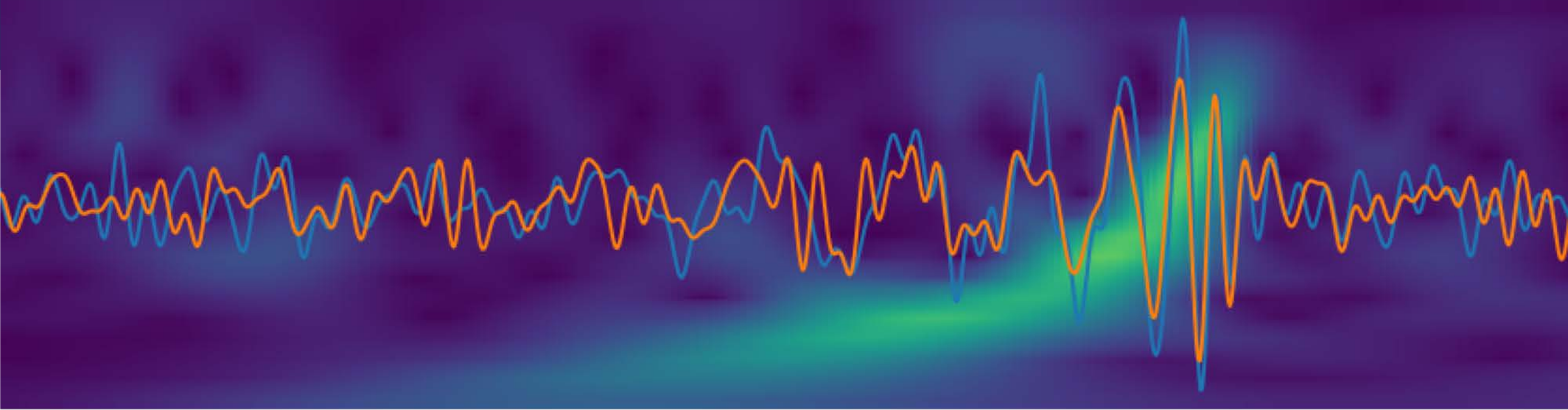




Data analysis tools for the detection of gravitational waves

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)

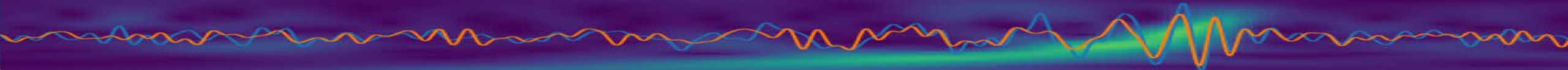
Playa del Carmen, Mexico

November 2018

Grupo de Gravitación y Análisis de Datos en Ondas Gravitacionales



www.gravitationalwaves.mx



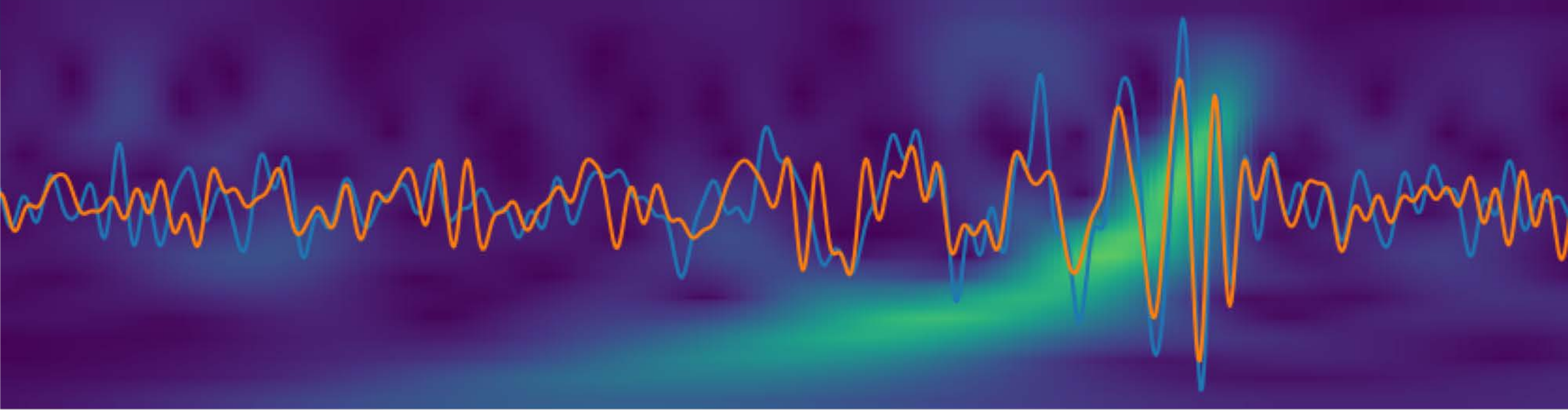
Outline

Session 1:

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

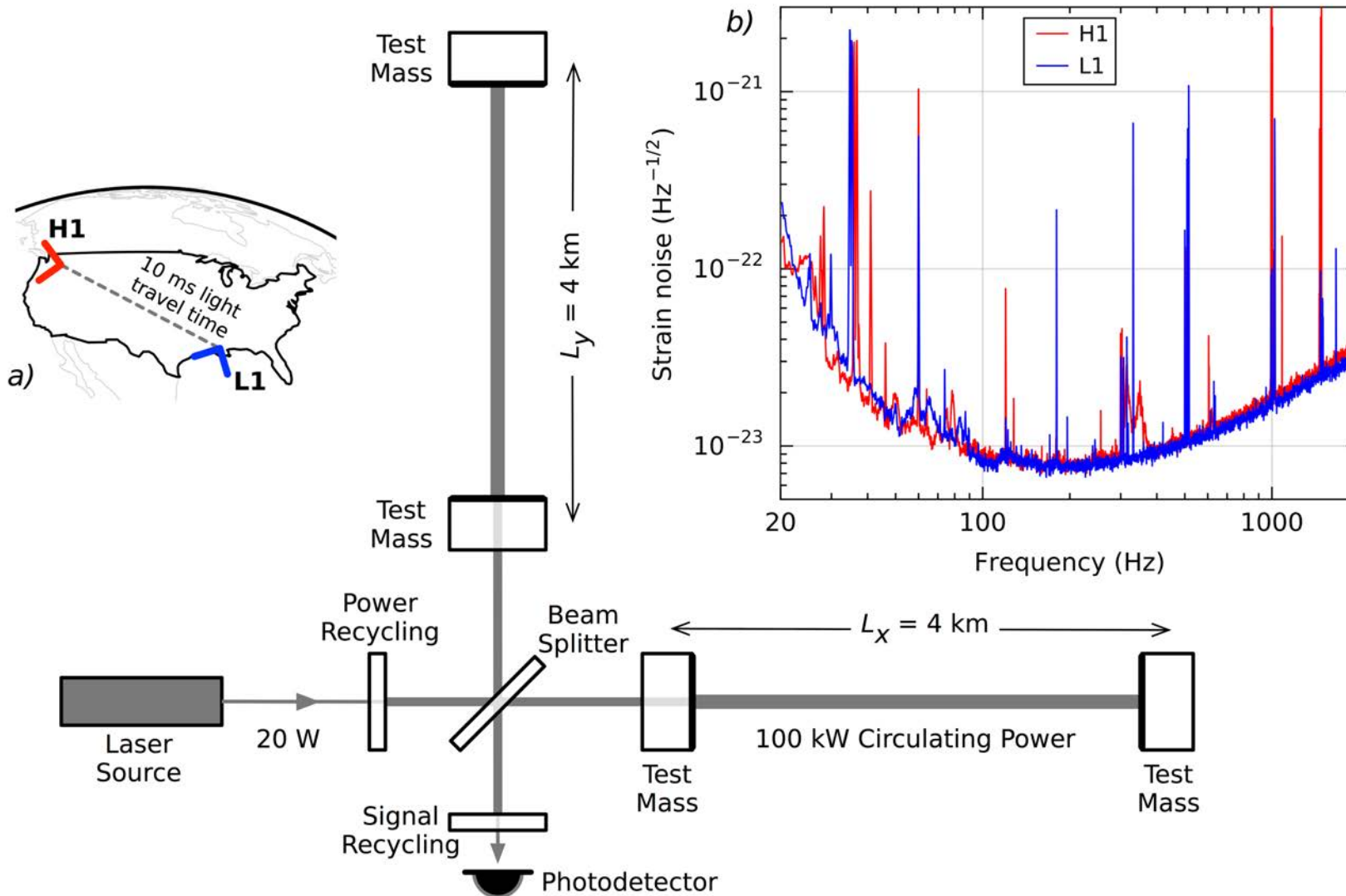
Session 2:

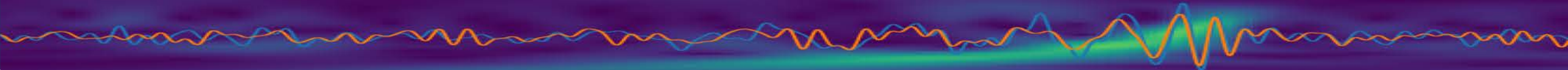
1. Tutorial: Part 2
 2. Hackathon winner
- 



Theoretical basics

Advanced LIGO



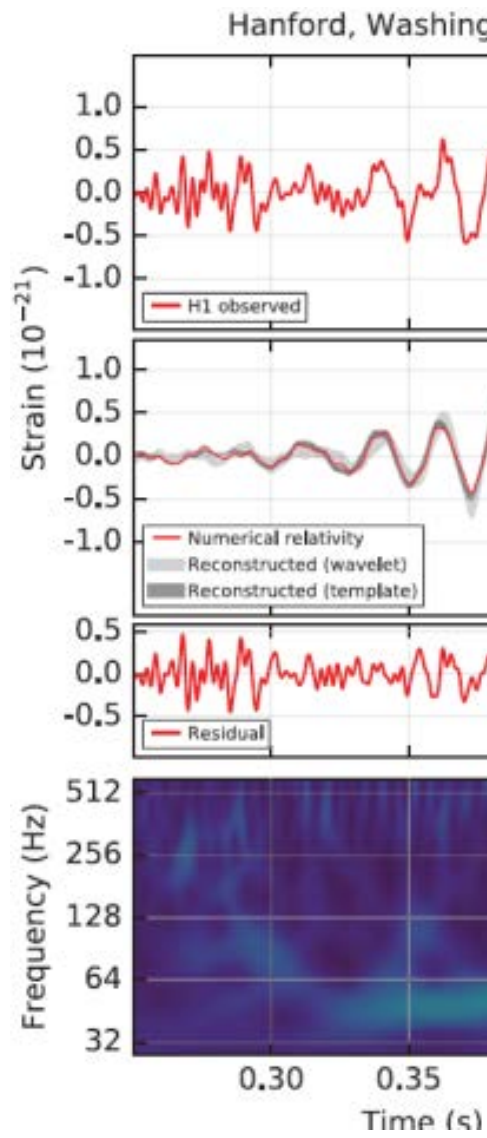


First science observation run: O1

- 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



(TOP) AND TIME-SERIES
ATION OF BLACK HOLE
(MIDDLE-BOTTOM)

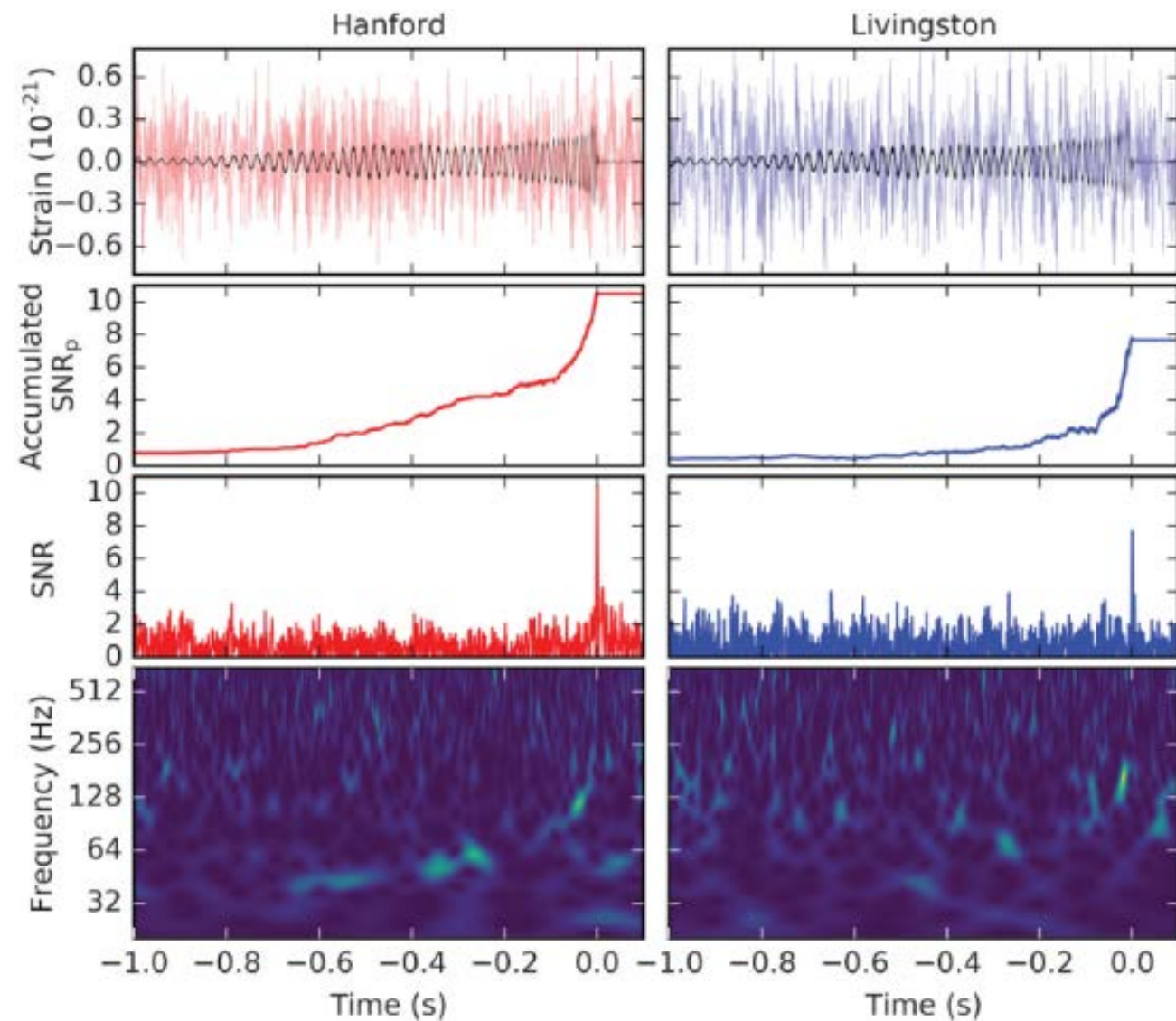
first direct observation

signal-to-noise ratio 24

0 Hz	~ 200 ms
0 Hz	~10
in	1×10^{-21}
nt of	± 0.002 fm
arms	
length	150 Hz, 2000 km
ain	
BHs	~ 0.6 c
osity	3.6×10^{56} erg s ⁻¹
ergy	2.5-3.5 M _⊙
wn freq.	~ 250 Hz
ing time	~ 4 ms
area	180 km, 3.5×10^5 km ²
th	passes all tests
ty?	performed
ound	$< 1.2 \times 10^{-22}$ eV
e of	2 to 400 Gpc ³ yr ⁻¹
olles	
ency	~ 3 min
pipelines	5
med	~ 50 million (=20,000 PCs run for 100 days)
, 2016	13
	~1000, 80 institutions in 15 countries

respond to 90% credible bounds.
ar= 9.46×10^{12} km; Mpc=mega
M_⊙=1 solar mass= 2×10^{30} kg

Event 2: GW151226

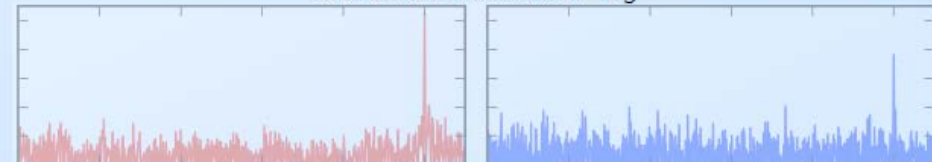


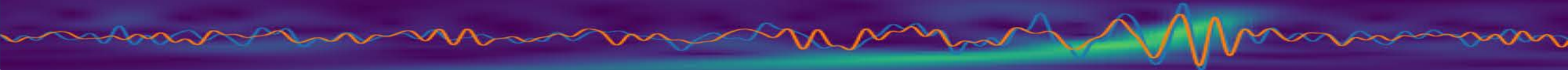
GW151226: FACTSHEET

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	$\sim 3.4 \times 10^{-22}$
redshift	0.05 to 0.13	peak displacement of interferometers arms	$\sim \pm 0.7$ am
signal-to-noise ratio	13	frequency/wavelength at peak GW strain	420 Hz, 710 km
false alarm prob.	~ 1 in 10 million	peak speed of BHs	~ 0.6 c
Source Masses $M_{\odot}$		peak GW luminosity	2 to 4×10^{56} erg s ⁻¹
total mass	20 to 28	radiated GW energy	0.8-1.1 $M_{\odot}$
primary BH	11 to 23	remnant ringdown freq.	~ 750 Hz
secondary BH	5 to 10	remnant damping time	0.00 ~ 1.3 ms
remnant BH	19 to 27		
mass ratio	> 0.28	remnant size, area	60 km, 3.5×10^4 km ²
spin of one of the black holes	> 0.2	online trigger latency	~ 67 s
remnant BH spin	0.7 to 0.8	# offline analysis pipelines	2
resolved to	~850 sq. deg.		

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, $M_{\odot}$ =1 solar mass= 2×10^{30} kg

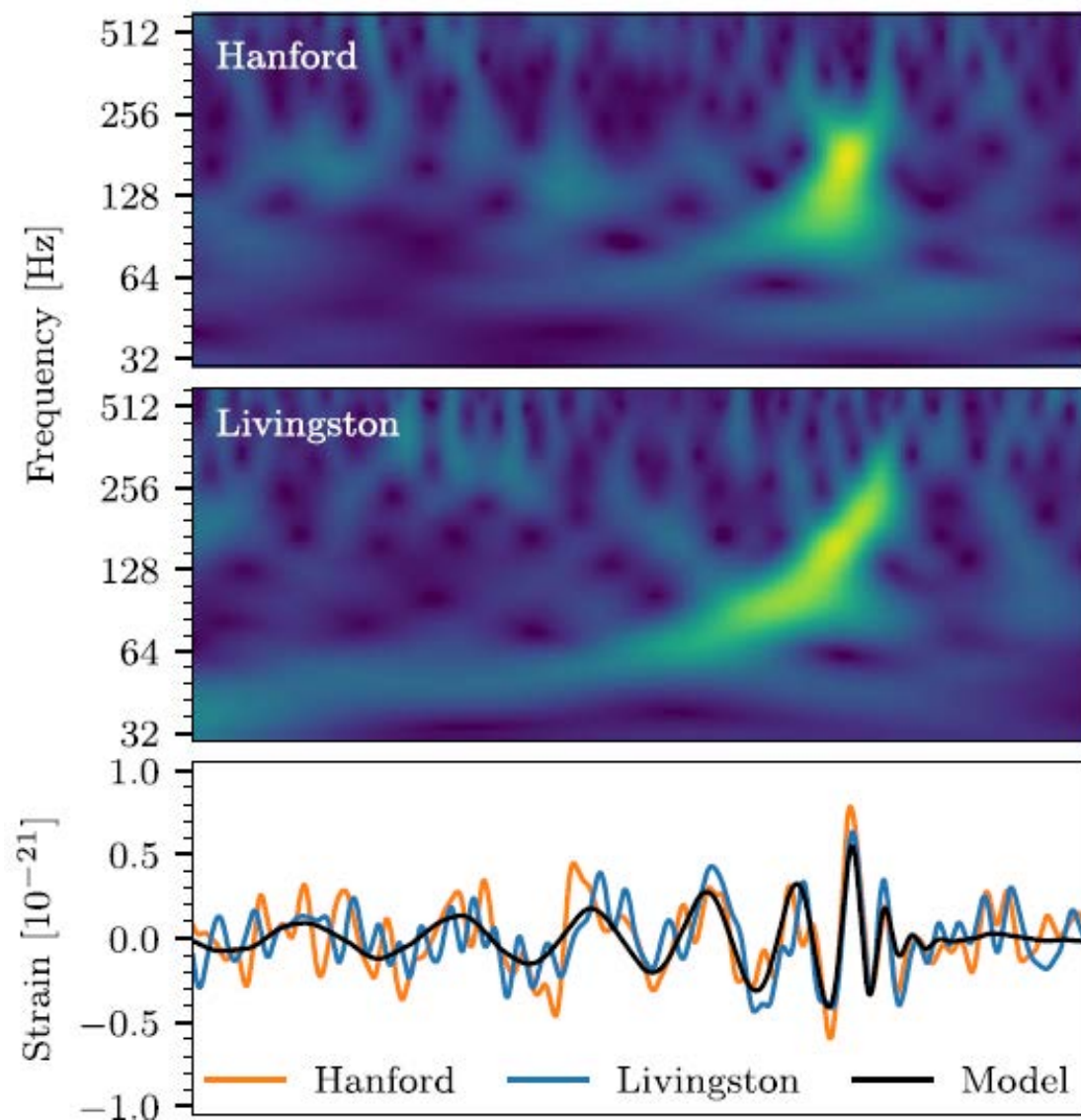




Second science observation run: O2

- 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)

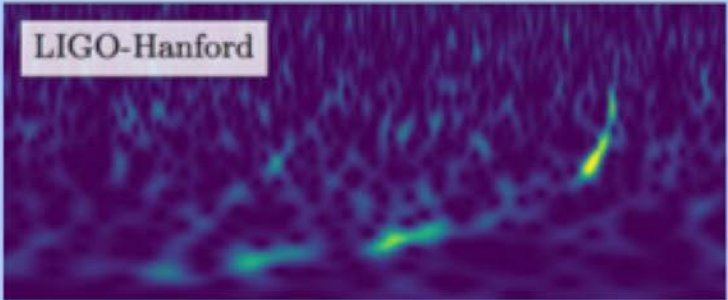
observed by	LIGO L1, H1	duration from 30 Hz	~ 0.25 to 0.31 s
source type	black hole (BH) binary	# of cycles from 30 Hz	~ 14 to 16
date	04 Jan 2017	signal arrival time delay	arrived at H1 3 ms before L1
time	10:11:58.6 UTC	credible region sky area	1200 sq. deg.
signal-to-noise ratio	13	peak GW strain	$\sim 5 \times 10^{-22}$
false alarm rate	< 1 in 70,000 years	peak displacement of interferometer arm	$\sim \pm 1$ am
probability of astrophysical origin	> 0.99997	frequency at peak GW strain	160 to 199 Hz
distance	1.6 to 4.3 billion light-years	wavelength at peak GW strain	1510 to 1880 km
redshift	0.10 to 0.25	peak GW luminosity	1.8 to 3.8×10^{56} erg s^{-1}
total mass	46 to 57 $M_{\odot}$	radiated GW energy	1.3 to 2.6 $M_{\odot}$
primary BH mass	25 to 40 $M_{\odot}$	remnant ringdown freq.	297 to 373 Hz
secondary BH mass	13 to 25 $M_{\odot}$	remnant damping time	2.5 to 3.2 ms
mass ratio	0.36 to 0.94	consistent with general relativity?	passes all tests performed
remnant BH mass	44 to 54 $M_{\odot}$	graviton mass combined bound	$\leq 7.7 \times 10^{-23}$ eV/ c^2
remnant BH spin	0.39 to 0.7	evidence for dispersion of GWs	none
remnant size (effective radius)	123 to 150 km		
remnant area	1.9 to 2.8×10^5 km 2		
effective spin parameter	-0.42 to 0.09		
effective precession spin parameter	unconstrained		

Parameter ranges correspond to 90% credible intervals.

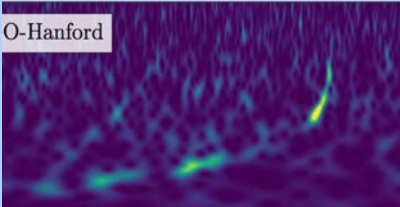
Acronyms:

L1/H1=LIGO Livingston/Hanford, am=attometer= 10^{-18} m, $M_{\odot}$ =1 solar mass= 2×10^{30} kg

GW170608 FACTSHEET

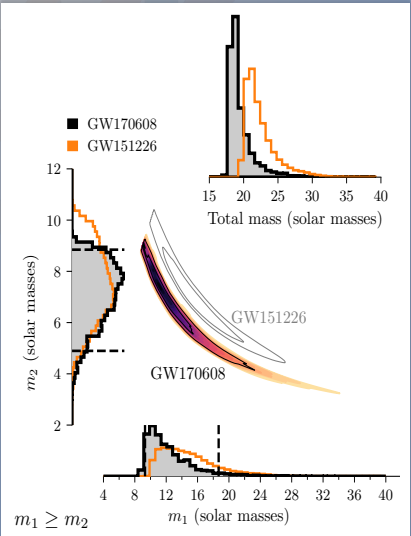


GW170608 FACTSHEET



detectors	H, L	duration from 30 Hz	~ 2 s
event type	black hole (BH) binary	# of GW cycles from 30 Hz	~ 100
date of merger	08 June 2017	signal arrival time delay	arrived at H ~ 7 ms before L
time of merger	02:01:16 UTC	HL sky area†	~ 520 deg ²
signal-to-noise ratio	13	peak GW strain (10 ⁻²²)	~ 4 (H), 3 (L)
false alarm rate	< 1 in 3 000 years	peak stretch of interferometer arm	~ ± 0.8 am (H), 0.6 am (L)
distance	0.7 to 1.5 billion light-years	frequency at peak GW strain	453 to 610 Hz
time of merger	0.04 to 0.1 s	wavelength at peak GW strain	492 to 662 km
primary BH mass	18 to 24 M _⊙	remnant ringdown frequency	745 to 1013 Hz
secondary BH mass	9 to 19 M _⊙	remnant damping time	1.0 to 1.4 ms
mass ratio	5 to 9 M _⊙	consistent with general relativity?	passes all tests performed
final BH mass	0.3 to 1.0		
final BH spin	17 to 23 M _⊙		
final size (Schwarzschild radius)	0.64 to 0.72		
final area	47 to 63 km		
final spin parameter	2.7 to 5.0 × 10 ⁴ km ²		
final precession parameter	-0.01 to 0.30		
GW luminosity	unconstrained		
radiated GW energy	1.8 to 3.9 × 10 ⁵⁶ erg s ⁻¹		
	0.68 to 0.91 M _⊙ c ²		

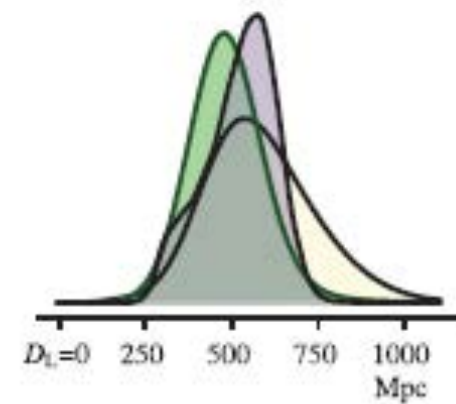
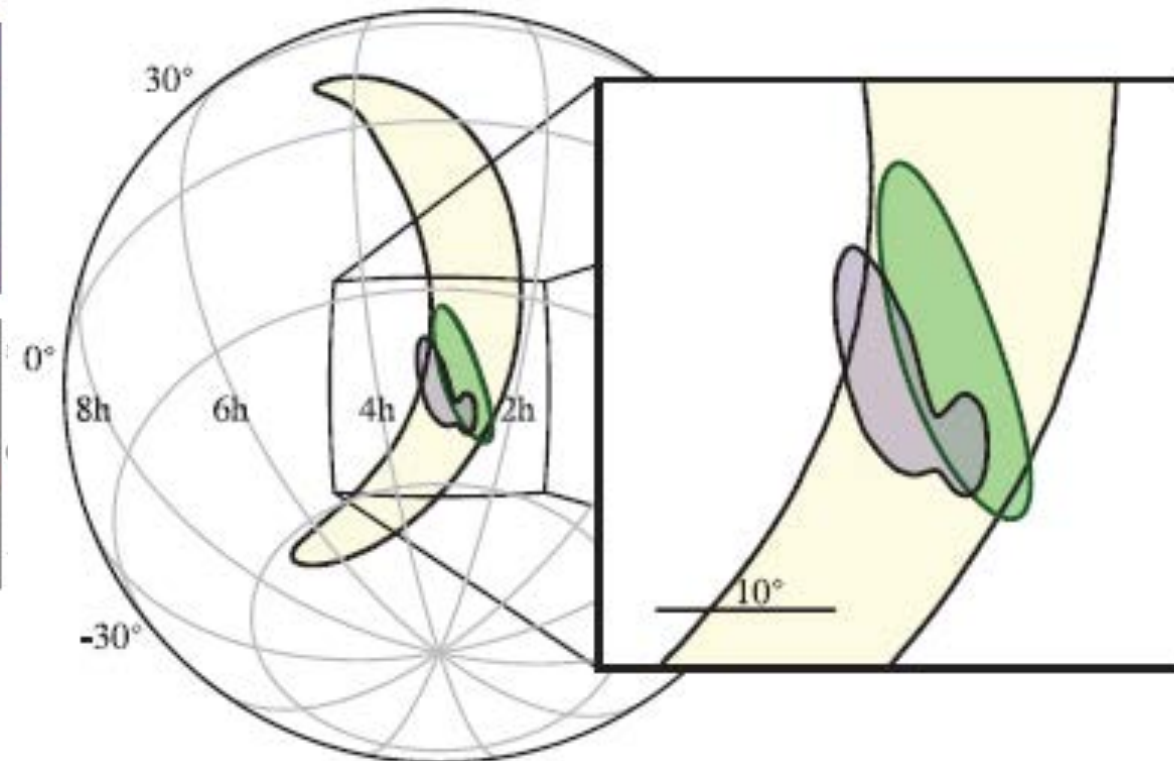
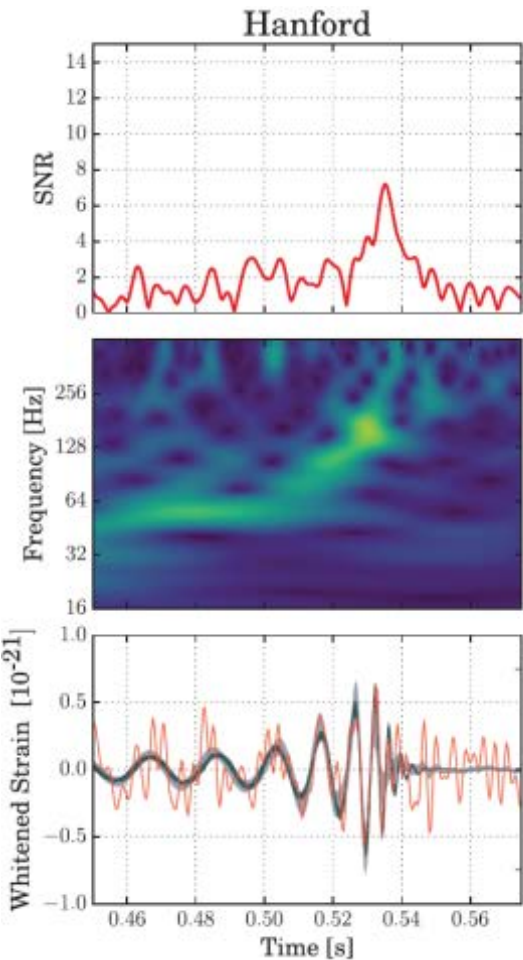
Images: time-frequency traces (top), mass distributions (bottom right)
gravitational wave, M_⊙=1 solar mass=2x10³⁰ kg,
ometer (10⁻¹⁸ m), H/L=LIGO Hanford/Livingston
rrometer ranges are 90% credible intervals.
†90% credible region



Event 5

Detectors network

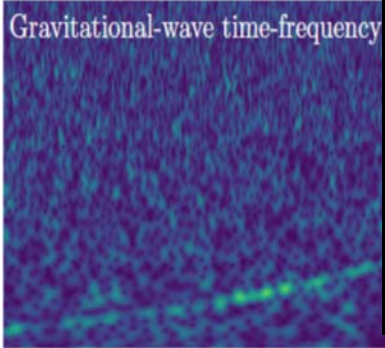
Improved source localization



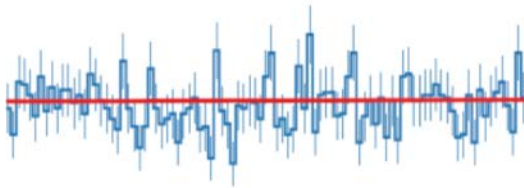
from 30 Hz	~ 0.26 to 0.28 s
from 30 Hz	~ 15 to 16
in sky area (V1)	60 deg ²
in sky area (V1)	1160 deg ²
longitude (arrival)	45° S, 73° W
direction	in direction of Eridanus constellation
ec	03 ^h 11 ^m , -44°57 ^m
main (10 ⁻²² V1)	~ 6, 6, 5
ching of ter arm (V1)	~ ± 1.2, 1.2, 0.8 am
it peak ain	155 to 203 Hz
at peak ain	1480 to 1930 km
minosity	3.2 to 4.2 × 10 ⁵⁶ erg s ⁻¹
/ energy	2.4 to 3.1 M _⊙ c ²
own freq.	312 to 345 Hz
ing time	3.1 to 3.6 ms
h general ty?	passes all tests performed
s for of GWs	none
intervals.	
M _⊙ =1 solar mass=2 × 10 ³⁰ kg	
(top), sky maps (middle), and time	
deled searches (bottom)	

Event 6

Gravitational-wave time-frequency



Multi-messenger astrophysics



SSS17a



August 17, 2017

Sv

Element Origins

Element Origins

1 H																	2 He		
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne		
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar		
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr		
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe		
55 Cs	56 Ba			72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn	
87 Fr	88 Ra																		
		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu			
		89 Ac	90 Th	91 Pa	92 U														

Merging Neutron Stars
Dying Low Mass Stars

Exploding Massive Stars
Exploding White Dwarfs

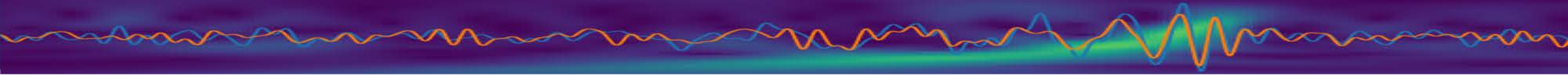
Big Bang
Cosmic Ray Fission

observed in
galaxy
RA, Dec
location
angle
t and with host
(identification)
constant inferred
host galaxy
cation

ages: time frequency traces (top), GW sky map
(left, HL = light blue, HLV = dark blue,
improved HLV = green,
optical source location = cross-hair)

W=gravitational wave, EM = electromagnetic,
 $M_{\odot}=1$ solar mass= 2×10^{30} kg,
H/L=V=LIGO Hanford/Livingston, V=Virgo

parameter ranges are 90% credible intervals.
*referenced to the time of merger
**maximum likelihood estimate
†90% credible region



The era of the GW astronomy

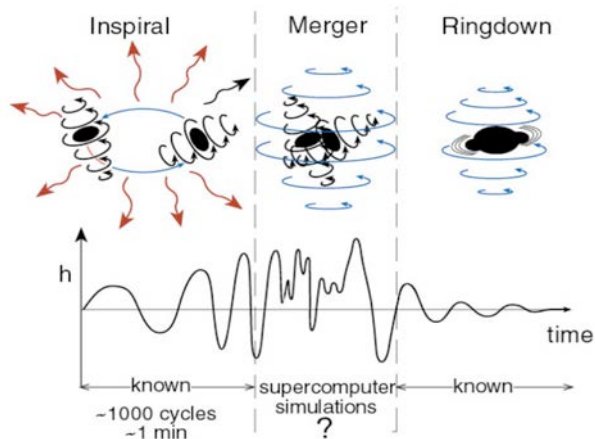
***Three main factors
allowed the beginning of
the GW astronomy***

The era of the GW astronomy

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

Einstein's equations:

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



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

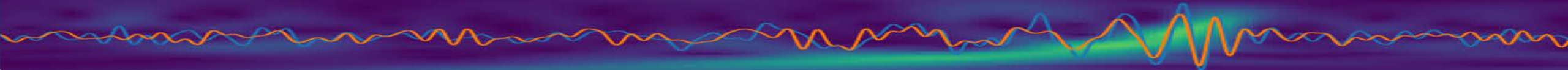
$$h_\times(t) = \frac{4}{r} \left(\frac{GM_C}{c^2} \right)^{5/3} \left(\frac{\pi f_{gw}(t)}{c} \right)^{2/3} \cos(i) \sin(\Phi(t)),$$

Orbital phase in the Newtonian approx.:

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

Orbital phase in the restricted post-Newtonian approx.:

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



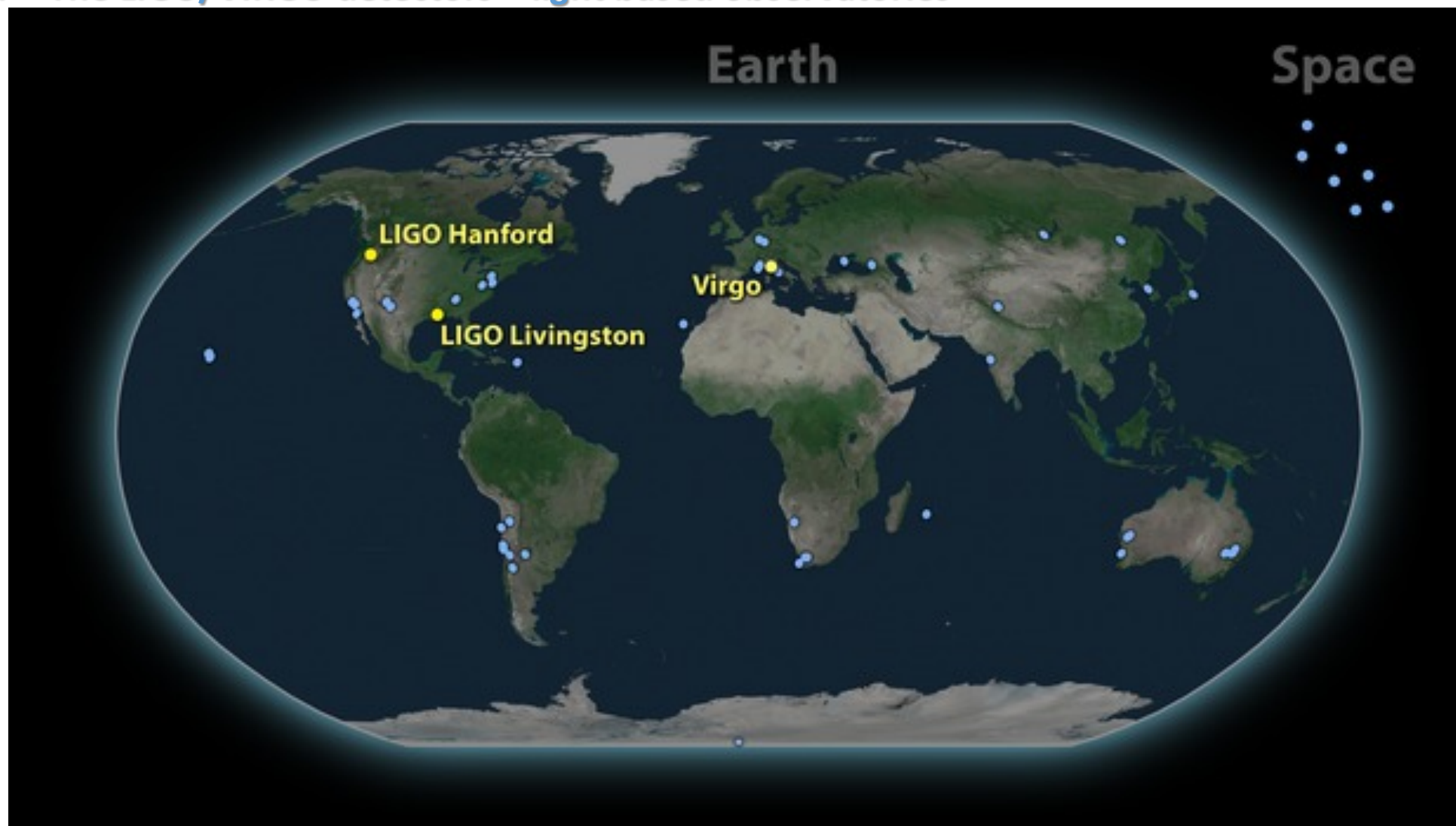
The era of the GW astronomy

2. The LIGO/VIRGO detectors + light based observatories



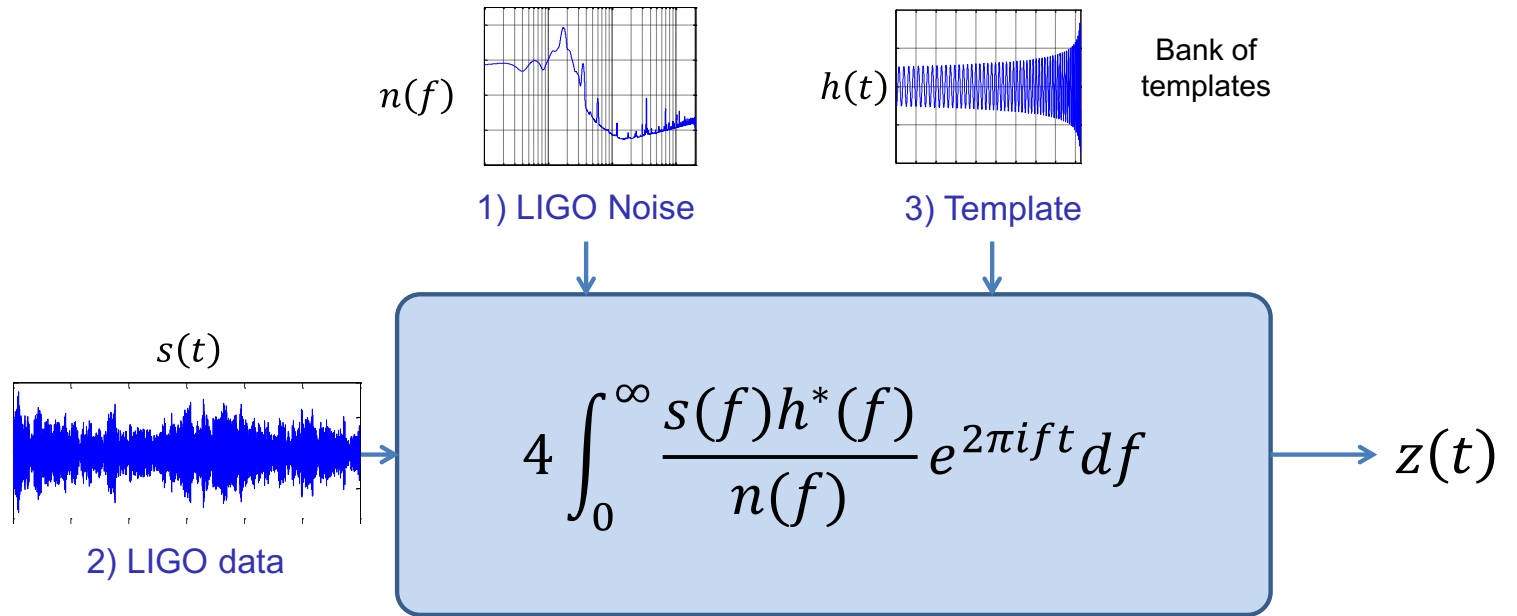
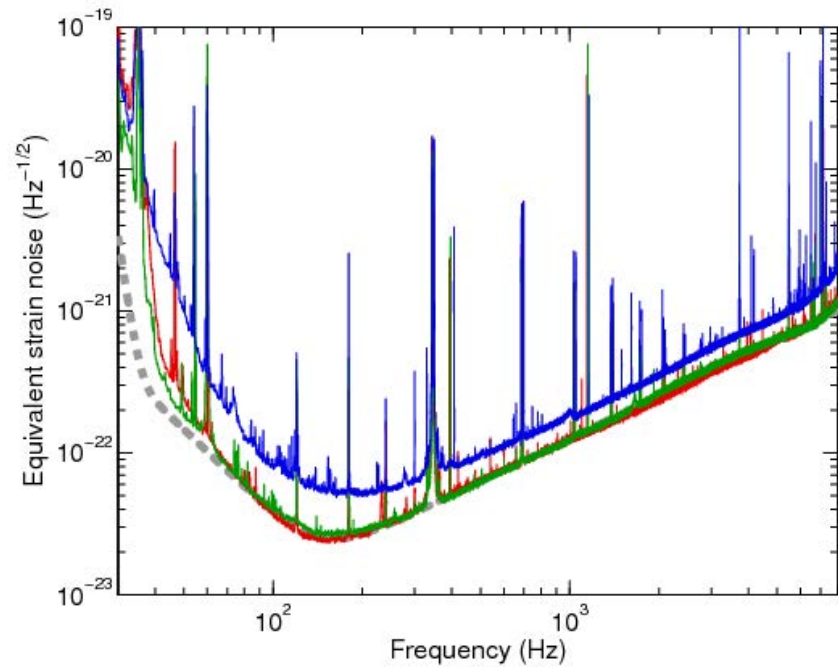
The era of the GW astronomy

2. The LIGO/VIRGO detectors + light based observatories

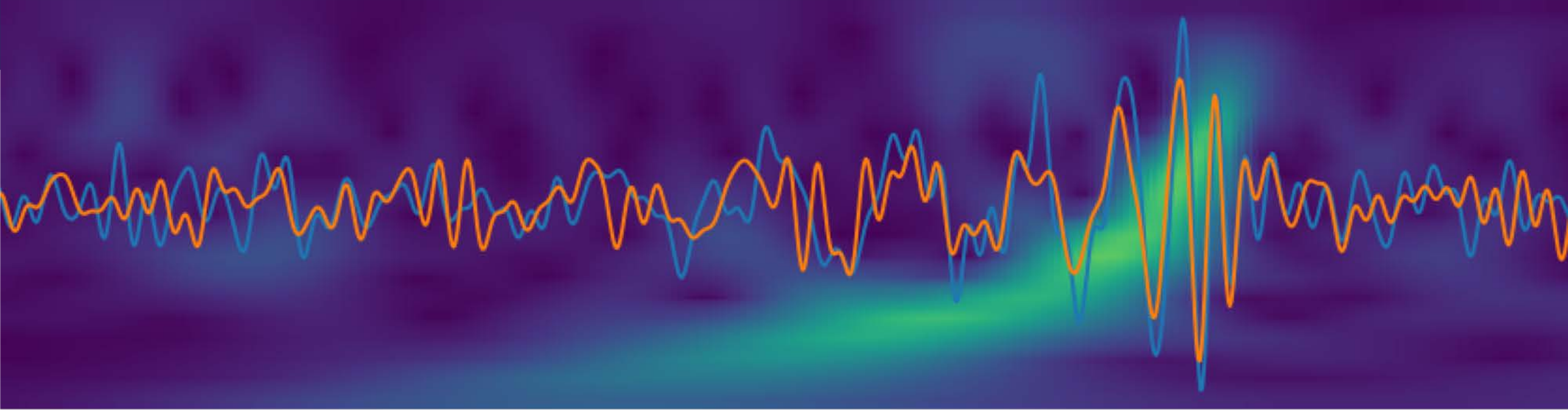


The era of the GW astronomy

3. The computational tools and the data analysis algorithms



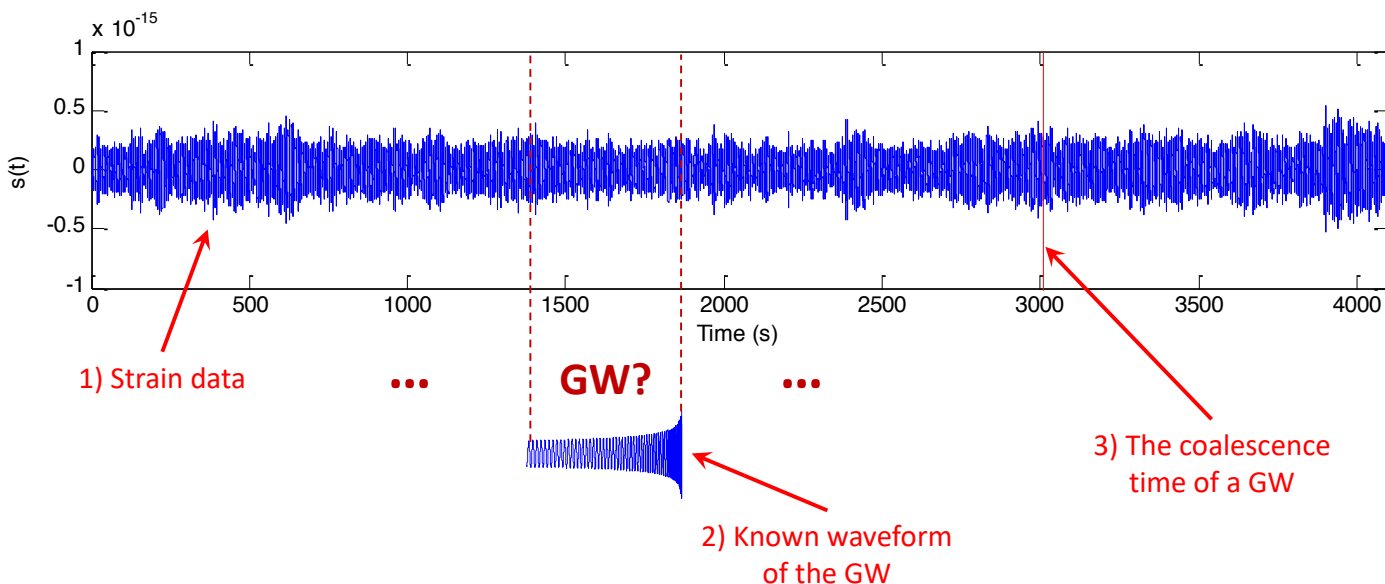
Detection and confirmation - **Localization** - **Parameter estimation**



Detection of GW from CBC

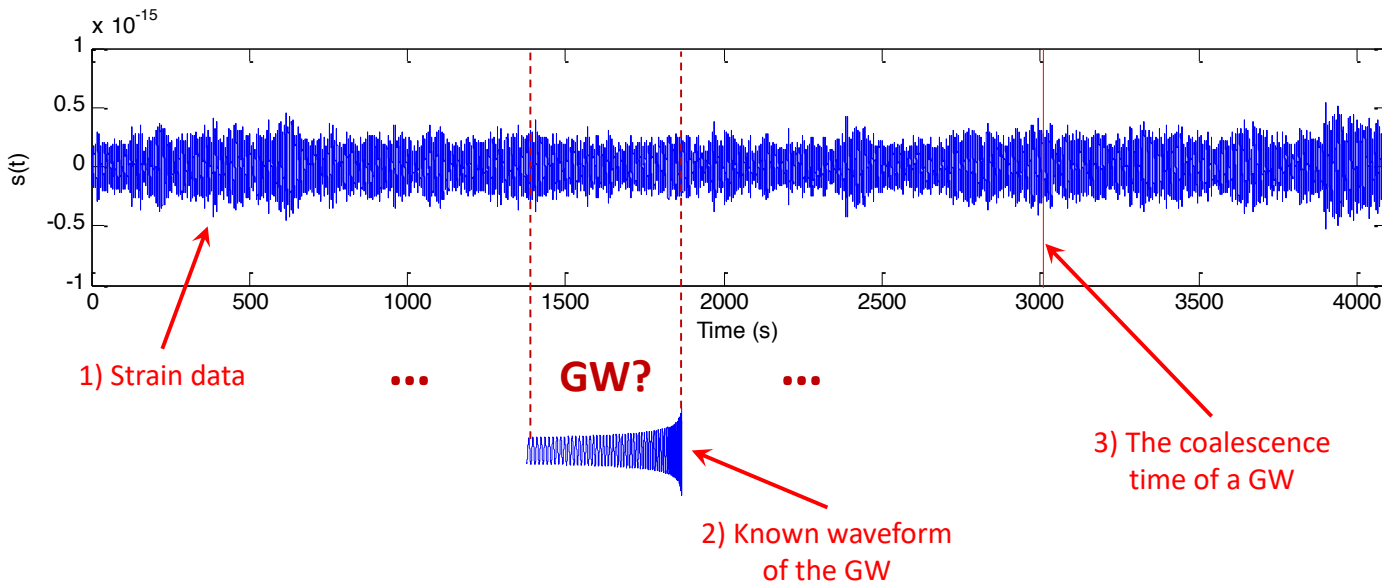
Detection of GW with known waveforms

Problem description



Detection of GW with known waveforms

Problem description



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

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

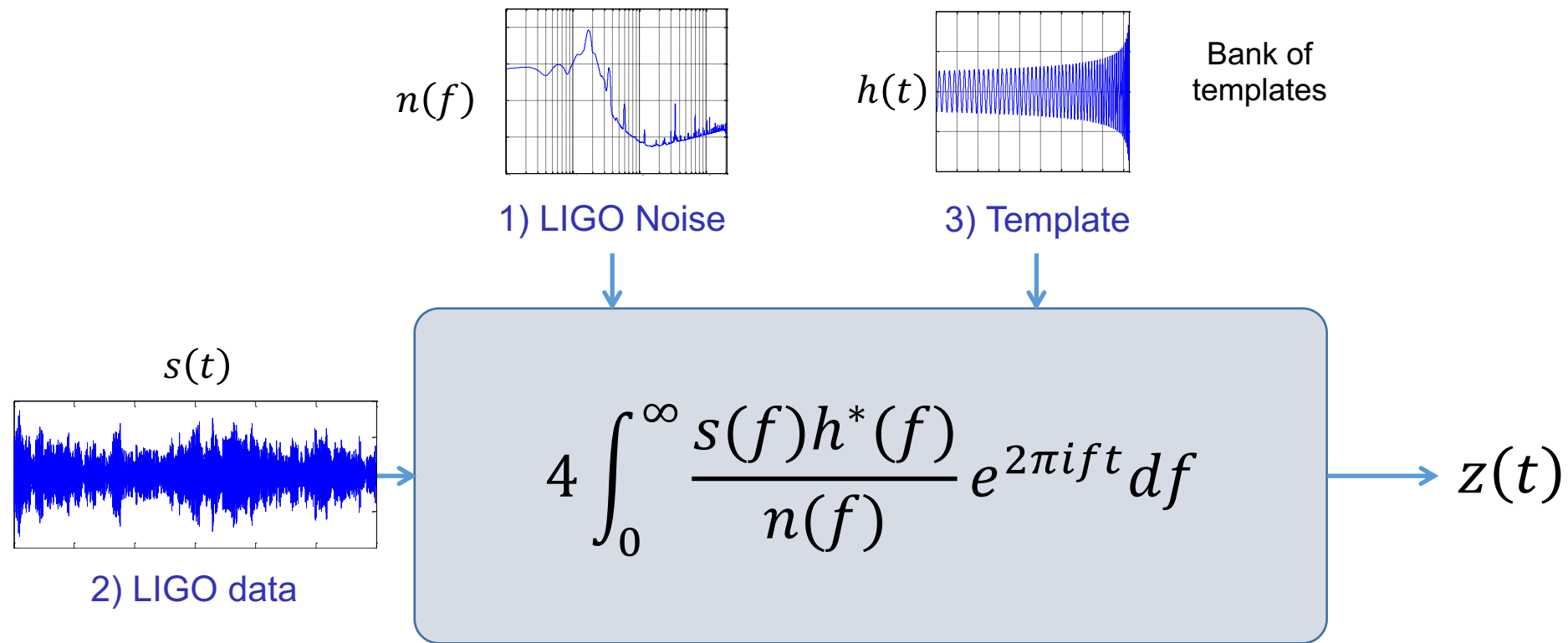
where,

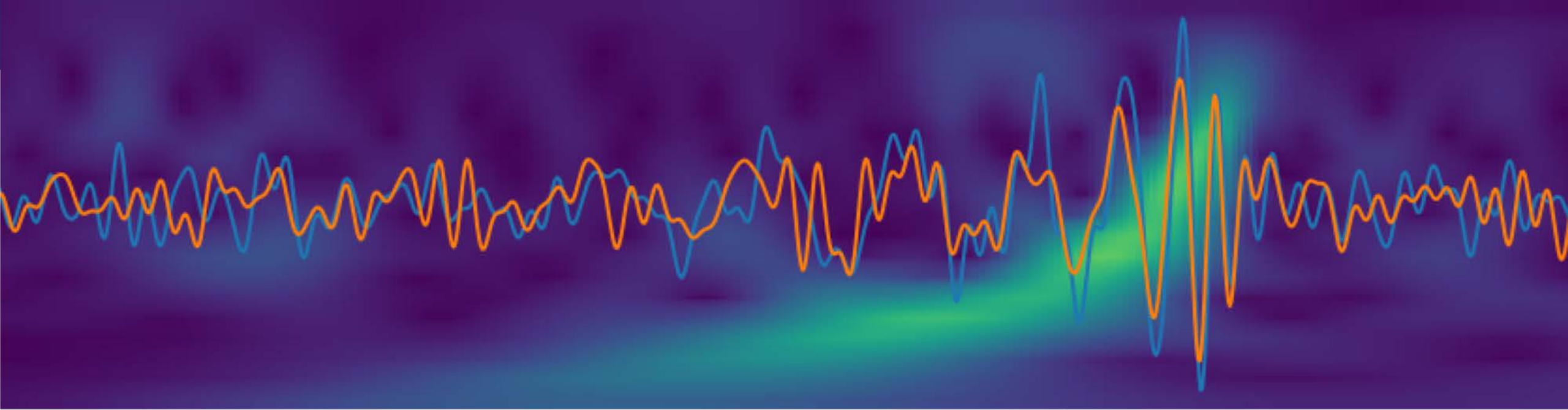
- $h(n) \Rightarrow$ known waveform of the GW
- $w(n) \Rightarrow$ noise in the detector (modelled with a PDF)

This is basically a problem of the *Detection theory*

Detection of GW with known waveforms

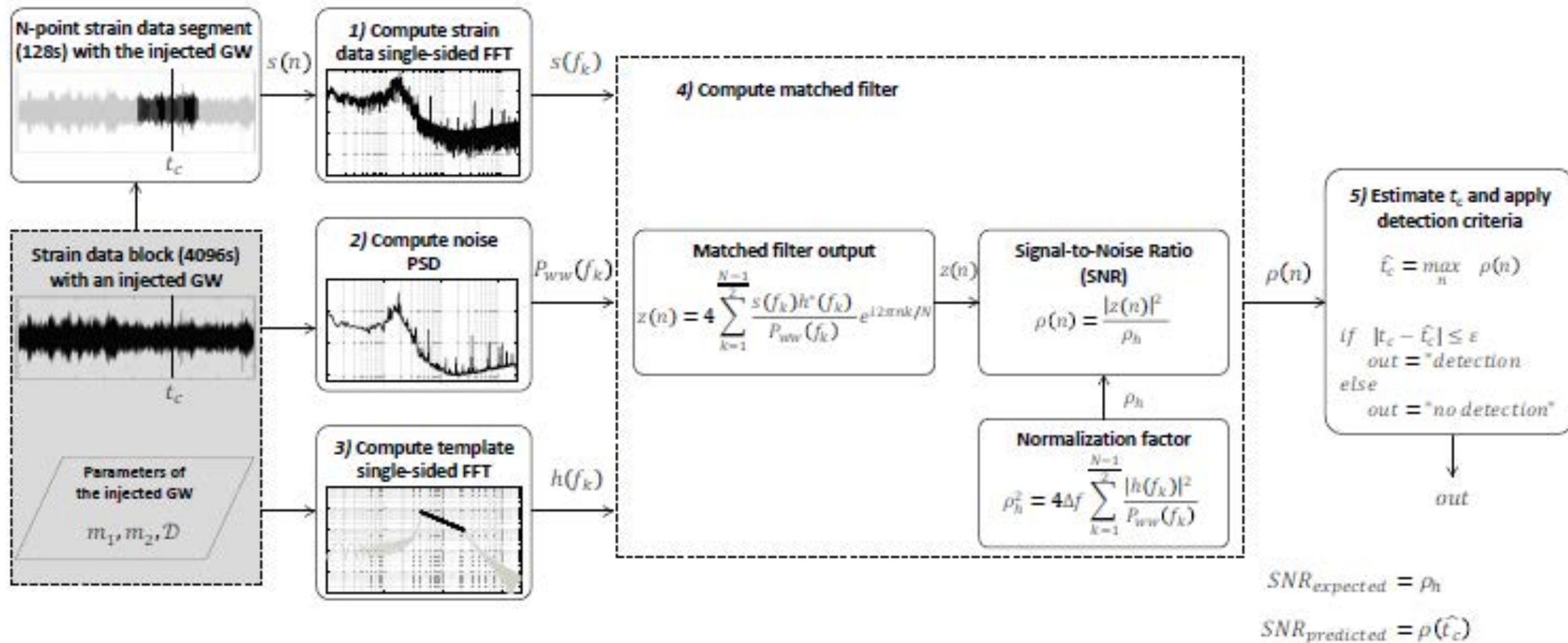
Matched filter





Some data analysis related projects
www.gravitationalwaves.mx

Recovering CBC GW injections

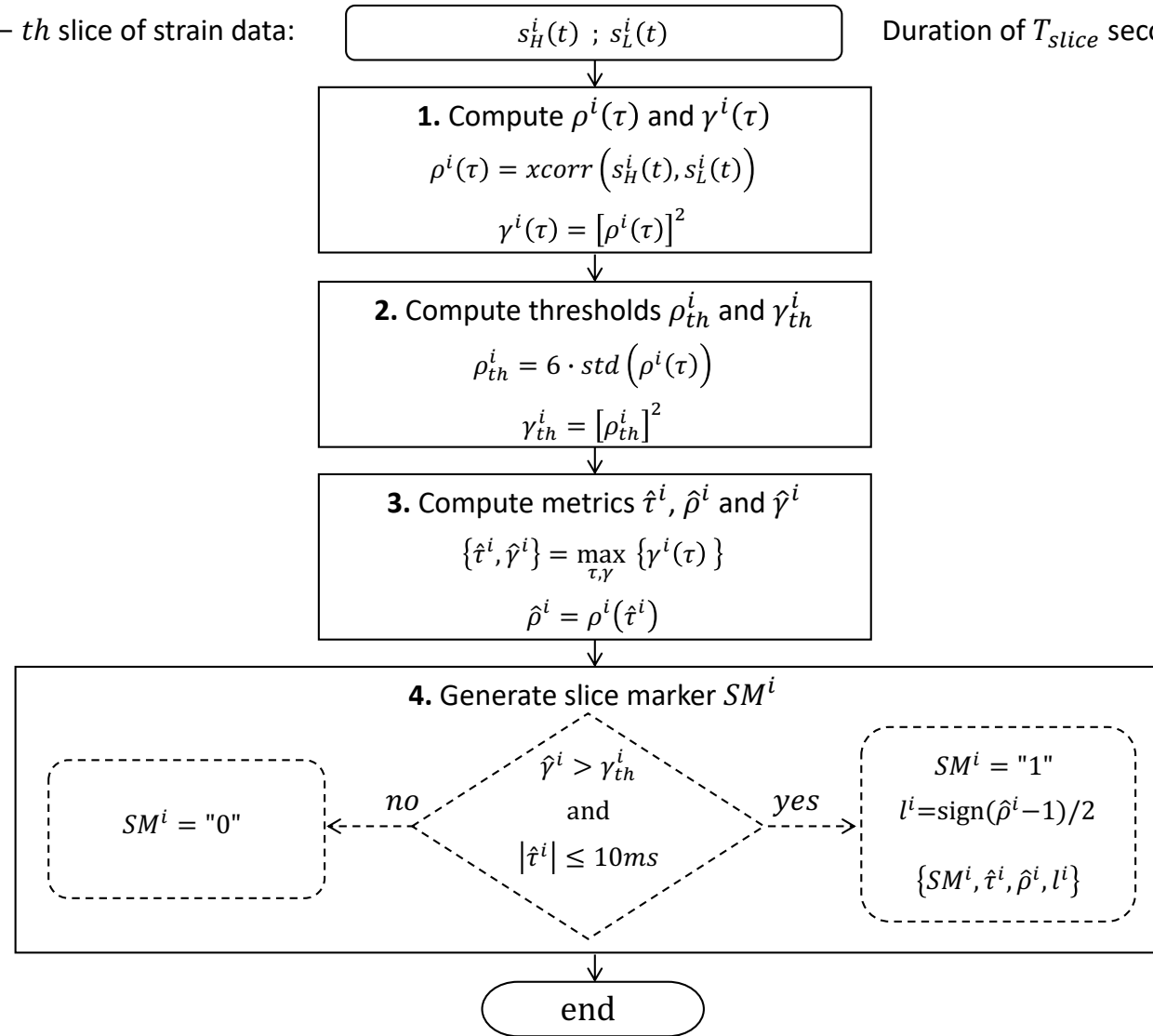


Independent search of GW in LIGO O1 data

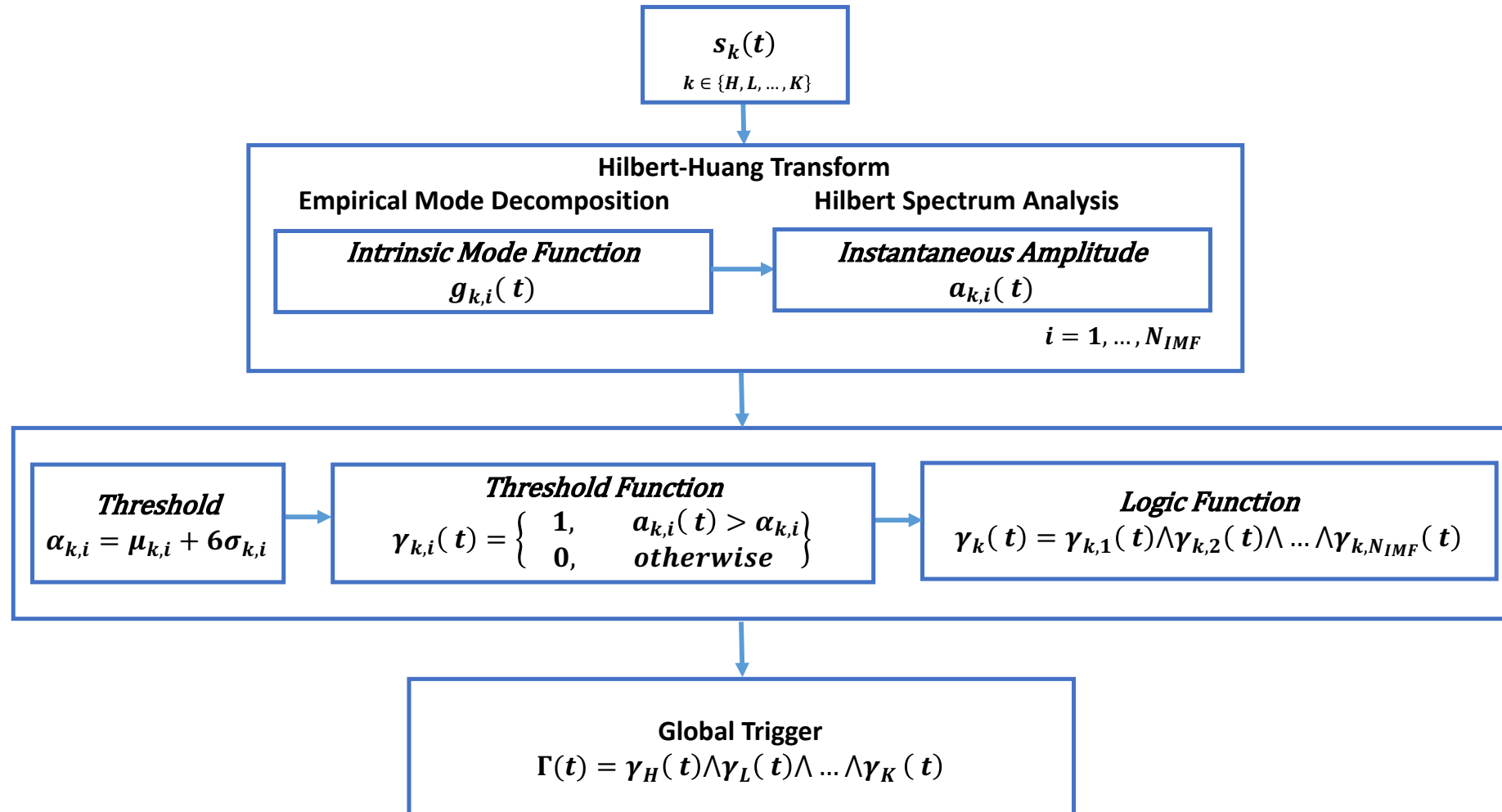
i – th slice of strain data:

$s_H^i(t) ; s_L^i(t)$

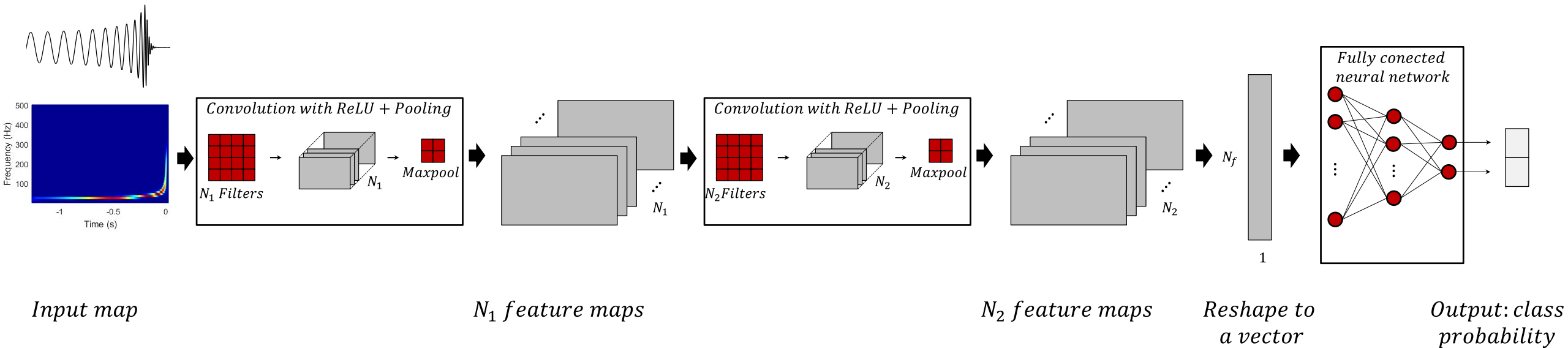
Duration of T_{slice} seconds



A new method for the detection using HHT

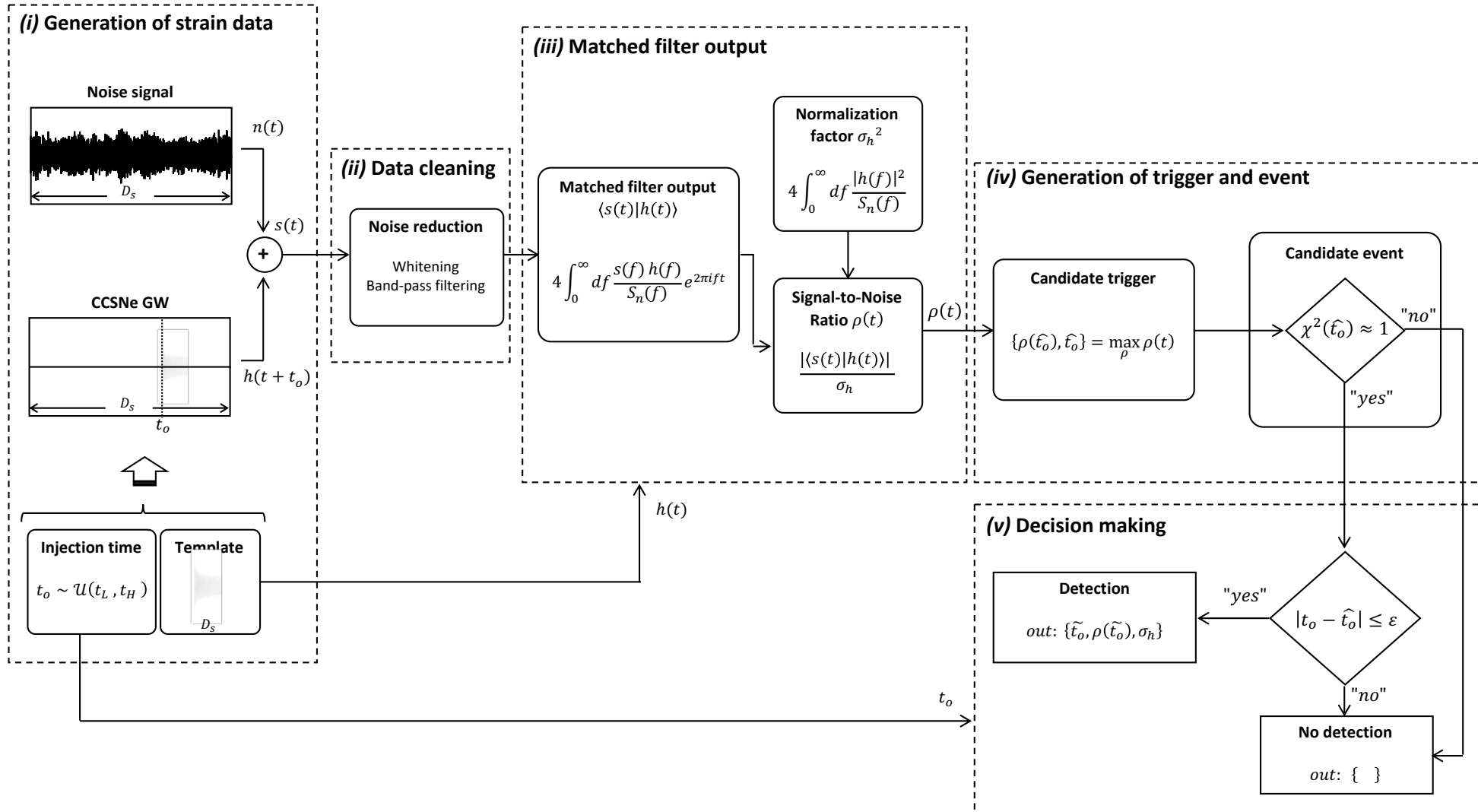


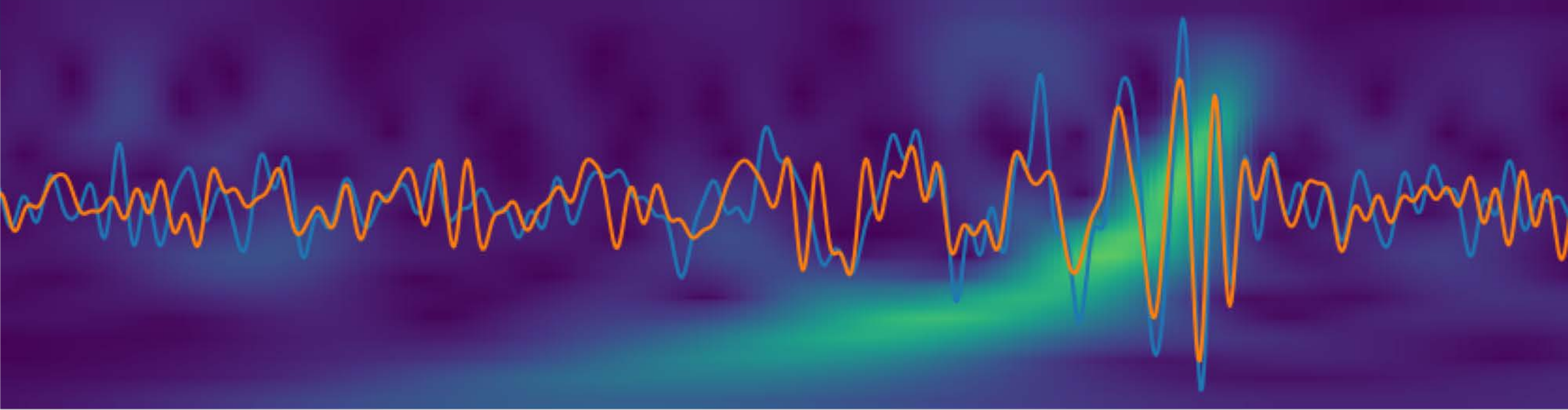
Deep Learning for detection and estimation



- 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 !