LIGO Laser Interferometer Gravitational-Wave Observatory
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Do Binary Black Hole Merger Events Observed by LIGO-Virgo in their Third Observing Run Agree with Waveforms from General Relativity? A Residual Study

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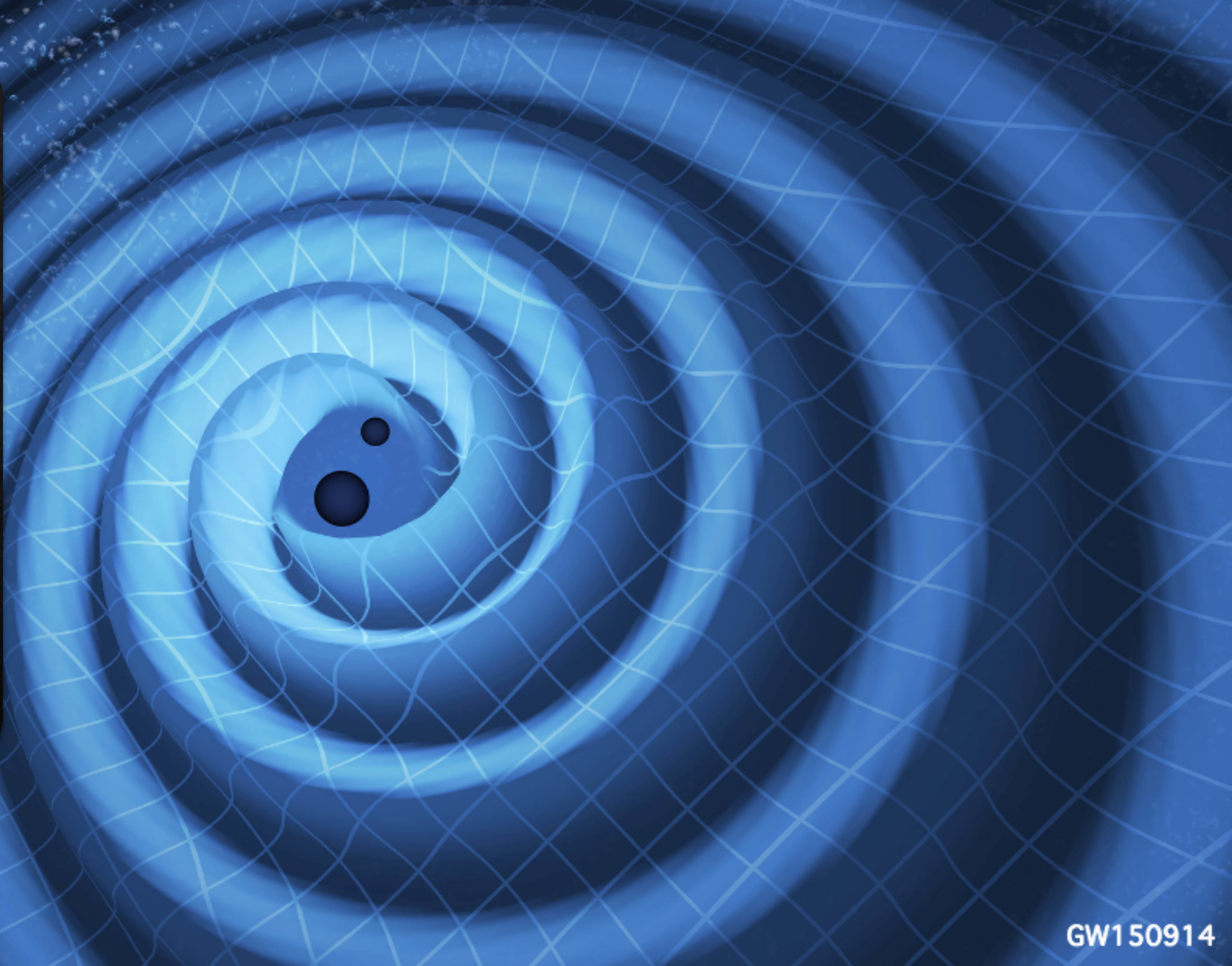
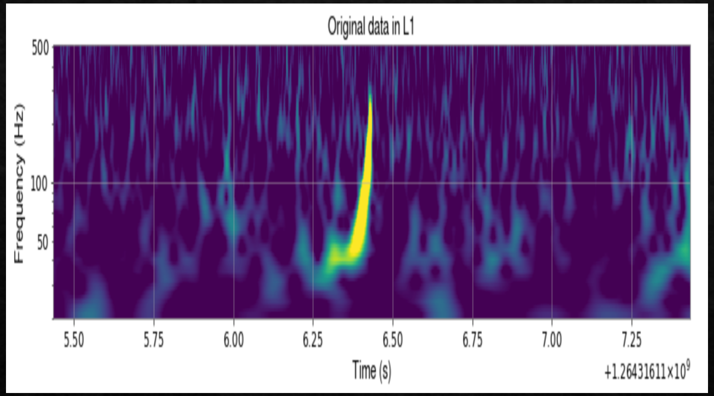
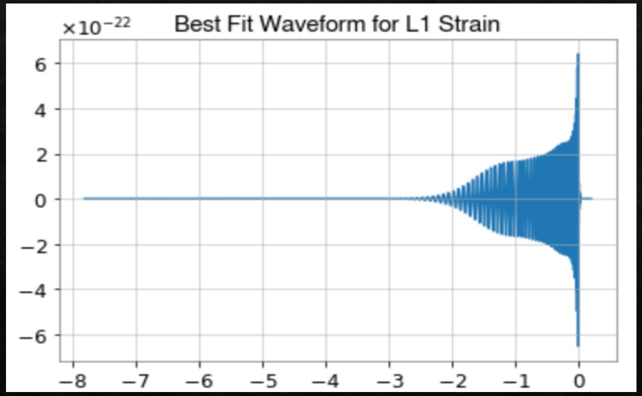


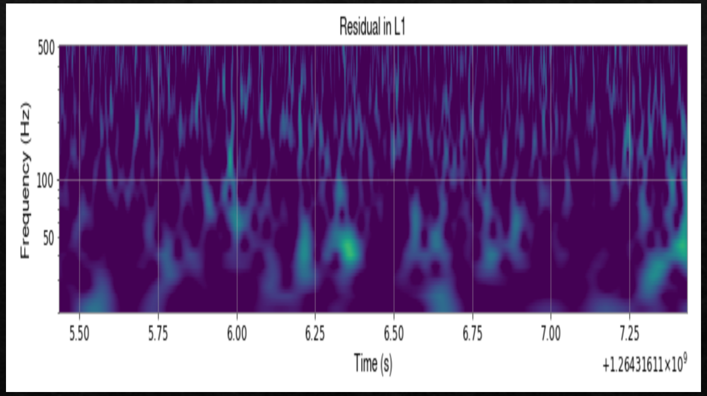
What is A Residual?

- LIGO data streams can be described as
  $d(t) = s(t) + n(t)$,
  where far away noise approximately Gaussian
- When a GR template [h(t)] is subtracted from the data series, what is left is known as a residual

$$r(t) = [s(t)-h(t)] + n(t) =?\ n(t)$$







Event S200129m (O3b)

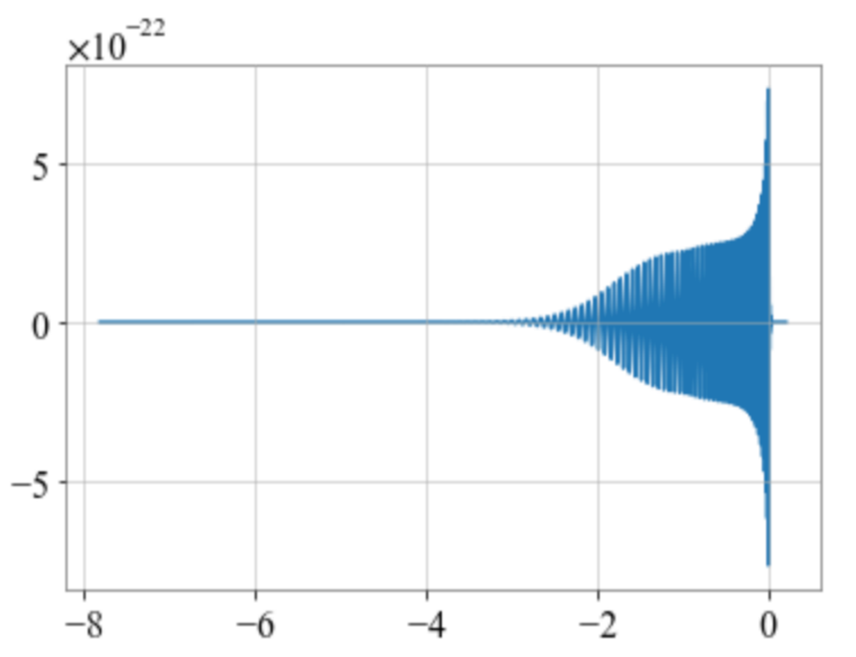
Motivation: Why is This Important?

- Are the signals observed in the LIGO detectors consistent with the waveforms derived from General Relativity?
- If they are, we can be **confident** that we understand the source of these signals
- If they aren't then:

- Perhaps the waveforms don't capture all the relevant physics such as spin precession, higher order modes, and eccentricity
- Perhaps the waveforms are insufficiently numerically accurate
- Perhaps there is excess noise in the detectors (glitches) that we don't understand
- Maybe General Relativity is wrong!!

Creating the Best Fit Waveform

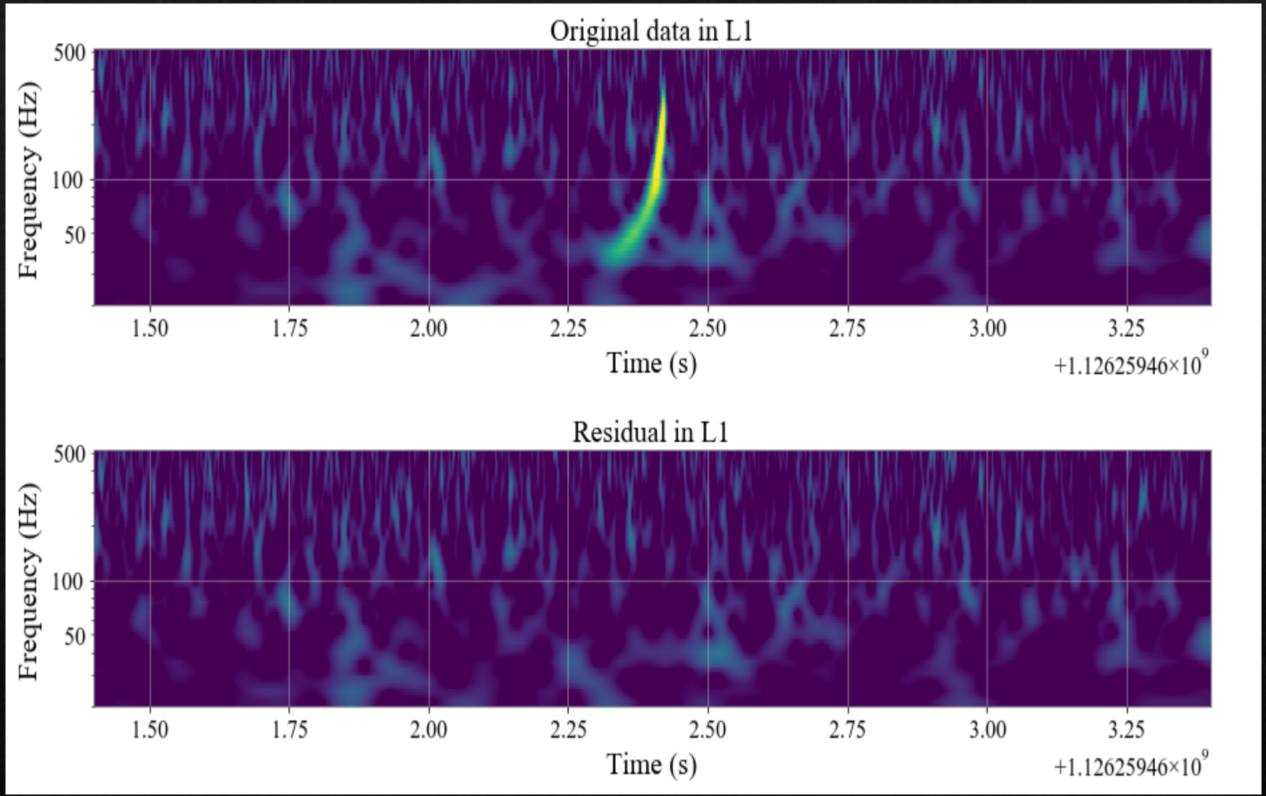
- Best fit waveforms are created from parameter estimation samples, which are generated by Bilby
- - 1. Includes all 15 BBH parameters along with the detector antenna response
- Using max likelihood value for each parameter will aid in creating more accurate waveform templates



Creating the Residual

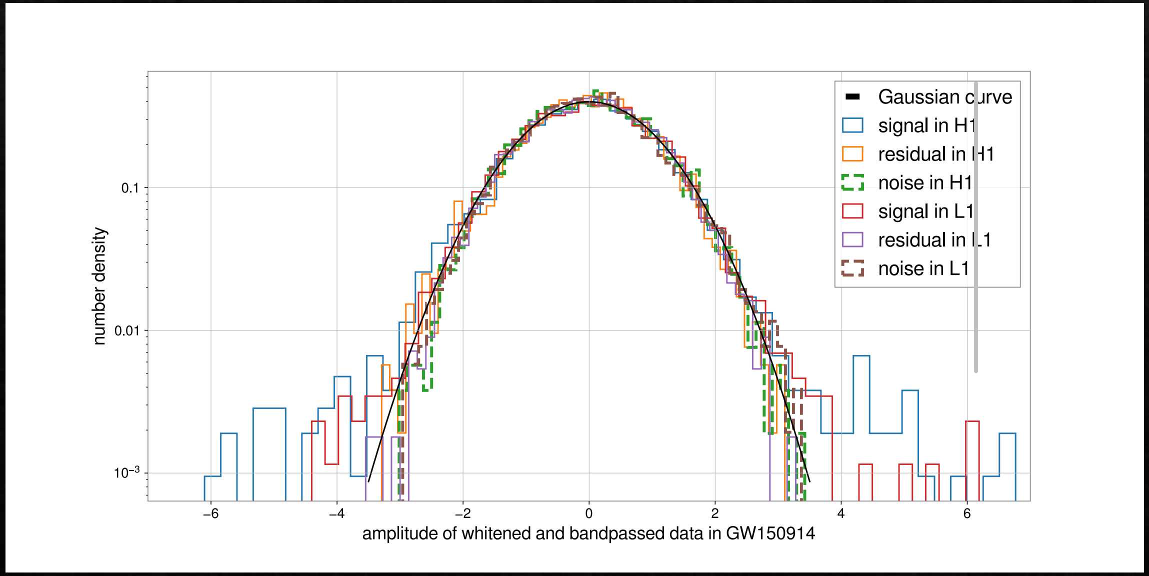
```
from pycbc.catalog import Merger
merger = Merger("GW150914")

# Get the data from the Livingston detector
strain = merger.strain('L1')

#subtract the waveform from the data
ht.resize(len(strain))
template = ht.cyclic_time_shift(ht.start_time)

dt = detime - strain.start_time
aligned = template.cyclic_time_shift(dt)

residual=strain-np.array(aligned)
```

```
for data, title in [(strain, 'Original data in L1'),(residual, 'Residual in L1')]:

        t, f, p = data.whiten(4, 4).qtransform(.001,
                                                logfsteps=100,
                                                qrange=(8, 8),
                                                frange=(20, 512))
        plt.figure(figsize=[15, 3])
        plt.title(title)
        plt.pcolormesh(t, f, p**0.5, vmin=1, vmax=6)
        plt.yscale('log')
        plt.xlabel('Time (s)')
        plt.ylabel('Frequency (Hz)')
        plt.xlim(merger.time- 1, merger.time + 1)
        plt.show()
```

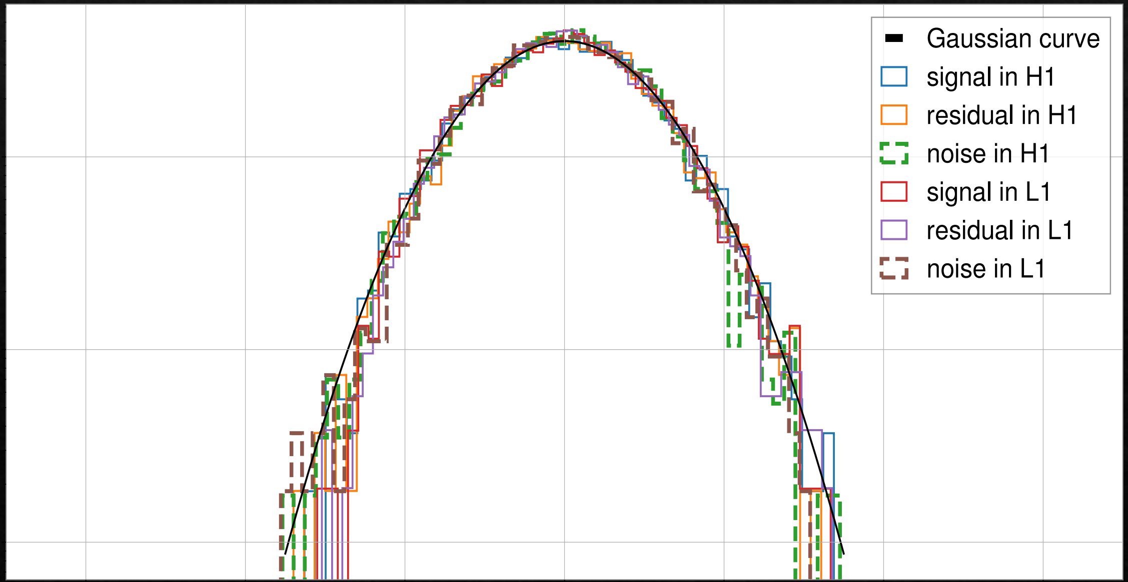


Gaussian Analysis

- As discussed last time, a Gaussianity test can be used to determine if the resulting residual consists of only instrumental noise
- However, this only works well for loud signals. How do can we double check that there isn't any left over signal in residuals of quieter events?



GW150914



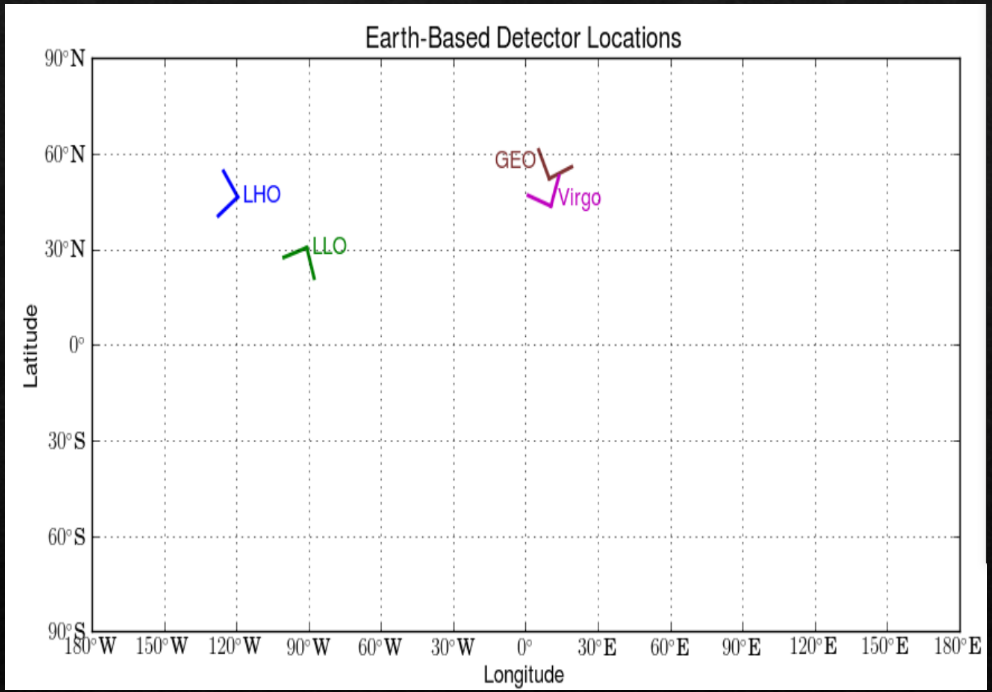
GW151012

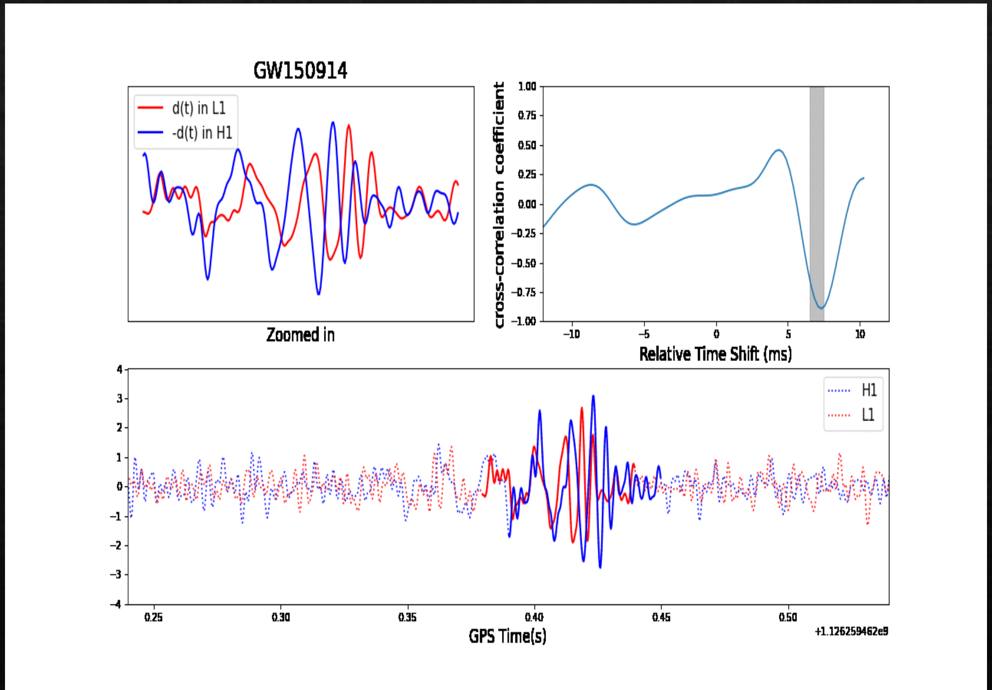
Correlation Analysis: And Why It’s Important

- Cross Correlation between the residual data from Hanford (H) with residual data from Livingston (L)
- Correlation Coefficient close to 1 or -1: data are correlated between the two detectors
- Correlation Coefficient close to 0: data are not correlated between detectors; signal subtraction is sufficiently precise

$$C(\tau; t, \omega) = \int_{t}^{t+\omega} \frac{H(t' + \tau)}{\sigma_H} \frac{L(t')}{\sigma_L} \mathrm{d}t'$$

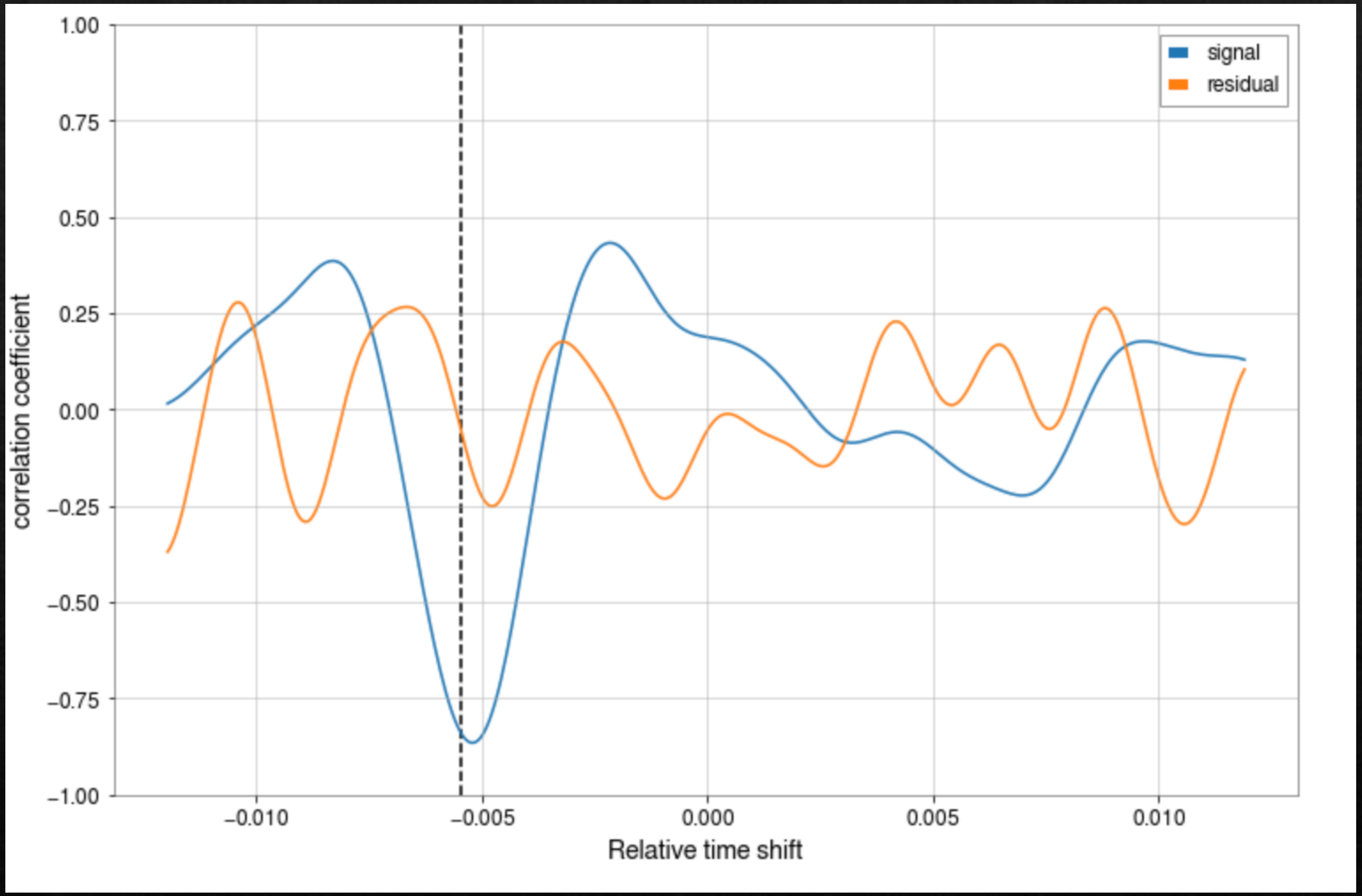
Correlation Analysis: And Why It's Important Cont.





Correlation Analysis of O3b Event S200129m

- Accounting for the time shift, the residual generated for the residual in both detectors for event S200129m has a correlation coefficient of -0.25, while the multiplied data series has a correlation coefficient of -0.8.



Future Short-term and Long-term Work

- Short-Term Goals:
  - We will want to apply this analysis to all 80+ events (GWTC-1, GWTC-2, GWTC-3)
  - We may find discrepancies requiring further investigation. We may even find evidence for waveforms that lack relevant physics or even failure of GR in the strong-field, highly dynamical regime that LIGO is probing.
- Long-Term Goals:
  - We want to automate this process so that can be applied to the much higher rate of gravitational waves from BBH events in O4.
  - Ultimately, we want to find out whether we truly understand gravitational waves from astrophysical sources, or whether there's more to be learned about the sources, the waves, and gravity itself.

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Any Questions?

Thank You for Listening!