ASTR 3800 Final Project

The final project combines the topics of time-domain astronomy, gravitational waves, galaxies, stellar-mass black holes, and cosmology. We will focus on LIGO, which detects inspiralling and merging stellar-mass compact objects.

We will work with the LIGO data release. Here is the plan:

- Week 1: Do Tutorial 12 on LIGO signal detection. Due November 11.
- Week 1.5: Analyze event demographics. Checkpoint on November 15.
- Week 2: Do "standard siren" analysis to determine H_0. Checkpoint on November 18.
- Week 3: Do your own exploration/analysis. Checkpoint on December 1.
- Week 4: Presentation of your work in a notebook or document. Due December 8.

The project (everything except Tutorial 12) will be due December 8 at 3:30 pm.

Everything you retrieve from online sources must be properly cited. If you work with anyone or receive help from anyone, please acknowledge their contribution.

Each checkpoint will include upload of your work so far to Canvas and submission of your questions or concerns, either in the comment field or in your notebook. Your uploaded work does not need to be correct or final, and can include pseudo code or algorithms, but it does need to show strong effort and progress.

Your submission for the project should include a presentation of your work and findings (including code and steps, similar to homework assignments) in `pdf` or `html` format. It should include all parts of the project except for Tutorial 12 (submitted separately). You may find it easier to submit your project as an exported Jupyter notebook, but it's up to you. You can also export your figures to include them in a document.

Scoring: Each checkpoint will be worth 5% (there are 3 of them), the Tutorial is 10%, Demographics and Standard Siren work are 20% each, your own exploration is 25%, and the remaining components in the submission will be 10%.

1 LIGO Signal Detection Demo

Please complete Tutorial 12.

2 Event Demographics

Visit the event list at https://www.gw-openscience.org/eventapi/html/GWTC/ (the description of the catalog columns is here: https://arxiv.org/pdf/2111.03606.pdf) and download your favored file format (bottom left of page).

Analyze the event demographics using descriptive statistics and plots to answer the following questions:

1. What seems to be the redshift or distance limit for LIGO?
2. Are the binary masses correlated with distance? Why or why not? Quantify your answers and assess significance.
3. What mass fraction is converted into gravitational waves, on average, and what is the spread in this fraction?
4. Calculate and plot the gravitational wave luminosities in units of the solar luminosity. You will have to assume a typical duration for the mergers. What is the spread in luminosities? Compare the most luminous merger to something else in the universe.
5. What is the distribution in binary mass ratio? What are the minimum and maximum mass ratios?

3 Standard Sirens

Gravitational wave sources can be used as "standard sirens" because the inspiral process (the chirp) reveals the black hole masses involved in creating the GW luminosity (so the luminosity can be measured from the chirp). The observed "flux" (dimensionless strain) can be combined with the luminosity to obtain the luminosity distance to each event:

$$D_L = \sqrt{\frac{L}{4\pi F}}$$

If the host galaxy of the merger can also be identified, then an optical redshift (z) can also be obtained, so one can use Hubble's Law to measure the Hubble Constant from

$$c\,z = H_0 D_L$$

(one technically should not use the luminosity distance for this, but that's an issue for a cosmology course).

In order to measure the Hubble Constant, one needs a electromagnetic (usually optical) redshift from a spectrum. This requires an "electromagnetic counterpart" to be identified as the source of GWs. The GW detector network can localize an event on the sky, but the "banana" regions are vast. Moreover, black hole-black hole mergers are not expected to make much (or any) light.

The only merger so far to be identified with a specific galaxy is the neutron star-neutron star merger GW170817. Since this did not involve black holes, it was observed with nearly every telescope on Earth and in space and was detected across the EM spectrum.

1. Find this merger in the event catalog and record its luminosity distance and the uncertainty.
2. An observed recession velocity of the host galaxy is 3017 ± 166 km/s. What is H_0?

3. Calculate the uncertainty in your value of H_0 and compare your value to other current measurements. Is it consistent with the CMB or the local measurements of H_0?

4. Estimate how many more such events you would need in order to reduce the uncertainty on H_0 to 10%. How about 1%?

4 Your Own Exploration and Analysis

Time to explore gravitational waves on your own!

1. Write down a question or questions that you would like to answer.
2. Can the answer to your question be quantified using data or theoretical calculations?
3. Attempt to answer your question. In the process, always make plots and support conclusions quantitatively. Cite your sources.

This exploration should be substantial and quantitative and include plots and/or tables.

Possible exploration pathways:

1. Analyze the effective spin parameter. What is it? What should its distribution look like, and how does this compare to the actual distribution in the data? Quantify the difference between expectation and reality and address the significance. Does the spin parameter correlate with any other quantities such as the mass ratio or GW luminosity?

2. Search for correlations in the event catalog data. Are there any hidden relationships? A correlation matrix would be helpful here. Or you could use machine learning tricks like Principal Component Analysis or classification schemes.

3. What is the chirp mass, and what does it mean? What does the cosmological redshift do to the observed chirp mass?

4. Examine a specific event in detail. Characterize its strain amplitude, duration, interpretation, location, etc.

5. Explore the connection between LISA events and LIGO events, specifically those that could be detected by LISA first and then detected by LIGO. Are there known LIGO events that could have been predicted by LISA if it were running?

6. Theory: How would the characteristics of a LIGO event change if two supermassive black holes merged? Be quantitative in your descriptions. What kind of detector would you need?

7. Theory: Calculate the dimensionless strain caused by various events, such as the Moon orbiting the Earth, a rabbit hopping around near the detector, or an earthquake. Compare your numbers to LIGO events.

8. Theory: What is the separation between two black holes when they merge? What is their orbital velocity when this happens, expressed as a fraction of the speed of light? Is the speed always the same at the merger point or does it depend on the masses or mass ratio of the binary? Apply your theoretical expectation to a specific event.

9. Examine the "banana" plot for a specific LIGO event and estimate the number of galaxies that could have hosted the event.

10. Theory: Suppose that low mass primordial black holes formed binaries and merged. What would that signal look like compared to a LIGO event? Be quantitative and list your assumptions.
11. Given the LIGO event rate, how many black holes merge in the observable universe every day? What would we need to do to hear all of them?
12. Theory: There could be primordial gravitational waves from the epoch of inflation in the early universe. What's that all about, and how could they be detected?
13. Theory: Would a mountain on a rotating spherical body make gravitational waves? Where would the energy come from? What would the signal look like for a 10 cm high mountain on a neutron star?

If you would like help with a different exploration topic of your own design, please ask!

5 Presentation

Present your work, including the following parts:

1. An abstract that summarizes your work and results.
2. An introduction to GWs and LIGO of at least two paragraphs that includes references.
3. Your analysis of the event demographics.
4. Your standard siren analysis.
5. Your own exploration and analysis. This should be substantial and quantitative and include plots and/or tables.
6. Acknowledgements.
7. References.

Your writeup should be submitted in `pdf` or `html` format. You may find it easier to submit your writeup as an exported Jupyter notebook, but it's up to you. You can also export your figures to include them in your favorite document production software.