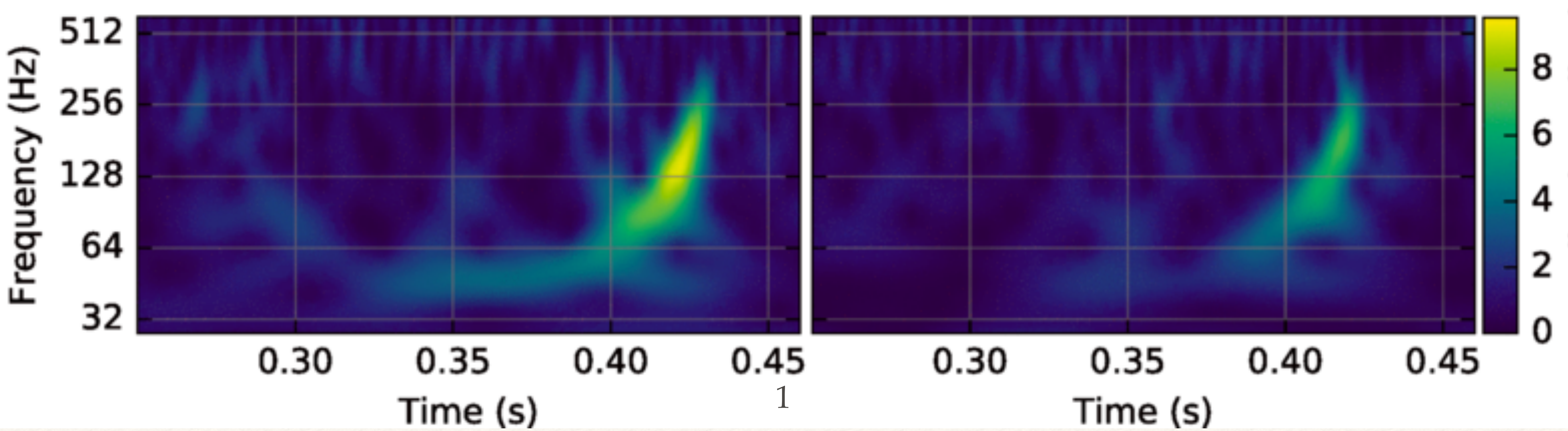
*Max Planck Institute for Gravitational Physics, Potsdam*

# Detecting colliding black holes with gravitational-wave observatories

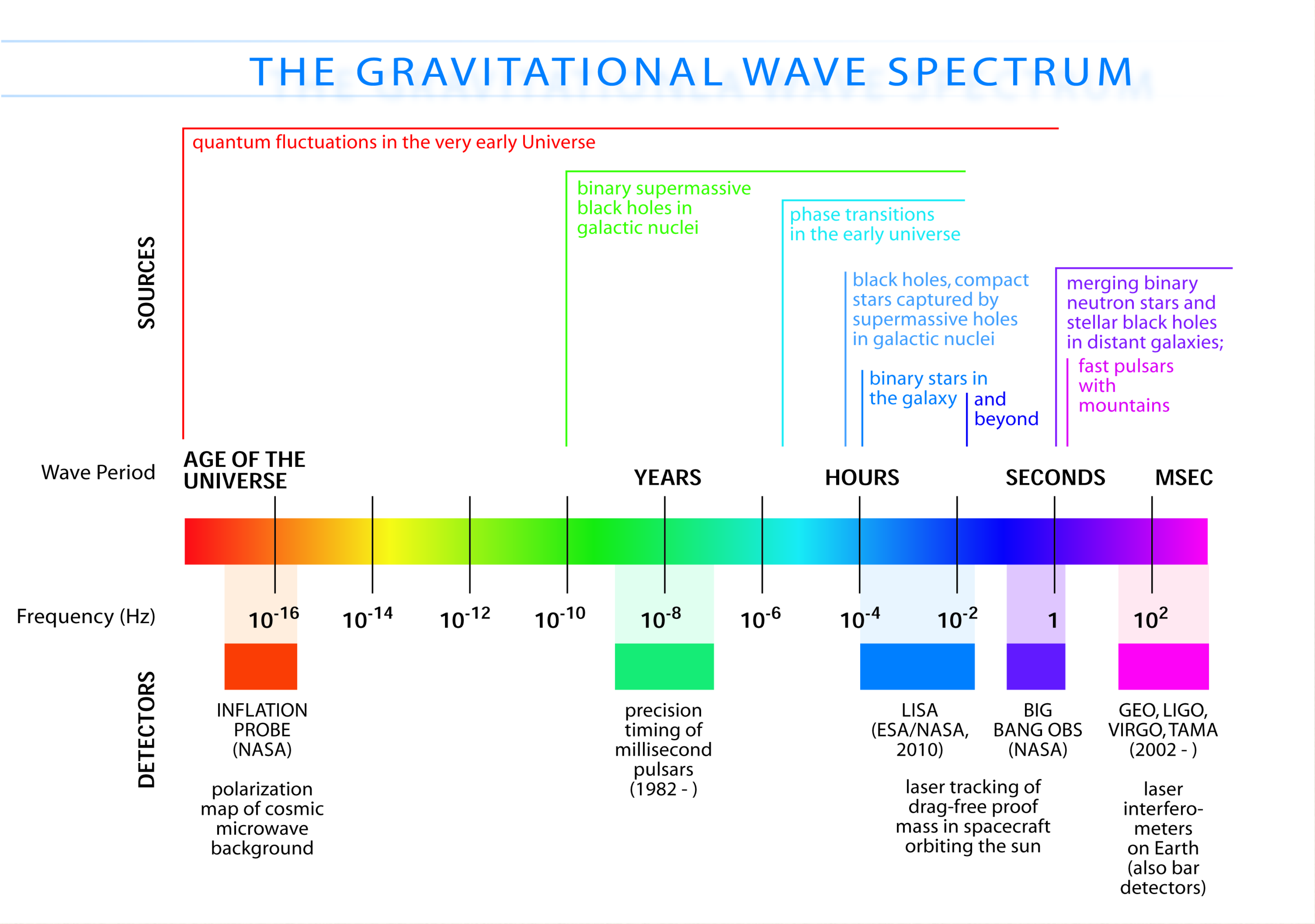
Ian Harry



# Talk layout

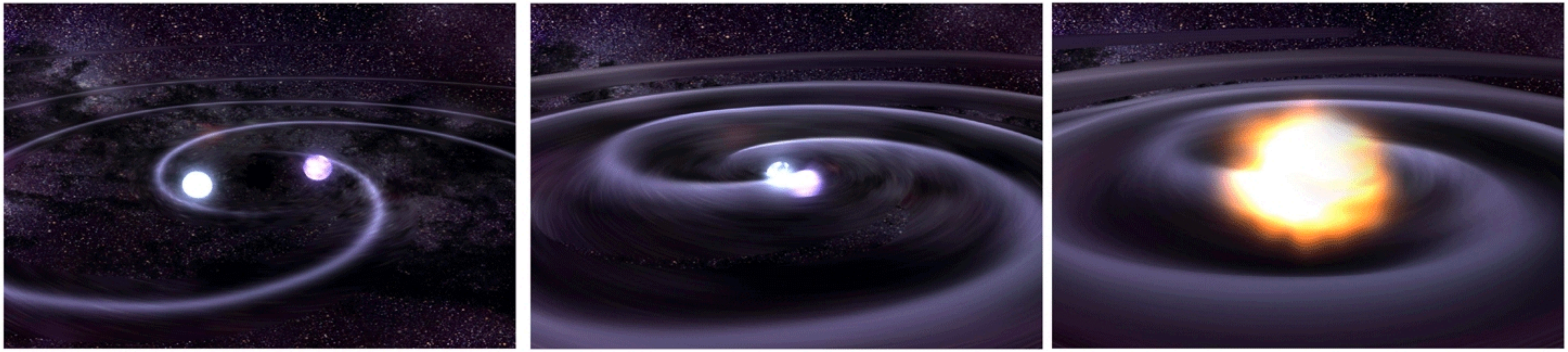
- Introduction and motivation
- What are we looking for (signal assumptions)?
- What does the data look like (noise assumptions)?
- How do we search for compact binary mergers in our data?
- Unmodelled searches as backup

# The gravitational-wave spectrum




Credit: University of Glasgow

# Focus here: Compact binary mergers



Credit: LIGO.org

# The current searches for colliding compact mergers

**Templated search codes**

- PyCBC (pycbc.org)
- MBTA
- GstLAL (https://lscsoft.docs.ligo.org/gstlal/)

**Non-templated search codes**

- Cwb

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# Searching for colliding black holes: What do we know about the signal?

# Modelling colliding black holes

- Einstein's equations from the 1910s exactly describe the dynamics of two black holes merging, and the gravitational-wave signal that would be emitted.
- However, it is not possible to analytically solve these equations.

# Modelling colliding black holes

**Approximate analytical solutions**

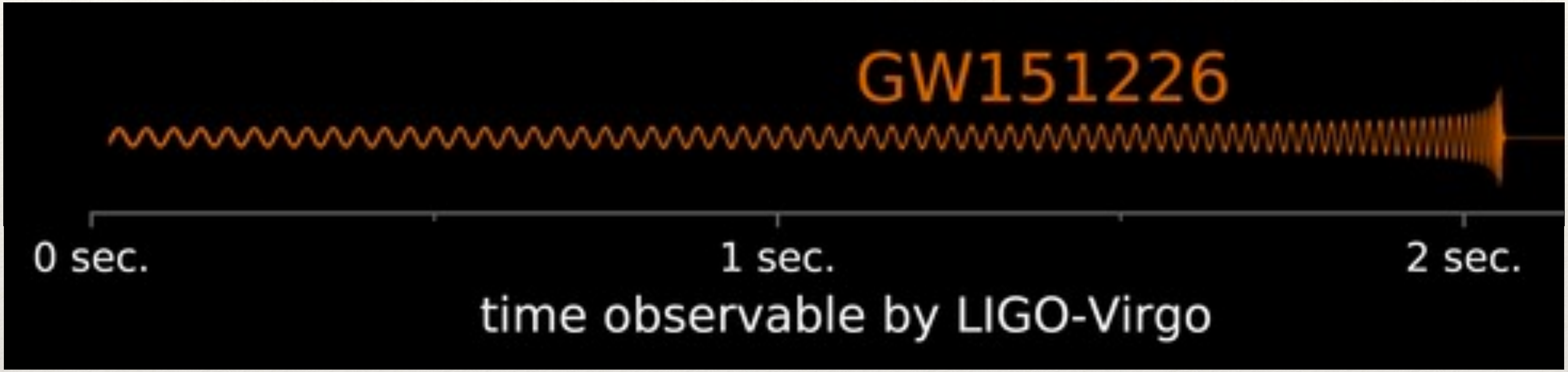
- Perturbative approaches can be used.
- Effective-one-body approach is one example of this
- Loses accuracy as the two black holes come close to merger

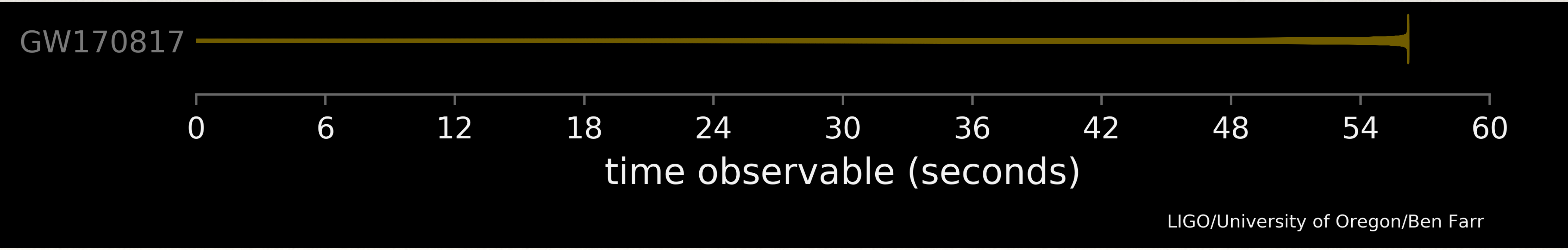
Buonanno and Damour Phys.Rev. D59 (1999) 084006
Buonanno et al., Phys.Rev. D80 (2009) 084043
Pretorius, Phys.Rev.Lett. 95 (2005) 121101
Campanelli et al., Phys.Rev.Lett. 96 (2006) 111101

**Numerical solutions**

- Einstein's equations can be solved directly using numerical evolution methods
- Very computationally expensive — cannot be used to model many orbits
- Can model the collision
- Some inaccuracy from numerical approach

# Waveforms






Credit: LIGO.org

# Compact binary parameters

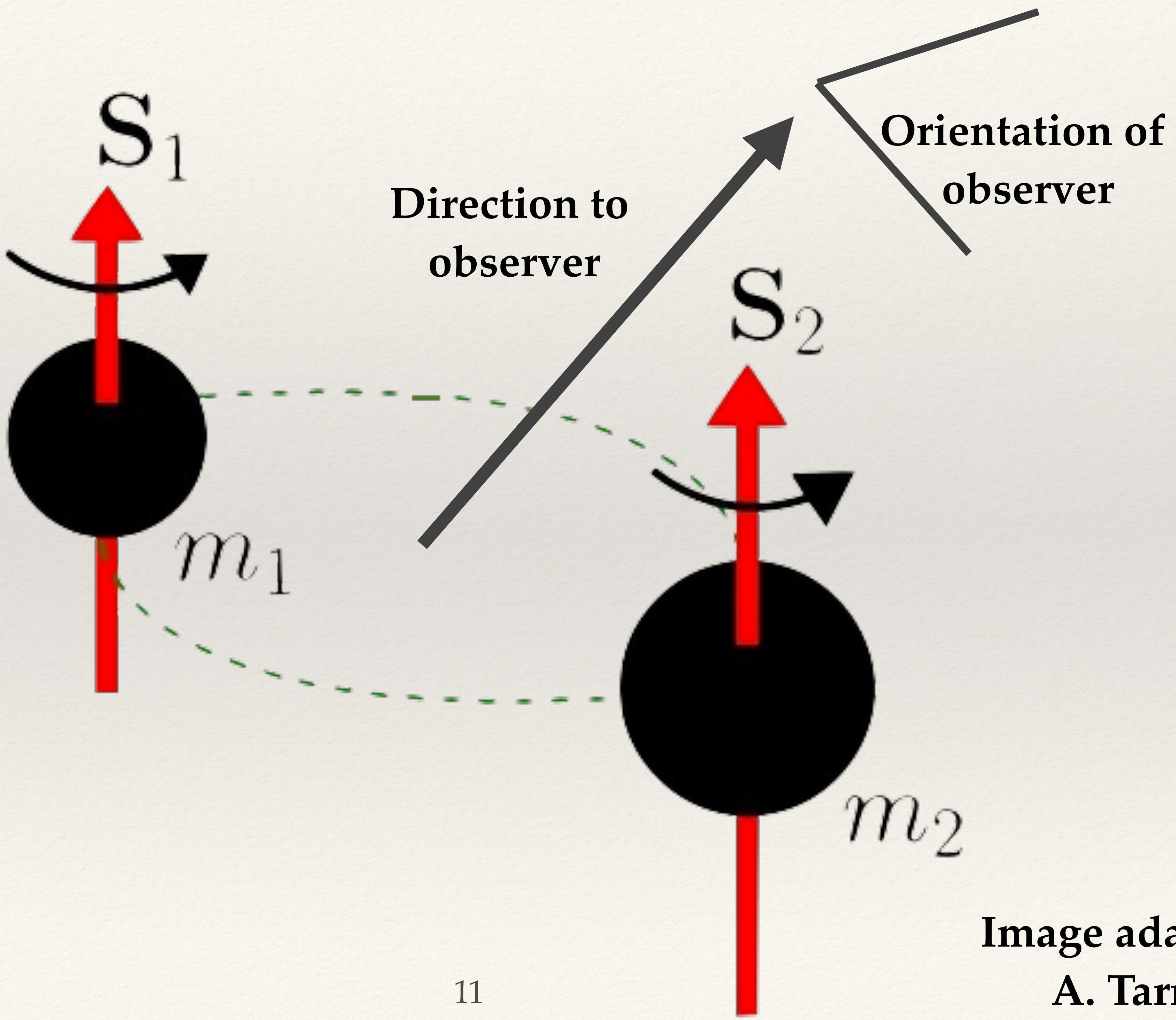
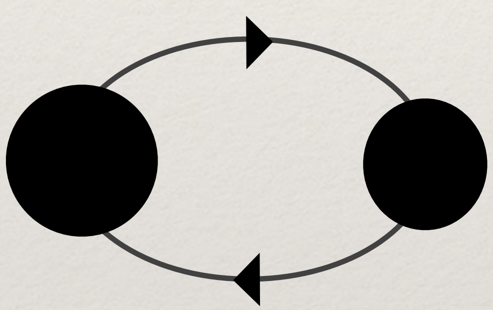
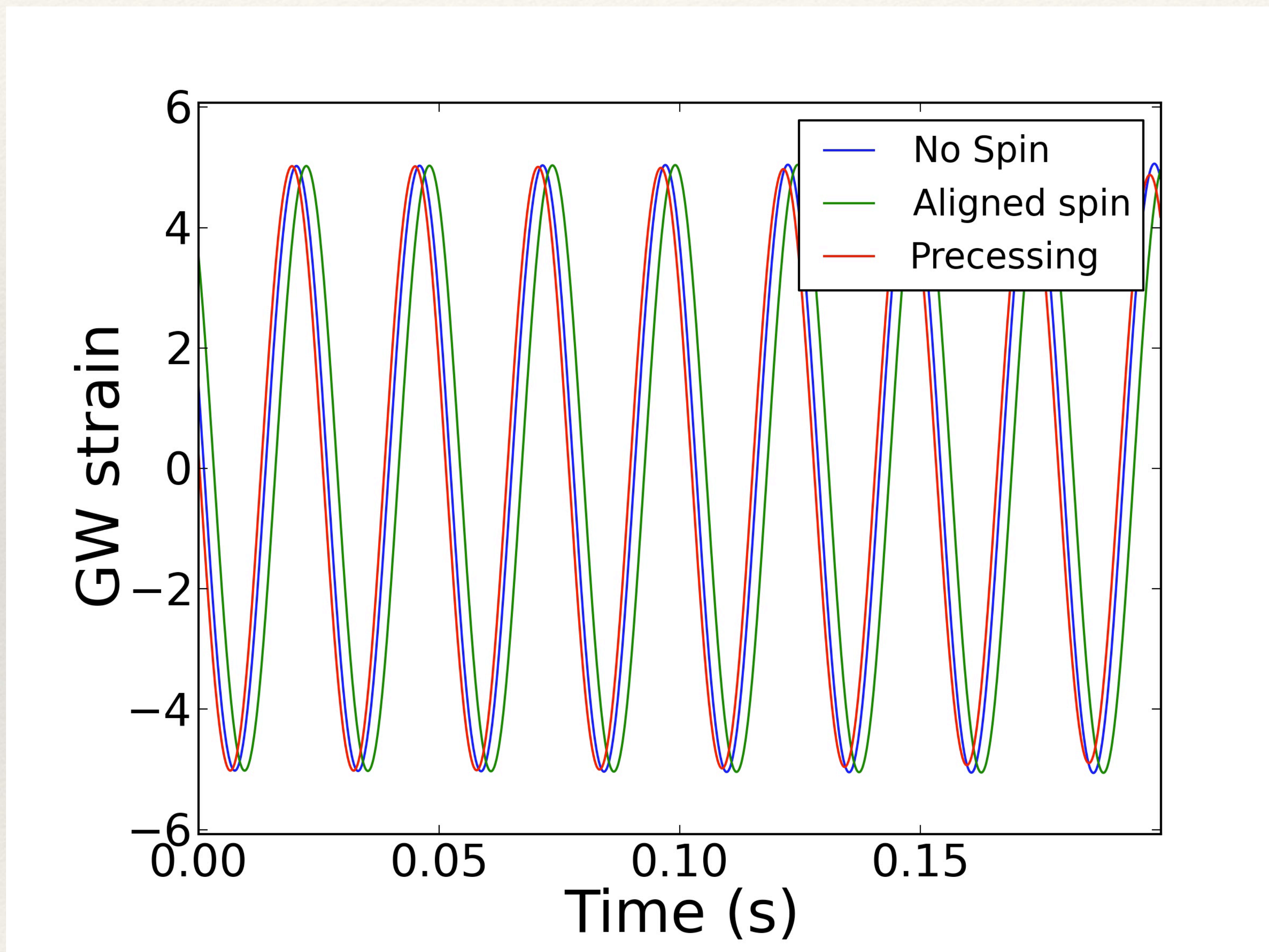


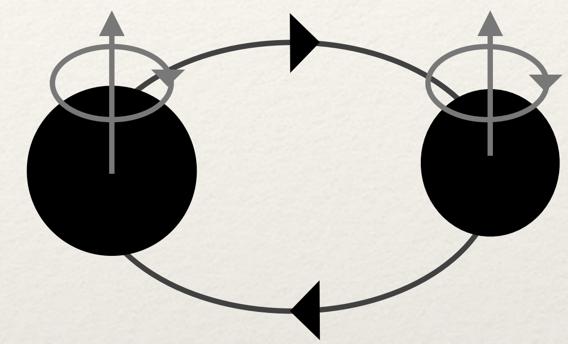

**Image adapted from A. Tarrachini**

# Effects of the components' angular momenta

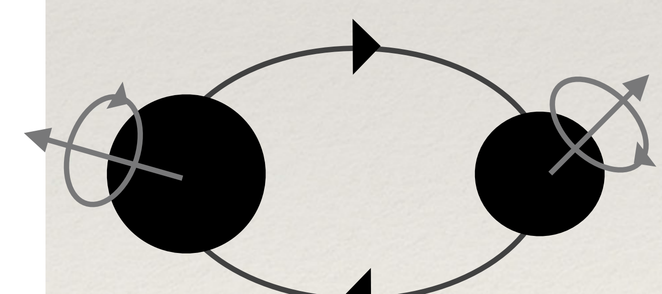


Non-spinning:
Blue



Aligned-spin:
Green



Precessing:
Red

"Credit": I. Harry

# Signal model - The equations

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

D: Distance, $\Theta$: Orientation of detector with respect to source

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

$\theta, \phi$ : sky location of observer with respect to source, $Y_{lm}$: spherical harmonics

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

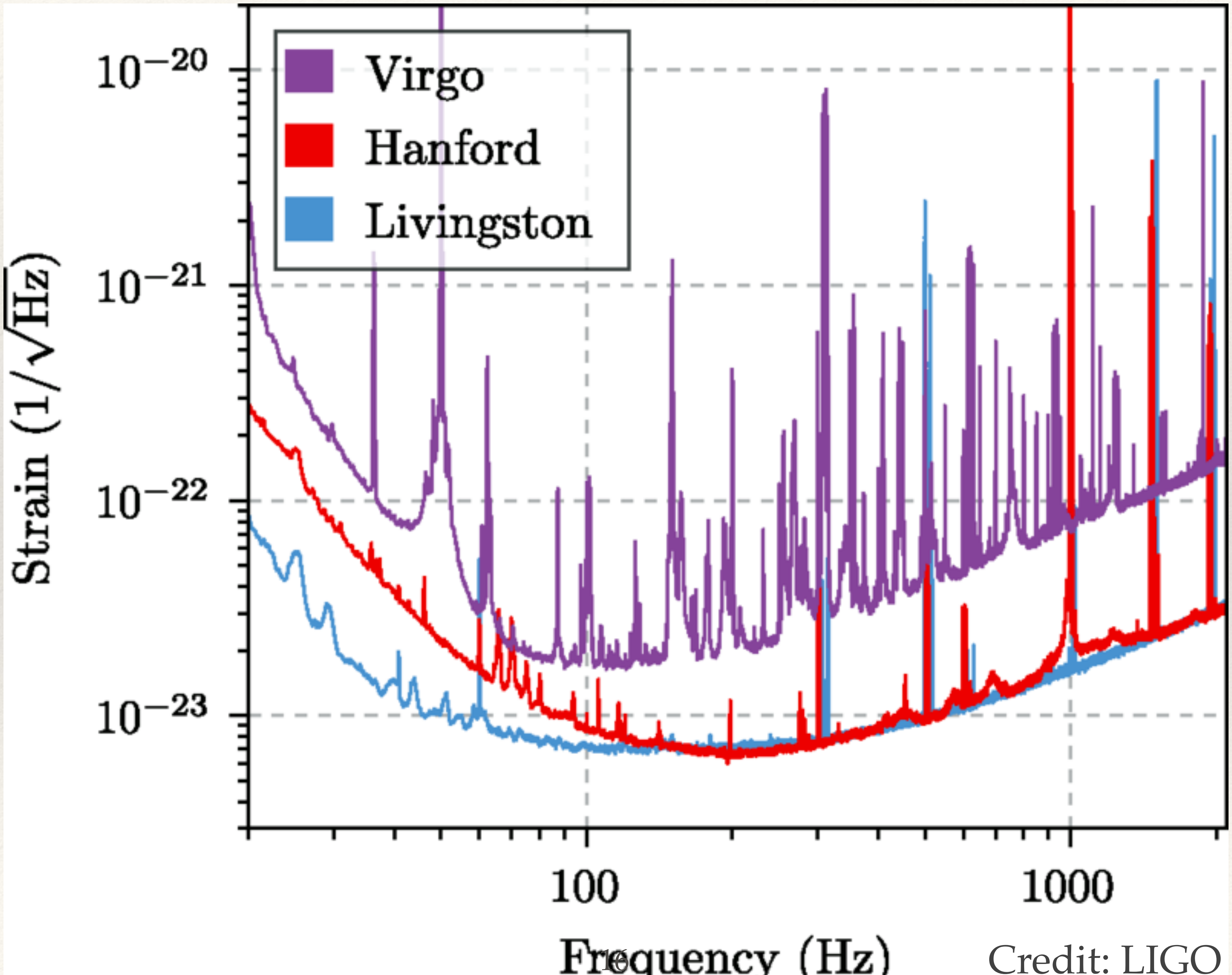
Amplitude and phase carries dependance on the "intrinsic" parameters of the source

# Signal model - Take home points

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

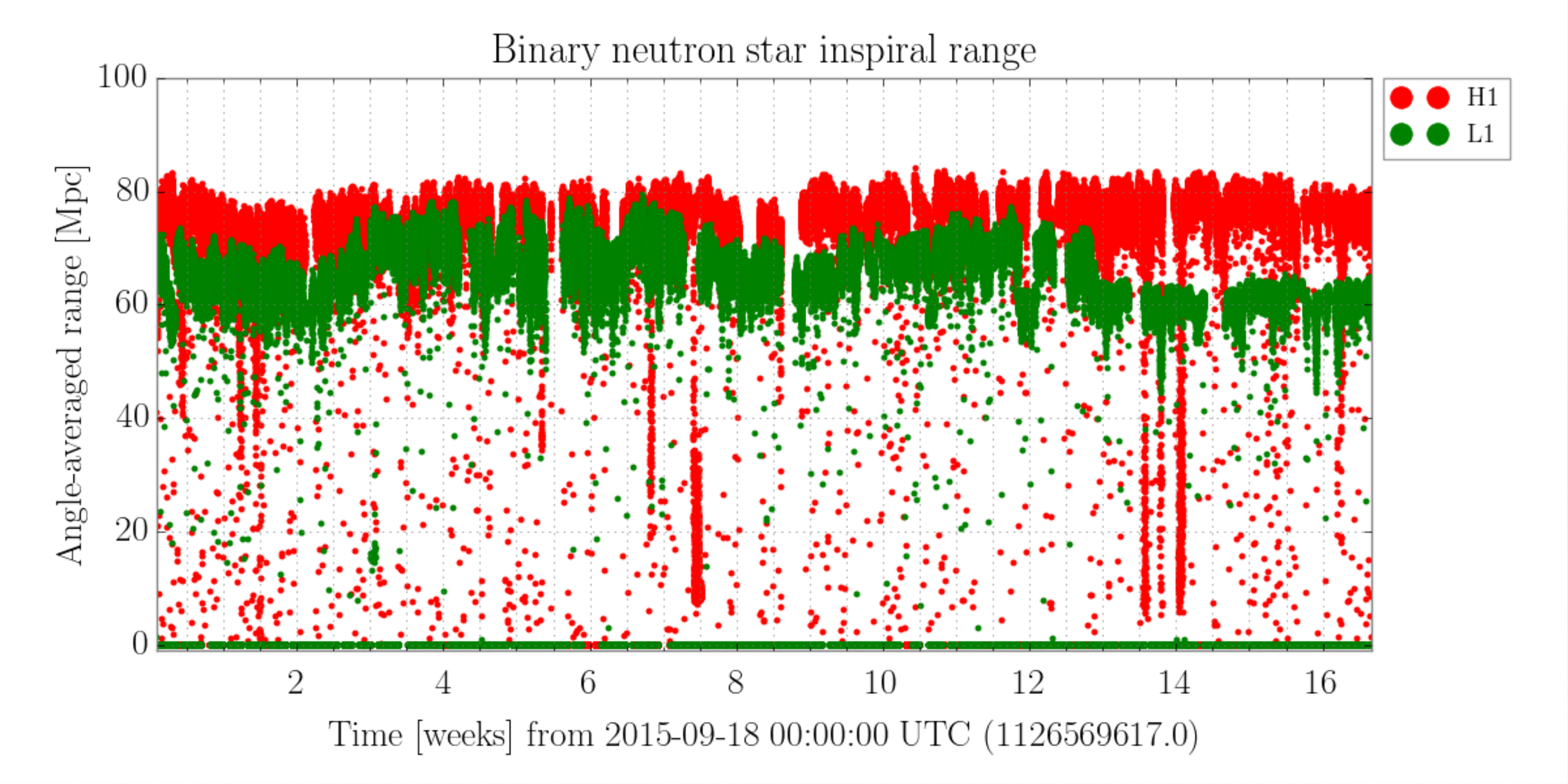
# Searching for colliding black holes: What do we know about the noise?

# LIGO/Virgo noise: Complex noise curve



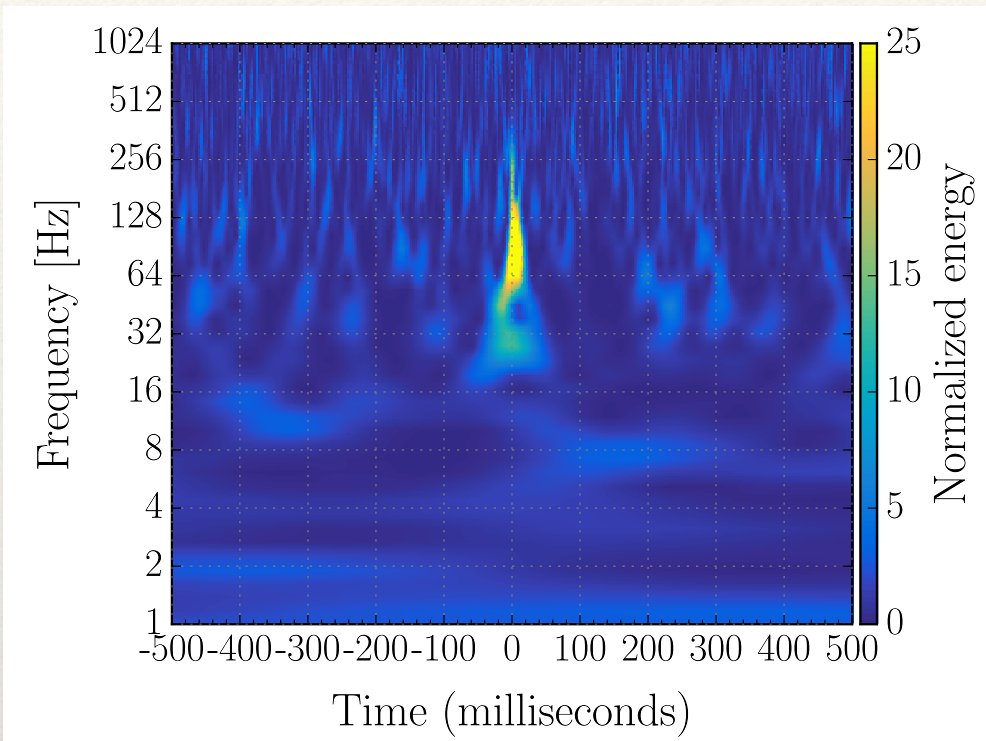

Credit: LIGO

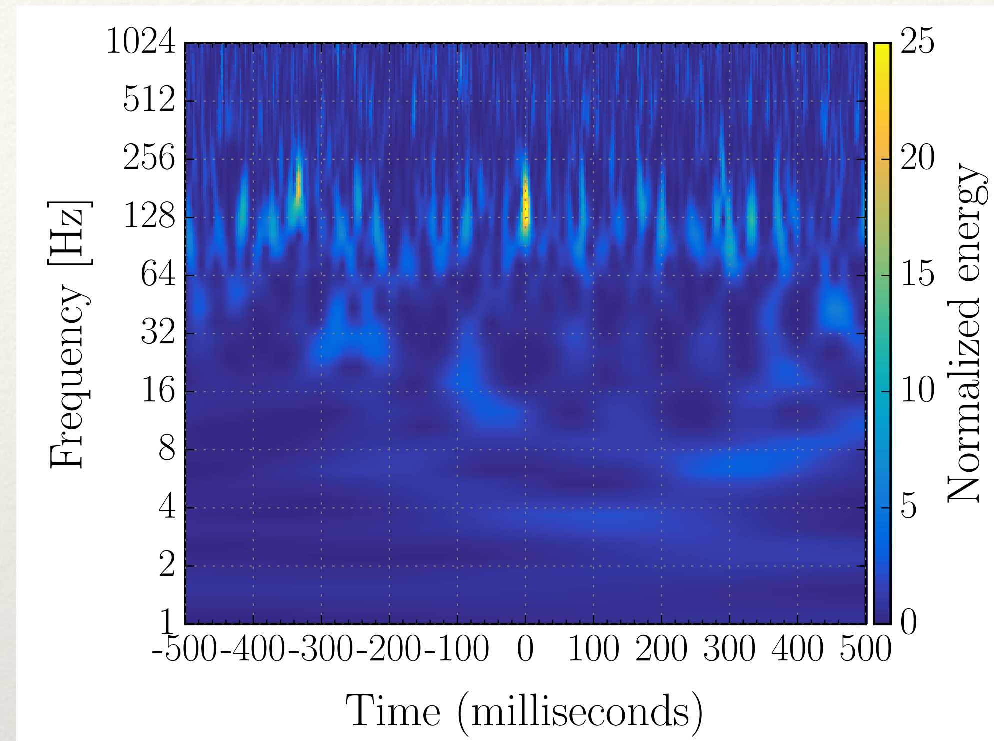
# LIGO/Virgo noise: Non-stationary

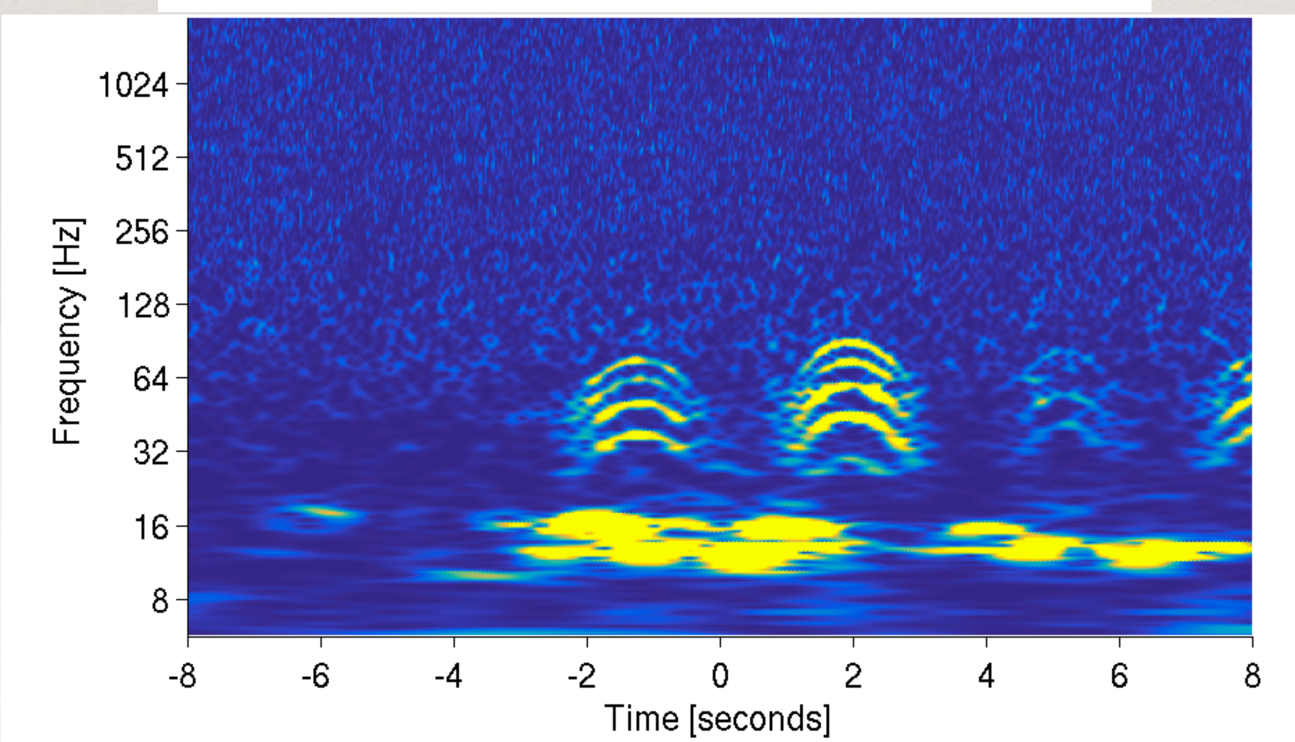


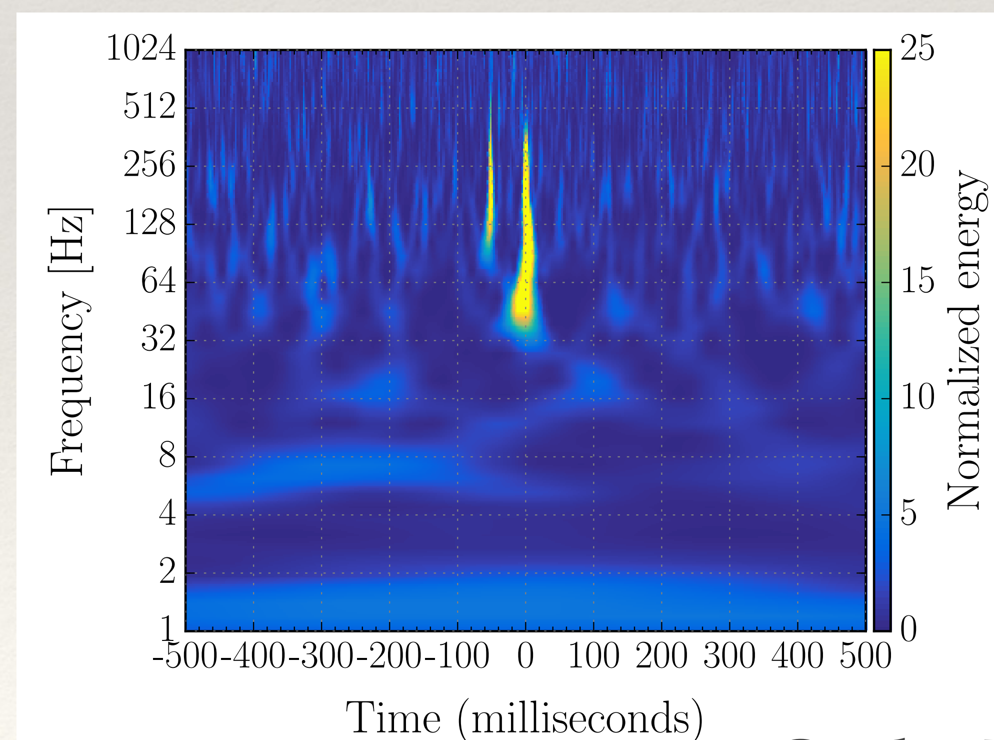

Credit: LIGO

# LIGO/Virgo noise: Non-Gaussian




Credit: LIGO

# LIGO/Virgo noise: Summary

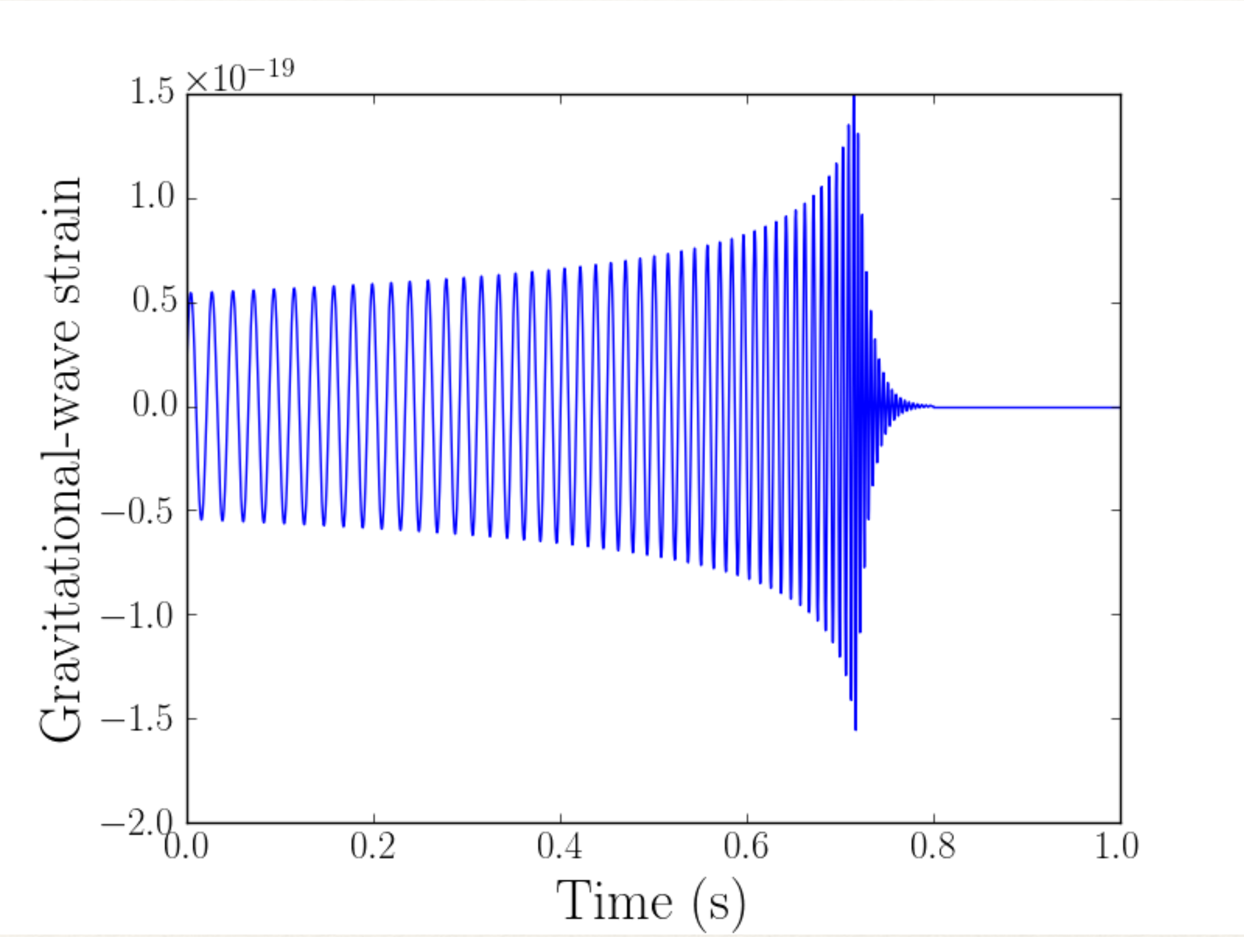
- The noise curves are complex, with many lines over a broadband sensitivity
- LIGO sensitivity is highly non-stationary (less so for Virgo)
- Instrumental artefacts ***regularly*** appear in the data

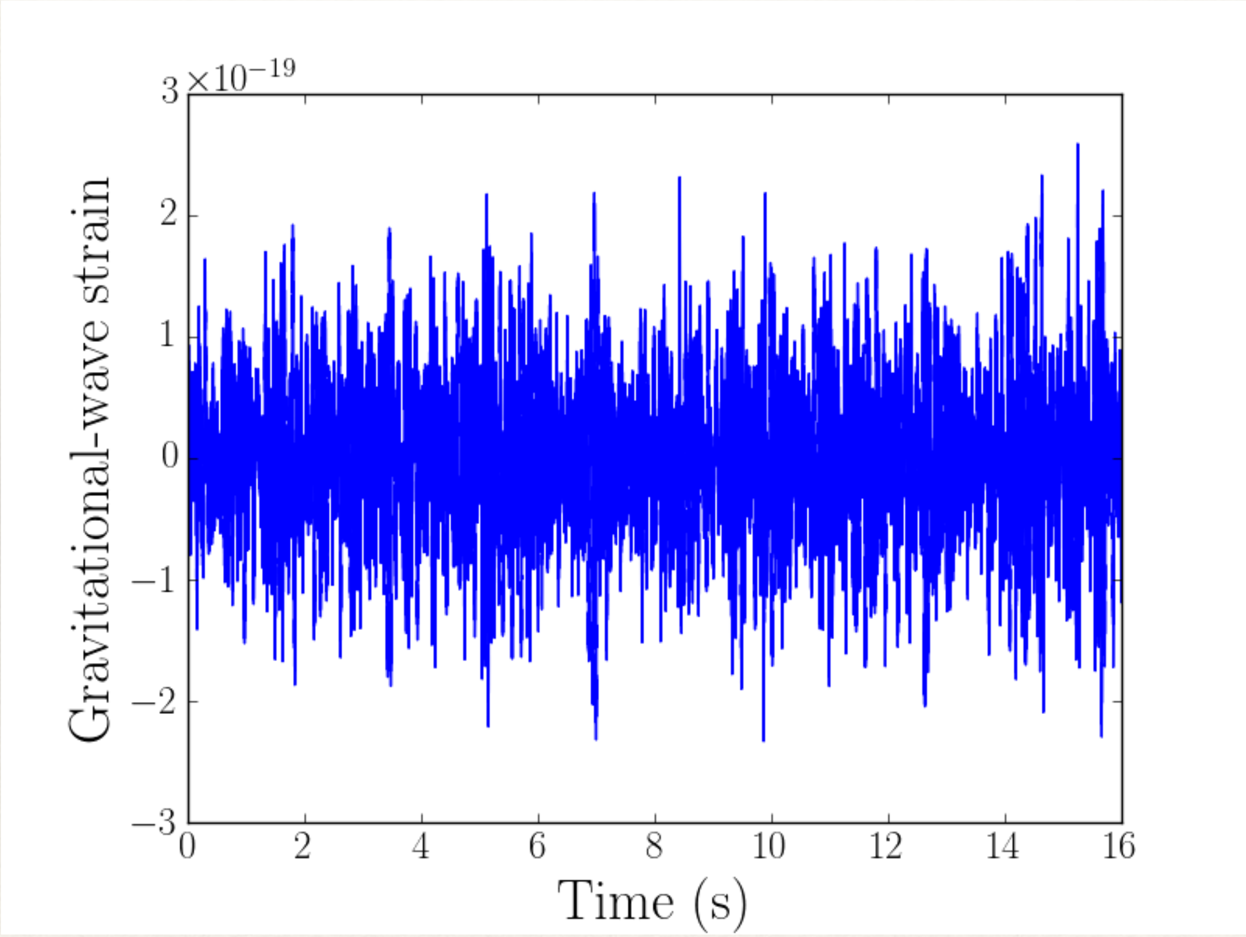
# Searching for colliding black holes: How do we actually search for them?

# Detection problem

We know what we're looking for

But signals will be buried in the detector noise

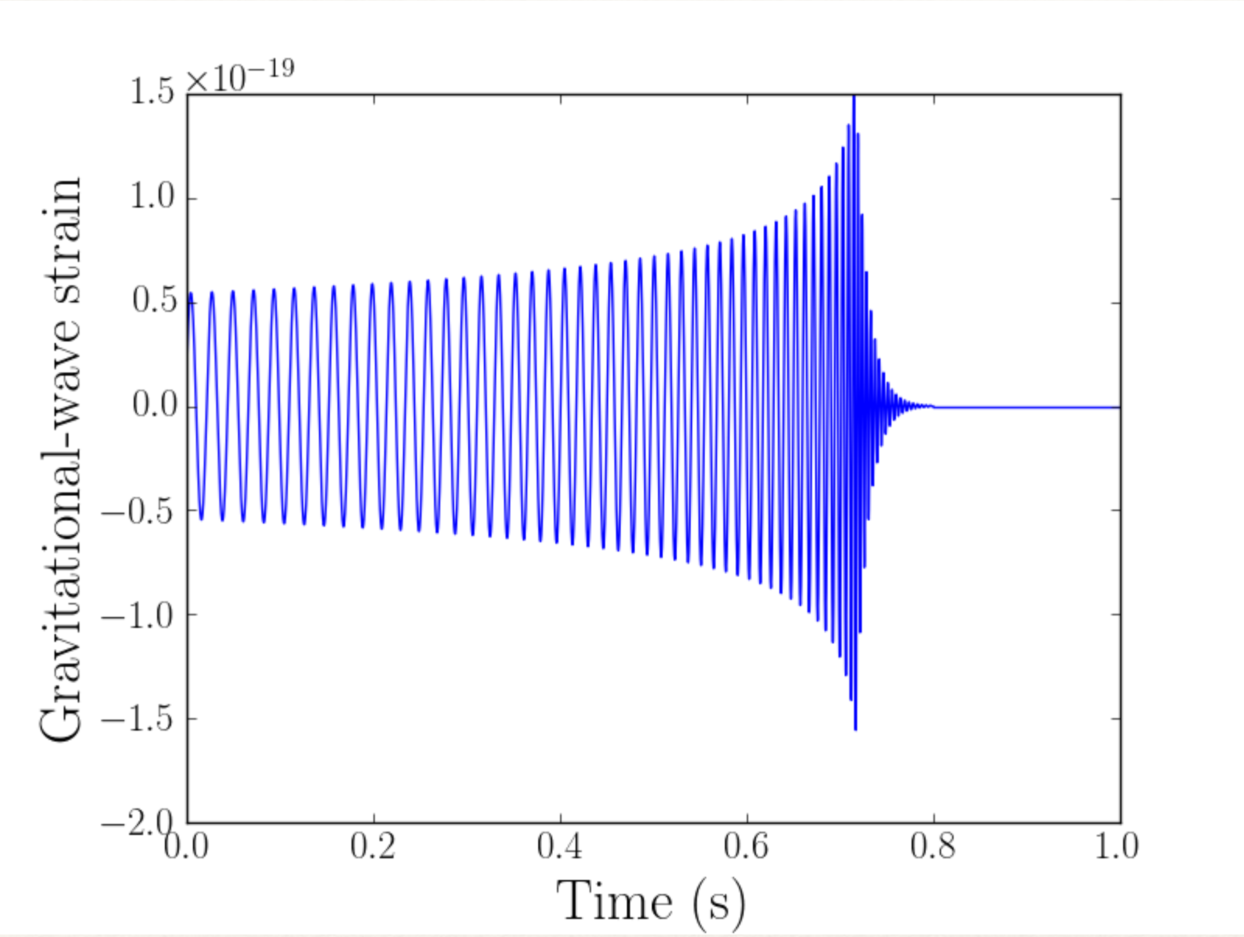



Plots and data courtesy of the GW open-science center: https://www.gw-openscience.org

# Detection problem

We know what we're looking for

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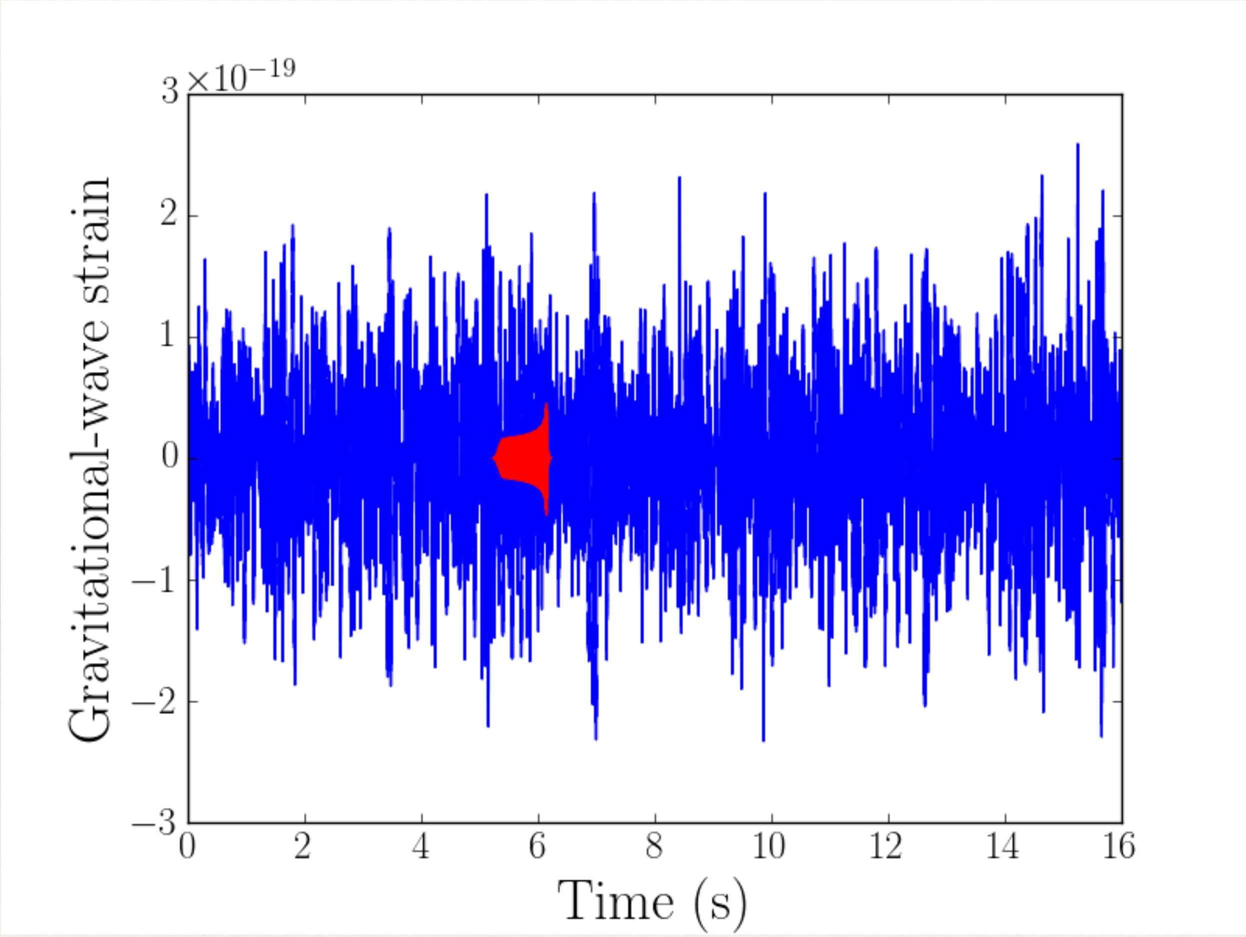



Plots and data courtesy of the GW open-science center: https://www.gw-openscience.org

# Matched filtering

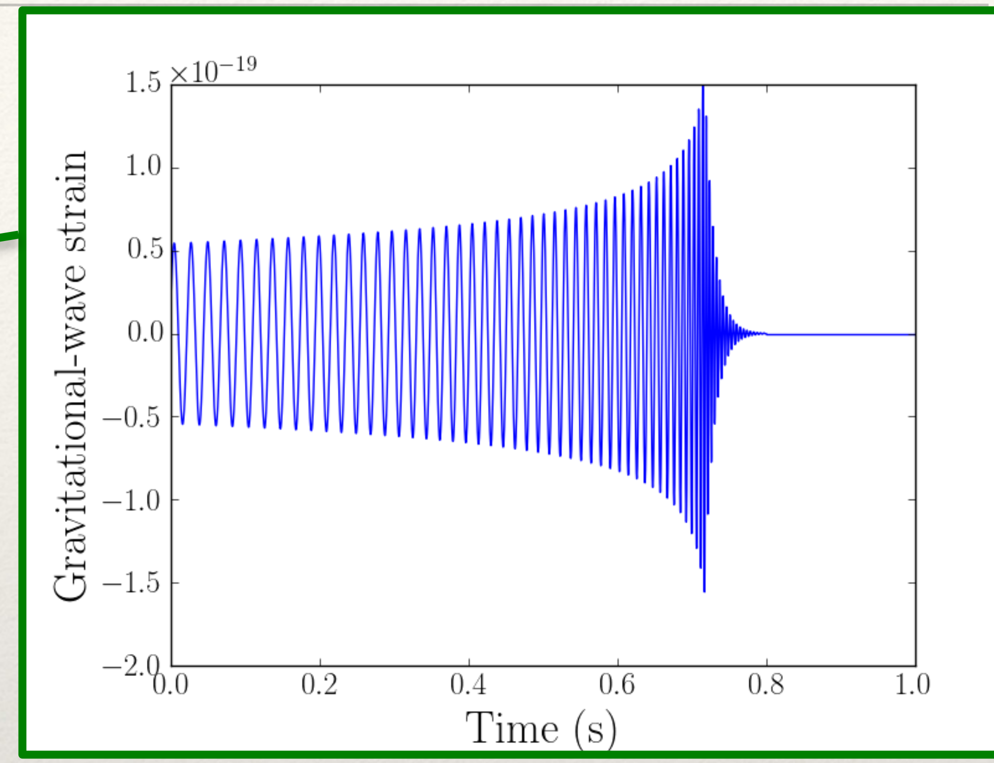
- Optimal if looking for a signal in stationary, Gaussian noise with known PSD

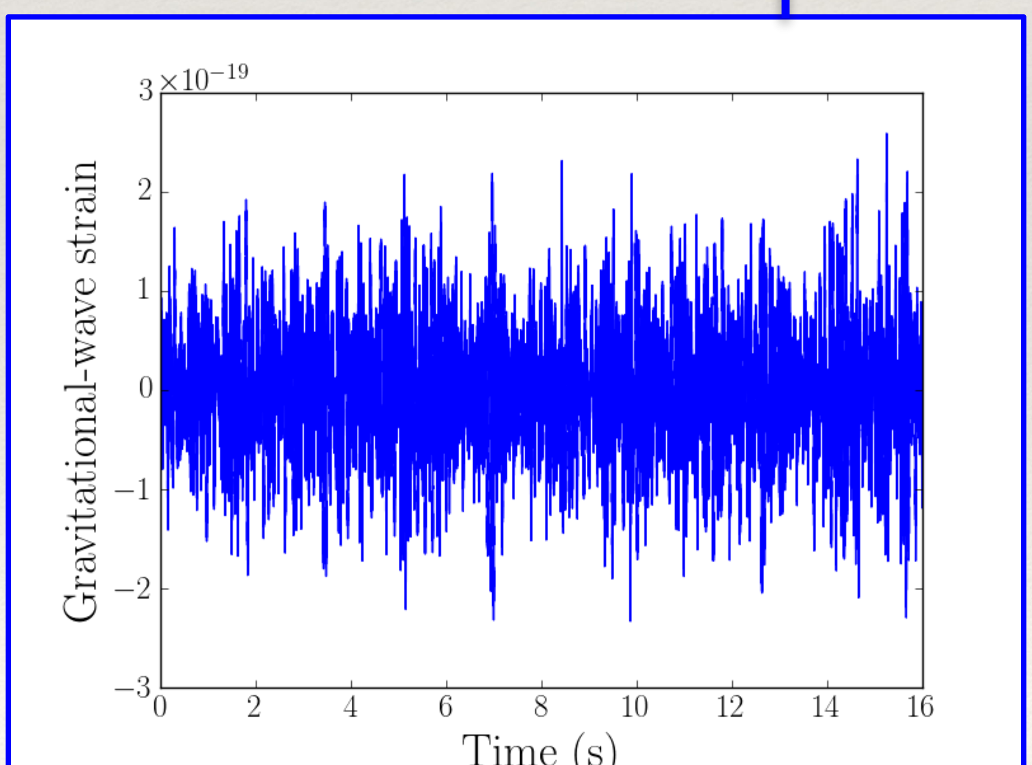
$$(s|h) = 4\Re \int_0^\infty \frac{\tilde{s}(f)\tilde{h}^\star(f)}{S_h(f)} df$$

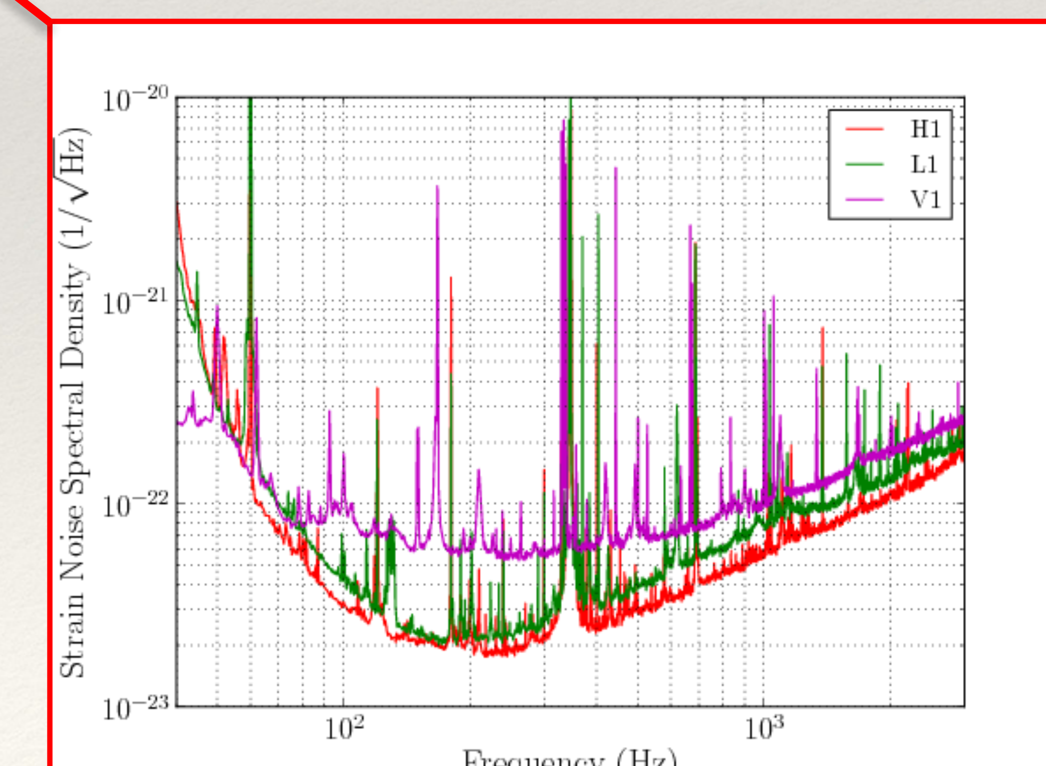
Wainstein and Zubakov "Extraction of signals from noise", 1962
Allen et al. Phys.Rev. D85 (2012) 122006
Babak, … ,IH, et al. Phys.Rev. D87 (2013) 024033

# Matched filtering

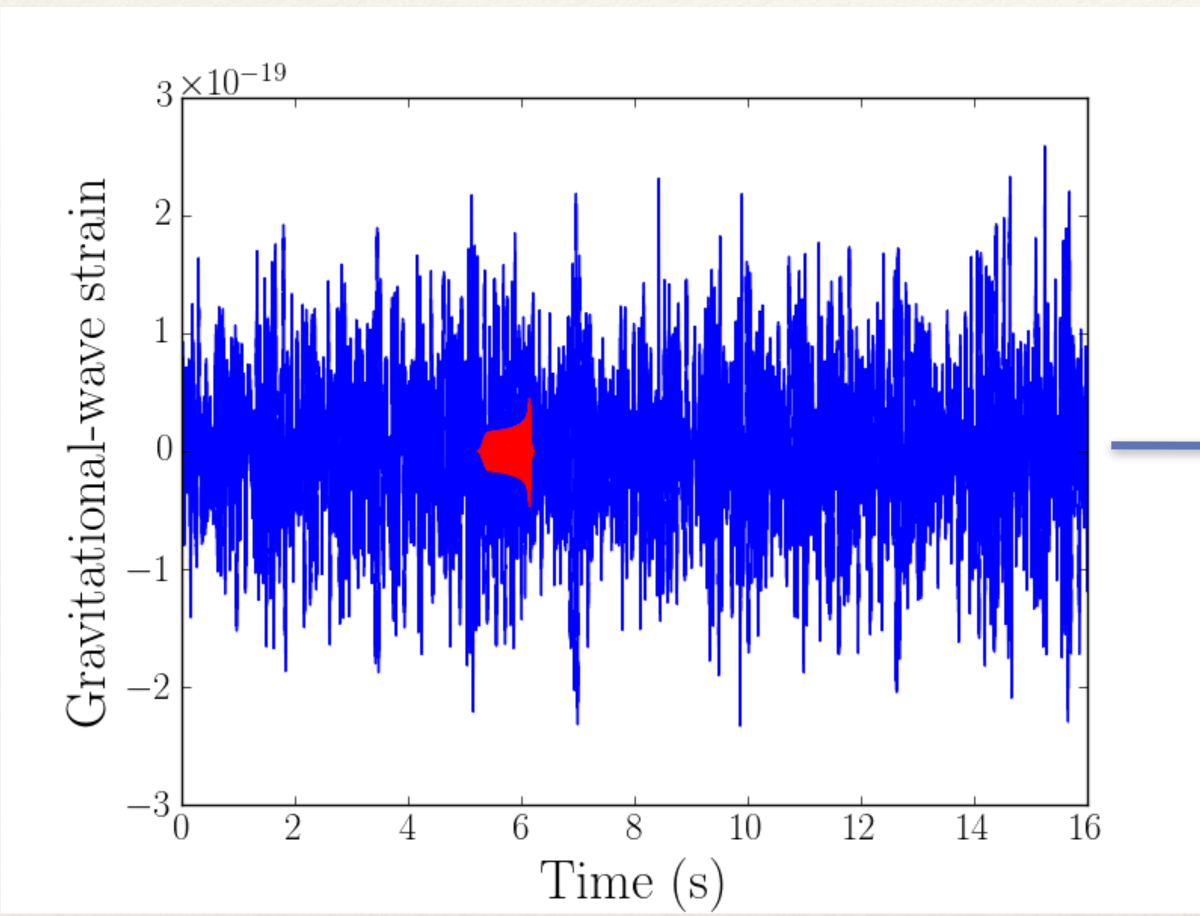
$$(s|h) = 4\Re \int_0^\infty \frac{\boxed{\tilde{s}(f)}\,\boxed{\tilde{h}^\star(f)}}{\boxed{S_h(f)}}\, df$$



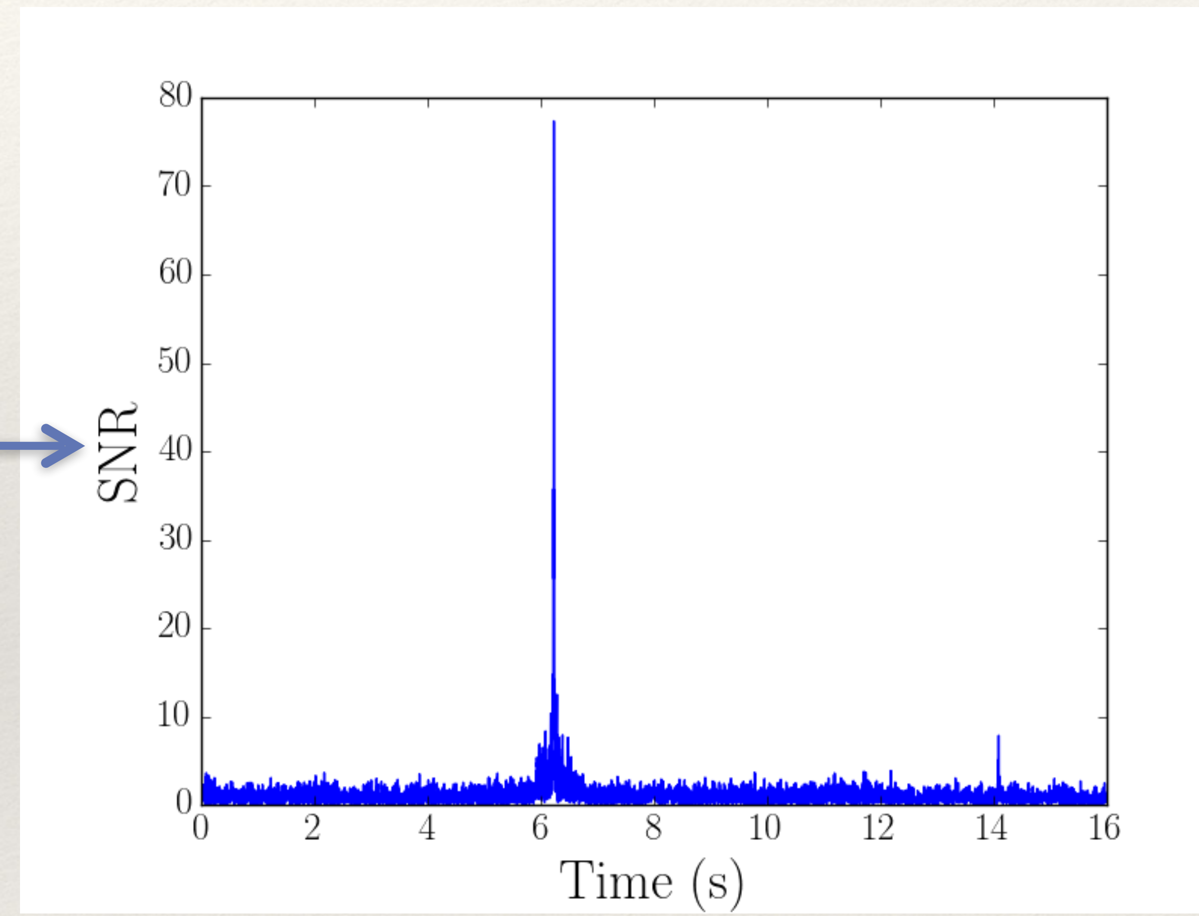



# Matched filtering




$s(t)$




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

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

# Dealing with a large parameter space

- Signals depend on at least 15 parameters
- Matched-filtering over a 15-D grid of waveforms is not computationally feasible
- Must reduce size of parameter space

# Reducing parameter space - ASSUMPTIONS!

- Assume that there is no precession of the orbital plane
- Assume that 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

$$\tilde{h}(f) = A(\Psi)\mathcal{M}^{5/6} f^{-7/6} \exp\left[i2\Phi(\Xi, f) + 2\Phi_0(\Psi) + 2\pi f t_c\right]$$

# Maximization

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

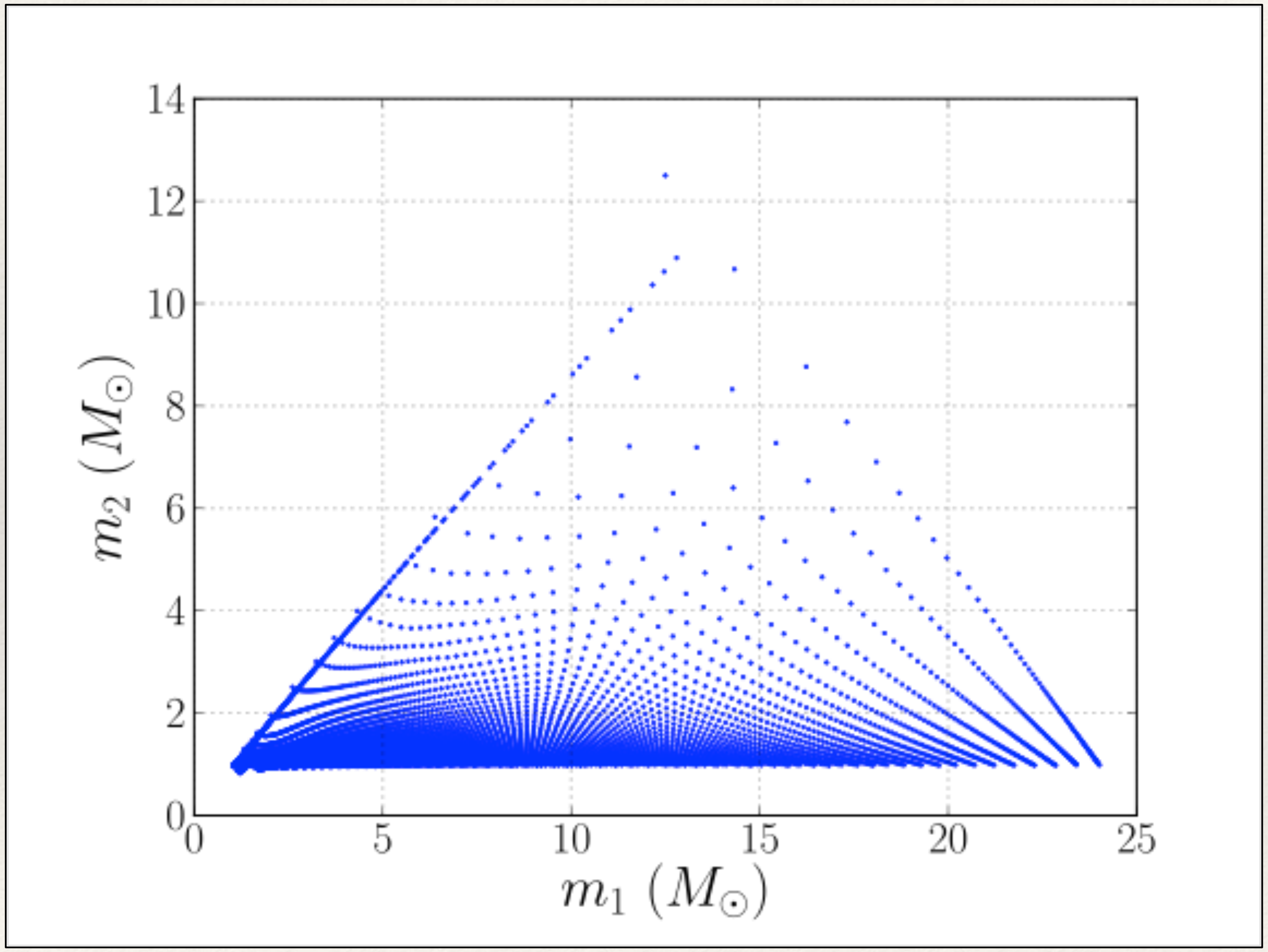
Maximise over orientation and location parameters

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

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

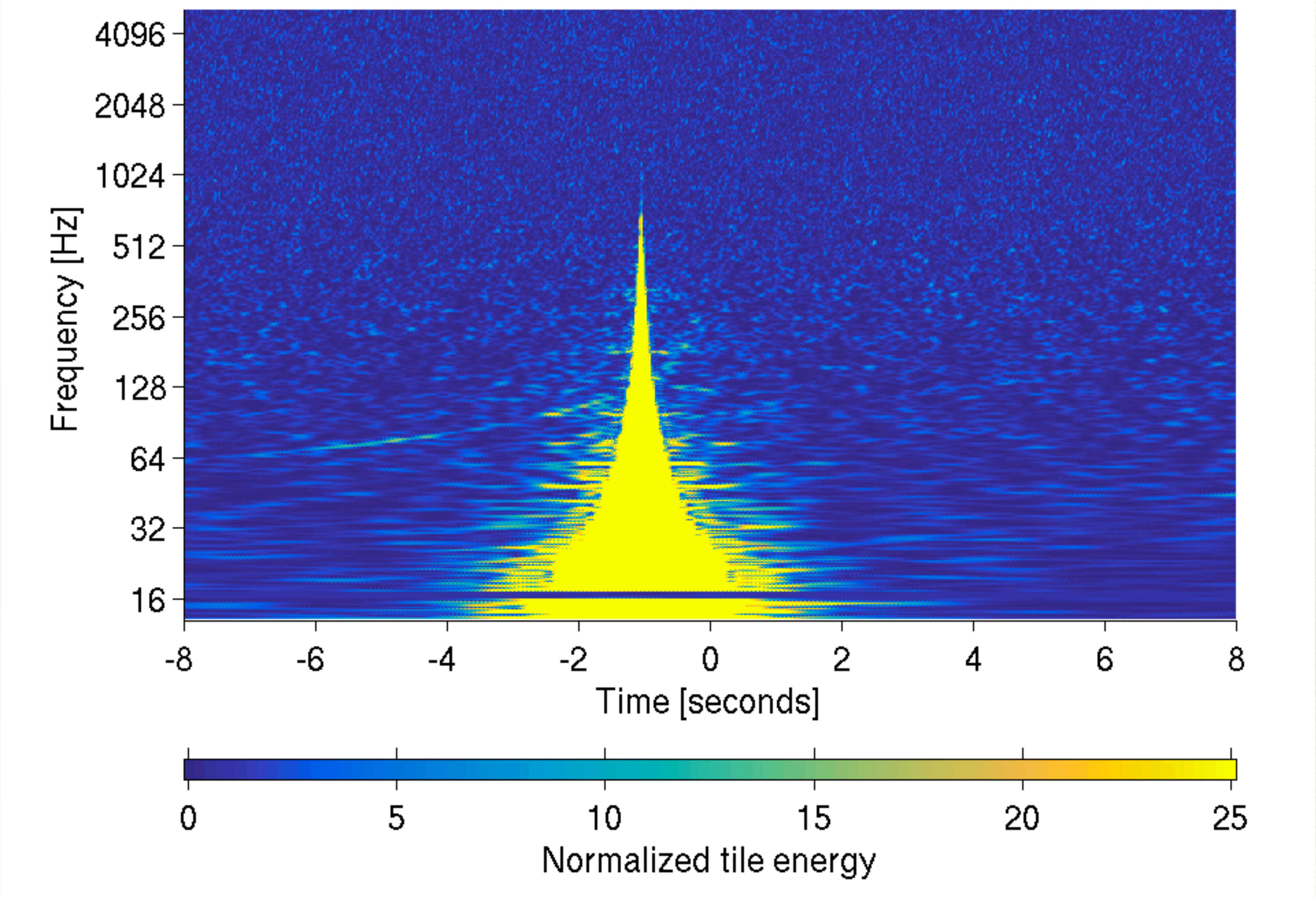
The template bank is chosen such that even for signals lying between the templates, we lose no more than 3% of the optimal matched-filter SNR.


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

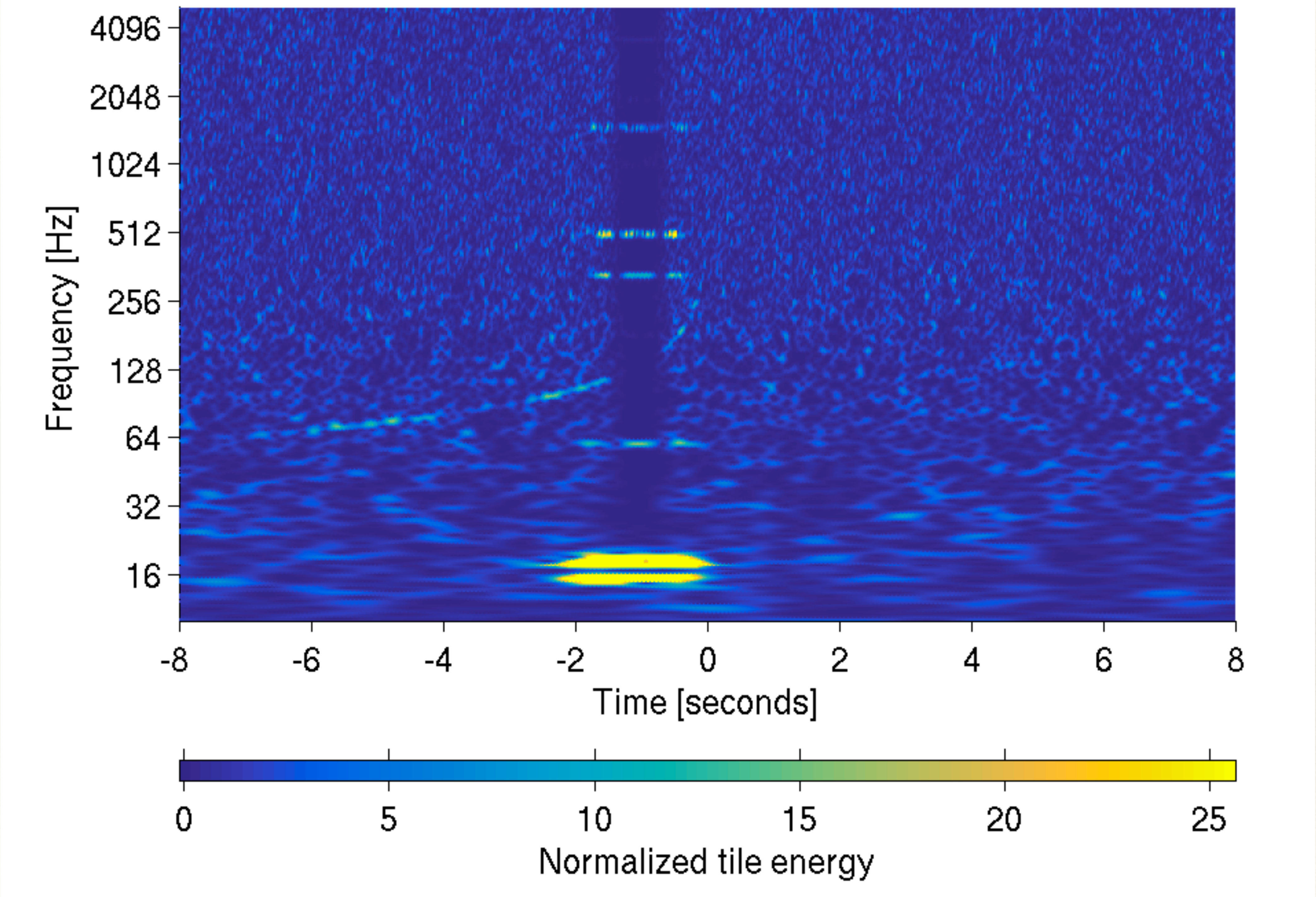
# Our first binary neutron-star observation






Phys. Rev. Lett. 119, 161101

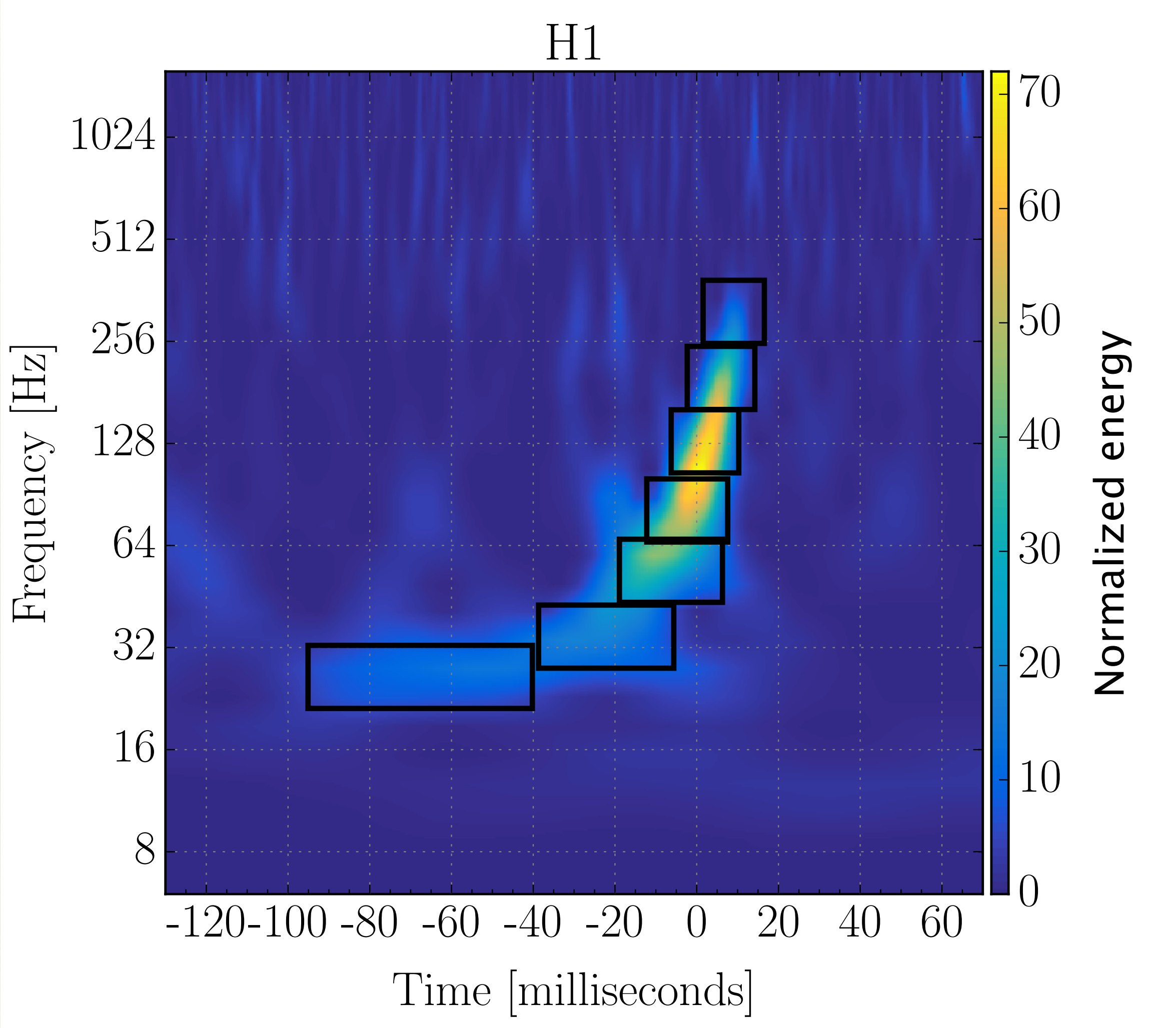
# Out first binary neutron-star observation



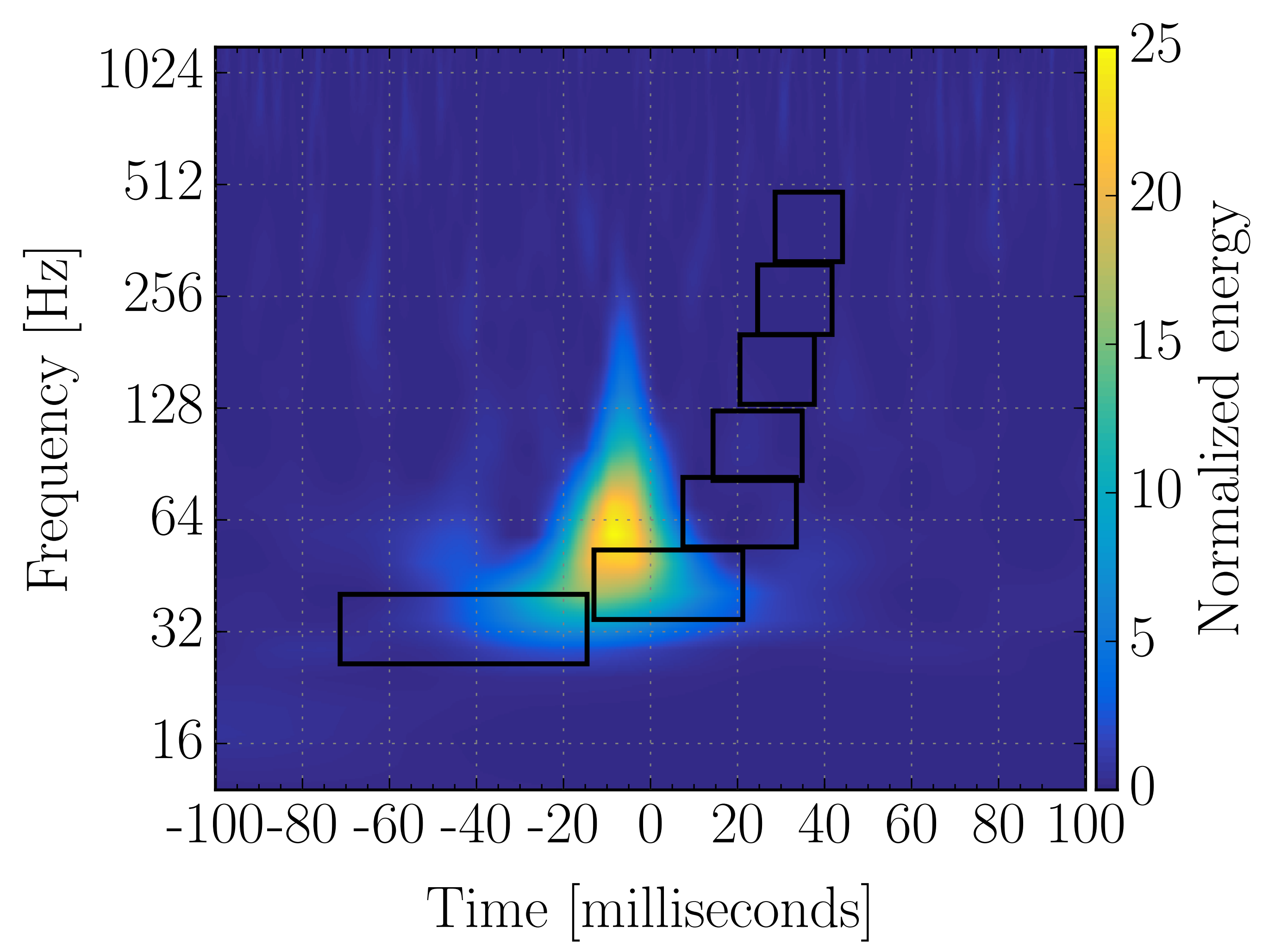



Phys. Rev. Lett. 119, 161101

# An ad-hoc chi-squared test



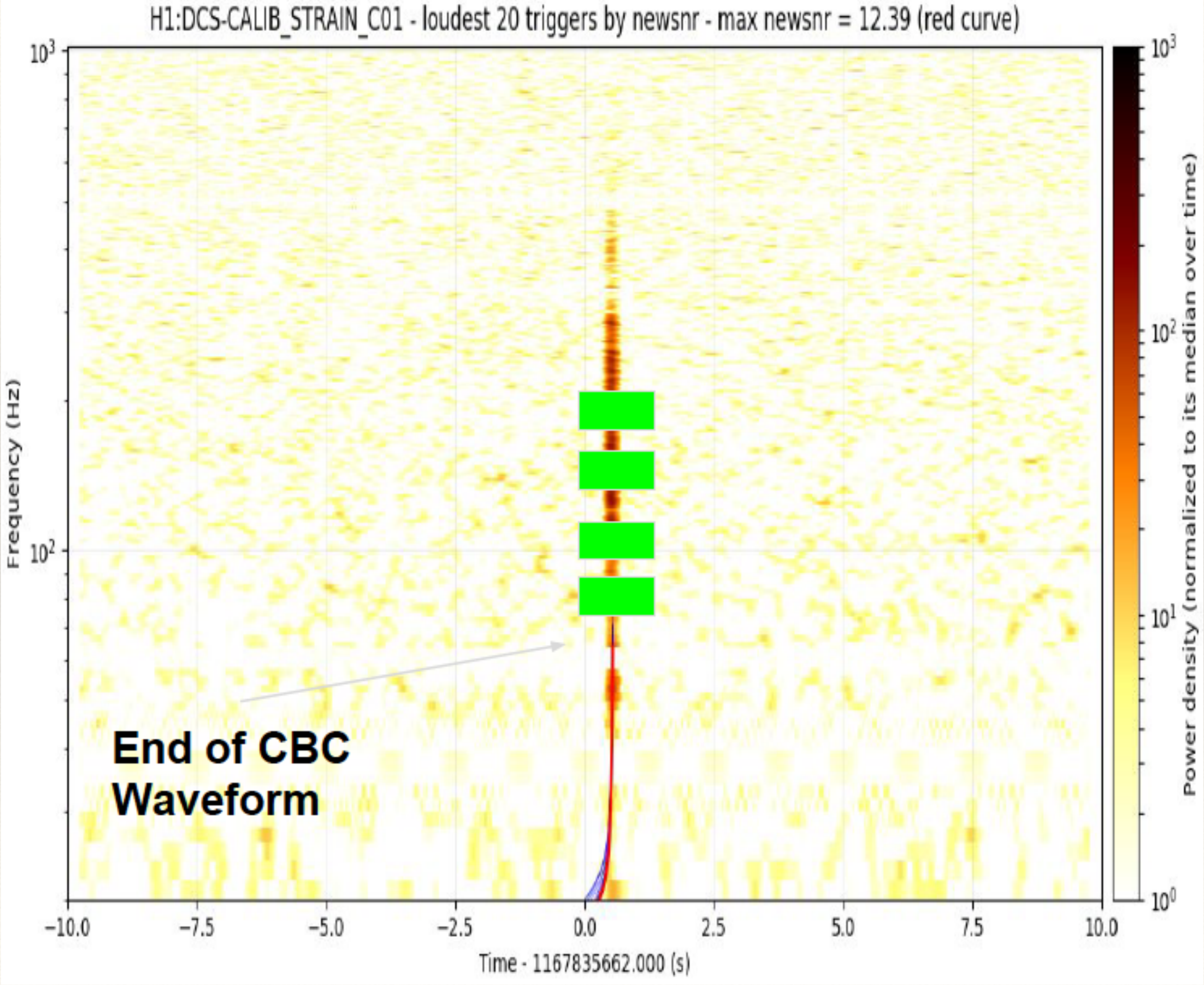

Real signal



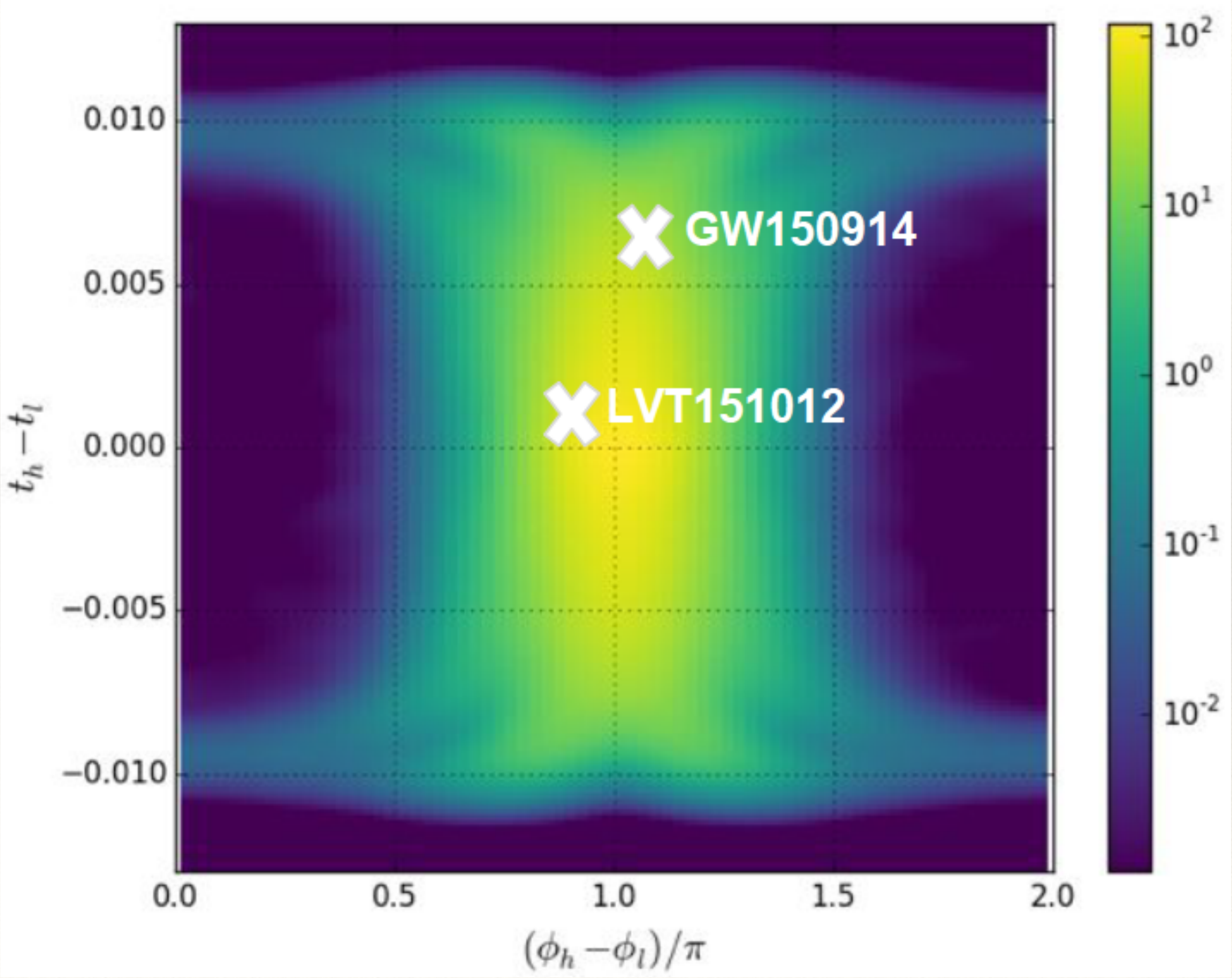

Instrumental artifact

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

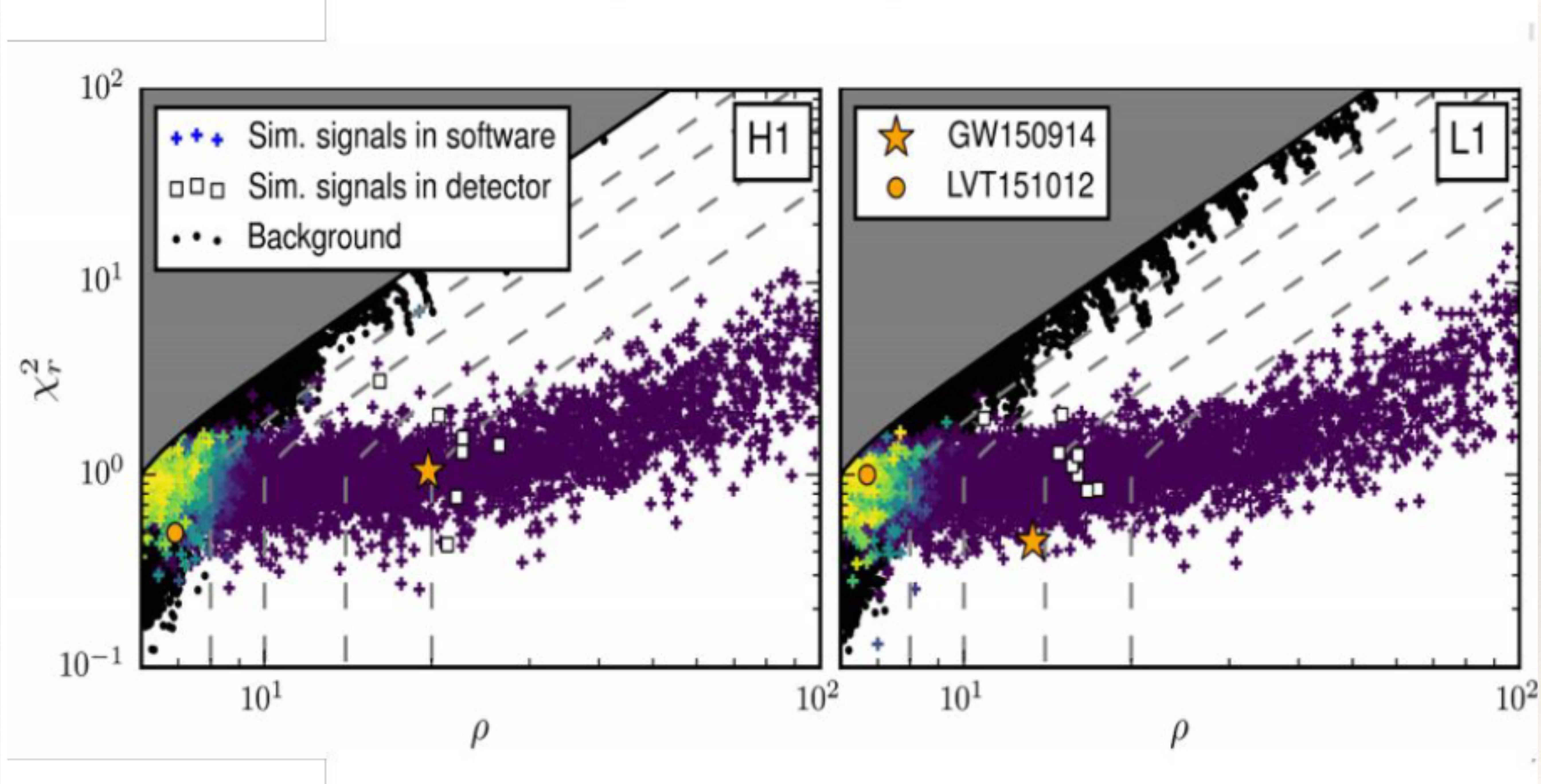
# Another chi-squared test



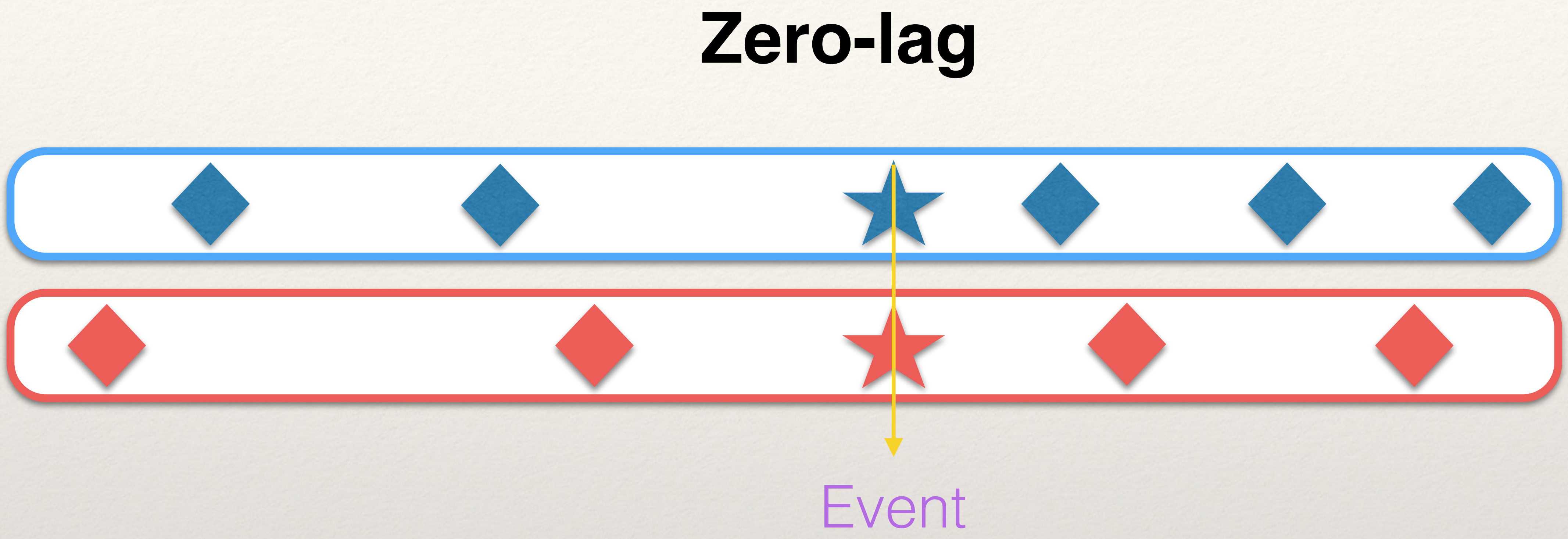
# H1L1 Consistency



# Ranking statistic - combining everything



# Calculating a significance (how many sigmas?)



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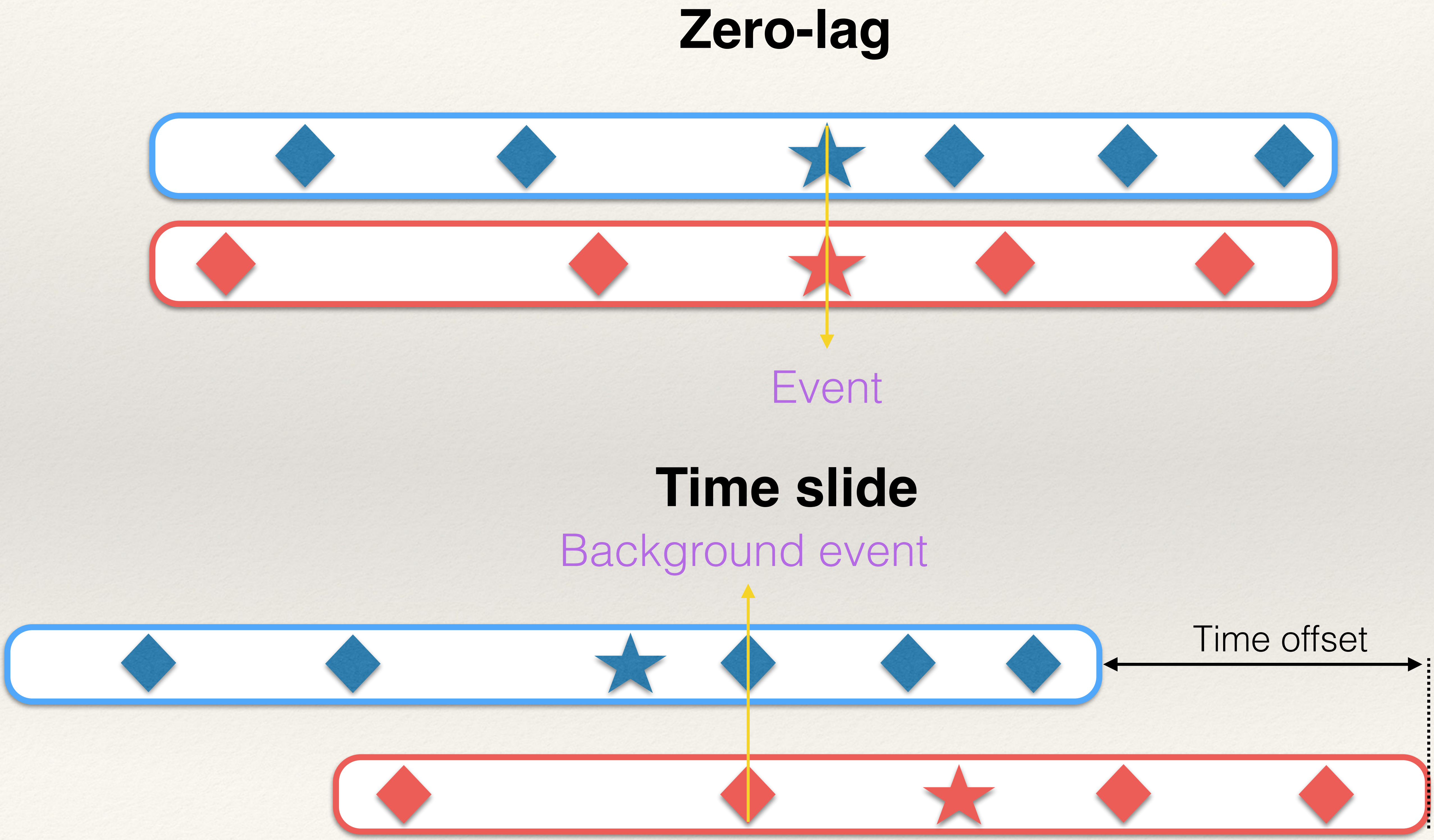
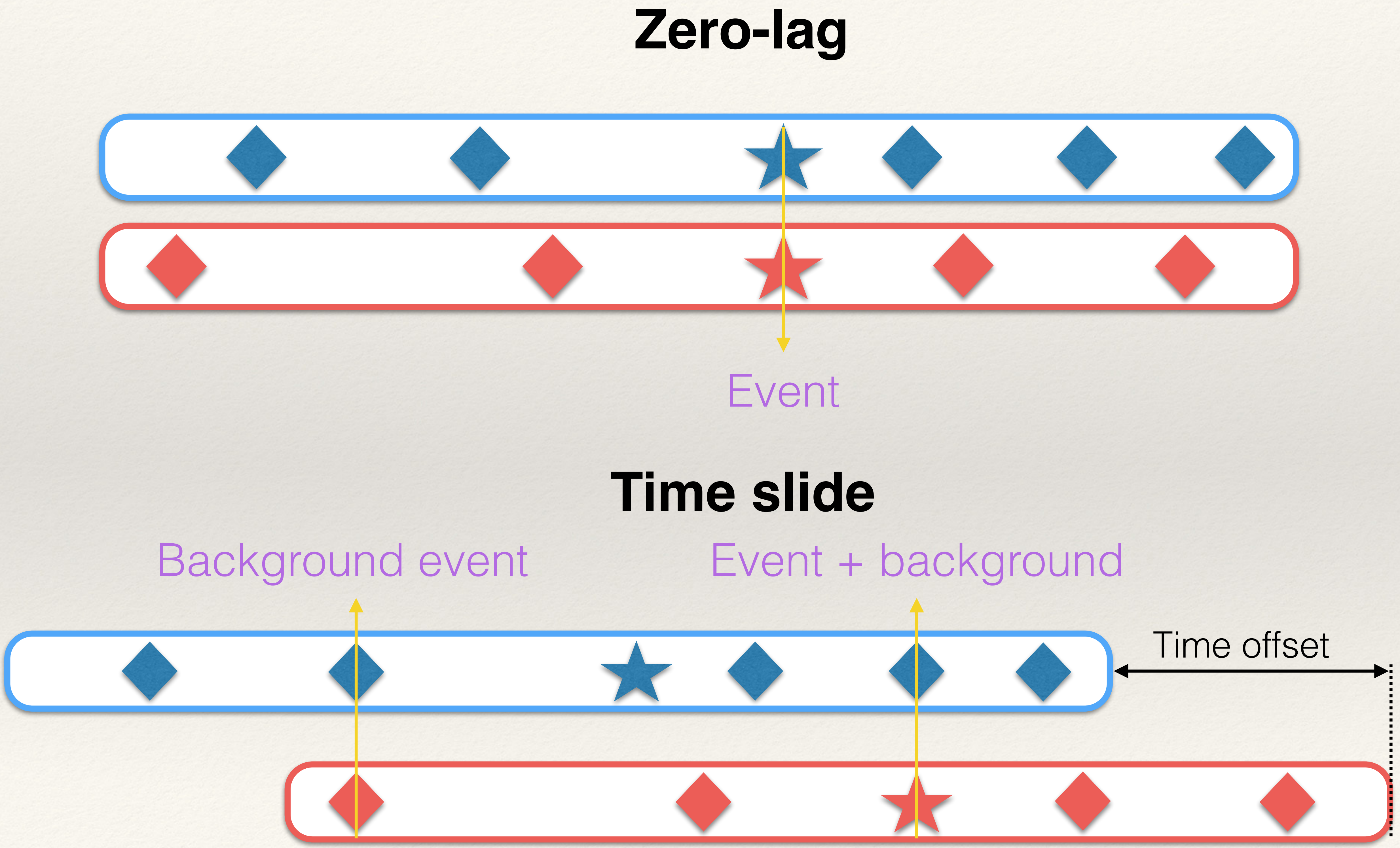


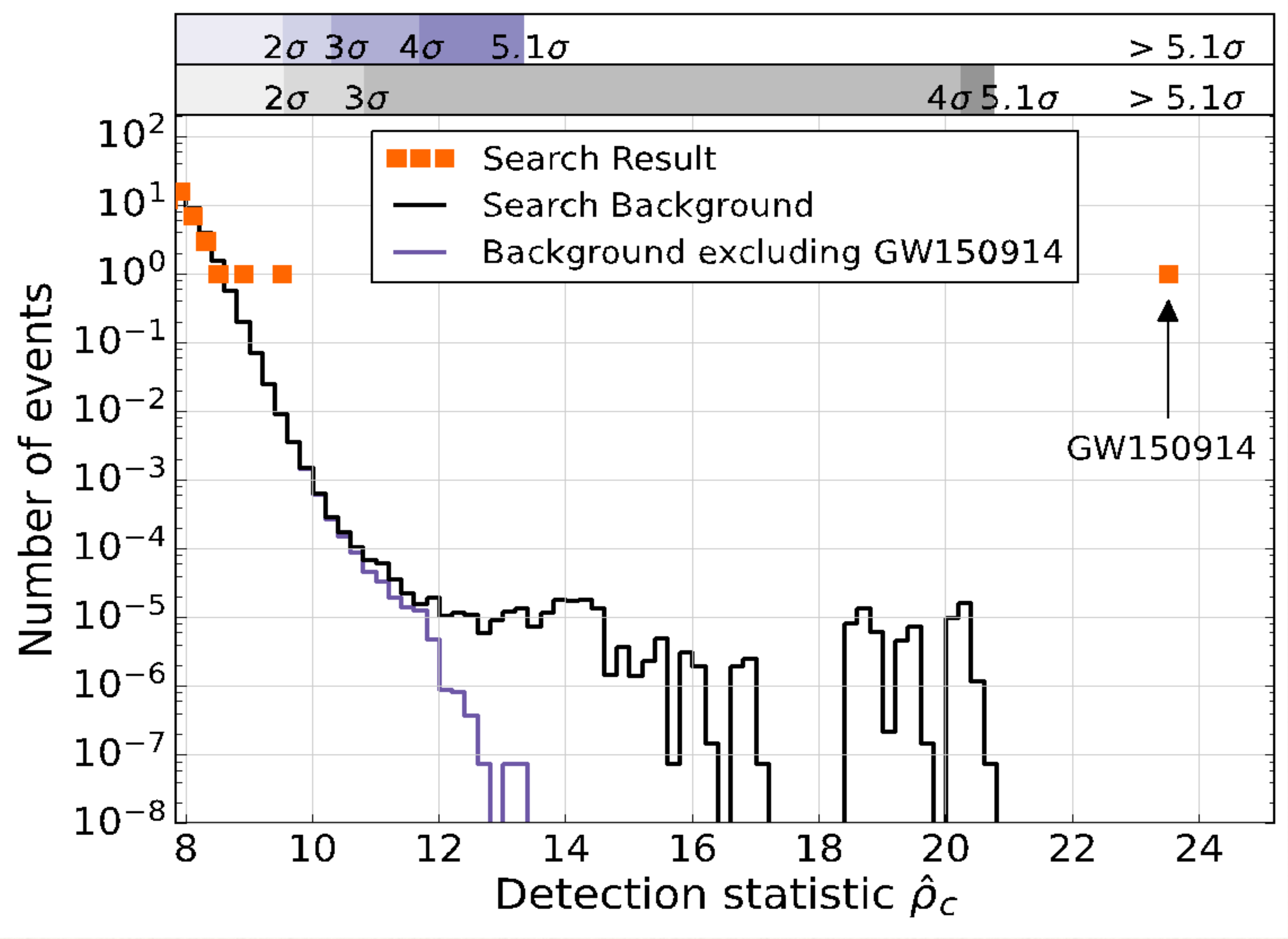
# Calculating a significance (how many sigmas?)



# 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.

# The final product

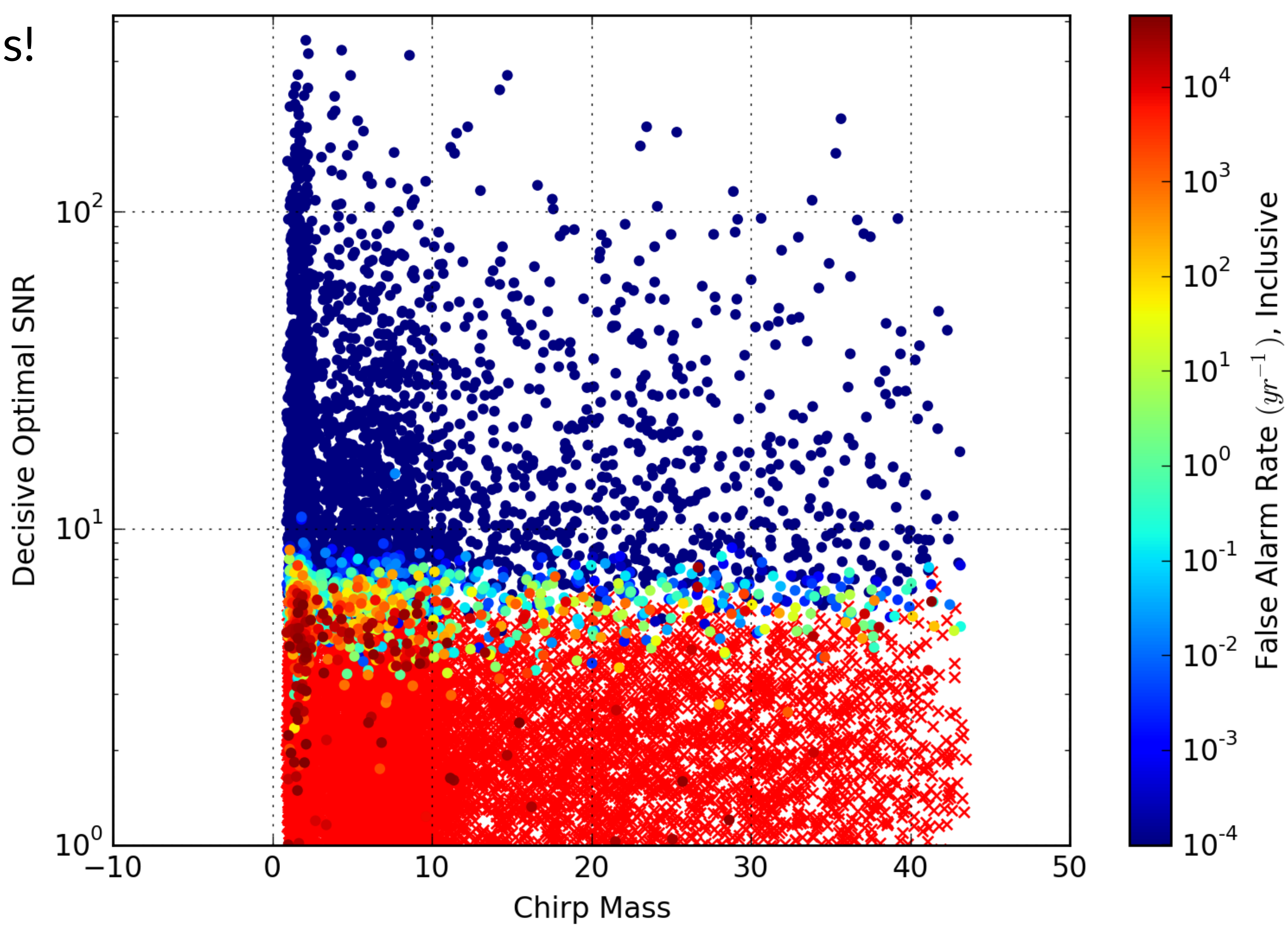





Phys. Rev. Lett. 116, 061102

# How do we validate the analysis?

Simulate lots of signals!

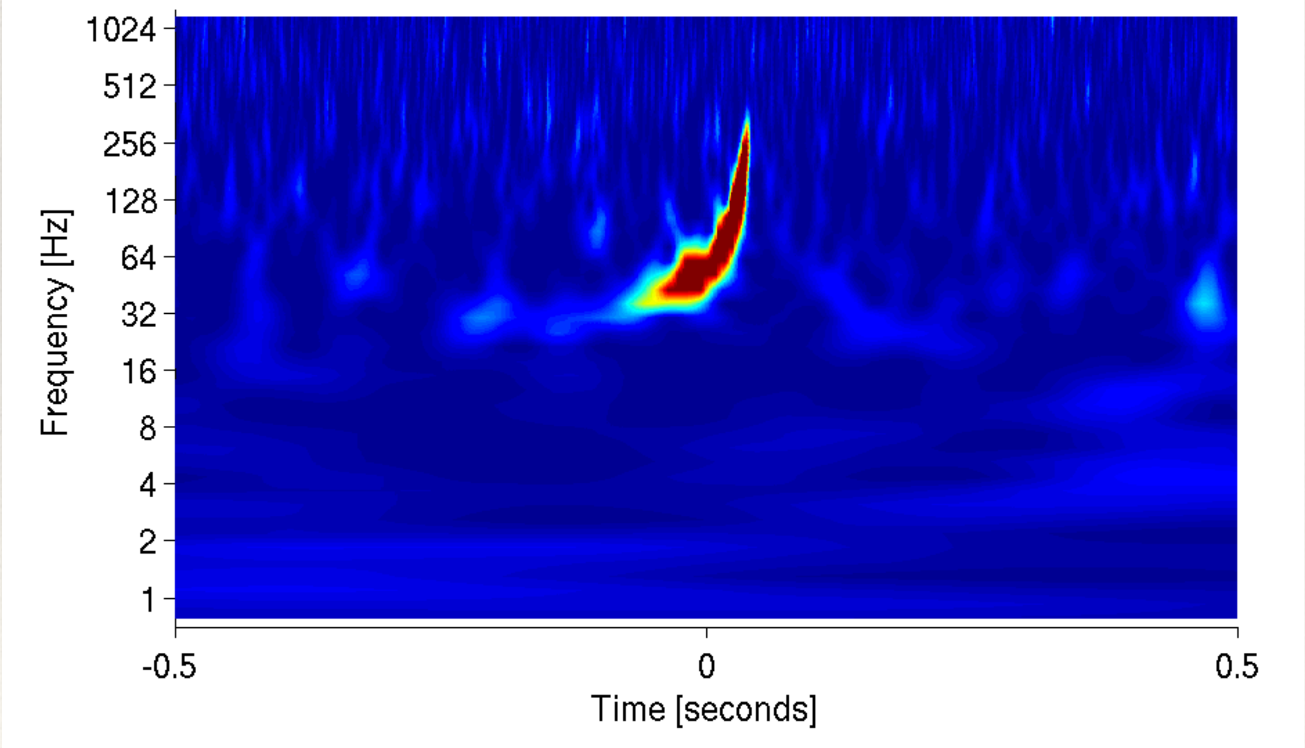


# Weakly modelled search techniques

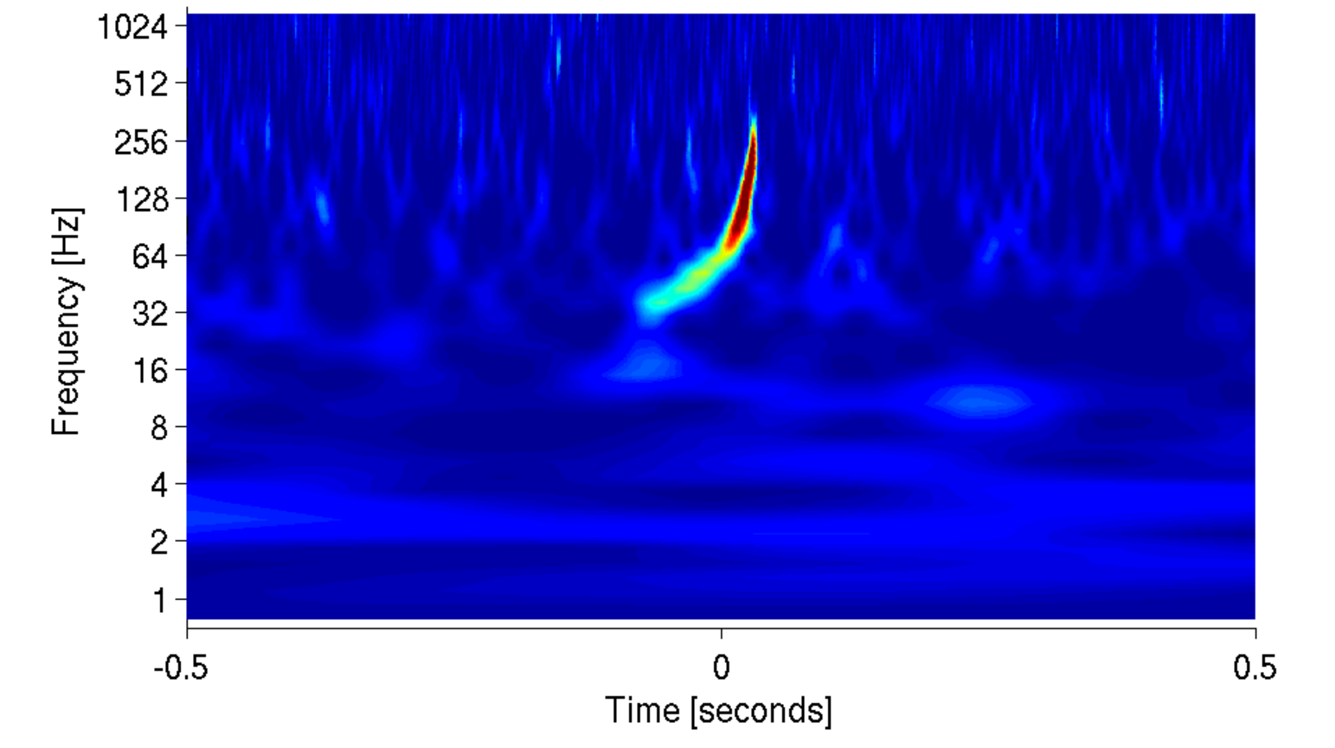
- We don’t **only** rely on matched-filtering
- Our search makes a number of assumptions
- Maybe our waveform models are wrong?
- Maybe general relativity is wrong?
- Maybe we have astrophysical sources that were not expected, or are not easily modelled (supernovae)?

# 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

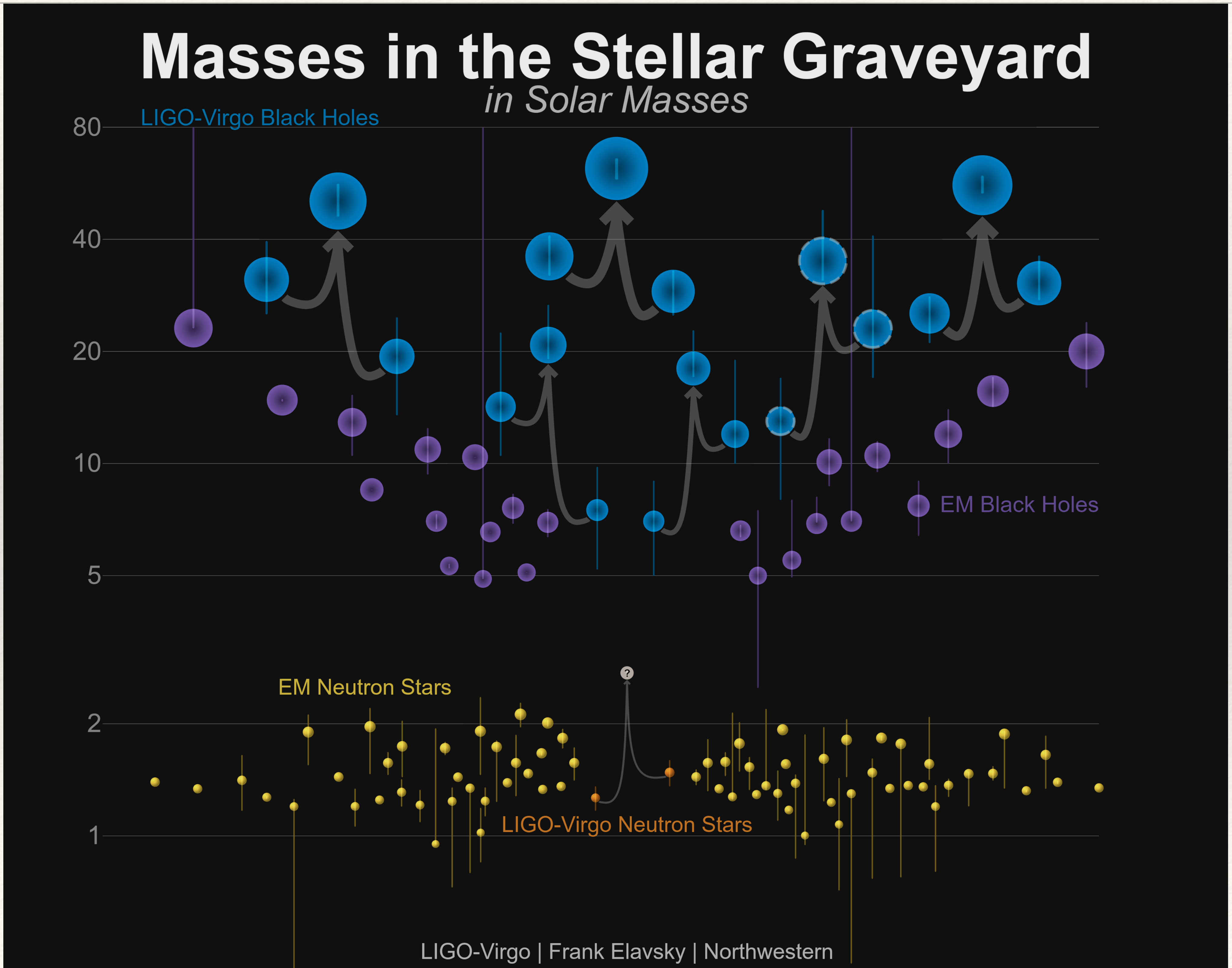



Livingston observatory



Phys. Rev. Lett. 116, 061102

# What's it all for?



# Conclusion

- Gravitational-wave astronomy continues to establish itself as a major new field in astronomy
- We can, for the first time, observe black holes directly.
- Current searches rely on matched-filtering, with ad-hoc statistics to account for non-Gaussianities
- Also use unmodelled searches to catch the unexpected
- Still much development needed, especially as we move towards more sensitive instruments, with broader sensitive curves
  - Broader sensitive curves = Way more filter waveforms needed

# References


- Klimenko et al., CQG. 25 (2008) 114029
- Allen et al., Phys.Rev. D85 (2012) 122006
- Babak, .., IH et al., Phys.Rev. D87 (2013) 024033
- Usman, Nitz, IH et al., CQG. 33 (2016), 215004
- Veitch et al. Phys.Rev. D91 (2015), 042003
- Creighton and Anderson, Gravitational-wave physics and astronomy: An introduction to theory, experiment and data analysis

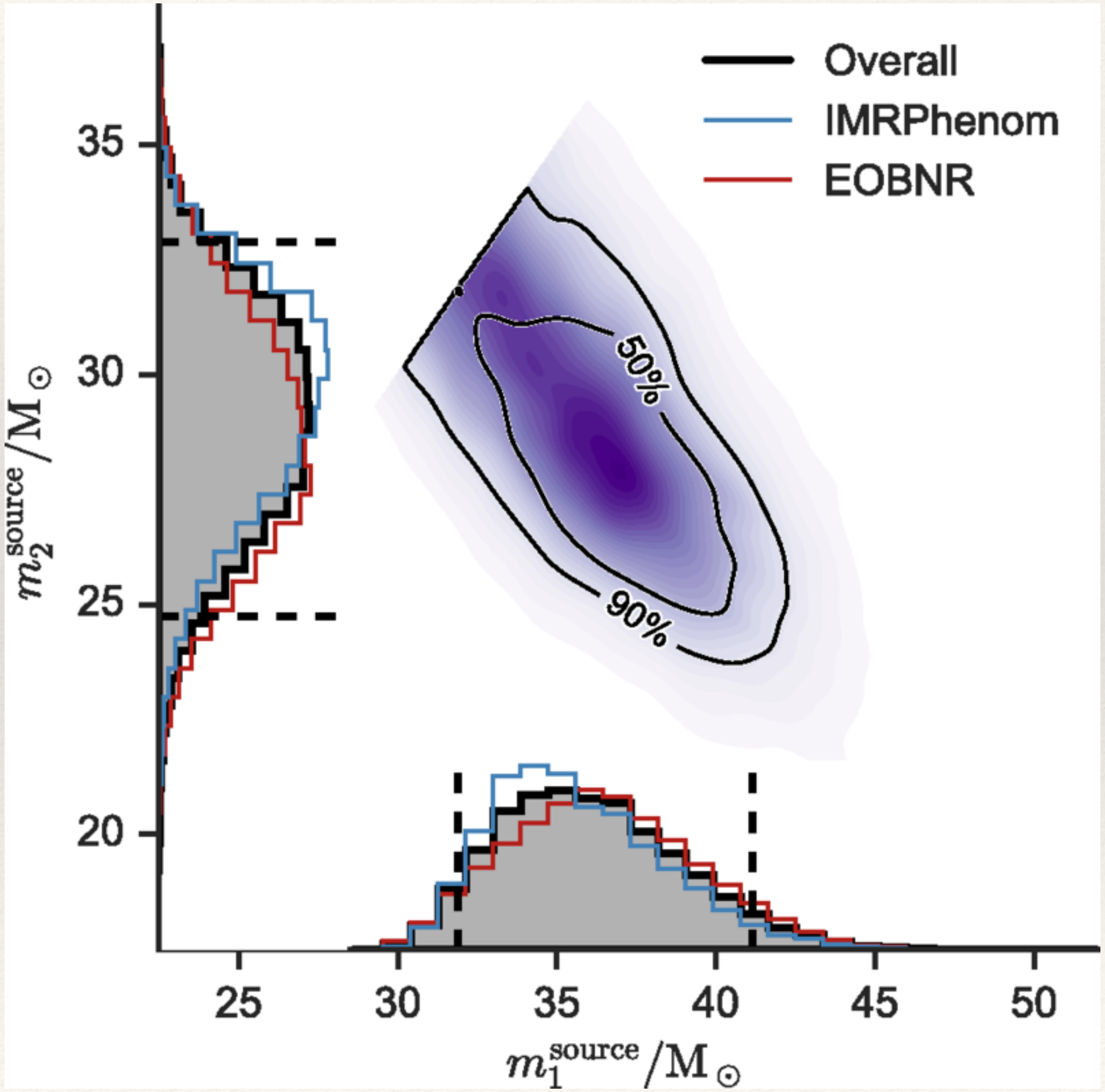
# Post-detection: Measurement of parameters

- Computed using Bayesian Likelihood (requires prior assumptions)

$$P(\xi_i|s) = \frac{P(\xi_i)}{P(s)} P(s|\xi_i)$$

$$P(s|\xi_i) \propto e^{-\langle s-h|s-h\rangle/2}$$

- Markov-chain Monte-Carlo techniques employed to evaluate this over a large parameter space






Phys. Rev. Lett. 116, 241102

# Signal model - Summary

- Computing the phase and amplitude of each of the modes can be computationally expensive
- Trying to speed this up is the focus of much development
- Basic idea is to define a reduced-basis representation of the waveform, combined with fits to how the various bases need to be combined as the parameters of the signal changes
    - Often been done "by hand" in the past, but recently been demonstrated also using machine-learning techniques

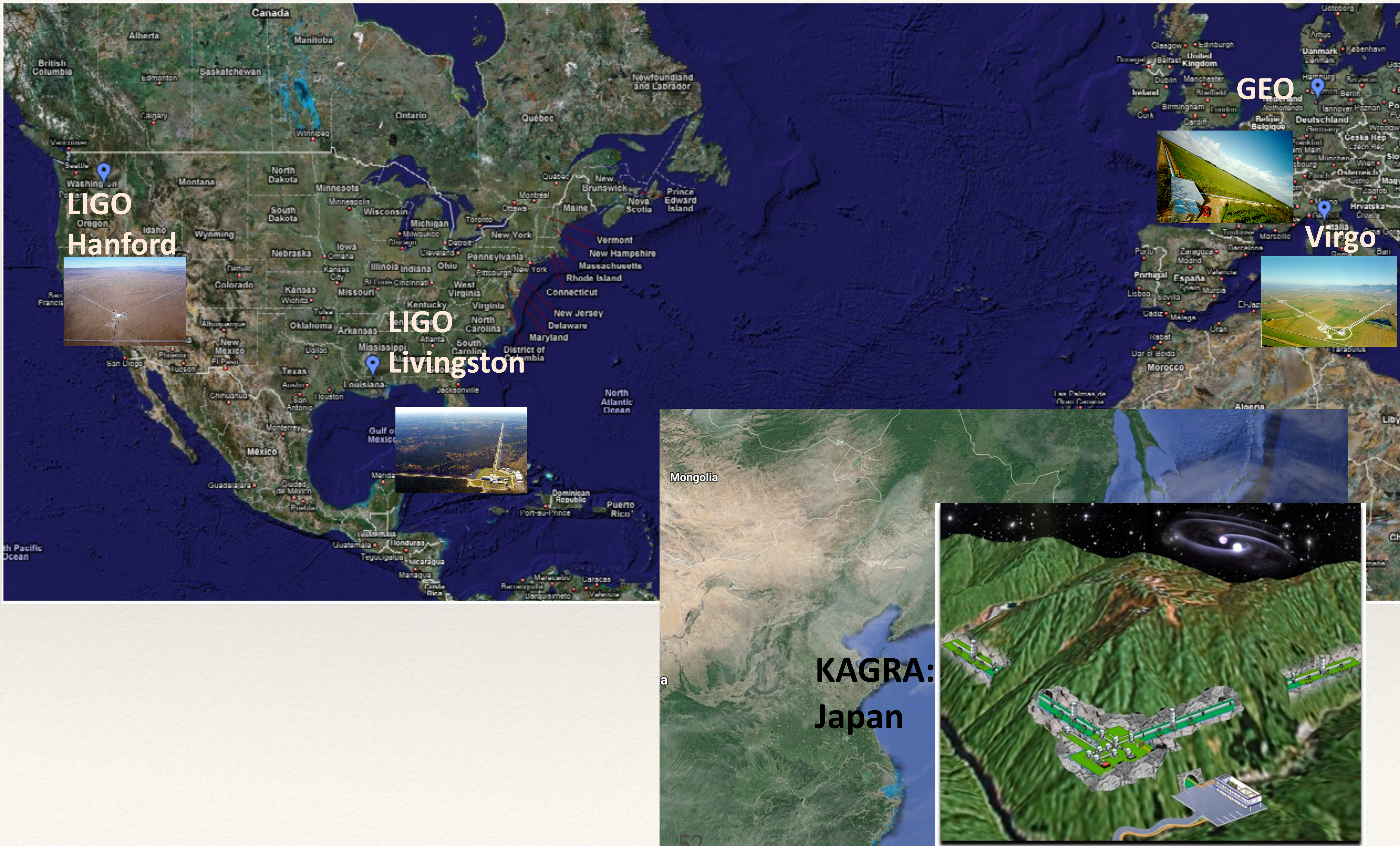
Pürrer, CQG. 31 (2014), 195010
Canizares et al., PRL. 114 (2015), 071104
Smith et al., PRD 94 (2016) no.4, 044031

# Observing gravitational-waves

**LIGO Hanford, WA**

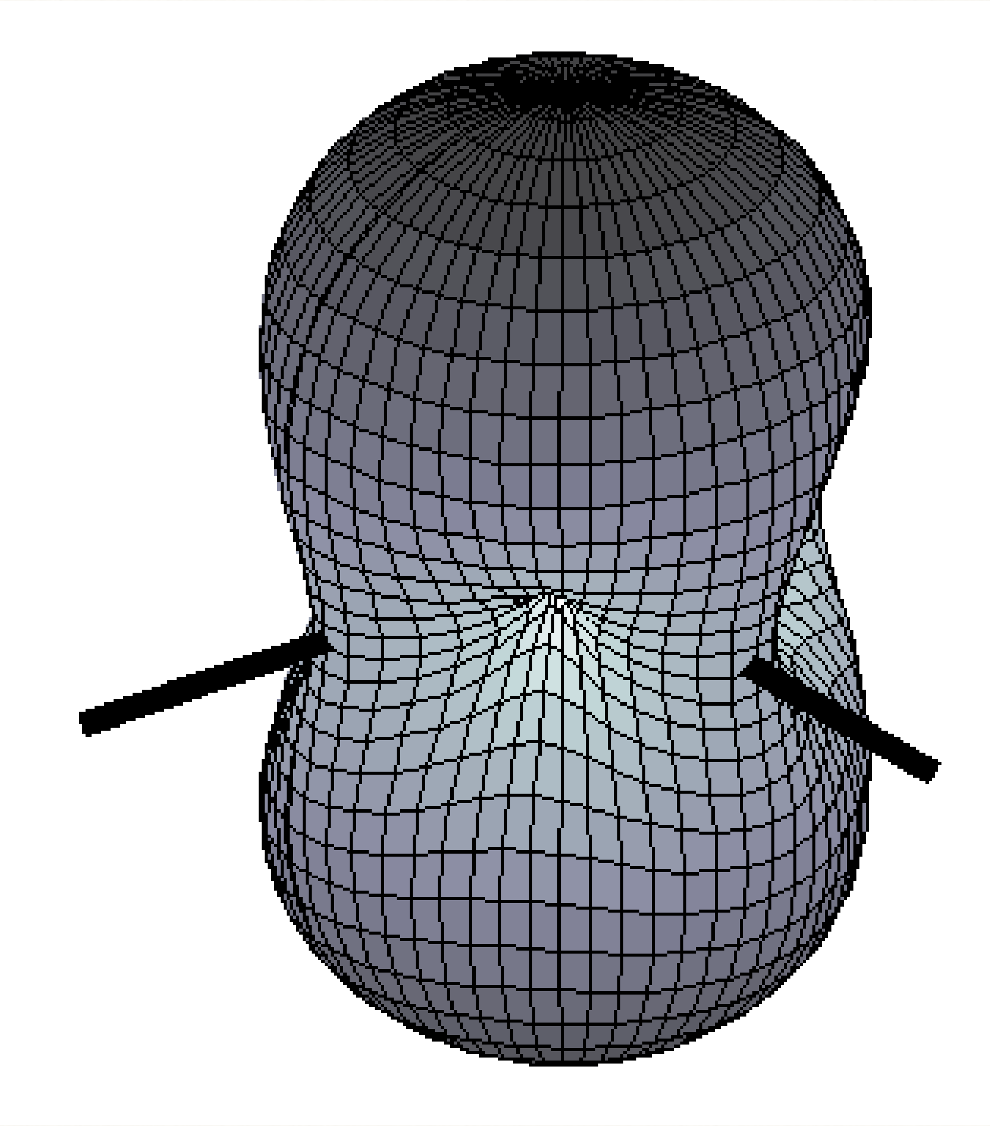
**Virgo, Cascina, Italy**

# A global network



# 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