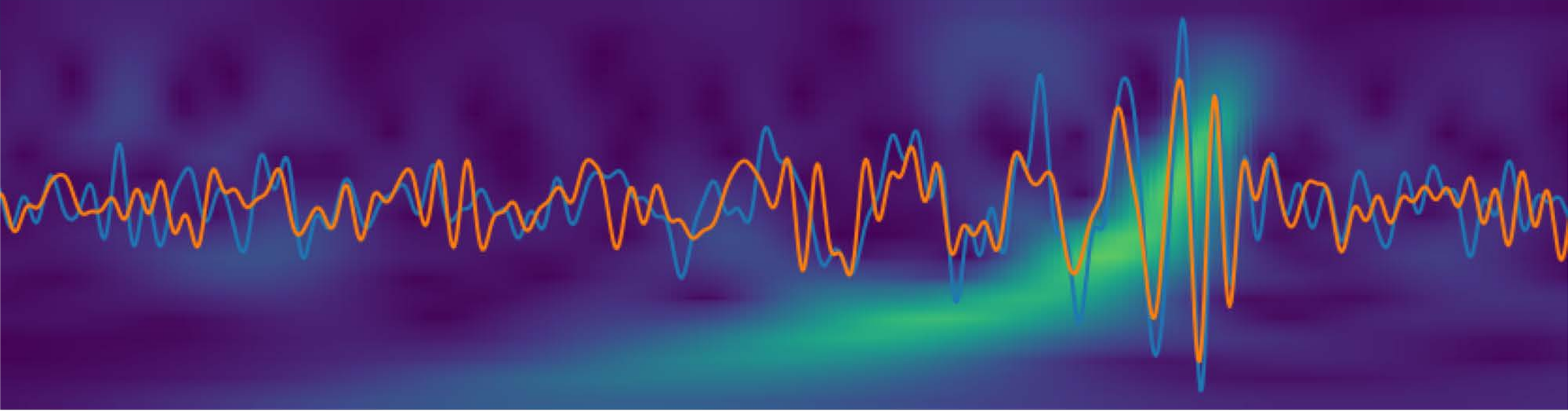


Data analysis tools for the detection of gravitational waves

Gravitational Waves and Data Analysis Group

XII Taller de la División de Gravitación y Física Matemática (DGFM)
3rd School of the Thematic Network of Black Holes and Gravitational Waves (ANyOG)

Playa del Carmen, Mexico
November 2018

Grupo de Gravitación y Análisis de Datos en Ondas Gravitacionales

www.gravitationalwaves.mx

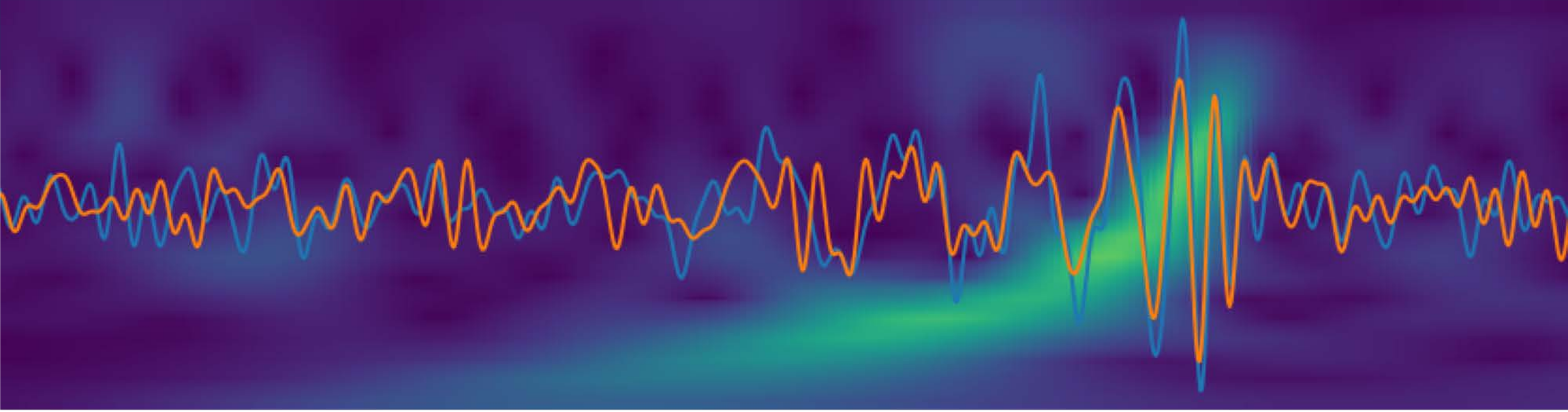
Outline

Session 1:

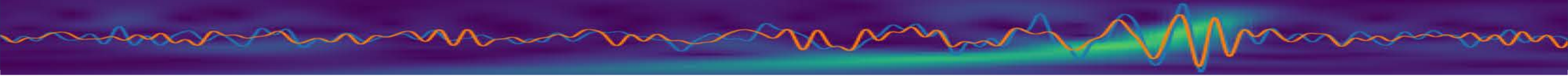
1. Theoretical basics
2. Tutorial: Part 1
3. Hackathon description

Session 2:

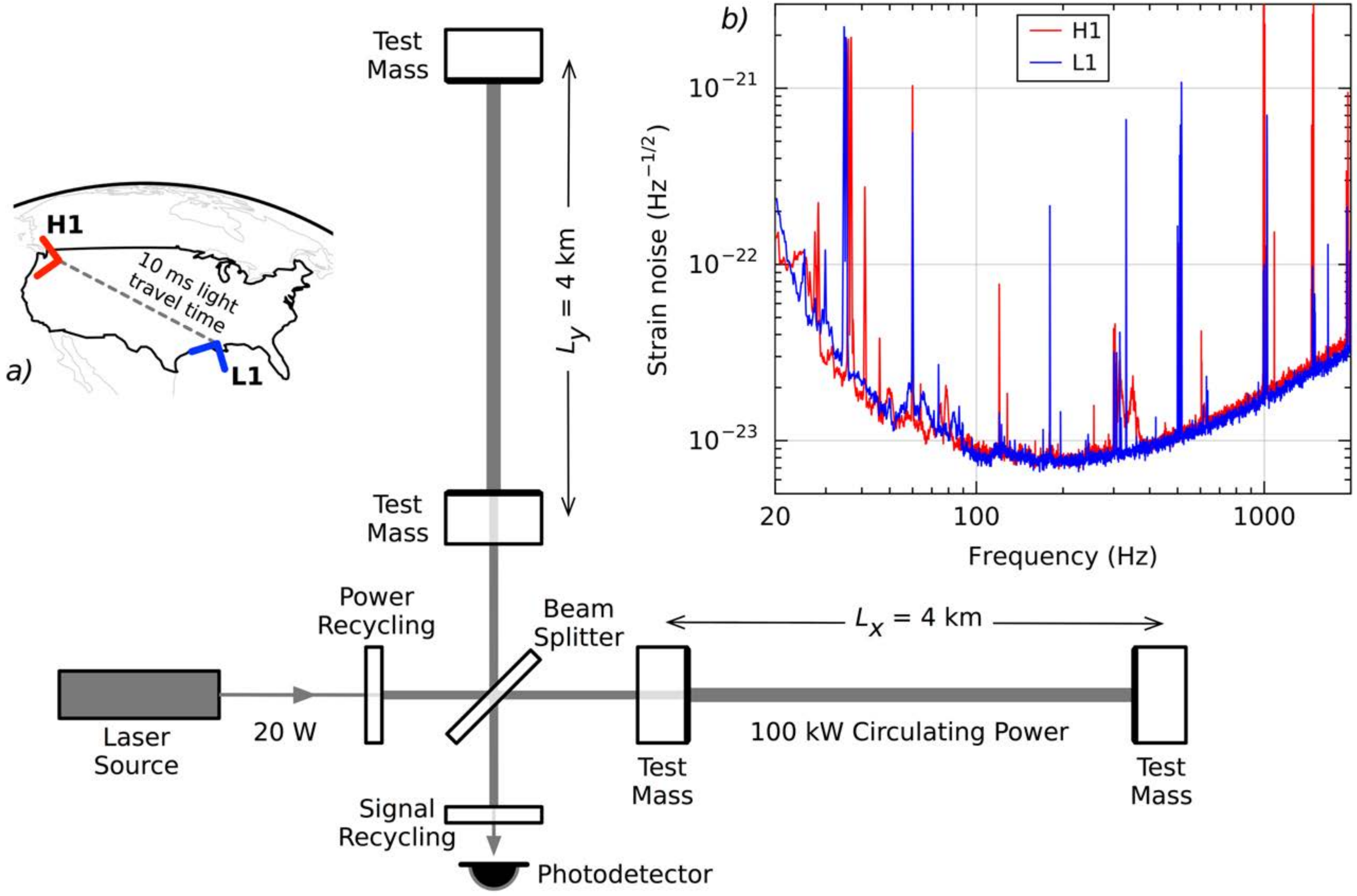
1. Tutorial: Part 2
2. Hackathon winner



Theoretical basics



Advanced LIGO

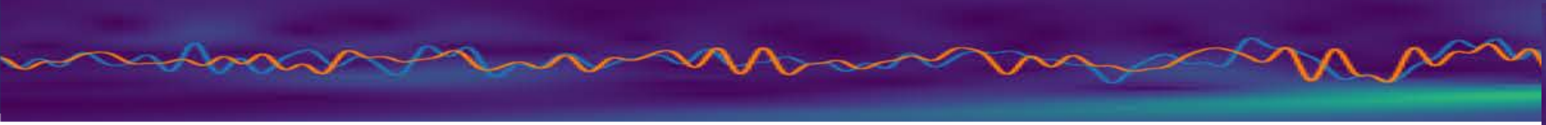


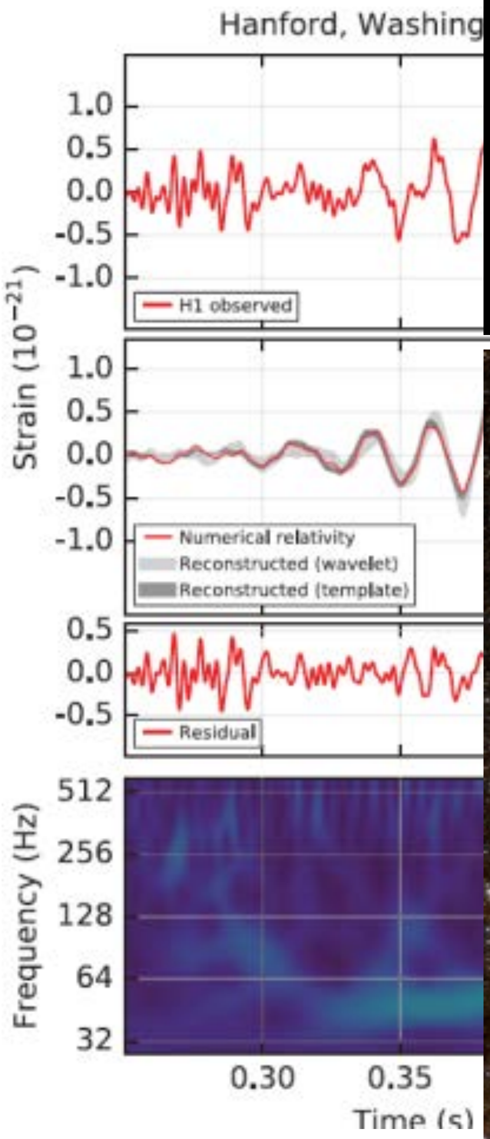
First science observation run: O1

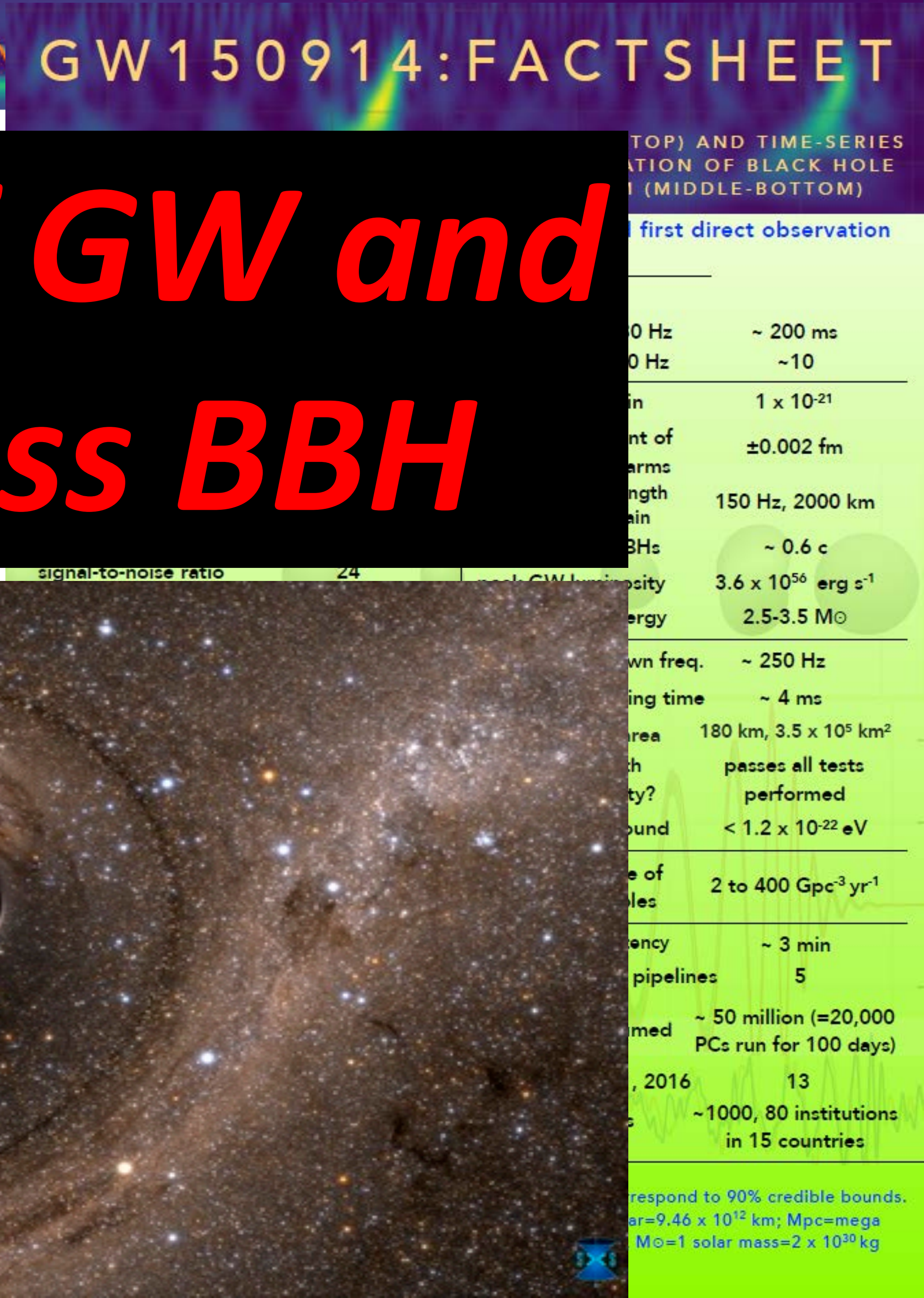
- Carried out from 12 September 2015 0:00 UTC (GPS time 1126051217) until 19 January 2016 16:00 UTC (GPS time 1137254417).
- Two events were confirmed (GW150914 and GW151226)
- Strain data was made public on 22 August 2017: https://www.gw-openscience.org/data/
- Also contains the strain of injected GW from CBC and Burst

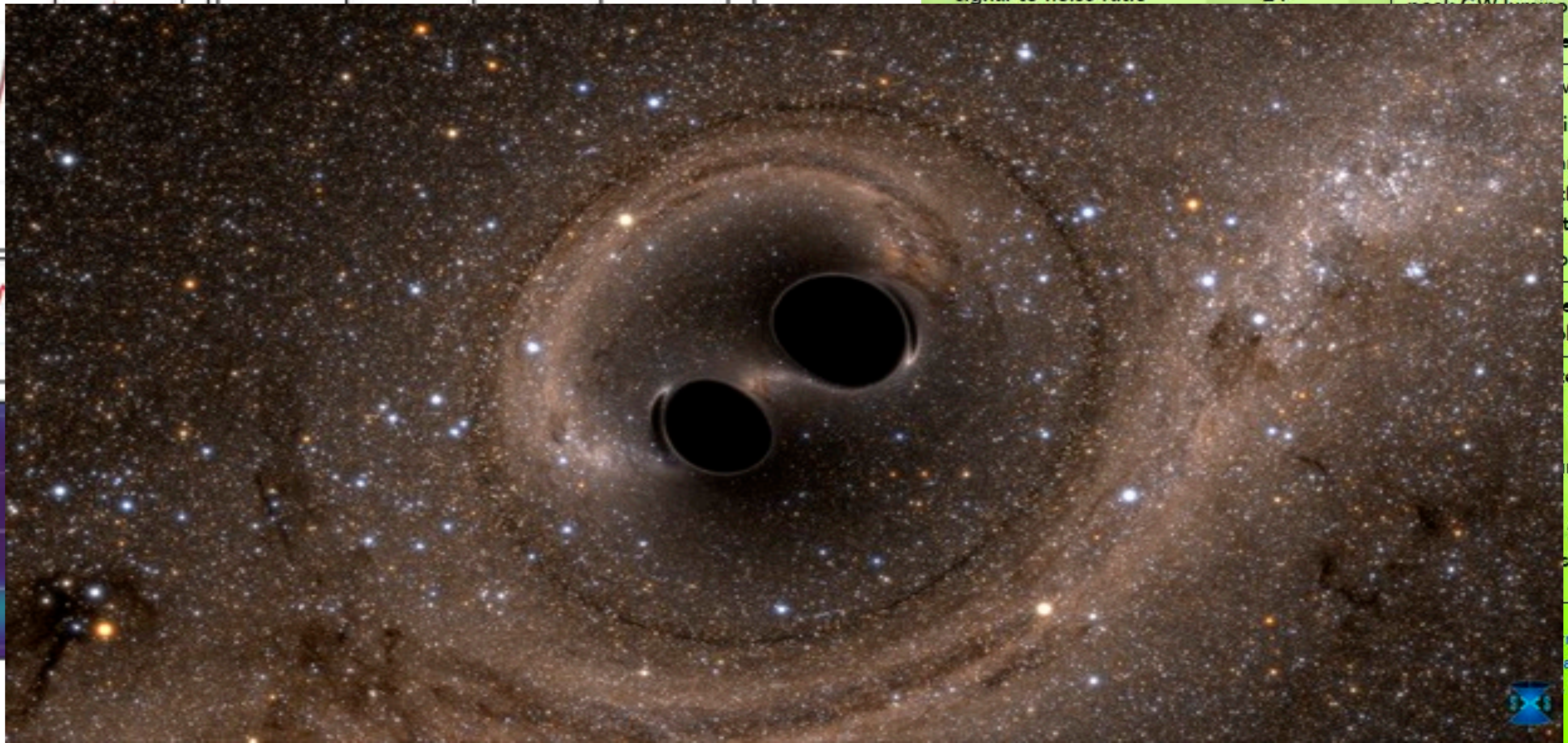
Event 1

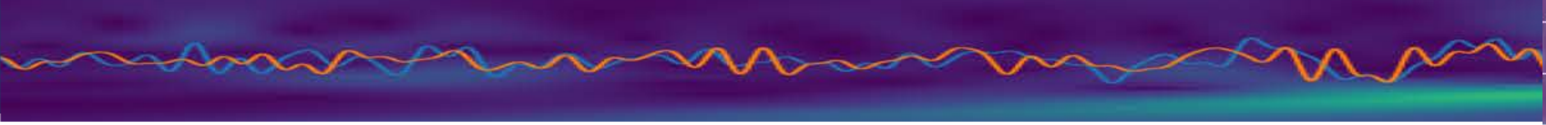
Existence of GW and stellar-mass BBH



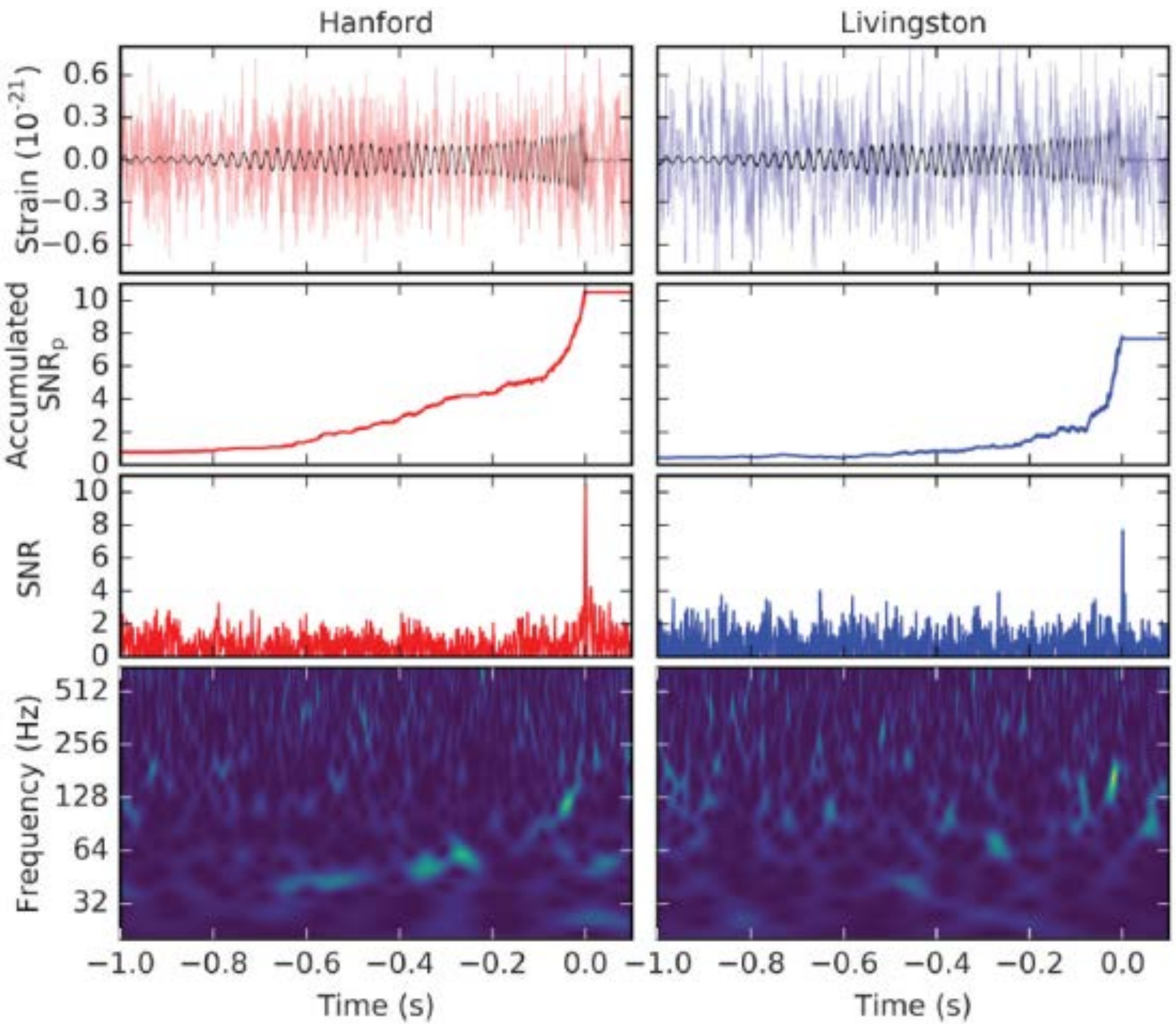








Event 2: GW151226

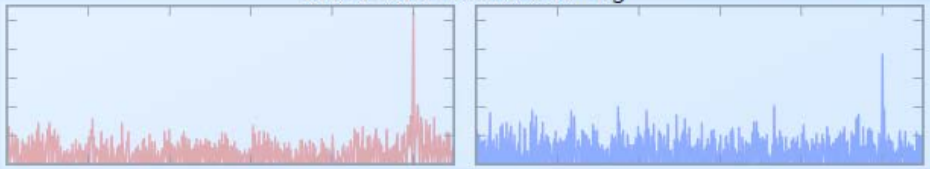


GW151226: FACTSHEET

BACKGROUND IMAGES: TIME-FREQUENCY TRACE (TOP) AND SIGNAL-TO-NOISE RATIO TIME-SERIES (BOTTOM) IN THE TWO LIGO DETECTORS; EXAMPLE WAVEFORM (MIDDLE)

observed by	LIGO L1, H1	duration from 35 Hz	~1 s
source type	black hole (BH) binary	# cycles from 35 Hz	~55
date	26 Dec 2015	signal arrival time delay	arrived in H1 1 ms after L1
time	03:38:53 UTC		
distance	250 to 620 Mpc	peak GW strain	~ 3.4×10^{-22}
redshift	0.05 to 0.13	peak displacement of interferometers arms	~ ±0.7 am
signal-to-noise ratio	13	frequency/wavelength at peak GW strain	420 Hz, 710 km
false alarm prob.	~ 1 in 10 million		
Source Masses	M⊙	peak speed of BHs	~ 0.6 c
total mass	20 to 28	peak GW luminosity	2 to 4 x 10^{56} erg s^{-1}
primary BH	11 to 23	radiated GW energy	0.8-1.1 M⊙
secondary BH	5 to 10	remnant ringdown freq.	~ 750 Hz
remnant BH	19 to 27	remnant damping time	~ 1.3 ms
mass ratio	> 0.28	remnant size, area	60 km, 3.5 x 10^4 km^2
spin of one of the black holes	> 0.2	online trigger latency	~ 67 s
remnant BH spin	0.7 to 0.8		
resolved to	~850 sq. deg.	# offline analysis pipelines	2

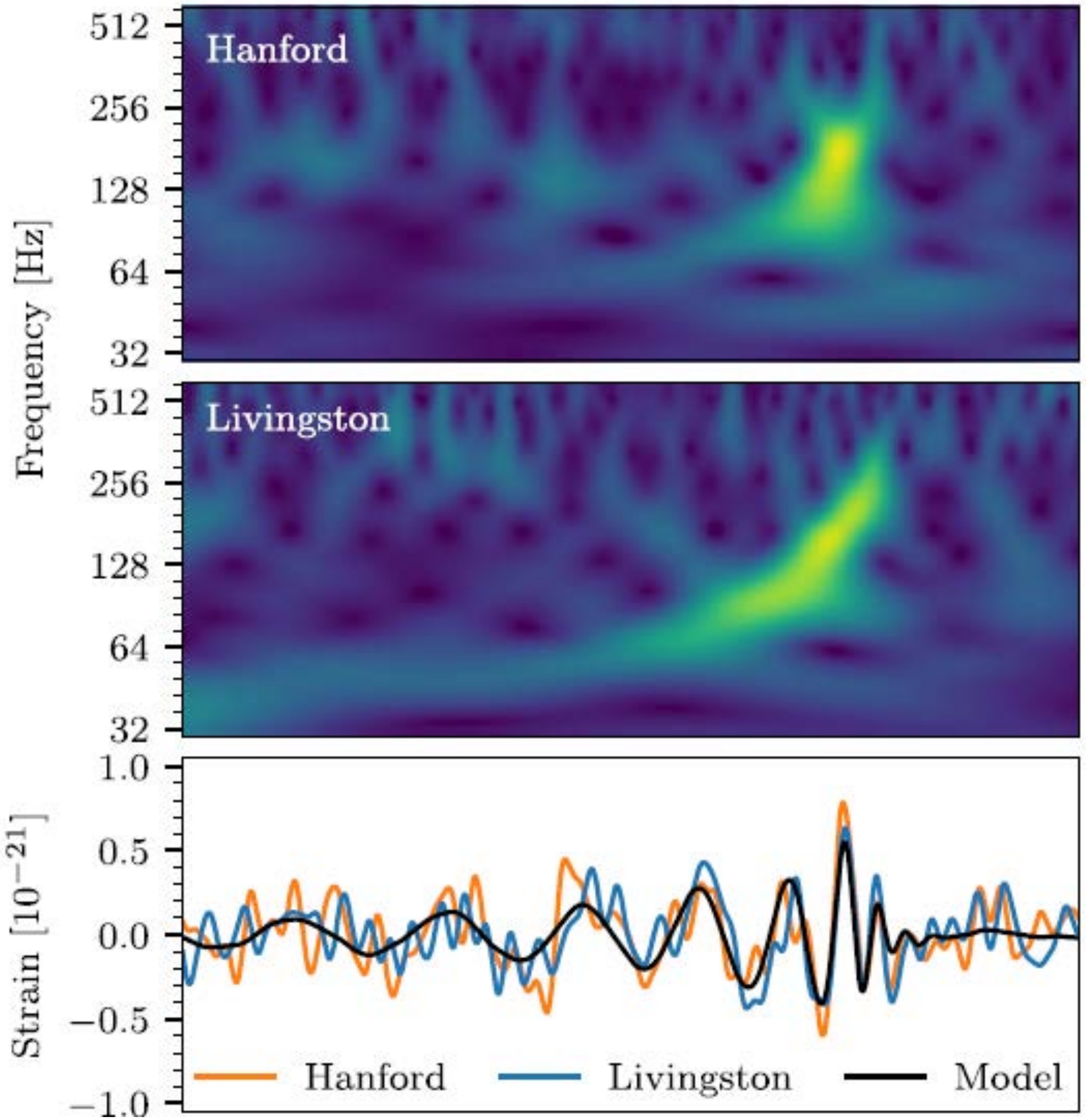
Parameter ranges correspond to 90% credible bounds. Acronyms: L1/H1=LIGO Livingston/Hanford; Mpc=mega parsec=3.2 million lightyear, am=attometer=10^{-18} m, M⊙=1 solar mass=2 x 10^{30} kg



Second science observation run: O2

- Observation began on November 30, 2016 to August 25, 2017
- Virgo also joined
- Four GW from BBH and BNS events were confirmed
- Only data from the events is currently public: https://www.gw-openscience.org/data/

Event 3: GW170104



GW170104:FACTSHEET

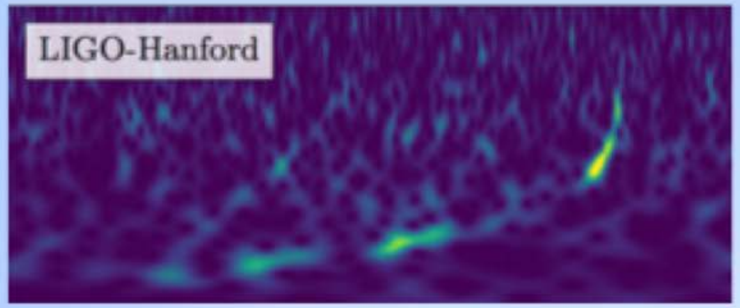
Background Images: time-frequency trace (top), H1 and L1 time series and maximum-likelihood binary black hole model (middle top), residuals between data and best-fit model (middle bottom), reconstructed waveforms from wavelet and binary black hole analyses (bottom)

observed by	LIGO L1, H1
source type	black hole (BH) binary
date	04 Jan 2017
time	10:11:58.6 UTC
signal-to-noise ratio	13
false alarm rate	< 1 in 70,000 years
probability of astrophysical origin	> 0.99997
distance	1.6 to 4.3 billion light-years
redshift	0.10 to 0.25
total mass	46 to 57 $M_\odot$
primary BH mass	25 to 40 $M_\odot$
secondary BH mass	13 to 25 $M_\odot$
mass ratio	0.36 to 0.94
remnant BH mass	44 to 54 $M_\odot$
remnant BH spin	0.39 to 0.7
remnant size (effective radius)	123 to 150 km
remnant area	1.9 to 2.8 x 10^5 km^2
effective spin parameter	-0.42 to 0.09
effective precession spin parameter	unconstrained

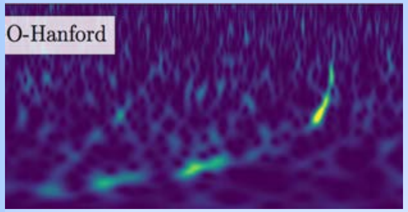
duration from 30 Hz	~ 0.25 to 0.31 s
# of cycles from 30 Hz	~ 14 to 16
signal arrival time delay	arrived at H1 3 ms before L1
credible region sky area	1200 sq. deg.
peak GW strain	~ 5 x 10^{-22}
peak displacement of interferometer arm	~ ± 1 am
frequency at peak GW strain	160 to 199 Hz
wavelength at peak GW strain	1510 to 1880 km
peak GW luminosity	1.8 to 3.8 x 10^{56} erg s^{-1}
radiated GW energy	1.3 to 2.6 $M_\odot$
remnant ringdown freq.	297 to 373 Hz
remnant damping time	2.5 to 3.2 ms
consistent with general relativity?	passes all tests performed
graviton mass combined bound	≤ 7.7 x 10^{-23} eV/c^2
evidence for dispersion of GWs	none

Parameter ranges correspond to 90% credible intervals.
Acronyms:
L1/H1=LIGO Livingston/Hanford, am=attometer=10^{-18} m, $M_\odot$=1 solar mass=2 x 10^{30} kg

GW170608 FACTSHEET



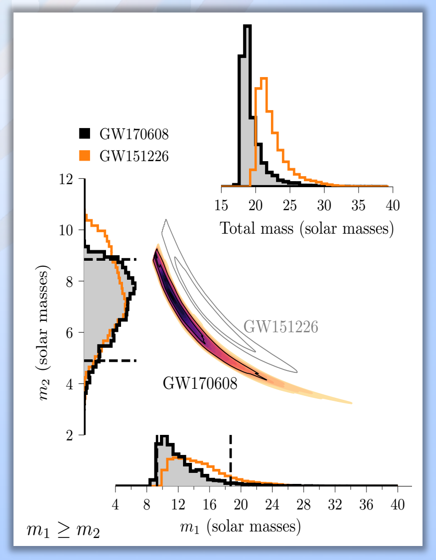
GW170608 FACTSHEET

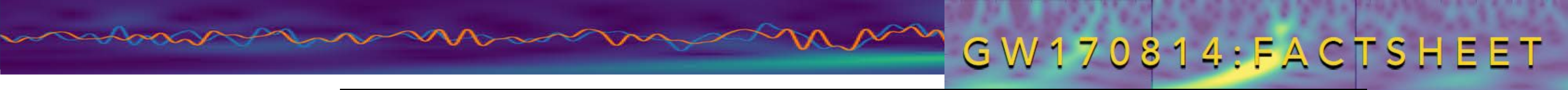


ved by	H, L
e type	black hole (BH) binary
	08 June 2017
f merger	02:01:16 UTC
-to-noise ratio	13
alarm rate	< 1 in 3 000 years
ce	0.7 to 1.5 billion light-years
ift	0.04 to 0.1
nass	18 to 24 $M_\odot$
ry BH mass	9 to 19 $M_\odot$
dary BH mass	5 to 9 $M_\odot$
ratio	0.3 to 1.0
ant BH mass	17 to 23 $M_\odot$
ant BH spin	0.64 to 0.72
ant size tive radius)	47 to 63 km
ant area	2.7 to 5.0 × 10^4 km^2
ve spin neter	-0.01 to 0.30
ve precession arameter	unconstrained
GW luminosity	1.8 to 3.9 × 10^{56} erg s^{-1}
ed GW energy	0.68 to 0.91 $M_\odot c^2$

Images: time-frequency traces (top), mass distributions (bottom right)
ravitational wave, $M_\odot$=1 solar mass=2x10^{30} kg,
ometer (10^{-18} m), H/L=LIGO Hanford/Livingston
arameter ranges are 90% credible intervals.
†90% credible region

duration from 30 Hz	~ 2 s
# of GW cycles from 30 Hz	~ 100
signal arrival time delay	arrived at H ~ 7 ms before L
HL sky area†	~ 520 deg^2
peak GW strain (10^{-22})	~ 4 (H), 3 (L)
peak stretch of interferometer arm	~ ± 0.8 am (H), 0.6 am (L)
frequency at peak GW strain	453 to 610 Hz
wavelength at peak GW strain	492 to 662 km
remnant ringdown frequency	745 to 1013 Hz
remnant damping time	1.0 to 1.4 ms
consistent with general relativity?	passes all tests performed

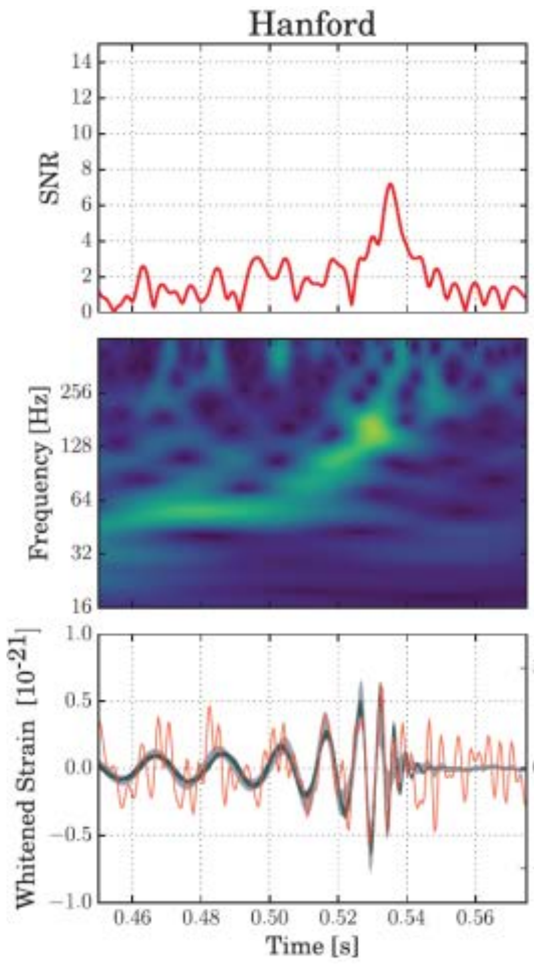


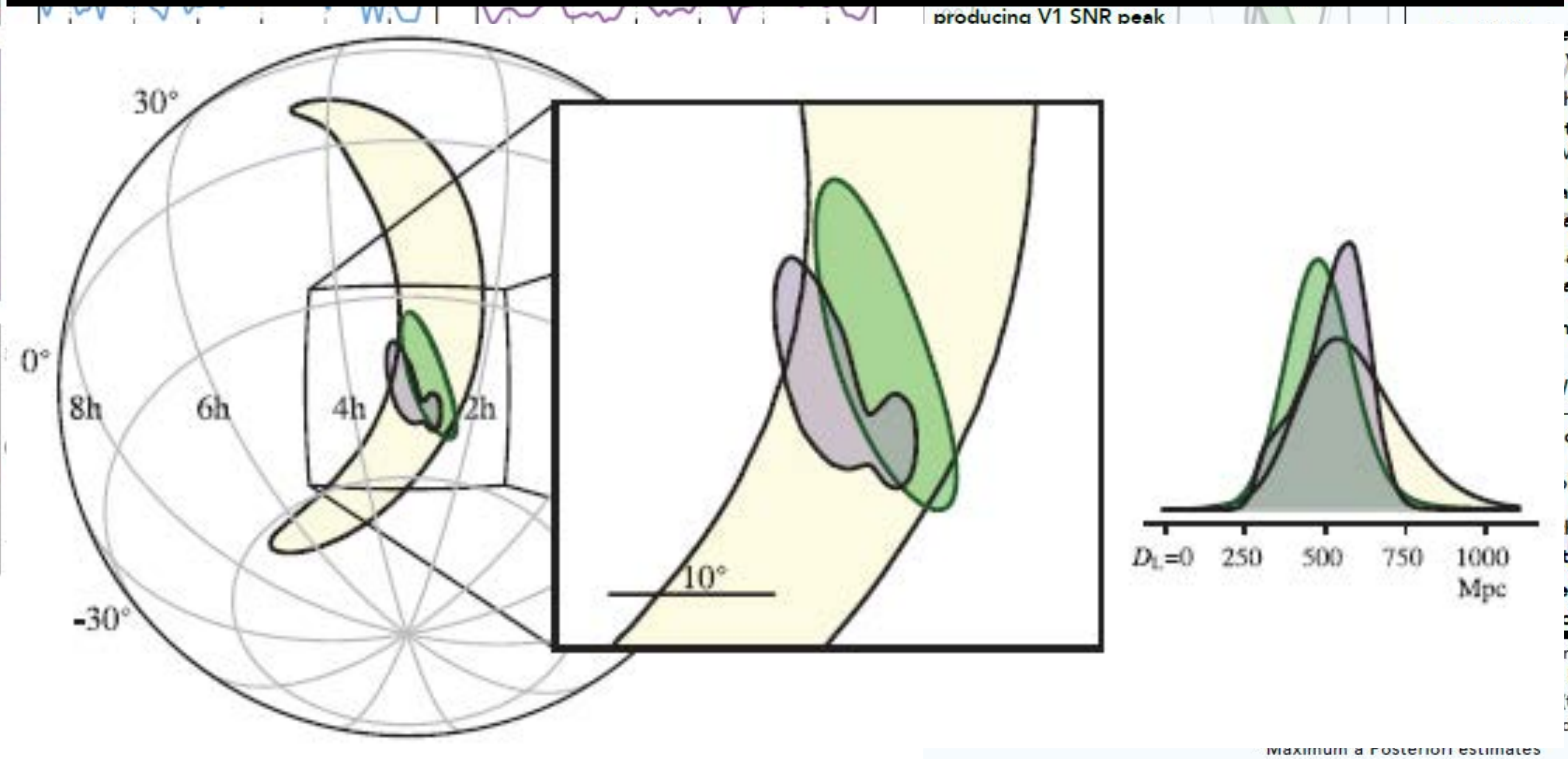


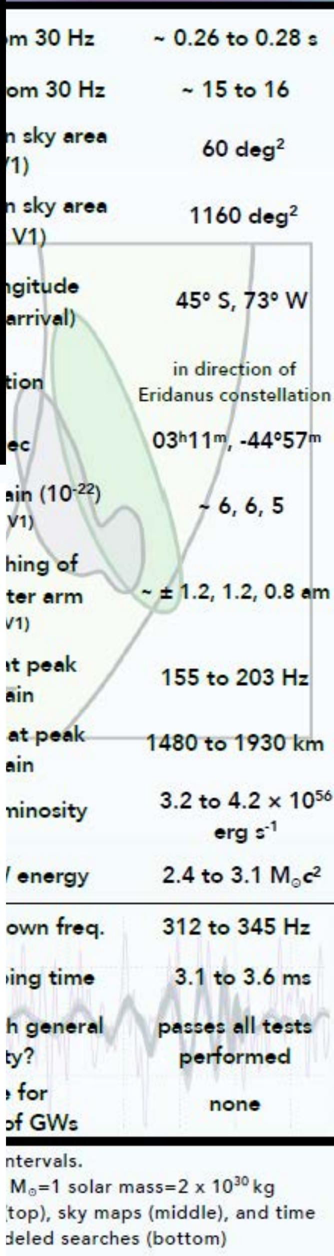
Event 5

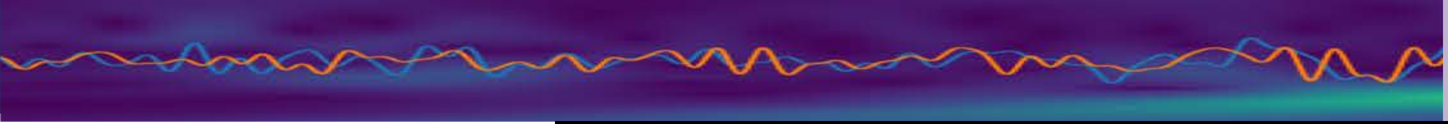
Detectors network

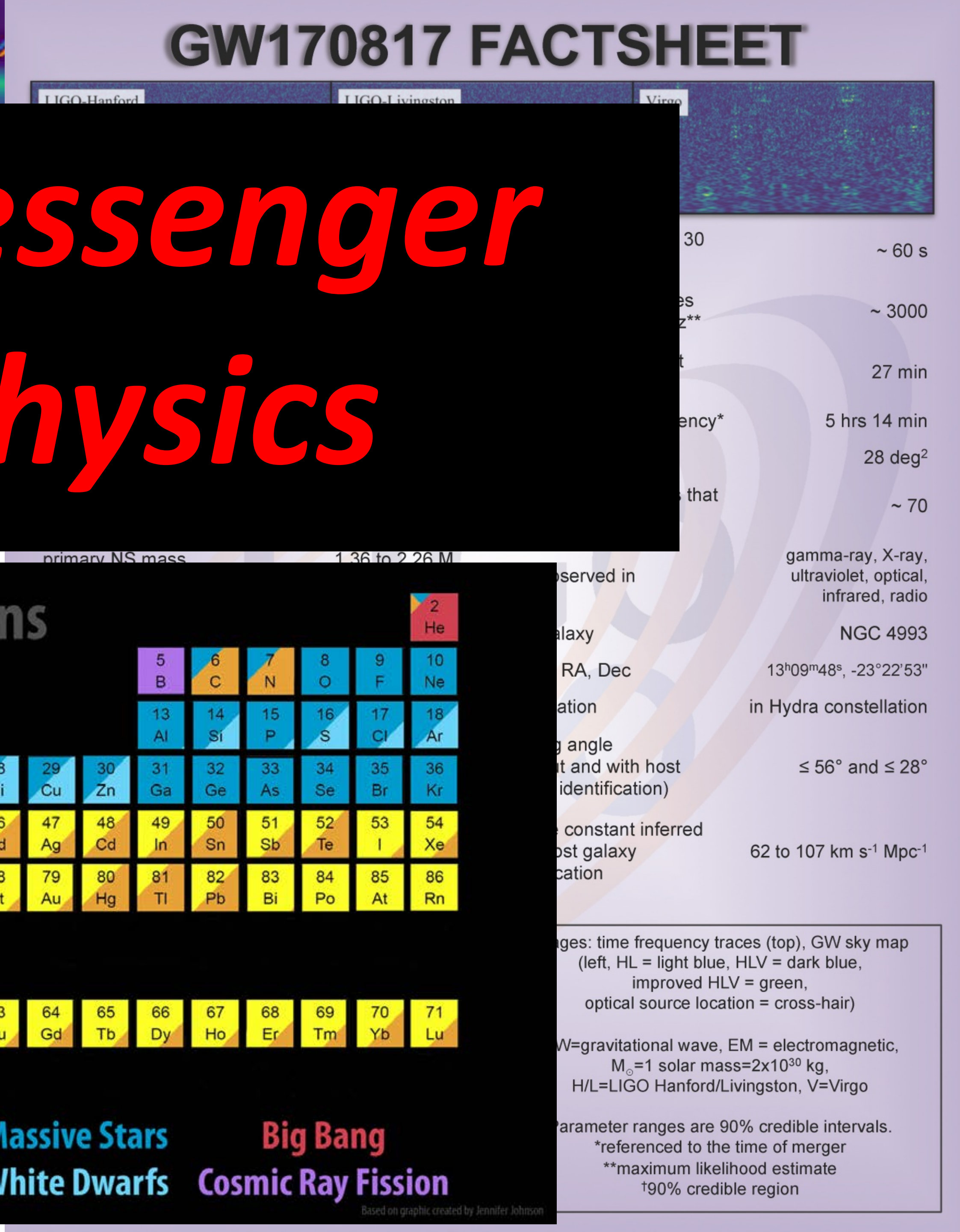
Improved source localization





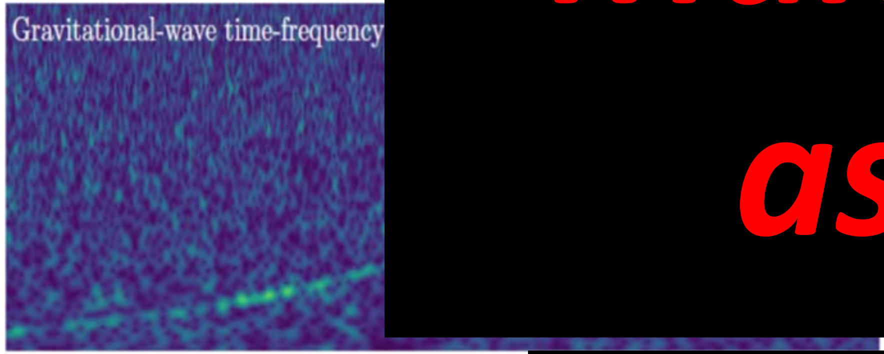


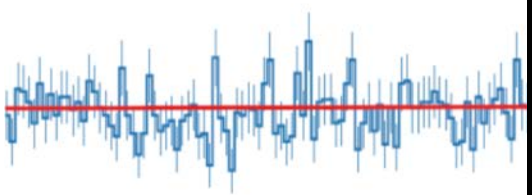


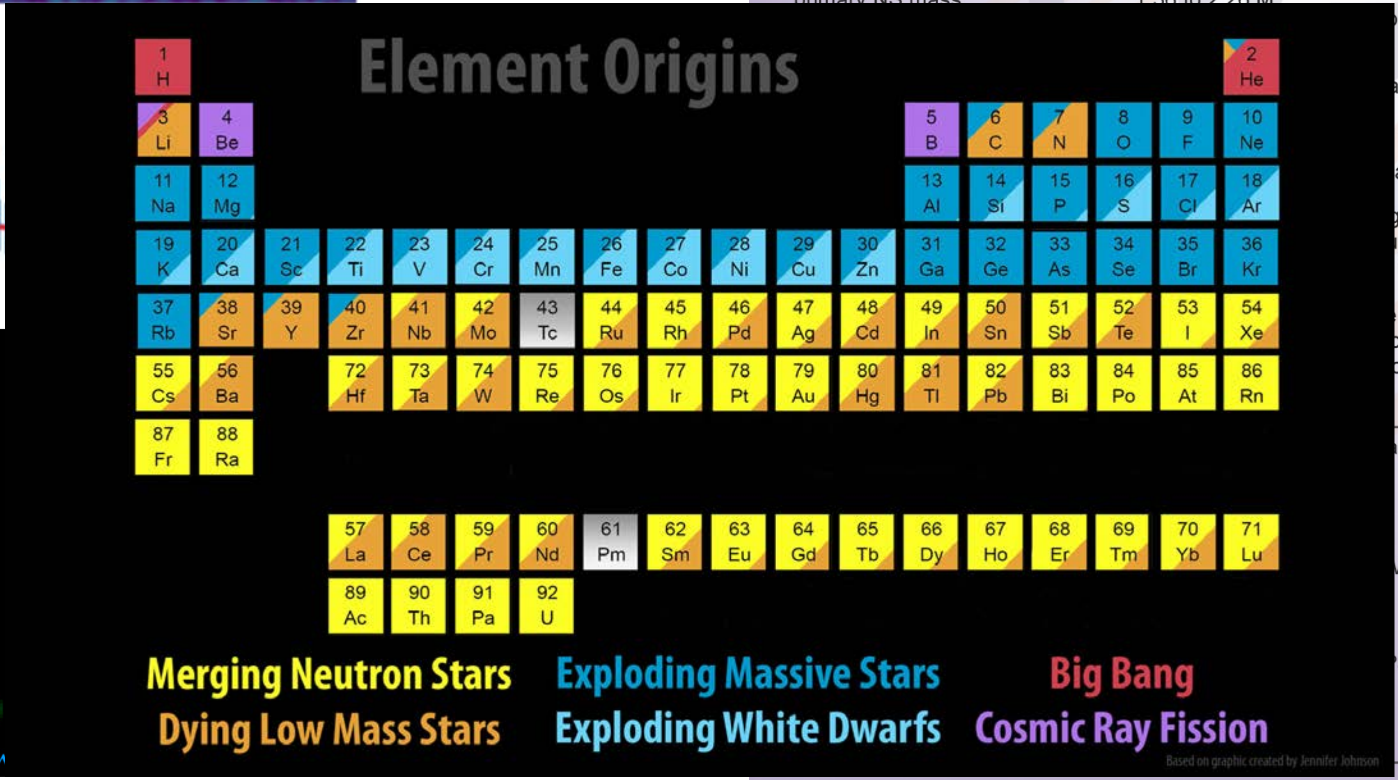


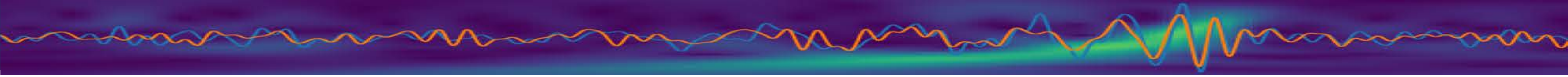
Event 6

Multi-messenger astrophysics









The era of the GW astronomy

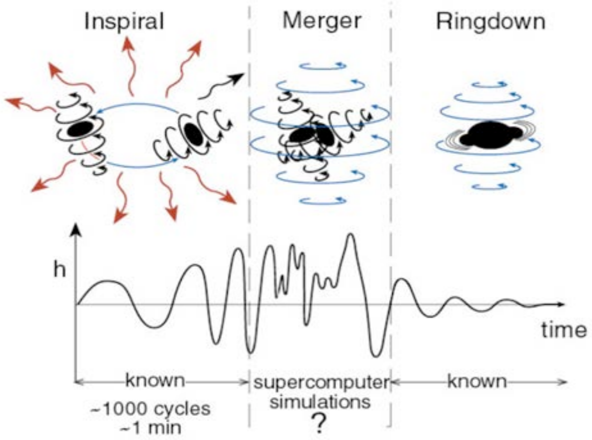
Three main factors allowed the beginning of the GW astronomy

The era of the GW astronomy

1. The solution of Einstein's equations and the understanding of their physical meaning

Einstein's equations:

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = 8\pi \, T_{\mu\nu}$$



$$h_+(t) = \frac{4}{r}\left(\frac{GM_C}{c^2}\right)^{5/3}\left(\frac{\pi f_{gw}(t)}{c}\right)^{2/3}\left(\frac{1+\cos^2(\iota)}{2}\right)\cos(\Phi(t)),$$

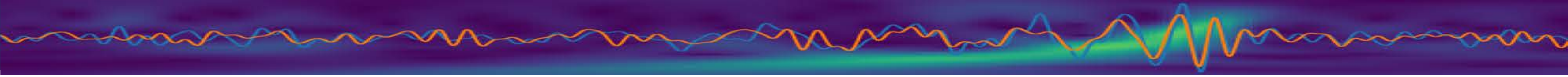
$$h_\times(t) = \frac{4}{r}\left(\frac{GM_C}{c^2}\right)^{5/3}\left(\frac{\pi f_{gw}(t)}{c}\right)^{2/3}\cos(\iota)\sin(\Phi(t)),$$

Orbital phase in the Newtonian aprox.:

$$\Phi(t) = -\frac{c^3}{5GM}[\Theta(t)]^{-3/8}(t_c - t),$$

Orbital phase in the restricted post-Newtonian aprox.:

$$\phi(t) = \phi_0 - \frac{1}{\eta}\left[\Theta^{\frac{5}{8}} + \left(\frac{3715}{8064} + \frac{55}{96}\eta\right)\Theta^{\frac{3}{8}} - \frac{3\pi}{4}\Theta^{\frac{1}{4}} + \left(\frac{9\,275\,495}{14\,450\,688} + \frac{284\,875}{258\,048}\eta + \frac{1855}{2048}\eta^2\right)\Theta^{\frac{1}{8}}\right]$$

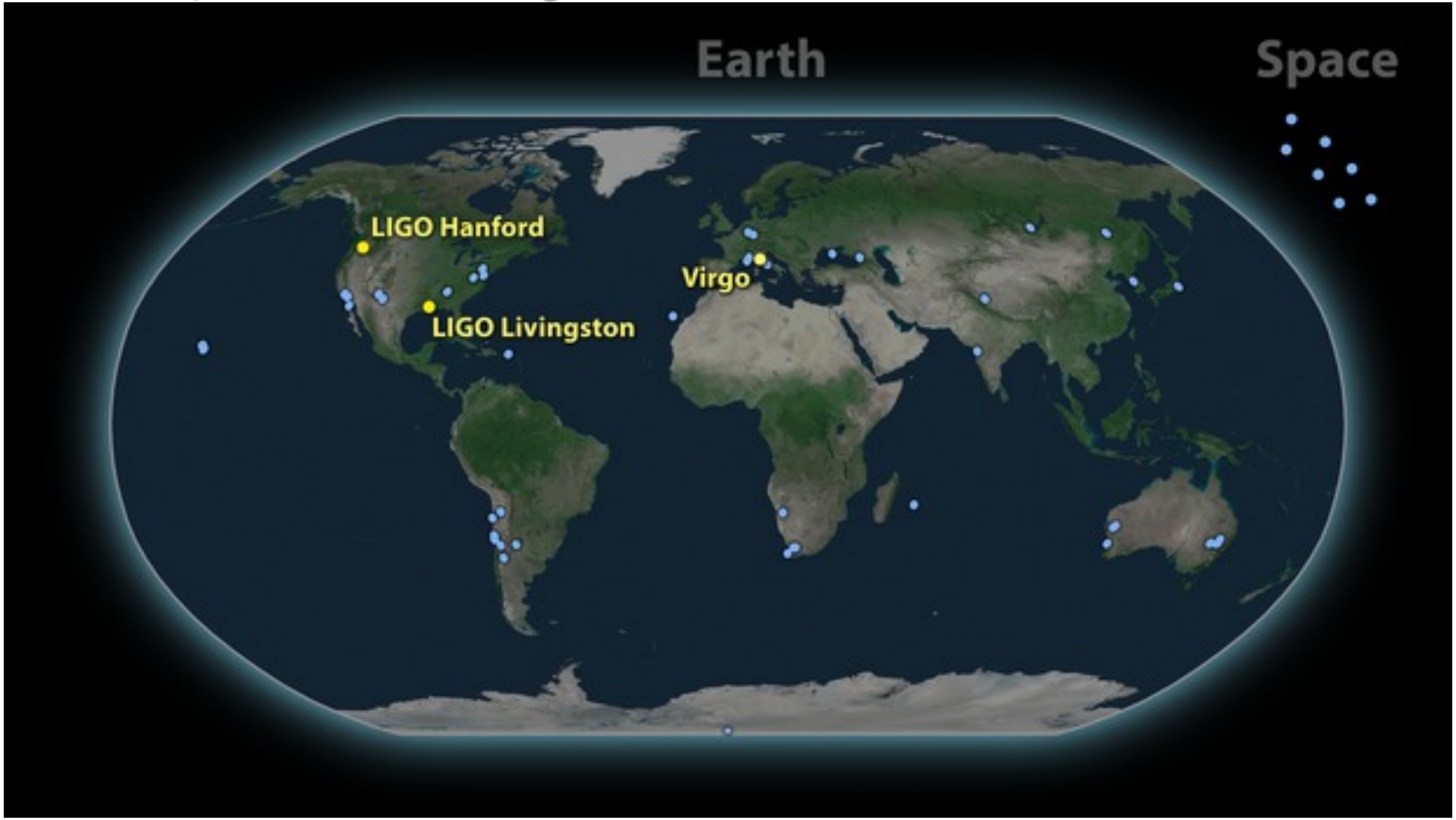


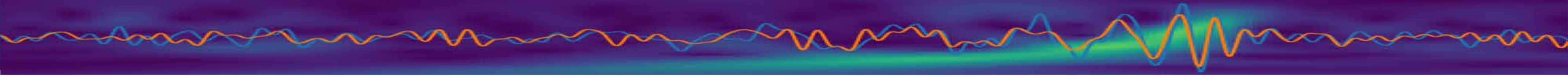
The era of the GW astronomy

2. The LIGO/VIRGO detectors + light based observatories

The era of the GW astronomy

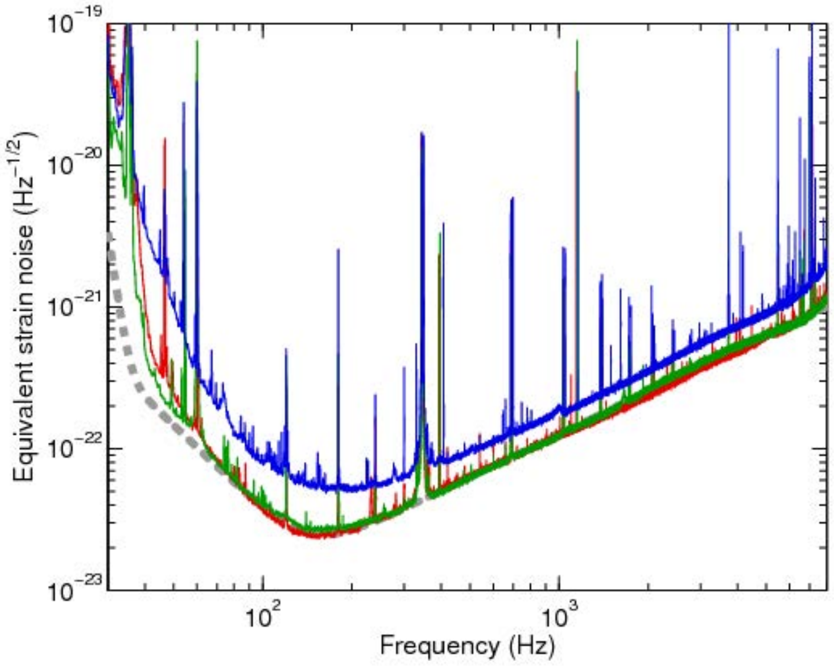
2. The LIGO/VIRGO detectors + light based observatories



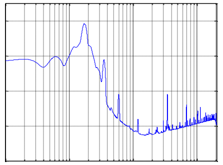


The era of the GW astronomy

3. The computational tools and the data analysis algorithms

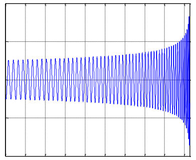


$n(f)$



1) LIGO Noise

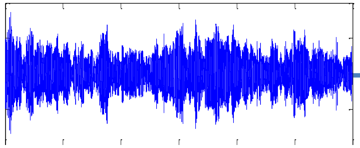
$h(t)$



3) Template

Bank of templates

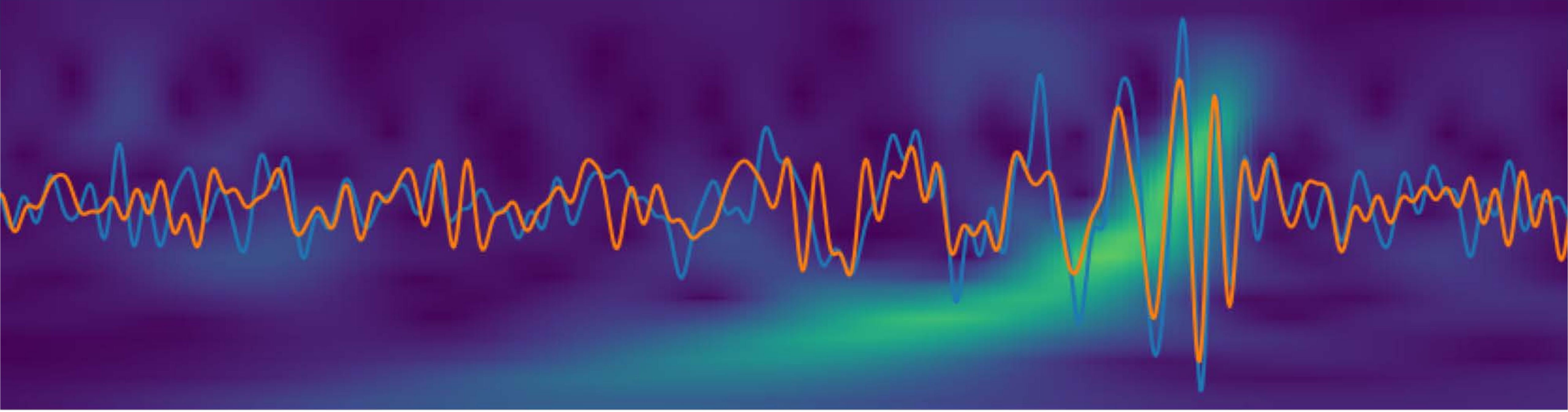
$s(t)$



2) LIGO data

$$4\int_0^\infty \frac{s(f)h^*(f)}{n(f)} e^{2\pi i f t} df \rightarrow z(t)$$

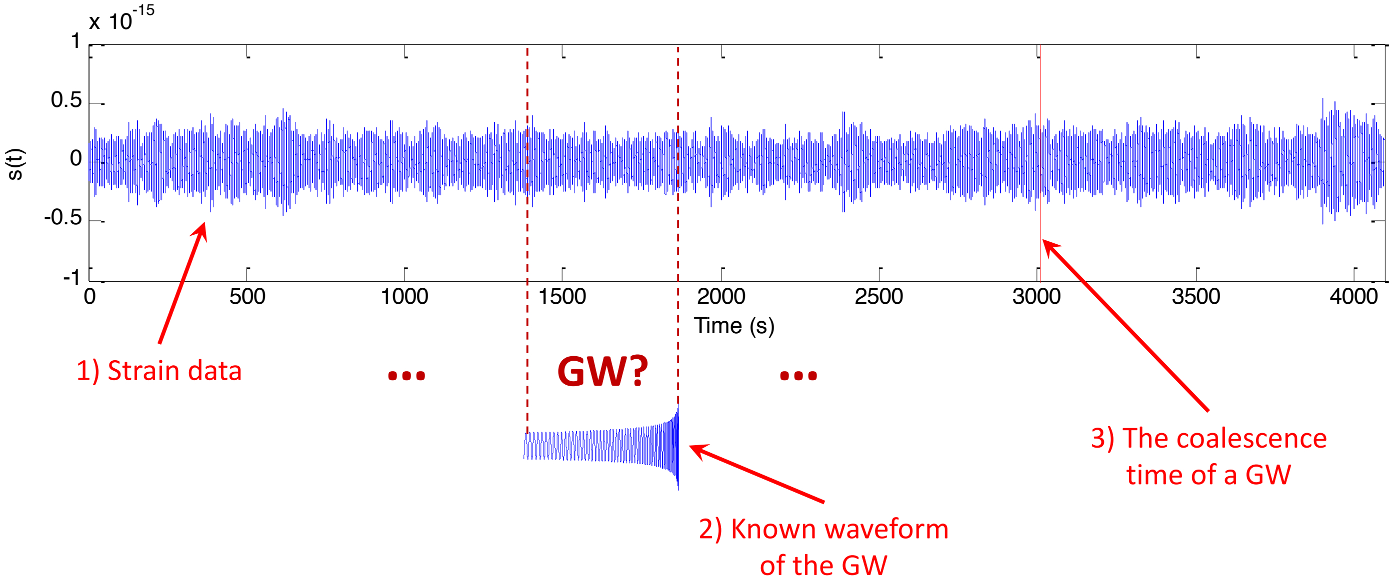
Detection and confirmation - Localization - Parameter estimation

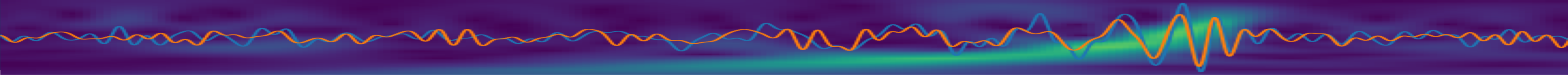


Detection of GW from CBC

Detection of GW with known waveforms

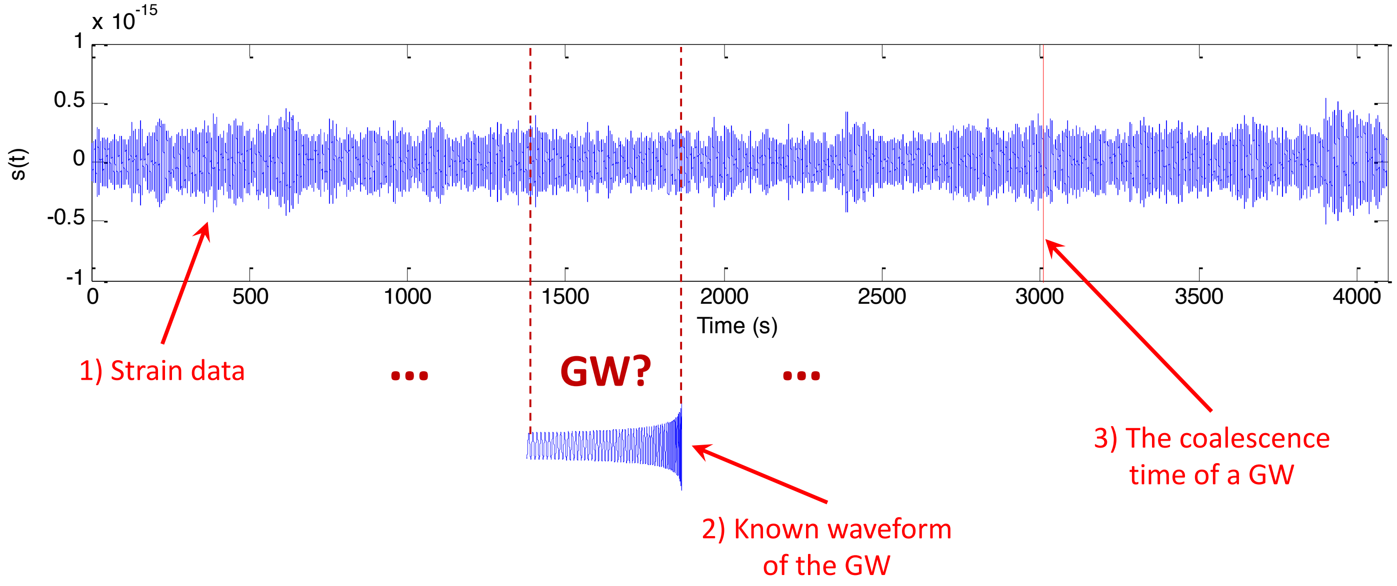
Problem description





Detection of GW with known waveforms

Problem description



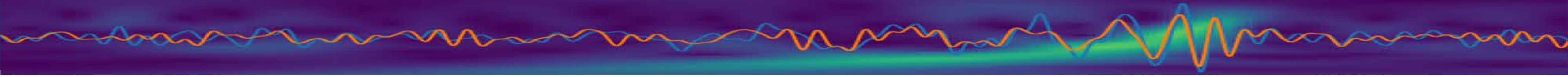
- Observations : $s(n) = [s(0), s(1), ..., s(N-1)]^T$
- Task : decide if $s(n)$ is only noise or if it contains a GW
- Aim : to select one of two mutually exclusive hypotheses

$$\begin{cases} H_0 : s(n) = w(n) & \text{GW signal is absent,} \\ H_1 : s(n) = w(n) + h(n) & \text{GW signal is present,} \end{cases}$$

where,

- $h(n) \Rightarrow$ *known* waveform of the GW
- $w(n) \Rightarrow$ noise in the detector (modelled with a PDF)

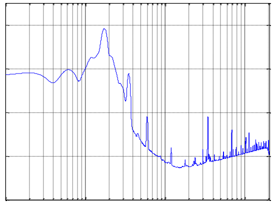
This is basically a problem of the *Detection theory*



Detection of GW with known waveforms

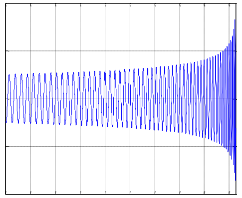
Matched filter

$n(f)$



1) LIGO Noise

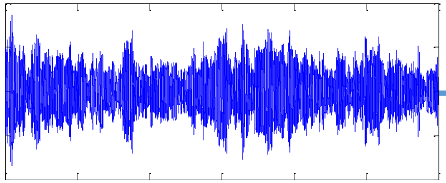
$h(t)$



Bank of templates

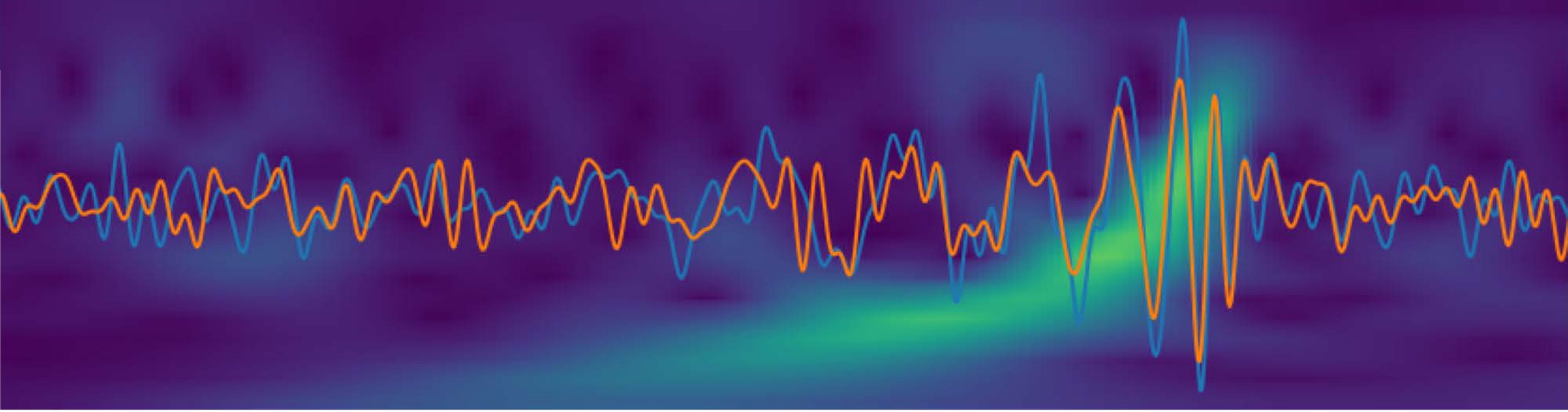
3) Template

$s(t)$



2) LIGO data

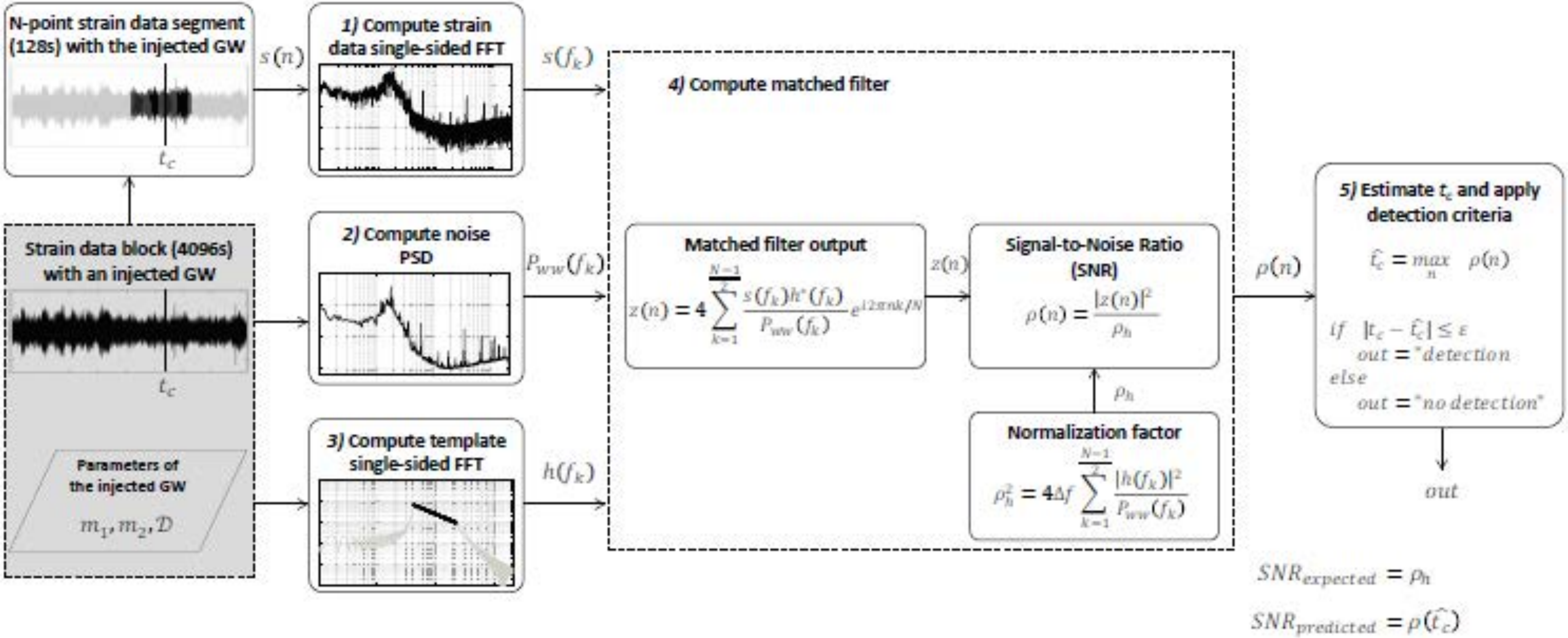
$$4\int_0^{\infty} \frac{s(f)h^*(f)}{n(f)} e^{2\pi i f t} df \rightarrow z(t)$$



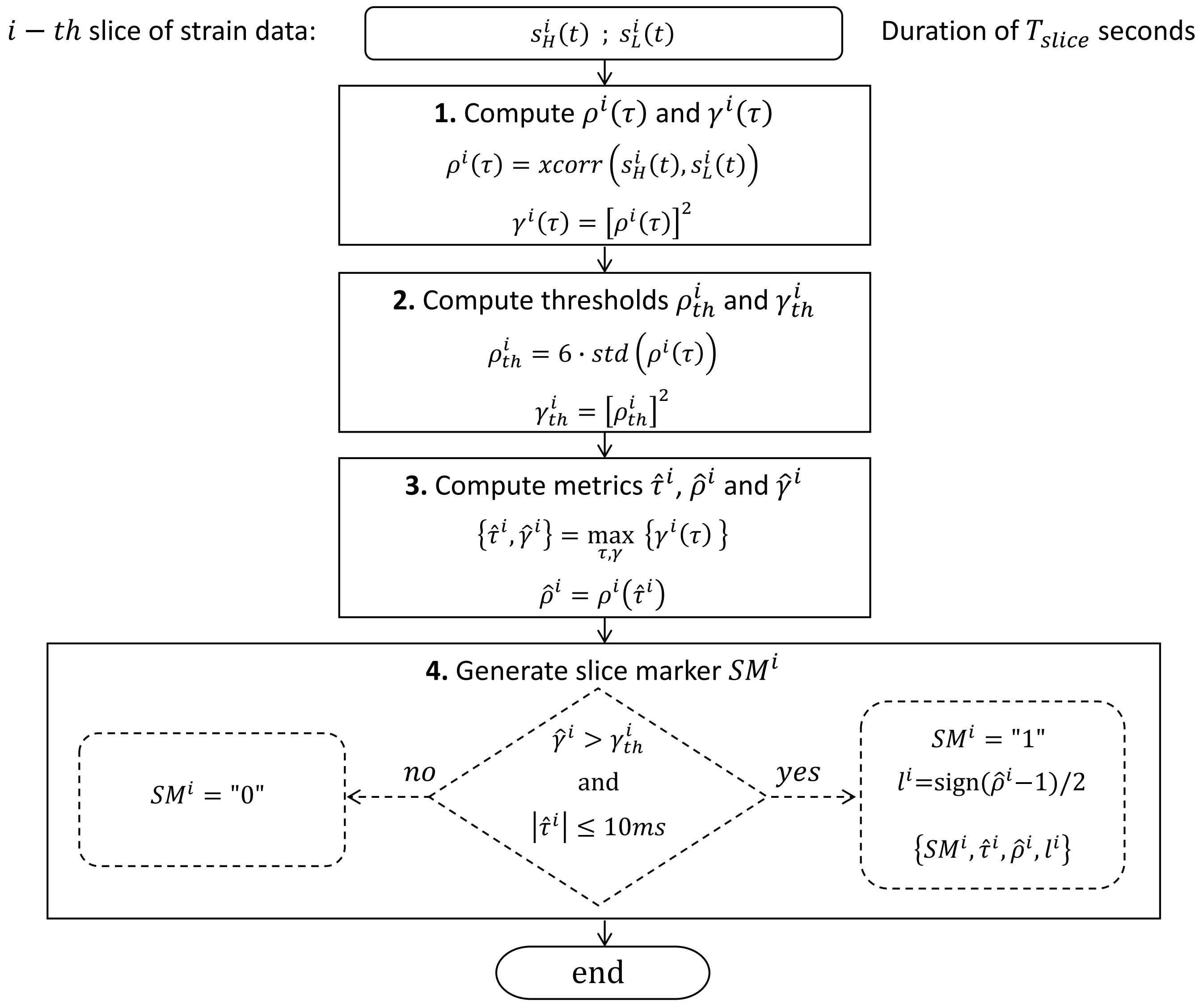
Some data analysis related projects

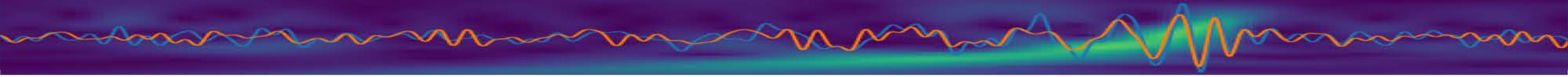
www.gravitationalwaves.mx

Recovering CBC GW injections

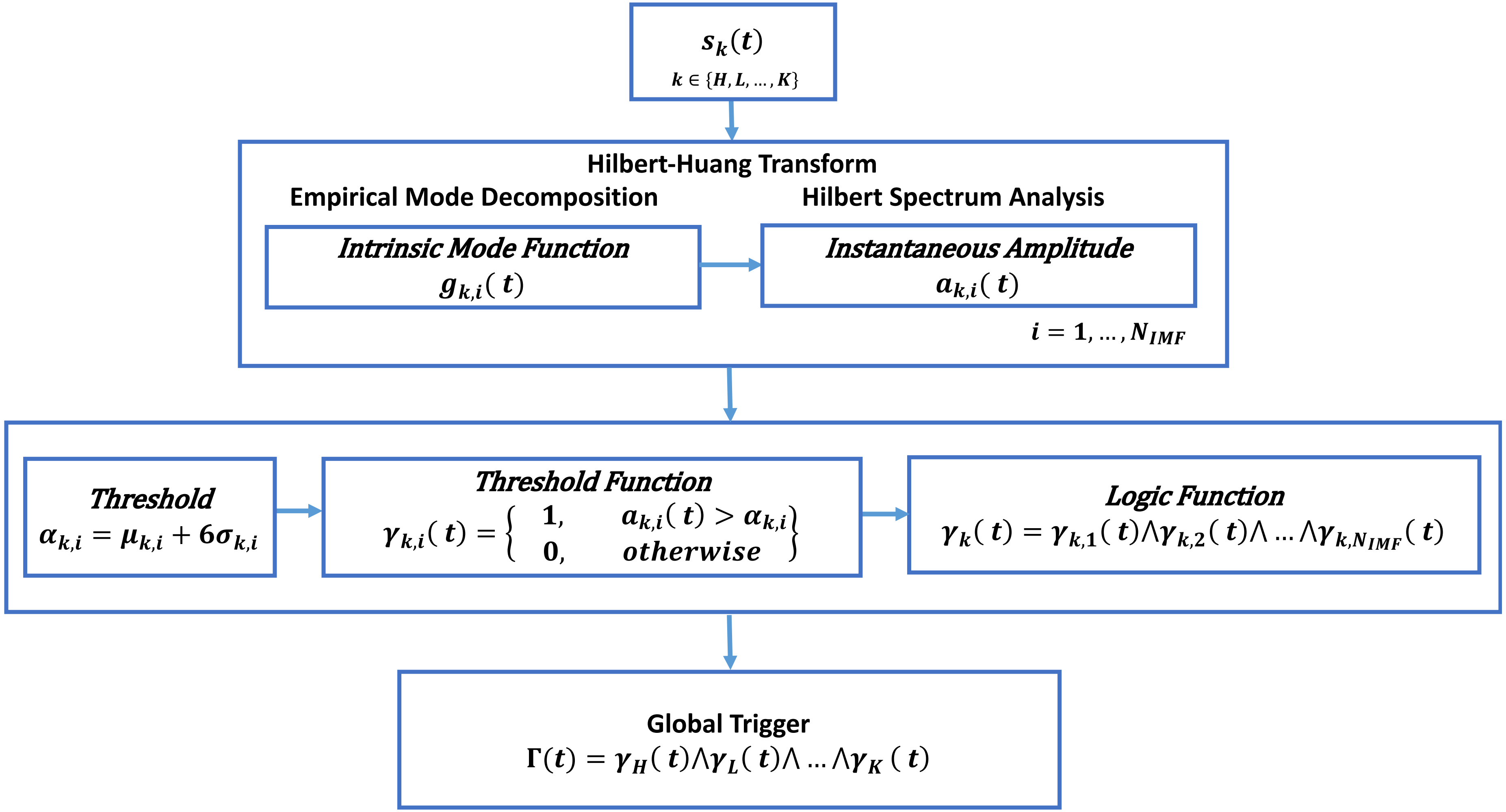


Independent search of GW in LIGO O1 data

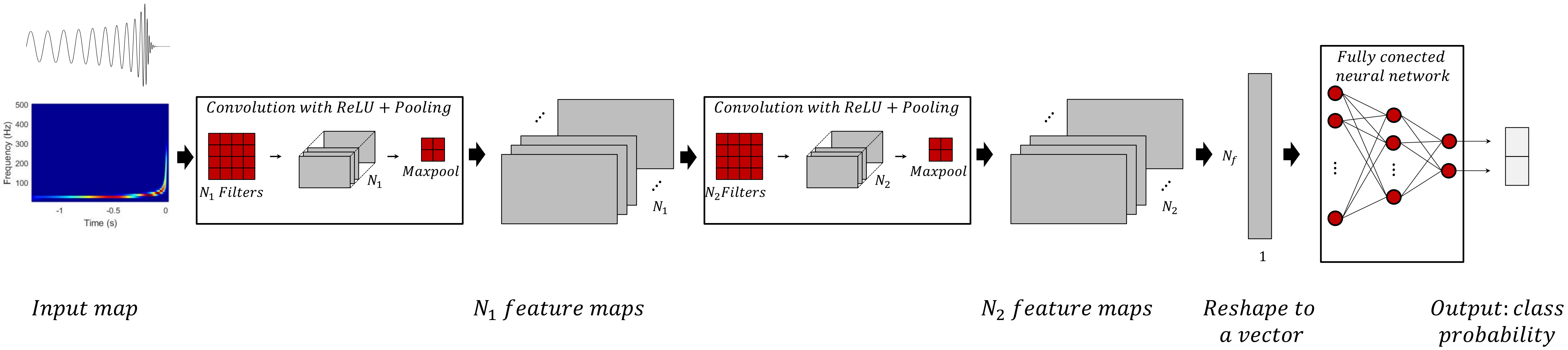




A new method for the detection using HHT

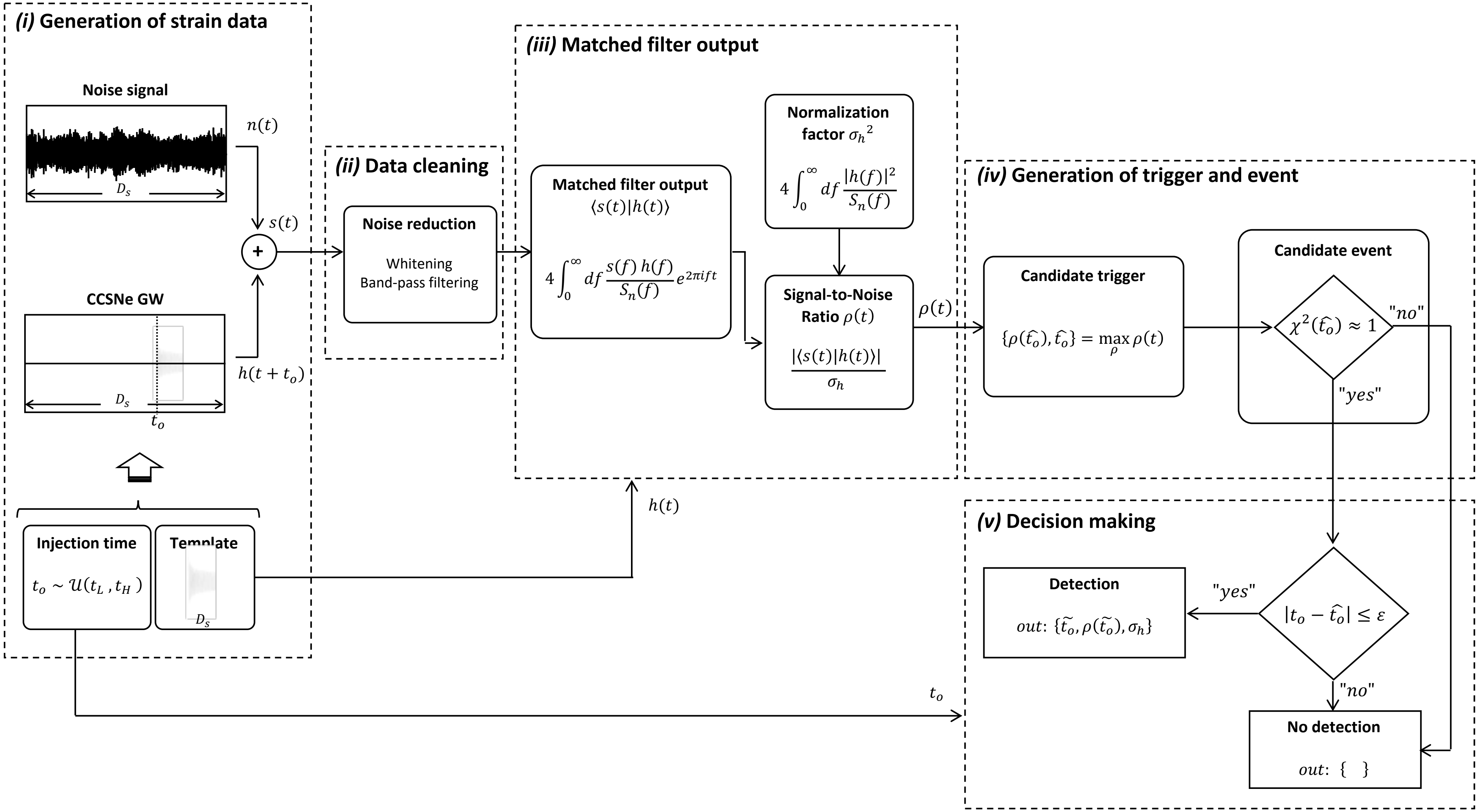


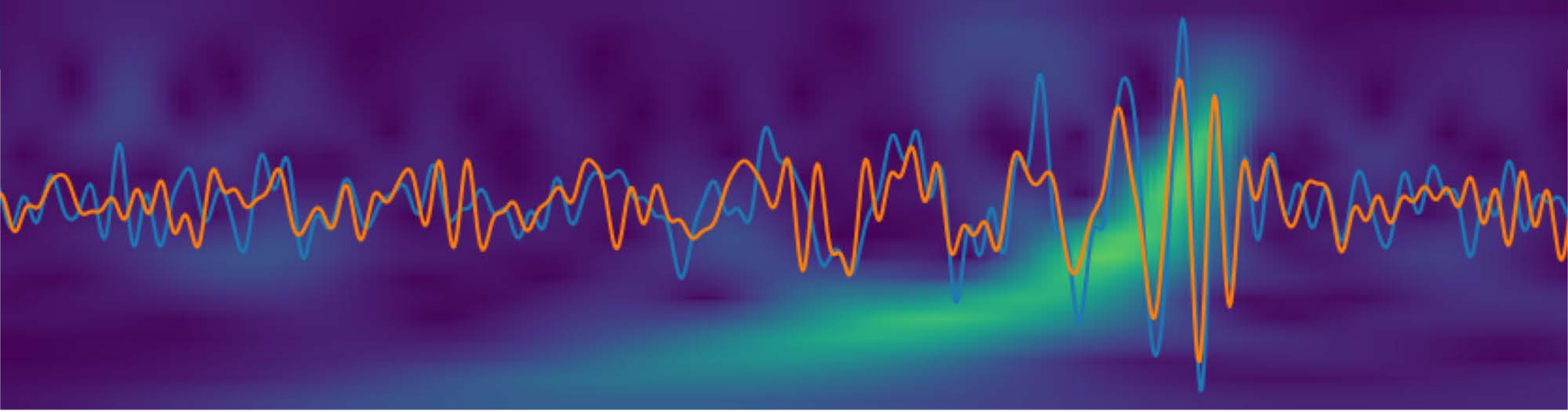
Deep Learning for detection and estimation



- Higher number of weights
- Bigger set of examples is needed
- Outstanding results in image recognition
- Tunable and learned parameters
- Training is computational cost
- Use of GPU

Search of CCSNe GW in LIGO O1 data





Let’s start with the tutorial !