Introduction to Searches for Gravitational Waves with PyCBC

Derek Davis
GW Open Data Workshop #3
May 2020

Adapted from Ian Harry's
[presentation at GW ODW #2]

Caltech
LIGO

Focus Questions

- Introduction
- What are we looking for (signal assumptions)?
- What does the data look like (noise assumptions)?
- How do we actually search for compact binary mergers in our data?
- What if we're not looking for the "right" signals?

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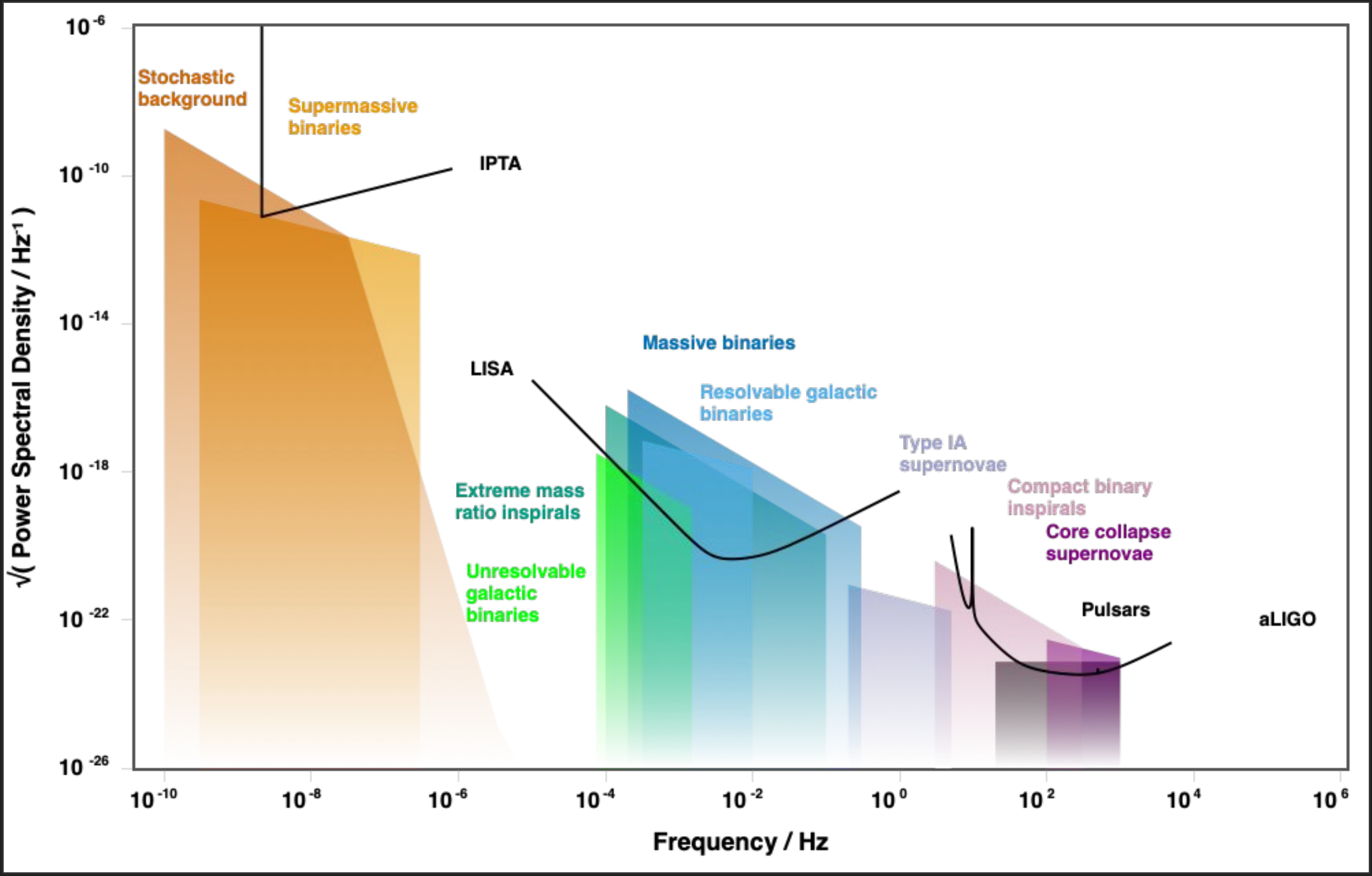
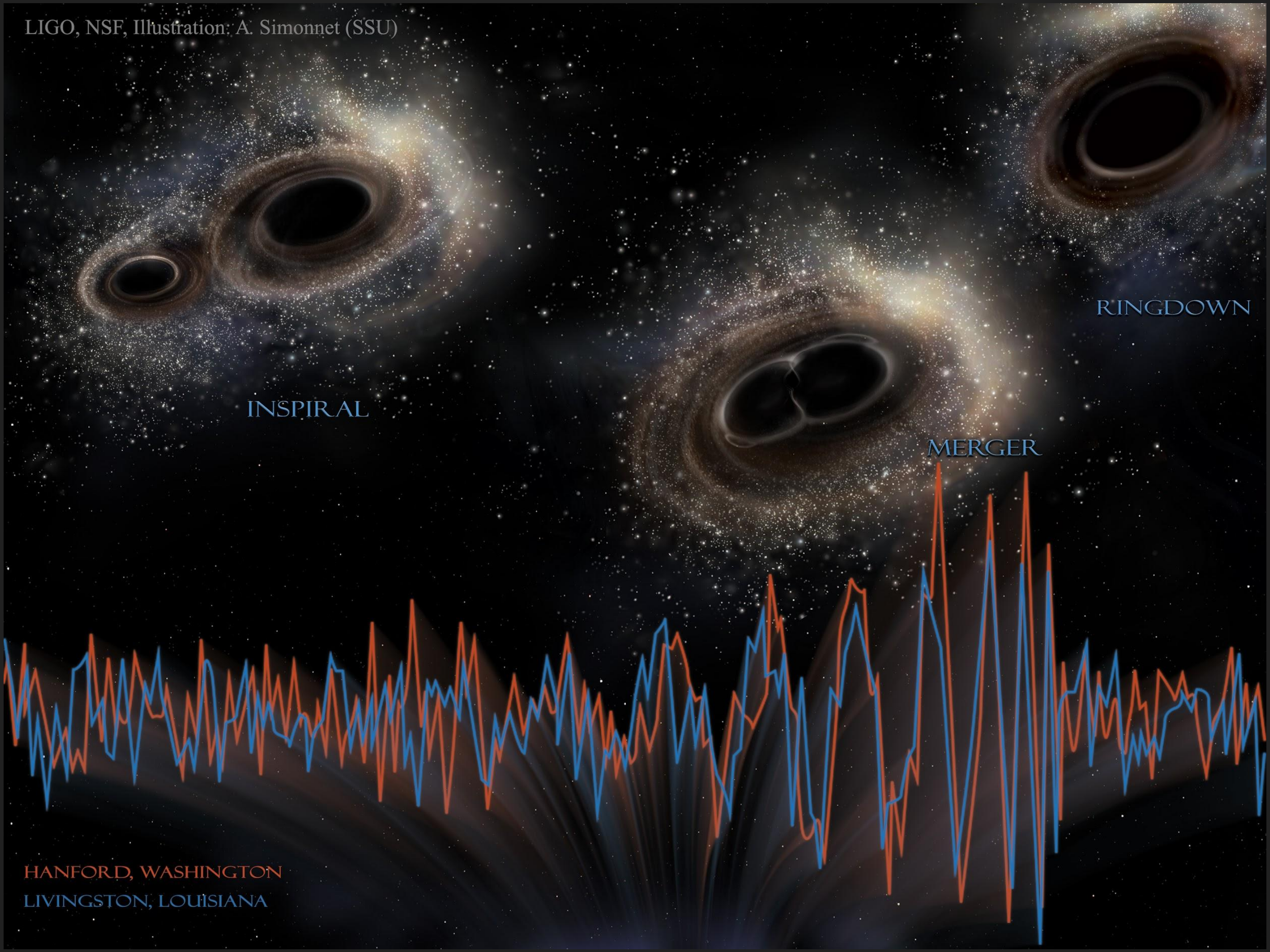
The gravitational-wave spectrum



Plotted using gwplotter.com

Focusing on compact binary mergers



Black holes: to scale!

GW150914

Current CBC searches in use by LVC

Modelled searches:

PyCBC - https://pycbc.org - Focus of this talk

GstLAL - https://lscsoft.docs.ligo.org/gstlal/

MBTA - T. Adams et al., Class. Quant. Grav., 33 175012 (2016)

SPIIR - Q. Chu, Ph.D. Thesis, The University of Western Australia. (2017)

Weakly-modelled searches:

cWB - https://gwburst.gitlab.io

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Modelling colliding black holes

General relativity gives us all the necessary tools to fully predict the gravitational-wave signal that we would observe here on Earth from two black holes merging

However, analytic solutions to this problem so not exist - we will need to use different approaches to understand what signals to look for and to interpret gravitational-wave signals we detect

Two main approaches are currently used:

- Approximate analytic solutions
- Numerical solutions

Waveform models

Approximate analytical solutions

- Multiple approaches can be used.to model the gravitational-wave signal
- Effective-one-body (EOB) and phenomenological (Phenom) approaches are examples
- Loses accuracy as spactime becomes highly warped as the black holes come close to merger

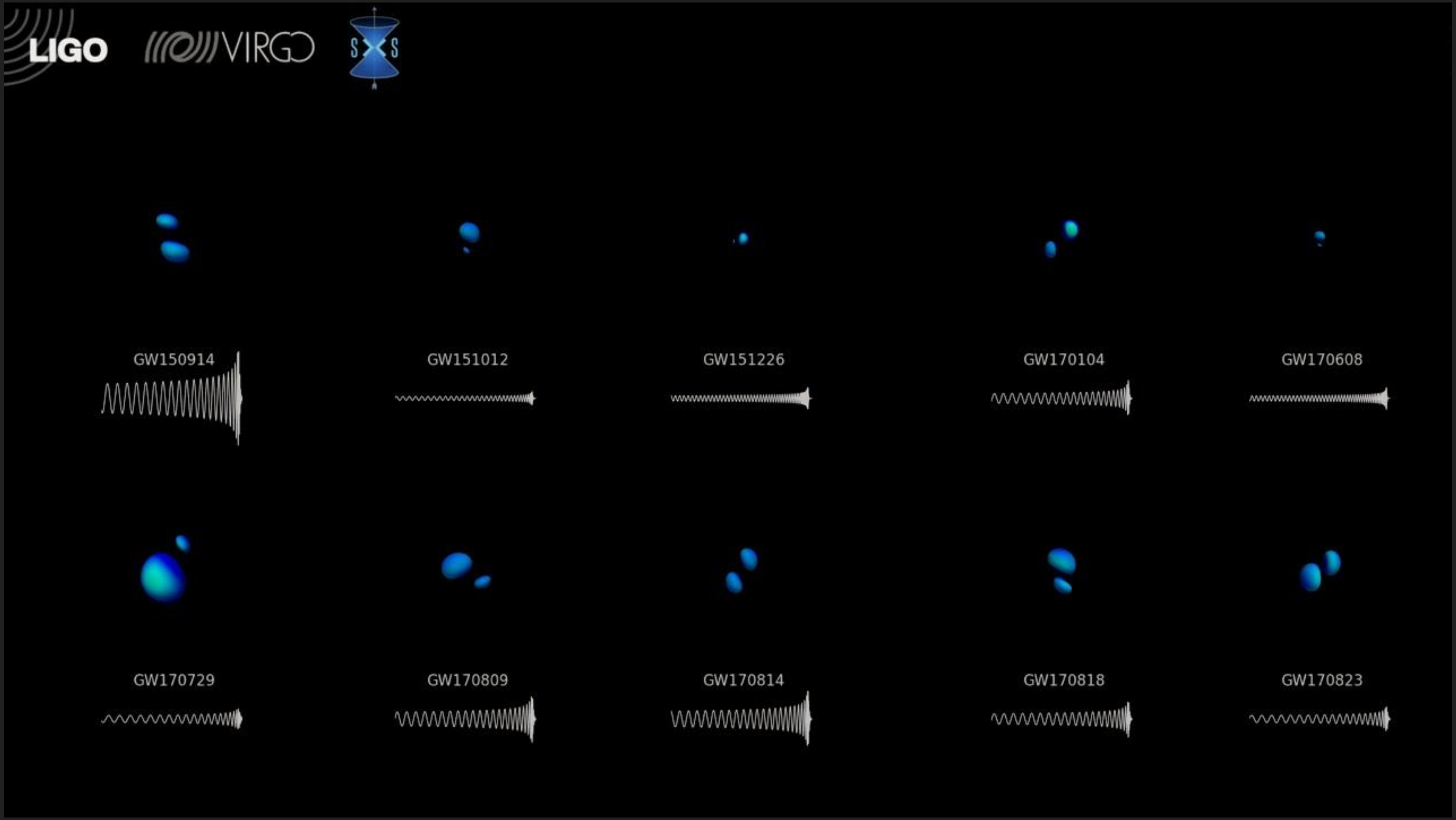
Numerical solutions

- Einstein's equations can be solved directly using numerical evolution methods
- Very computationally expensive - cannot be used to model many orbits or a large number of simulations
- Can model the collision well
- Some inaccuracy from numerical approach

A. Buonanno and T. Damour Phys.Rev. D 59 084006 (1999)
A. Buonanno et al., Phys.Rev. D 80 084043 (2009)
P. Ajith et al., Class. Quantum. Grav. 24 S689 (2007)
P. Ajith et al., Phys. Rev. D 77 104017 (2008)

F. Pretorius, Phys .Rev .Lett. 95 121101 (2005)
M. Campanelli et al., Phys.Rev.Lett. 96 111101 (2006)

Compact binary waveforms

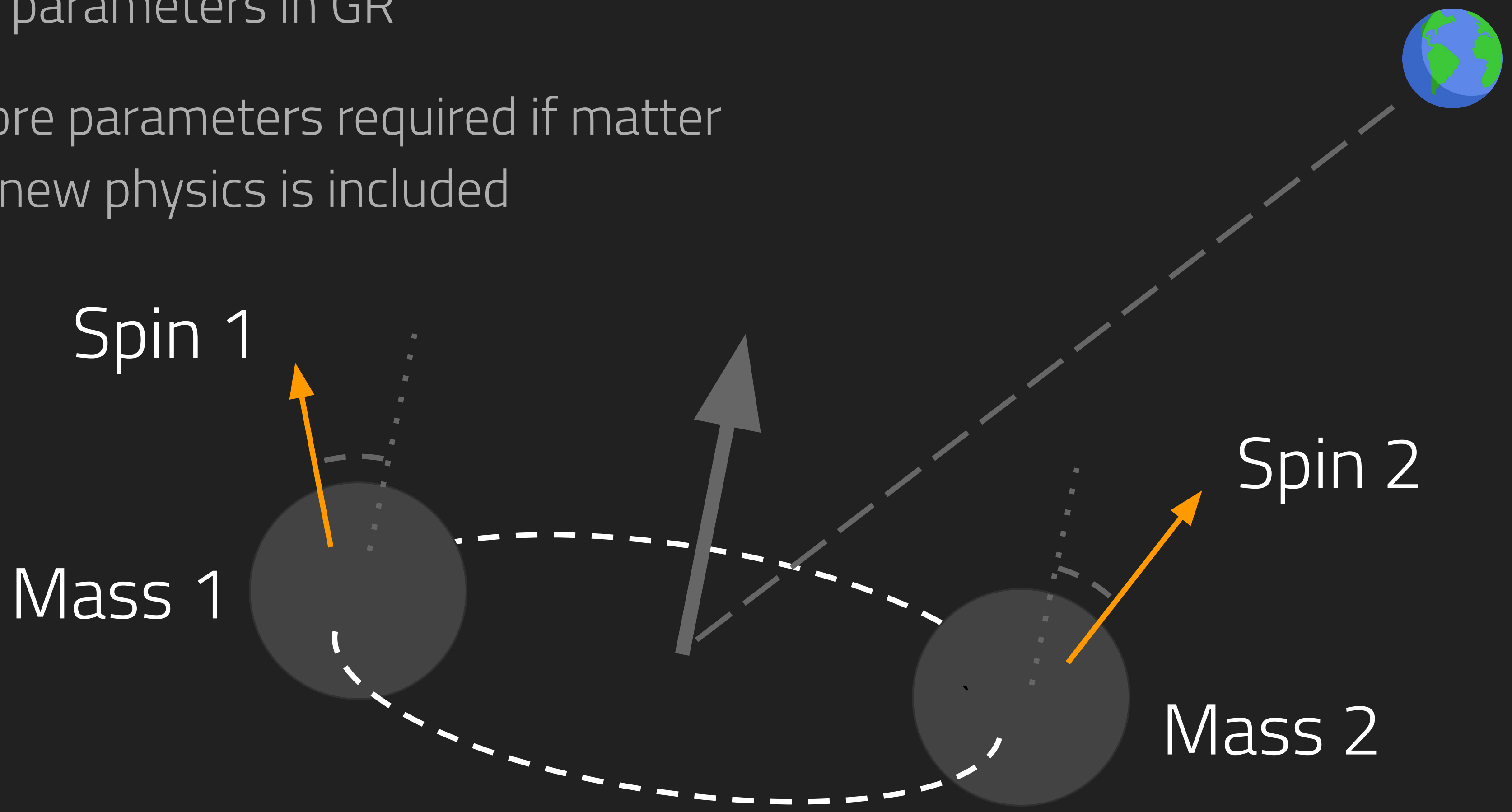


Teresita Ramirez/Geoffrey Lovelace/SXS Collaboration/LIGO-Virgo Collaboration

Compact binary parameters

A black hole binary is described by 15 parameters in GR

More parameters required if matter or new physics is included



Signal model equations

Plus polarization

$$h(t) = \frac{1}{D}\left(F_+(\Theta)h_+(t) + F_\times(\Theta)h_\times(t)\right)$$

GW strain

IFO antenna pattern

Cross polarization

Distance

Spherical harmonics

$$h_+(t) - ih_\times(t) = \sum_{l=2}^{\infty}\sum_{m=-l}^{l} H_{l,m}(t)Y_{l,m}(\theta,\phi)$$

Sky location

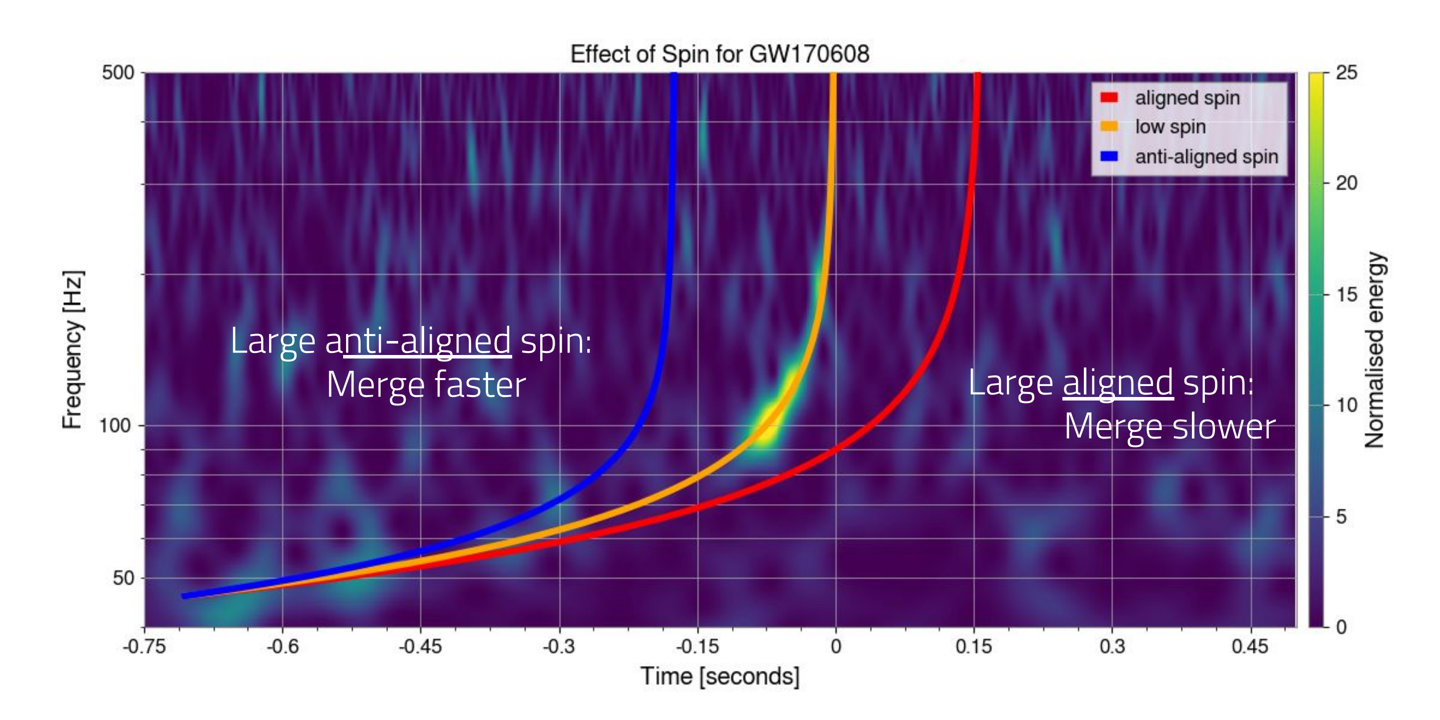
GW phase

$$H_{l,m} = A_{l,m}(t)e^{i\Phi_{l,m}(t)}$$

GW amplitude

Impact of different parameters

Masses and spins of the components have the largest impact on the observed GW signal



Plot produced using code from Tutorial 1.3

Inspiral track calculated using PyCBC - tutorial found here:
http://pycbc.org/pycbc/latest/html/waveform.html#plotting-frequency-evolution-of-td-waveform

Signal model: Summary

We can use general relativity to develop models of what gravitational-wave signals we expect to observe from merging black holes

Developing and improving compact binary signal modelling is a large field of research, which has made very rapid progress (and still is)

For now, current waveform models are good enough for most purposes

There are still areas for improvement (e.g. high-mass ratio signals, misaligned spins, extremal spins, exotic objects or non-GR waveforms)

Learn more about the theory behind compact binary signals in Alan Weinstein's lecture

Learn more about inferring the source properties of compact binary signals in Sylvia Biscoveanu's lecture

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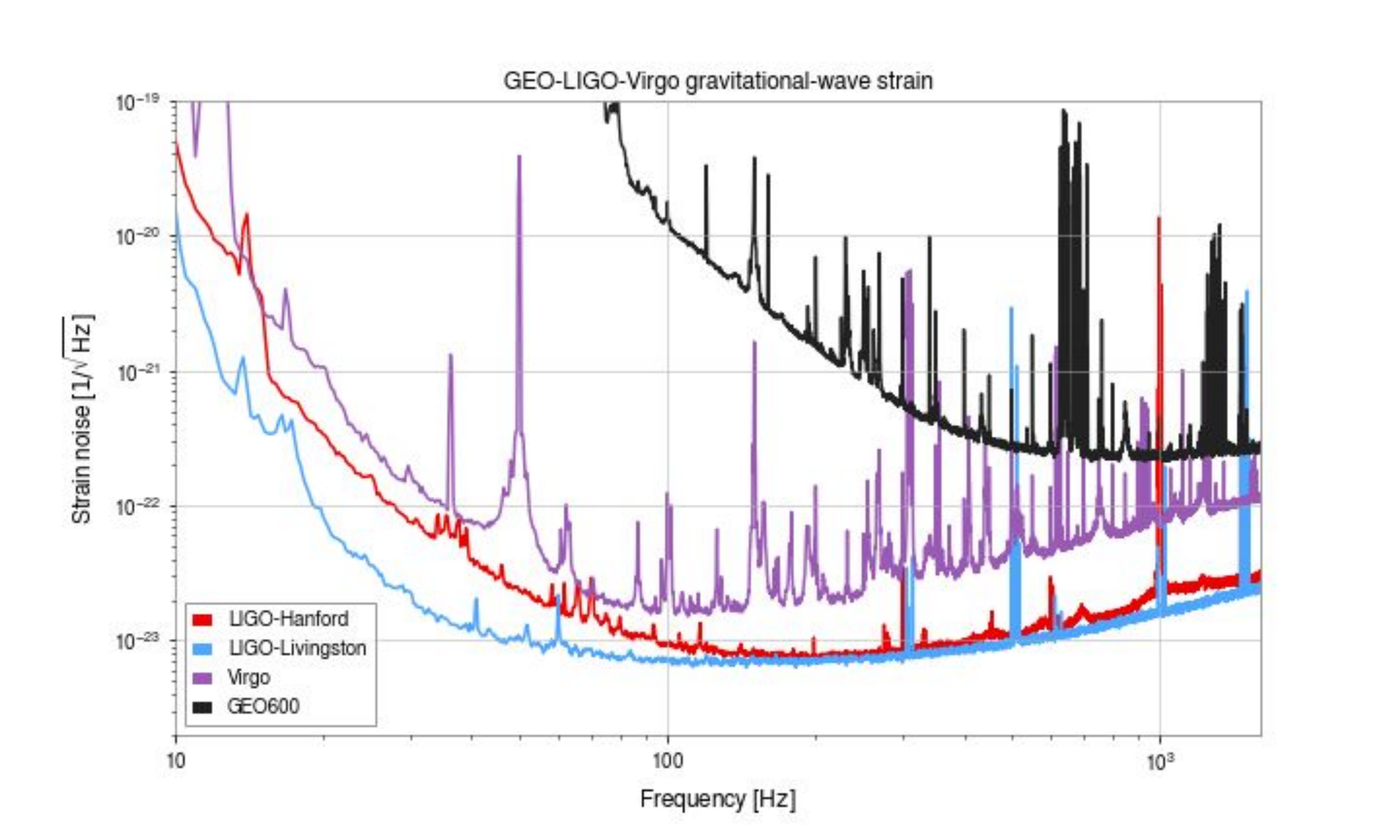
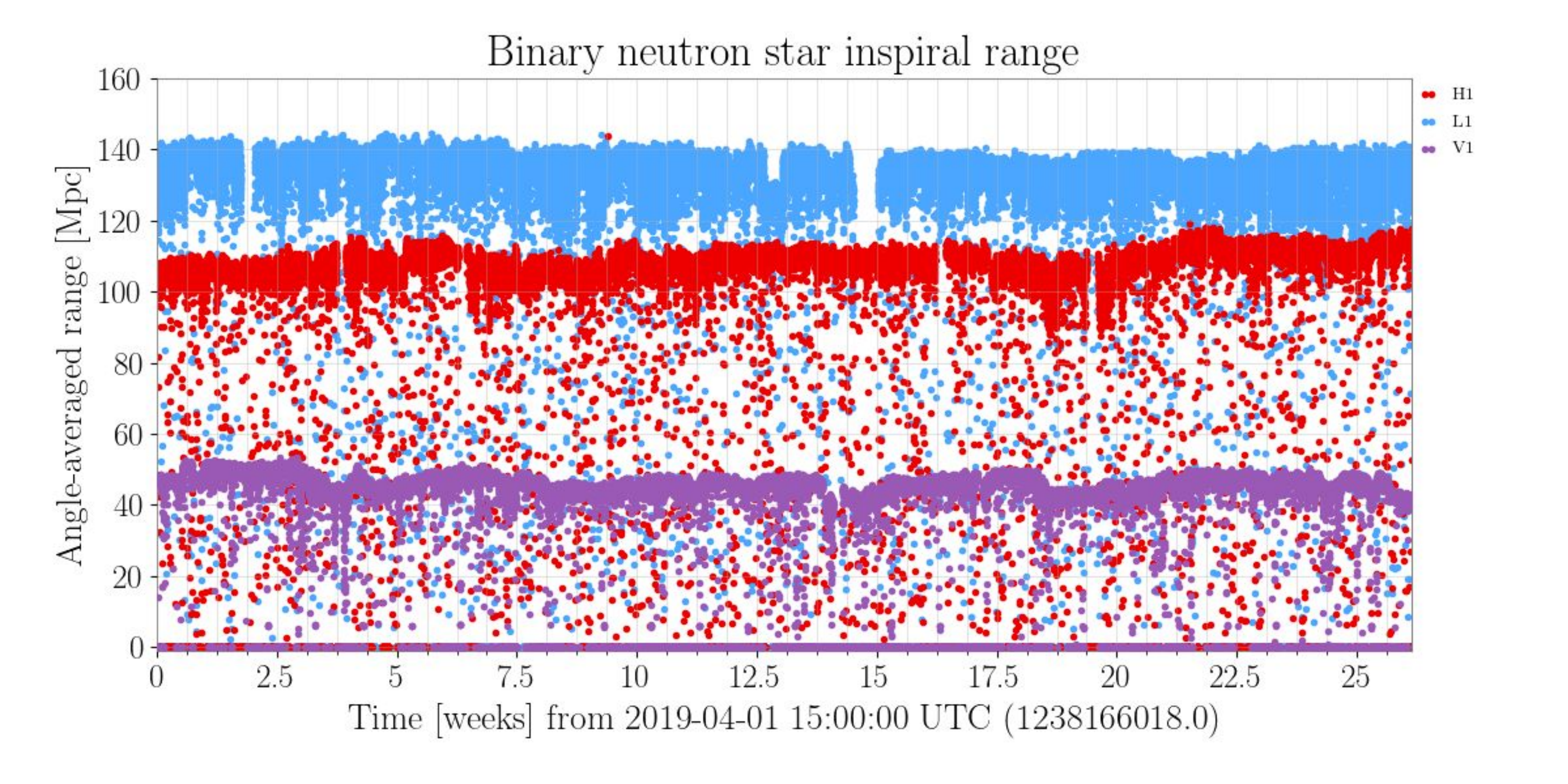
LIGO-Virgo noise - complex noise curve



Plot produced using code from Tutorial 1.2

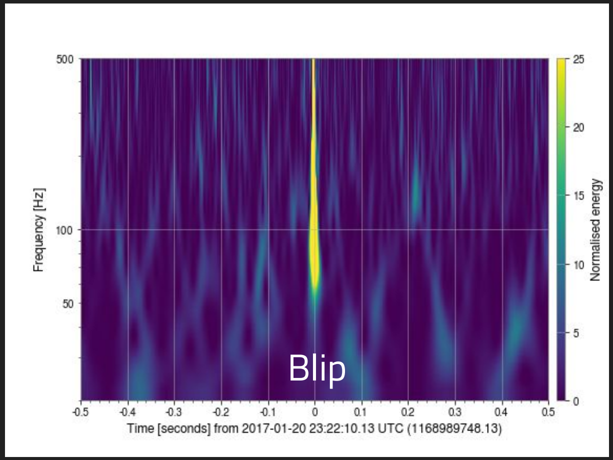
LIGO-Virgo noise - non-stationary

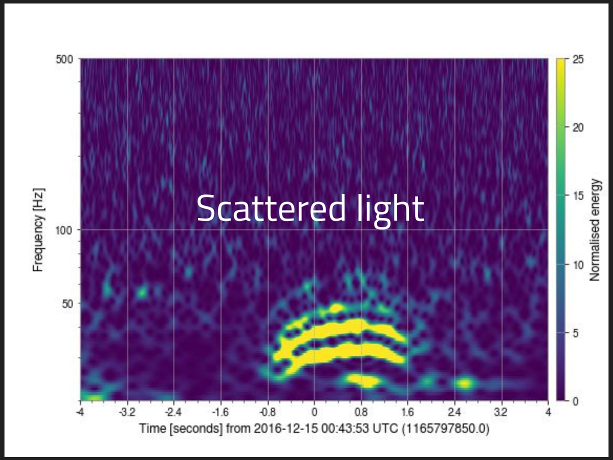


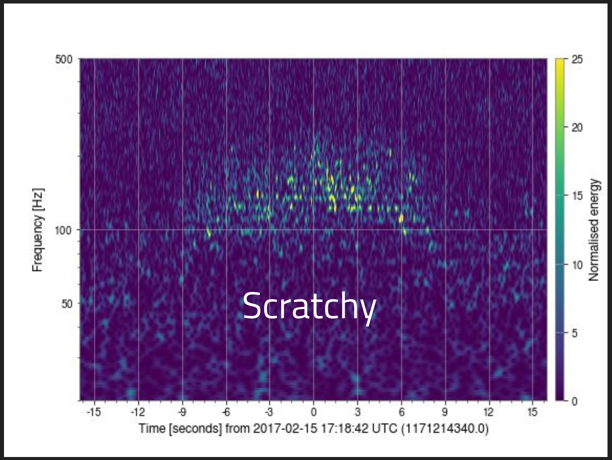
Plot produced using gwpy - tutorial found here:
https://gwpy.github.io/docs/stable/examples/miscellaneous/range-timeseries.html

LIGO-Virgo noise - non-Gaussian

Instrumental artifacts are present in the data, including a large number of short duration noise transients we call *glitches*







Plots produced using code from Tutorial 1.3

LIGO-Virgo noise: Summary

In practice, LIGO-Virgo data differs drastically from what is expected from an idealized interferometer

The noise curves contain complex narrow lines and broadband features

The noise curve (and hence the sensitivity) changes over both hour and second timescales

Large number of instrumental artifacts in the data with many (potentially unknown) sources

Learn more about LIGO-Virgo data quality in Marissa Walker's lecture

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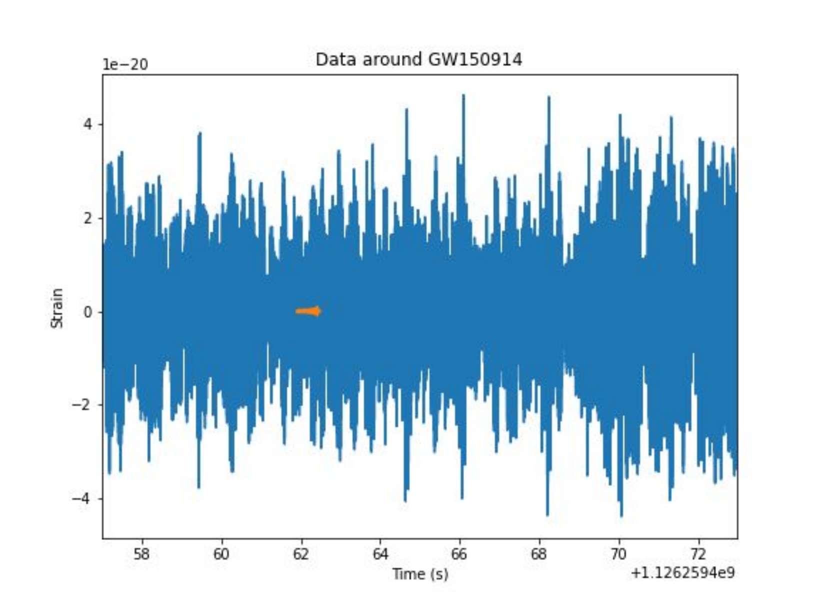
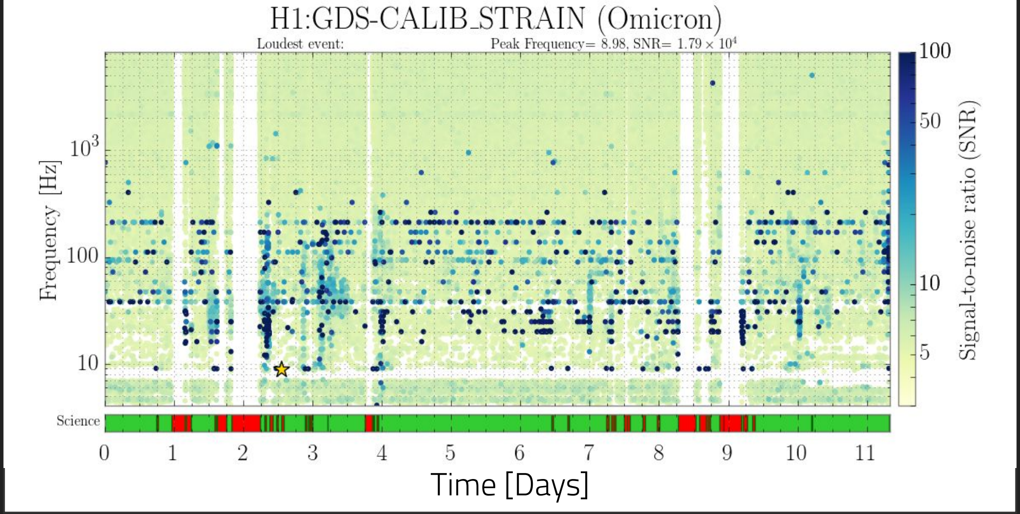
Detection problem

Gravitational-wave signals are hidden underneath the broadband noise in our detectors

Large number of instrumental artifacts in the data that could be confused with a signal



Plot produced using code from Tutorials 2.1 and 2.2

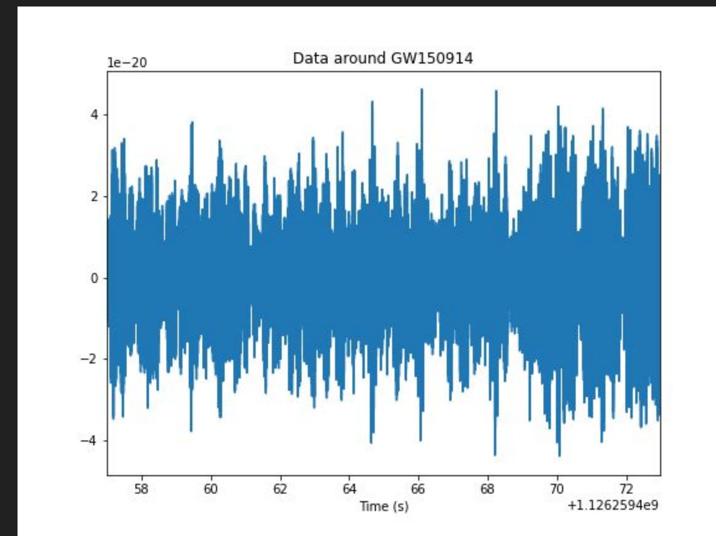


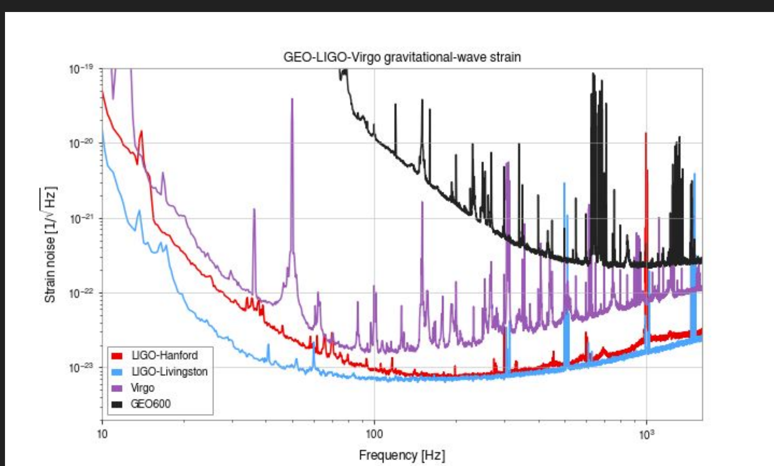
Plot produced using gwpy - tutorial found here:
https://gwpy.github.io/docs/stable/examples/table/scatter.html

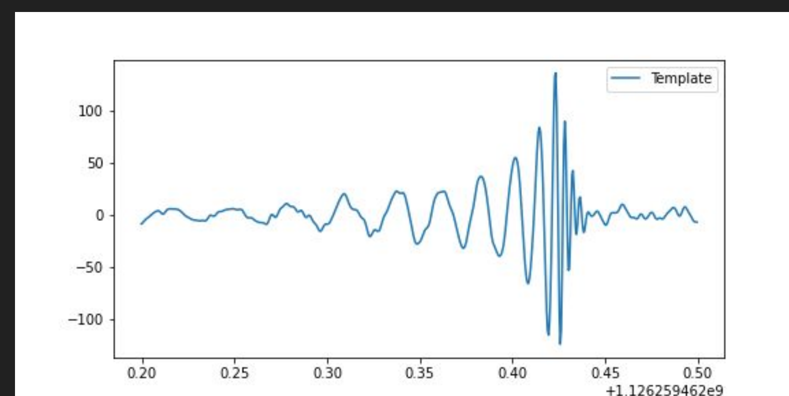
Focus of tutorials 2.1 and 2.2

Matched filtering

$$(s|h) = 4\mathcal{R}\int_0^\infty \frac{\tilde{s}(f)\tilde{h}^\star(f)}{S_h(f)}df$$



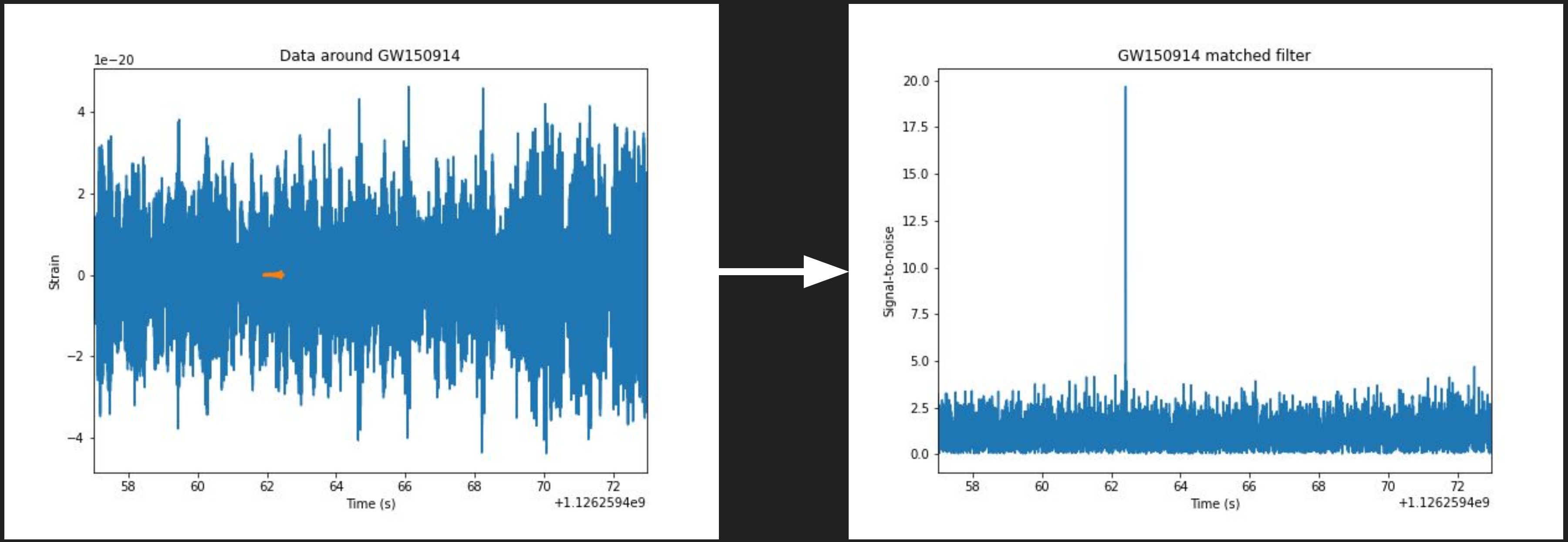




Plots produced using code from Tutorials 1.2 and 2.2

Wainstein and Zubakov "Extraction of signals from noise, (1962)
B. Allen et al. Phys. Rev. D 85 122006 (2012)

Matched filtering result



Plots produced using code from Tutorials 2.1 and 2.2

Large parameter space

Only considering black hole binaries, signals depend on 15 parameters

It is not computationally possible to search for every possible combination of parameters in this 15+ dimensional space

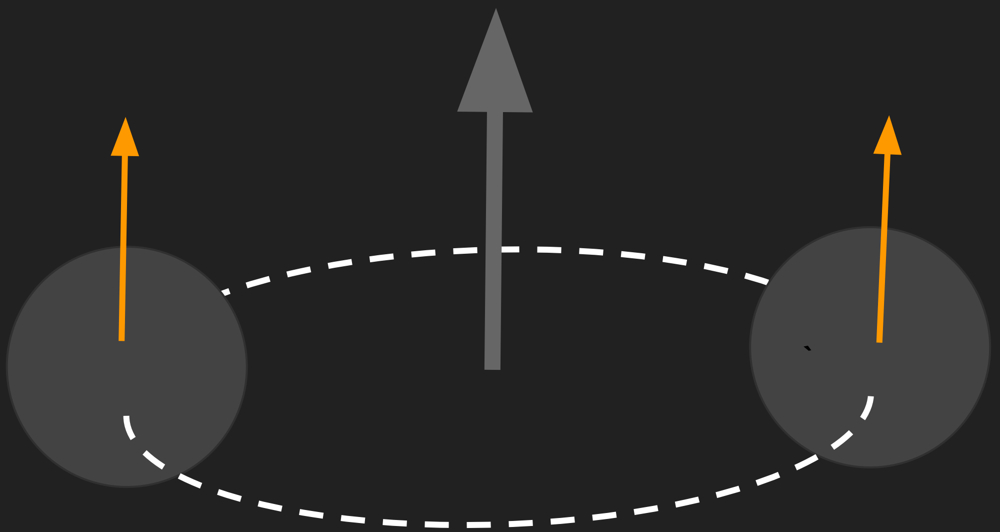
In order to detect unknown gravitational-wave signals, we must significantly reduce the size of the parameter space

Simplifying the search - assumptions

In previous PyCBC searches, we make the following assumptions:

- No in-plane black hole spins
- Both bodies are black holes
- Restrict to the dominant mode of the signal
- Orientation and location parameters now enter as overall constant amplitude, time or phase shifts

Simplified signal model:

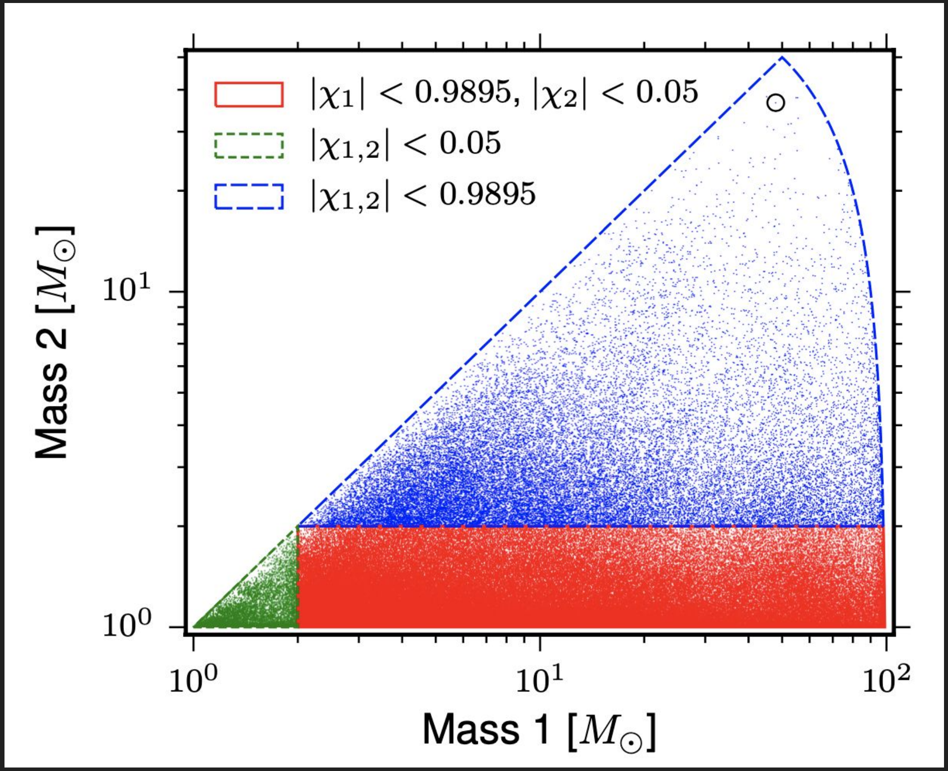


Template Bank

Even with these assumptions, we can not fully cover the parameter space

But we can still cover the space well enough to find signals!

We include enough templates so that only 3% of the matched filter SNR is lost for any given signal over our target parameter space



B. P. Abbott et al. Phys. Rev. D 93 122003 (2016)
T. Dal Canton and I. Harry. Arxiv:1705.01845 (2017)

What about the noise?

If LIGO-Virgo data was stationarity and Gaussian, all we would need is the matched filter

However, we know that over the timescales we need to analyze, these assumptions are definitely not the case

- Data is non-stationary and non-Gaussian

In order to identify gravitational-wave signals, we need additional methods to separate signals from noise

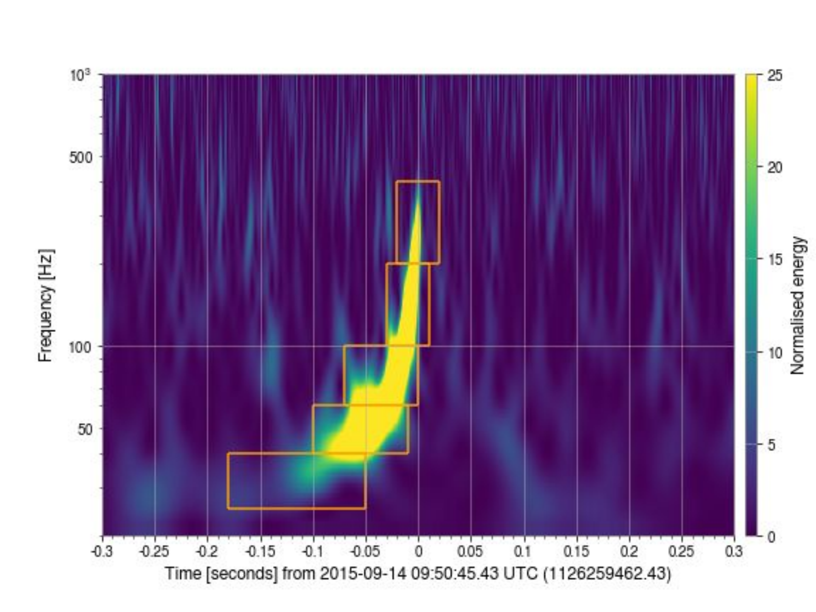
We can use our knowledge of CBC signals to help reject noise artifacts

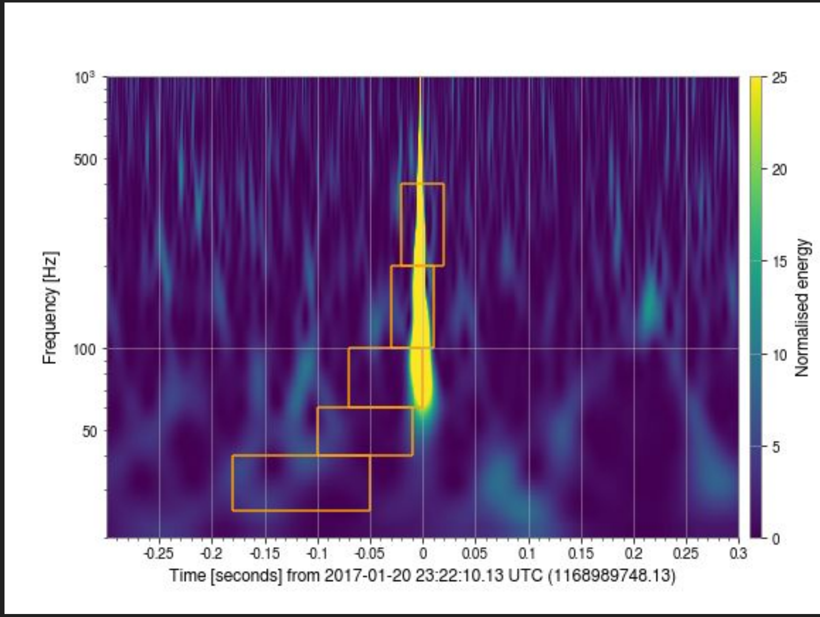
Focus of tutorial 2.3

Signal consistency tests

A core signal consistency check is the “Chi-squared test”, which checks if signal power is distributed as expected for a CBC signal

Chunk up signal into bins and measure power in each bin





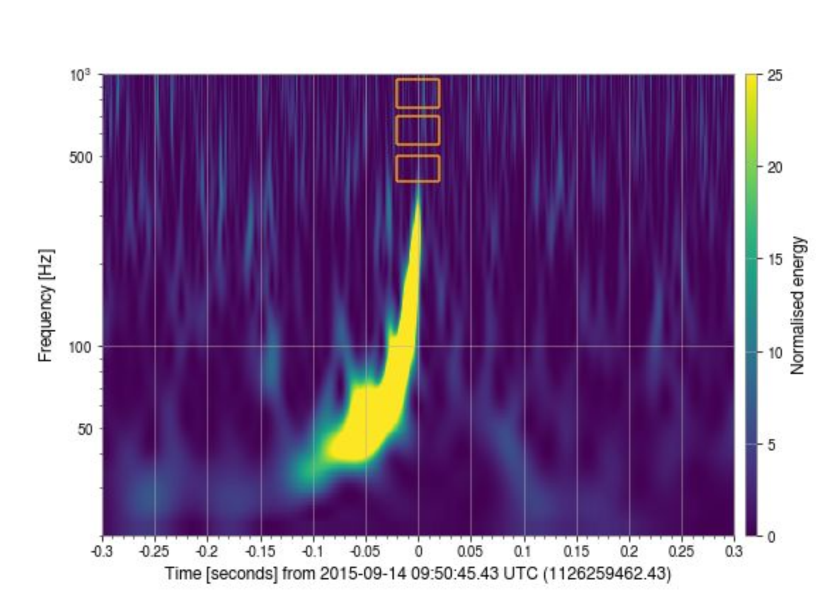
Plots produced using code from Tutorial 1.3

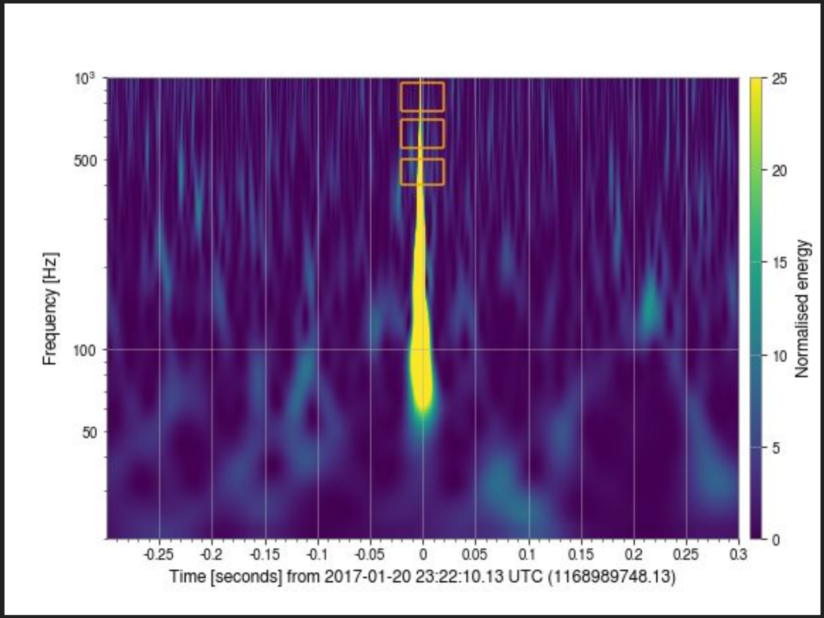
B. Allen et al. Phys. Rev. D 85 122006 (2012)

Another signal consistency test

Compact binaries merge at a known frequency - don’t expect large amounts of signal above this frequency

We can check if candidates have power above this cut-off frequency

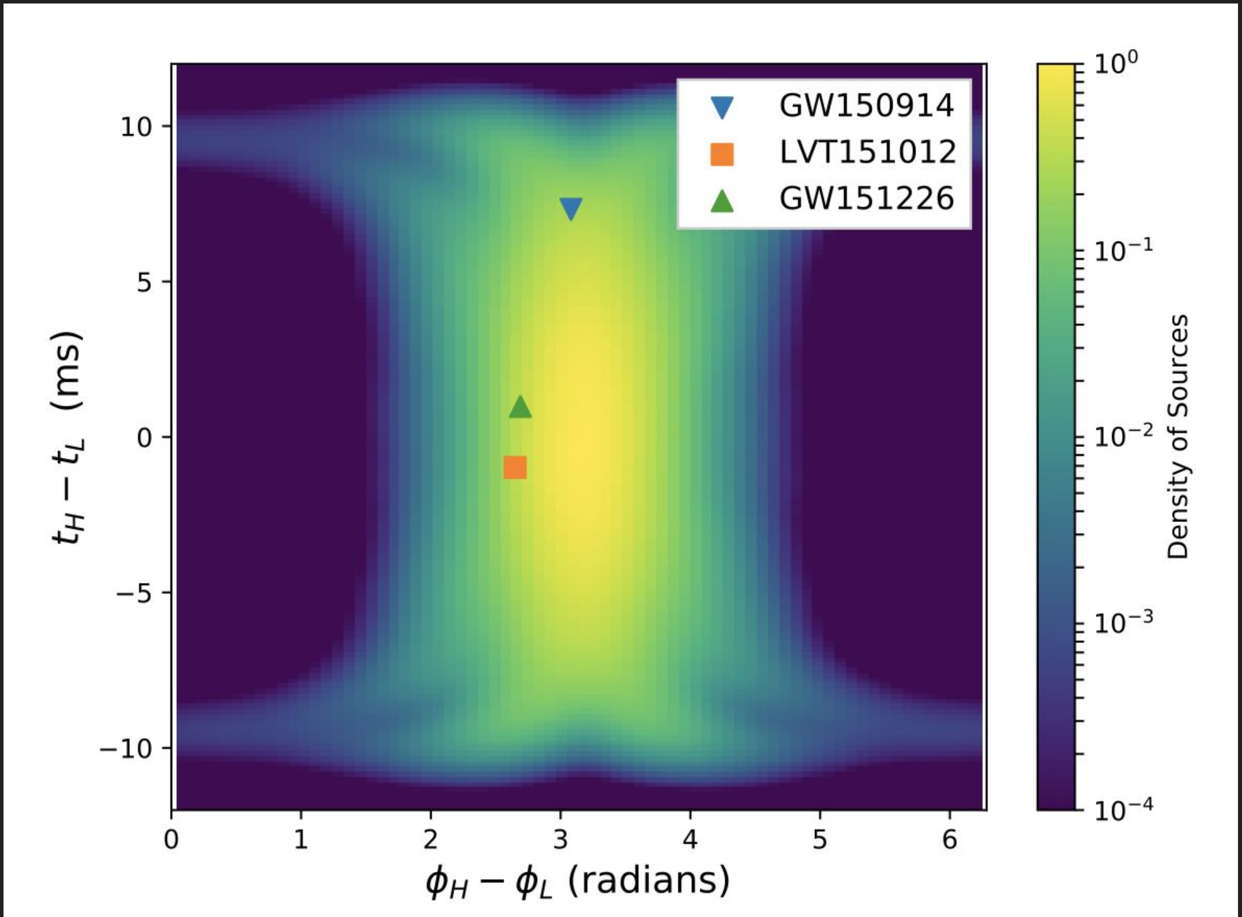




Plots produced using code from Tutorial 1.3

A. H. Nitz Class. Quant. Grav. 35 035016 (2018)

Consistency across detectors



A. H. Nitz et al. Astrophys.J. 849 118 (2017)

Long duration non-stationarity

To cope with changing noise in instrument, one simple method is to continually measure the PSD of the data

Need to balance a short enough to capture variation, but large enough window so that signal does not bias the PSD measurement

In PyCBC, this measurement duration was chosen to be 512 seconds

Use Welch's method to reduce impact of non-Gaussian artifacts

S. A. Usman et al. Class. Quant. Grav. 33 215004 (20186

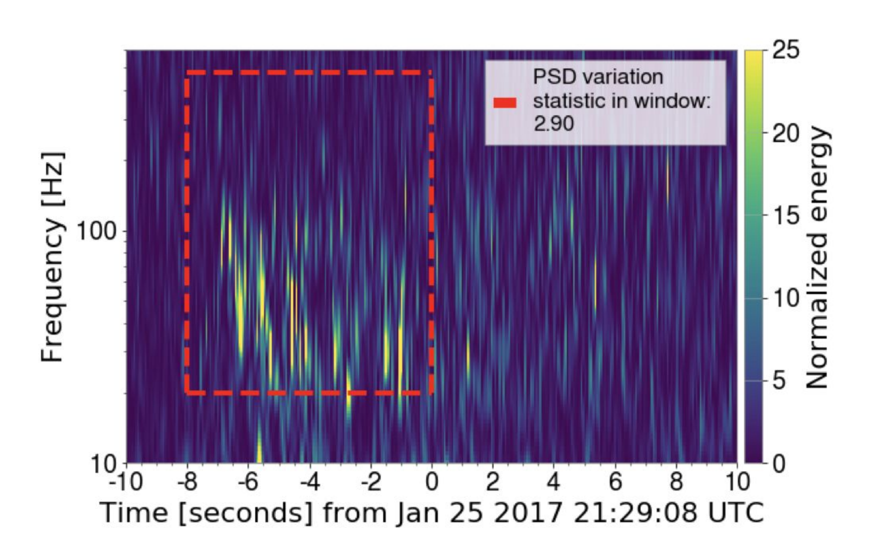
Short duration non-stationarity

LIGO-Virgo noise also changes on very short timescales

Many ways to account for this in the search pipeline

PyCBC addresses short changes in the noise with the PSD variation statistic

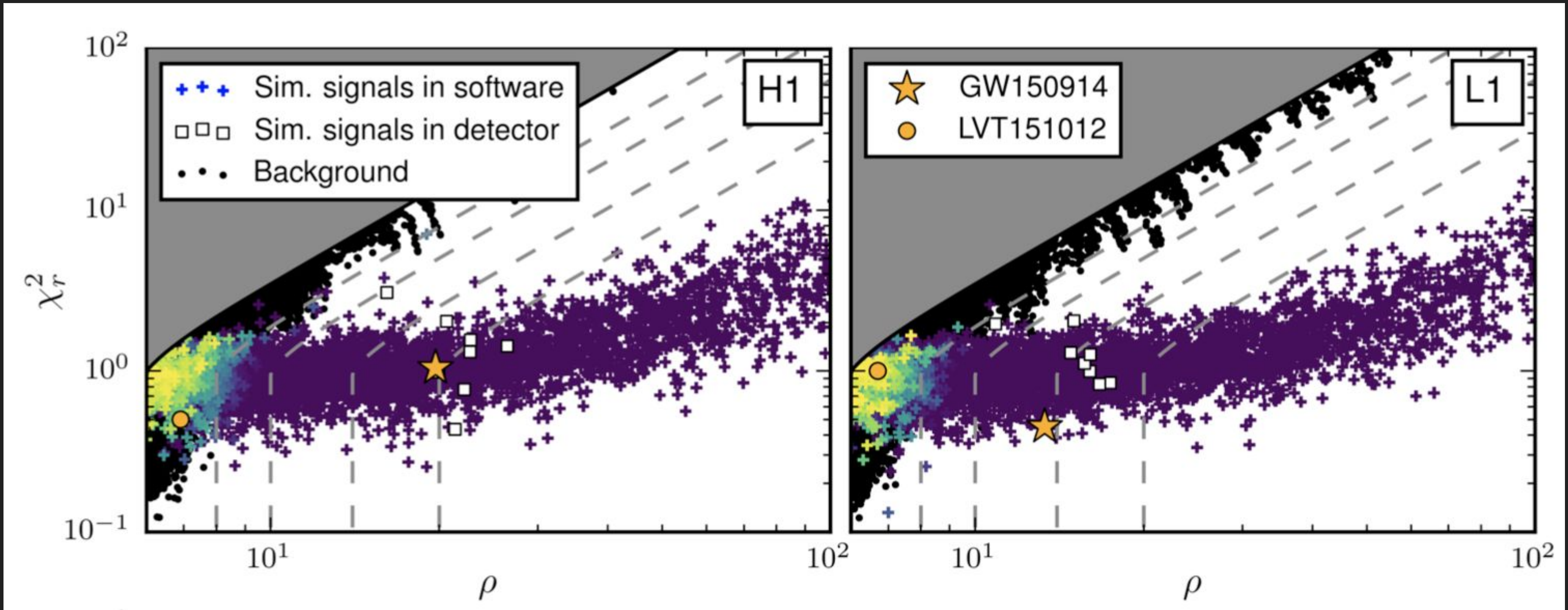
Other signal consistency checks used by pipeline further reduce the impact of short-duration noise



S. Mozzon et al. Arxiv:2002.09407

Ranking statistic

Combining all of these tests, we can better separate signals from instrumental artifacts



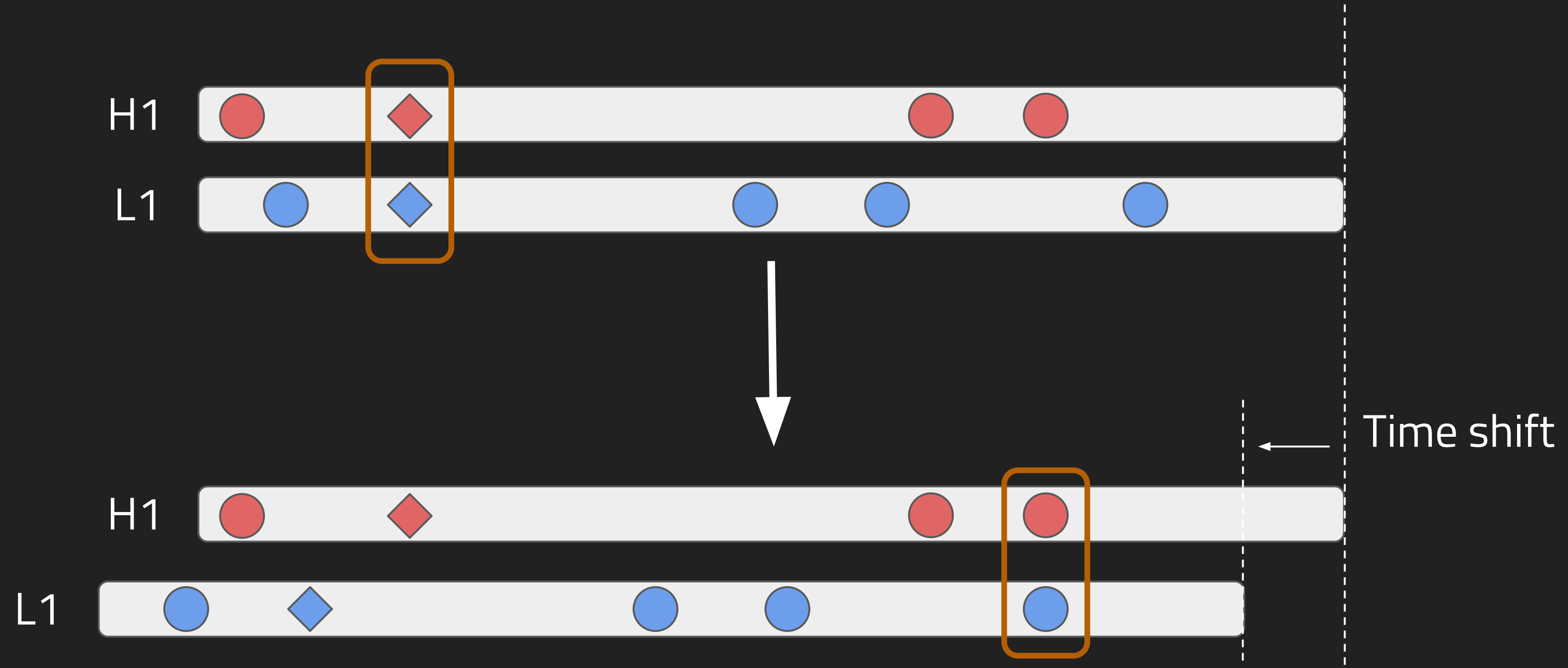
B. P. Abbott et al. Phys. Rev. D 93 122003 (2016)

Focus of tutorial 2.3

Calculating significance

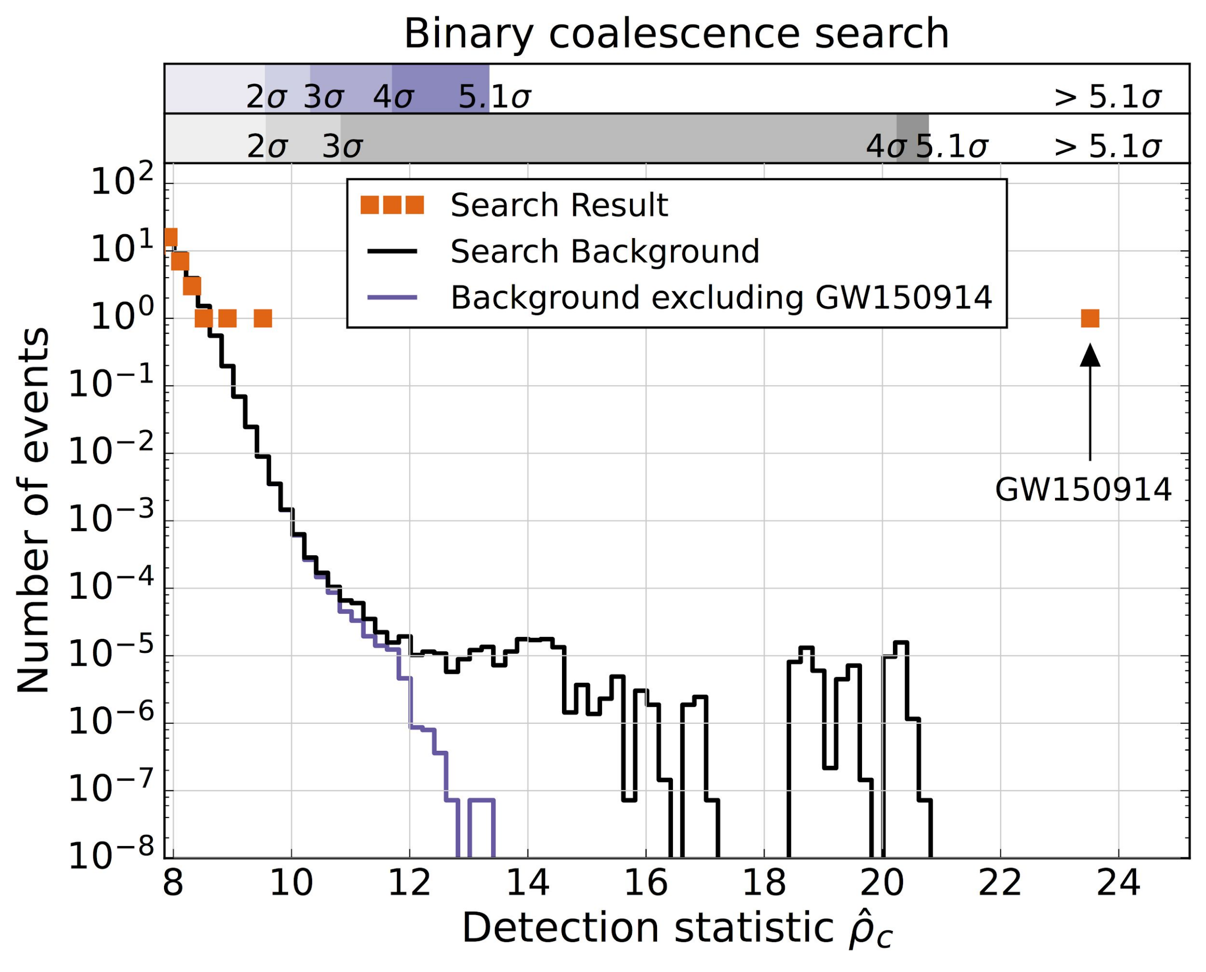
Multiple ways to calculate significance of candidates

PyCBC primarily uses the timeslides method for coincident signals



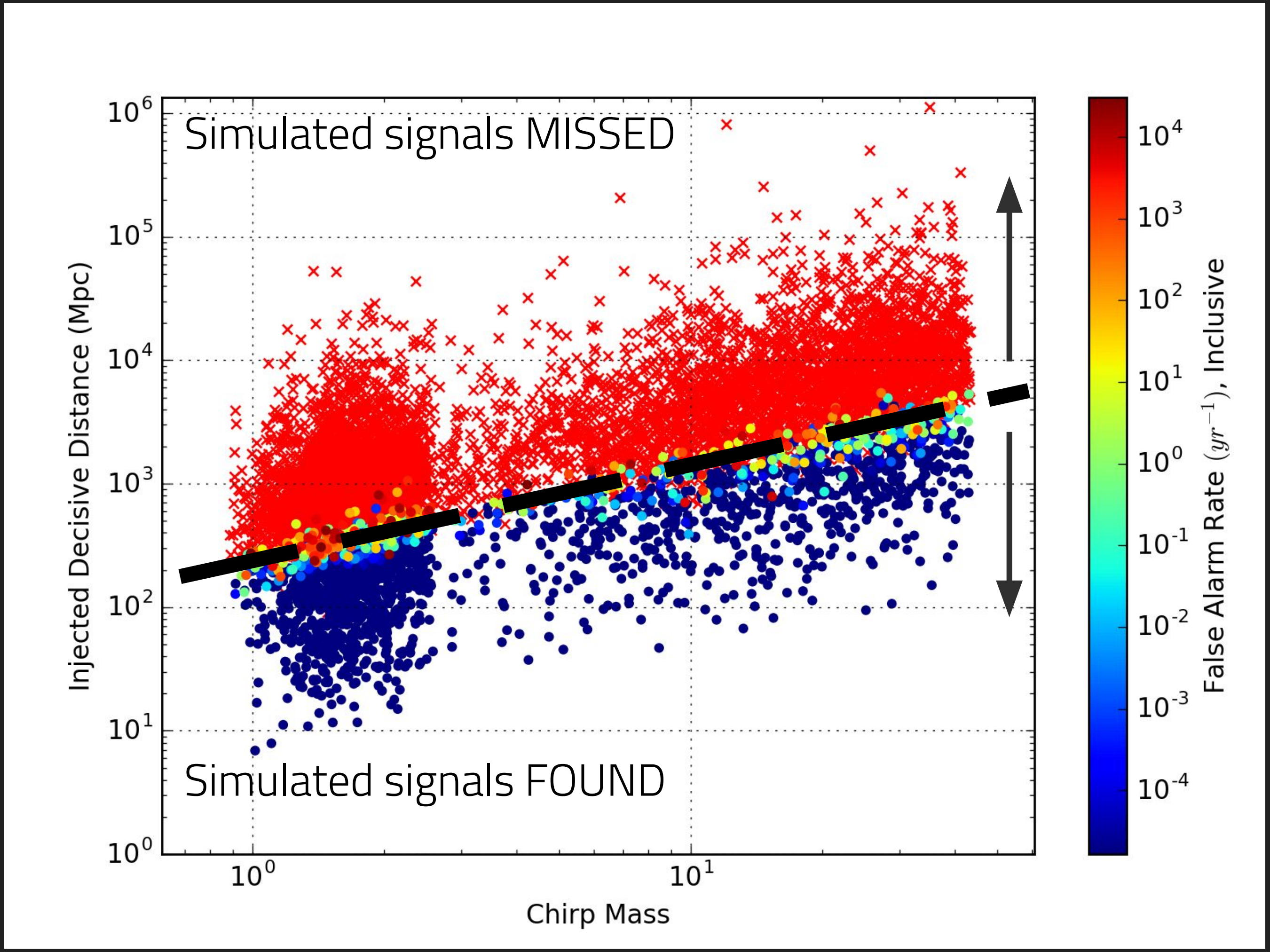
S. A. Usman et al. Class. Quant. Grav. 33 215004 (2016)

Putting it all together



B. P. Abbott et al. Phys. Rev. Lett. 116 061102 (2016)

How do we check this works?



Plot produced using PyCBC - pycbc_page_foundmissed executable

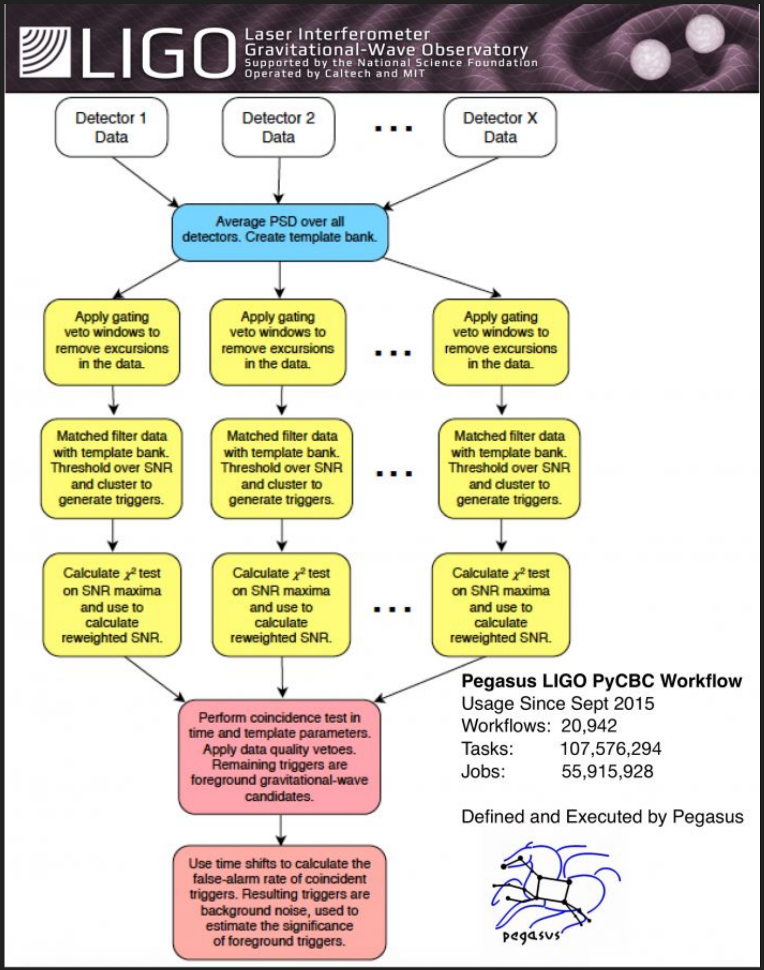
How much effort is all this?

Brute force methods used in searches are extremely computationally expensive

GWTC-1 PyCBC analyses took 75 years of computing time

Need to parallelize this process to complete analysis in reasonable timescale

PyCBC searches take advantage of the open science grid: https://opensciencegrid.org



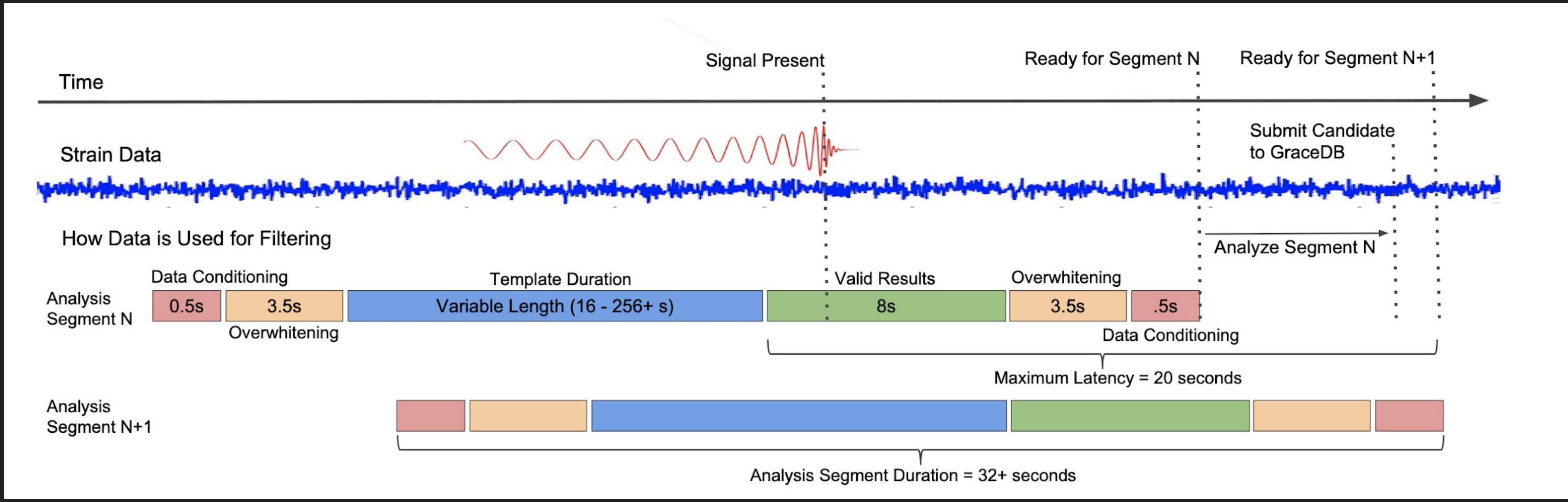
S. A. Usman et al. Class. Quant. Grav. 33 215004 (2016)

Low-latency searches

Low-latency searches aim to analyze the data as efficiently as possible

In PyCBC, this is accomplished by analyzing the data in 8 second chunks as the data is recorded

The significance is estimated using the previous 5 hours of data



A, H. Nitz et al. Phys. Rev. D 98 122000240503 (2018)

Challenges of low-latency searches

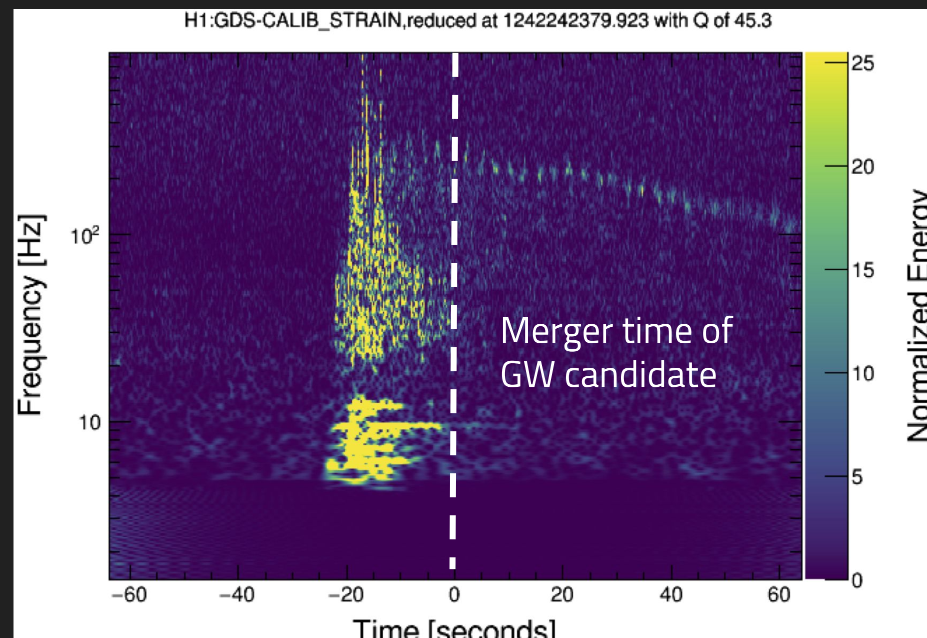
Interferometer data is full of artifacts

Online searches may not be able to always account for new noise features in the data

Online searches have an increased risk of a false alarm

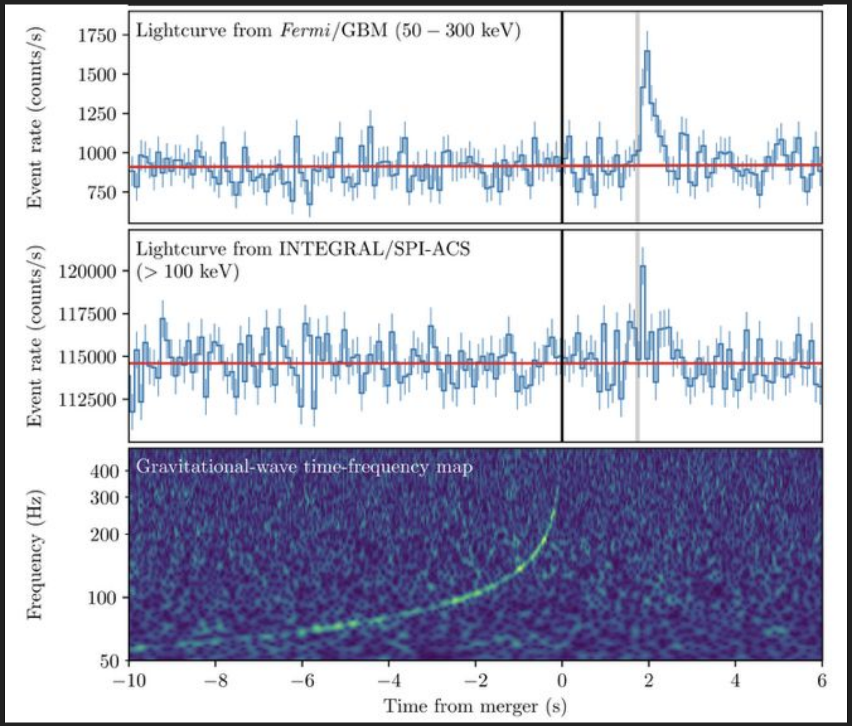
Looking for candidates in only a single detector has an even larger risk of a false alarm

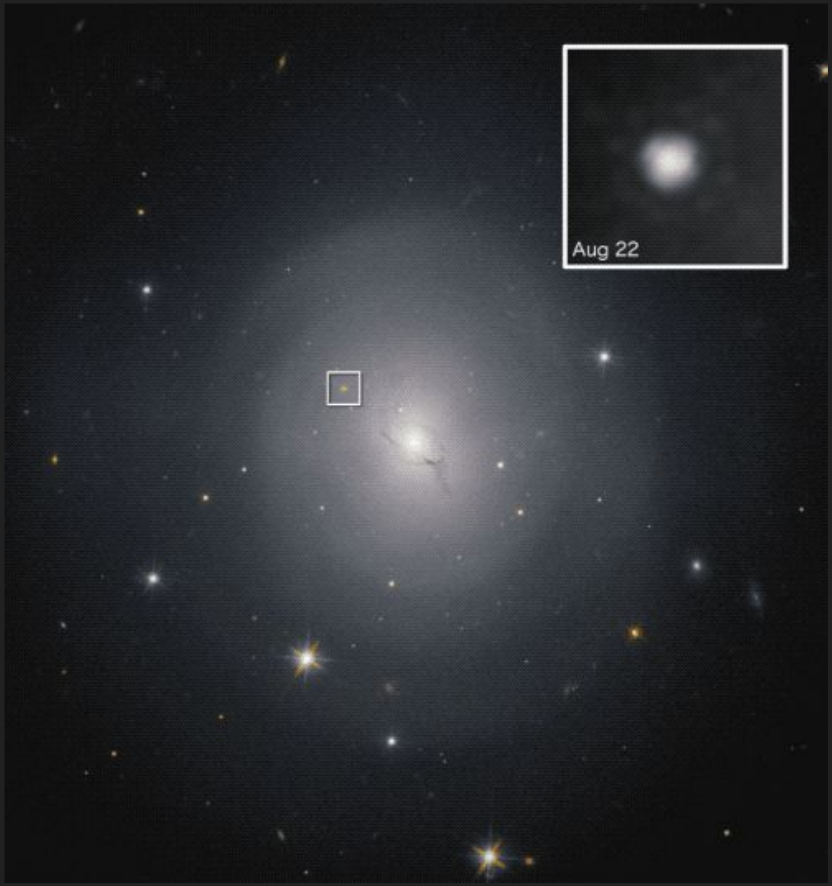
UID	Labels
S190602aq	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190524q	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190521r	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190521g	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S19051[illegible]	[illegible]OK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S19051[illegible]b	ADVNO SKYM[illegible]P_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S19051[illegible]	[illegible]OK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190513bm	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT



LIGO-Virgo Collaborations, GCN 24591

Benefits of low-latency searches





B. P. Abbott et al. Phys. Rev. Let. (2018); Image: HST/NASA/ESA

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Weakly modelled searches

With a templated search, you can only find what you're looking for

Thankfully GR gives us very good predictions

Lots of other what-ifs

- What if the source isn't a CBC?
- What if we simplified our signal model too much?
- What if there's new physics in our signals?
- What if GR is wrong?

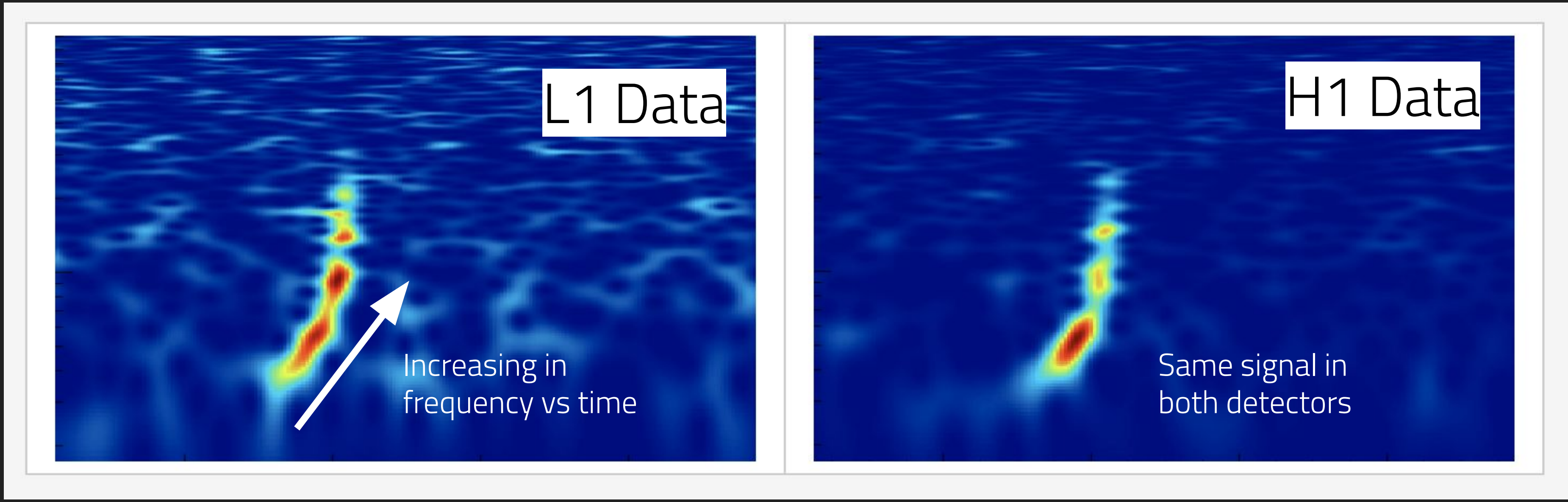
We can relax many of assumptions (including matched filtering!) to make sure we are able to detect such an exciting new signal

S. Klimenko et al., Phys. Rev. D 93 042004 (2016)
S. Klimenko et al., Class. Quant. Grav. 25 114029 (2008)

Basic idea of burst searches

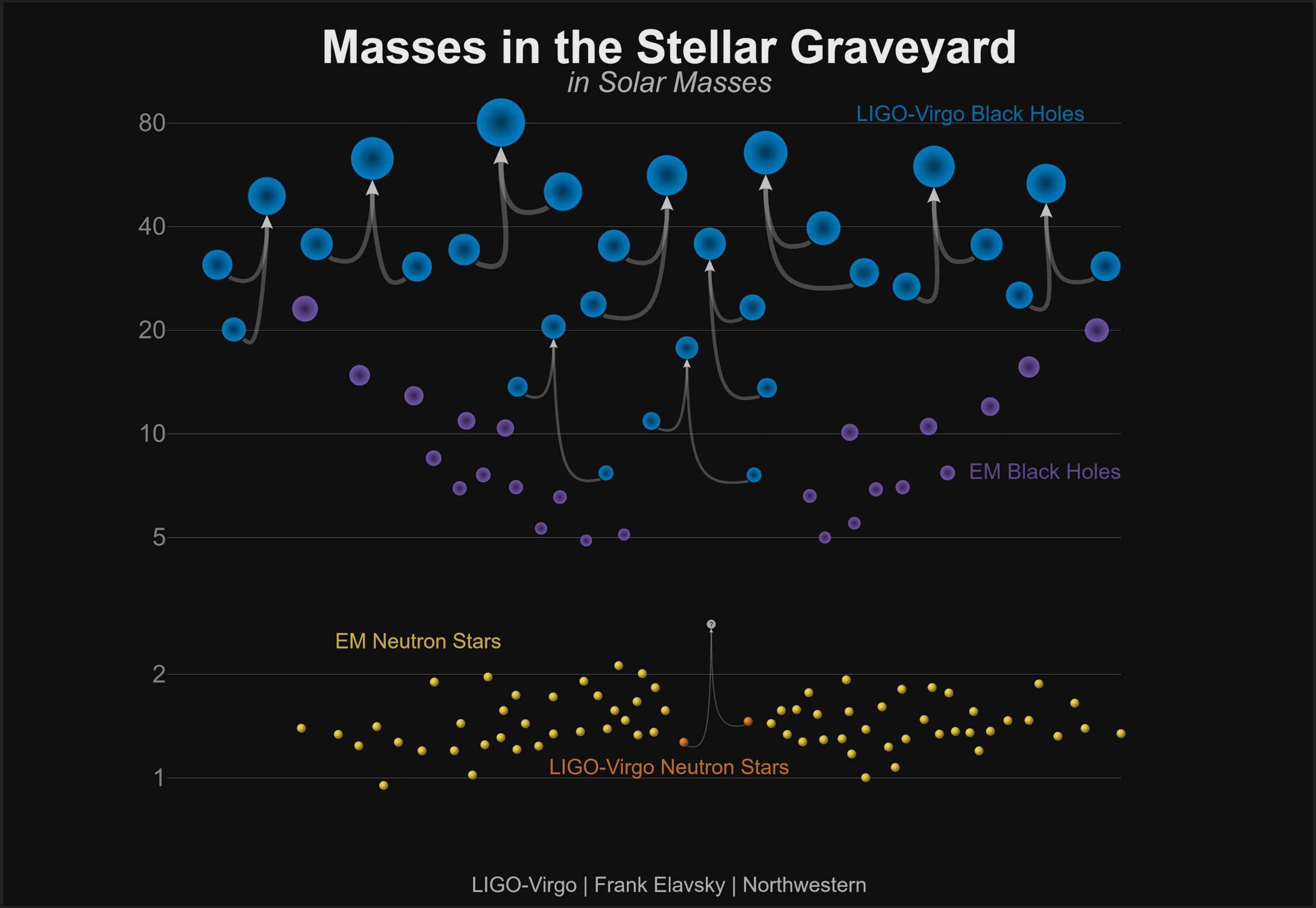
A simple "burst search" involves producing spectrograms of the data and identifying signals in both detectors

cWB can focus on CBC-like signals by only looking for candidates with increasing frequency vs time



https://gwburst.gitlab.io
B. P. Abbott et al. Phys. Rev. D 93 122004 (2016)

What have we found so FAR?



Perhaps more?

- Ongoing efforts to analyze O3 data
  - Planned publication of special event papers
  - Planned publication of catalogs covering entire observing run
- Ongoing efforts to re-analyze open data
  - Many studies of O1, O2, and O3 open data already published

Conclusions

Predictions from GR allow us to search for gravitational waves from compact binary mergers using large numbers of waveform templates

LIGO-Virgo noise features present challenges for identification of gravitational-wave signals

Matched filtering and signal consistency tests allow PyCBC to accurate separate signals from noise

Weakly modelled searches can identify gravitational waves with fewer assumptions, and still discover compact binary mergers

Large population of gravitational-wave signals from compact binary mergers already discovered, more being found as detector sensitivity and analysis methods improve

Thank you!
Any questions?

Explore the principles behind searches for GW signals from compact binary mergers further in
tutorials 2.1, 2.2, and 2.3