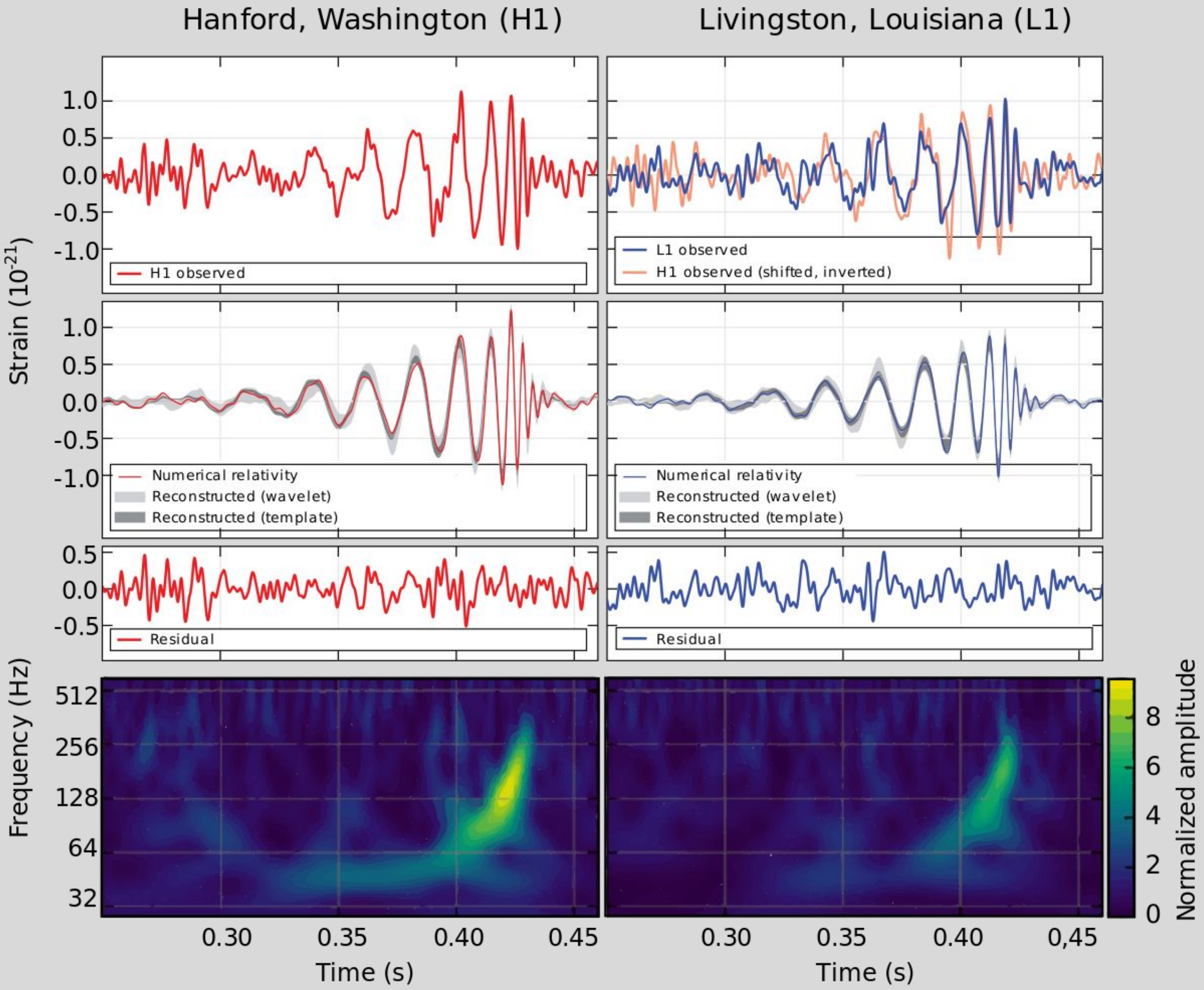
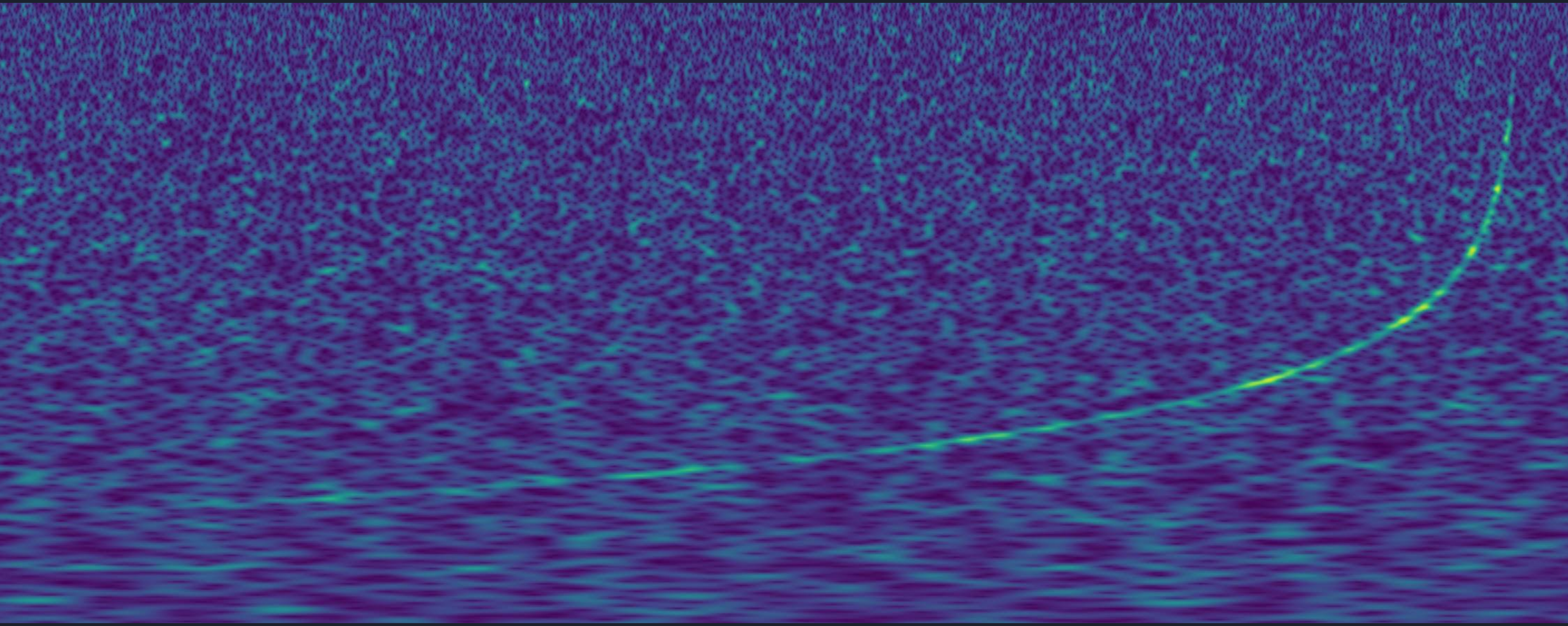
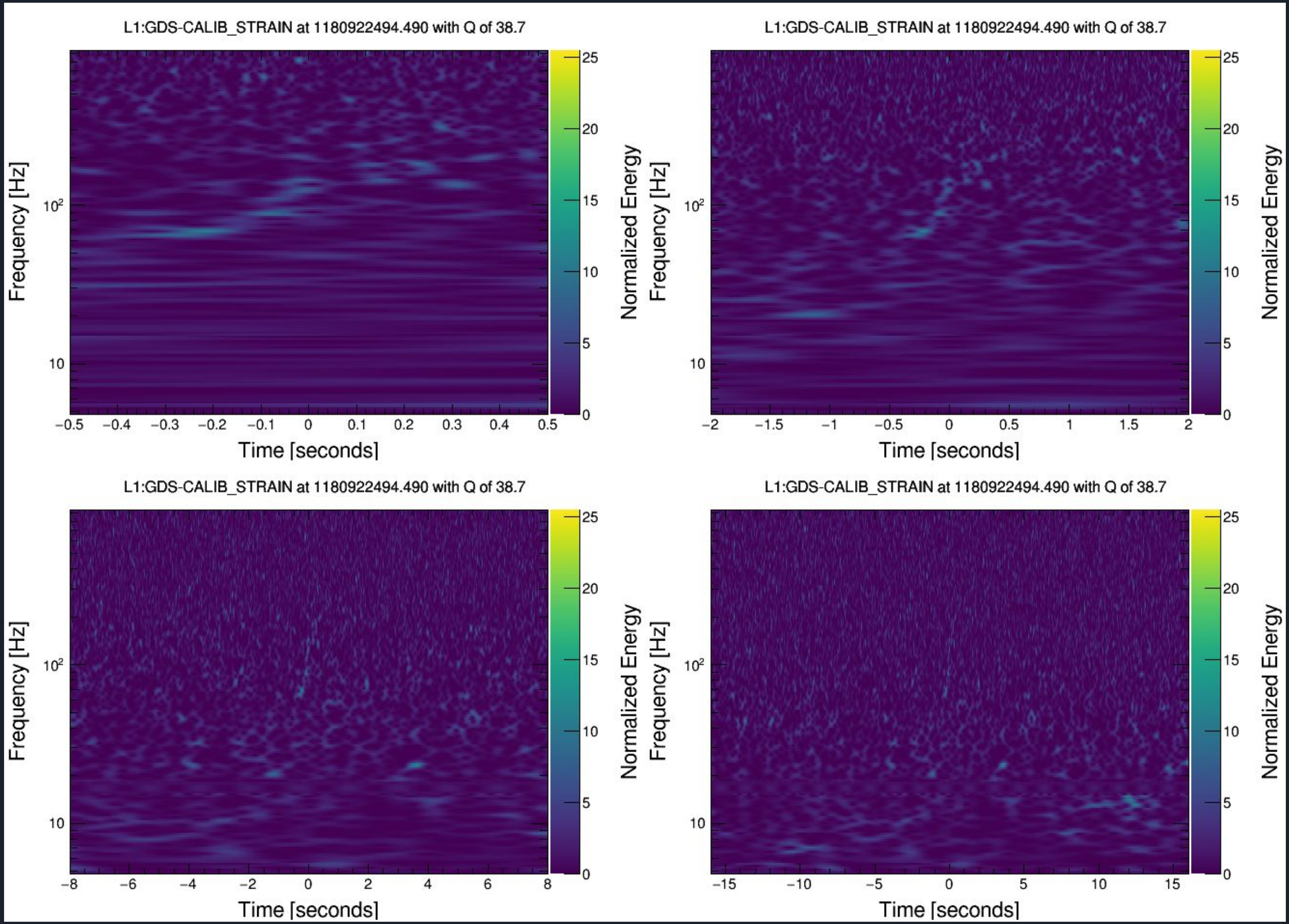
Searching for Compact Binary Mergers

LSC Open Data Workshop, March 2018
Alex Nitz

MAX-PLANCK-GESELLSCHAFT


Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^-21)
1.0
0.5
0.0
-0.5
-1.0
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
512
256
128
64
32
Normalized amplitude
0
2
4
6
8
0.30
0.35
0.40
0.45
0,45
Time (s)




L1:GDS-CALIB_STRAIN at 1180922494.490 with Q of 38.7
Frequency [Hz]
Time [seconds]
Normalized Energy
10
10²
0
5
10
15
20
25
−0.5 −0.4 −0.3 −0.2 −0.1 0 0.1 0.2 0.3 0.4 0.5
L1:GDS-CALIB_STRAIN at 1180922494.490 with Q of 38.7
Frequency [Hz]
Time [seconds]
Normalized Energy
−2 −1.5 −1 −0.5 0 0.5 1 1.5 2
L1:GDS-CALIB_STRAIN at 1180922494.490 with Q of 38.7
Frequency [Hz]
Time [seconds]
Normalized Energy
−8 −6 −4 −2 0 2 4 6 8
L1:GDS-CALIB_STRAIN at 1180922494.490 with Q of 38.7
Frequency [Hz]
Time [seconds]
Normalized Energy
−15 −10 −5 0 5 10 15

LIGO data analysis in a nutshell

Template Searches

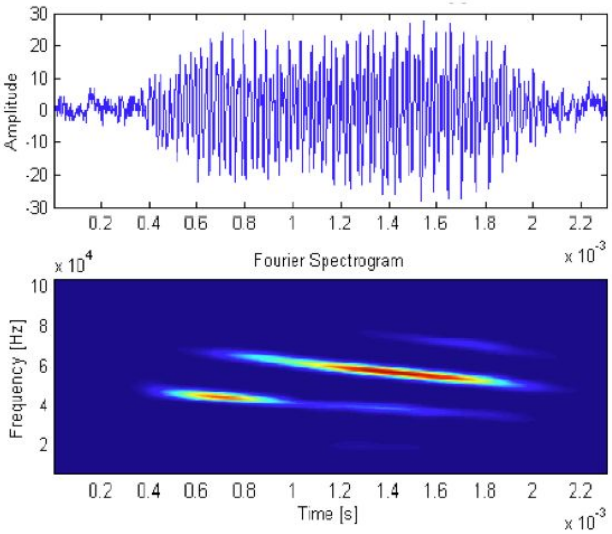
Templates:

anticipated GR waveforms as a function of (limited) source parameters

find template that fits data best

- Confident detection & parameter estimation
- need exact source model, may fail, if theory does not match Nature

Burst Searches



- Look for excess power time – frequency patterns consistent in multiple detectors
- can search for un-modeled & un-expected sources

LIGO data analysis in a nutshell

Template Searches

PyCBC

gstLAL

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cWB

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- “Tiles” are clustered such that frequency increases over time

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- **Found GW150914 while running in low latency!**

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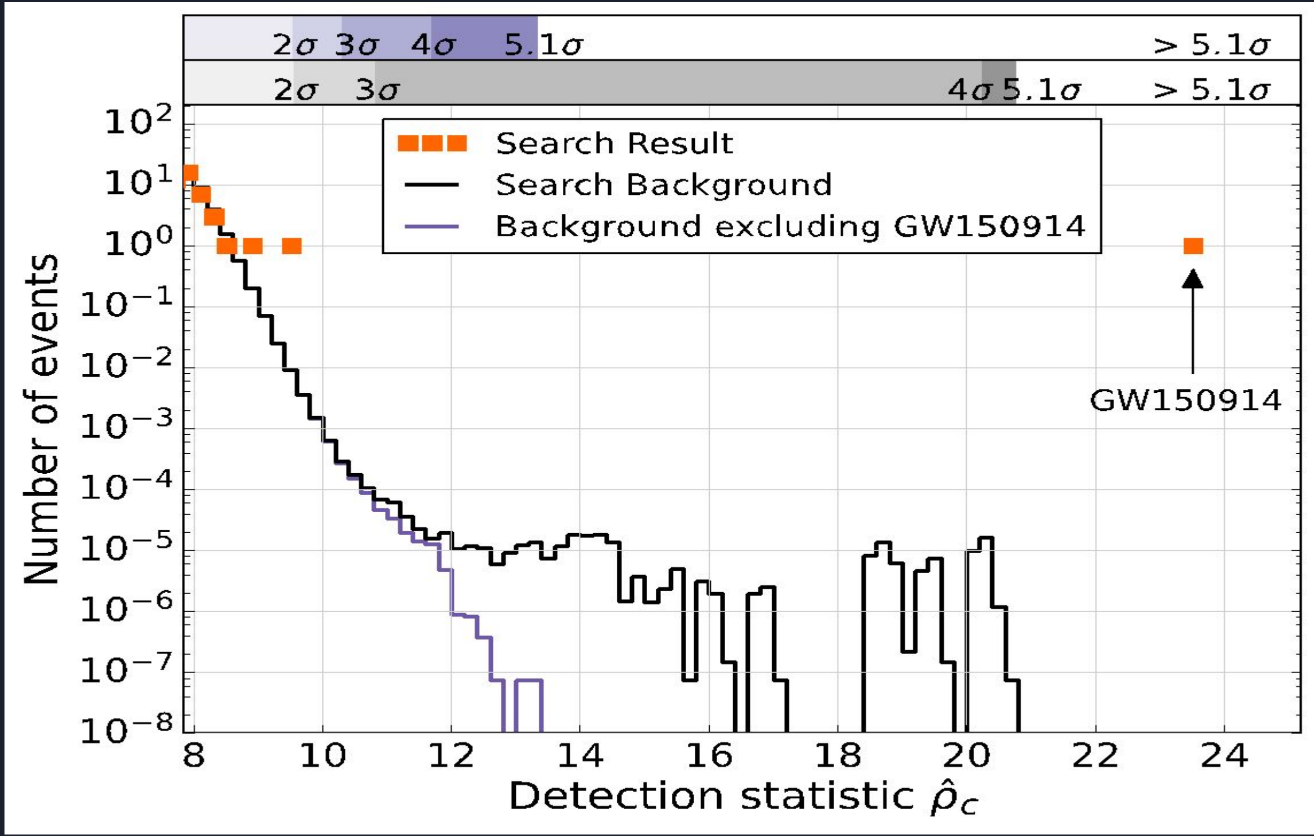
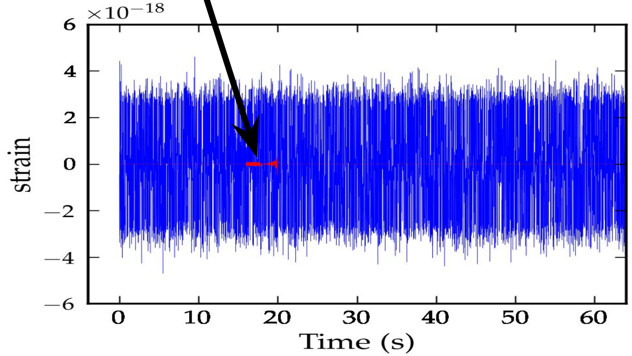
Goal will be to explain this plot.



Phys. Rev. Lett. **116**, 061102

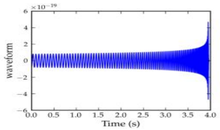
Matched Filtering to extract the signal

Signal embedded in strain data **s(t)**



$\otimes$

Model waveform filters: **h(t)**



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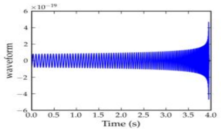
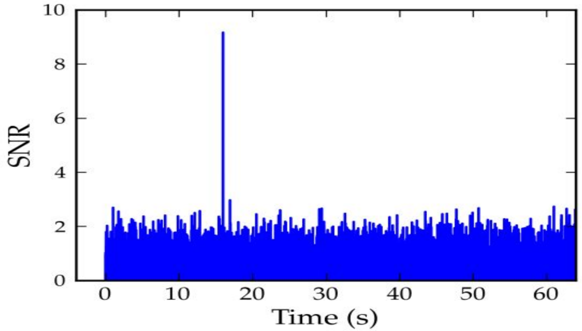
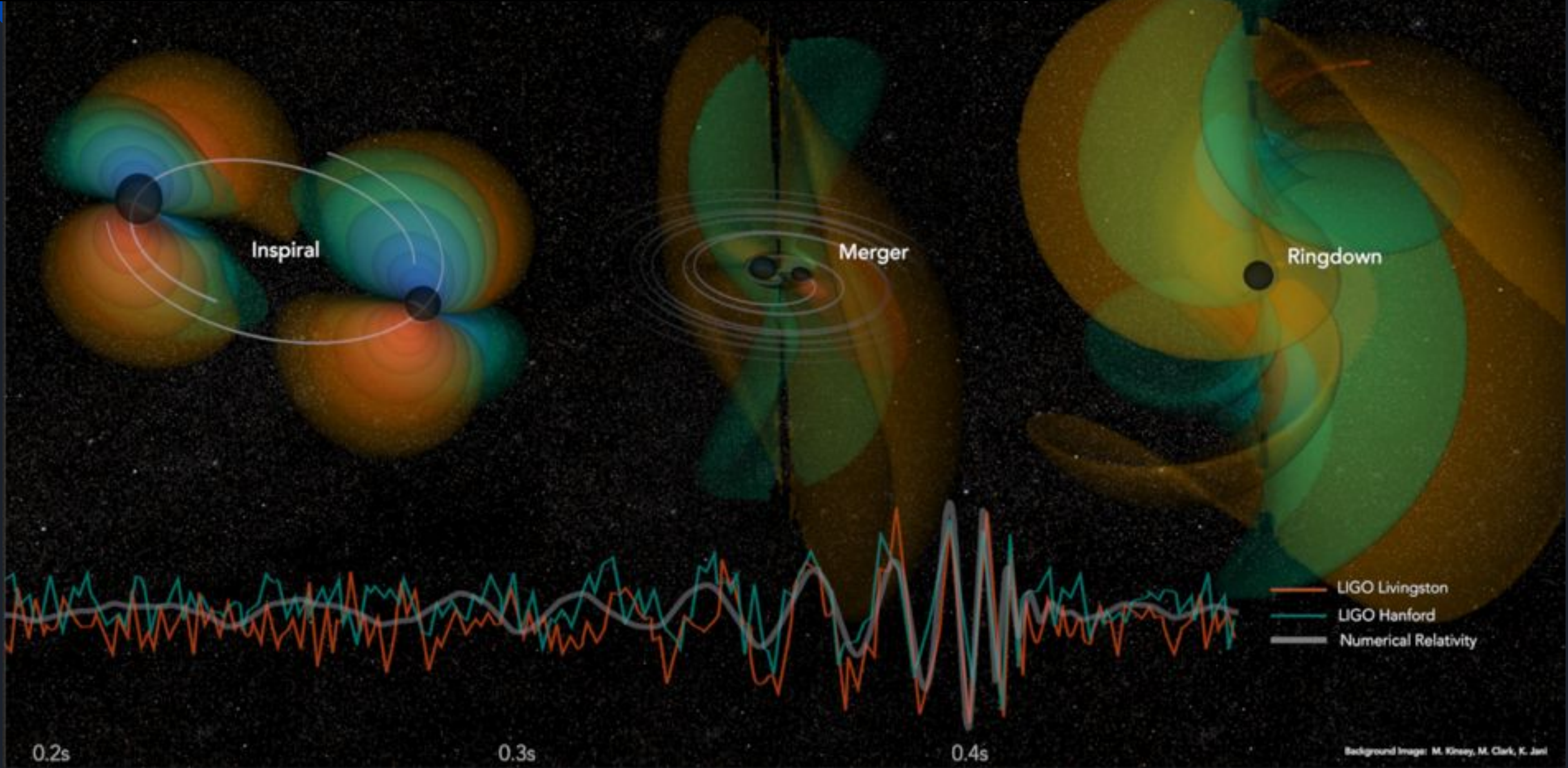




$$\rho = \frac{(s|h)}{\sqrt{(h|h)}} \qquad (a|b) = 4\int_0^\infty \frac{\tilde{a}(f)\tilde{b}^\star(f)}{S_n(f)}\, df$$

Optimal filter for **Gaussian** noise.

Gravitational-wave Waveform



Gravitational Waveform Models

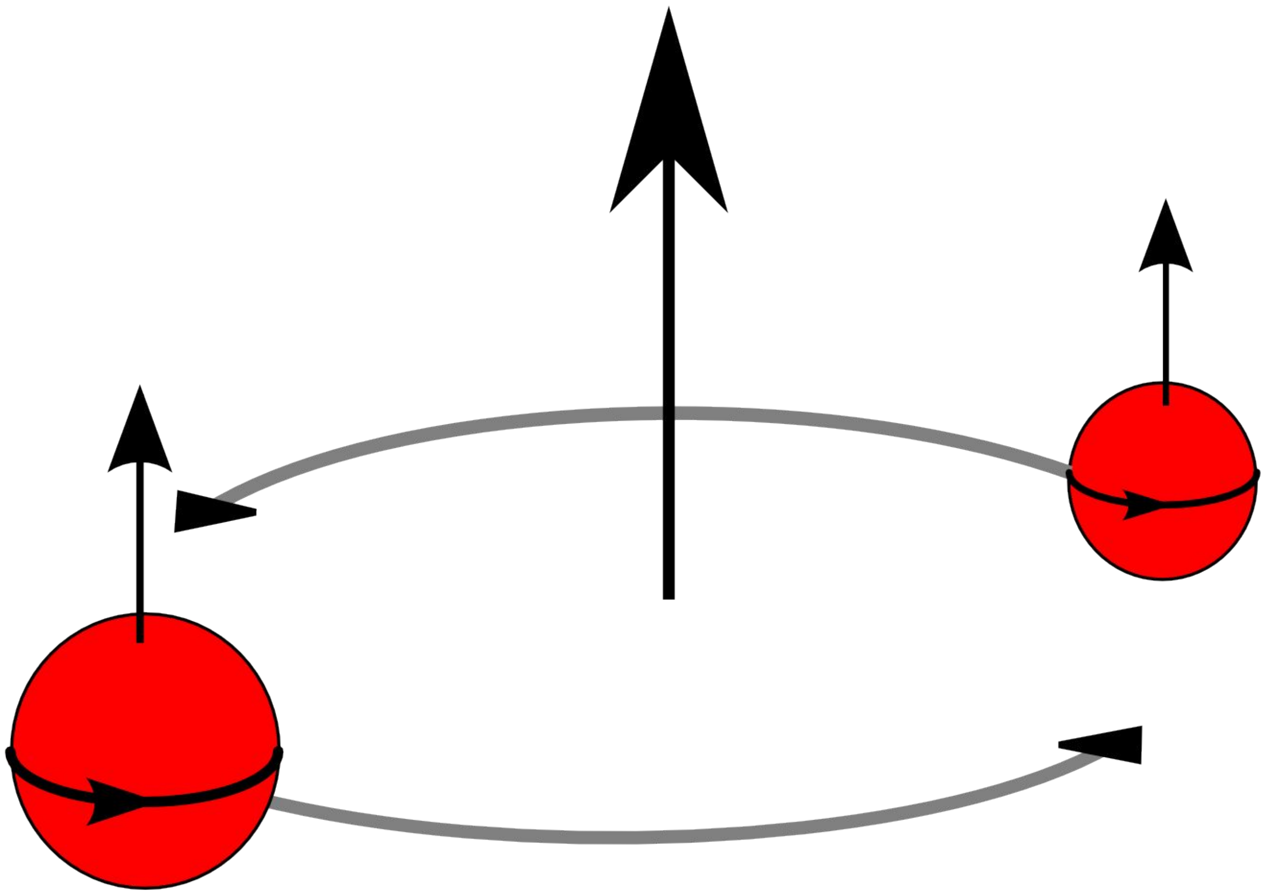
Some key sources of information

- Numerical Relativity
  - Can be very accurate
  - Slow (tradeoff in how long a waveform to generate)
- post-Newtonian
  - Valid for low velocity regime ($v / c << 1$)
  - Valid for early inspiral and binary neutron star waveforms
  - Models include TaylorF2 (used to detect GW170817)

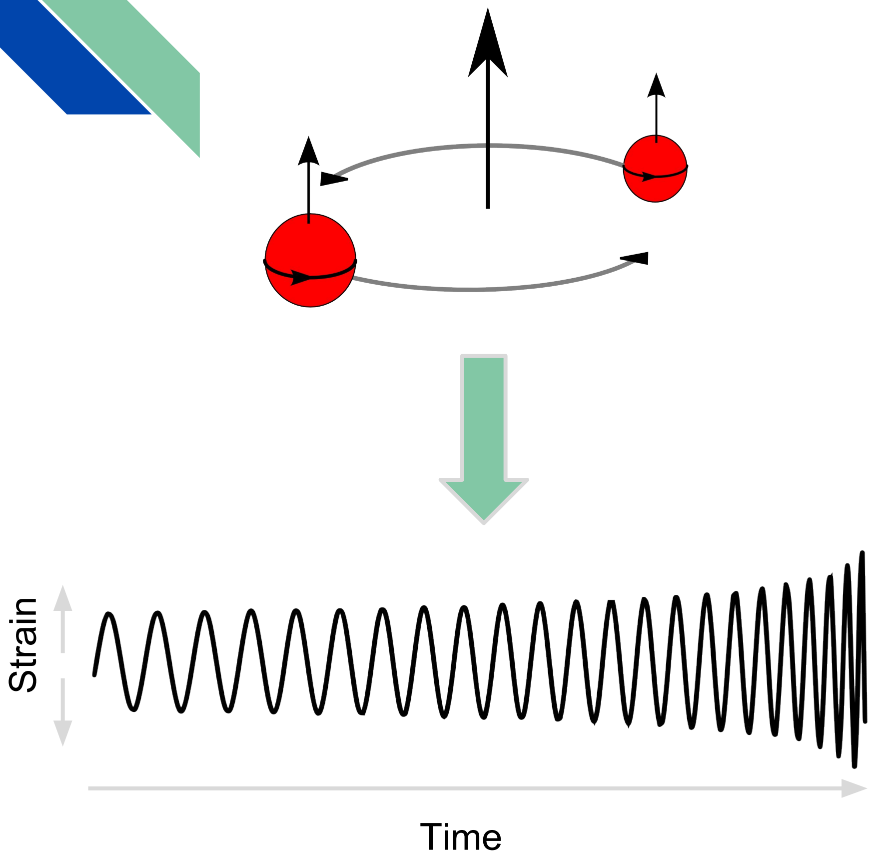
Inspiral-merger-ringdown models

- Combine post-Newtonian and fits to numerical relativity
- Models include the EOBNR (effective one-body NR) family of waveforms and the IMRPhenom family of waveforms.

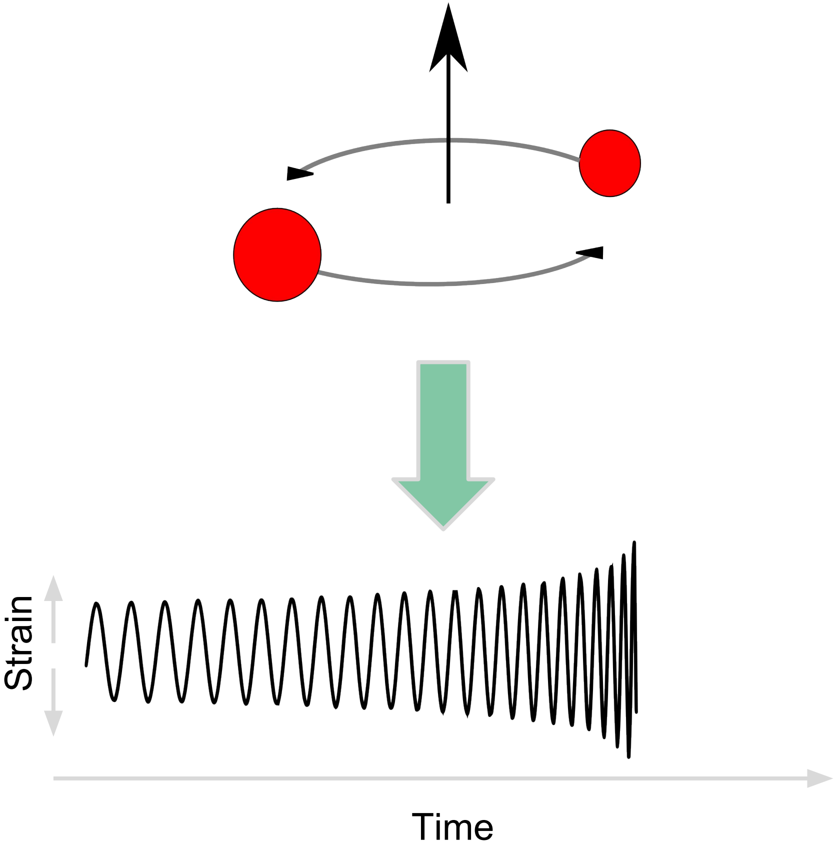
Binary System



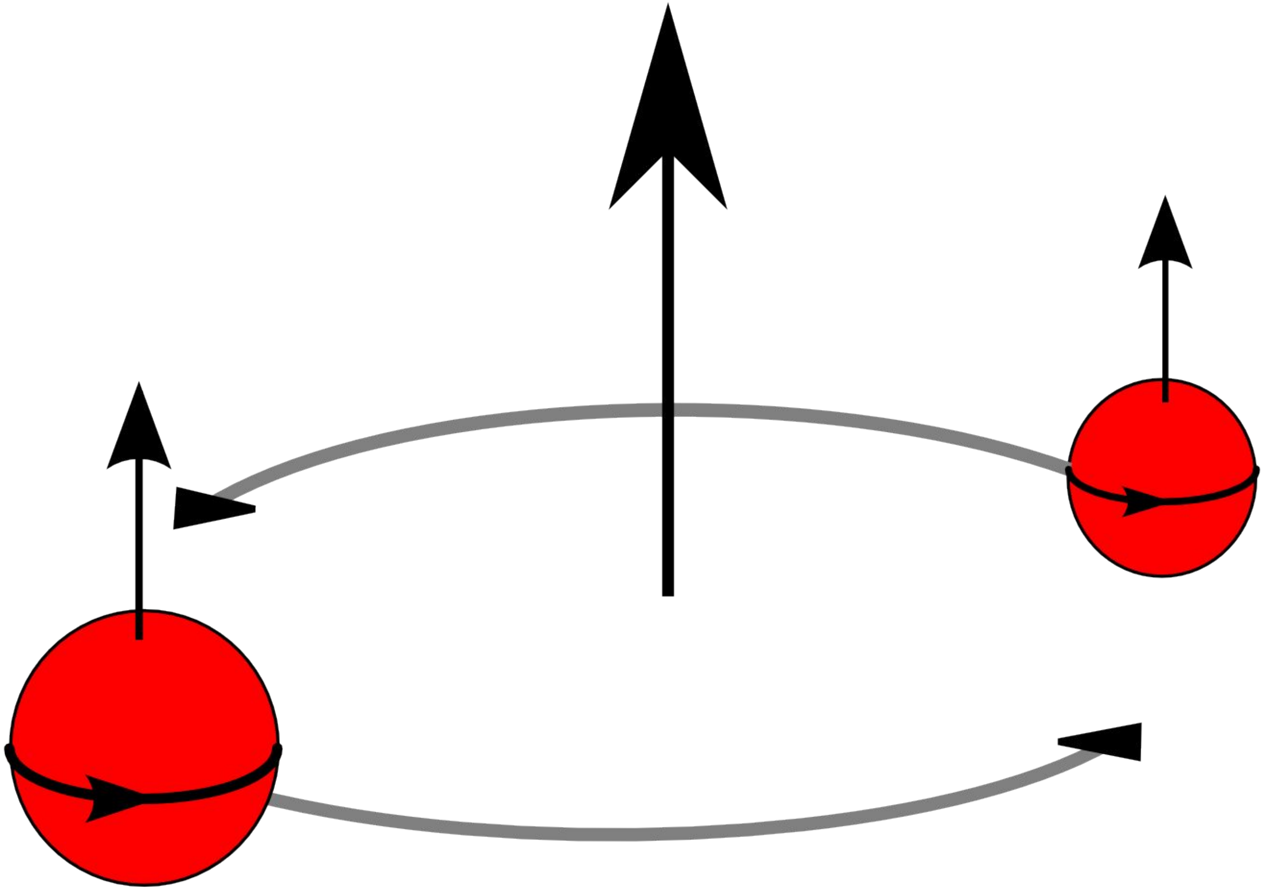
Aligned Spin



Non-spinning



Binary System



Building a bank of templates

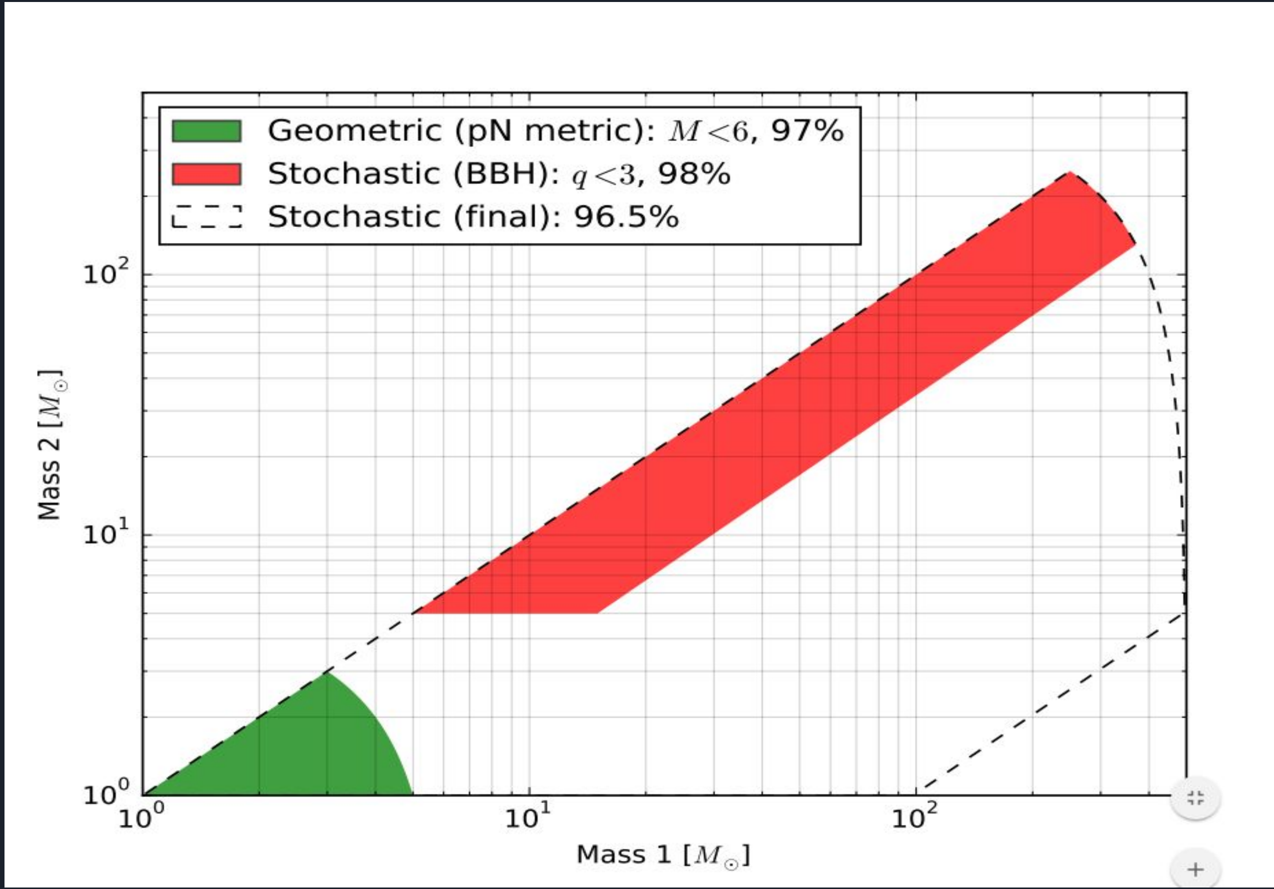
- What is the metric?
  - Mis-match between templates as a function of waveform parameters
- Construction
  - Stochastic placement
  - A geometric lattice can be built where an analytic and flat metric is known (only for low mass systems)
- What effects do we model in our bank of template waveforms?
  - Component mass of each object
  - Spin aligned with the orbital angular momentum
  - Only the dominant mode (spherical harmonics)
- What is not (yet) included?
  - Matter effects (tidal deformability, spin-quadrupole)
  - Spin *not* aligned with the orbital angular momentum. This leads to precession.
  - Eccentricity of the orbit

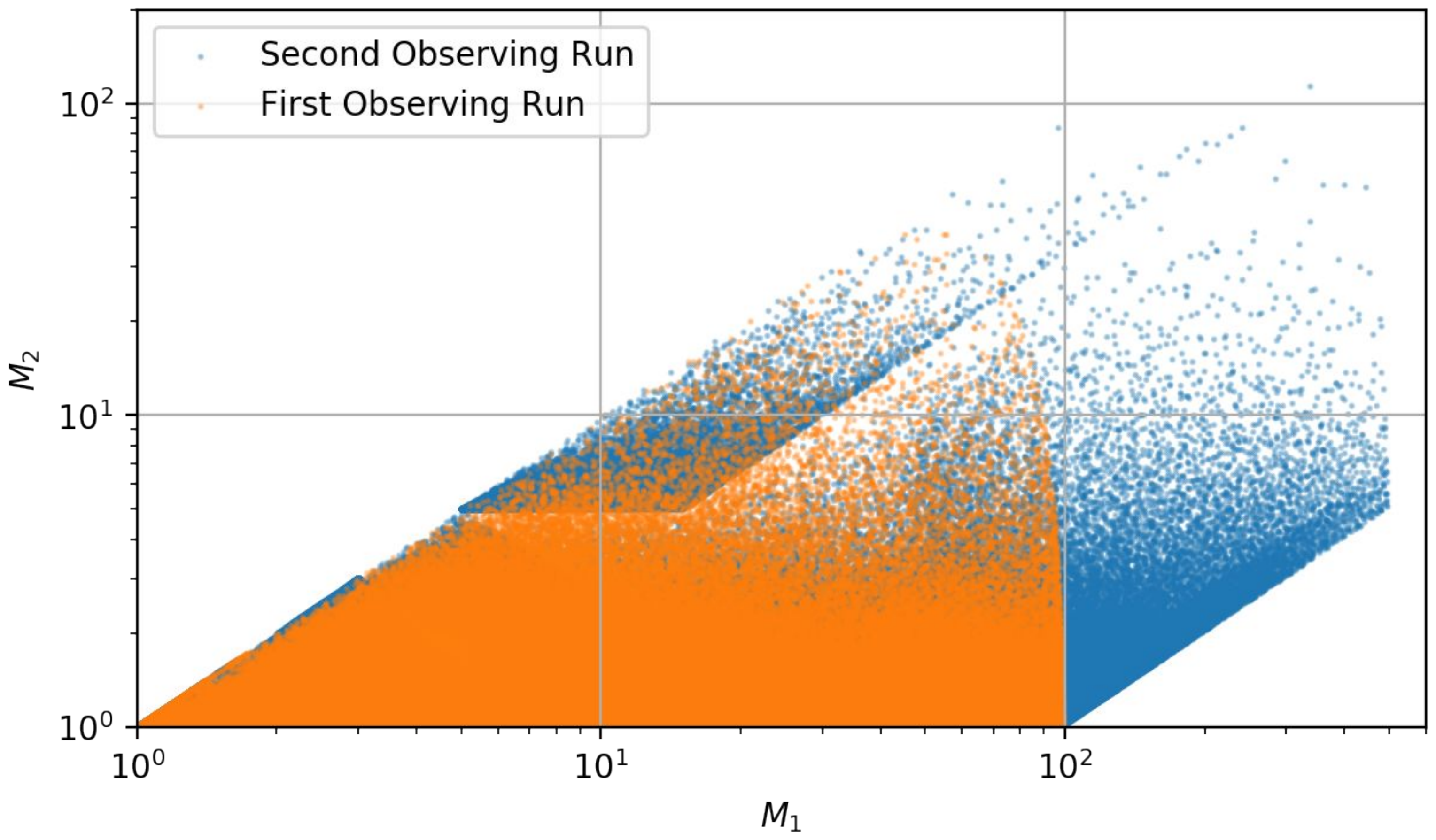
$$(a|b) = 4 \int_0^\infty \frac{\tilde{a}(f)\tilde{b}^\star(f)}{S_n(f)}\, df$$

$$m = \frac{(a|b)}{\sqrt{(a|a)}\sqrt{(b|b)}}$$

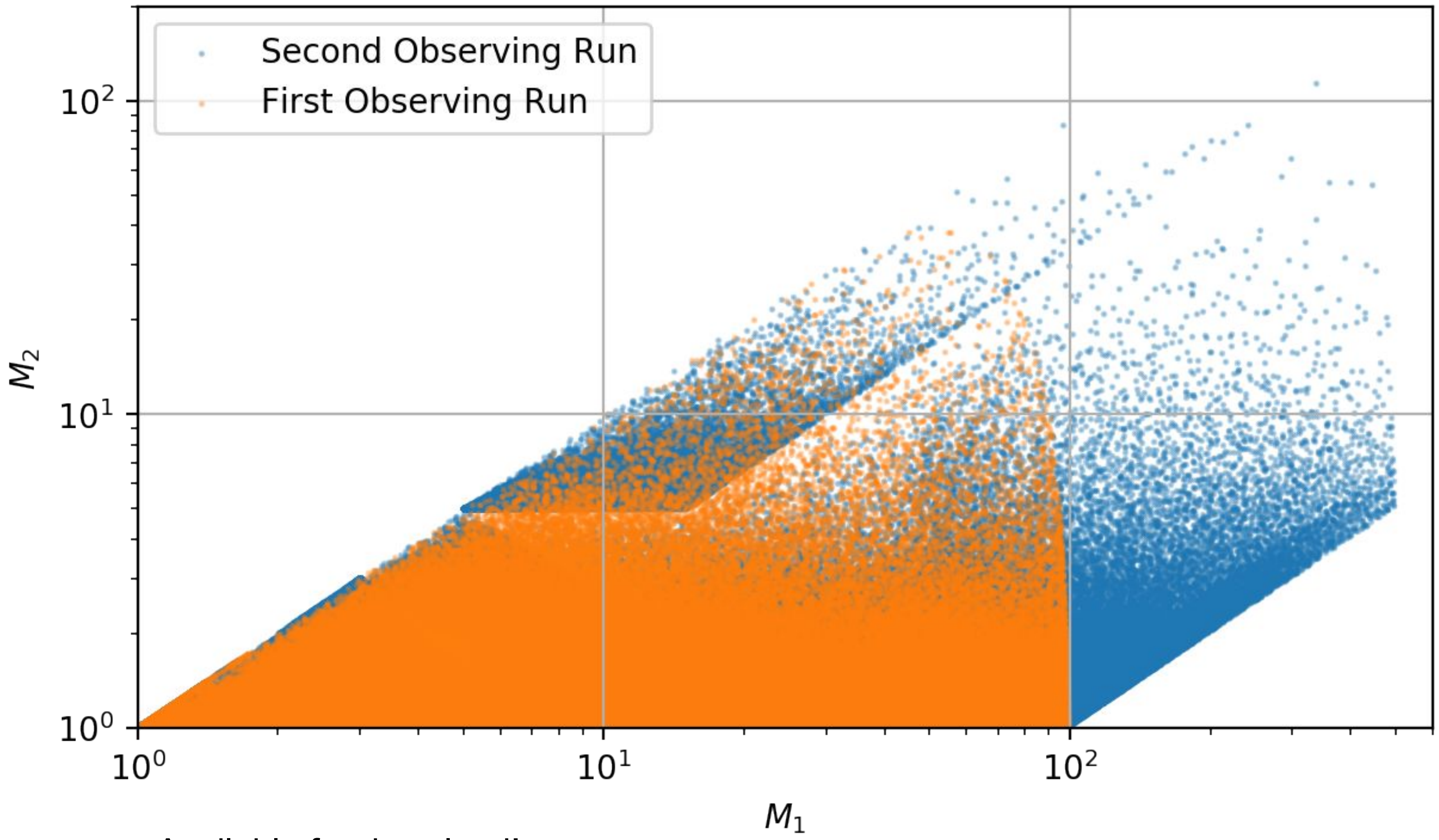
Require that we lose no more than 10% of signals anywhere in our parameter space.

Bank of Waveforms in the Second Observing Run

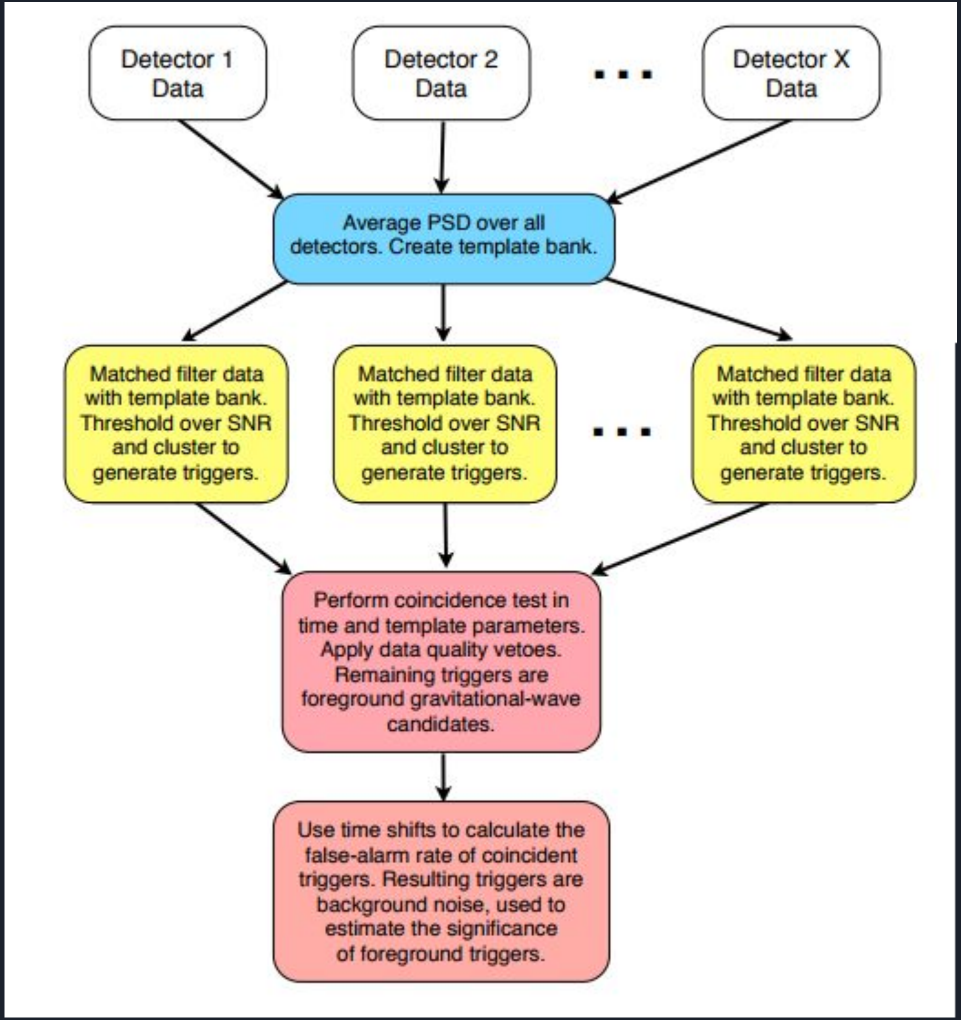


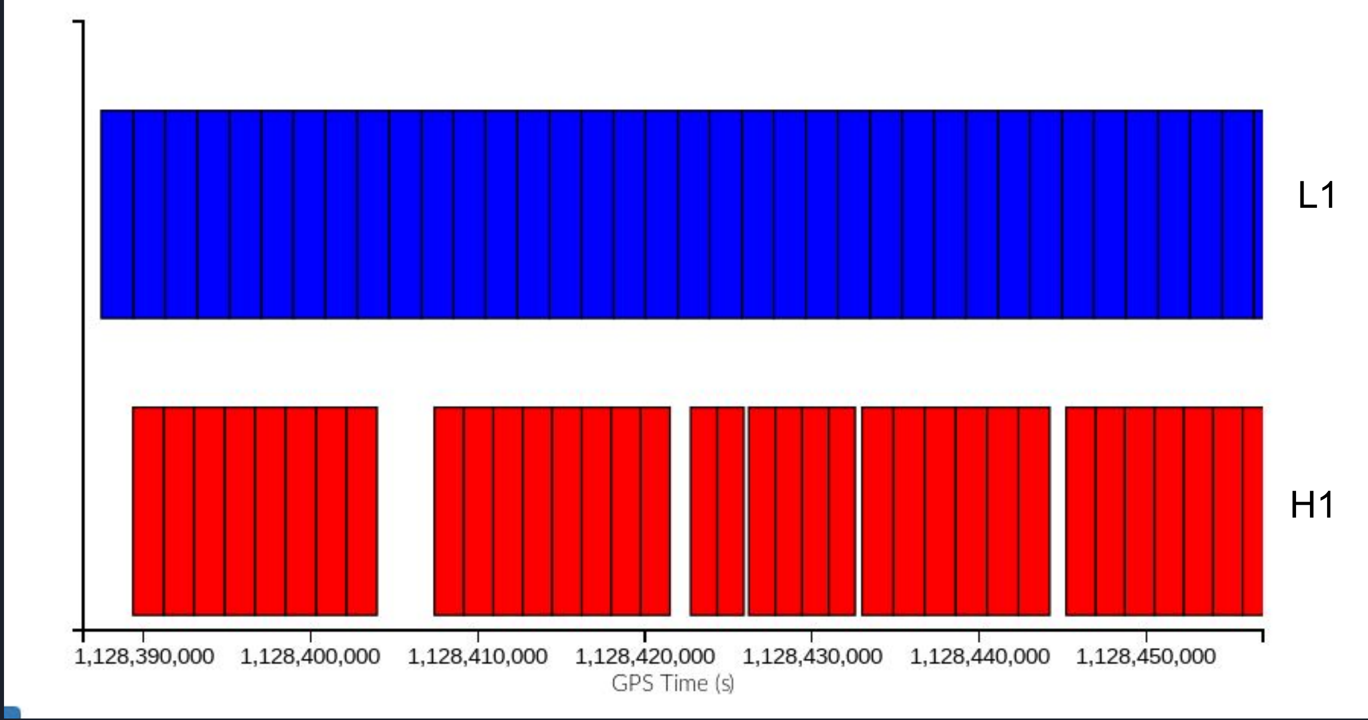


Second Observing Run
First Observing Run
10^2
10^1
10^0
M_2
M_1

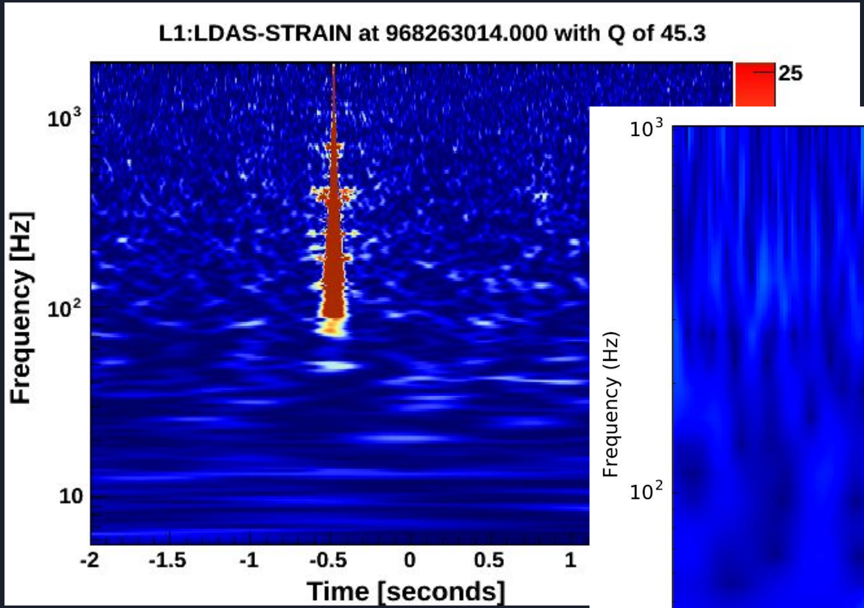


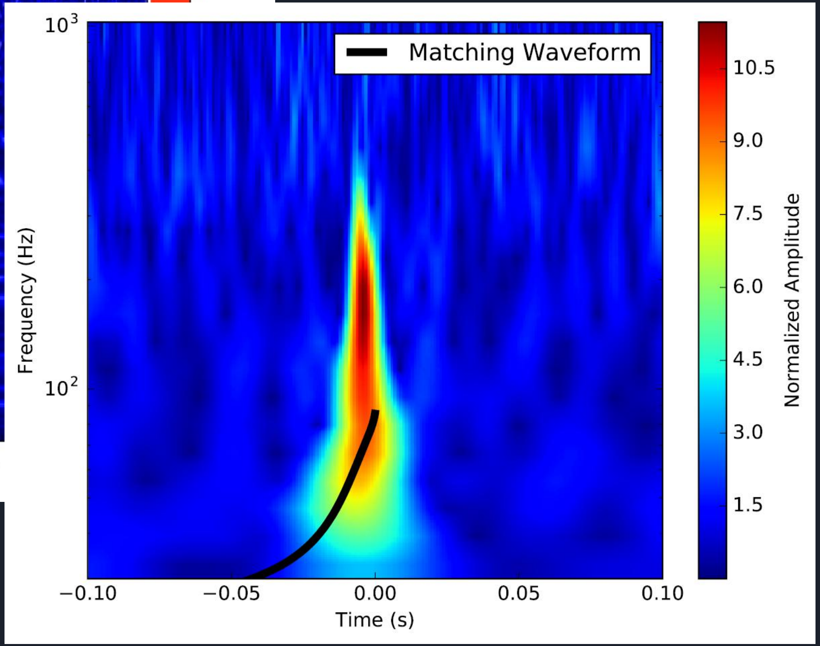
Available for download!
https://github.com/ligo-cbc/pycbc-config/tree/master/O1/bank
https://github.com/ligo-cbc/pycbc-config/tree/master/O2/bank


Detector 1 Data
Detector 2 Data
...
Detector X Data
Average PSD over all detectors. Create template bank.
Matched filter data with template bank. Threshold over SNR and cluster to generate triggers.
Matched filter data with template bank. Threshold over SNR and cluster to generate triggers.
...
Matched filter data with template bank. Threshold over SNR and cluster to generate triggers.
Perform coincidence test in time and template parameters. Apply data quality vetoes. Remaining triggers are foreground gravitational-wave candidates.
Use time shifts to calculate the false-alarm rate of coincident triggers. Resulting triggers are background noise, used to estimate the significance of foreground triggers.


L1
H1
1,128,390,000
1,128,400,000
1,128,410,000
1,128,420,000
1,128,430,000
1,128,440,000
1,128,450,000
GPS Time (s)

… but our data is not entirely Gaussian!





How to survive encounters with non-Gaussian noise

- Check auxiliary channels for environmental and instrumental causes
    - Apply CAT1 / CAT2 vetoes

Refer back to Data Quality Talk by
Jess McIver

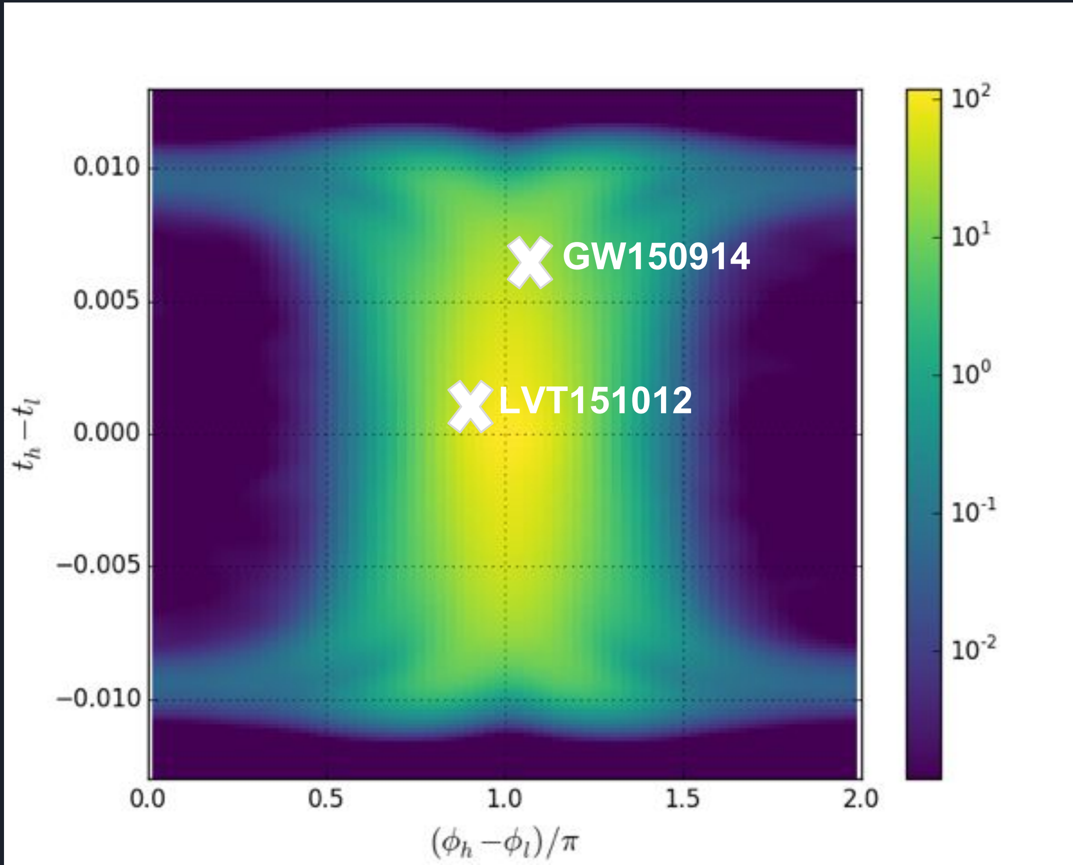
How to survive encounters with non-Gaussian noise

- Witness by Multiple Observatories
  - Within light travel time between the observatories
  - Relative amplitude and phase of observed signal consistent with astrophysical source
  - Signal morphology is consistent betwee observatories

- Consistency between signal model and observed data
  - SNR contribution by frequency band
  - Autocorrelation function
  - SNR distribution over template bank

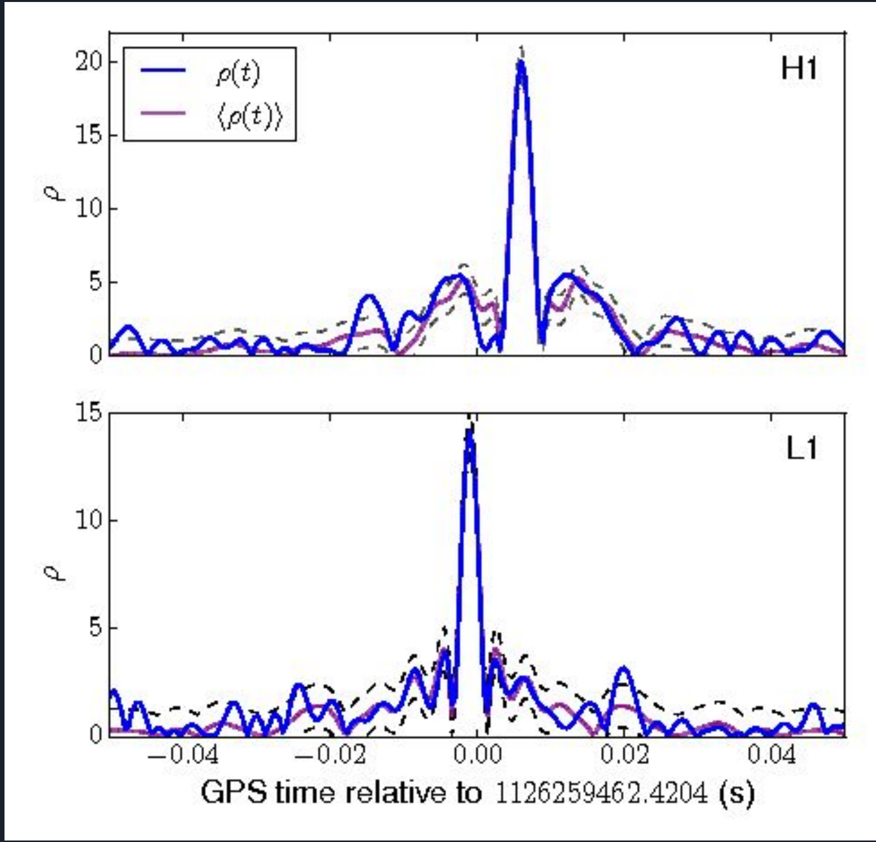
Phase and Time Consistency (new in O2)

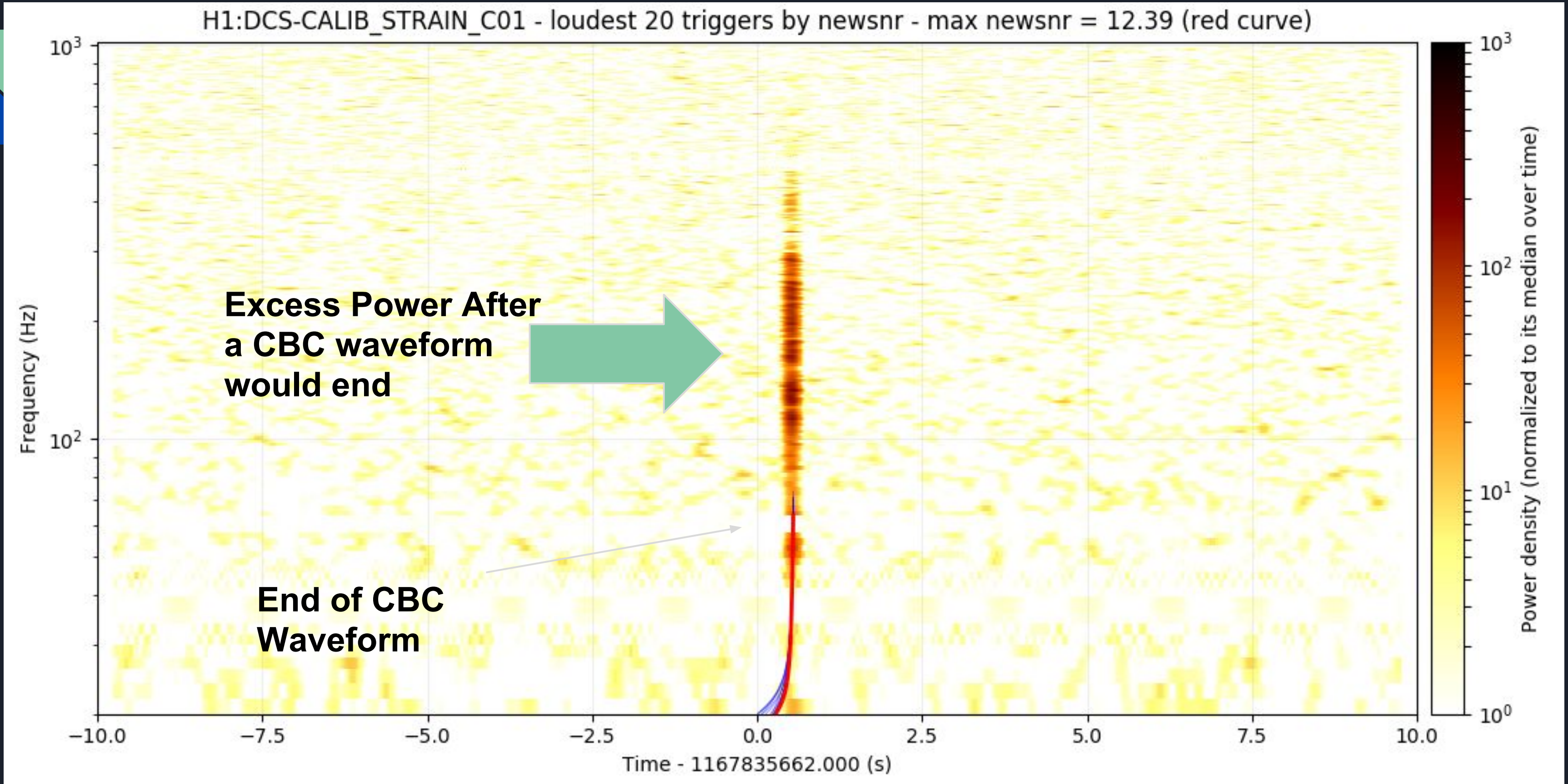
- Any phase difference and time delay < ~10 ms is possible between 2 detectors
- Due to the antenna pattern of the detectors, signals are more likely to have certain phase and time differences.
- Noise has a uniform distribution



Nitz, et al. *Detecting Binary Compact-object Mergers with Gravitational Waves: Understanding and Improving the Sensitivity of the PyCBC Search,* Astrophys.J. 849 (2017) no.2, 118

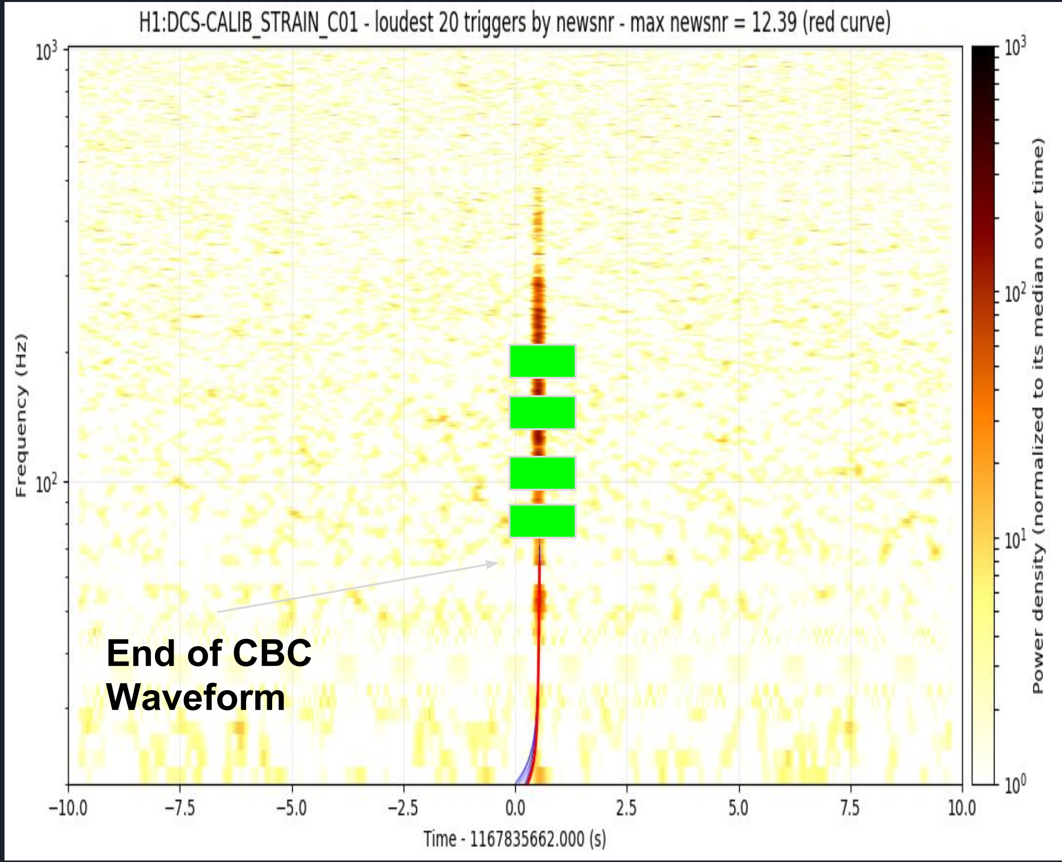
Autocorrelation




H1:DCS-CALIB_STRAIN_C01 - loudest 20 triggers by newsnr - max newsnr = 12.39 (red curve)
Frequency (Hz)
Time - 1167835662.000 (s)
Power density (normalized to its median over time)
Excess Power After a CBC waveform would end
End of CBC Waveform

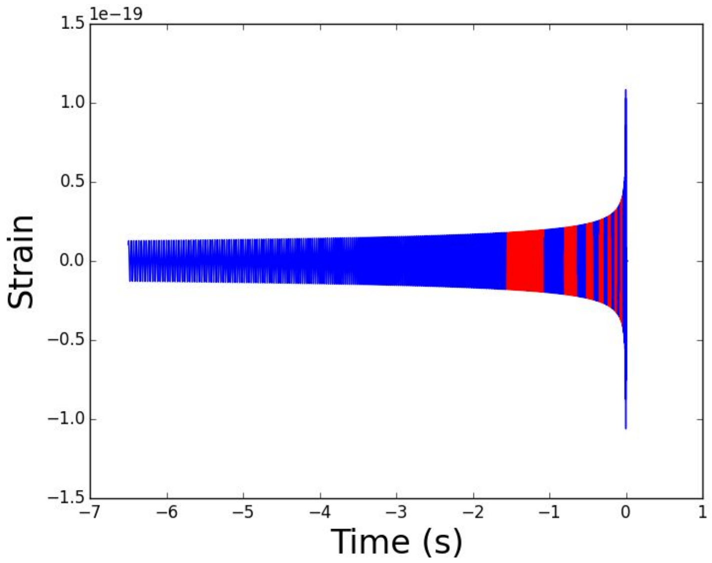
Look for Excess Power

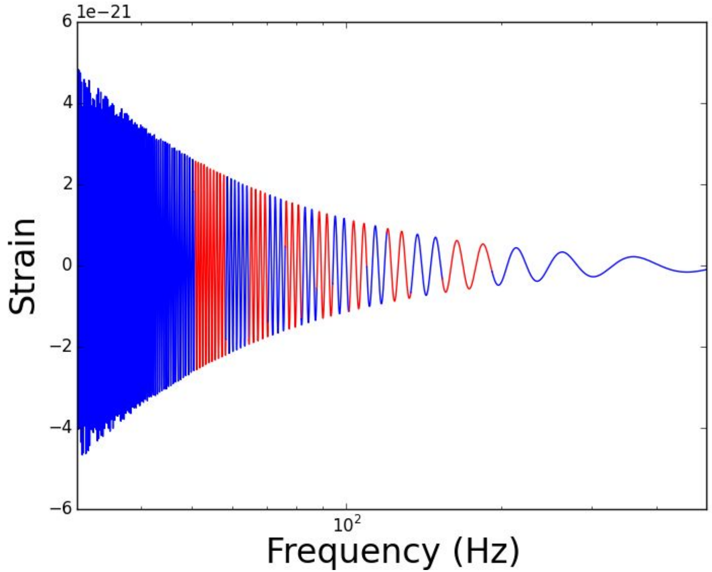
- For each trigger, look for excess power at frequencies beyond where the template waveform should have ended.
- Tiles of Sine-Gaussians with configurable Q and central frequencies
- Define a new $\chi 2$ based on the sum of the squared SNRs



Alexander Nitz, *Distinguishing short duration noise transients in LIGO data…*, Class.Quant.Grav. 35 (2018) no.3, 035016

Distribution of SNR contributions by frequency band



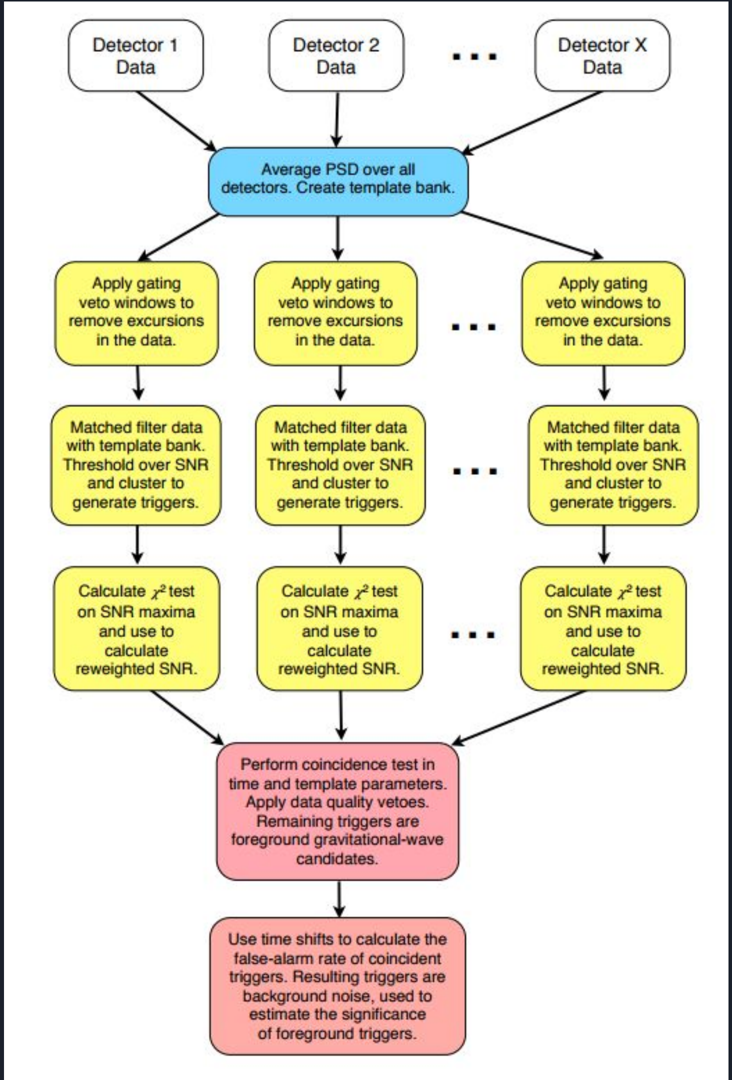


Divide the template into frequency bands of equal expected power

$$\chi^2 \propto \sum (\rho_l - \rho / N_{bins})^2$$

How we searched for gravitational waves in O1 (pycbc)

- Make use of how SNR is accumulated as a signal consistency test
- Require observation by *both* LIGO observatories
  - Require that SNR peaks be observed within 15 ms of each other
- Require that the *same* template finds a candidate event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Detector 2 Data
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Calculate χ^2 test on SNR maxima and use to calculate reweighted SNR.
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Perform coincidence test in time and template parameters. Apply data quality vetoes. Remaining triggers are foreground gravitational-wave candidates.
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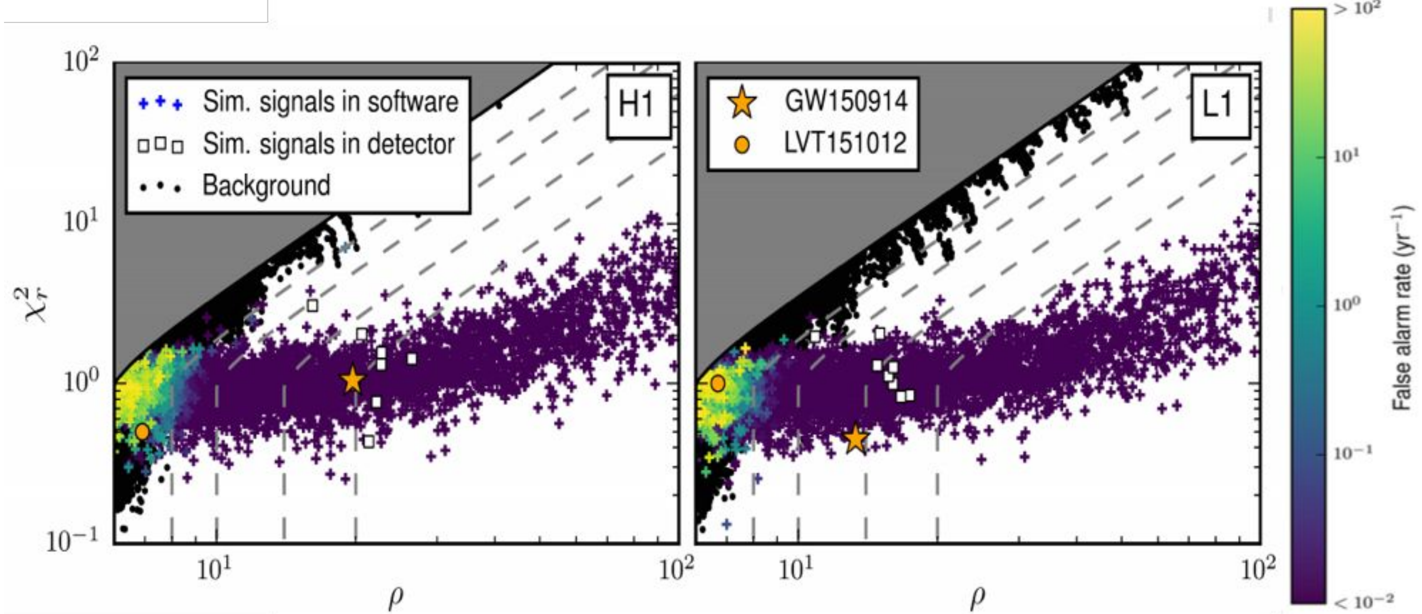
Suppressing non-Gaussian noise

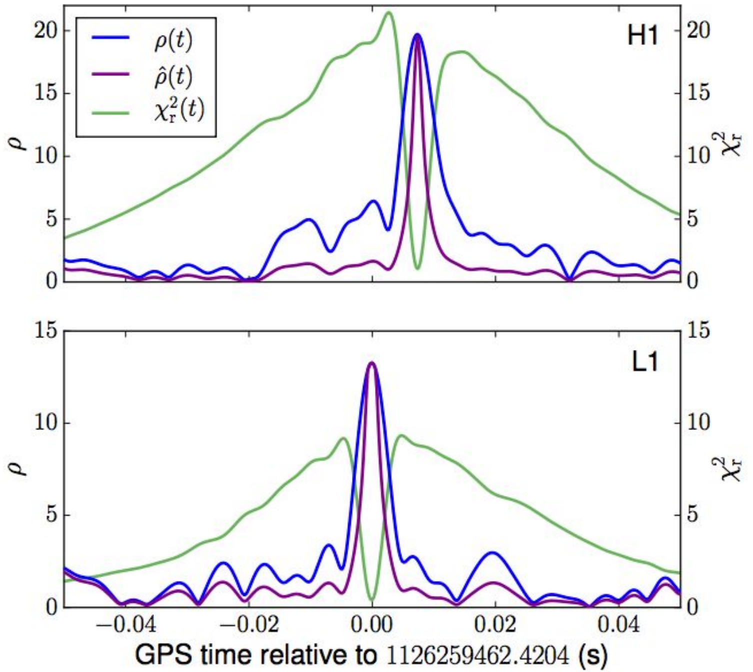
Re-weight the SNR by a time frequency chisq



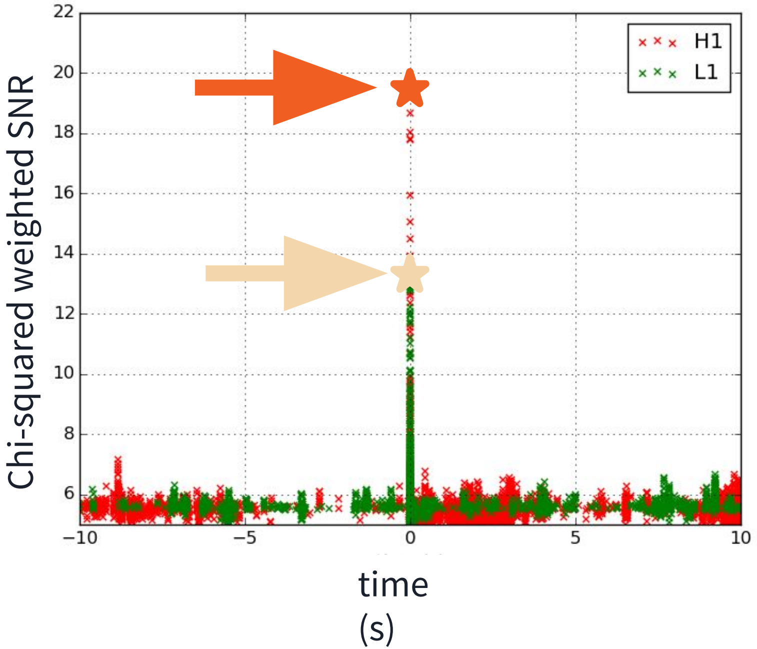
$$\hat{\rho} = \begin{cases} \rho & \text{for } \chi^2 \leq n_{\rm dof} \\ \rho[\frac{1}{2}(1+(\frac{\chi^2}{n_{dof}})^3)]^{-\frac{1}{6}} & \text{for } \chi^2 > n_{\rm dof}, \end{cases}$$

Abbot et al. 2016 arXiv:1602.03839

Examination of GW150914



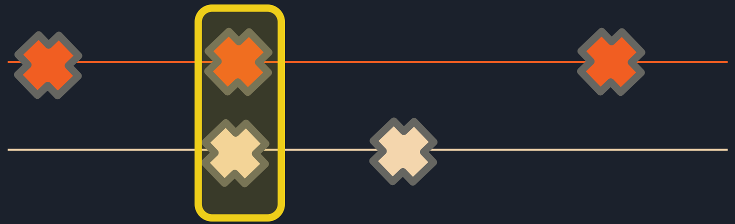
Abbot et al. 2016 arXiv:1602.03839



Ranking candidate events seen by multiple detectors

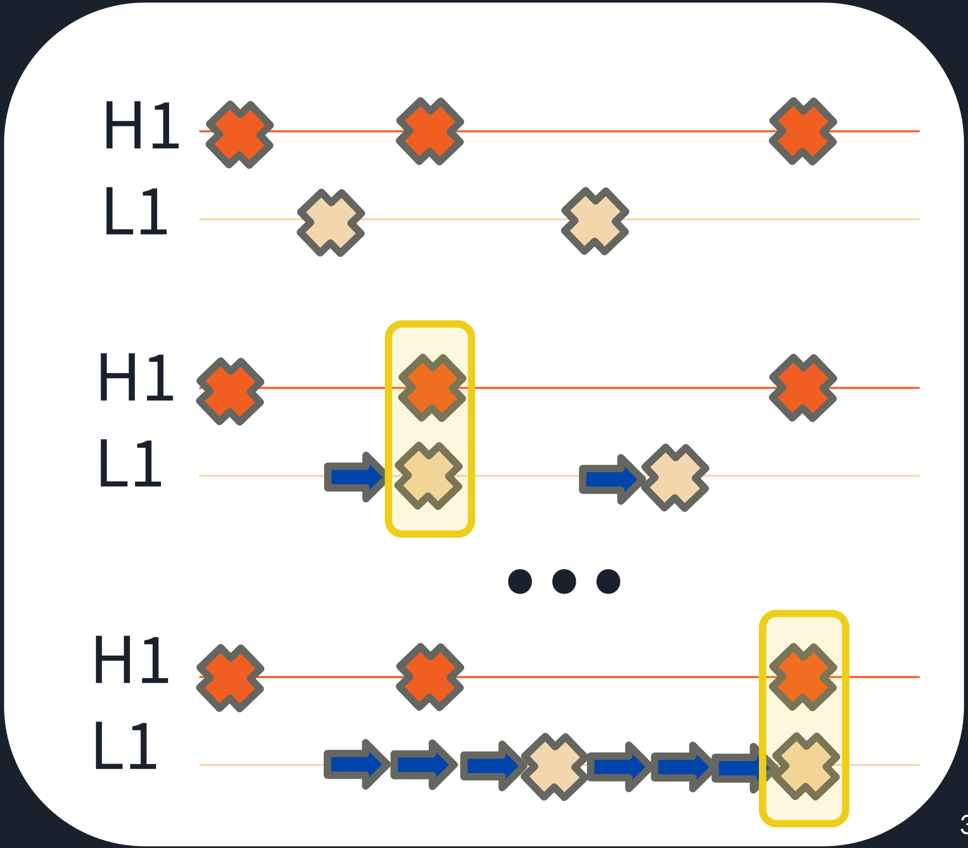
- Candidate events are ranked by the quadrature sum of the re-weighted SNRs from each observatory
- Events must be observed by two or more detectors within the light travel time and an allowance for timing error. (Currently total is +- 15 ms)

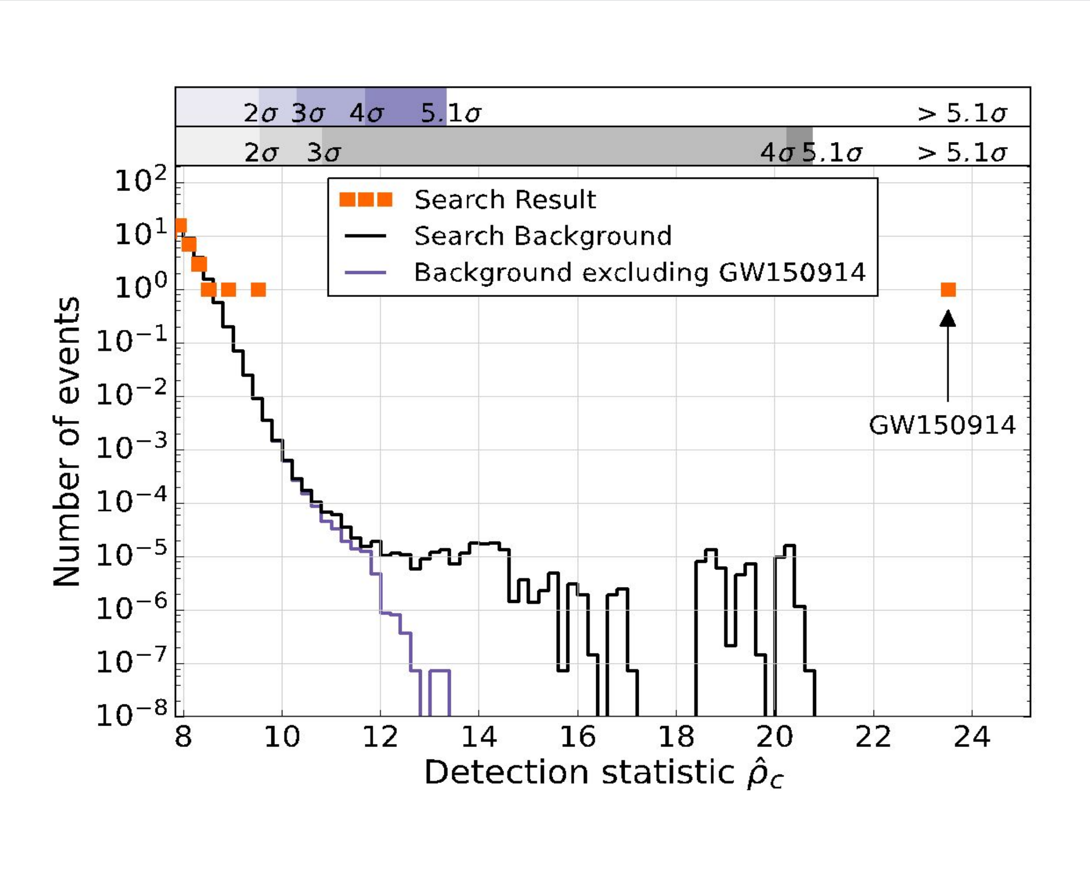
$$\hat{\rho}_{c} = \sqrt{\hat{\rho}^2_{H1} + \hat{\rho}^2_{L1}}$$



Background Estimation

- We time shift the data of one detector relative to the other
- Coincidences in time slides are background triggers
- This assumes that the dominant noise sources in our background are not correlated in time between the two detectors.

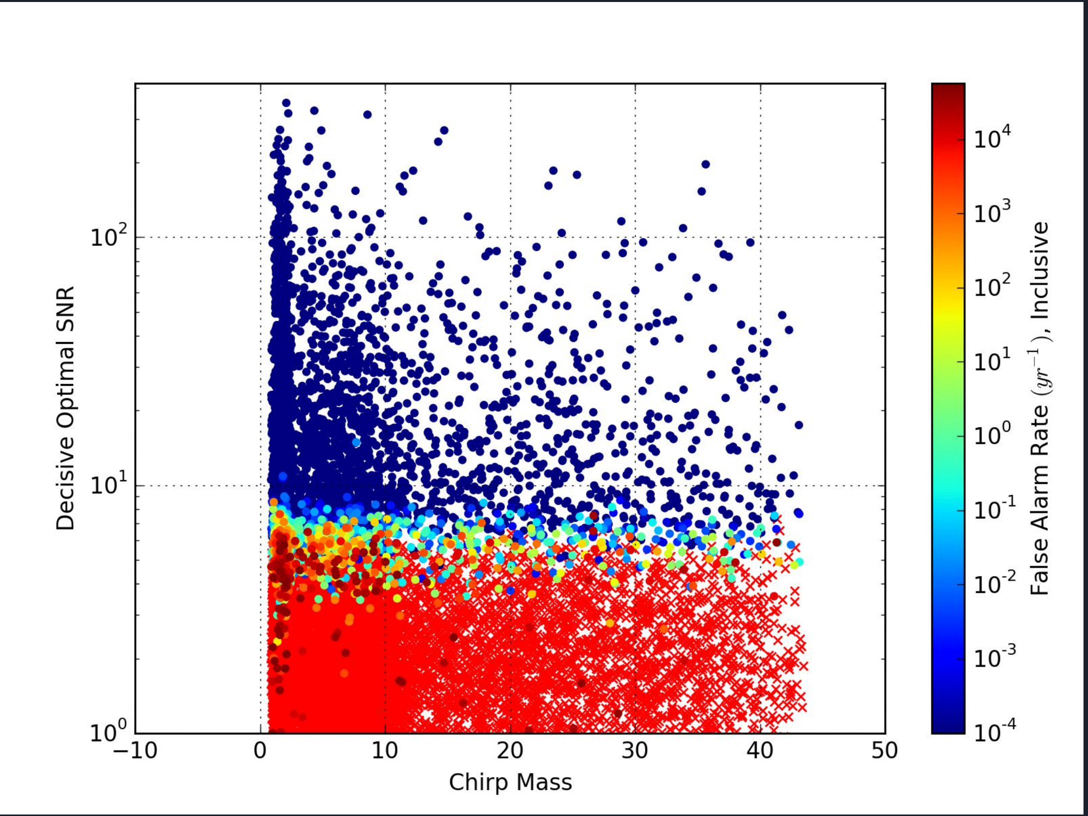




Phys. Rev. Lett. **116**, 061102

Why do we think the analysis can detect signals?

Lots of simulated signals!



Questions?