Characterization of Hardware Injections in LIGO Data

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Objectives

- Data from S6 run contains simulated signals from compact binary coalescences (CBCs) that were injected into the H1 and L1 detectors.
- Signals were produced by physically moving test masses.
- We're seeking to retrieve these signals through matched filtering.
- The injection times and merger times of the injections are recorded, so the signal to noise ratios (SNRs) should be easily retrieved.

Compact Binary Coalescences

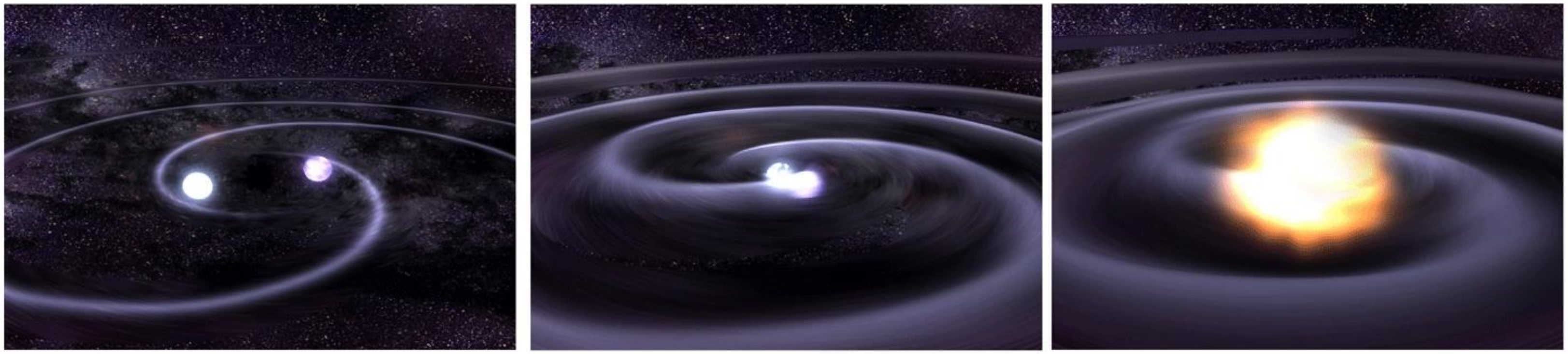


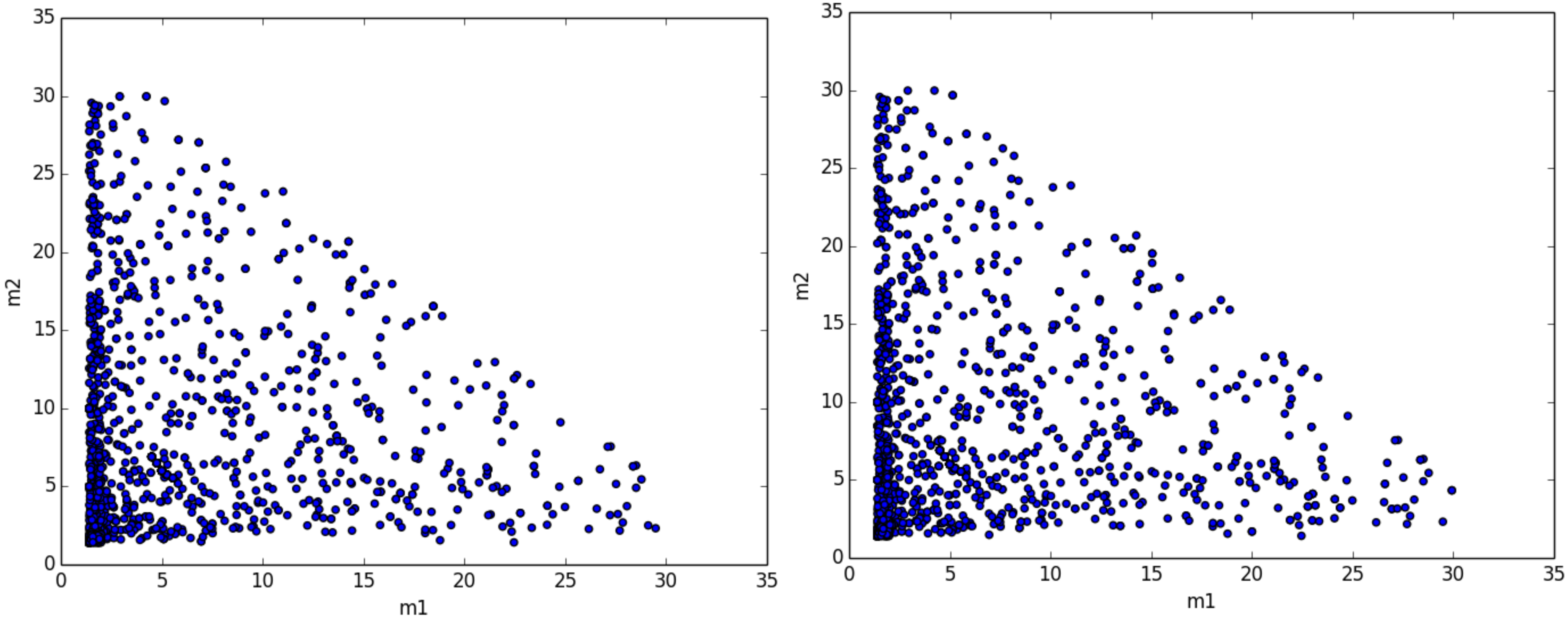
Image from ligo.org

- Three stages: inspiral, merger, ringdown
- Three types: neutron star-neutron star (NSNS), neutron star-black hole (NSBH), black hole-black hole (BHBH)

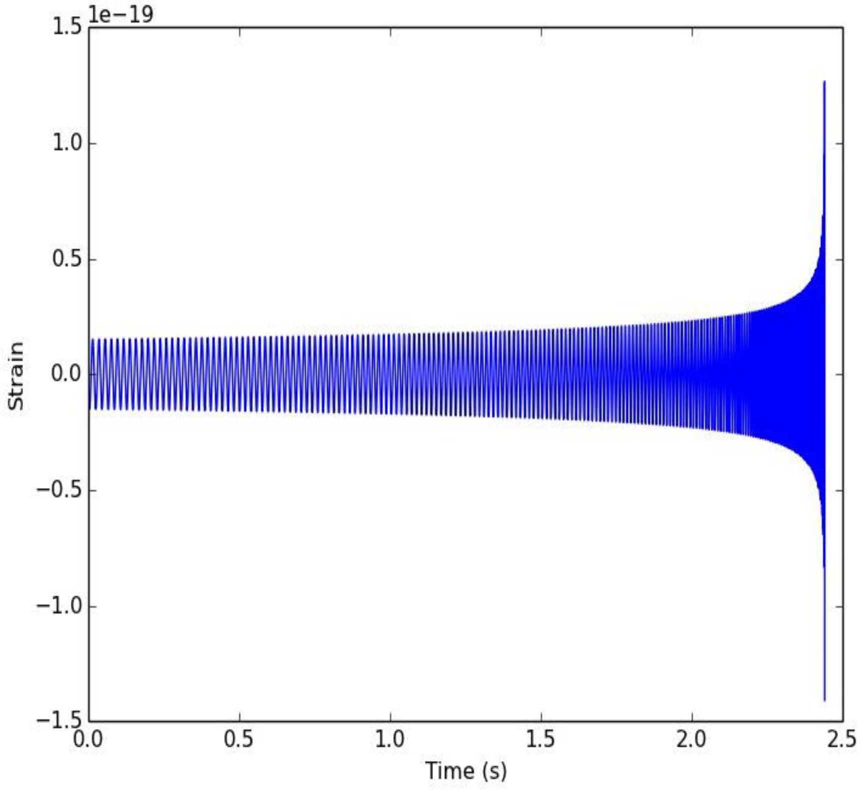
Chirp Waveform

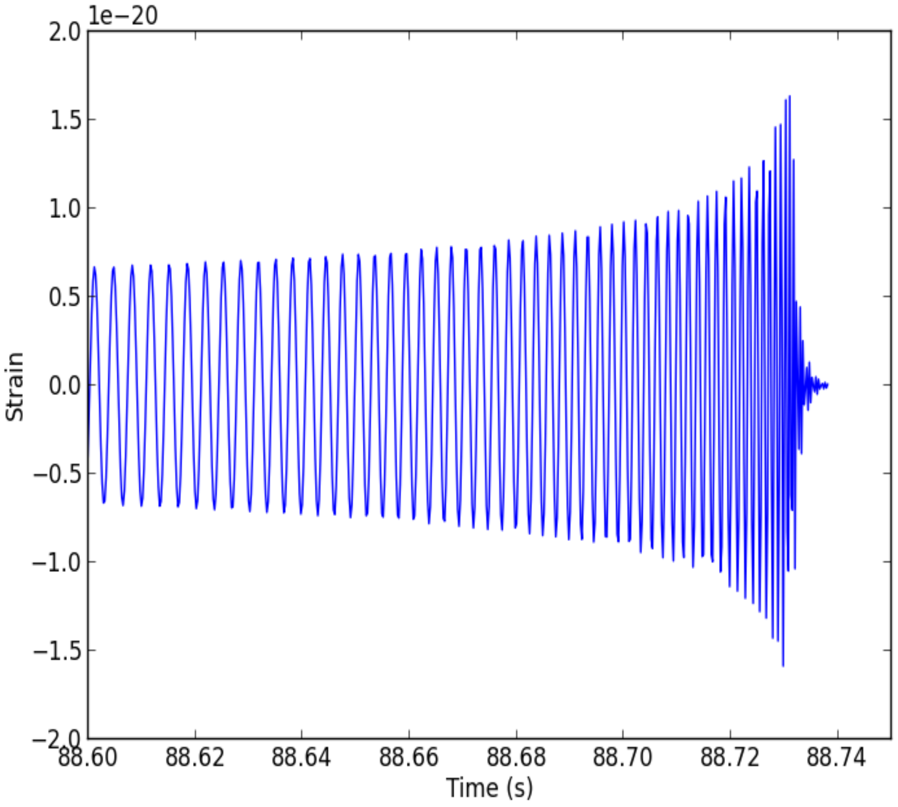
- Signals appear in data as chirp waveforms.
- Chirp waveforms are determined by the masses of the binaries.
- NSNS have the longest waveforms, because they reach the merger phase at high frequencies.
- BHBH have the shortest waveforms, because they reach the merger phase at low frequencies.

Distribution of Masses



Chirp Waveform (cont.)





Matched Filter

$$z(t) = 4\int_0^\infty \frac{\tilde{s}(f)\tilde{h}^*_{template}(f)}{S_n(f)} e^{2\pi i f t} df$$

$$\sigma_m^2 = 4\int_0^\infty \frac{|\tilde{h}_{1Mpc,m}(f)|}{S_n(f)} e^{2\pi i f t} df$$

$$\rho_m(t) = \frac{|z_m(t)|}{\sigma_m}$$

Power Spectral Density

- Took average power spectrum
- Took the mean of the power spectrum of eight segments
- Segment defined as the length of the data that is later multiplied by the template

Hardware Injections

- EOBNRpseudoFourPN: makes up the bulk of the injections.
- GeneratePPNtwoPN: can be reasonably approximated using FindCHIRP template.
- SpinTaylorT4threePointFivePN: has spin.

Final Approach

- Used lalapp coinj to make the templates used to produce the injections.

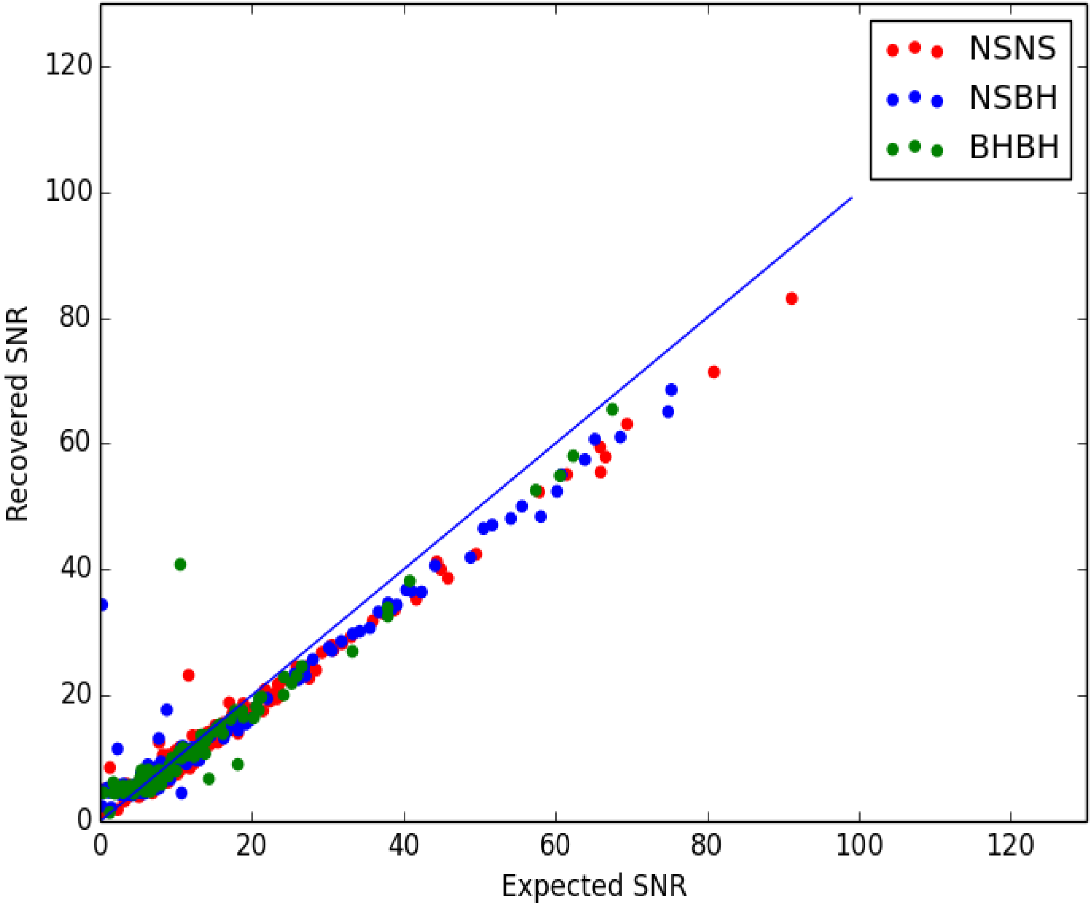
- Took 100 seconds of data because the templates are 100 seconds long.

- Wrote script to identify the template using the injection time.

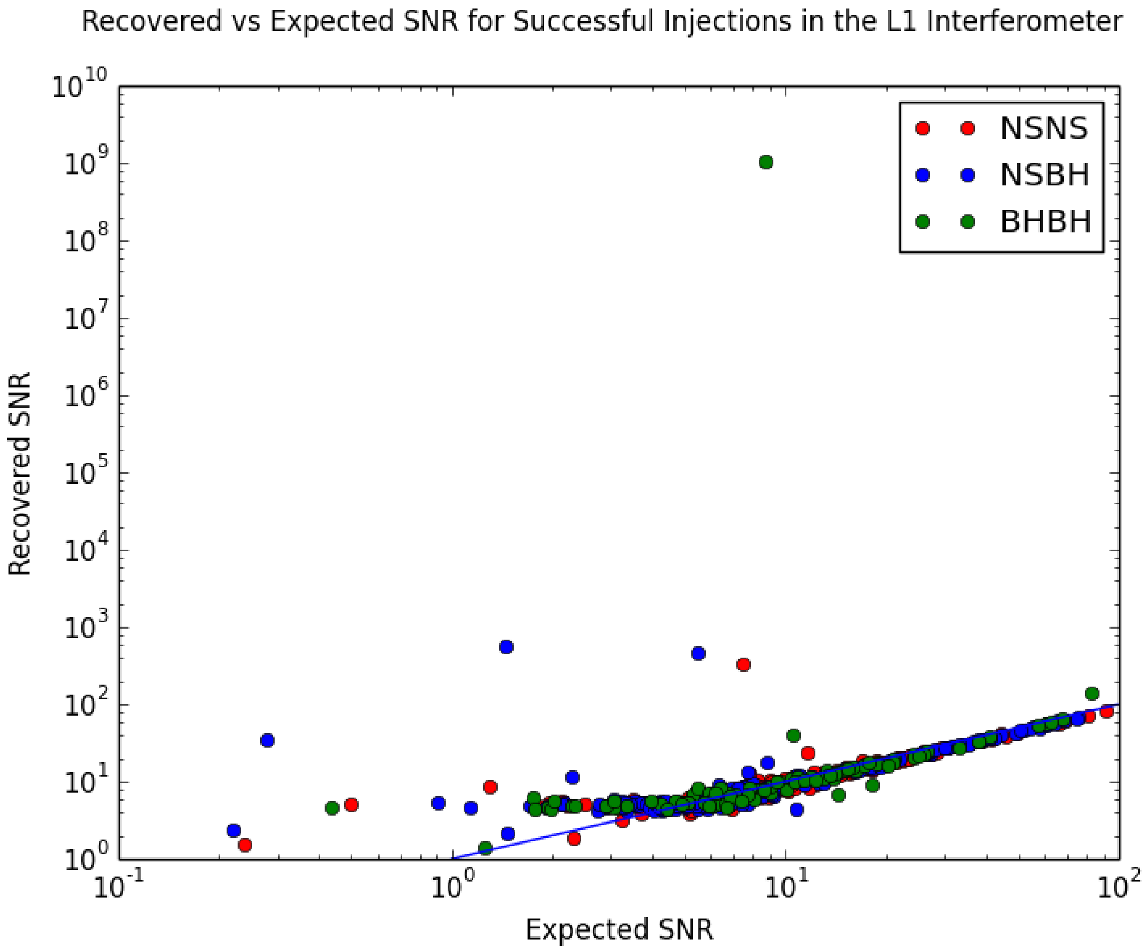
Lessons Learned

- Neglected windowing – take care so that the merger is centered in the data.
- Offset in recovered time = injection time + 100 – merger time
- Templates already normalized to effective distance.
- Edit xml files so that coinj works.

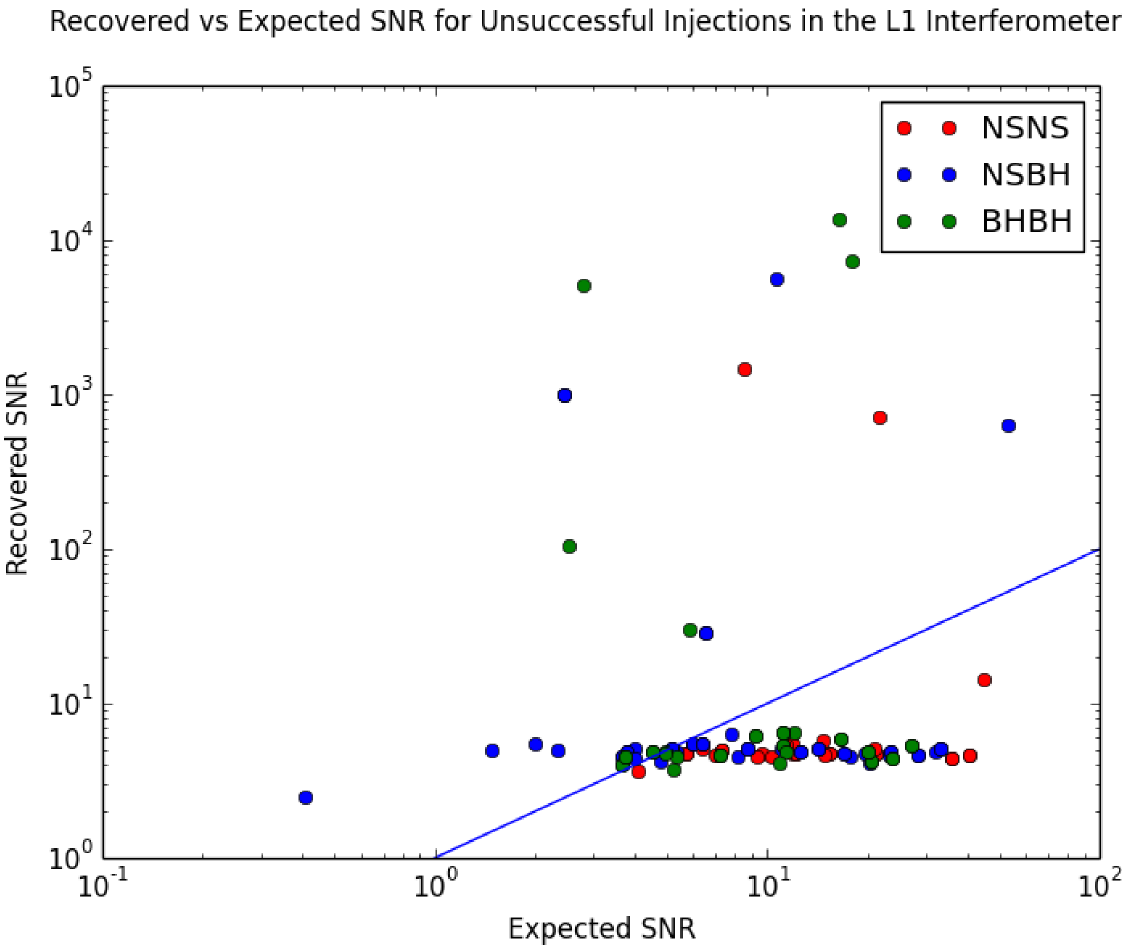
Recovered SNRs for L1



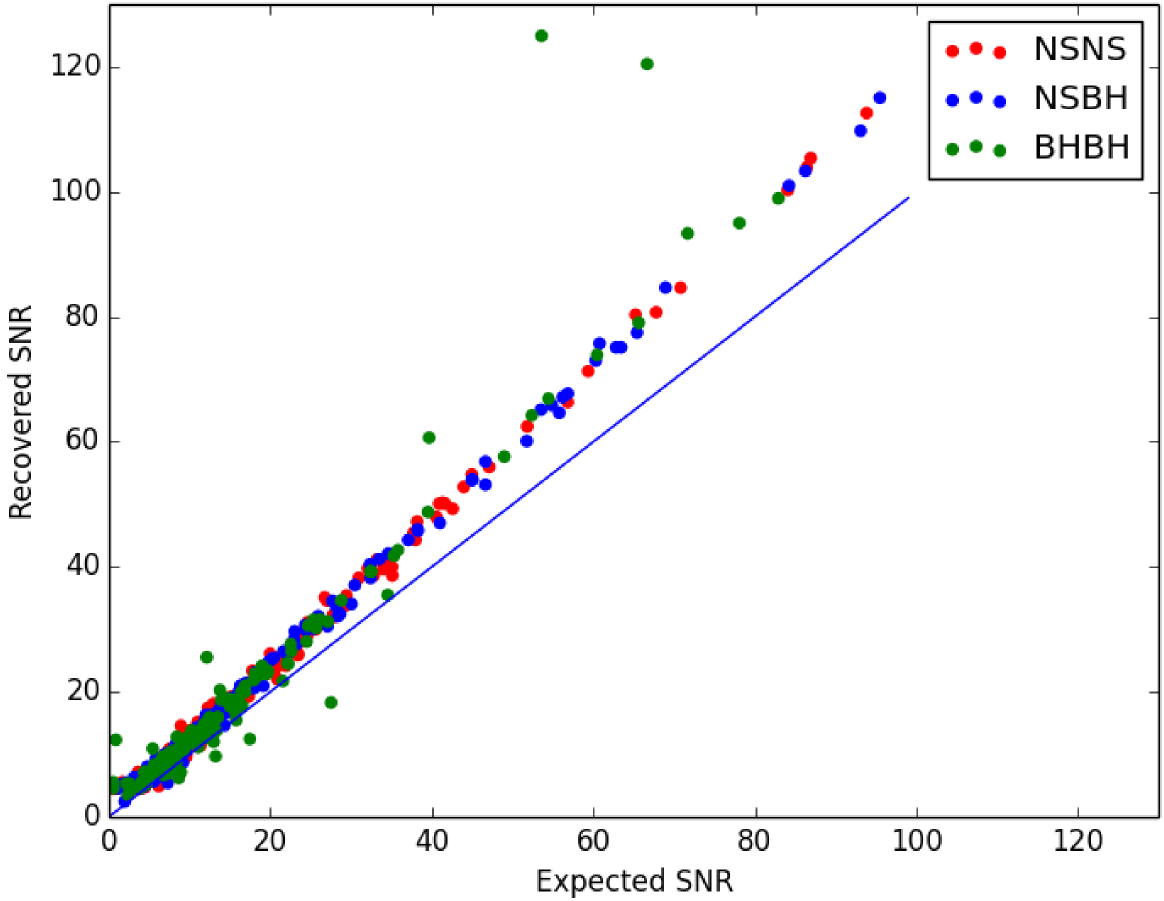
Recovered SNRs for L1



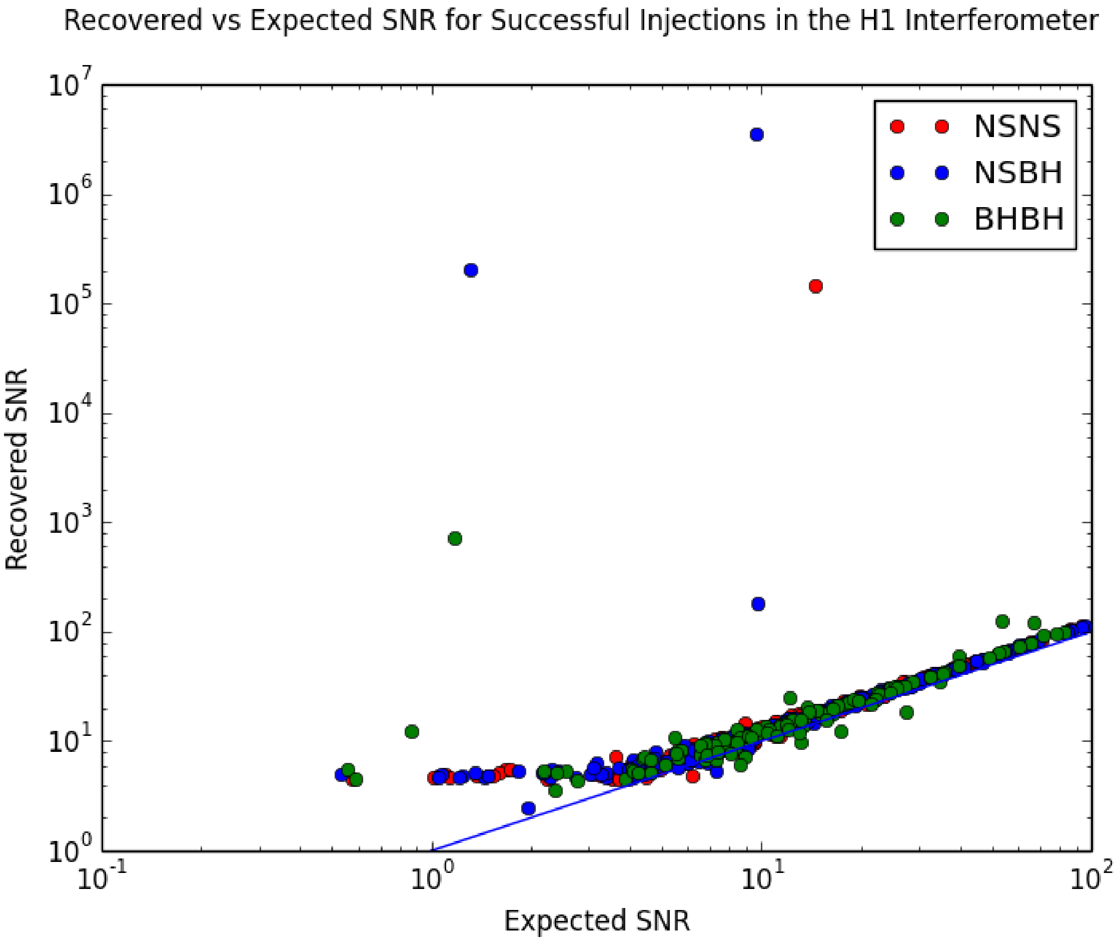
Unsuccessful Injections in L1



Recovered SNRs for H1

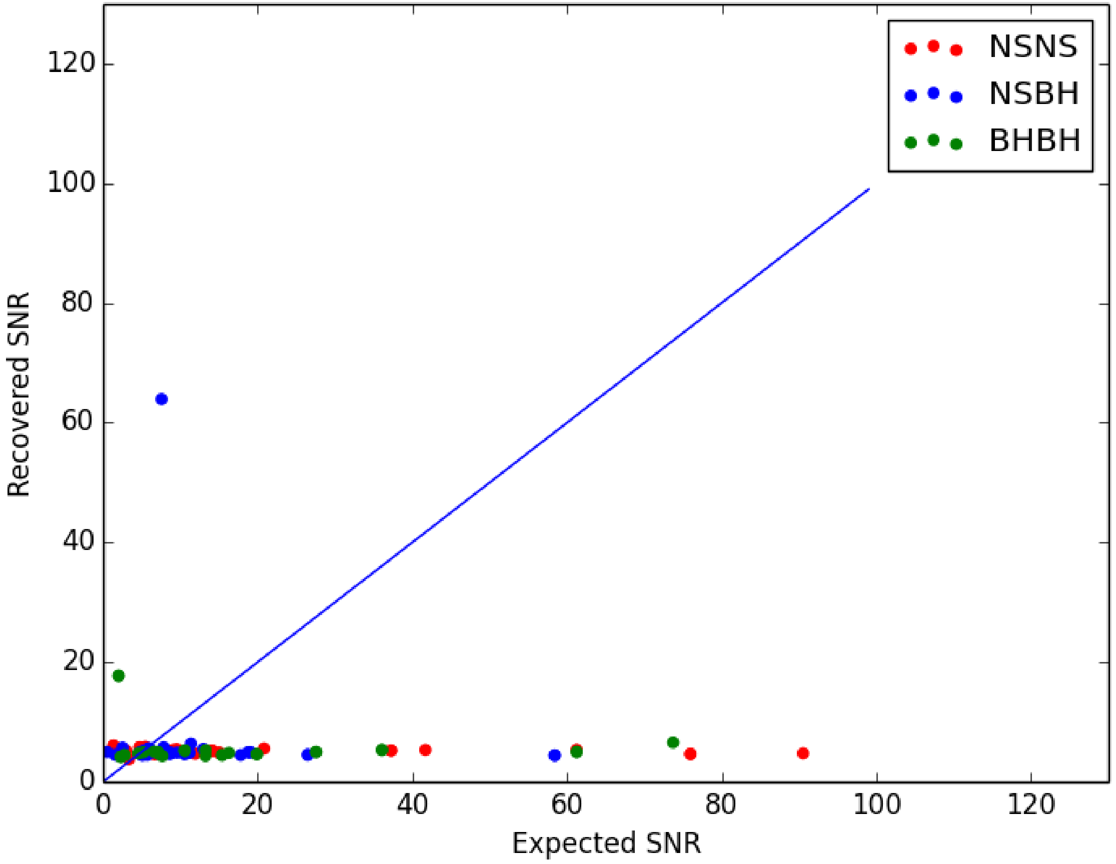


Recovered SNRs for H1



Unsuccessful Injections in H1

Truncated Recovered vs Expected SNR for Unsuccessful Injections in the H1 Interferometer



Discrepancies

- Unexpected: possible signals when status is recorded as "Not in science mode," "GRB alert," and "Injection compromised."
- Anomalies: when the ratio of the recovered to the expected SNR is lower than 0.5 or higher than 2, and expected SNR is higher than 6.
- Deceptive: injection marked as "Successful" but the recovered time differs greatly from the merger time.
- Shorties: injections that don't have 100 seconds of data.

Discrepancies

- 85 injections that produced questionable results
- Could plot Fourier-transformed data against frequency template and average power spectrum as sanity check
- Could run omega scan on both merger and recovered times as sanity check

Accounting for Shorties

- Still grabbed 100 seconds of data using getsegs from readligo.py.
- If data missing from end of segment, zero-padded end.
- If data missing from beginning of segment, zero-padded beginning.

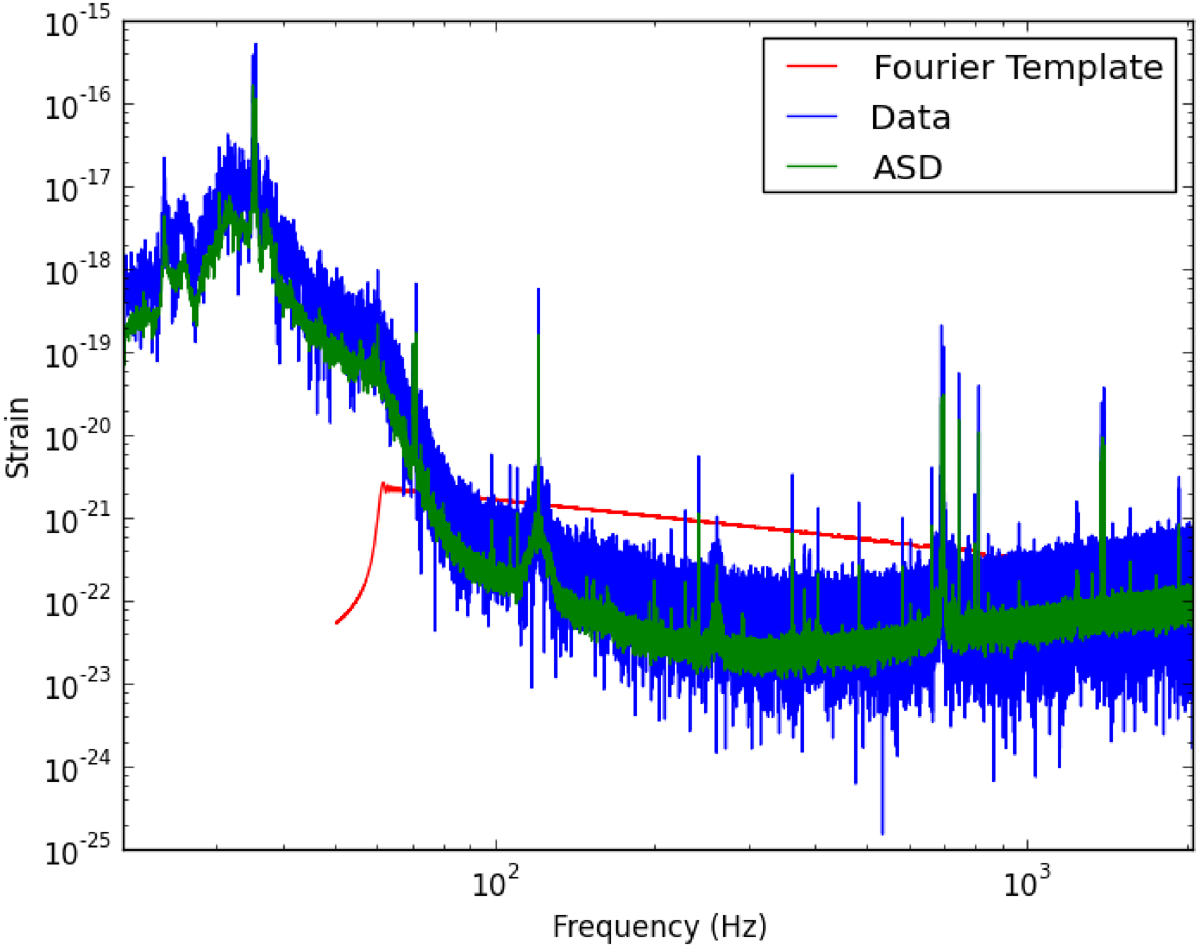
Discrete Fourier Transform

$$\tilde{x}[k] = \Delta t \sum_{j=0}^{N-1} x[j] \mathrm{e}^{-2\pi i j k/N}$$

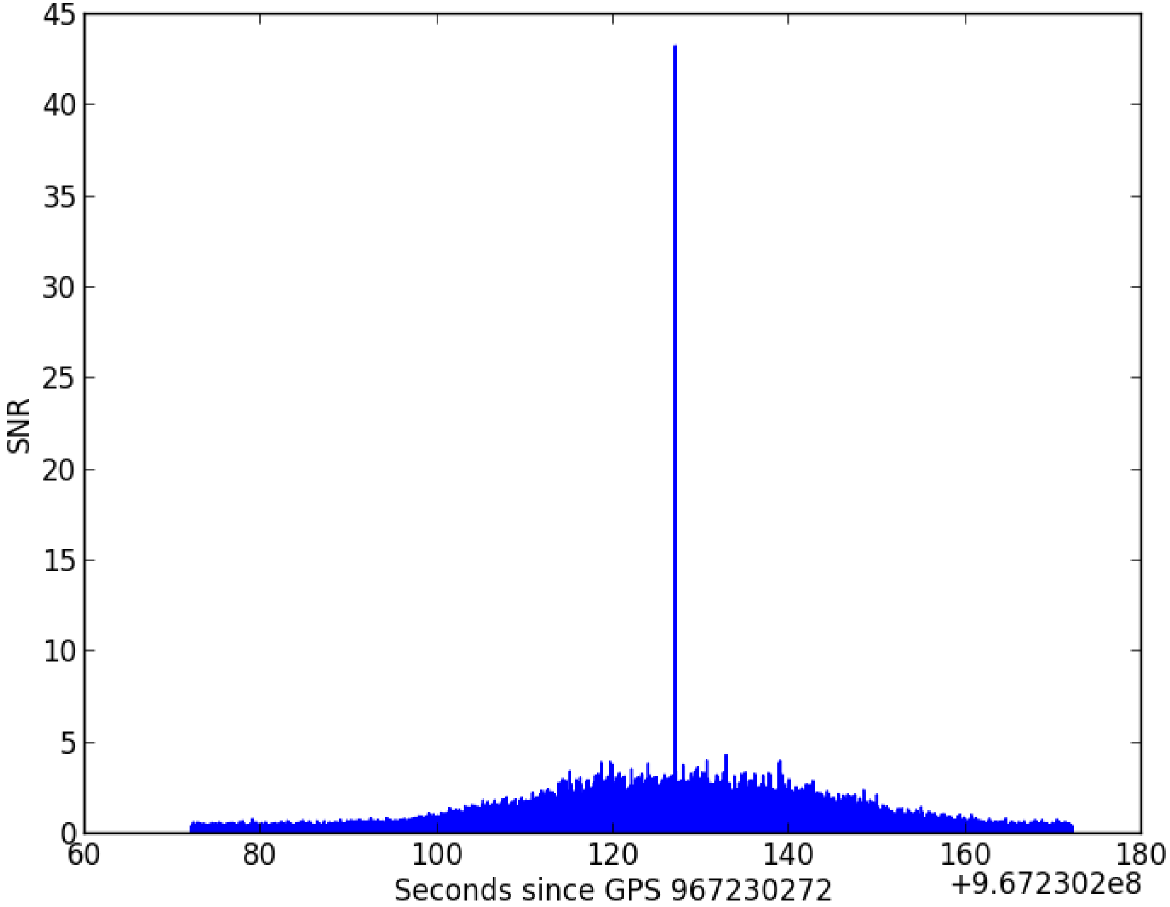
$$\tilde{x}[k] \approx \tilde{x}(k\Delta f) \text{ for } 0 \leq k \leq \lfloor N/2 \rfloor$$

- The discrete Fourier transform approximates the continuous Fourier transform at frequency kΔf.
- The nature of the transform is that the length of the template affects the outcome of the transform.

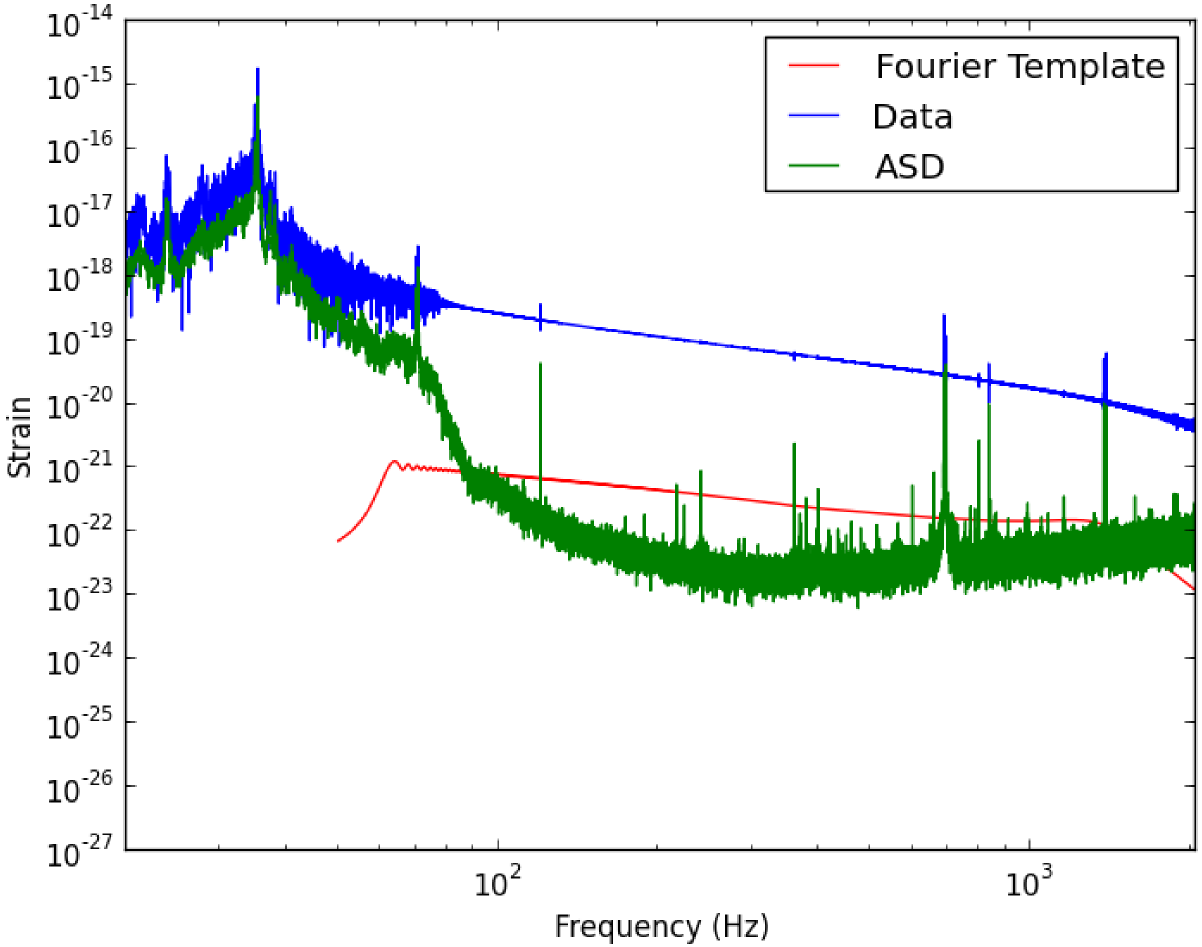
Successful Injection



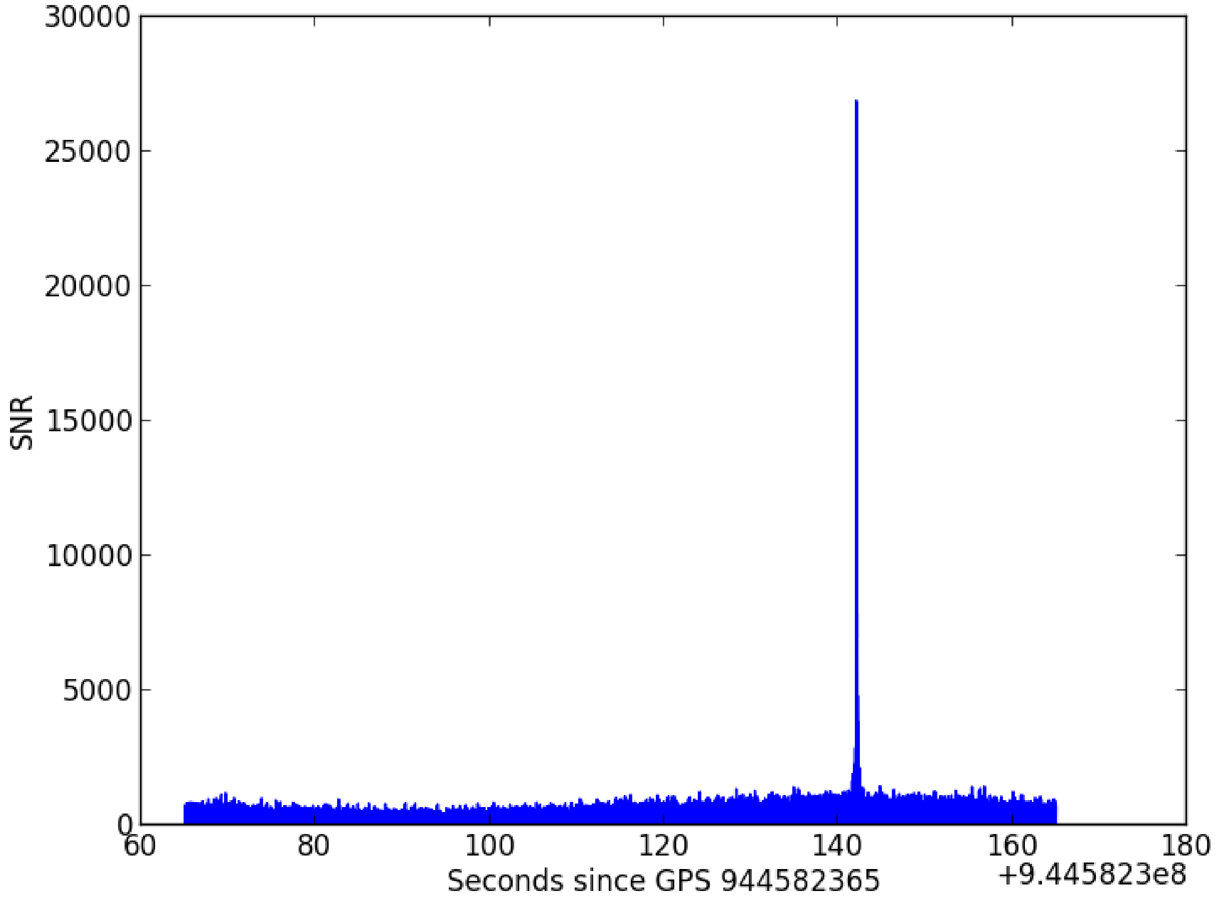
Successful Injection



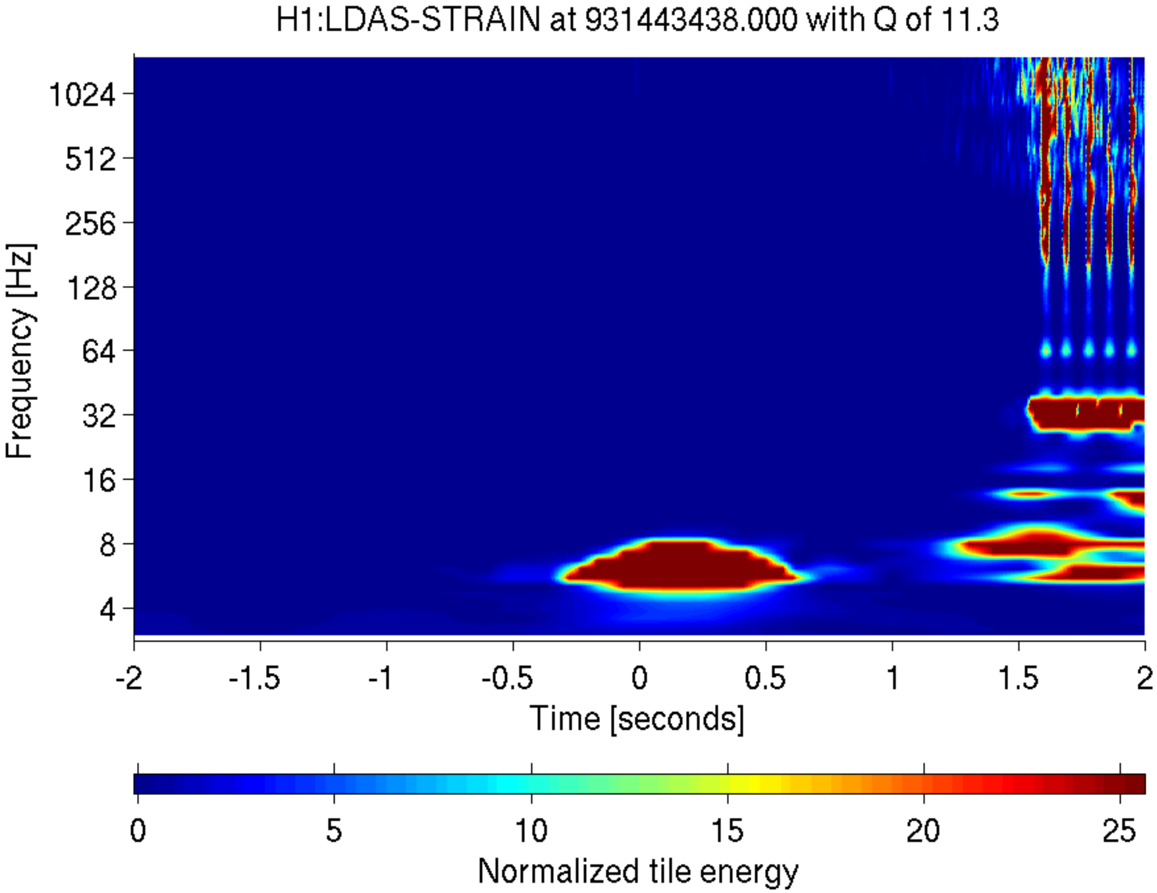
Unsuccessful Injection



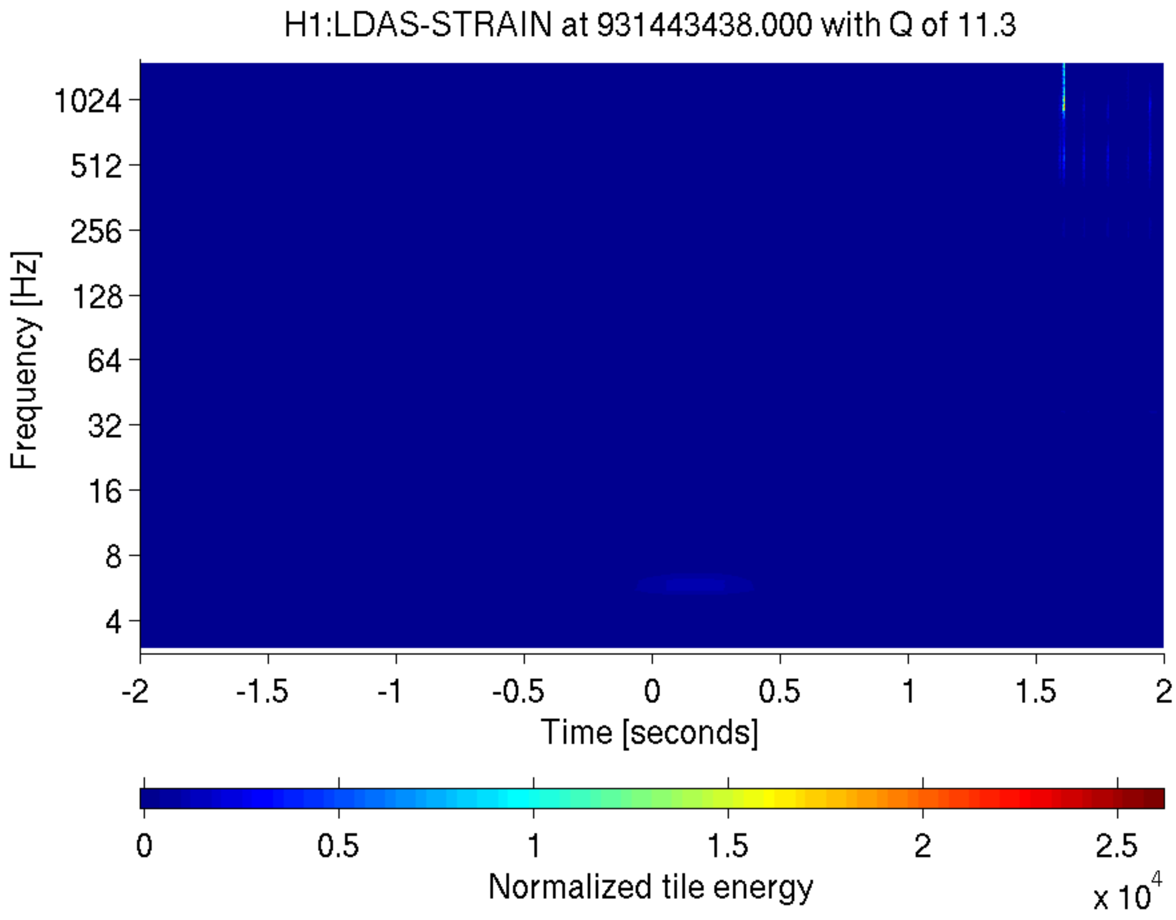
Unsuccessful Injection



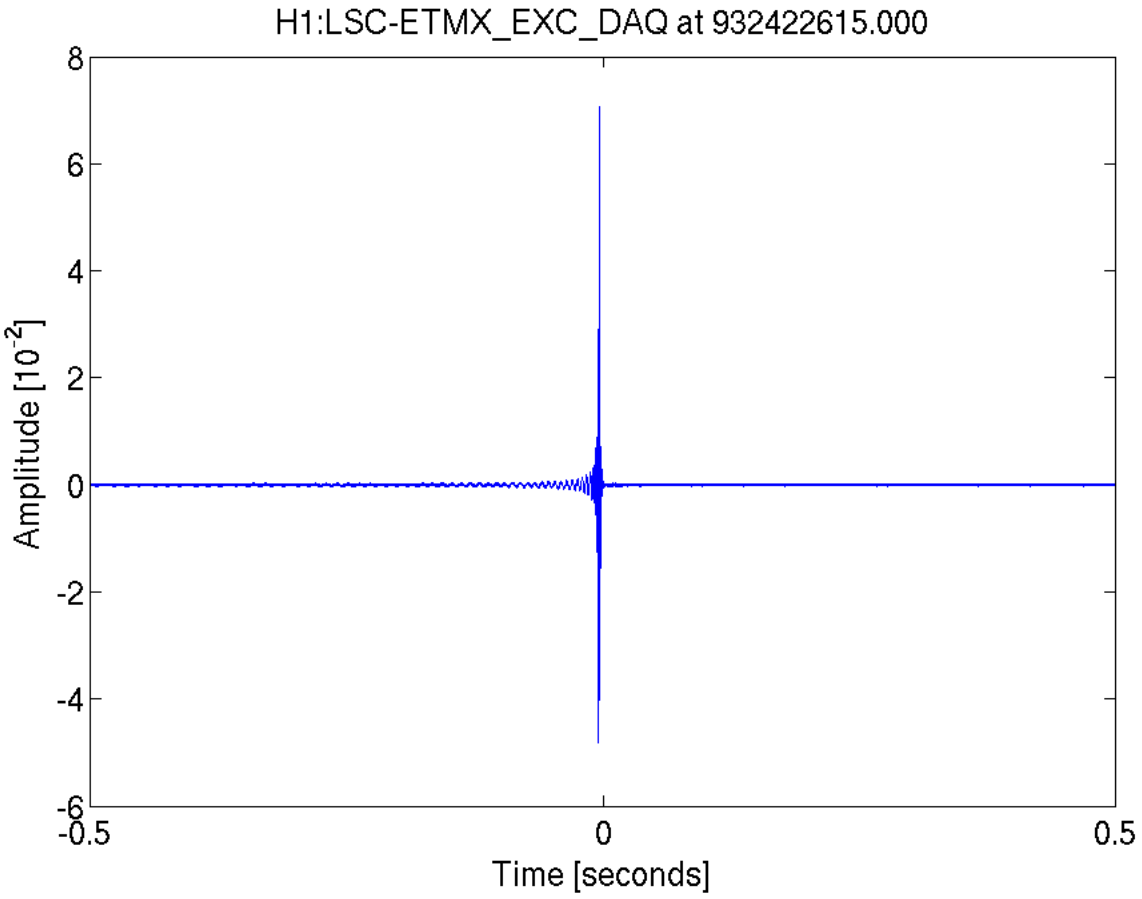
Omega Scan - Glitch



Omega Scan – Glitch



Omega Scan – Injection Present



Future Work

- Currently we're working with the lists H1biinjlist.txt and L1biinjlist.txt.
- We need to ascertain that those two lists contain all of the hardware injections.
- There are six injections in the H1biinjlist.txt that cannot be matched to any injection in the parameter files.
- The burst injections also need to be retrieved.

Acknowledgements

Thank you to…

Jonah Kanner
Alan Weinstein
Tom Tombrello

Backup Slides

Chirp Waveform (cont.)

$$h_+(t) = -\frac{1+\cos^2\iota}{2}\left(\frac{G\mathcal{M}}{c^2D}\right)\left(\frac{t_c - t}{5G\mathcal{M}/c^3}\right)^{-1/4} \times \cos[2\phi_c + 2\phi(t - t_c; M, \mu)], \tag{3.1a}$$

$$h_\times(t) = -\cos\iota\left(\frac{G\mathcal{M}}{c^2D}\right)\left(\frac{t_c - t}{5G\mathcal{M}/c^3}\right)^{-1/4} \times \sin[2\phi_c + 2\phi(t - t_c; M, \mu)] \tag{3.1b}$$

- Plus and cross represent the two polarizations.
- D is distance from source.
- M is total mass; μ is reduced mass; η is reduced mass over total mass; slanted M *M* is chirp mass, or $\eta^{3/5}$M.

FindCHIRP Approach

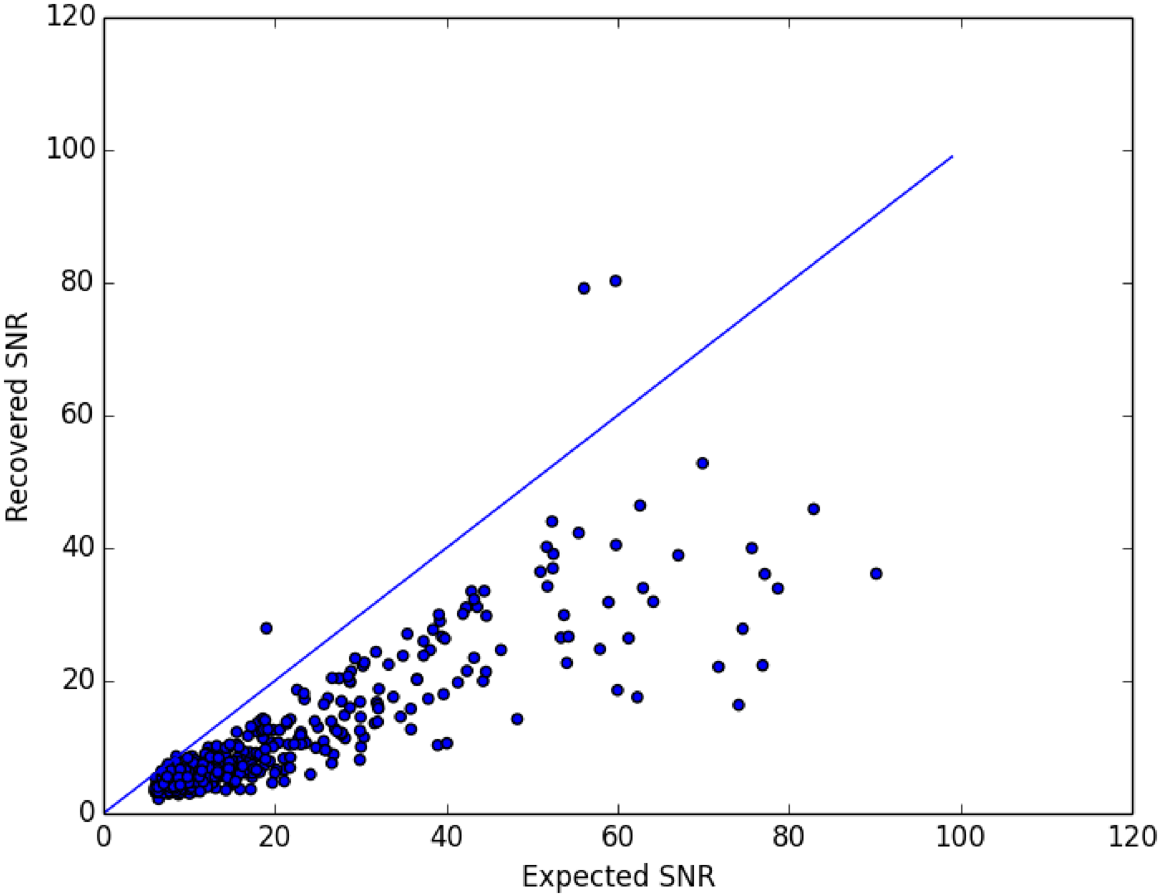
$$\tilde{h}(f) = -\left(\frac{5\pi}{24}\right)^{1/2}\left(\frac{G\mathcal{M}}{c^3}\right)\left(\frac{G\mathcal{M}}{c^2 D_{\mathrm{eff}}}\right)\left(\frac{G\mathcal{M}}{c^3}\pi f\right)^{-7/6} \mathrm{e}^{-i\Psi(f;M,\mu)} = \left(\frac{1\,\mathrm{Mpc}}{D_{\mathrm{eff}}}\right)\mathcal{A}_{1\,\mathrm{Mpc}}(M,\mu)\, f^{-7/6}\mathrm{e}^{-i\Psi(f;M,\mu)}$$

$$\mathcal{A}_{1\,\mathrm{Mpc}}(M,\mu) = -\left(\frac{5}{24\pi}\right)^{1/2}\left(\frac{GM_\odot/c^2}{1\,\mathrm{Mpc}}\right)\left(\frac{\pi G M_\odot}{c^3}\right)^{-1/6}\left(\frac{\mathcal{M}}{M_\odot}\right)^{-5/6}$$

$$\begin{aligned}\Psi(f;M,\mu) &= 2\pi f t_0 - 2\phi_0 - \pi/4 \\ &\quad + \frac{3}{128\eta}\left[v^{-5} + \left(\frac{3715}{756} + \frac{55}{9}\eta\right)v^{-3} - 16\pi v^{-2} + \left(\frac{15\,293\,365}{508\,032} + \frac{27\,145}{504}\eta + \frac{3085}{72}\eta^2\right)v^{-1}\right]\end{aligned}$$

$$v = \left(\frac{GM}{c^3}\pi f\right)^{1/3}$$

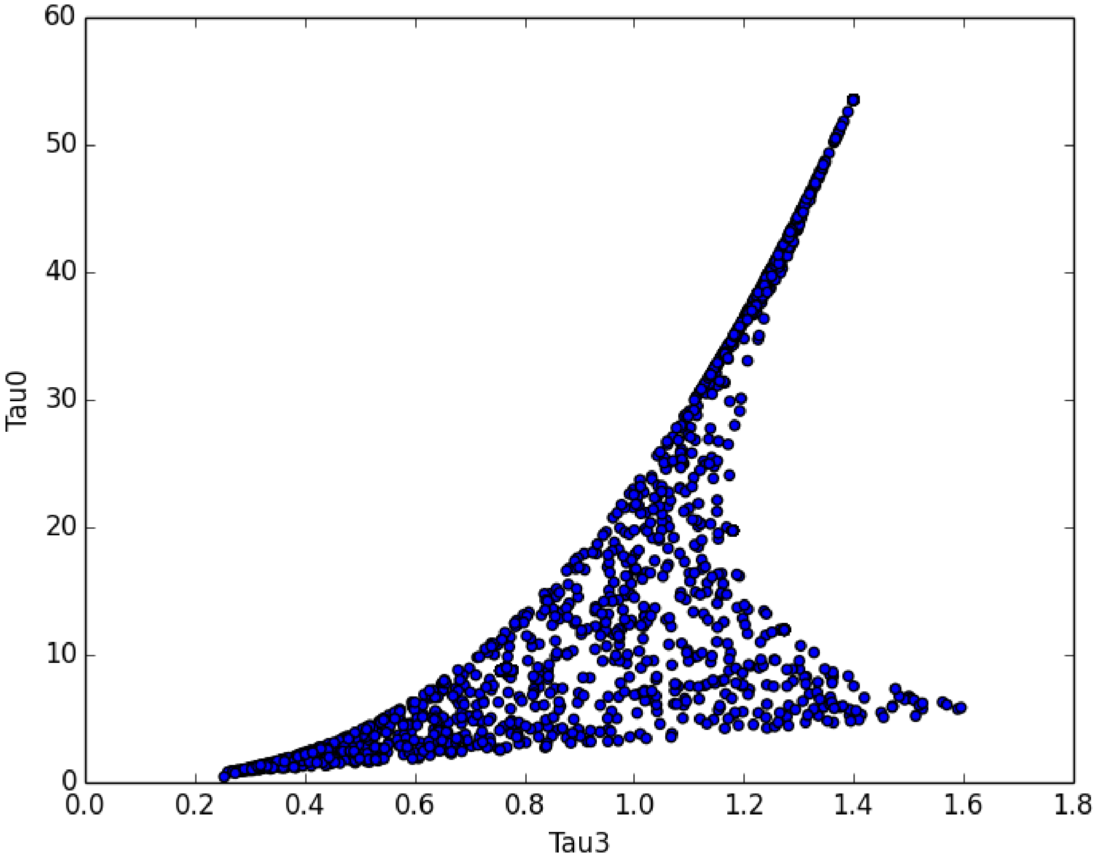
Problems Encountered



Initial Attempts

- Tried running FINDChirp matched filter on S5 hardware injections.
- Results were successful, which confirmed that the templates were correct.
- Switched to third order Post-Newtonian approximation for frequency template.
- Switched window from 4 seconds to 16 seconds and then 32 seconds

Initial Attempts (cont.)



- Chirp times are the durations of signals that start at the lowest frequencies and end at the frequencies at which the systems coalesce

$$\tau_0 = \frac{5}{256\,\pi\,\nu\,f_{\rm L}}\,(\pi M\,f_{\rm L})^{-5/3}\,;$$

$$\tau_3 = \frac{1}{8\,\nu\,f_{\rm L}}\,(\pi M\,f_{\rm L})^{-2/3}$$

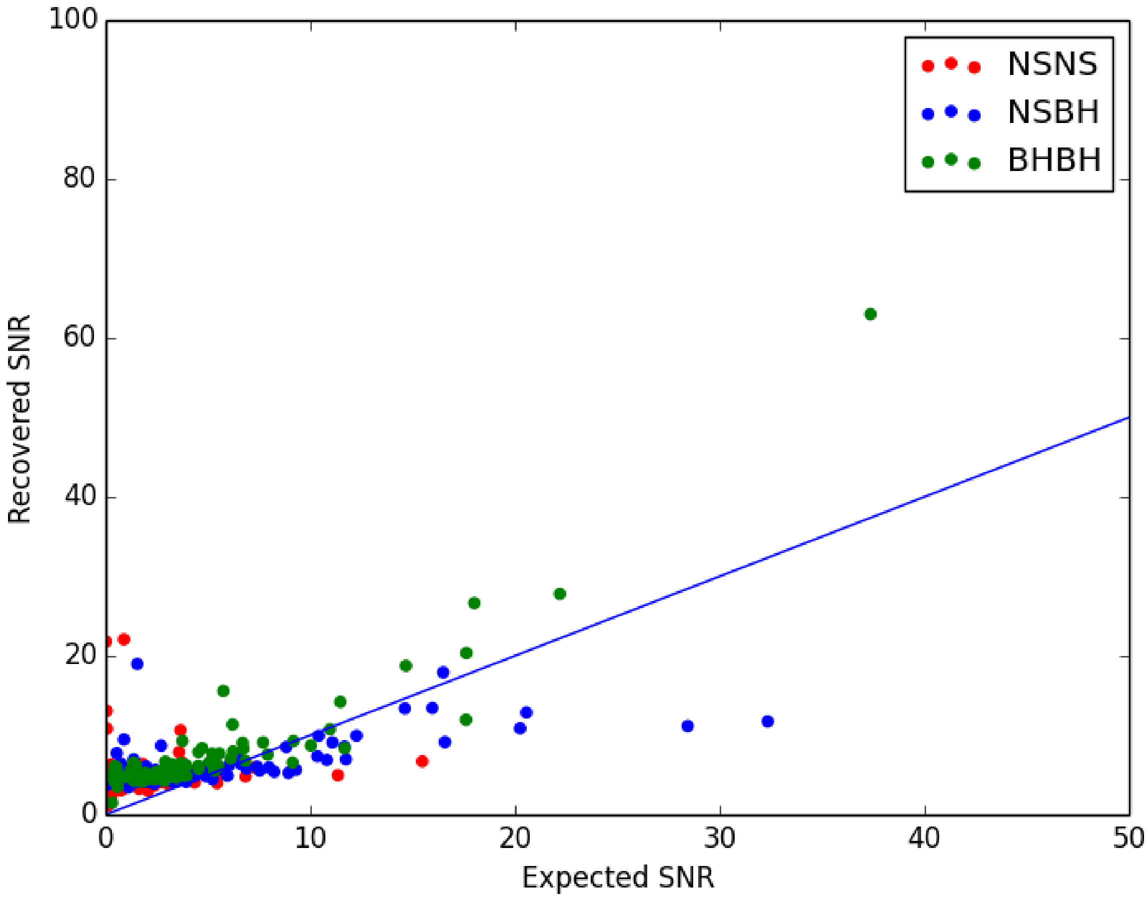
LALSuite Approach

- First tried IMRPhenomC from XLALSimInspiralChooseFDWaveform.
- Employed EOBNRv2 from waveforms.py in LALSuite.
- Could not find original EOBNR function.

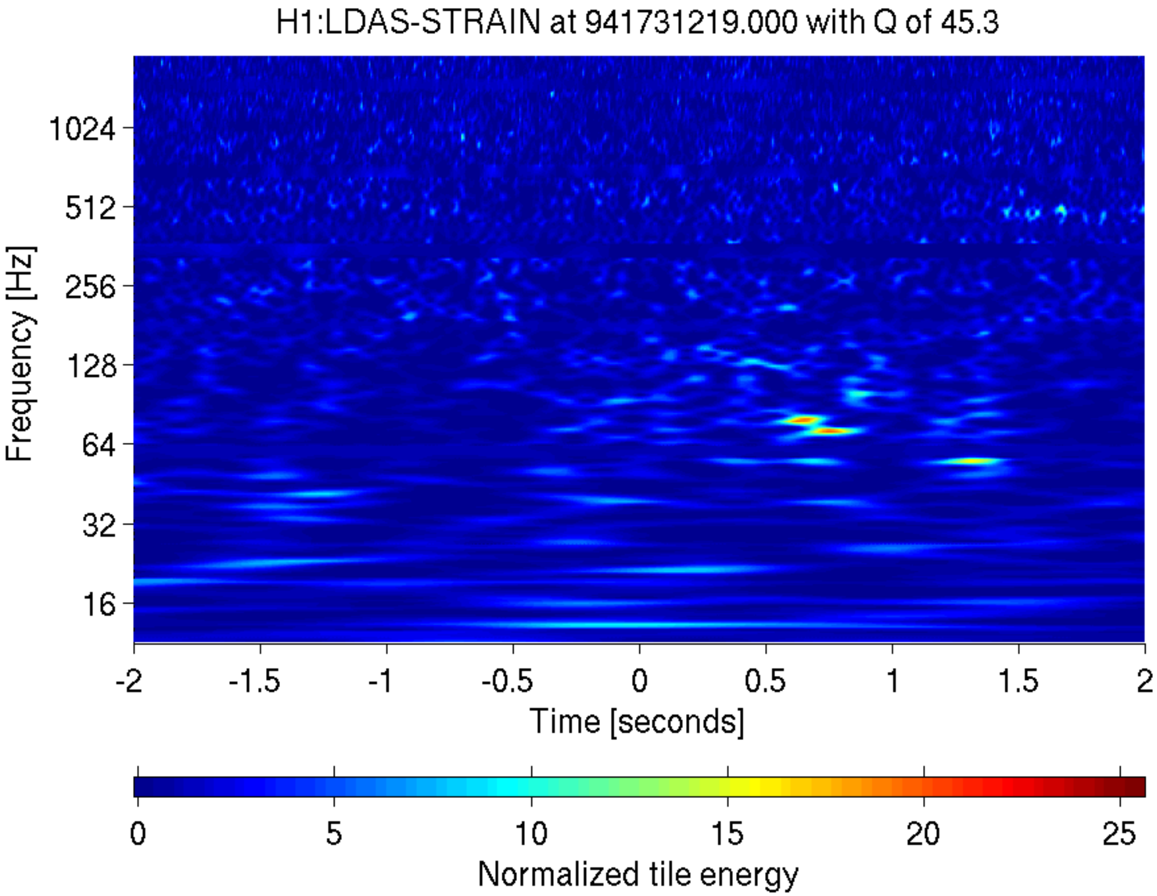
Problems Encountered

- NSNS binaries had worst recovered vs expected SNR ratio.
- EOBNRv2 produces EOBNRv2pseudoFourPN templates.

Signals Recovered



Omega Scan – No Glitch



Omega Scan – No Injection