LIGO Scientific Collaboration
VIRGO

EINSTEIN TELESCOPE

INFN LNS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Sud

Search for GW in coincidence with burst sources during O3

Iara Tosta e Melo

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INFN
Istituto Nazionale di Fisica Nucleare

Outline

- Introduction

- GW Multimessenger Astronomy

- Triggered analysis: X-pipeline

- GRB analysis during O3
    - GRB O3a/O3b analysis

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- Final remarks

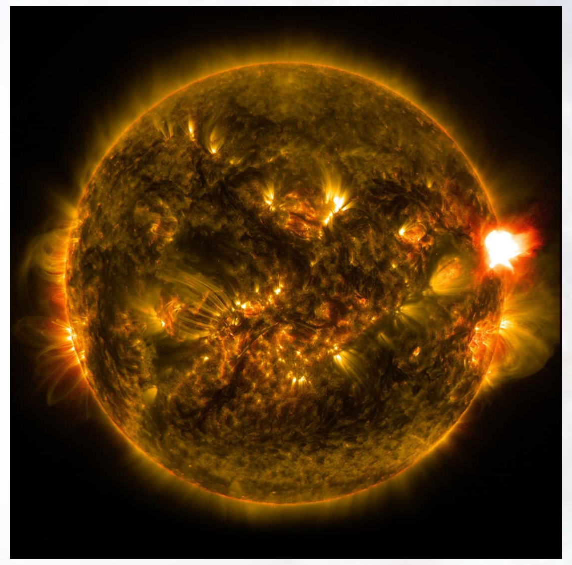
Introduction

Traditional astronomy is no longer the only way of exploring the Universe → electromagnetic observations (EM)

The multi-messenger astronomy was born when new astronomical messengers as non-electromagnetic origin were observed:

cosmic rays

In 1940s: Some cosmic rays were identified as forming in solar flares (Spurio, Maurizio (2015)

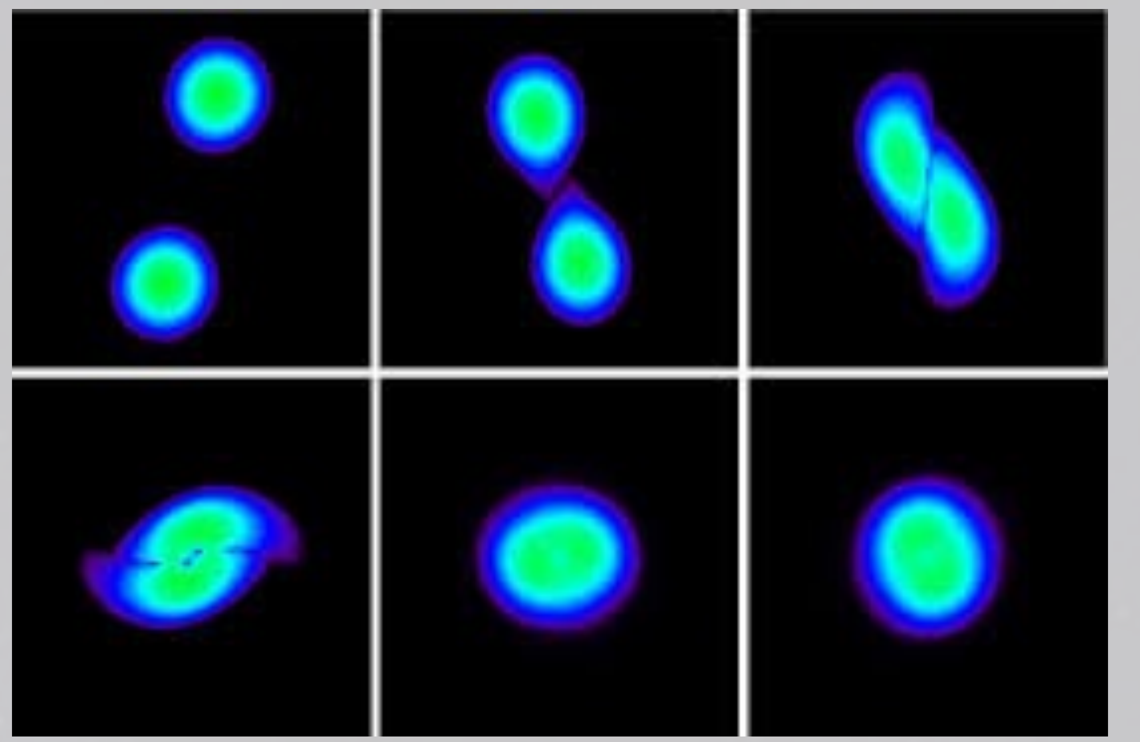


Neutrinos

1987: Supernova SN 1987A emitted neutrinos that were detected at the Kamiokande-II, IMB and Baksan neutrino observatories, a couple of hours before the supernova light was detected with optical telescopes

Gravitational waves

The first observation from the inspiral and merger of a binary black-hole system (BBH) by the advanced LIGO interferometers marked the onset of GW astronomy (GW150914, Abbott et al. 2016a)



- BH :35.6 solar masses
- BH: 30.6 solar masses
- Post-merge BH (remanet): 63.1 solar masses and
- The energy radiated in form of GW: 3.1 solar masses travelling at the speed of light.

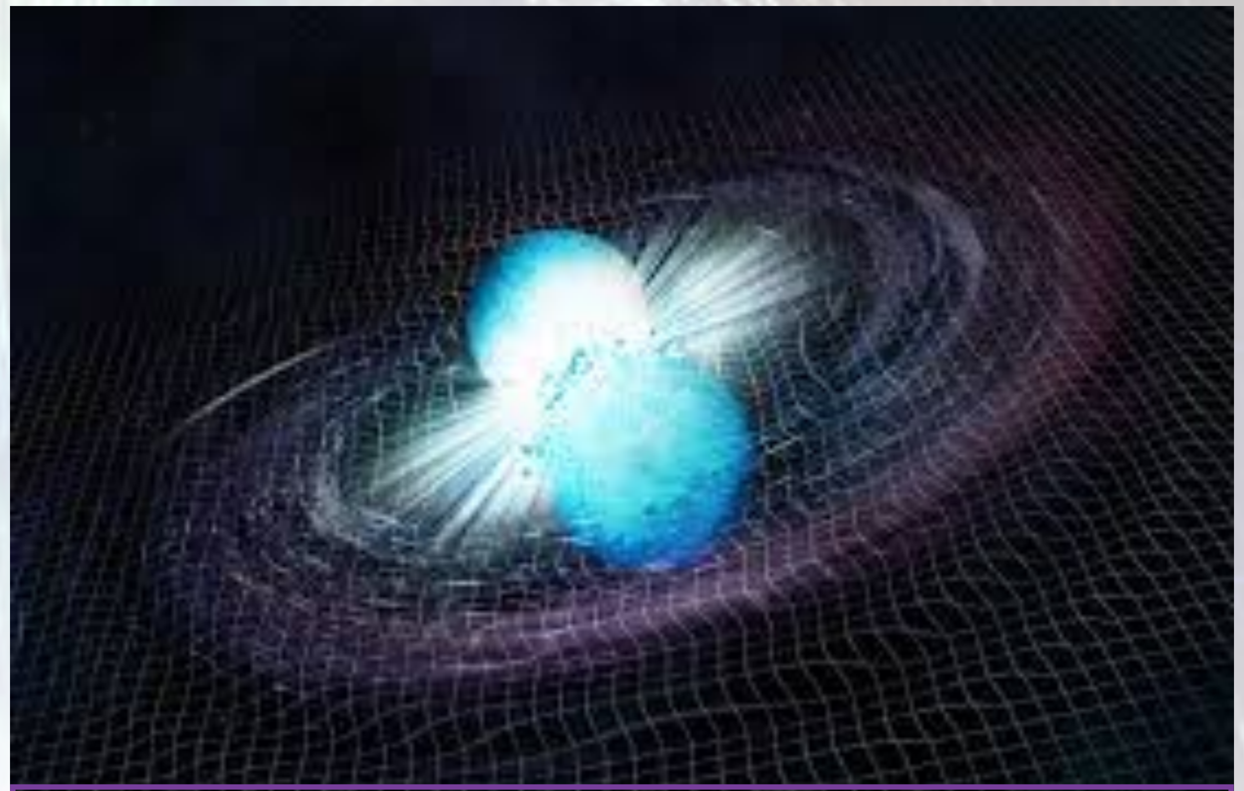
↓

GW astronomy was born

GW Multimessenger Astronomy

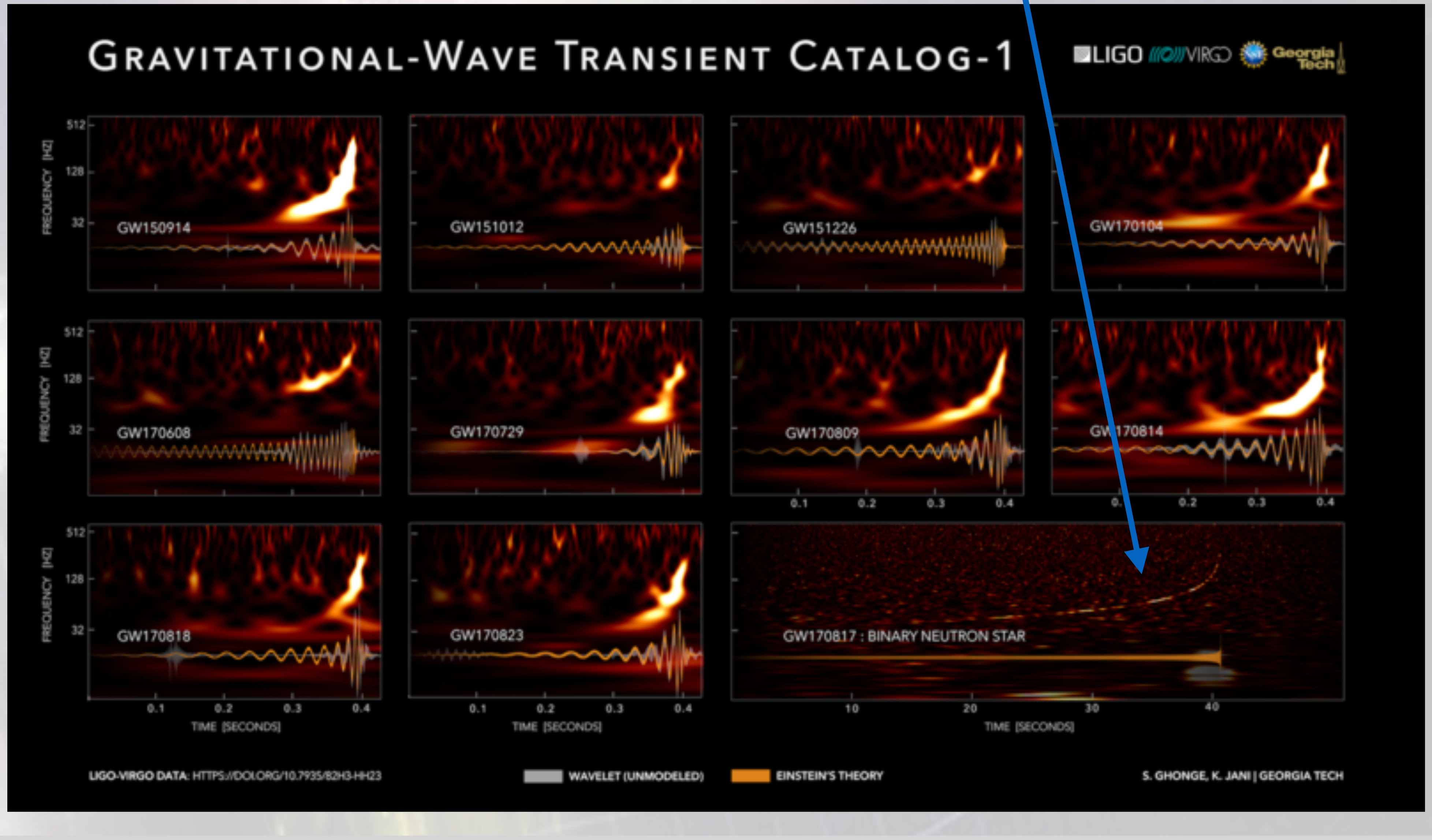
GW170817 and GW Multimessenger Astronomy

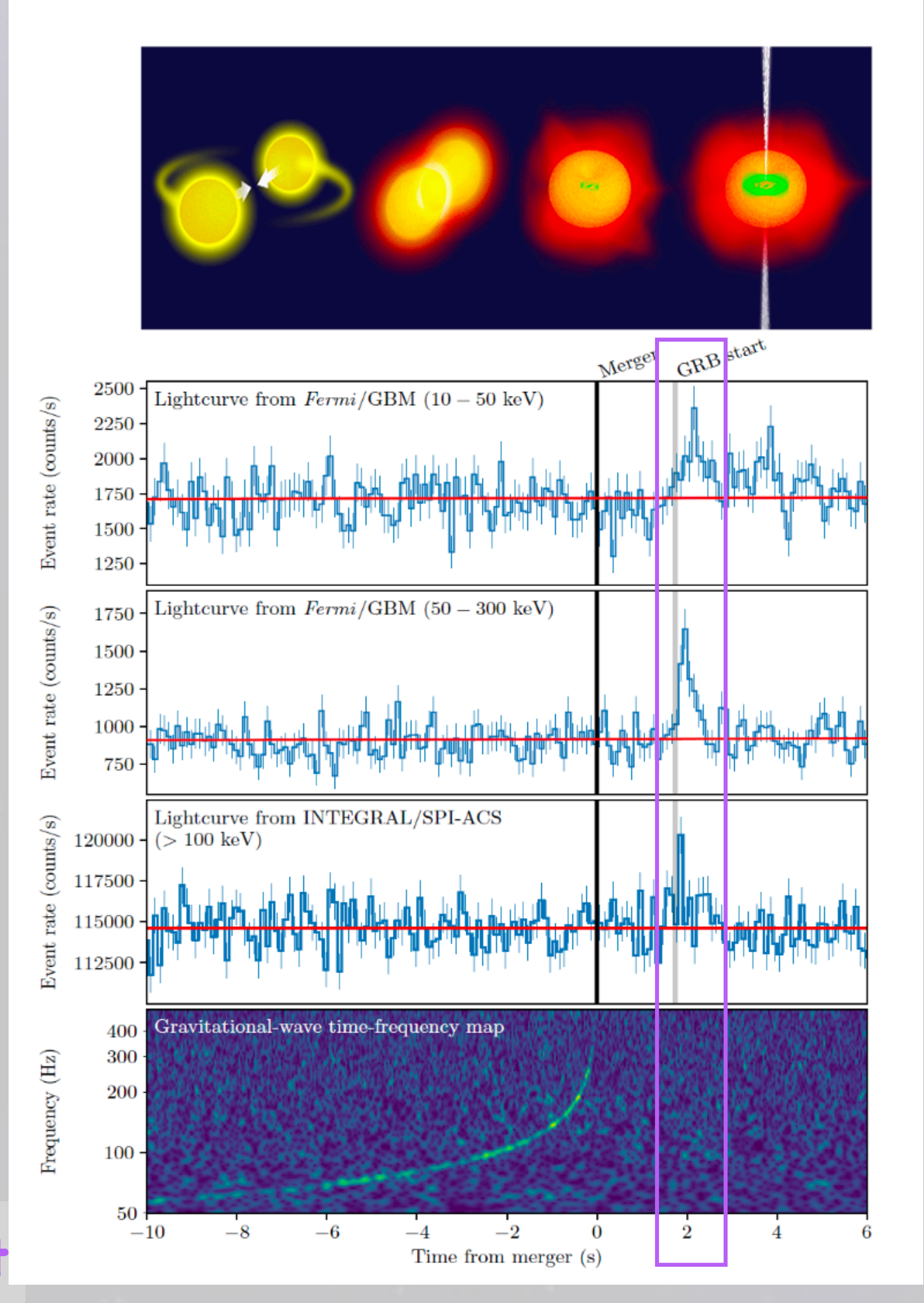
On 17th of August 2017, multi-messenger astronomy related to GWs had its breakthrough: the LIGO-Virgo network observed a GW signal of two low-mass compact objects consistent with a neutron star binary (GRB170817, GRB170817A, Abbott et al. 2017).



The individual masses of the NS were 1.46 $M_\odot$ and 1.27 $M_\odot$, resulting in a final NS mass of 2.74 $M_\odot$. The energy radiate in form of GW was about $\geq 0.04\, c^2 M_\odot$

The event had a duration of approximately 40 seconds, and shows the characteristics in intensity and frequency expected of the inspiral of two neutron stars





On the same day of the GW170817 event, the **Fermi Gamma-ray Burst Monitor** independently detected a **gamma-ray burst (GRB 170817A)** with a time delay of about 1.7s concerning the merger time

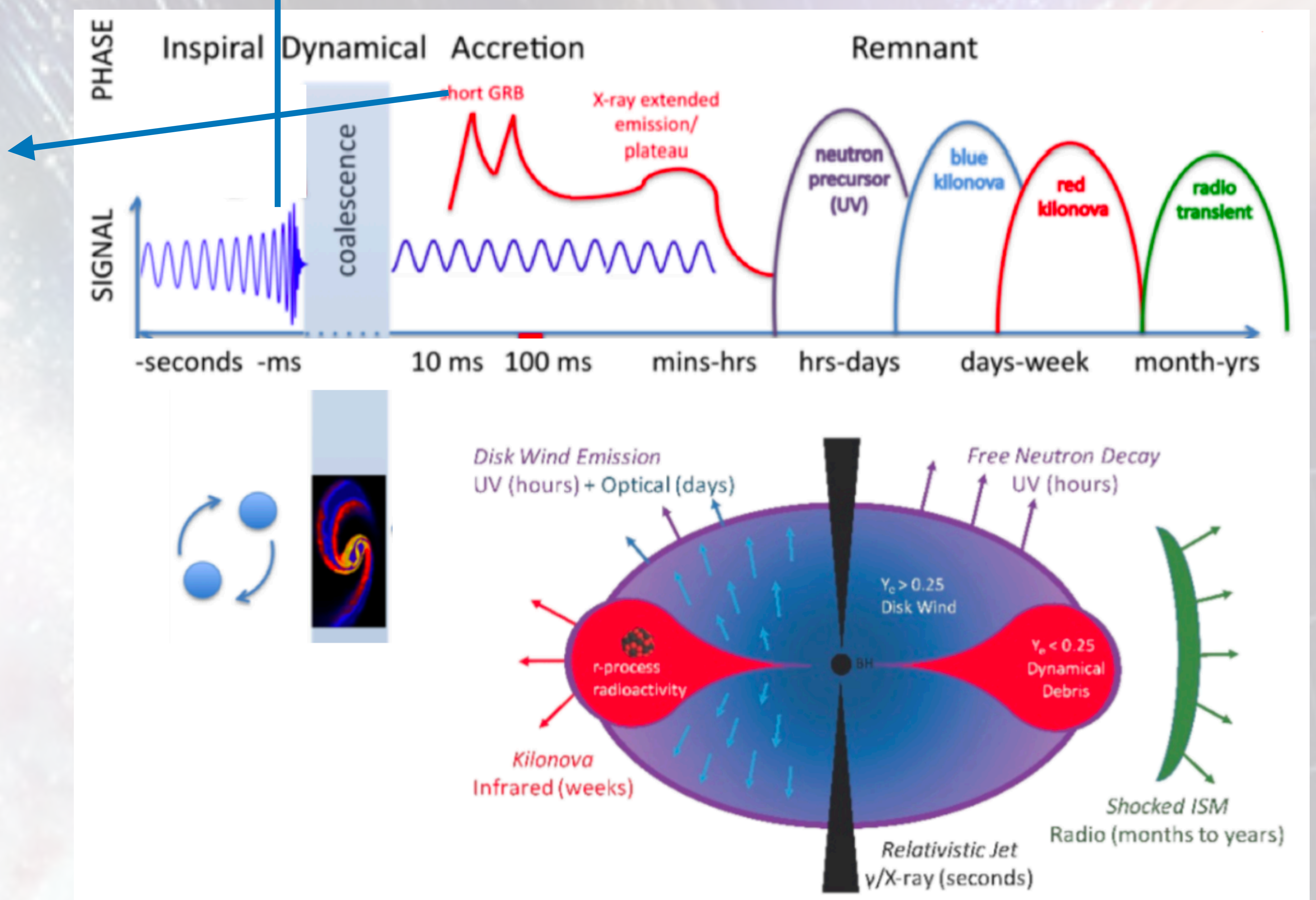
GW Multimessenger Astronomy

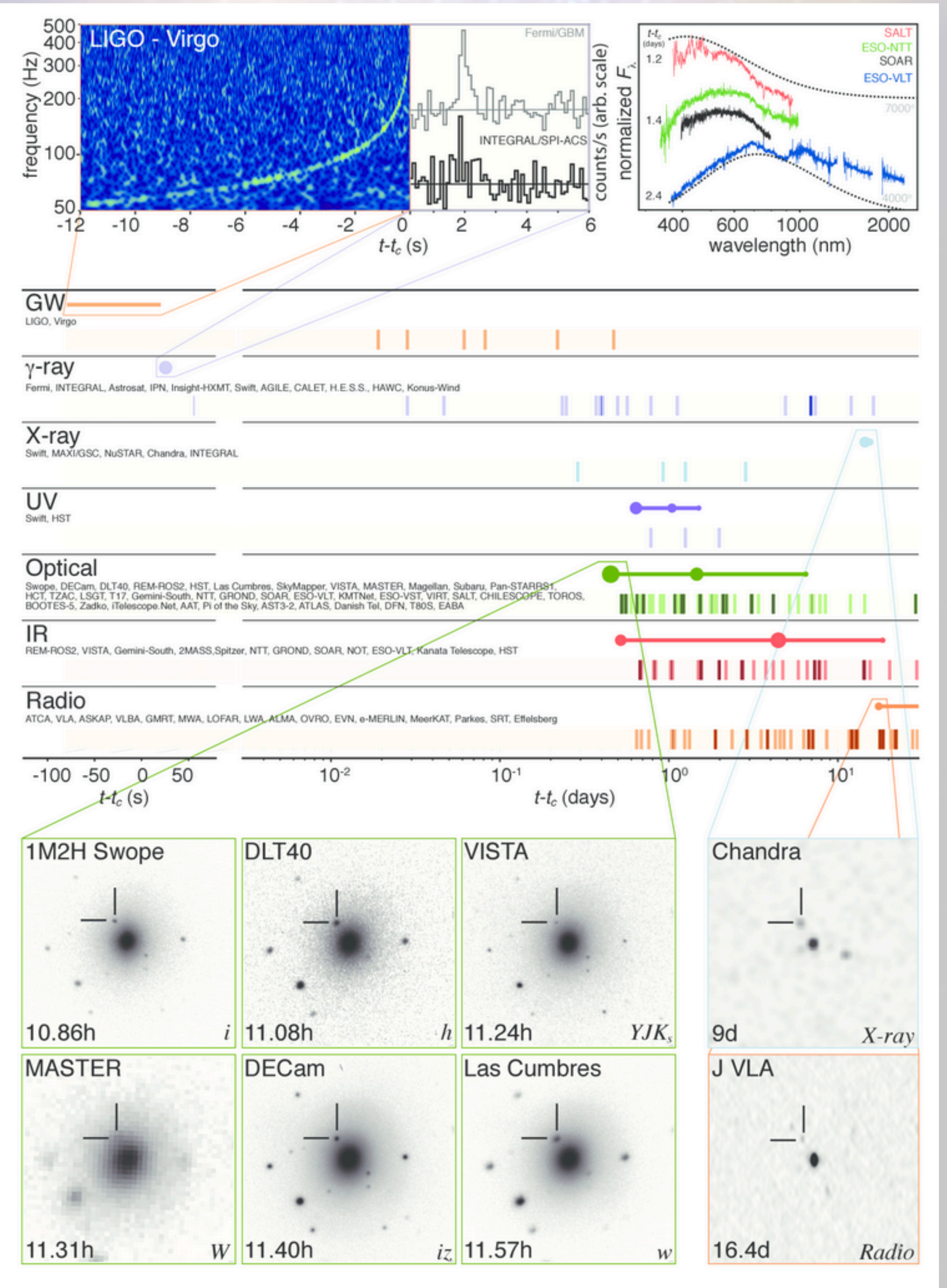
- Events including at least one NS are thought to emit short GRB followed by an optical afterglow and a kilonova powered by the radiocative decay of heavy nuclei freshly synthetized

GWs are emitted: inspiral phase, merger and ringdown

After the merger, short gamma ray bursts can be emitted

The prompt gamma ray bursts (within seconds) can be followed by an optical afterglow emission in optical and than a Kilonova





GW170817

An optical transient named AT2017gfo was found 11 hours after the GW signal in the galaxy NGC4493. Other emissions were observed by numerous telescopes, from radio to X-ray wavelengths over the following days and weeks

It was the first detection of GWs which happened to have electromagnetic counterparts.

Born of GW multi-messenger

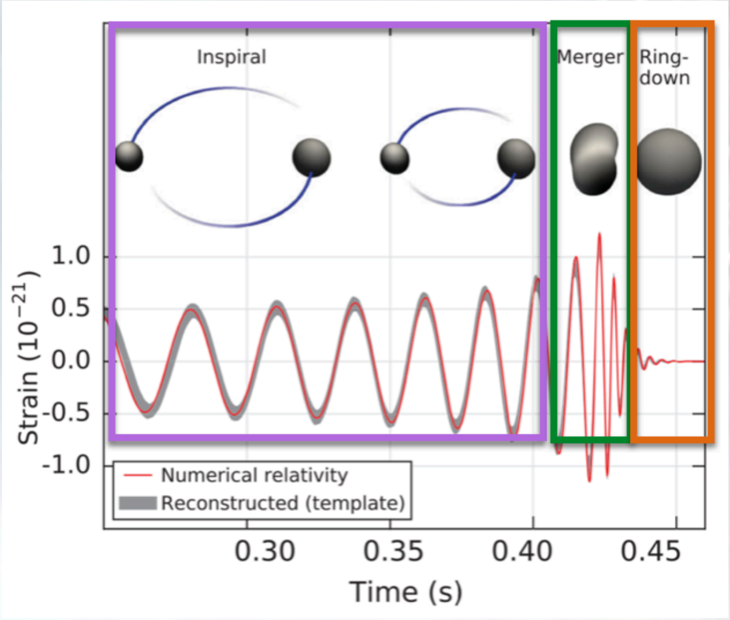
GW Multimessenger Astronomy

Expected transient GW sources detectable by LIGO/Virgo

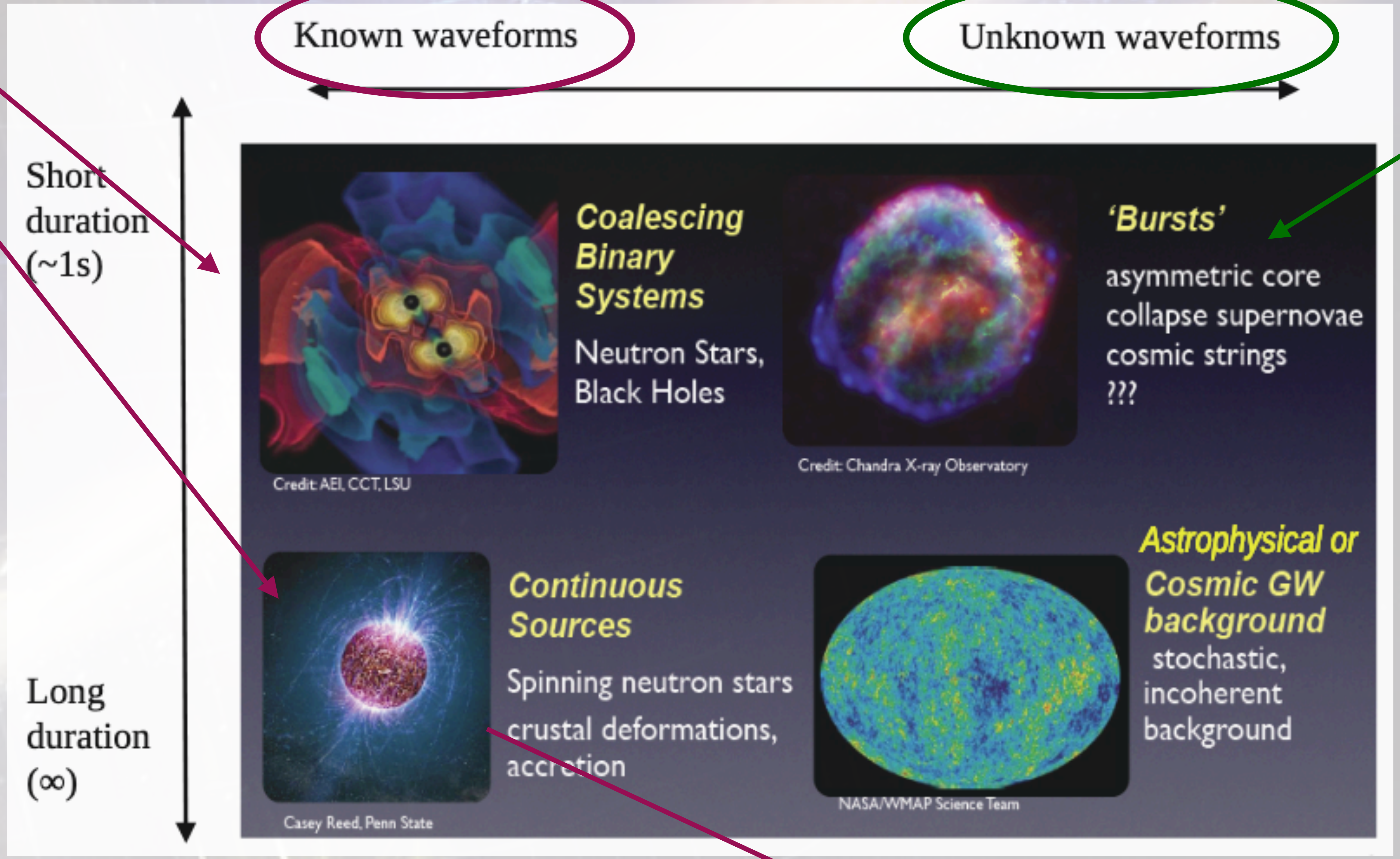
Waveforms in two categories

The waveform of a signal is the shape of a GW in function of time

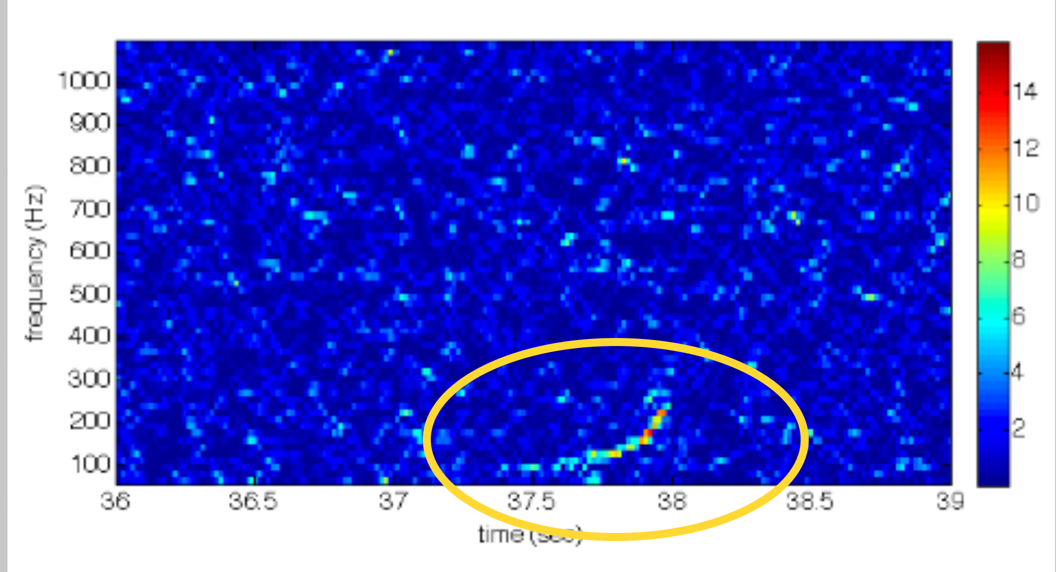
GW signal compatible with the inspiral of a BNS, NSBH binary or spinning neutron stars
Their signal is well modelled



Templates: model of the dynamical evolution of a binary compact system from its inspiral phase until its ringdown

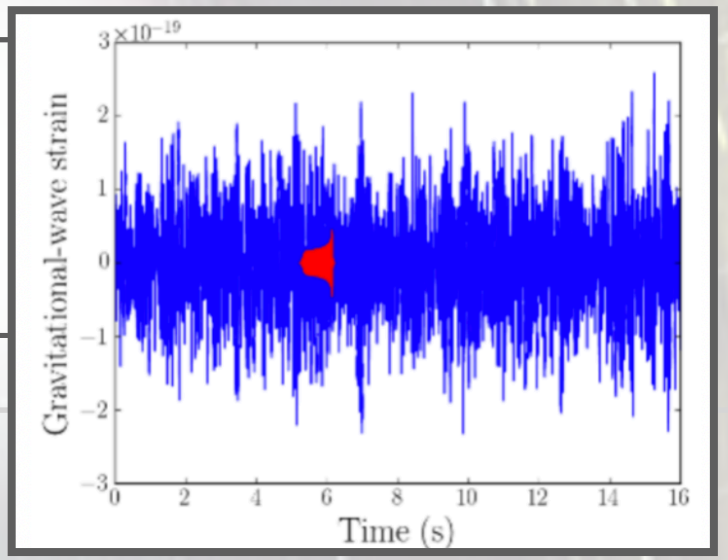


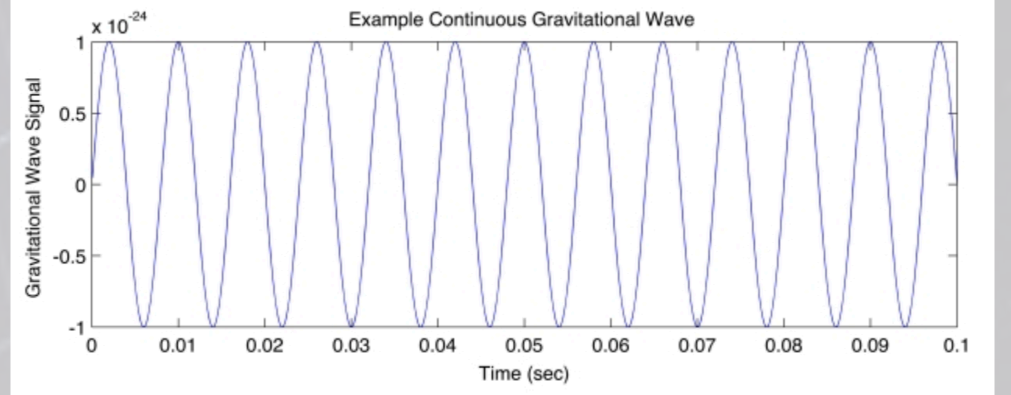
Use robust detection methods that do not rely on having a model of the signal
Looks for excess power that is coherent across the network of GW detectors in a time-frequency plot after decomposing the data stream



The cluster with highest pixel values is marked as an probable event

Match filtering
We injected templates into the data and check the compatibility of each template to find the best fit





Triggered GW analysis: X-pipeline

X-Pipeline is a software package designed to perform autonomous searches for gravitational-wave bursts associated with astrophysical triggers

- Searches for GW transient signals, or bursts, require identification of weak signals in the background noise
- Real detectors do not have purely stationary Gaussian noise, but instead their noise contains *glitches*, which are short transients that can mimic gravitational-wave burst signals

Coherent method: combine data from multiple detectors before processing, and create a single list of candidate events for the whole network

Searches for GW bursts, namely transient signals, typically of unknown waveform, require identification of weak signals in background detector noise.

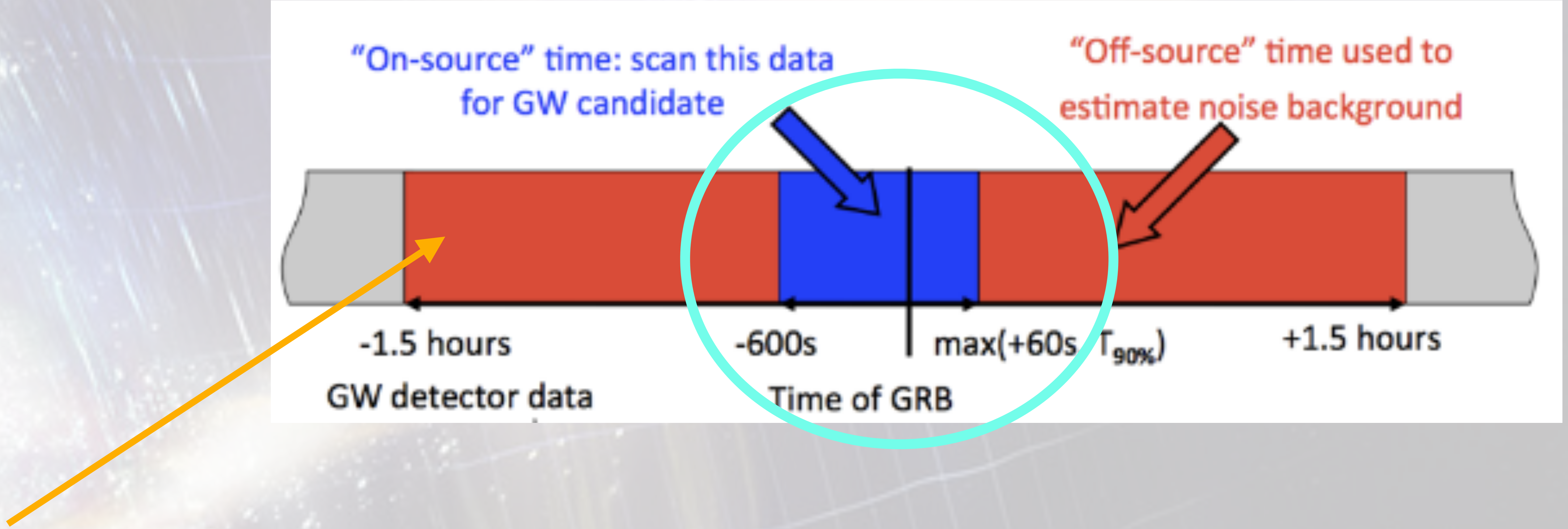
- To improve the sensitivity of the search:

A priori knows the position of the source therefore analyzes the corresponding localization of some astrophysical source of interest
In our case the both **GRB and FRB sources**
Can be up to 20% more sensitive than an all-sky search on the same data, with the improvement depending on the accuracy of the sky position measurement (telescopes)

Triggered GW analysis: X-pipeline

In order to claim a gravitational wave detection, we need to be able to establish with high confidence that a candidate event is statistically inconsistent with the noise background.

This is done using the loudest event statistic, adopted in order to compare a candidate with the background distribution. As the loudest event, we identify the cluster in the on-source interval that has the largest significance and which survives the application of all the available vetoes



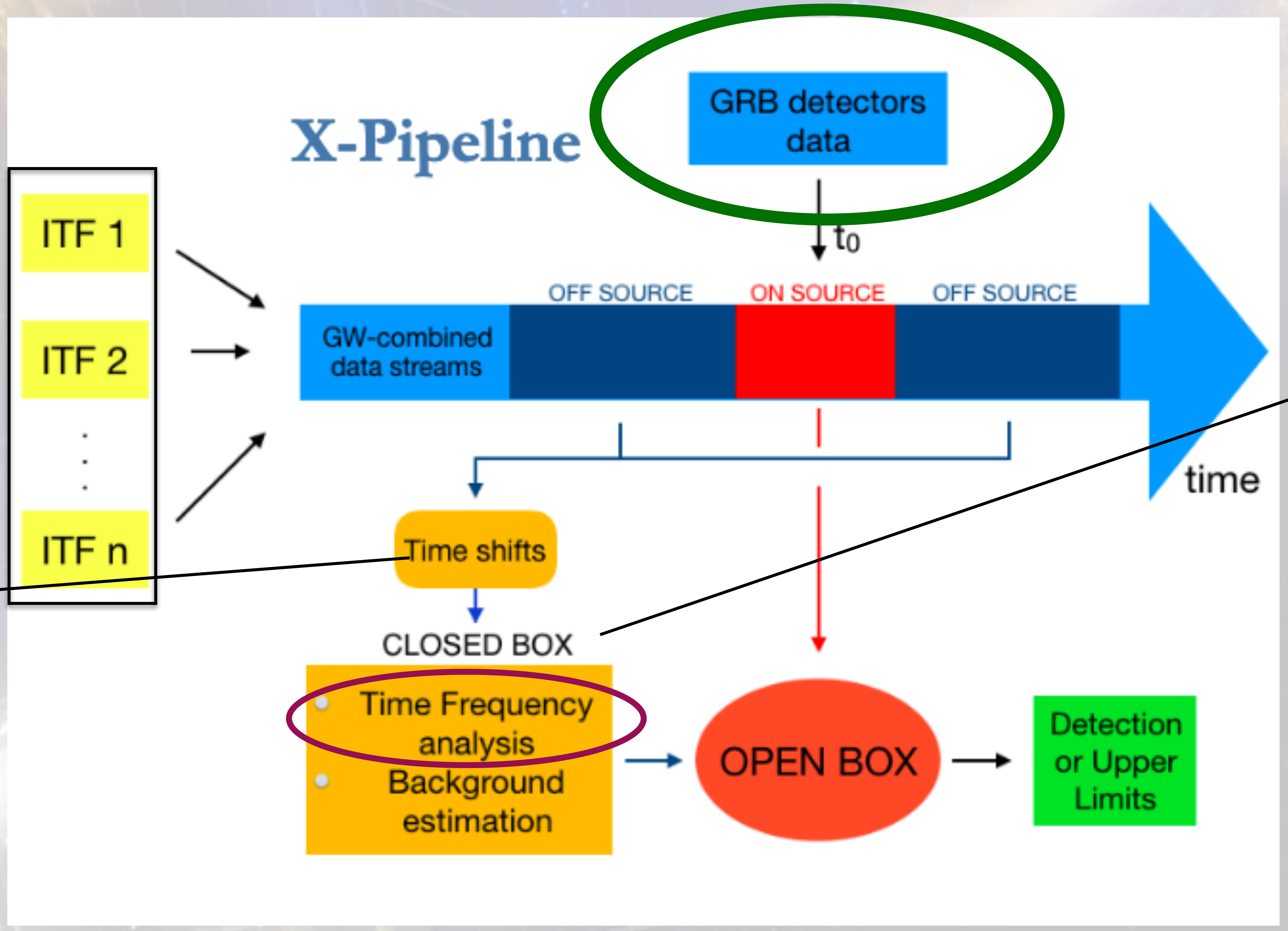
On-source window is chosen to allow all possible delays between the GW event and the astronomical signal

- As we have a population of unidentified glitches, we first analyze the background distribution from times near the trigger, but outside the on-source interval: the off-source window
- To evaluate the significance of results: background estimation are statistically independent
- Off-source of ± 1.5 hours to assure that the background do not contain any GW signal but at the same time it has similar statistical features as the on-source window; detectors should have been operating in similar conditions as during the on-source interval

Triggered GW analysis: X-pipeline

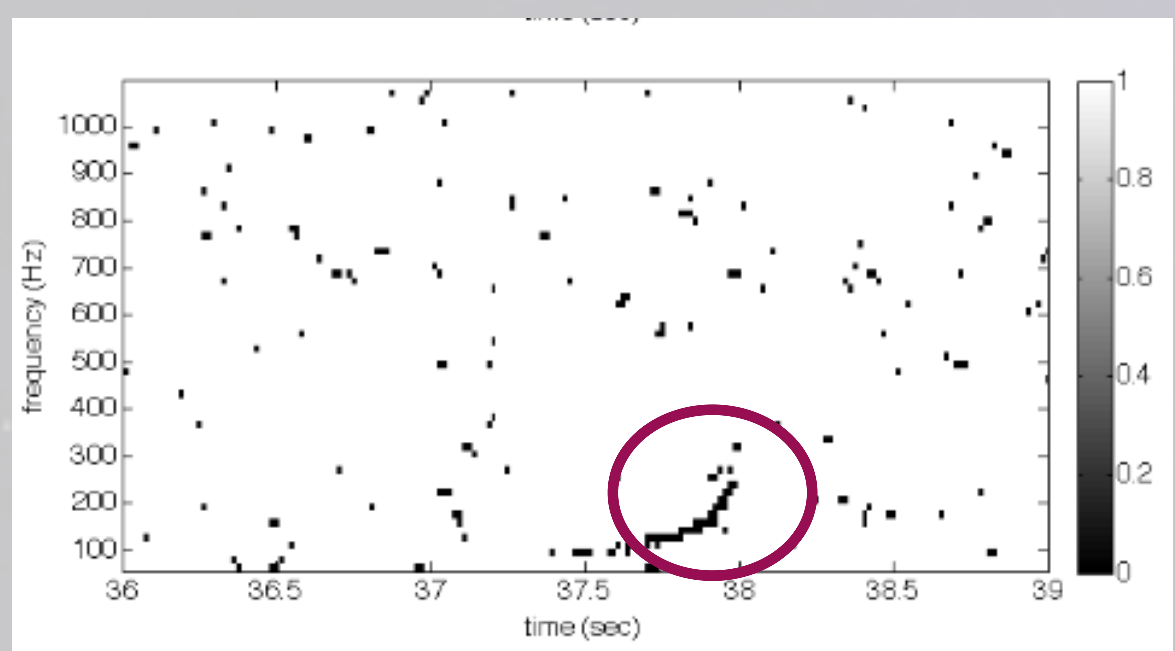
It takes loads the data from different interferometers based on the GPS time of the GRB detected: it needs the information from a network of at least two detectors

The method consists in time shifting the data from the different detectors in the network



Closed box:
1. X-pipeline sum the data shifted of the off-source in the time-frequency domain

Based on the energy criteria, X-pipeline does a pixel clustering: The pixels with the highest value in the current map are marked as black pixels



This process gives a list of candidates events of off-source data

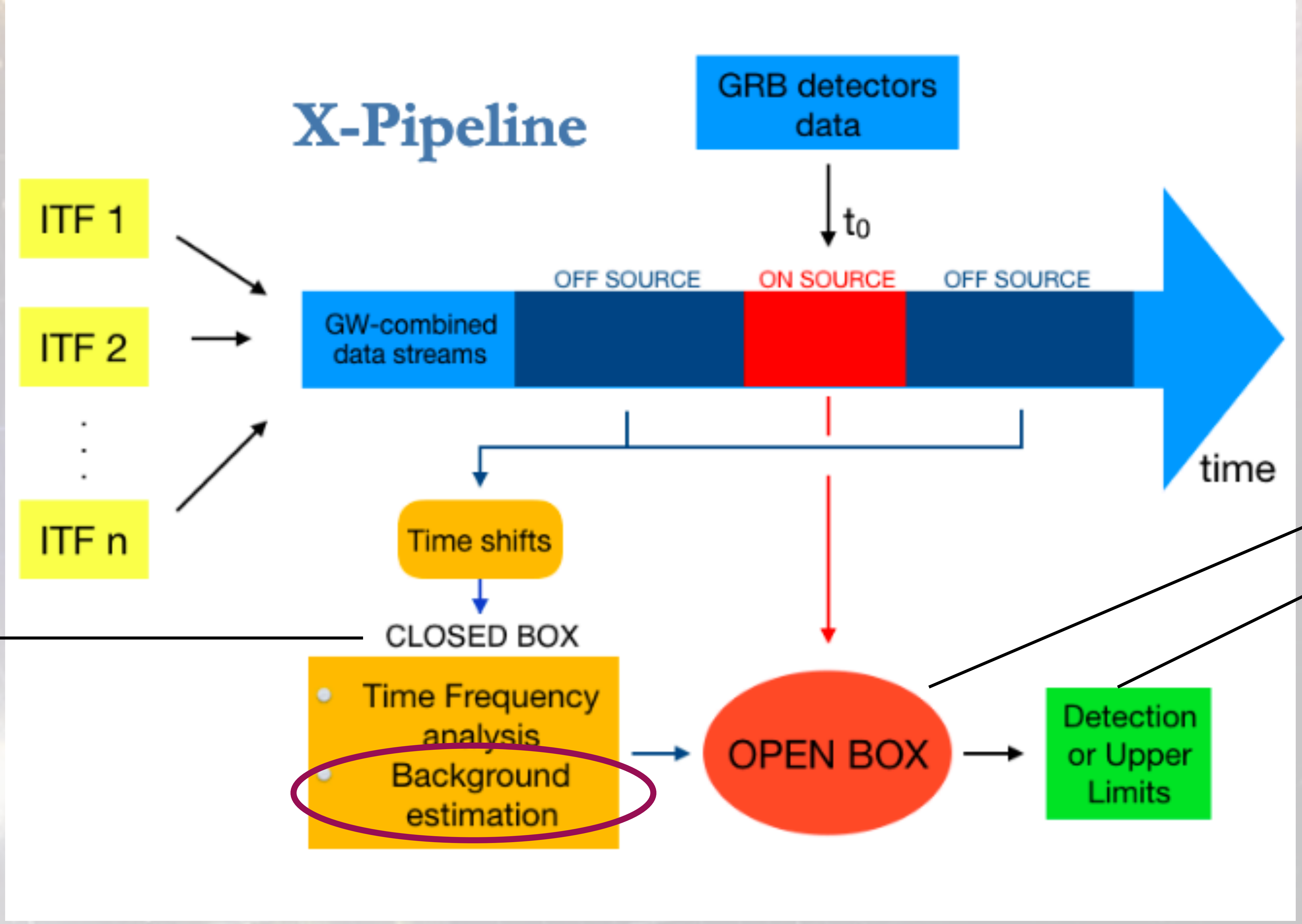
The underlying assumption is that the noise in different detectors is uncorrelated, this is true for most sources of glitches. The only remaining source of correlated “glitches” are GWs and we use time slides in the background estimation method to remove this correlation

Triggered GW analysis: X-pipeline

Closed box

2. For background estimation

- Vetoes are applied in all clusters pre-selected and the loudest surviving trigger is recorded with its significance
- Once the background distribution is obtained, we set a threshold such that the probability for a cluster to be produced by noise in the off-source window is a reasonably small
- The presence of GWs is much less likely in the off-source than in the on-source region
- Meaning that the quality of the data is good and the presence of glitches local glitches have not influenced the efficiency of the search
- The off-source clusters will not contain a gravitational-wave signal associated with the GRB, and so they can be treated as samples of the noise background.



A closed-box analysis estimates the pipeline sensitivity using the off-source and injection data, but not the on-source data

If a candidate in the off-source window has a very low significance

After the on-source data are analyzed

If the loudest surviving cluster have a significant value, it will be we consider a candidate for a GW detection

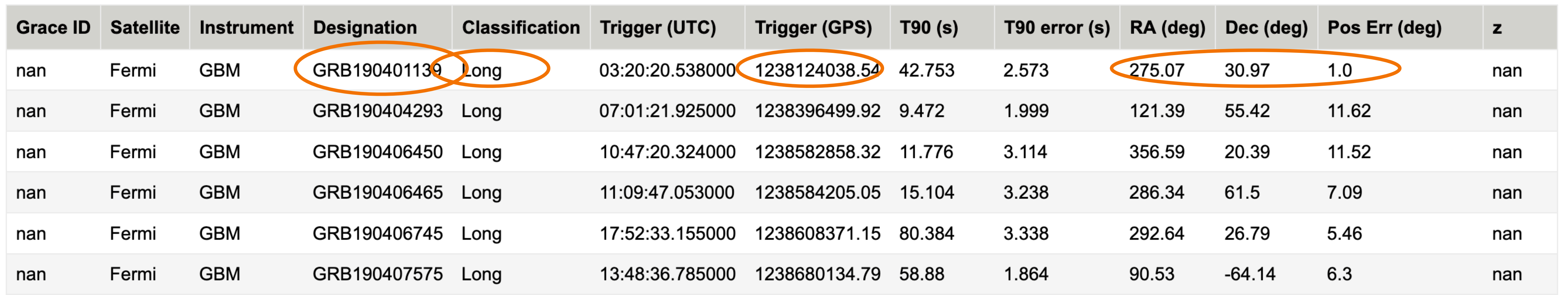
Otherwise we can set an upper limit on the strength of GW emission associated with the astrophysical trigger in question

GRB analysis - O3

Unmodelled search for GW transients associated with gamma-ray bursts detected by the Fermi and Swift satellites during the first part of the third observing run of Advanced LIGO and Advanced Virgo

GRBs

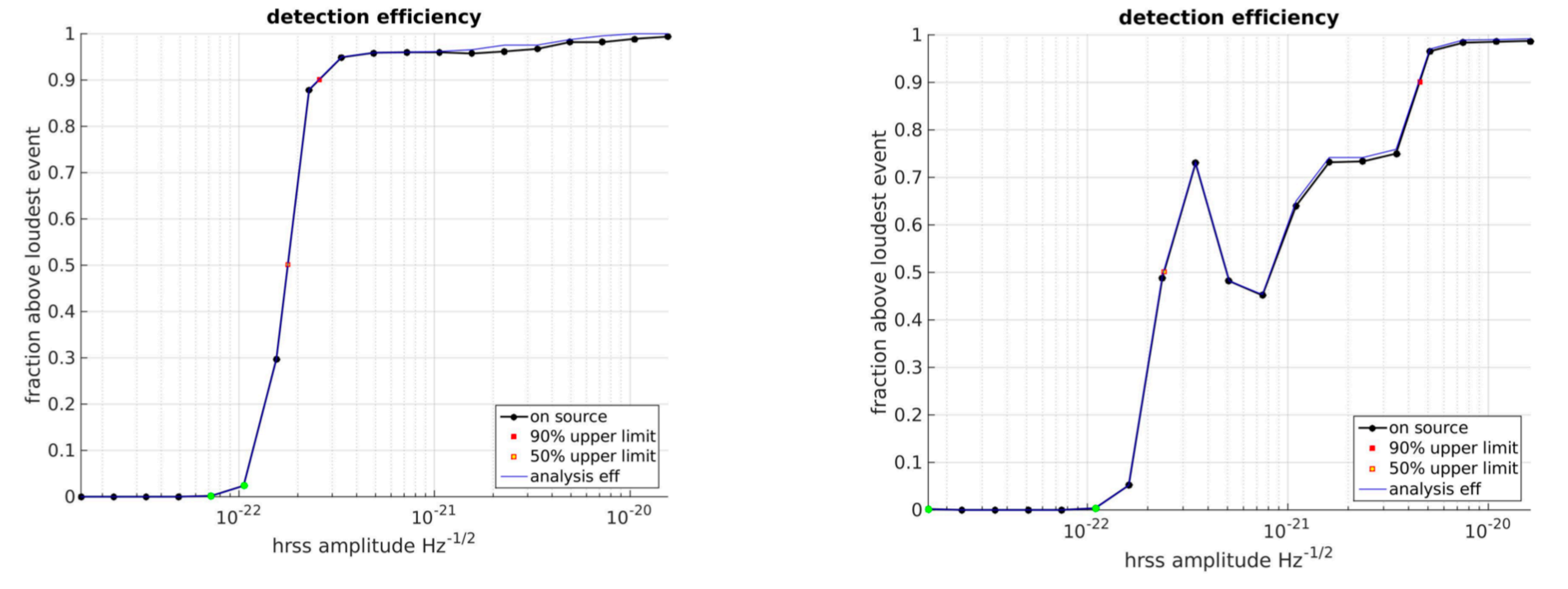
- GRBs are transient flashes of γ-radiation of cosmological origin observed at a rate of about 1 per day (Nakar 2007)
- The interaction of matter with a compact central object, e.g., an accreting BH (Woosley 1993; Popham et al. 1999) or a magnetar (Usov 1992; Zhang & Meszaros 2001), is believed to drive highly-relativistic jets which power the prompt emission of these astrophysical events:
    - Long GRBs have durations greater than 2s and are associated by optical observations to the collapse of massive stars (Staneket al. 2003; Hjorth & Bloom 2012), and GWs are expected to be radiated by the core collapse process (Fryer & New 2011)
    - The unambiguous association of NS binary merger GW170817 (Abbottet al. 2017, 2019) and short GRBs (Savchenko et al. 2017) has confirmed that compact binary mergers of this kind can produce short GRBs



Grace ID	Satellite	Instrument	Designation	Classification	Trigger (UTC)	Trigger (GPS)	T90 (s)	T90 error (s)	RA (deg)	Dec (deg)	Pos Err (deg)	z
nan	Fermi	GBM	GRB190401139	Long	03:20:20.538000	1238124038.54	42.753	2.573	275.07	30.97	1.0	nan
nan	Fermi	GBM	GRB190404293	Long	07:01:21.925000	1238396499.92	9.472	1.999	121.39	55.42	11.62	nan
nan	Fermi	GBM	GRB190406450	Long	10:47:20.324000	1238582858.32	11.776	3.114	356.59	20.39	11.52	nan
nan	Fermi	GBM	GRB190406465	Long	11:09:47.053000	1238584205.05	15.104	3.238	286.34	61.5	7.09	nan
nan	Fermi	GBM	GRB190406745	Long	17:52:33.155000	1238608371.15	80.384	3.338	292.64	26.79	5.46	nan
nan	Fermi	GBM	GRB190407575	Long	13:48:36.785000	1238680134.79	58.88	1.864	90.53	-64.14	6.3	nan

Analysis details

- Analyzed chunk: April 1st - October 1st 2019
- 141 GRBs reported by Fermi and Swift telescopes
    - 105 analyzed
- Data quality
    - Issue: loud glitches
    - Typical example of GRB with DQ issues
    - Gating: files specifying the times to be gated for each detector



ADI-B (9s duration)

ADI-C (236s duration)

GRB analysis - O3

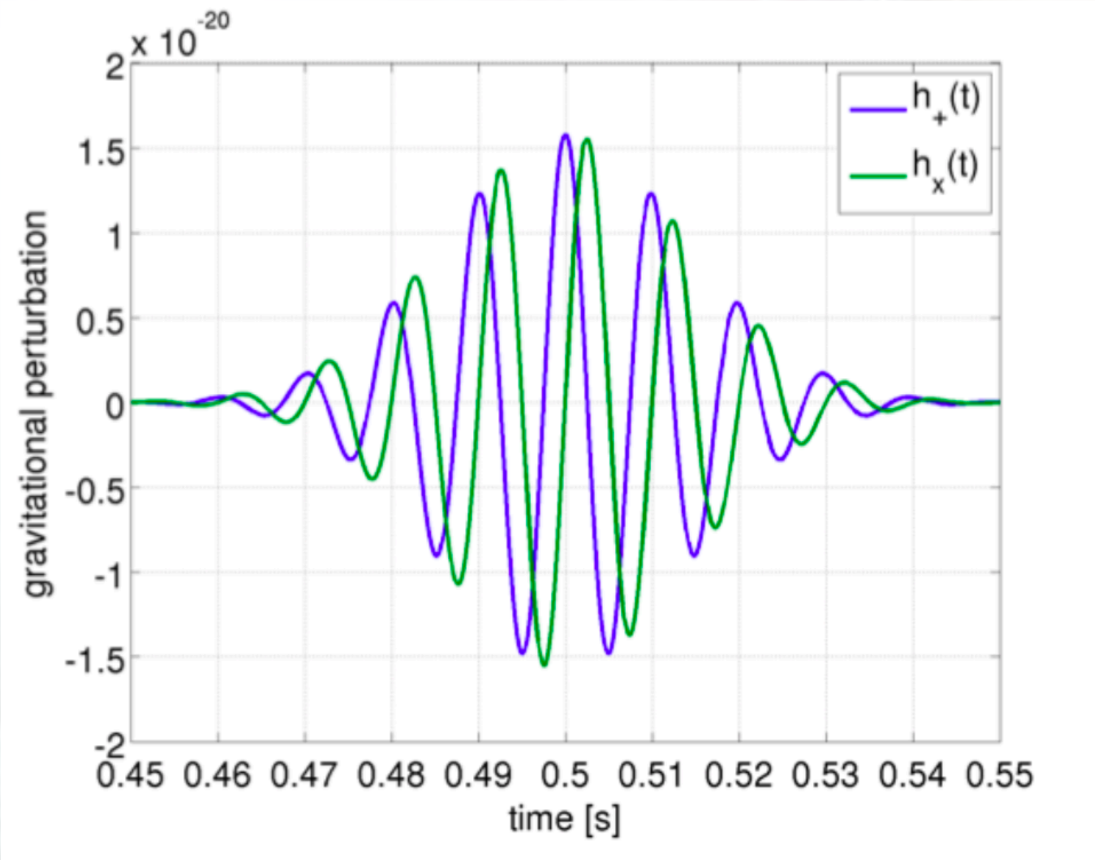
Search parameters

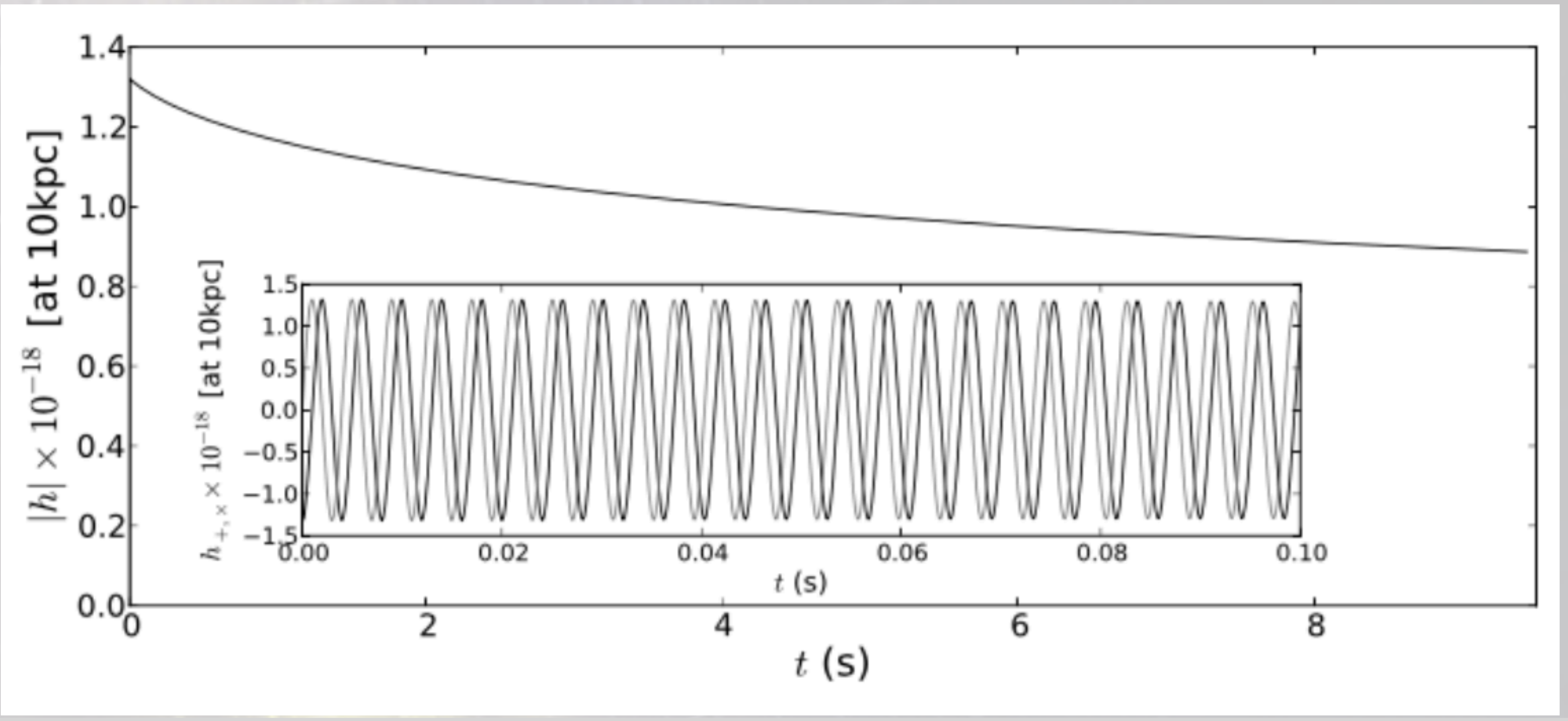
- Frequency band:
  - Restrict the search to the most sensitive frequency band of the GW detectors of 20–500 Hz

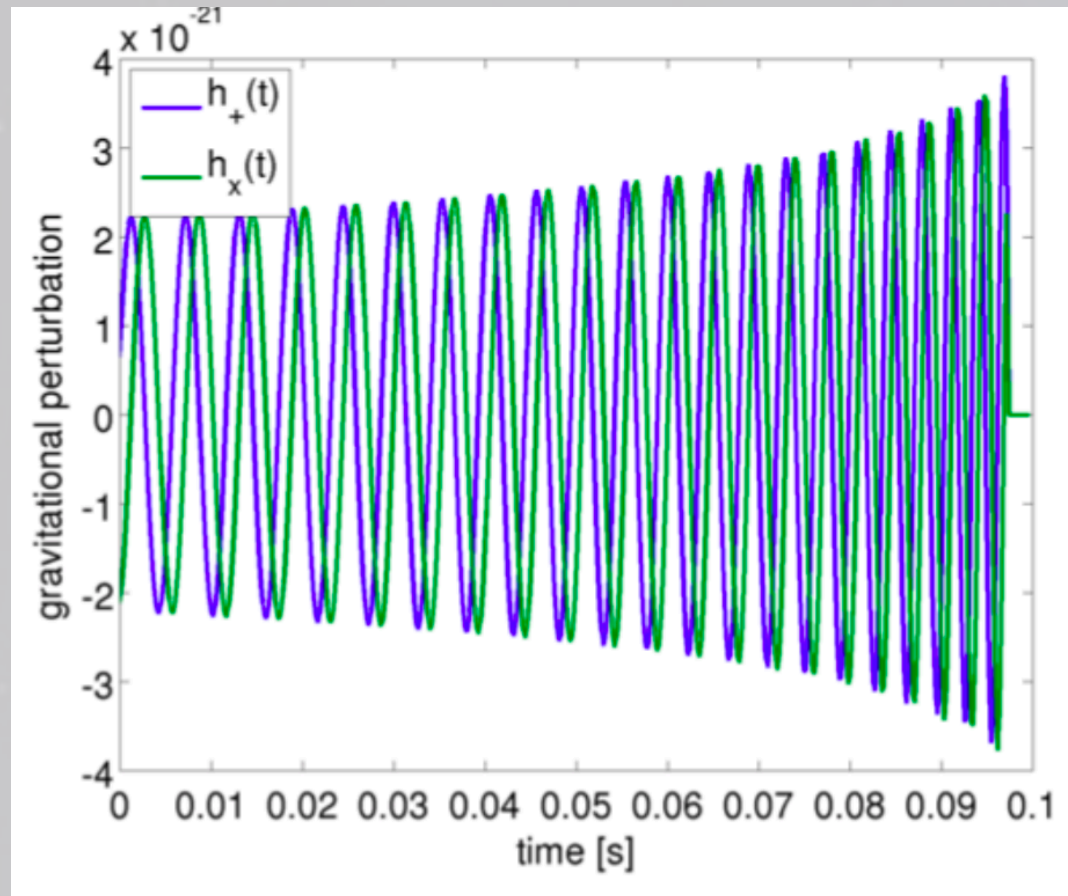
- Time window:
  - [-600; +60]s
  - Allow possible delays between the two messengers coming from the same source

- Waveforms set:
  - Sine-Gaussian chirplets: GW produced in a stellar collapse
  - Accretion disk instabilities: GW emission from a collapsar model for long GRBs - a stellar-mass BH forms, surrounded by a massive accretion disk
  - Inspirals waveforms: Coalescences of BNS or a NSBH. BNS: These waveforms are assumed to be emitted at a distance of 10 Mpc with both NS having masses of 1.4 $M_\odot$. BNS: These waveforms are assumed to be emitted at a distance of 20 Mpc. The BH mass of 10 $M_\odot$ while the NS mass of 1.4 $M_\odot$.

Analytic formula: The waveform is computed on-the-fly using a formula Basic parameters that describe some characteristic of the waveforms are needed







GRB analysis

Results: O3a

P-value

The gravitational wave candidate event is defined as the loudest trigger found in the on-source window which passes all quality and coherent consistency tests. The p-value, that is the probability of the loudest event to be due to background fluctuations only.

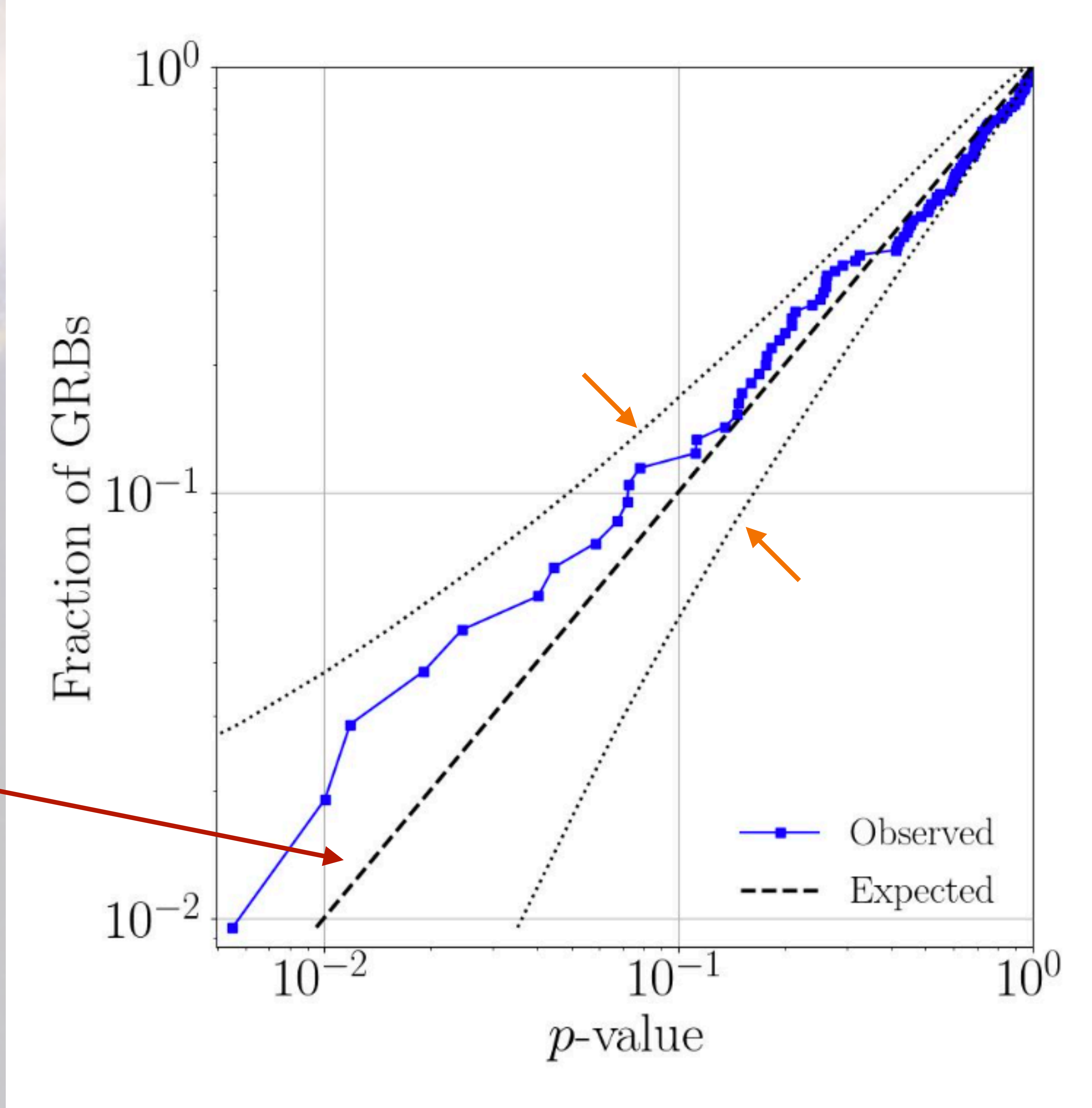
To select significant events that deserve a more detailed followup we set a priori a threshold of p-value at 1%.

If loudest on-source event is greater than the threshold, we consider it as a candidate for a gravitational wave detection. Otherwise we can set an upper limit on the strength of gravitational wave emission associated with the GRB.

The expected background distribution under the no-signal hypothesis is shown by the dashed line, and its 2σ limits are indicated by the two dotted lines.

The cumulative distributions of the GRBs are within the 2σ lines and therefore compatible with the no-signal hypothesis

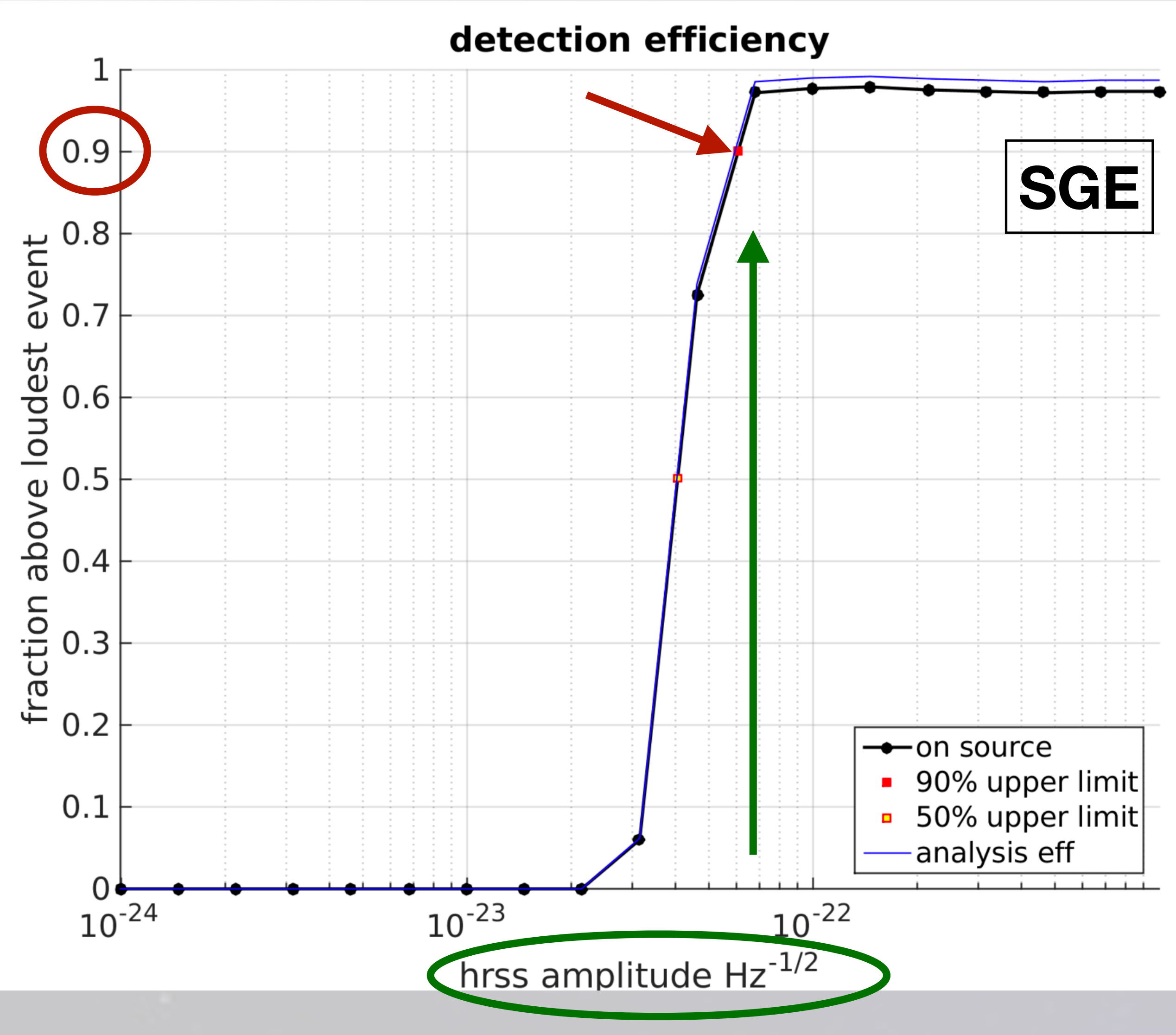
- Loudest surviving on-source event:
  - p-value: 5.5×10^{-3}
  - GRB 190804058
  - Not statistically significant given that we analyzed 105 GRBs; trial factor considered
- Combined p-value: 0.30



GRB analysis

Results: O3a

Exclusion distances

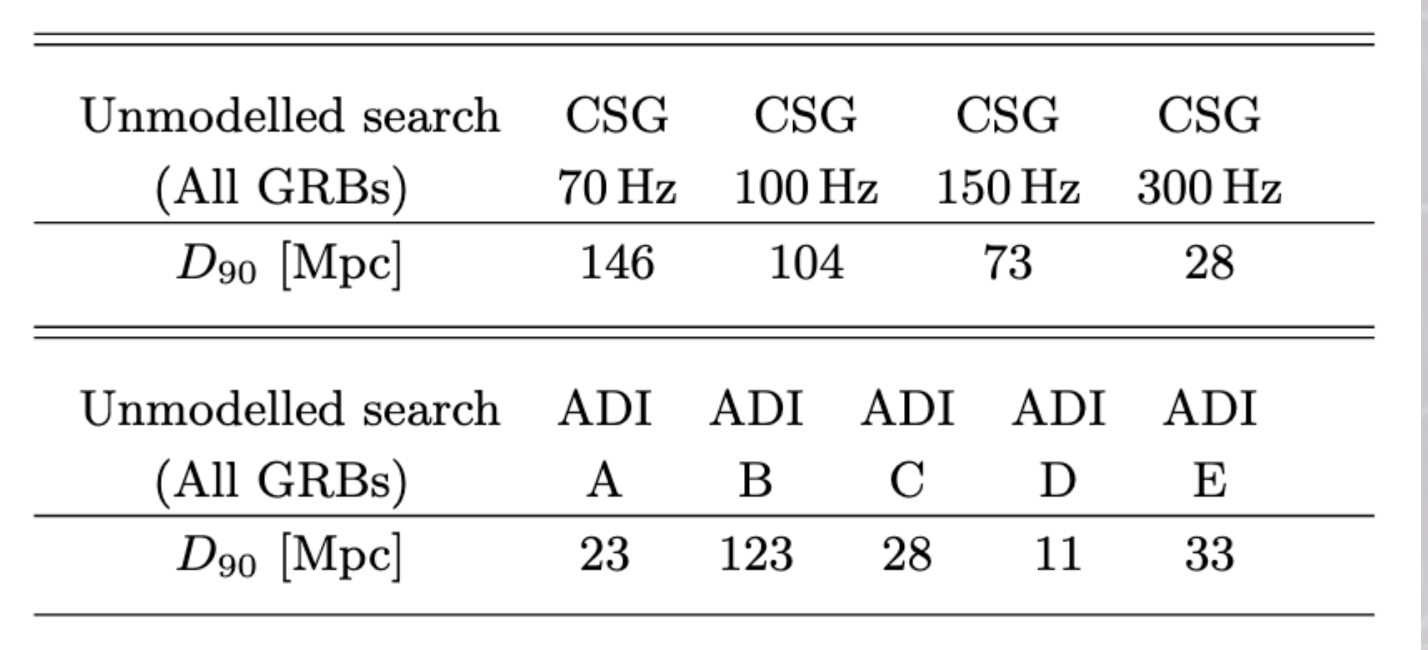


When no statistically significant signal is present in the on-source interval, we set a frequentist upper limit on the strength of gravitational waves associated with the GRB in analysis

For each one of the waveforms, the define an upper limit on the signal amplitude at the 90% confidence level. The minimum amplitude of a gravitational wave strain for which there is a 90% or higher probability that such a signal, if present in the on-source data

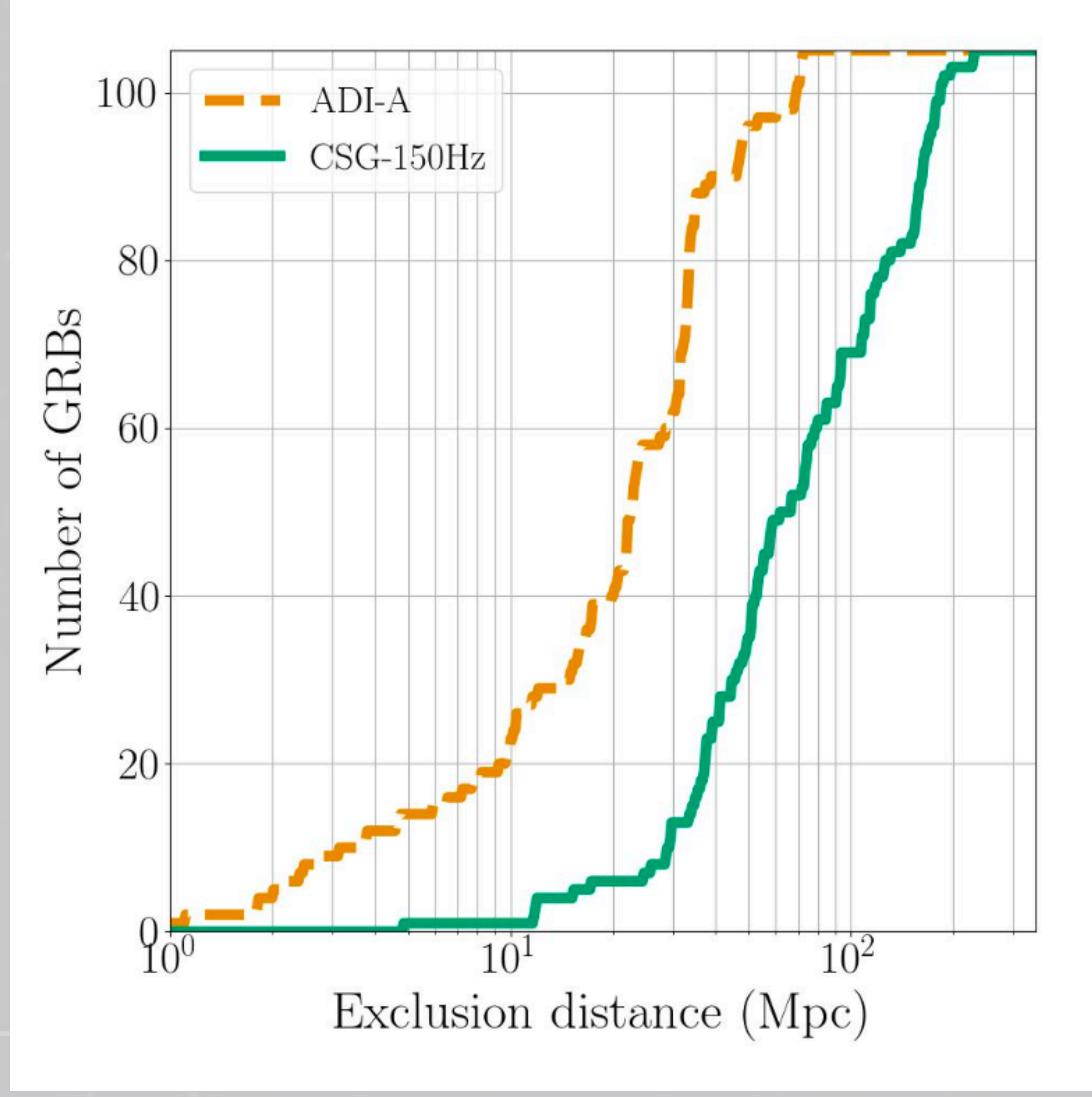
Cumulative 90% exclusion distances for the GRBs: given signal morphology, the GW analysis efficiently recovers signals up to a certain distance that depends on the sensitivity of the detectors at the time and sky position of a given GRB event.

We quote a 90% confidence level lower limit on the distance D90% to each GRB progenitor



Unmodelled search (All GRBs)	CSG 70 Hz	CSG 100 Hz	CSG 150 Hz	CSG 300 Hz
D_{90} [Mpc]	146	104	73	28

Unmodelled search (All GRBs)	ADI A	ADI B	ADI C	ADI D	ADI E
D_{90} [Mpc]	23	123	28	11	33



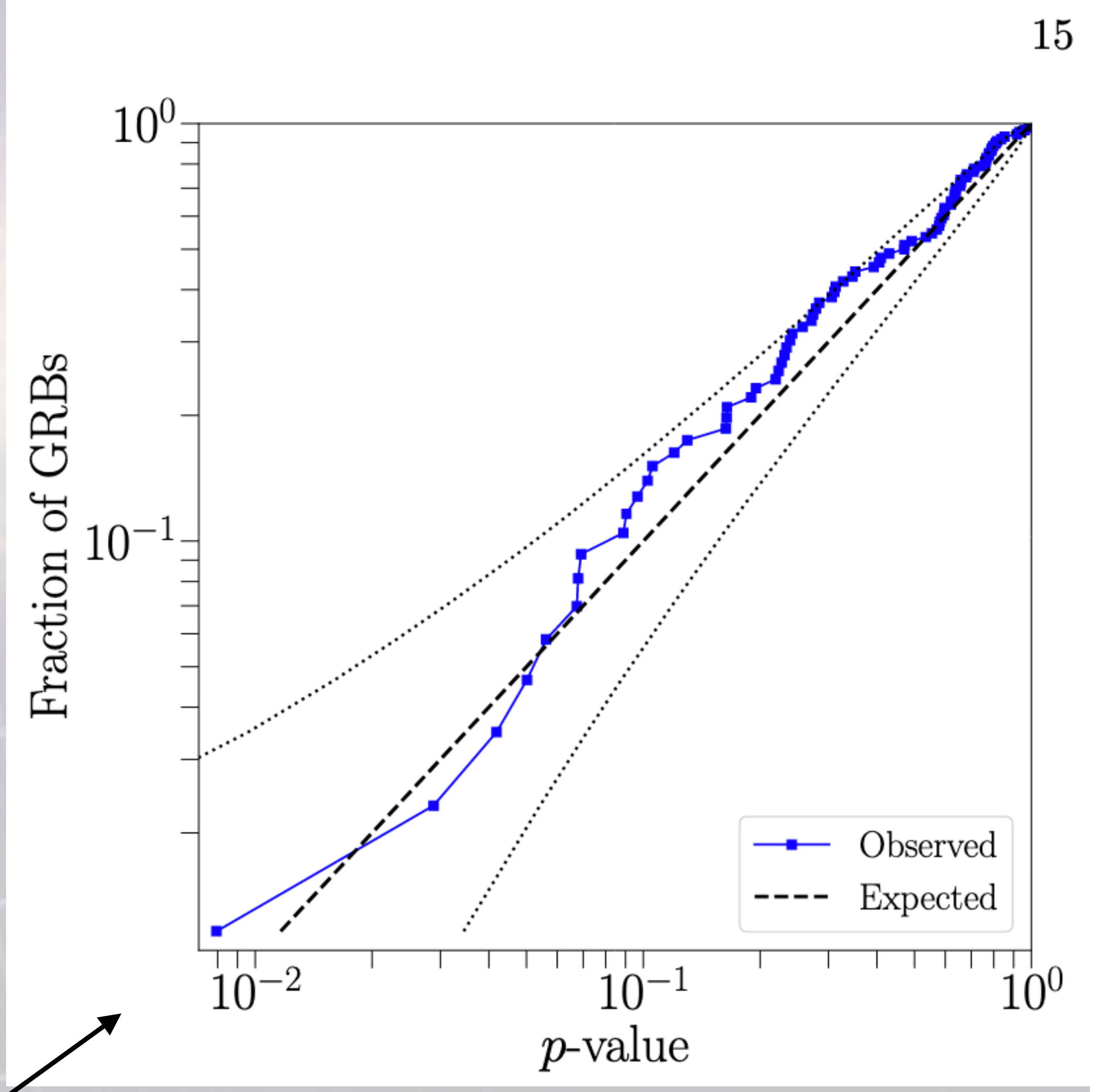
GRB analysis - O3b

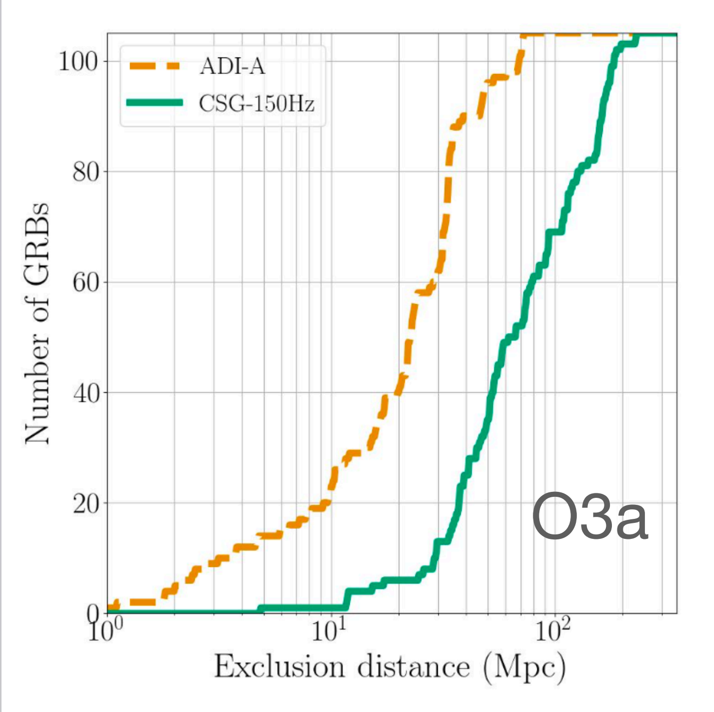
Unmodelled search for GW transients associated with gamma-ray bursts detected by the Fermi and Swift satellites during the second part of the third observing run of Advanced LIGO and Advanced Virgo

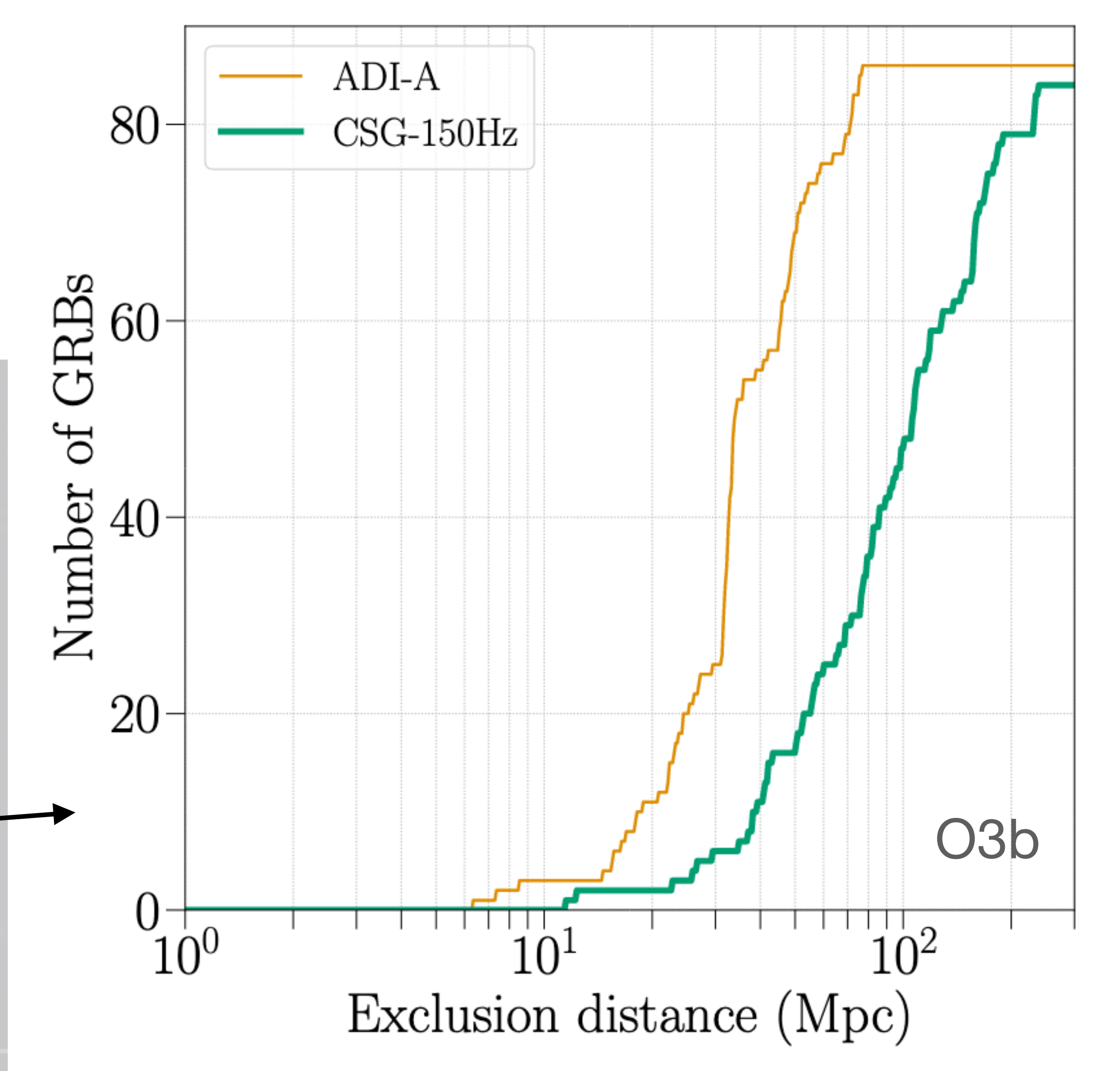
Analysis details (unmodelled)

- Period analyzed: O3b - Nov 1st 2019 until March 27th 2020
- 109 GRBs reported by Fermi and Swift
  - 89 analyzed
- Data quality
  - Implementation of autogating
  - The whitened data from a single detector is gated if the average energy over a one second window exceeds a user-specified threshold (e.g. due to a loud glitch). The gate is cancelled if the average energy in any other detector exceeds another threshold at the same time; this is to minimise the chance of accidentally gating a loud GW signal.
- Search parameters identical to O3a

No significant event: results are consistent with the previously predicted detection rate of 0.07–1.8 per year for O3
Results improved with automating compared; better data implies in a exclusion distance for this set







FRB analysis - O3a

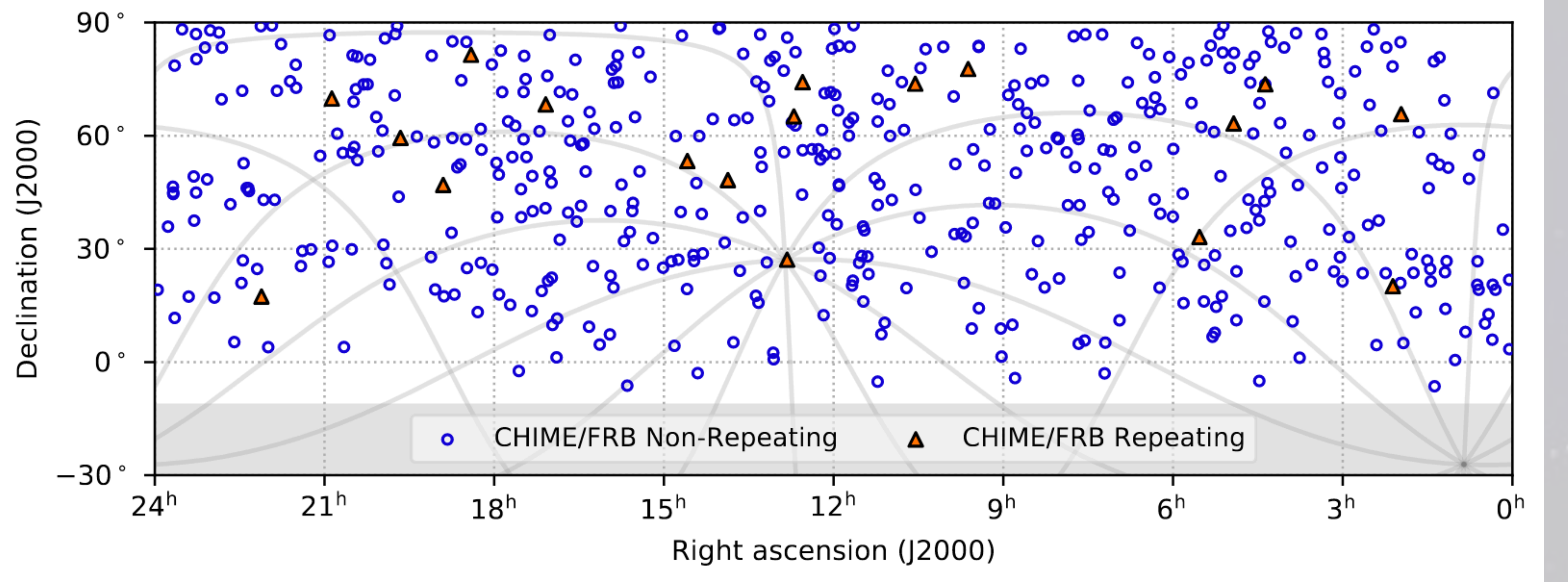
Unmodelled search for GW transients associated with fast radio bursts detected by CHIME during the first part of the third observing run of Advanced LIGO and Advanced Virgo

FRBs

- FRBs are bright, highly dispersed millisecond duration radio transients, and they were discovered over a decade ago (Lorimer et al. 2007)
- Studies connect them to GW sources and as such CBCs, and generic burst sources
  - GW could be related to the activity of magnetars or powerful pulses of energetic radio pulsars, which would have been formed from the merger of NS (Ravi et al. 2019)
  - GW from the merger of BH-NS star systems; during the inspiral of a BH-NS system the magnetic field lines of the NS may thread around the BH event horizon
  - GW BNSs systems, as GW170817; At the time of coalescence, the magnetic fields of NSs are synchronized to binary rotation and a coherent radiation can be generated due to magnetic fields (Totani 2013)
- Two categories: repeaters and non-repeaters

Analysis details

- Analyzed chunk: April 1st - October 1st 2019
- FRBs reported by CHIME
  - 40 FRBs non-repeaters within 500 Mpc
- IFOs sensitivity for O3a (BNS)
  - 45 Mpc for Virgo, 108 Mpc for Hanford and 135 Mpc for Livingston
- Data quality
  - Autogating



Sky distribution of 18 repeating sources and 474 sources that have not been observed to repeat (M. Amiri,et al 2021)

FRB analysis - O3a

Search parameters

- Frequency band:
  - Set an upper limit for the frequency compared to GRB searches
  - The choice of 2kHz is supported by astrophysical studies:

    Given the recent **magnetar association** a good frequency to use is 1500 Hz as magnetar's search found upper limit results up to this frequency (Abbott et al. 2019)

    Predictions from oscillation modes for **neutron starquakes**

    f-modes analyzing GW170817 to happen between 1.67 - 2.18 kHz (Wen et al. 2019);

    g-modes: between 10-100 Hz (Li et al. 2019);

    f-modes: ~1.5 to 2 kHz (Li et al. 2019);

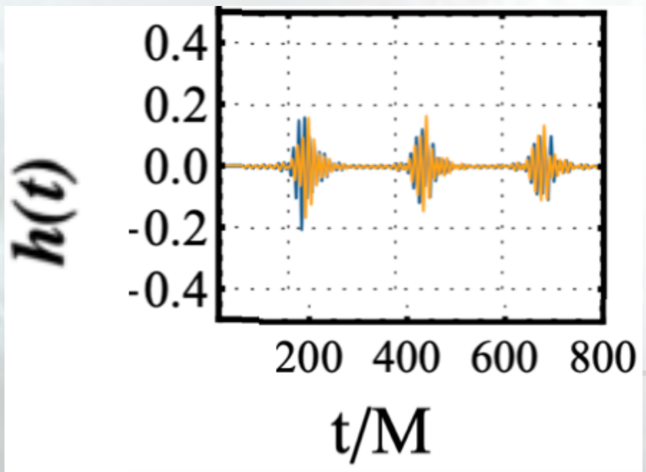
- Time window:
  - [-600; +120]s
  - Allow possible delays between the two messengers coming from the same source

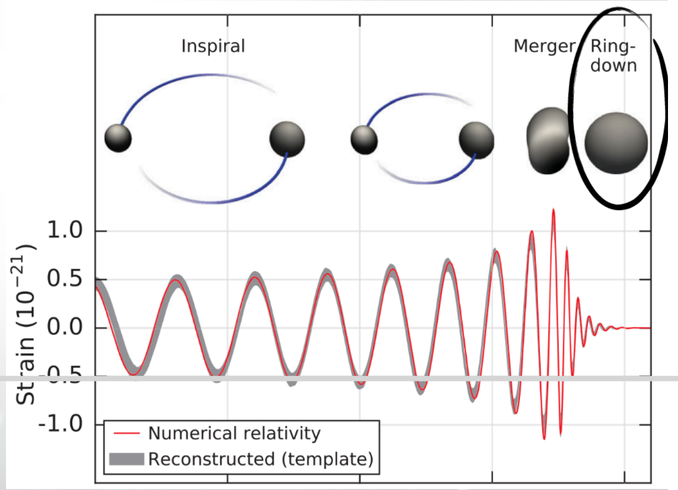
- Waveforms set:
  - Same waveforms of GRB search as we considering GRBs and FRBs having a common source
  - Magnetars waveforms:

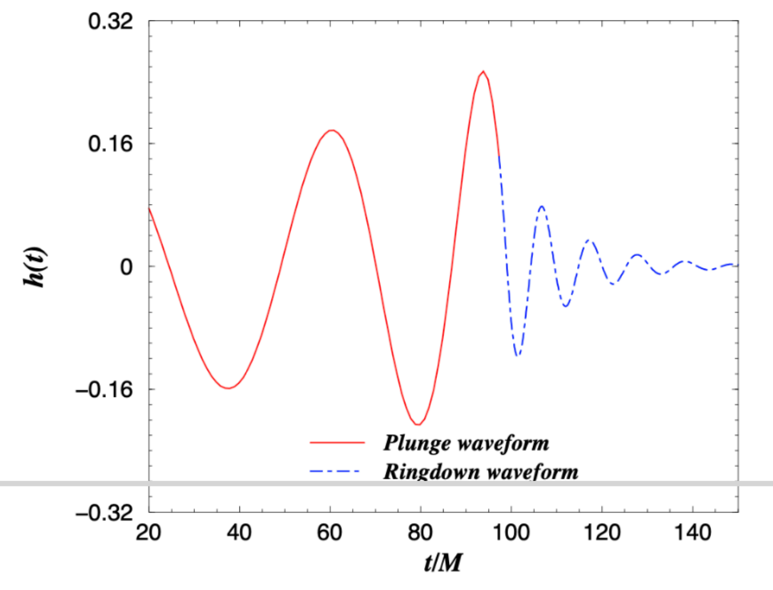
    Sine gaussians with higher central frequencies

    White noise burst and damped sinusoid ringdowns:

    oscillation modes of neutron stars







The main parameters of the waveform injections used for the generic transient search

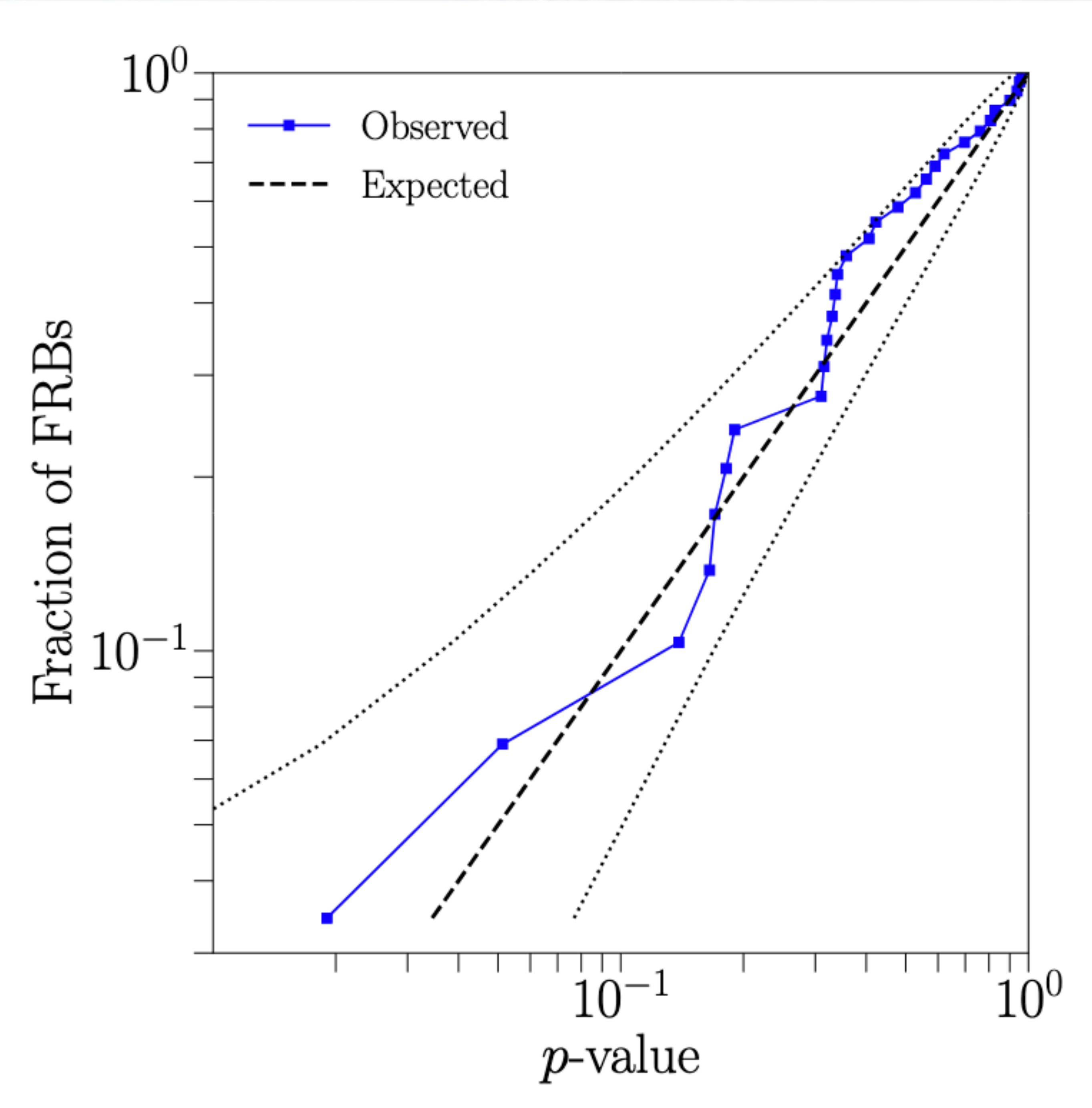
Label	Frequency [Hz]	Duration Parameter [ms]
	Sine–Gaussian Chirplets	
SG-A	70	14
SG-B	90	11
SG-C	145	6.9
SG-D	290	3.4
SG-E	650	1.5
SG-F	1100	0.9
SG-G	1600	0.6
SG-H	1995	0.5
SG-I*	2600	0.38
SG-J*	3100	0.32
SG-K*	3560	0.28
SG-L*^{c}	1600	0.6
SG-M*^{c}	1995	0.5
	Ringdowns	
DS2P-A	1500	100
DS2P-B	1500	200
	White noise bursts	
WNB-A	150 (100–200)	11
WNB-B	150 (100–200)	100
WNB-C	550 (100–1000)	11
WNB-D	550 (100–1000)	100

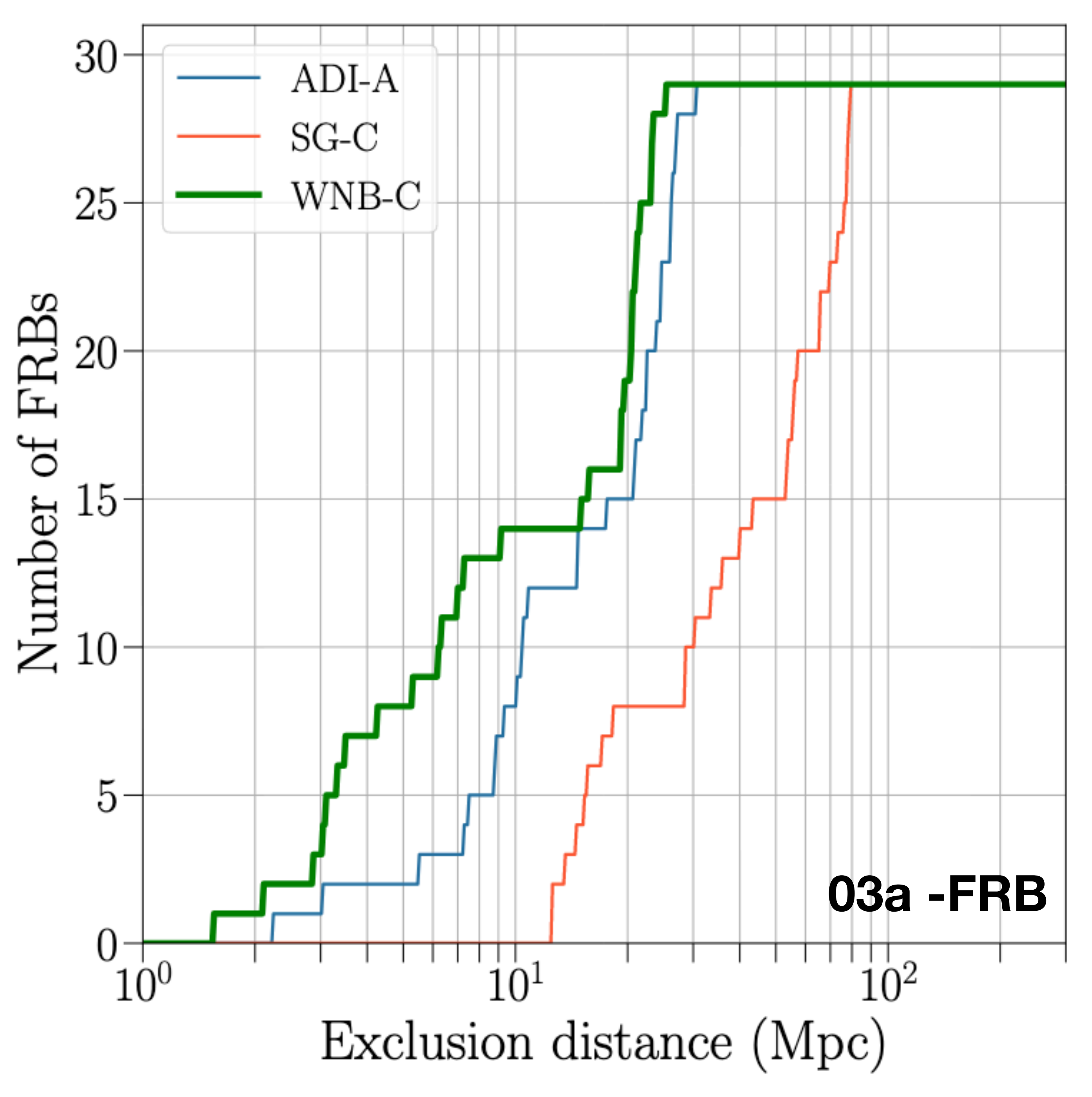
FRB analysis - O3a

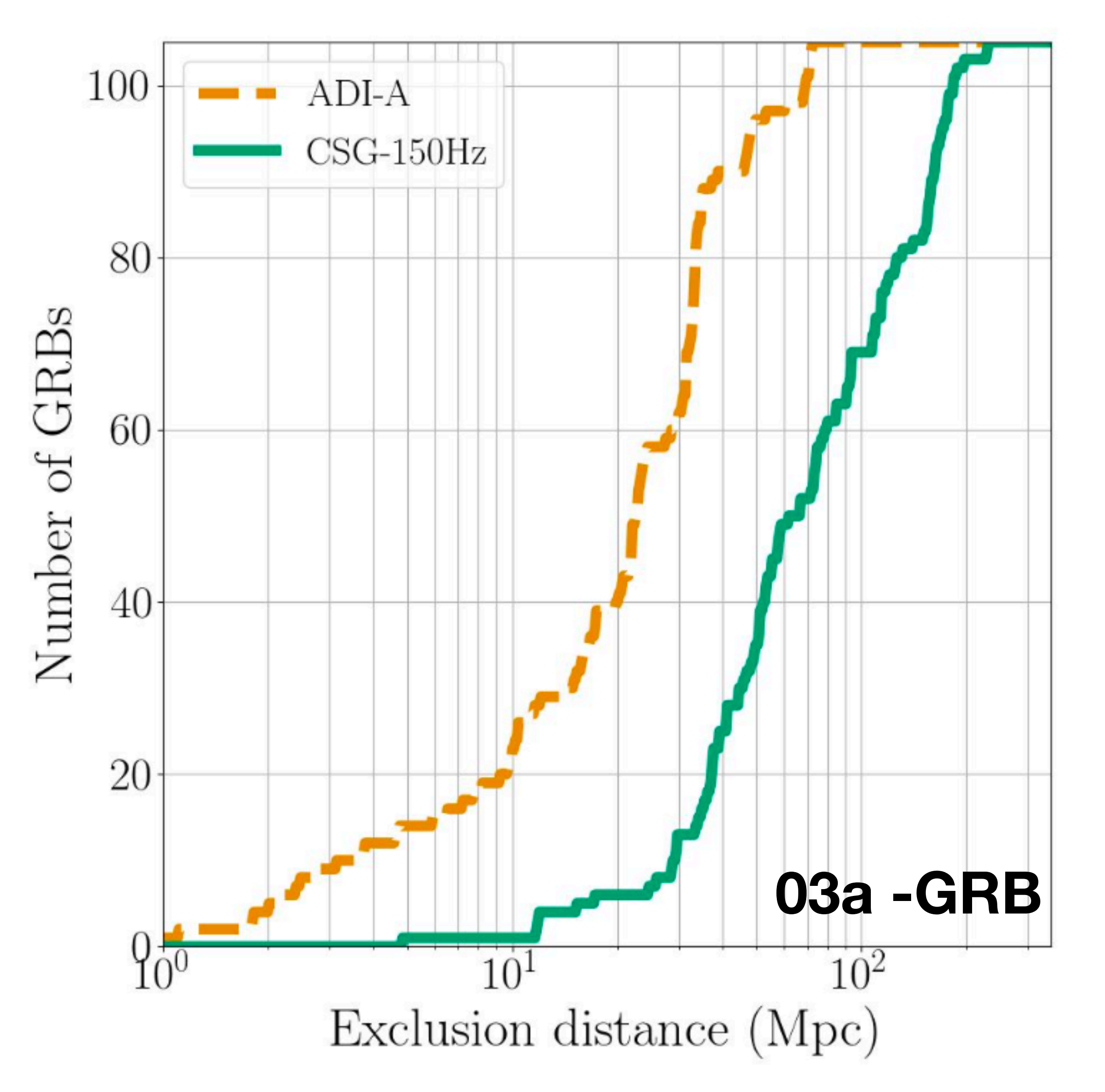
Results:

- The cumulative distributions of the GRBs are within the 2σ lines and therefore compatible with the no-signal hypothesis

- In comparison with D90 values obtained in the O3a GRB paper are almost systematically a factor of 2 smaller for the SG and ADI models used in that study.
- We find that this is a result of the sky locations surveyed by CHIME corresponding with a region of weak sensitivity for the Virgo interferometric detector, due to their relative locations on the surface of the Earth.







- No significant GW candidate was found in association with the analyzed FRBs
- For the FRBs analyzed the limits on the energy to determine the energy emitted through GWs: for the most sensitive trigger an energy of 10^54-10^55 erg was found, value above predictions for GW emissions from f-modes of NSs (about 10^47 erg)

Final Remarks

- **What's next?**
  - Analysis for FRB O3b

- **Conclusions**
  - Applied un-modelled GRB-triggered searches for GWs in LIGO-Virgo run O3
  - No GWs detected in coincidence with GRB triggers in O3a
  - Consistent with predicted 0.07-1.80 detections per year

  - For FRB search, for the first time CHIME data was used to perform such a search
  - Unmodelled search was applied for generic GWs transients on 40 FRBs
  - No significant evidence for a GW association
  - Values of about order 10^51–10^57 erg as total energy for the FRBs corresponding to different emission models with central GW frequencies in the range 70–3560 Hz, above the predictions for GW emissions