ASTR 2030 Black Holes Spring 2019. In class group Project 5. Fri Apr 26.

Scribe's name:

Names of other members of the group:

LIGO

The Laser Interferometer Gravitational-Wave Observatory (LIGO) observed gravitational waves from the merger of a pair of black holes for the first time on 2015 September 14, an event tagged GW150914. The observation ushered in the era of gravitational wave astronomy, and was a spectacular confirmation of the predictions of general relativity in a strongly gravitating system. During two observing runs over the next two years, LIGO, joined during the second run by the European gravitational wave observatory VIRGO, detected a total of 9 black hole mergers and 1 neutron star merger.

1. The quantity measured by LIGO is the **strain** h, defined to be

$$\text{strain } h = \frac{\text{Change in distance between mirrors}}{\text{Normal 4 kilometer distance between mirrors}} \ . \tag{1}$$

   Judging from Figure 1, approximately what strain is LIGO able to measure? What change in distance between mirrors is LIGO able to measure? Express this distance in terms of something familiar, such as the size of a human hair (10^{-4} meters), an atom (10^{-10} meters), or a proton (10^{-15} meters).

2. Describe qualitatively the shape of the "chirp" waveform that the detectors saw from GW150914, Figure 1. My answer describes four salient features.

3. The orbital frequency f of a binary containing two objects of combined mass M a distance R apart is approximately

$$f \approx \sqrt{\frac{GM}{R^3}} \ . \tag{2}$$

   When the orbital separation R has decreased to approximately the Schwarzschild diameter, $R \approx 4GM/c^2$, the two objects merge into a single black hole. When a binary system merges to a black hole, which produces higher frequency gravitational waves, a more massive or a less massive binary system?

4. Interpret qualitatively the description you gave in part 2 in terms of the frequency given in part 3. [Hint: A binary system produces gravitational waves with a frequency approximately equal to[1] the orbital frequency.]

5. The combined mass of the merging black holes in GW150914 was approximately $M = 60$ solar masses. What aspect of the waveform was most important in determining that mass?

6. In the neutron star merger event GW170817, the combined mass of the two neutron stars before they merged was $M = 2.8$ solar masses (the masses of the individual stars is harder to disentangle). What is the significance of this mass?

7. The LIGO detectors are sensitive to frequencies of 30 Hertz (that is, 30 times per second) and higher. From Figure 1, for roughly how long was GW150914 visible prior to merger? Why was the neutron star merger event GW170817 visible for a much longer time (almost a minute!) prior to merger. [Hint: Your answer to part 3 is relevant here.]

8. Why are the arms of the LIGO detectors in Hanford, Washington and Livingston, Louisiana 4 kilometers long? [Hint: Why might long arms permit smaller strains to be measured? Why must the arm length be much less than a wavelength of a gravitational wave, in order to track it accurately? Expected wavelengths of gravitational waves from merging black holes are 10s to 1000s of kilometers.]

9. Why are two LIGO detectors 3,000 kilometers apart needed, one in Washington and the other in Louisiana, in order to detect robust signals from astronomical sources? [Hint: Optical telescopes are built far from light pollution. The LIGO detectors are exquisitely sensitive to vibrations from the surroundings, including traffic and seismic noise.]

10. If a gravitional wave is a wave of spacetime that changes distances between things, won't it also change the lengths of rulers that measure distances, making it impossible to measure gravitational waves? Discuss.

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[1] Actually the gravitational wave frequency is twice the orbital frequency, in accord with a fundamental prediction of general relativity that gravitational waves have spin 2.

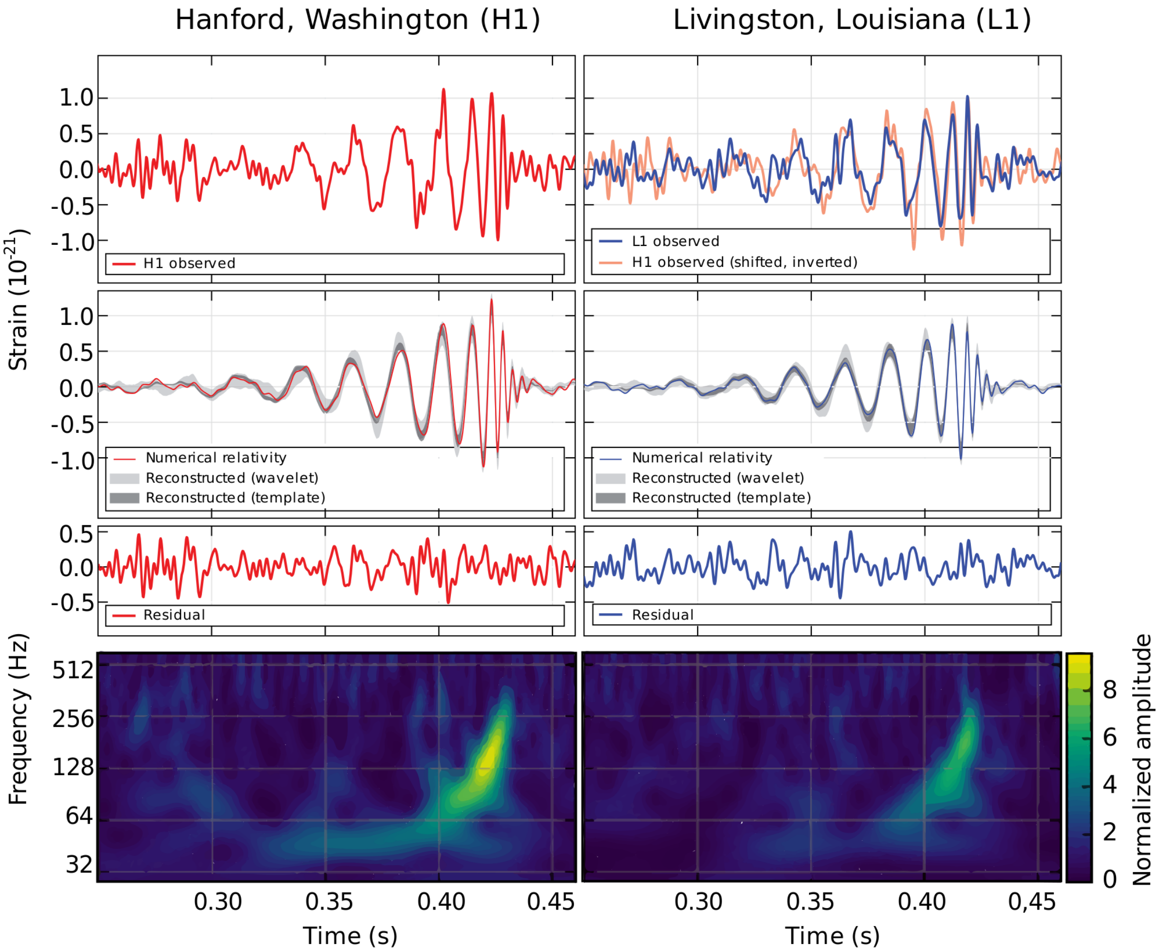

Figure 1: Gravitational waveform "chirp" measured for GW150914.