# Distinguishing Primordial and Astrophysical Binary Black Holes in the Lower Mass Gap

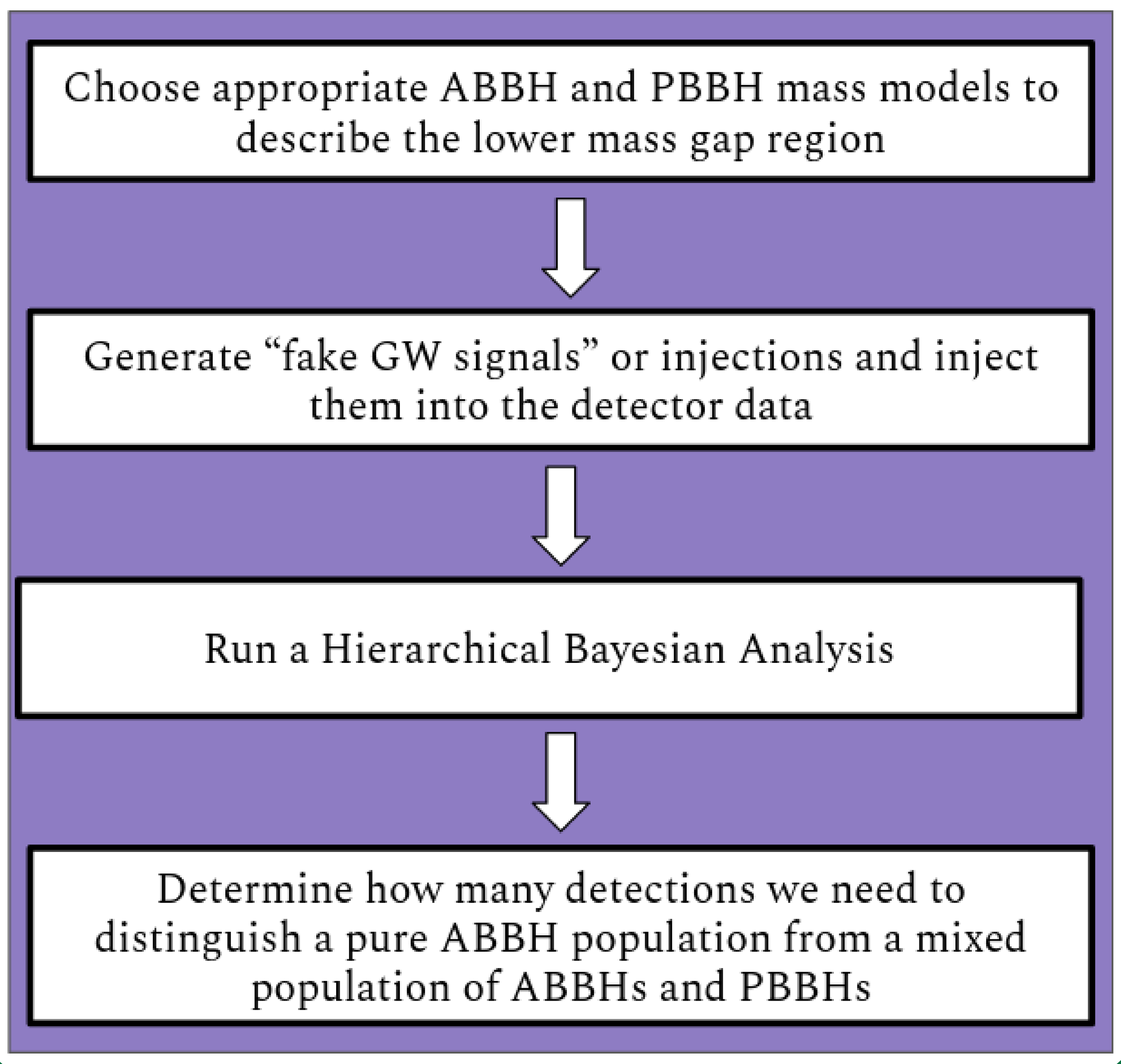
Sumedha Biswas[1] and Sarah Caudill[2]
[1,2]Nikhef, Amsterdam, The Netherlands
[1]sumedha.biswas@ligo.org [2]sarah.caudill@ligo.org

LIGO-Virgo-KAGRA Collaboration Meeting 2020
DCC: LIGO-G2001475

## Abstract

Primordial Black Holes are hypothetical objects, formed in the radiation-dominated era of the early universe by non-stellar formation mechanisms. We explore the possibility of detecting these black holes in the lower mass gap region (3-5 $M_\odot$) using gravitational waves. Since most stellar theories fail in this region, detecting PBHs might be significantly easier. To distinguish primordial binary black holes **(PBBH)** from astrophysical binary black holes **(ABBH)** in the lower mass gap, we develop two power-law models. One of which describes a population of purely stellar BHs with no support in the lower mass gap region *(Astro Model)* while the other describes a mixture population including PBBHs with support in the lower mass gap *(Mix_M2 Model)*. We use hierarchical Bayesian inference (BILBY) to combine information from multiple GW sources and determine the number of GW detections that we need before we can distinguish a pure ABBH population from a mixture population of ABBHs and PBBHs in the lower mass gap. Effectively, we set up a flexible and model-dependent framework for similar analyses in the future that could ultimately help us verify the existence of PBBHs.

## 1. Method




## 2. Selecting Mass Models in the Lower Mass Gap

The first and one of the most important steps of this analysis is choosing appropriate models to describe the lower mass gap region and subsequently simulate a population of ABBHs and PBBHs. We assume power-law distributions for the primary mass $m_1$ as the canonical distributions for both.

**ABBH:**

$$p(m_1) \propto m_1^{-\alpha} \tag{1}$$

The value of $\alpha$ is determined from hierarchical analyses and at the 90% credible level: we assume $\alpha = 2.35$. *(Abbott et al 2016)*

**PBBH:**

$$p(m_1) \propto m_1^{\gamma-1} \; where \; \gamma = \alpha + 1; \tag{2}$$

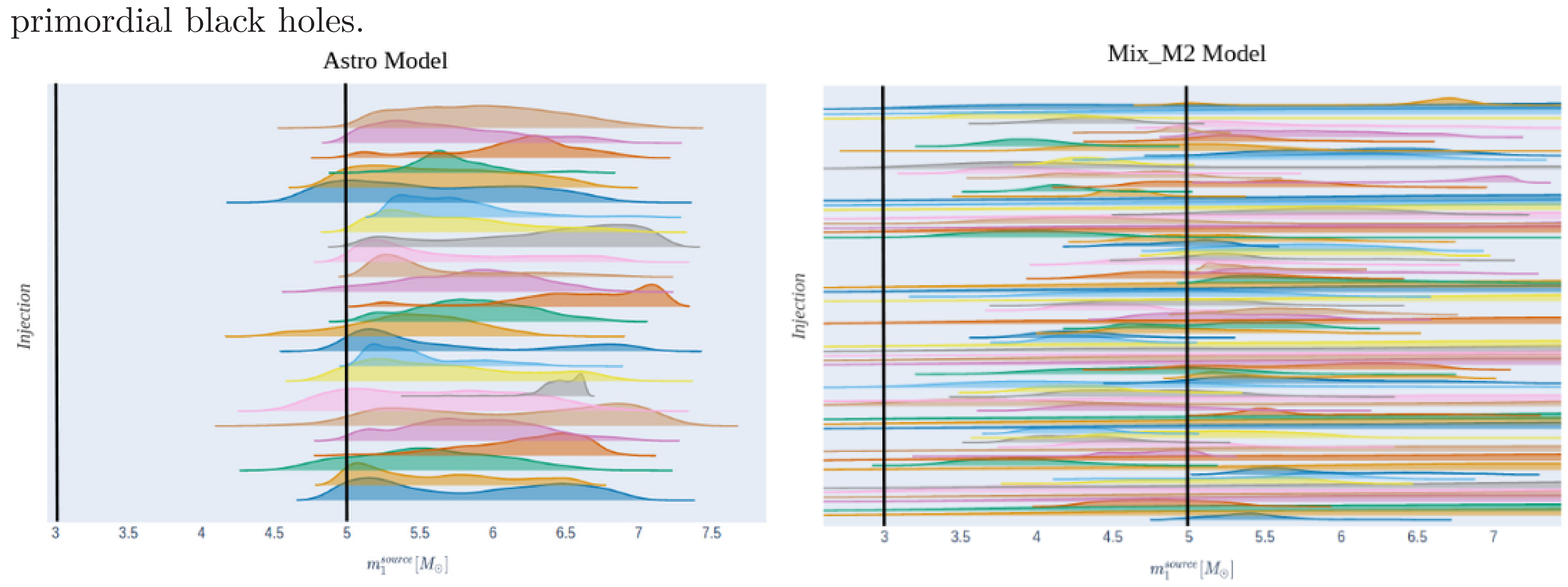
According to *Carr 1975*, the PBH spectrum would look like this if the early universe consisted of small density fluctuations superposed on a Friedmann background. With this kind of model, the PBH mass spectrum depends on two things - the equation of state **w** and the nature of the initial density fluctuations. The relation between w and $\gamma$ is given by $\gamma = \alpha + 1 = -\frac{2w}{1+w}$ where we specifically consider w = 1. This corresponds to the vacuum era of the universe where the PBBHs are predicted to exist today. This leads us to choose $\alpha = -2$.

## 3. Gravitational Wave Population Simulation Scenarios

| Model Name | Scenario | Mass Range of ABBHs $M_\odot$ | $\alpha$ | Mass Range of PBBHs $M_\odot$ | $\alpha$ |
|---|---|---|---|---|---|
| Astro | 100% ABBHs | 5 - 10 | 2.35 | - | - |
| Mix_M2 | 80% ABBHs + 20% PBBHs | 5 - 10 | 2.35 | 3 - 10 | -2 |

## 4. Results Using Hierarchical Bayesian Analysis (BILBY)

Our final goal is to calculate the Bayes factor $log\mathcal{B}^{PBBH}_{ABBH}$ which gives us information about which model is more likely to fit the lower mass gap population. It also helps us determine the number of detections we need before we can draw a conclusion strong enough to verify the existence of primordial black holes.

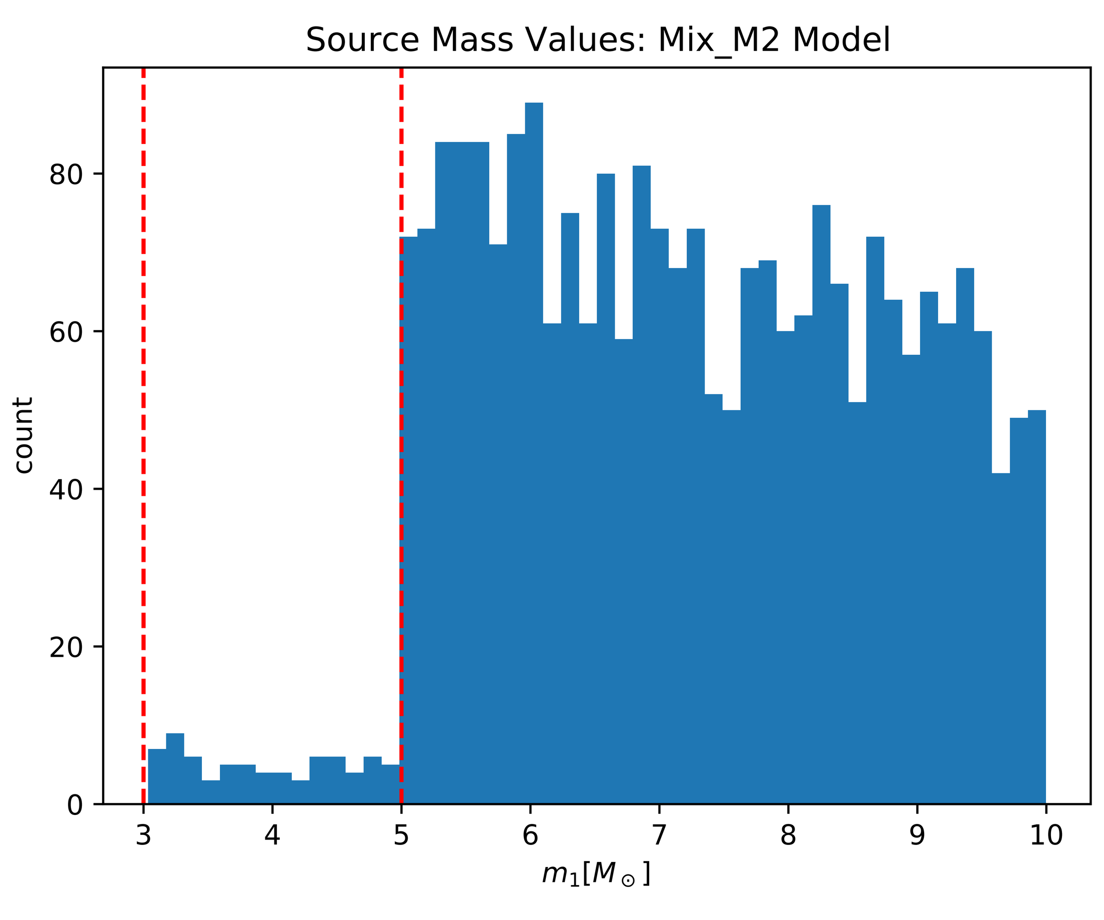



However, we notice a discrepancy in our Bayesian inference results of the simulated lower mass gap population, as seen in the figure. We obtain negative $log\mathcal{B}^{PBBH}_{ABBH}$ values which means that neither model is favoured in the lower mass gap and this is unexpected.

## 5. Analysis Caveats

1. For a preliminary analysis, we chose simple 1-parameter power-law models. In future projects, we intend to use more accurate models to describe the nature of ABBHs and PBBHs in the lower mass gap.

2. The 80:20 ratio that we chose to simulate our populations, in favour of ABBHs is mostly an arbitrary choice. This choice is reflected in the number of injections falling in the lower mass gap region. Different ratios might lead to different results.




***Injected*** $\mathbf{m_1} [\mathbf{M_\odot}]$ ***values***

## 6. Conclusion: How many detections do we need to make a distinction?

1. We conclude that neither model seemingly describes the lower mass gap region well. We attribute this to the analysis caveats. Currently, we are working on developing and including more cosmologically accurate models.
2. We have succeeded in setting up an effective and flexible framework for future analyses - we only need to change the first step i.e. choose better models. With more accurate models describing the ABBH and PBBH populations, there is a higher chance of verifying the existence of PBHs.

## Acknowledgements

We thank Dr. Khun Sang Phukon and Dr. Otto Akseli Hannuksela, both from *Nikhef*, for their valuable contributions and helpful discussions.