GW150914: L’evento registrato il 14/9/15

Elena Cuoco
elena.cuoco@ego-gw.it

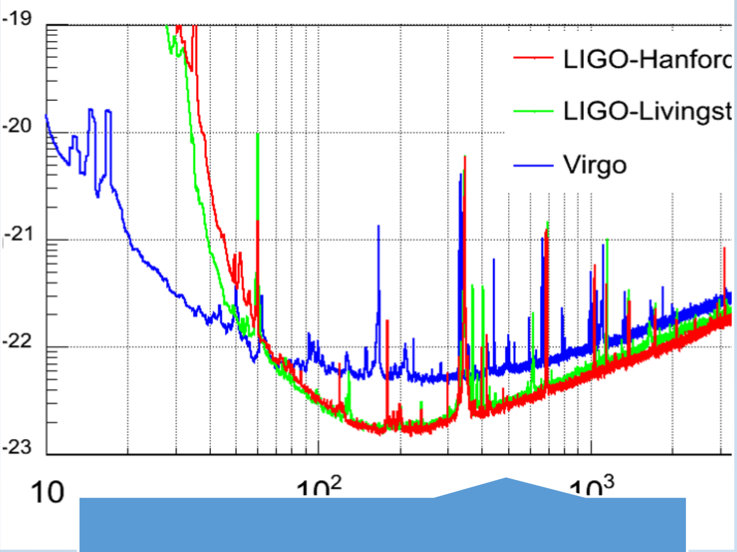
European Gravitational Observatory

Outline

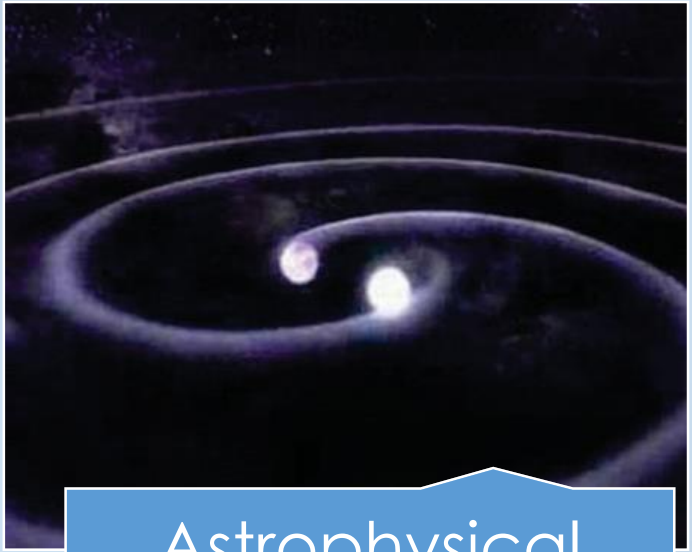
- The meaning of word ‘Detection’ for GW community
- Matched filter and cWB
- Detector characterization
- The Event: GW150914

For the content of this presentation, many thanks to
M. Drago (one of cWB developers)
and
G.M. Guidi (CBC Virgo-Ligo co-chair)

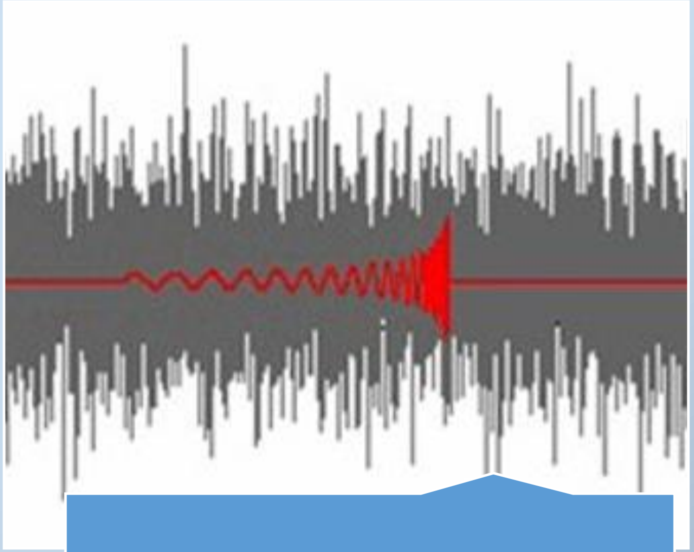
What is a GW detection



Detector

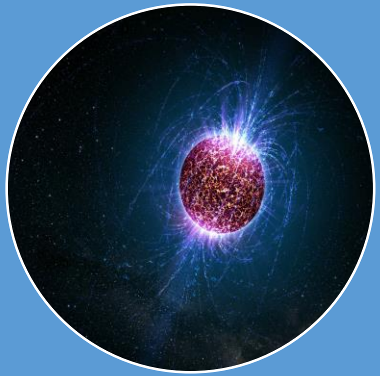


Astrophysical signal



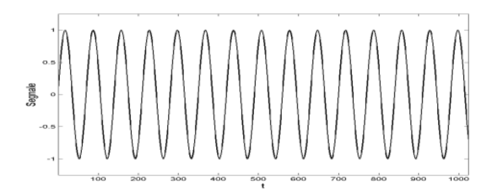
Signal extraction

Gravitational Waves Signals



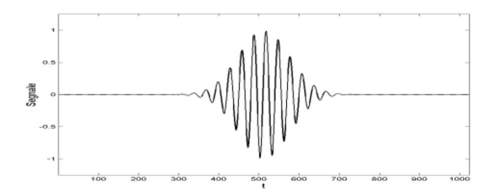
Periodic signals

- Rotating Neutron Stars



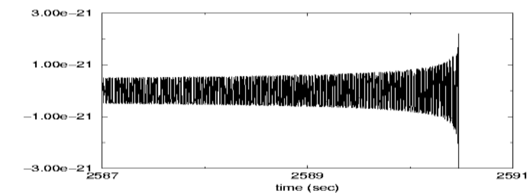
Short transient signals

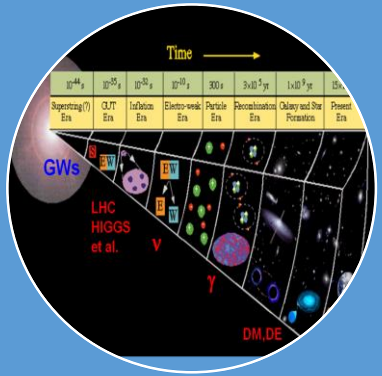
- Supernovae



Transient signals

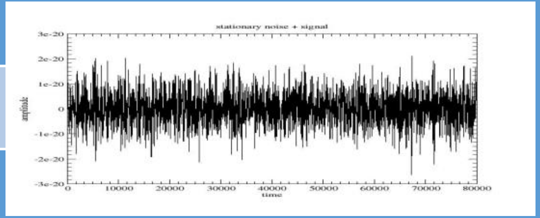
- Compact Coalescing Binaries





BroadBand signals

- Stochastich GW background

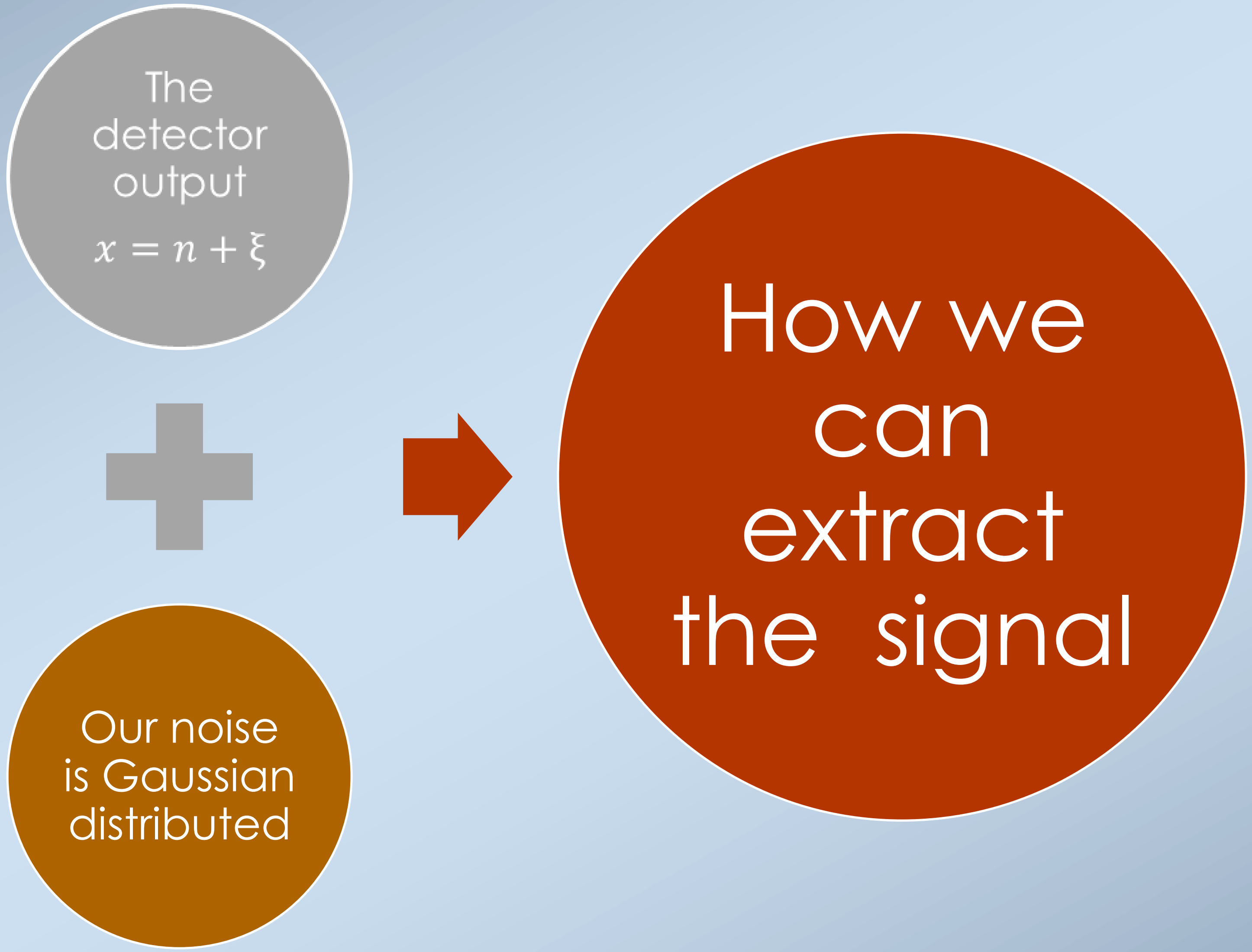


Transient signals

How we detect them

- Optimal Filter
- What to do if we don’t know the signal
- Noise and data quality
- Sky localization
- Parameter estimation

Ideal world: Optimal filter



The detector output

$x = n + \xi$

Our noise is Gaussian distributed

How we can extract the signal

Hypothesis test

		Signal presence	
		Yes	No
Decision rule	Yes	True Alarm	False Alarm
	No	False Dismissal	True Dismissal

At each time the signal could be present or not

Hypothesis test

		Signal presence	
		Yes	No
Decision rule	Yes	True Alarm	False Alarm
	No	False Dismissal	True Dismissal

At each time the signal could be present or not

At each time we can decide that the signal is present or not (decision rule)

Hypothesis test

		Signal presence	
		Yes	No
Decision rule	Yes	True Alarm	False Alarm
	No	False Dismissal	True Dismissal

At each time the signal could be present or not

At each time we can decide that the signal is present or not (decision rule)

4 situations: two right and other wrong

Neyman-Pearson criterion

		Signal presence	
		Yes	No
Decision rule	Yes	True Alarm	False Alarm
	No	False Dismissal	True Dismissal

At each time the signal could be present or not

At each time we can decide that the signal is present or not (decision rule)

4 situations: two right and other wrong

Neyman-Pearson criterion**: best decision rule gives greater True Alarm Rate at the same False Alarm Rate**

Maximum Likelihood

Likelihood Ratio

$$L = \frac{p(x \mid h)}{p(x \mid 0)}$$

If our noise is Gaussian

- Noise model: Gaussian Noise

$$p(x \mid 0) \propto \exp[-x^2 / \sigma^2]$$

- Signal model:

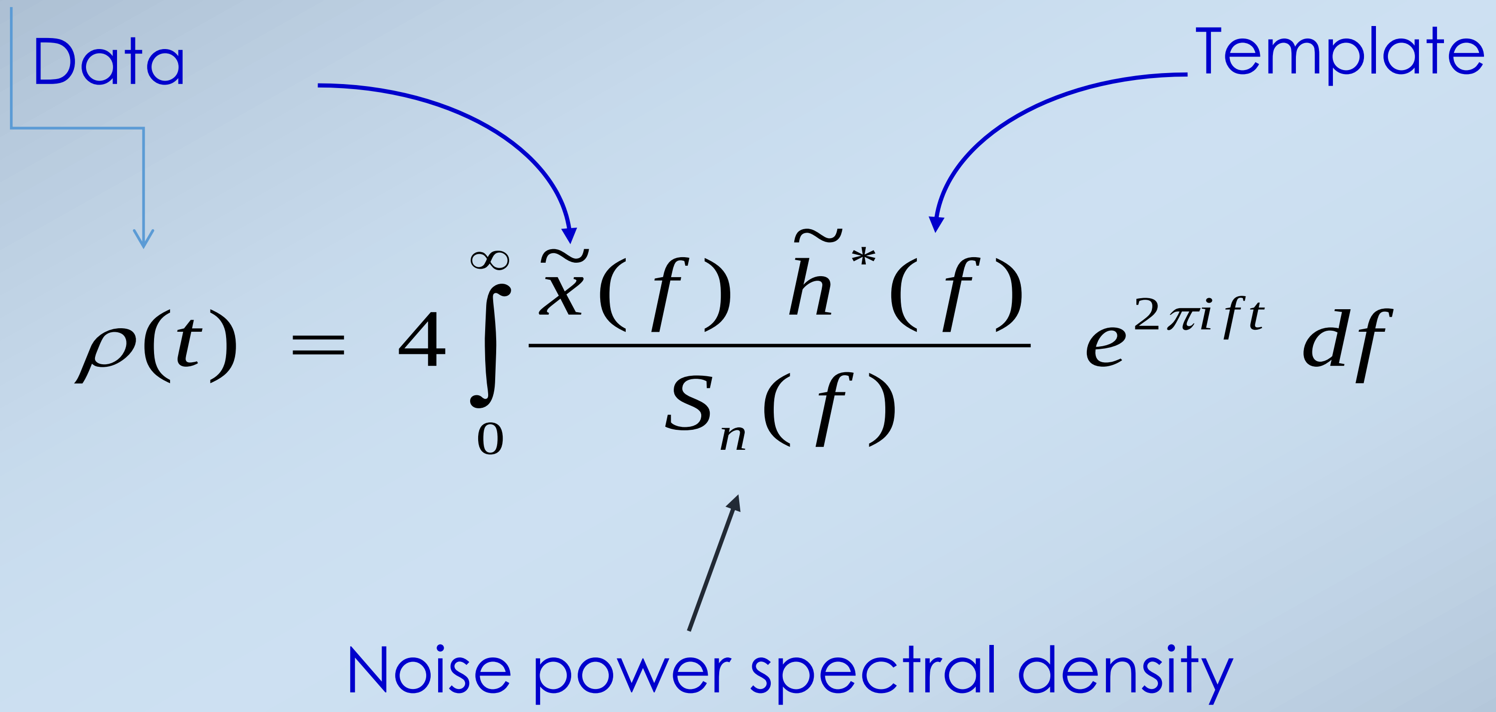
$$p(x \mid h) \propto \exp[-(x-h)^2 / \sigma^2]$$

Detector Noise Variance

Signal

Optimal Filter is: Matched Filter

Maximizing the likelihood



Data

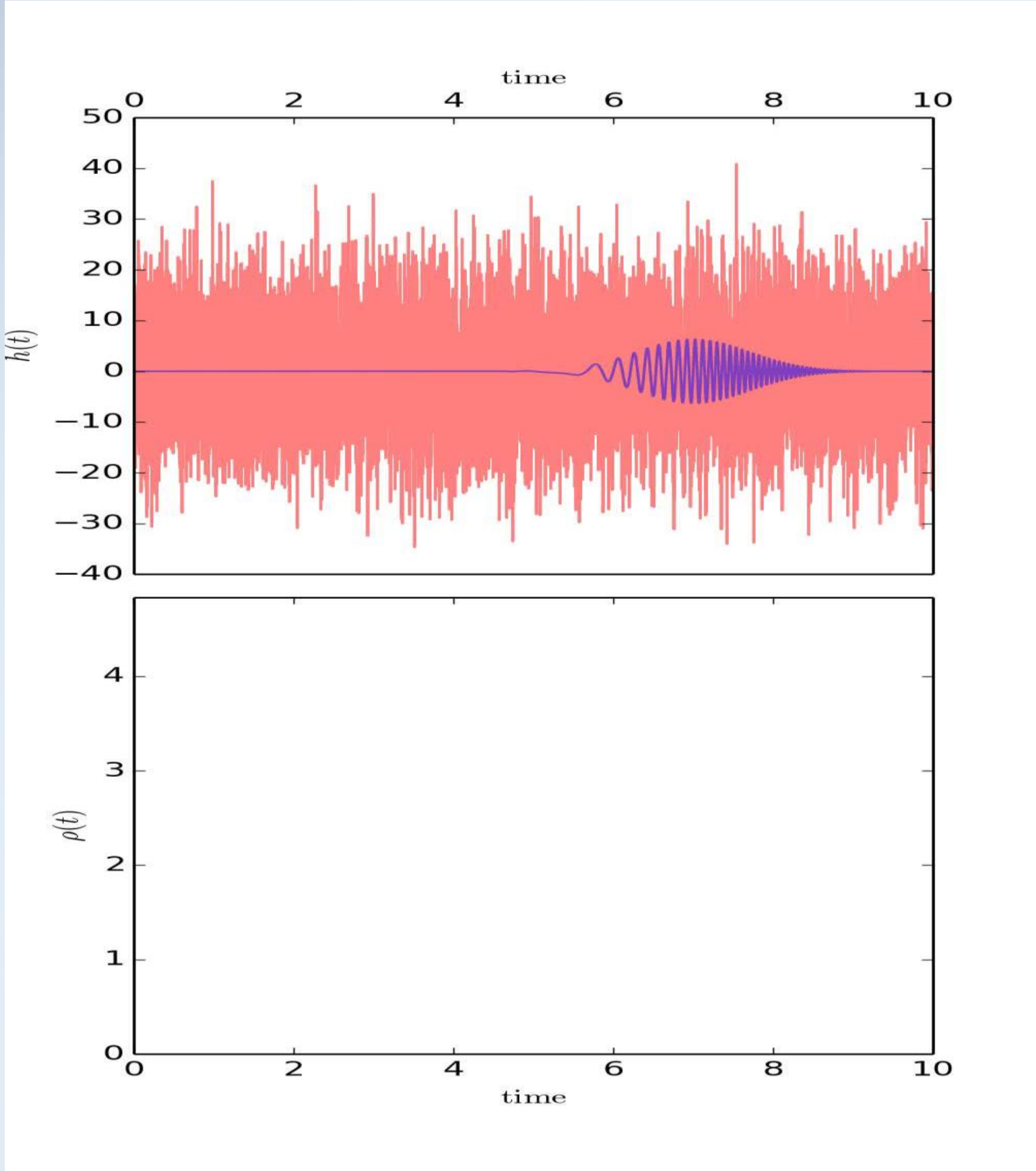
Template

$$\rho(t) = 4\int_0^{\infty} \frac{\tilde{x}(f)\;\tilde{h}^*(f)}{S_n(f)}\, e^{2\pi i f t}\, df$$

Noise power spectral density

Look for maxima of $|\rho(t)|$ above some threshold ➔ trigger

Matched filter search



Signal to Noise Ratio (SNR)

A key definition for the signal in the detector noise is its SNR

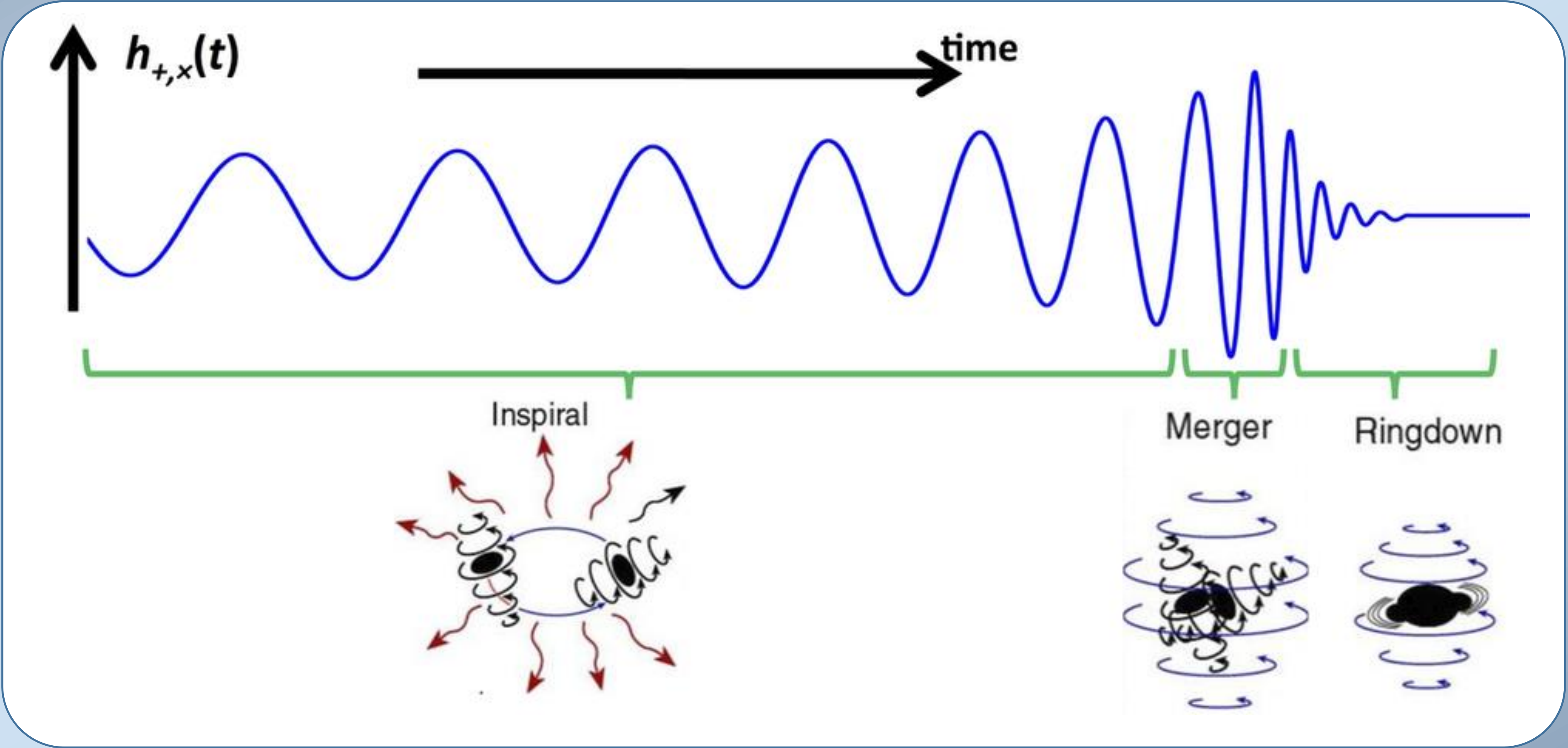
Signal

$$SNR = 2\left[\int_0^\infty \frac{|\tilde{h}(f)|^2}{S_n(f)}\, df\right]^{1/2}$$

Noise power spectral density

CBC Matched Filtering

We need a template waveform to use to extract the signal from the background



Detector responce and Antenna Patterns

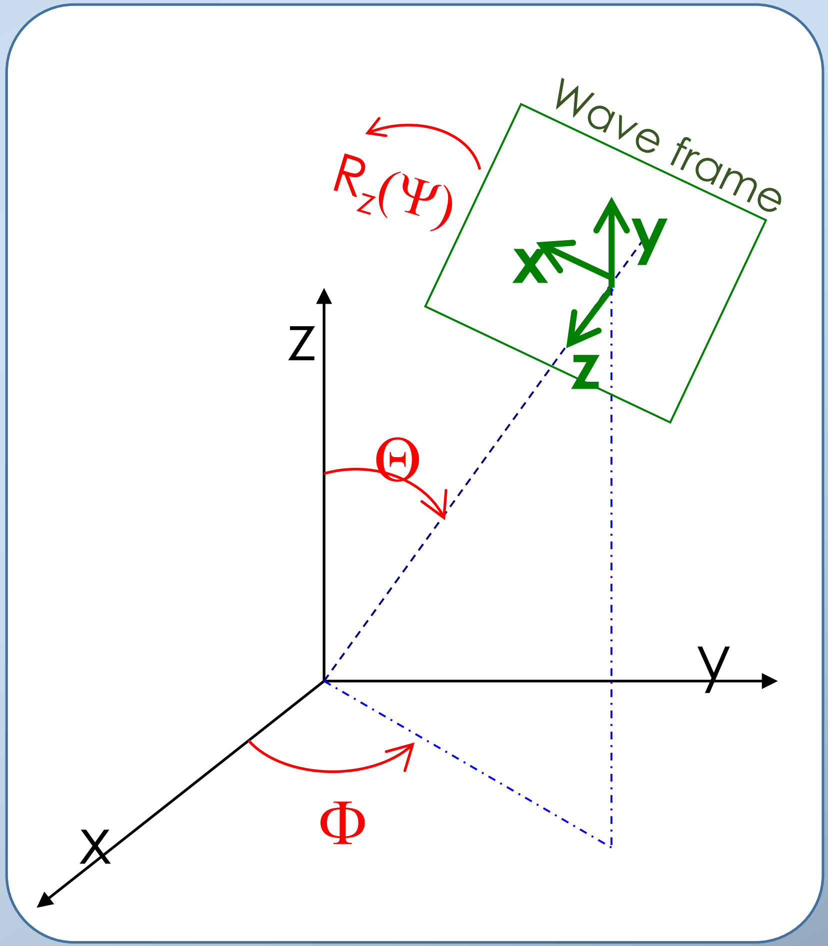
Detector response in the TT gauge can be written as:

$$\xi(t) = F_{+}(\Theta,\Phi,\Psi)h_{+}(t) + F_{\times}(\Theta,\Phi,\Psi)h_{\times}(t)$$

Where F_+ and $F_\times$ depend on the arms orientation respect to the wave propagation and the wave polarization

$$F_{+}(\Theta,\Phi,\Psi) = \frac{1}{2}(1+\cos^2\Theta)\cos 2\Phi \cos 2\Psi - \cos\Theta \sin 2\Phi \sin 2\Psi$$

$$F_{\times}(\Theta,\Phi,\Psi) = \frac{1}{2}(1+\cos^2\Theta)\cos 2\Phi \sin 2\Psi - \cos\Theta \sin 2\Phi \cos 2\Psi$$



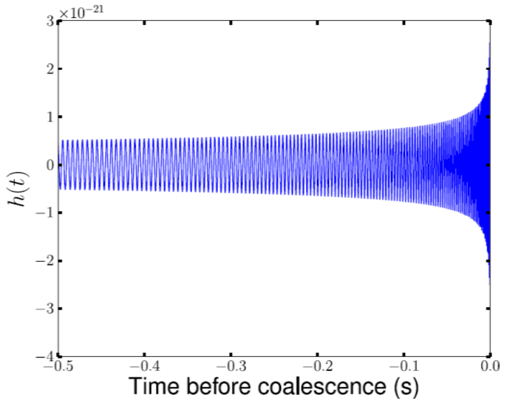
Emission: inspiral phase

$$h_+(t) = A_{\rm GW}(t)\left(1+\cos^2\iota\right)\cos\phi_{\rm GW}(t)$$

$$h_\times(t) = -2A_{\rm GW}(t)\cos\boxed{\iota}\sin\phi_{\rm GW}(t)$$

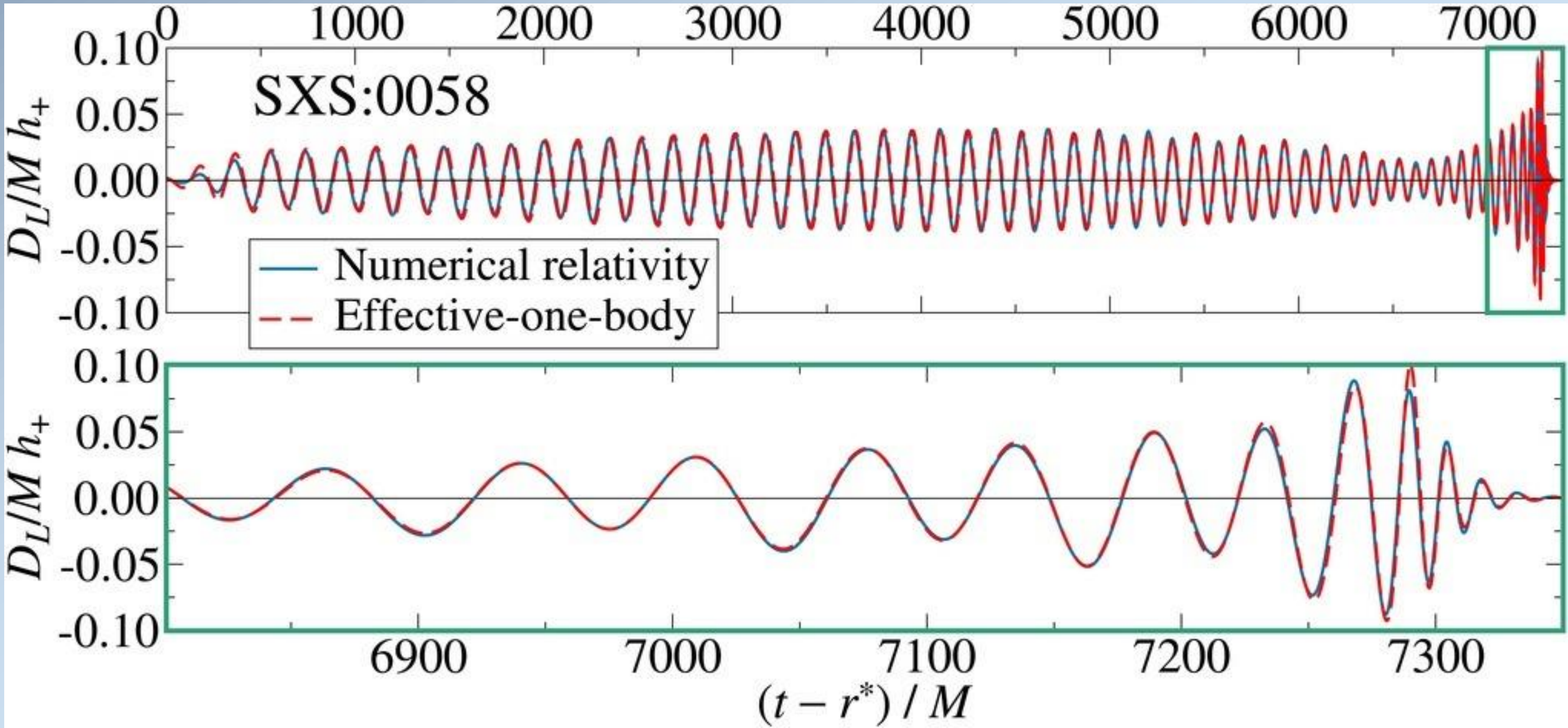
the inclination angle between the direction of the detector as seen from the binary's center-of-mass, and the normal to the orbital plane

During the inspiral, if the phase ϕ_{GW} is computed using PN expansion,at the leading order the phase evolution depends on the chirp mass



$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3}\dot{f}\right]^{3/5}$$

Merger and ringdown

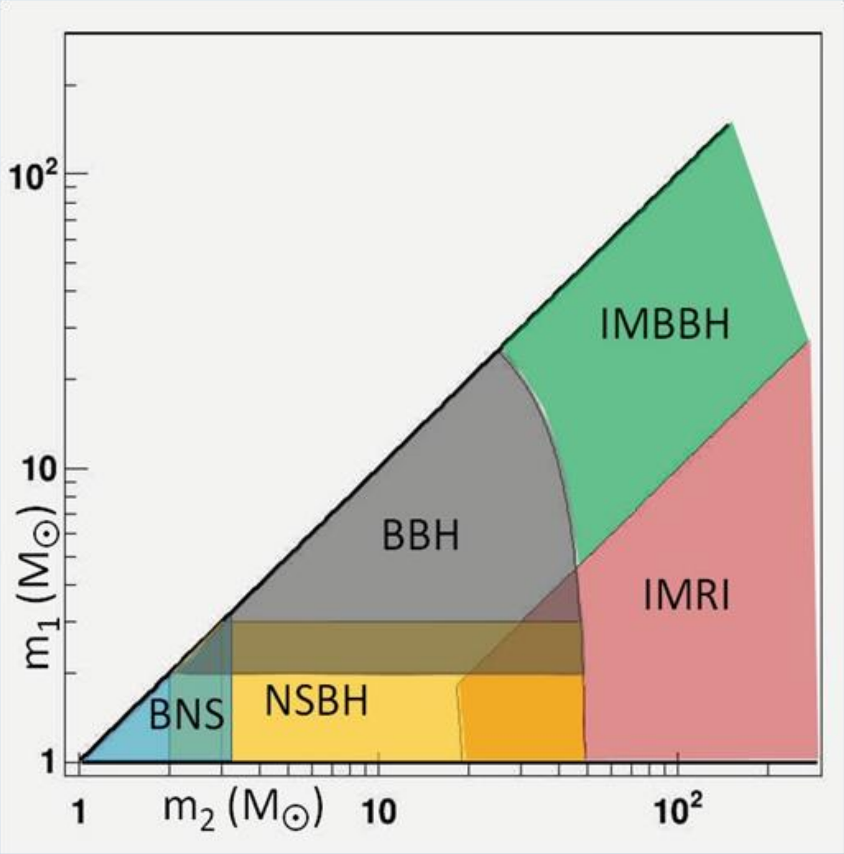


Comparison of the effective-one-body model to a numerical-relativity waveform of a precessing black-hole binary. © A. Taracchini/AEI

Building templates bank

- To cover in efficient way the parameters space, we build a templates bank requiring that the signal can be detected with a maximum loss of 3% of its SNR
- A mismactch between templates is defined as

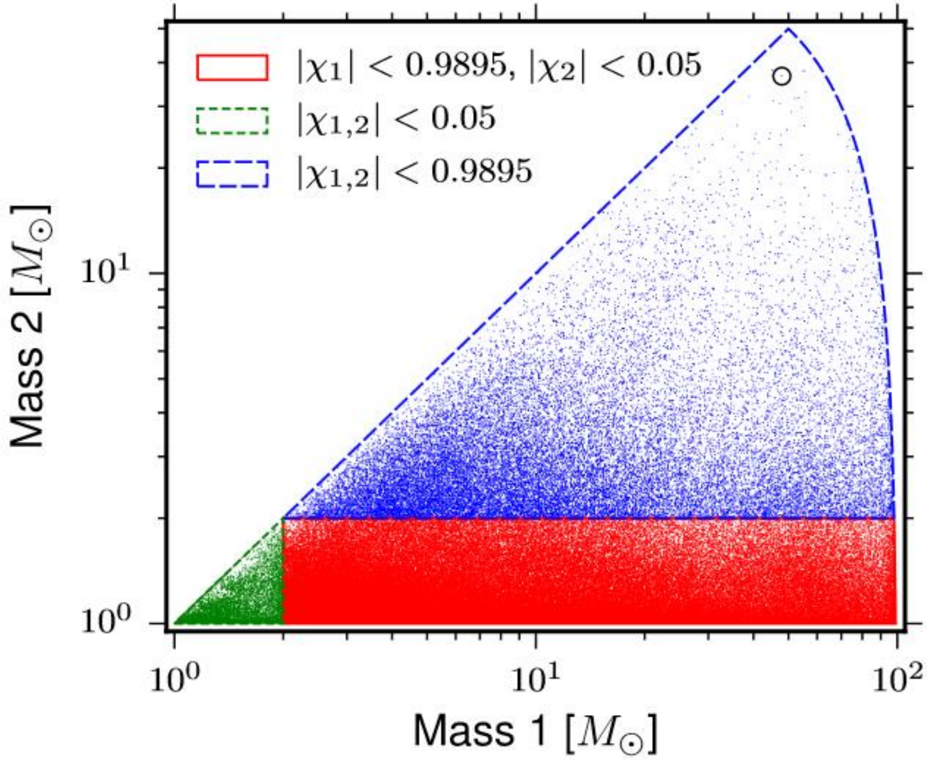
$$\mathscr{M}(T_j, T_k) = \frac{(T_j;T_k)}{\sqrt{(T_j;T_j)\,(T_k;T_k)}}$$



The template bank

- **~ 250000 waveforms**
- Component masses: [1,99] $M_\odot$
- Total Mass: <100 $M_\odot$
- Dimensionless spins: <0.99 (0.05 for m<2$M_\odot$)

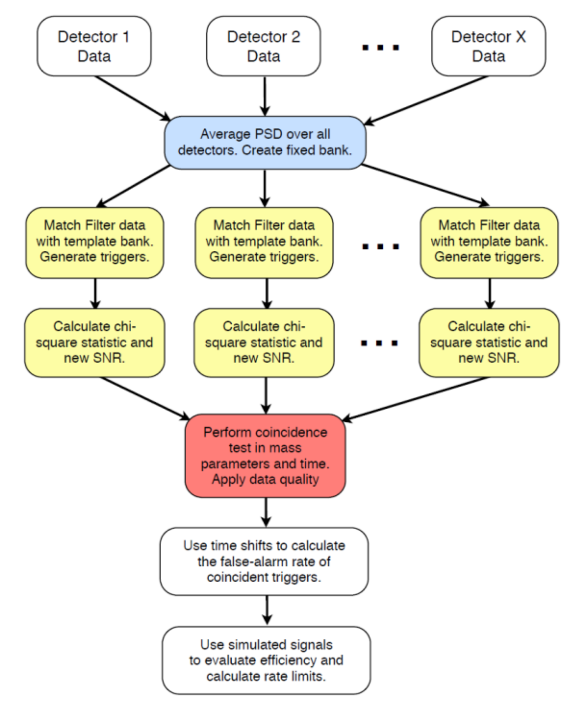
arXiv: 1602.03839



Candidate and background events are divided into three search classes (red, green, blue) based on template length

Ligo-Virgo CBC pipelines

Currently three pipelines are used to detect gravitational waves through match filtering



Detector 1 Data

Detector 2 Data

...

Detector X Data

Average PSD over all detectors. Create fixed bank.

Match Filter data with template bank. Generate triggers.

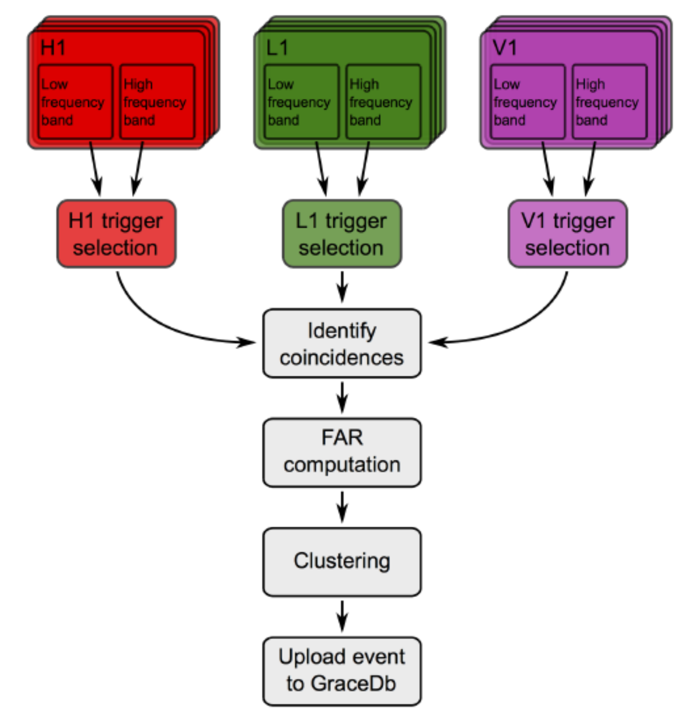
Calculate chi-square statistic and new SNR.

Perform coincidence test in mass parameters and time. Apply data quality

Use time shifts to calculate the false-alarm rate of coincident triggers.

Use simulated signals to evaluate efficiency and calculate rate limits.

pyCBC
(Usman et al, 2015)



H1 trigger selection

L1 trigger selection

V1 trigger selection

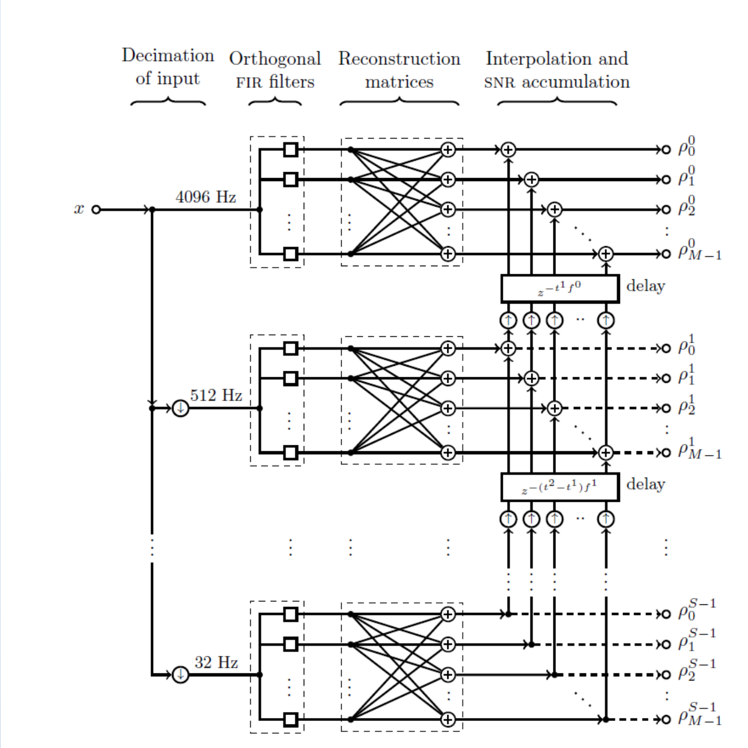
Identify coincidences

FAR computation

Clustering

Upload event to GraceDb

MBTA
(Adams et al. 2015)



gstlal-SVD
(Cannon et al. 2012)

Generic transient signals search

What if we don't know the signal

What to do if our noise is not Gaussian

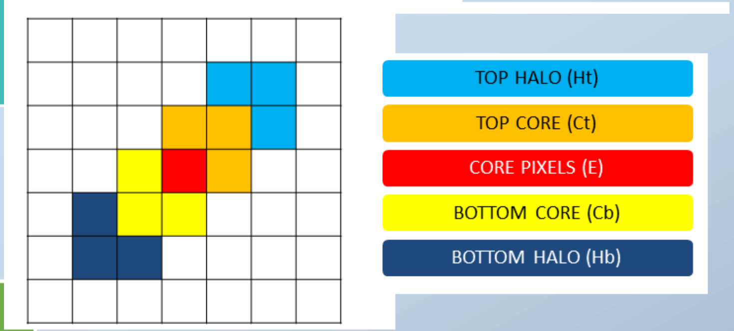
We need some pipeline which does not rely on the knowledge of waveform

Coherent WaveBurst

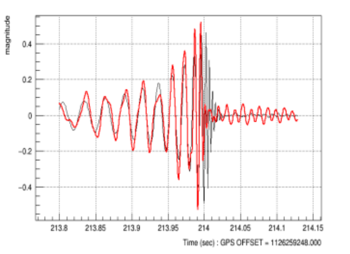
Excess power are selected from a set of wavelet time-frequency maps

Data from both detector are combined together

Triggers are analyzed coherently to estimate signal waveform, wave polarization, source location, using the constrained likelihood method



Selects the best fit waveform which corresponds to the maximum likelihood statistic over a 200000 sky positions



The event are ranked using a variable η_c

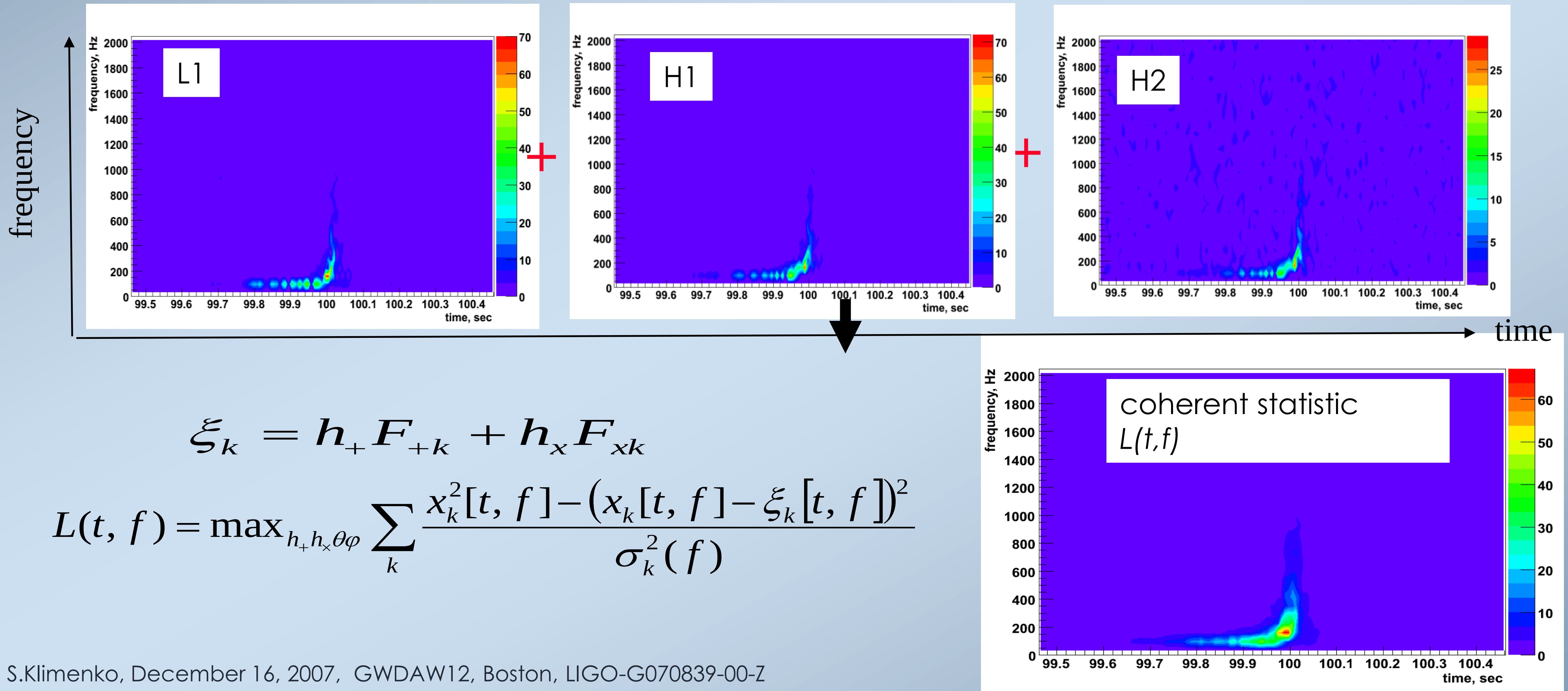
E_c ➔ Normalized coherent energy between the two detectors

E_n ➔ normalized noise energy derived by subtracting the reconstructed signal from the data

$$\eta_c = \sqrt{\frac{2E_c}{(1+E_n/E_c)}}$$

Coherent WaveBurst

- End-to-end multi-detector coherent pipeline
  - construct coherent statistics for detection and rejection of artifacts
  - performs search over the entire sky
  - estimates background with time shifts

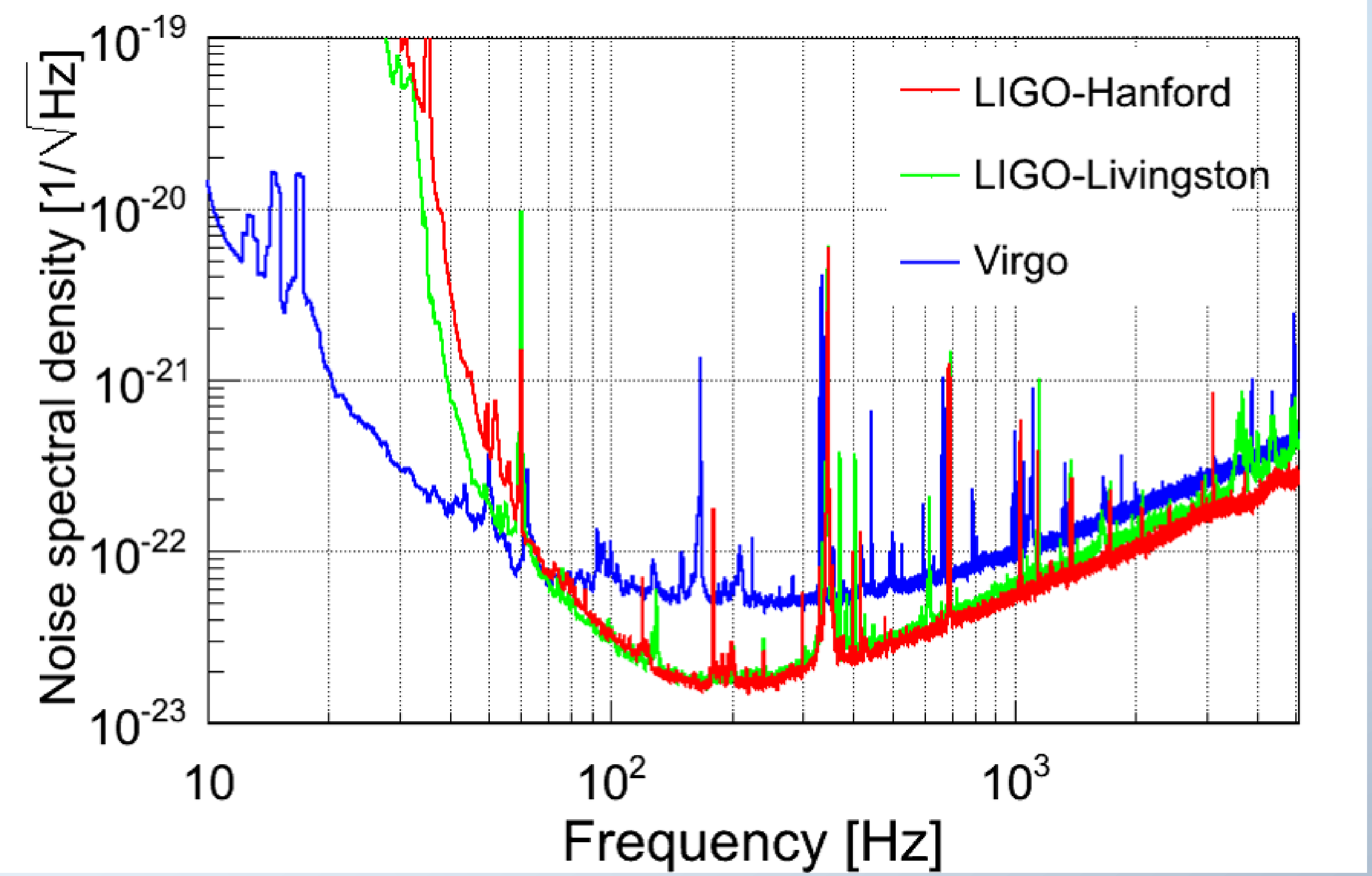


$$\xi_k = h_+ F_{+k} + h_\times F_{\times k}$$

$$L(t,f) = \max_{h_+ h_\times \theta\varphi} \sum_k \frac{x_k^2[t,f] - \left(x_k[t,f] - \xi_k[t,f]\right)^2}{\sigma_k^2(f)}$$

The noise

How to deal with noise

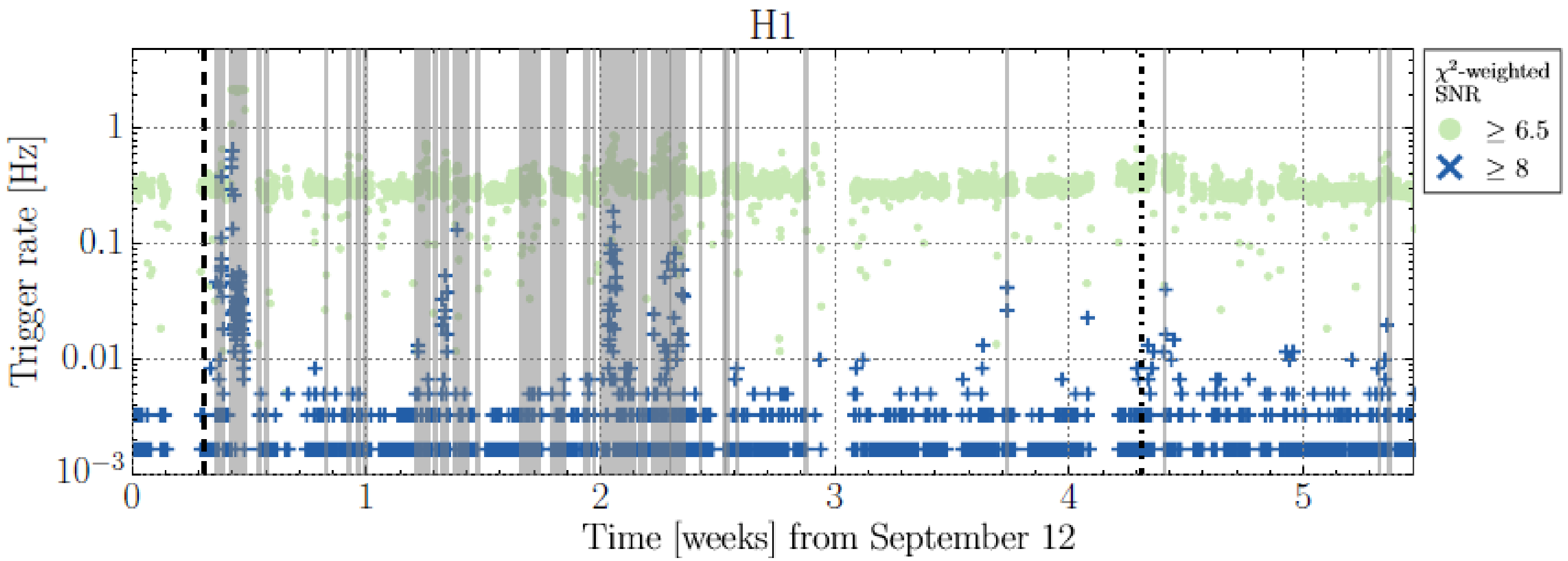


The detector noise

- Not stationary
- Not Gaussian
- Contaminated by a lot of spurious events
- ....

Identifyng noise source

- Transient noise (**glitches**) can occur within the targeted frequency range
- More than **200000 auxiliary channels** are recorded to monitor instrument behaviour and environmental conditions
- In the case of clear correlation within glitches in gravitational wave channel and auxiliary ones, data are discarded from the analysis (**vetoed**)



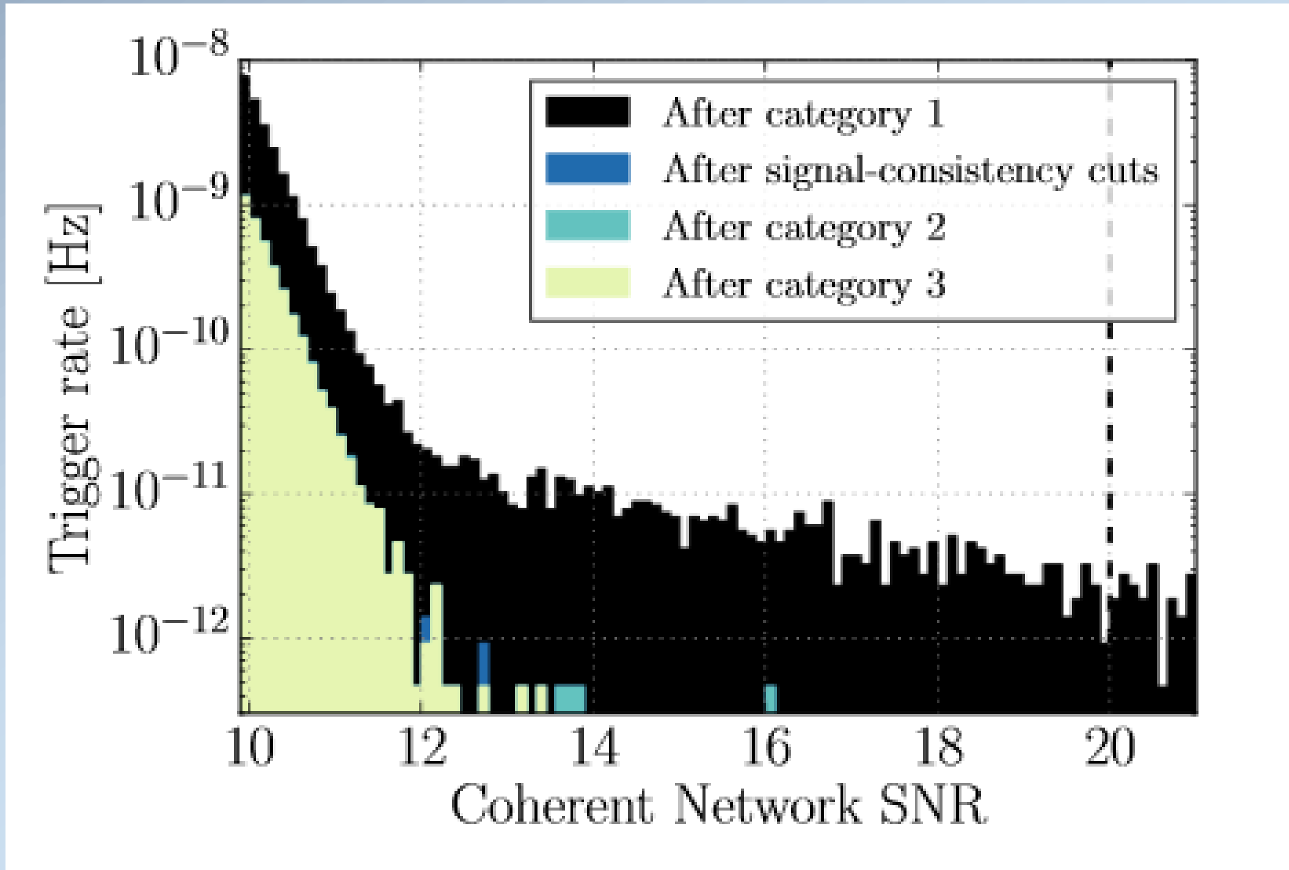
arXiv:1602.03844

Data quality

- **Data quality flags**: exclude periods on the order of seconds to hours when known noise couplings is met
  - ***Category 1***: critical issue
  - ***Category 2***: known coupling active
  - ***Category 3***: coupling mechanism not understood
- **Data quality triggers**: short duration vetoed generated by algorithms that identify significant correlations between triggers in h(t) and auxiliary channels
  - Category 3

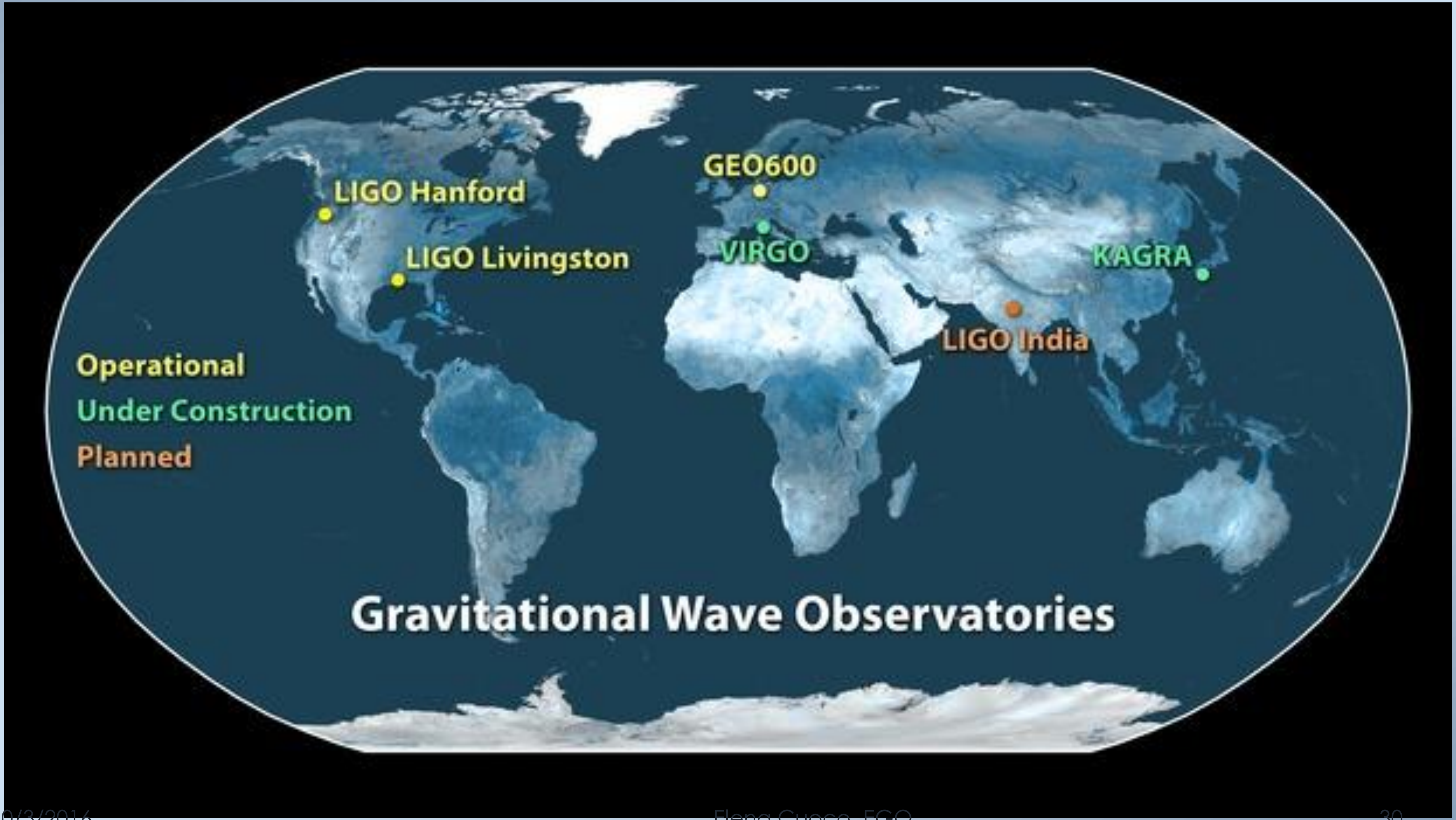
Data quality effects

arXiv: 1602.03844

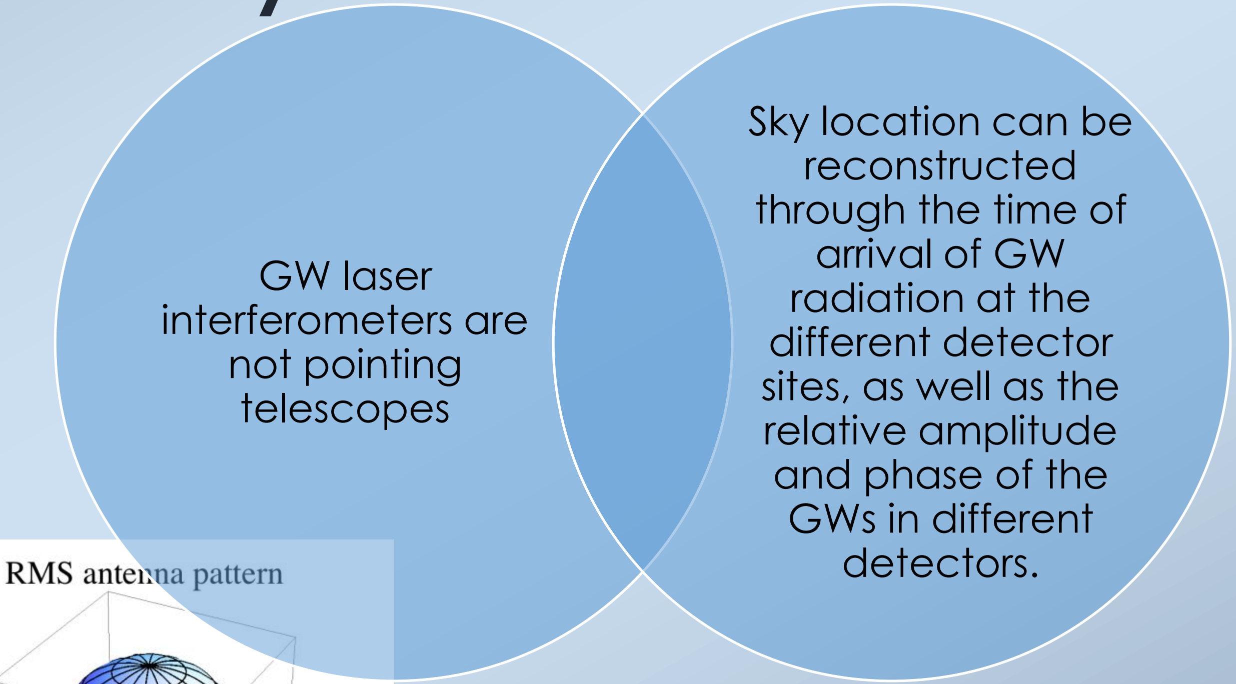


The impact of data-quality vetoes and signal consistency requirements on the background trigger distribution from the cWB search for gravitational-wave bursts by coherent network SNR. The detected coherent network SNR of

The network

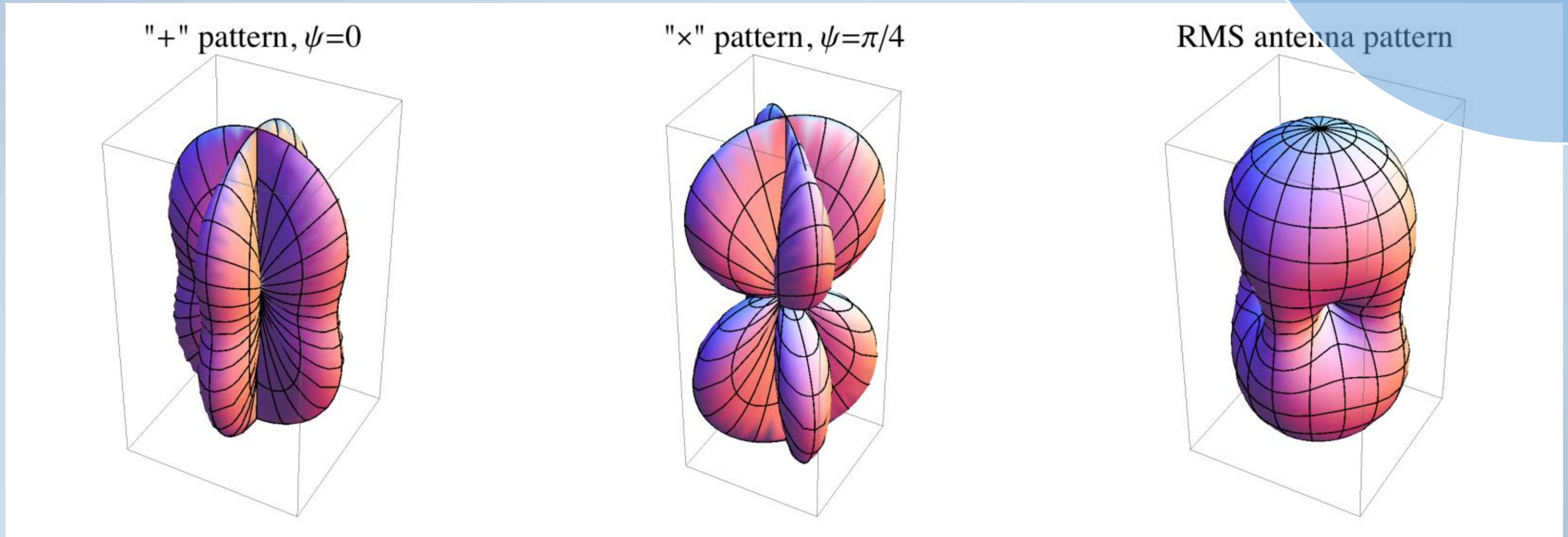

GEO600
LIGO Hanford
LIGO Livingston
VIRGO
KAGRA
LIGO India
Operational
Under Construction
Planned
Gravitational Wave Observatories

Location in the sky

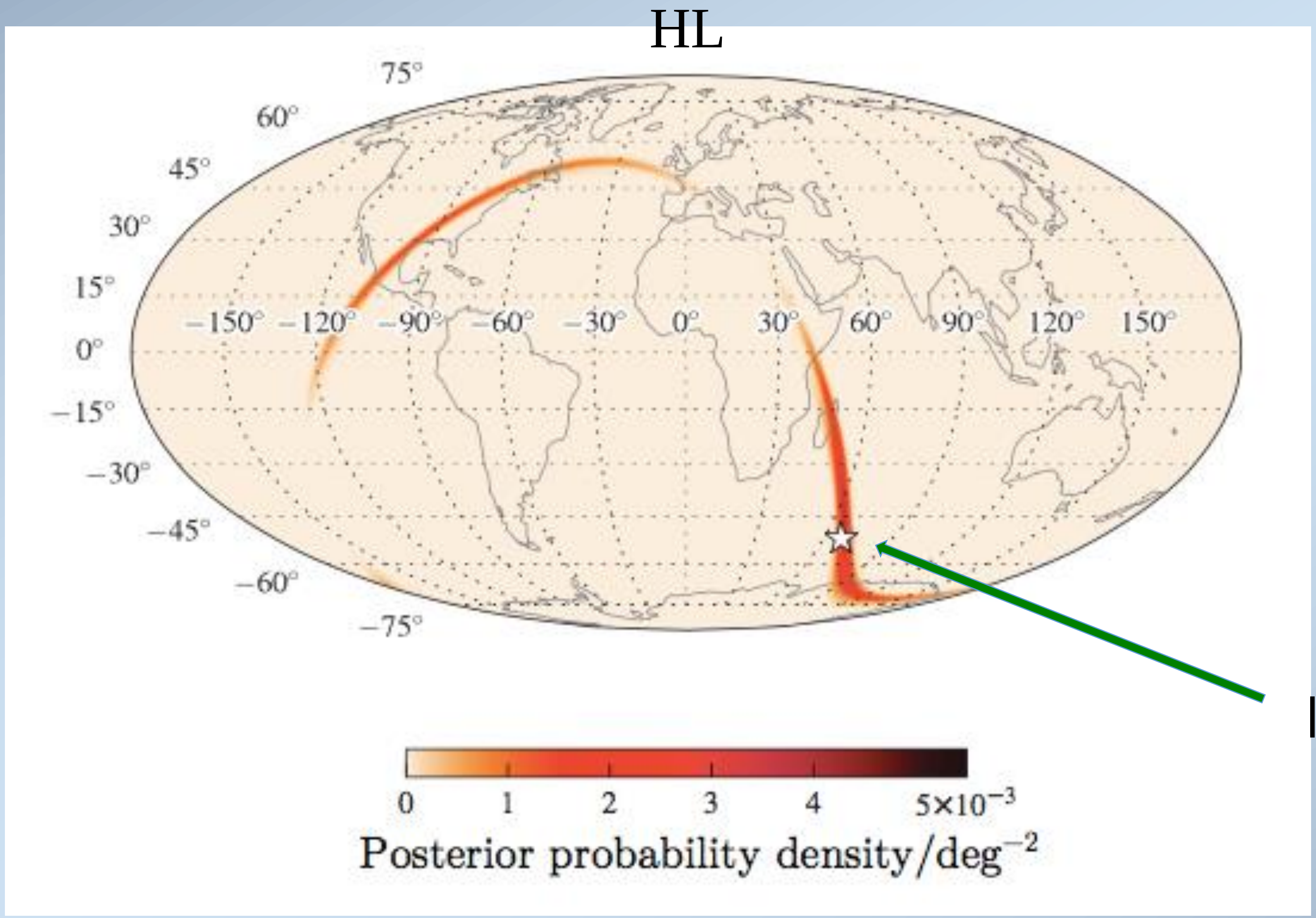


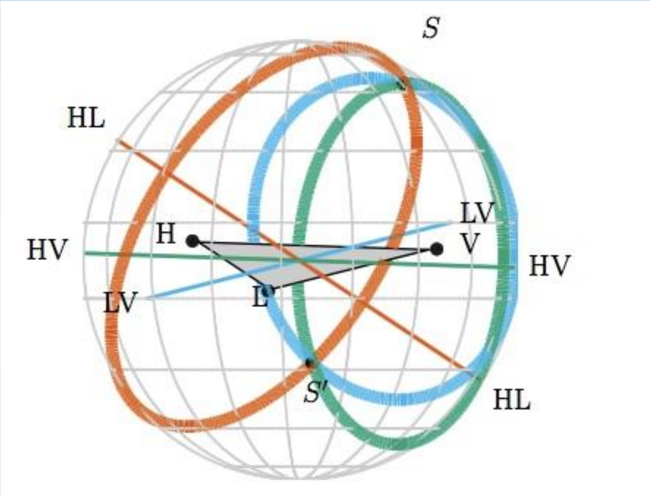
GW laser interferometers are not pointing telescopes

Sky location can be reconstructed through the time of arrival of GW radiation at the different detector sites, as well as the relative amplitude and phase of the GWs in different detectors.



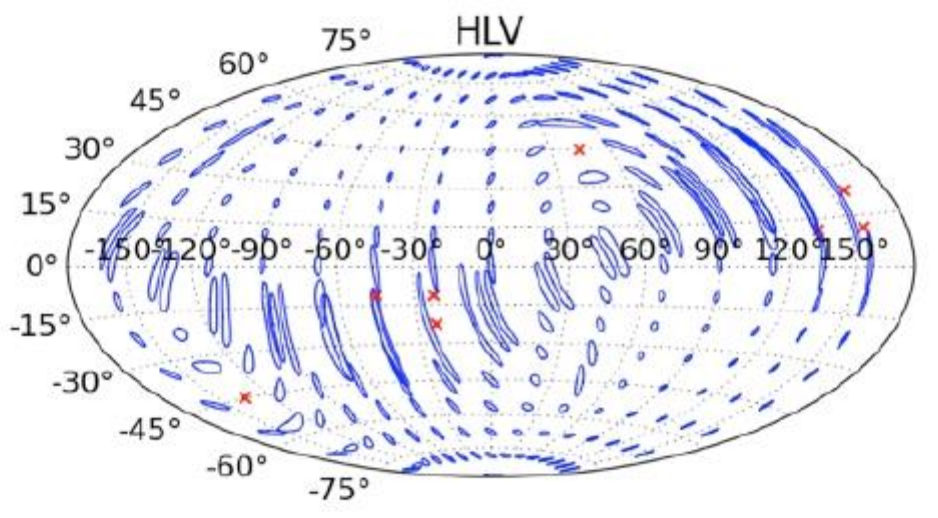
Transient Source Localization:
2 detectors

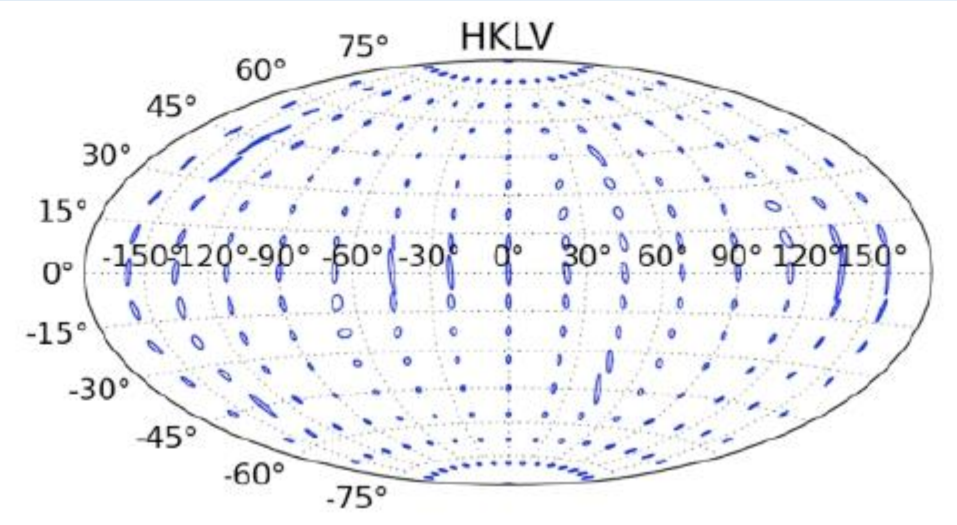

HL

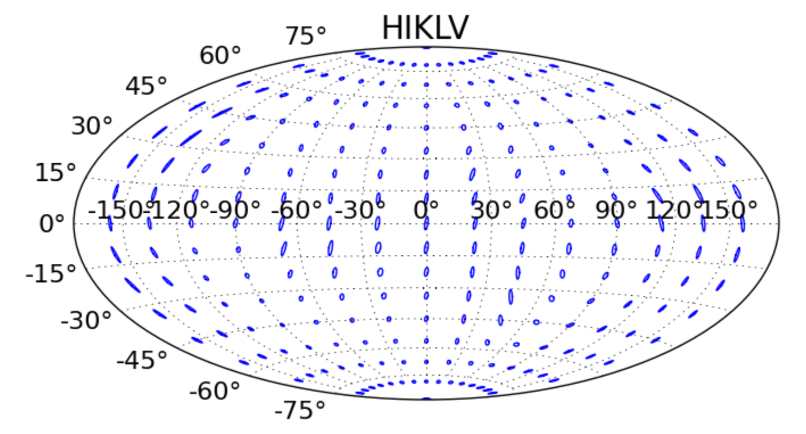


Injected signal

Transient Source Localization



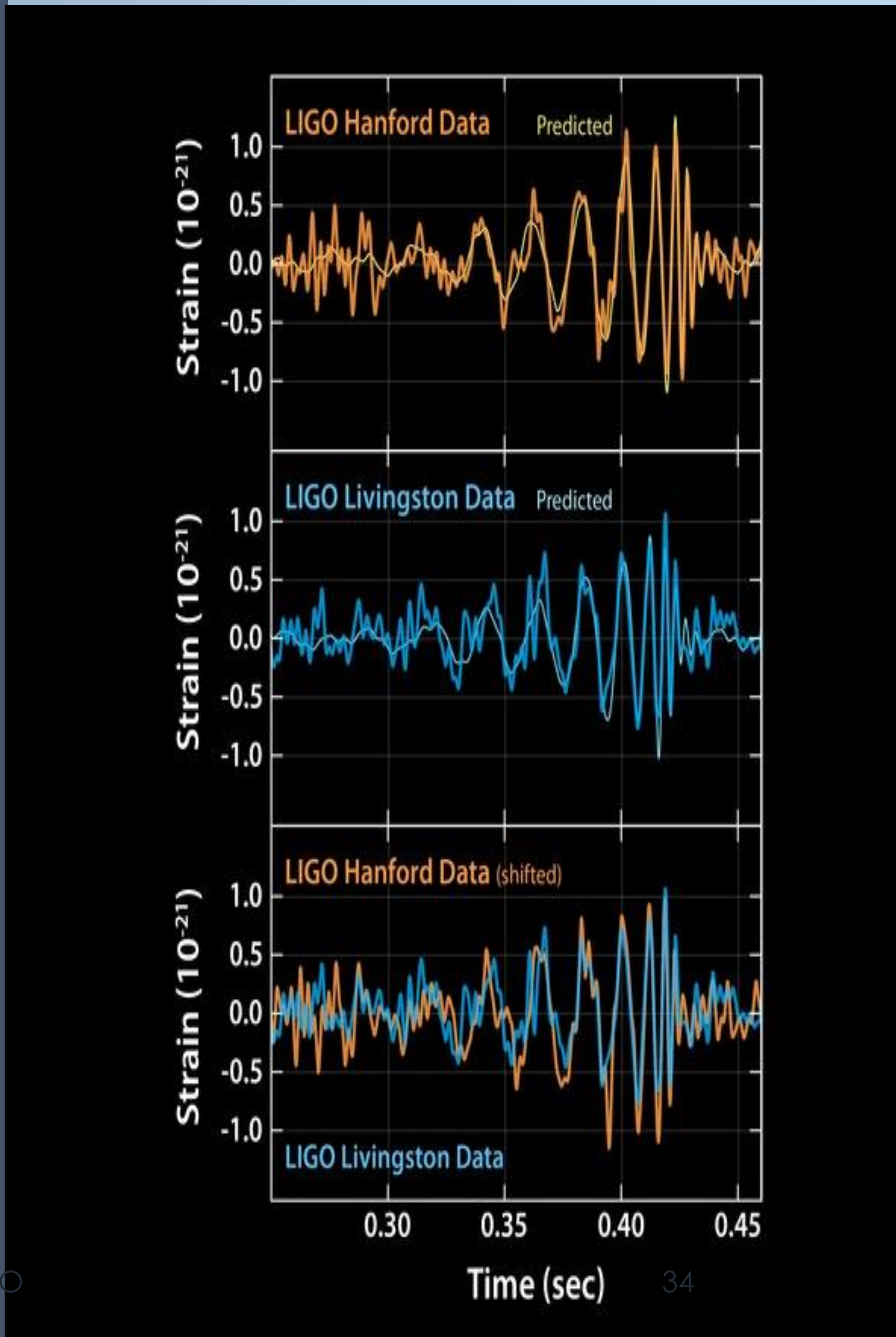




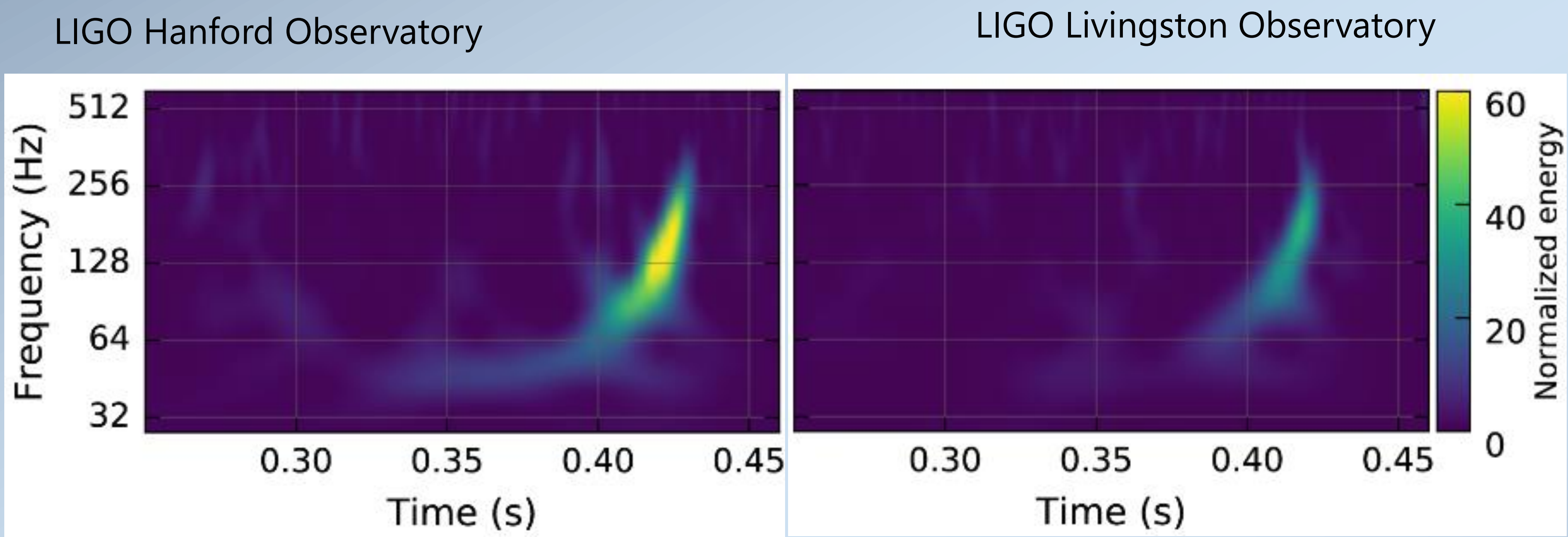
Credit: S. Fairhurst

The event GW150914

14 September 2015

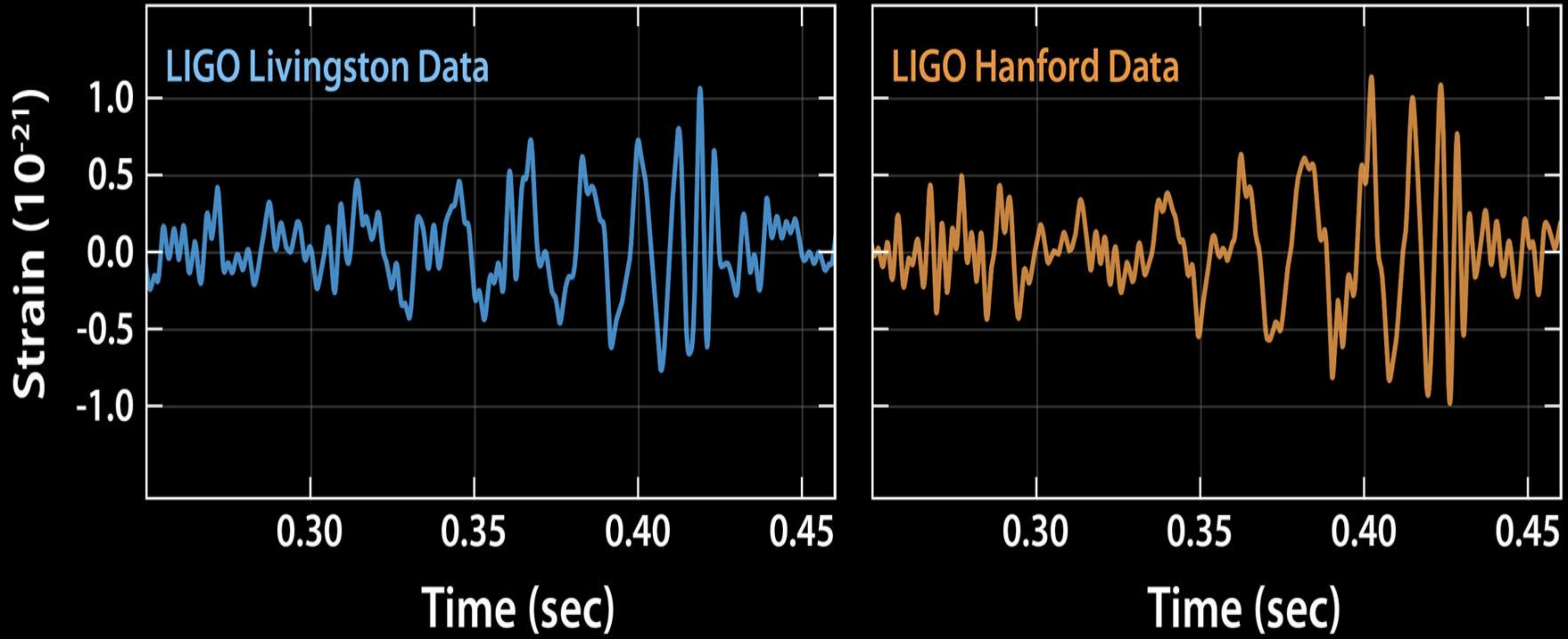


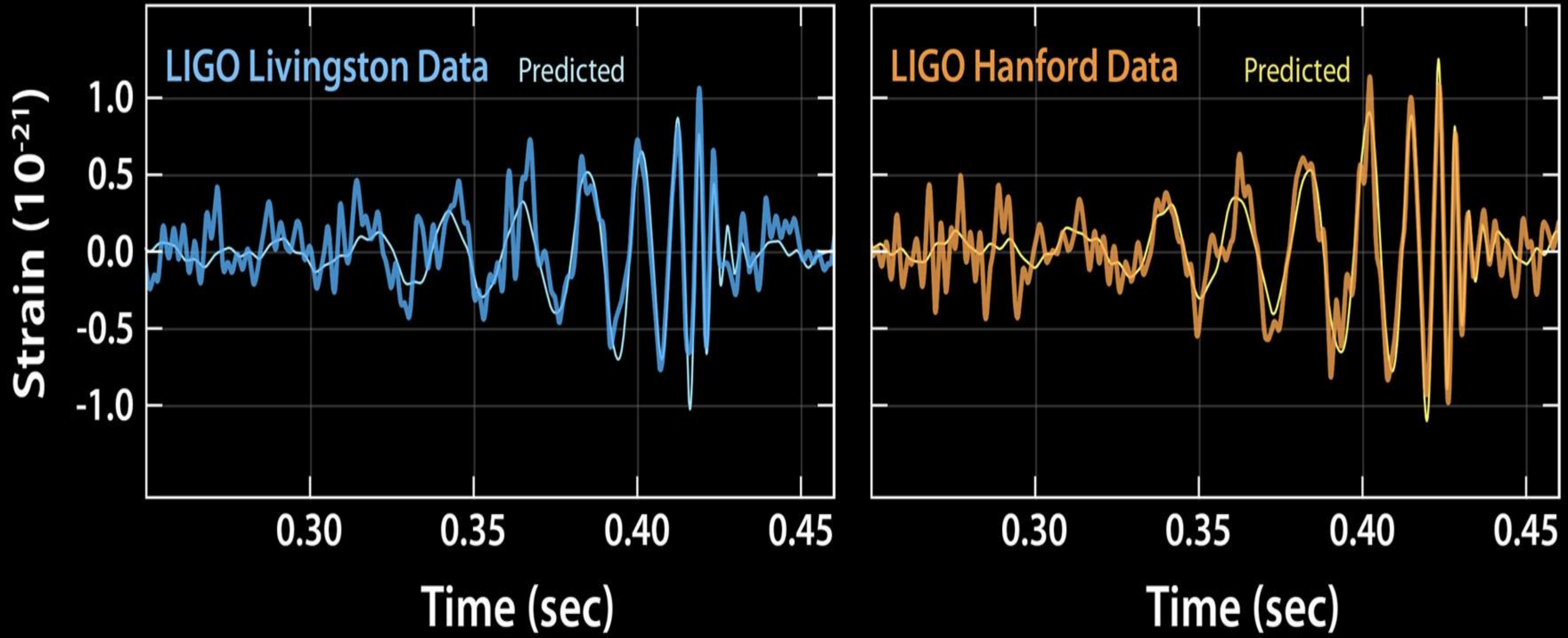
September 14, 2015 – 11:50:45 CET



Initial detection made by a low latency searches for generic GW transients: **Coherent WaveBurst**

Reported within 3 minutes after data acquisition

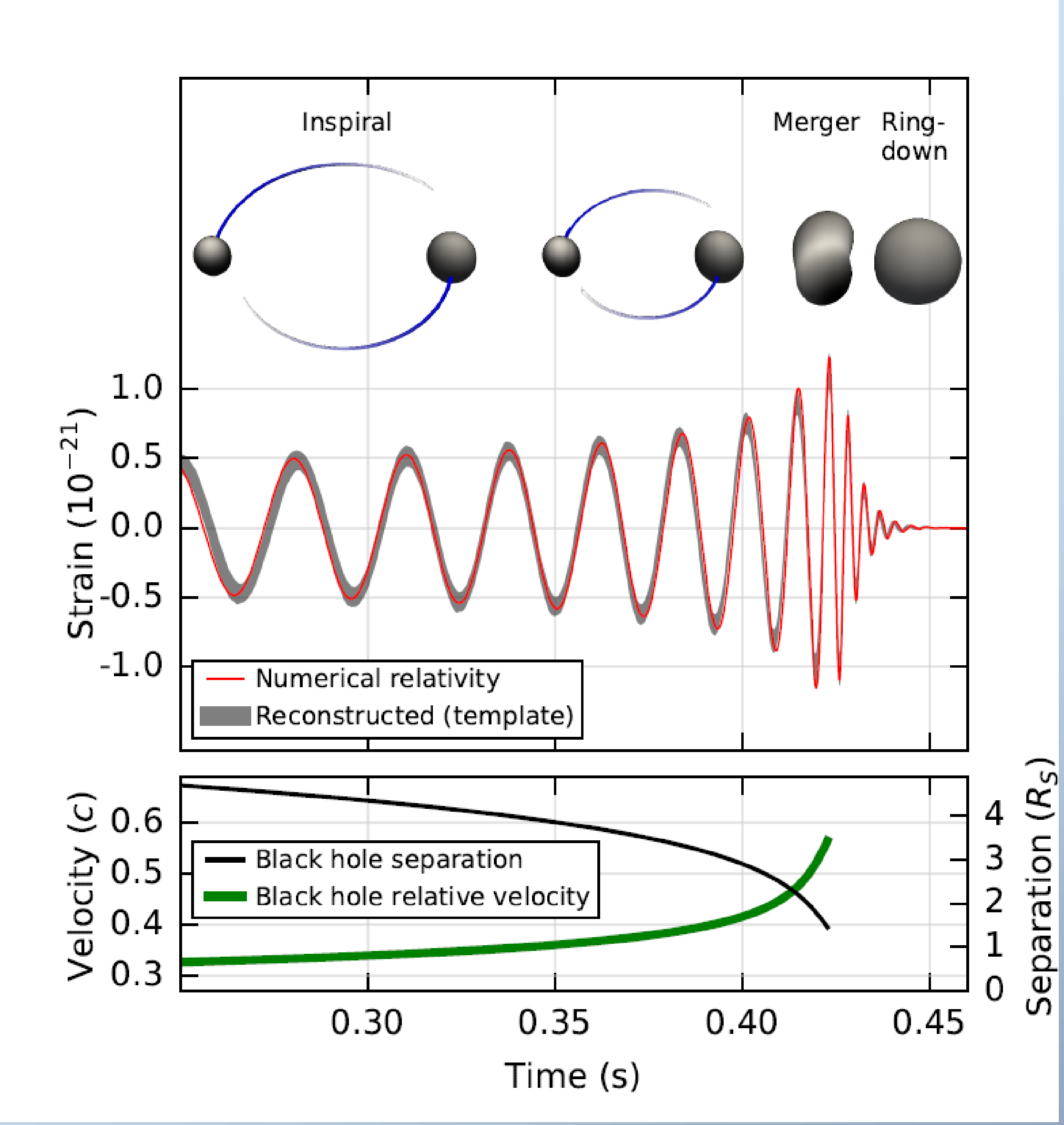

LIGO Livingston Data
LIGO Hanford Data
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)
Time (sec)


LIGO Livingston Data
Predicted
LIGO Hanford Data
Predicted
Strain (10⁻²¹)
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)
0.30
0.35
0.40
0.45
Time (sec)

Estimated GW Strain Amplitude

Full bandwidth waveforms without filtering. Numerical relativity models of black hole horizons during coalescence

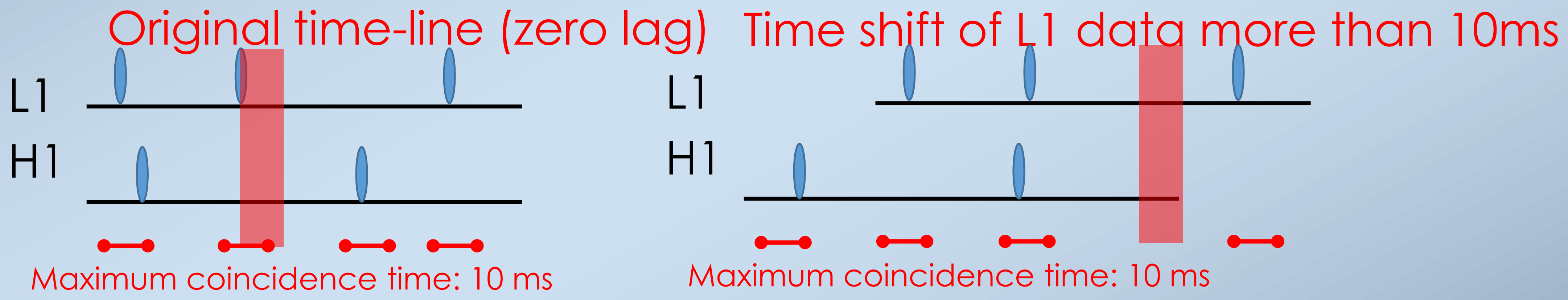
Effective black hole separation in units of Schwarzschild radius ($R_s=2GM/c^2$); and effective relative velocities given by post-Newtonian parameter $v/c = (GM\pi f/c^3)^{1/3}$



Assessing the statistical significance of the event

False Alarm

- Noise artefacts in more detectors can for chance produce coincidences
- Time-shift procedure: characterize statistically the rate of this accidental coincidences



Original time-line (zero lag)

Maximum coincidence time: 10 ms

Time shift of L1 data more than 10ms

Maximum coincidence time: 10 ms

- Re-sampling many times give enough statistics to assess confidence to an event on the zero lag (Background)

cWB statistical significance

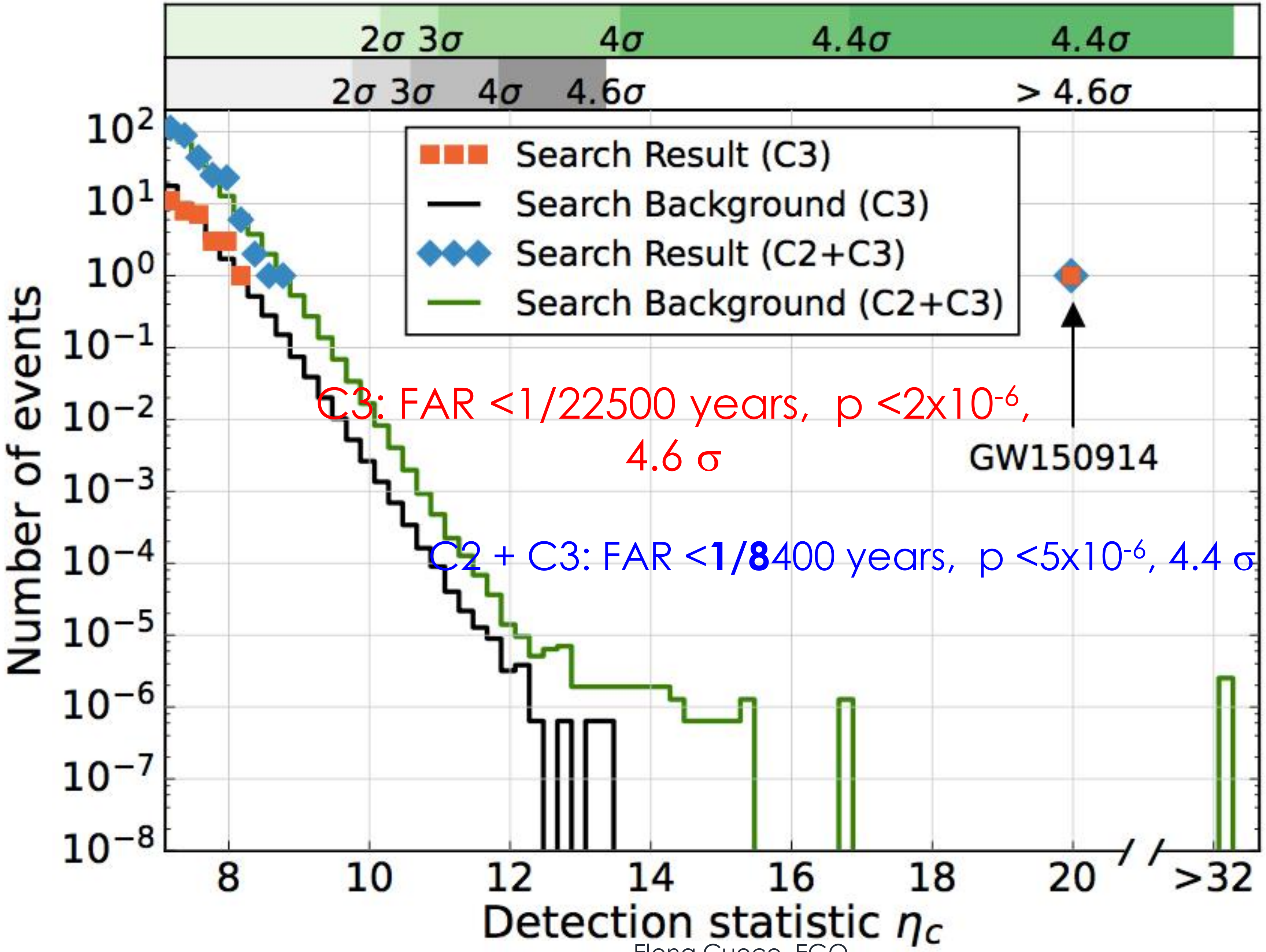
cWB version off-line: data reanalyzed to assess the statistical significance

Events classified in 3 different classes:

- C1 class ➔ events with time-frequency morphology of known populations of noise transients: excluded;
- C3 class ➔ events with frequency that increases with time;
- C2 class ➔ all remaining events.

Background evaluation ➔ Based on the time shift method:

Number of shift produced an equivalent to 67400 years



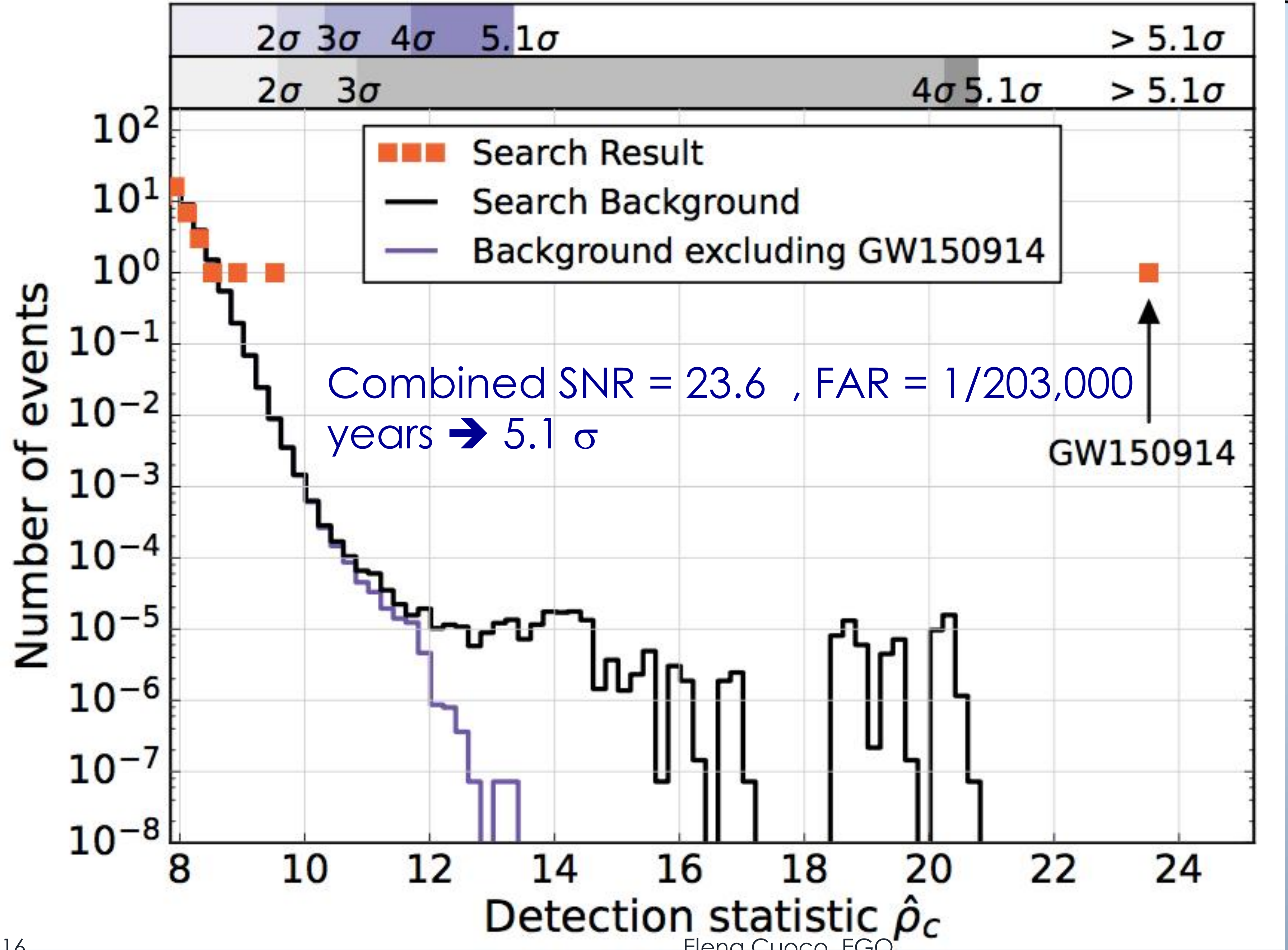
C3: FAR <1/22500 years, p $<2\times10^{-6}$, 4.6 σ

C2 + C3: FAR <**1/8**400 years, p $<5\times10^{-6}$, 4.4 σ

Binary Coalescence search

Search for GW emission by binary system: total mass range 1- 99 M$_\odot$

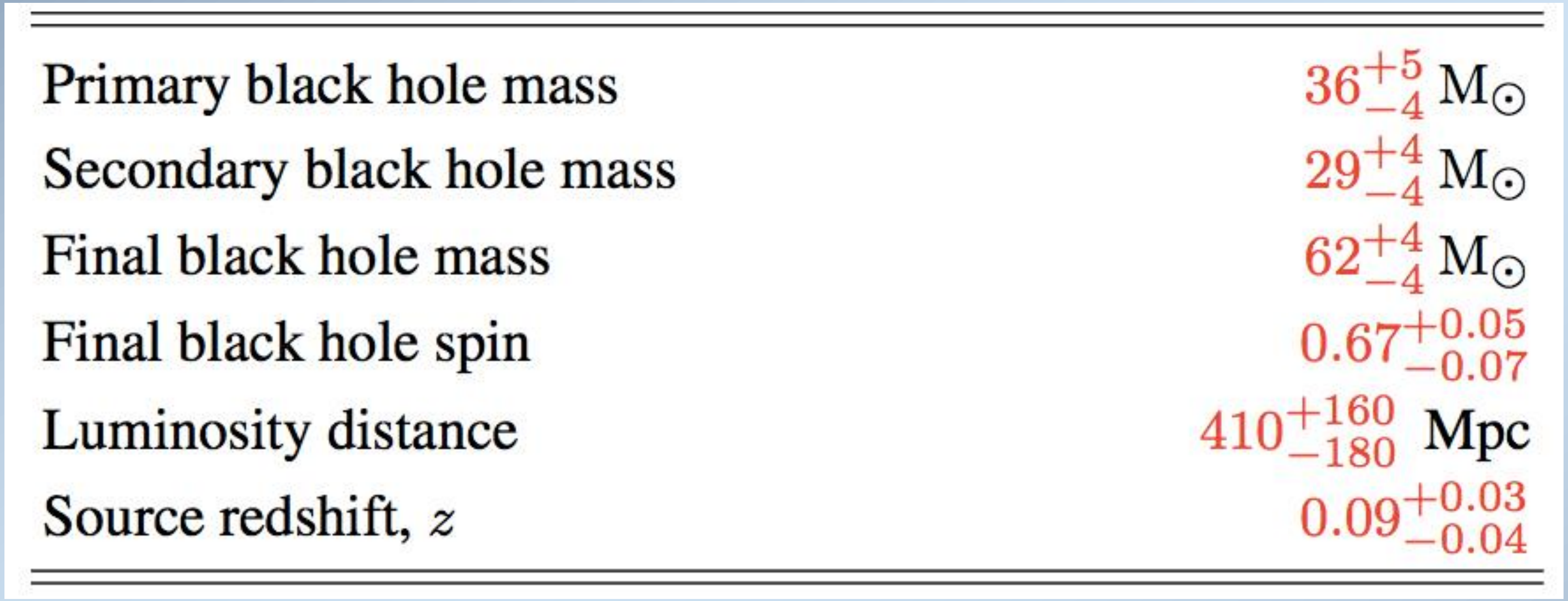
- > 4 M$_\odot$ Model based on PN, BH perturbation theory and NR
- ~ 2.5 x 10^5 wave forms used to cover the parameter space
- SNR of the Matched filter computed as function of time $\rho(t)$ and identify maxima and calculate c^2 to test consistency with the matched template, then apply detector coincidence within 15 ms
- Calculate $\rho(t)_C^2 = \rho(t)_H^2 + \rho(t)_L^2$ of the SNR of each detector
- Background computed by shifting 10^7 times equivalent to 608,000 years
- Combined SNR = 23.6 , FAR = 1/203,000 years
5.1 sigma



Combined SNR = 23.6 , FAR = 1/203,000 years ➔ 5.1 σ

The Parameter Estimation

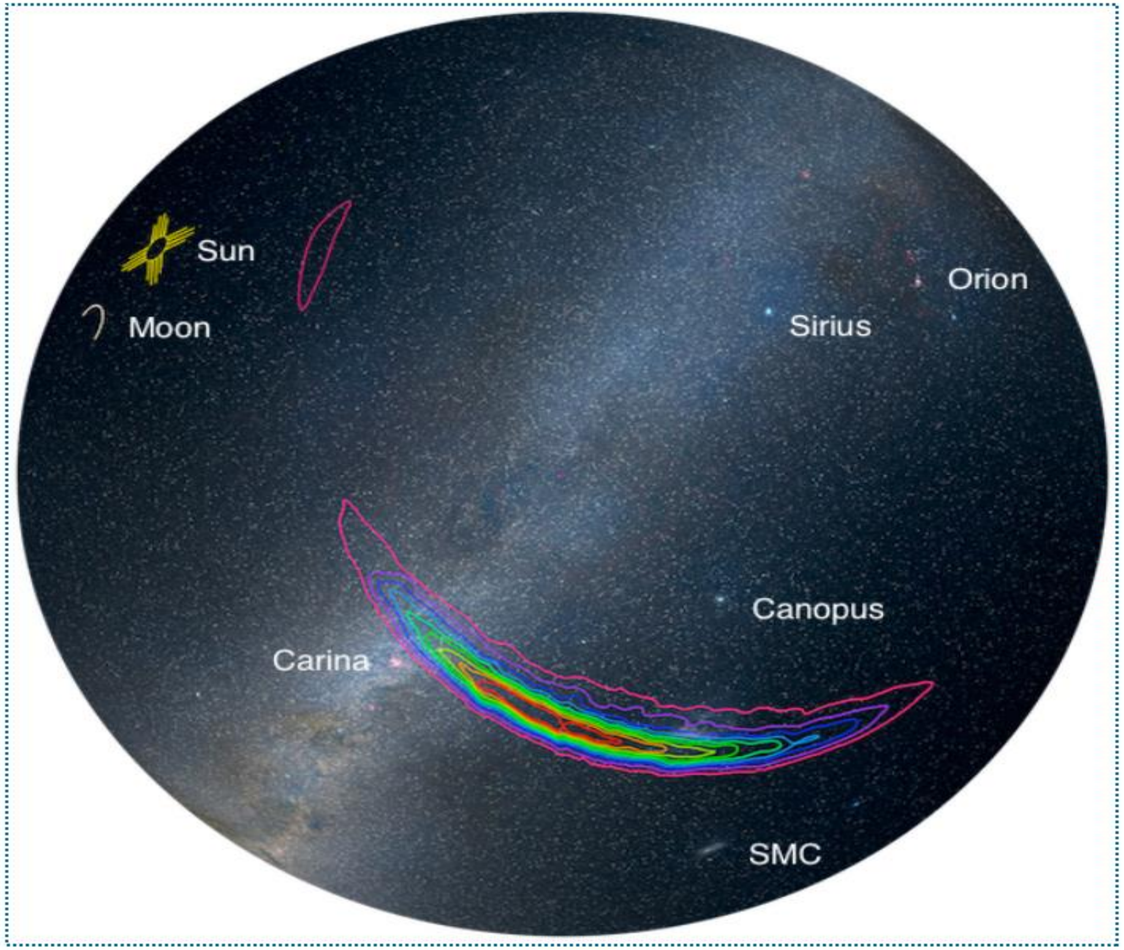
Source parameters for GW150914



Primary black hole mass	$36^{+5}_{-4}\ \mathrm{M}_\odot$
Secondary black hole mass	$29^{+4}_{-4}\ \mathrm{M}_\odot$
Final black hole mass	$62^{+4}_{-4}\ \mathrm{M}_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift, z	$0.09^{+0.03}_{-0.04}$

Estimated source parameters from GW150914. We report median values with 90% credible intervals that include statistical errors from averaging the results of different waveform models. Masses are given in the source frame: to convert in the detector frame multiply by (1+z)

Sky location

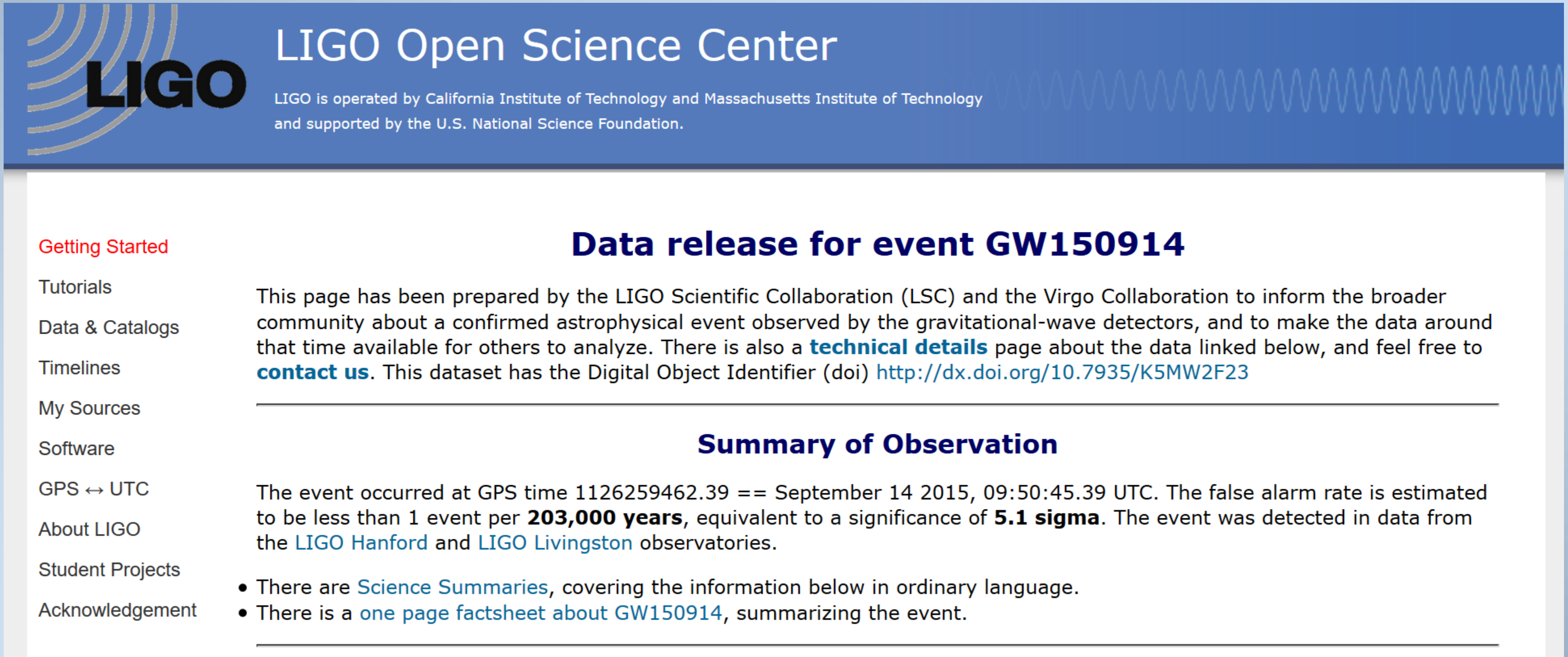


Sky at the time of the event, with the LALInference skymap, contoured in deciles of probability. View is from the South Atlantic Ocean, North at the top, with the Sun rising and the Milky Way diagonally from NW to SE.

Source location with large uncertainty ~ 600 deg^2

LOSC

https://losc.ligo.org/events/GW150914/



LIGO Open Science Center

LIGO is operated by California Institute of Technology and Massachusetts Institute of Technology and supported by the U.S. National Science Foundation.

Data release for event GW150914

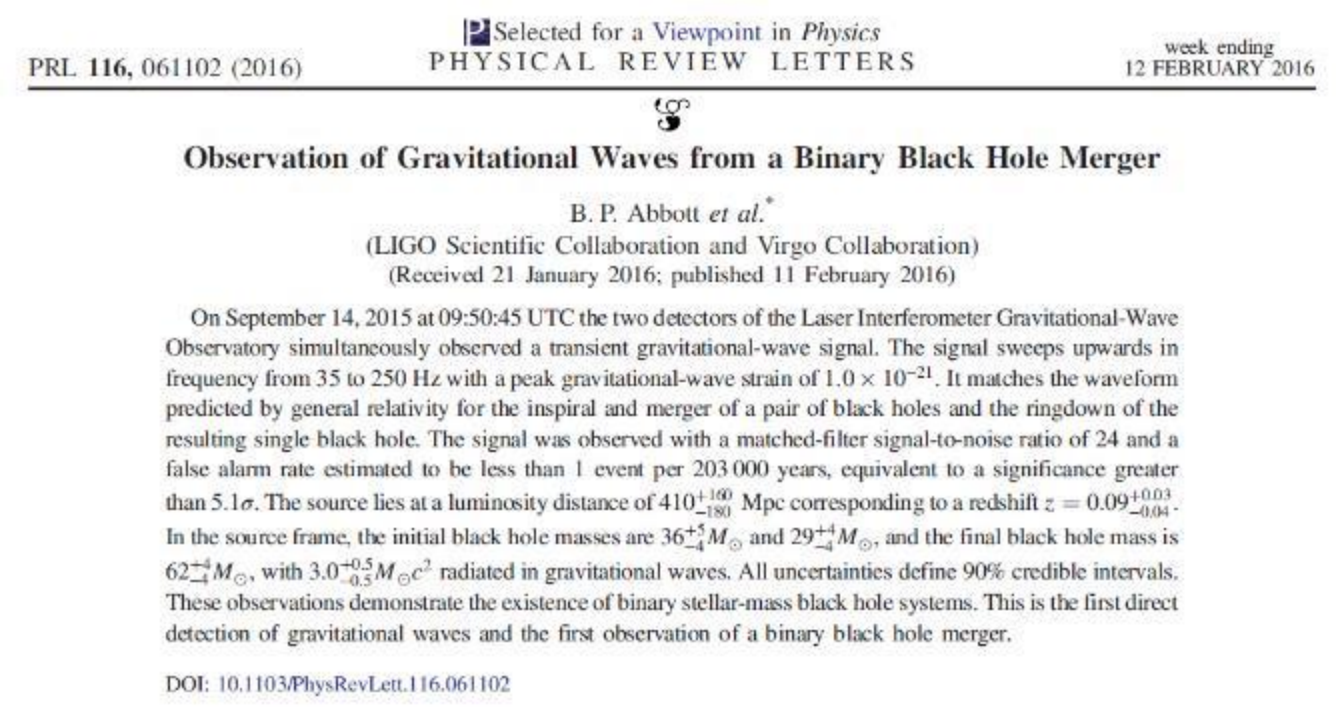
This page has been prepared by the LIGO Scientific Collaboration (LSC) and the Virgo Collaboration to inform the broader community about a confirmed astrophysical event observed by the gravitational-wave detectors, and to make the data around that time available for others to analyze. There is also a **technical details** page about the data linked below, and feel free to **contact us**. This dataset has the Digital Object Identifier (doi) http://dx.doi.org/10.7935/K5MW2F23

Summary of Observation

The event occurred at GPS time 1126259462.39 == September 14 2015, 09:50:45.39 UTC. The false alarm rate is estimated to be less than 1 event per **203,000 years**, equivalent to a significance of **5.1 sigma**. The event was detected in data from the LIGO Hanford and LIGO Livingston observatories.

- There are Science Summaries, covering the information below in ordinary language.
- There is a one page factsheet about GW150914, summarizing the event.

Thanks



Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]

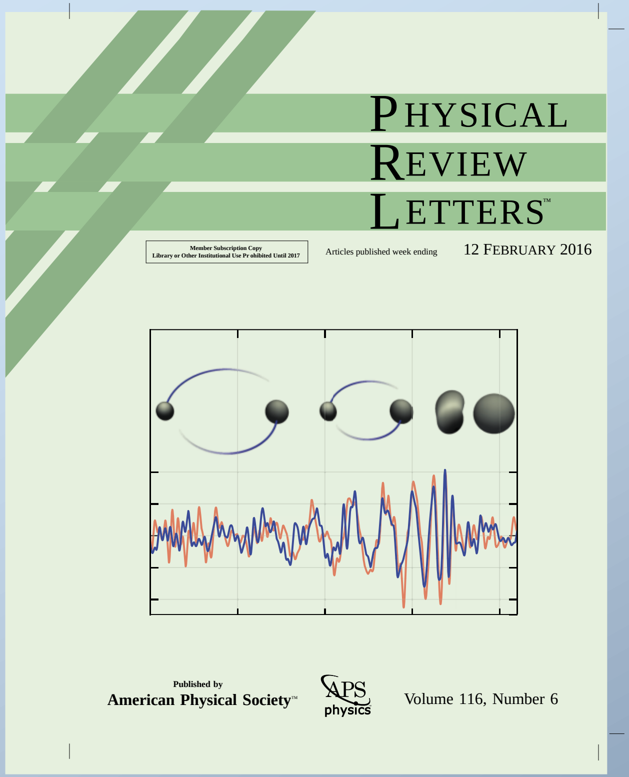
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

Phys. Rev. Lett. 116, 061102 (2016)



PHYSICAL REVIEW LETTERS

Member Subscription Copy
Library or Other Institutional Use Prohibited Until 2017

Articles published week ending 12 FEBRUARY 2016

Published by
American Physical Society

APS physics

Volume 116, Number 6