peak DW model ($\beta_1$ = 1, $\delta_1$=1).

- While the addition of the second peak changes the values of $\beta_1$ and $\delta_1$, we keep the same spectral slope for high frequencies ($\beta_2 = 1$). The CBC background uses the usual values for $\alpha = {}^2/_3$ and $f_{ref} = 25Hz$.

- We are left with 9 free parameters for which we need to select priors for our Bayesian analysis in the O1+O2+O3 LVK data using the *Bilby* library (Aston, G. et al. 2018).



# Power Spectrum Modelling

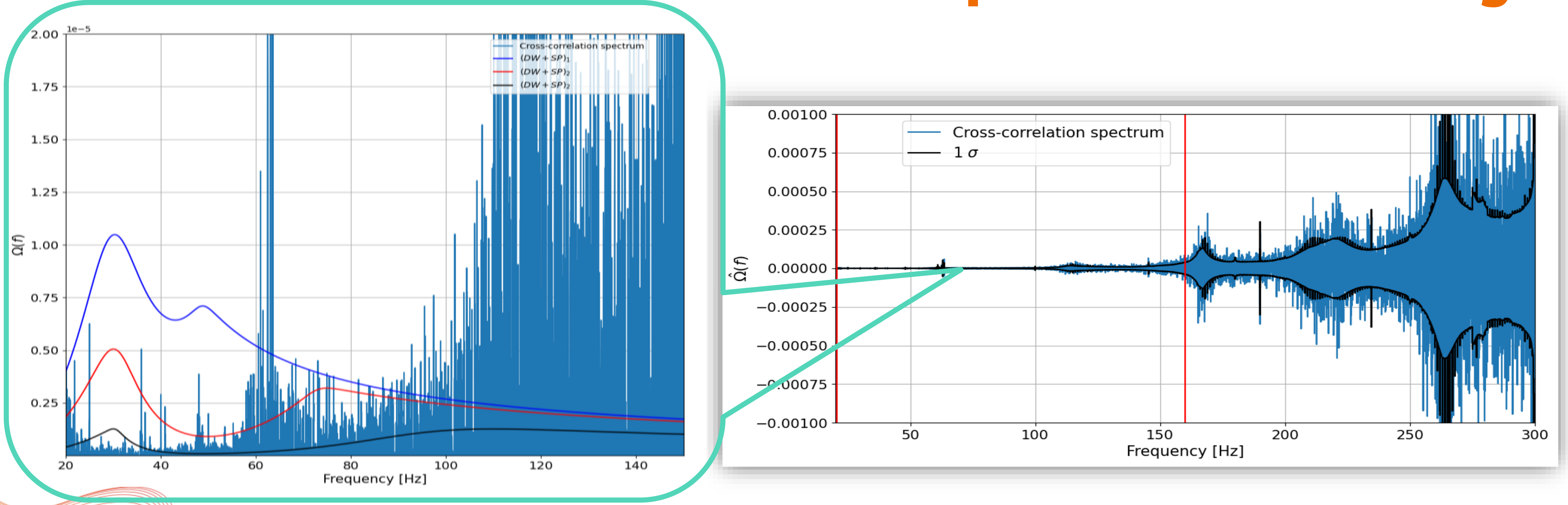


**Fig. 1.** (**Right plot**) Cross-correlation spectrum from O1+O2+O3 observing runs. As the signal is expected to be extremely fain, focusing on the highest detector sensitivity region could be useful: 20-160Hz (between the vertical red lines).
(**Left plot**) Examples of the shape of the parametrized SGWB power spectrum, for three different parameter combinations. The amplitudes are highly exaggerated.

# Search Results

**Priors for wide search (Fig. 2)**

| Param. | Prior type | Prior Range | Comments |
|---|---|---|---|
| $\Omega_{ref}$ | LogUniform | $(10^{-10}, 10^{-6})$ | |
| $\Omega_{*1}$ | LogUniform | $(10^{-10}, 10^{-6})$ | |
| $f_{*1}$ | Uniform | (20Hz, 200Hz) | |
| $\Omega_{*2}$ | LogUniform | $(10^{-10}, 10^{-6})$ | $< \Omega_{*1}$ |
| $f_{*2}$ | Uniform | (20Hz, 200Hz) | $> f_{*1} + 20Hz$ to distinguish the peaks |
| $\beta_1$ | Uniform | (1, 9) | |
| $\gamma_2$ | Uniform | (1, 9) | |
| $\delta_1$ | Uniform | (0.1, 1) | Low $\delta$ -> sharp peak |
| $\delta_2$ | Uniform | (0.1, 1) | Low $\delta$ -> sharp peak |

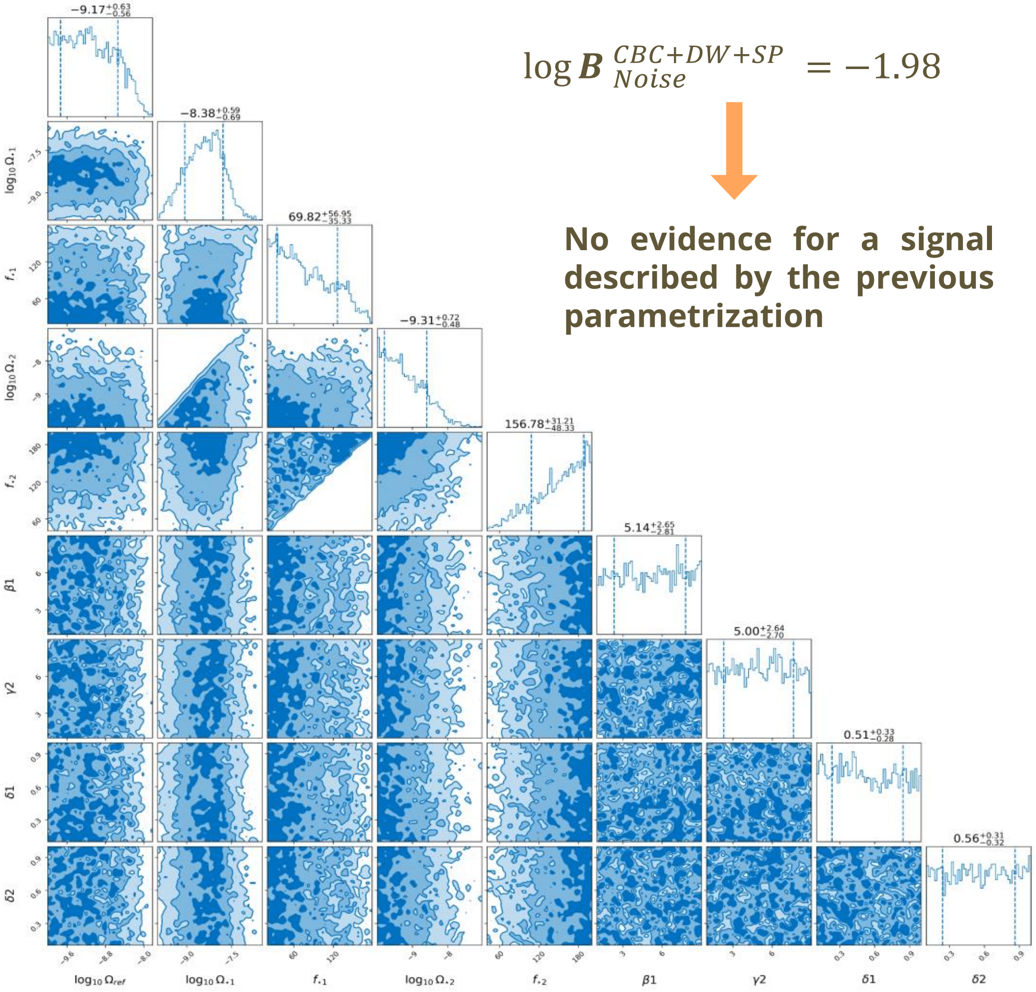


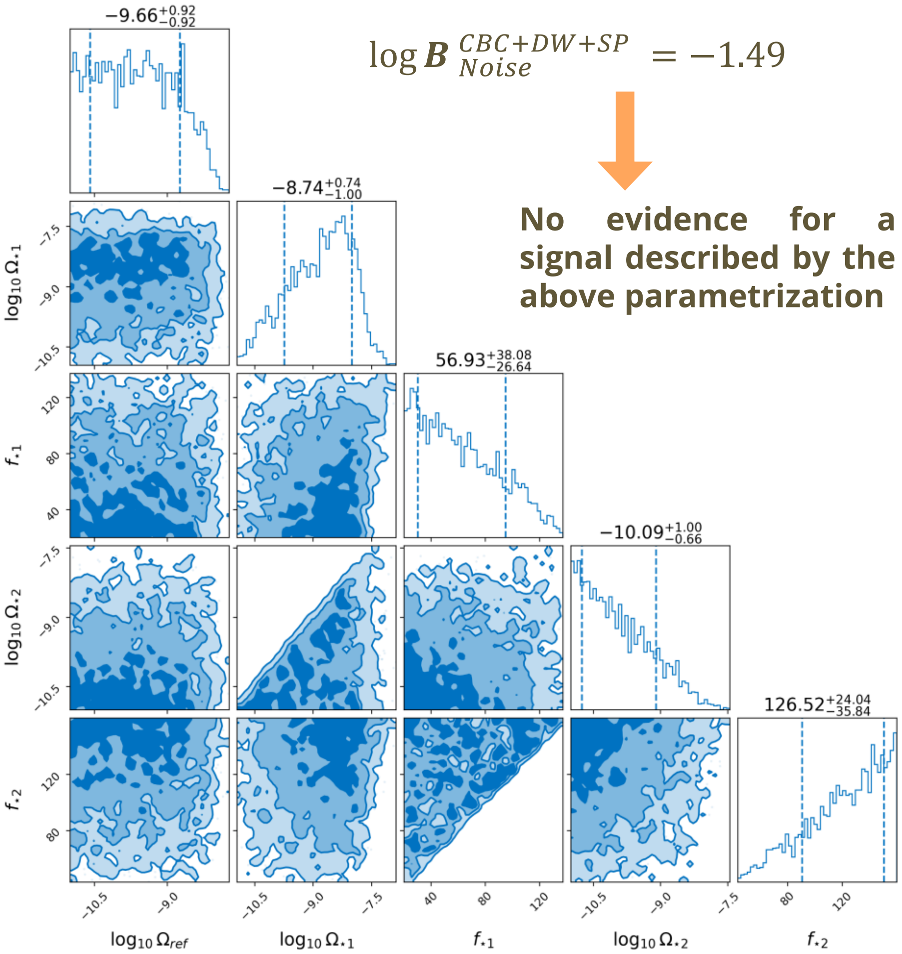
**Fig. 2**. Posterior distributions of the parameters for the Bayesian search in O1+O2+O3 data using the priors described in the table above. For the exponents, we obtain flat posteriors, indicating no preference for any particular value. Thus, in the following search (Fig. 3) we fix values for these parameters. For the amplitudes, we obtain the following upper limits, with a 95% confidence level: $\boldsymbol{\Omega_{ref} = 5.5 \times 10^{-9}}$, $\boldsymbol{\Omega_{*1} = 3.5 \times 10^{-8}}$, $\boldsymbol{\Omega_{*2} = 6.6 \times 10^{-9}}$.

$$\log \boldsymbol{B}\,^{CBC+DW+SP}_{Noise} = -1.98$$

↓

**No evidence for a signal described by the previous parametrization**

# Search Results



$$\log B^{\,CBC+DW+SP}_{\,Noise} = -1.49$$

↓

**No evidence for a signal described by the above parametrization**

**Fig. 3.** Posterior distributions resulting from the Bayesian search using the priors described in the table below. For the amplitudes, we obtain the following upper limits, with a 95% confidence level: $\boldsymbol{\Omega_{ref} = 4.85 \times 10^{-9}}$, $\boldsymbol{\Omega_{*1} = 2 \times 10^{-8}}$, $\boldsymbol{\Omega_{*2} = 2.3 \times 10^{-9}}$.

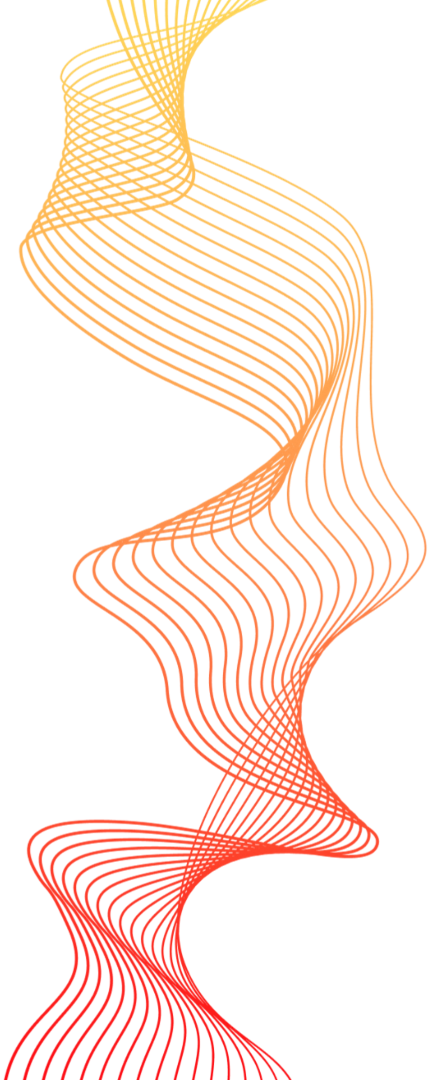
**Priors for benchmark search (Fig. 3)**

| Param. | Prior type | Prior Range | Const. Values |
|---|---|---|---|
| $\Omega_{ref}$ | LogUniform | $(10^{-11}, 10^{-6})$ | $\beta_1 = 1$ |
| $\Omega_{*1}$ | LogUniform | $(10^{-11}, 10^{-6})$ | $\gamma_2 = 3$ |
| $f_{*1}$ | Uniform | (20Hz, 160Hz) | $\delta_1 = 0.1$ |
| $\Omega_{*2}$ | LogUniform | $(10^{-11}, 10^{-6})$ | $\delta_2 = 0.1$ |
| $f_{*2}$ | Uniform | (20Hz, 160Hz) | |

# Future work

- A phenomenological parametrization of the two peaks will be executed, with the first peak of the SGWB power spectrum depending on parameters such as **annihilation temperature** of the domain walls $\boldsymbol{T_*}$, the number of **relativistic degrees of freedom** $\boldsymbol{g_*}$, the domain wall **surface energy density σ**, while the exact phenomenological parametrization of the second peak is still under development.

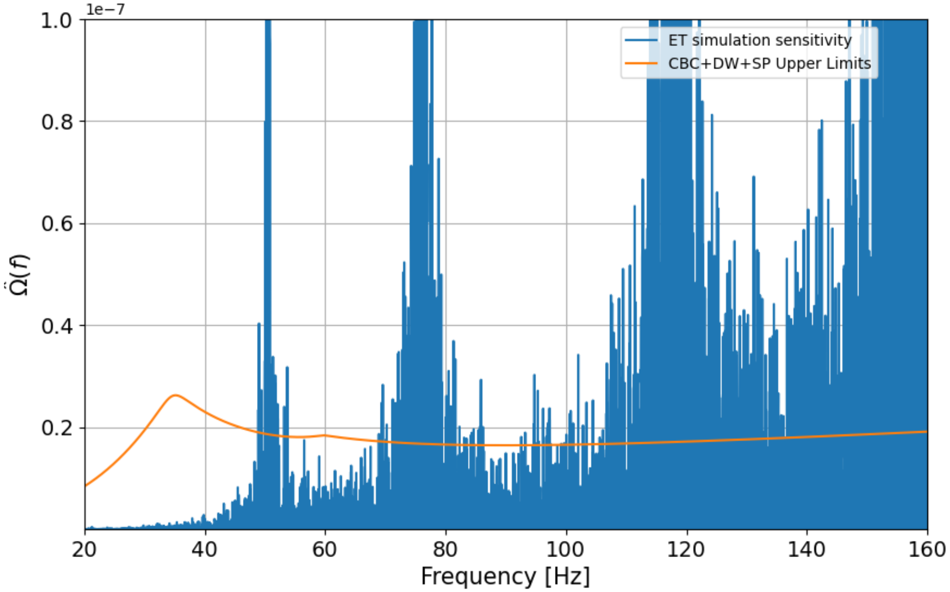
- While the analysis performed was motivated by the expected behaviour of oscillons, other combinations of cosmological phenomena could give rise to a double-peaked SGWB power spectrum. The agnostic parametrization used here could be relevant in those situations.



# Future work

- ☐ With the construction of 3rd generation GW detectors such as the Einstein Telescope (ET) in Europe and Cosmic Explorer in the US, an increased sensitivity is expected and the detection of a SGWB will hopefully be achieved (Fig. 4).

**Fig. 4.** As an example, the SGWB power spectrum has been plotted (orange) using the upper limits from Fig. 3 on top of the simulated cross-correlation spectrum expected for ET (blue). $f_{*1}$ was chosen to be 35Hz, and $f_{*2}$ was chosen to be 60Hz. If the physical values are close to the upper limits, we expect a detection. If no detection will be achieved, stronger constraints will be placed on the parameters of the model.



# Thank you for your time!
# Questions?