Computational Physics Project / LIGO

This project involves finding a gravitational wave in the LIGO data set. If you do not know what LIGO is ... *find out!* This is probably the most significant physics result of your lifetime. It is a close race between cosmic acceleration, the Higgs particle, and this, anyway.

In this project, you will use Fourier techniques to find the merging black hole signal `GW150914`. Write a Python program to read in the LIGO data, do some simple cleaning, and find the signal.

LIGO has two independent observatories, one in Livingston, LA and the other in Hanford, WA. Both detectors must see a signal within 10ms of each other for it to count. A window of data (32 seconds) around the time of the event is available for download here:

- `https://losc.ligo.org/s/events/GW150914/H-H1_LOSC_4_V1-1126259446-32.hdf5`
- `https://losc.ligo.org/s/events/GW150914/L-L1_LOSC_4_V1-1126259446-32.hdf5`

These are `HDF5` files, a binary file format often used in science. These files are much smaller and quicker to read/write than plain text files. The `h5py` library (included in Anaconda and available through `pip`) interacts with these files. A function to do so is:

```
def loadLIGOdata(filename):
    f = h5py.File(filename, "r")
    strain = f['strain/Strain'][...]
    t0 = f['strain/Strain'].attrs['Xstart']
    dt = f['strain/Strain'].attrs['Xspacing']
    t = t0 + dt * np.arange(strain.shape[0])
    f.close()
    return t, strain
```

This returns the time (in seconds) and the strain (which has no units). The measurements in this data set are evenly sampled at 4096 Hz.

The strain $h(t)$ is what is measured by LIGO. You can think of it as the fractional change in the length of the 4km interferometer arms: $\Delta L/L$.

- Plot the strain as a function of time for both detectors. Gravitational waves from astrophysical sources produce a maximum strain on Earth of about 10^{-21}. Can you see a gravitational wave in the data? No. You cannot. Most of the strain is "noise" coming from various physical effects in the detector.
- To find how the noise affects the data, plot the *periodogram* $P_{hh} = |h_k|^2$ of the data for each detector using an FFT. The periodogram is a simple (not very optimal) estimate of

the *power spectrum*, which indicates how much power is in each Fourier mode of the data. The periodogram shows a lot of power for $f < 30$ Hz, and many spectral lines. These lines correspond to resonances in the LIGO machinery (the cables suspending the mirrors, the 60 Hz electrical frequency, etc). These are clearly noise!

- Filtering out particular modes in Fourier space is not difficult, simply multiply the FFT of your data h_f by a *transfer function* $H(f)$, where $|H(f)| < 1$, then perform the inverse transform to see the filtered data. Here are two very simple filters:

$$H_{\rm step}(f) = \frac{1}{1+(f/f_0)^{2n}} , \tag{1}$$

$$H_{\rm gauss}(f) = 1 - \exp\left(-\frac{(f-f_0)^2}{2\sigma_f^2}\right) . \tag{2}$$

  In the above, f_0 is the location of the filter and n or σ_f control the width. Describe in words what each filter does. Construct some test data, and use the filters on it, that demonstrate what these filters do.

- LIGO is most sensitive between 35 Hz and 350 Hz. Use H_{step} with $n \sim 8$ to filter out the modes outside this band. Plot the resulting waveform and periodogram.

- See a signal yet? Use the $H_{\rm gauss}$ filter to remove spectral lines from the data as well. Plot the resulting waveform and periodogram.

- This dataset contains the *first ever* detection of a binary black hole merger! What time does it occur at? Remember: a real signal appears in both data sets with a time delay of no more than $10ms$.