Gamma-ray bursts and gravitational waves joint analysis with the LIGO-Virgo network

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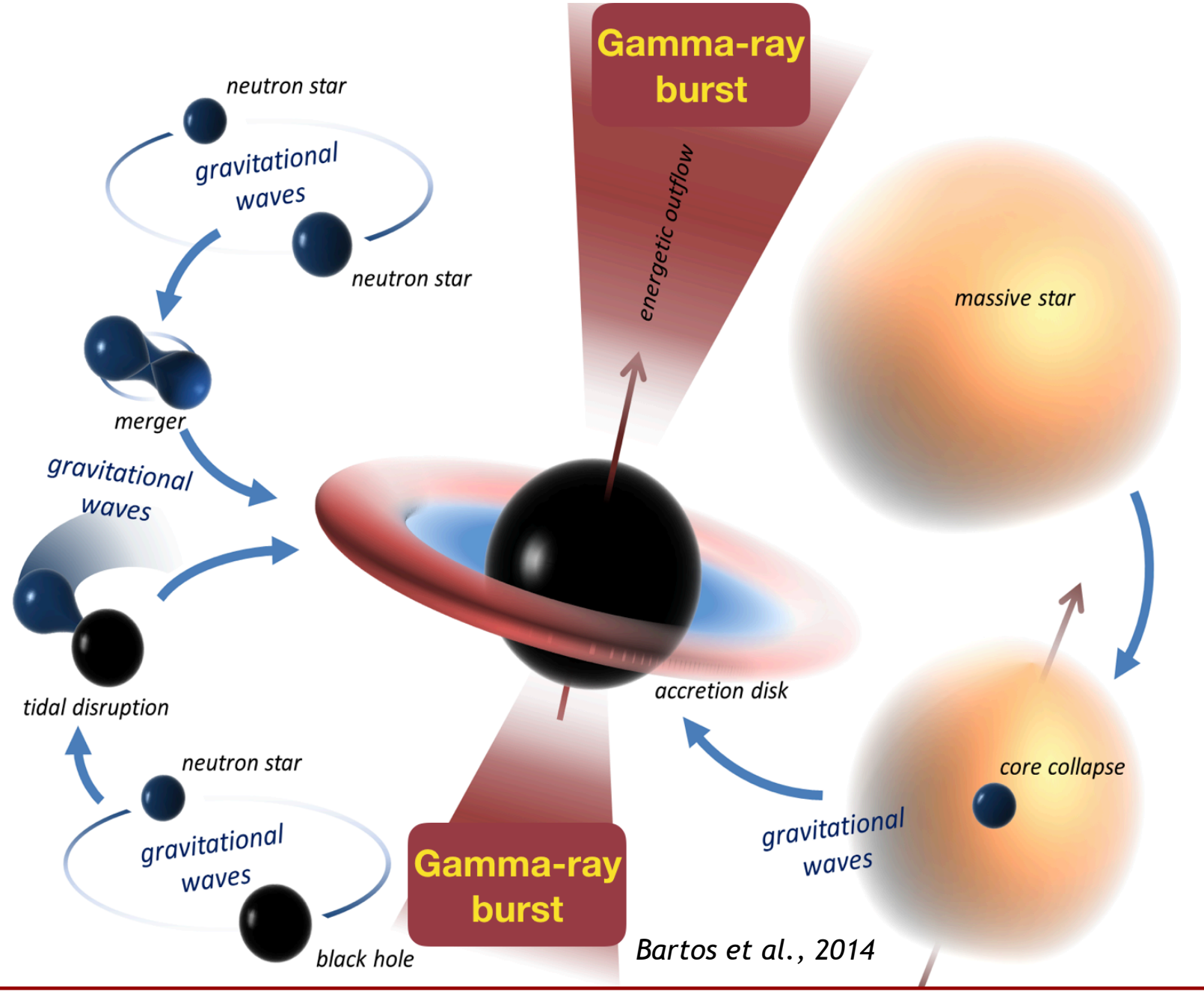
Abstract

In the context of the unmodelled search for gravitational waves (GW) associated to *gamma-ray bursts* (GRB), we present a sensitivity study conducted using *X-Pipeline*, a software which combines the data from LIGO and Virgo in correlation with the GRB direction in the sky to increase the sensitivity. The goal is to understand how the addition of Virgo to the network of interferometers impacts the sensitivity of the search, which is limited by non-stationary noise and that is estimated through the efficiency in recovering simulated gravitational wave signals injected in the data. Then, this sensitivity is compared to that obtained without including Virgo. We find that the crucial factor is the ratio between the detector angular response and its noise power spectrum: when this quantity computed for Virgo is smaller than for LIGO, the Virgo inclusion results in a better sensitivity. This gives us a metric for the Virgo inclusion in this search for the next observing run.

1 - Gamma-ray bursts and gravitational waves

Coalescence of a binary system of two Neutron Stars or Neutron Star - Black Hole

- ✴Gravitational waves emitted in the inspiral and merger phases
- ✴Short GRB progenitor (confirmed by GW170817)



Bartos et al., 2014

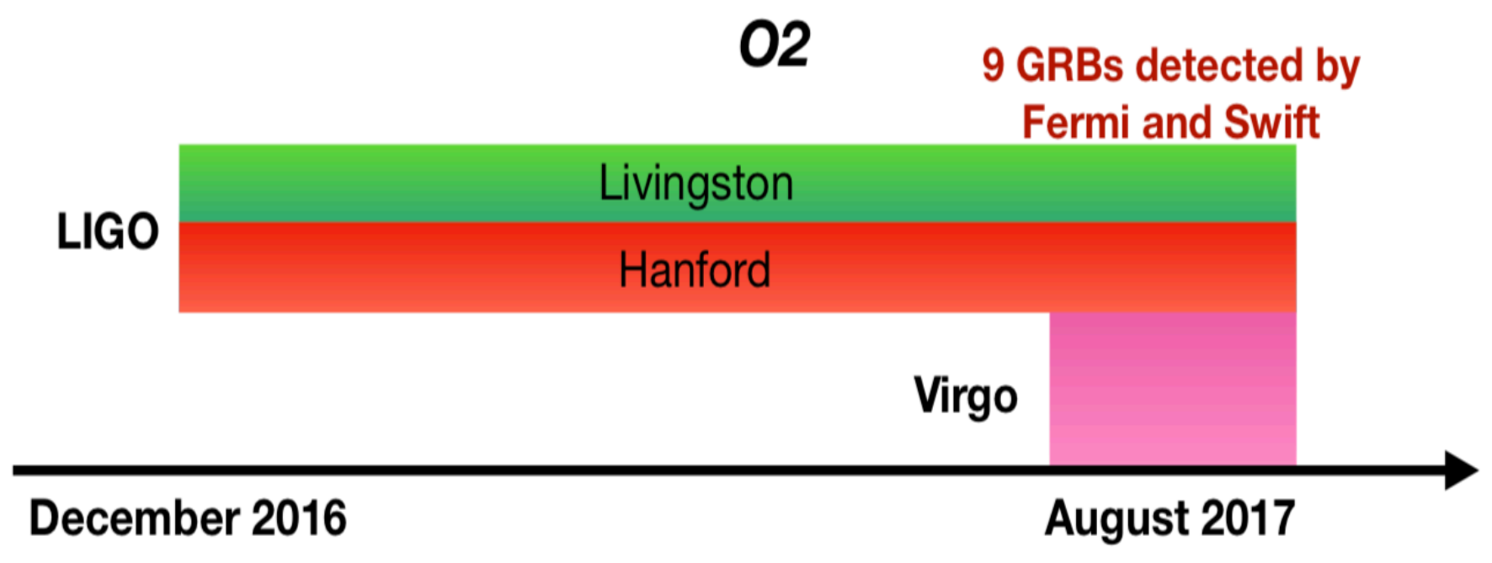
Collapse of a rapidly rotating massive star (Collapsar)

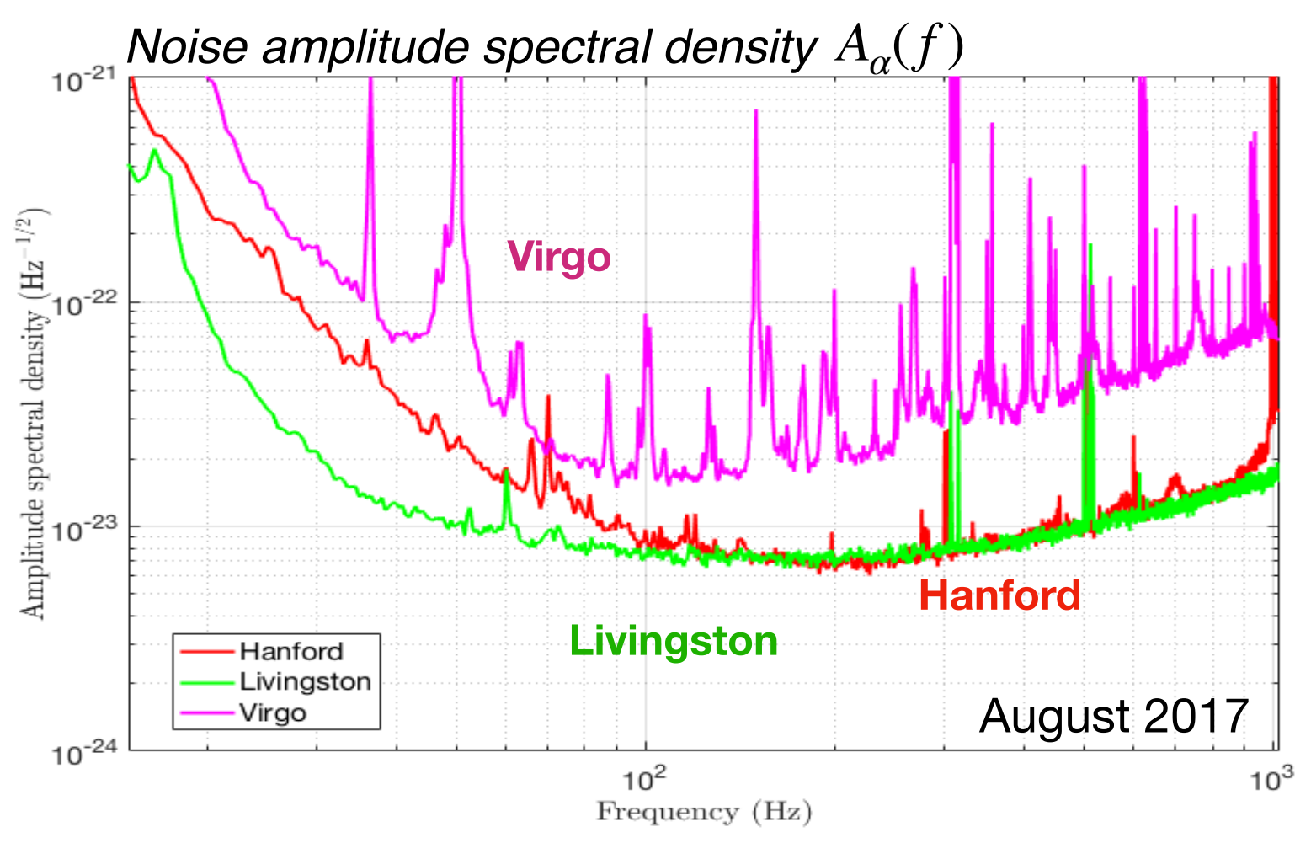
- ✴Gravitational waves emission expected during the core collapse or from instabilities in the black hole accretion disk
- ✴Long GRB progenitor

2 - The thesis

We focus on the search for gravitational waves associated with GRBs detected during the LIGO-Virgo second observing run (O2).

The search has been already completed by the LIGO-Virgo Collaboration for all the (~100) GRBs detected during O2, but using only the data of the two LIGO detectors, without including Virgo, that is less sensitive.





We considered 9 GRBs detected in August 2017, the only period when the three detectors were jointly operating.

The goal is to answer the following question:
Does adding Virgo to the network improve the search sensitivity?

3 - Coherent and unmodelled search: X-Pipeline

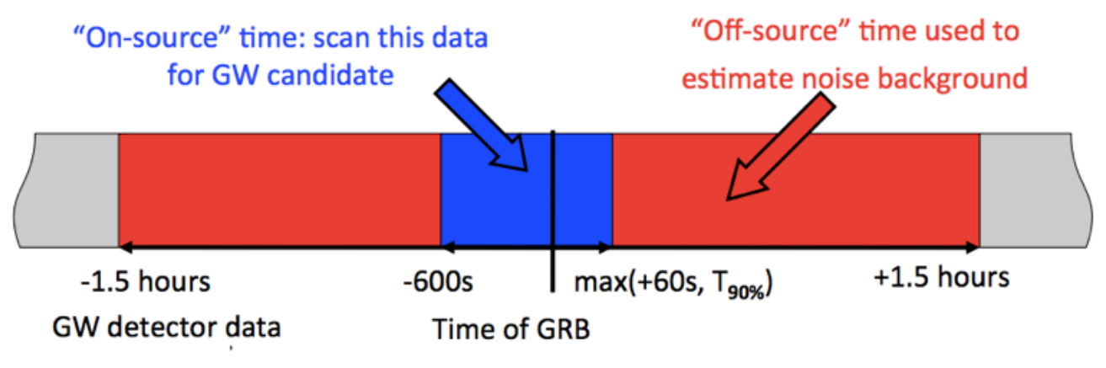
Overview

X-Pipeline performs a search for GWs associated with GRBs with no assumption on the signal waveform.

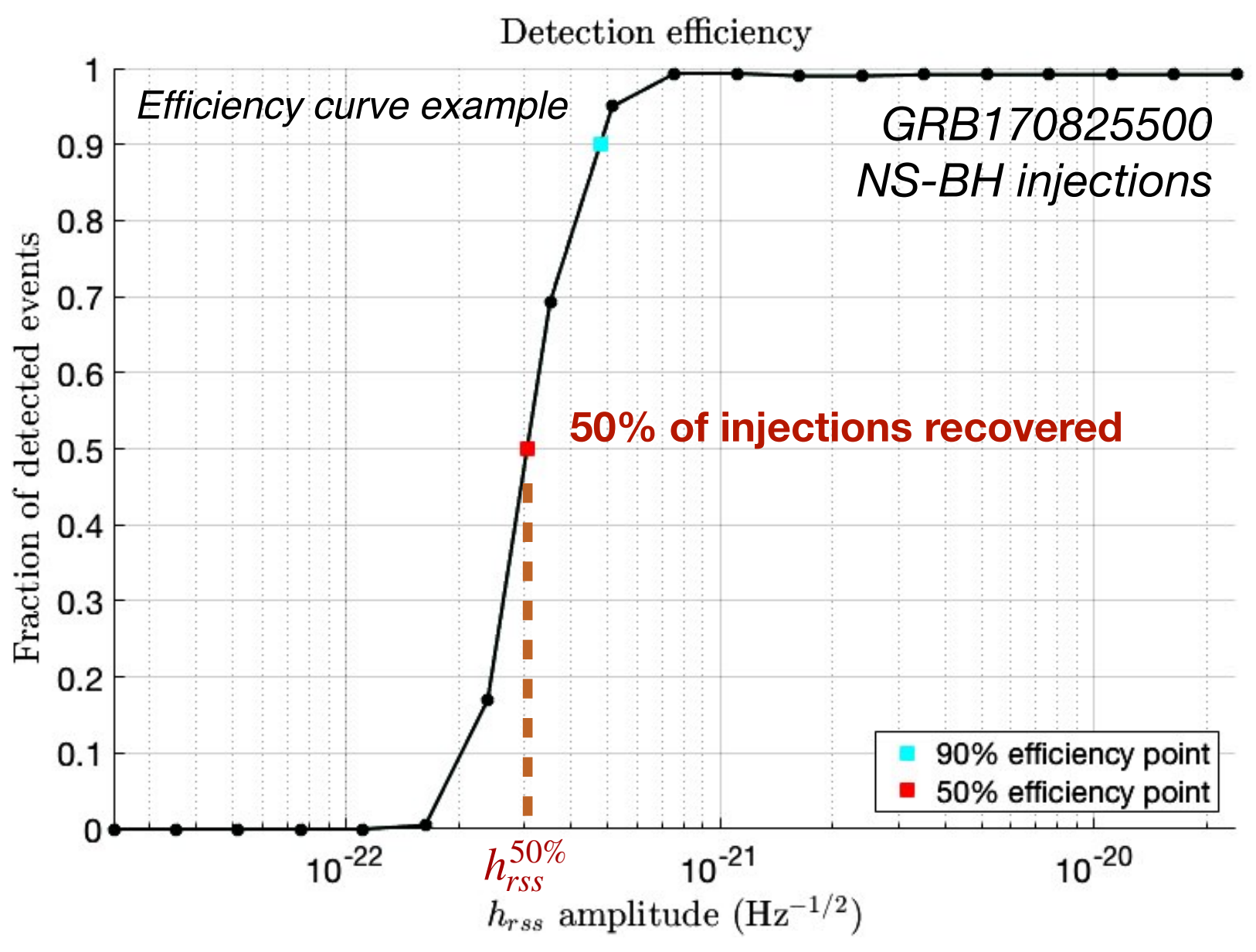
- ✴The data from each detector α are time shifted in correlation with the GRB direction. Then they are summed in the time-frequency domain, being weighted by the detector noise amplitude power spectral density

$$\tilde{d}_{w\alpha} = \frac{\tilde{d}_\alpha(f)}{A_\alpha(f)}$$

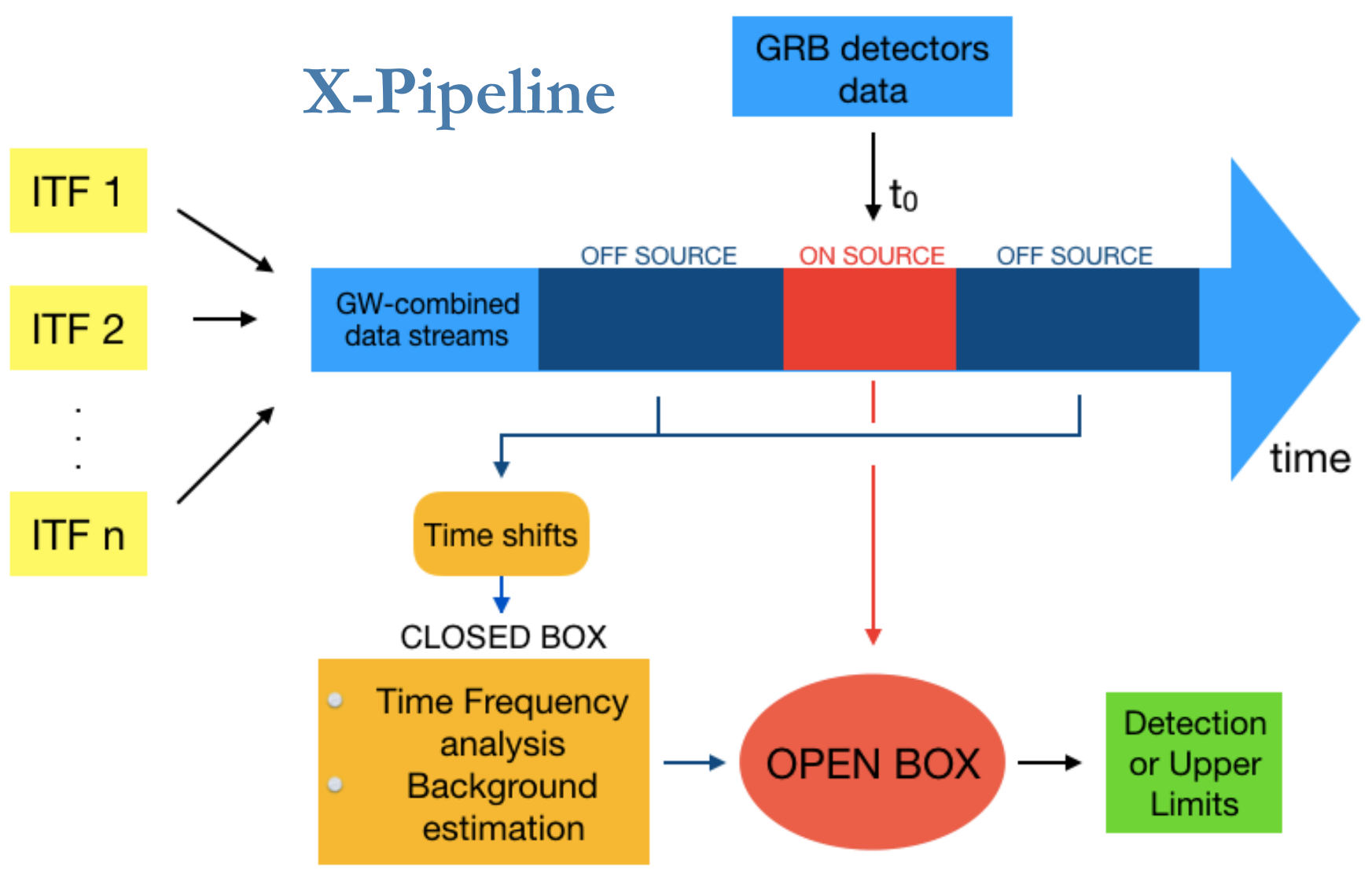
- ✴Loud pixels in the time frequency map are grouped together into *clusters*, considered as GW candidates
- ✴Data quality vetoes and consistency tests are applied on the clusters to reject noise.



- ✴The background distribution of the search is estimated in the 'Closed box analysis': considering an *off-source* time window which shares the same statistical properties with the *on-source* window, that is physically motivated.
- ✴In the following 'Open box analysis', events in the *on-source* window that are sufficiently inconsistent with the background can be considered as detections



X-Pipeline



GRB detectors data

ITF 1
ITF 2
ITF n

GW-combined data streams

t_0

OFF SOURCE
ON SOURCE
OFF SOURCE

time

Time shifts

CLOSED BOX

- Time Frequency analysis
- Background estimation

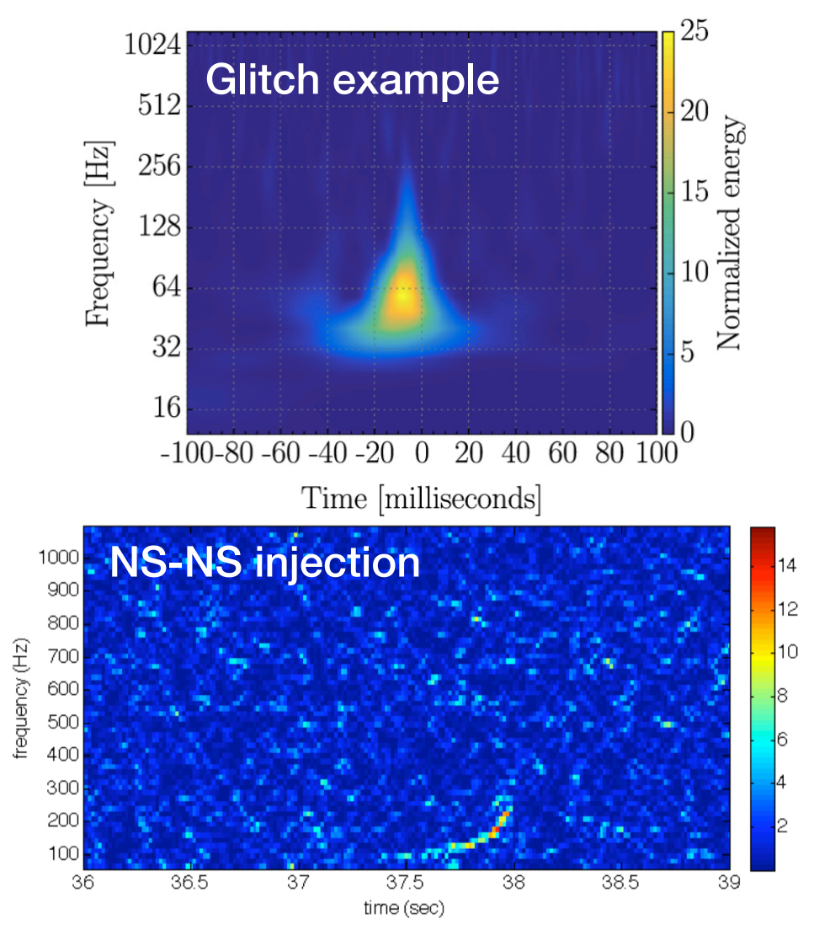
OPEN BOX

Detection or Upper Limits

Detector α output:

$$d_\alpha(t) = \underbrace{F^{+}_{\alpha}(\hat{\Omega})}_{\text{Angular response}}\underbrace{h_{+}(t)}_{} + \underbrace{F^{\times}_{\alpha}(\hat{\Omega})}_{}\underbrace{h_{\times}(t)}_{\text{Signal (if present)}} + \overset{\text{Noise}}{n_\alpha(t)}$$

Real instrument noise is dominated by non-Gaussian and non-stationary transients called *glitches*, of various origins. They can mimic a true GW signal.



Sensitivity

The sensitivity of the search, is estimated during the Closed box analysis through the efficiency in recovering simulated gravitational wave signals previously injected in the data, at random times and with different amplitudes around the interesting time window, using several types of waveforms:

- ✴Sine-Gaussian chirplets (SGC)
- ✴Inspirals waveforms (BNS - NSBH)
- ✴Accretion Disk Instabilities waveforms (ADI)

We select the amplitude at which 50% of the injected signals are correctly detected by the pipeline as a measure of our sensitivity with respect to that specific class of signals.

4 - Analysis and results

We performed a fully coherent analysis using a network of three interferometers, triggered by the 9 detected GRBs in August 2017, using X-Pipeline. Here we present the results of the study on how the addition of Virgo to the network of interferometers impacts the overall sensitivity of the search, considering Closed box analyses, with and without the use of different vetoes linked to the quality of the data. If vetoes are applied on the data, they discard noise, but cause dead observation time. We created new vetoes (called Category 2) to be applied to each GRB and to the whole set of GRBs. For each GRB we performed 3 runs with the following setups:

- ✴**Run 1 (Closed box)**
  only added Virgo, without vetoes
- ✴**Run 2 (Closed box)**
  added Virgo, with the same veto for all the GRBs
- ✴**Run 3 (Closed box)**
  added Virgo, with an optimised veto for each GRB

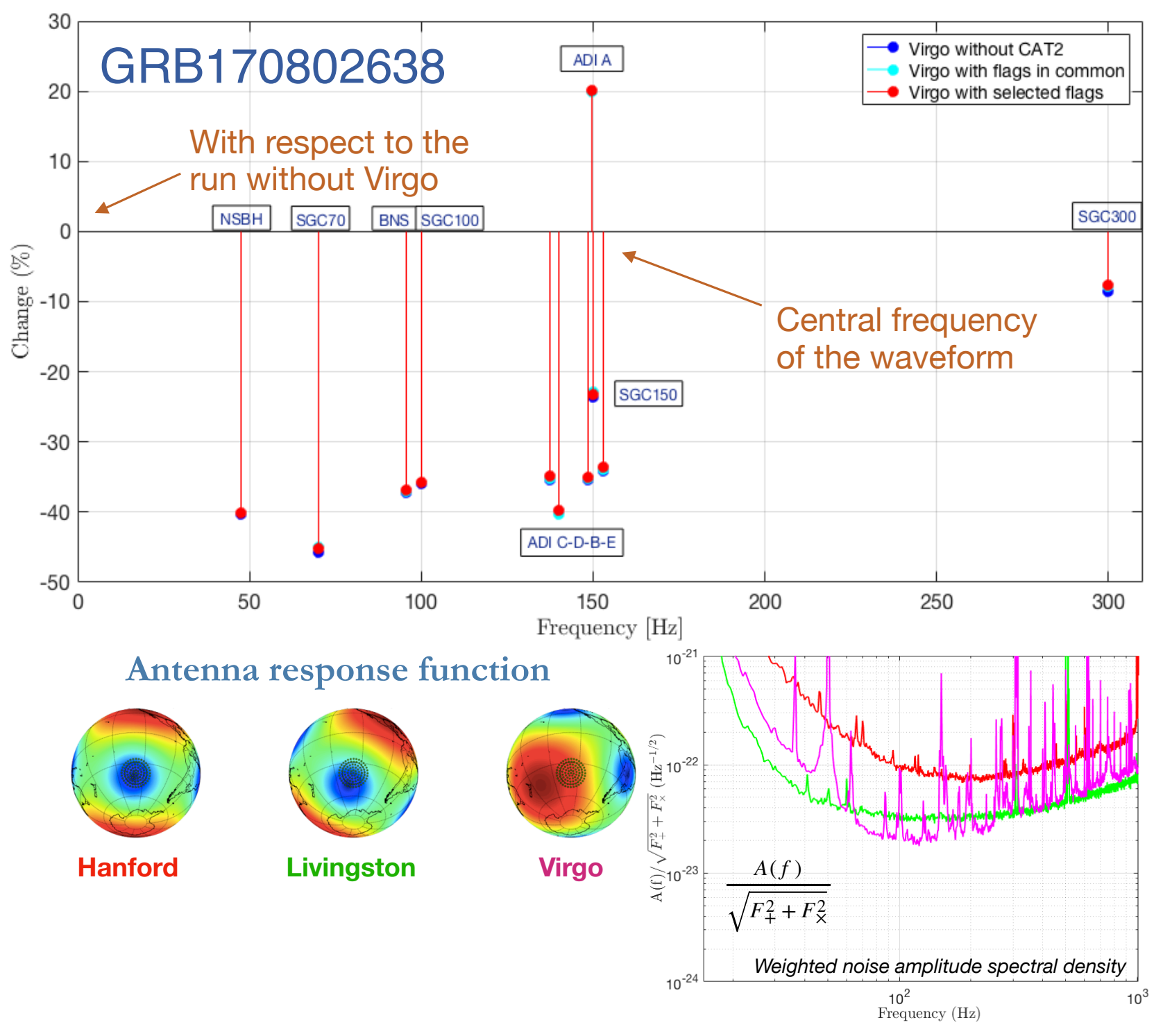
- ✴On-source time window: **[-600, +60] s** with respect to the GRB detection time
- ✴Off-source interval: **[-1.5, +1.5] hours** centered on GRB detection time
- ✴Frequency band: **[20, 500] Hz**
- ✴Same vetoes for Hanford and Livingston as the LIGO-only search

The sensitivity computed with our analysis is then compared to that obtained without including Virgo in the network. **We compute, for each GRB, the percentage change in the 50% upper limits for 11 injected waveforms:**

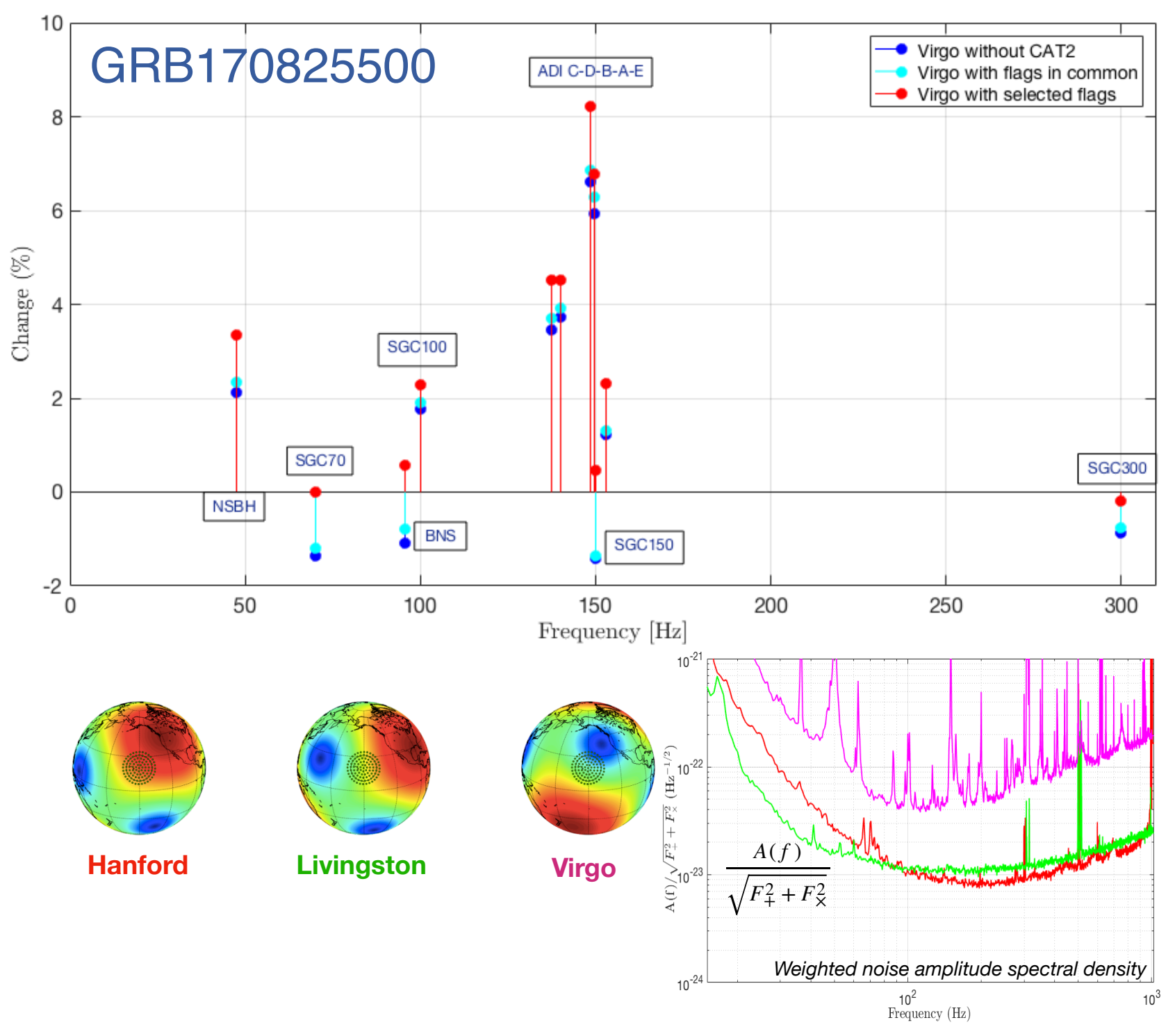
$$\textbf{Change} = 100 \cdot \left(\frac{h^{50\%}_{rss}}{h^{50\%}_{rss,without\ Virgo}} - 1 \right)$$

The upper limits depend on the different noise background for different GRBs, on the pipeline efficiency in rejecting it and on the type and frequency of the waveforms injected. We have 4 GRBs for which the sensitivity improves and 5 for which adding Virgo result in higher upper limits, namely lower sensitivity. We show two examples:

Increasing sensitivity



Decreasing sensitivity



Overall results for the 9 available GRBs:

GRB Name	Detected by	Classification	Search sensitivity change
GRB170802638	Fermi-GBM	Ambiguous	Improvement up to 45%
GRB170803172	Fermi-GBM	Ambiguous	Decrease up to 30%
GRB170816258	Fermi-GBM	Long	Decrease up to 20%
GRB170816599	Fermi-GBM	Short	Improvement up to 25%
GRB170825500	Fermi-GBM	Long	Decrease up to 8%
GRB170825784	Fermi-GBM	Long	Improvement up to 60%
GRB170807A	Swift-BAT	Long	Decrease up to 15%
GRB170822A	Swift-BAT	Long	Improvement up to 15%
GRB170823A	Swift-BAT	Long	Decrease up to 10%

The crucial factor, which determines the increase or decrease in sensitivity, is the ratio between the detector angular response and its noise power spectrum. This quantity is inversely proportional to the coefficient that weights the data of each interferometer in the X-pipeline coherent combination. An increase in sensitivity with Virgo is only possible for directions in which Virgo itself has a larger angular response than one of the two LIGO detectors. Variability is given by the non-stationary noise. The veto application further increases the sensitivity for the 4 "improving" GRBs.

5 - Conclusions

When adding Virgo, considering the GRB direction, the sensitivity improves in the frequency range in which we have:

$$\frac{A_{Virgo}(f)}{\sqrt{F_+^2 + F_\times^2}} \lesssim \frac{A_{LIGO}(f)}{\sqrt{F_+^2 + F_\times^2}}$$

This estimation will be used to decide when to include the Virgo data for this kind of searches in O3, the next joint LIGO-Virgo scientific run, scheduled to start in Spring 2019.

The results of this work will be included in the LIGO-Virgo Collaboration paper *(still in preparation)* on the search for gravitational waves associated to GRBs during O2.

Main references

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