WISHEPP
3rd Winter School in HEP

November 10-16, 2018 An-Najah N. University, Nablus, Palestine

Detection of gravitational waves

- → Gravitational-wave detectors
- → LIGO-Virgo detector network
- → Signal extraction methods
- → Detector's noise

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Gravitational wave detection

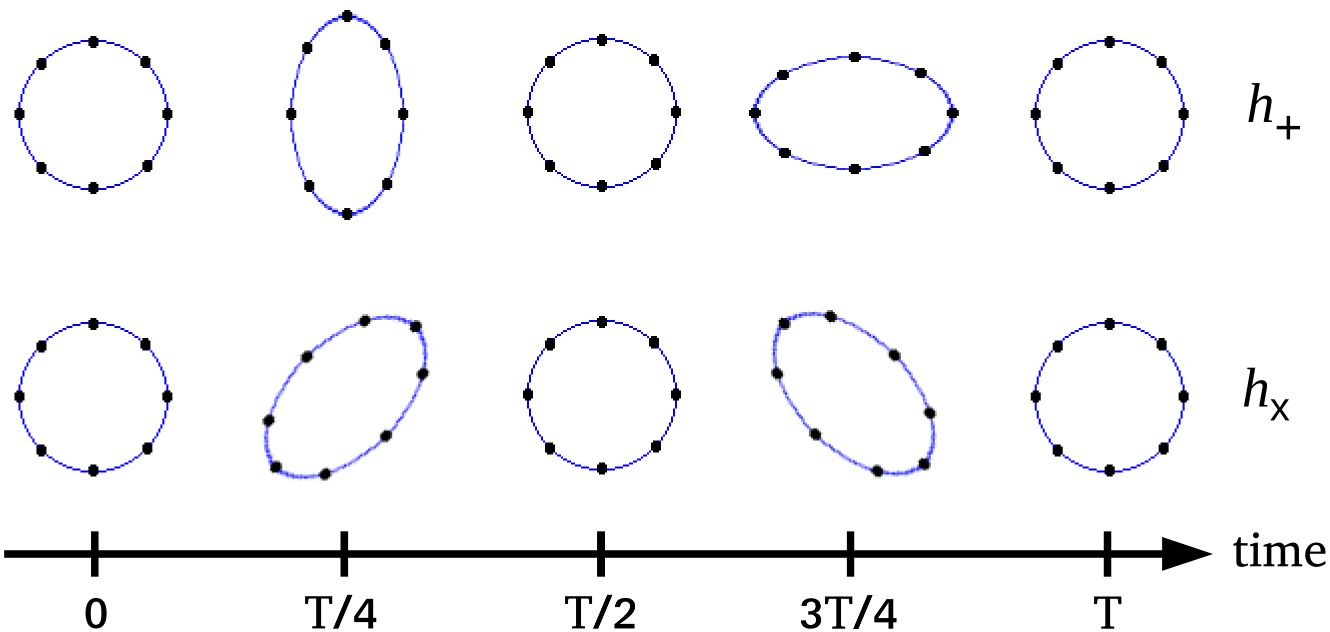
Add a small perturbation to the Minkowski metric: $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ $|h_{\mu\nu}| \ll 1$

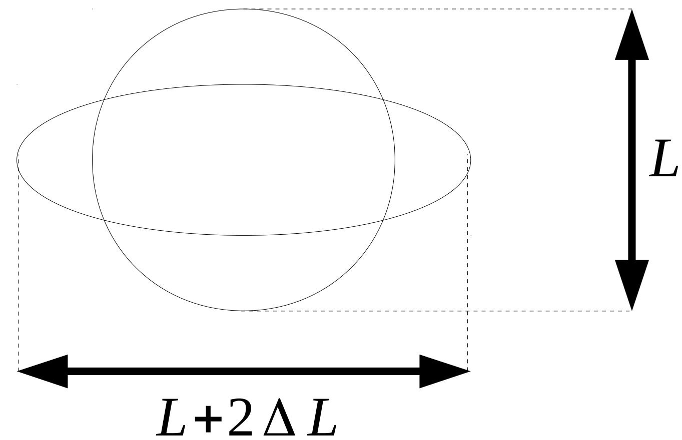
– h obeys a plane-wave equation

– the wave propagates at the speed of light

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

→ **Gravitational waves**





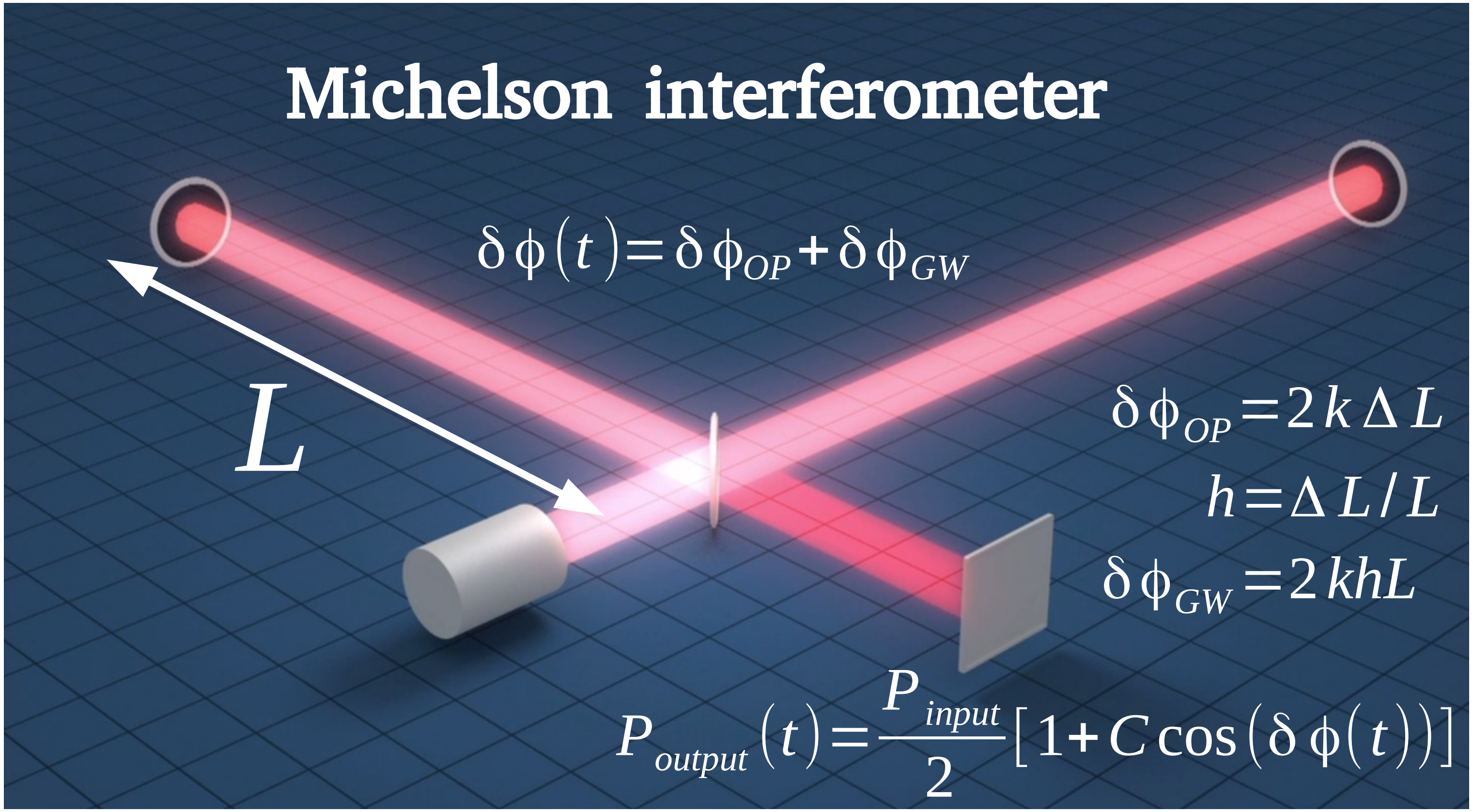
$$h = 2\frac{\Delta L}{L}$$

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



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

→ **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

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

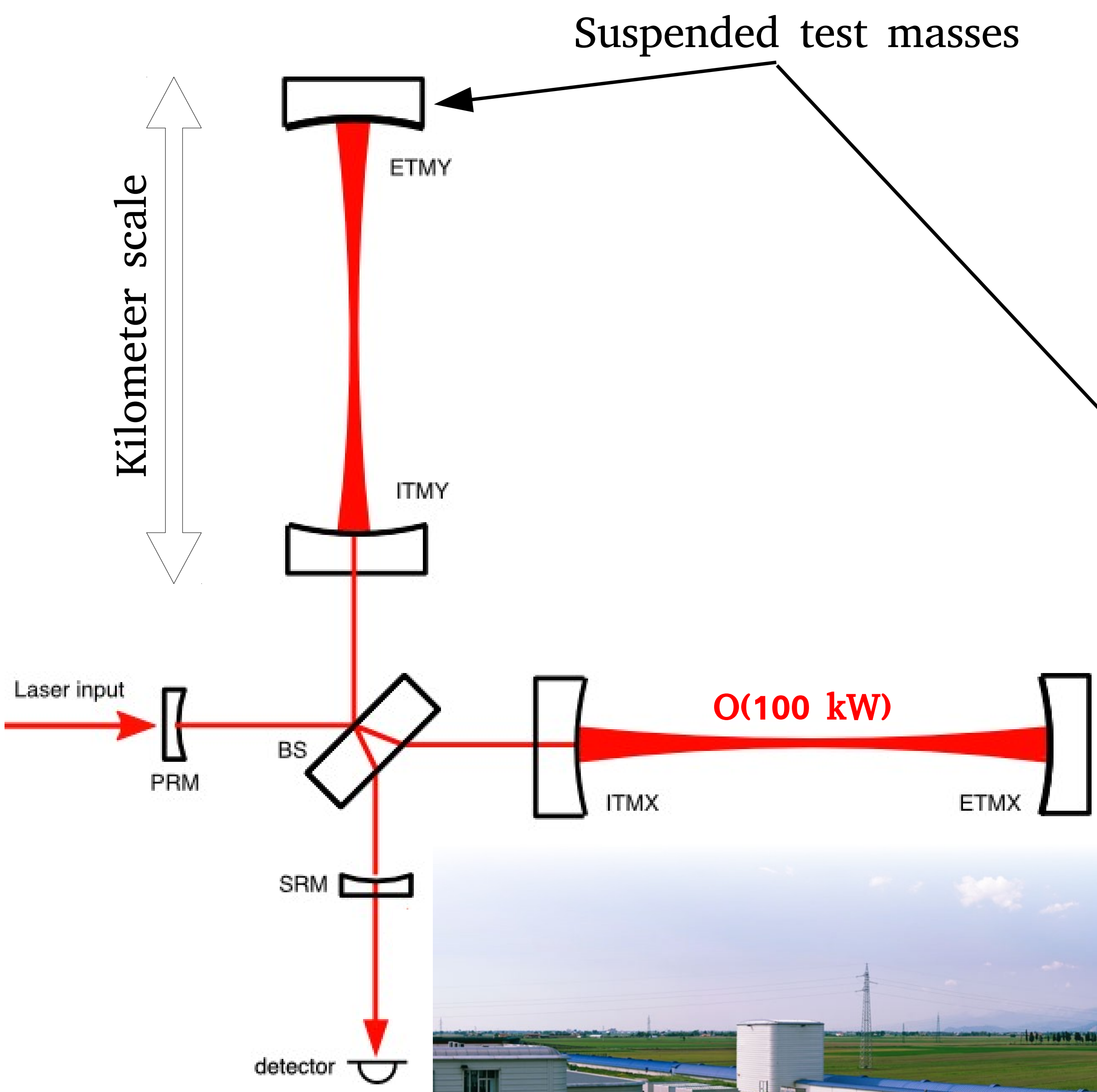
Signal-to-noise ratio

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

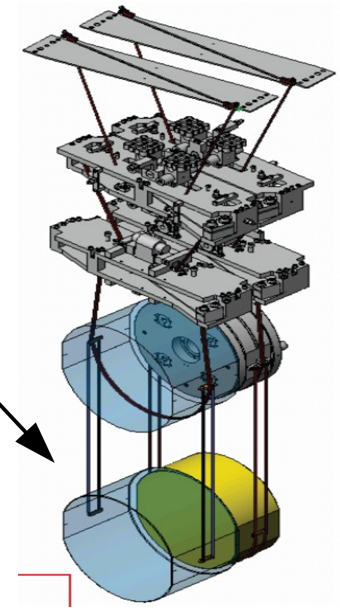
If $\frac{S}{B} = 1 \rightarrow$ $h_{shot\,noise} \propto \frac{1}{L\sqrt{P_{input}}}$

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

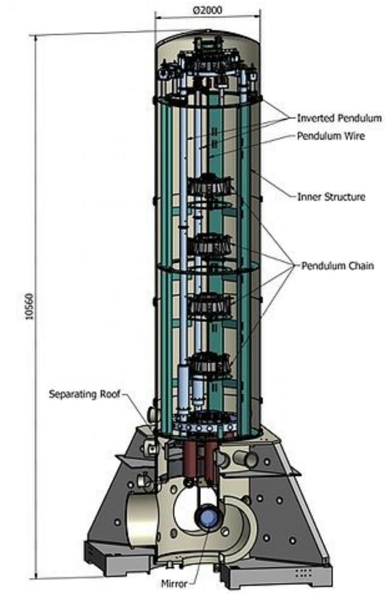
Gravitational wave detectors



LIGO suspensions



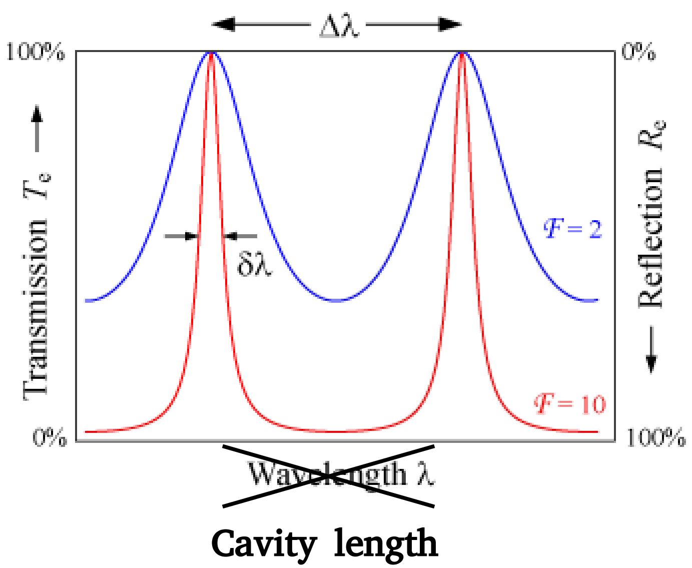
Virgo suspensions

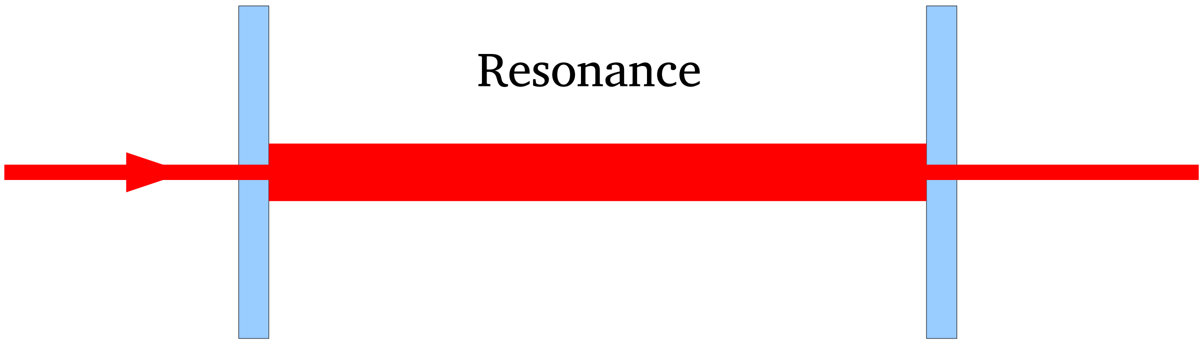


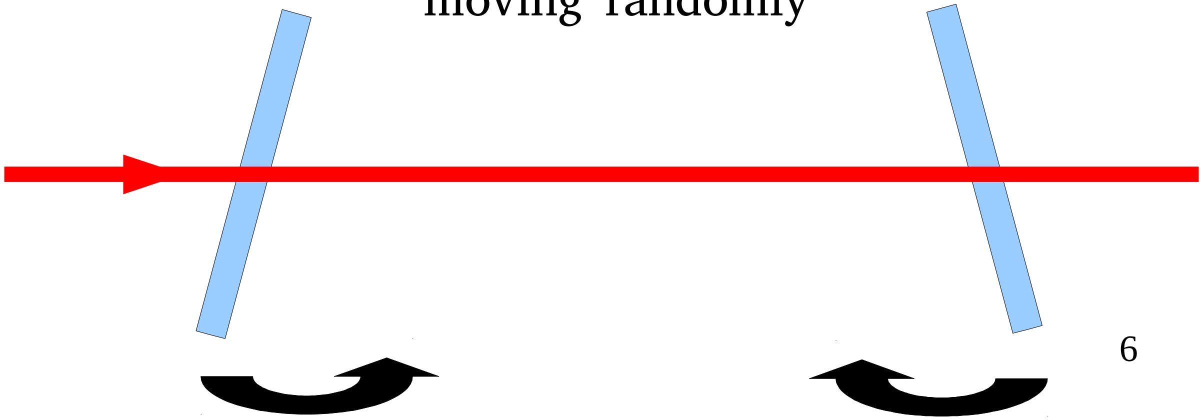
Virgo interferometer

Lock control

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







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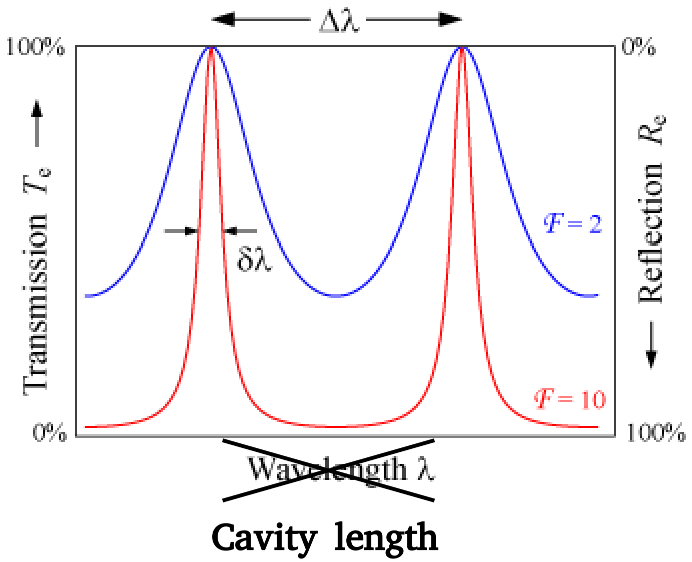
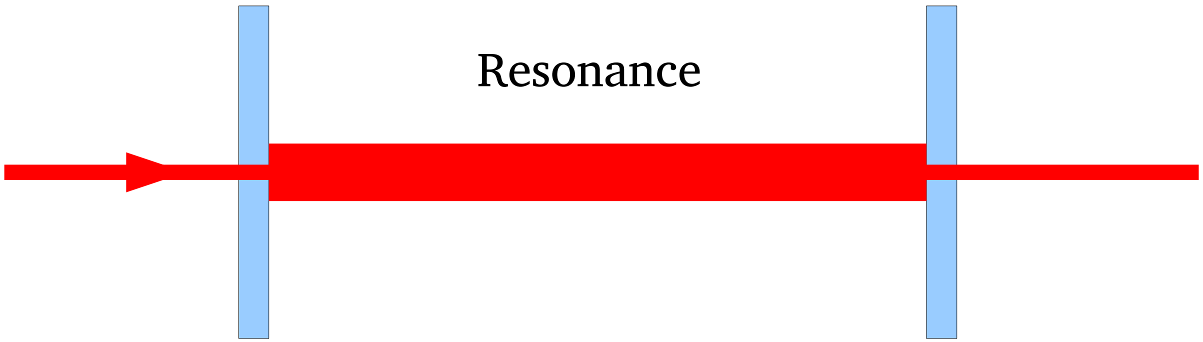
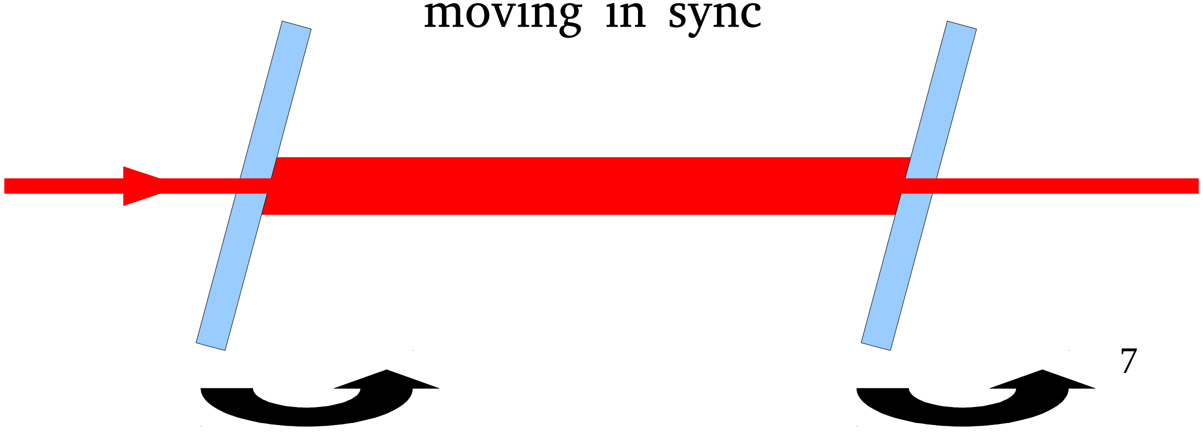


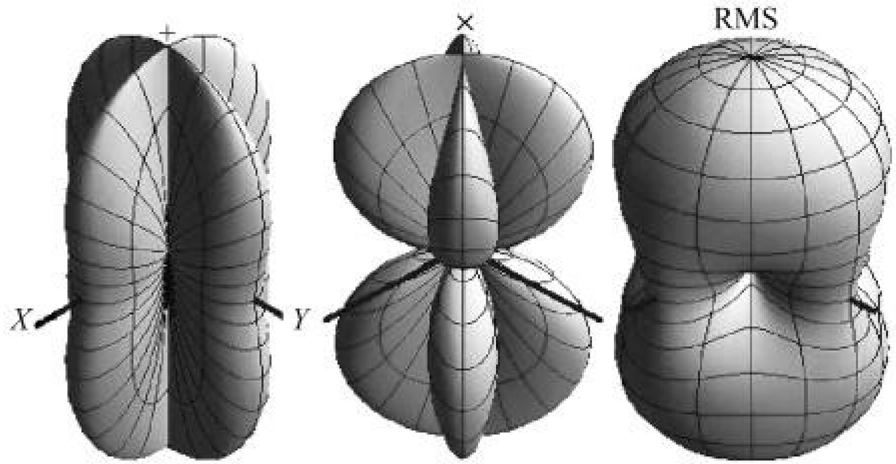




A control loop is activated to bring (and maintain) the mirrors at resonance

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)

Power spectral density

Fourier transform

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

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

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

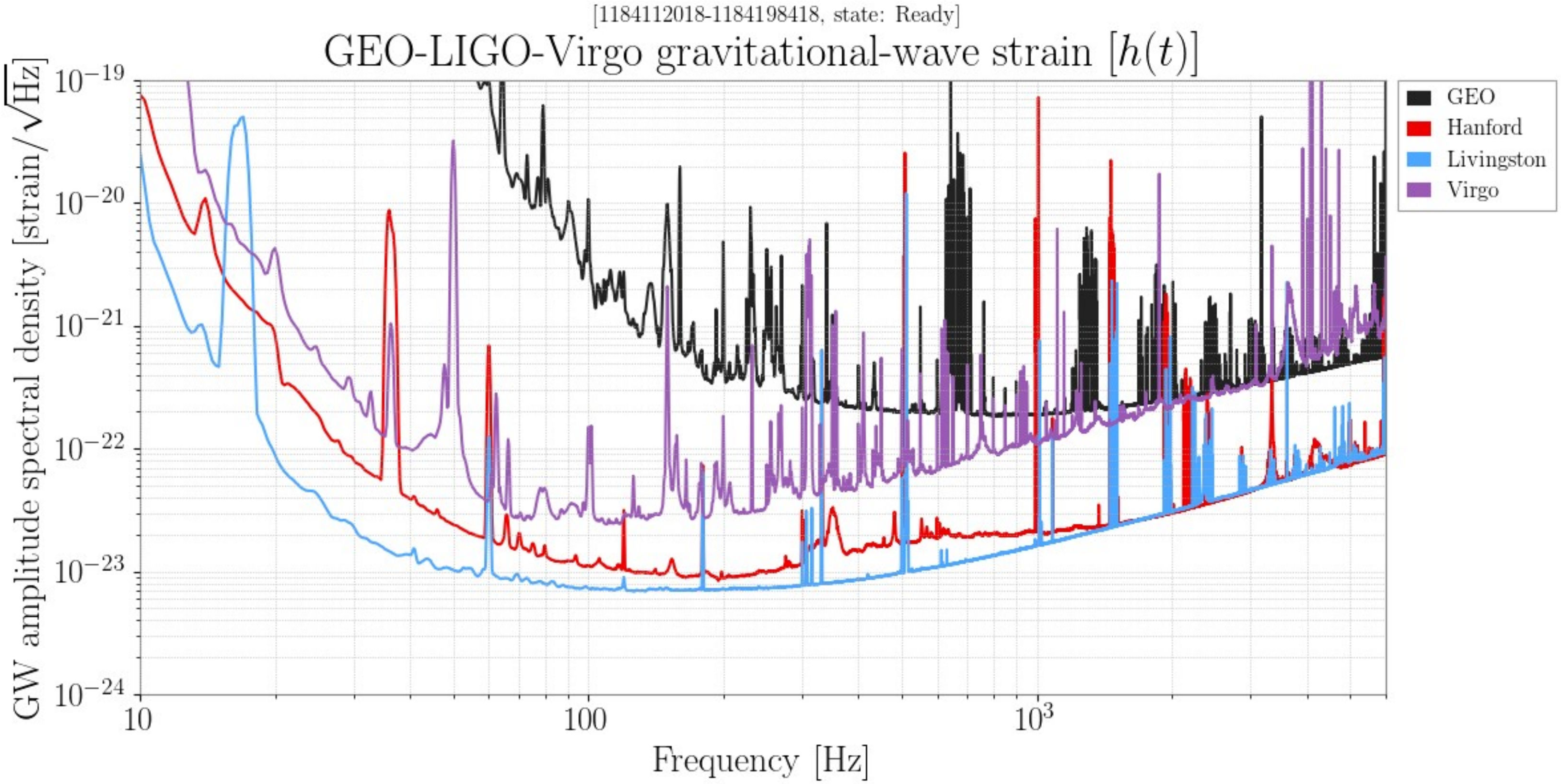
The signal is decomposed in characteristic frequencies

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

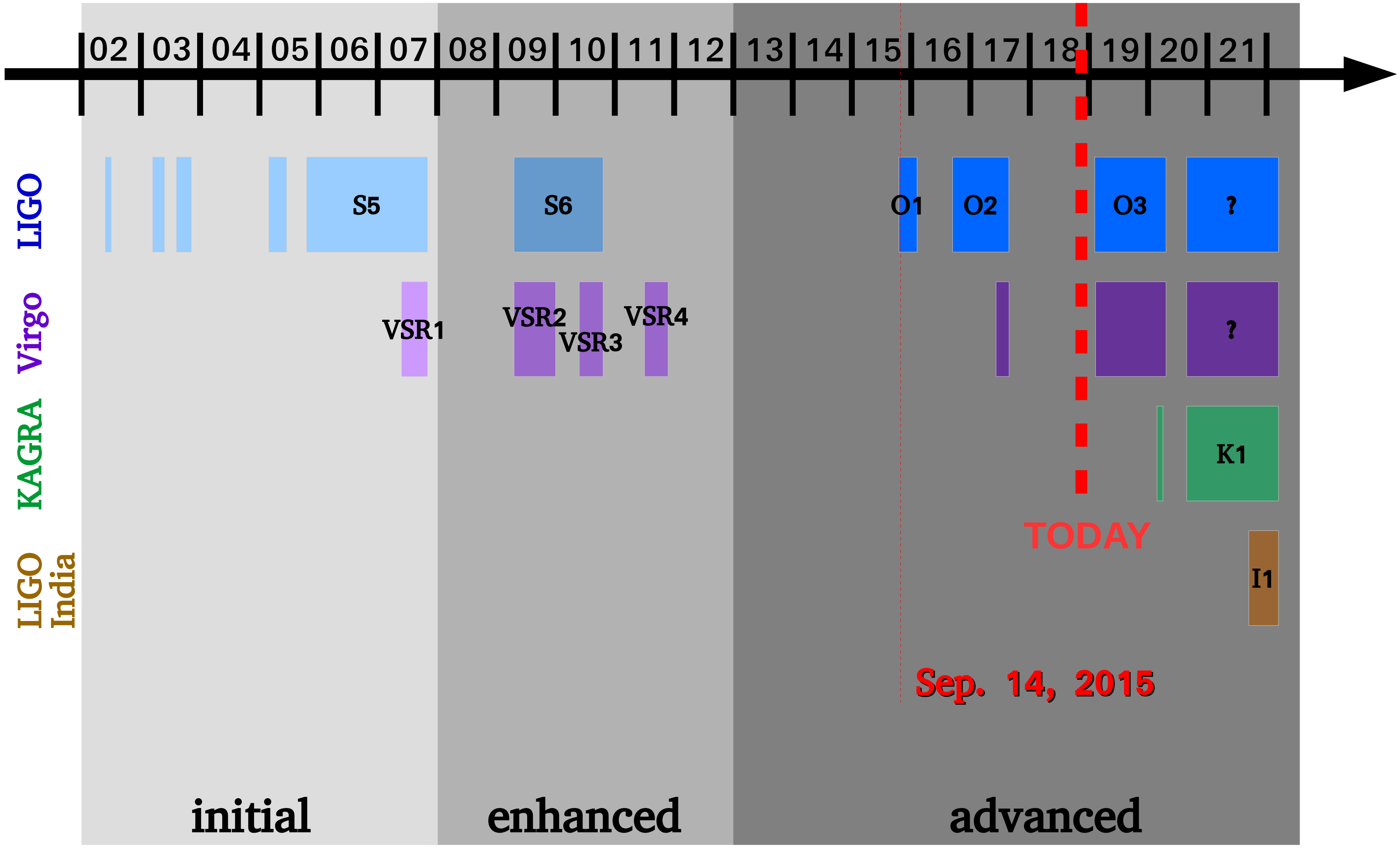


Fundamental noises:

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

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

Scientific runs

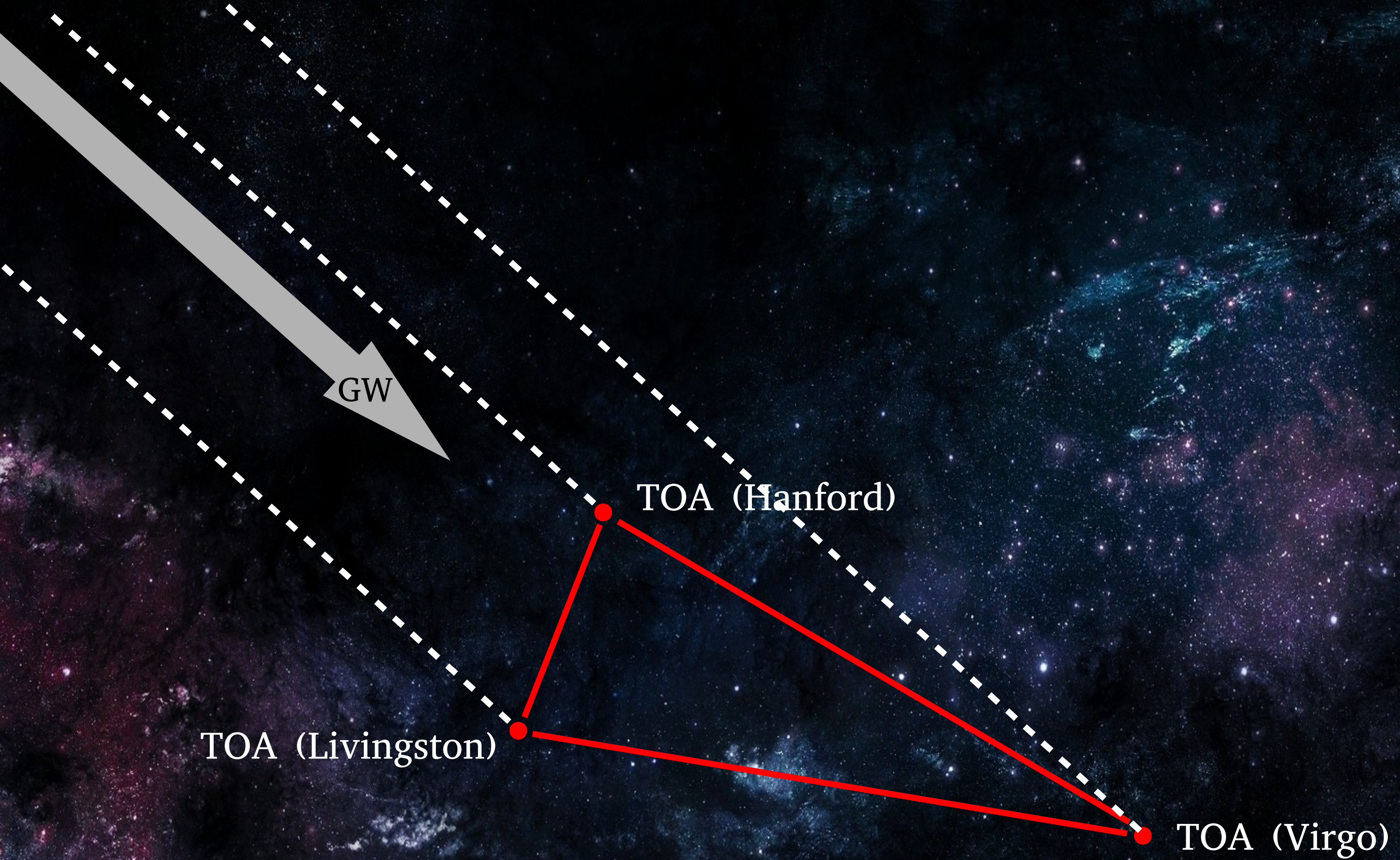


Data analysis :

- 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

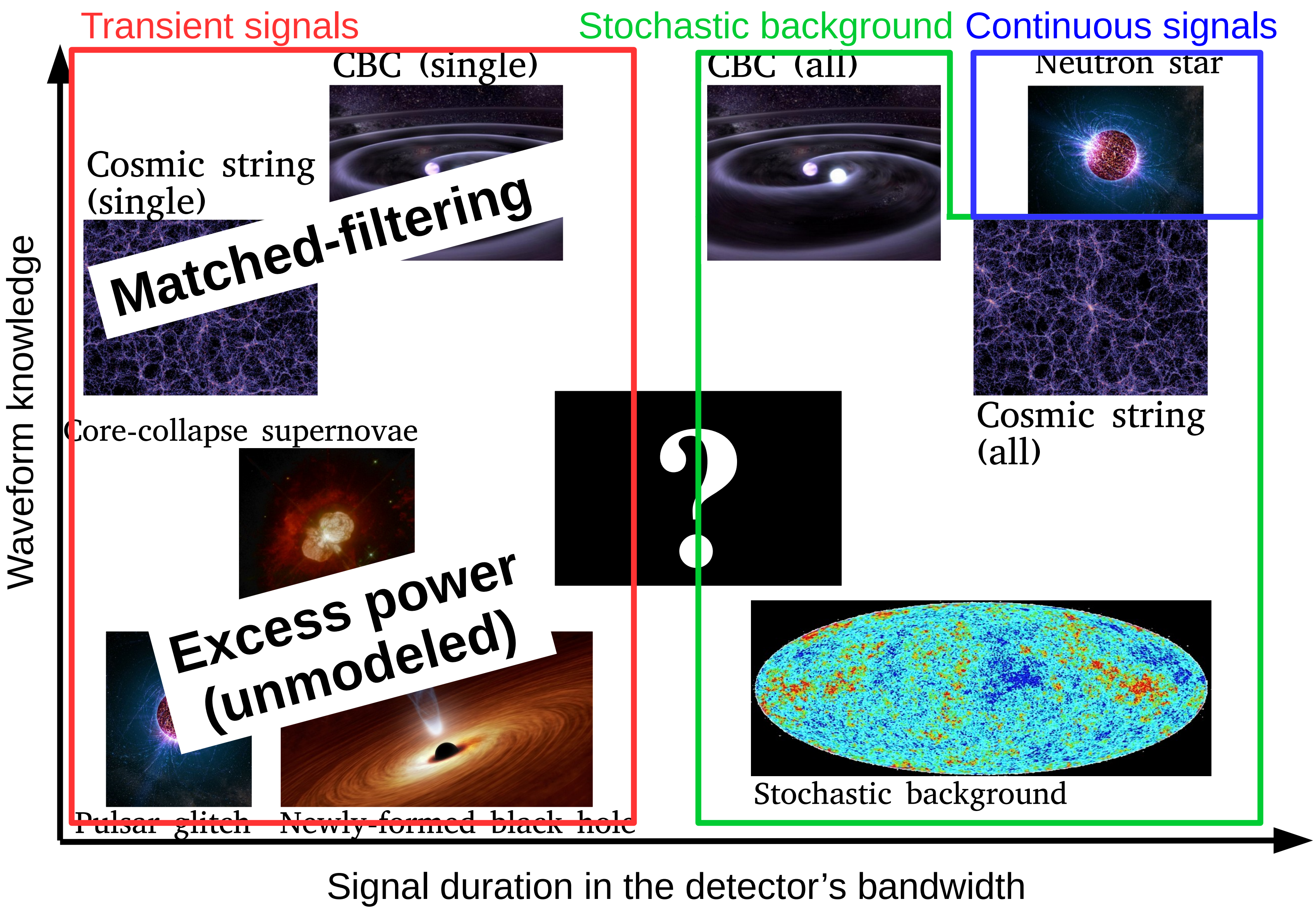
- to perform a coincident search
- to test the signal consistency across the network
- to estimate your background noise
- to locate the source of gravitational waves



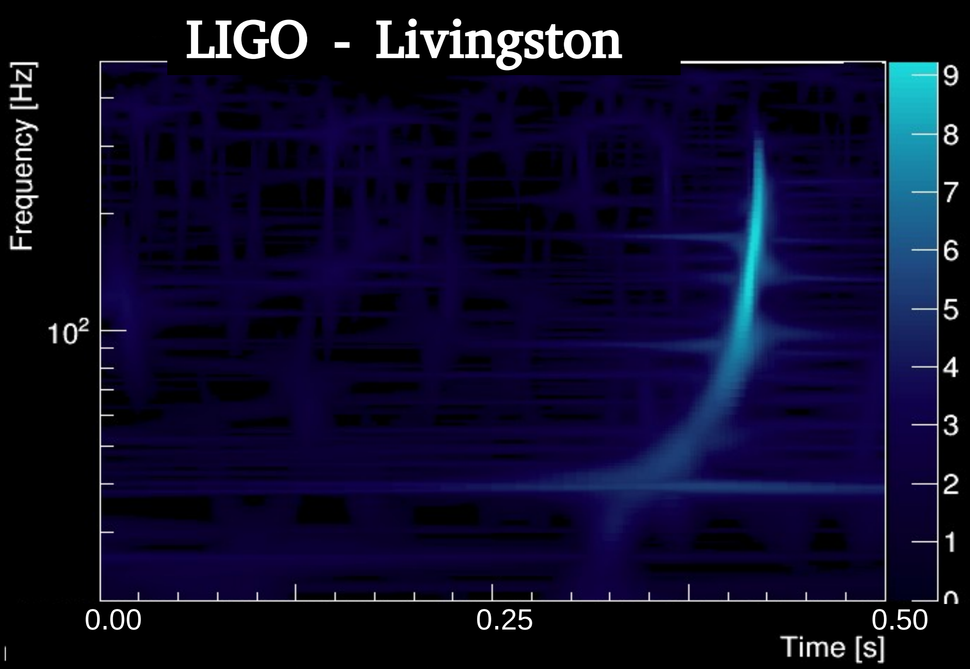
The direction of the source is triangulated using the signal times of arrival

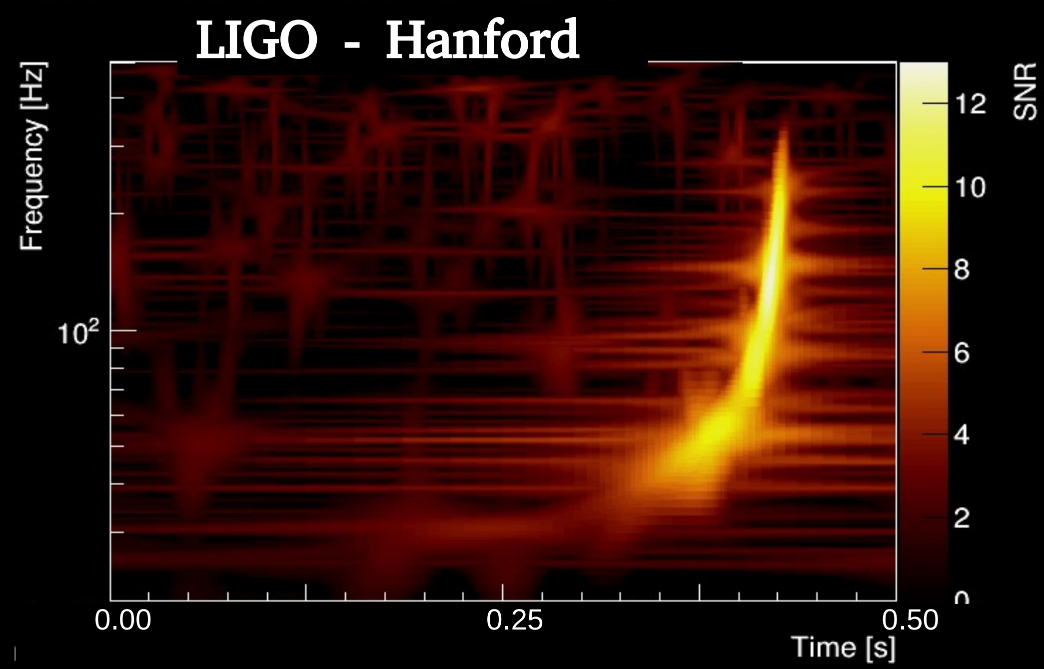
→ Follow-up in other channels (e.g. EM)

Source classification: search method



Unmodeled searches

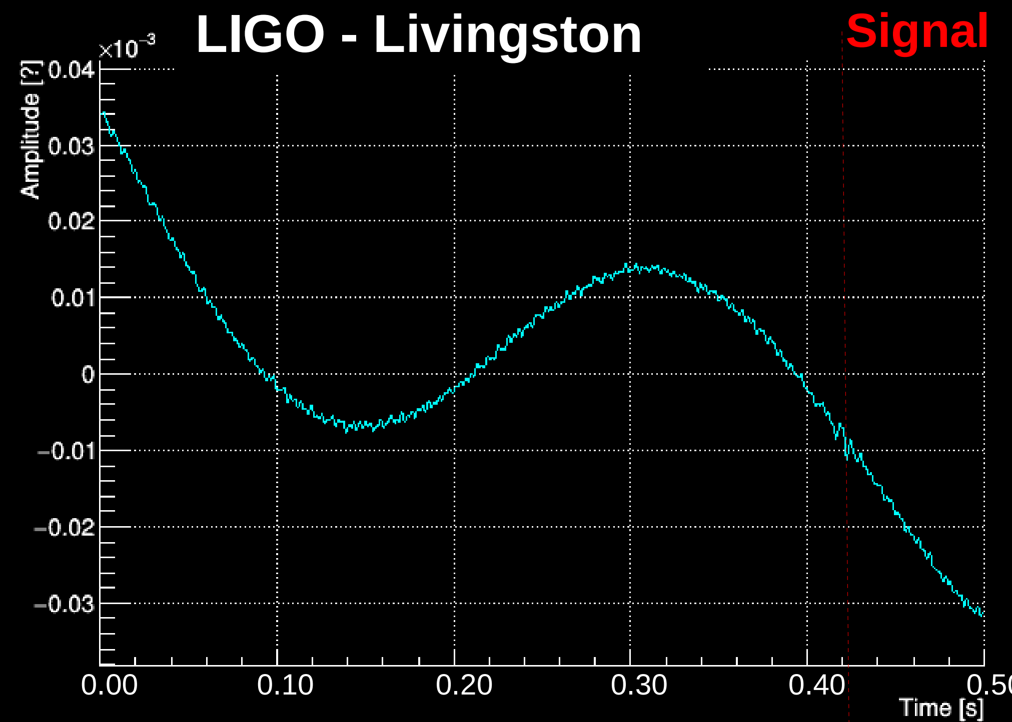


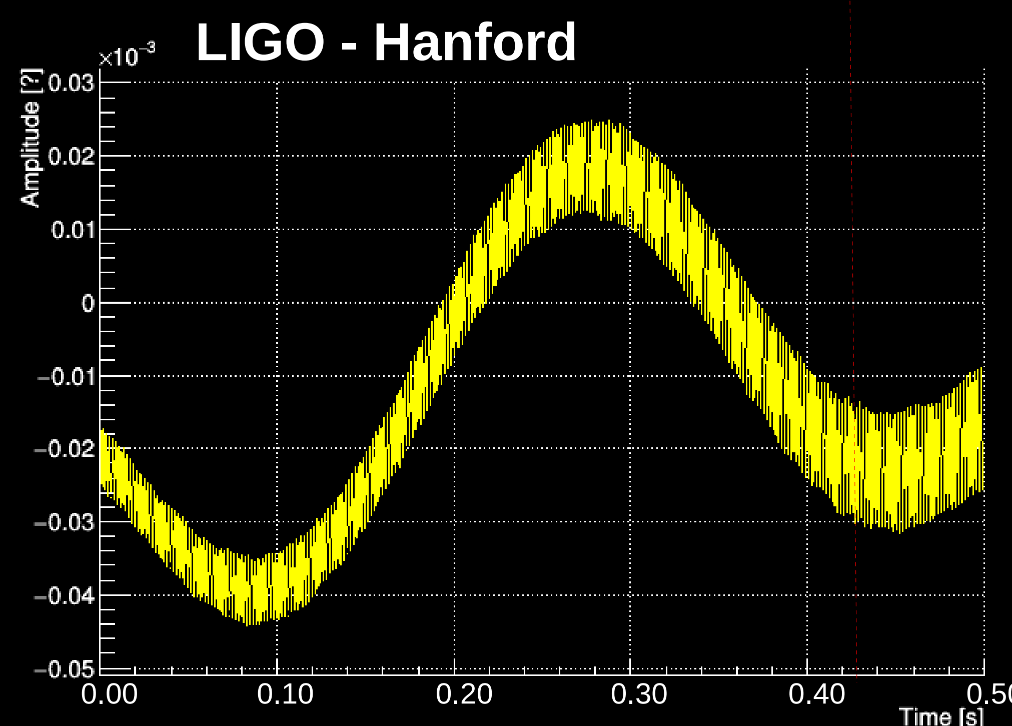


→ Time-frequency decomposition → noise events + (maybe) GW events
→ Coincidence between detectors (time + other parameters)
→ Noise rejection
→ Classify events using a “smart” recipe
→ Estimate background
→ Compare events with your background
→ Measure the probability for each events to be true GW signal

GW150914

Output power

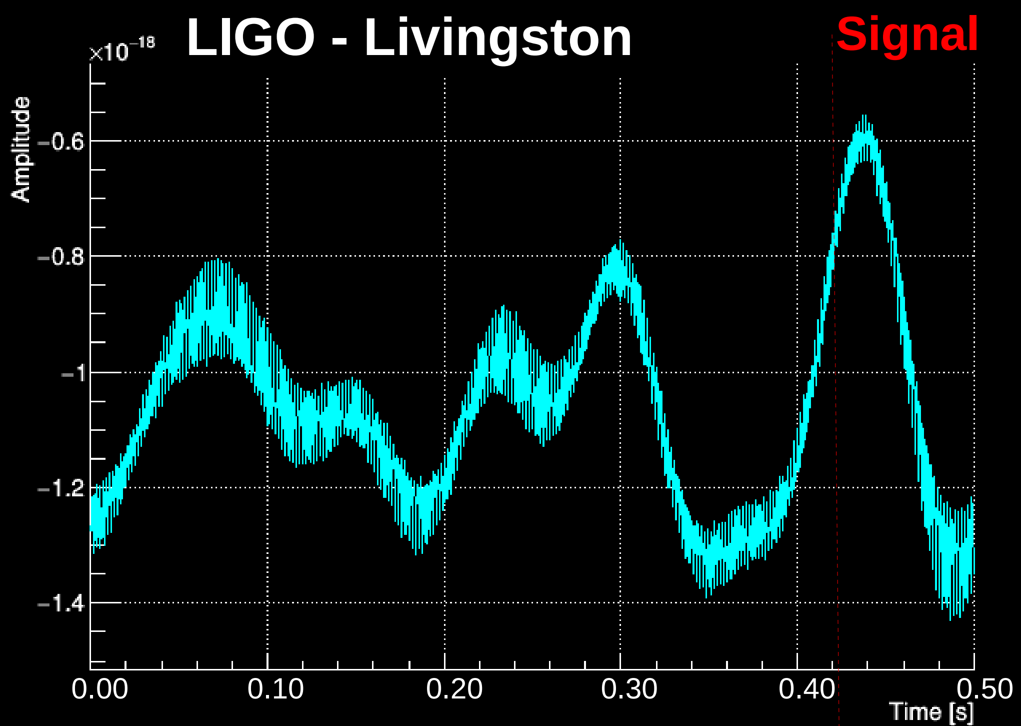




Output power

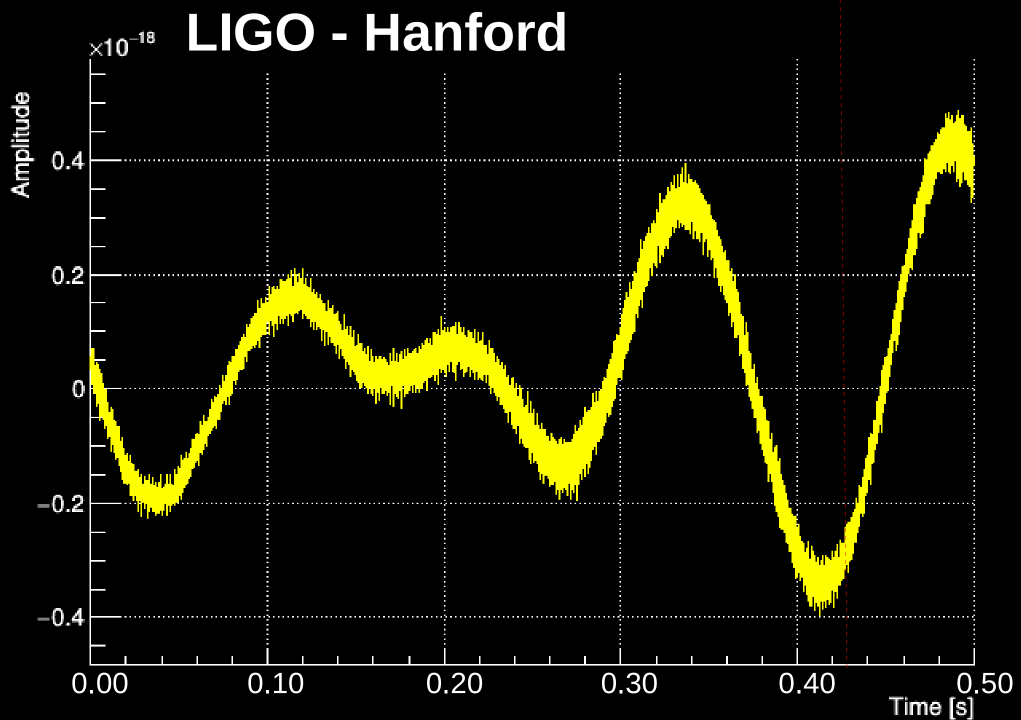
GW150914

$h(t)$



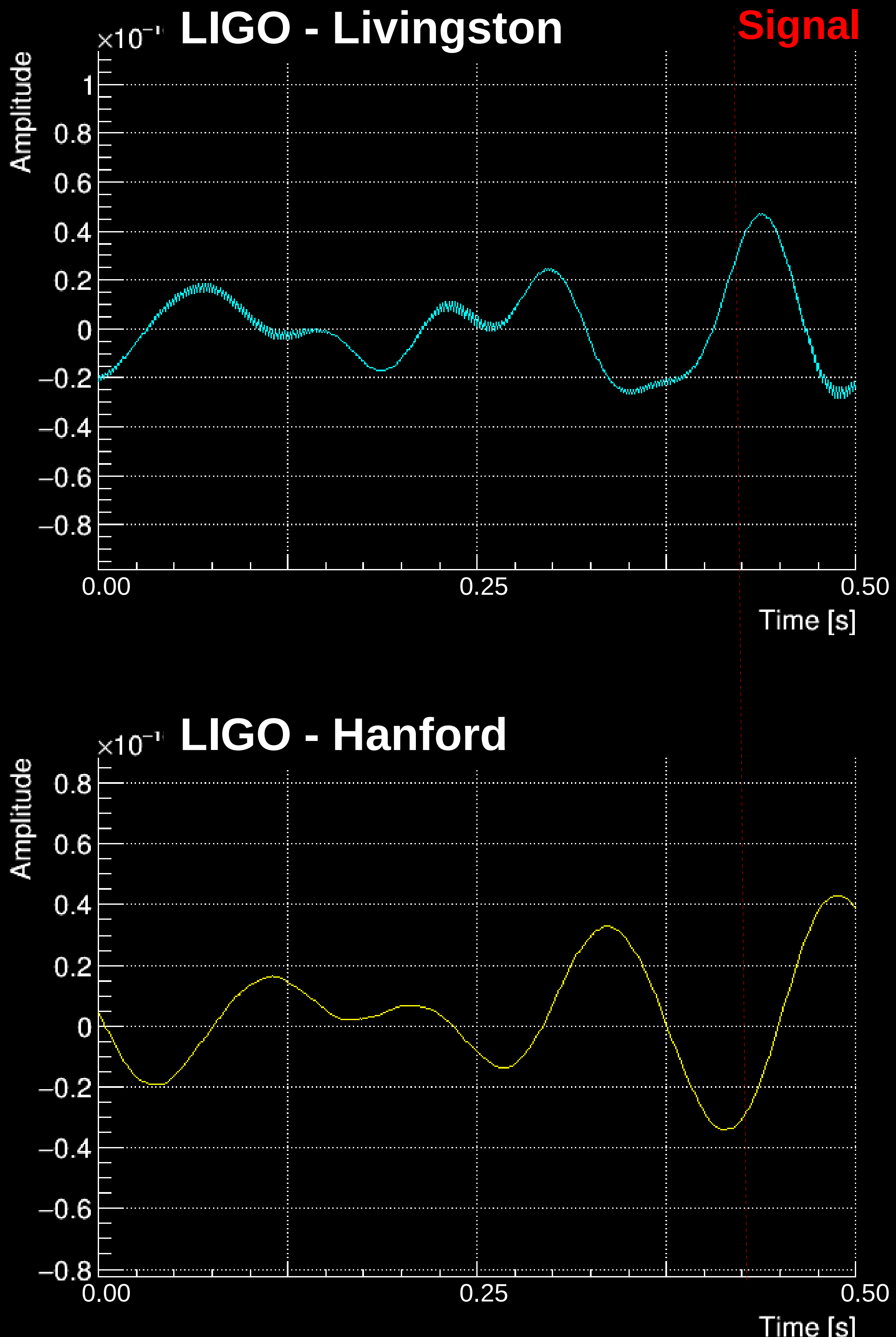
Data is calibrated
→ GW strain amplitude *h(t)*
(including high-pass filter f > 10 Hz)

$h(t)$



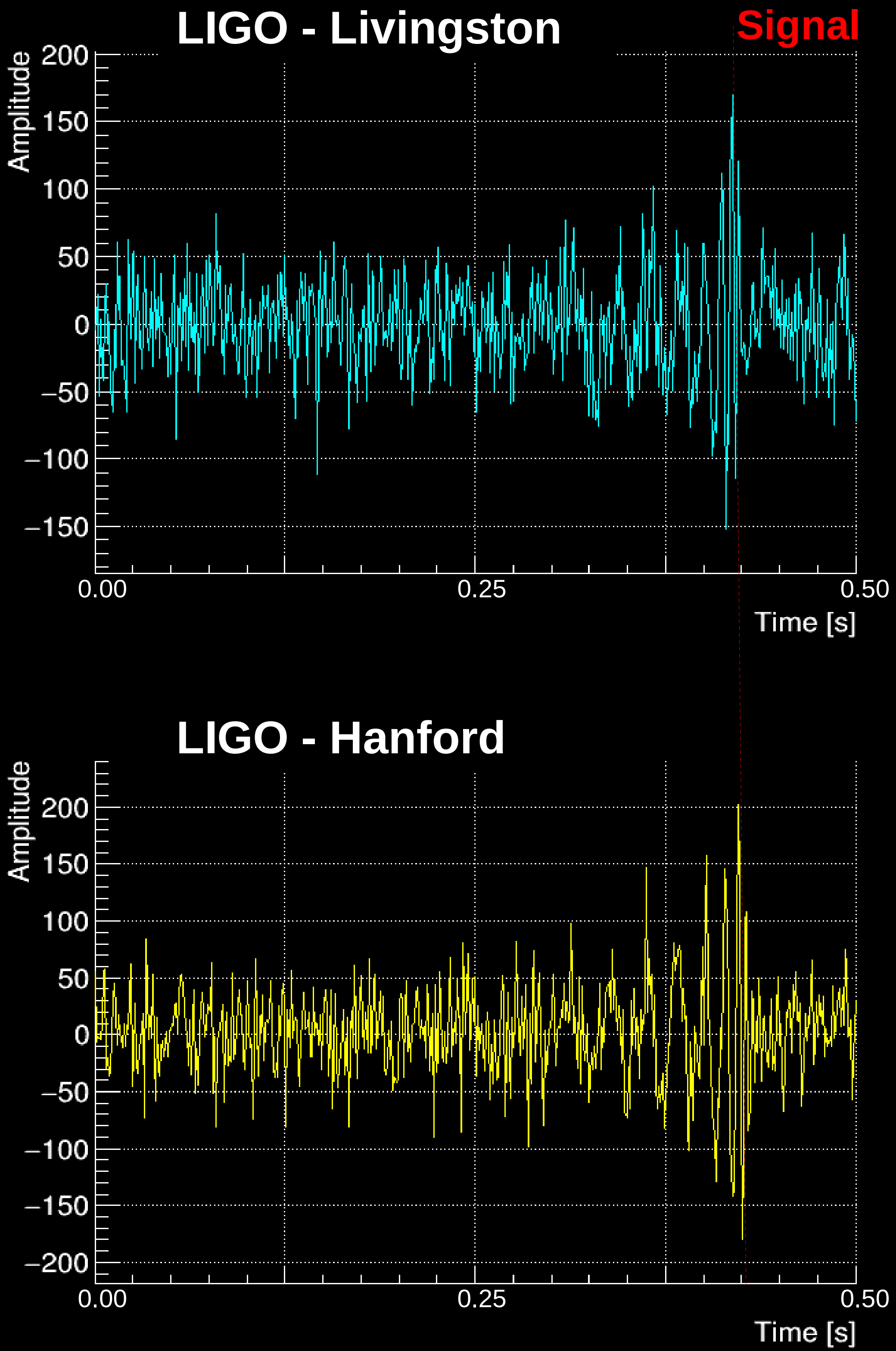
GW150914

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

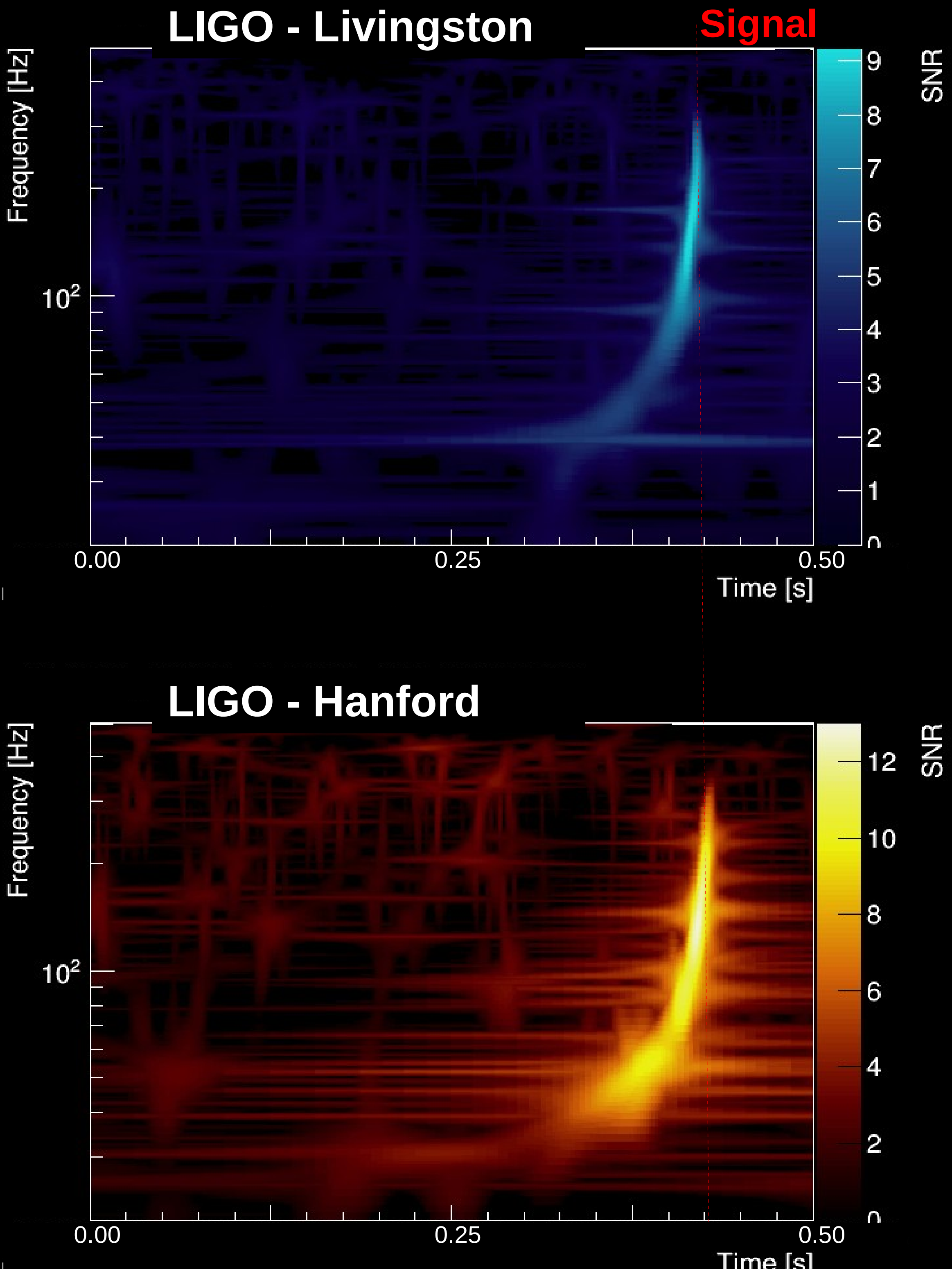


GW150914

Data are whitened



GW150914



Time-frequency decomposition
(Short Fourier transforms)

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

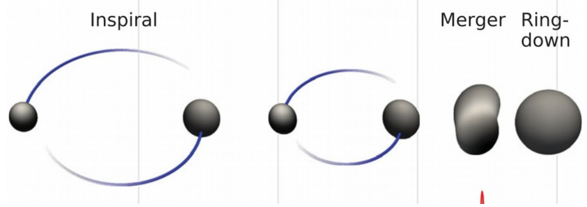
Modeled search

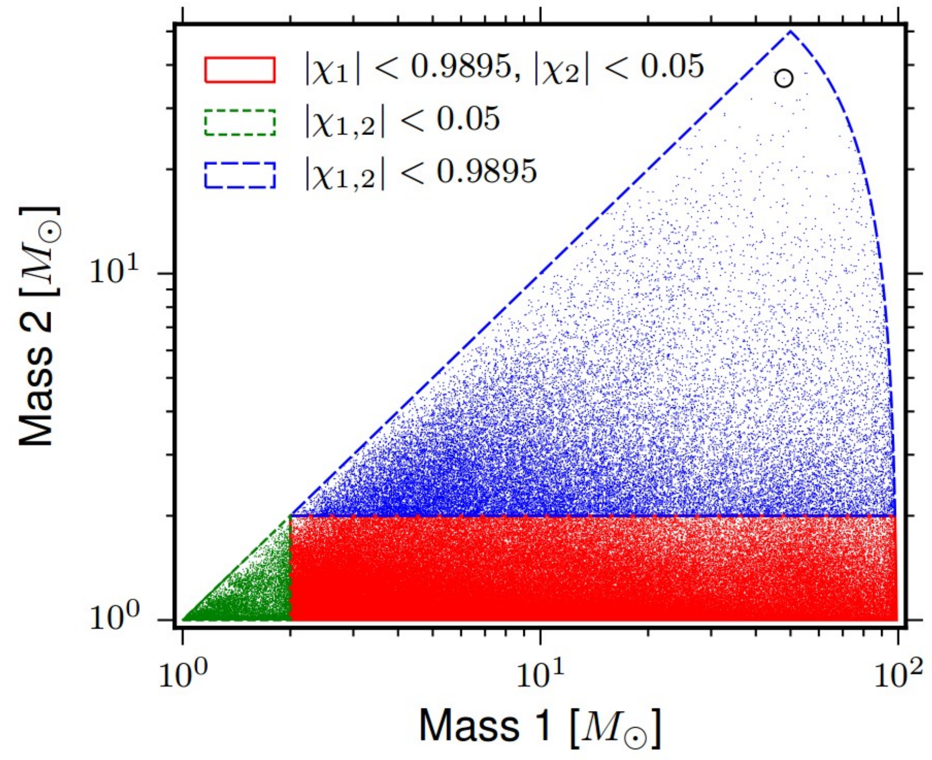
Theoretical input:

– 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

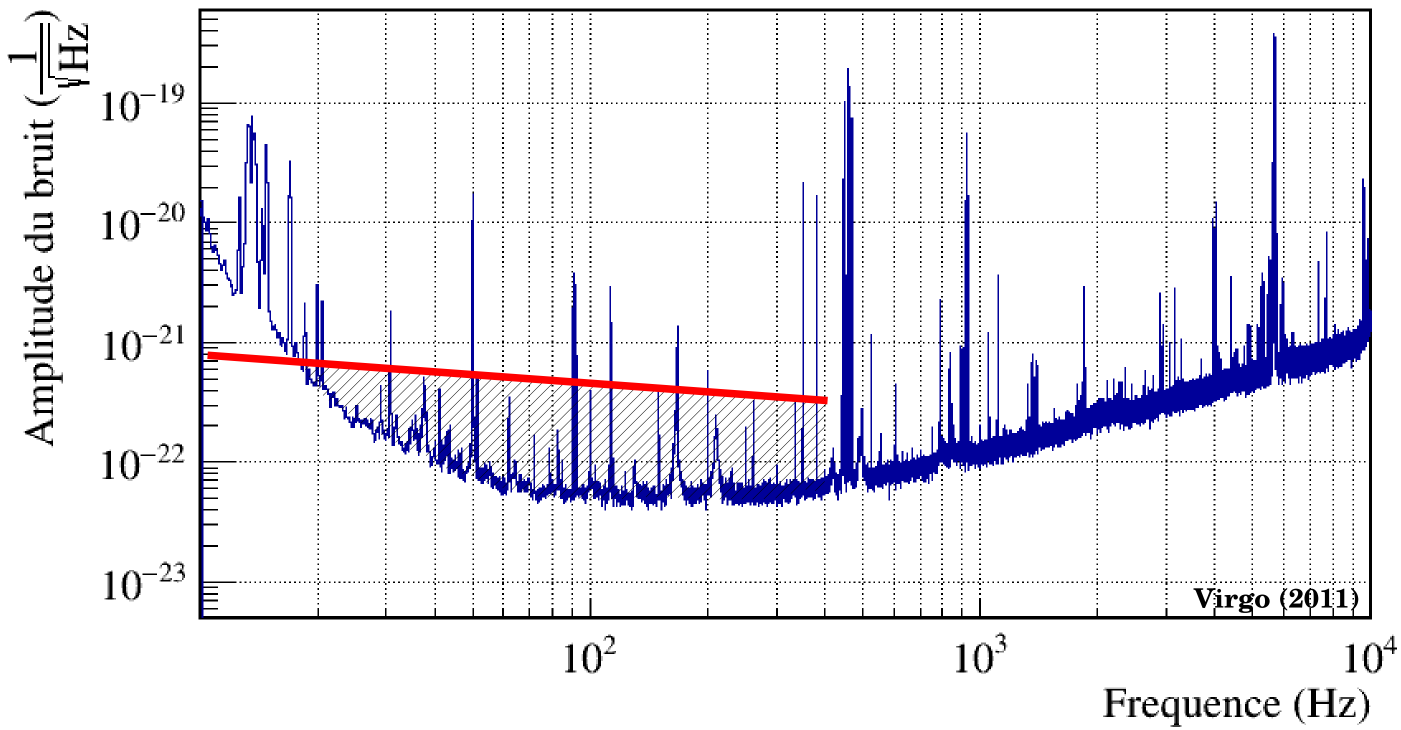
$$\frac{\tilde{h}(f)\,\tilde{h}_c^{\star}(f)}{S_n(f)}$$

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

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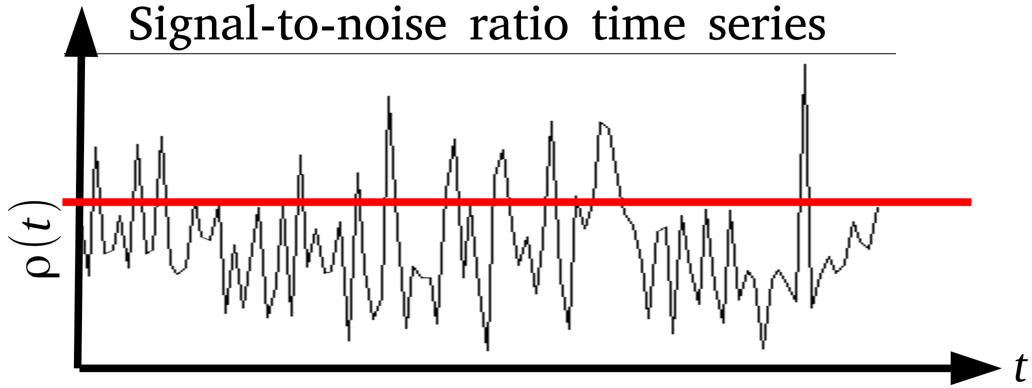


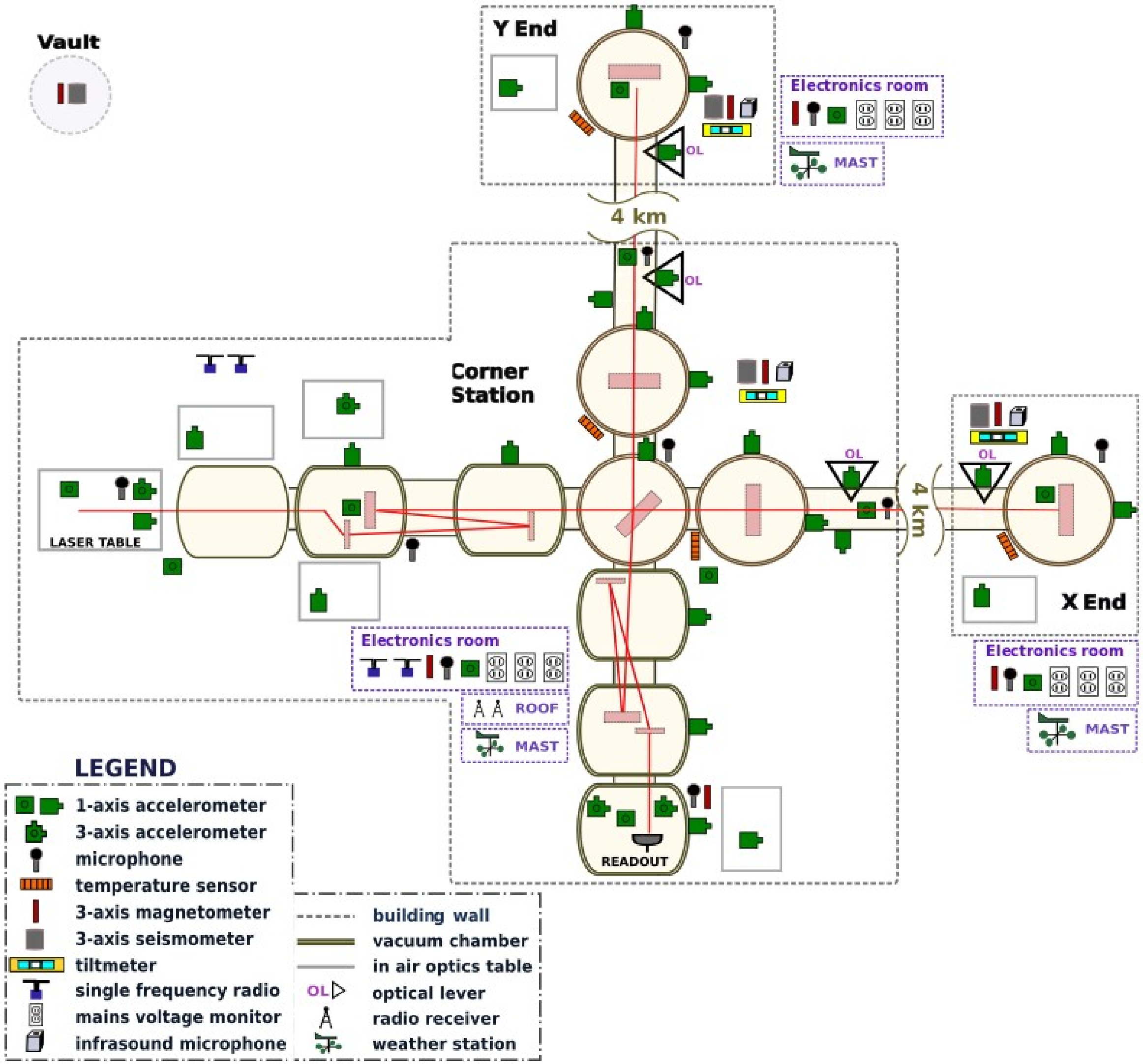
A list of events is produced:
- start/end/peak times
- SNR
- template parameters (masses, spins)

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

Monitoring noise

Thousands of auxiliary channels are used to monitor the instruments

- environmental sensors
- detector sub-systems
- detector control



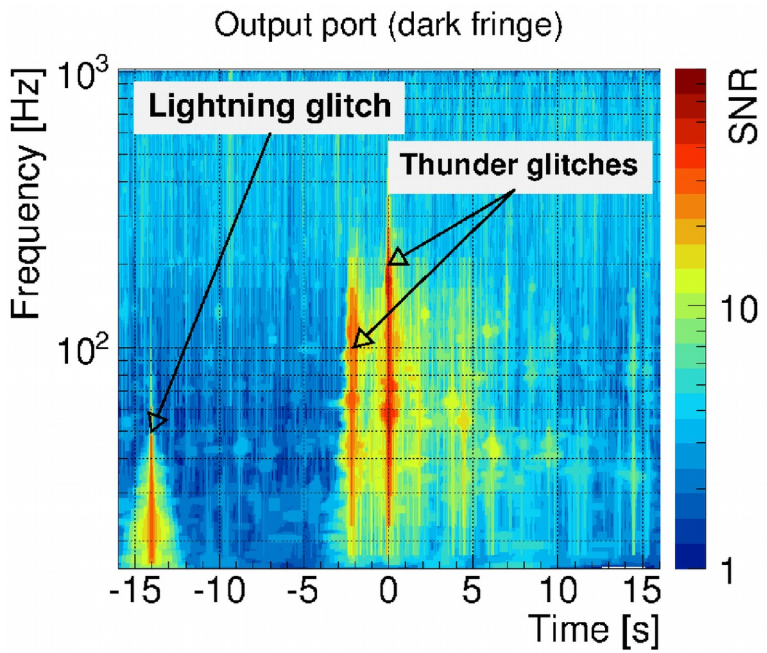
Noise injection campaigns are conducted to identify the detector's response to different noise stimulation

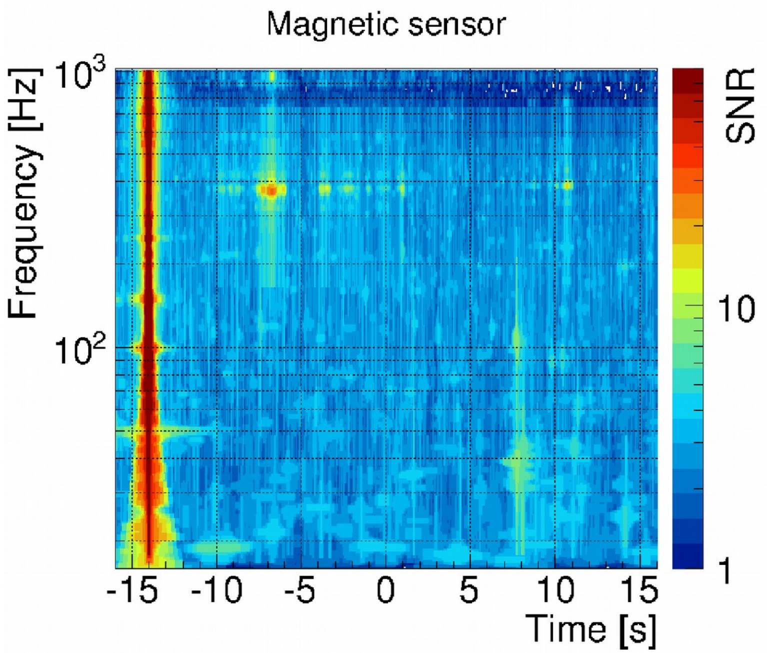
Multiple transient noises were identified during the run

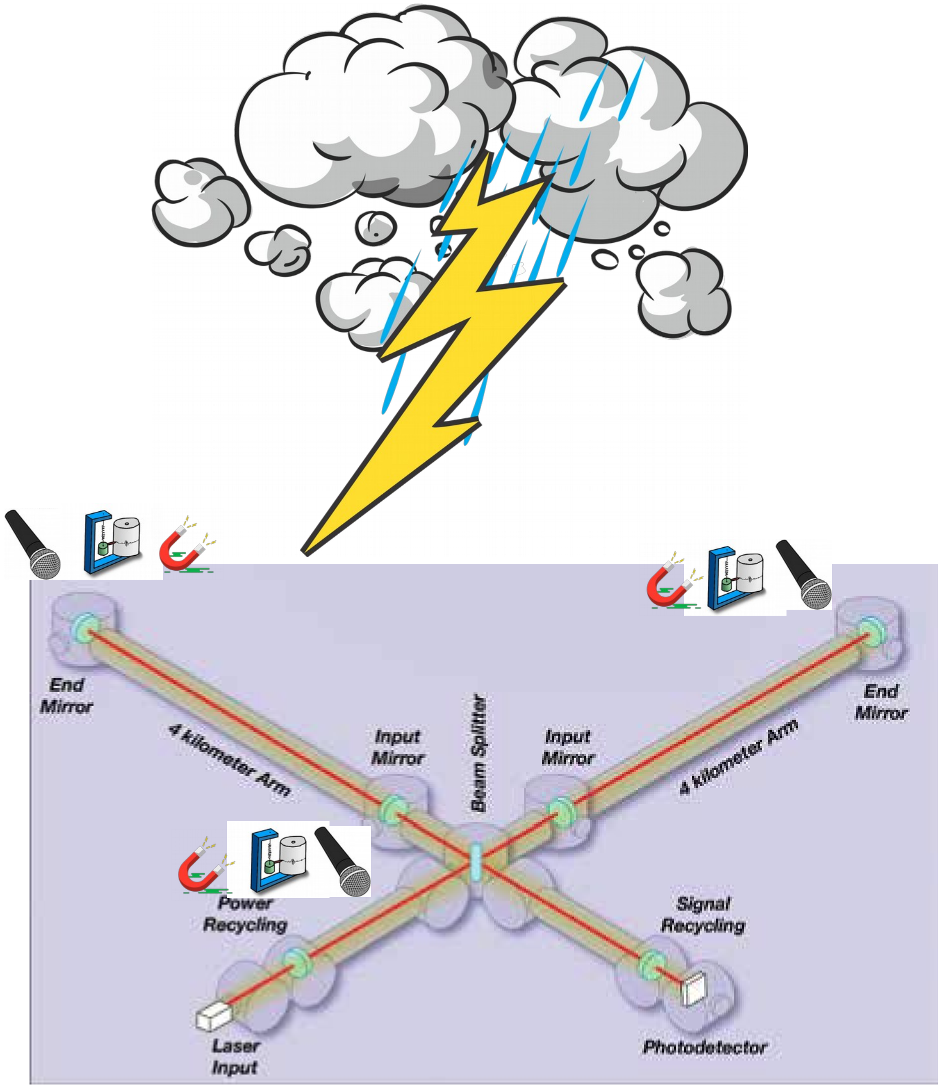
→ Anthropogenic noise
→ Earthquakes
→ Radio-frequency modulation
→ ...

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

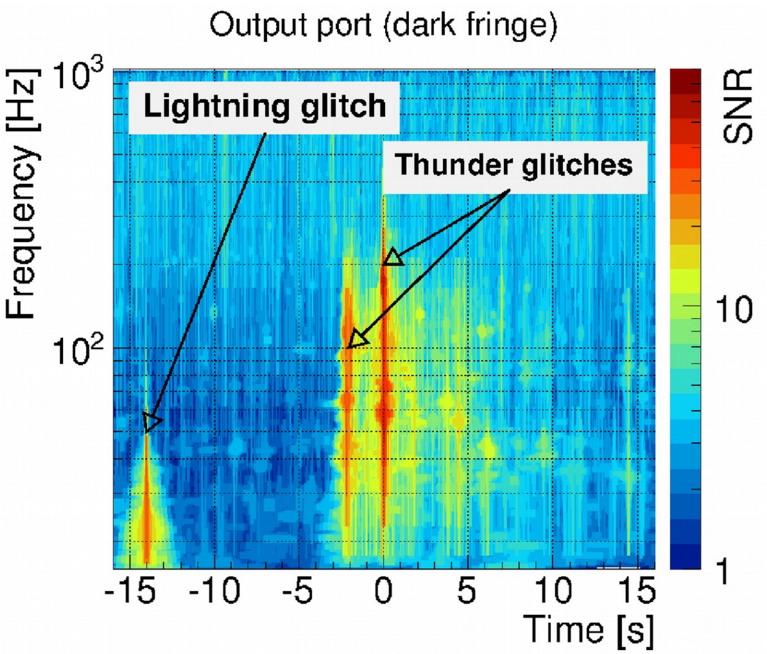
Monitoring noise

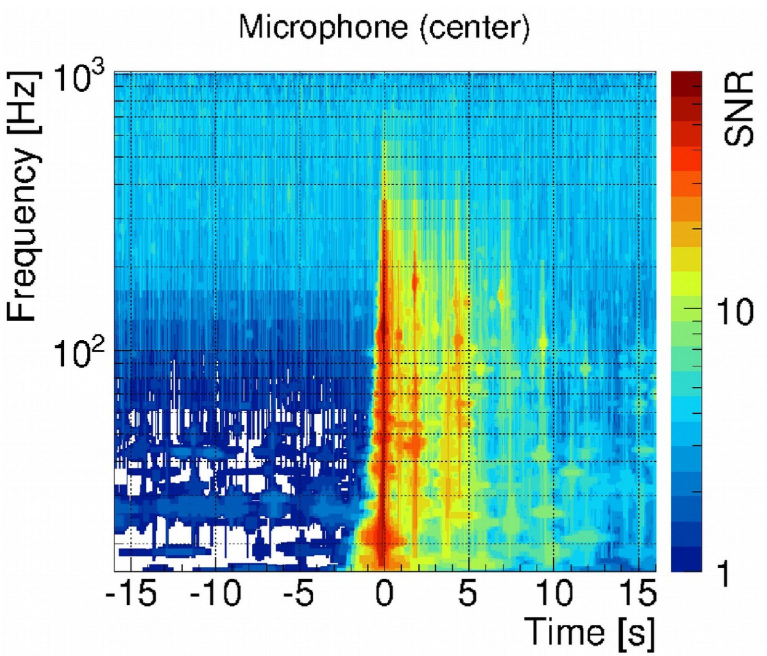


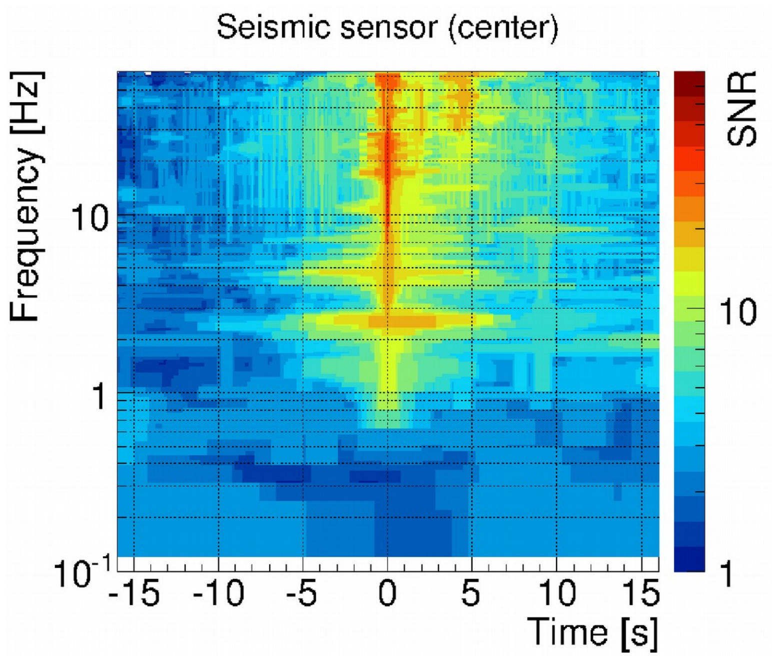




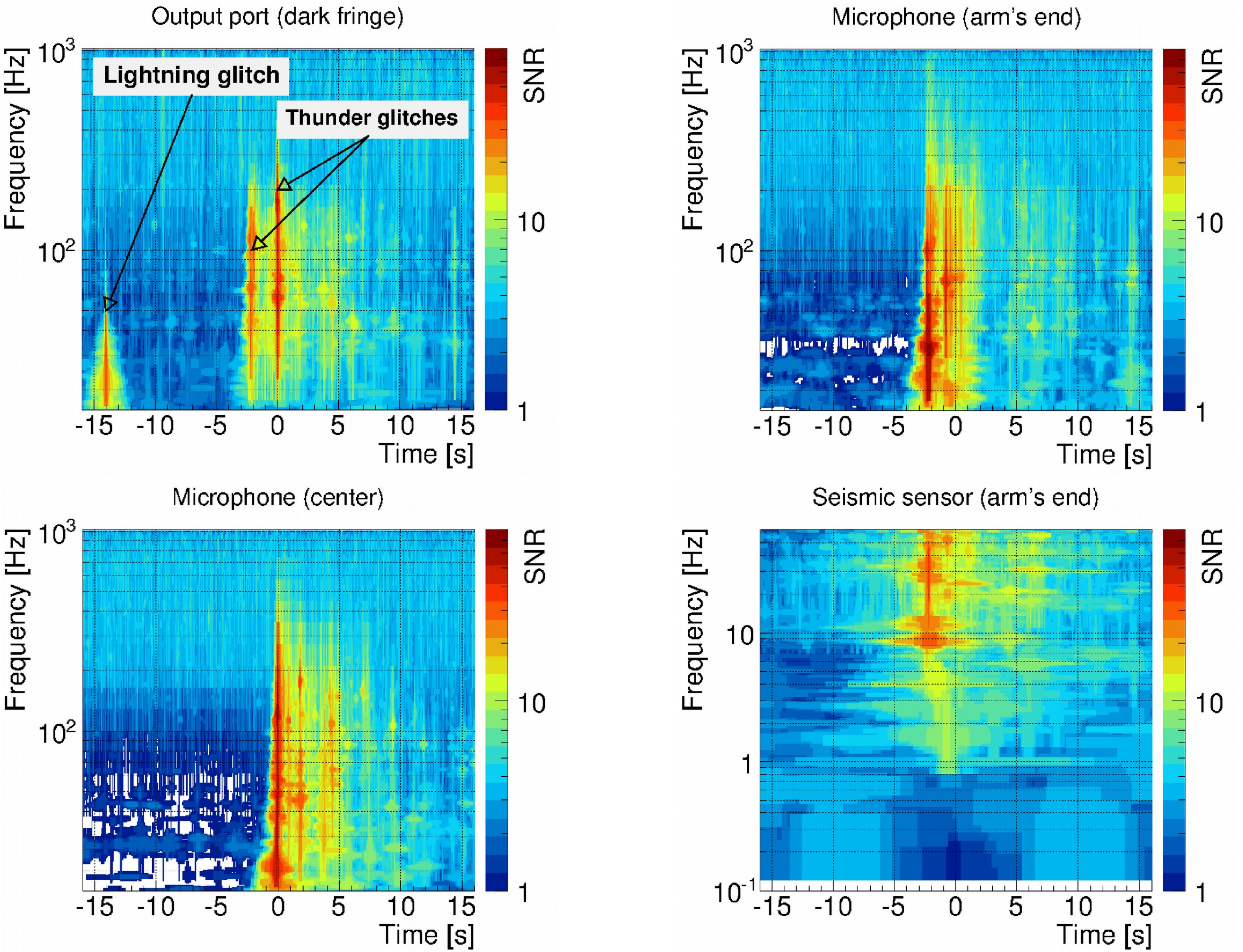
Monitoring noise



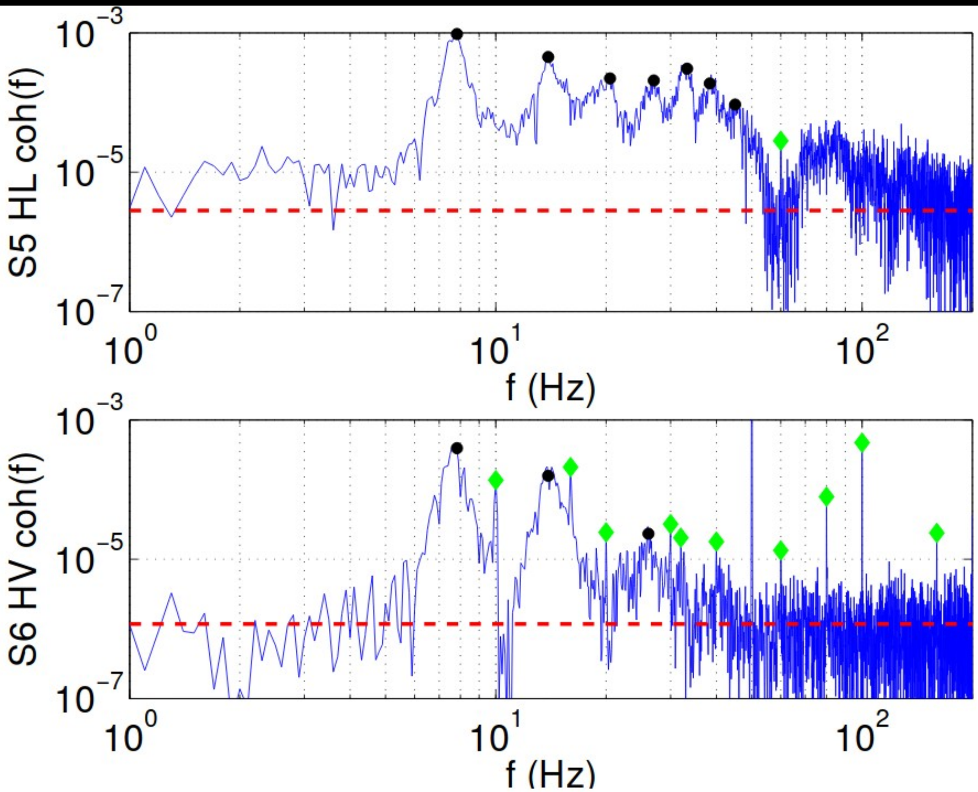




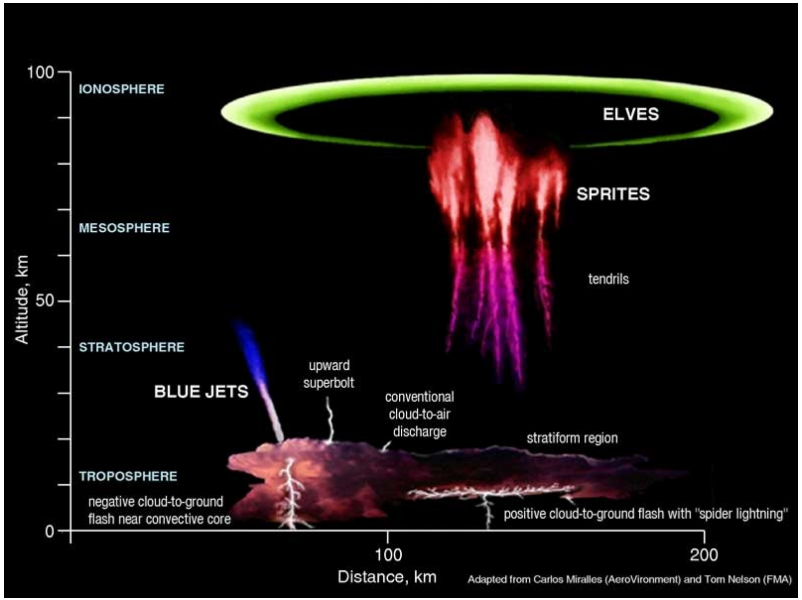
Monitoring noise

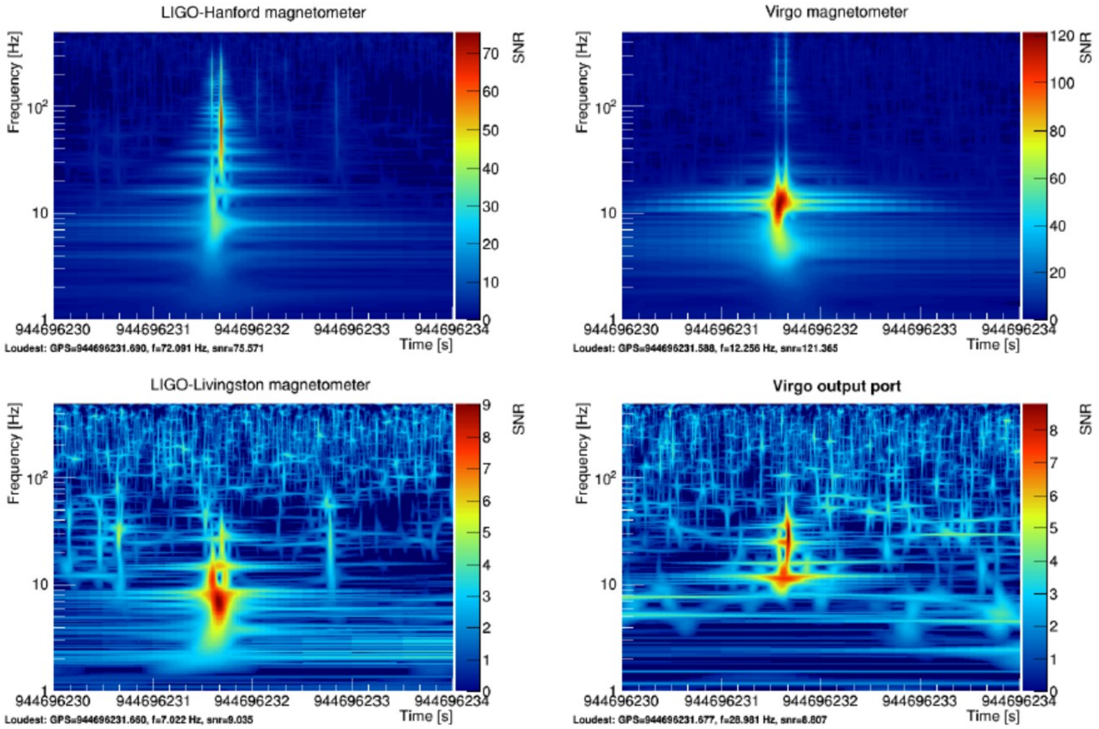


Correlated noise



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