

Black Hole Or Neutron Star? Predictions On The Secondary Mass In GW190814

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AUTHOR BIO

Youyang Xia is a junior at YK Pao School in Shanghai, China. She has a strong interest in physics, with a wide range that includes astrophysics, nuclear physics, and geophysics. Apart from the intense academic life of the IBDP course, she is also a student athlete in fencing. Youyang hopes to pursue studies in physics at university, while also maintaining a high level of athletics.

ABSTRACT

This paper aims to predict the identity of the secondary mass in gravitational wave event GW190814. The mysterious secondary mass falls between the mass gap of neutron stars and black holes, specifically from 2.5 to 5 solar masses, creating a long-lasting debate regarding the identity of the celestial body. The paper would first approach the estimation by literature review, comparing the event with other events of similar parameters to obtain a possible suggestion of the identity. Then, the paper would present statistical models that summarize all existing gravitational wave events, revealing the population relations of different parameters and the secondary mass's identity. By locating the parameters of GW190814 on these graphs, possibility percentages could be made. After weighing all estimations, the conclusion of the secondary mass of GW190814 being a black hole is made.

Keywords: *Gravitational Wave, Compact Binary Inspiral Gravitational Waves, Binary Black Hole Events, Neutron Star-Black Hole Binary Events, GW190814, Chirp Mass, Effective Inspiral Spin, Statistical Models.*

COMPARATIVE ANALYSIS

While the 23 solar masses primary body of GW190814 is mostly certain to be a black hole, the identity of the secondary body of 2.6 solar masses, falling into the mass gap of 2.5 to 5 solar masses that is known to be heavier than neutron stars and lighter than black holes, remains a debate (Abbott et al., 2020). One way to identify the secondary body is by comparing the event with others that have similar properties. If GW190814 exhibits closer resemblance to either black hole neutron star (BHNS) or binary black hole (BH) binaries, it may suggest the identity of the secondary body.

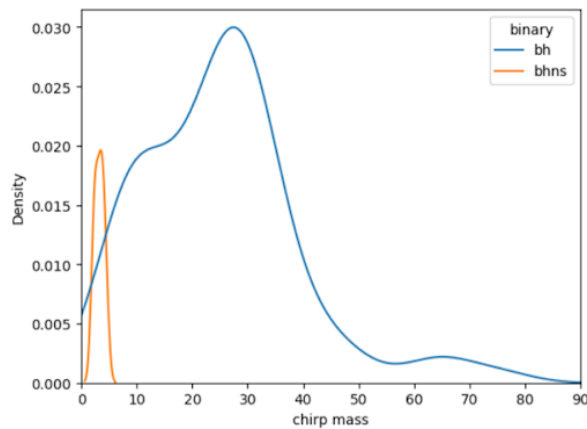
GW190814 has a relatively heavy black hole when compared to known BHNS binaries. With 23.2 solar masses, the GW190814 black hole is only lighter than the black holes of the BHNS binaries GW191219 and GW200210, with 31.1 and 24.1 solar mass respectively.

The effective inspiral spin parameter describes how aligned the spin of the two bodies is in a binary system. Interestingly, GW190814 and GW191219 both have the effective inspiral spin parameter of 0, while having a significant difference in final spin of 0.28 and 0.14, respectively (The LIGO Scientific Collaboration et al., 2023). Therefore, there might not be valuable suggestions drawn from comparing effective inspiral spins.

Chirp mass is the inspiral dynamics and gravitational-wave emission, which is calculated with the masses of the binary. The chirp masses of GW190814 and GW191219 are 6.11 and 4.31 solar masses, respectively, while the final spin of GW190814 is double that of GW191219. From which we can observe that chirp mass might positively affect the final spin. A similar hypothesis could be made when considering GW200210, whose effective inspiral spin parameter of 0.02 can be regarded as none. Its chirp mass of 6.56 solar masses, as well as final spin of 0.34, are the highest among the three events (The LIGO Scientific Collaboration et al., 2023). Therefore, we can assume chirp mass positively impacts the final spin to some extent when the effective inspiral spin parameter is almost 0 for BHNS binaries. On the contrary, no such observation is made regarding BH binaries. For example, GW190512 and GW200302 have similar almost-zero effective inspiral spin parameters of 0.02 and 0.01, respectively, and have different chirp masses of 14.6 and 23.4, respectively. However, their final spins are both 0.66, not increasing as the chirp mass increases (The LIGO Scientific Collaboration et al., 2023). Since the relation is limited to BHNS binaries, the secondary body of GW190814, which follows the assumption, should be a neutron star.

STATISTICAL ANALYSIS

Other than trying to observe trends about two parameters, plotting the parameters against the density they own is more effective because it gives the probabilities directly. In this case, I used the tool Seaborn, a Python data visualization library, to create my graphs. I used Seaborn's code for kdeplot. A kdeplot (short for kernel density estimate plot) is similar to a histplot, but instead it draws continuous curves, making it easy to visualize and predict trends. The parameters for all events were obtained from the GWTC-3 catalogue (The LIGO Scientific Collaboration et al., 2023).



From Figure 3, we can clearly infer that there is an abundance of BH binaries with chirp mass around 28 solar masses, and the chirp mass of BHNS binaries does not usually exceed 10 solar masses.

I only used BH binaries and BHNS binaries for simplicity, as I only wish to hypothesize the identity of secondary objects in binary merger events that fall between the mass gap. Since the primary objects in those events are ascertained black holes, there is no need to include NS binaries. I am also assuming the identity of those objects is either black holes or neutron stars, but there are possibilities of being neither.

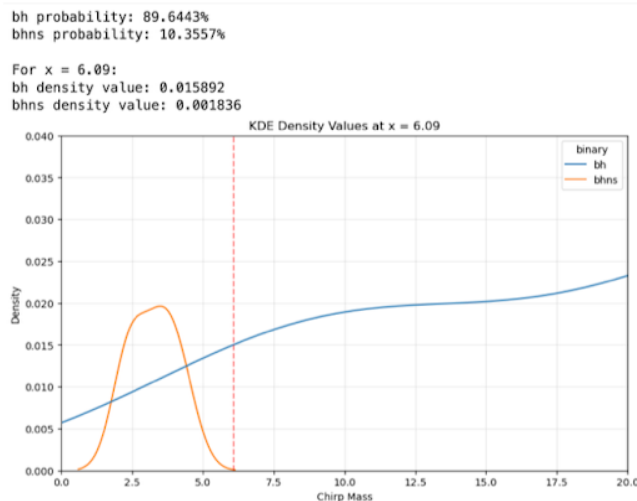


Figure 4

To get the estimated probability of the type of binary shown in Figure 4, the code must find the two density values for a certain chirp mass import. Then, it will calculate using the formula:

$Probability = \frac{Density_1}{Density_2 \times Density_3} \times 100\%$. The figure below shows the probabilities of GW190814. With a chirp mass of 6.09 solar masses, the binary is 89.6% likely to be a BH binary. I further generated more graphs and relative possibilities depending on different variables, shown in Figures 5 to 7. Interestingly, different variables give different estimations. For example, when tracing the unknown object's mass, or the secondary mass in its binary, against the graph of all the secondary masses, there is a 3 out of 4 chance that the mass is a black hole. This is slightly counterintuitive, as 2.6 solar mass is so much closer to 2.5 than 5 of the range of the mass gap. This could be considered valuable, as it is calculated and graphed by the computer; though, this might be caused by the extremely larger amount of data in BH binaries than BHNS binaries, causing the curved line to extend to areas that its data did not directly reflect. In fact, we should keep this skepticism in mind while viewing all these estimations.

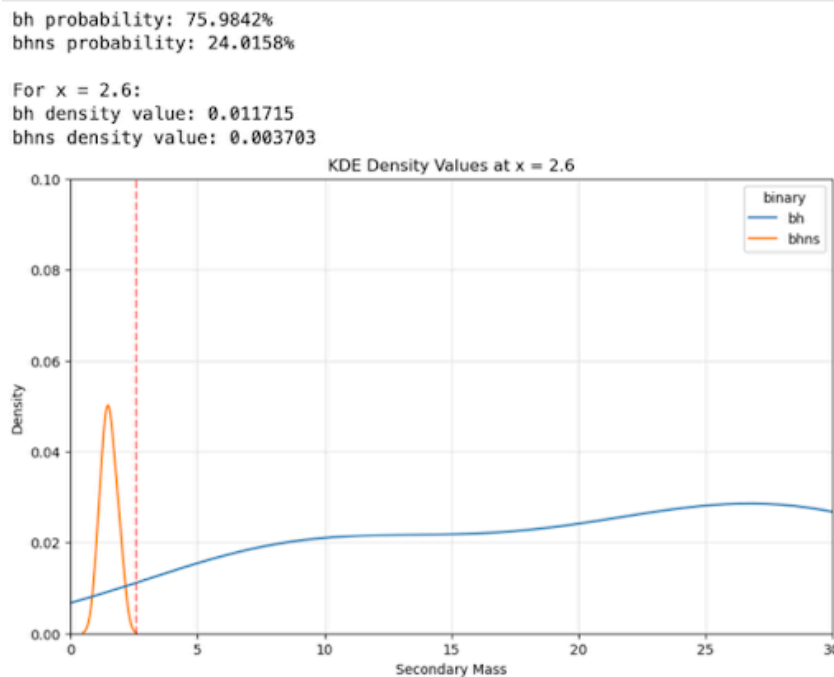


Figure 5

However, Figures 6 and 7 both suggest a greater possibility of it being a BHNS binary, contradicting earlier estimations. Figure 6, in particular, suggests that there is no possibility of it being a BH binary. This is reasonable if considering the variable it used: the spin of the remnant. Being much less in weight overall, BHNS binaries would produce a remnant with less spin because there is less energy for it to use.

bh probability: 0.0000%
bhns probability: 100.0000%

For $x = 0.28$:
bh density value: 0.00000
bhns density value: 1.858070

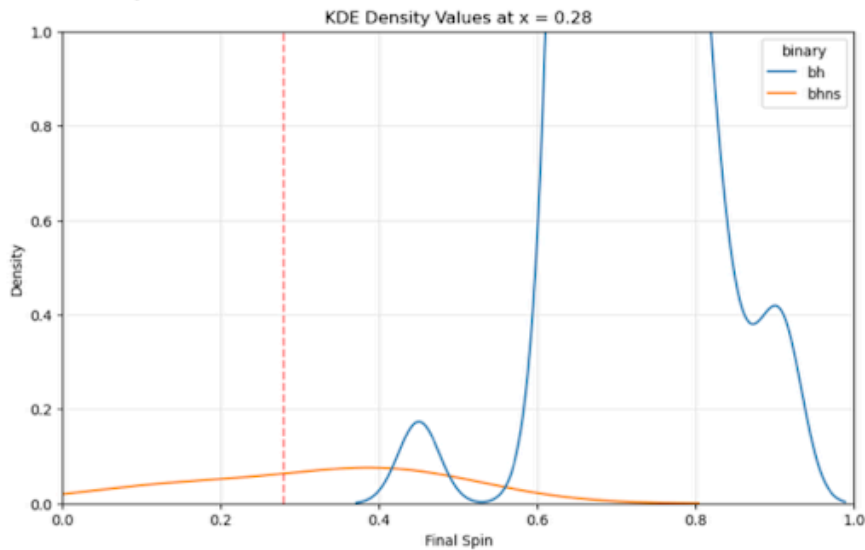


Figure 6

We also might put effective inspiral spin, which happens to be the variable of Figure 7, into consideration for the production of final spins, as it might also impact the outcome. However, as shown in Figure 7, the densest area of the effective inspiral spin measurement of the two types of binaries is quite close together. So, just for justification of the outcome from final spin as a variable, we can ignore the differences the effective inspiral spin makes.

bh probability: 35.6819%
bhns probability: 64.3181%

For $x = -0.002$:
bh density value: 2.557687
bhns density value: 4.610328

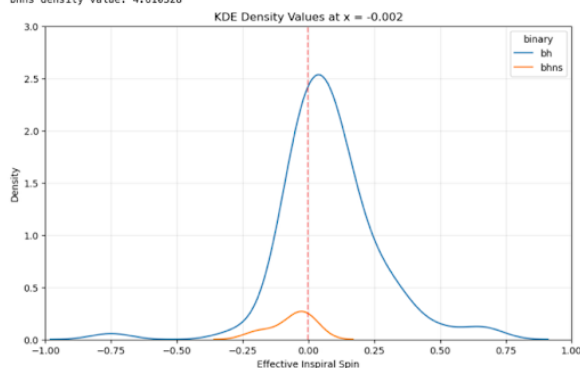


Figure 7

While using a variable does provide us with some decent valid considerations, a more valuable estimation could be made by visualizing two variables at the same time. In the next few graphs, I used Seaborn's code of "third variable with a hue semantic to show conditional distributions".

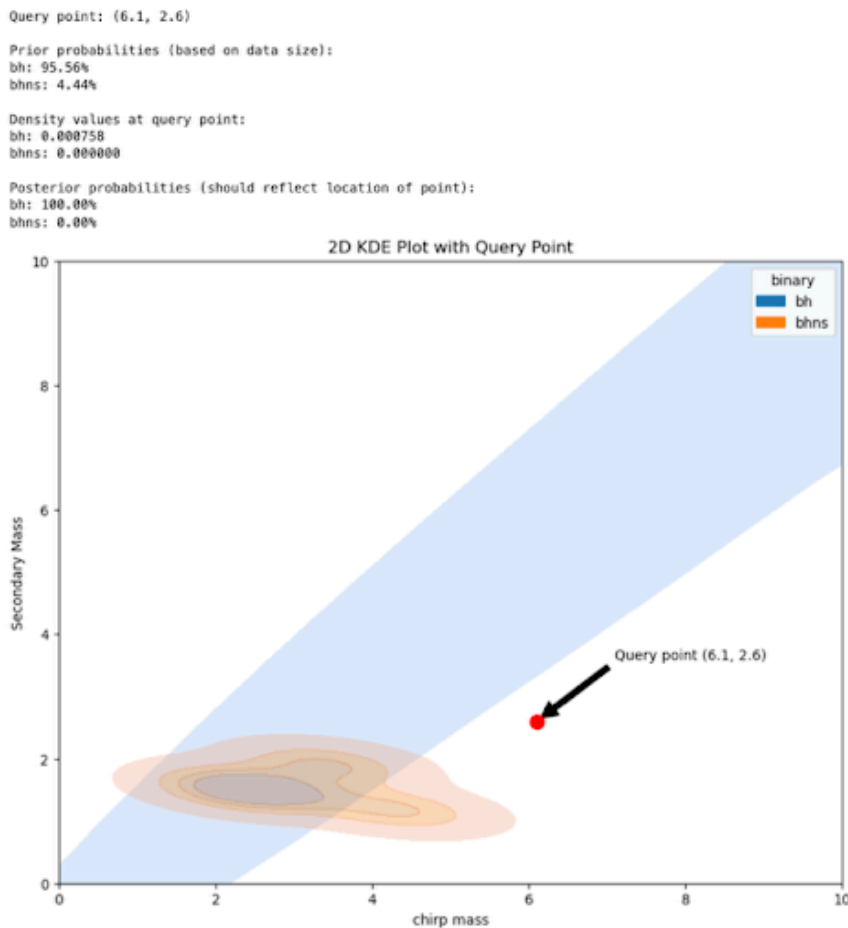


Figure 8

In Figure 8, the conditional distributions of chirp mass against secondary mass are shown. I limited both axes to 10 solar masses for clarity, but the range does reach around 100 solar masses. This graph visualizes how much of an outlier GW190814 can be seen as, which is not that much. The best part is, with some coding, the computer can estimate the possibilities straight from the graph. For GW190814, there is almost a 96% chance of being a black hole by comparing both chirp mass and secondary mass. This result is consistent with estimations with only the variable of chirp mass or of secondary mass. In fact, the two-variable estimation is more confident in the binary being a BH binary.

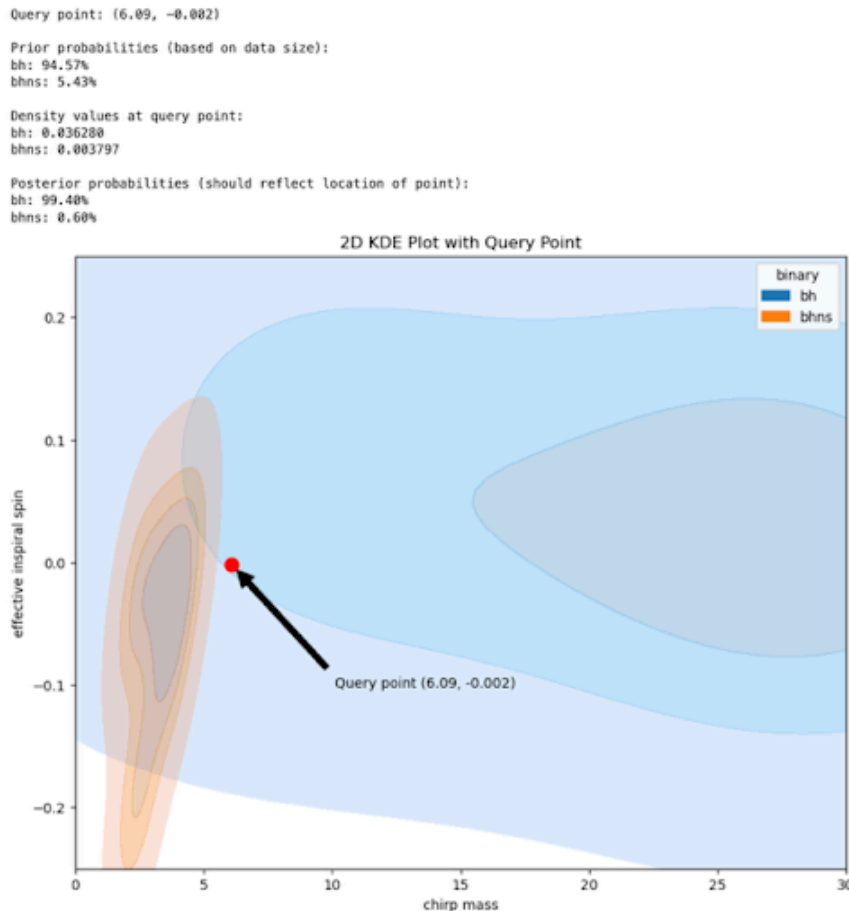


Figure 9

For Figure 9, the two variables are chirp mass and the effective inspiral spin. The estimation of the single variable effective inspiral spin suggests a higher possibility of a BHNS binary. However, in combination with the chirp mass density, the estimation came out to be about 95% BH binary. This is very surprising, as the singular variable of chirp mass estimation being a BH binary is 90%, even less than the combined estimation. With this example, the two-variable, combined estimation may be considered more reliable, as it avoids narrow estimations based on only one variable by allowing the data to interact with one another.

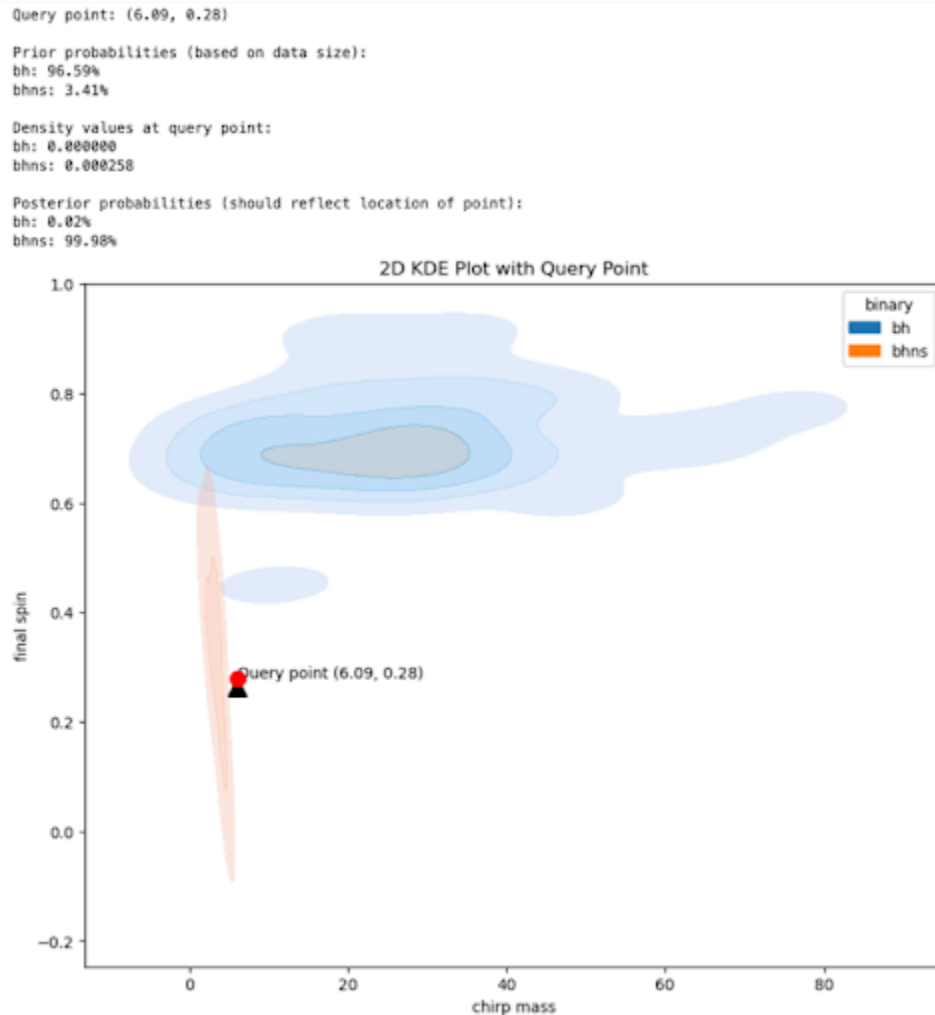


Figure 10

For Figure 10, the code made some interesting conclusions. Unlike the previous graphs with similar prior and posterior probabilities, this graph gives completely opposite probabilities: a 96% chance of being a black hole drawn from prior probability; a 100% chance of being a neutron star drawn from posterior probability. In short, prior probability is an estimation made without including the data of GW190814 in the dataset, while posterior probability considers the data. Because the identity of the secondary mass from GW190814 is still unknown, we should not consider the posterior probability, as it does not offer any value in the identification of the mass. Still, posterior probability gives us a hint of the complexity of the relation between the chirp mass and the final spin. The graph shows a majority of BH binaries producing remnants with spin higher than 0.6, with notable exceptions of chirp masses about 5 to 15 solar masses producing remnants with spin from 0.4 to 0.5. This isolation suggests some other variable will affect the remnant spin, but it is only applicable to some binaries with chirp mass about 5 to 15 solar

masses. The BHNS binary area, represented in orange, is easier to understand. The long shape is due to a focused chirp mass around 3 solar masses, which is because the small masses of neutron stars would not result in large chirp masses. However, the final spins range from 0 to almost 0.7. This might be because neutron stars' properties do not allow them to produce as much energy as black holes do, resulting in small remnant spins.

CONCLUSION

In an overview, even if an estimation gives more probability for the mass to be a neutron star in one variable density graph, combining that specific variable with chirp mass to form a two-variable density graph would give estimations of about 96% for the secondary mass of GW190814 to be a black hole. Therefore, it is reasonable to suggest the mass to be a black hole rather than a neutron star. Although I only created two variable density graphs with one variable being the chirp mass, which might lead to narrow results that curve towards the conclusion of chirp mass, the one-variable estimations of chirp mass predicted fewer chances, 90% to be exact, than two variable estimations. From these behaviors, we could assume that including another variable, even when it gives more probability of a neutron star on its own, is building on the credibility and reliability of the prediction of the mass being a black hole.

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