WISHEPP
4th Winter School in HEP
November 9-15, 2019 An-Najah N. University, Nablus, Palestine
Bruno Mazoyer LAL 2019

Detection of gravitational waves

→ Gravitational-wave detectors

→ LIGO-Virgo detector network

→ Signal extraction methods

→ Detector's noise

CNRS LAL Laboratoire de l'Accélérateur Linéaire

Florent Robinet
Laboratoire de l'Accélérateur Linéaire
robinet@lal.in2p3.fr


LIGO Hanford, USA
Virgo Pisa, Italy
LIGO Livingston, USA

Gravitational wave detection

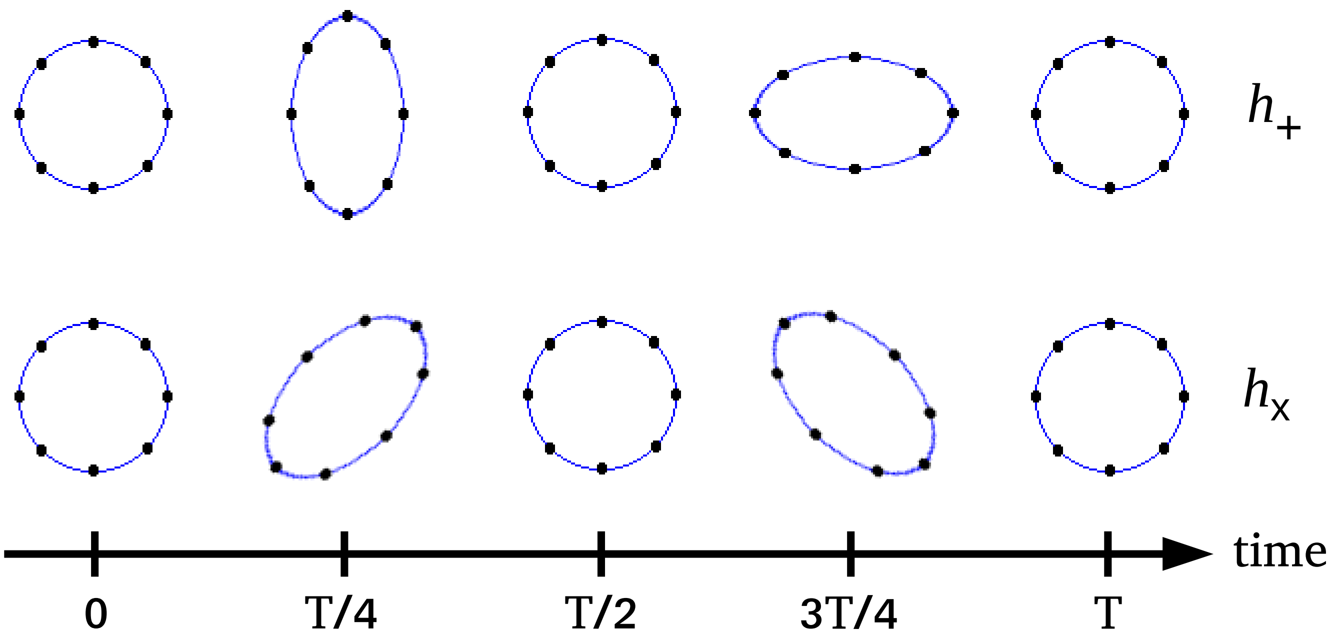
Add a small perturbation to the Minkowski metric: $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ $\quad |h_{\mu\nu}| \ll 1$

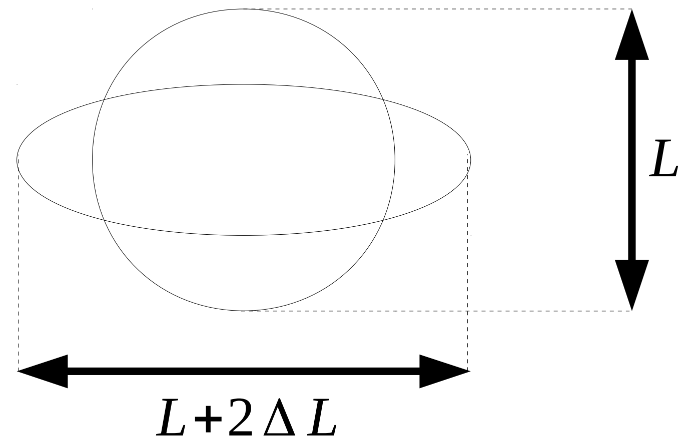
– h obeys a plane-wave equation

– the wave propagates at the speed of light

– 2 degrees of freedom: h_+ and $h_\times$

→ **Gravitational waves**



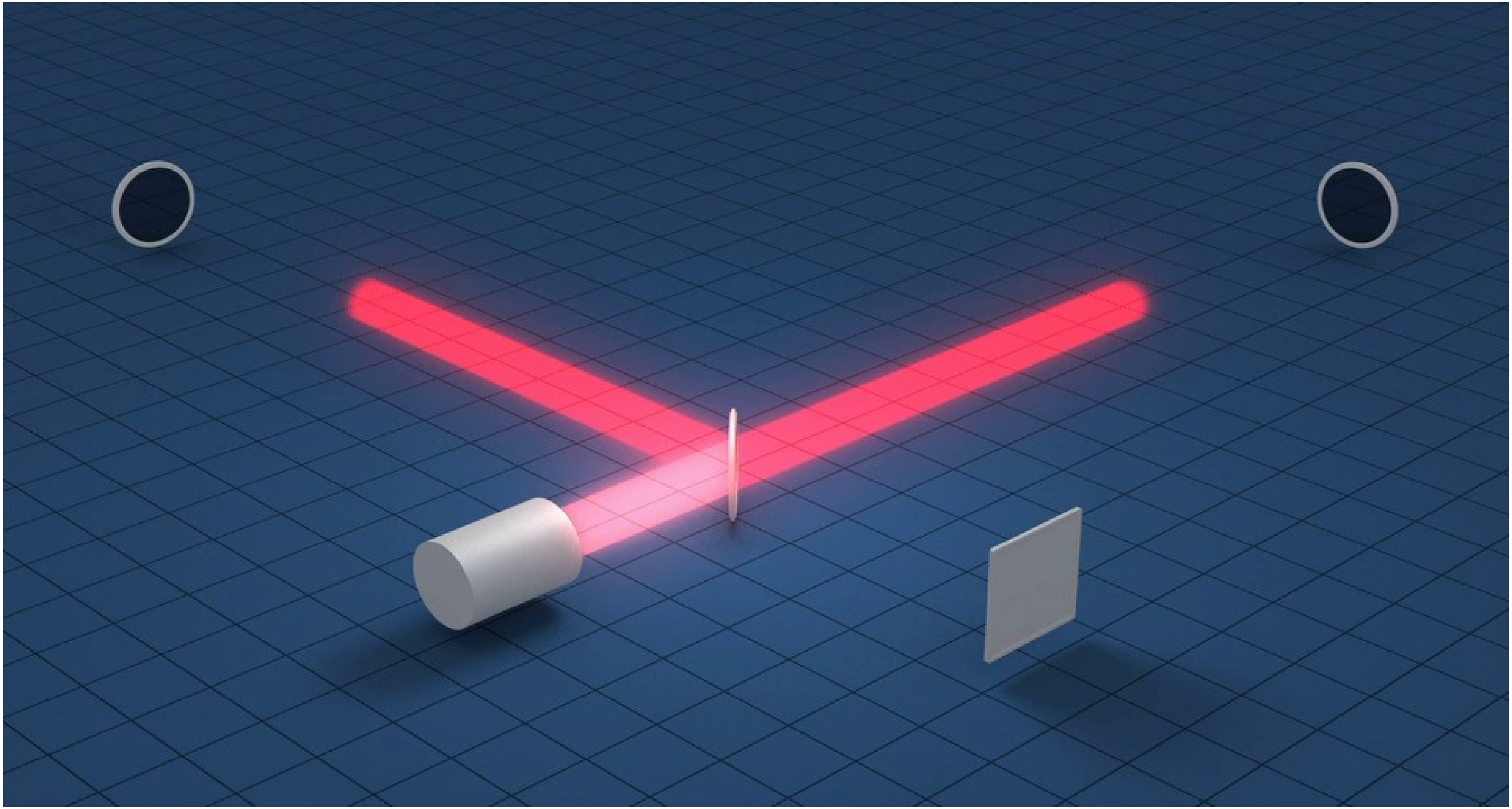


$$h = 2\frac{\Delta L}{L}$$

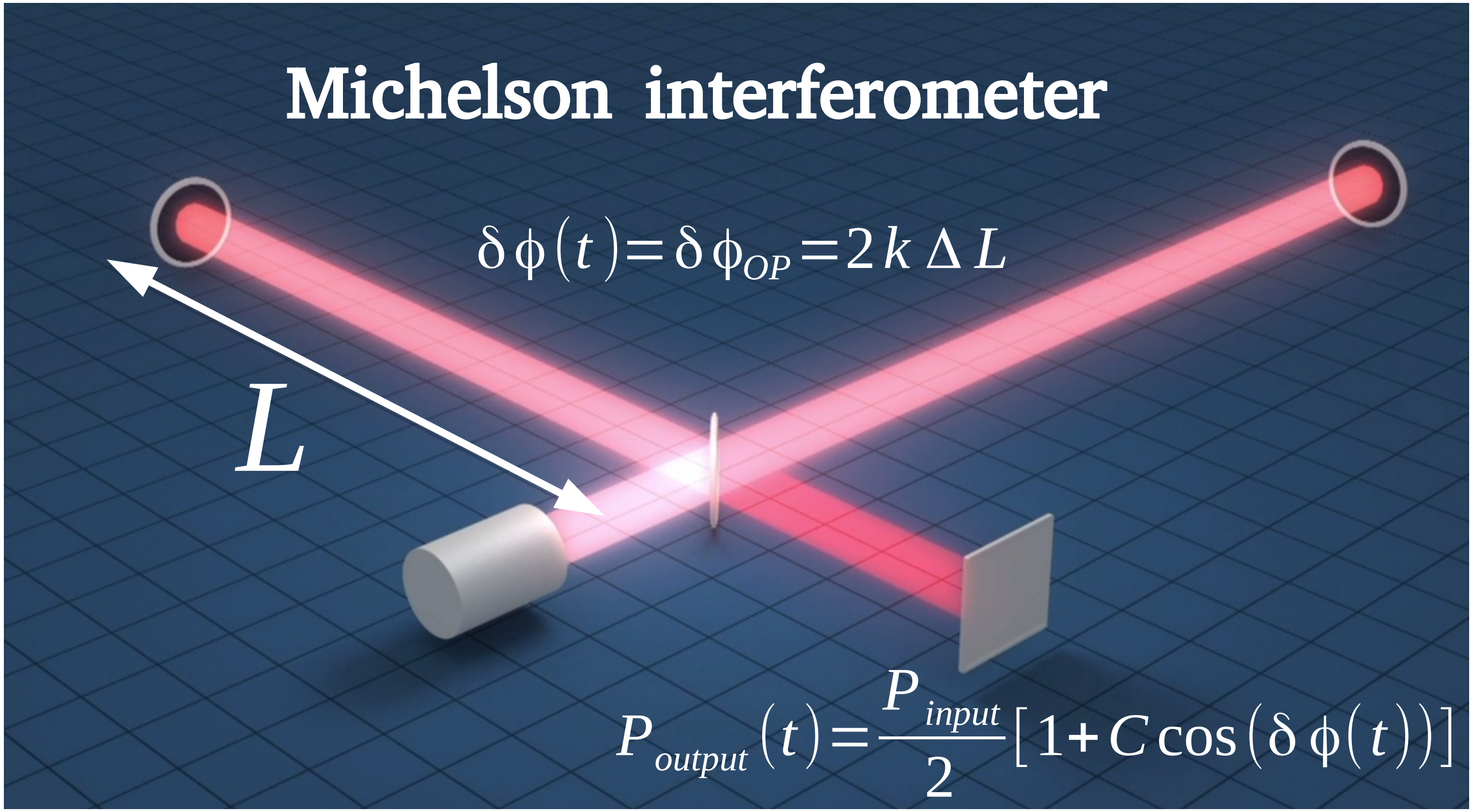
When they propagate, gravitational waves
– do not interact with matter
– are attenuated by 1/r

→ **Gravitational waves are the perfect probe!**
→ **BUT... h~10^{-21}**

Gravitational wave detectors

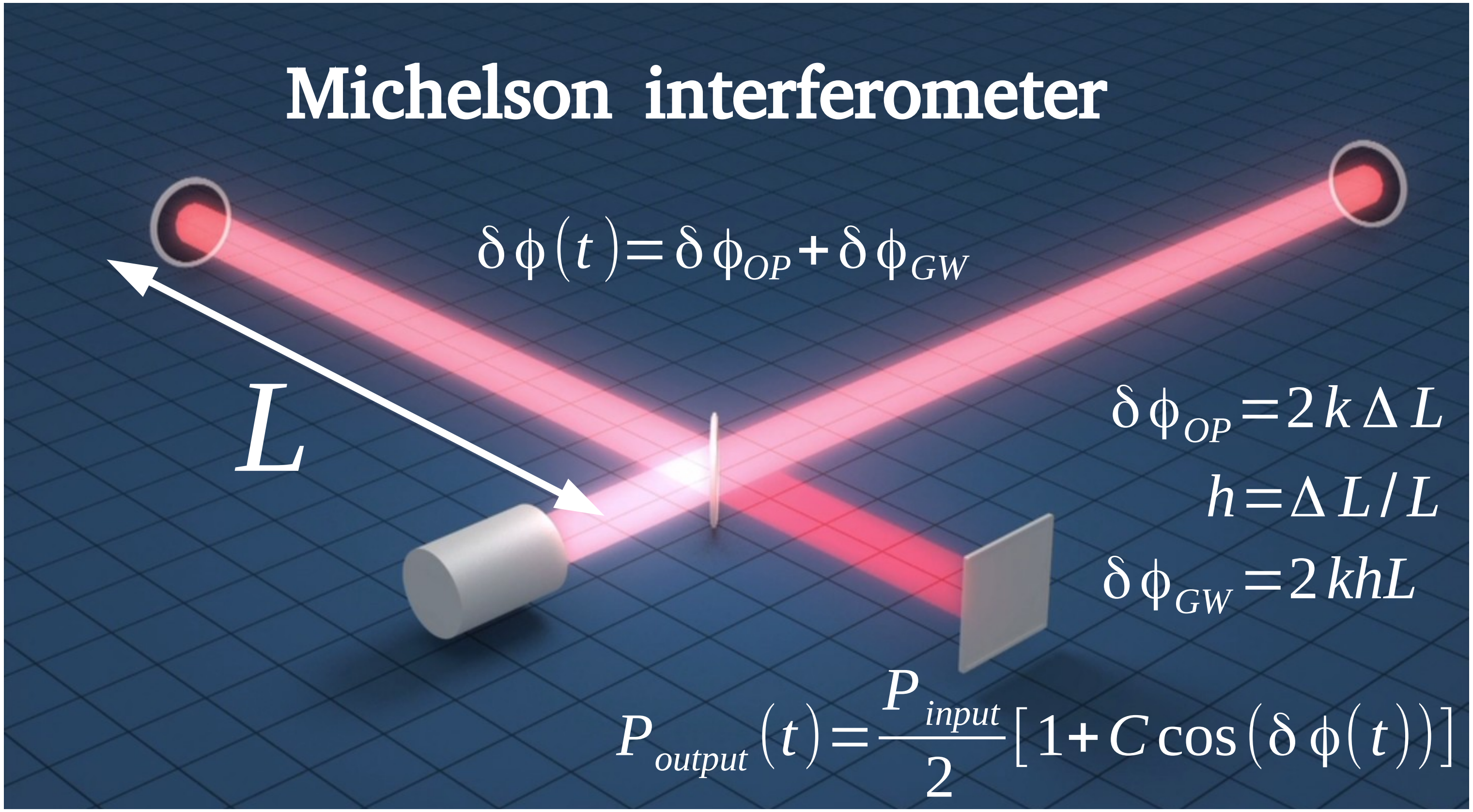


Gravitational wave detectors



Operation: set output on a dark fringe

Gravitational wave detectors



$$P_{output}(t)\simeq\frac{P_{input}}{2}[1+C\cos(\delta\phi_{OP})-C\sin(\delta\phi_{OP})\times\delta\phi_{GW}(t)]$$

→ A gravitational wave is detected as a power variation

Sensitivity limited by noise

The detector's sensitivity to h is limited by noise

For example: shot noise due to uncertainty in photon counting rate

$$N_{photon} \propto P_{output} \quad \rightarrow \quad \delta N_{photon} \propto \sqrt{N_{photon}} \quad \rightarrow \quad \delta P_{shot\,noise} \propto \sqrt{P_{output}}$$

Signal-to-noise ratio

$$\frac{S}{B} = \frac{\delta P_{GW}}{\delta P_{shot\,noise}} \propto L \sqrt{P_{input}}\, h$$

If $\frac{S}{B} = 1 \quad \rightarrow \quad h_{shot\,noise} \propto \frac{1}{L\sqrt{P_{input}}}$

Table-top Michelson interferometer → 10^{-17}

Astrophysical sources → 10^{-21}

Boosting the sensitivity

$$\delta P_o = G_{PR} P_i C \frac{2\pi}{\lambda} \sin\left(\frac{4\pi}{\lambda}\Delta L_0\right)\frac{2F}{\pi}\delta\Delta L$$

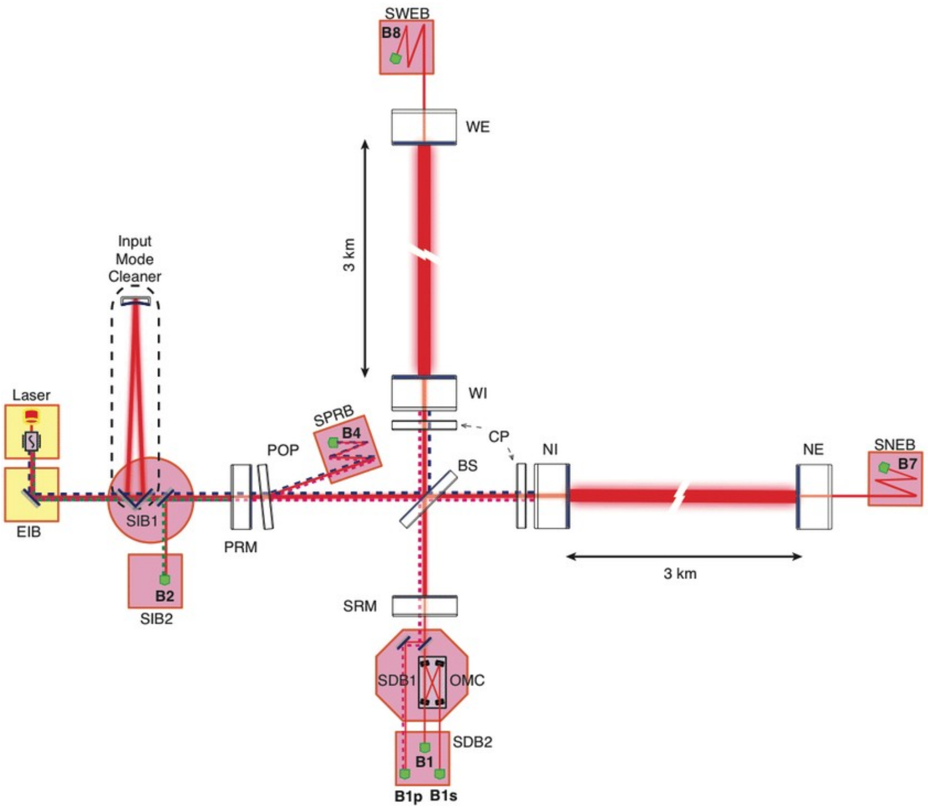
Typical shot noise at 50 mW:

$$\delta P_{shot} \sim 0.1\, nW$$

$$\delta\Delta L \sim 5\times10^{-20}\, m$$

Strain amplitude (reconstruction)

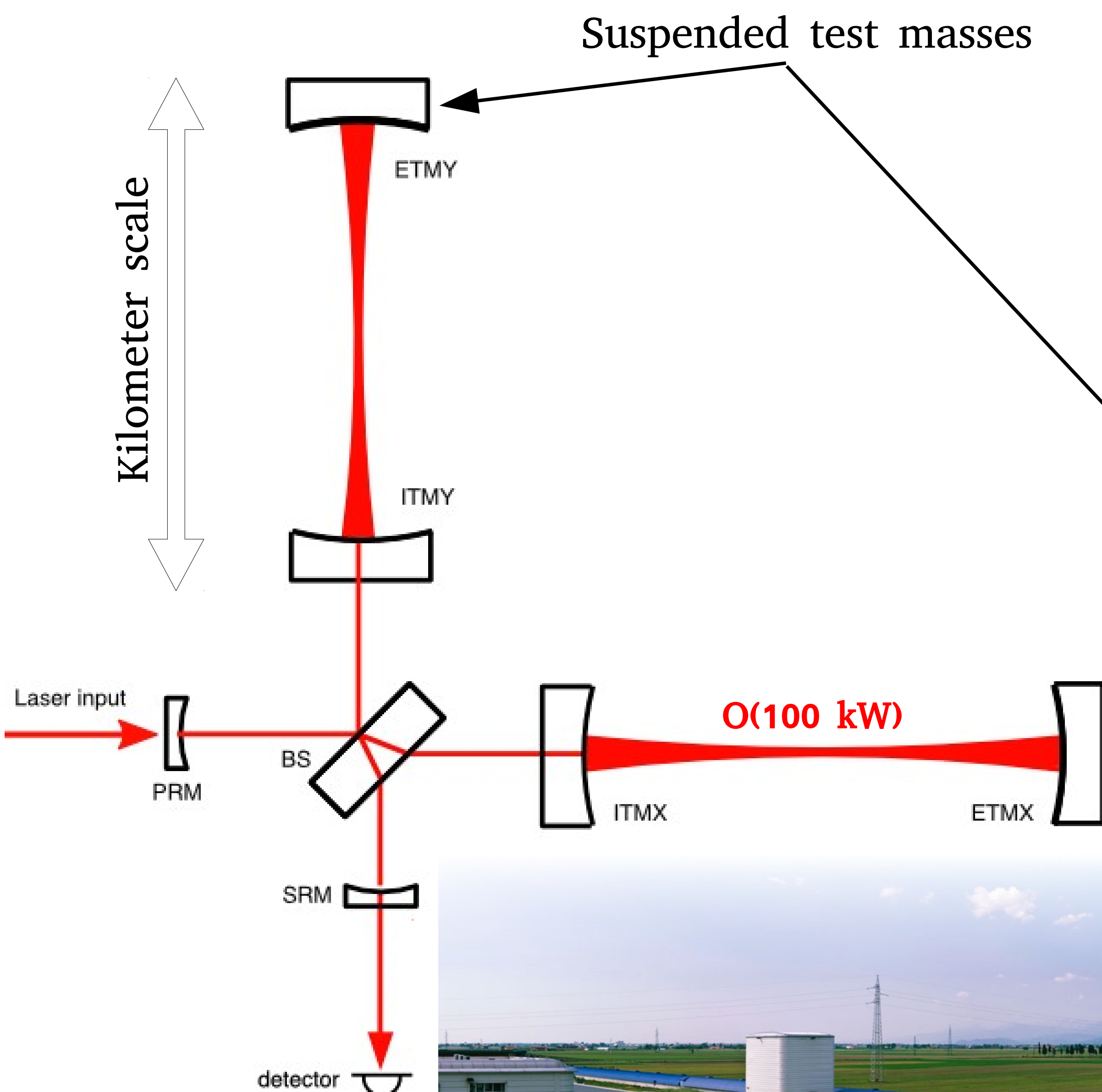
$$h = \frac{\delta\Delta L}{L_0} \sim 10^{-23}$$



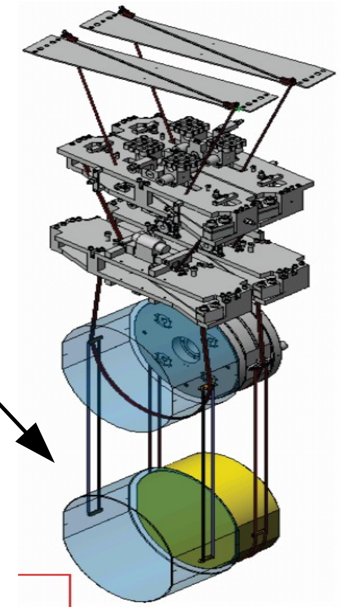
$\lambda = 1064\, nm$
$P_i = 100\, W$
$\Delta L_0 = 10^{-11}\, m$
$F = 450$
$C = 1$
$G_{PR} = 38$

⚠ In reality the reconstruction is frequency dependent

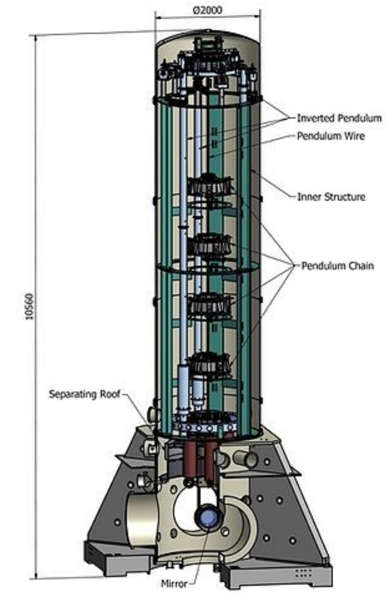
Gravitational wave detectors



LIGO suspensions



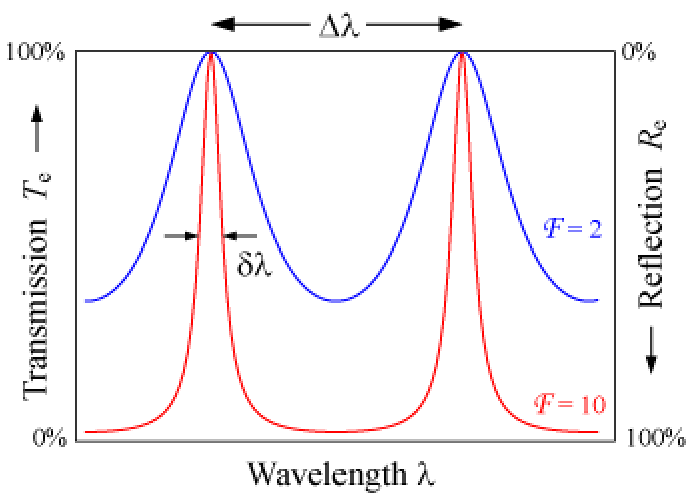
Virgo suspensions



Virgo interferometer

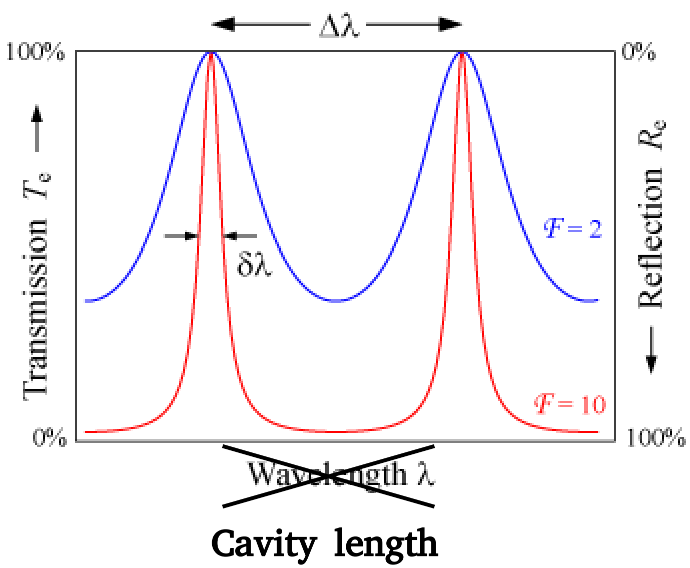
Lock control

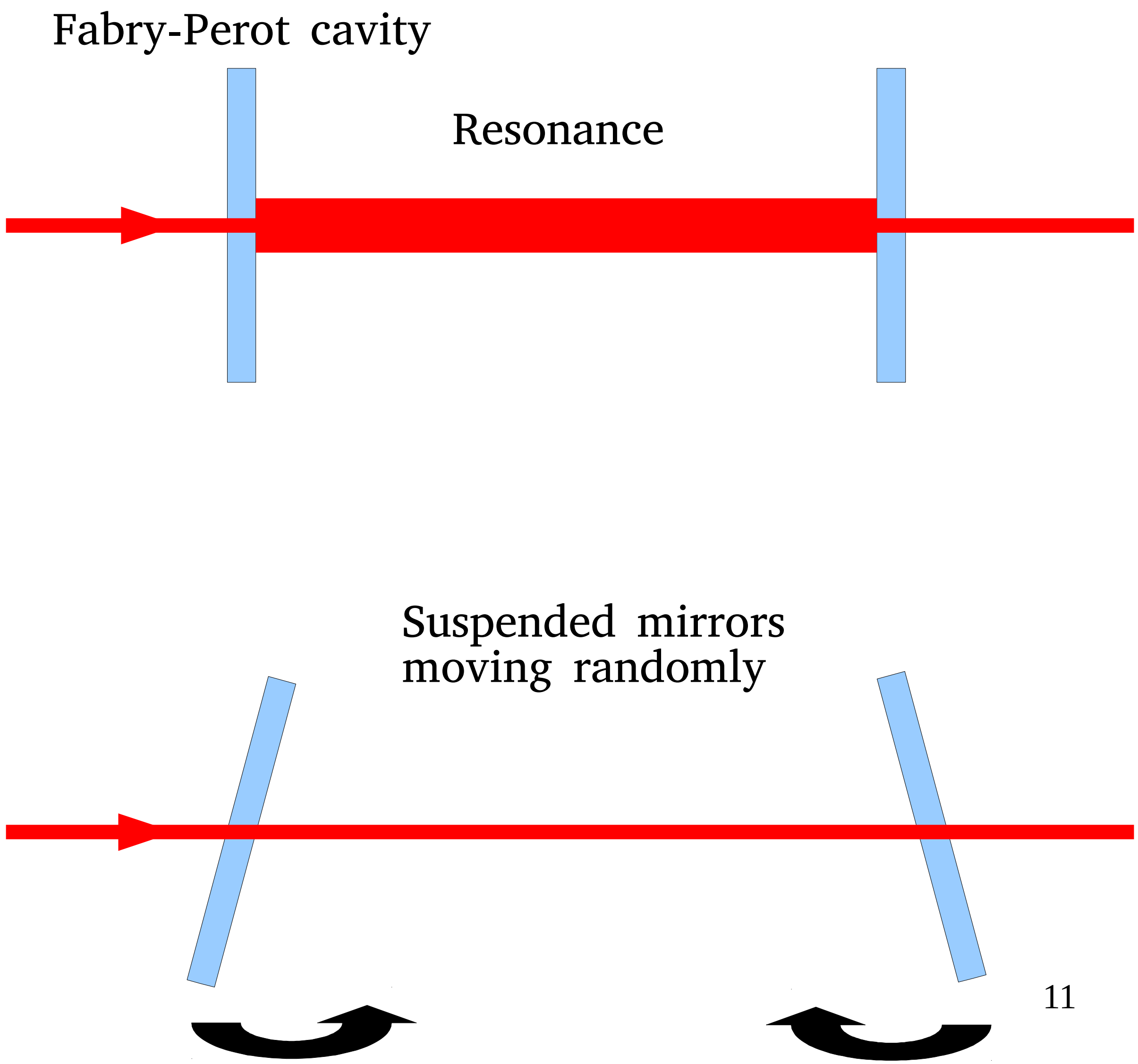
The detector's mirrors must be "controlled" to lock and maintain the cavities at resonance



Lock control

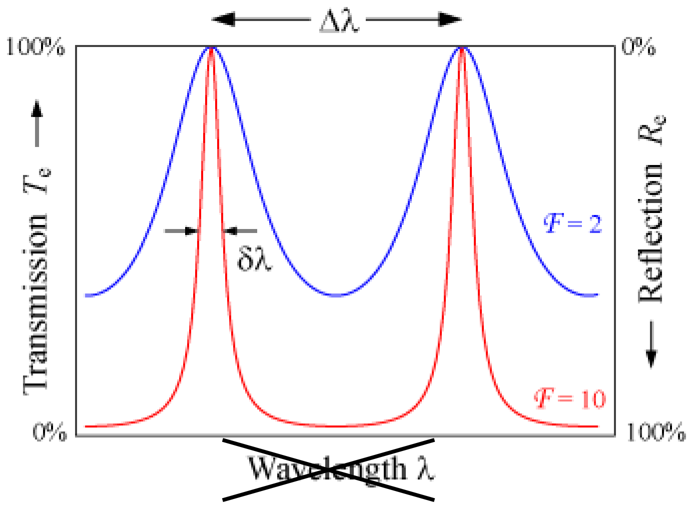
The detector's mirrors must be "controlled" to lock and maintain the cavities at resonance





Lock control

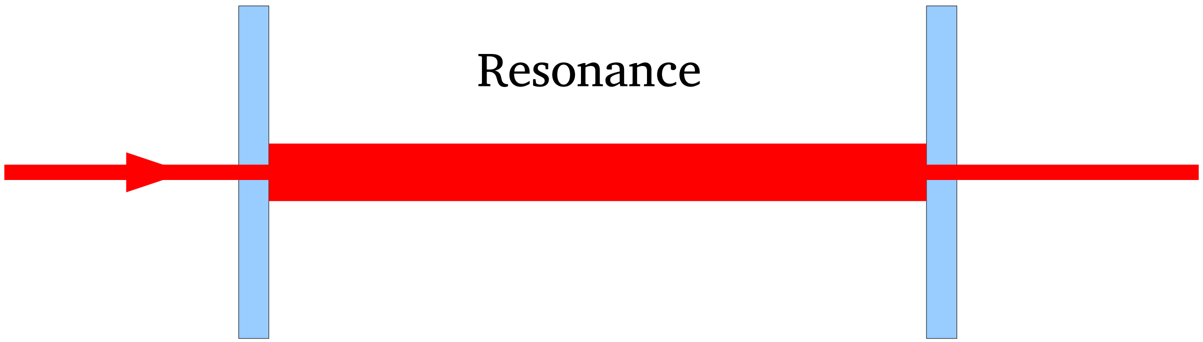
The detector's mirrors must be "controlled" to lock and maintain the cavities at resonance



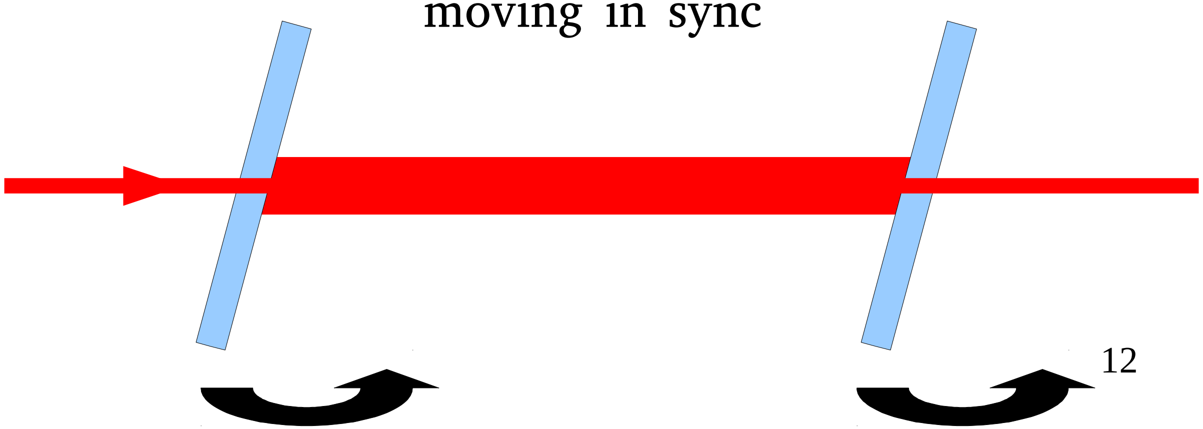
Cavity length

Fabry-Perot cavity

Resonance



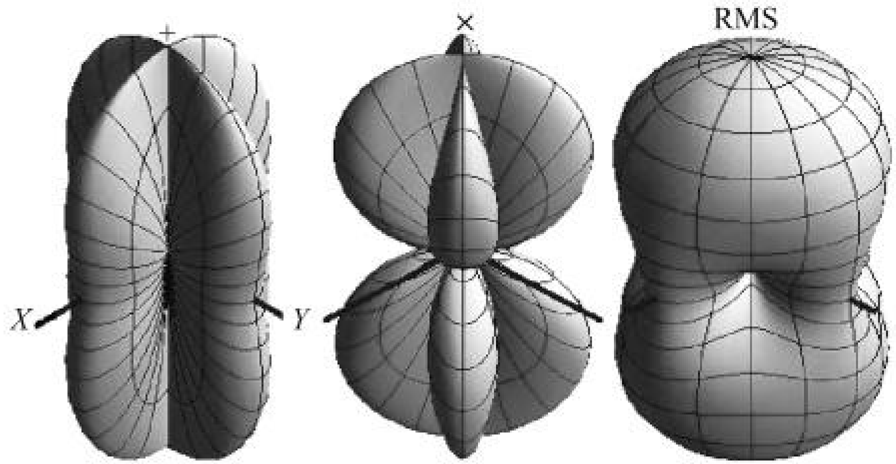
Suspended mirrors moving in sync



A control loop is activated to bring (and maintain) the mirrors at resonance

Sky coverage

The detector's sensitivity over the sky is not uniform



$$h_{det}(t) = F_{+}(t, ra, dec, \Psi) \times h_{+}(t) \; + \; F_{\times}(t, ra, dec, \Psi) \times h_{\times}(t)$$

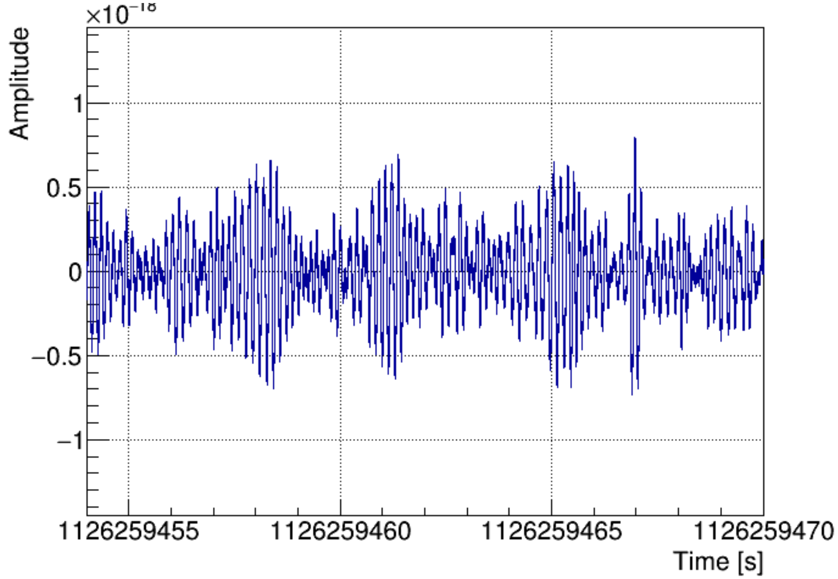
Source position (t, ra, dec)

Source polarization angle (Ψ)

Gravitationl-wave data

GW detectors' readout system provides at any instant an estimate of strain: a quantity that is sensitive to arms' length difference:

→ Digitized discrete time series: raw(t) (sampled at **16384** Hz or **20000** Hz) and synchronized with GPS clocks.
→ Calibration of raw(t): apply a frequency dependent factor [in reality this is a bit more complicated ...]



→ $h_{det}(t)$ time series that is detector noise plus all hypothetical GW signals

$$h_{det}(t) = n(t) + GW(t)$$

Power spectral density

Fourier transform

A time series *s(t)* can be projected over a basis of sinusoidal functions:

$$\tilde{s}(f)=\int_{-\infty}^{\infty} s(t)e^{-2i\pi ft}dt \qquad \text{(forward)}$$

$$s(t)=\int_{-\infty}^{\infty} \tilde{s}(f)e^{2i\pi ft}df \qquad \text{(backward)}$$

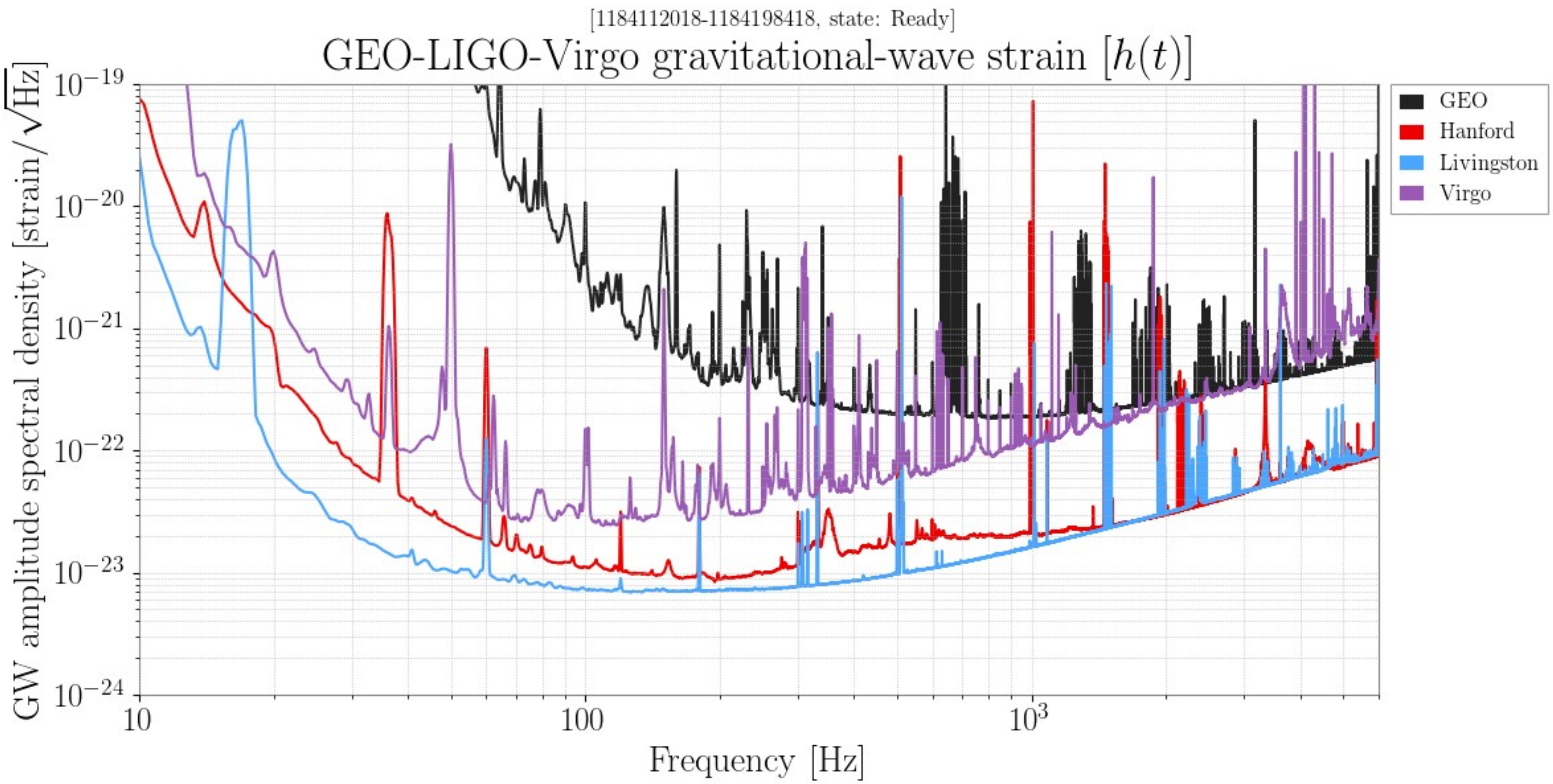
The signal is decomposed in characteristic frequencies

A noise source *n(t)* limiting the extraction of a signal *s(t)* is completely characterized by the power (amplitude) spectral density $S_n(f)$

$$S_n(f)=2|\tilde{n}(f)|^2 \qquad A_n(f)=\sqrt{S_n(f)}$$

Detector sensitivity

LIGO-Virgo sensitivity – 2017



Fundamental noises:

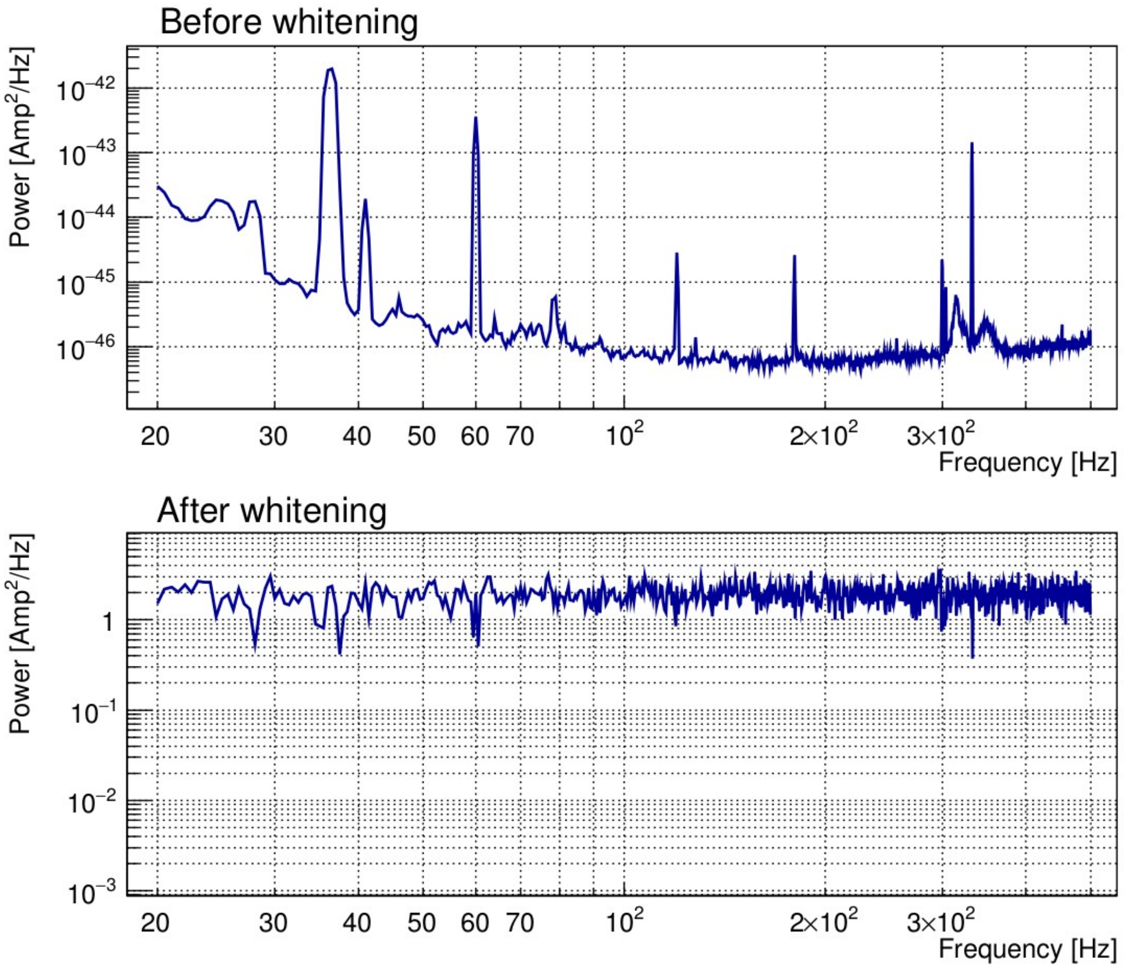
- **f < 10 Hz** → **seismic noise**
- **10 Hz < f < 200 Hz** → **thermal noise**
- **f > 200 Hz** → **quantum shot noise**

+ technical noise (environment, scattered light, control...)

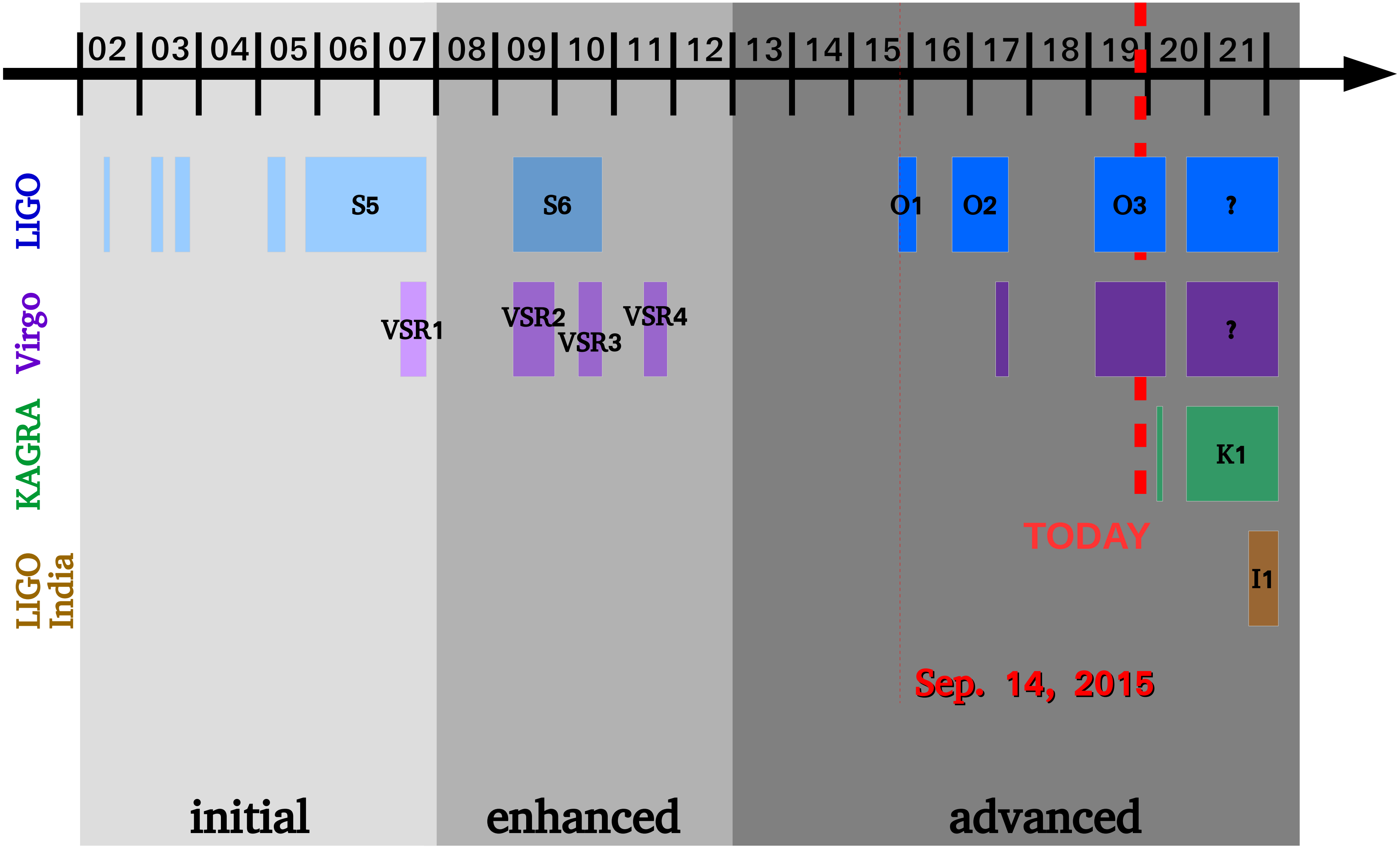
Data whitening

GW data must be whitened. Several methods are used :
- reweighting of frequency bins
- linear prediction

→ white noise is mandatory for statistical interpretation of the data



Scientific runs

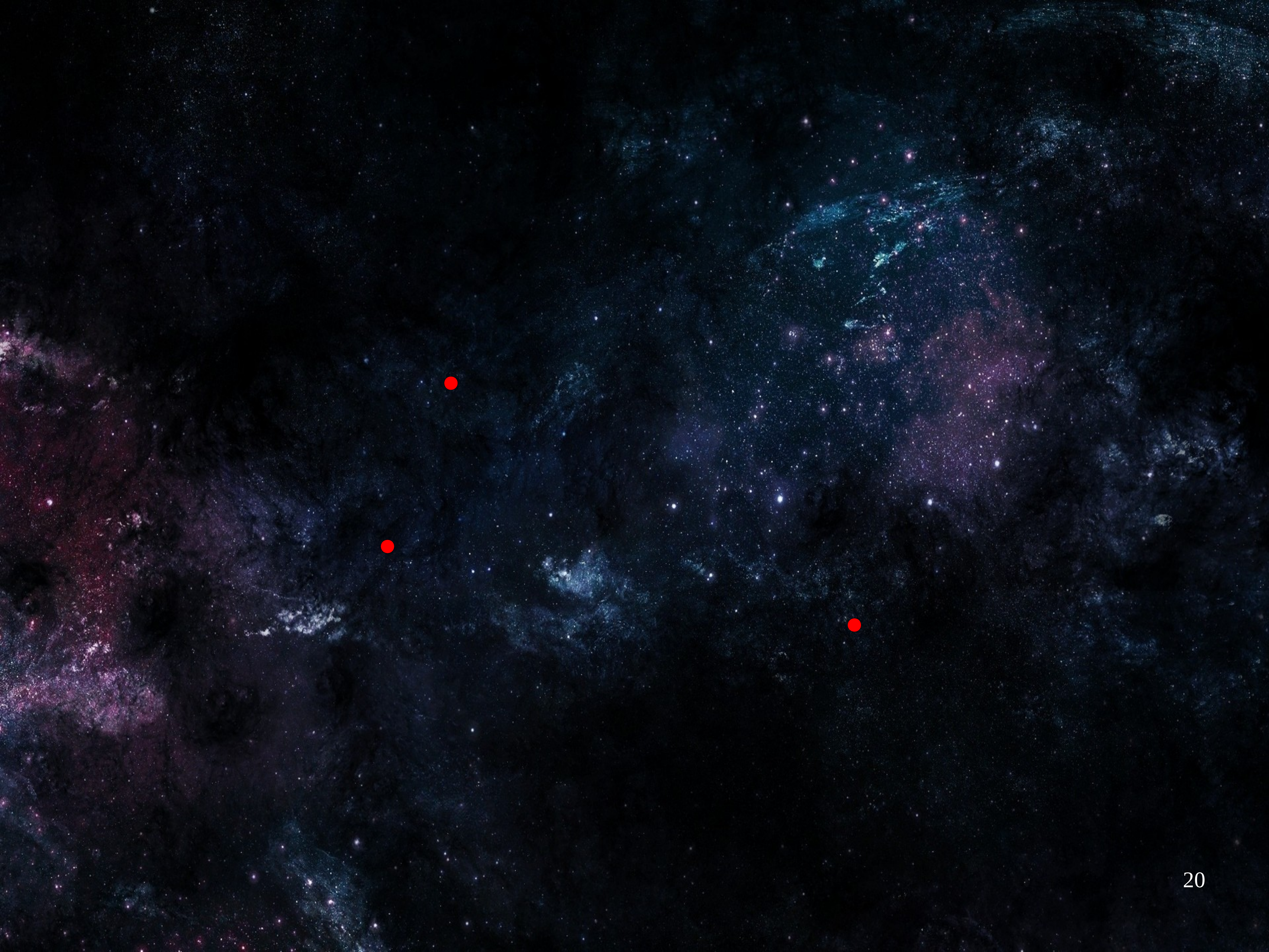


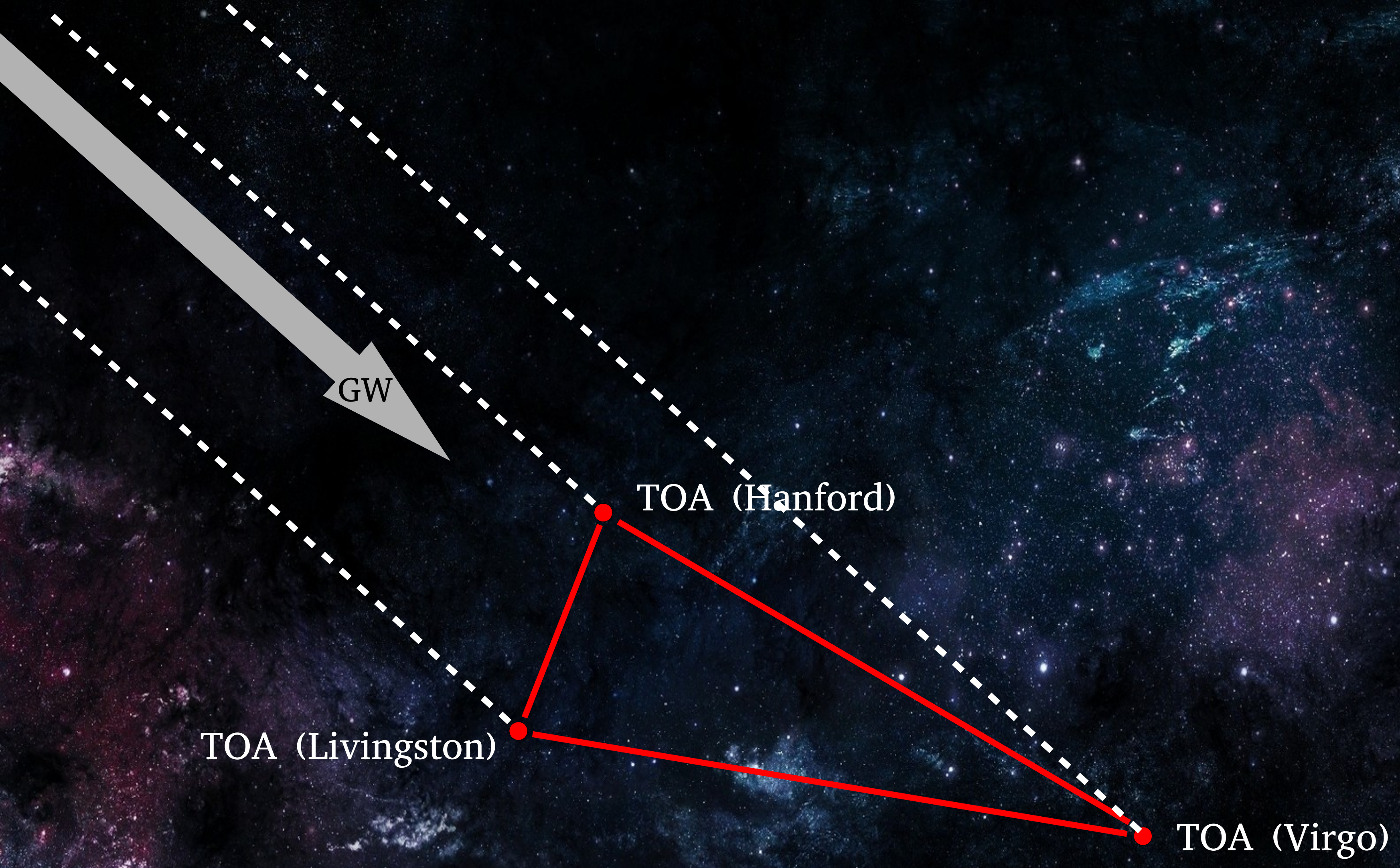
Data analysis :

- O1 : ~50 days of data, 2 detectors
- O2 : ~100 days of data, 2(+1) detectors
- *O3 : ~200 days of data, 3 detectors*

Working with a network of detectors is mandatory

- to perform a coincident search
- to test the signal consistency across the network
- to estimate your background noise
- to locate the source of gravitational waves

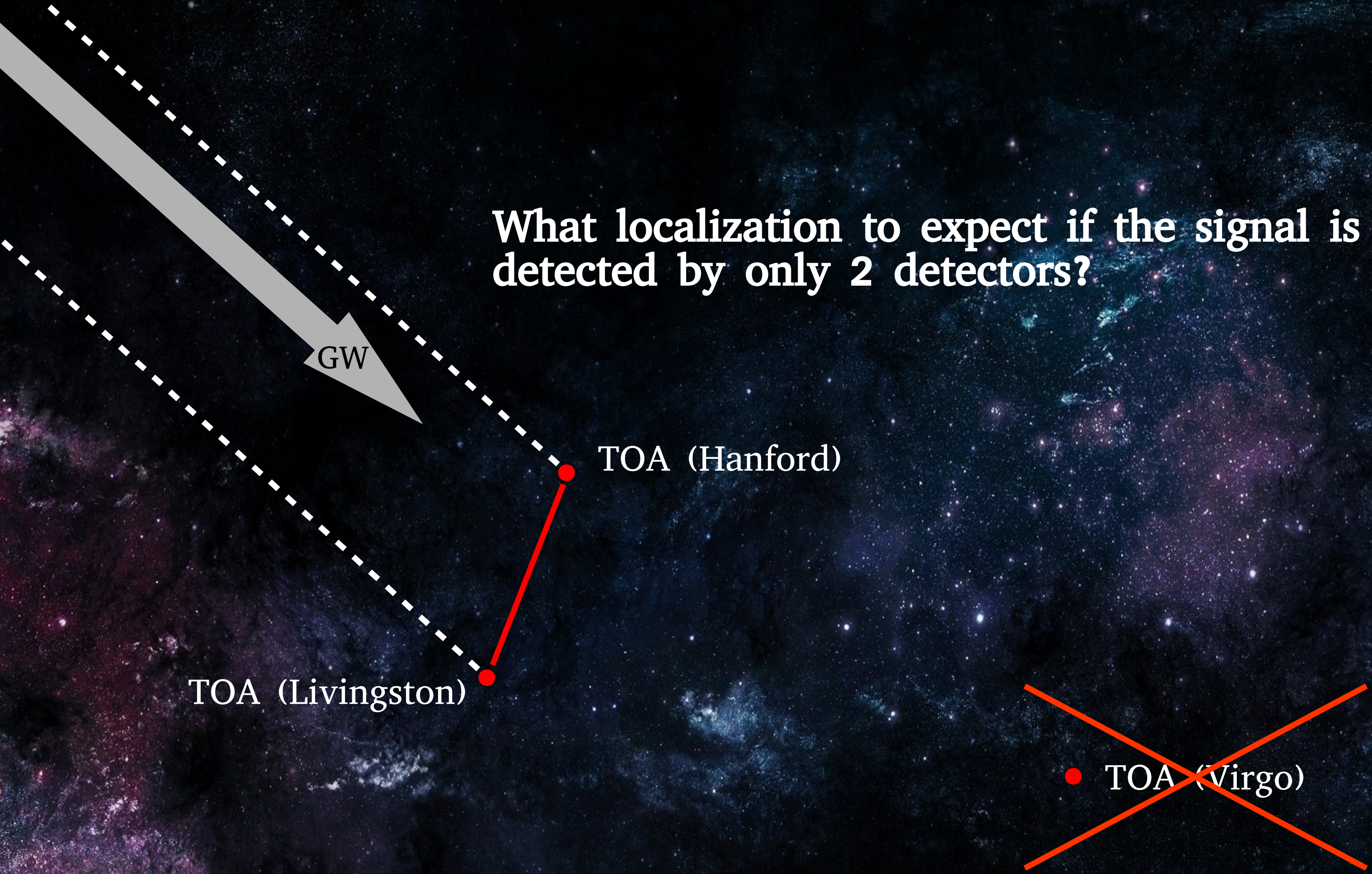




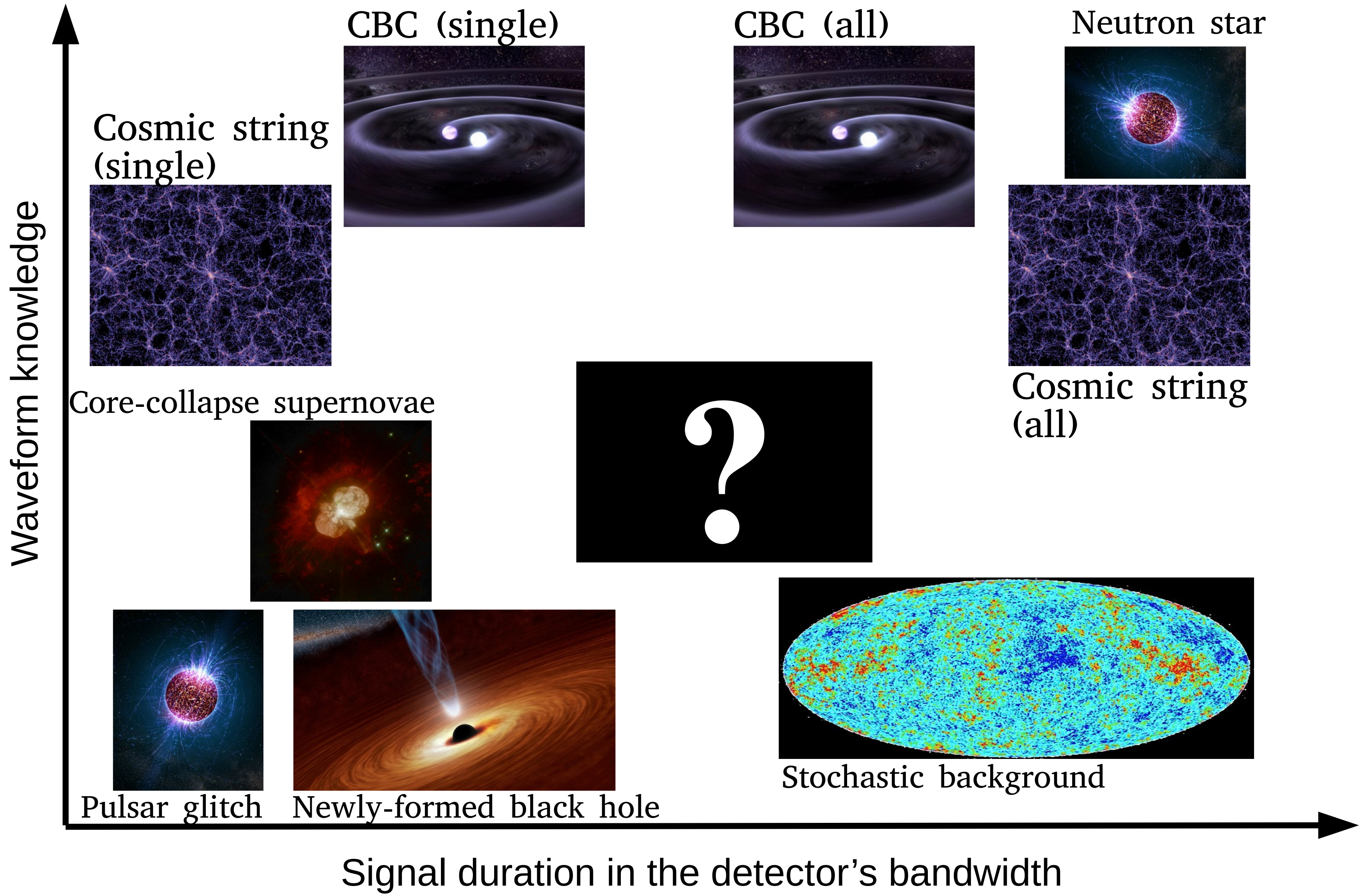
The direction of the source is triangulated using the signal times of arrival

→ Follow-up in other channels (e.g. EM)

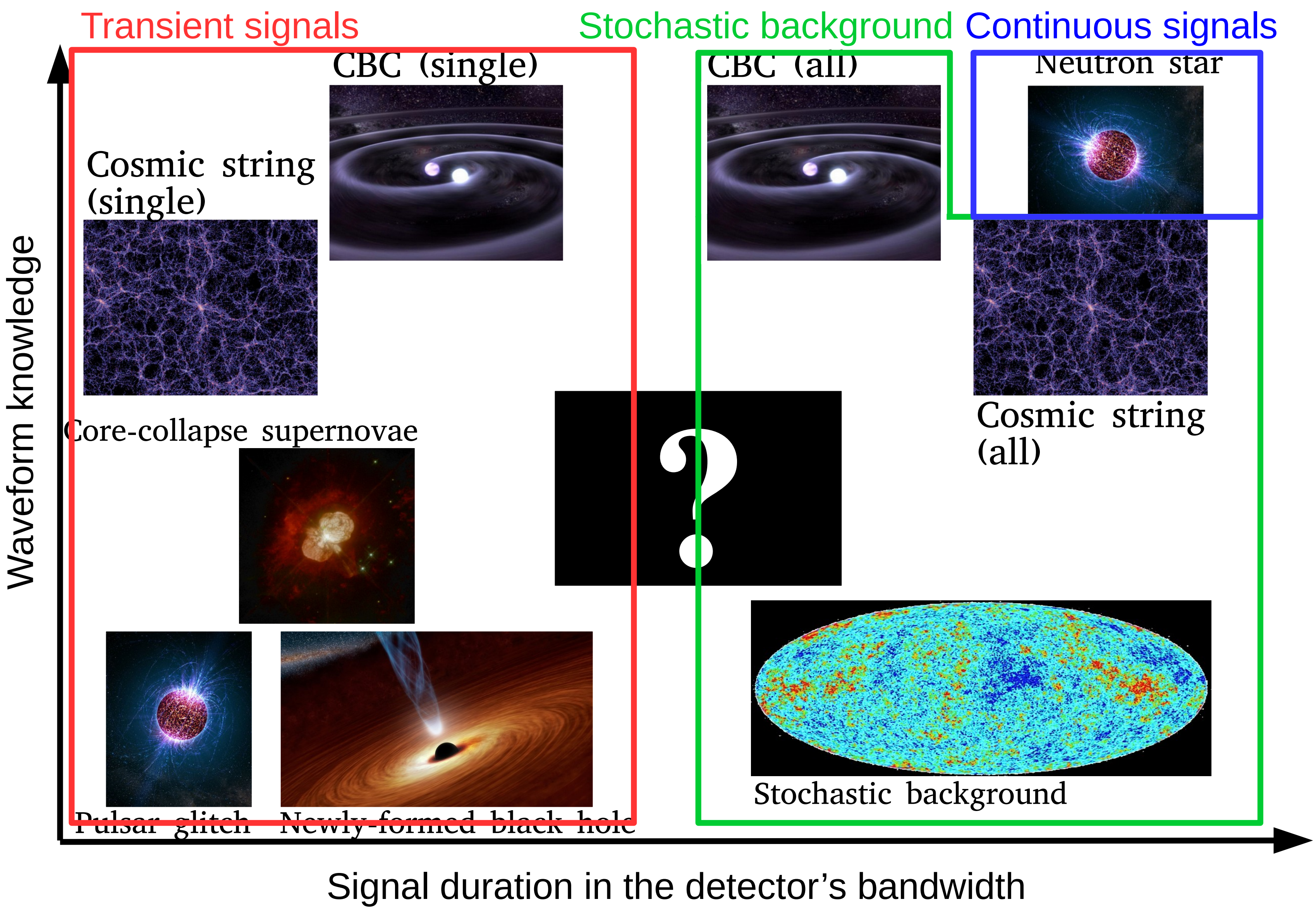
What localization to expect if the signal is detected by only 2 detectors?



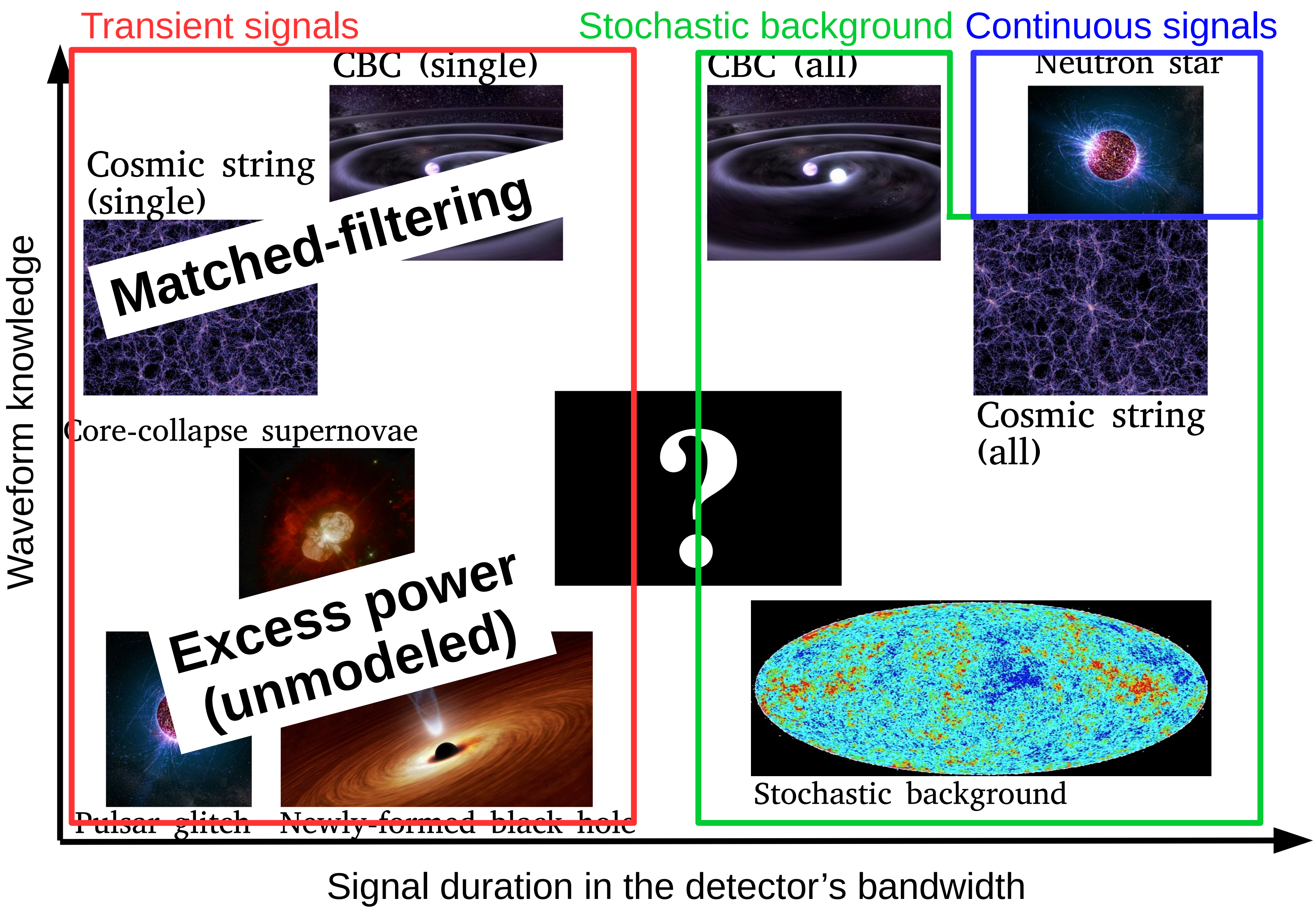
Source classification: search method



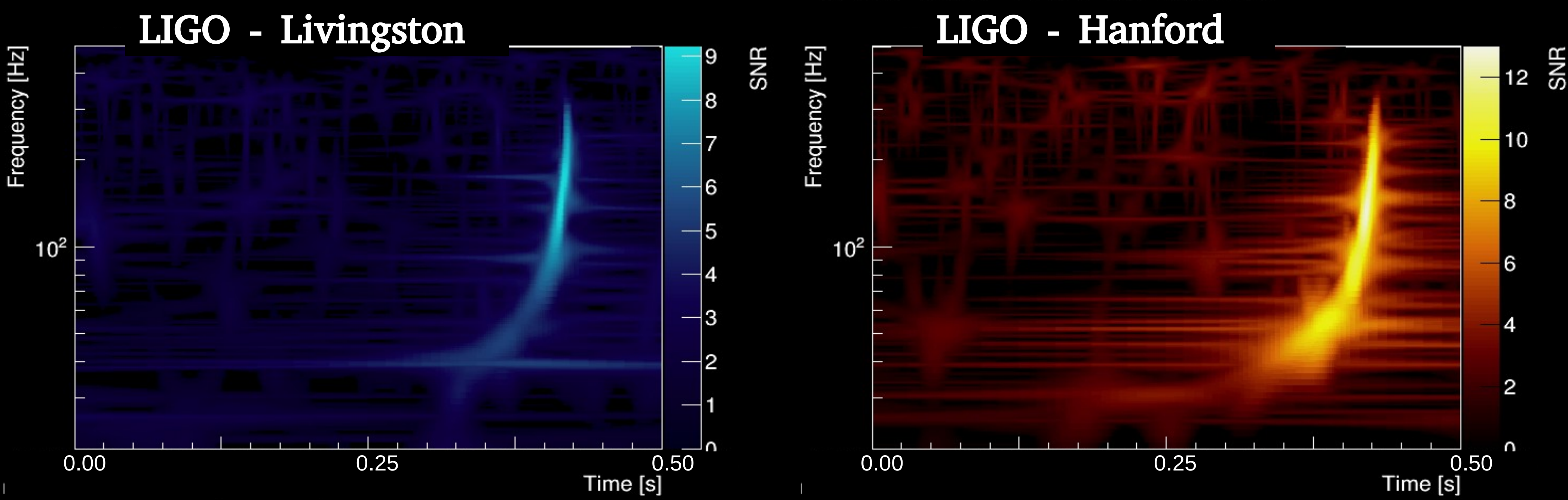
Source classification: search method



Source classification: search method



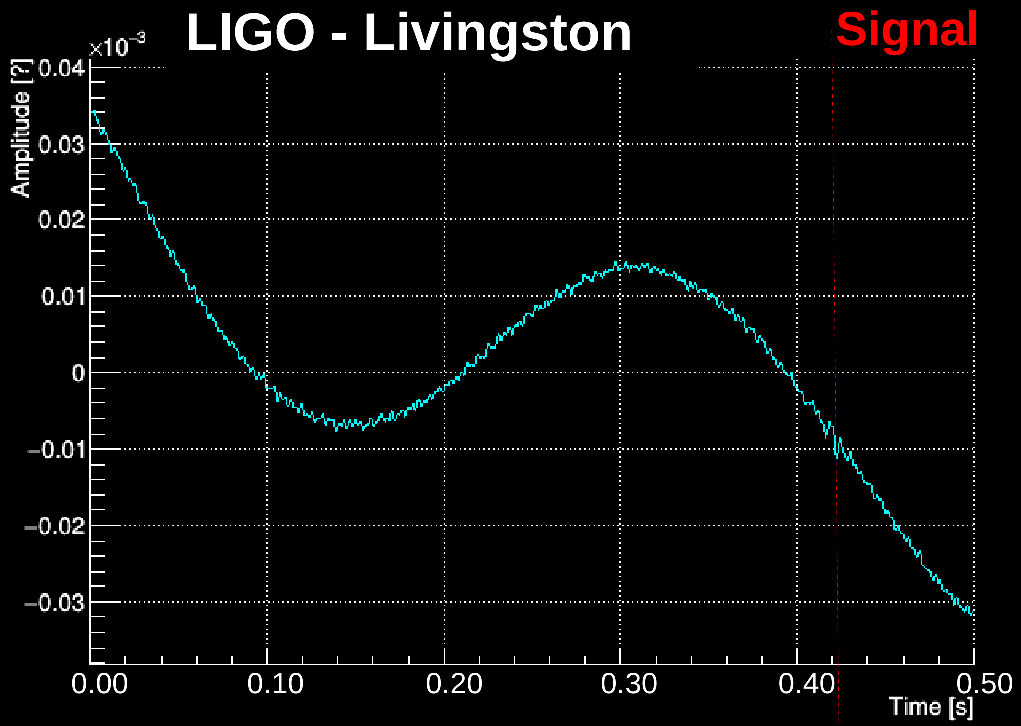
Unmodeled searches



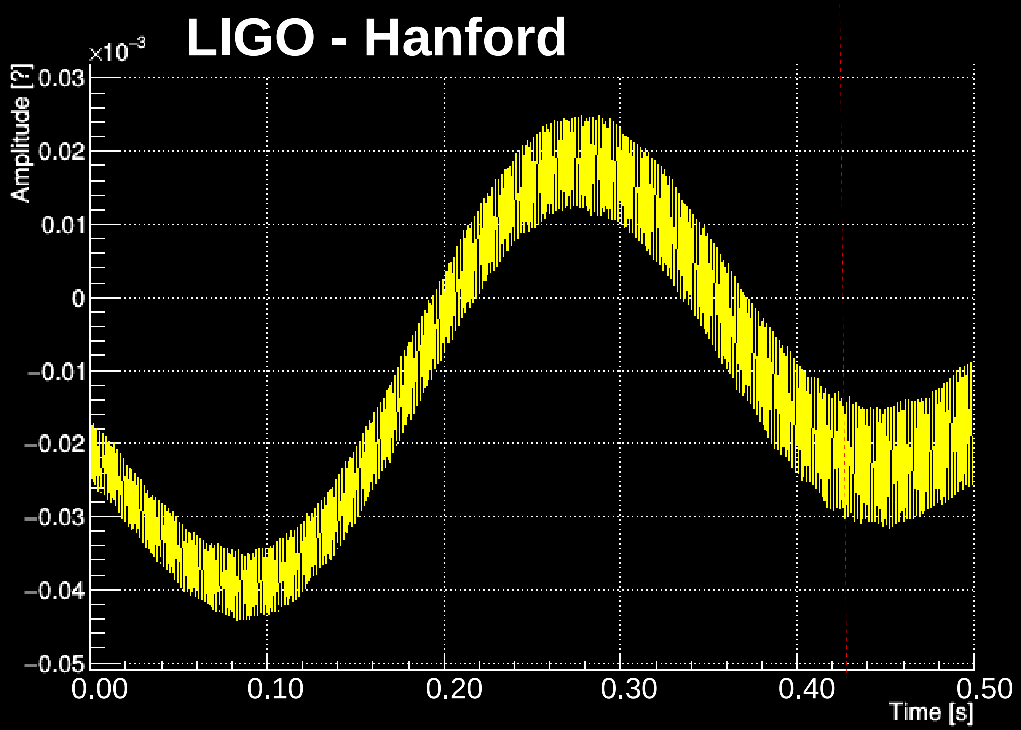
→ Time-frequency decomposition → noise events + (maybe) GW events
→ Coincidence between detectors (time + other parameters)
→ Noise rejection
→ Classify events using a "smart" recipe
→ Estimate background
→ Compare events with your background
→ Measure the probability for each events to be true GW signal

GW150914

Output power

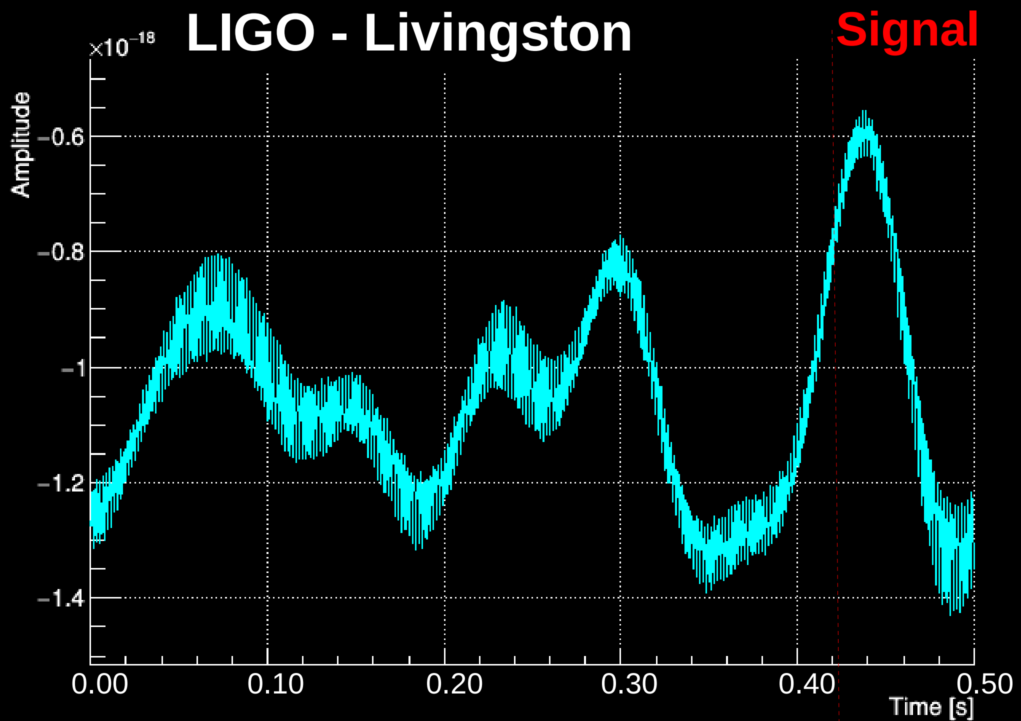


Output power



GW150914

$h(t)$

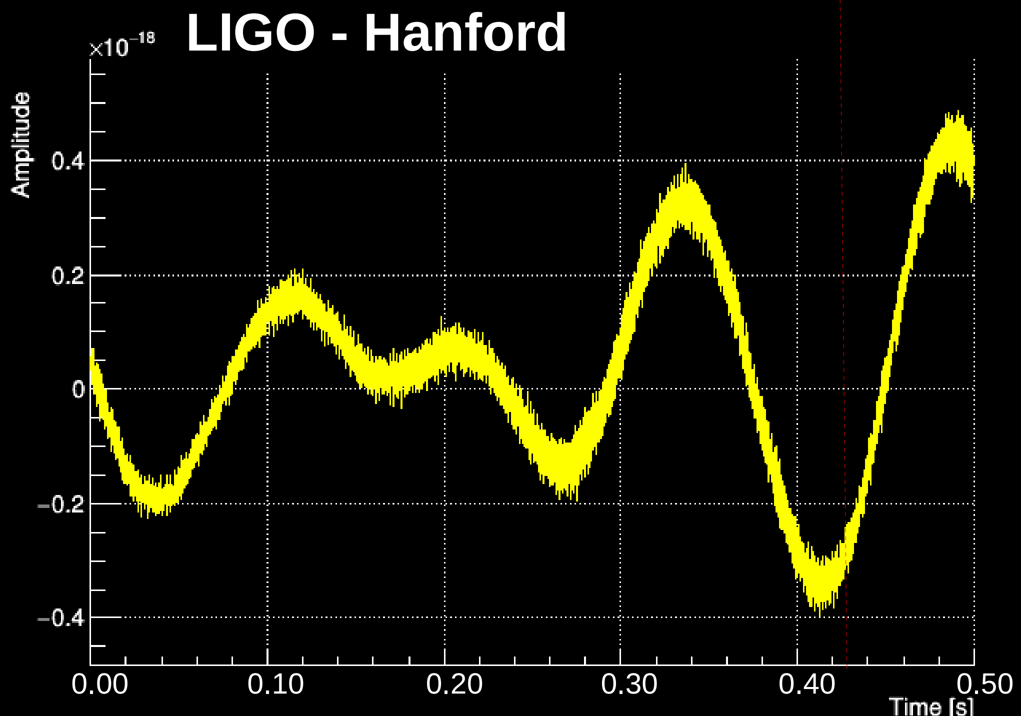


Data is calibrated

→ GW strain amplitude *h(t)*

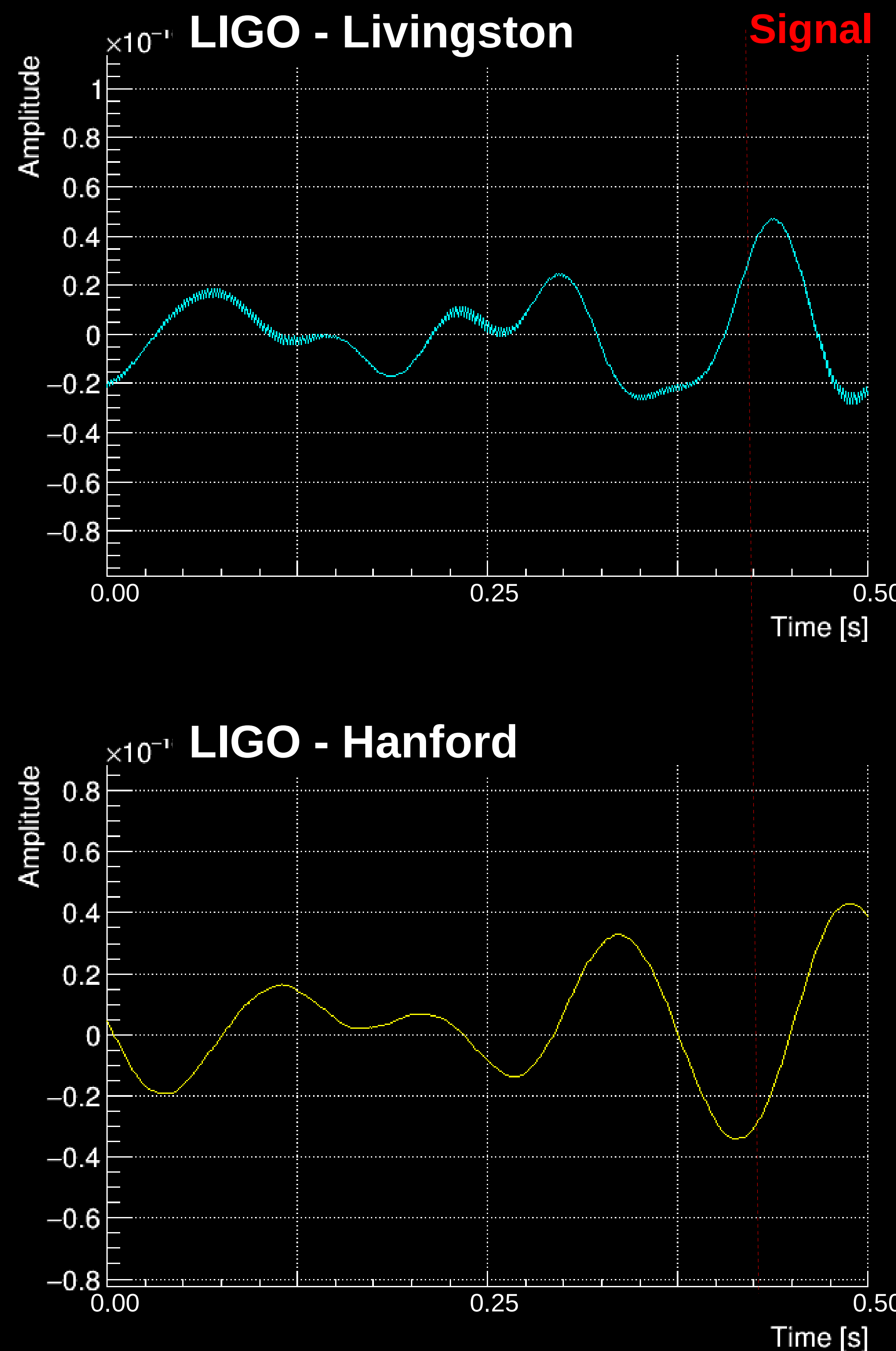
(including high-pass filter f > 10 Hz)

$h(t)$



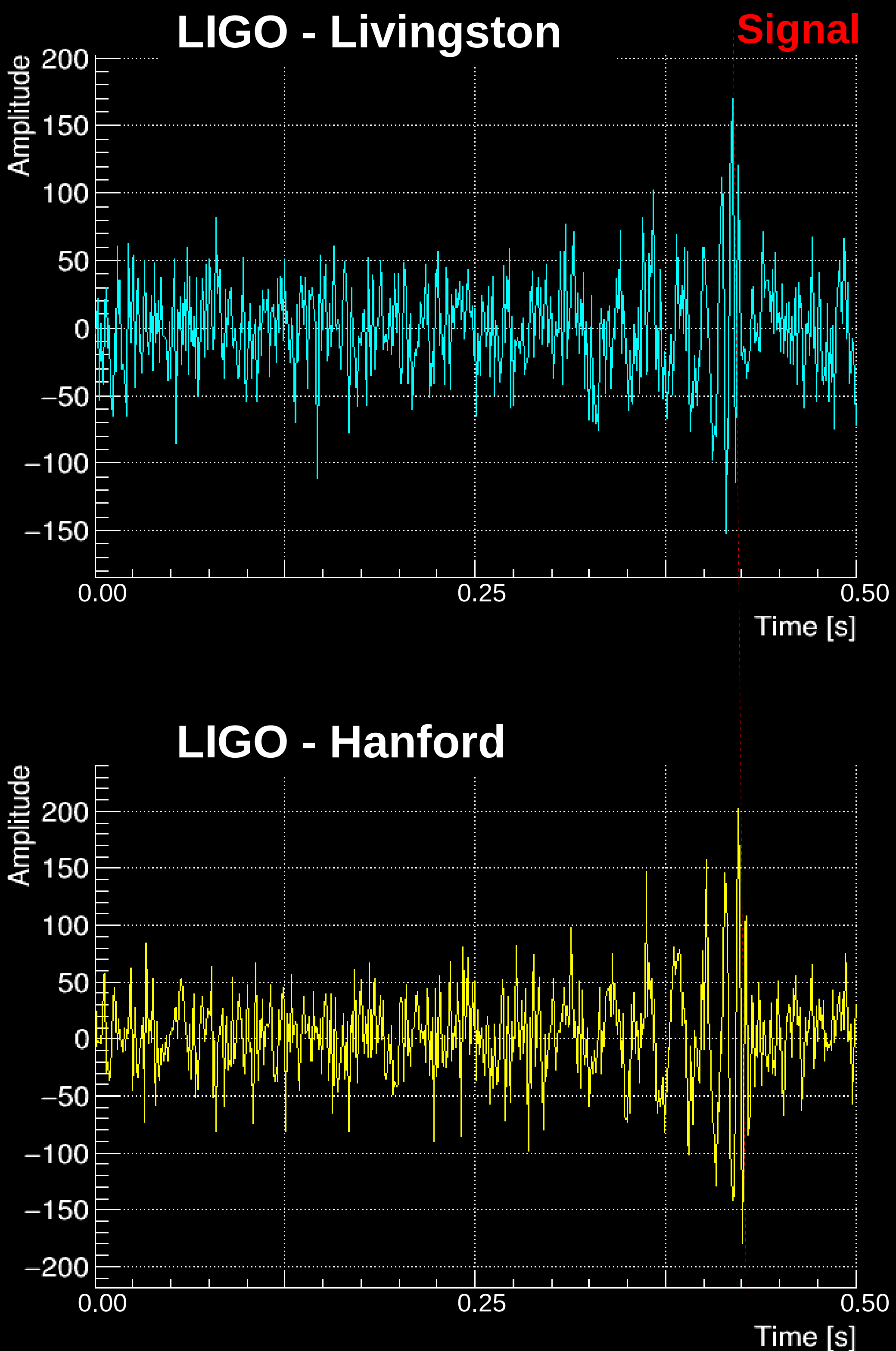
GW150914

Data are low-pass filtered
(here, < 500 Hz)

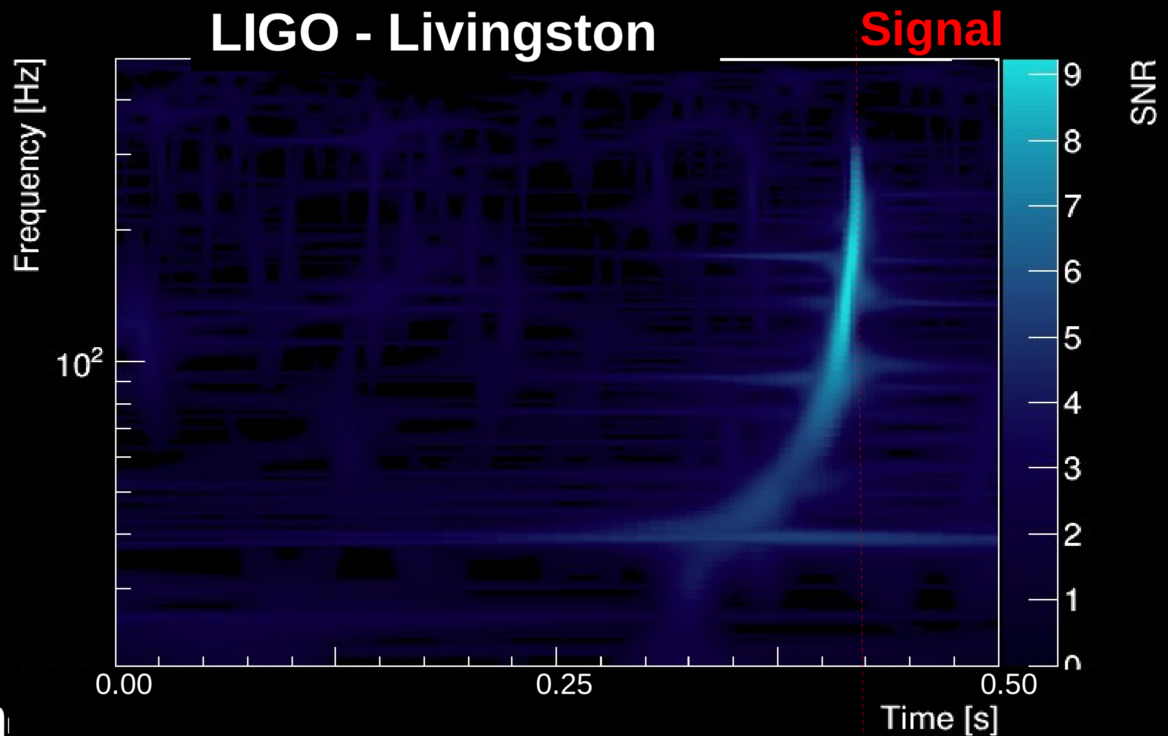


GW150914

Data are whitened

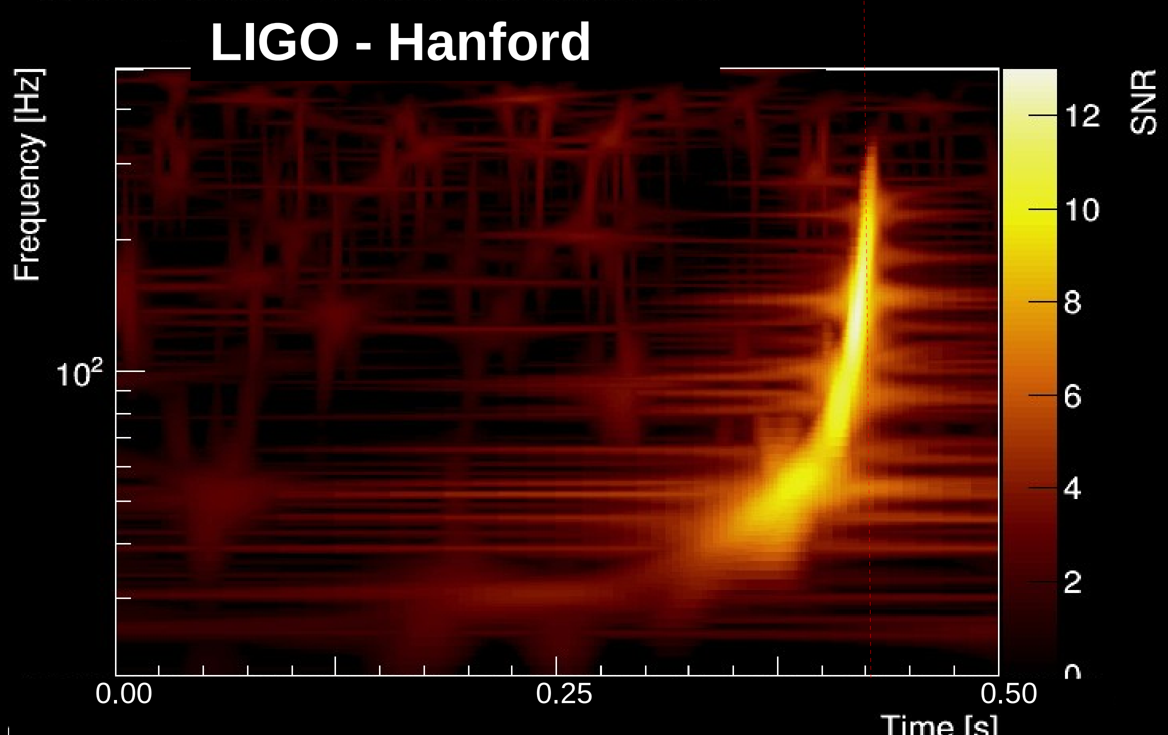


GW150914



Time-frequency decomposition
(Short Fourier transforms)

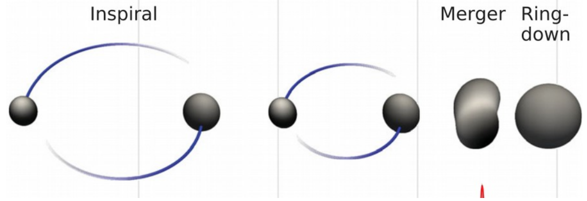
$$X(\tau,\phi,Q)=\int_{-\infty}^{+\infty} h_{det}(t)\,w(t-\tau,\phi,Q)\,e^{-2i\pi\phi\tau}\,dt$$

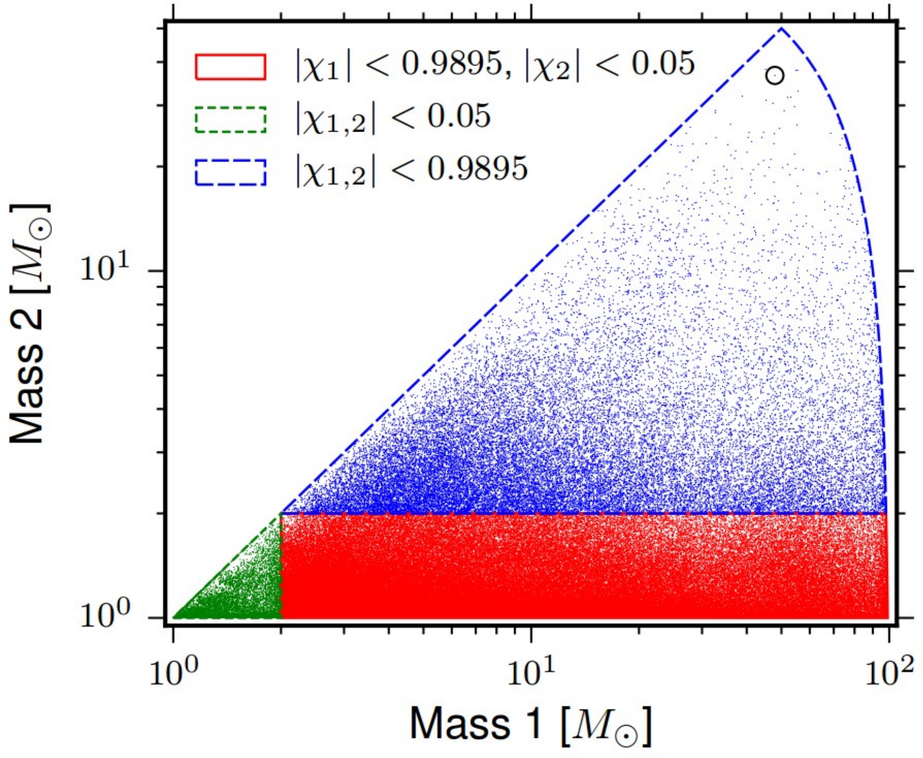


Modeled search

Theoretical input:

- 90s: CBC PN waveforms (Blanchet, Iyer, Damour, Deruelle, Will, Wiseman, ...)
- 00s: CBC Effective One Body "EOB" (Damour, Buonanno)
- 06: BBH numerical simulation (Pretorius, Baker, Loustos, Campanelli)





The intrinsic waveform parameters:

- Masses:

$$M_{tot} = M_1 + M_2$$

- Spins and orbital angular momentum:

$$\vec{S}_{tot} = \vec{S}_1 + \vec{S}_2 + \vec{J}$$

The waveform models used for the search:

- Inspiral, PN3.5 for $M_{tot} < 4\, M_{sun}$
- Inspiral/Merger/Ringdown EOB + numerical relativity for $M_{tot} > 4\, M_{sun}$
- Spins and orbital angular momentum are aligned

Template bank → match-filtering technique

Match filtering

data

waveform template

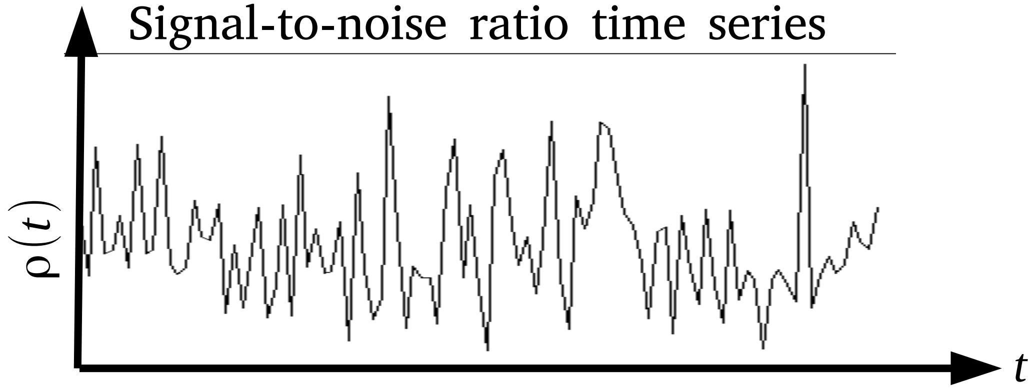
$$\frac{\tilde{h}(f)\,\tilde{h}_c^{*}(f)}{S_n(f)}$$

Noise spectral density

Match filtering

$$\rho_c(t) = 4\,\Re\left[\int_0^\infty \frac{\tilde{h}(f)\,\tilde{h}_c^*(f)}{S_n(f)} e^{2i\pi f t}\, df\right]$$

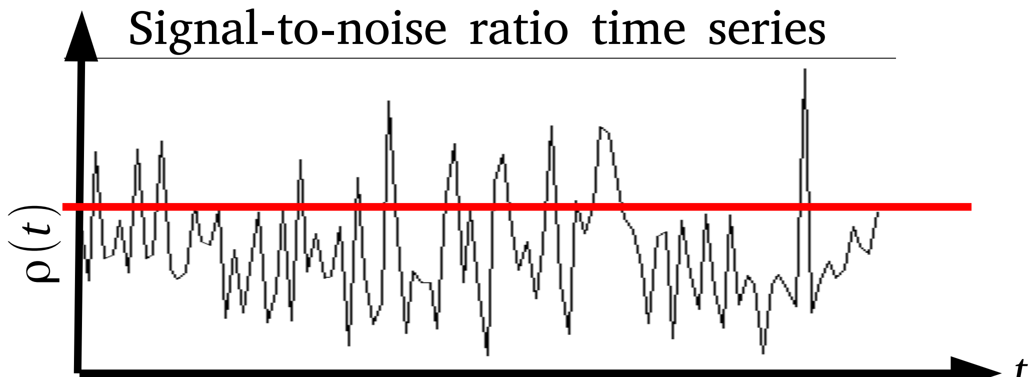
A signal-to-noise ratio (SNR) is computed for each template



Match filtering

$$\rho_c(t) = 4\,\Re\left[\int_0^\infty \frac{\tilde{h}(f)\,\tilde{h}_c^*(f)}{S_n(f)}\, e^{2i\pi f t}\, df\right]$$

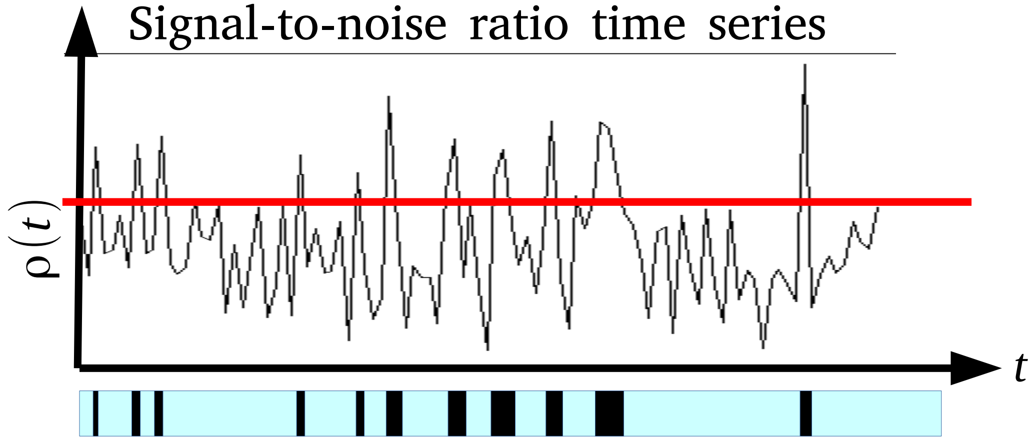
A signal-to-noise ratio (SNR) is computed for each template



A list of events is produced:
- start/end/peak times
- SNR
- template parameters (masses, spins)

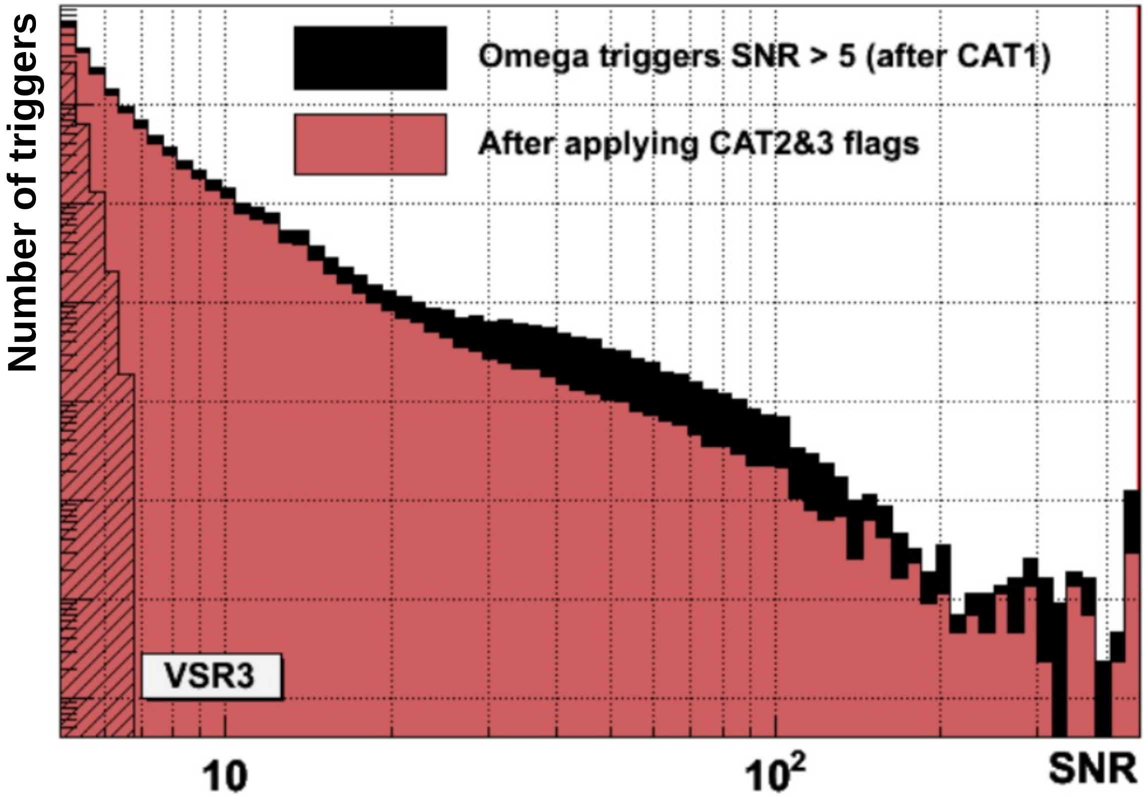
Now the challenge is to reject noise events to better isolate true signals

Single-detector triggers



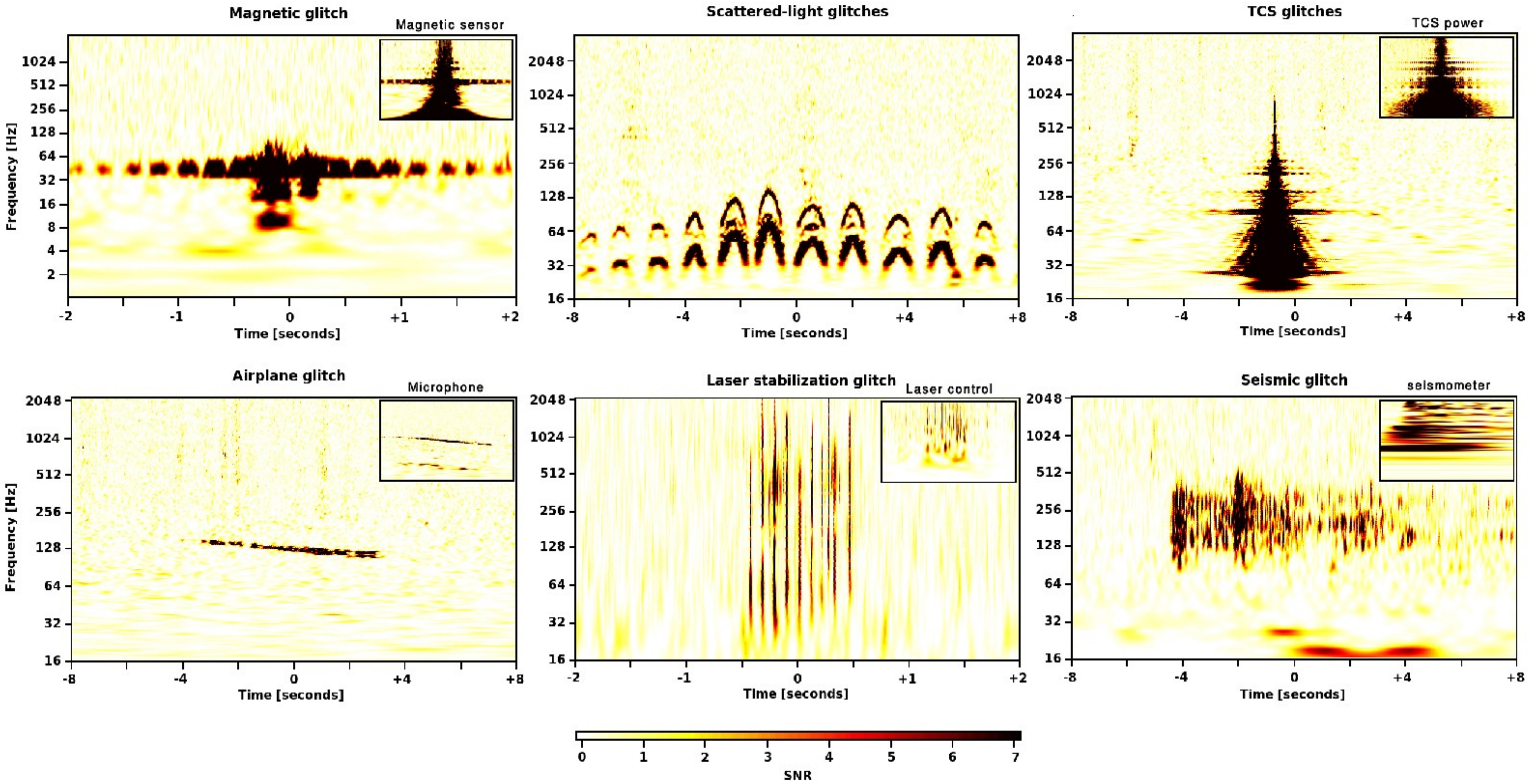
A list of events is produced:
- start/end/peak times
- SNR
- template parameters (masses, spins)

Now, the challenge is to reject noise events to better isolate true signals

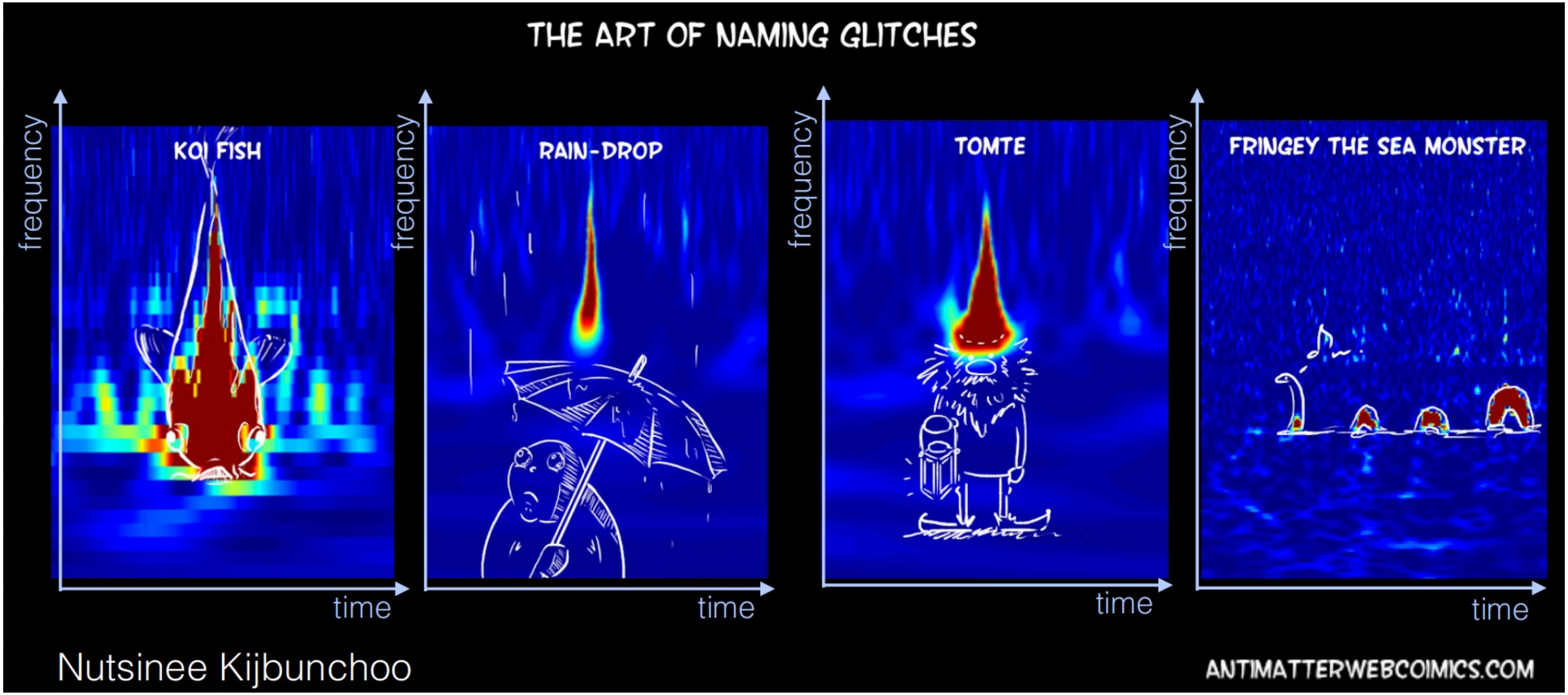


The noise distribution is highly non-Gaussian !

Single-detector noise



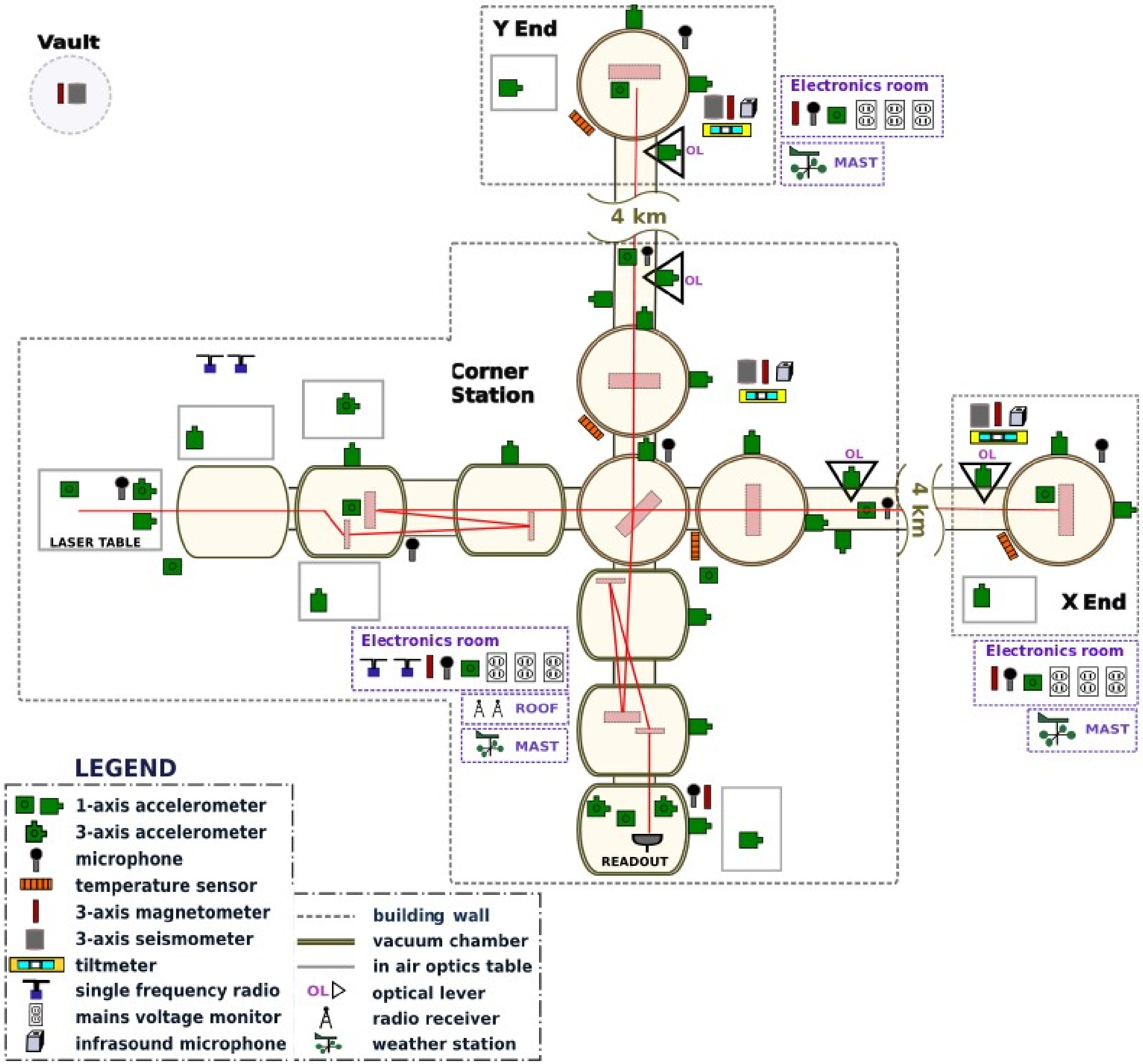
Single-detector noise



Monitoring noise

Thousands of auxiliary channels are used to monitor the instruments

- environmental sensors
- detector sub-systems
- detector control



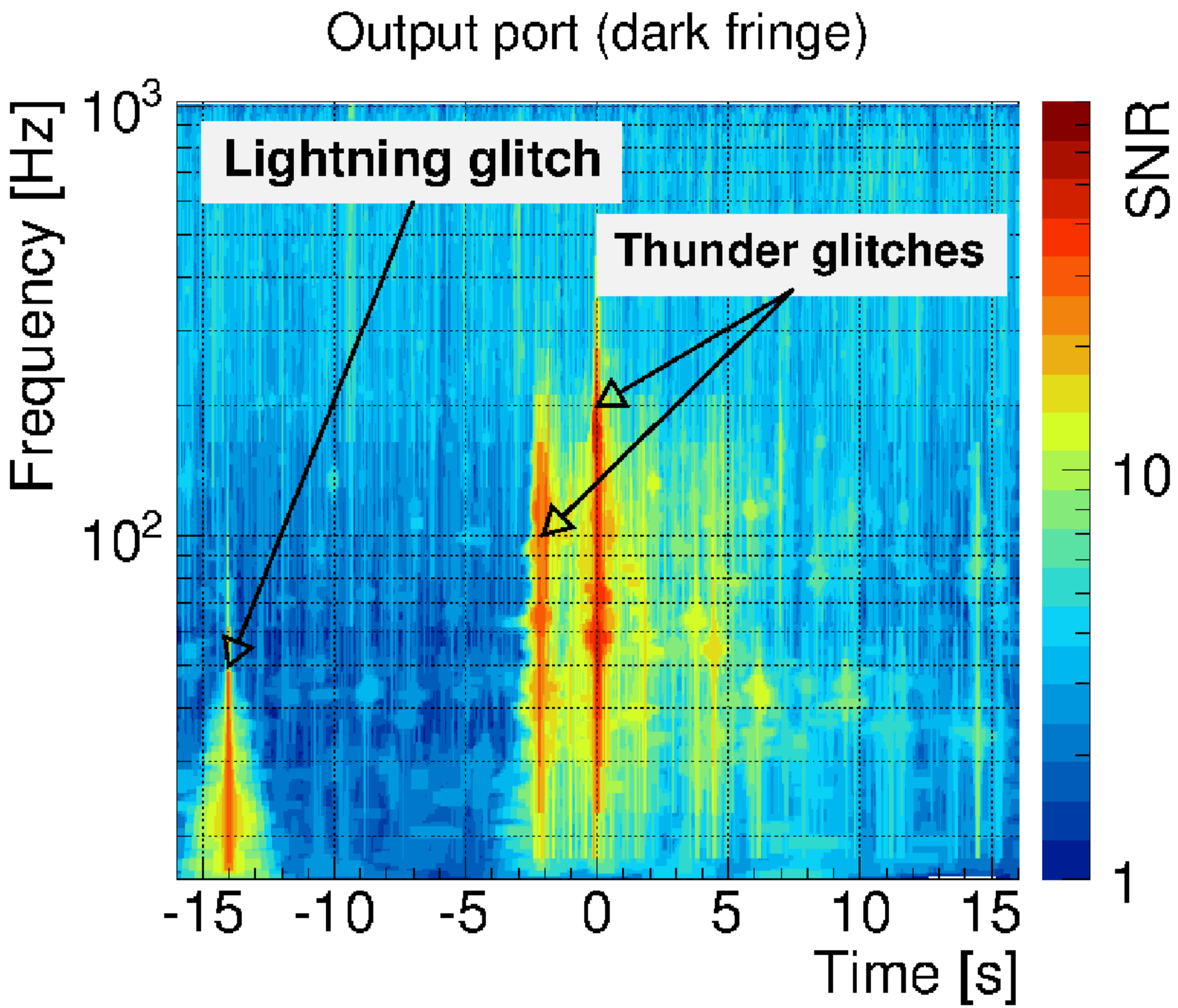
Noise injection campaigns are conducted to identify the detector's response to different noise stimulation

Multiple transient noises were identified during the run

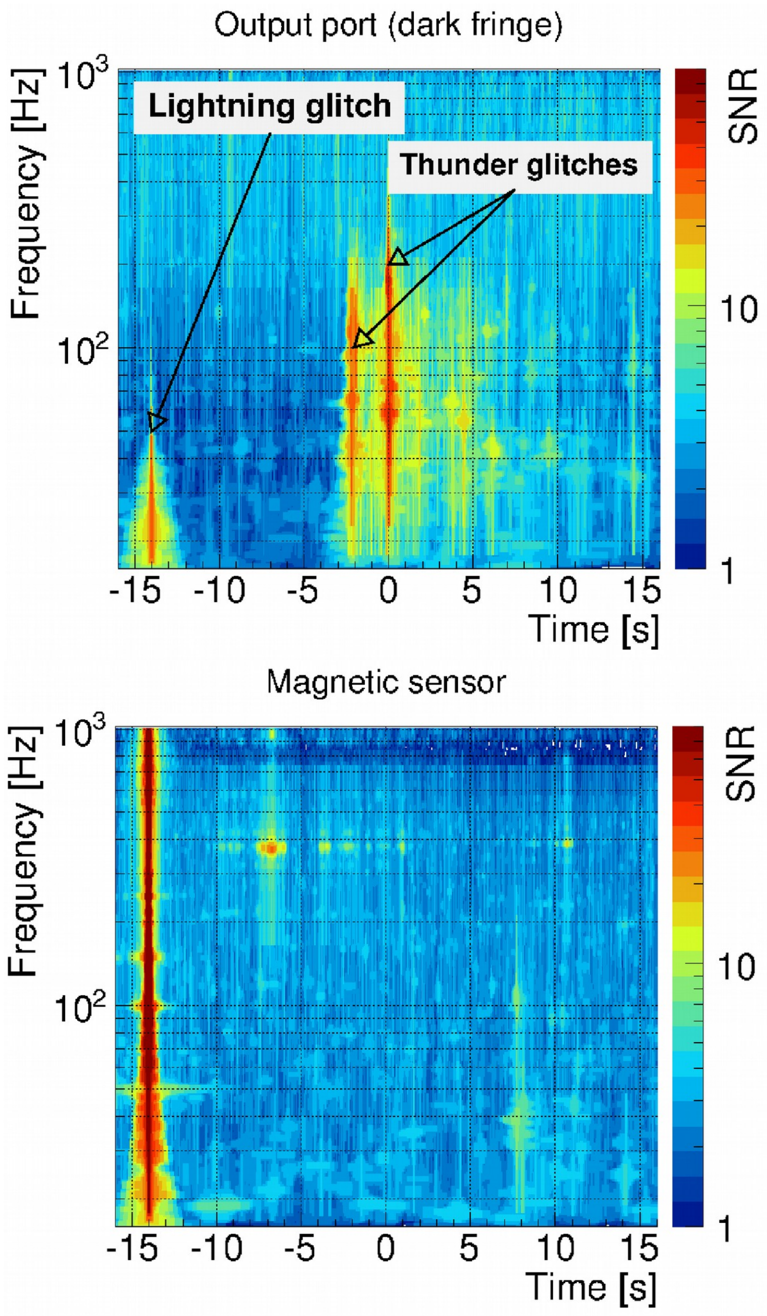
→ Anthropogenic noise
→ Earthquakes
→ Radio-frequency modulation
→ …

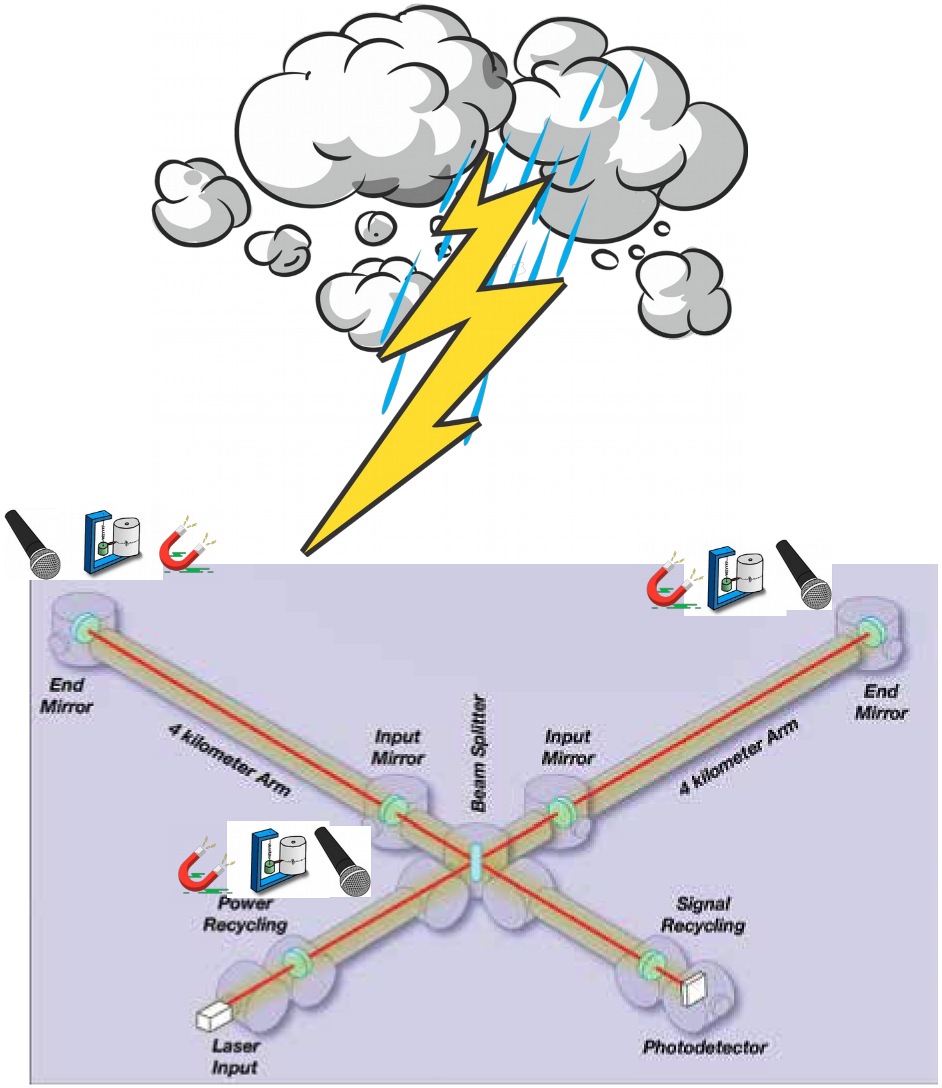
Option #1: fix the detector
Option #2: remove transient events in the data

Monitoring noise

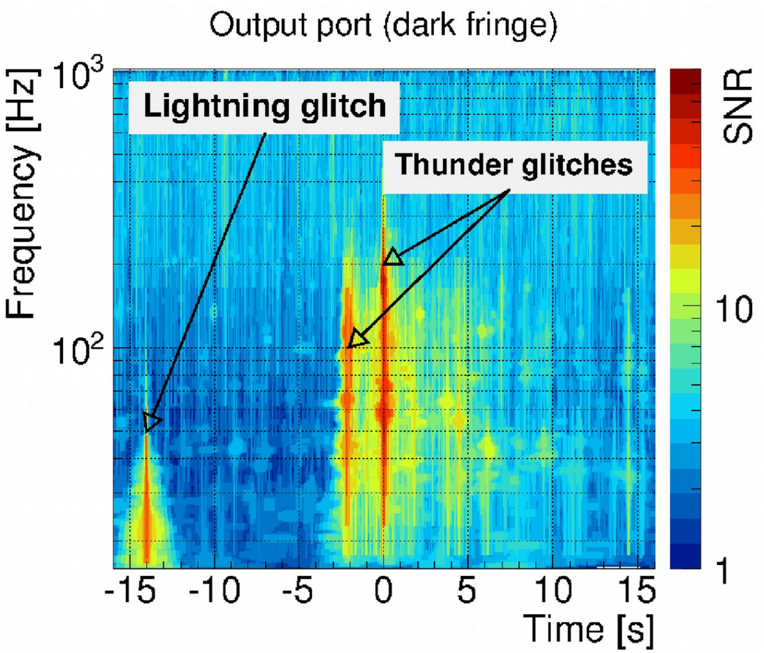


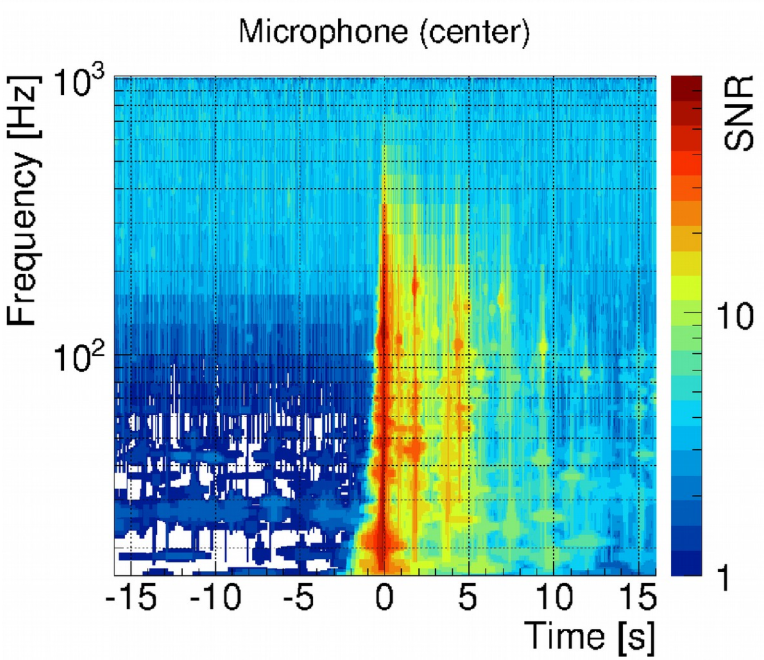
Monitoring noise

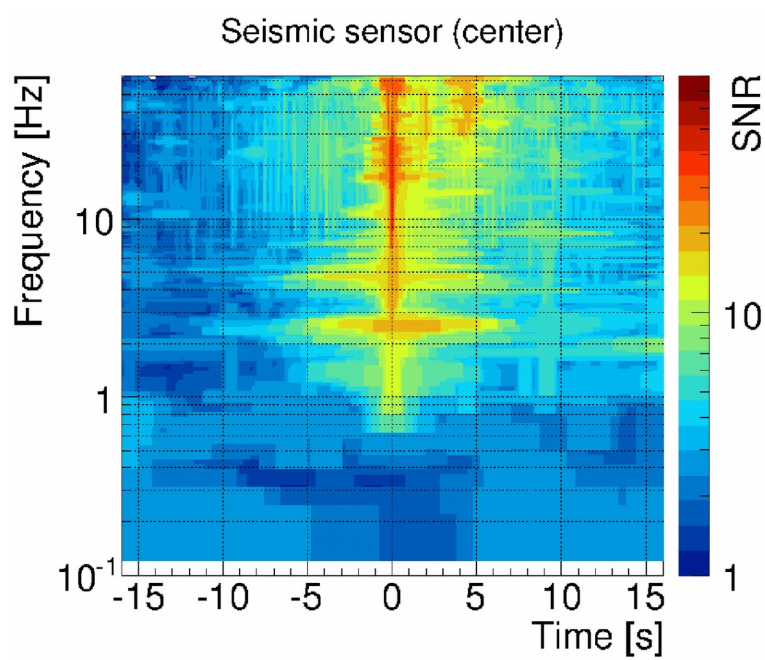




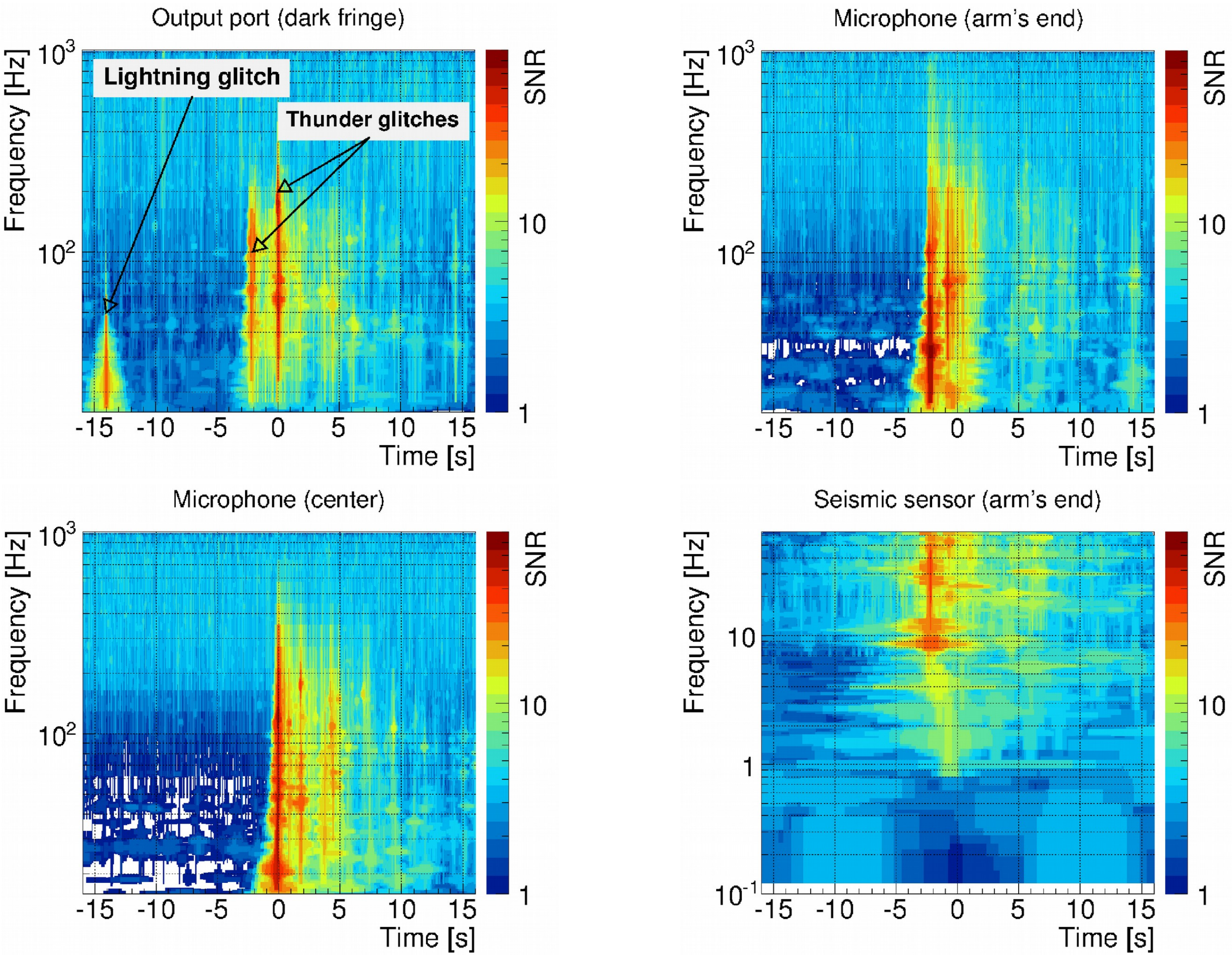
Monitoring noise



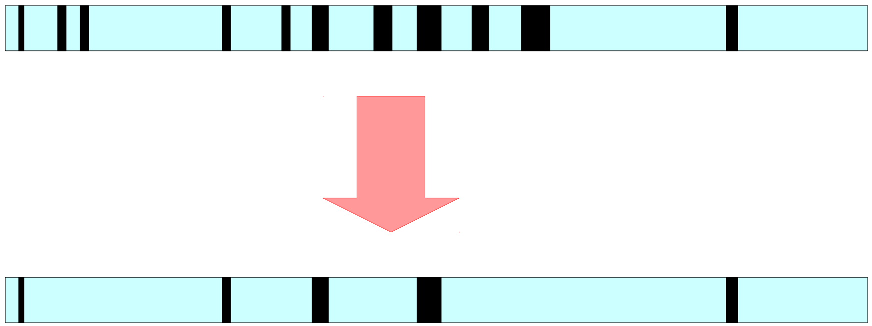




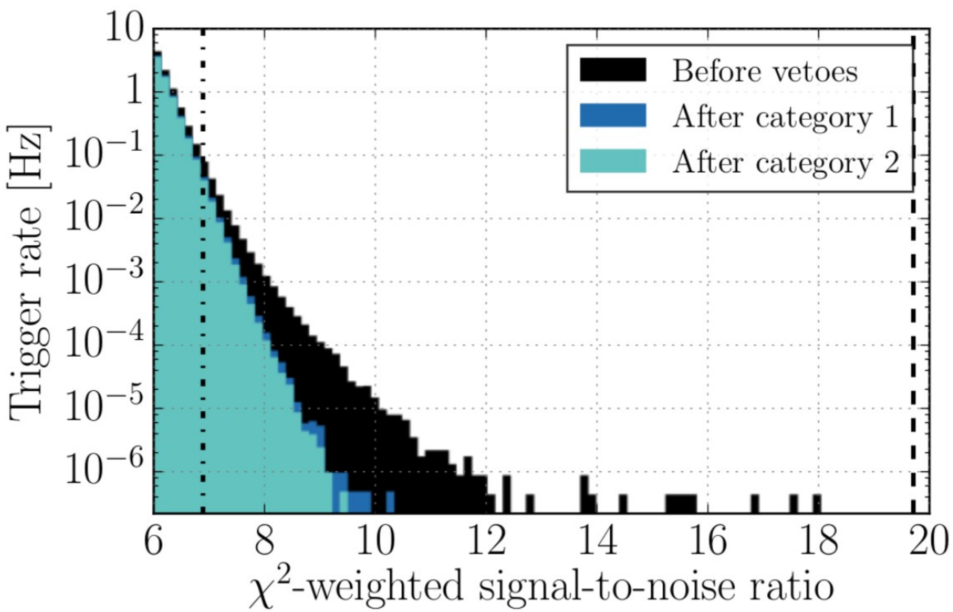
Monitoring noise



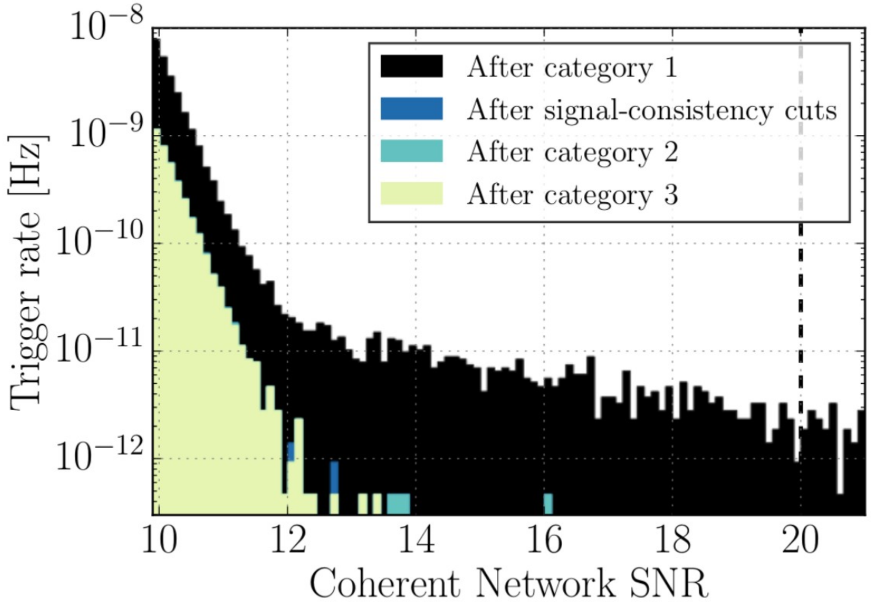
Rejecting noise



CBC search



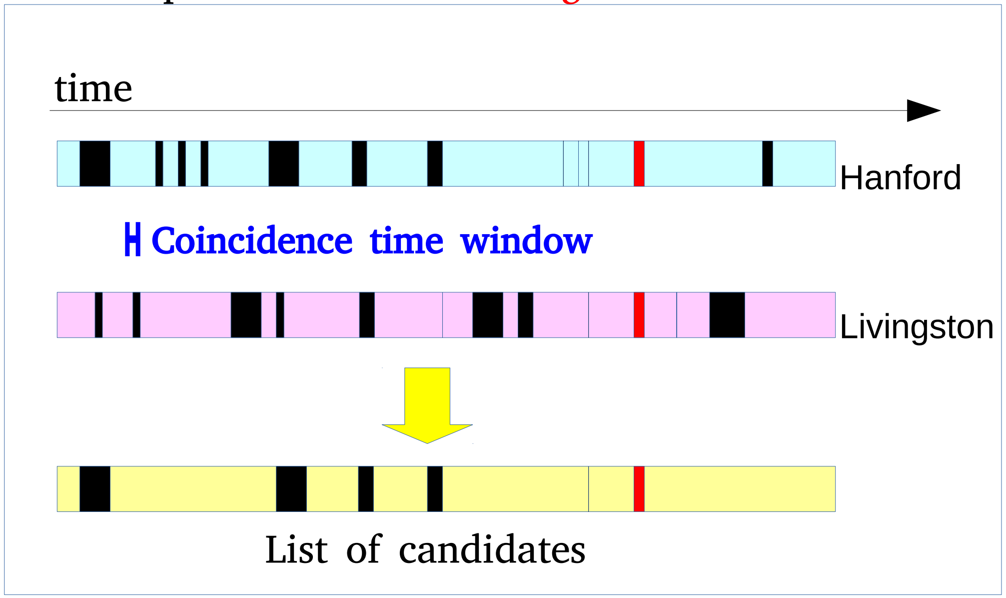
Burst search



Multi-detectors coincidence

A gravitational-wave signal is detected by multiple detectors almost simultaneously

True experiment = noise + signal



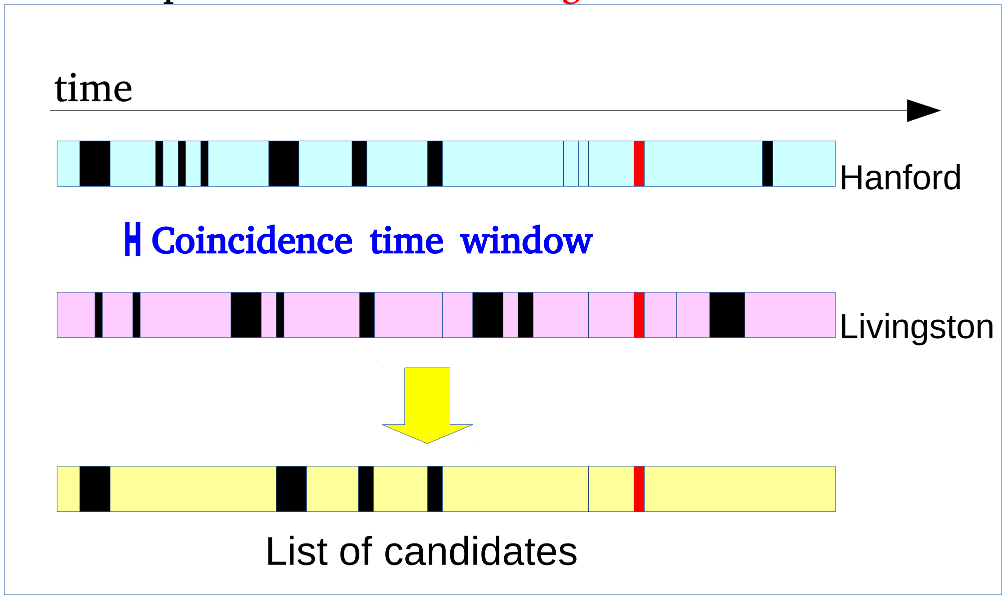
Coincidence rate:

$$R_{coinc} \sim R_H R_L \Delta t_{win}$$
$$\sim (1\,Hz) \times (1\,Hz) \times (10^{-2}\,s) = 10^{-2}\,Hz$$

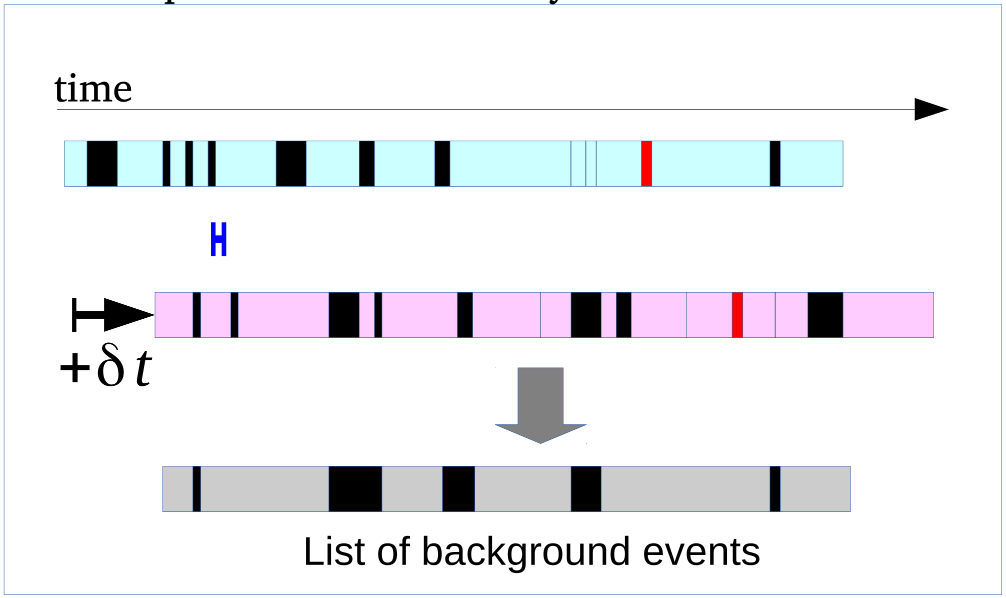
Multi-detectors coincidence

The background of a gravitational-wave search is estimated using the time-slide technique
Assumption = uncorrelated noise between detectors

True experiment = noise + signal



Fake experiment = noise only

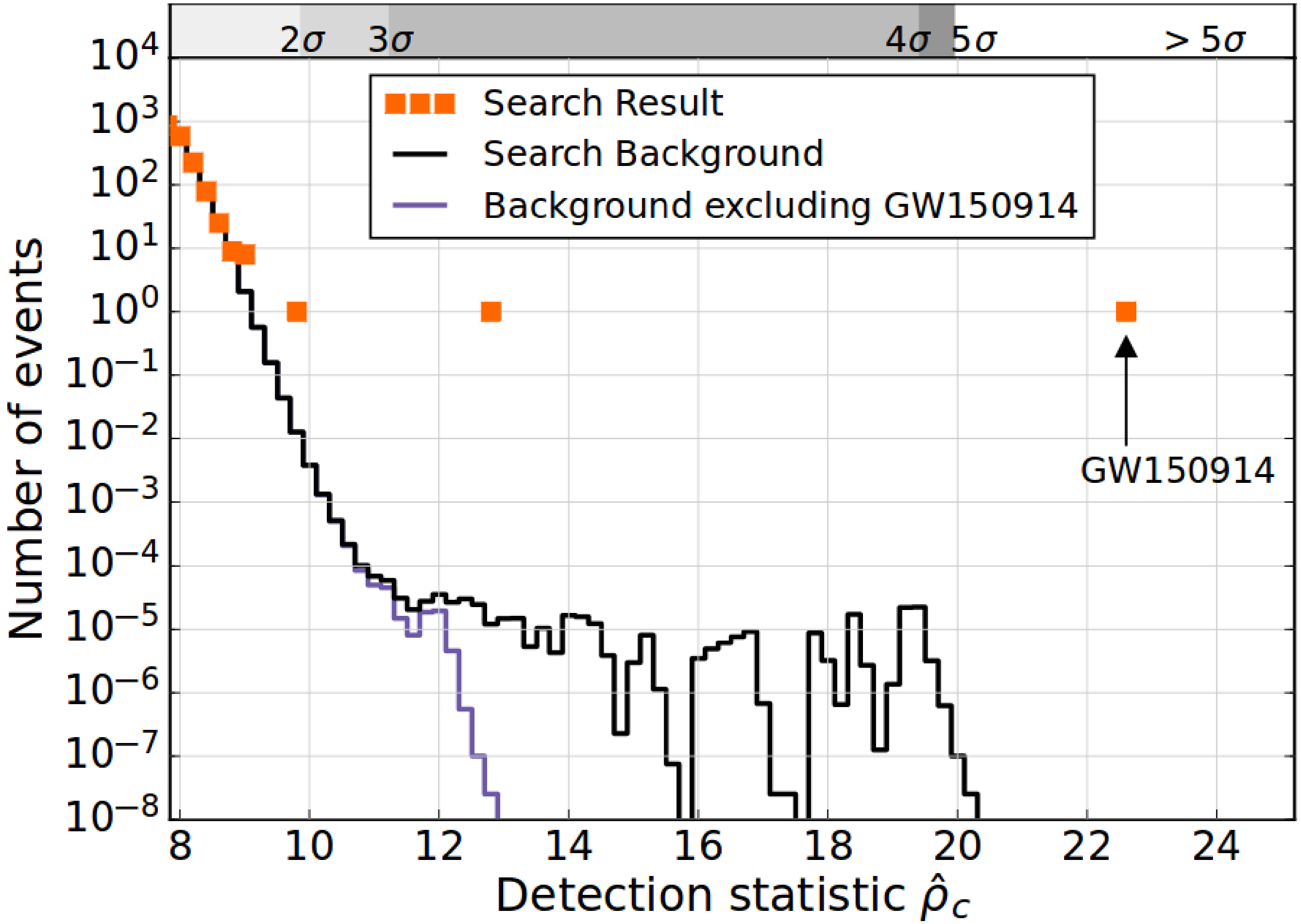


A very large number of fake experiments can be simulated using multiple offsets

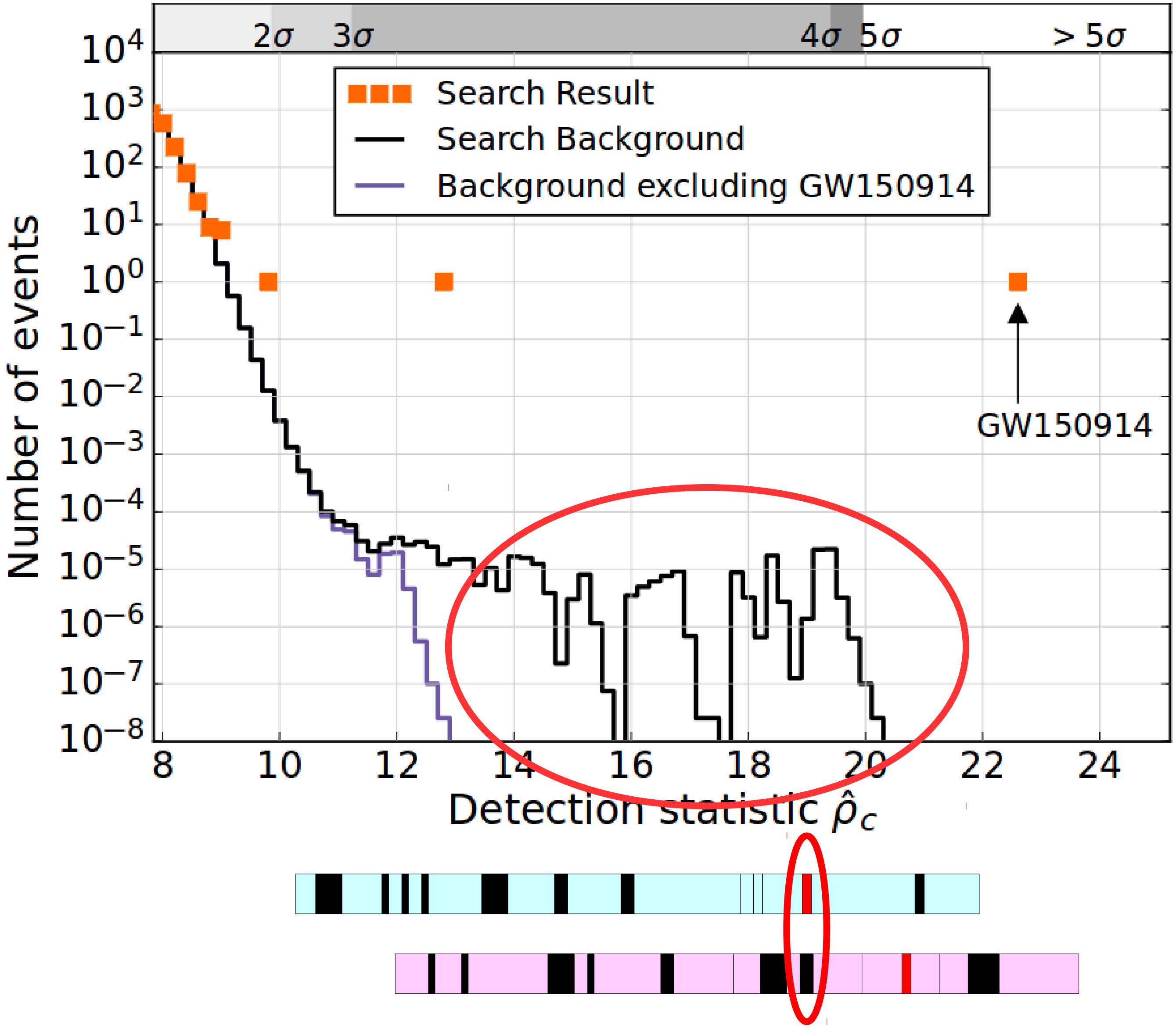
LIGO O1 analysis:
– $O(10^6)$ time offsets

→ background estimated using a fake experiment of O(100,000 years)

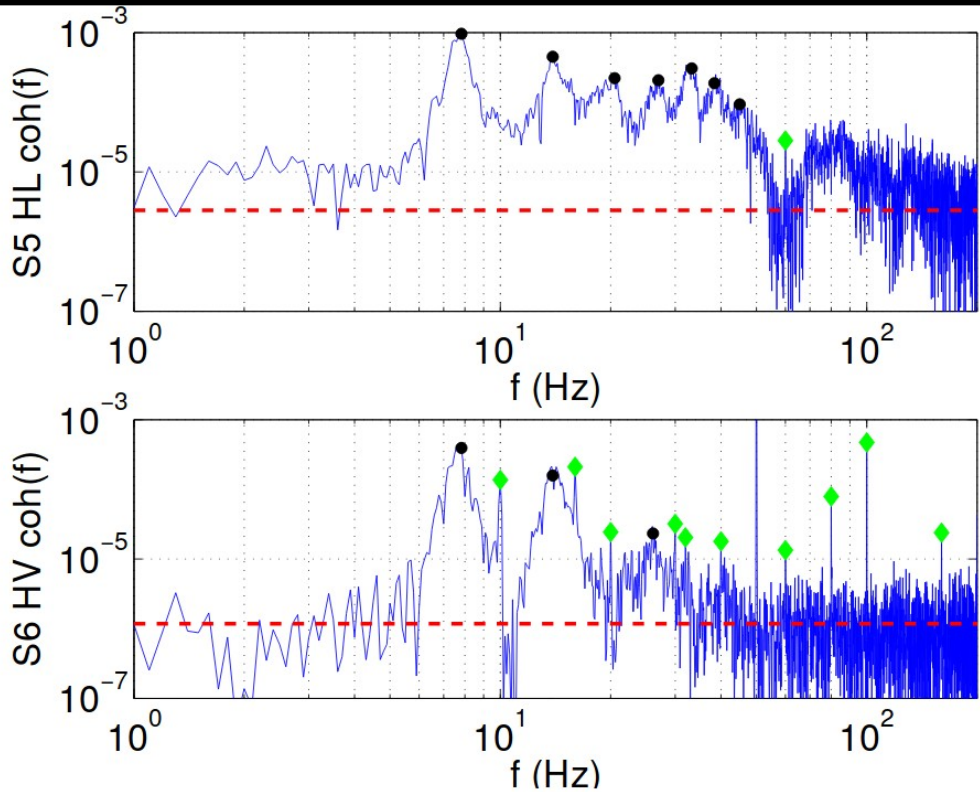
Event significance



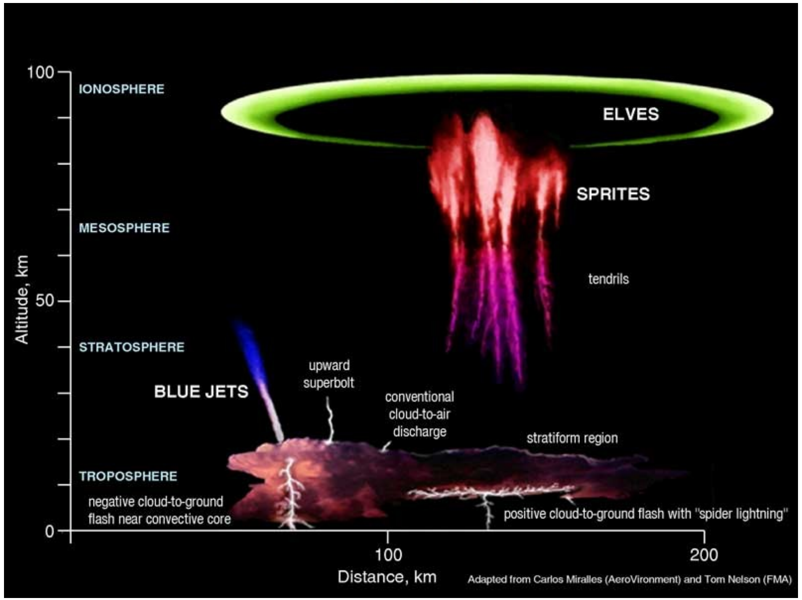
Event significance

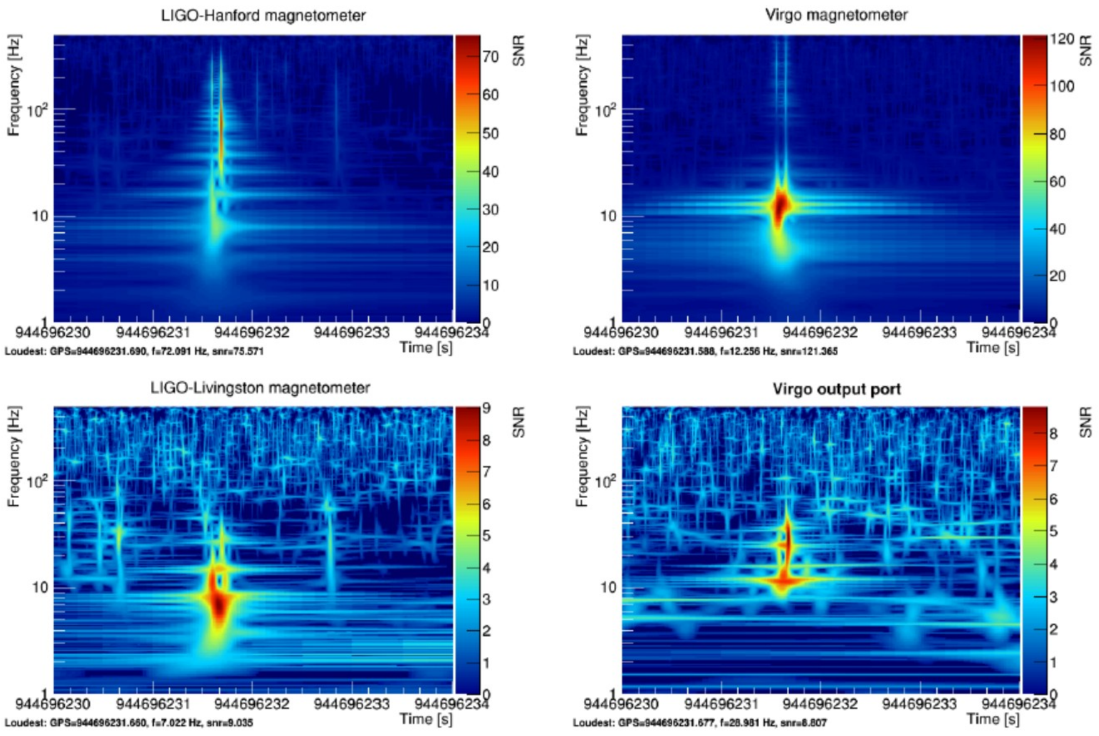


Correlated noise



Schumann resonance





Conclusions

→ First detection achieved by ground-based interferometers (LIGO-Virgo)

→ A network of detectors is needed
- – to detect a gravitational-wave with confidence
- – to localize the source
- – to estimate the parameters of the source

→ Analysis pipelines are used to analyze the data

→ Gravitational-wave detectors are very sensitive instruments

→ Multiple noise sources