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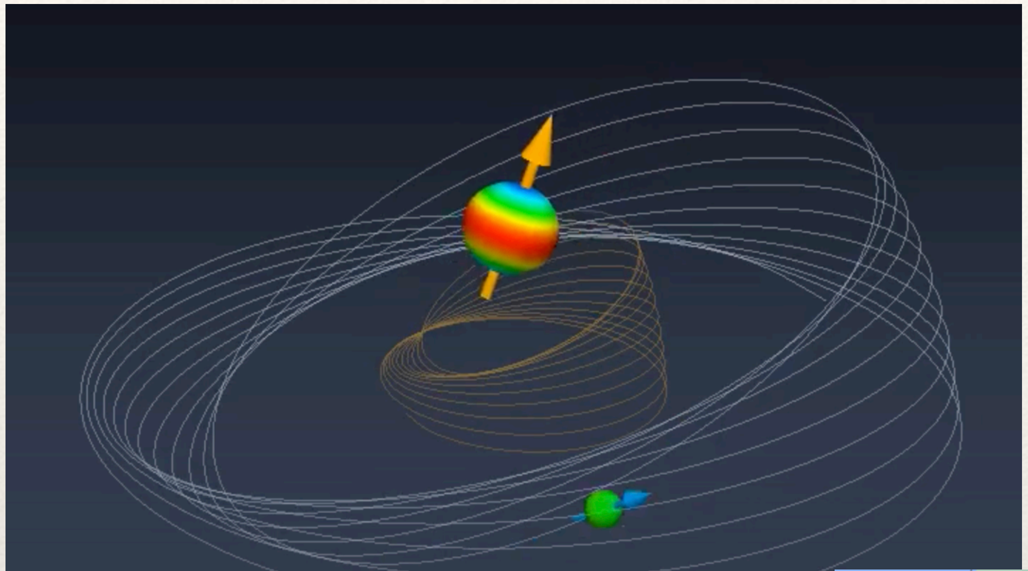
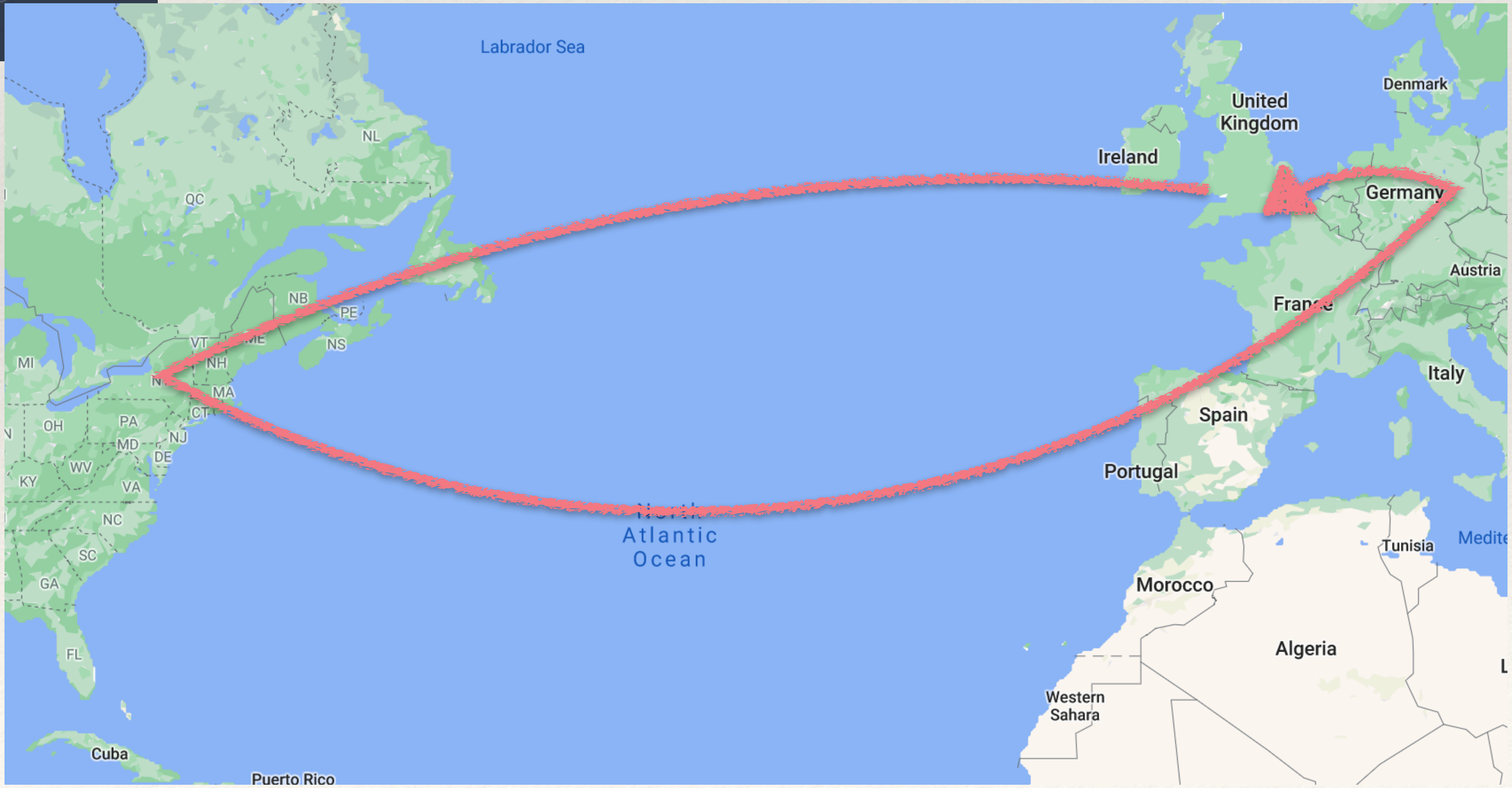
How to find gravitational-wave signals buried in the detector noise?

Dr Ian Harry

Who am I?



PyCBC



What am I going to talk about?

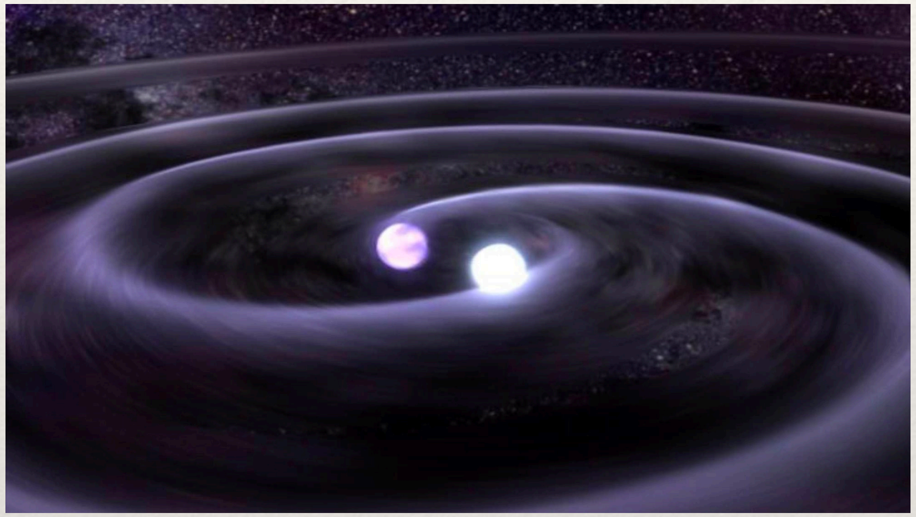
- How do we find gravitational-wave signals buried in detector noise?

Four classes of search targets

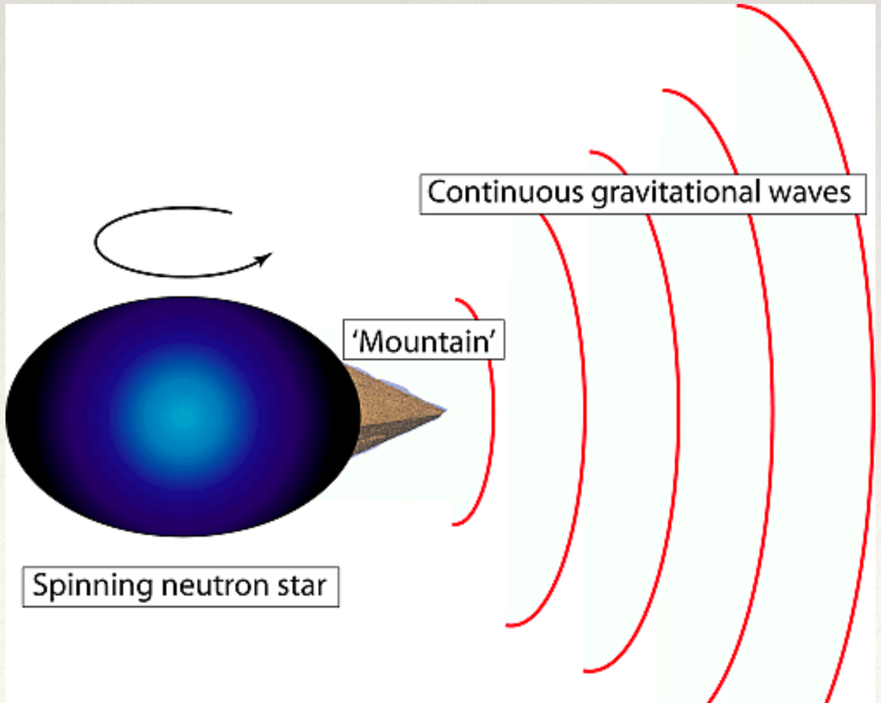
Well modelled sources

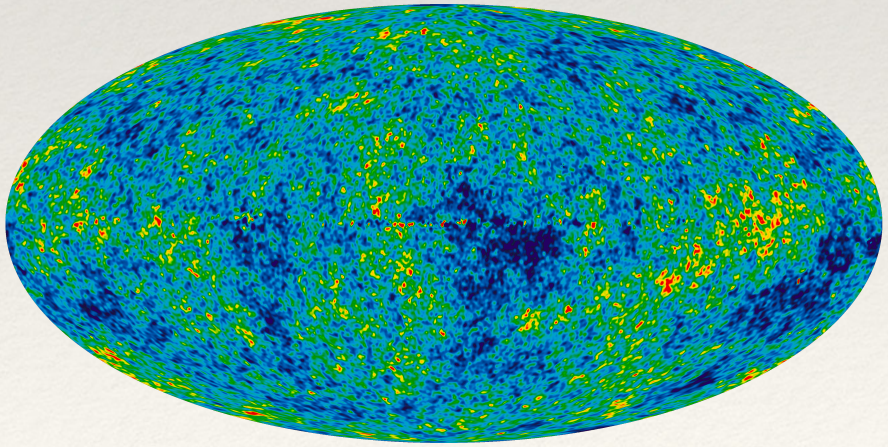
Unmodelled sources

Short duration



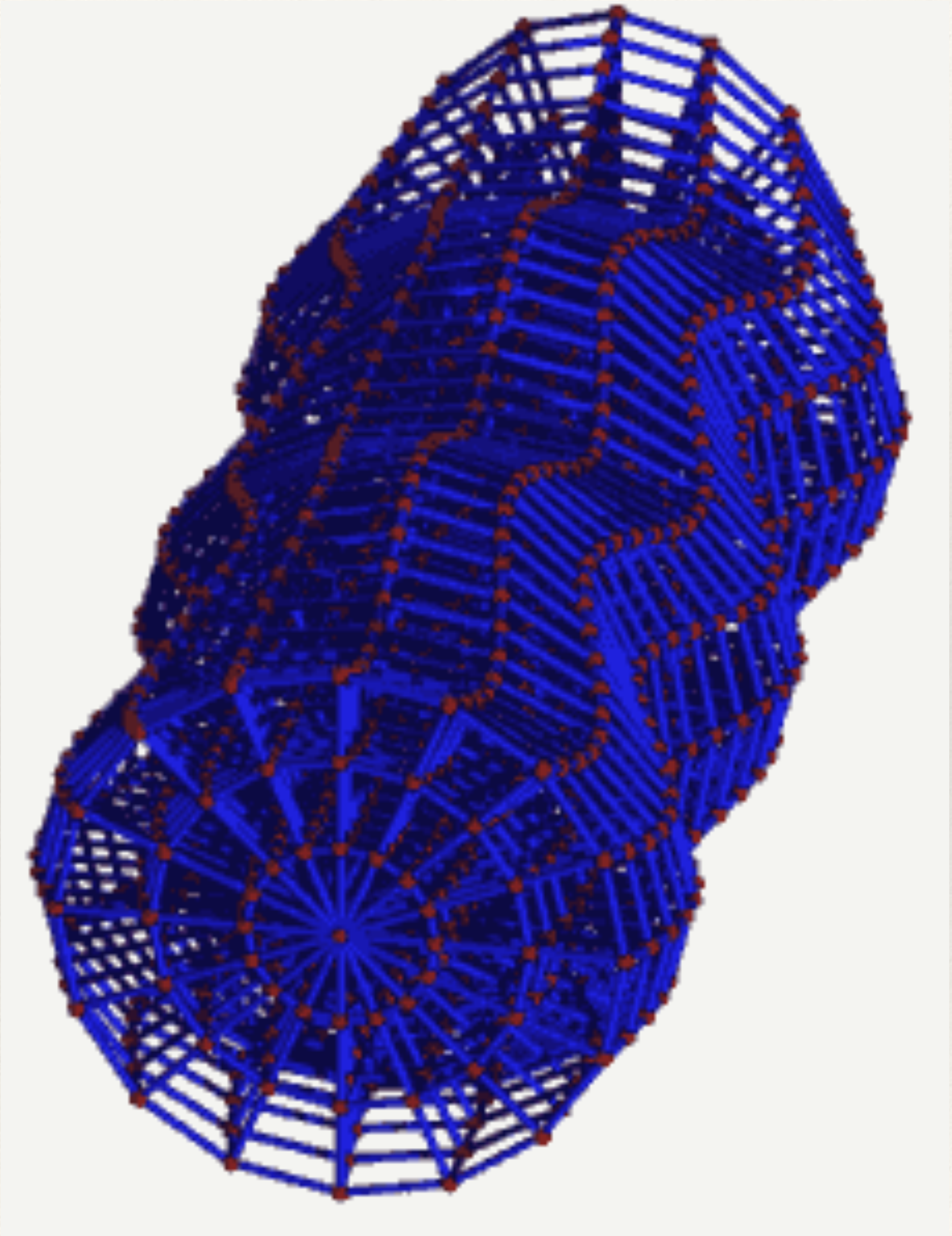
Long duration



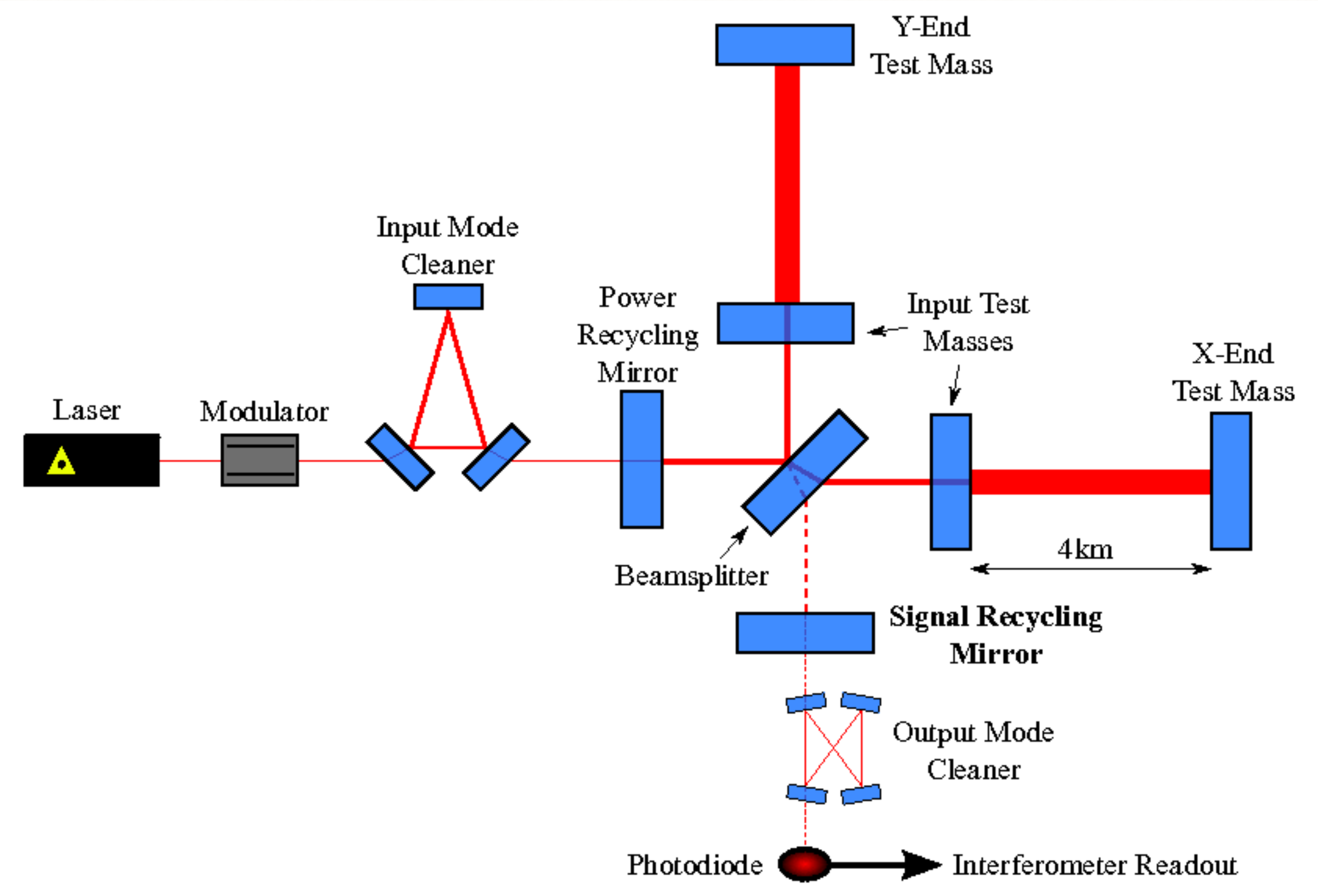


What I will assume you know

- All particles affected by gravitational-wave passage
- Passing wave can cause a deformation in a ring of particles
- However, interaction with matter is *extremely* weak
- Observed signals have a strain of 10^{-21}.

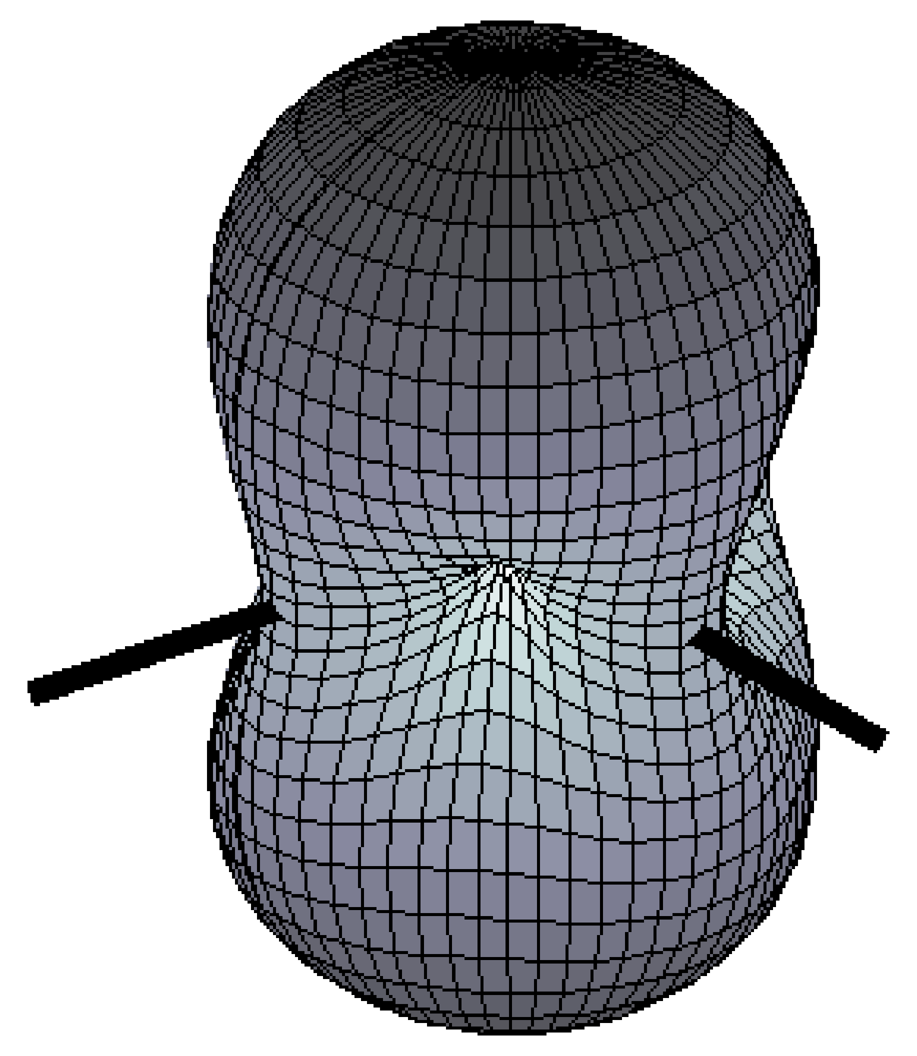


What I will assume you know



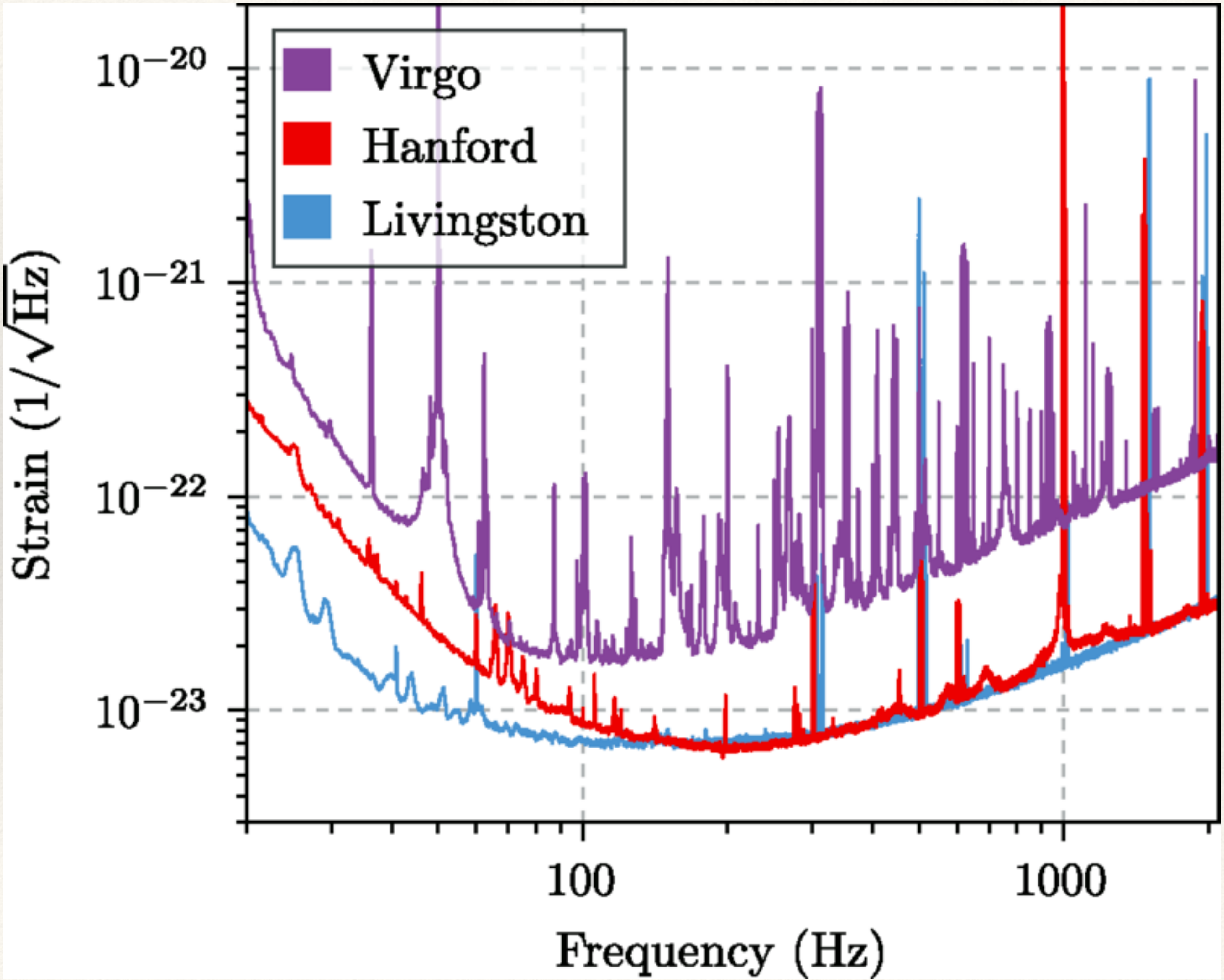
Broad sky sensitivity

- Sensitivity to most points on the sky
- Best sensitivity to sources overhead (or underhead)
- But difficult to know where in the sky a source came from!

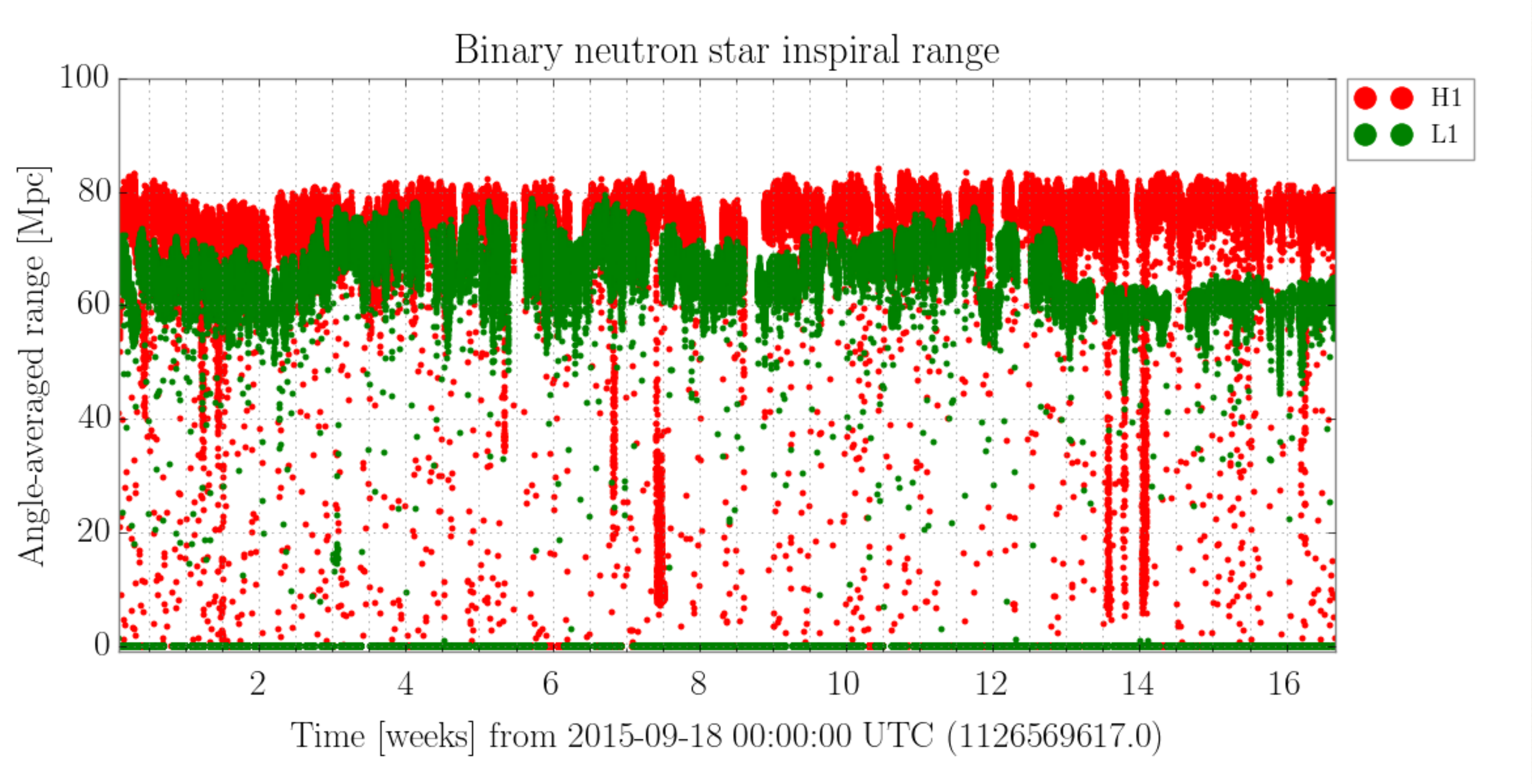


Rept.Prog.Phys. 72 (2009) 076901

What I will assume you know

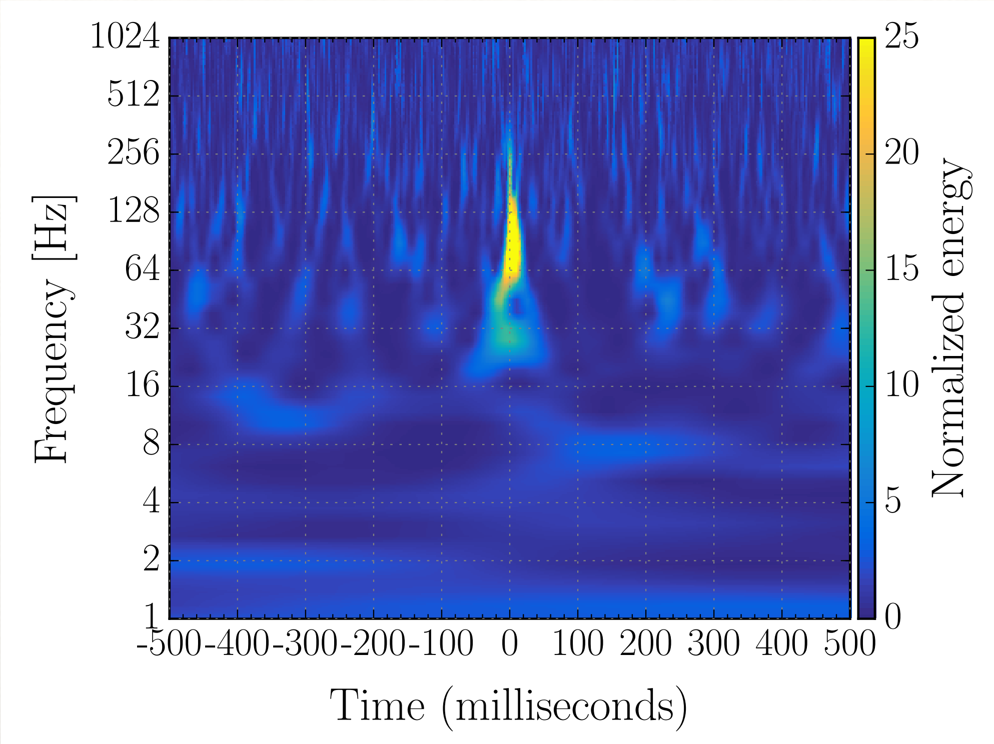


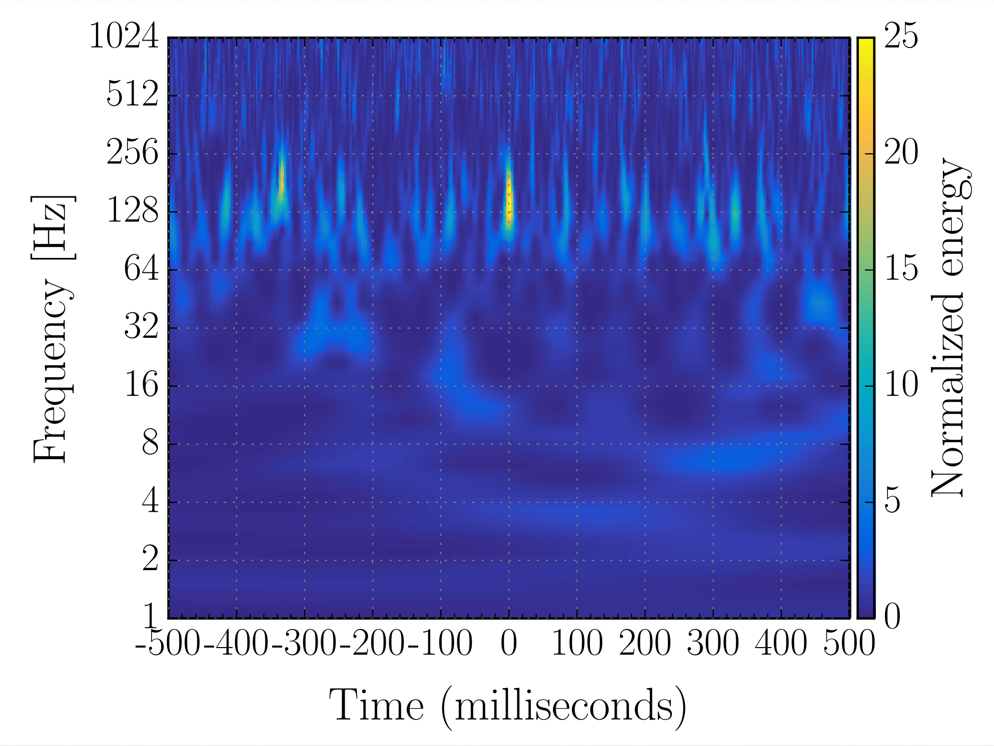
LIGO noise: Non-stationary

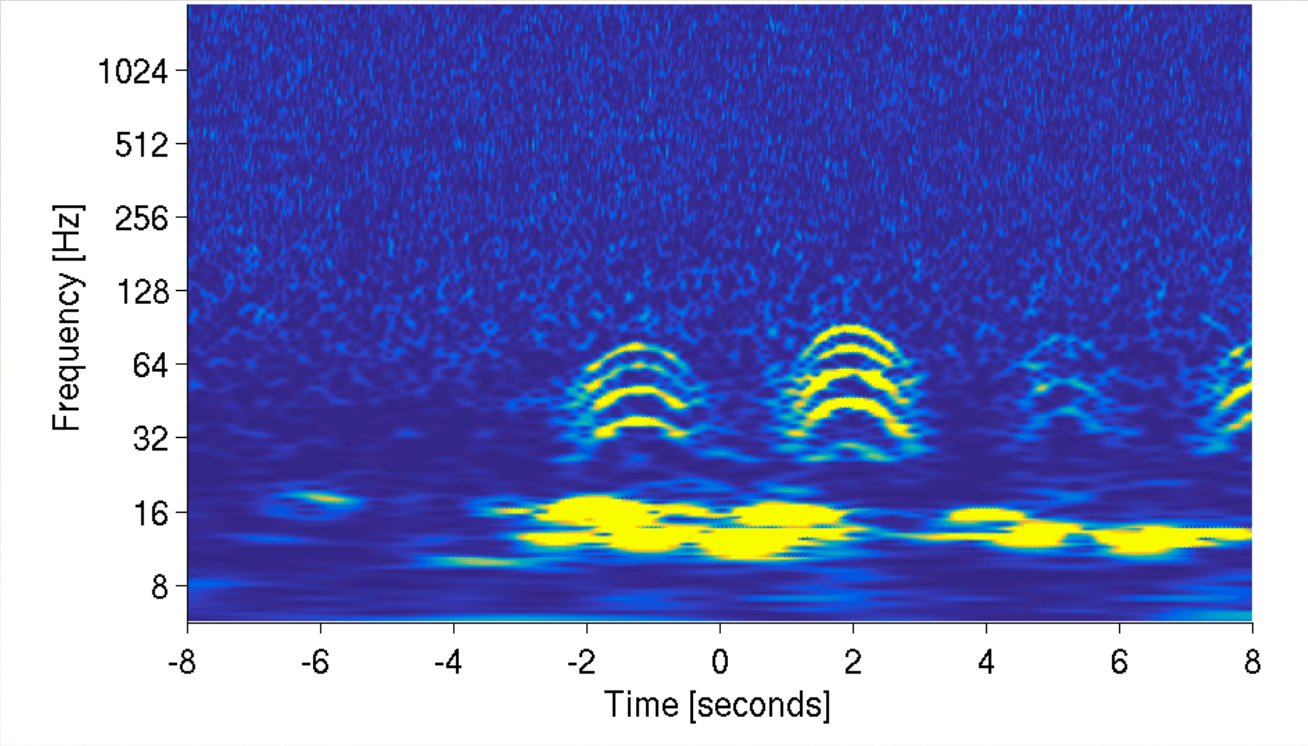


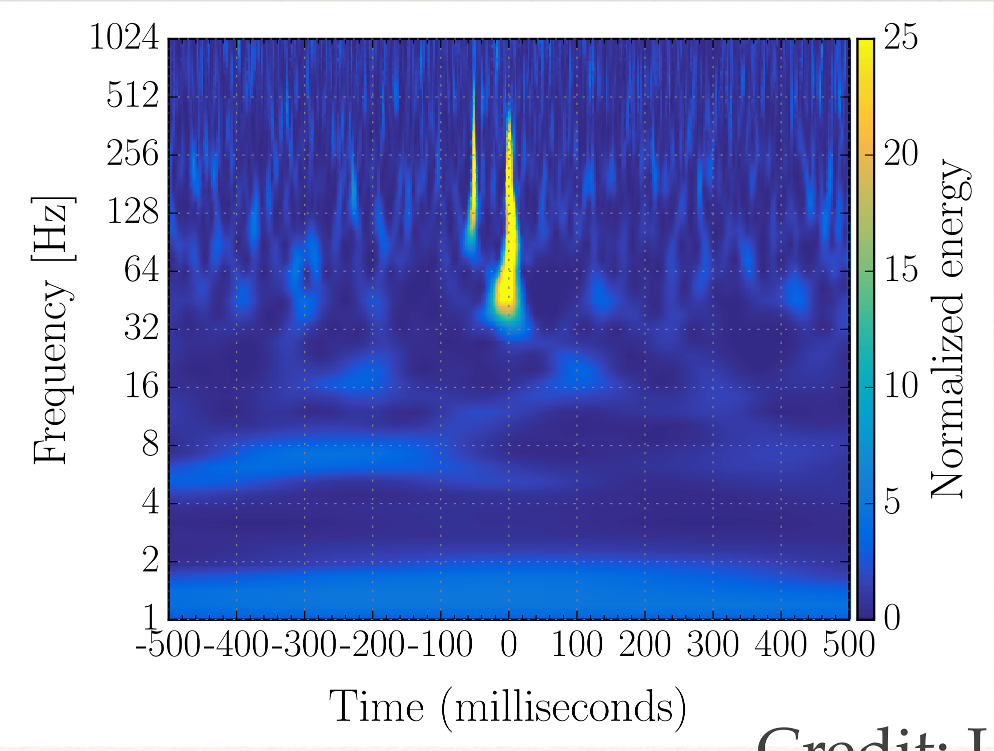
Credit: LIGO

LIGO noise: Non-Gaussian



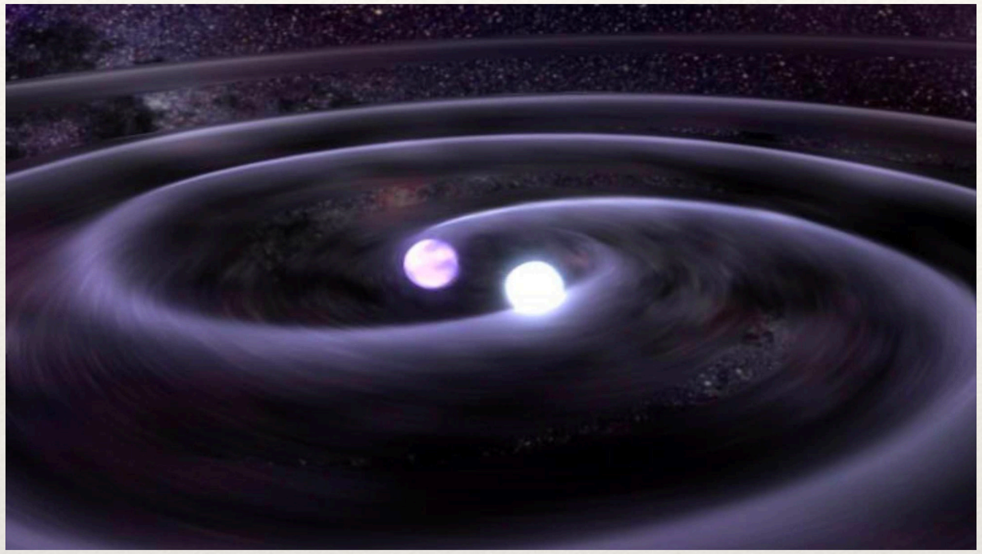


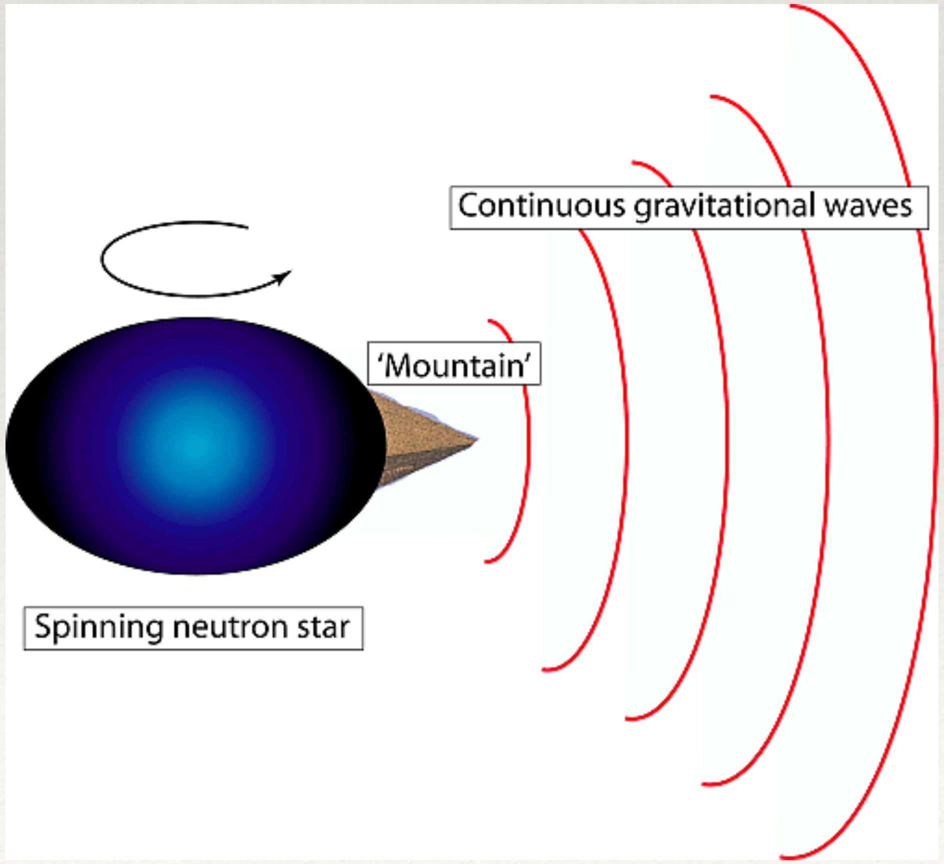


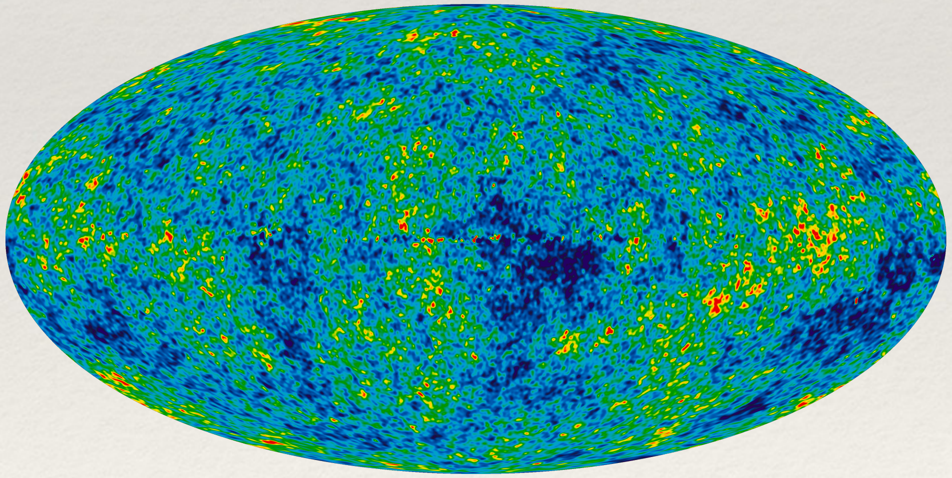


Credit: LIGO

What I will assume you know





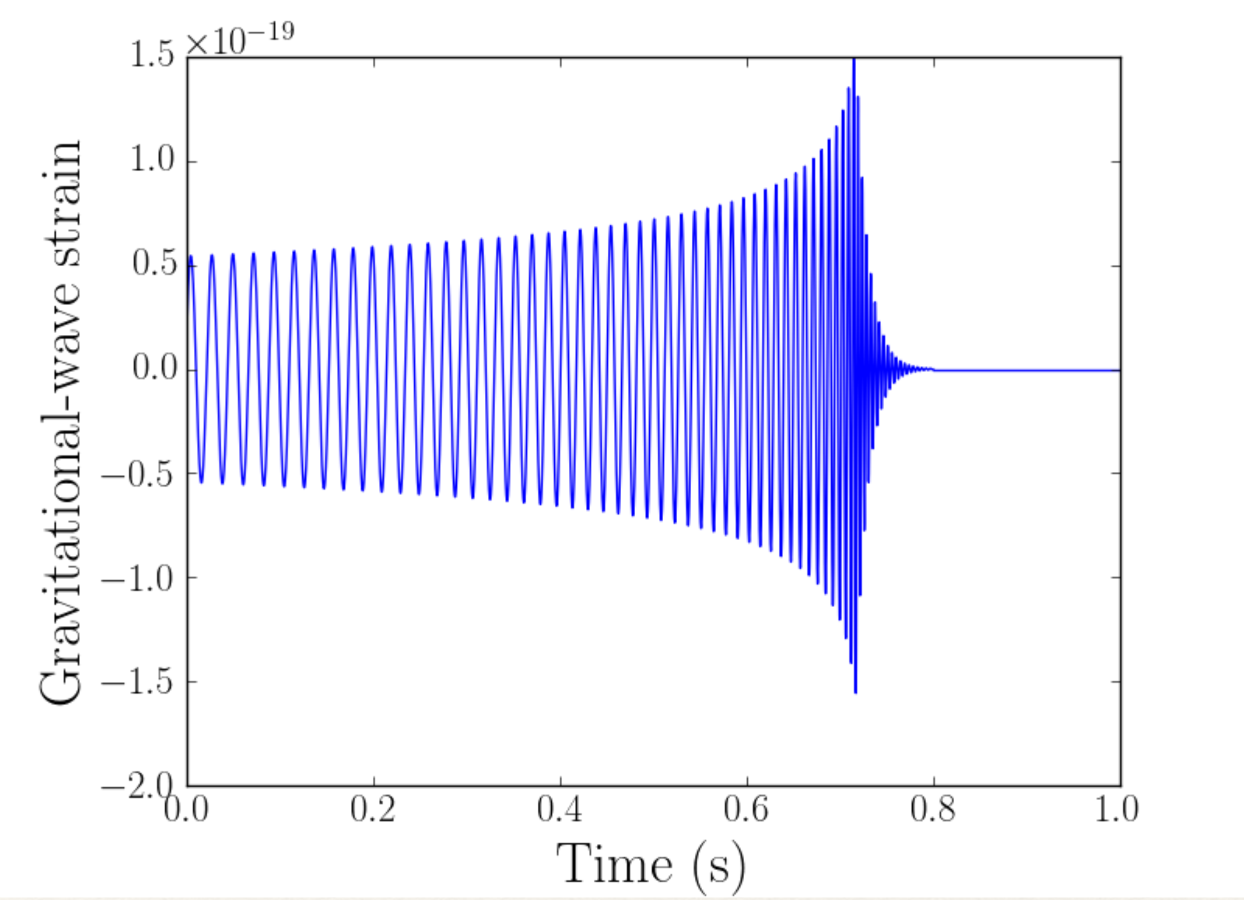


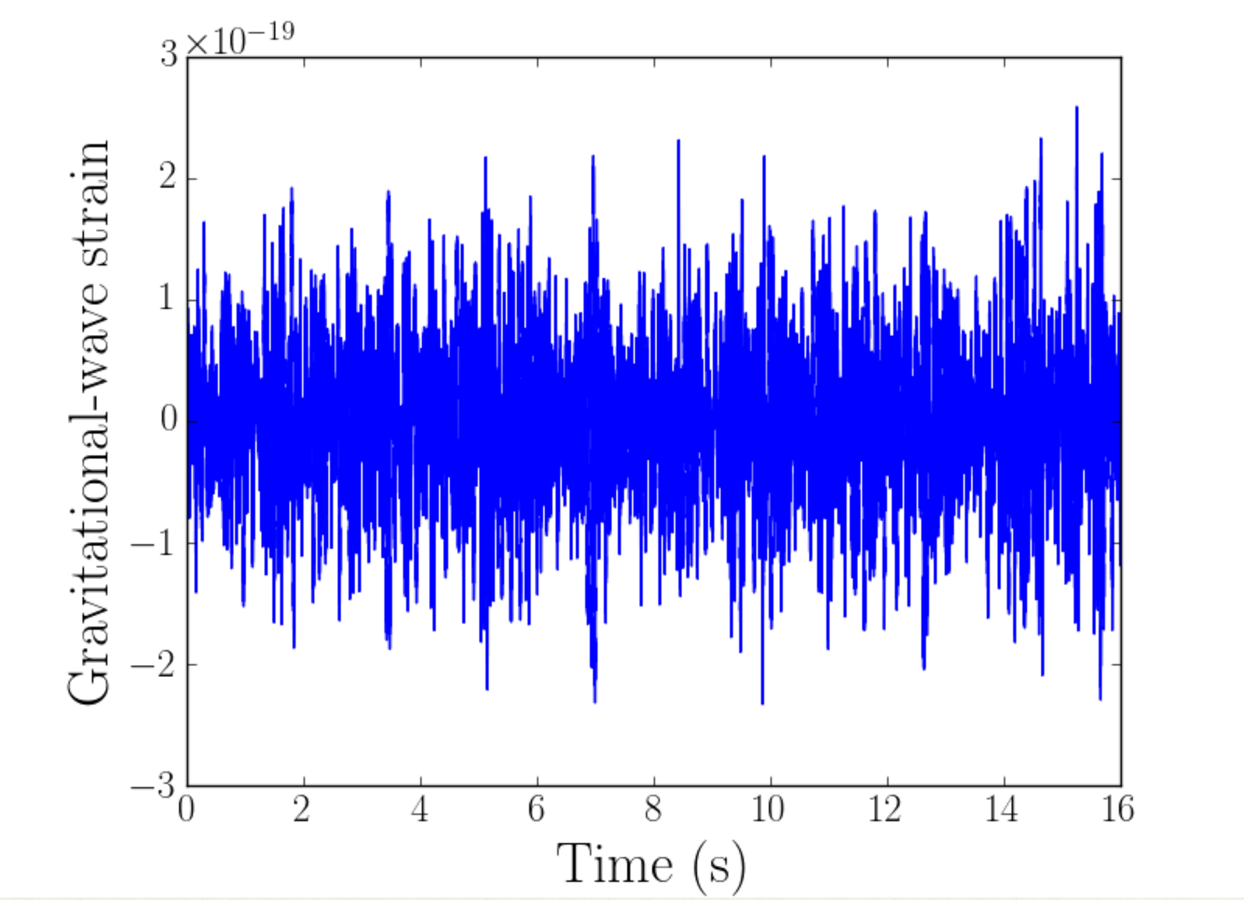
Short and known: Collisions of Compact Objects

Detection problem

We know what we're looking for

But signals will be buried in the detector noise

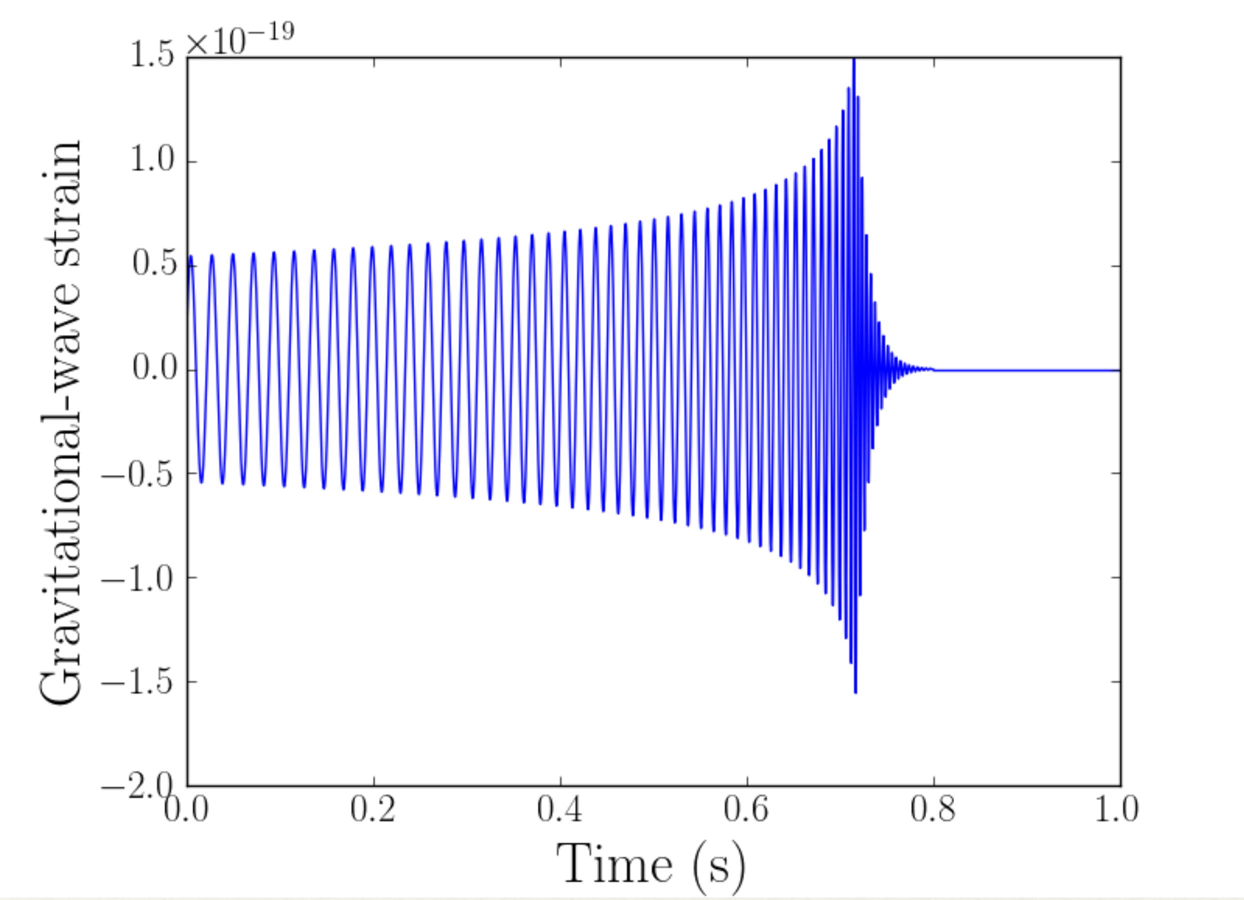




Plots and data courtesy of the GW open-science center:
www.gw-openscience.org

Detection problem

We know what we're looking for



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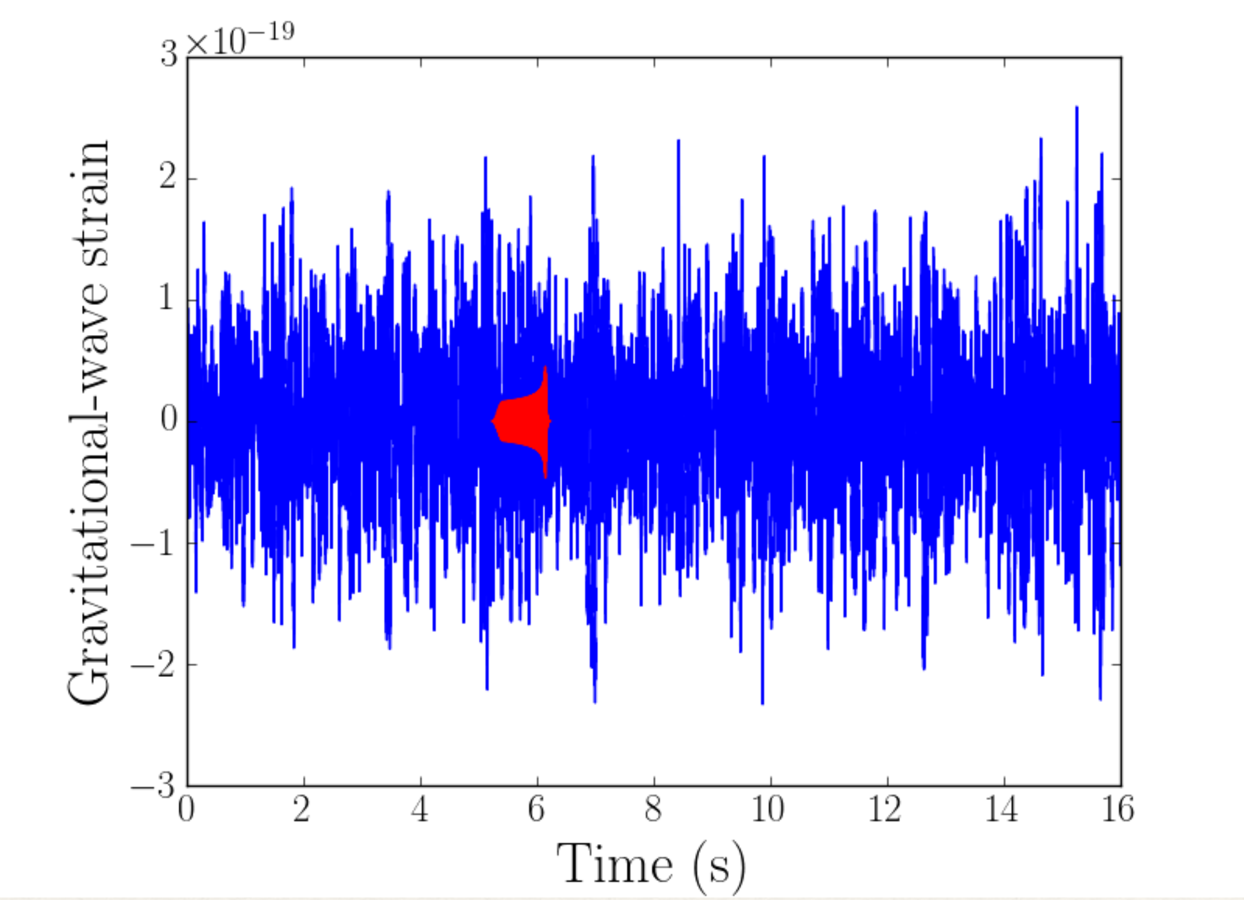

Plots and data courtesy of the LIGO open-science center: http://losc.ligo.org

Matched filtering

- Optimal if looking for a signal in stationary, Gaussian noise with known PSD

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

Wainstein and Zubakov "Extraction of signals from noise", 1962
Allen et al. Phys.Rev. D85 (2012) 122006
Babak, … ,IH, et al. Phys.Rev. D87 (2013) 024033

Matched filtering

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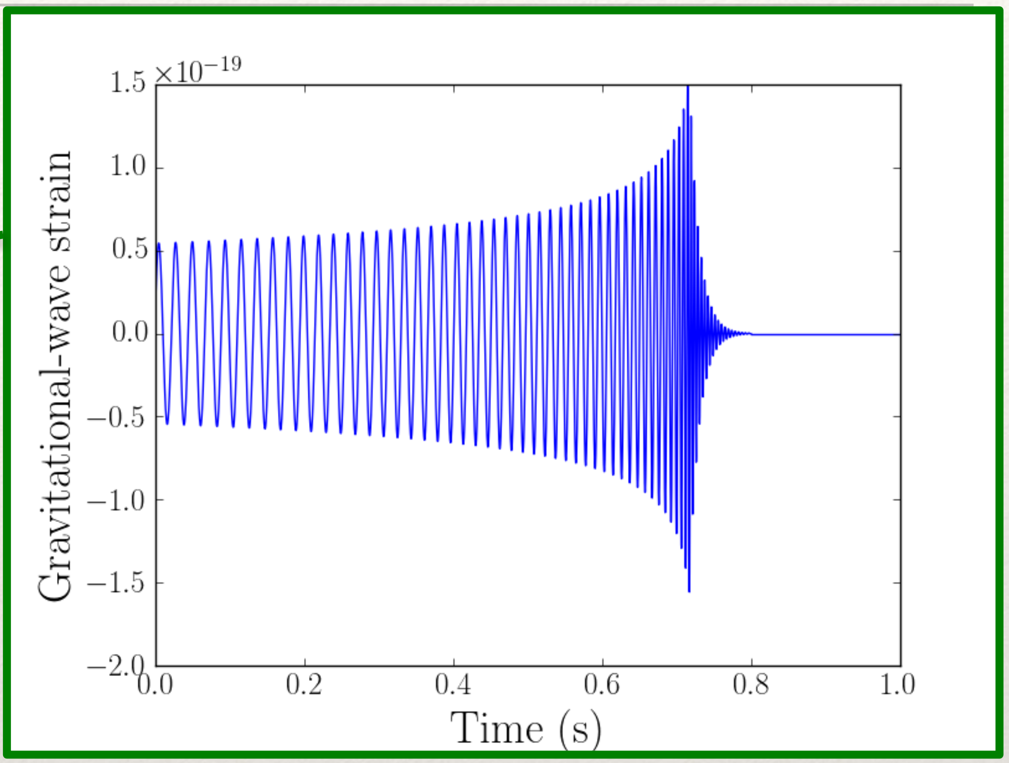
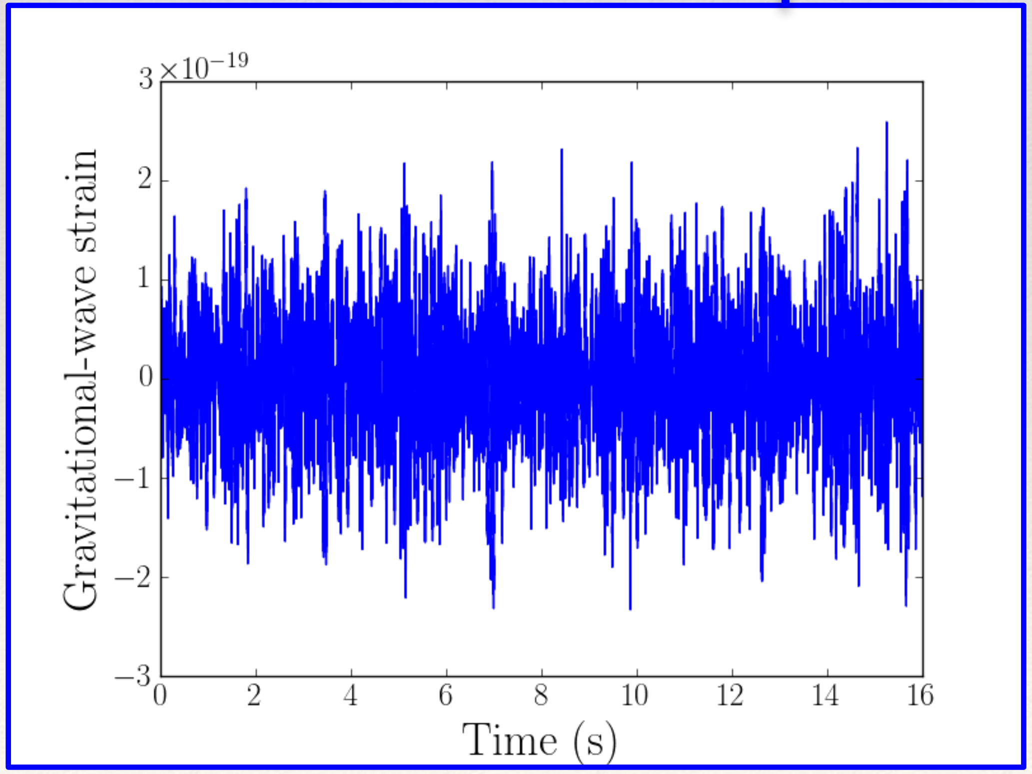
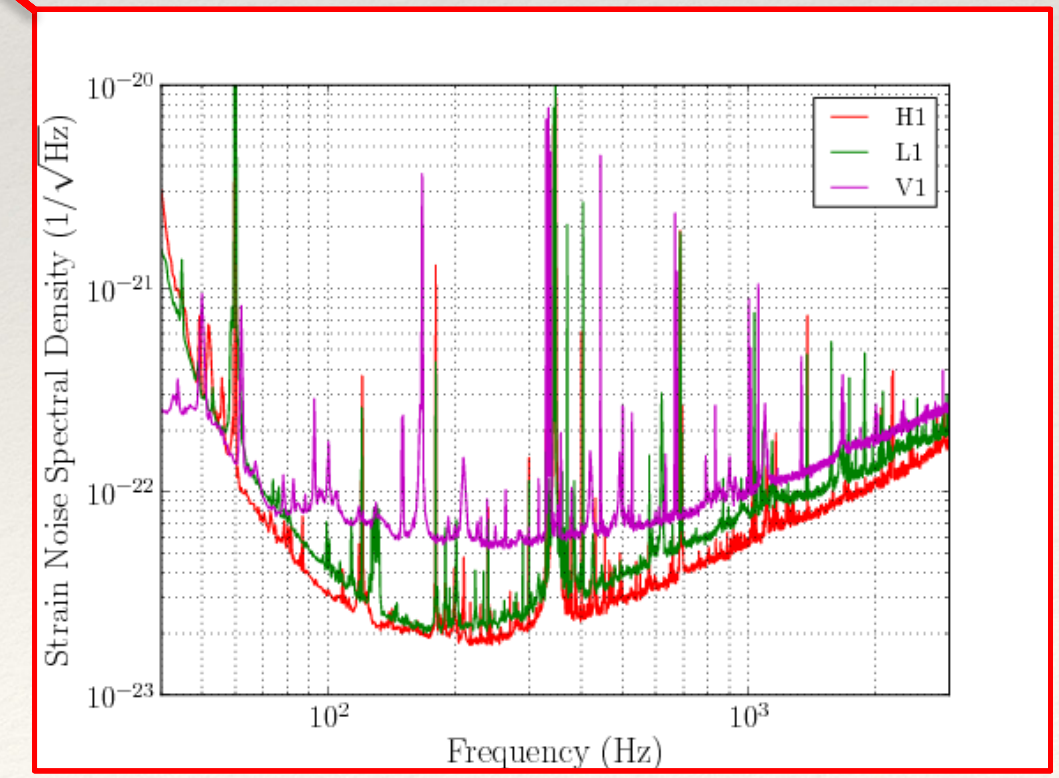
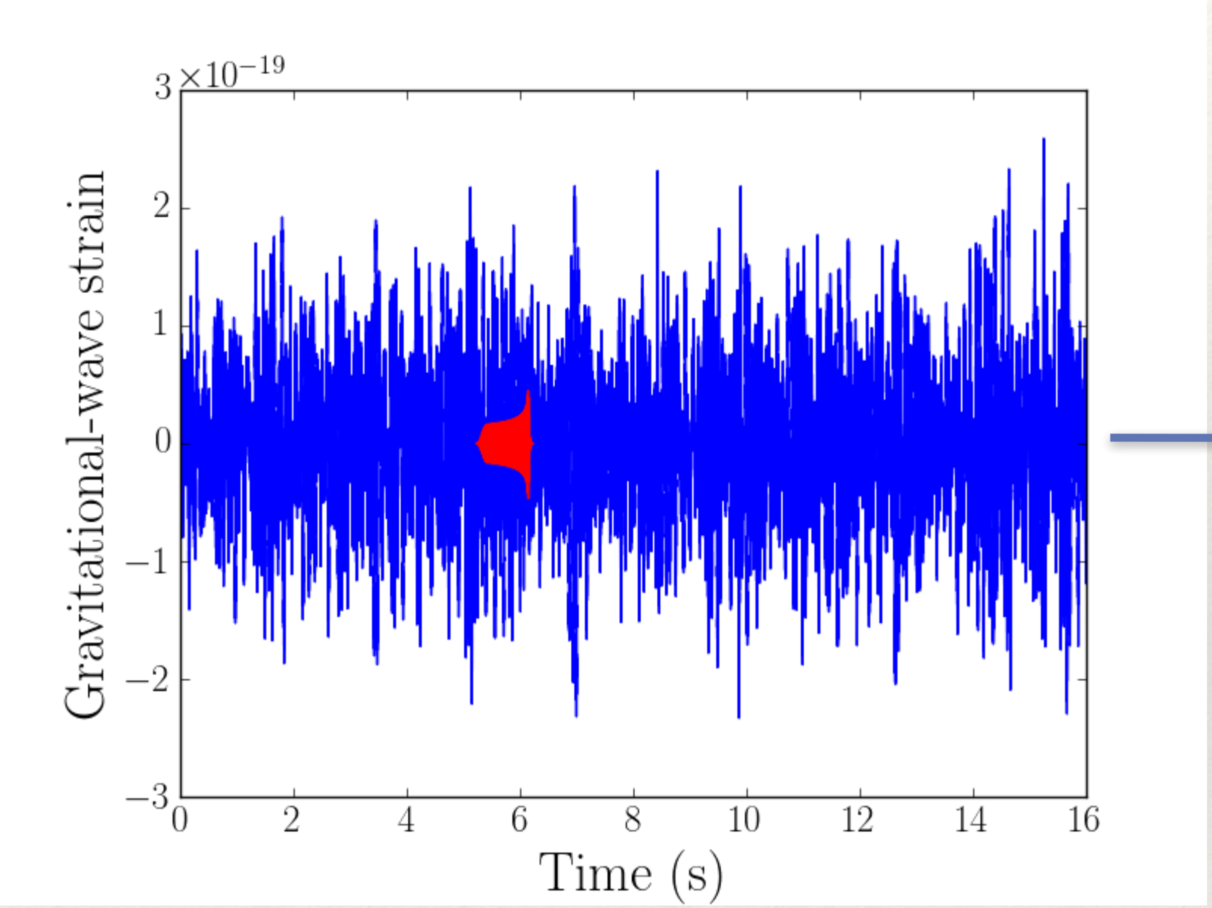


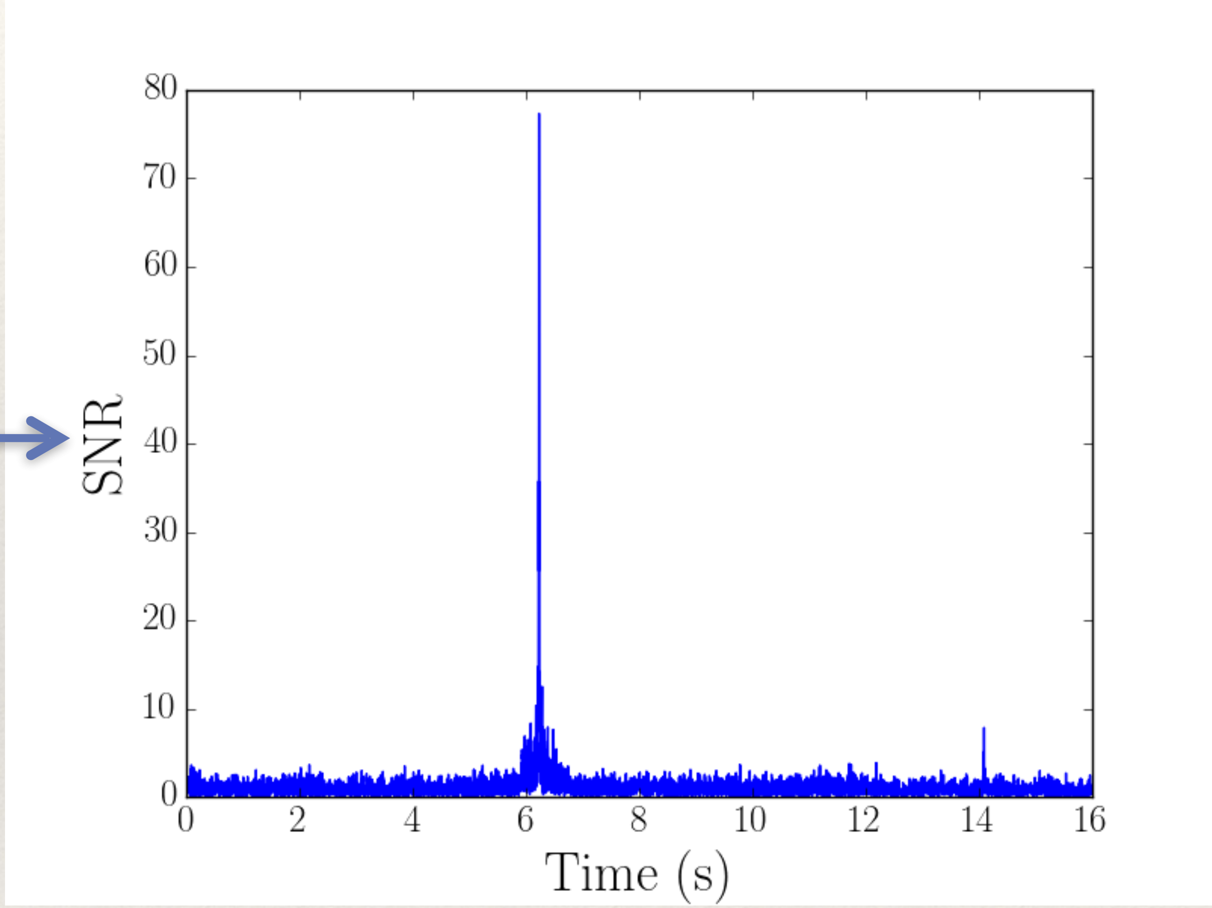




Matched filtering



$$s(t)$$



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

Plots and data courtesy of the GW open-science center: http://www.gw-openscience.org

Dealing with a large parameter space

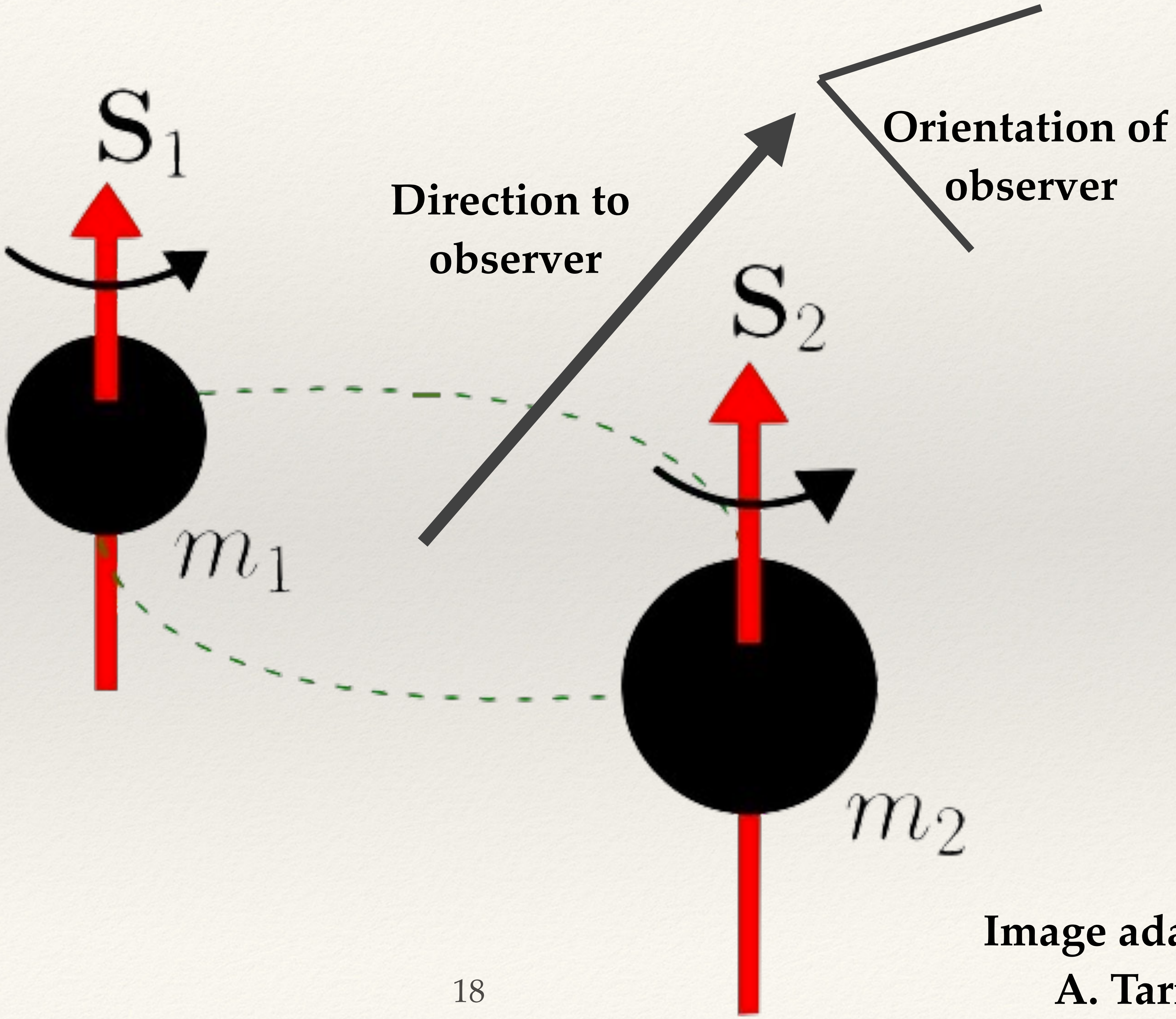


Image adapted from
A. Tarrachini

Step 1: Make a bunch of assumptions

- Assume that there is no precession of the orbital plane
- Assume that the orbital is circular (no eccentricity)
- Assume that any neutron stars are actually black holes
- Restrict to the dominant mode of the signal
    - Orientation and location parameters now enter as constant amplitude, time or phase shifts.

Step 2: Some maximisation

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

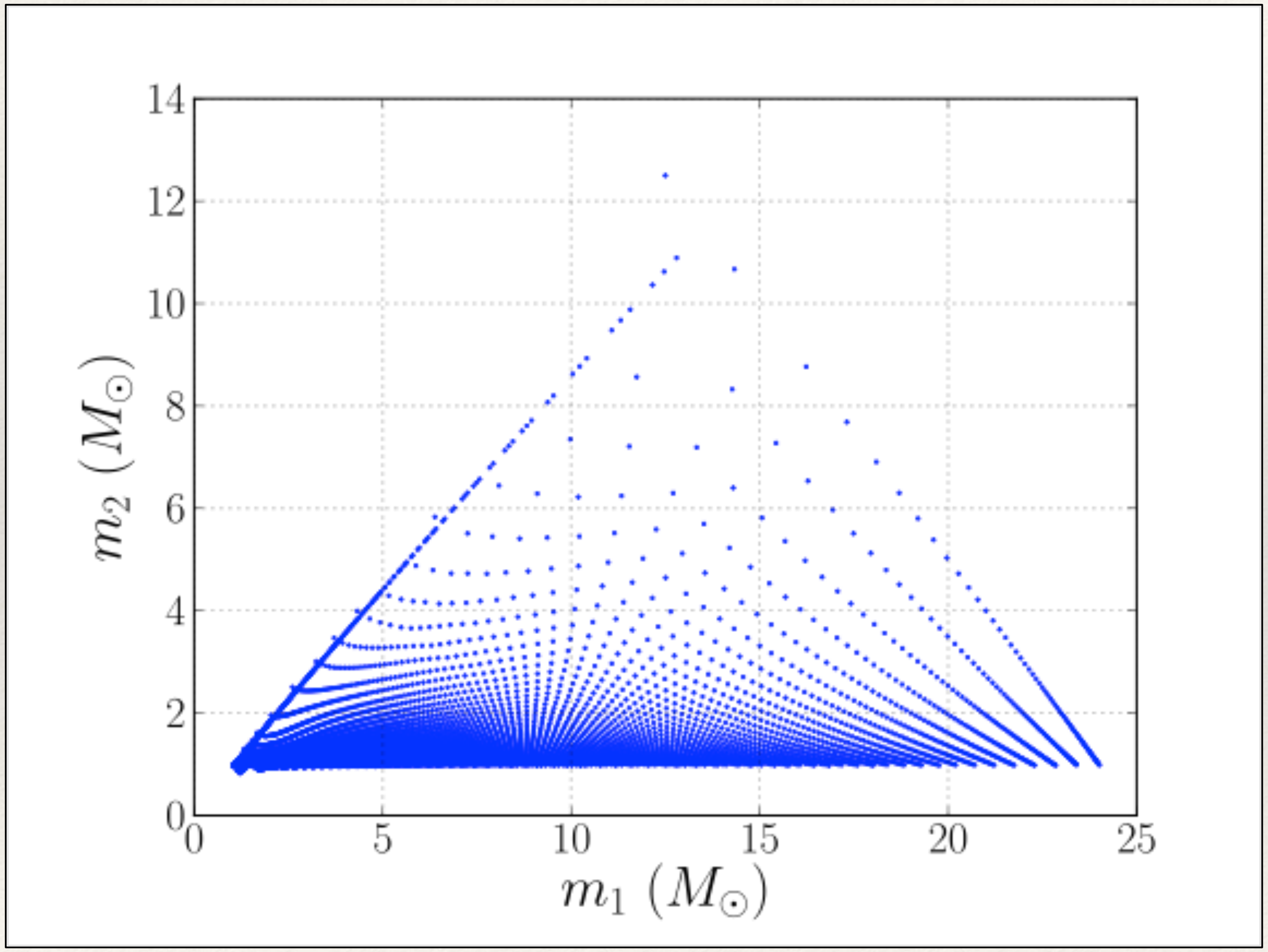
Maximise over orientation ↓ and location parameters

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

As a function of ↓ the coalescence time

$$(s|h)(t_c) = 4\left|\int_0^\infty \frac{\tilde{s}(f)\tilde{h}^\star(f)}{S_h(f)} e^{-i2\pi f t_c} df\right|$$

The “template bank”



No trick to deal with the possible values of the masses and angular momenta of the components: A large set of filter waveforms must be used, which we call a template bank.
Must cover 4 dimensions!

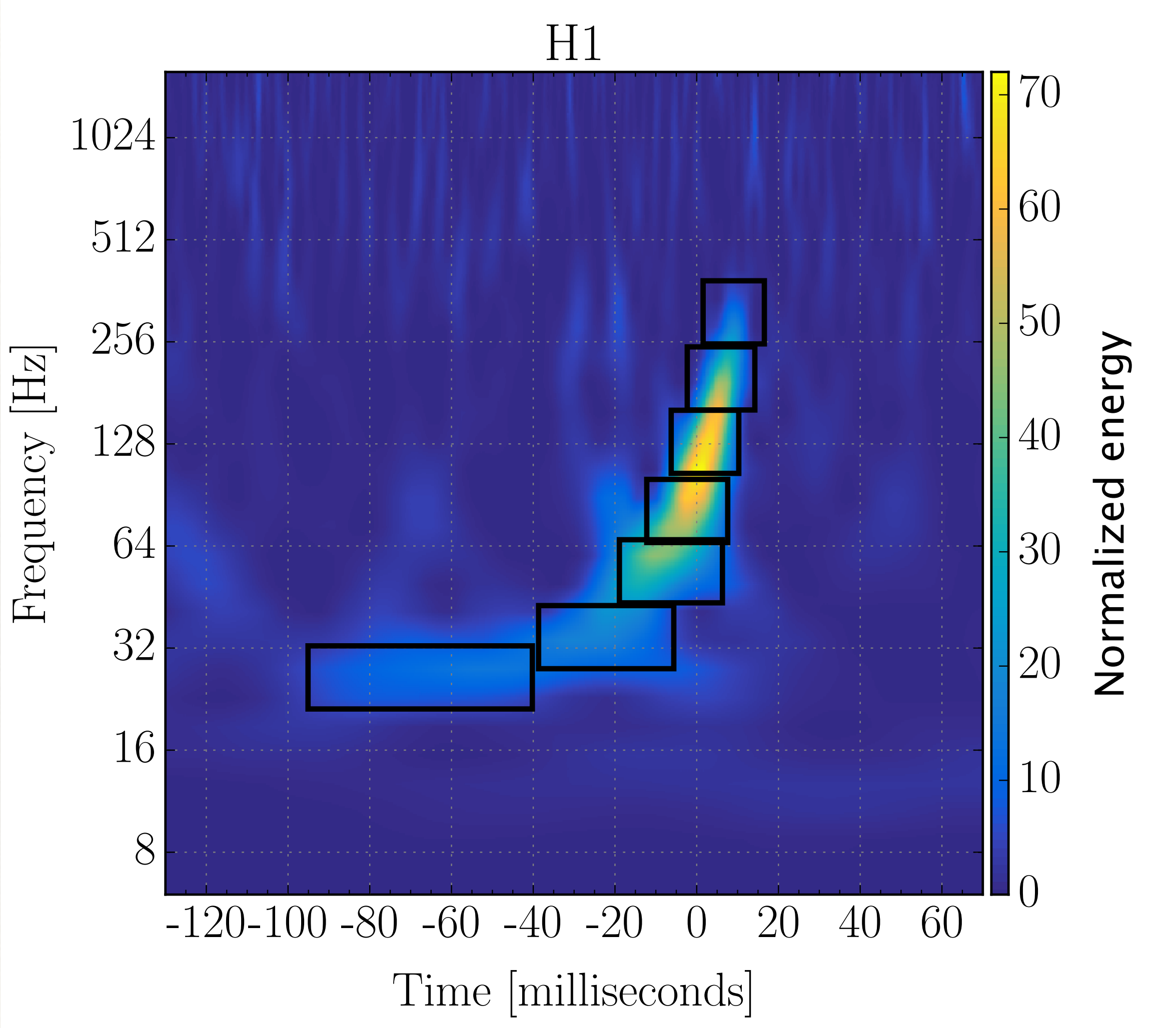
The template bank is chosen such that even for signals lying between the templates, we lose no more than 3% of the optimal matched-filter SNR.

Cokelaer, Phys.Rev. D76 (2007) 102004
IH et al, Phys.Rev. D80 (2009) 104014
IH et al, Phys.Rev. D86 (2012) 084017

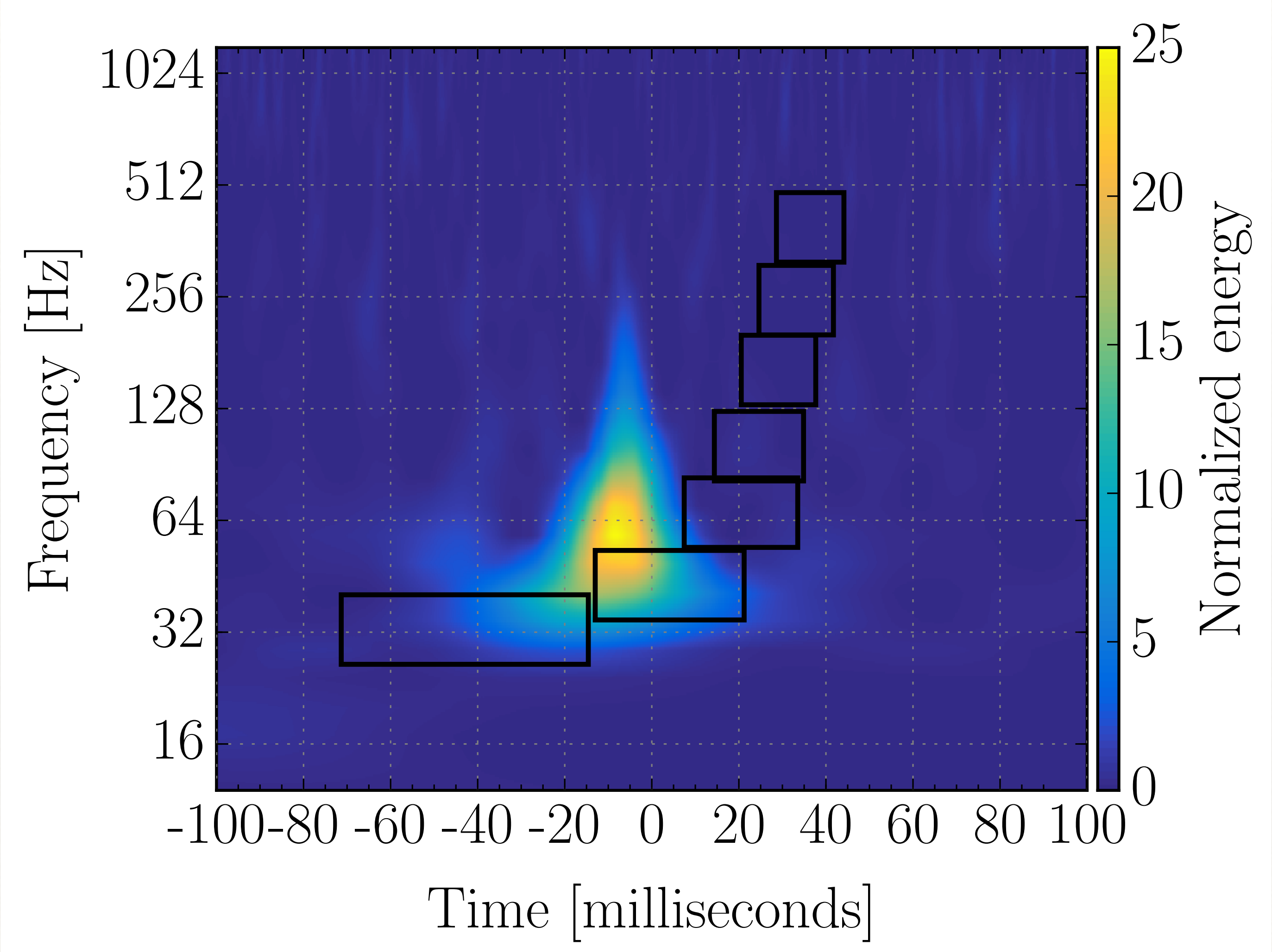
Non Gaussianities

- This method would work well if the data were Gaussian.
- Significance could be computed analytically
  - N waveform filters, but not all independent
- However data is not Gaussian, non-Gaussian artefacts also produce large values of SNR
  - Need to be able to distinguish such artefacts from real signals
  - Make use of empirically tuned ad-hoc statistics to do this

An ad-hoc chi-squared test



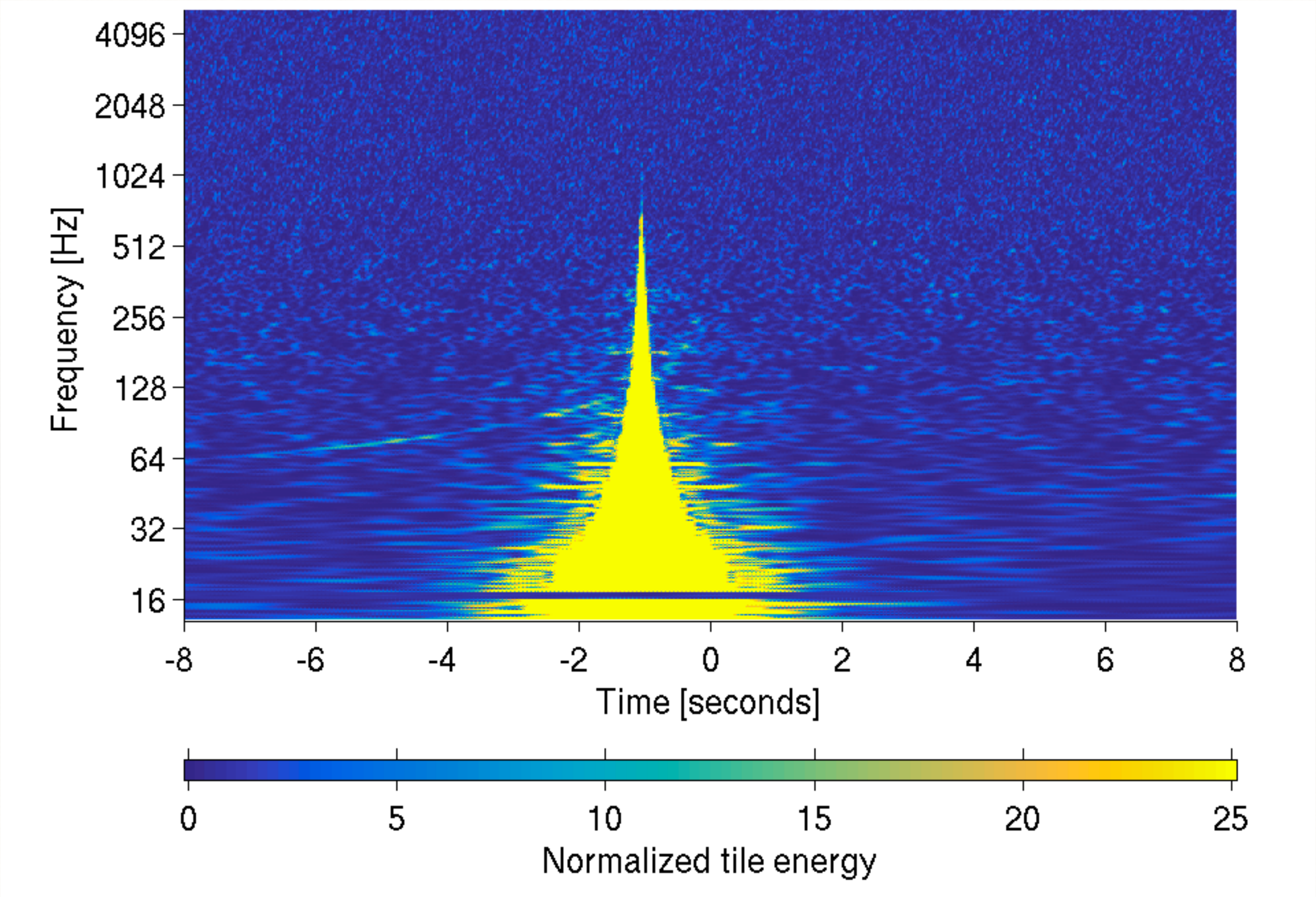
Real signal



Instrumental artifact

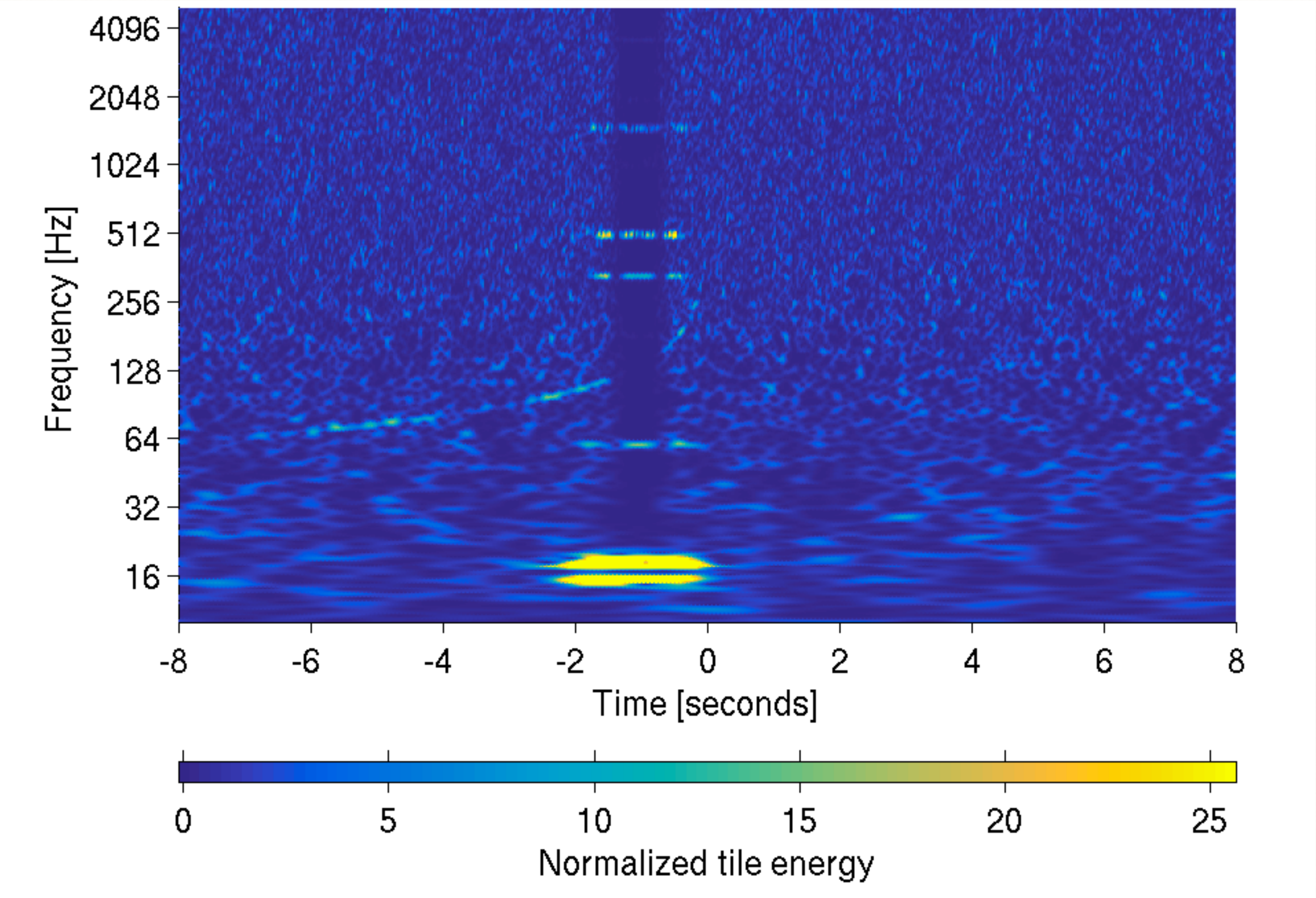
Allen PRD 71 (2005) 062001
SB, …, IH, SP et al. PRD 87 (2013) 024003

Out first binary neutron-star observation



Phys. Rev. Lett. 119, 161101

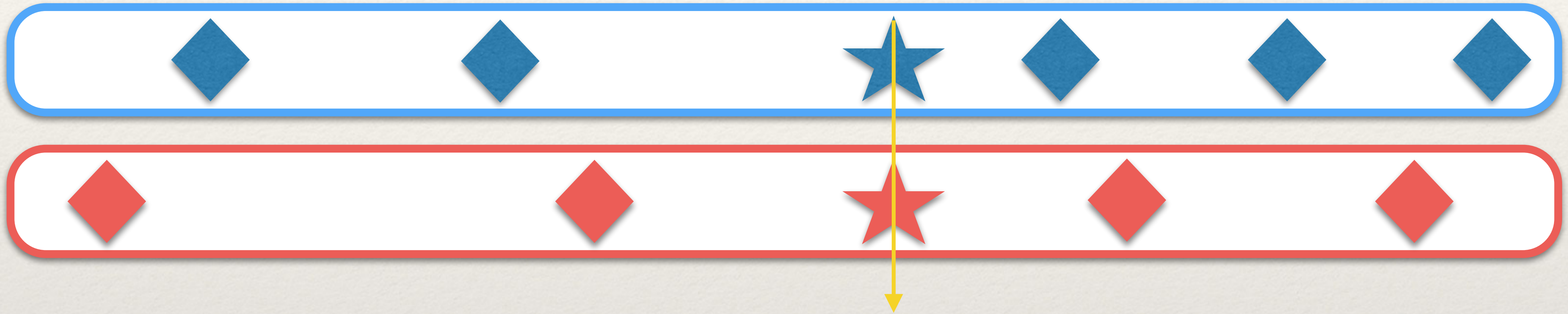
Out first binary neutron-star observation



Phys. Rev. Lett. 119, 161101

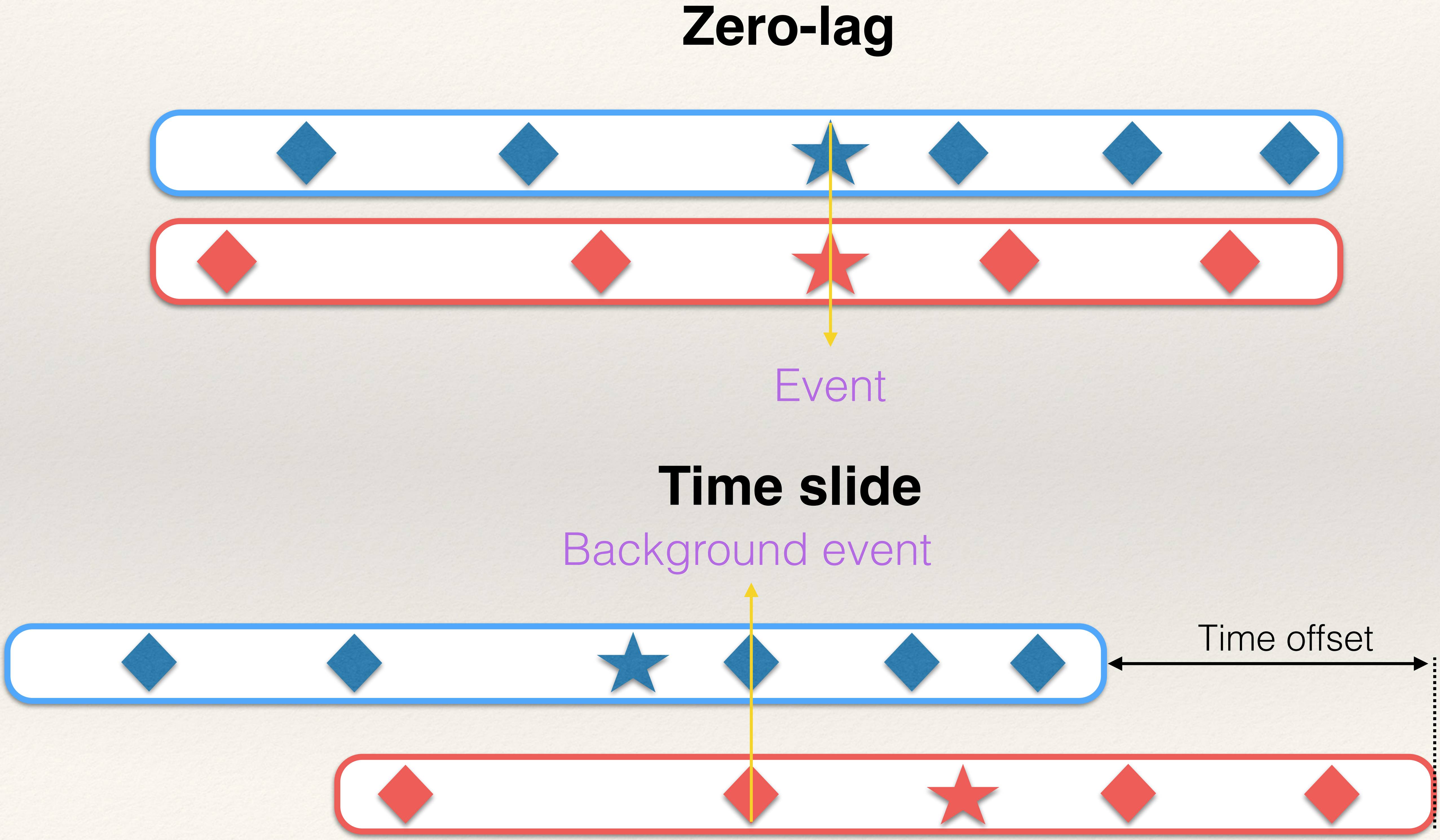
Calculating a significance (how many sigmas?)

Zero-lag



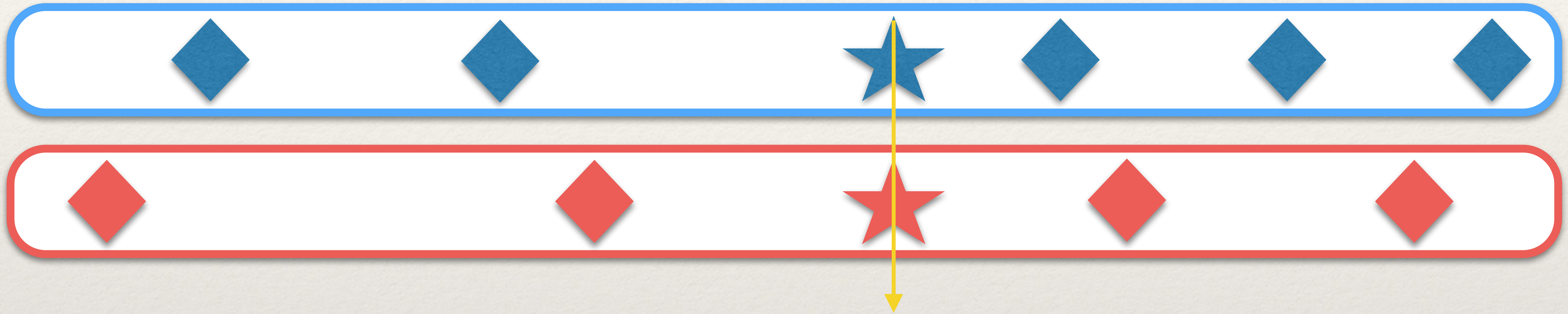
Event

Calculating a significance (how many sigmas?)



Calculating a significance (how many sigmas?)

Zero-lag

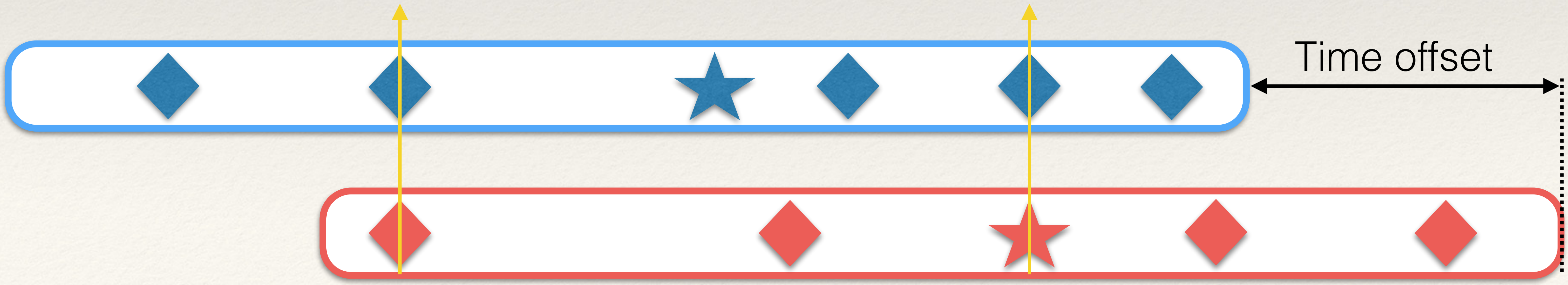


Event

Time slide

Background event

Event + background

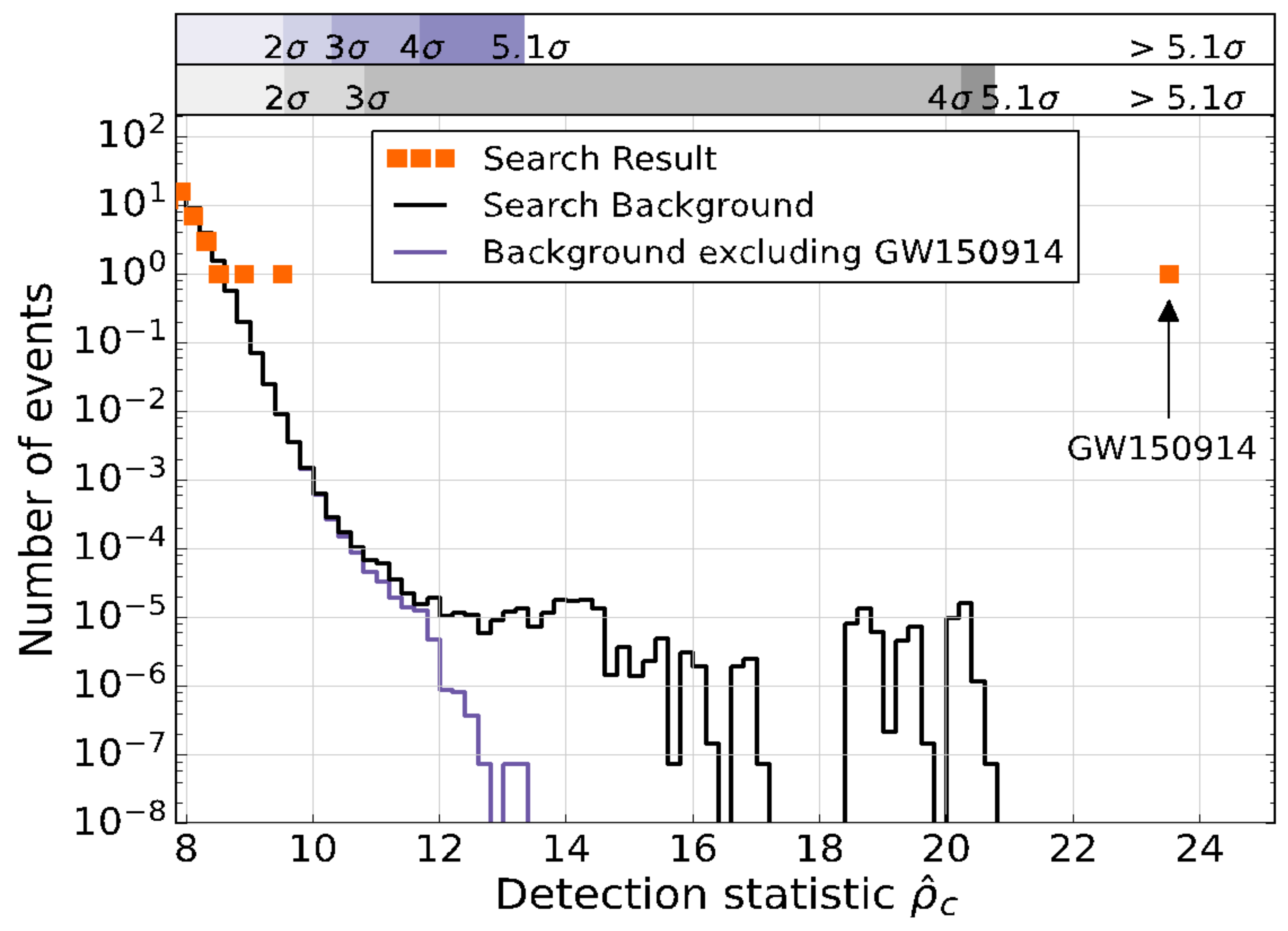


Time offset

Non-stationarity

- Basic idea to cope with non-stationarity is to keep re-measuring the power-spectral density
- Don't want signals in the data to appear in the measured power-spectral density!
- Use Welch's method every 512s
- If the noise curve changes on timescales less than 512s it will impact sensitivity, but will not affect the validity of a significance measurement.

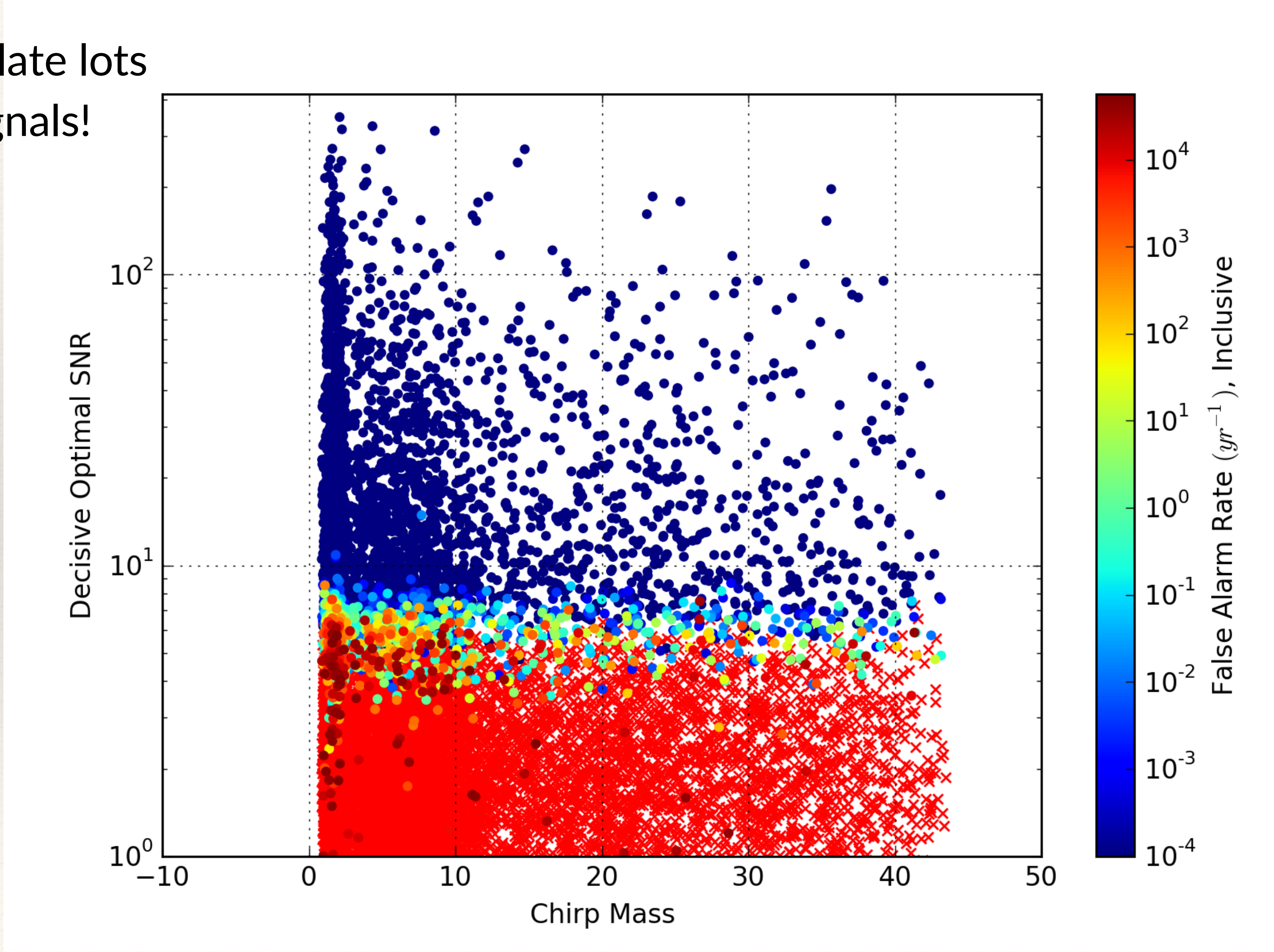
Putting it all together



Phys. Rev. Lett. 116, 061102

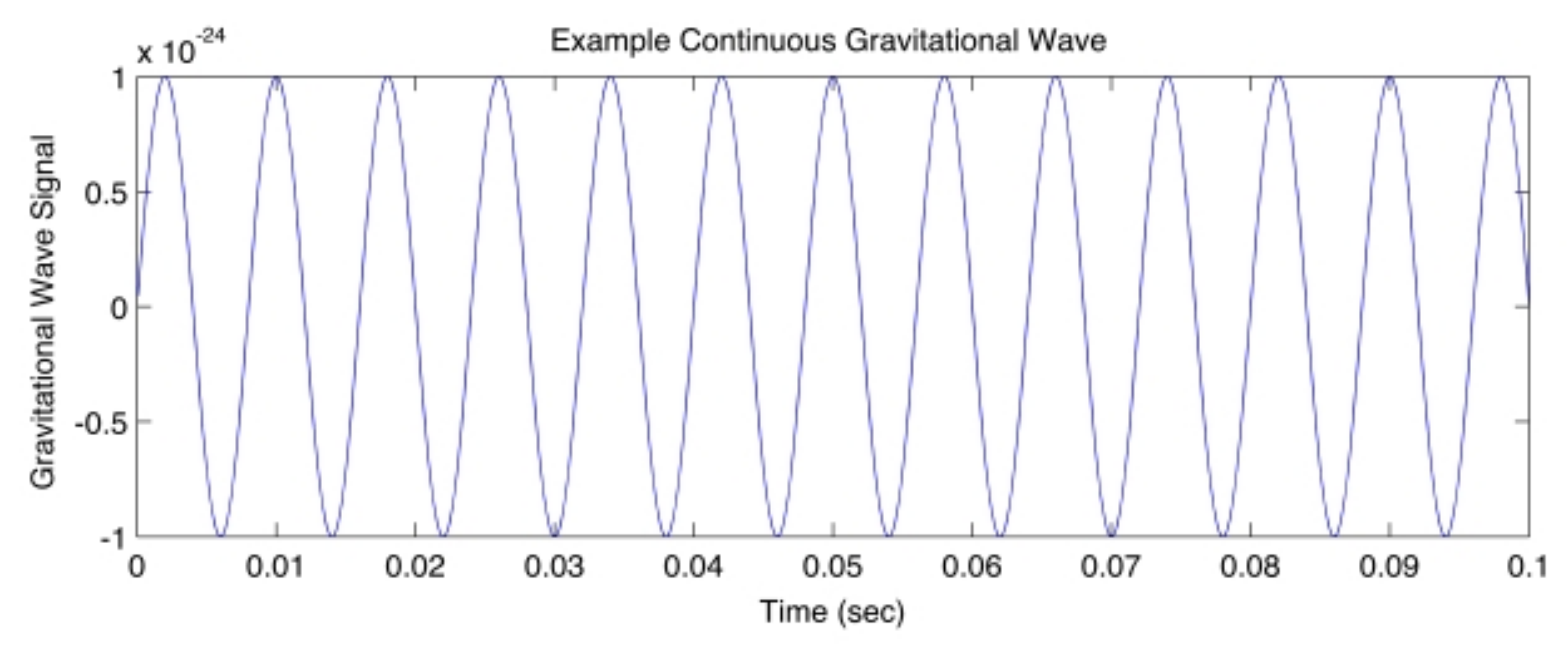
How do we validate the analysis?

Simulate lots of signals!



Long and known: Rotating neutron stars (with asymmetries)

Simple signal model



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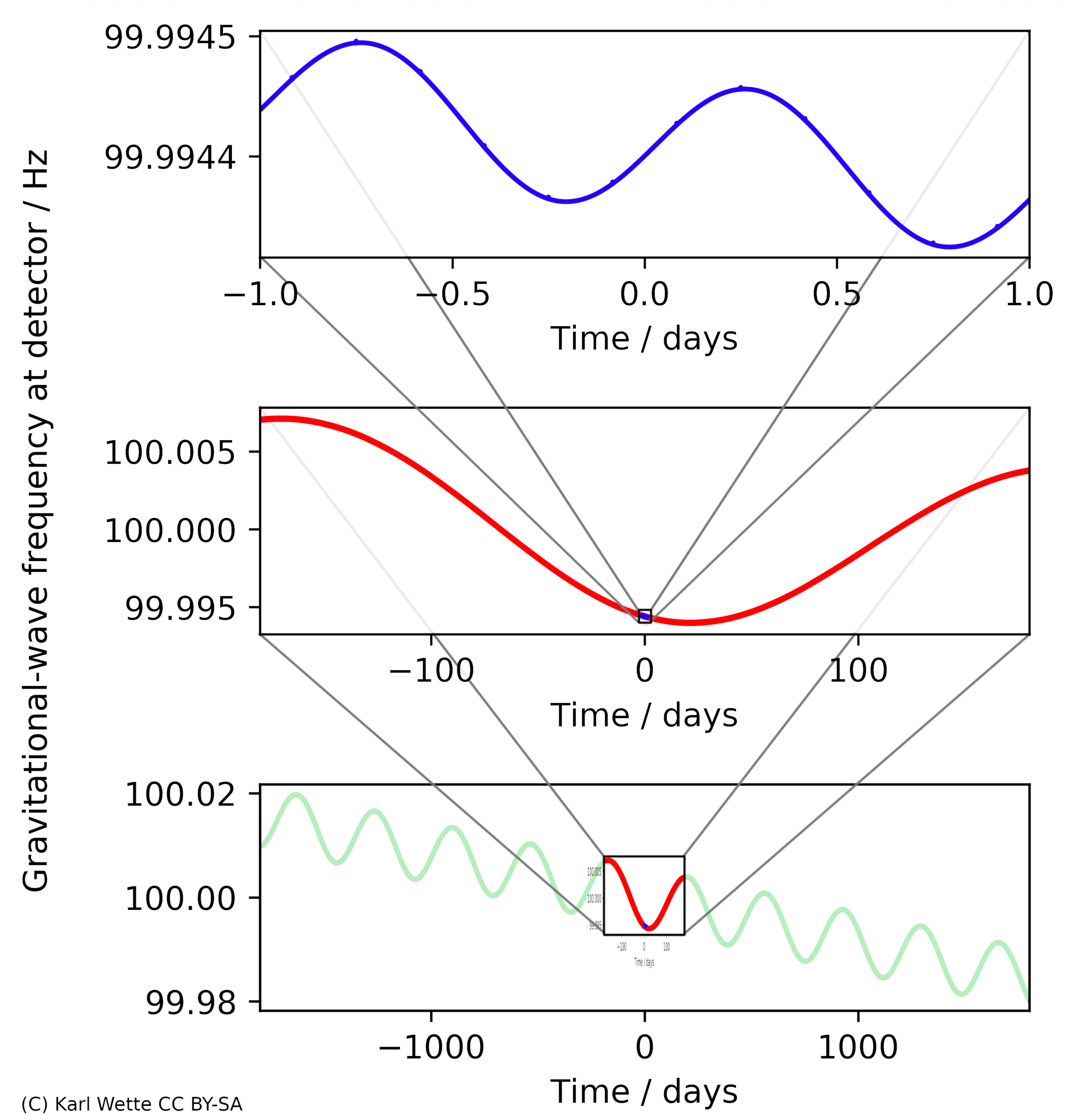
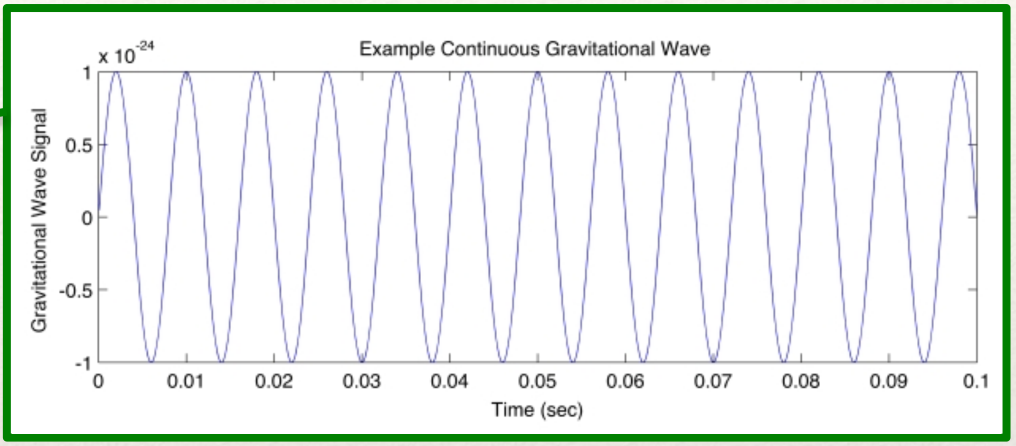
… Although perhaps not *that* simple

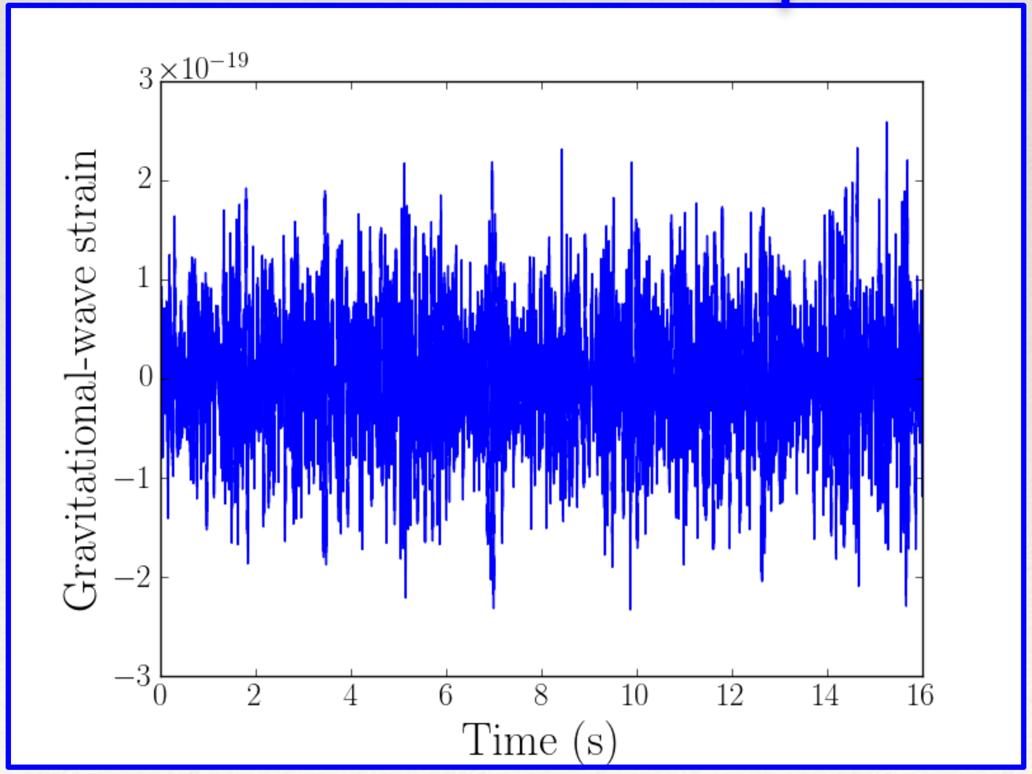


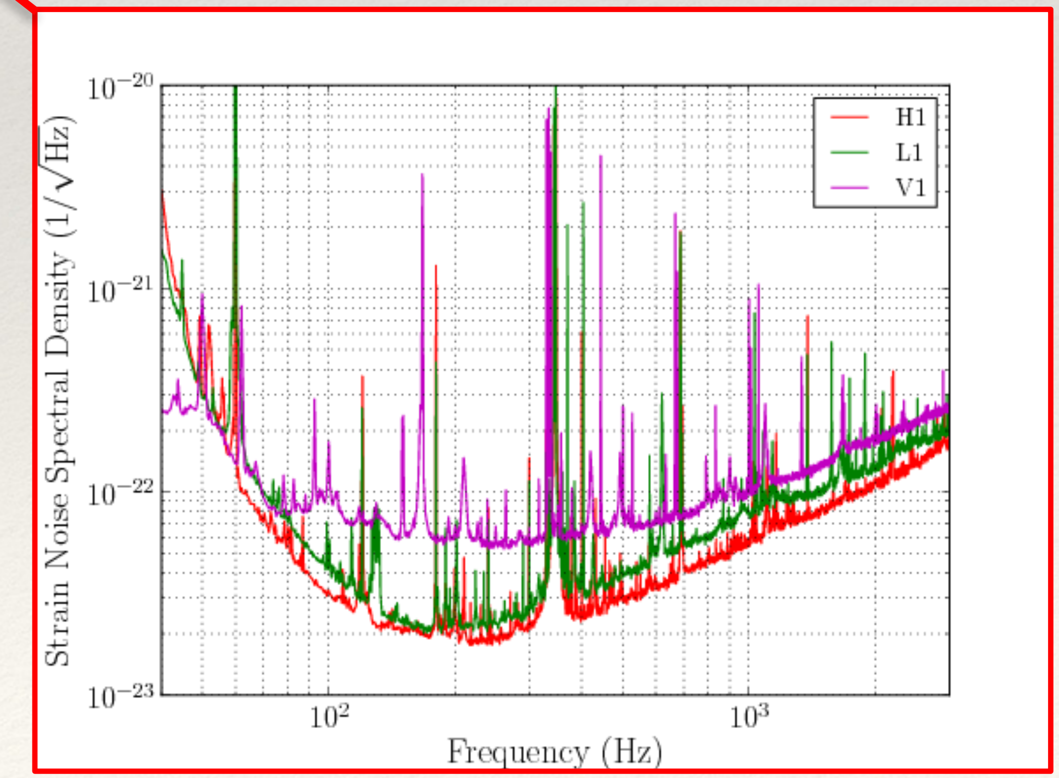
(C) Karl Wette CC BY-SA

Matched filtering

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



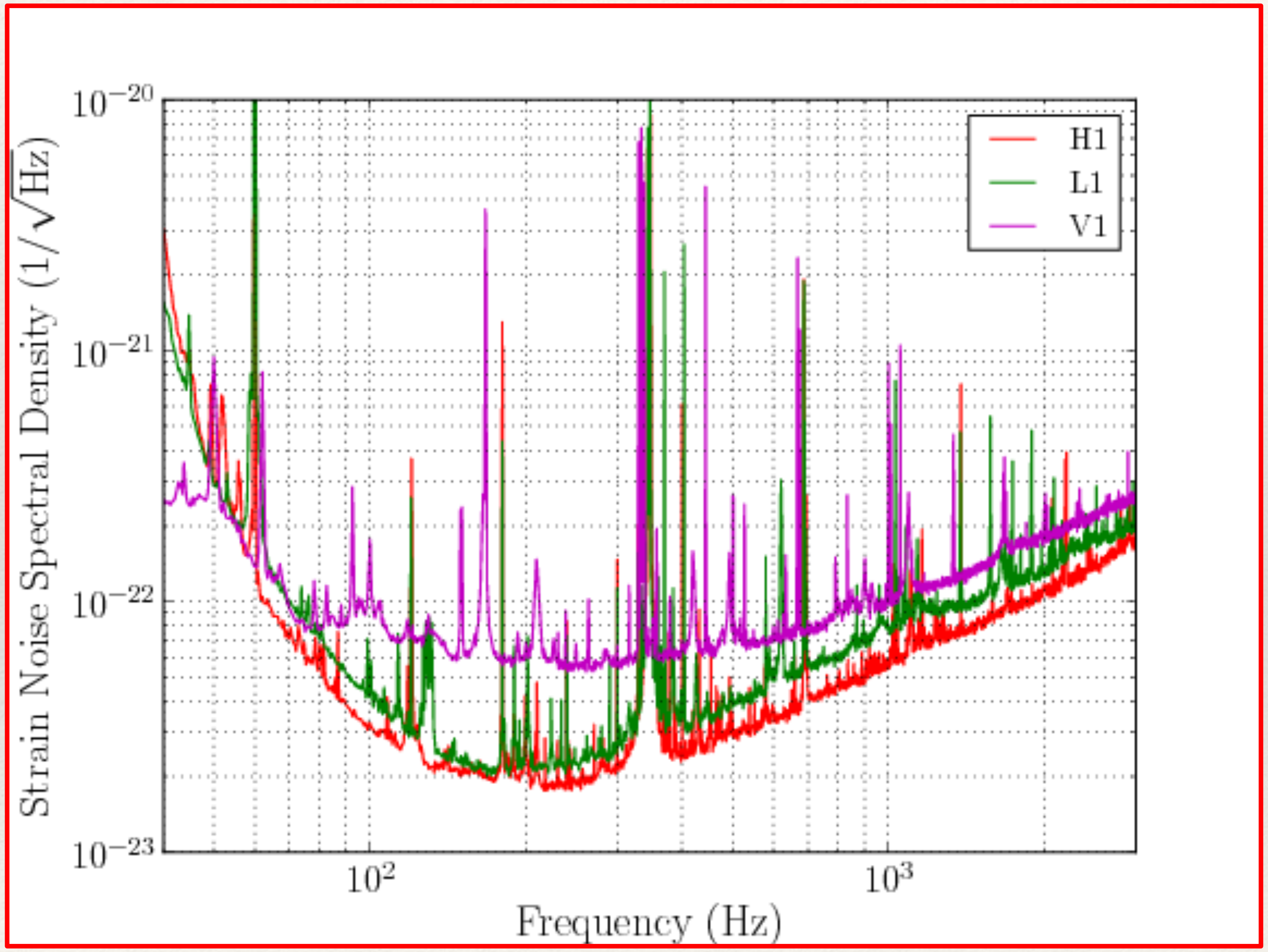




PROBLEMS: Long filter length - semi-coherent search

- These signals are always, and will always, be present.
- We must matched-filter the entire data for the signal.
- Template banks to search for any possible CW signal would contain orders of magnitude more templates than could be handled.
- Have to apply "semi-coherent" methods
  - Analyse the data in shorter blocks
  - Join the results from different blocks together
  - Does result in some reduction in sensitivity as signal phase is not continuous over block boundaries

Problem: Lines in the PSD



- Also expect quieter lines.
- Should not show daily and yearly variation

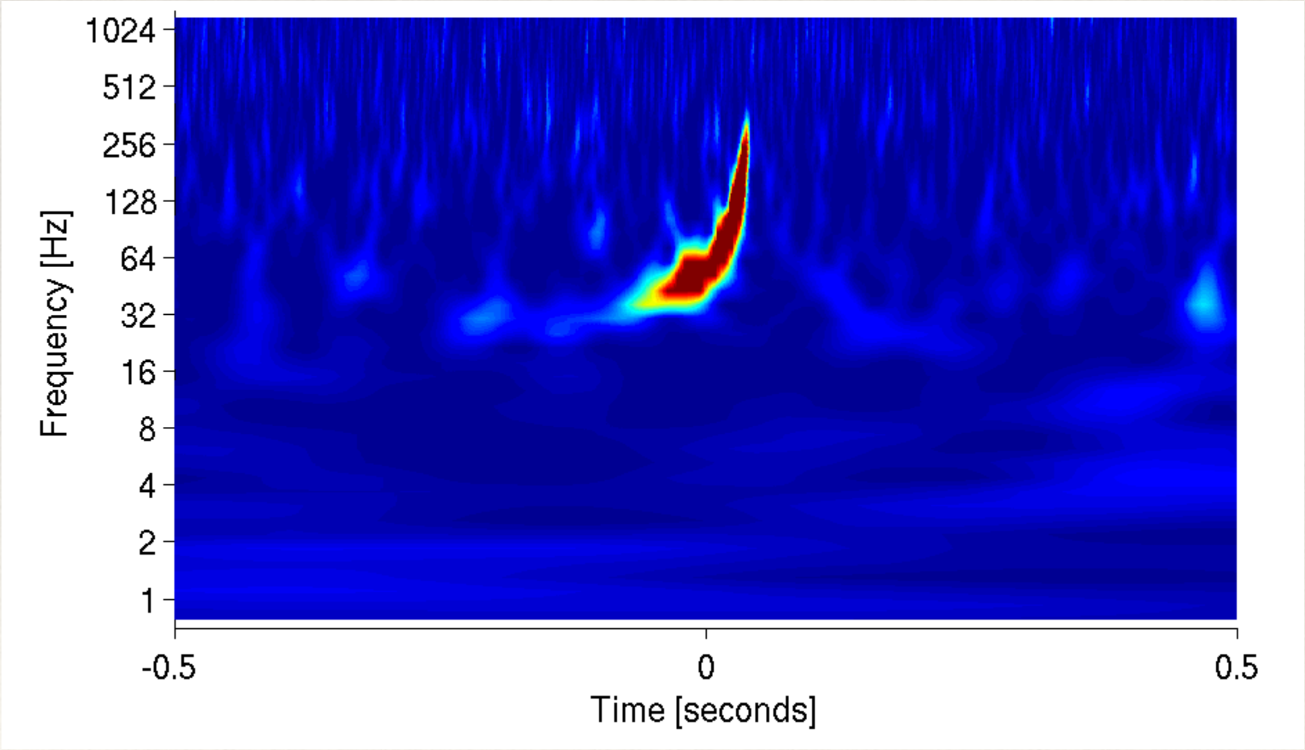
Problem: How to claim a detection?

- The time-slide technique cannot easily work here, as the signals remain in the data at all time.
    - Computational cost would also be a big problem.
- Not a problem that has been solved to date!

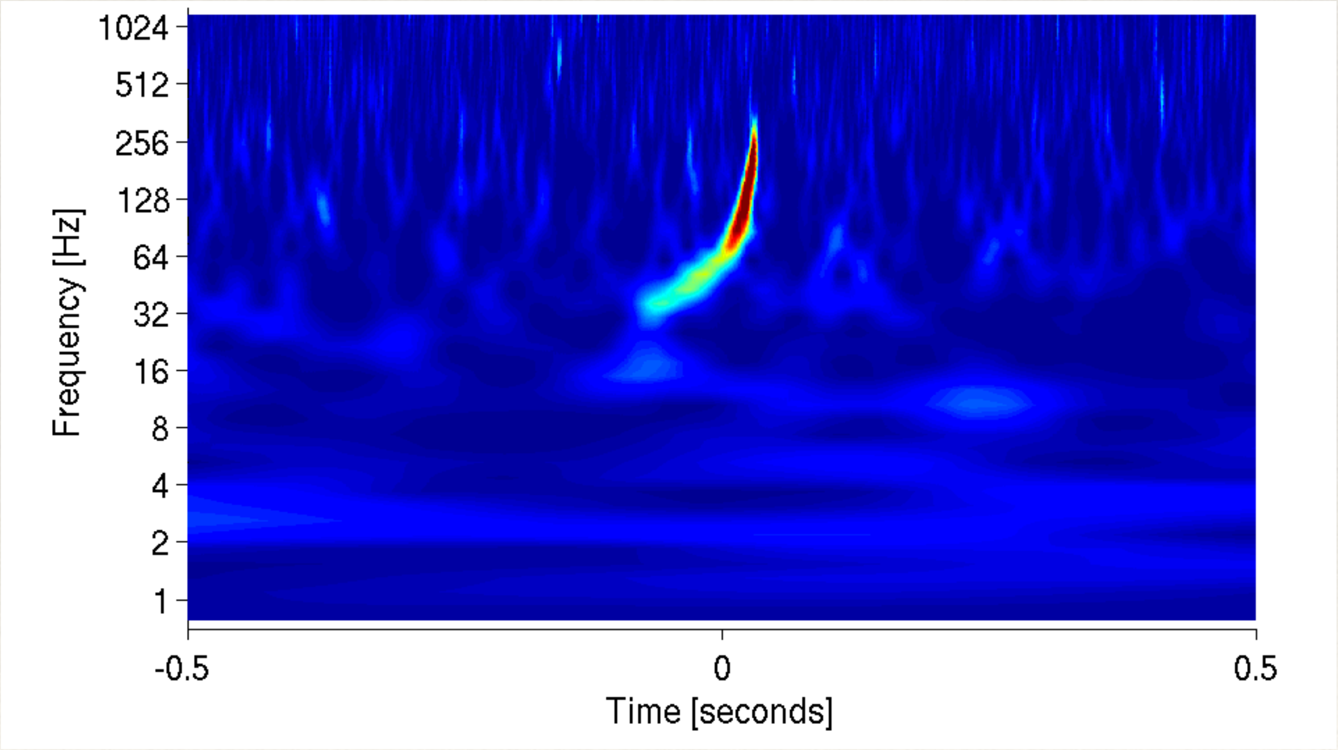
Short and unknown: "Burst" signals

Basic idea of “burst” searches

- Create q-transform spectrograms of data at all times
- Look for features standing out from the noise
- Look for consistent morphology in both observatories



Hanford observatory

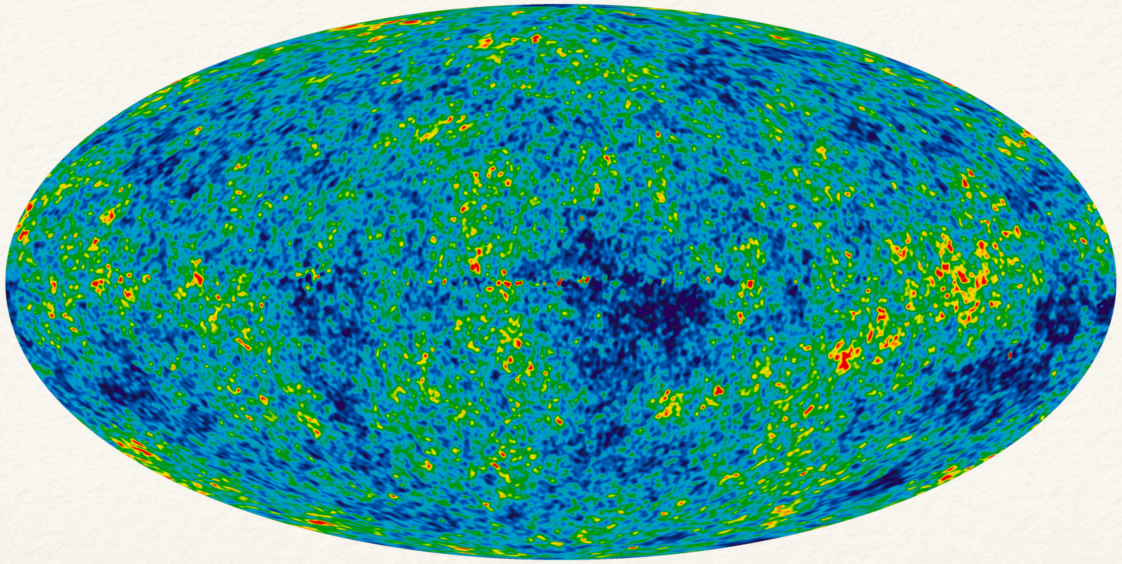


Livingston observatory

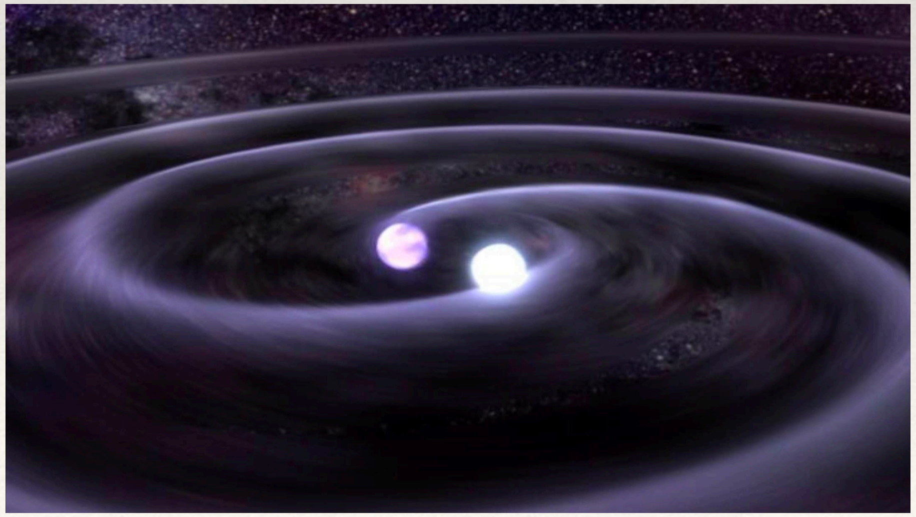
Phys. Rev. Lett. 116, 061102

Burst searches: Significance

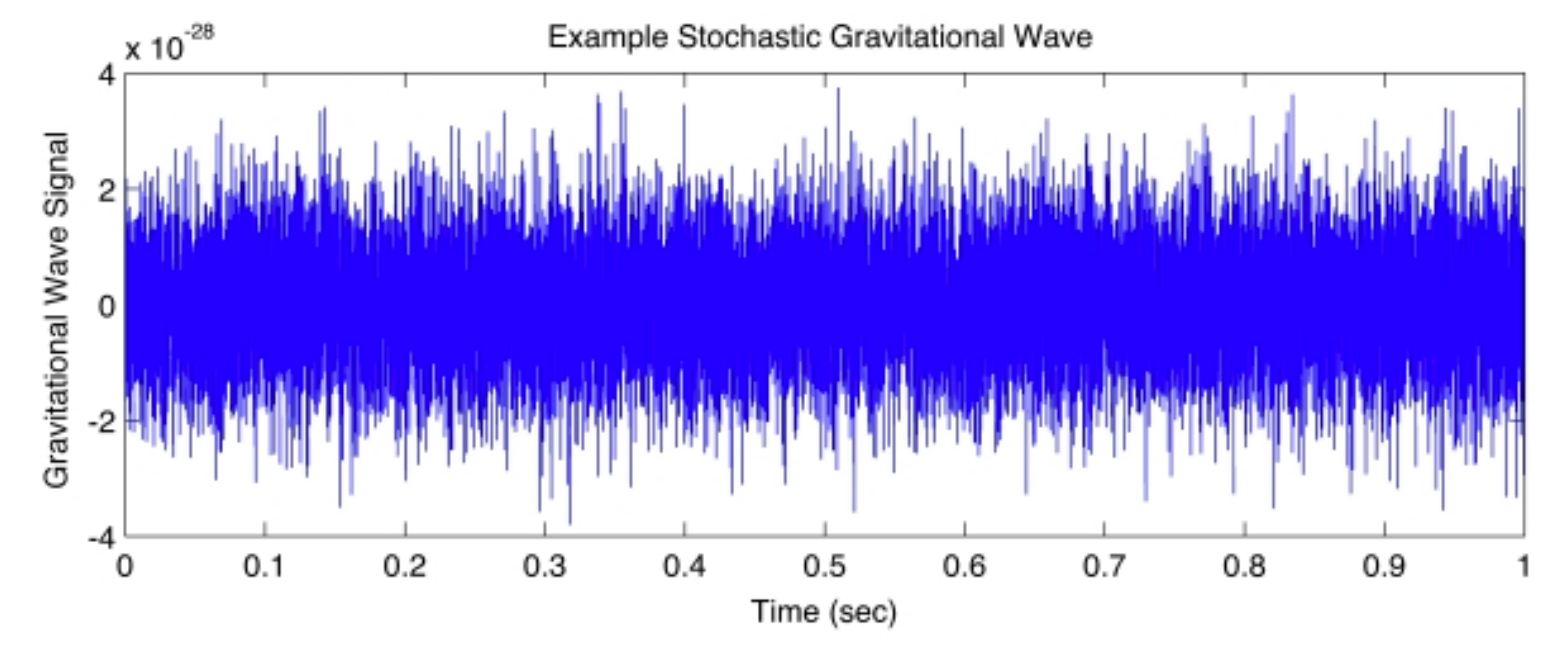
- Similar to short-and-known
- Time slides can be used to estimate significance
- Ad-hoc statistics and classifiers can be used to separate glitches from real events (although harder to tune for real events!)



Long and unknown: Stochastic signals



Just looks like noise!



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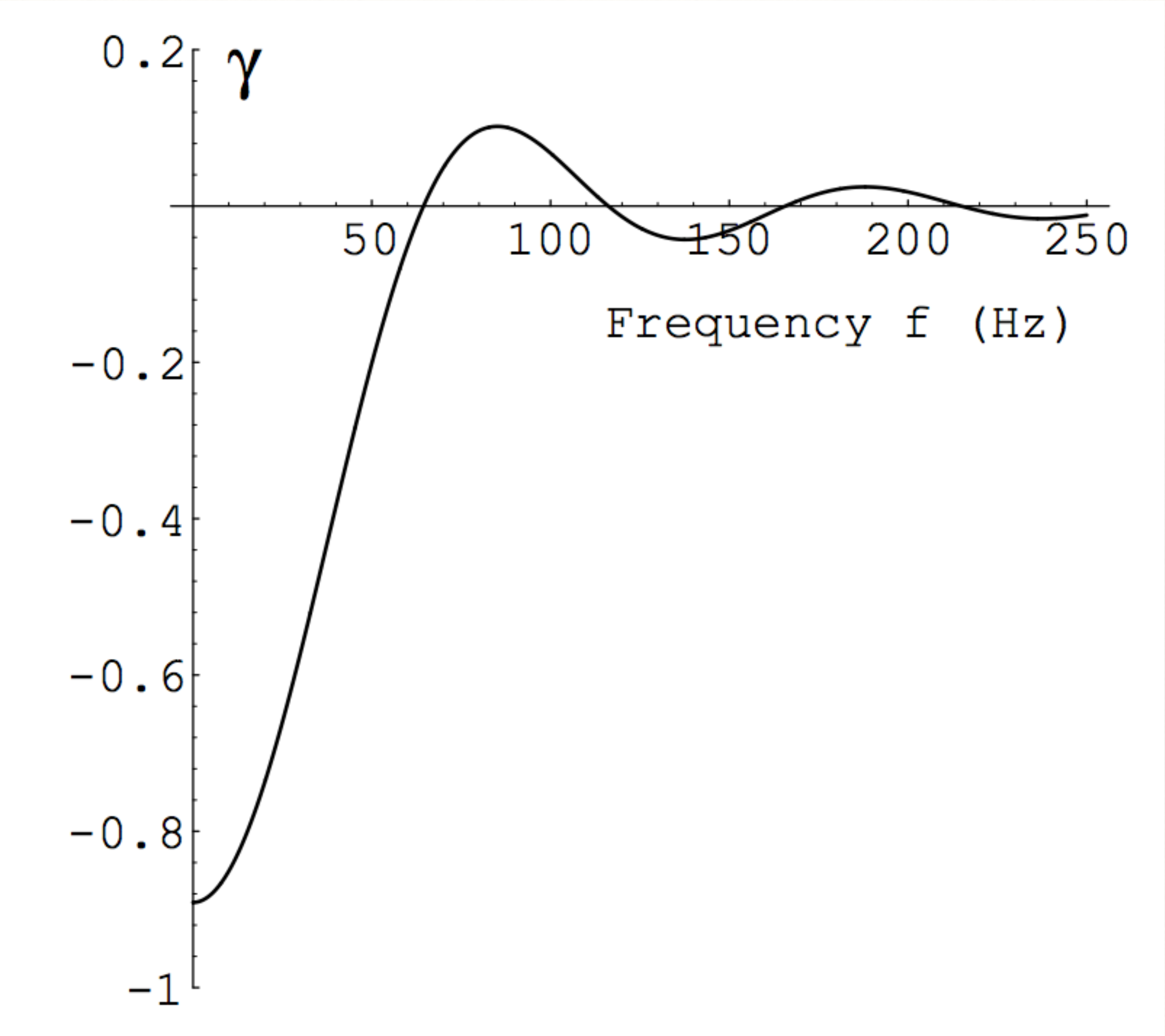
Observing stochastic signals

- Basic idea: Multiply outputs of two independent detectors, and integrate (cross-correlation).
- Better idea: Include the shape of the PSD and expected distribution of stochastic signal as a linear filter in the cross-correlation.

Response function

- Signal is coming from all parts of the sky at all times.
- Detectors must be close together! If not they will not see the same signal.
    - This is frequency dependent

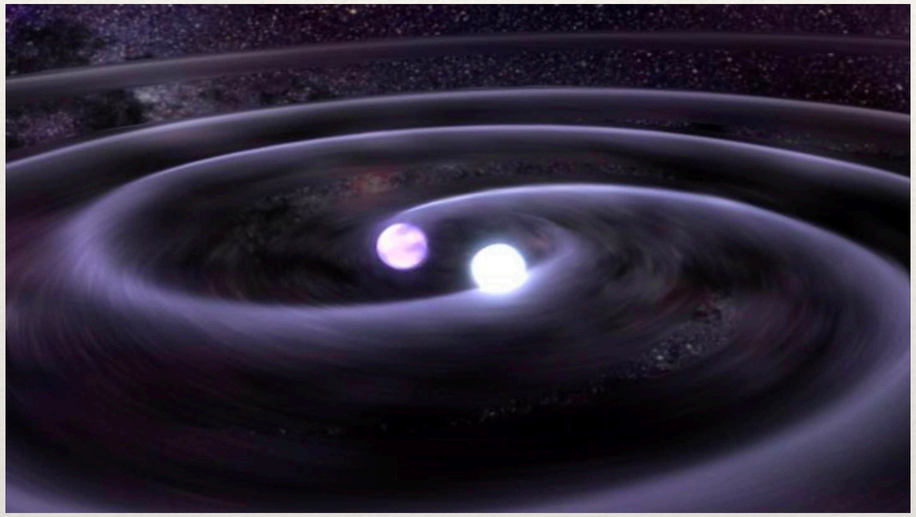
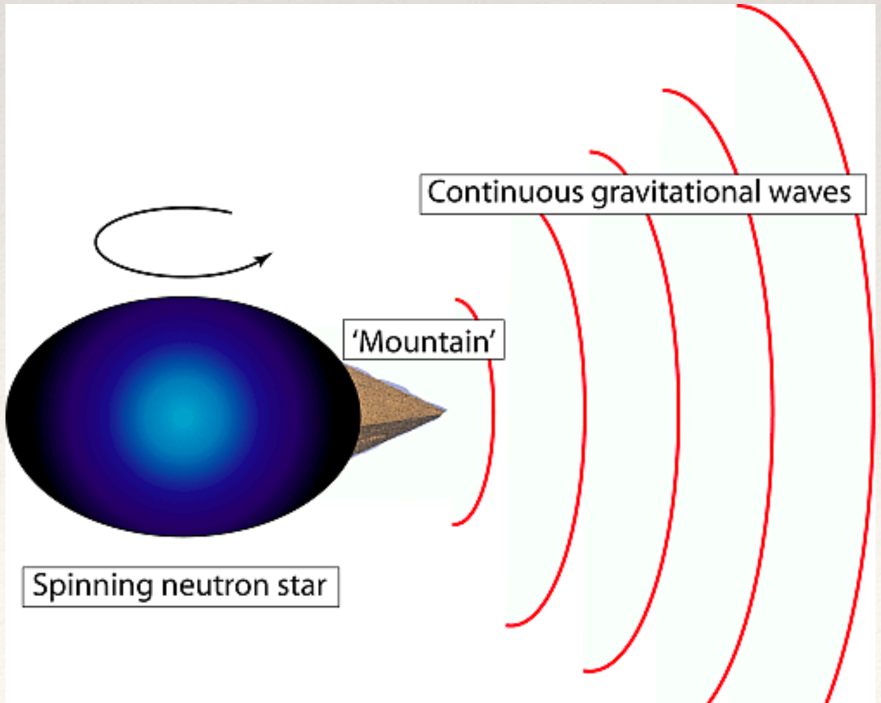
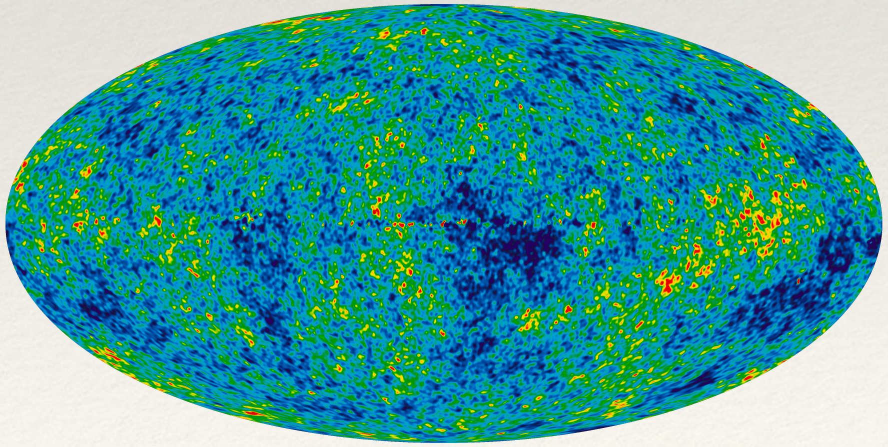


Allen, arXiv:gr-qc/9604033

Significance

- Time sliding could be used here.
- If there is *any* source of correlated noise between detectors, it could be a problem though!

Four classes of search targets

	Well modelled sources	Unmodelled sources
Short duration		
Long duration		

Some hands-on examples (CBC) and a small challenge

- https://www.gw-openscience.org/static/workshop4/program.html
- https://pycbc.org/
- A challenge: If you have designed a detector with a given PSD, at what distance could it detect an optimally oriented:
  - Neutron star binary (both components 1.35 solar mass)
  - Binary black hole (both components 20 solar mass)