A Search for Multi-Peak Structures in the Stochastic Gravitational Wave Background Using LIGO-Virgo-KAGRA O1–O3 Data

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Outline

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Stochastic Gravitational Wave Background

- Superposition of signals from many unresolved gravitational-wave sources
- Persistent, random signal across the sky
- Characterized by its energy density per logarithmic frequency interval, and compared to the critical energy density of the Universe ρ_c

$$\Omega_{GW}(f) = \frac{1}{\rho_c} \frac{d\rho_{GW}(f)}{d\ln(f)}$$

- Origin: **Astrophysical** (BBHs, BNSs) or **Cosmological** (Inflation, Cosmic Strings, Domain Walls, Phase Transitions)

LIGO-Virgo-KAGRA (LVK) Data Searches

- We build a **Cross-correlation estimator** $\widehat{\boldsymbol{C}_{ij}}(\boldsymbol{f};\boldsymbol{t})$ between Fourier transforms of the time-series outputs of the detectors $\tilde{s}_i(f;t)$

$$\widehat{C_{ij}}(f;t) = \frac{2}{T}\frac{Re[\tilde{s}_i^*(f;t)\tilde{s}_j(f;t)]}{\Gamma_{ij}(f)S_0(f)}$$

- In absence of correlated noise, $\langle\widehat{C_{ij}}(f)\rangle$ is an estimator for $\Omega_{GW}(f)$ - point estimate spectrum [1]
- Magnetic noise could be a source of correlated noise through Schumann resonances [2]

Bayesian Statistics

- We build the likelihood:

Model of SGWB

$$p\left(\hat{C}_k^{IJ} \mid \Theta\right) \propto \exp\left[-\frac{1}{2}\sum_{I<J}\sum_k\left(\frac{\hat{C}_k^{IJ} - \Omega_M(f_k \mid \Theta)}{\sigma_{IJ}(f_k)}\right)^2\right]$$

- We use **BILBY** [3] to perform a statistical analysis, starting with priors for the parameters Θ and computing their posterior distributions
- We calculate Bayes factors to compare two competing models and determine which one is better supported by the data

Double-Peak Search – Motivation

- Most standard SGWB searches assume power-law or single-peaked spectra — insufficient for capturing richer early-universe dynamics
  - CBCs [4]:

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

  - Cosmic strings [5]:

$$\Omega_{GW}(f) = \Omega_{ref}$$

  - Phase transitions [6]:

$$\Omega_{GW}(f) = \Omega_{*1}\left(\frac{f}{f_{*1}}\right)^{n_1}\left[\frac{1}{2}\left(1+\left(\frac{f}{f_{*1}}\right)^{\Delta_1}\right)\right]^{\frac{(n_2-n_1)}{\Delta_1}}$$

Double-Peak Search – Motivation

Many early-universe models predict **multi-peaked** GW spectra due to:

- Multistep first-order phase transitions [7]
- Sequential symmetry breaking [8]
- Oscillons and spectator fields [9]

Double-Peak Search: Parametrization

$$\Omega_{GW}(f) = \Omega_{CBC}(f) + \Omega_{Cosmo}(f)$$

$$\Omega_{GW}(f) = \Omega_{ref}\left(\frac{f}{f_{ref}}\right)^{\alpha} + \Omega_{*1}\left(\frac{f}{f_{*1}}\right)^{n_1}\left[\frac{1}{2}\left(1 + \left(\frac{f}{f_{*1}}\right)^{\Delta_1}\right)\right]^{\frac{(n_2 - n_1)}{\Delta_1}}$$

$$+P \times \Omega_{*1}\left(\frac{f}{f_{*1} + \Delta f}\right)^{n_3}\left[\frac{1}{2}\left(1 + \left(\frac{f}{f_{*1} + \Delta f}\right)^{\Delta_2}\right)\right]^{\frac{(n_4 - n_3)}{\Delta_2}}$$

13 free parameters

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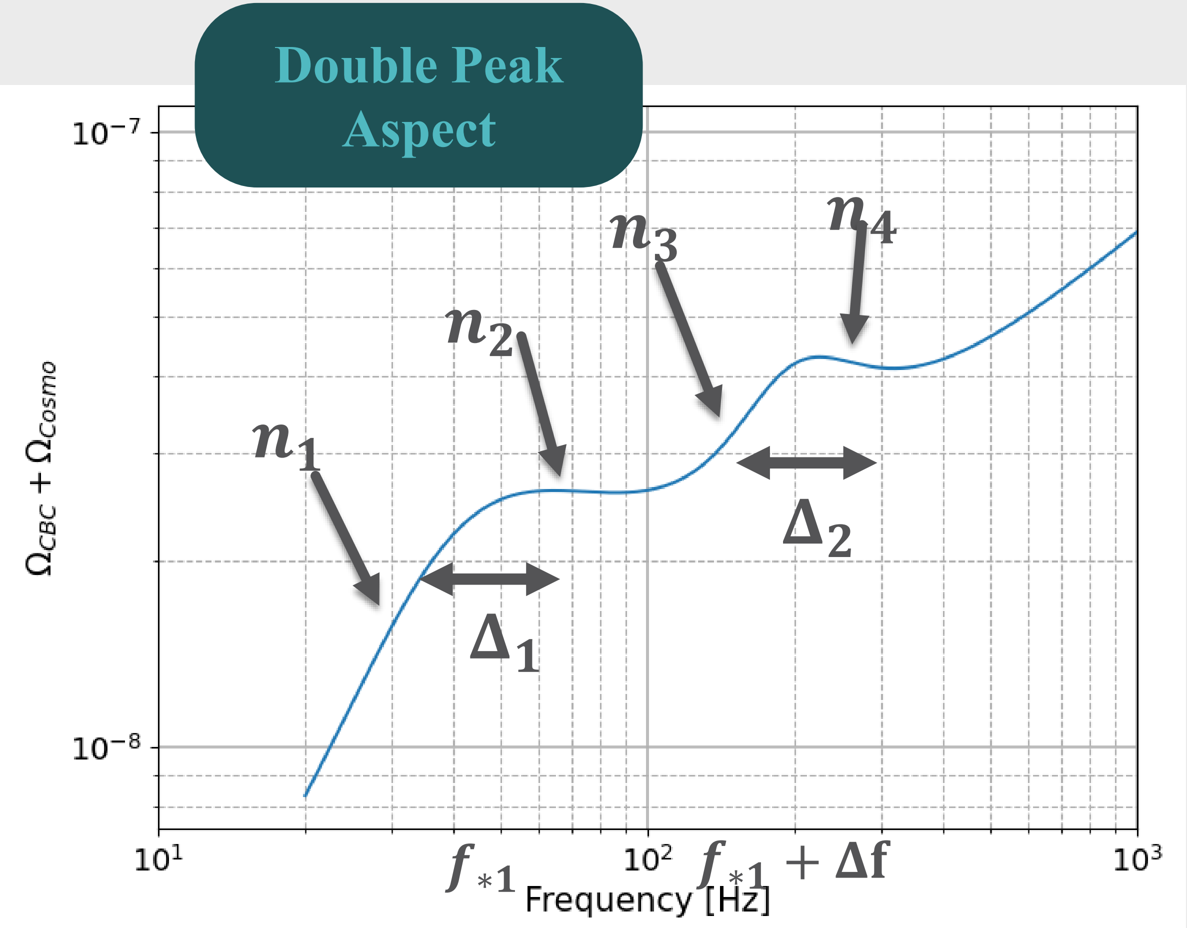
Double-Peak Search: Parametrization



Double-Peak Search: Analysis

Set parameters:

- $\alpha = \frac{2}{3}$
- $f_{ref} = 25Hz$
- $n_1 = 3\ (causality)$

Two different approaches:

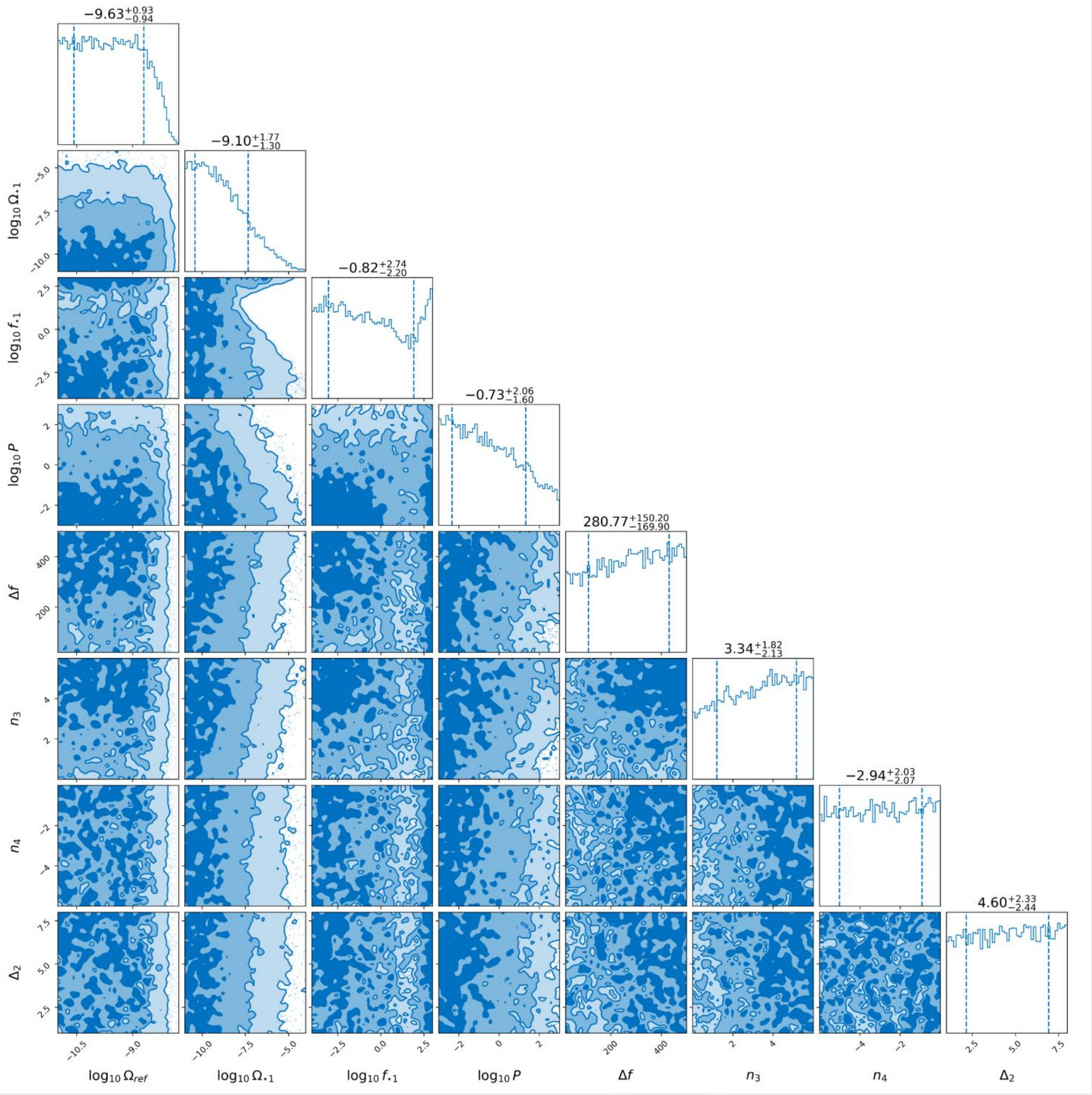
I. First peak fixed, second peak varies

2. First and forth slopes fixed, the valley between the peaks varies

Analysis 1: First Peak Fixed

- $n_2 = -1$
- $\Delta_1 = 4$

Param.	Prior type	Prior range
Ω_{ref}	LogUniform	$(10^{-11}, 10^{-4})$
Ω_{1*}	LogUniform	$(10^{-11}, 10^{-4})$
f_{1*}	LogUniform	$(10^{-4}Hz, 10^{3}Hz)$
P	LogUniform	$(10^{-3}, 10^{3})$
Δf	LogUniform	$(20Hz, 500Hz)$
n_3	Uniform	$(0, 6)$
n_4	Uniform	$(-6, 0)$
Δ_2	Uniform	$(1, 8)$



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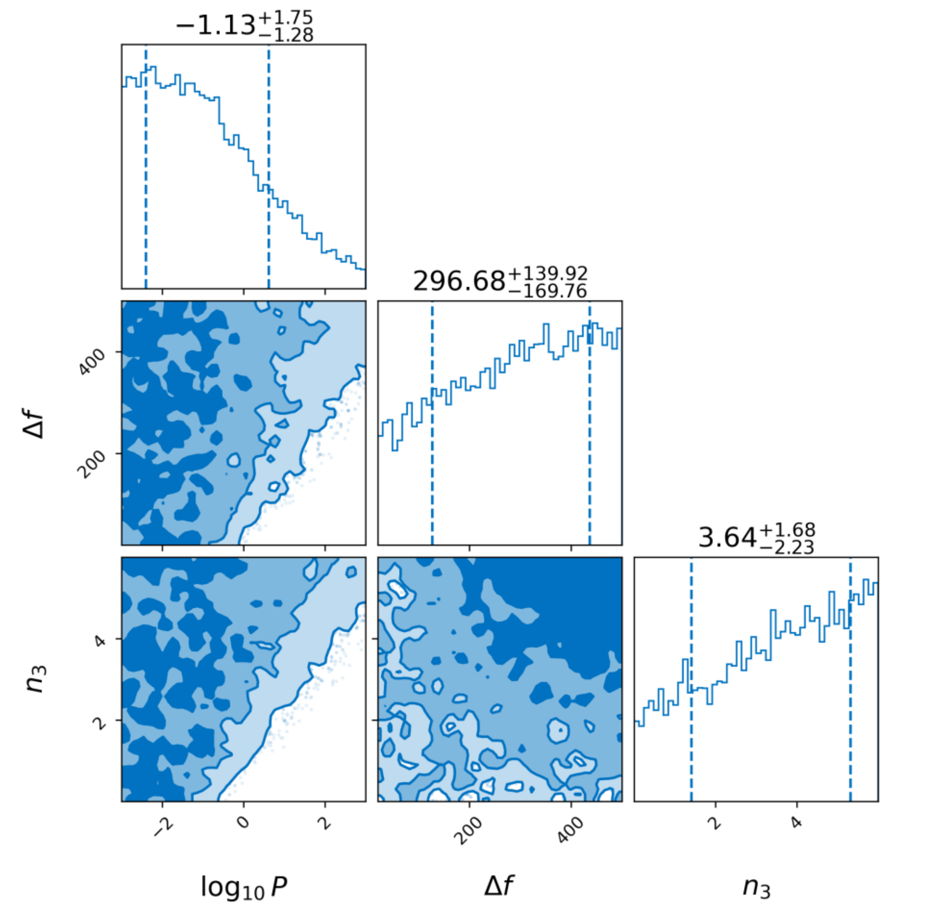
Analysis 1: First Peak Fixed - Results

Additional constraints:

- $n_4 = -3$
- $\Delta_2 = 4$
- $\Omega_{ref} = 10^{-8.3}$
- $\Omega_{*1} = 10^{-7.85}$
- $f_{*1} = 40$ Hz

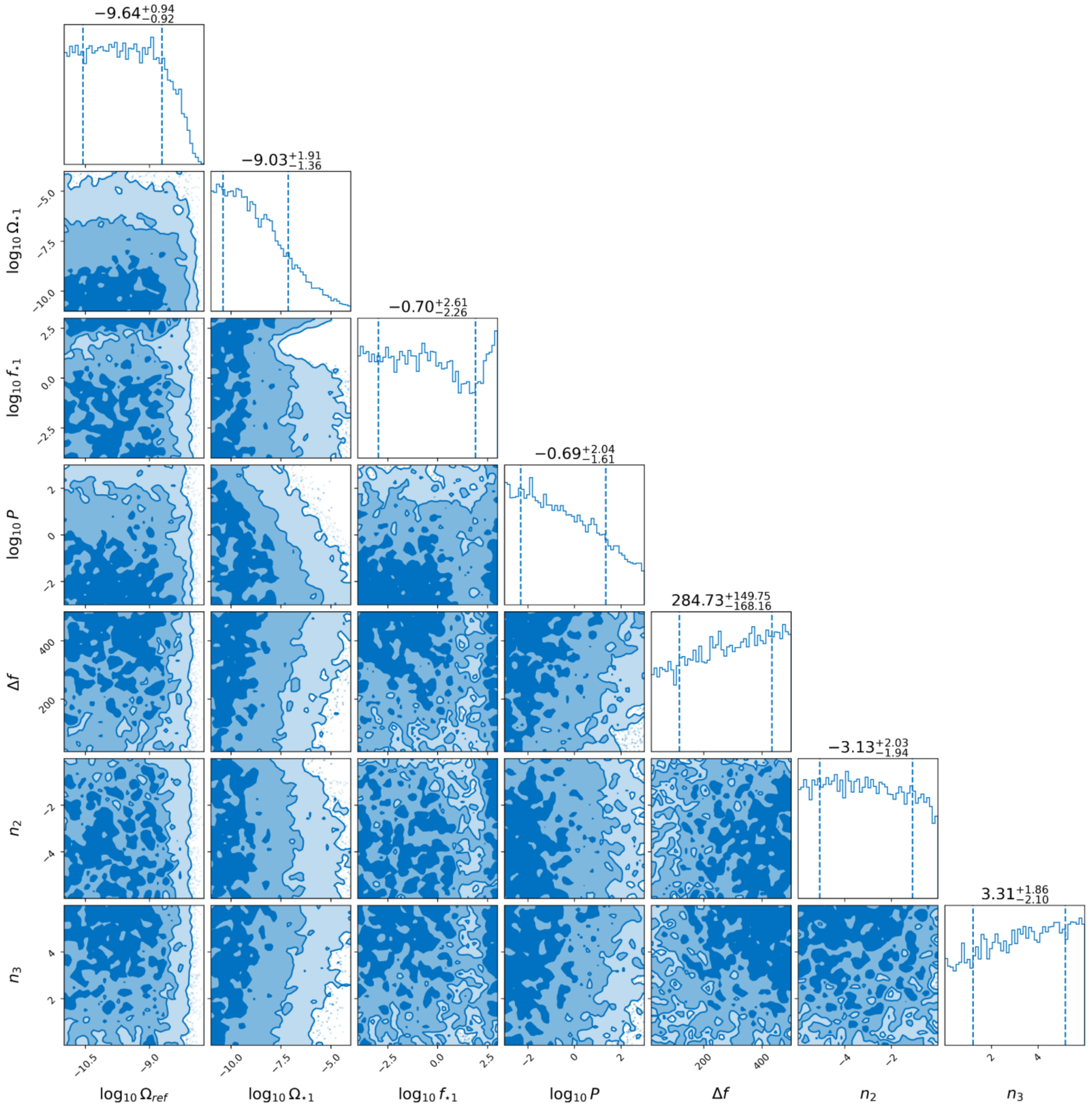
$$\log B^{CBC+Cosmo}_{Noise} = -3.52$$



Analysis 2: The Valley Between The Peaks Varies

- $\Delta_1 = 4$
- $n_4 = -1$
- $\Delta_2 = 4$

Param.	Prior type	Prior range
Ω_{ref}	LogUniform	$(10^{-11}, 10^{-4})$
Ω_{1*}	LogUniform	$(10^{-11}, 10^{-4})$
f_{1*}	LogUniform	$(10^{-4}Hz, 10^{3}Hz)$
P	LogUniform	$(10^{-3}, 10^{3})$
Δf	LogUniform	$(20Hz, 500Hz)$
n_2	Uniform	$(-6, 0)$
n_3	Uniform	$(0, 6)$



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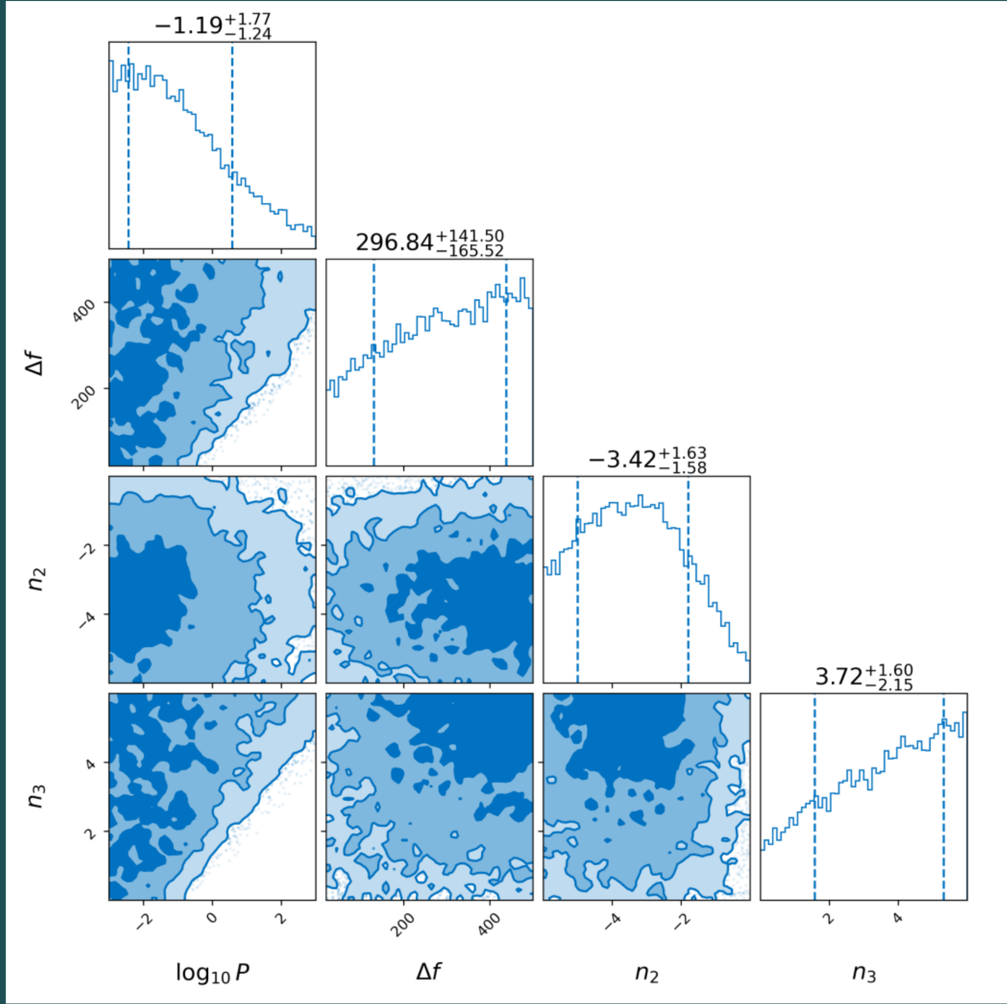
Analysis 2: The Valley Between The Peaks Varies - Results

Additional constraints:

- $\Omega_{ref} = 10^{-8.3}$
- $\Omega_{*1} = 10^{-7.85}$
- $f_{*1} = 40$ Hz

$$\log B^{CBC+Cosmo}_{Noise} = -6.99$$



Conclusion

- Double-Peak Search:
  - Negative Bayes factors – no detection
  - Some exclusion zones – could be linked to limits on physical parameters
- Future work:
  - Correspondence between the mathematical description and phenomenological models

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Thank you for your time!
Questions?