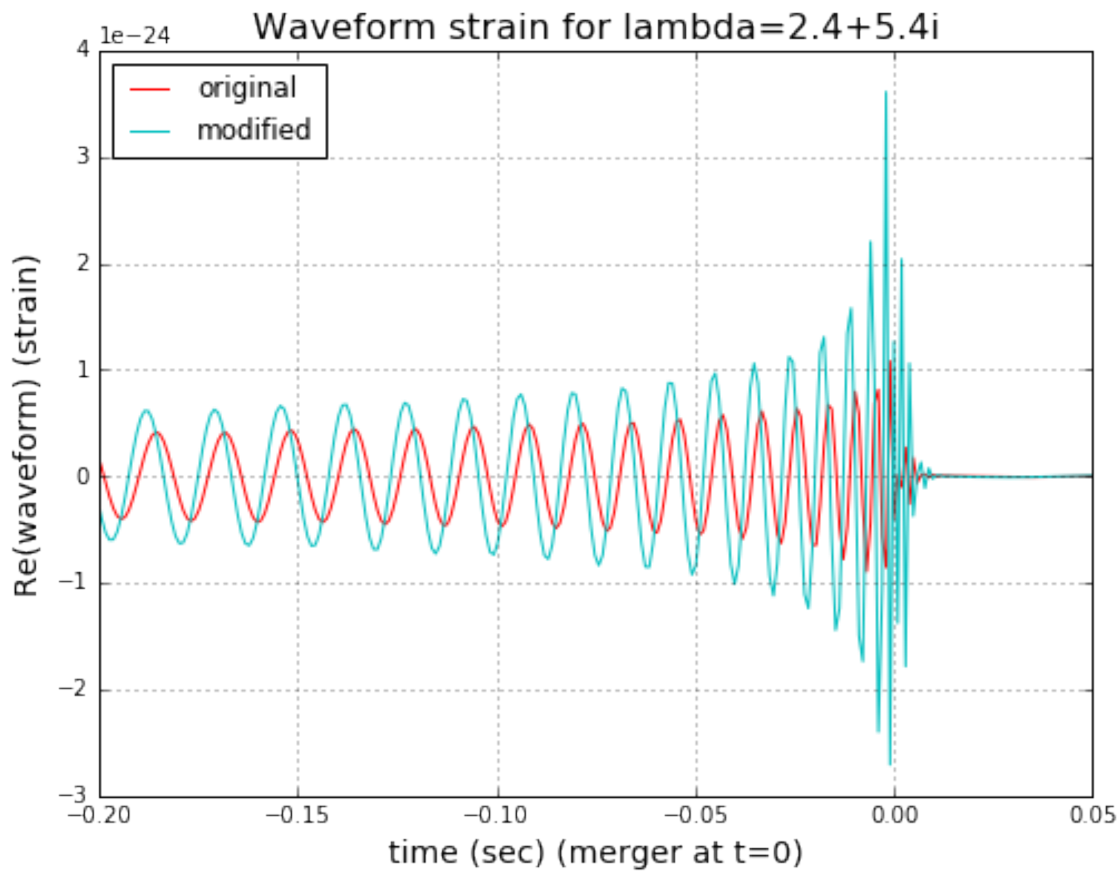
Quantifying Deviations from General Relativity

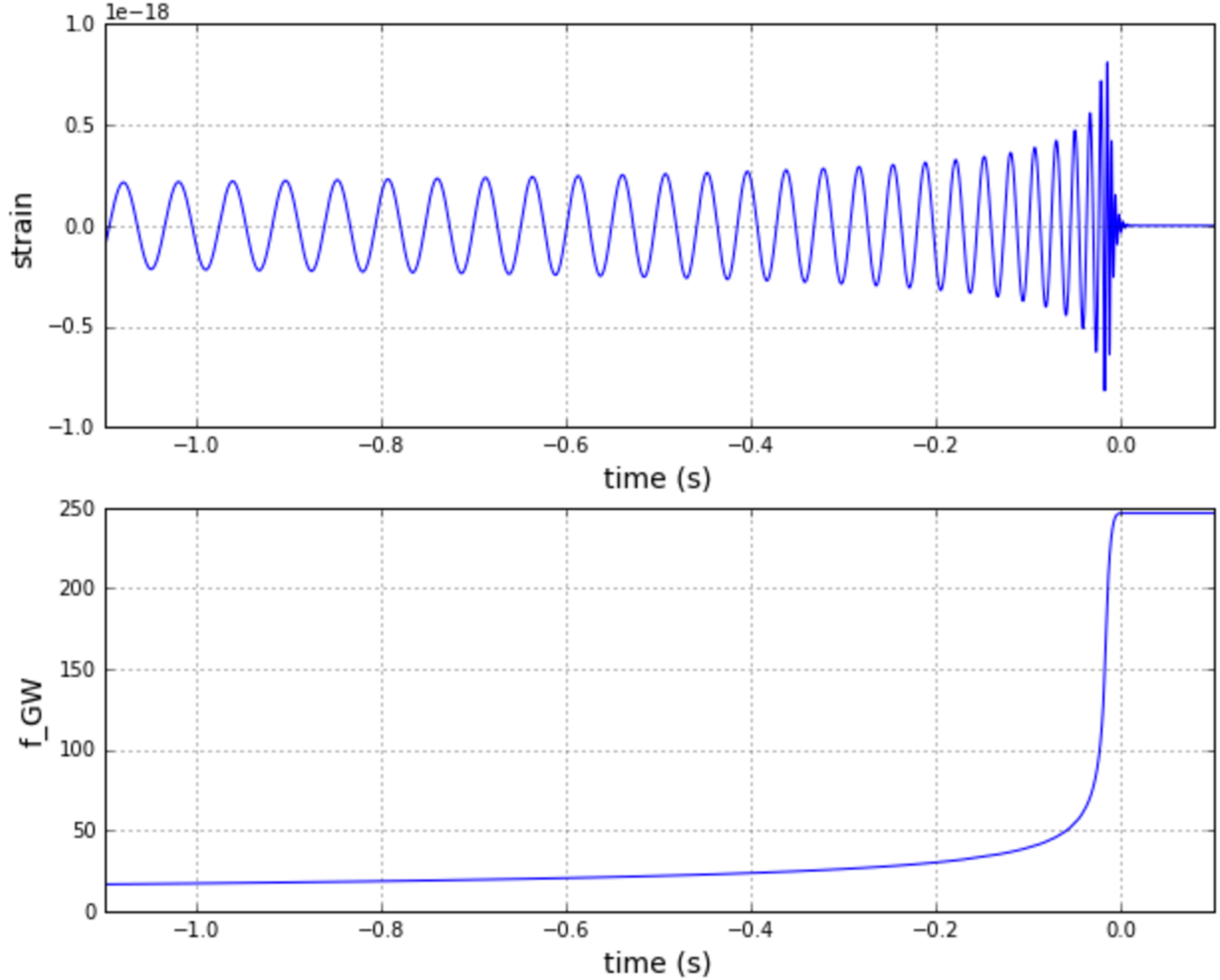


Radha Mastandrea, MIT
LIGO SURF 2017

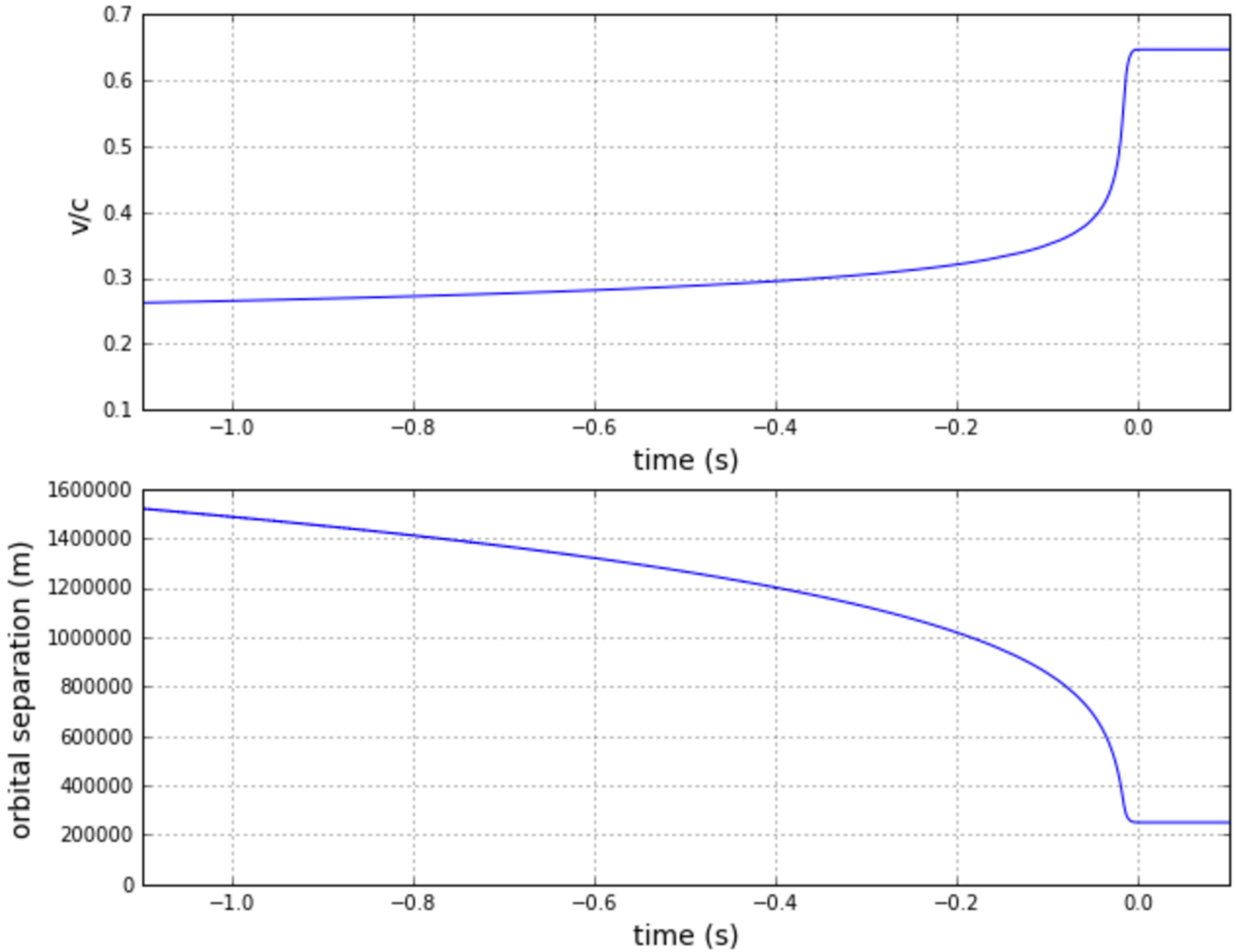
Mentor: Alan Weinstein, Caltech
8/25/2017

T1700224-v1

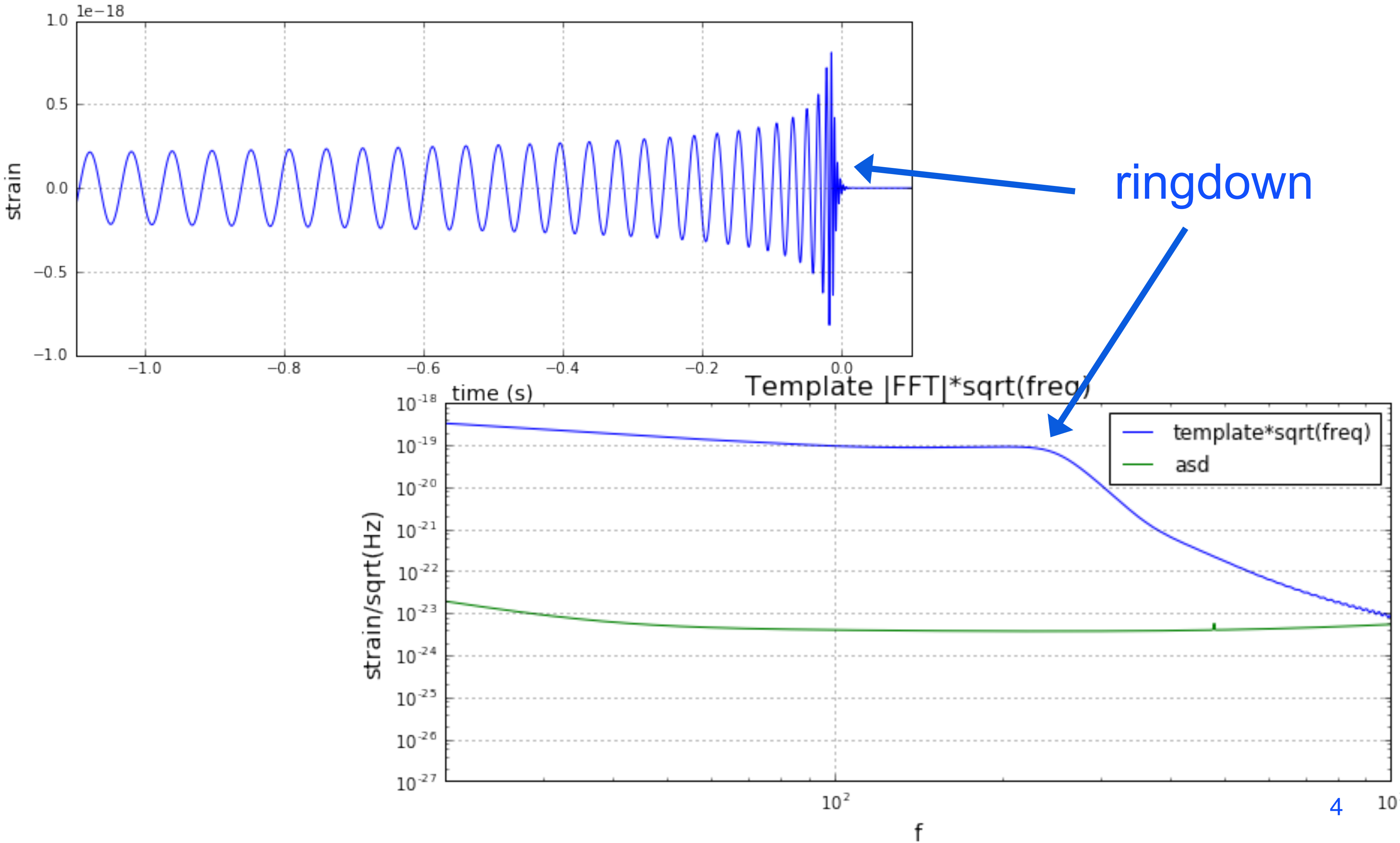
GW Waveforms: GW150914 Template



GW Parameters: GW150914 Template



Inspiral, Merger, Ringdown



Kepler's Third Law

- Strong-field gravity is characterized by v/c
- Any deviations from GR will probably have some dependence on v/c

$$\frac{v^2}{c^2} \Rightarrow \frac{4\pi^2 r(f)^2}{P^2 c^2} \Rightarrow \frac{GM_{tot}}{r(f)c^2}$$

Quasi-circular motion

Kepler's 3rd law

derived classically…but still used in GR!

$$P = \frac{1}{f_o}$$

$$f_{GW} = 2 f_o$$

Waveform Modulation

- So, we'll model deviations from GR as being an extra multiplicative factor

$$\tilde{h}_{non-GR}(f) = e^{\lambda \frac{GM_{tot}}{r(f)c^2}} \tilde{h}_{GR}(f) = e^{\mathrm{Re}(\lambda)\frac{GM_{tot}}{r(f)c^2}} A(f) e^{i\left(\mathrm{Im}(\lambda)\frac{GM_{tot}}{r(f)c^2} + \Phi(f)\right)}$$

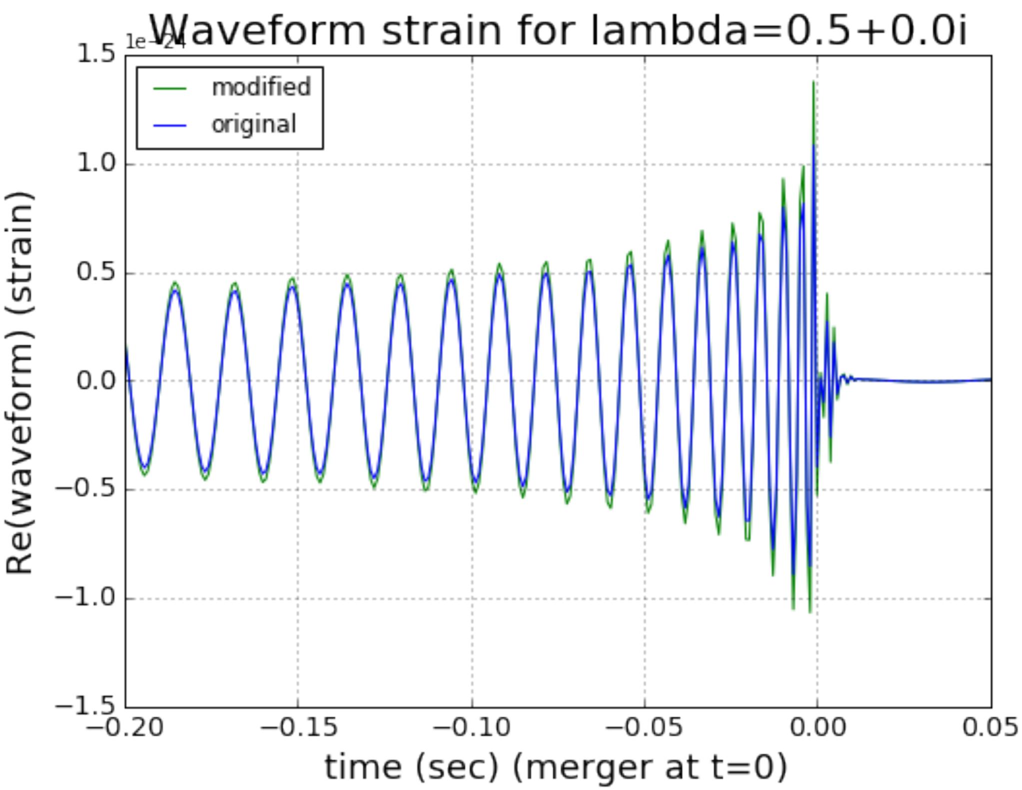
where

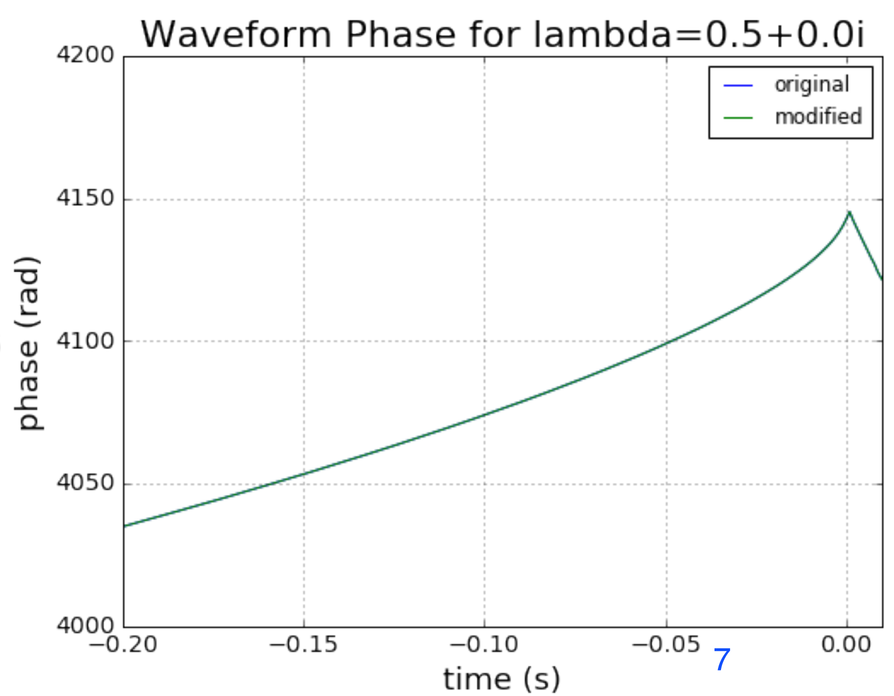
$$\tilde{h}_{GR}(f) = A(f) e^{i\Phi(f)}$$

If λ=0, we're working with Einstein's GR

- λ is complex
- Re(λ) corresponds to an amplitude modulation
- Im(λ) corresponds to a phase modulation

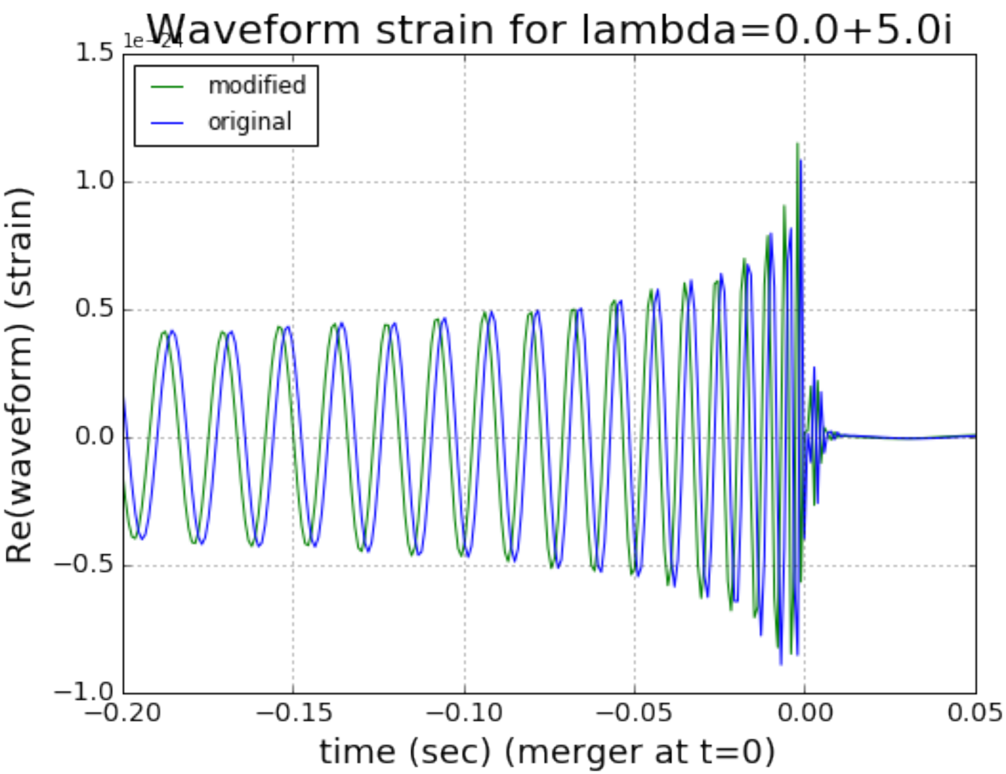
Examples: Low Mass System

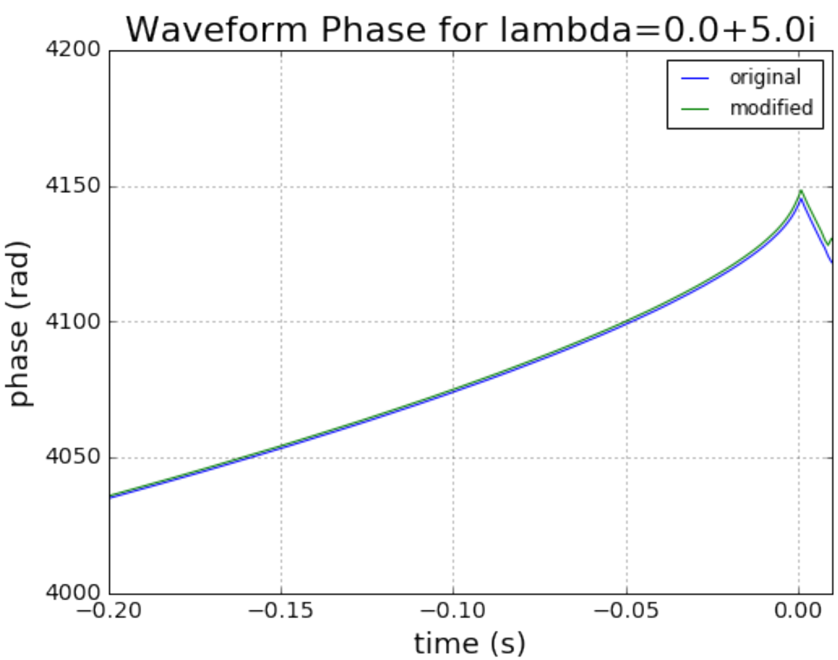




M1=20Msol
M2=10Msol
D=50Mpc

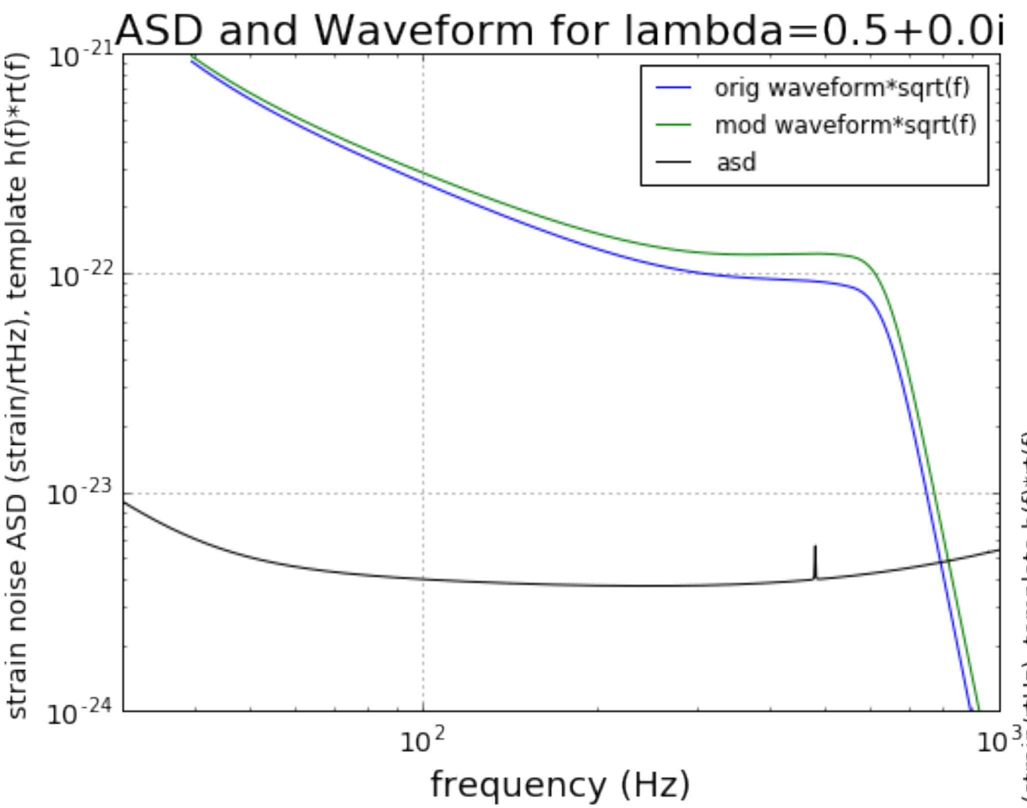
Examples: Low Mass System

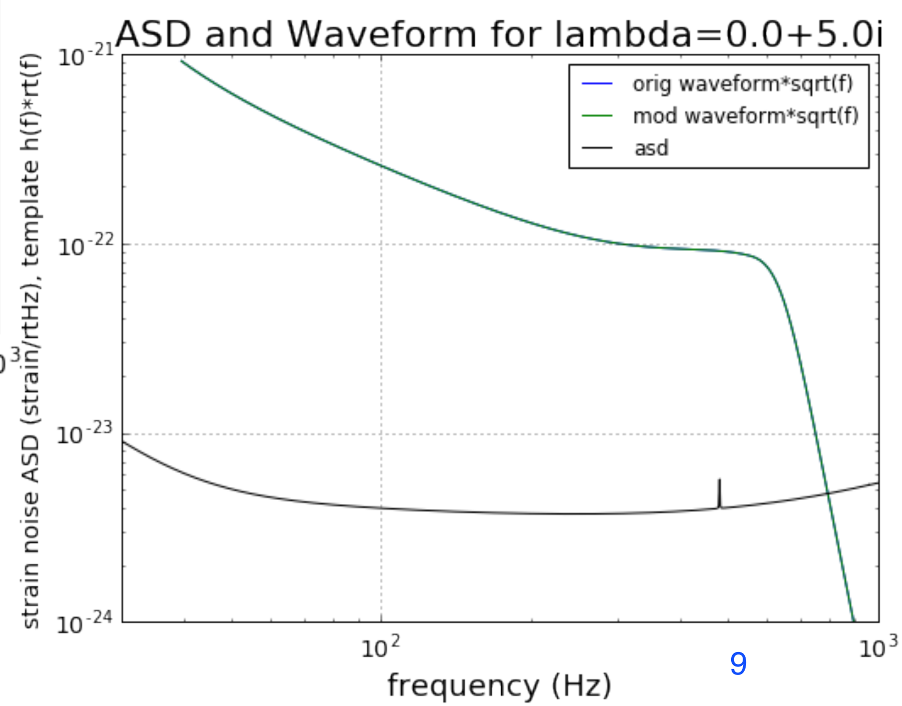




M1=20Msol
M2=10Msol
D=50Mpc

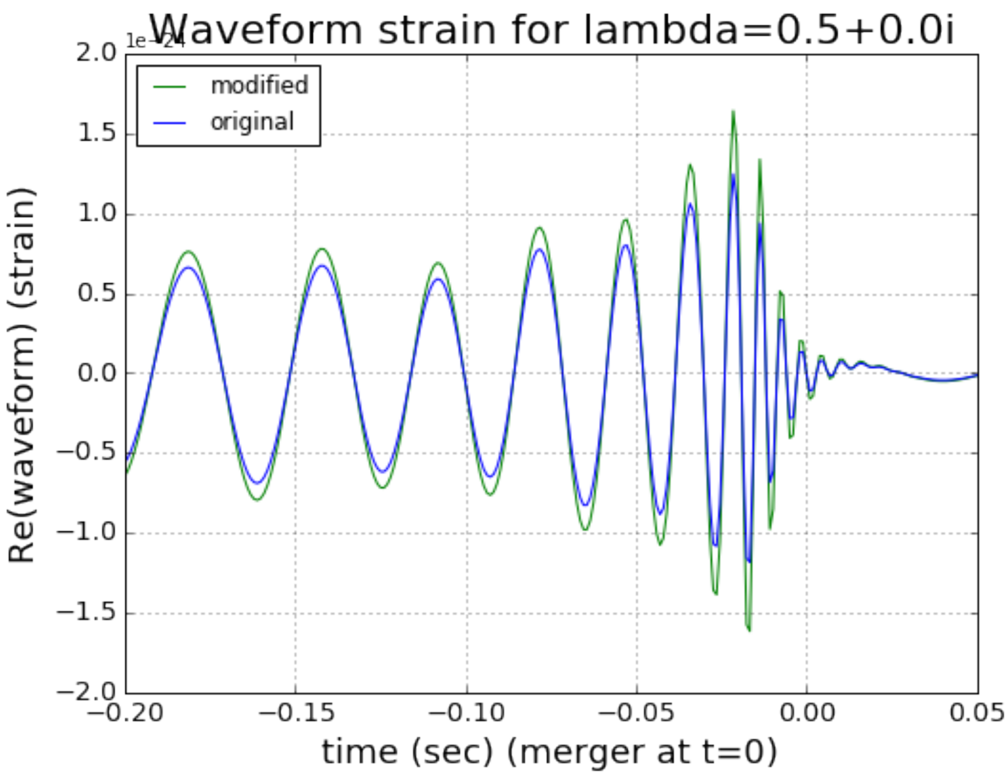
Examples: Low Mass System

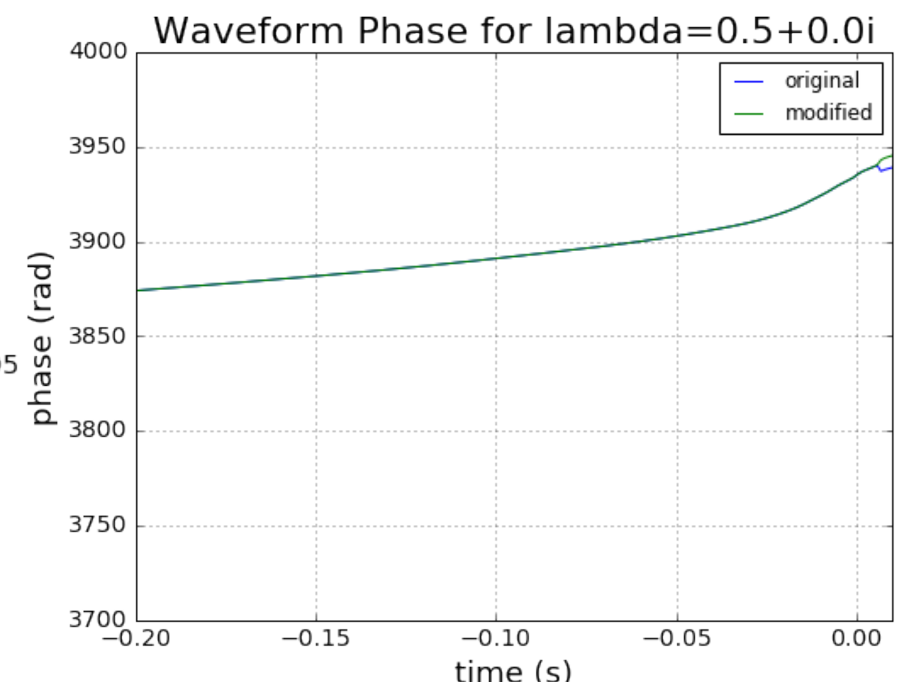




M1=20Msol
M2=10Msol
D=50Mpc

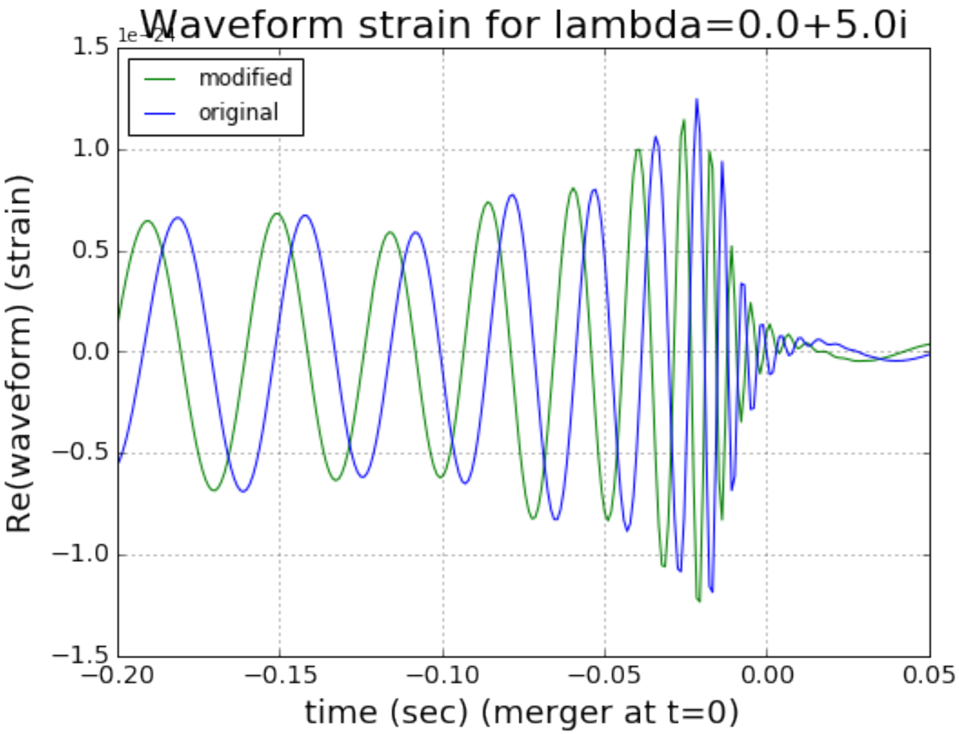
Examples: High Mass System

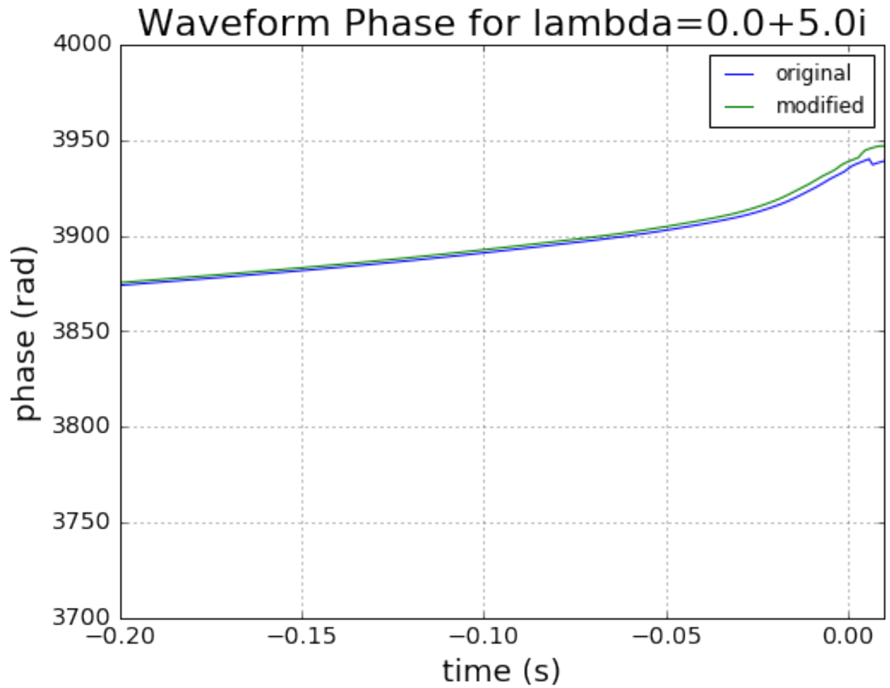




M1=60Msol
M2=50Msol
D=200Mpc

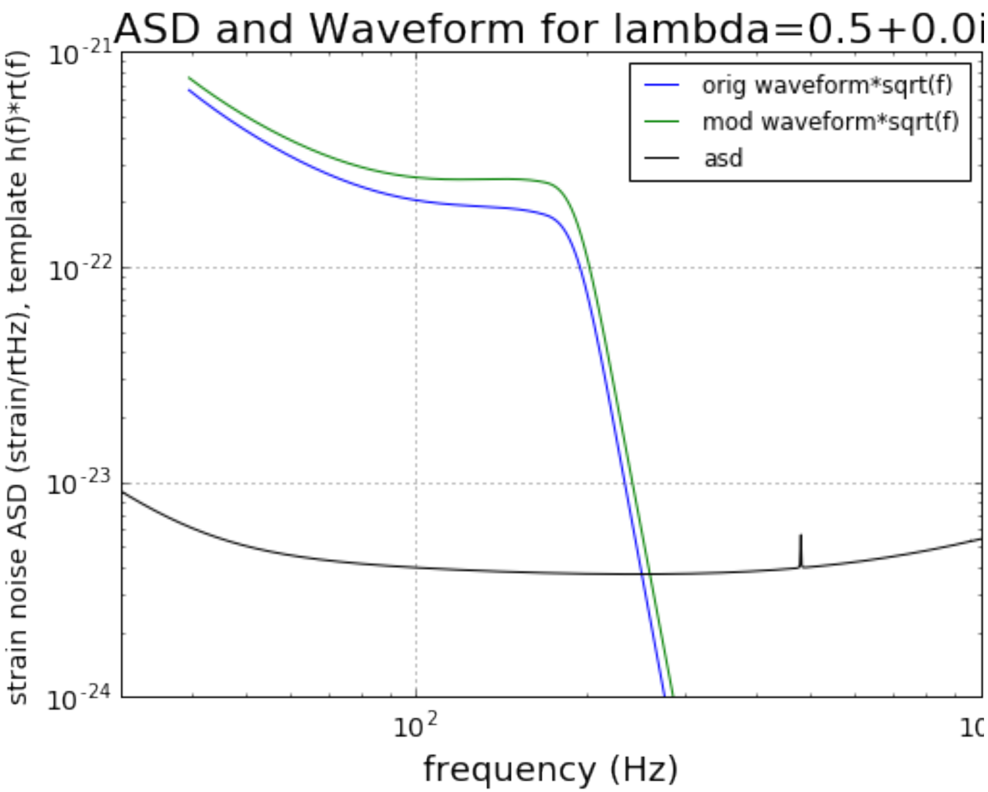
Examples: High Mass System



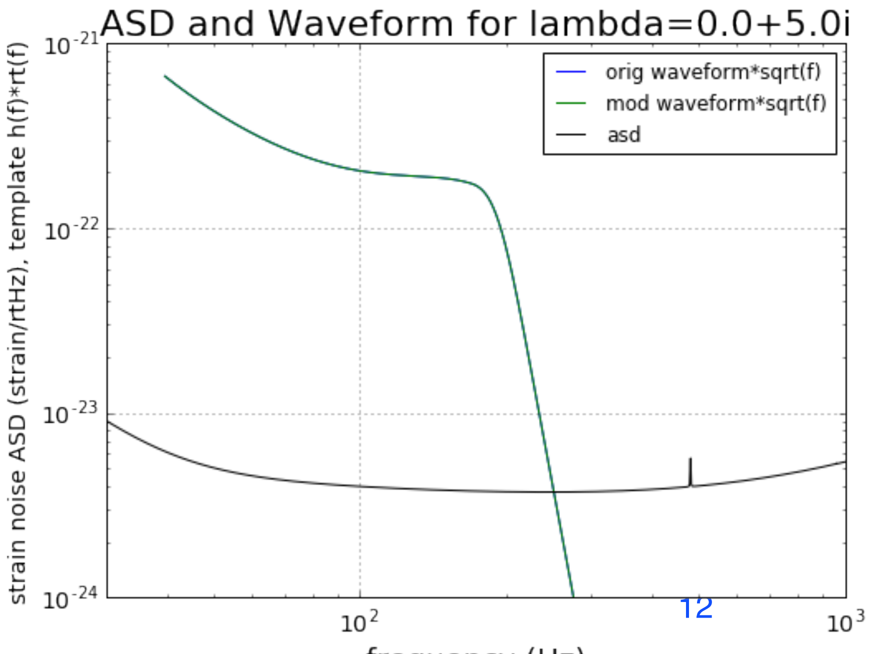


M1=60Msol
M2=50Msol
D=200Mpc

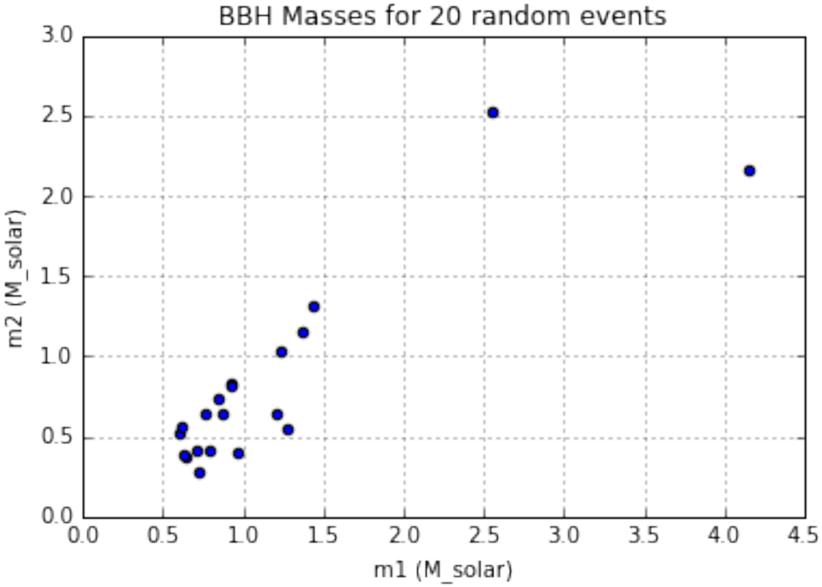
Examples: High Mass System

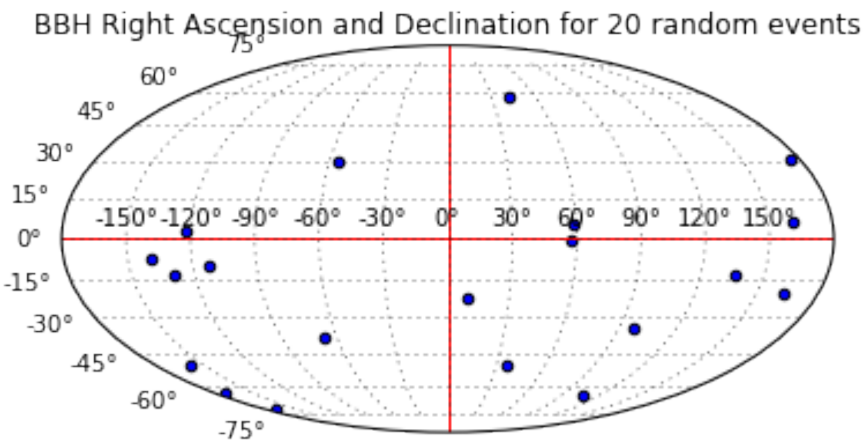


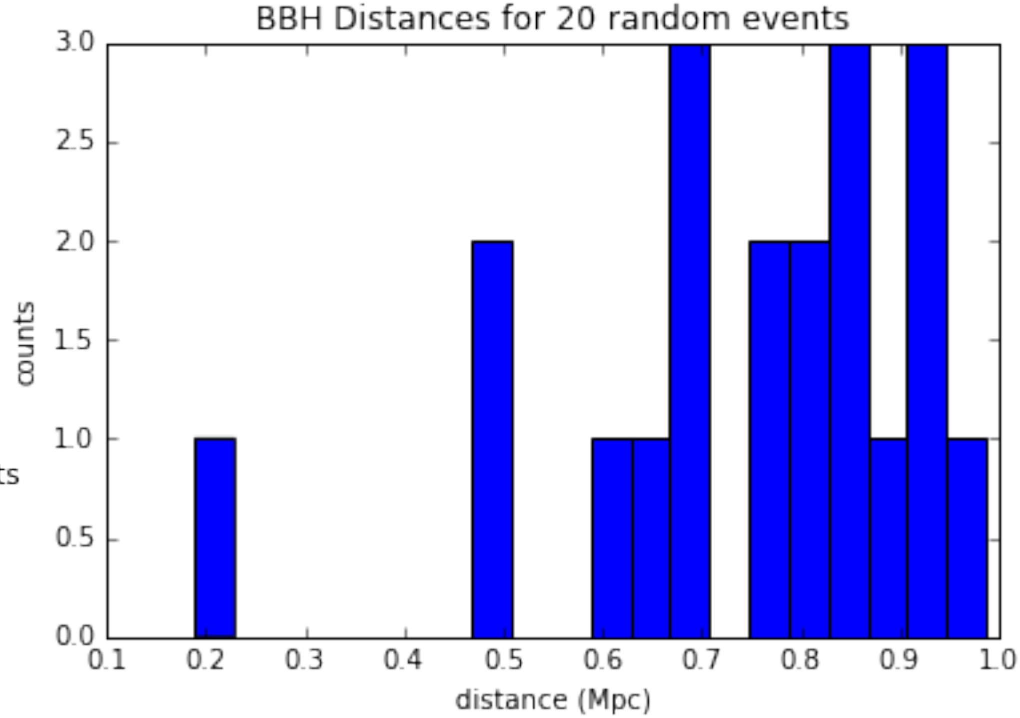
M1=60Msol
M2=50Msol
D=200Mpc



The Simulated Mergers







Bayesian Parameter Estimation

Likelihood

Prior

Posterior distribution

$$P(\theta, d) = \frac{P(d, \theta) P(\theta)}{P(d)}$$

evidence

θ = λ
d = data
the evidence normalizes the pdf

Bayesian Probabilities (Testing phase)

The prior:
Jeffreys (uninformative) prior

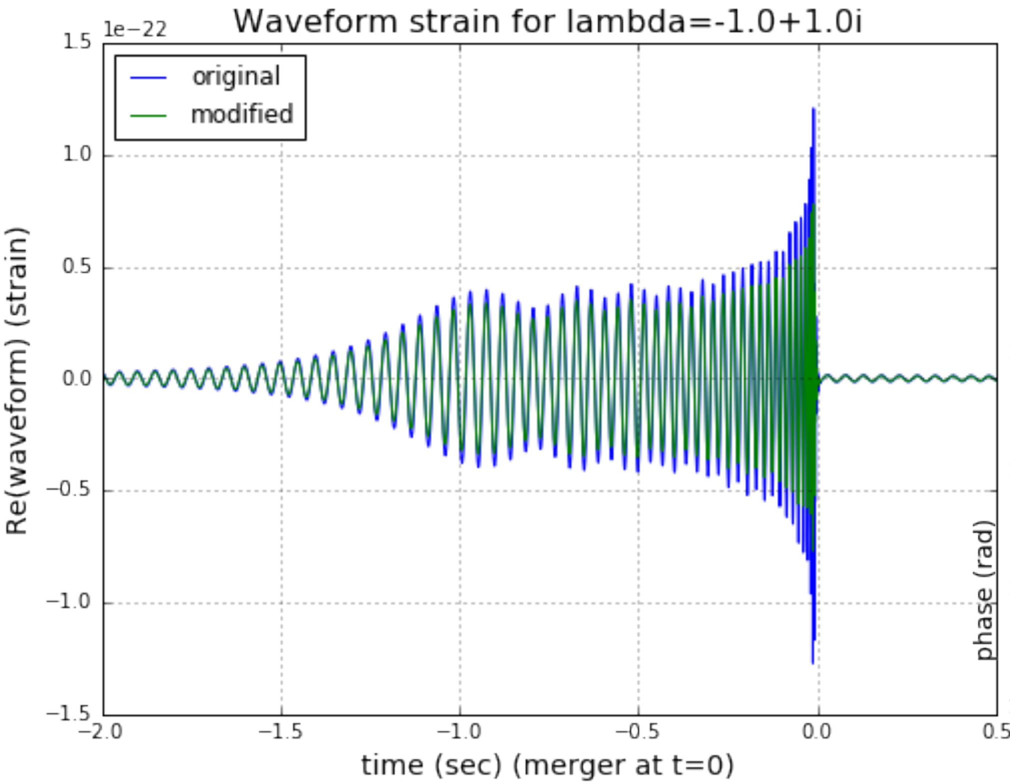
$$P(\lambda) = \frac{1}{|\lambda|}$$

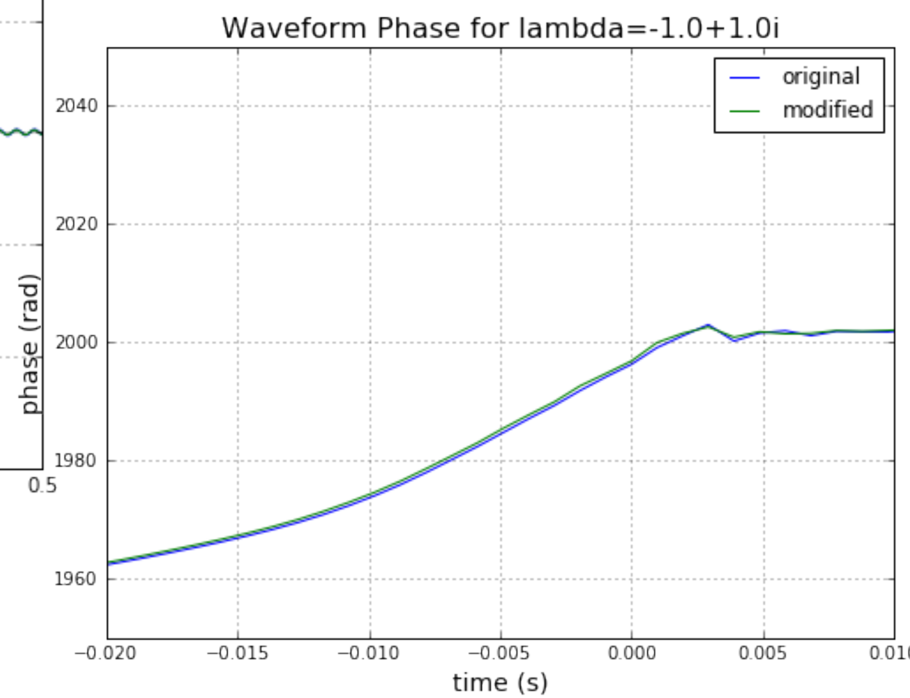
$$p(\mathrm{Re}(\lambda), \mathrm{Im}(\lambda))d\lambda = \frac{d\lambda}{|\lambda|} = d\ln\lambda$$

$$P(d,\theta)$$

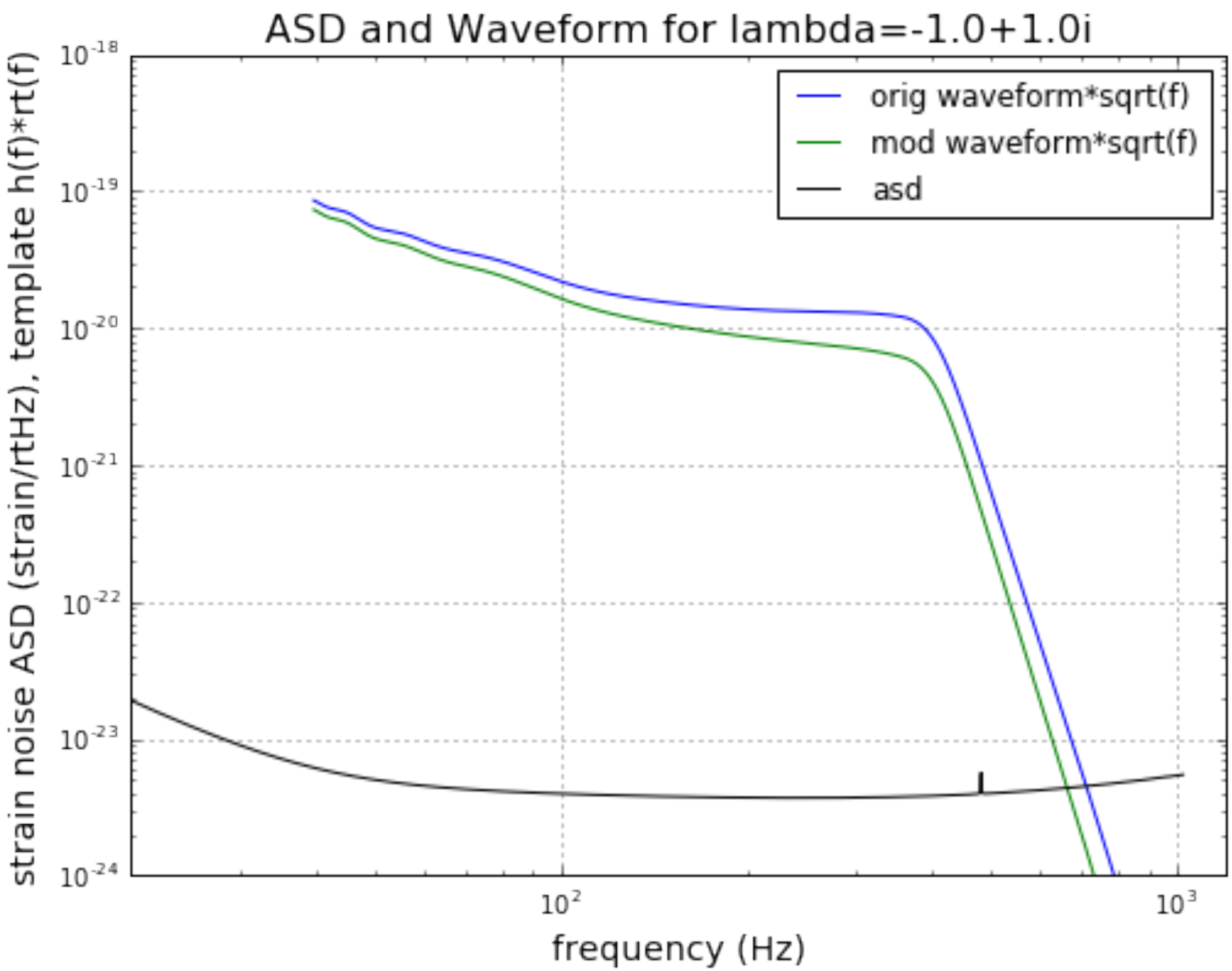
The likelihood:
normalized SNR maximized over time
data = modified waveform (1 λ)
template = modified waveform (sampling λ)

Test #1: Noiseless Waveforms

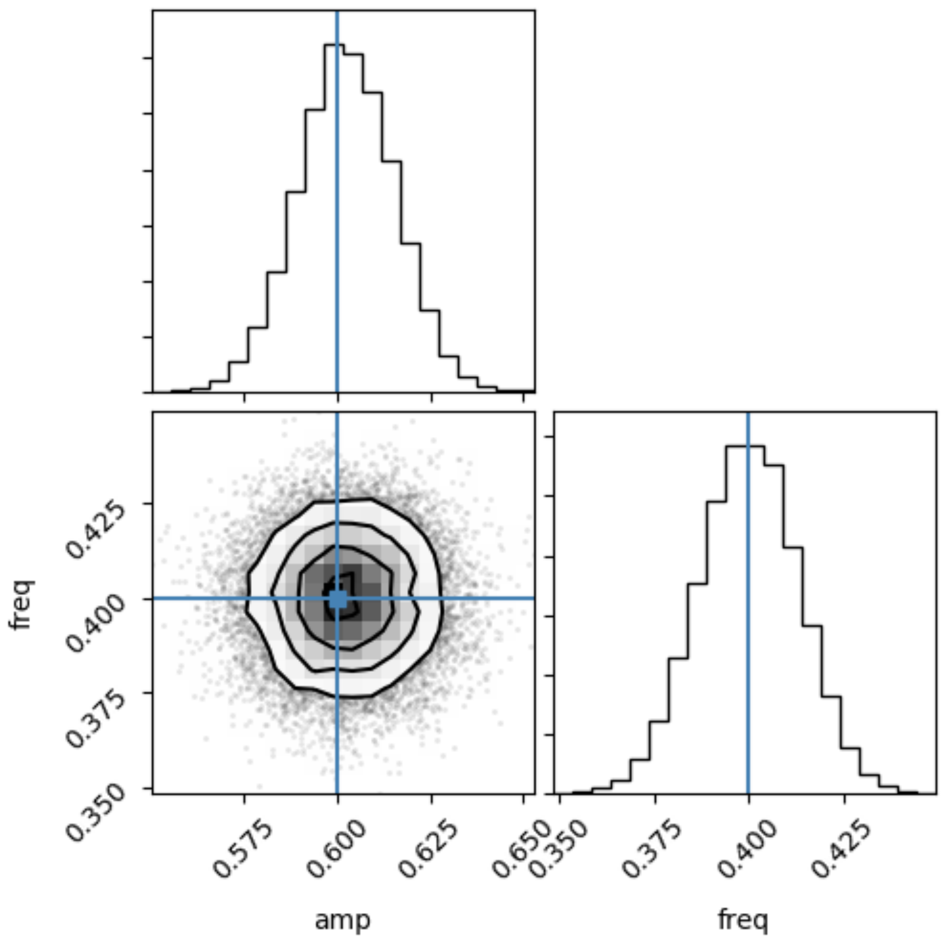




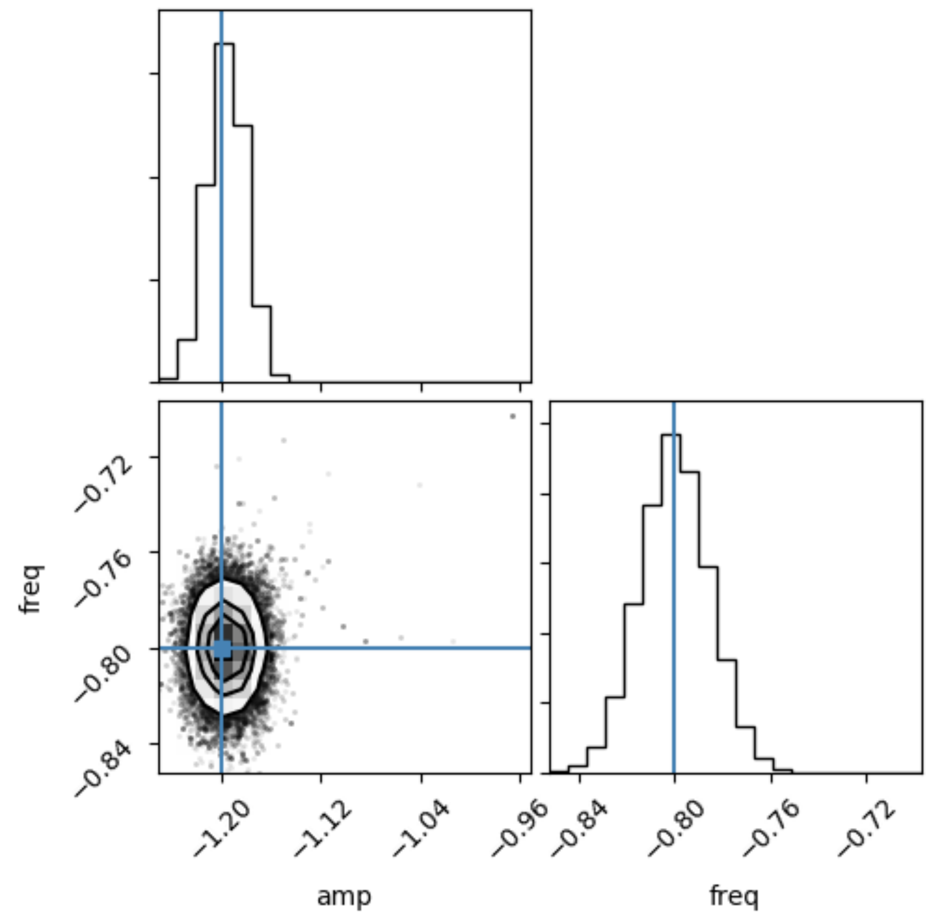
Test #1: Noiseless Waveforms



Test #1: Results

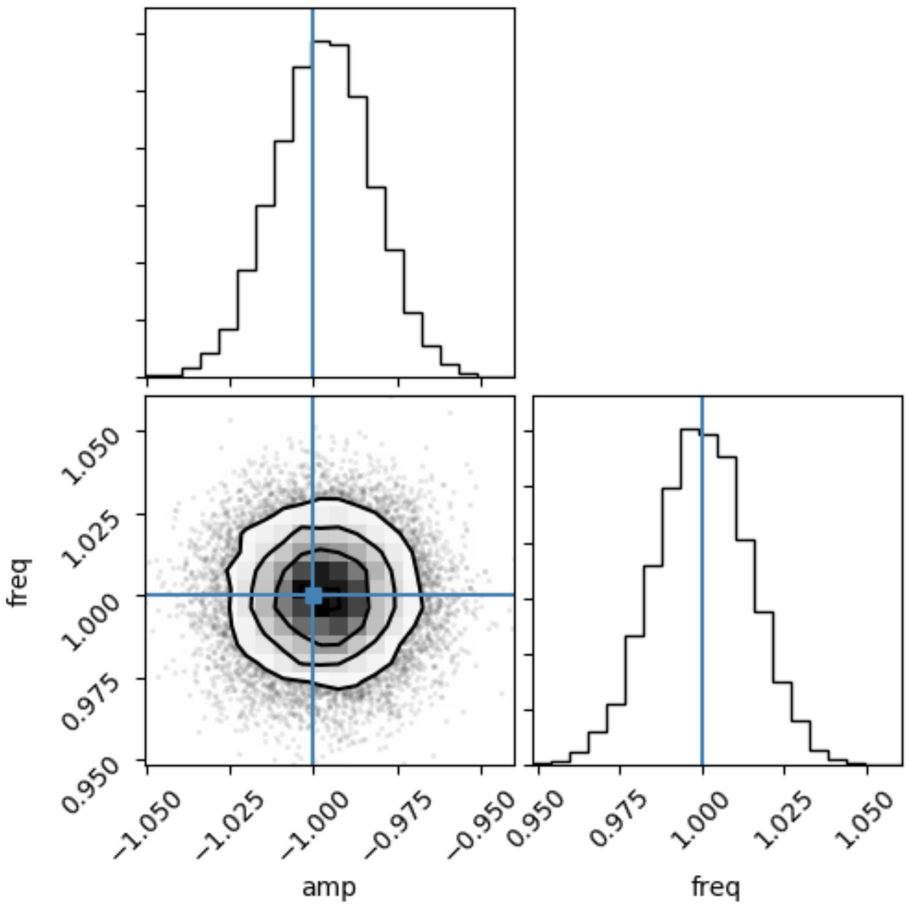


λ=.6+.4i

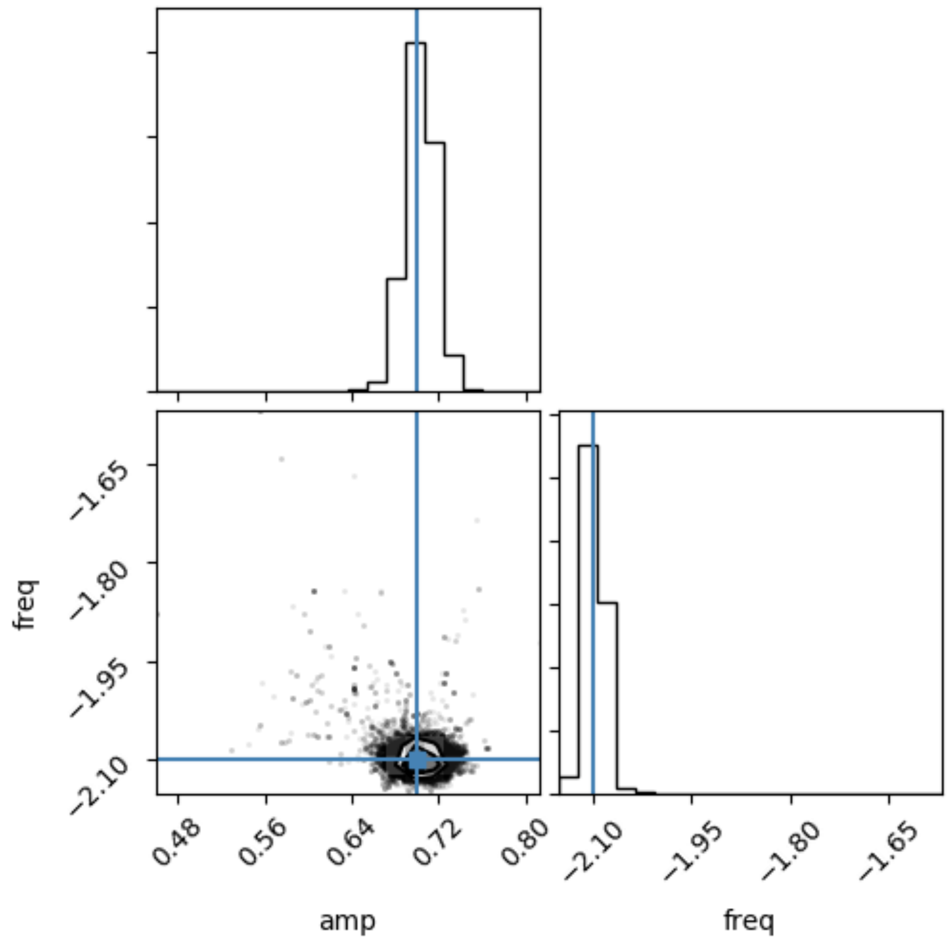


λ=-1.2-.8i

Test #1: Results



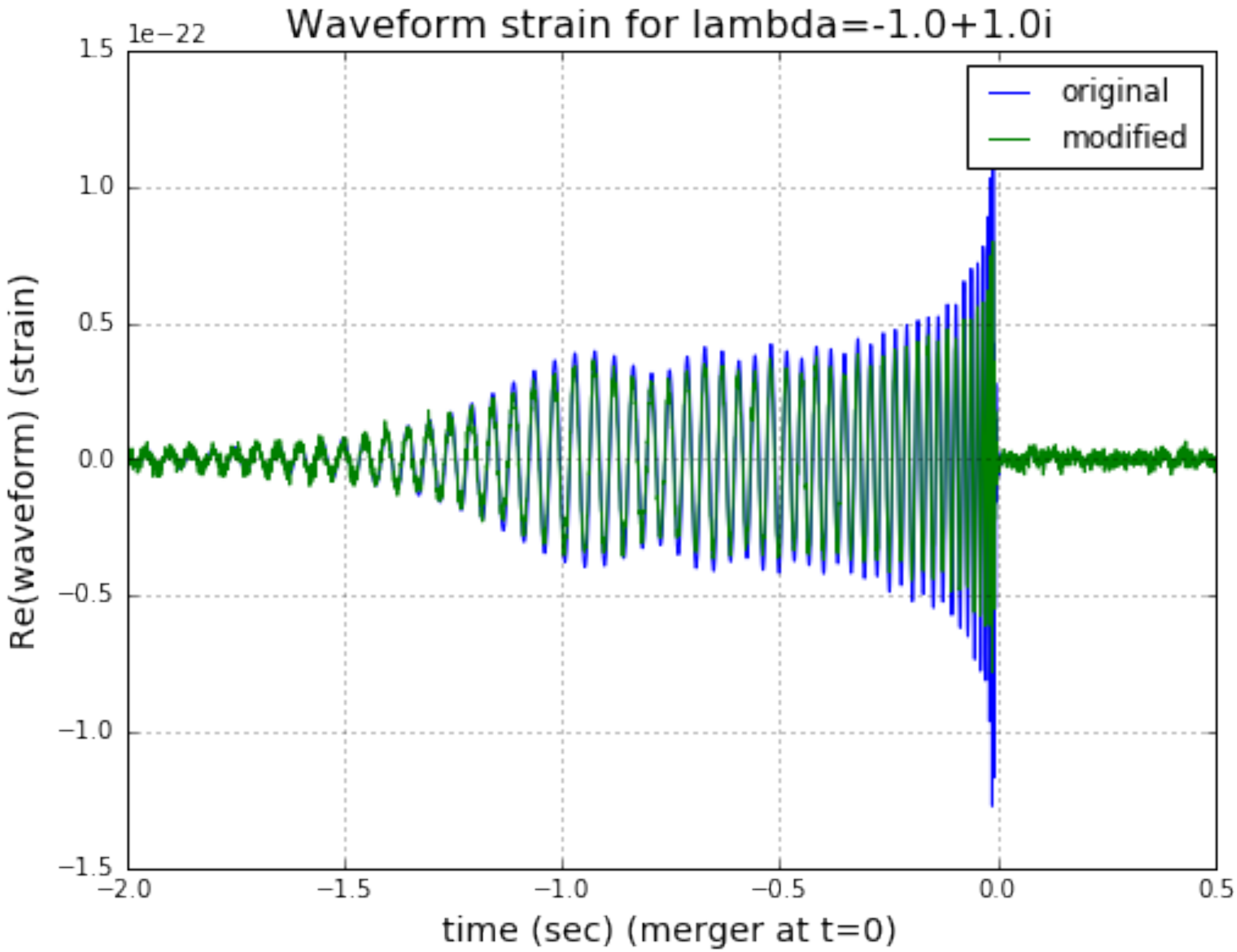
λ=-1+i



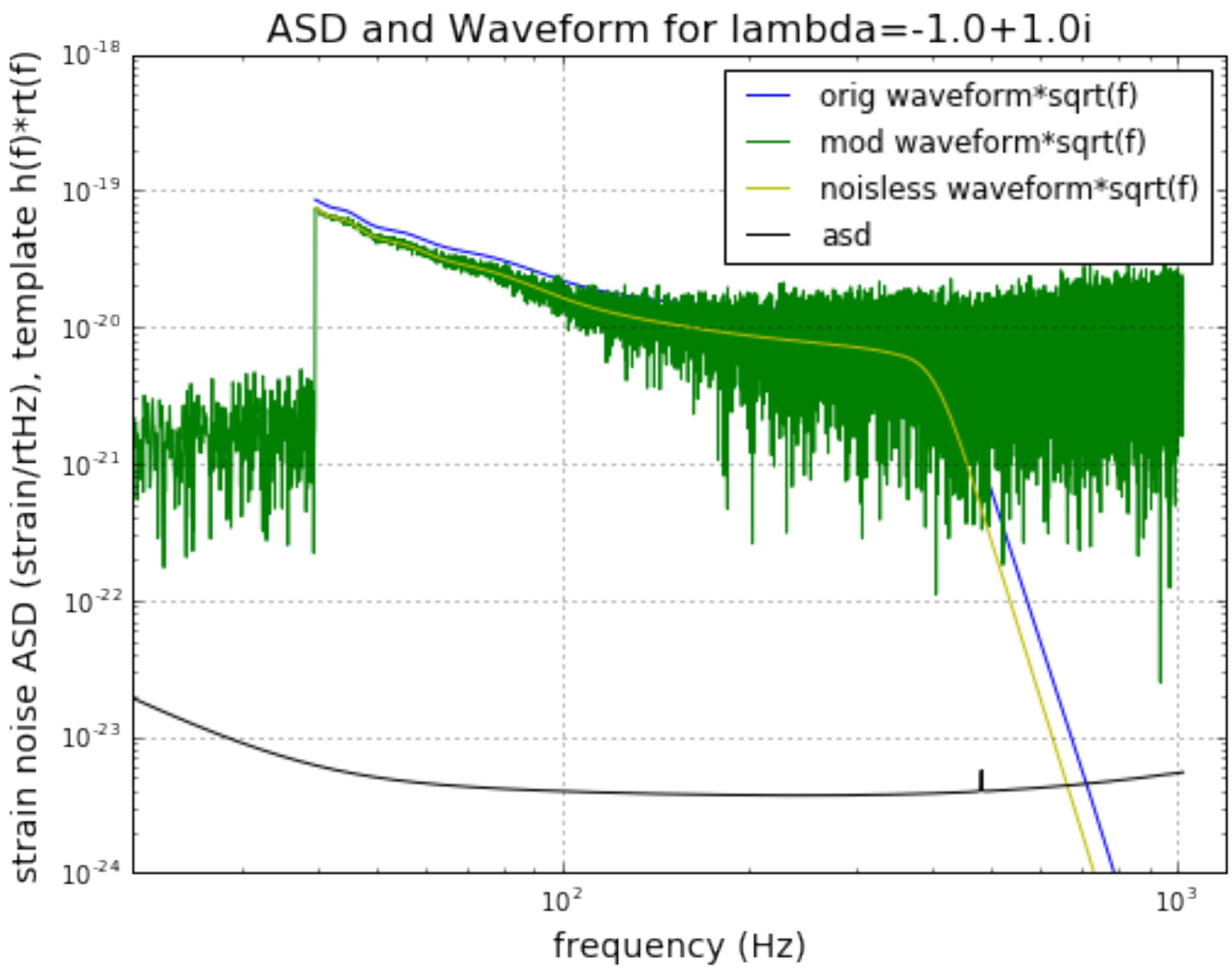
λ=.7-2.1i

LIGO

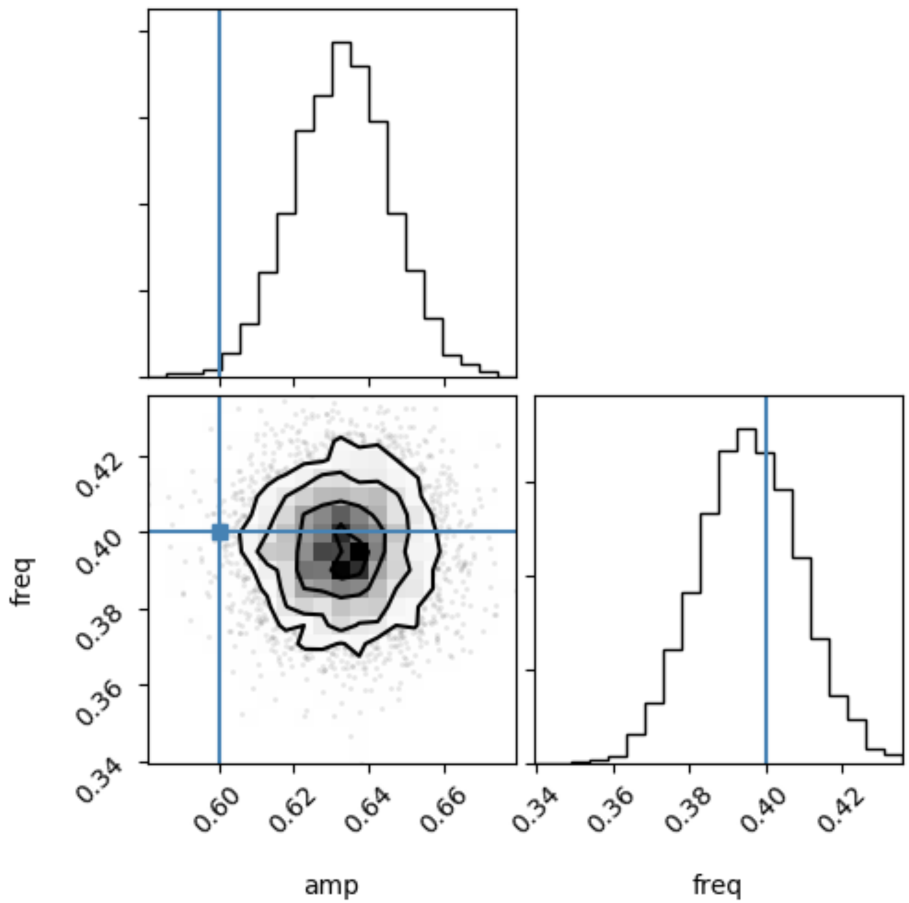
Test #2: Waveforms + WGNoise



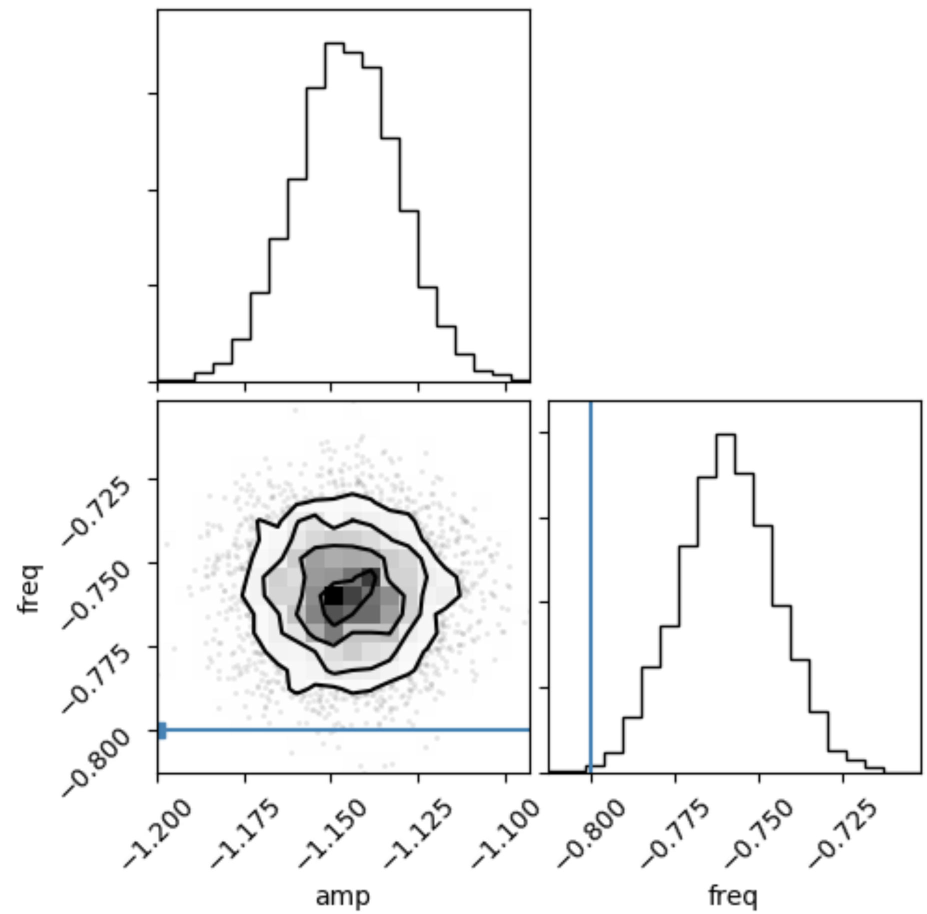
Test #2: Waveforms + WGNoise



Test #2: Results

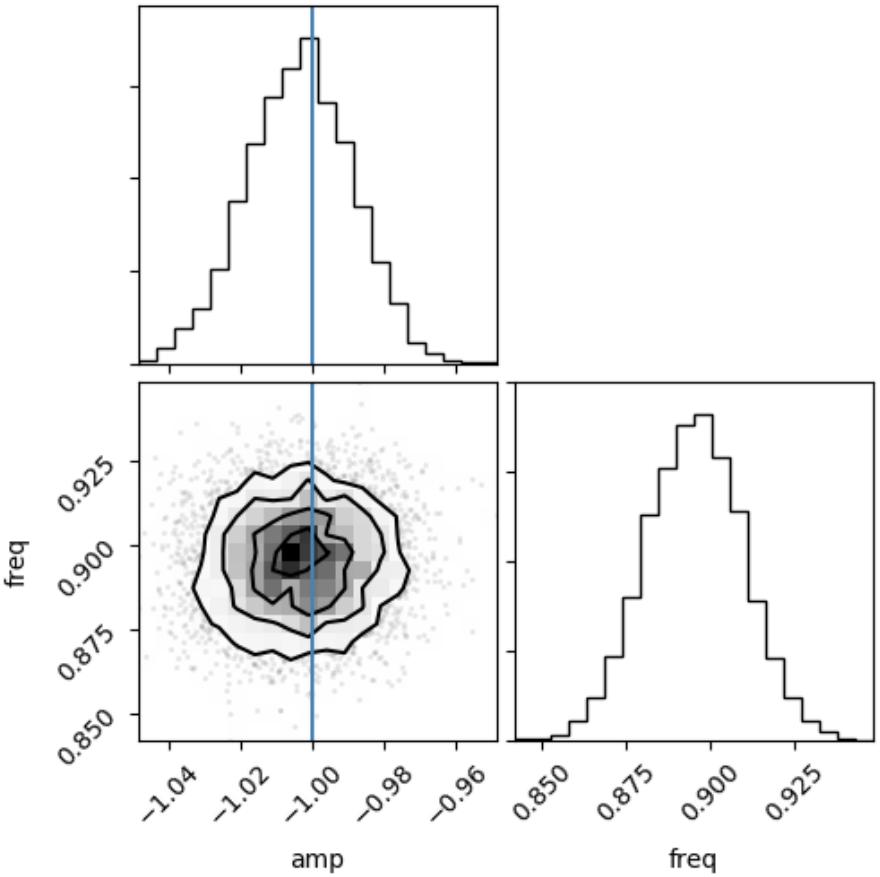


λ=.6+.4i

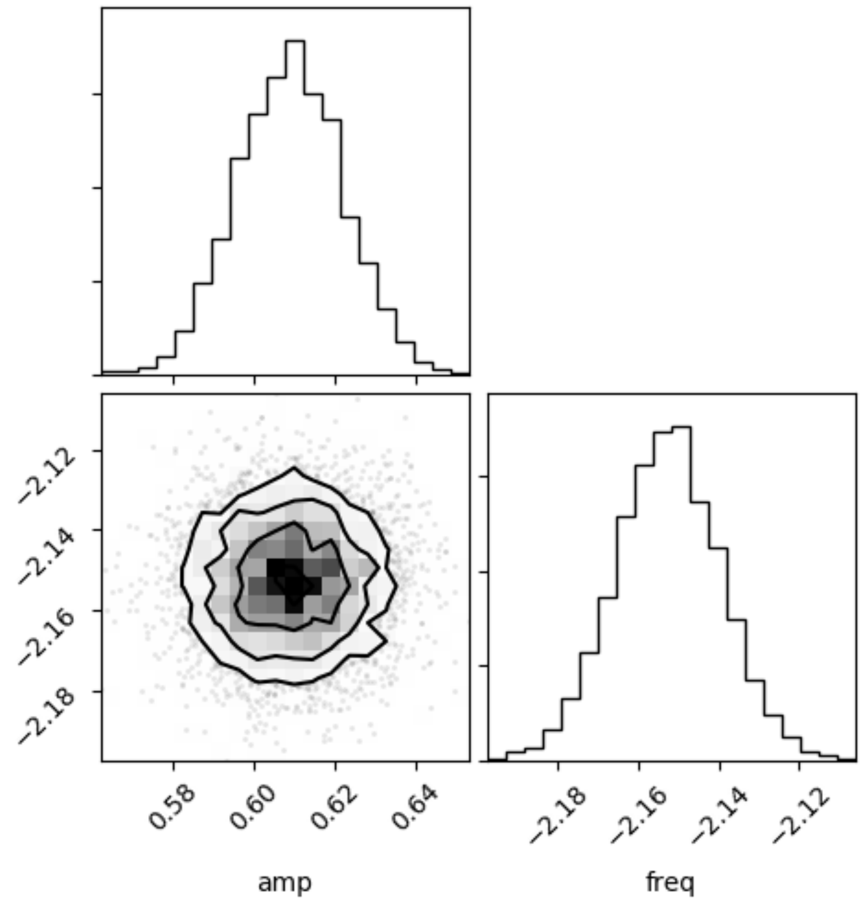


λ=-1.2-.8i

Test #2: Results



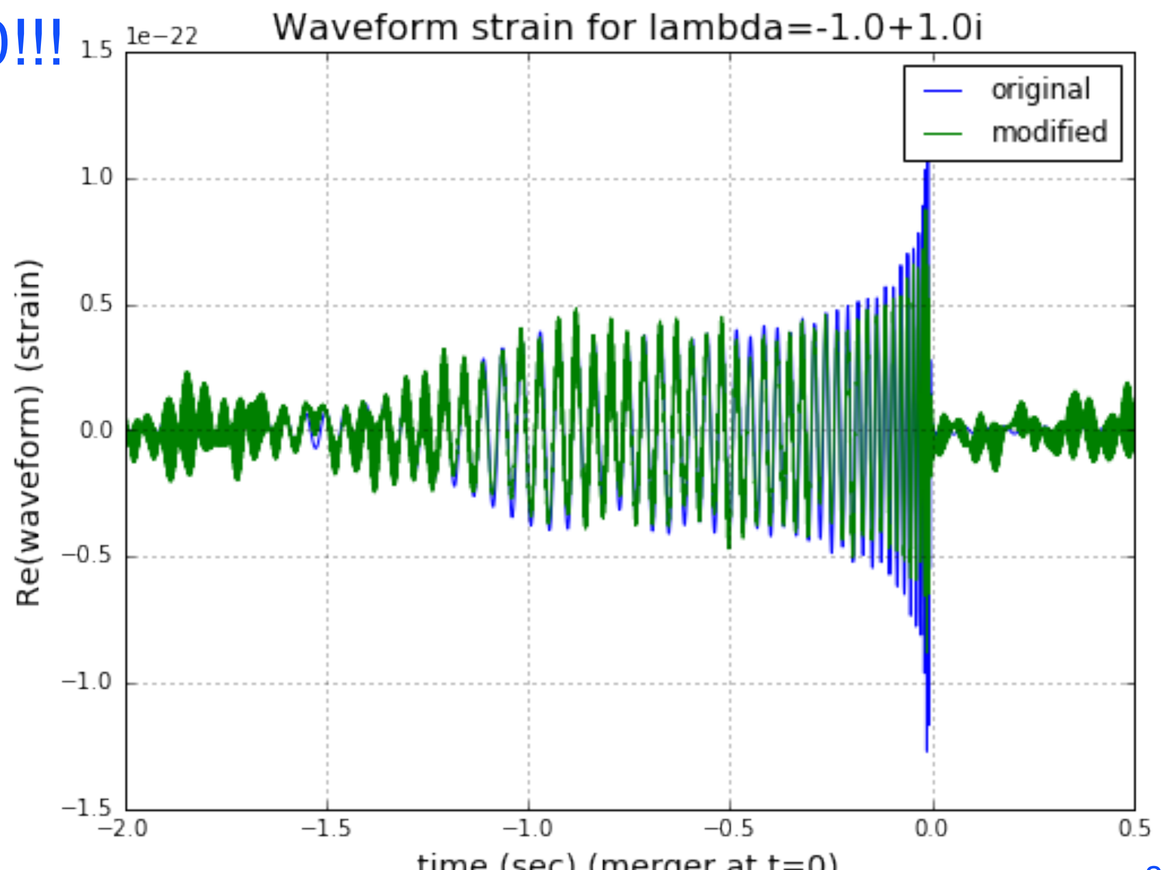
λ=-1+i



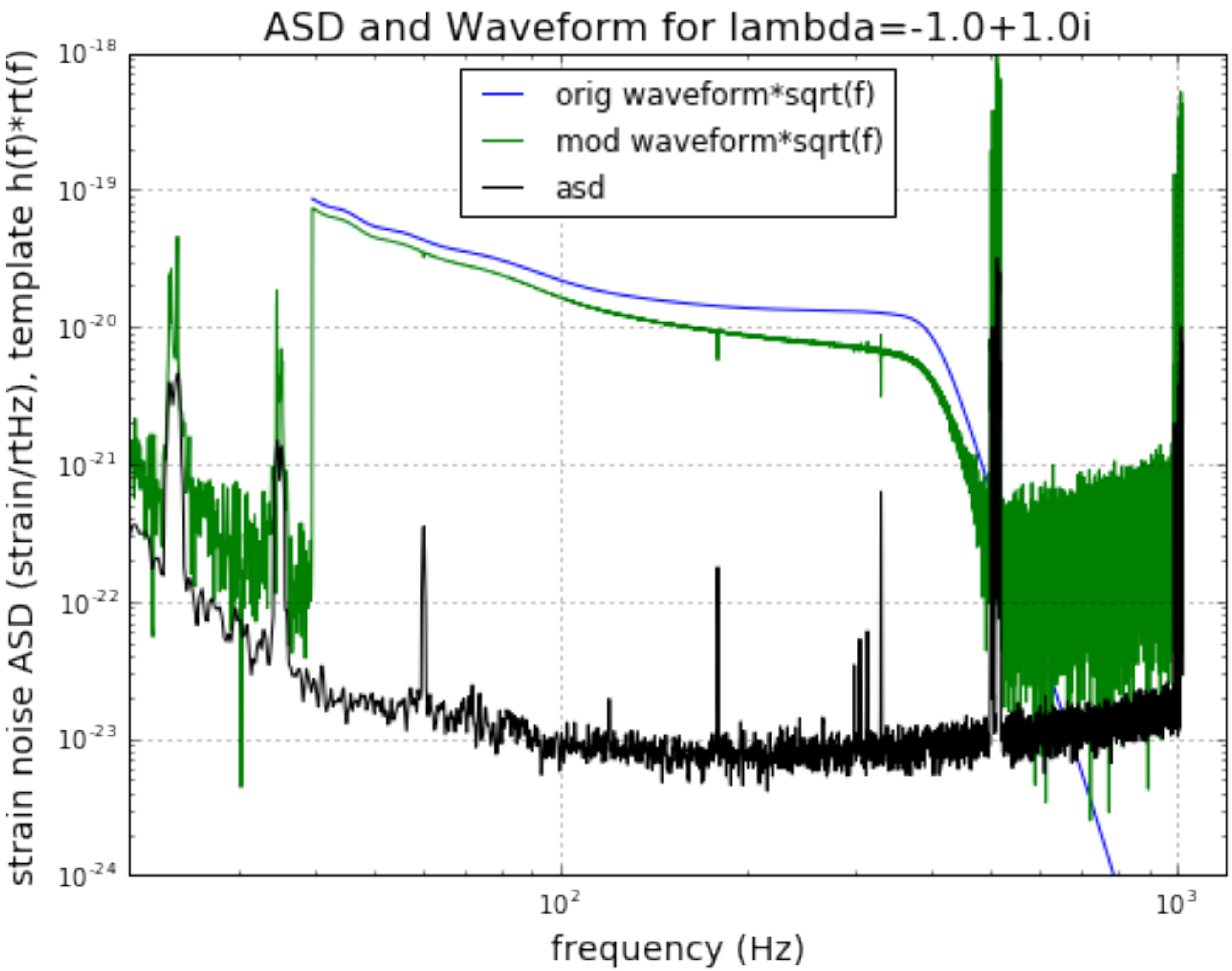
λ=.7-2.1i

Test #3: Waveforms + LIGONoise

- Noise taken from GW150914 away from the event
- SNR ~ 1000!!!

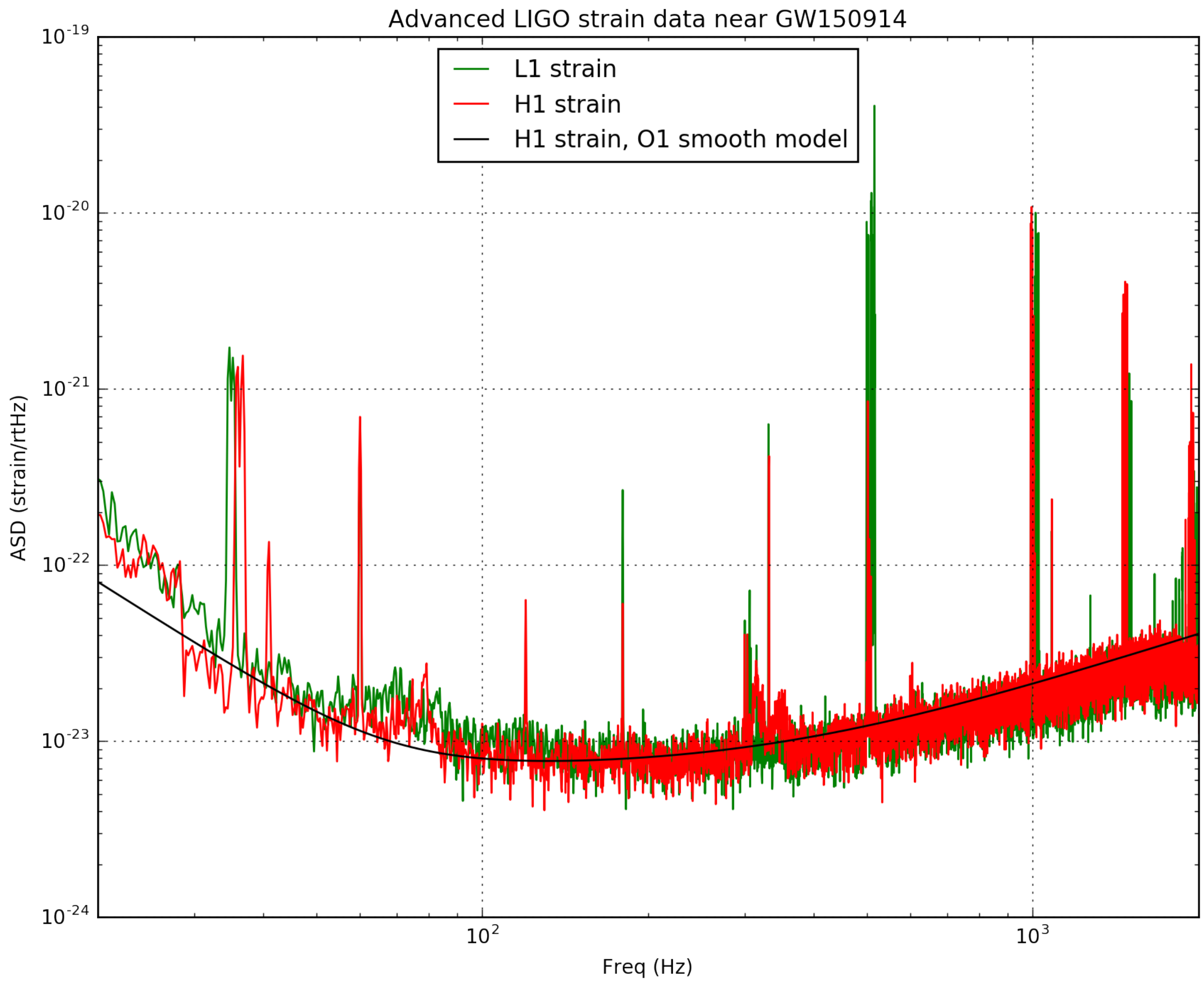


Test #3: Waveforms + LIGO Noise

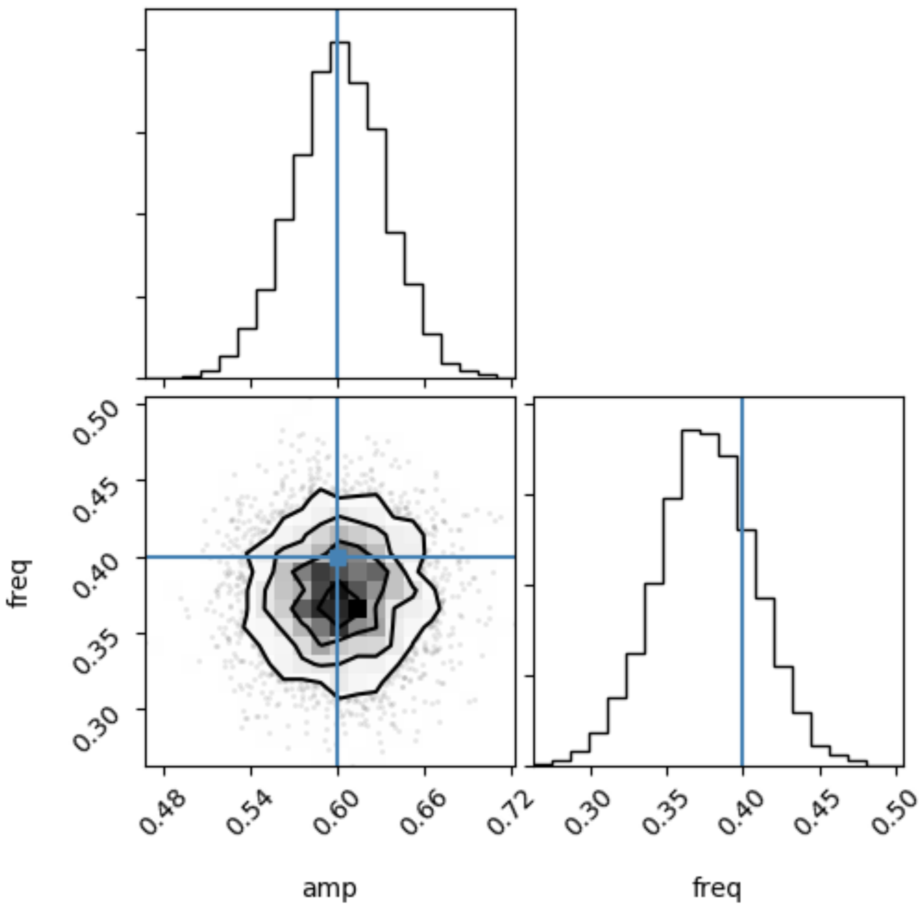


For comparison…

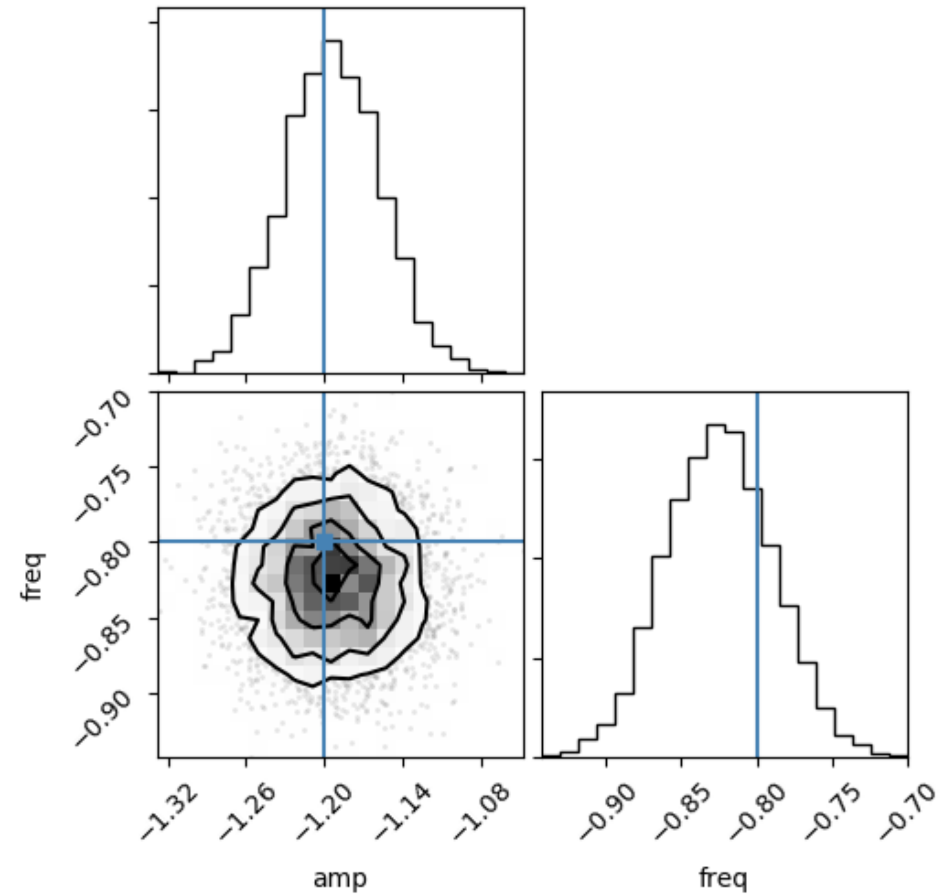
for GW150914:



Test #3: Results

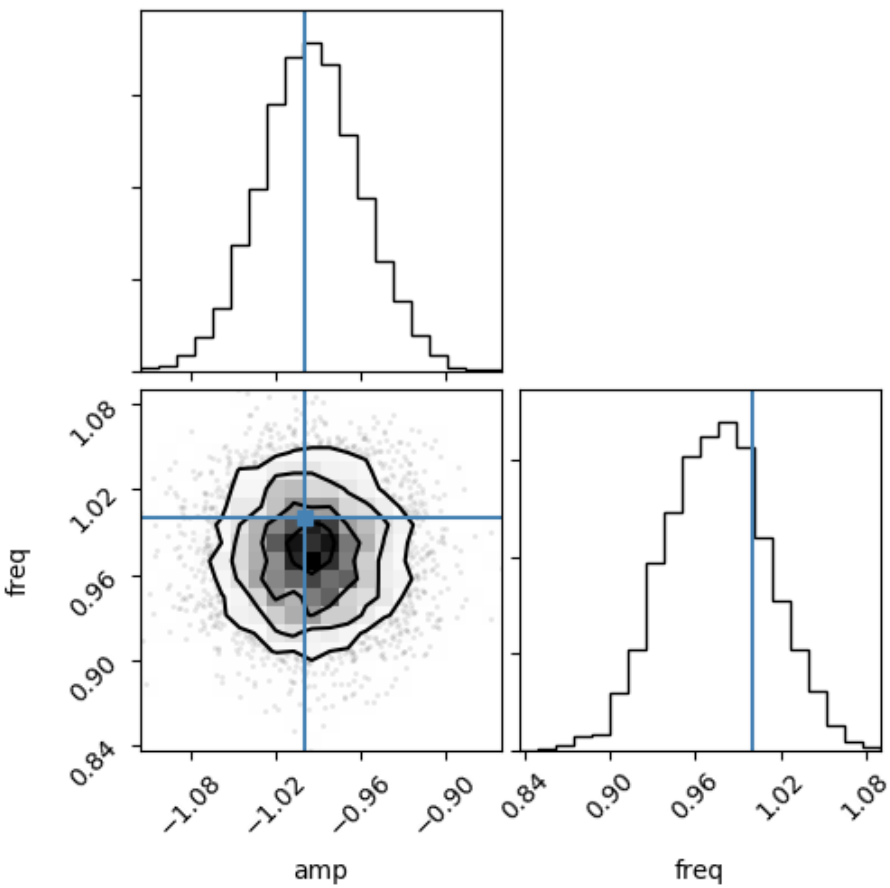


λ=.6+.4i

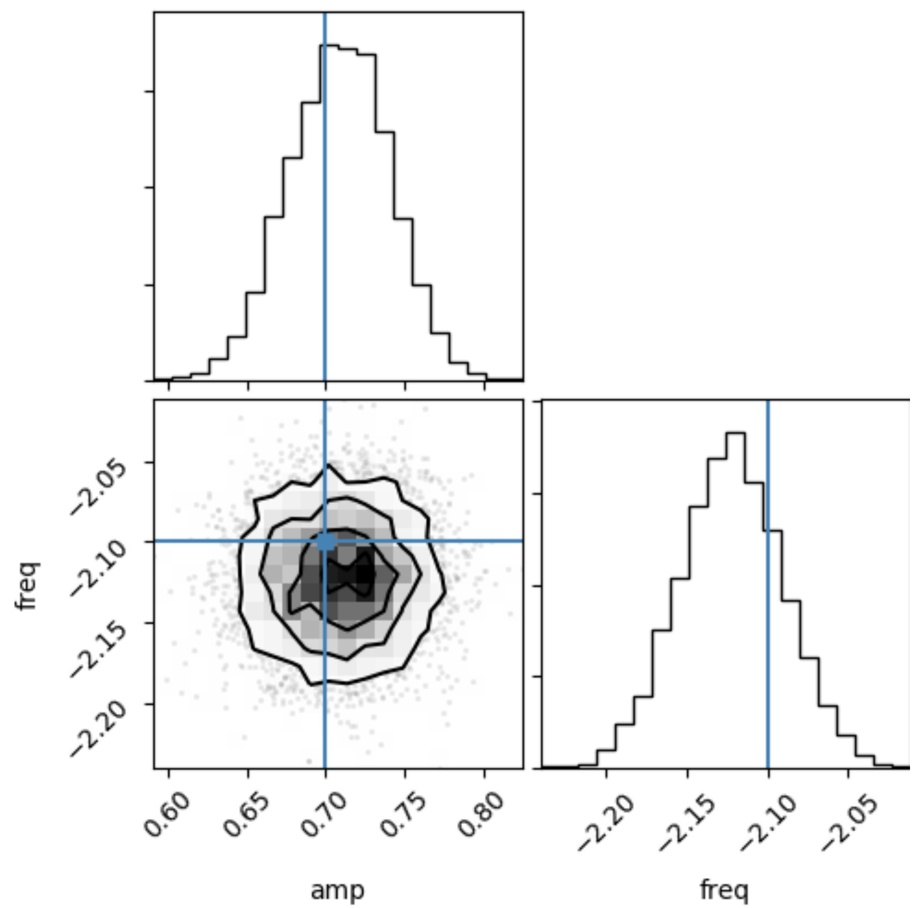


λ=-1.2-.8i

Test #3: results



λ=-1+i



λ=.7-2.1i

LIGO LSC

Bayesian Probabilities

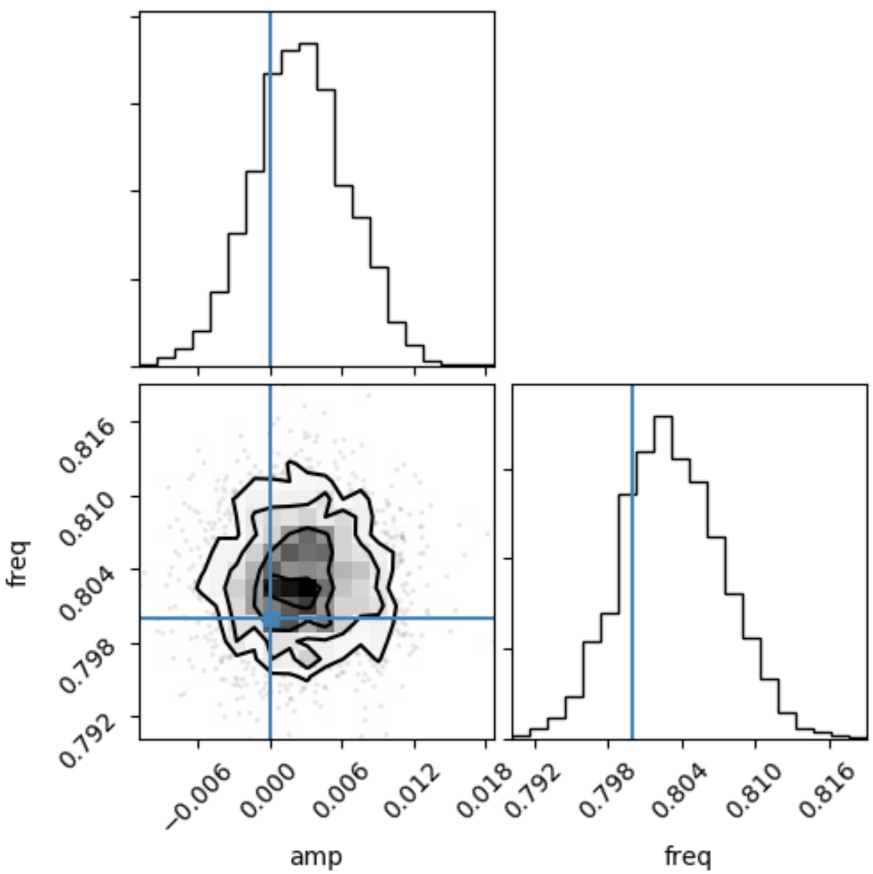
The prior:
Jeffreys (uninformative) prior

$$p(\mathrm{Re}(\lambda),\mathrm{Im}(\lambda))d\lambda = \frac{d\lambda}{|\lambda|} = d\ln\lambda$$

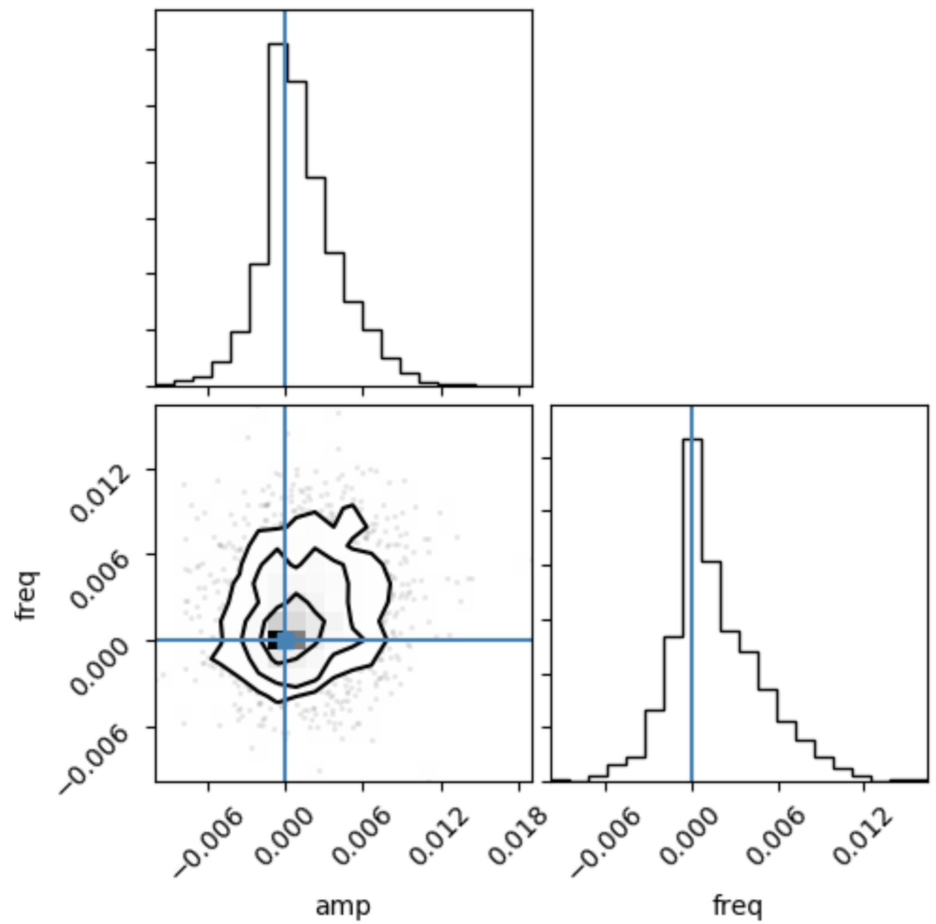
$$P(d,\theta)$$

The likelihood:
normalized SNR maximized over time
20 events

A Few Results

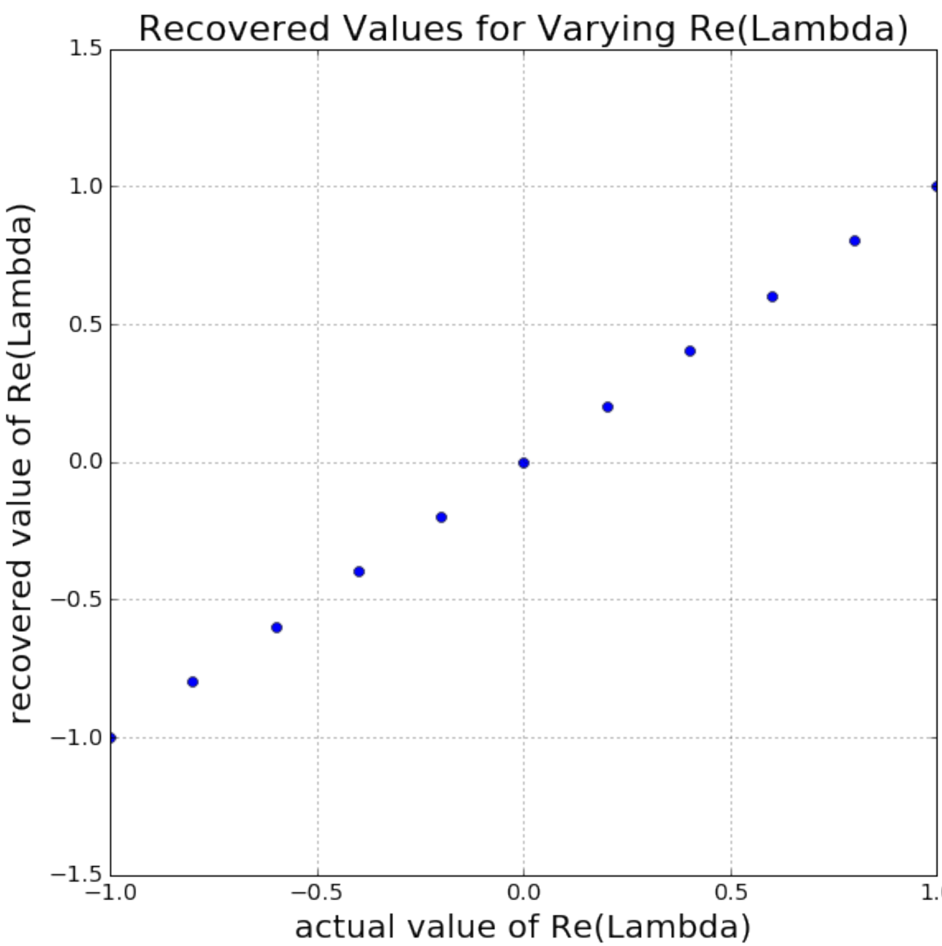


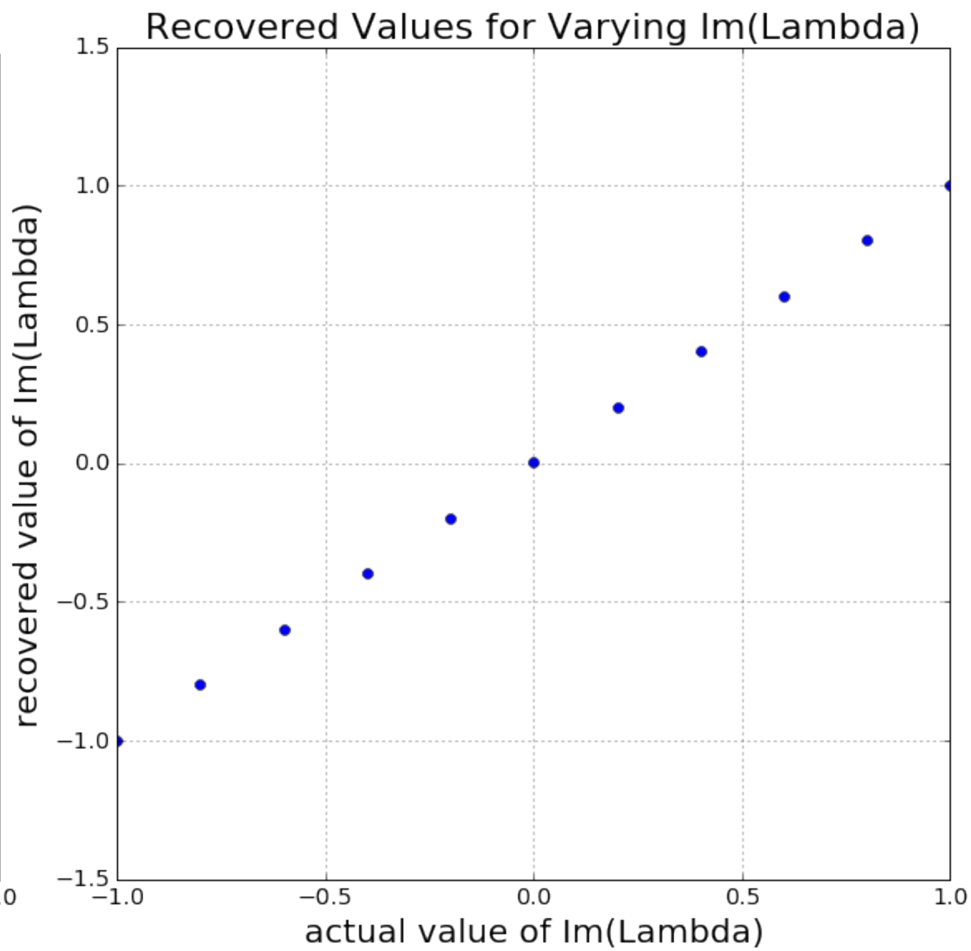
λ=.8i



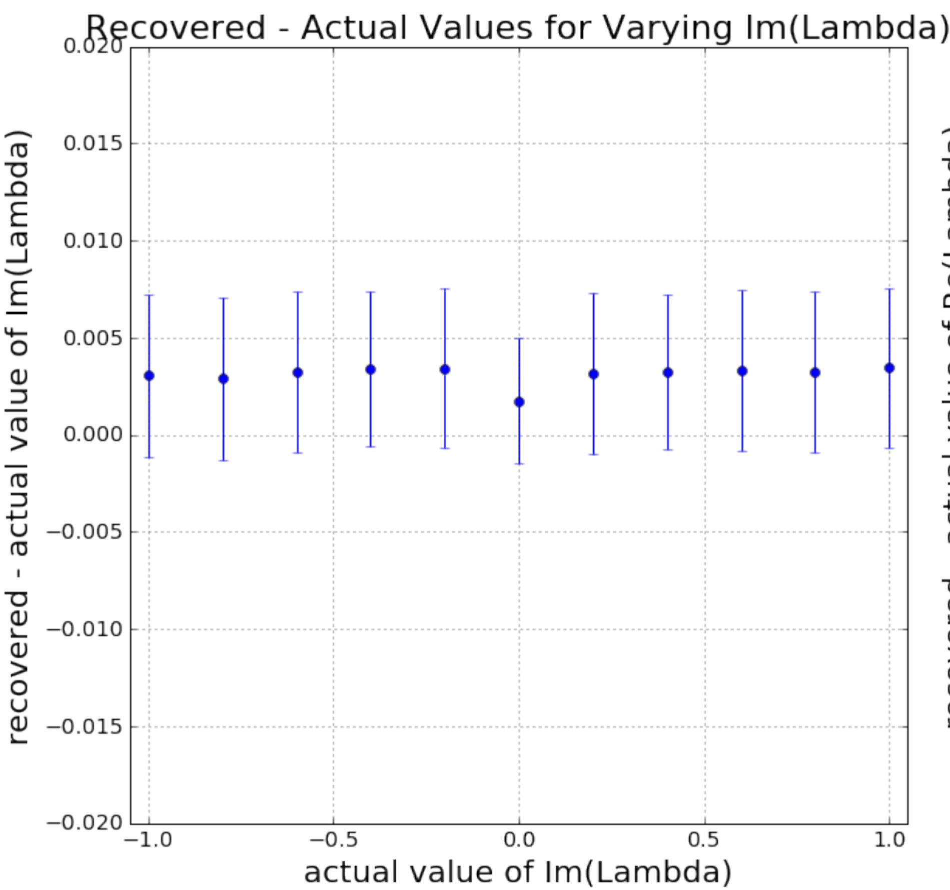
λ=0

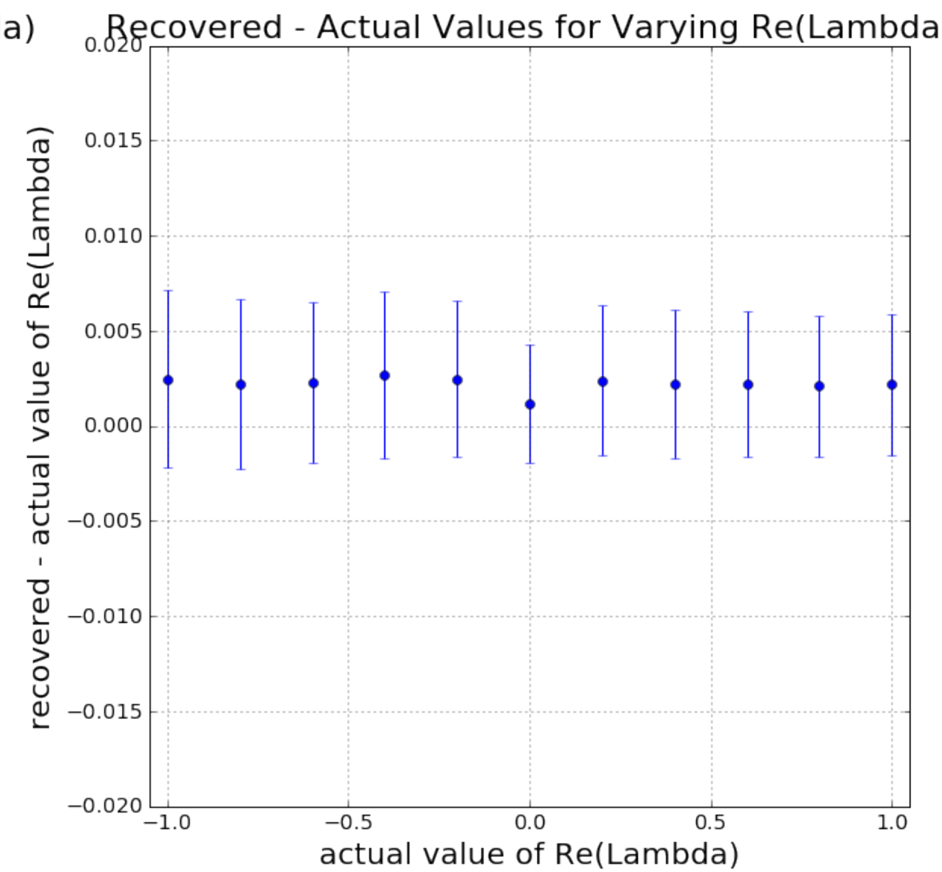
Recovering Lambda



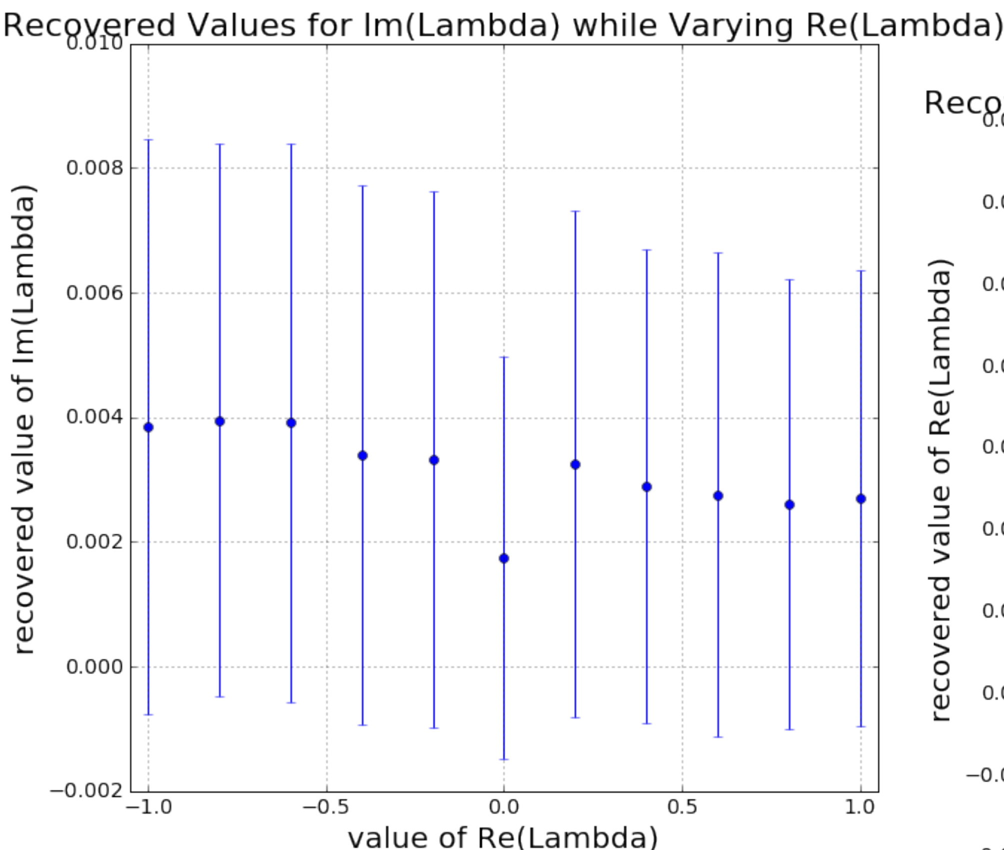


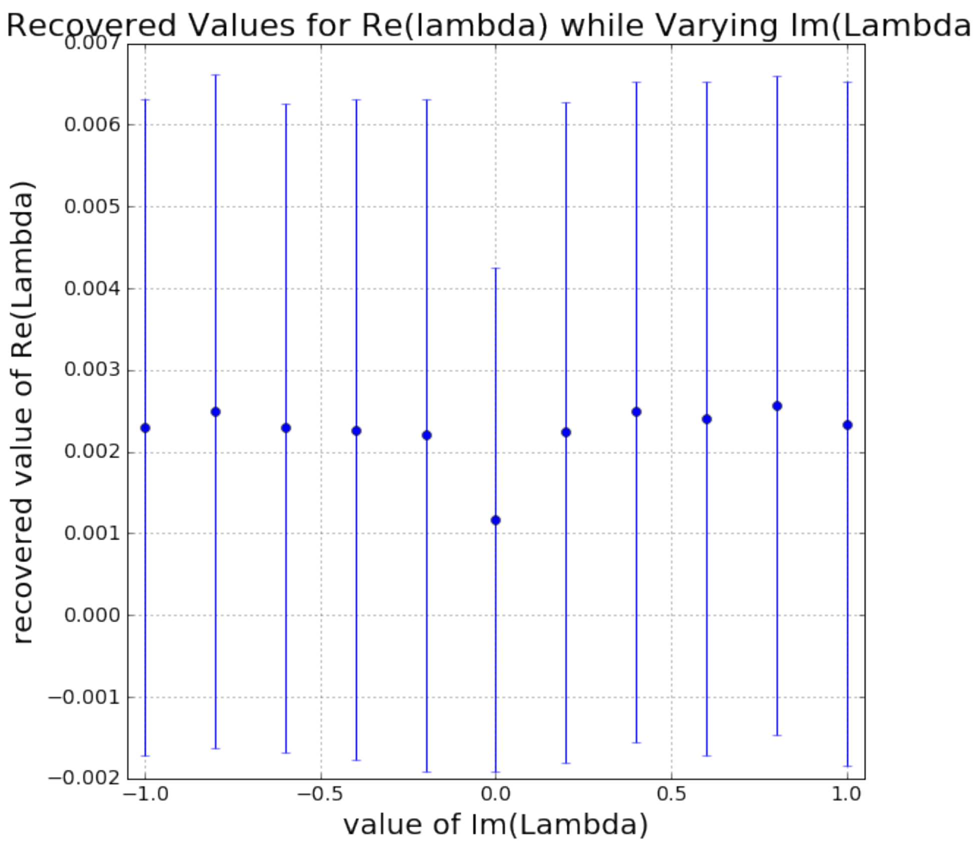
Recovering Lambda



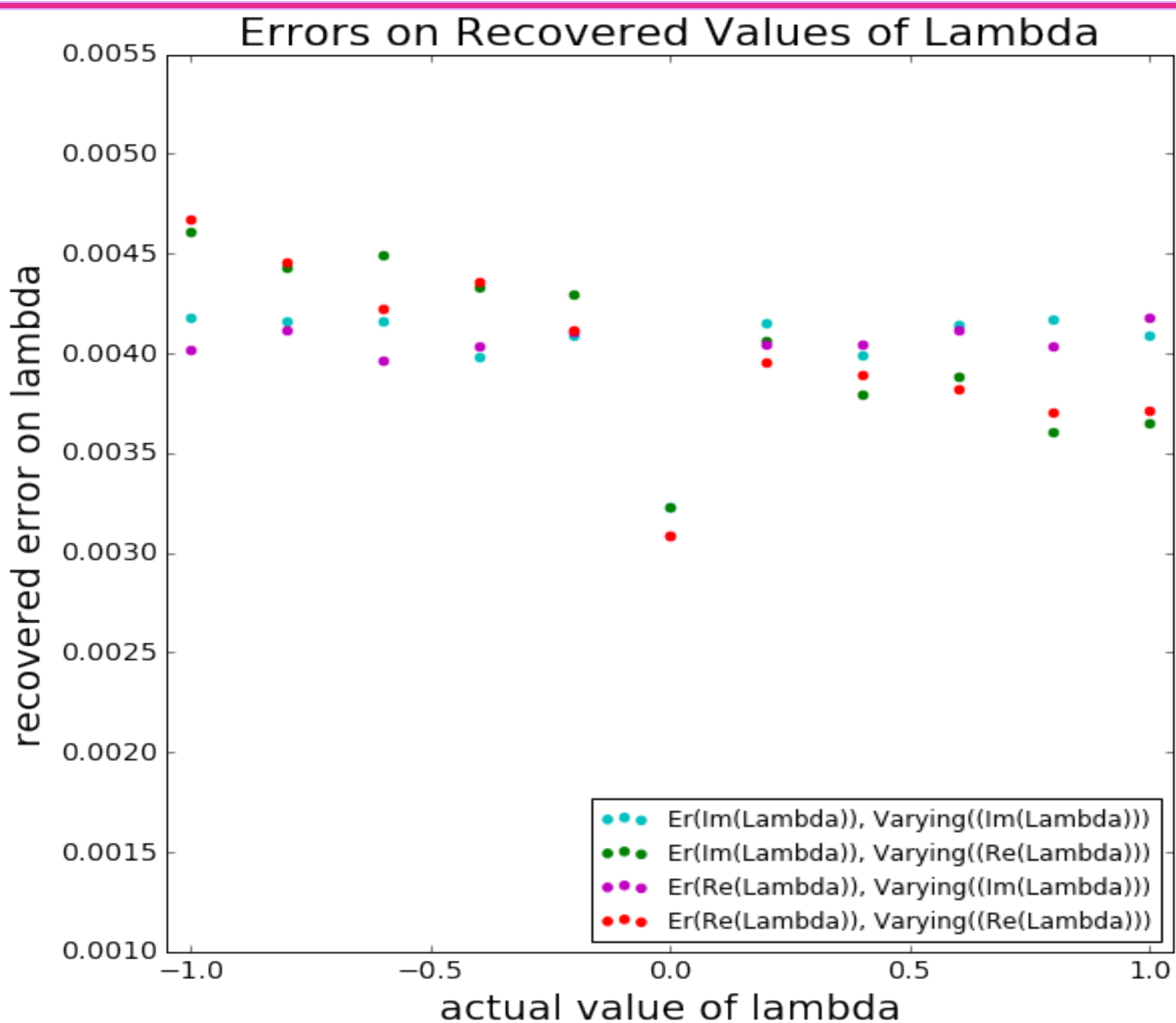


Recovering Lambda





Recovering Lambda



Summary and conclusions

- Summary
  - Using only 20 events we can pin down a given value of λ very precisely

- Conclusions
  - White gaussian noise is not a good model for LIGO noise
  - There may or may not be a correlation between the real and imaginary parts of λ

Next steps

- Short term:
  - » More reasonable events and SNRs
  - » Figuring out the consistent overestimation of λ
  - » Figuring out why $\lambda = 0$ has lower errors
  - » changing both Re(λ) and Im(λ)
- Long term:
  - » How many events to constrain λ by a certain amount
  - » Letting all 15 (17) parameters vary
  - » Running on the actual data

Acknowledgments

- NSF / SURF
- LIGO Caltech
- Rory Smith
- Rico
- Osase
- Alan