# Analysis of a subsolar-mass compact binary candidate from the second part of the third observing run of Advanced LIGO

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**Abstract**

Gravitational wave astronomy has opened new windows for the detection of theoretical black holes of primordial origin. Primordial Black Holes may have formed from the collapse of overdense regions in the very early Universe. The detection of such objects would have ground-breaking implications for astrophysics and fundamental physics. Unlike stellar black holes, the cosmological origin of those primordial black holes does not prevent them from existing at subsolar masses. In 2022, a search for binary black hole mergers with at least one subsolar mass component was carried out by the LIGO-Virgo-KAGRA collaboration, with several candidates discovered. In this work, we aim to analyze one of the most promising of these candidates in order to infer the masses of the two compact objects that generated the gravitational wave signal. We perform a complete Bayesian parameter estimation on the candidate and find that the signal, if originating from a compact binary coalescence, has both components subsolar with $m_1 = 0.50^{+0.03}_{-0.01}$ and $m_2 = 0.32^{+0.01}_{-0.02}$ solar masses (with 68 % credible interval). These masses are below the minimum mass of a neutron star, discarding the hypothesis that the signal is a binary neutron star. The significance of the candidate is also evaluated. The goal is to quantify the odds that the signal comes from a gravitational wave event rather than generated by noise in the detector. The statistical tests performed seem to favor the signal hypothesis.

## 1 Candidate

**Table 1: Subsolar-mass black holes candidate events from the third observational run of the Advanced LIGO-Virgo [1].** In red is the candidate studied in this work. SSM170401 is a candidate from the O2 observing run (2019 [2]) analyzed in detail in [3].

| Candidate | FAR [$\text{yr}^{-1}$ ] | SNR$_{tot}$ | Detector | Pipeline | $m_1$ [$M_\odot$] | $m_2$ [$M_\odot$] |
|---|---|---|---|---|---|---|
| C1 | 0.20 | 8.90 | HL | GstLAL & MBTA & PyCBC | 0.78 | 0.23 |
| C2 | 2.04 | 10.09 | HLV | MBTA & PyCBC | 1.24 | 0.53 |
| C3 | 1.56 | 9.10 | HL | GstLAL & MBTA & PyCBC | 1.52 | 0.27 |
| C4 | 1.37 | 10.25 | HLV | MBTA & PyCBC | 0.40 | 0.24 |
| SSM170401 | 0.41 | 8.67 | HL | GstLAL | 4.89 | 0.77 |

**The false alarm probability (FAP)** of this candidate, based on the result of the search, is:

$$\texttt{FAP} = 1 - \exp(-\texttt{FAR} \cdot T_{obs}) \tag{1}$$

given that the time of operation with at least two detectors observing for O3b is $T_{obs} = 125.5$ days [4]. Therefore, purely according to the search, the candidate has a 6.5% probability of having a noise origin.

## 2 Method

The data for the candidate signals are directly obtained from the O3b open-access data. There are minor non-gaussianities more than 200s before coalescence, we did not subtract them. In analyzing the data, I choose the waveform template `IMRPhenomXPHM` [5] with the spin parameters measured at a reference frequency of $f_{ref} = 100$ Hz to fit our candidate GW signal. The PSD used in the PE was computed using Welch's method on 512s of data before and after the analysis window [6]. I use `Bilby Pipe` on the LIGO Hanford Computing Cluster (node `ldas-pcdev1.ligo-wa.caltech`). **The codes and results are all available on** github.

| **Parameters** | **Range** | **Distribution** |
|---|---|---|
| Mass $m_1$ | (0.1 $M_\odot$, 2 $M_\odot$) | Uniform |
| Mass $m_2$ | (0.1 $M_\odot$, 2 $M_\odot$) | Uniform |
| Chirp mass $M_c$ | (0.34 $M_\odot$, 0.36 $M_\odot$) | Uniform |
| Mass ratio | (0.05, 1) | Uniform |
| Component spin magnitude $a_1, a_2$ | (0,1) | Uniform |
| Spin tilt angles $\theta_1, \theta_2$ | (0,$\pi$) | Sine |
| Difference between azimuthal spin angles: $\theta_{12}$ | (0,2$\pi$) | Uniform |
| Phase between orbital and total angular momentum $\phi_{jl}$ | (0,2$\pi$) | Uniform |
| Inclination of the orbit $\theta_{JN}$ | (0,$\pi$) | Sine |
| Orbital phase $\phi_c$ | (0,2$\pi$) | Uniform |
| Geocentric time $t_c$ | trigger time + (0.2s, -0.2s) | Uniform |
| Luminosity distance $d_l$ | (5Mpc, 300Mpc) | Uniform Volume |
| Right ascension $\alpha$ | (0,2$\pi$) | Uniform |
| Declination $\delta$ | (-$\pi$/2,$\pi$/2) | Cosine |

**Table 2:** Priors of the parameters for the Bayesian parameter estimation.

| | |
|---|---|
| Sampler | `dynesty` |
| Live Points | 500 |
| walks | 25 |
| number of autocorrelation times | 5 |
| dlogz | 0.1 |
| Duration [sec] | 200 |
| npool | 16 |
| Sampling frequency [Hz] | 4096 |
| Minimum frequency [Hz] | 45 |
| Maximum frequency [Hz] | 1800 |
| Waveform Approximant | `IMRPhenomXPHM` |
| Reference frequency [Hz] | 100 |
| Calibration Marginalization | False |
| Distance Marginalization | True |
| Phase Marginalization | True |
| Time Marginalization | True |

**Table 3:** `BILBY` settings.

# 3 Results

**Coherence Test** In [7] and [8] has been developed a new *coherence test* which can discriminate between a *signal coherent model* and a *incoherent signal model*. The Bayesian coherence ratio (BCR) computes the odds between the hypothesis that a coherent CBC signal is present in the data $H_S$ and the hypothesis that instead, the data presents incoherent instrumental features. Those instrumental features can be of two natures; each detector has either a glitch in Gaussian noise ($H_G$) or pure Gaussian noise ($H_N$). For a network of D detectors:

$$BCR = \frac{Z^S}{\prod_{i=1}^{D} Z_i^N + Z_i^G} \tag{2}$$

$Z^S$ is the same as above, $Z_i^N$ corresponds to the noise evidence for a single detector, and $Z_i^G$ models a glitch which appears exactly as a real GW would in a single detector.
In the script, setting `coherence-test` to `True` performs the parameter estimation for each detector separately in addition to the default joint one. This mode computes the evidence for each detector $Z_i$ and allows to calculate the BCR.

| **Parameter** | Values |
|---|---|
| Primary mass ($M_\odot$) | $0.50^{+0.03}_{-0.01}$ |
| Secondary mass ($M_\odot$) | $0.32^{+0.01}_{-0.02}$ |
| Final mass ($M_\odot$) | $0.82^{+0.01}_{-0.01}$ |
| Mass ratio ($m_2/m_1 < 1$) | $0.64^{+0.02}_{-0.04}$ |
| Chirp Mass | $0.35^{+0.00}_{-0.00}$ |
| $\chi_{eff}$ | $-0.17^{+0.01}_{-0.01}$ |
| $\chi_p$ | $0.72^{+0.13}_{-0.14}$ |
| Luminosity Distance (Mpc) | $18.04^{+7.91}_{-4.43}$ |
| Signal-to-noise ratio | 10.62 |
| P($m_1$< 1 $M_\odot$) | 100% |
| P($m_2$< 1 $M_\odot$) | 100% |

**Table 4:** Results of the parameter estimation for C1. All masses are in the source frame. The statistical uncertainty of all the parameters is quantified by the 68% credible intervals about the median of the marginalized one-dimensional posteriors.

| $\log \mathcal{B}_{\mathcal{HL}}$ | $\log \mathcal{B}_{\mathcal{H}}$ | $\log \mathcal{B}_{\mathcal{L}}$ | $\log \mathcal{BCR}$ |
|---|---|---|---|
| 12.44 | 4.67 | still running | - |

**Table 5:** Natural logarithm of the Bayes factors of the signal versus noise hypotheses obtained from the PE in the data of Hanford-Livingstion $\log \mathcal{B}_{\mathcal{HL}}$, only Hanford $\log \mathcal{B}_{\mathcal{H}}$, only Livingston $\log \mathcal{B}_{\mathcal{HL}}$ and the natural logarithm of the Bayes factor of the coherent versus incoherent hypothesis computed with eq.2.

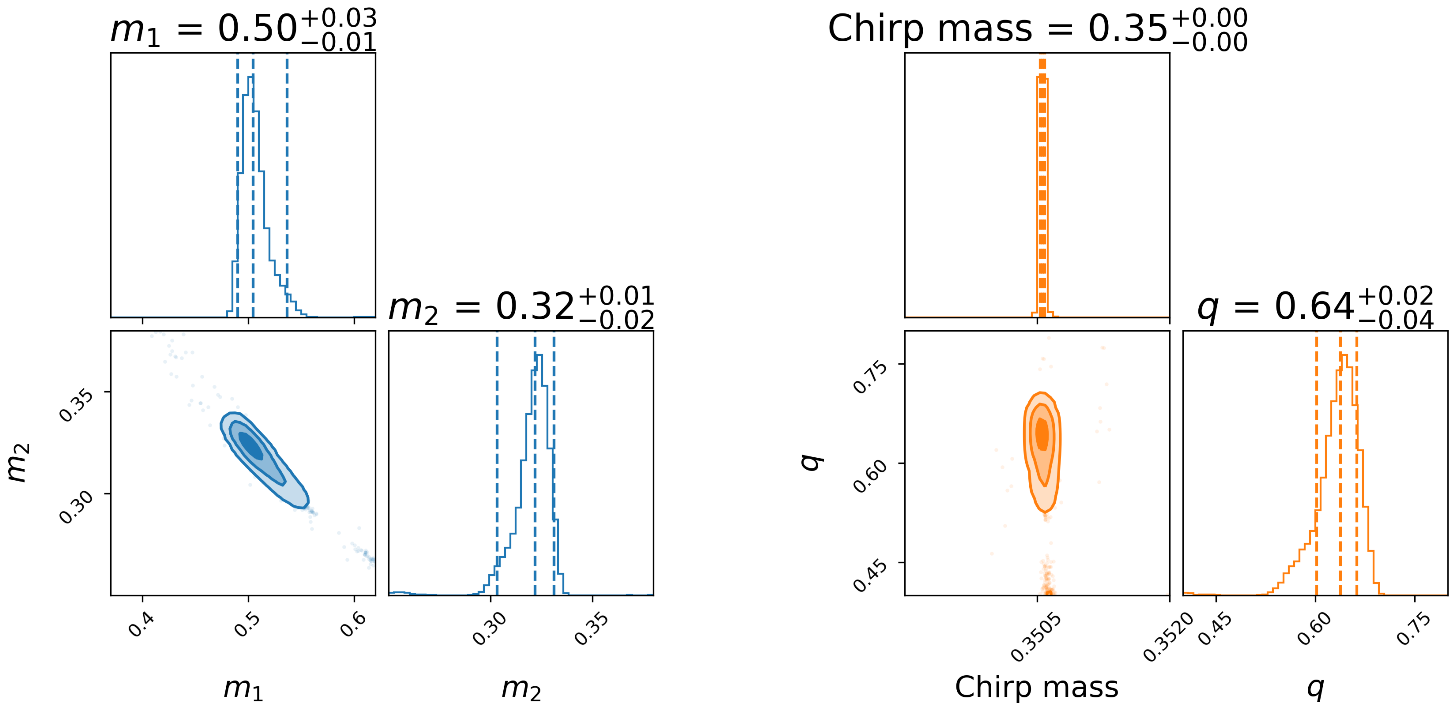


**Figure 1: Left:** Corner plot for the black hole masses. The marginalized distribution for each parameter is shown in the histograms. For each parameter is reported the median value and 1-sigma error. The contours of the joint posterior distribution correspond to the range of the symmetric 39%, 86%, and 99% credible interval with respect to the median. **Right:** Corner plot for the chirp mass and mass ratio.

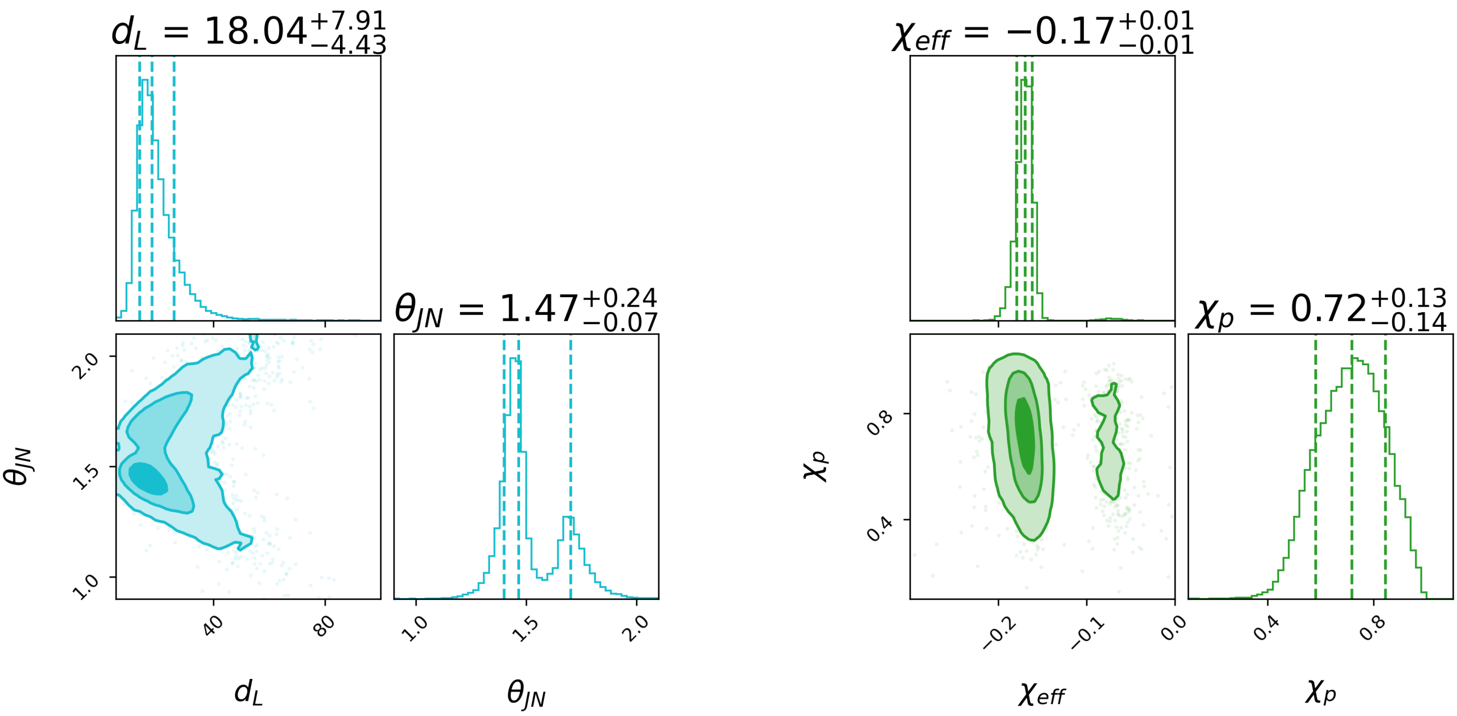


**Figure 2: Left :** Corner plot for the luminosity distance and $\theta_{JN}$. In green are shown the prior distribution for $d_L$ -uniform-in-volume prior between 5 and 300 Mpc- and $\theta_{JN}$. **Right :** Corner plot for $\chi_{eff}$ and $\chi_p$.

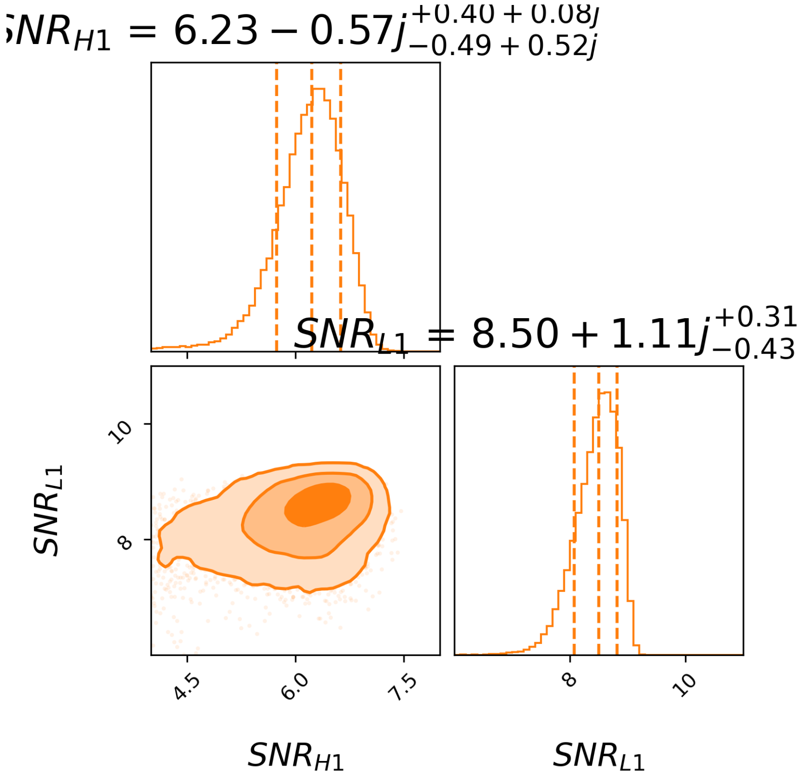


**Figure 3:** Corner plot showing the complex value of the total matched filter SNR for C1.

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