CRLS Astrophysics Lecture Series: Gravitational waves and coins

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Week 1

Goals

This activity aims to make the student familiar with gravitational waves and the analysis of their detection by simulating a gravitational wave signal through the recording of the sound produced by a coin spinning down. This activity is based on the paper "Student project: Of spinning coins and merging black holes" by Bland-Hawthorn & Sudiwala (2016), arXiv:1611.00070.

Reading list

- The New York Times: *Gravitational Waves Detected, Confirming Einstein's Theory*
- The Washington Post: *A brief history of gravity, gravitational waves and LIGO*
- The Washington Post: *A year later, scientists keep listening to gravitational waves, the soundtrack of the cosmos*
- NASA: *NSF's LIGO Has Detected Gravitational Waves*
- NASA: *What is a gravitational wave?*
- NASA: *Gravitational waves*
- JPL: *Gravitational Waves Detected 100 Years After Einstein's Prediction*

Week 2

Goals

Students will simulate a gravitational wave by recording the sound made by a spinning coin and analyzing the resulting signal.

Equipment

1. Computer
2. Recording equipment
3. Anaconda Python platform, downloadable from https://www.continuum.io/downloads

4. The ligo-coin jupyter notebook: https://github.com/guillochon/ligo-coin/blob/master/ligo-coin.ipynb For convenience, the notebook is attached below.

Activity

Students should split into groups of 2-3, load the ligo-coin jupyter notebook (it would be best if the notebook is pre-loaded on the students' computers) and follow the instructions in the notebook.

ligo-coin

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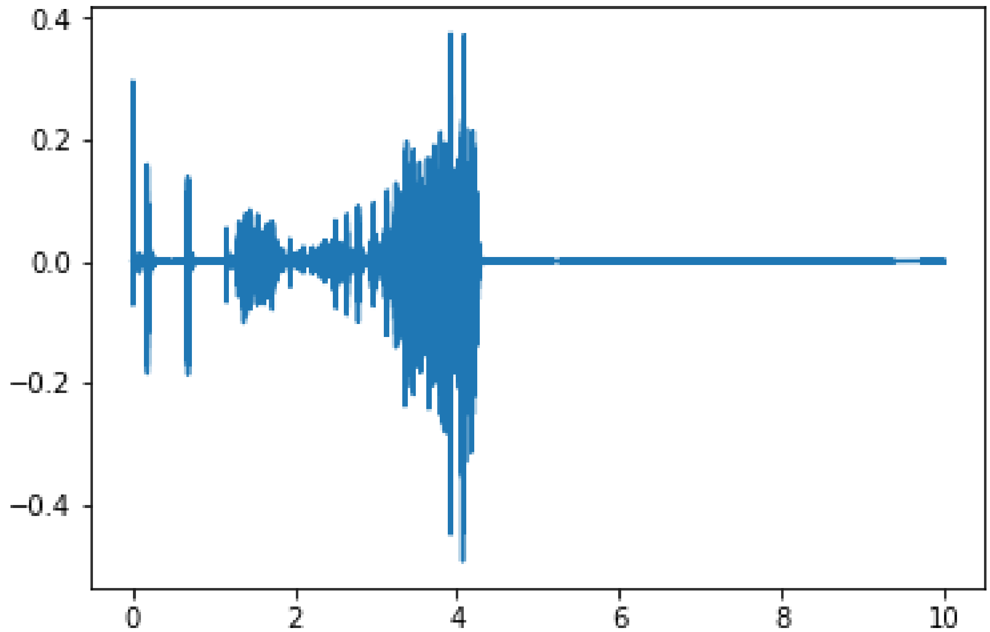
1. Record your coin spinning!
Click the code in the rectangle below, then press shift+return to evaluate.

```
In [5]: %matplotlib inline

        import sounddevice as sd
        import matplotlib.pyplot as plt
        import numpy as np
        from scipy import signal as sig

        fs = 48000  # sampling rate (measurements per second)
        duration = 10  # seconds (10 is a good value)
        recording = sd.rec(int(duration * fs), samplerate=fs, channels=1)
        print('Recording for the next {} seconds...'.format(duration))
        sd.wait(); print('Done!')
```

```
Recording for 10 seconds...
Done!
```

2. Plot the raw sound. (again, click in the cell then shift+return)

```
In [13]: ts = np.linspace(0, duration, duration*fs)
         signal = np.array([y[0] for y in recording])
         plt.plot(ts, signal);
         plt.show();
```

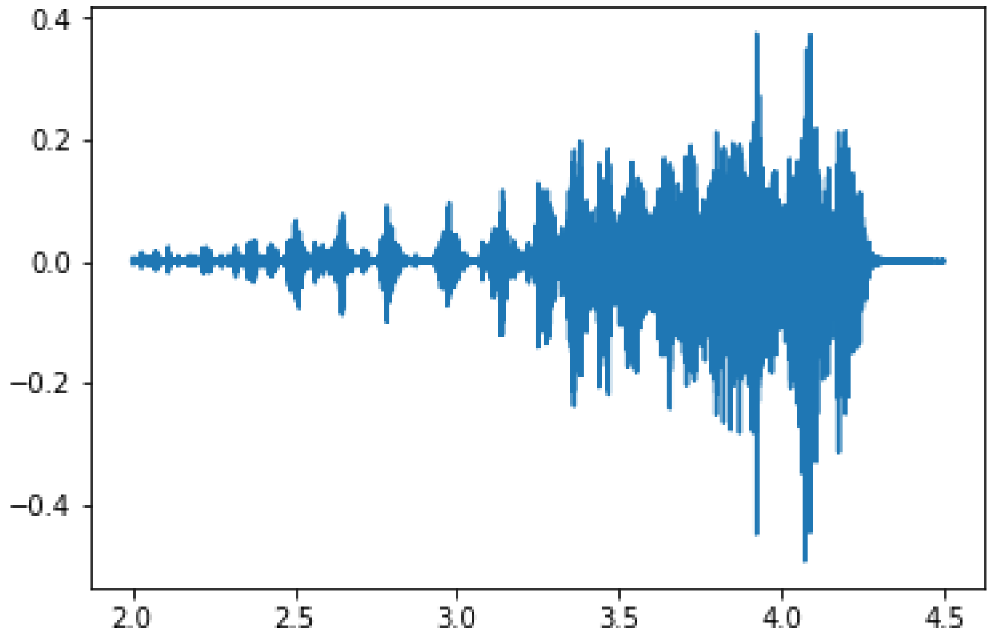


3. Play back the full recording

```
In [7]: sd.play(10*signal, fs)
        sd.wait()
```

4. Choose `start_t` and `end_t` such that only the spinning coin signal is visible.

```
In [14]: start_t = 2;
         end_t = 4.5;

         ind = np.logical_and(ts >= start_t, ts <= end_t)
         s1 = signal[ind]
         t1 = ts[ind]
         plt.plot(t1, s1)
         plt.show()

         sd.play(10*s1, fs)
```

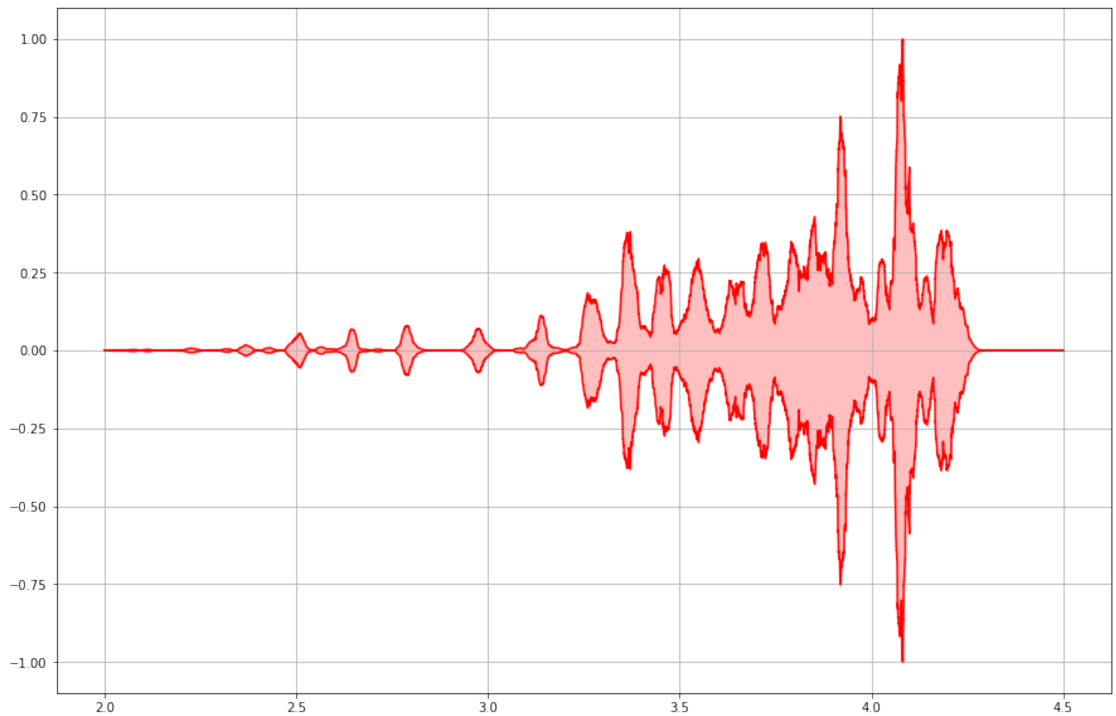


5. Let's look at the spectrum of the above signal.

```
In [ ]:
```

6. Generate a smoothed version of the signal to remove high-frequency noise.

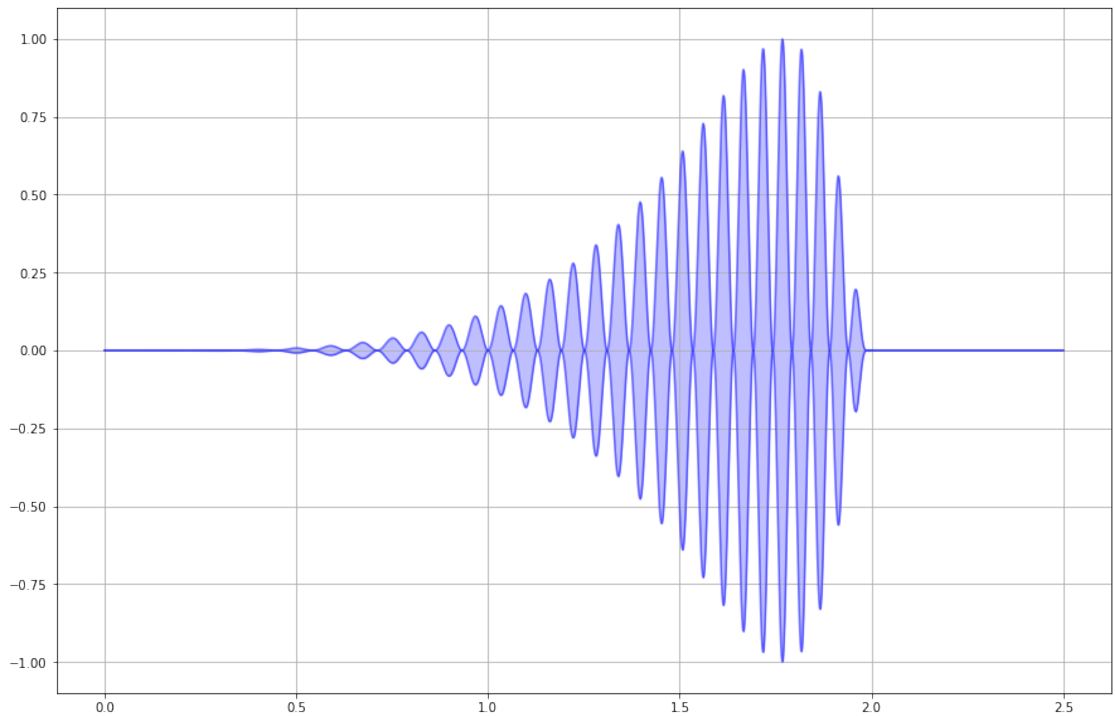
```
In [21]: def smooth(y, box_pts):
             box = np.ones(box_pts)/box_pts
             y_smooth = np.convolve(y, box, mode='same')
             return y_smooth

         # Adjust this number!
         nwindow = 1000   # 1000 is a good starting value

         ta = t1
         sa = smooth(s1**2, nwindow)

         plt.figure(figsize=(15,10));
         ya = sa/np.max(sa)
         plt.plot(ta, -ya, 'r');
         plt.plot(ta, ya, 'r');
         plt.fill_between(ta, -ya, ya, alpha=0.25, color='r')
         plt.grid()
```



7. Let's make a model of the signal.
We'll construct a model that looks like the following:

$$A = \left(\frac{t}{t_0}\right)^{\alpha} \sin\left[2\pi f t \left(\frac{t}{t_0}\right)^{\beta}\right] \max\left[1 - \exp\left(\frac{t-\tau_{\text{ring}}}{\tau_{\text{ring}}}\right), 0\right]$$

In [16]:
```
# Play with these numbers:
t0 = 1.0;   # 1.0
tring = 2.0;   # 2.0
ringtau = 0.1;   # 0.1
omega = 5.0;   # 5.0
phase = 0.0;   # 0.0
alpha = 2.0;   # 2.0
beta = 0.5;   # 0.5
# End

tmt = ta - min(ta);
yp = np.array([((t/t0)**alpha*np.sin(2*np.pi*omega*(t + phase)*(t/t0)**beta)*
                max(1 - np.exp(-(tring - t)/ringtau), 0))**2 for t in tmt]);
yp = yp/np.max(yp)

plt.figure(figsize=(15,10));
plt.plot(tmt, -yp, 'b', alpha=0.5);
plt.plot(tmt, yp, 'b', alpha=0.5);
plt.fill_between(tmt, -yp, yp, alpha=0.25, color='b');
plt.grid()
```

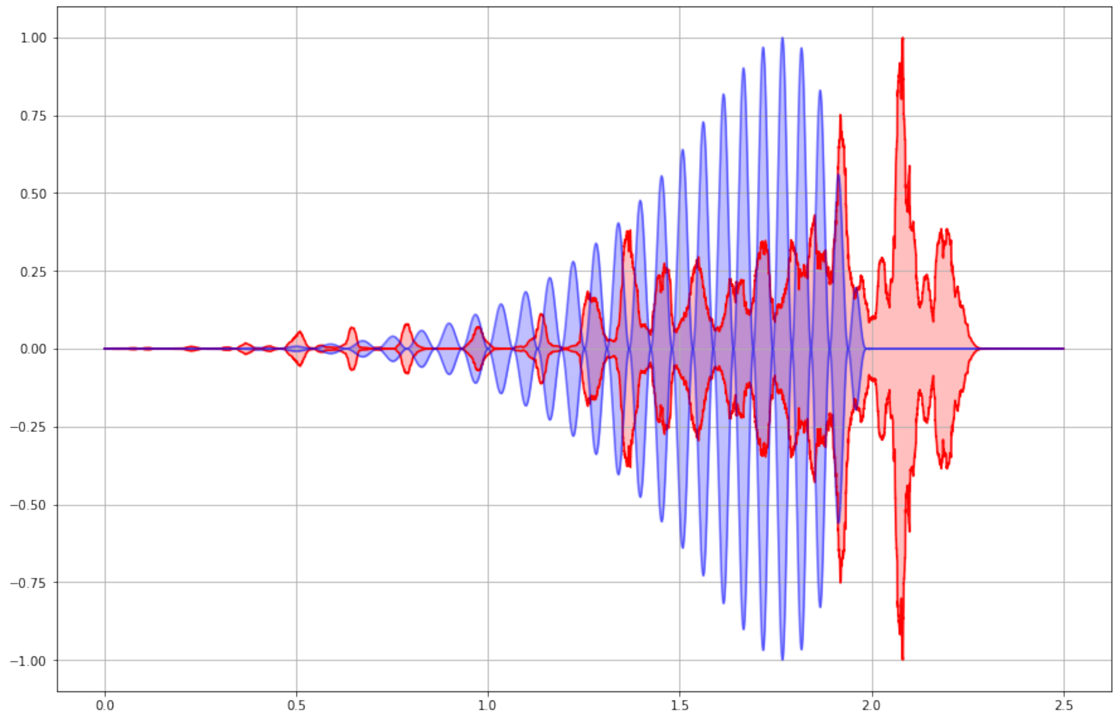


8. Play with the numbers defined below to find the best match to the coin signal:

In [18]:
```
# Play with these numbers:
t0 = 1.0;   # 1.0
tring = 2.0;   # 2.0
ringtau = 0.1;   # 0.1
omega = 5.0;   # 5.0
phase = 0.0;   # 0.0
alpha = 2.0;   # 2.0
beta = 0.5;   # 0.5
# End

# Don't edit below this line, that would be cheating! :-0
tmt = ta - min(ta);
yp = np.array([((t/t0)**alpha*np.sin(2*np.pi*omega*(t + phase)*(t/t0)**beta)*
                max(1 - np.exp(-(tring - t)/ringtau), 0))**2 for t in tmt]);
yp = yp/np.max(yp)

score = 1.0/(np.sum(abs(yp - ya)**2)*(100.0/len(tmt)));
print('Score is: {:6.2f}, can you do better?'.format(score))

plt.figure(figsize=(15,10));
plt.plot(tmt, -ya, 'r');
plt.plot(tmt, ya, 'r');
plt.fill_between(tmt, -ya, ya, alpha=0.25, color='r')
```

```
plt.plot(tmt, -yp, 'b', alpha=0.5);
plt.plot(tmt, yp, 'b', alpha=0.5);
plt.fill_between(tmt, -yp, yp, alpha=0.25, color='b');
plt.grid()
```

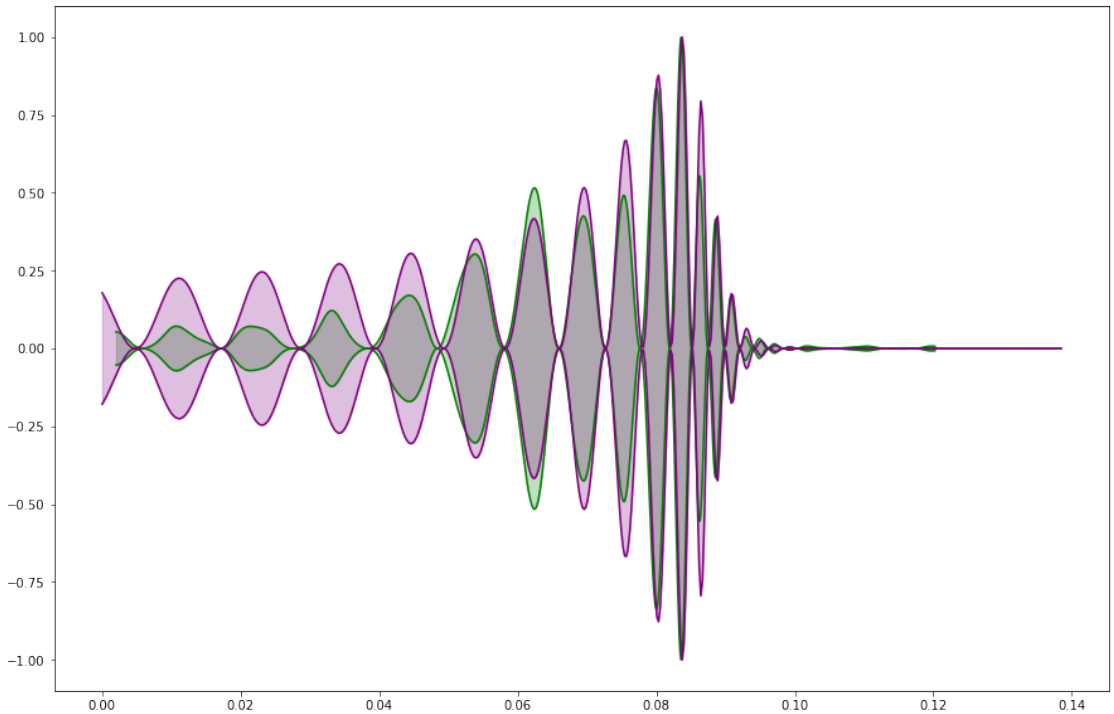
```
Score is:   0.22, can you do better?
```



9. Let's look at what the LIGO signal of two merging black holes looked like!
Data acquired from: https://losc.ligo.org/s/events/GW150914/GW150914_tutorial.html

In [346]:
```
offset = 0.002;

plt.figure(figsize=(15,10));
fdata = tuple(open('fig1-waveform-H.txt', 'r'))
fdata = [[float(y) for y in x.split()] for x in fdata[1500:-2]]
gwx, gwy = np.transpose(np.array(fdata));
gwy = (gwy/max(gwy))**2
gwx = gwx - min(gwx) + offset
plt.plot(gwx, -gwy, 'g')
plt.plot(gwx, gwy, 'g')
plt.fill_between(gwx, -gwy, gwy, alpha=0.25, color='g')

fdata = tuple(open('GW150914_4_NR_waveform.txt', 'r'))
fdata = [[float(y) for y in x.split()] for x in fdata[2200:-2]]
```

```
gwx, gwy = np.transpose(np.array(fdata));
gwy = (gwy/max(gwy))**2
gwx = gwx - min(gwx)
plt.plot(gwx, -gwy, 'purple')
plt.plot(gwx, gwy, 'purple')
plt.fill_between(gwx, -gwy, gwy, alpha=0.25, color='purple')

plt.show()
```



Extras: Don't use the cells below unless instructed.

```
In [12]: import pickle
         recording = np.array(pickle.load(open('coin.pickle', 'rb')));
```

```
In [115]: import pickle
          with open('coin.pickle','wb') as f:
              pickle.dump(recording, f)
```