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Less Travelled Path of Dark Matter (2020)

Search for the stochastic gravitational-wave background induced by primordial curvature perturbations in LIGO's second observing run

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Based on Kapadia et al (2020) arXiv:2009.05514 arXiv:2005.05693

Motivation

- Primordial Black Holes (PBHs) :
  - Sourced by primordial curvature perturbations
  - Very broad mass range: min mass —>10^{-5}g.
  - Predicted by several models of inflation
- Could answer many open questions :
  - Dark Matter candidates
  - Potential GRB sources
  - Formation of supermassive BHs

Ultralight PBHs

- Hawking Radiation (HR) :
  - Masses ("**ultralight**") $\lesssim 10^{15} g$ $(10^{-18} M_\odot)$
    - Not verified experimentally
- Non-GW searches for ultralight PBHs :
  - Extra Galactic Photon Background
  - Big Bang Nucleosynthesis
  - HR dependent

Ultralight PBHs in this work

- We focus on PBHs formed in RD era
  - Associated with mass-scale $10^{13}g - 10^{15}g$
- Would lead to formation of SGWB :
  - Second order
  - Scalar-scalar mode coupling
- **Can we detect them in LVK data ?**

Curvature Power Spectrum $P_\zeta(k)$

- Popular models (True shape unknown) :
  - Gaussian: $P_\zeta = \frac{A}{\sqrt{2\pi\sigma}} \exp\left(-\frac{\log(k/k_0)^2}{2\sigma^2}\right)$
- k_0 = central wavenumber associated with a PBH mass-distribution function f(M)
- Hyper-parameters A, k_0, σ need to be constrained from data

From Power Spectrum to Measurable Quantities

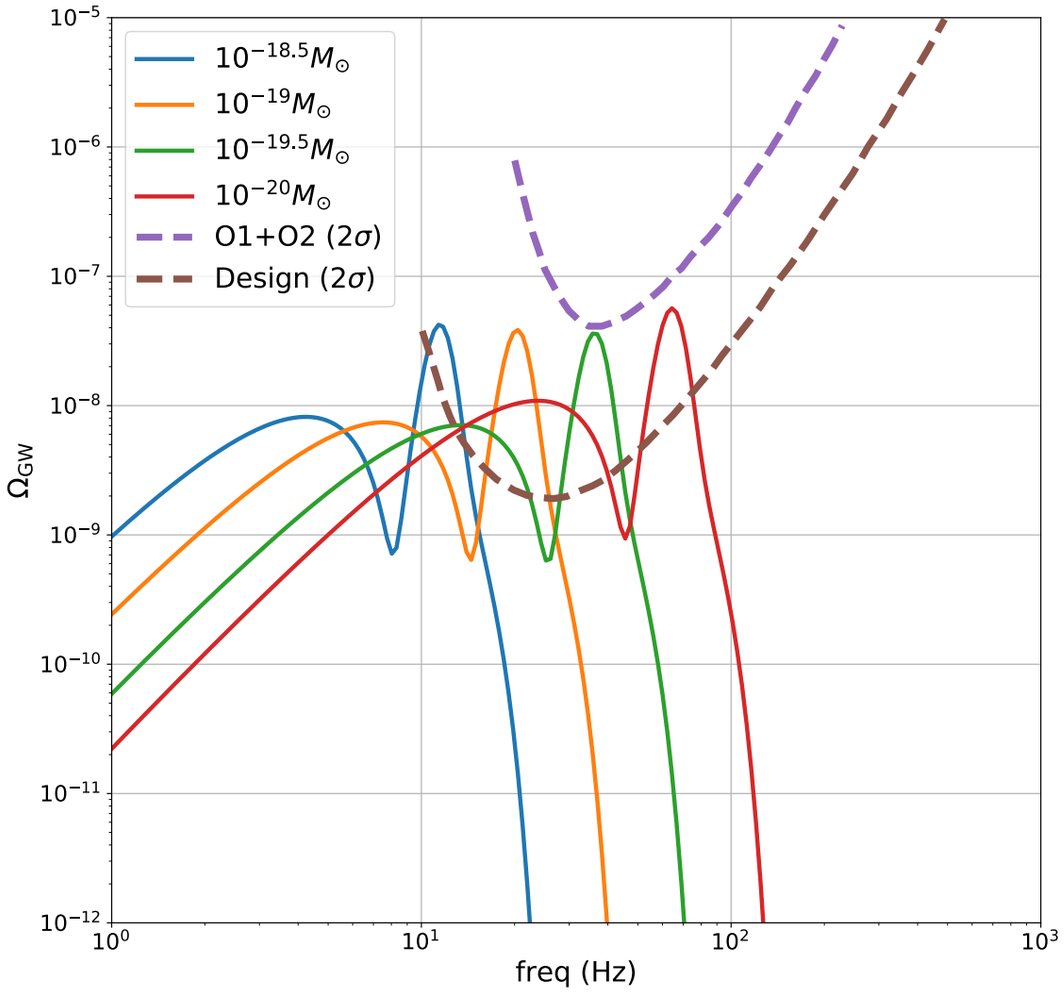
$$\Omega_{\mathrm{GW}} = \frac{1}{\rho_c}\frac{d\rho_{\mathrm{GW}}}{d\log f}$$

$$\Omega_{\mathrm{GW}} \propto \left(\frac{k}{aH}\right)^2 \bar{P}_h, \quad \bar{P}_h \equiv \text{time averaged power spectrum}$$

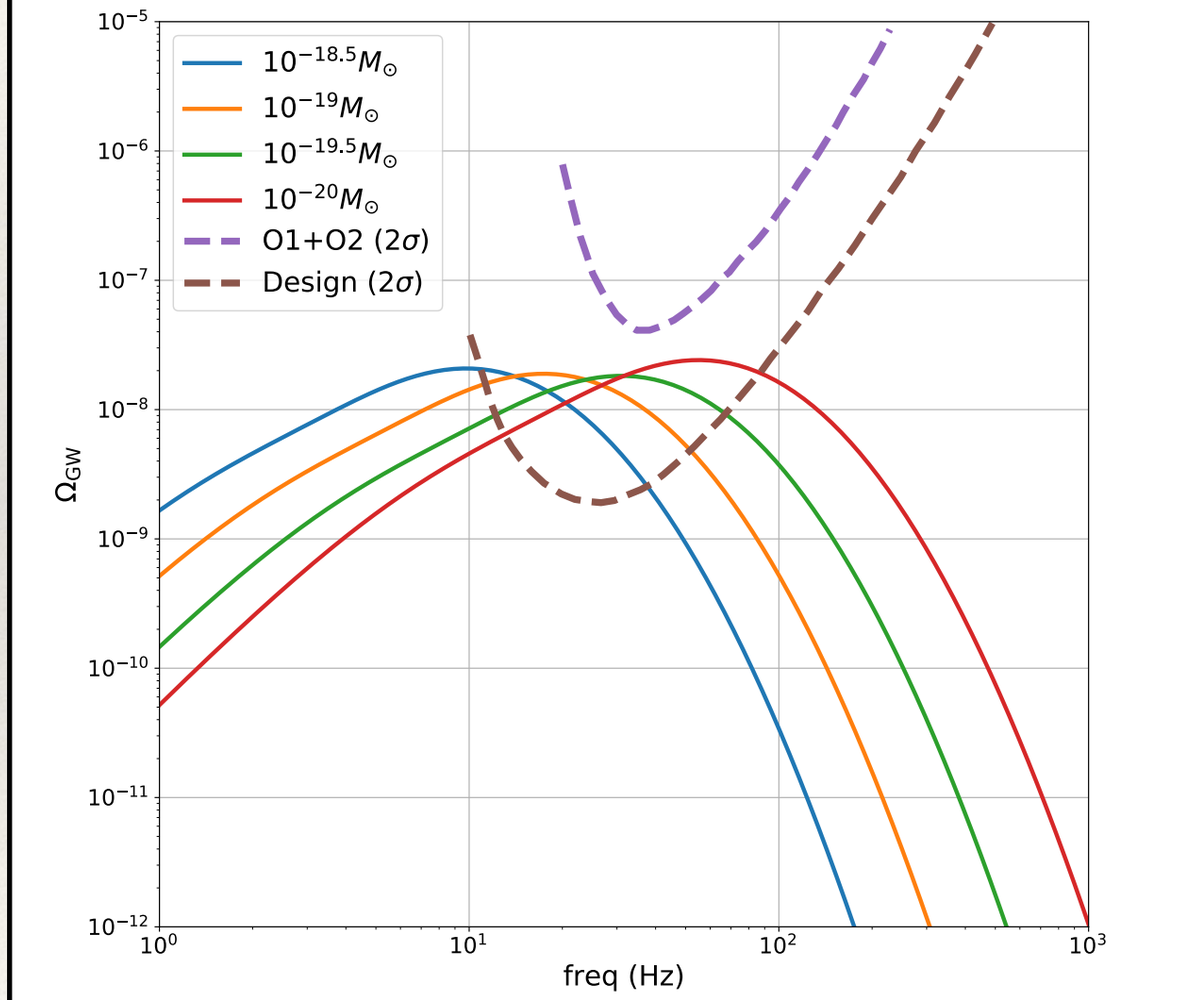
Wavenumber k, Scale Factor a, Hubble Parameter H

Stochastic Backgrounds

Narrow: $\sigma = 0.1$



Broad: $\sigma = 0.88$



PBH Abundance

$$\beta' \propto \frac{\rho_{\rm GW}}{\rho}$$

Abundance at Formation time

PBH mass function today

$$f(M) \equiv \frac{1}{\Omega_{\rm CDM}} \frac{d\Omega_{\rm PBH}}{d\log M/M_\odot}$$

$$f_{\rm PBH} = \int_{-\infty}^{\infty} f(M) d\log M/M_\odot$$

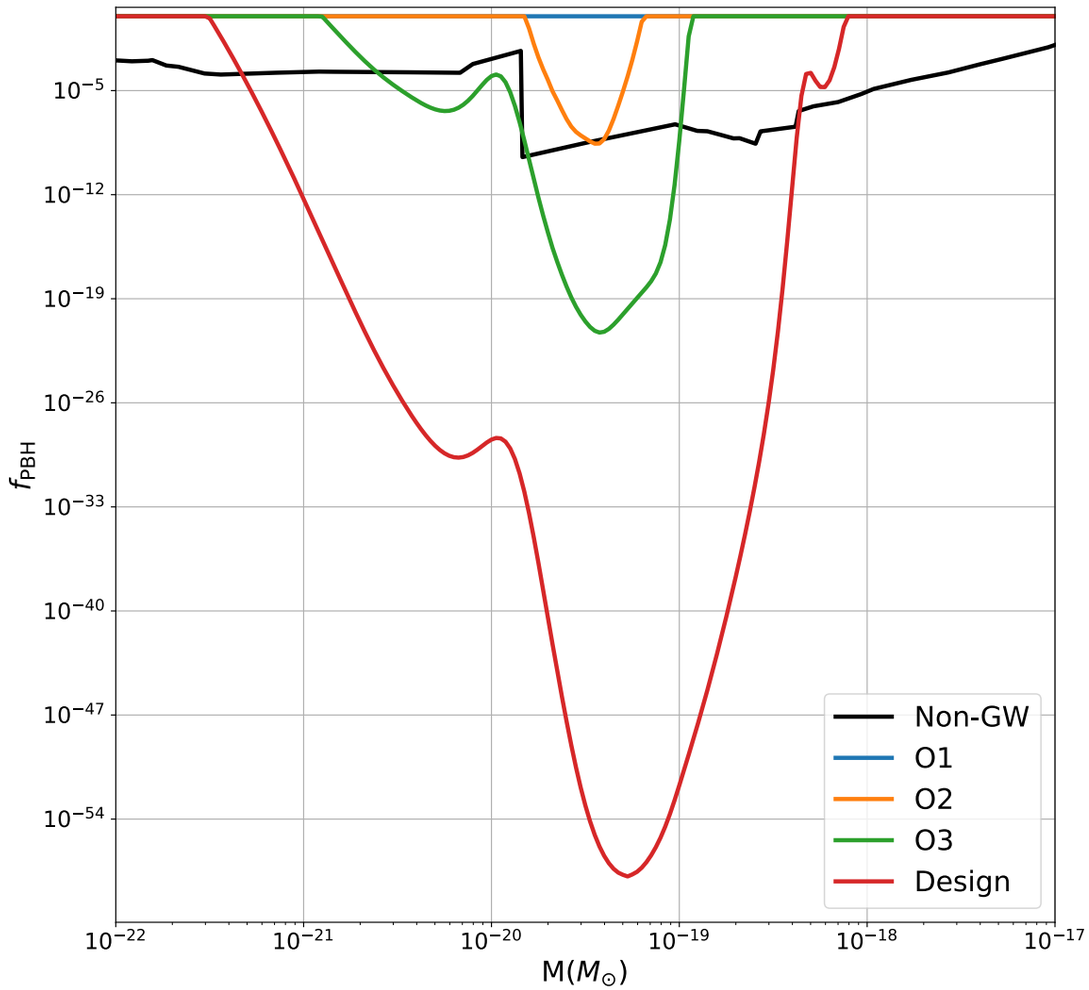
Fraction of DM as PBH

Slight Redefining of the Curvature Power Spectrum $P_\zeta(k)$

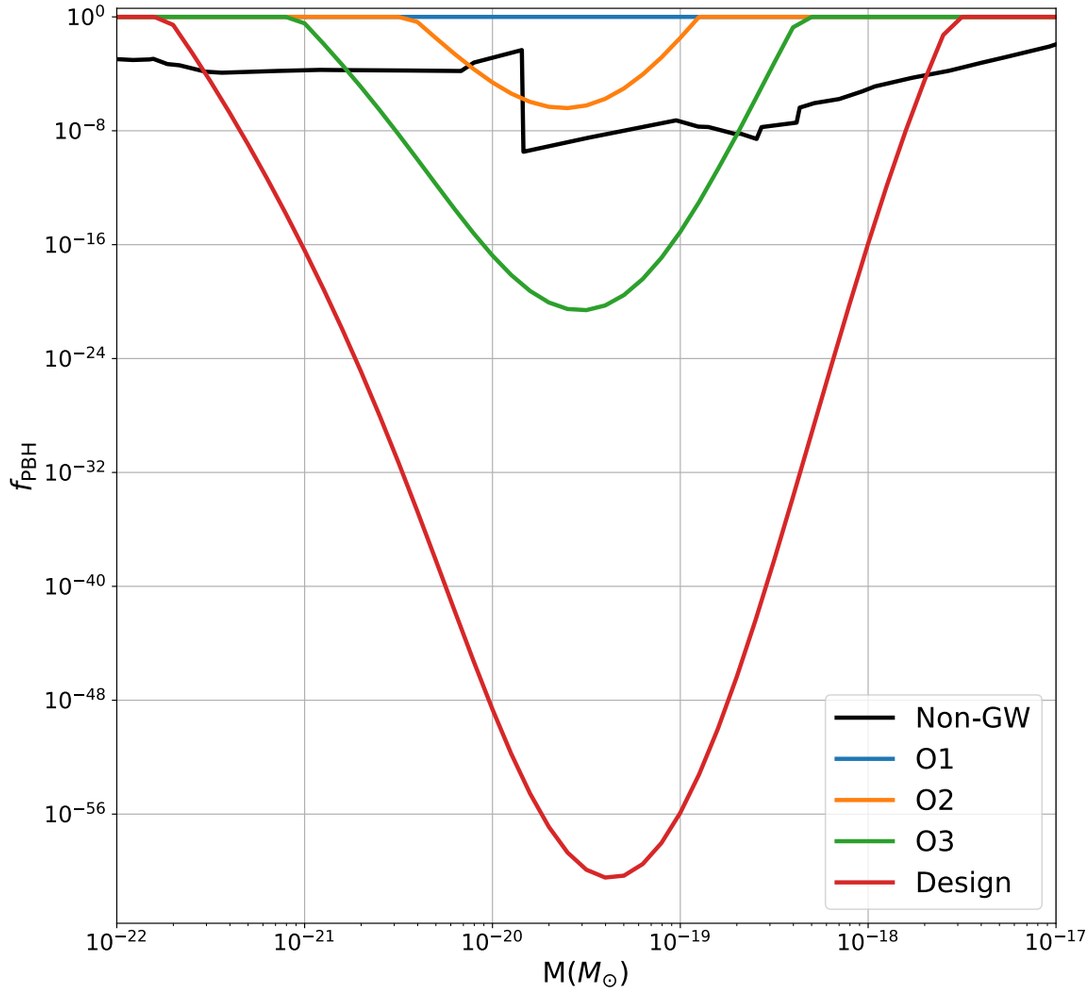
- Lognormal: $P_\zeta = \frac{A}{\sqrt{2\pi}\sigma} \exp\left(-\frac{\log(k/k_0)^2}{2\sigma^2}\right)$
- k_0 = central wavenumber associated with a PBH mass-distribution function f(M)
- Hyper-parameters A, k_0, σ need to be constrained from data

Prospective f_{PBH} upper limits

Narrow: $\sigma = 0.1$



Broad: $\sigma = 0.88$



Cross-Correlation Search

Cross-Correlation Statistic and its Variance

$$\hat{C}(f) = \frac{2}{T}\frac{\mathrm{Re}[\tilde{s}_1^{\star}(f)\,\tilde{s}_2(f)]}{\gamma_{\mathrm{T}}(f)\,S_0(f)},$$

$$\sigma_C^2(f) \approx \frac{1}{2T\Delta f}\frac{P_1(f)P_2(f)}{\gamma_T^2(f)S_0^2(f)},$$

LIGO-T1900058/public (1903.02886)

$$\hat{\Omega}_{\mathrm{ref}} = \frac{\sum_j w(f_j)^{-1}\hat{C}(f_j)\sigma_C^{-2}(f_j)}{\sum_j w(f_j)^{-2}\sigma_C^{-2}(f_j)},$$

$$\sigma_\Omega^{-2} = \sum_j w(f_j)^{-2}\sigma_C^{-2}(f_j),$$

$$w(f) := \Omega_{\mathrm{GW}}(f_{\mathrm{ref}})/\Omega_{\mathrm{GW}}(f)$$

$$\mathrm{SNR} = \frac{\hat{\Omega}_{\mathrm{ref}}}{\sigma_\Omega}$$

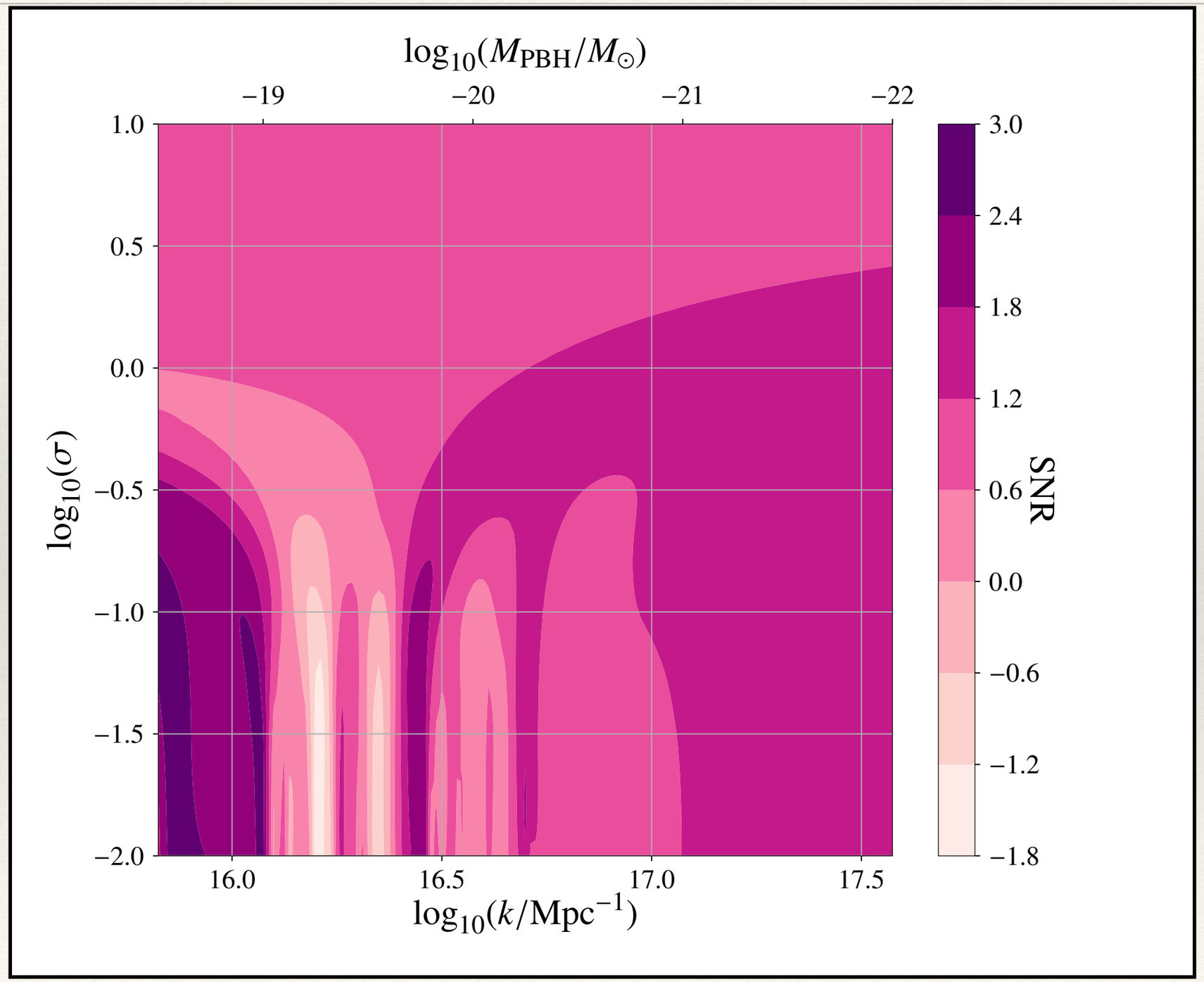
Cross-Correlation PE

Parameter Estimation Likelihood

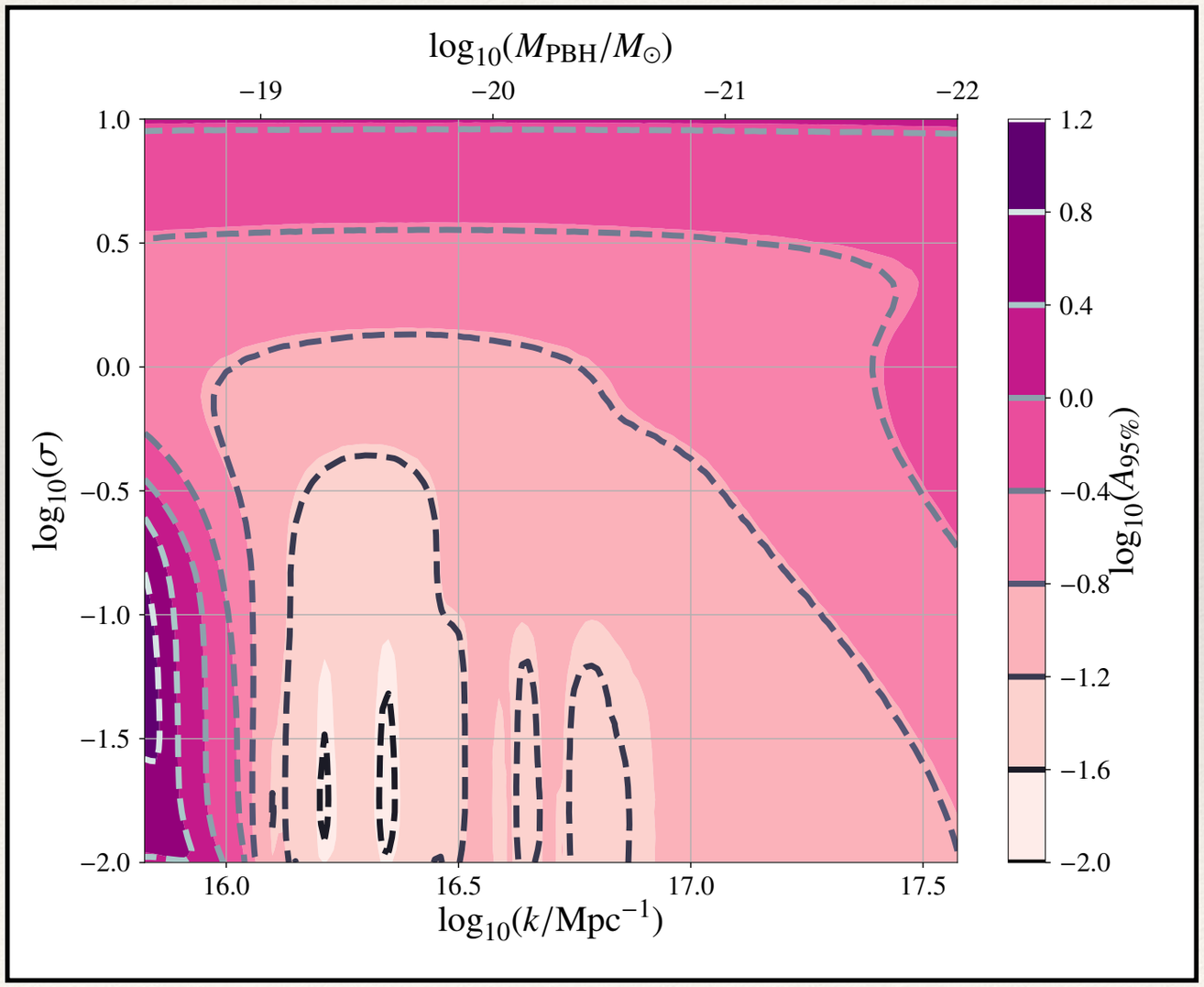
$$p(\hat{C} \mid \Theta) \propto \prod_j \exp\left(\frac{-[\hat{C}(f_j) - \Omega_{\rm GW}(f_j;\Theta)]^2}{2\sigma_C^2(f_j)}\right).$$

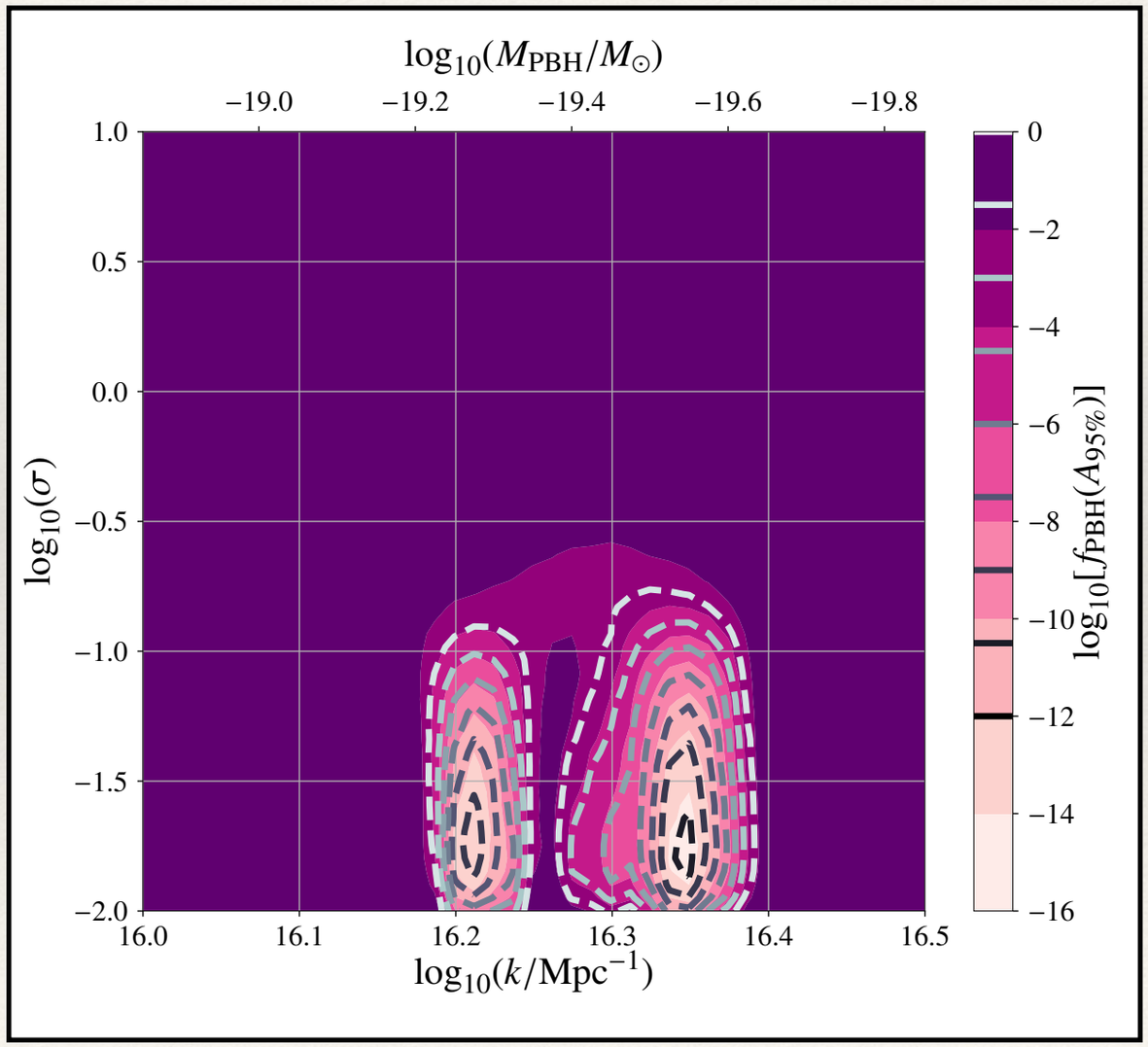
Model Hyper-parameters

Search SNRs

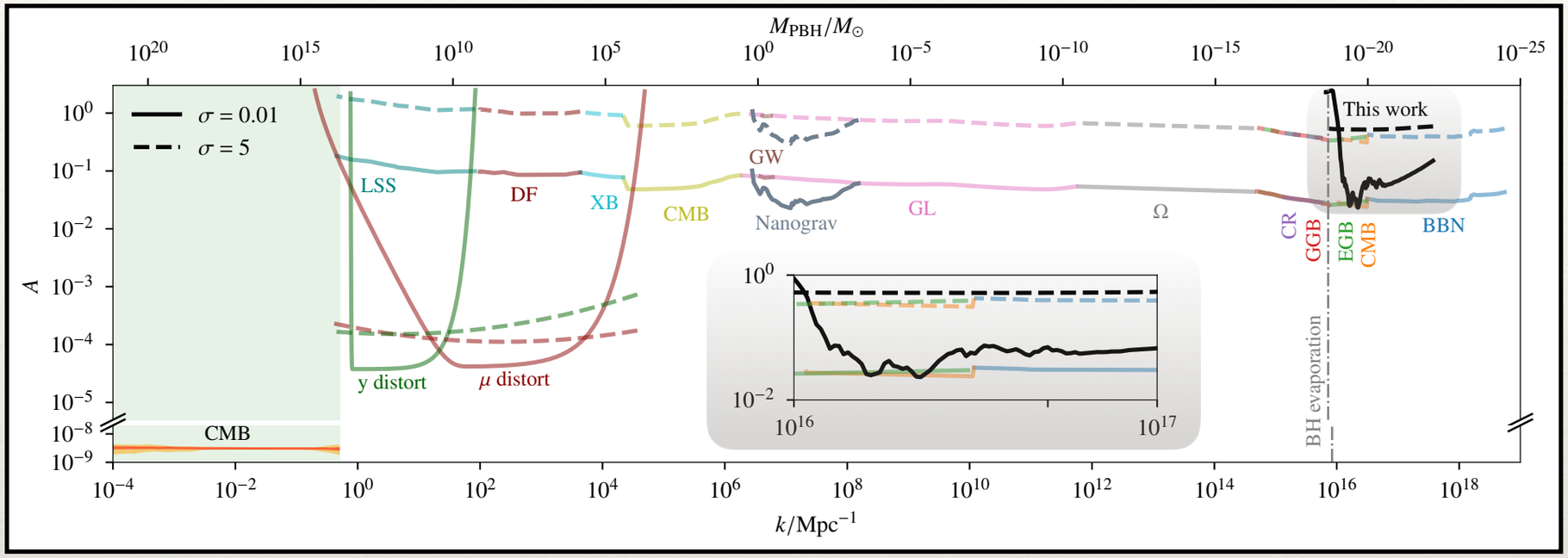

$\log_{10}(M_{\rm PBH}/M_\odot)$
−19
−20
−21
−22
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
$\log_{10}(\sigma)$
16.0
16.5
17.0
17.5
$\log_{10}(k/{\rm Mpc}^{-1})$
SNR
3.0
2.4
1.8
1.2
0.6
0.0
−0.6
−1.2
−1.8

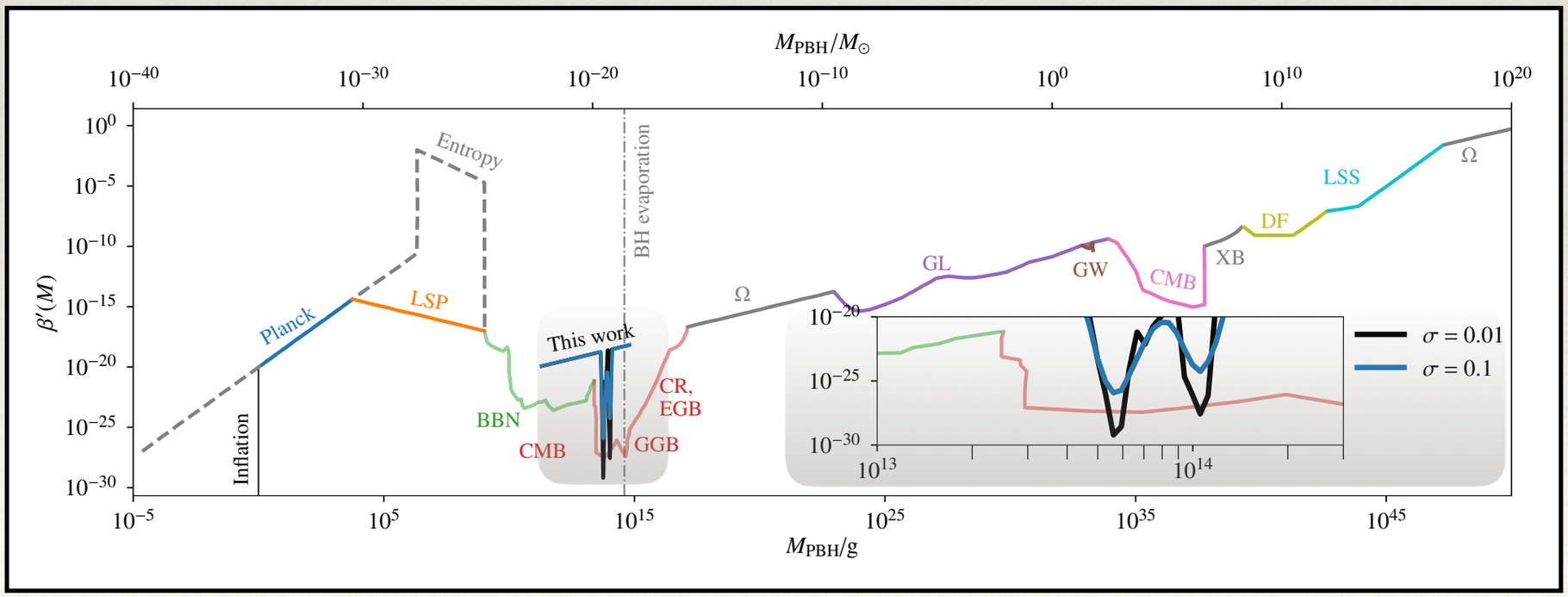
Amplitude and Abundance





Global Perspective of Our Constraints





Conclusions

- We search for stochastic background from primordial curvature perturbations
- We use O2 data cross-correlation data made publicly available
- No conclusive evidence of a signal
- Upper limits on A and β' (or f_{PBH} by neglecting HR)
  - Very first from GW search and PE
  - Should get significantly stronger with O3 and O4 data