Detecting Non-Power Law Stochastic Gravitational Wave Background

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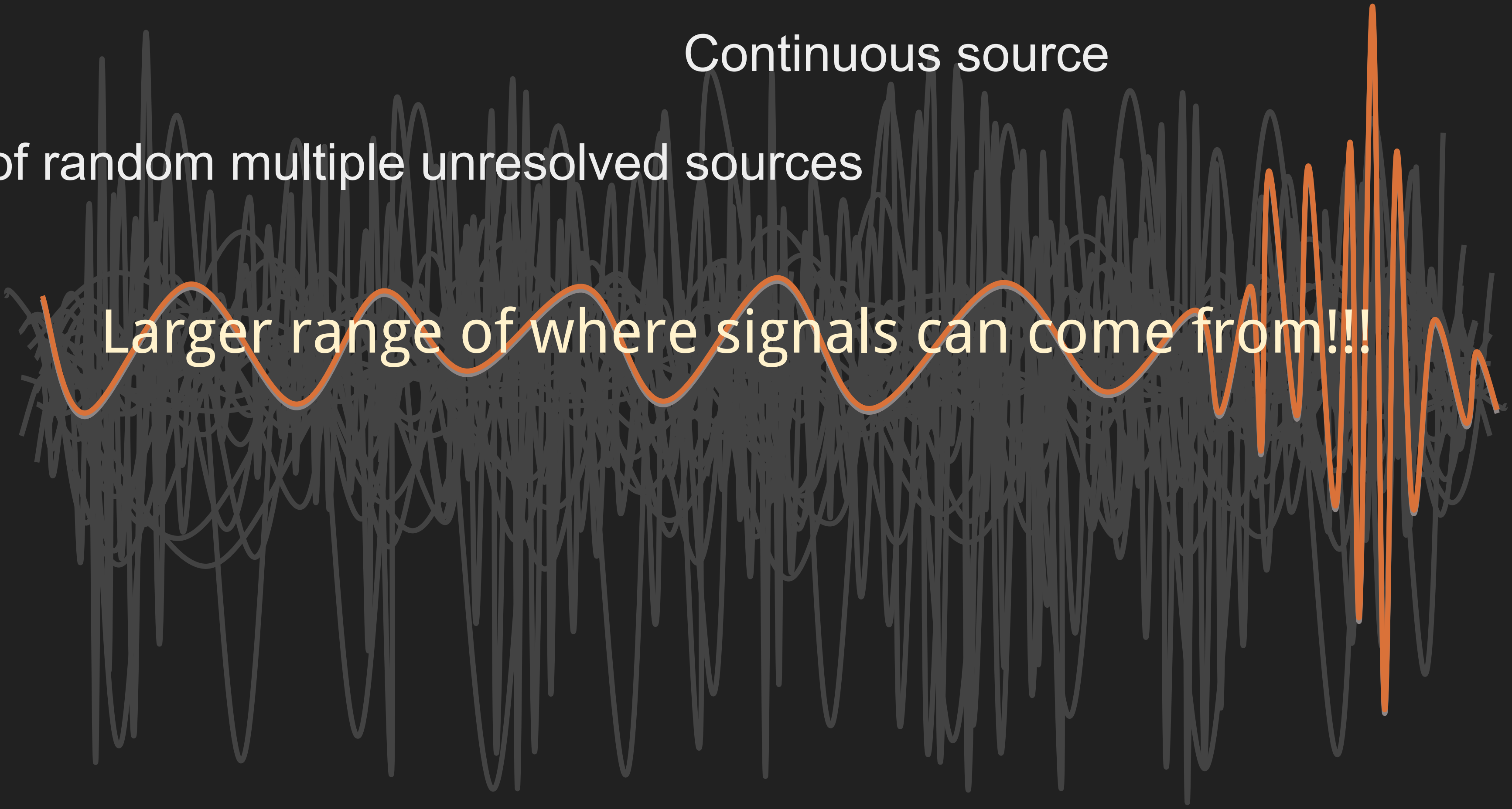
Outline

- What is the Stochastic Gravitational Wave Background SGWB
- Motivations for Project
- Project details
- Summer work
- Results

What is the SGWB?

Continuous source

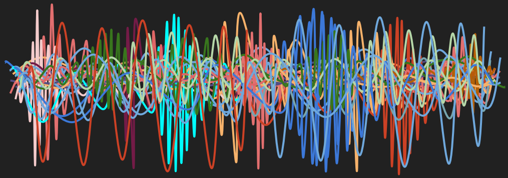
of random multiple unresolved sources



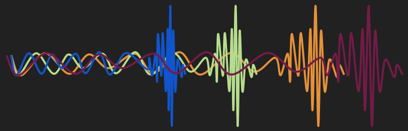
Larger range of where signals can come from!!!

What types of Signals can be in the SGWB

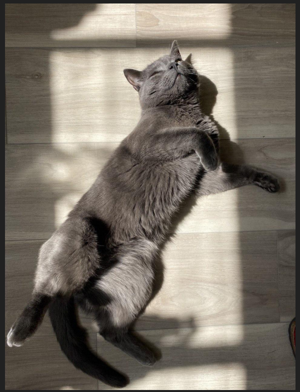
- Remnants of the early universe



- Compact Binary Coalescence CBCs



- Astrophysical sources (low redshift)
- Cosmological sources (high redshift)



⋆COSMO⋆

The current state of SWGB research

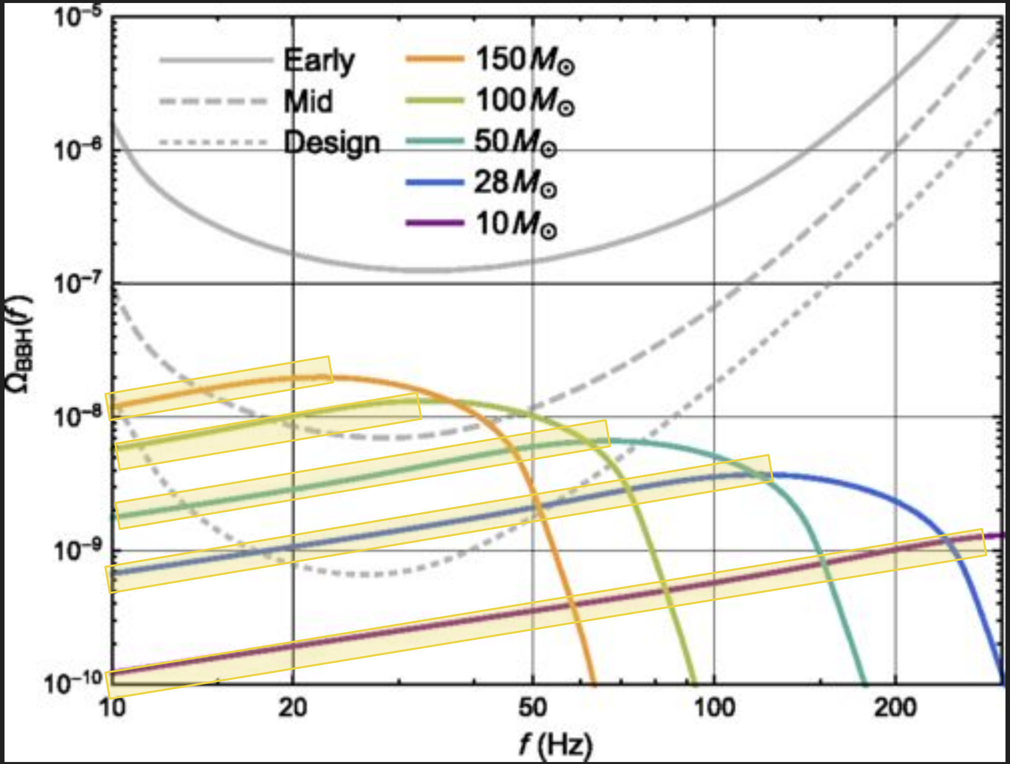


Figure reproduced from [2]. We show the binary black hole's background with various chirp masses with the Fiducial model for SGWB (colored lines). Power-law integrated curves for one year with Advanced LIGO (grey lines).

Current sensitivity works well to define the SGWB with power-law models.

$$\Omega_{GW}(f) = \Omega_{GW}(f_{ref})(f / f_{ref})^{\alpha}$$

$\Omega_{GW}(f)$ = GW energy density

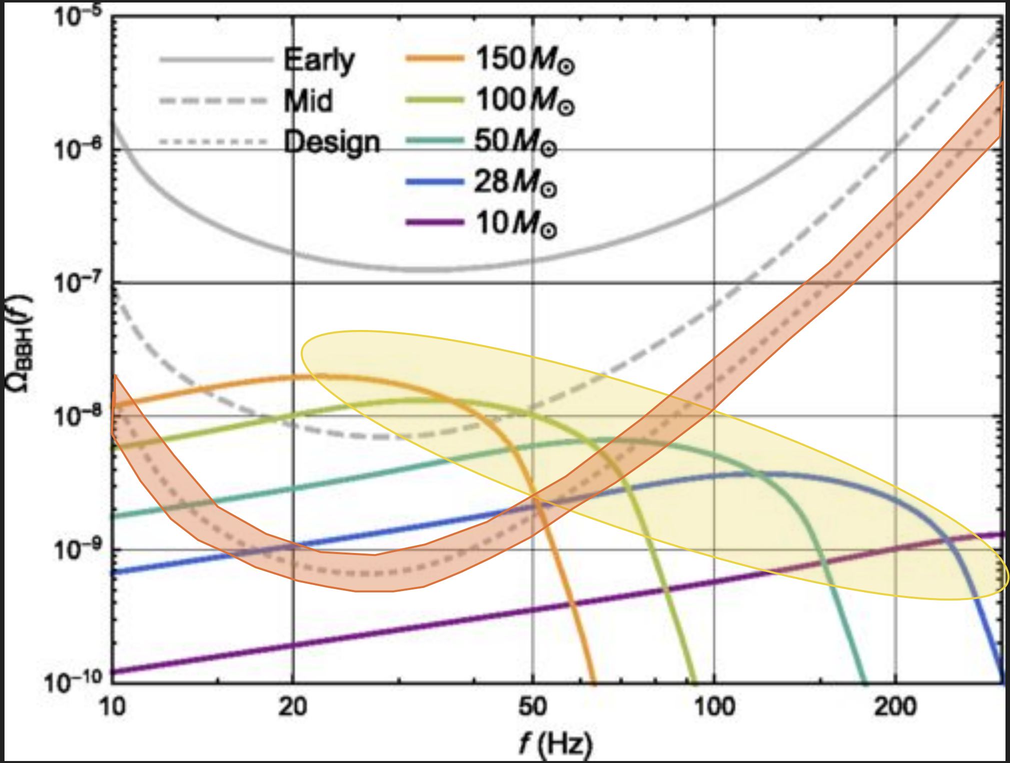
$1/\rho_c * d\rho_{GW}(f)/d \ln f$

F_{ref} = reference frequency

α = spectral index of the signal

⅔ in our case

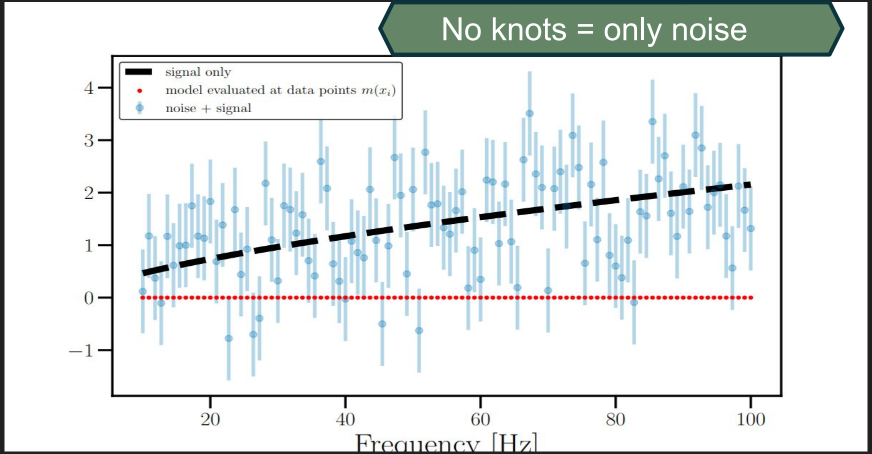
What we want to do….

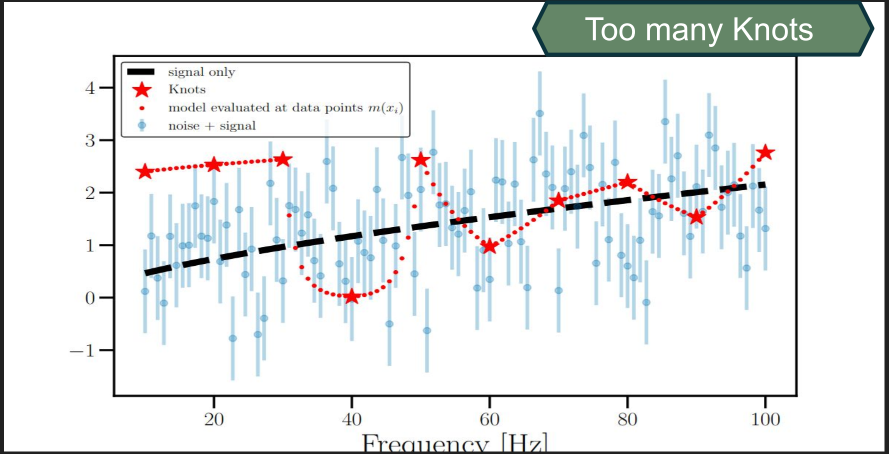


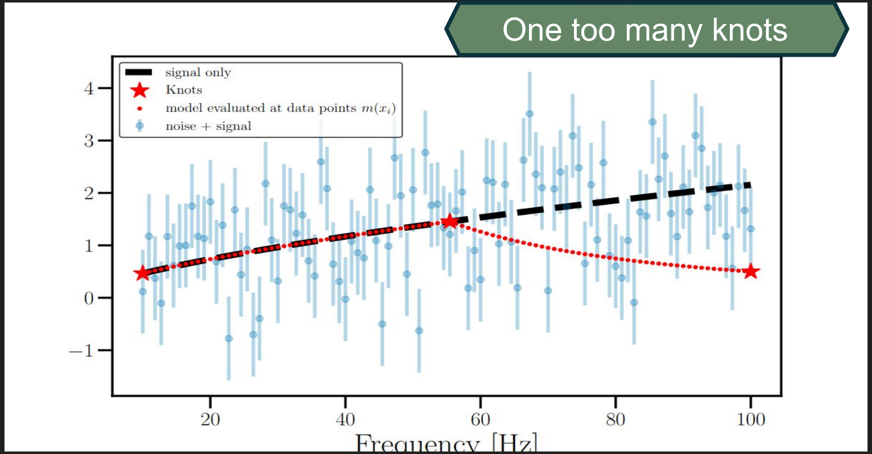
Current sensitivity works well to define the SGWB with power-law models.

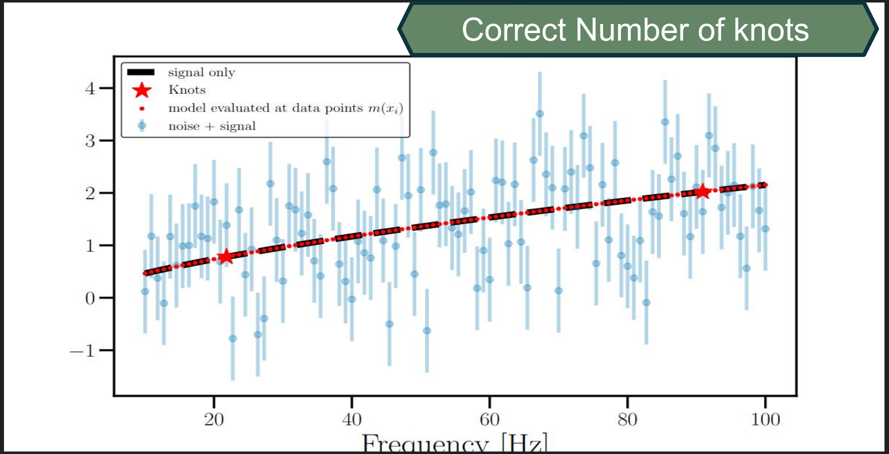
As sensitivity increases the predicted smooth turnover will be detected and will need a new model to describe it.

Proposed method : interpolation with varying # of knots

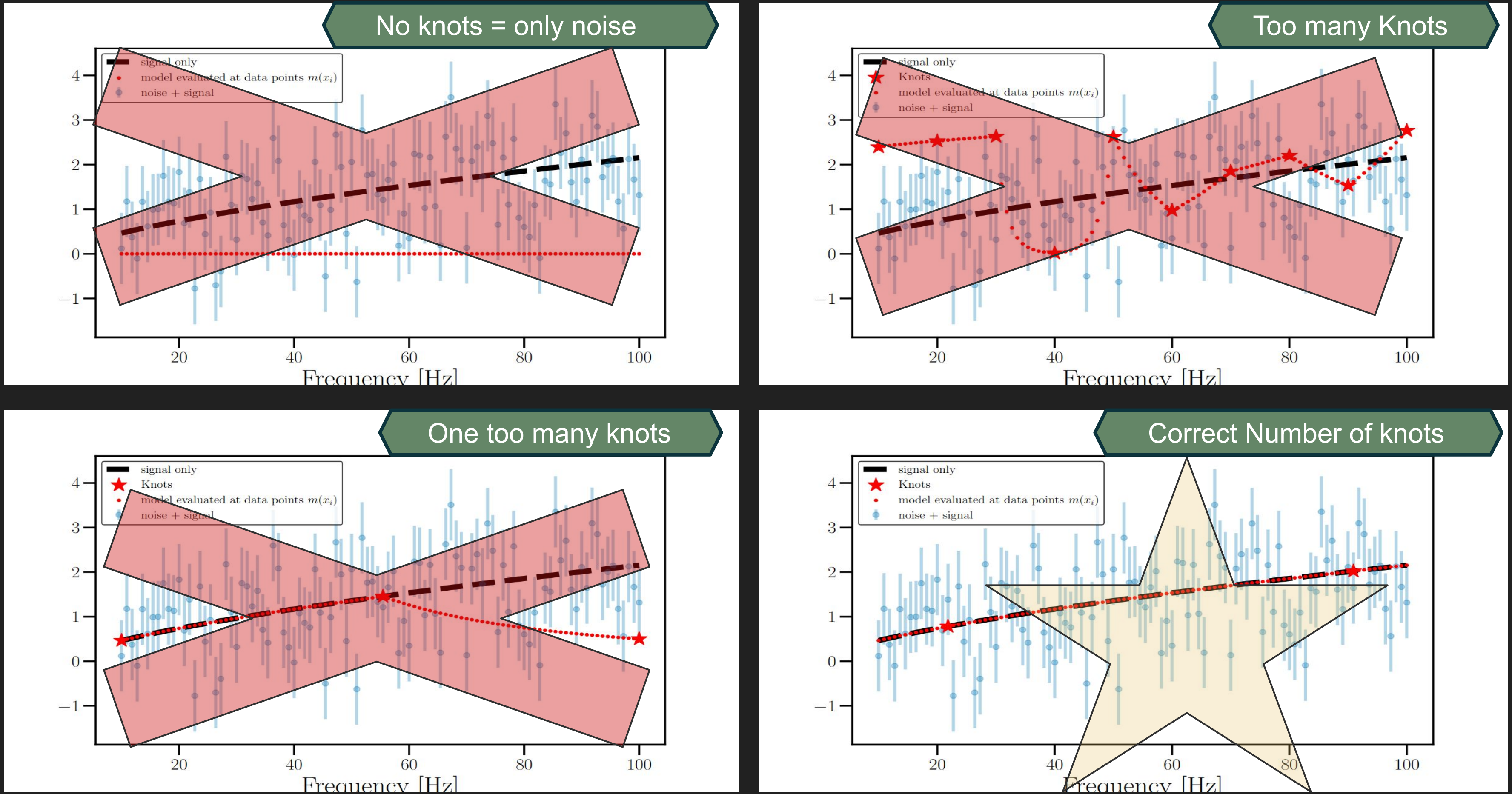








Proposed method : interpolation with varying # of knots



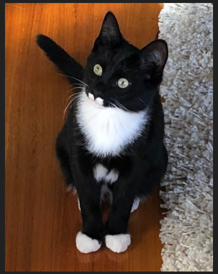
What we want to do…

A GENERAL & GENERIC MODEL = Describe all non-power laws

Interpolation Model

Westley:

- Generic fitting of injected signals with certain frequencies (or Knots)
- Gives the parameters to run an rjmcmc
  - Iterations, proposals



⋆WESTLEY⋆

Reverse Jump Markov Chain Monte Carlo (RJMCMC)

- Proposes knots deaths, births, and moves
- Allows to the number of knots to vary »»» number of parameters vary

pygwb + pygwb_pipe
(Hybrid analysis) : Frequentist & Bayesian statistics

bilby
Bayesian statistics

Our Statistics method

- Current models use Signal to Noise ratio (SNR) and Bayes Factor(BF)
  - Where Ĉ is the data and σ is standard deviation of the noise.

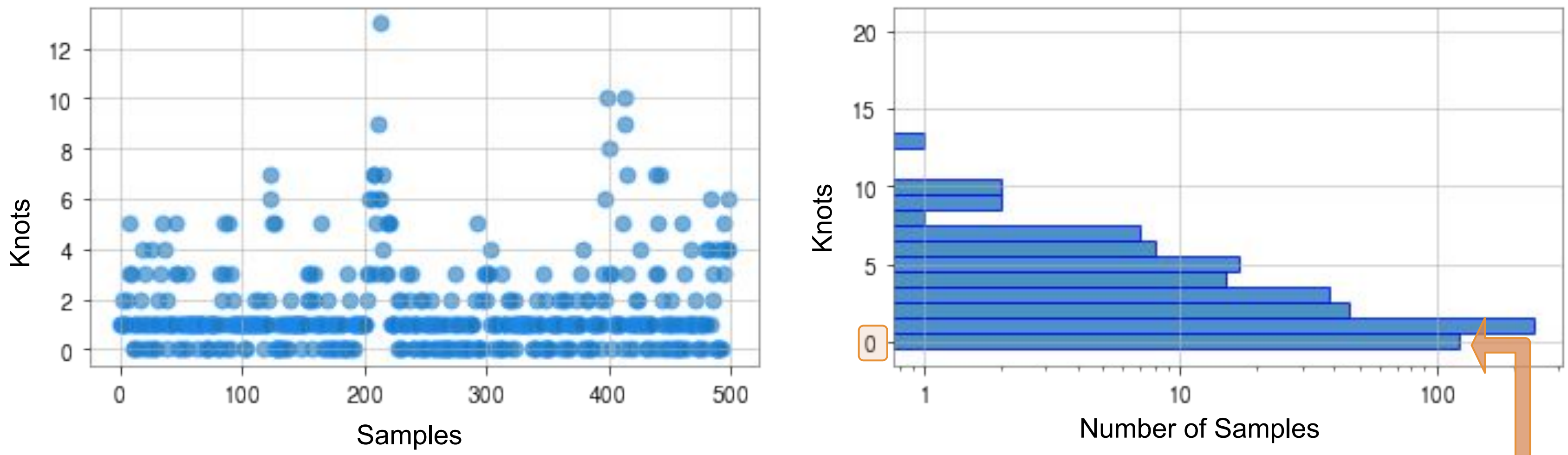
$$SNR_{TOT} = \frac{C_{TOT}}{\sigma_{TOT}} \quad , \quad BF = \frac{P(\widehat{C}(f)|signal)}{P(\widehat{C}(f)|noise)}$$

- Our model has a new proposed Bayes factor method
  - With the MCMC there are given number of Knots (control point) and establishes Births (turned on) and Deaths (turned off) to best fit the data
  - A knot is turned on when our model includes a signal
    - A sample with no knots means our model includes only noise

$$BF_{Our\ Method} = \frac{N_{\geq 1}}{N_0}$$

A closer look at our Bayes factor method…

From the first practices on westley



Count of runs that were only noise

* If curious : our log BF for this run was ≈ 1.3

Explaining

SNR and Bayes Factor

$$C_{TOT} = \frac{\sum_{i=1}^{N} \hat{C}(f)/\sigma(f)^{2}}{\sum_{i=1}^{N} \sigma(f)^{-2}}$$

$$\sigma_{TOT} = \left(\sum \sigma(f)^{-2}\right)^{-1/2}$$

$$SNR_{TOT} = \frac{C_{TOT}}{\sigma_{TOT}}$$

$$P(\bar{\theta}|\widehat{C}_i) = \frac{P(\hat{C}|\bar{\theta})P(\bar{\theta})}{P(\hat{C})}$$

$$P(0|\widehat{C}_i) = \frac{P(\hat{C}|0)P(0)}{P(\hat{C})}$$

$$P(\hat{C}|signal) = \int d\bar{\theta}\, P(\hat{C}|\bar{\theta})P(\bar{\theta})$$

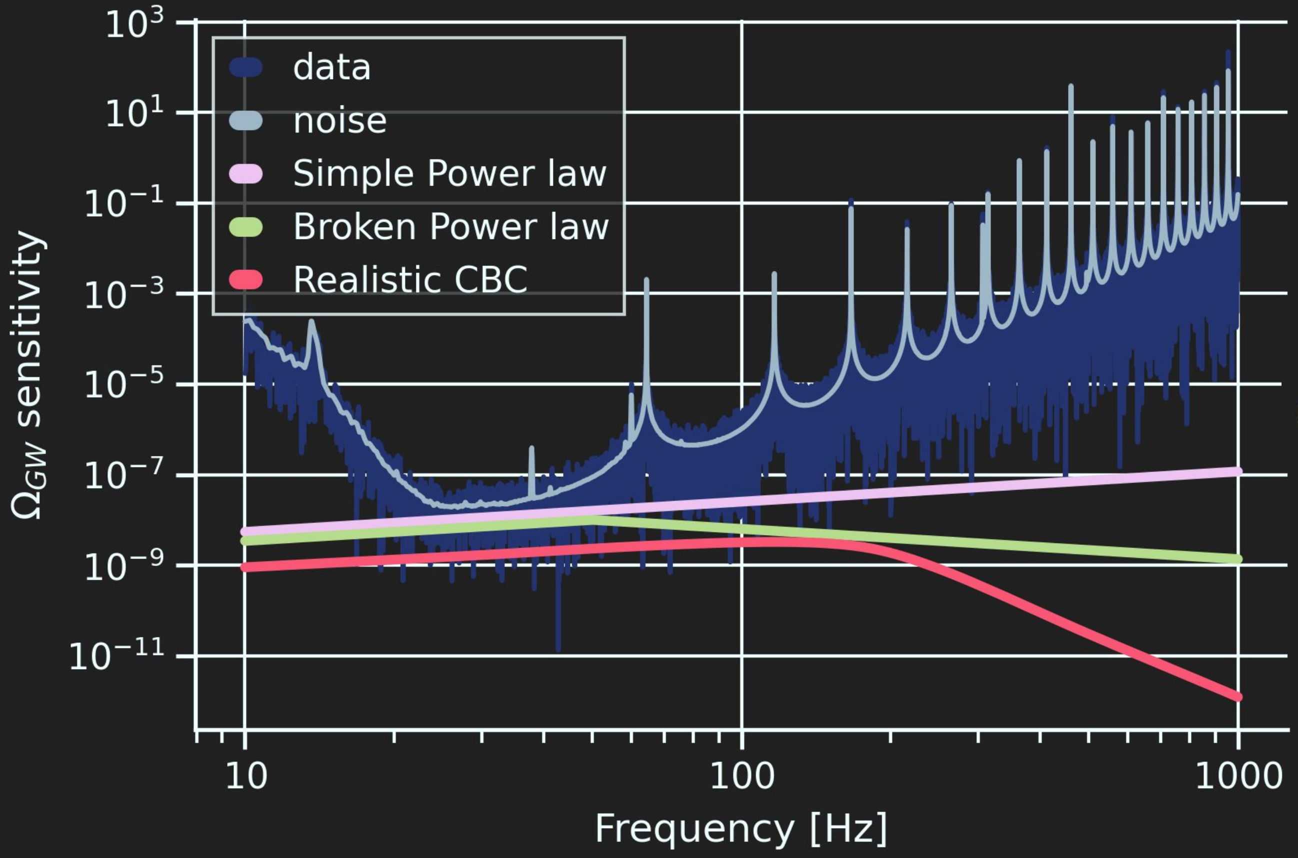
How westley changed this summer

1. Contains methods to inject simple power-law, broken power-law, and CBC signal.
   a. Parameters: Omega_ref, f_{knee} (when the power-law breaks), iterations of rjmcmc
2. Now takes data in the frequency domain.
   a. Faster- doesn't have to run pygwb every time.
   b. Uses $\sigma^2(f) \approx \frac{1}{2\Delta f} \frac{P_1(f)P_2(f)}{\gamma_T^2(f)\, S_0^2(f)},\ S_0(f) = \frac{3H_0^2}{10\pi^2 f^3}$ error to simulate data.


Script named after ⋆CHARLIE⋆

3. Made a script that runs the generic fitting 10^7 with different amplitudes, Ω_{GW}.
4. Runs jobs on condor in parallel, cut run time significantly!

Performance with O4 data



Injected power law :

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

Injected Broken Power Law :

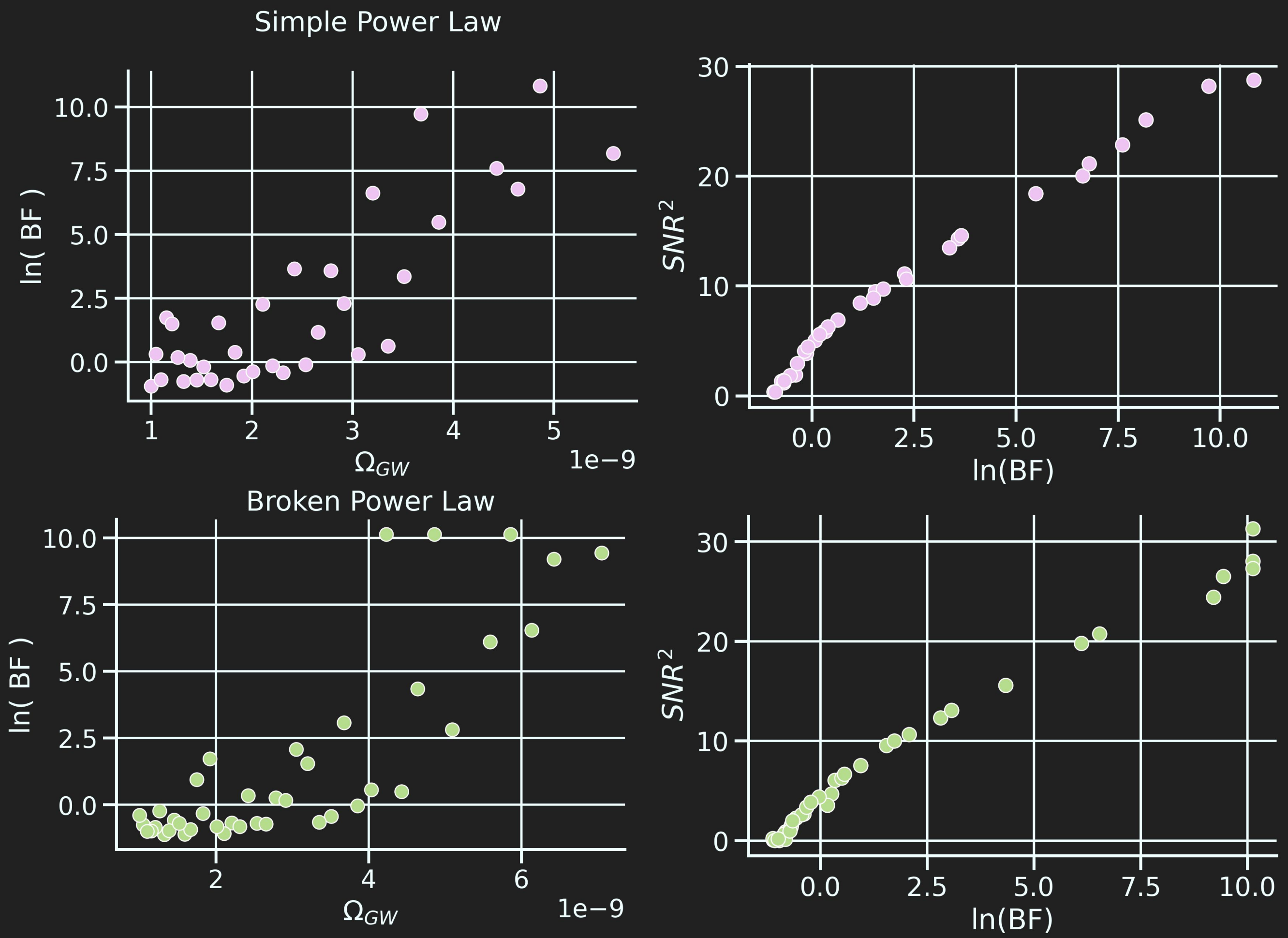
$$\Omega_{GW}(f) = \begin{cases} \Omega_{peak}(f/f_{peak})^{\alpha_1} & for\ f \leq f_{peak.} \\ \Omega_{peak}(f/f_{peak})^{\alpha_2} & for\ f \leq f_{peak.} \end{cases}$$

Injected Realistic CBC signal:

(From Taylor's project!)

$$[\ \Omega_{ref}(f)\ ,\ f\ ]$$

Performance

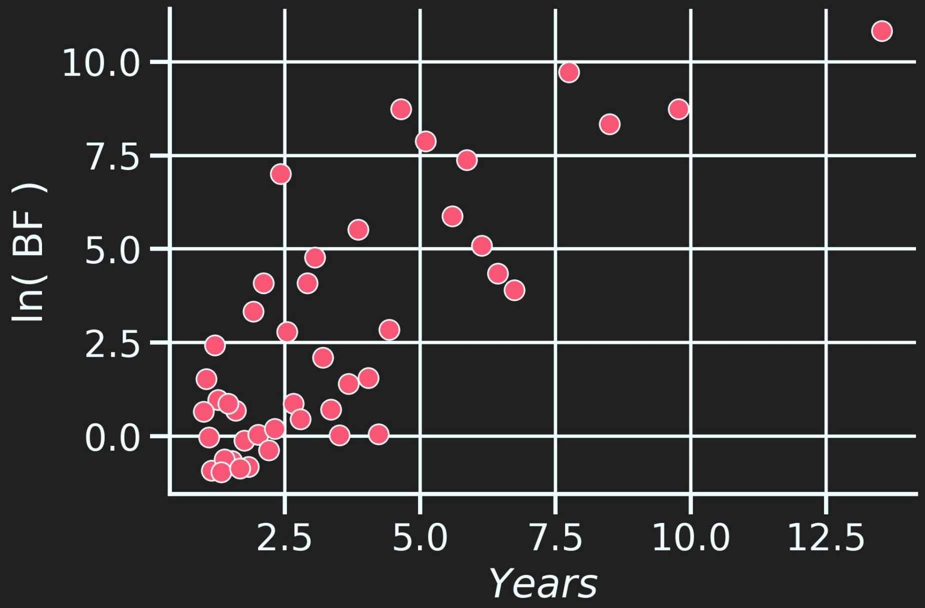


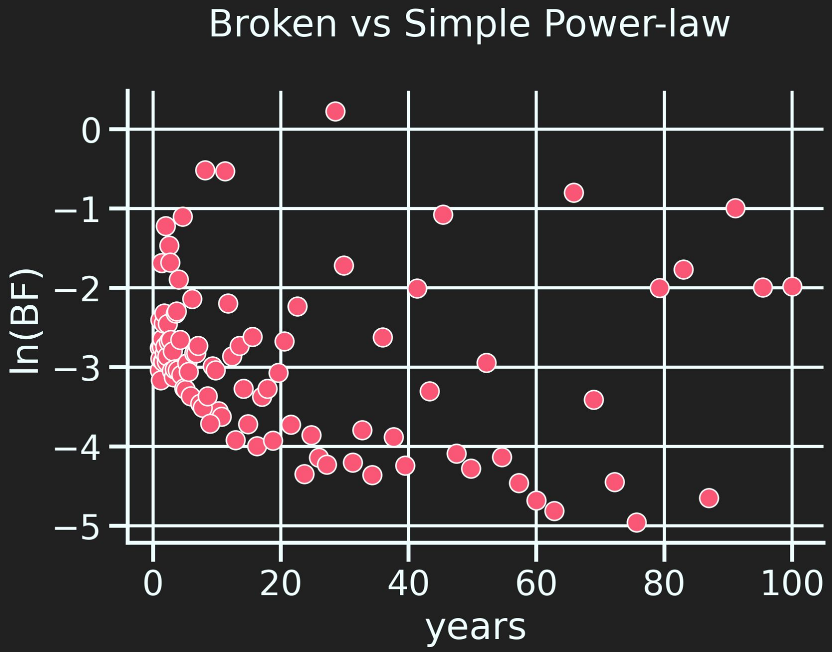
Contains 100 simulations with varying amplitude (10^7 iterations each)

CHECK LIST

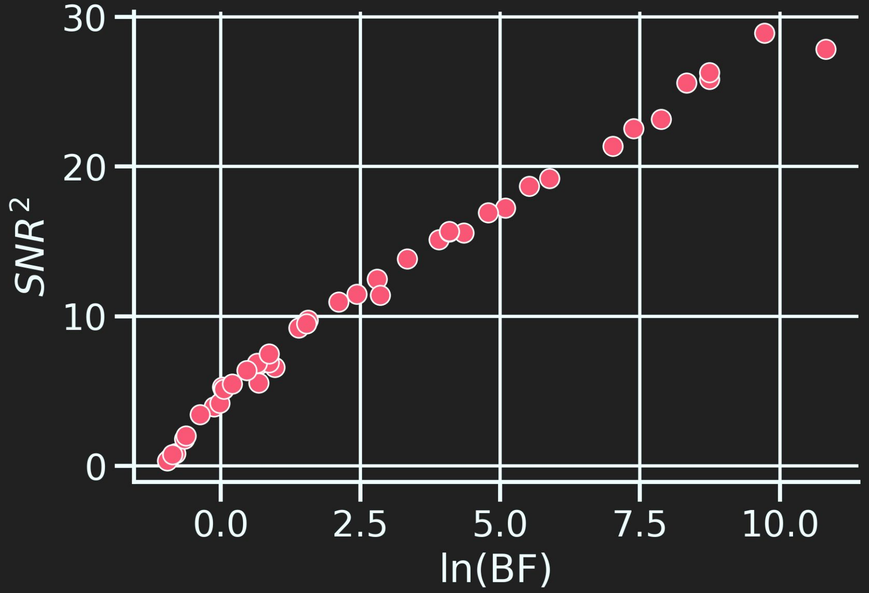
- ❑ Ω_{GW} vs. ln(BF) increases quadratically
- ❑ ln(BF) vs. SNR^2 increases linearly

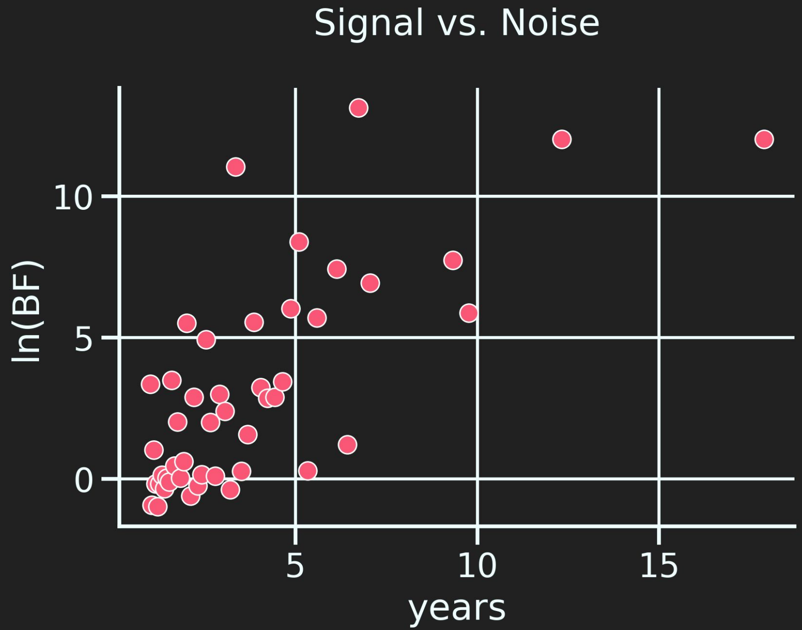
Westley: Taylor's Signal





CBC signal





- SNR^2 and ln(BF) increase linearly. Yay!!
- We would see this type of signal in ~10 years
- For O4, there is not enough time to see a difference in power law and broken power law

Key points

- SGWB are persistent therefore always present.
  - Containing CBC, information of the early universe, astrophysical and cosmological sources.
- Once sensitivity in detectors increase current models will run into issues to describe signals analytically .
- We want a generic and general model that will detect all non-power laws.
- Our generic fitter `westley` passed its tests with simple and broken power laws.
- `westley` can detect CBC signals, shown from using Taylor's signal.

References

[1] Bruce Allen. The Stochastic gravity wave background:Sources and detection. In Les Houches School of Physics:Astrophysical Sources of Gravitational Radiation, pages 373–417, 4 1996.

[2] Thomas Callister, Letizia Sammut, Shi Qiu, Ilya Mandel, and Eric Thrane. Limits of astrophysics with gravitational-wave backgrounds. Phys. Rev. X, 6:031018, Aug 2016.

[3] Arianna I. Renzini, Boris Goncharov, Alexander C. Jenkins, and Pat M. Meyers. Stochastic Gravitational Wave Backgrounds: Current Detection Efforts and Future Prospects. Galaxies, 10(1):34, 2022.

[4] Surabhi Sachdev, Tania Regimbau, and B. S. Sathyaprakash. Subtracting compact binary foreground sources to reveal primordial gravitational-wave backgrounds. Phys. Rev. D, 102(2):024051, 2020.

[5] B. P. Abbott et al. Search for the isotropic stochastic background using data from Advanced LIGO's second observing run. Phys. Rev. D, 100(6):061101, 2019.

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Thank you !
Any Questions?