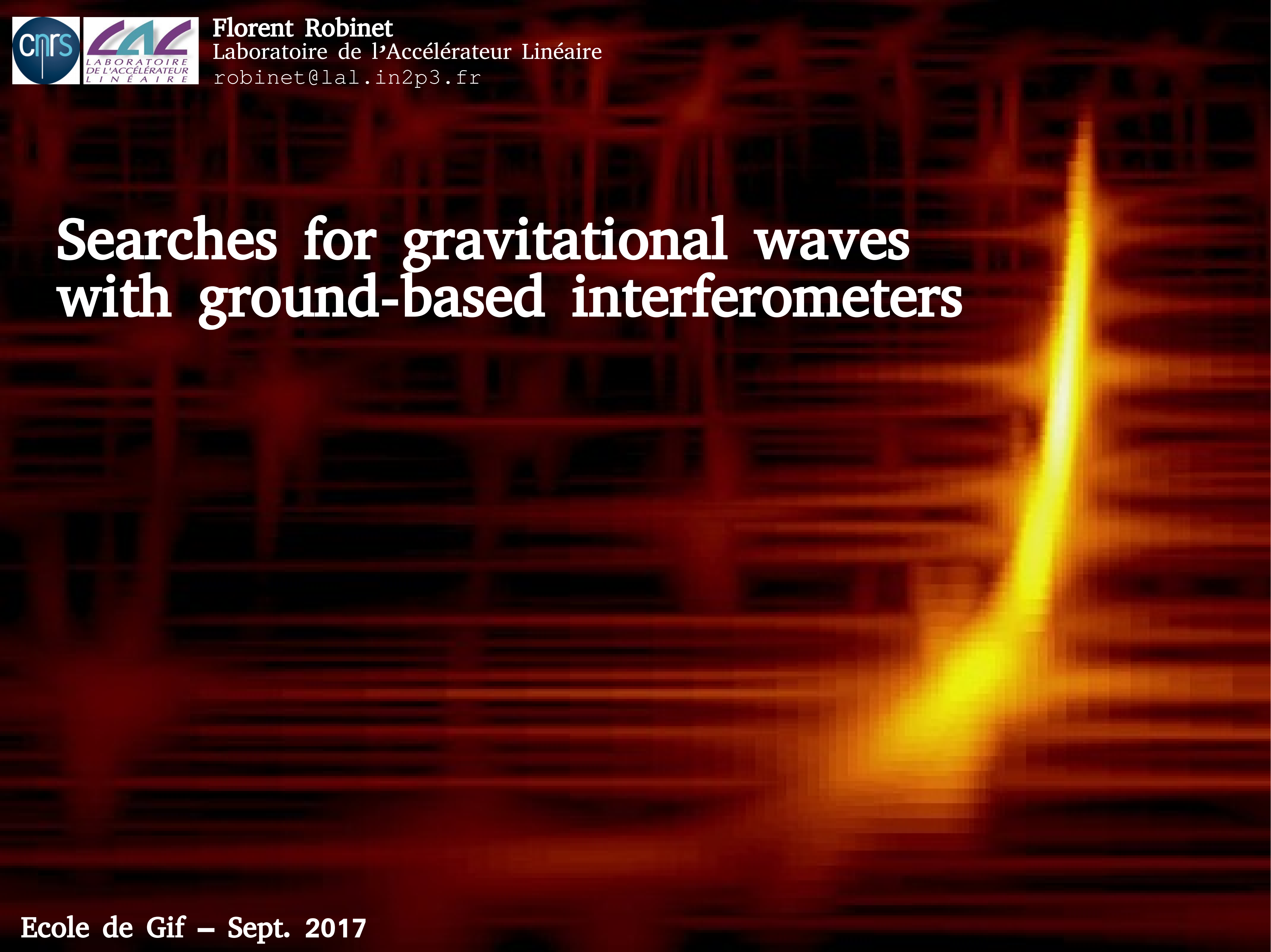
Florent Robinet
Laboratoire de l'Accélérateur Linéaire
robinet@lal.in2p3.fr



Searches for gravitational waves with ground-based interferometers

Ecole de Gif – Sept. 2017

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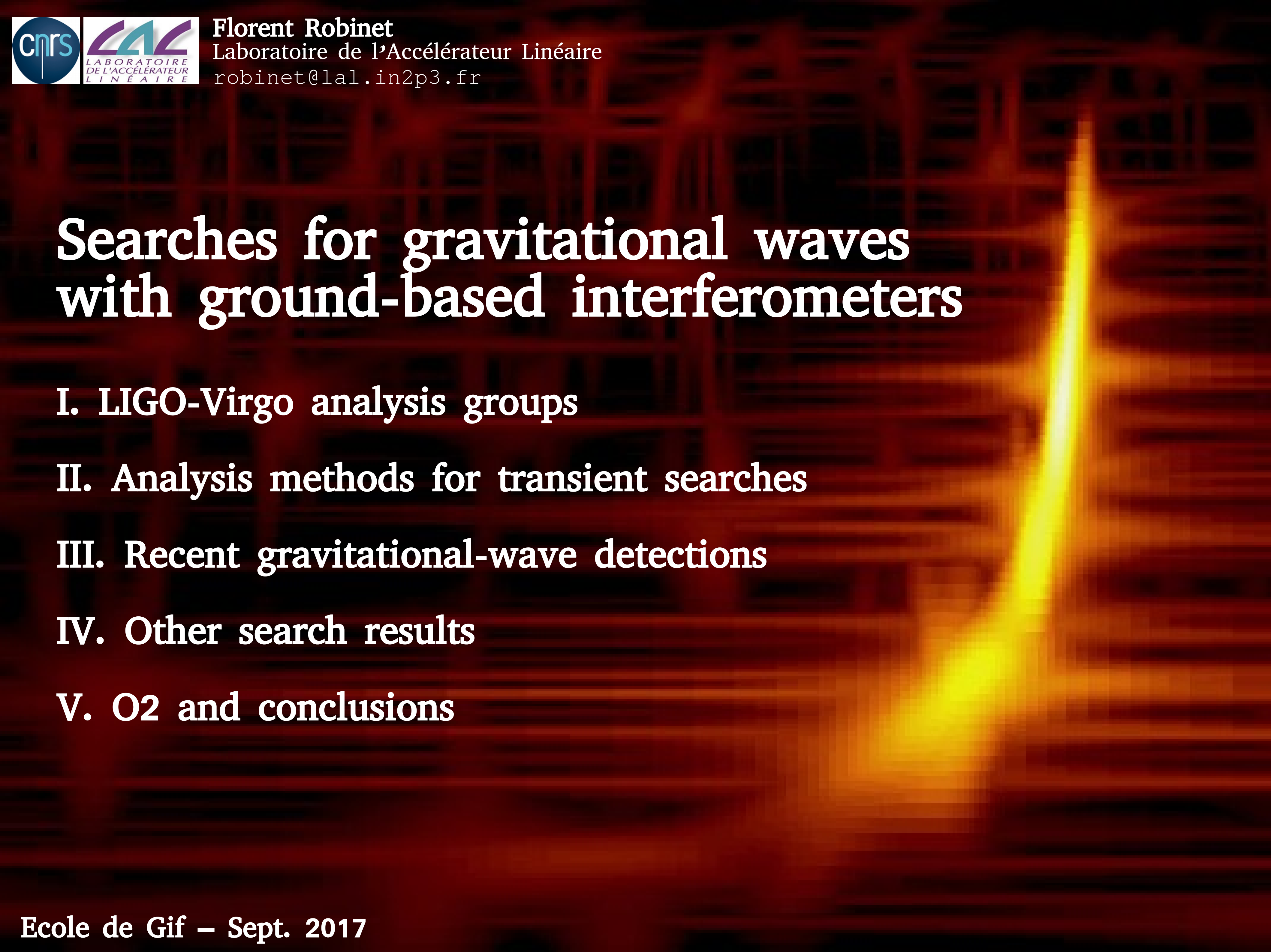


Searches for gravitational waves with ground-based interferometers

I. LIGO-Virgo analysis groups

II. Analysis methods for transient searches

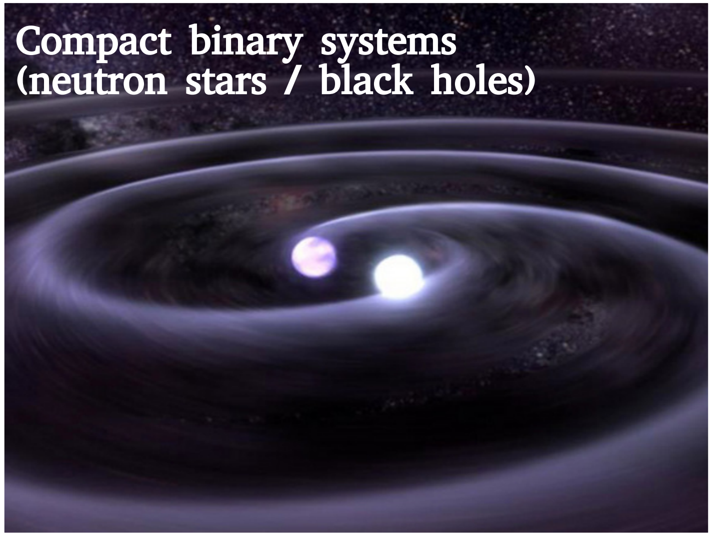
III. Recent gravitational-wave detections

IV. Other search results

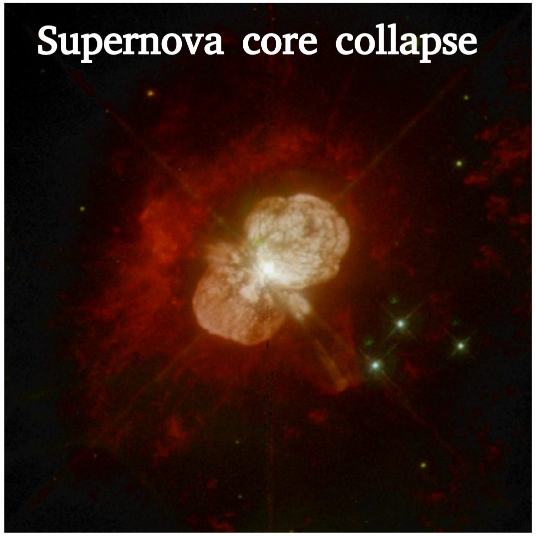
V. O2 and conclusions

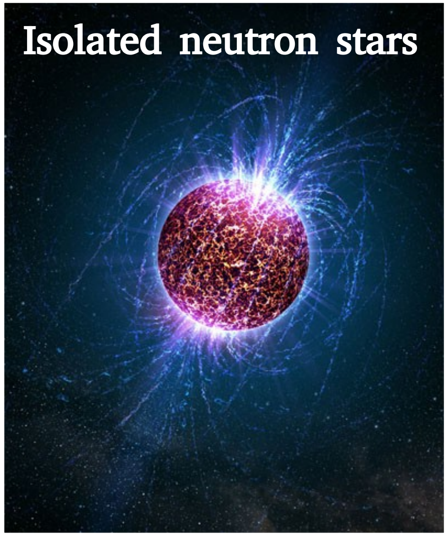
Ecole de Gif – Sept. 2017

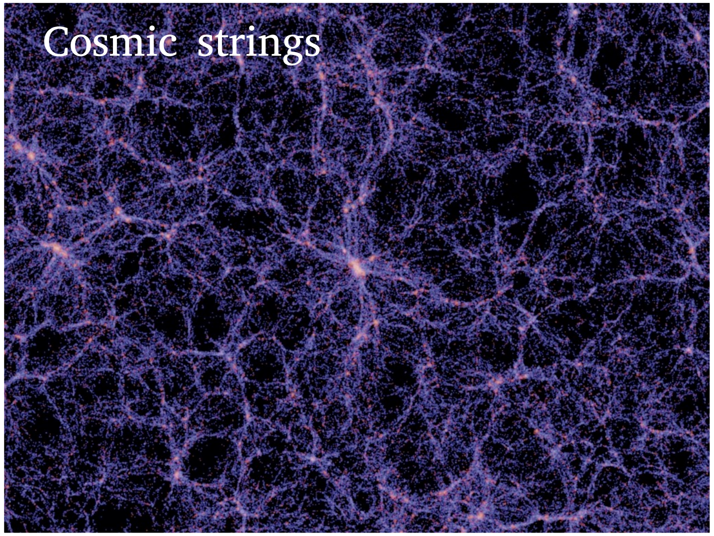
Relevant GW Sources: 10 Hz < f_{GW} < 10000 Hz

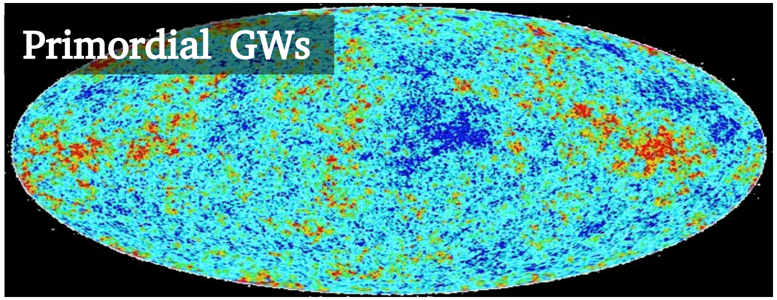

Compact binary systems
(neutron stars / black holes)


newly-formed black holes


Supernova core collapse


Isolated neutron stars


Cosmic strings


Primordial GWs

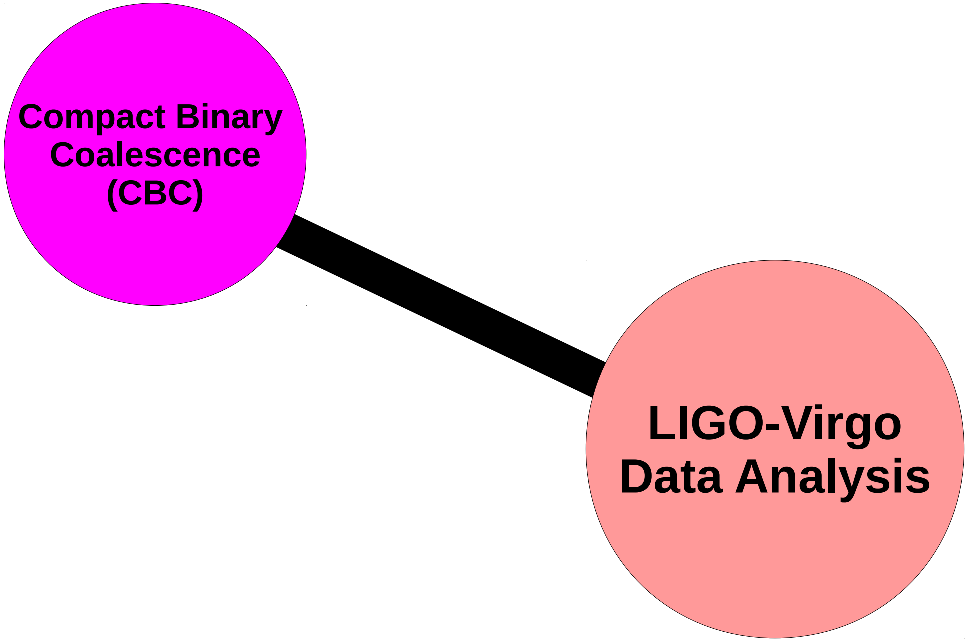
Unknown sources

?

LIGO-Virgo analysis groups

LIGO-Virgo Data Analysis

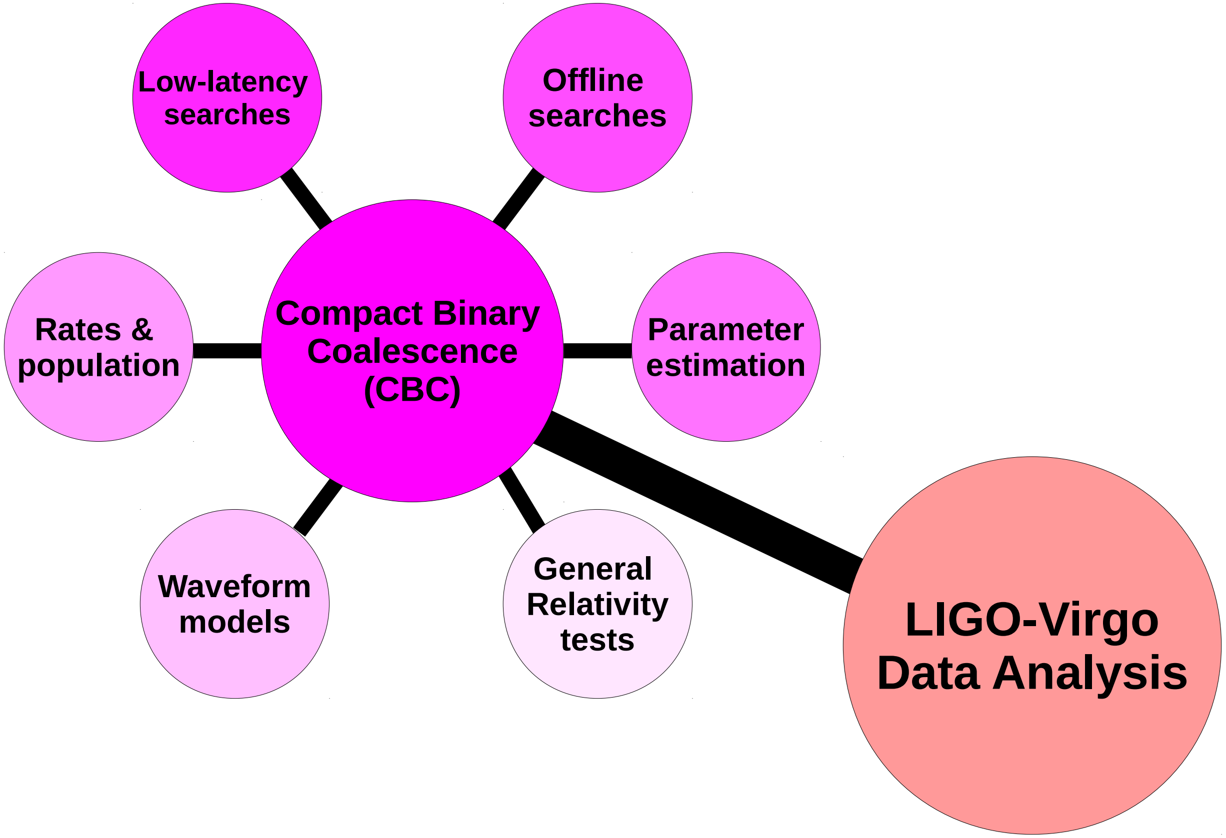
LIGO-Virgo analysis groups



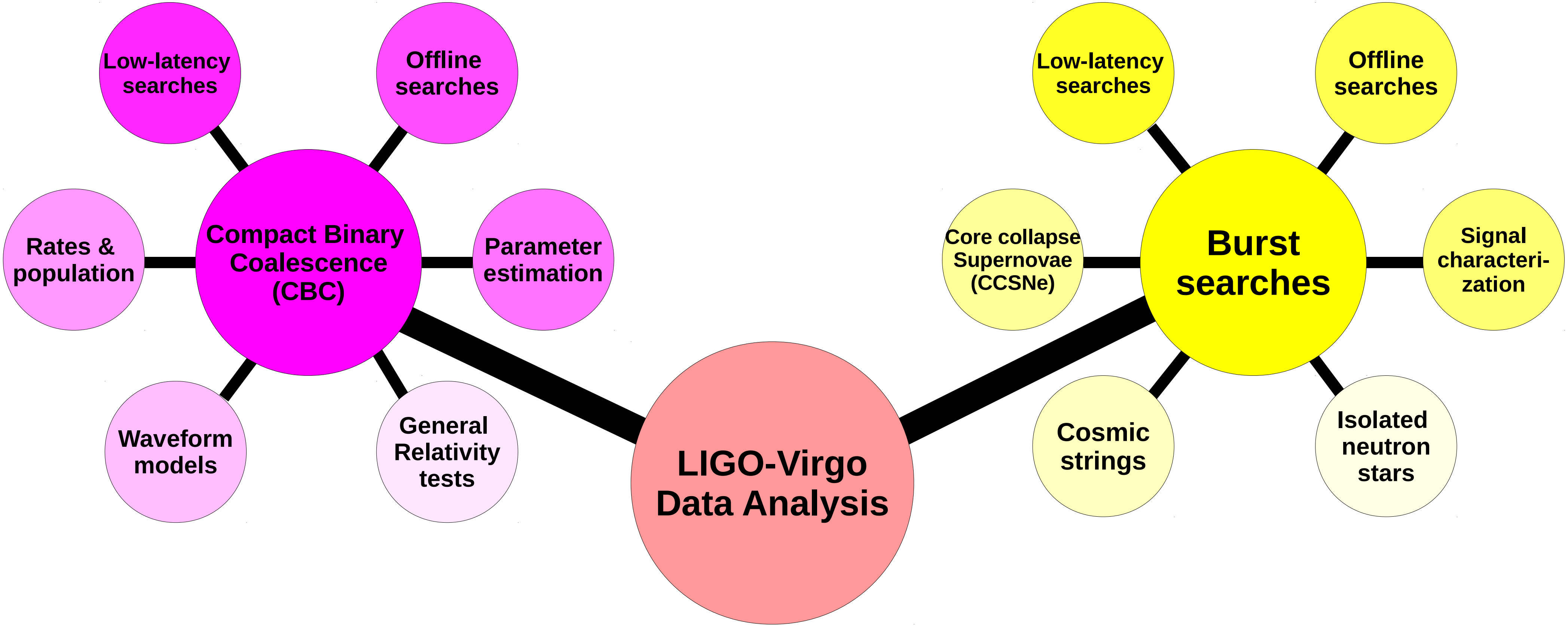
Compact Binary Coalescence (CBC)

LIGO-Virgo Data Analysis

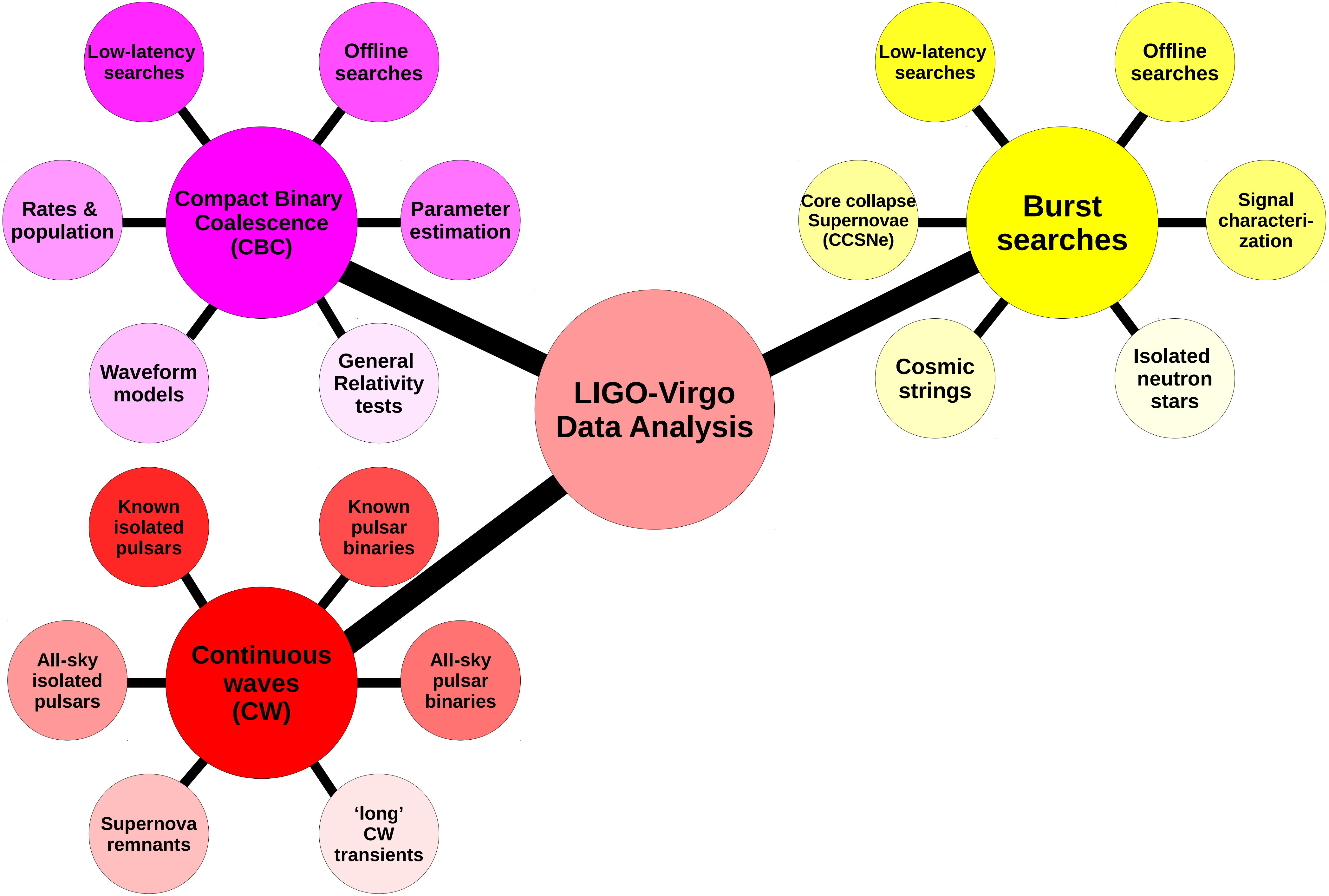
LIGO-Virgo analysis groups



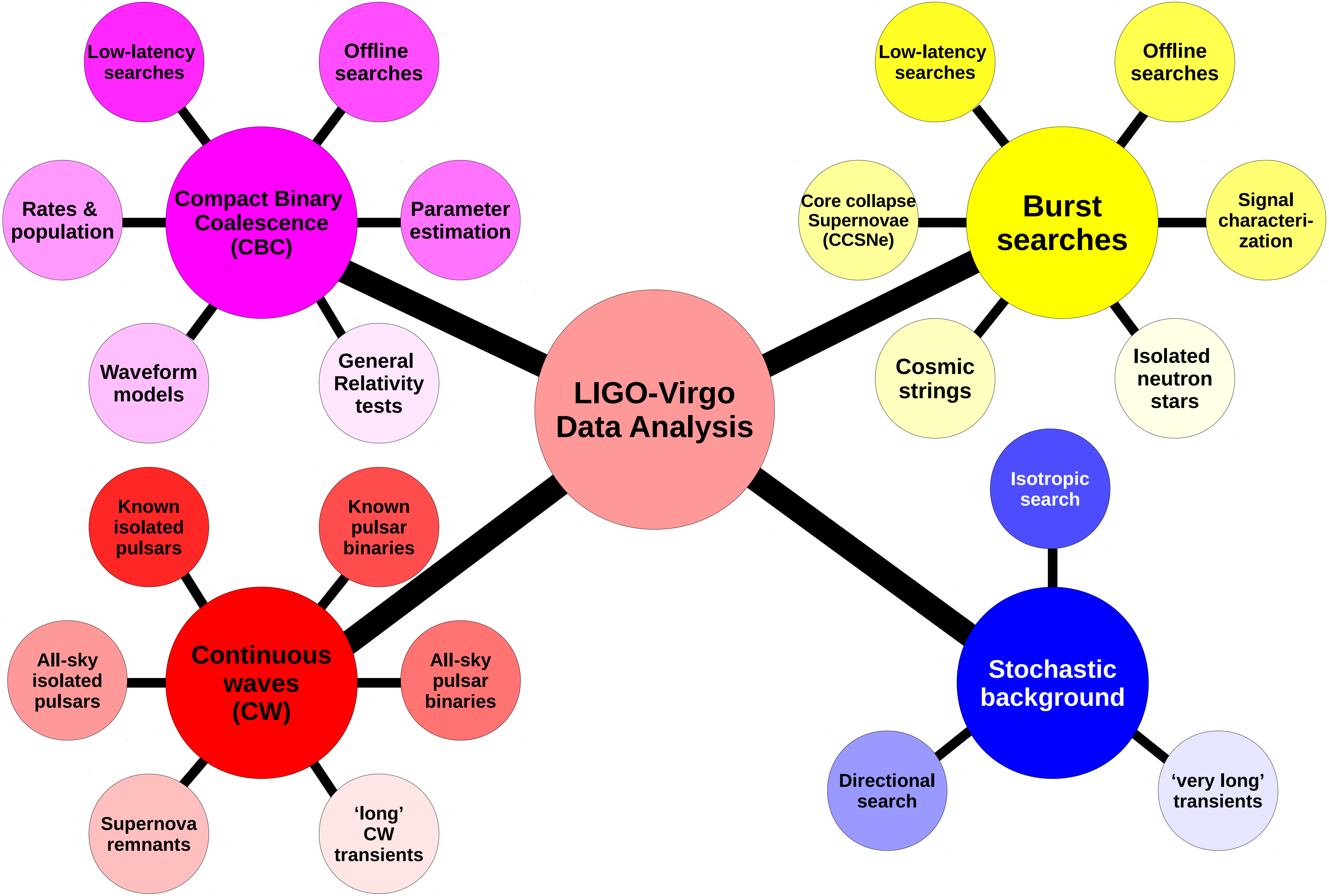
LIGO-Virgo analysis groups



LIGO-Virgo analysis groups

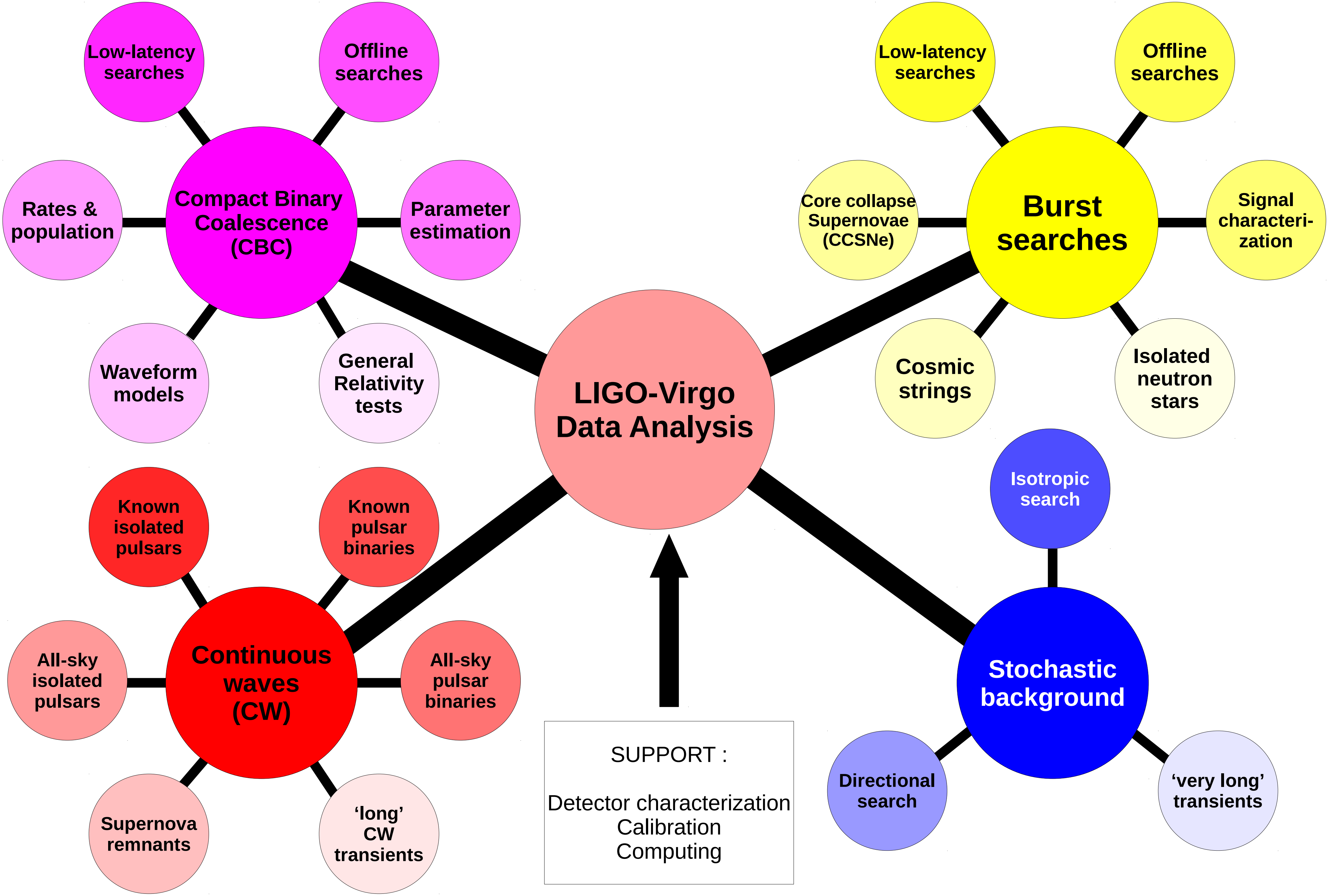


LIGO-Virgo analysis groups



- LIGO-Virgo Data Analysis
  - Compact Binary Coalescence (CBC)
    - Low-latency searches
    - Offline searches
    - Parameter estimation
    - General Relativity tests
    - Waveform models
    - Rates & population
  - Burst searches
    - Low-latency searches
    - Offline searches
    - Signal characteri-zation
    - Isolated neutron stars
    - Cosmic strings
    - Core collapse Supernovae (CCSNe)
  - Continuous waves (CW)
    - Known isolated pulsars
    - Known pulsar binaries
    - All-sky pulsar binaries
    - 'long' CW transients
    - Supernova remnants
    - All-sky isolated pulsars
  - Stochastic background
    - Isotropic search
    - 'very long' transients
    - Directional search

LIGO-Virgo analysis groups



LIGO-Virgo Data Analysis

- **Compact Binary Coalescence (CBC)**
  - Low-latency searches
  - Offline searches
  - Rates & population
  - Parameter estimation
  - Waveform models
  - General Relativity tests
- **Burst searches**
  - Low-latency searches
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  - Isotropic search
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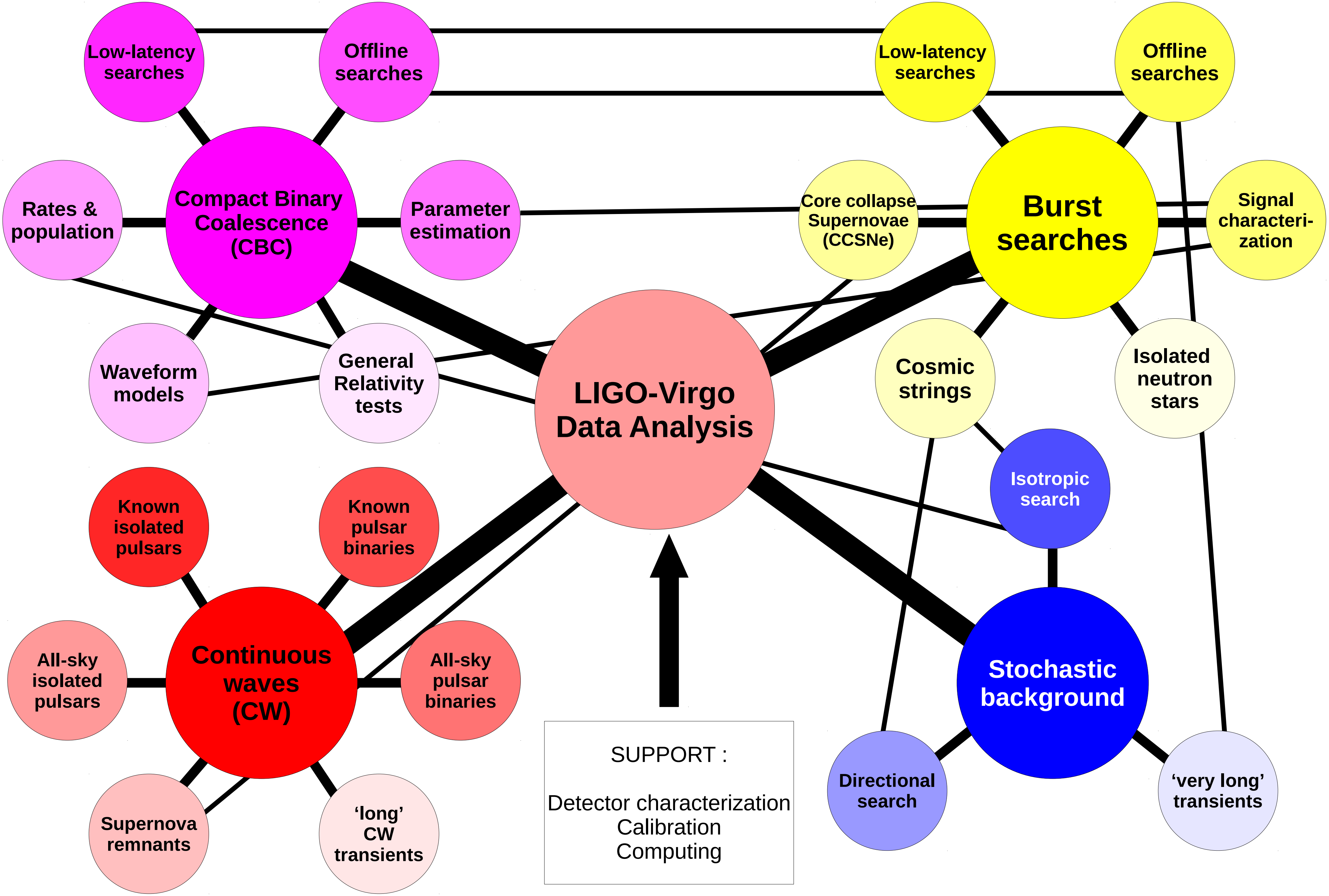
  - ‘very long’ transients

SUPPORT :

Detector characterization
Calibration
Computing

LIGO-Virgo analysis groups



SUPPORT :

Detector characterization
Calibration
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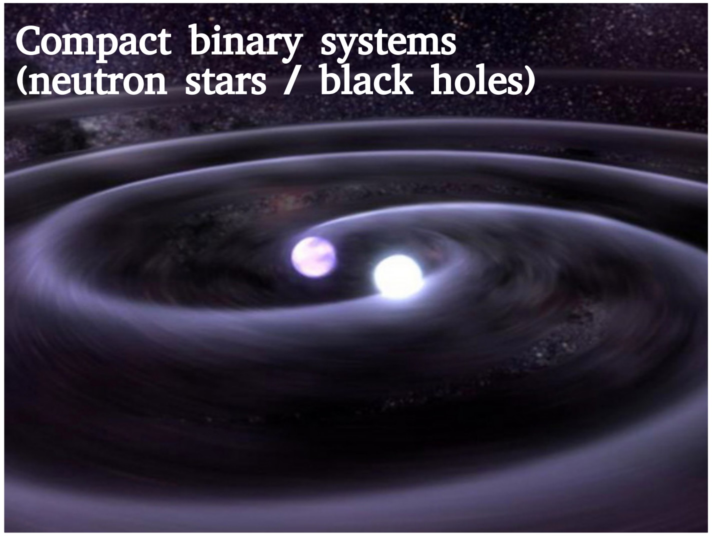
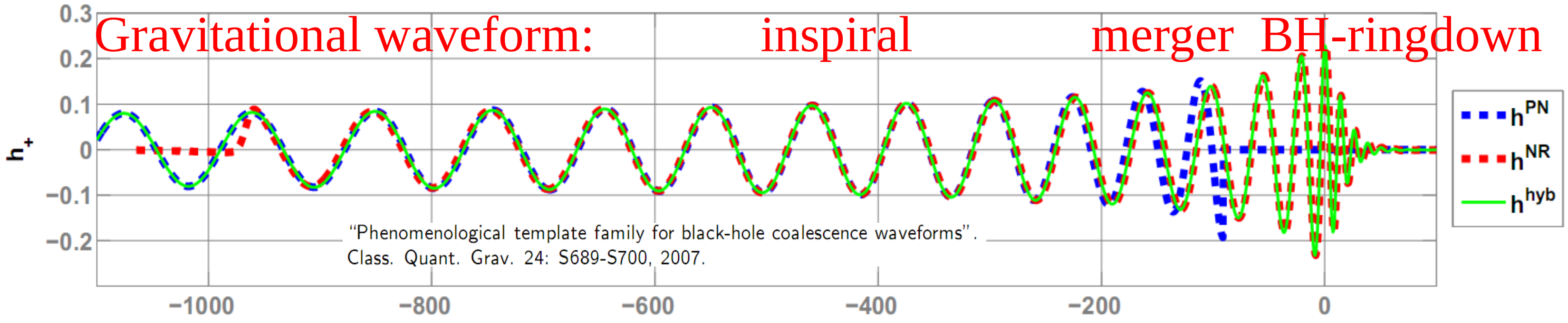
CBC searches



Compact binary systems (neutron stars / black holes)

- Compact binary objects: Two neutron stars and/or black holes.
- Inspiral toward each other. Emit gravitational waves as they inspiral.
- Amplitude and frequency of the waves increases over time, until the merger.
- Waveform relatively well understood, → matched template searches.
- Unique way to study string field gravity and the structure of the nuclear matter in the most extreme conditions

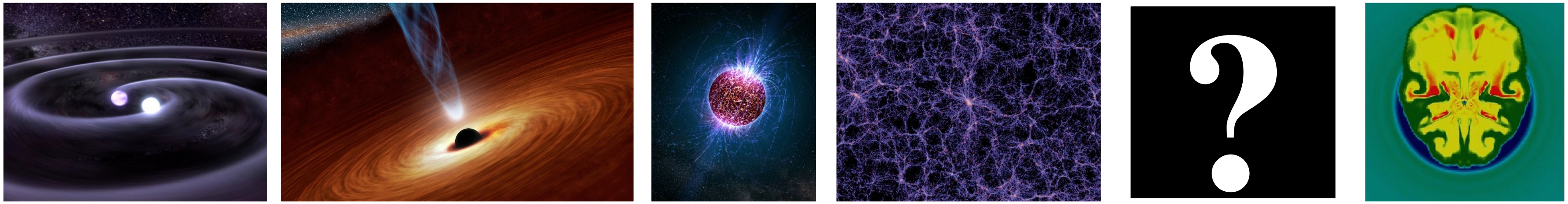


Gravitational waveform: inspiral merger BH-ringdown

"Phenomenological template family for black-hole coalescence waveforms". Class. Quant. Grav. 24: S689-S700, 2007.

Waveform carries lots of information about binary masses, orbit, merger, spins, ...

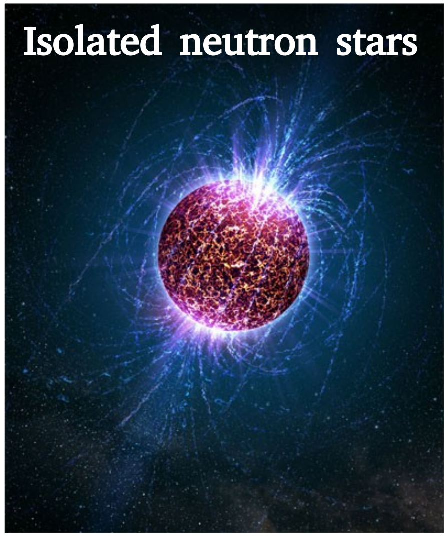
Burst searches

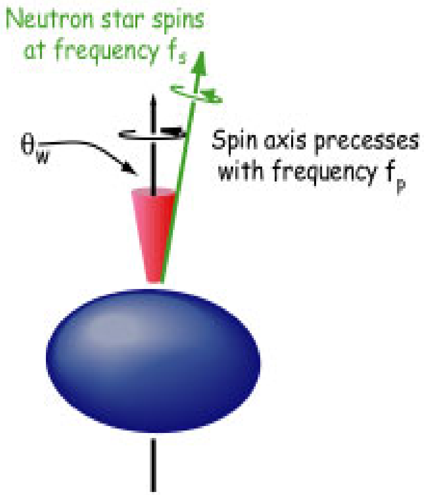


- Many transient sources:
    - CBC
    - Supernovae: probe the explosion mechanisms.
    - Gamma Ray Bursts: collapse of rapidly rotating massive stars or neutron star mergers.
    - Pulsar glitches.
    - Cosmic strings cusps and kinks.

- Models are ok, but not essential:
    - Search for power excess in the data.
    - Search for any short signal with measurable strain signal.

Pulsar searches





Persistent signals associated to sources with mass quadrupole moment varying in time in a nearly periodic way

- Pulsars with mass non-uniformity:
  - distortion due to elastic stresses or magnetic field
  - distortion due to matter accretion
  - free precession around rotation axis
  - excitation of long-lasting oscillations (e.g. r-modes)
- Produce gravitational-waves, often at twice the rotational frequency.
- Waveform well-understood:
  - Sinusoidal but Doppler modulated
- Continuous source

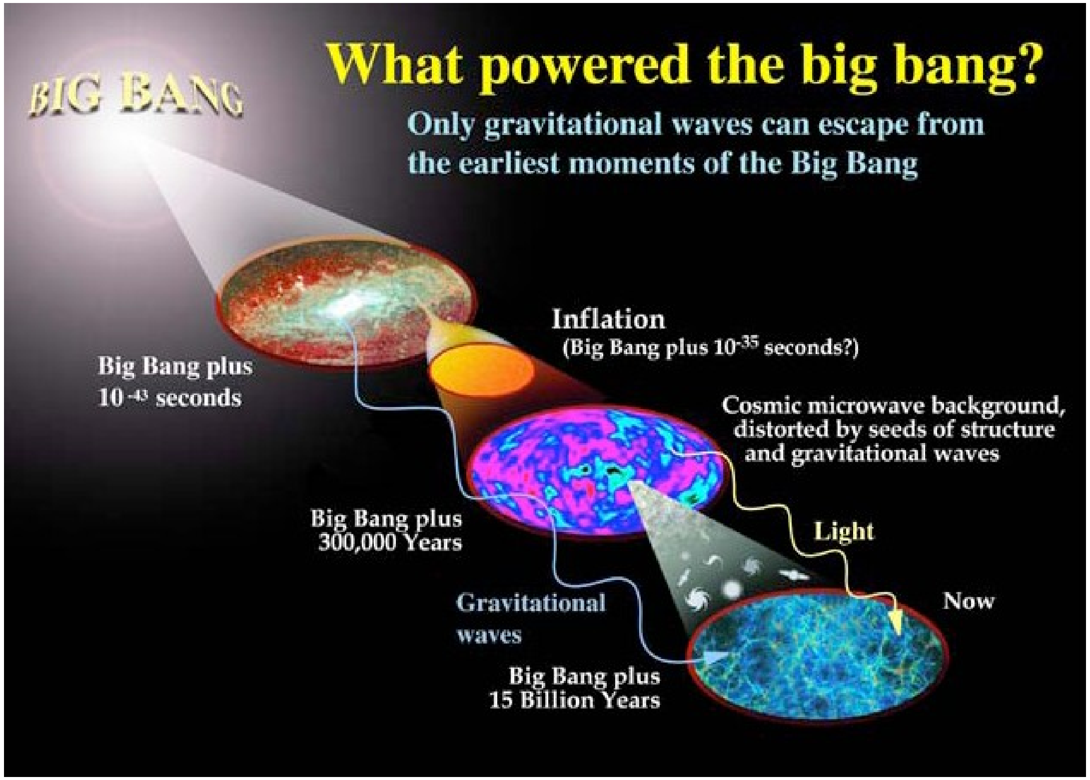
Signal amplitude:

$$h_0 \cong 10^{-27}\left(\frac{I_{zz}}{10^{38}\,kg\cdot m^2}\right)\left(\frac{10kpc}{r}\right)\left(\frac{f}{100Hz}\right)^2\left(\frac{\varepsilon}{10^{-6}}\right)$$

ε : ellipticity (adimensional number measuring the star's degree of asymmetry)
f : signal frequency, proportional to star rotation frequency

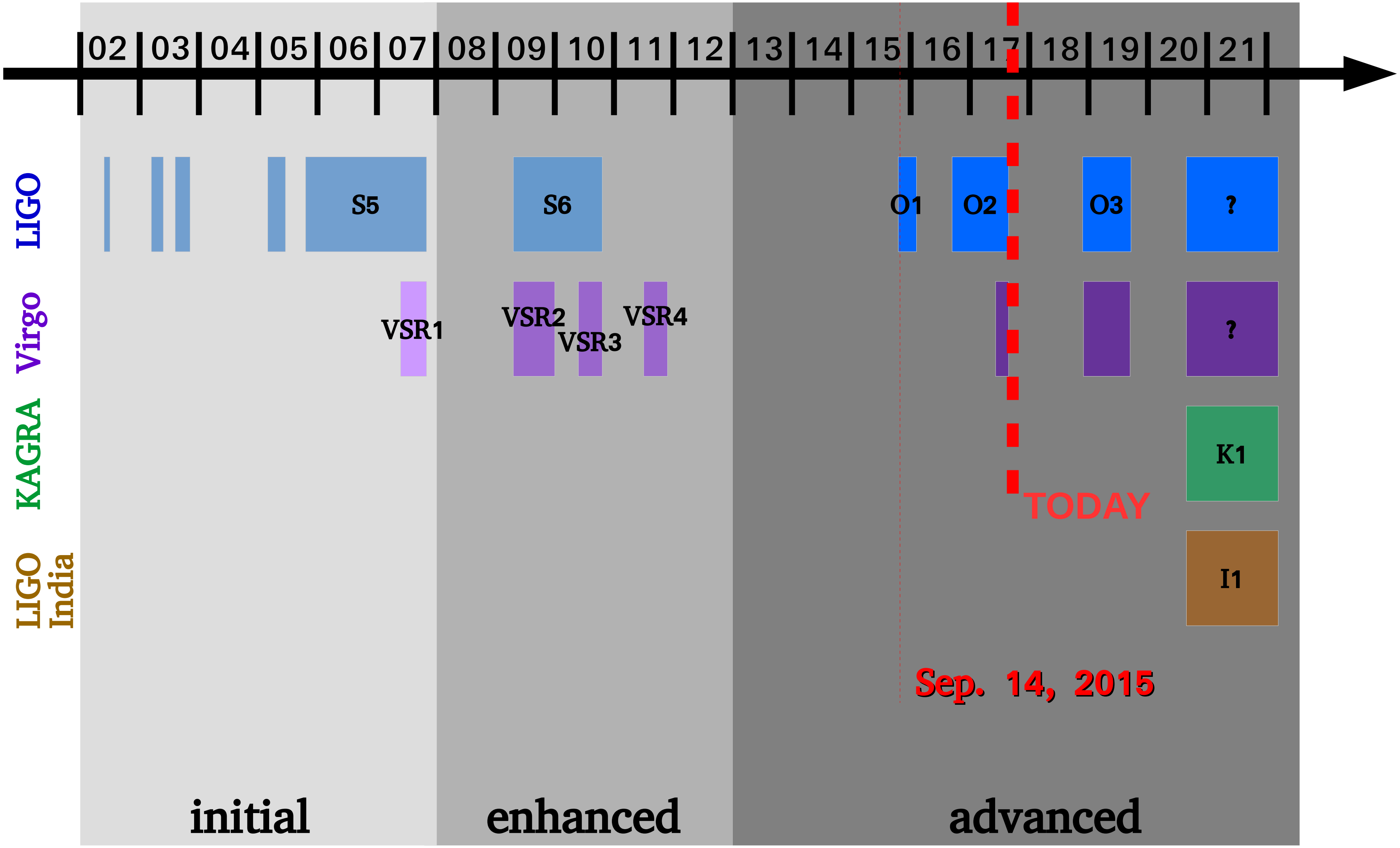
Stochastic background searches

- Incoherent superposition of many unresolved sources.
- Cosmological:
  - Inflationary epoch, preheating, reheating
  - Phase transitions
  - Cosmic strings
  - Alternative cosmologies
- Astrophysical:
  - Supernovae
  - Magnetars
  - Binary black holes
- Potentially could probe physics of the very-early Universe.

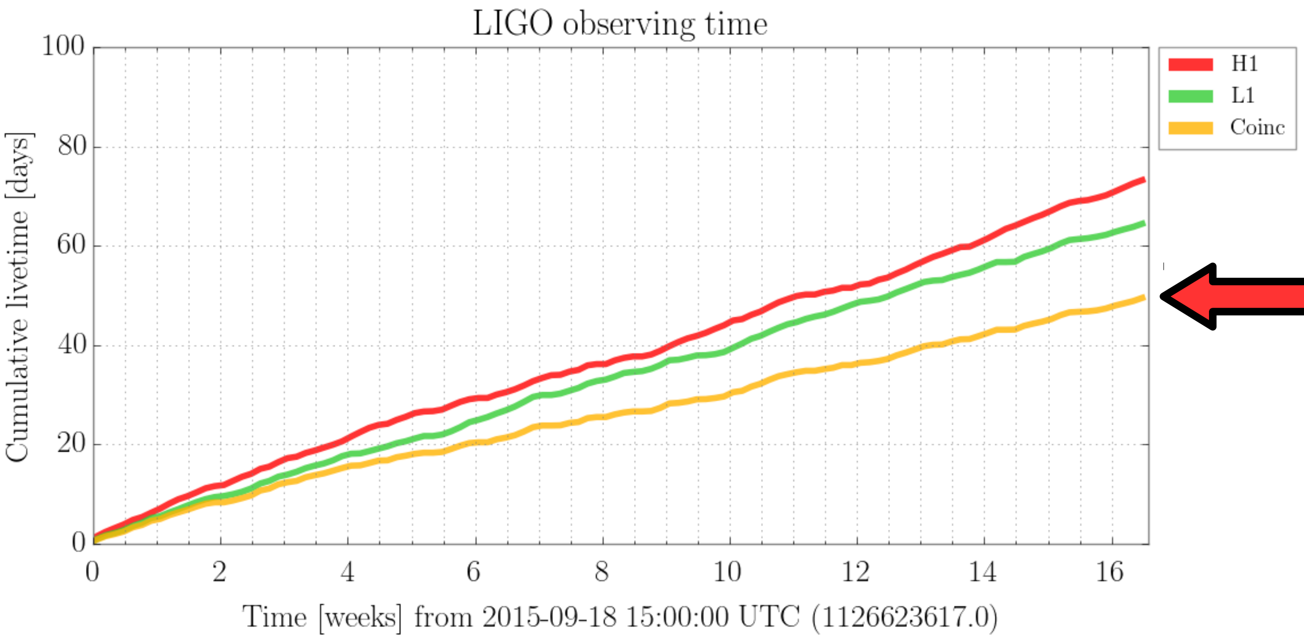


$$\Omega_{GW}(f) = \frac{f}{\rho_c}\frac{d\rho_{GW}}{df}$$

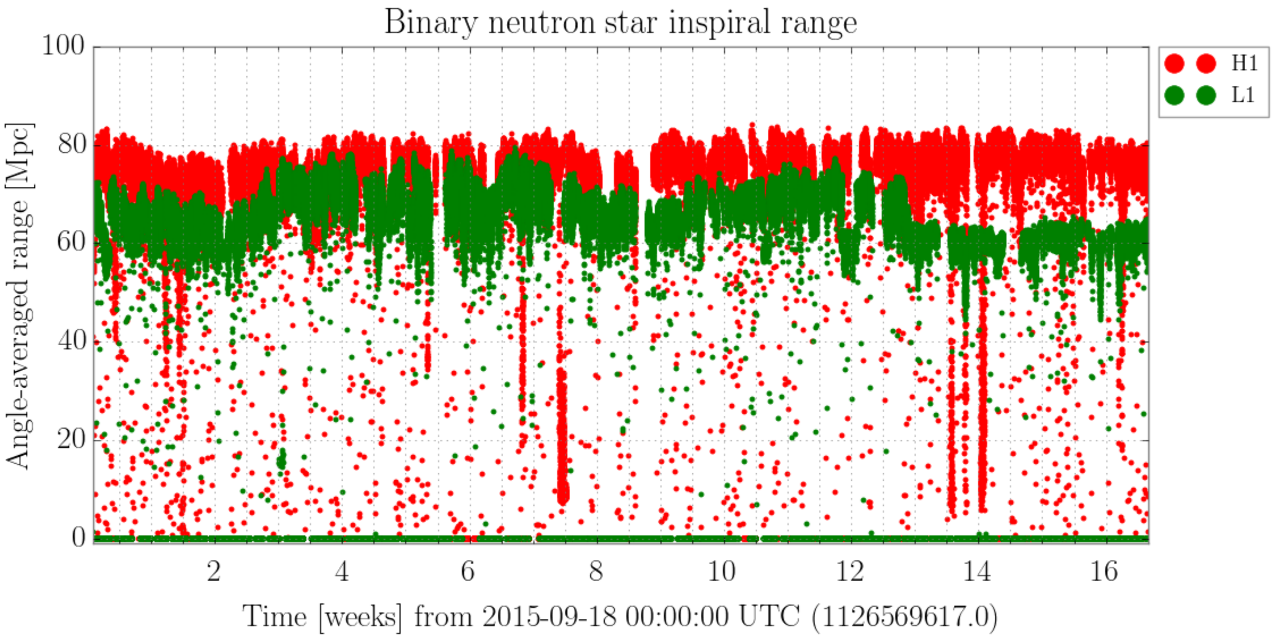
20 years of searches



LIGO first observing run (O1, 2015)



~49 days of double coincidence



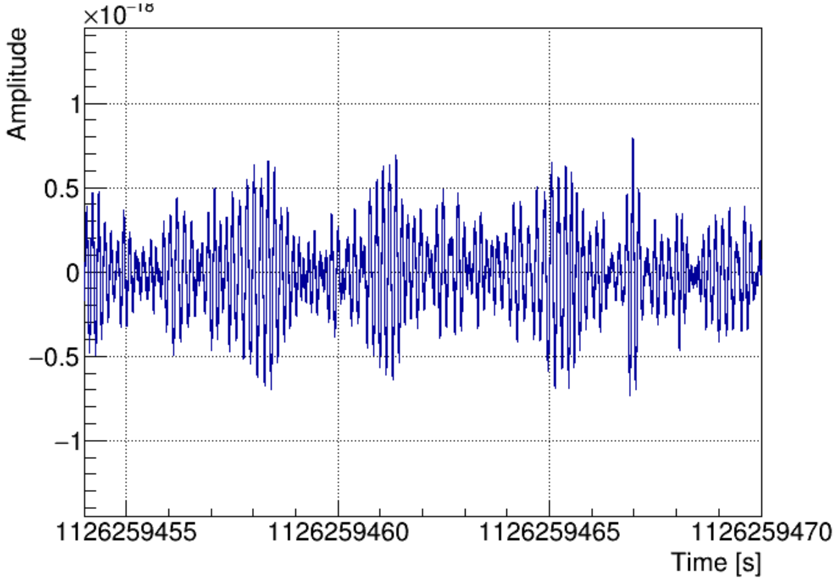
LIGO-Hanford (H1)

LIGO-Livingston (L1)

GW data

GW detectors' readout system provides at any instant an estimate of strain: a quantity that is sensitive to arms' length difference:

→ Digitized discrete time series: raw(t) (sampled at 16384 Hz or 20000 Hz) and synchronized with GPS clocks.
→ Calibration of raw(t): apply a frequency dependent factor [in reality this is a bit more complicated ...]

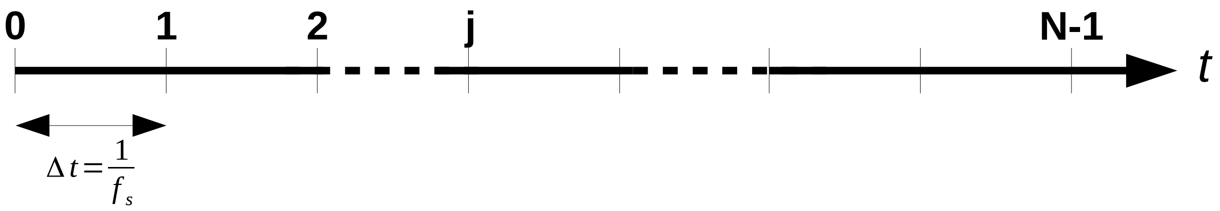


→ h_{det}(t) time series that is detector noise plus all hypothetical GW signals

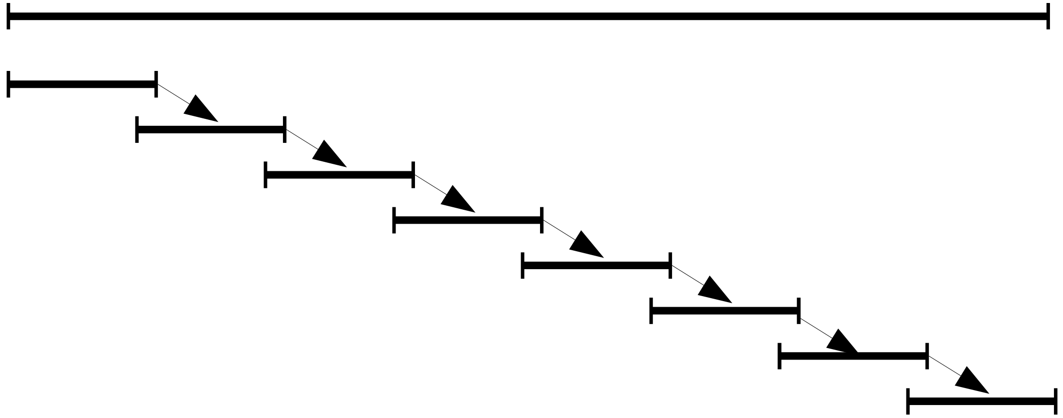
$$h_{det}(t) = n(t) + \color{red}{GW(t)}$$

GW data: discrete time series

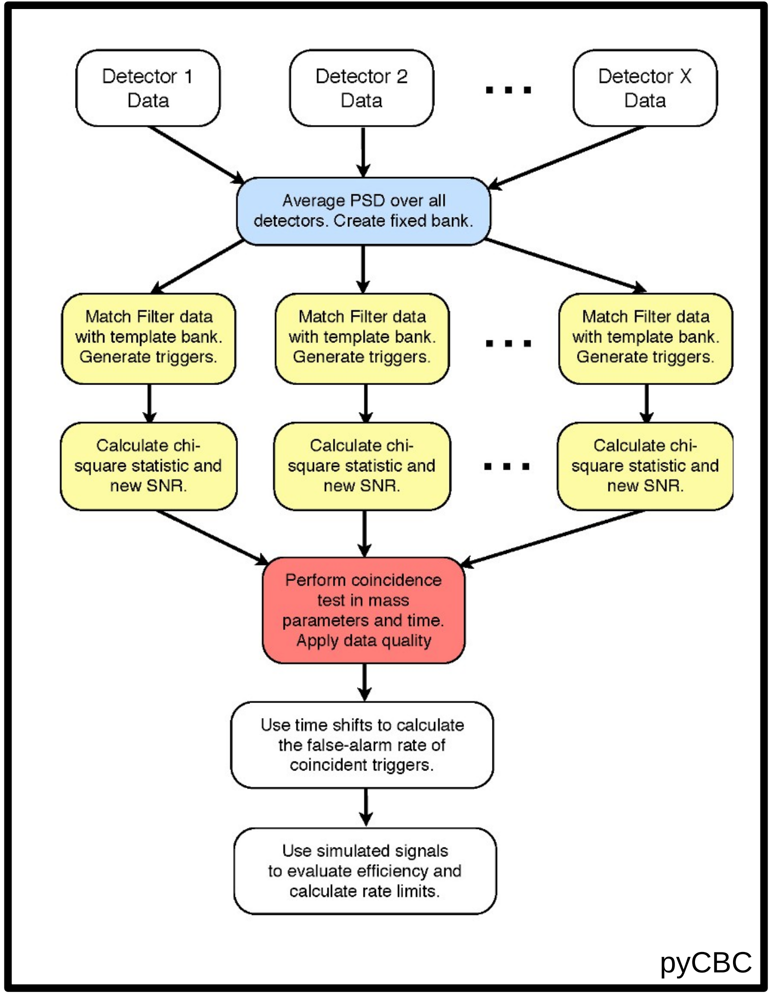
$$h_{det}(t) \rightarrow h_{det}[j]$$



GW search: load the data iteratively (analysis window)



Analysis pipeline



Detector 1 Data

Detector 2 Data

Detector X Data

Average PSD over all detectors. Create fixed bank.

Match Filter data with template bank. Generate triggers.

Match Filter data with template bank. Generate triggers.

Match Filter data with template bank. Generate triggers.

Calculate chi-square statistic and new SNR.

Calculate chi-square statistic and new SNR.

Calculate chi-square statistic and new SNR.

Perform coincidence test in mass parameters and time. Apply data quality

Use time shifts to calculate the false-alarm rate of coincident triggers.

Use simulated signals to evaluate efficiency and calculate rate limits.

pyCBC

Fourier transform

Fourier transform

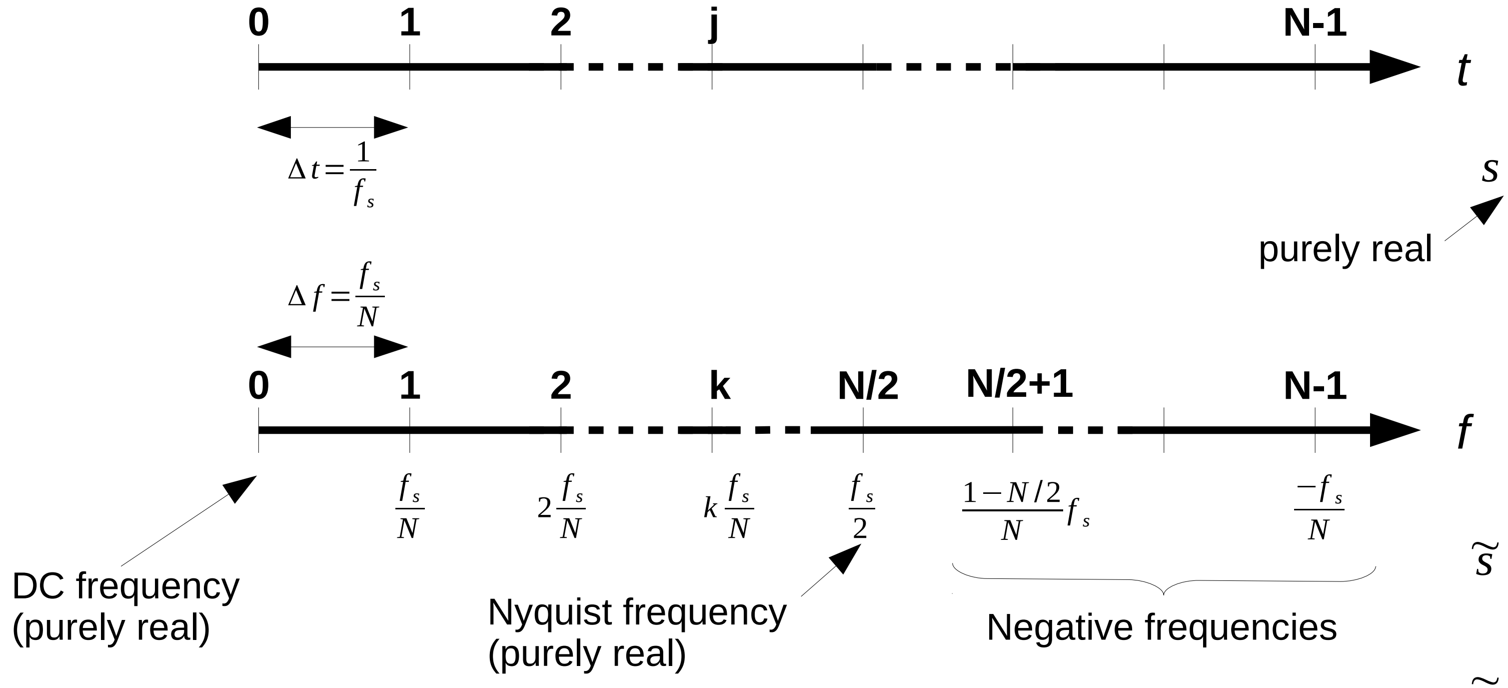
A time series *s(t)* can be projected over a basis of sinusoidal functions:

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

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

The signal is decomposed in characteristic frequencies

Discrete Fourier transform



$$s[j]=\frac{f_s}{N}\sum_{k=0}^{N-1}\tilde{s}[k]\,e^{+2i\pi kj/N}$$

$$\tilde{s}[k]=\frac{1}{f_s}\sum_{j=0}^{N-1}s[j]\,e^{-2i\pi kj/N}$$

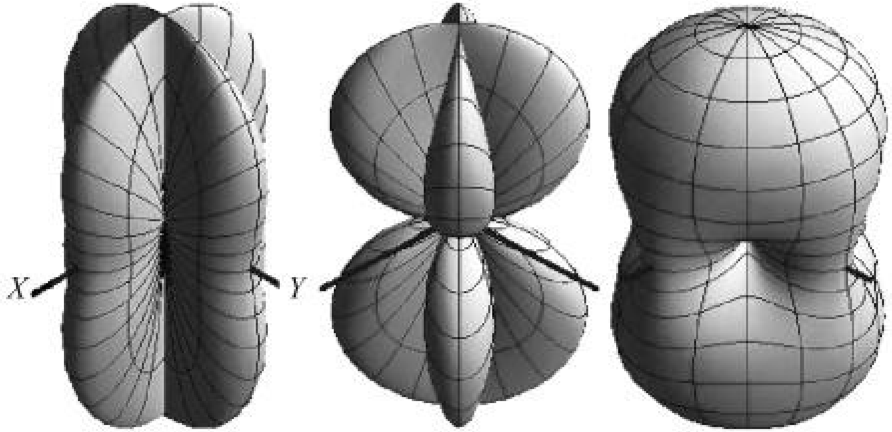
$$\tilde{s}[k]=\tilde{s}^*[N-k]$$

Detector strain time series

$$h_{det}(t) = n(t) + GW(t)$$

GW strain time series

The detector's sensitivity over the sky is not uniform



F_+ $\quad$ $F_\times$ $\quad$ $\sqrt{F_+^2 + F_\times^2}$

$$GW(t) = F_+(\underbrace{t, ra, dec}_{\text{Source position}}, \underbrace{\Psi}_{\text{Source polarization angle}}) \times h_+(t) + F_\times(t, ra, dec, \Psi) \times h_\times(t)$$

Detector’s noise

Power spectral density: $\lim_{T\to\infty} \frac{1}{T}|\tilde{x}_T(f)|^2$
(PSD)

Power spectral density estimator for finite data set: Periodogram **=** $\frac{1}{T}|\tilde{x}_T(f)|^2$

Improved estimator:
- average multiple periodograms (M) to reduce the variance
- noise is non-stationary: T should not be too long (a few minutes)
- use windowed data to limit spectral leakage
- Welch approach: average of periodograms computed over overlapping windowed data segments

Sensitivity measured using the noise power spectral density :

$$S_n(k) = Median_{0\le m<M}\left\{\frac{1}{Nf_s}\left|\sum_{j=0}^{N-1} x_m[j]w[j]e^{-2i\pi jk/N}\right|^2\right\}$$

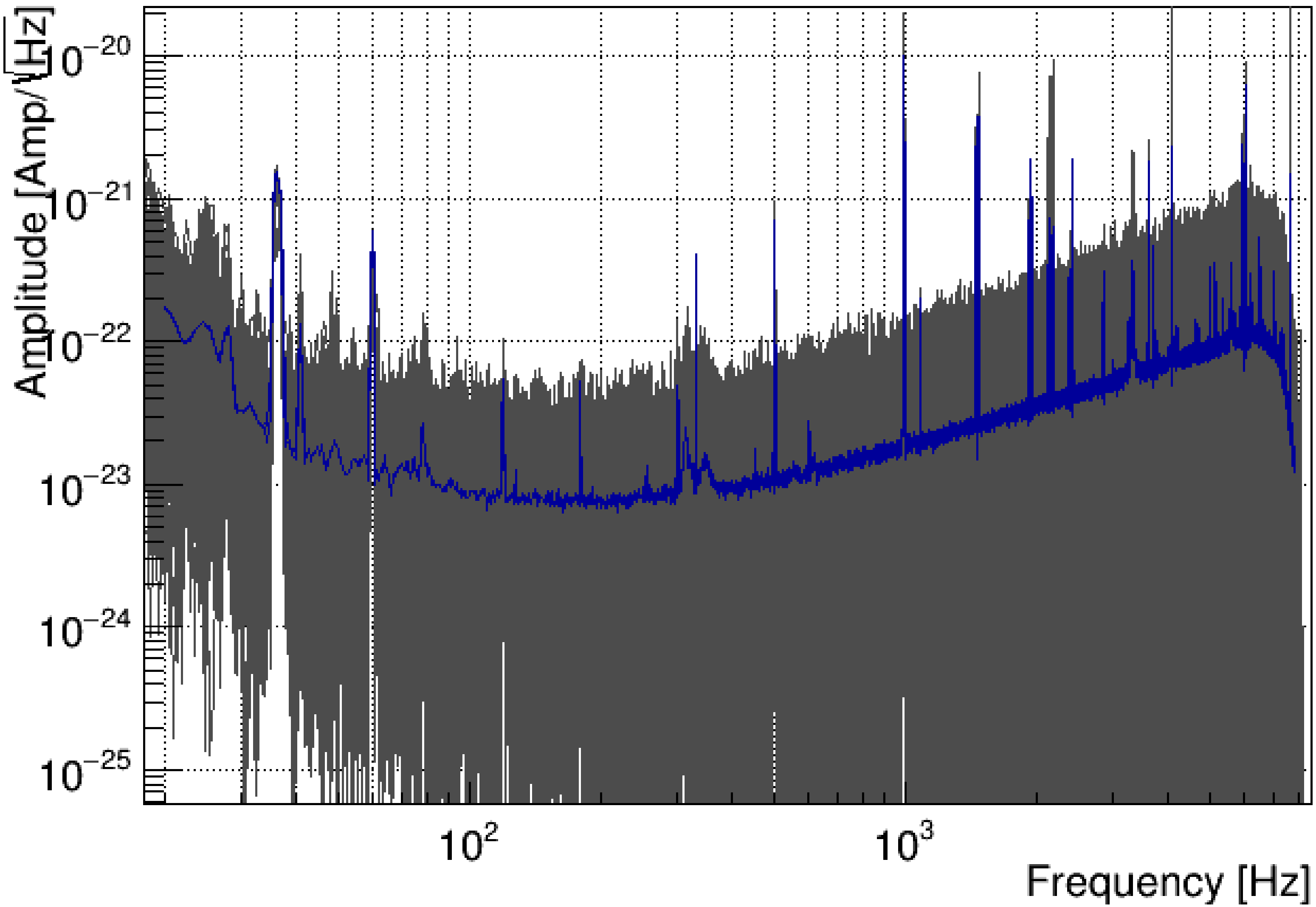
+ median-to-mean correction

One-sided **/** Two sided PSDs

Amplitude power spectral density: $\sqrt{S_n(k)}$

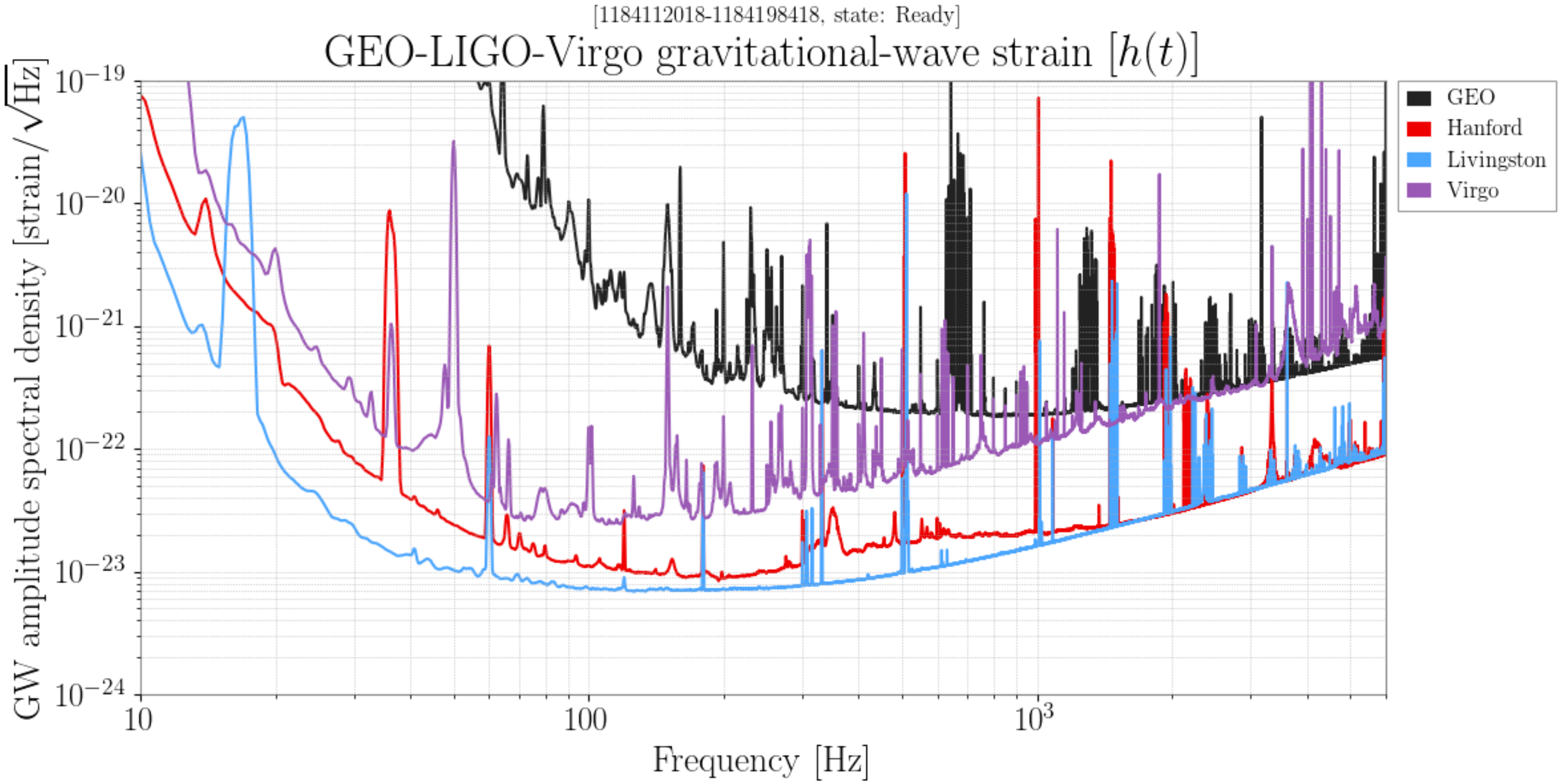
Detector sensitivity

Noise amplitude spectral density of $h_{det}(t) = n(t)$



LIGO Hanford (O1)

Detector sensitivity

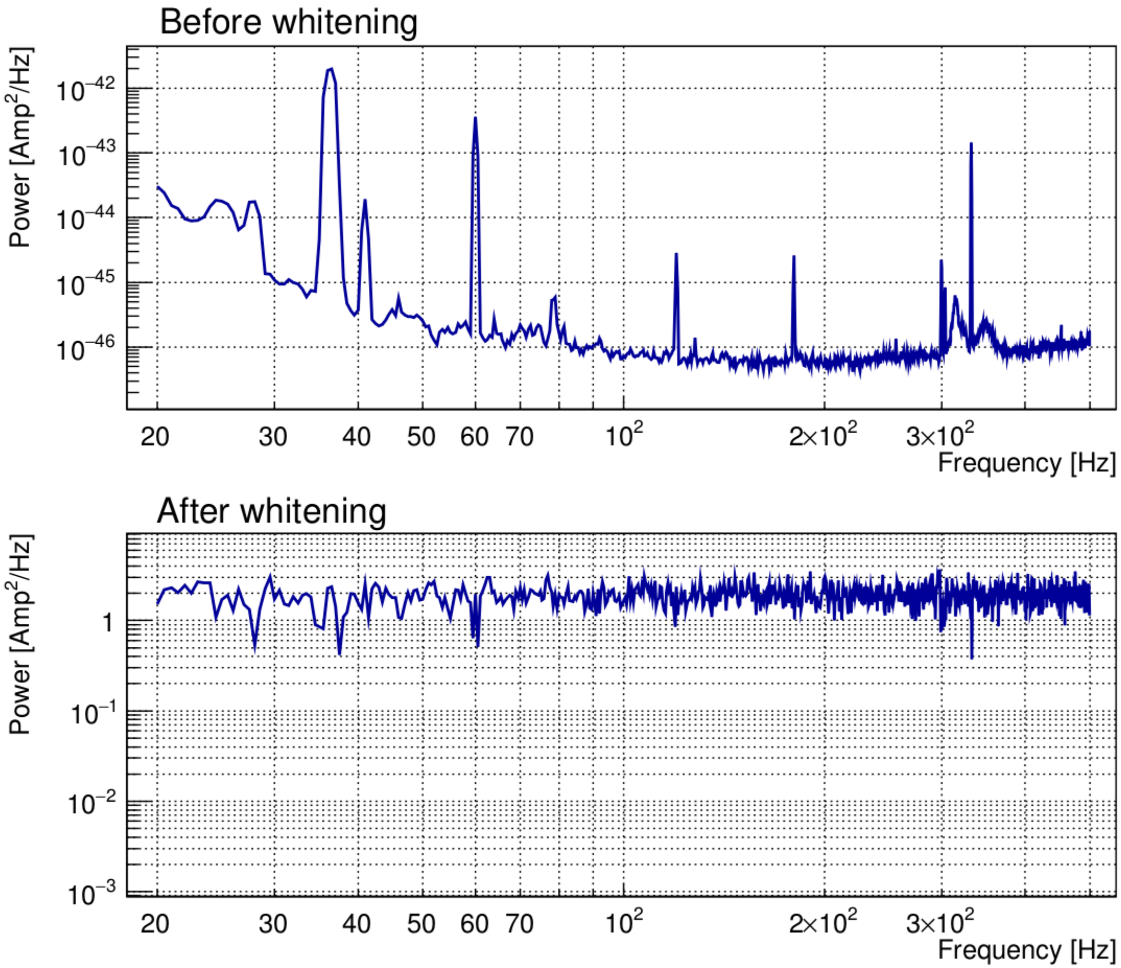


O2 Best noise spectrum achieved by **LIGO Hanford**, **LIGO Livingston** and **Virgo**

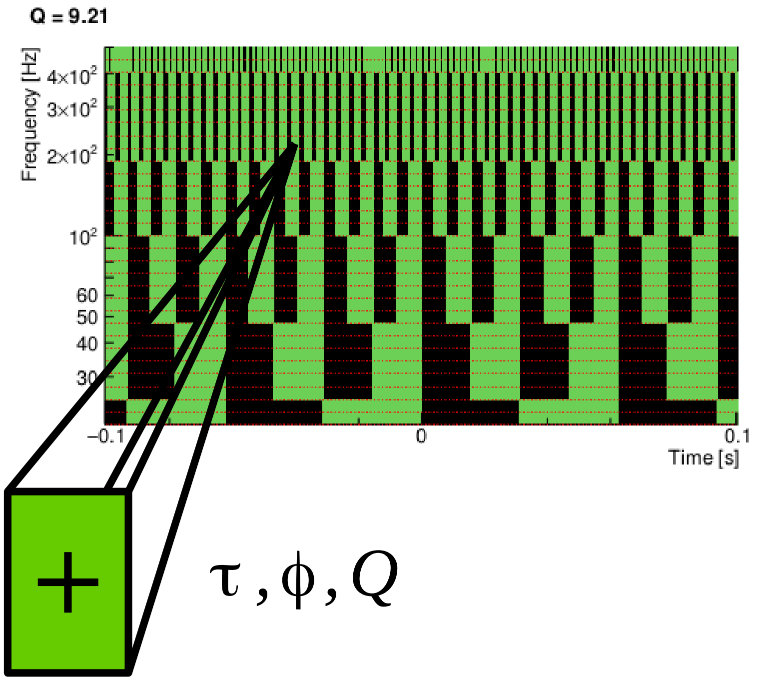
Data whitening

GW data is whitened: $\tilde{h}_{det}(f) \rightarrow \tilde{h}^{w}_{det}(f) = \frac{\tilde{h}_{det}(f)}{S_n(f)}$

→ white noise is mandatory for statistical interpretation of the data



Time-frequency analysis (unmodeled)



Example : Q-transform

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

→ window width $\sim 1/\phi$

~ short Fourier transform with a Gaussian window

→ Goal : cover a parameter space as large as possible

Noise only: $\langle |N(\tau,\phi,Q)|^2\rangle=\int_{-\infty}^{+\infty} |\tilde{w}(\phi-f,\phi,Q)|^2 S_n(f)\,df$

Whitened noise + window normalization: $\langle |N^w(\tau,\phi,Q)|^2\rangle=1$

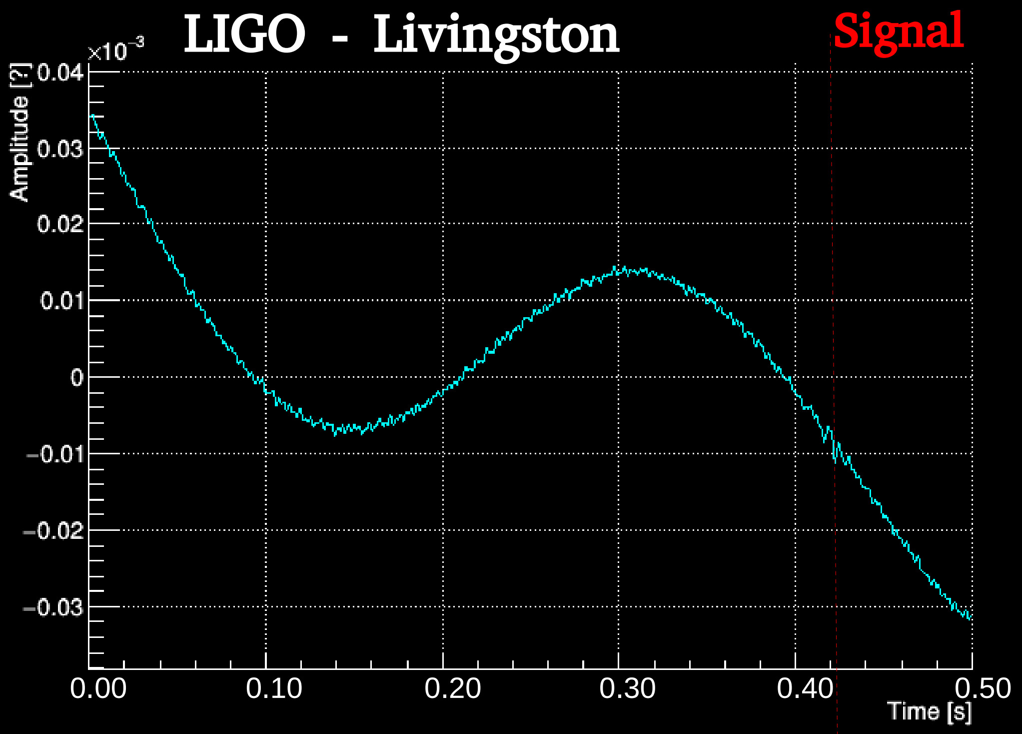
→ Signal-to-noise ratio estimator

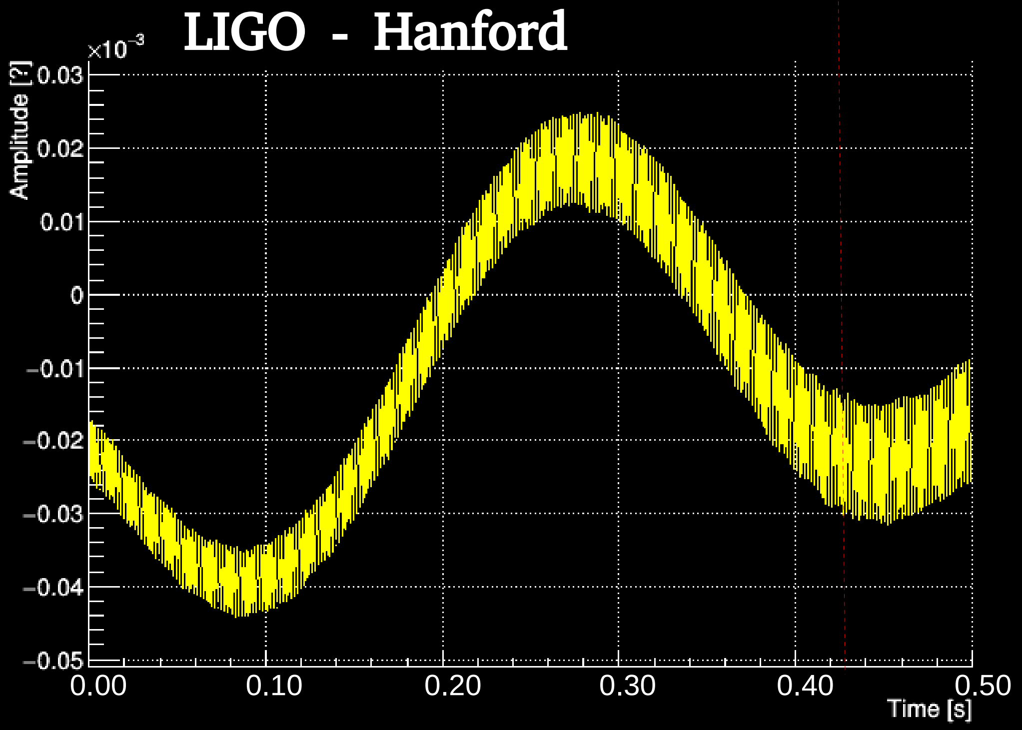
$$\hat{\rho}^2(\tau,\phi,Q)=|X^w(\tau,\phi,Q)|^2-\langle |N^w(\tau,\phi,Q)|^2\rangle=|X^w(\tau,\phi,Q)|^2-1$$

↳ Statistical interpretation: noise is Gaussian-distributed with unit variance

GW150914

Output power


LIGO - Livingston

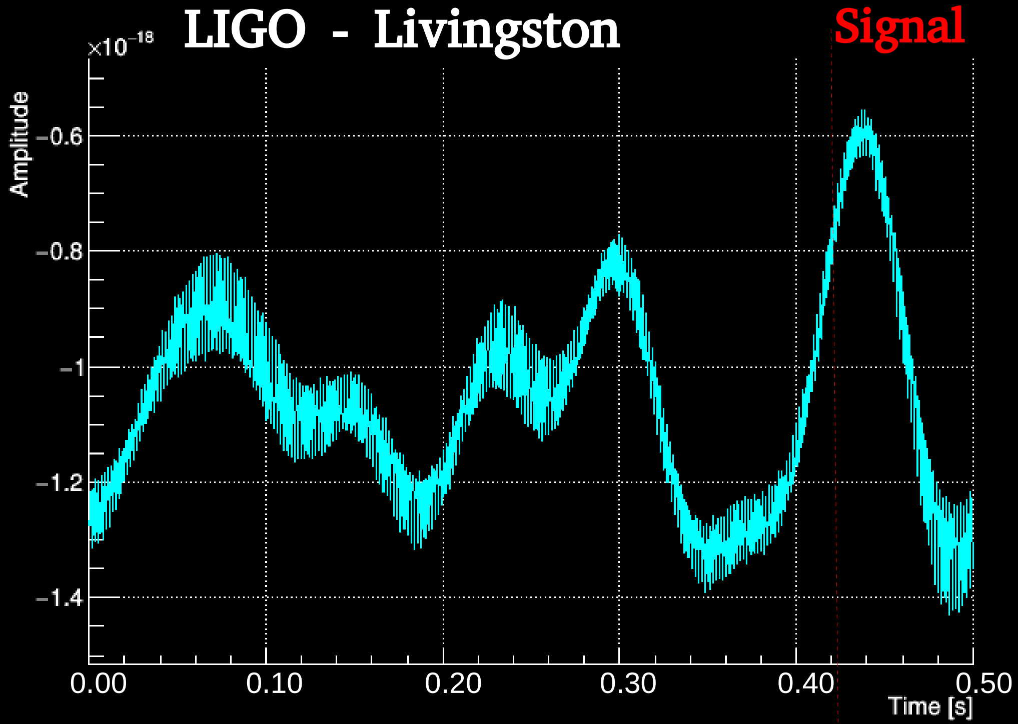

LIGO - Hanford

Output power

GW150914

$h(t)$

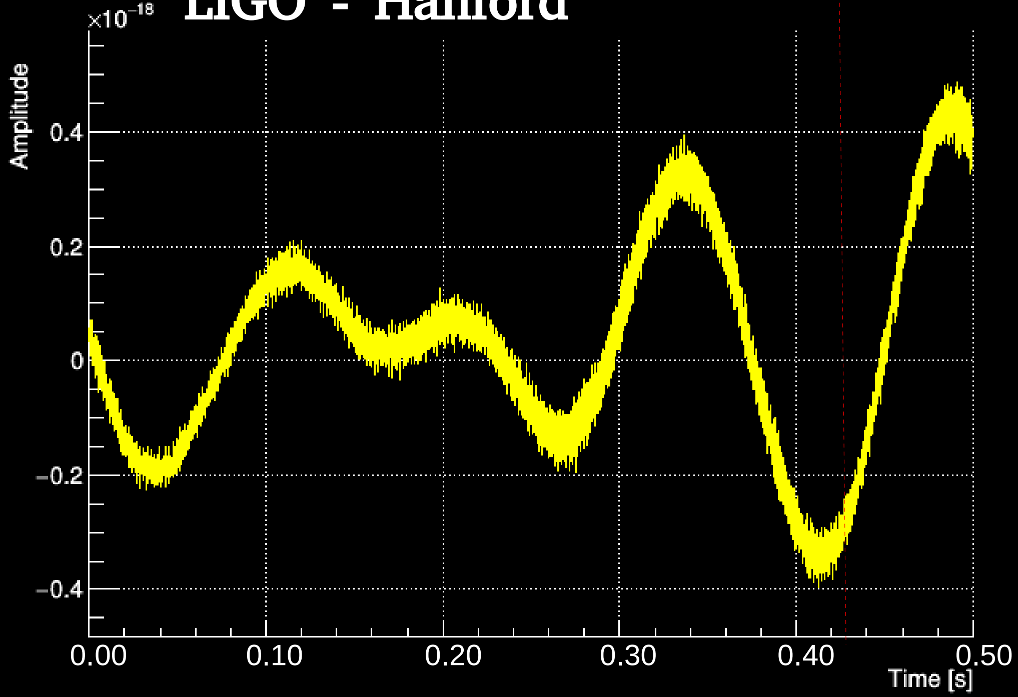
LIGO - Livingston



Data is calibrated
→ GW strain amplitude *h(t)*

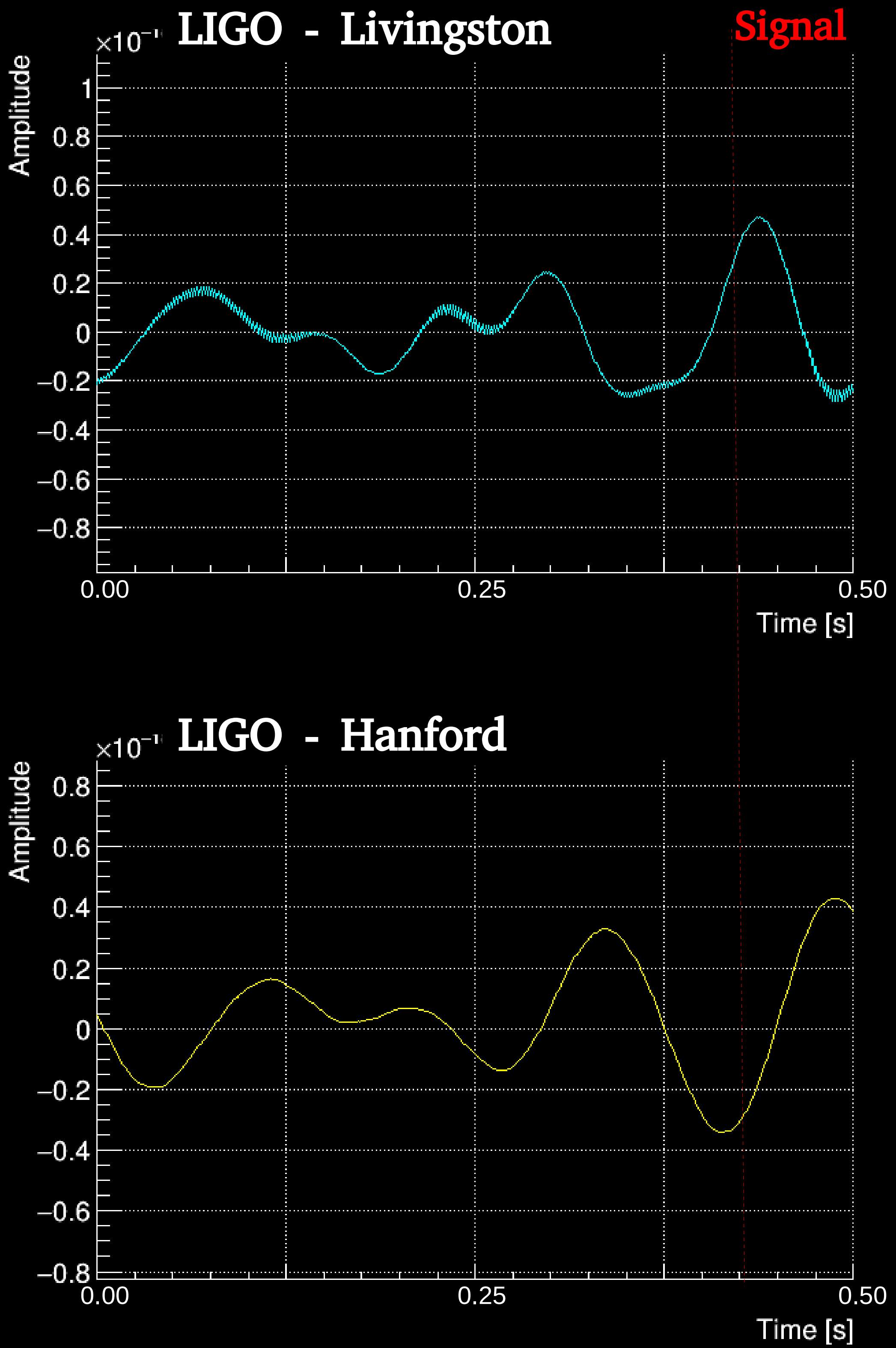
$h(t)$

LIGO - Hanford

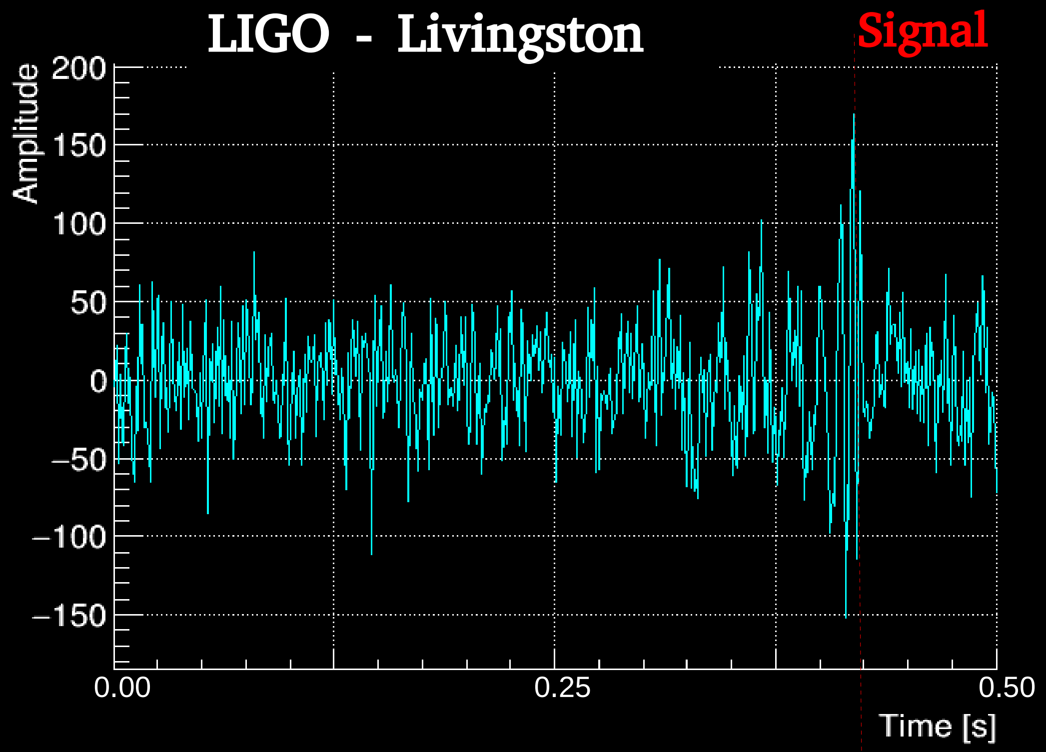


GW150914

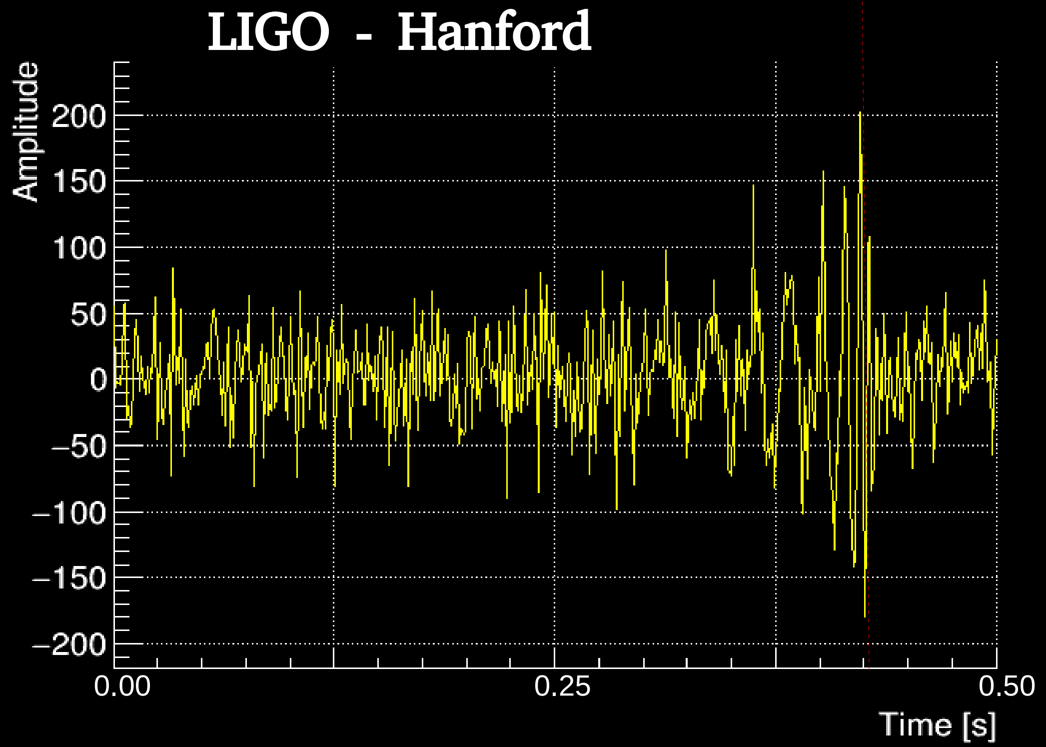
Data are low-pass filtered (here, < 500 Hz)



GW150914


LIGO - Livingston

Data are whitened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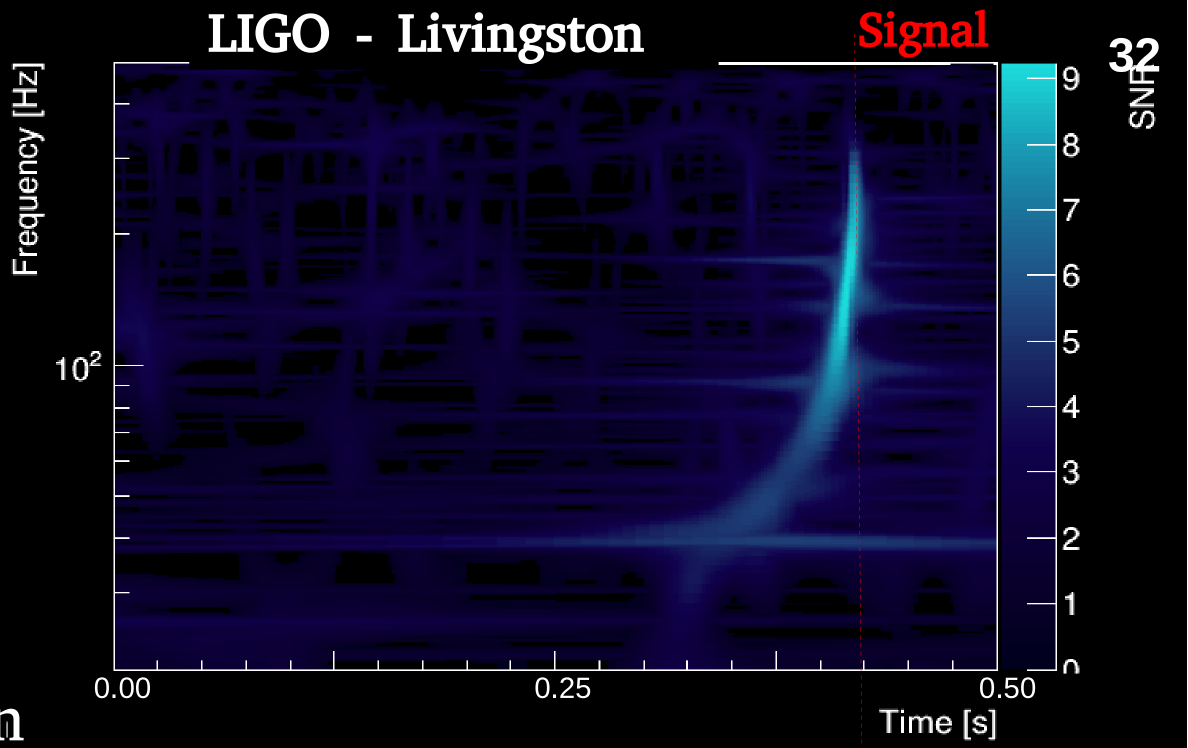
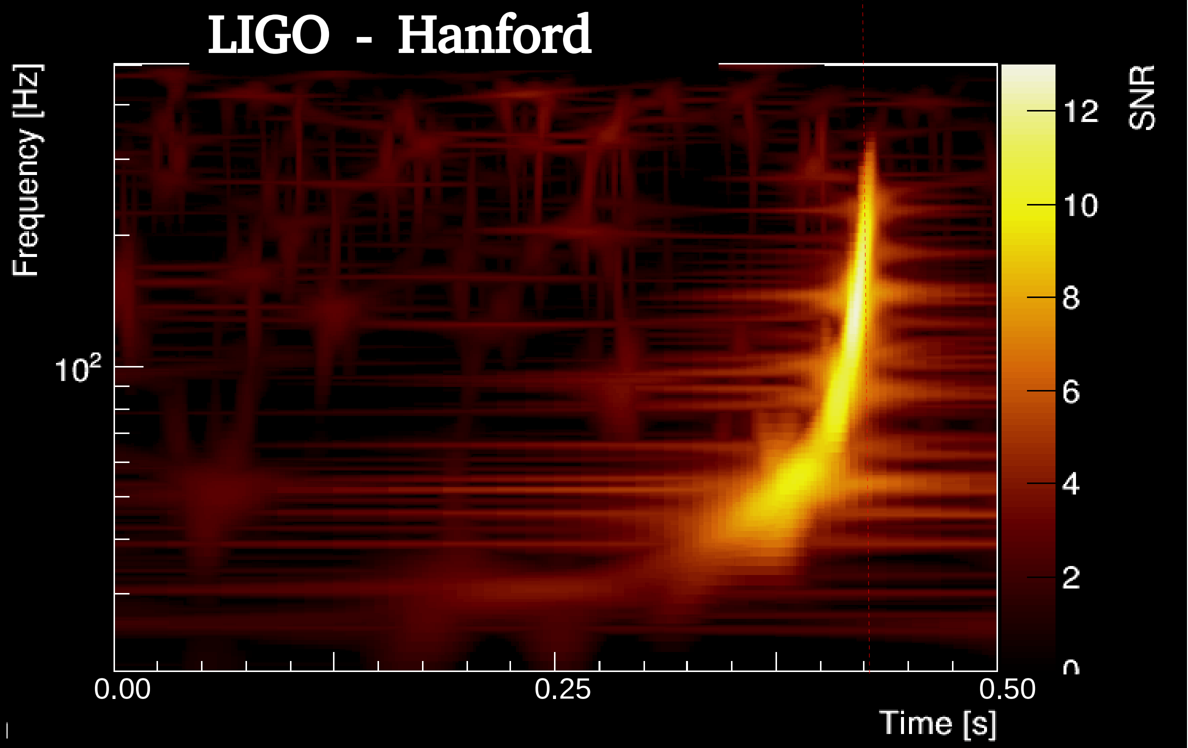
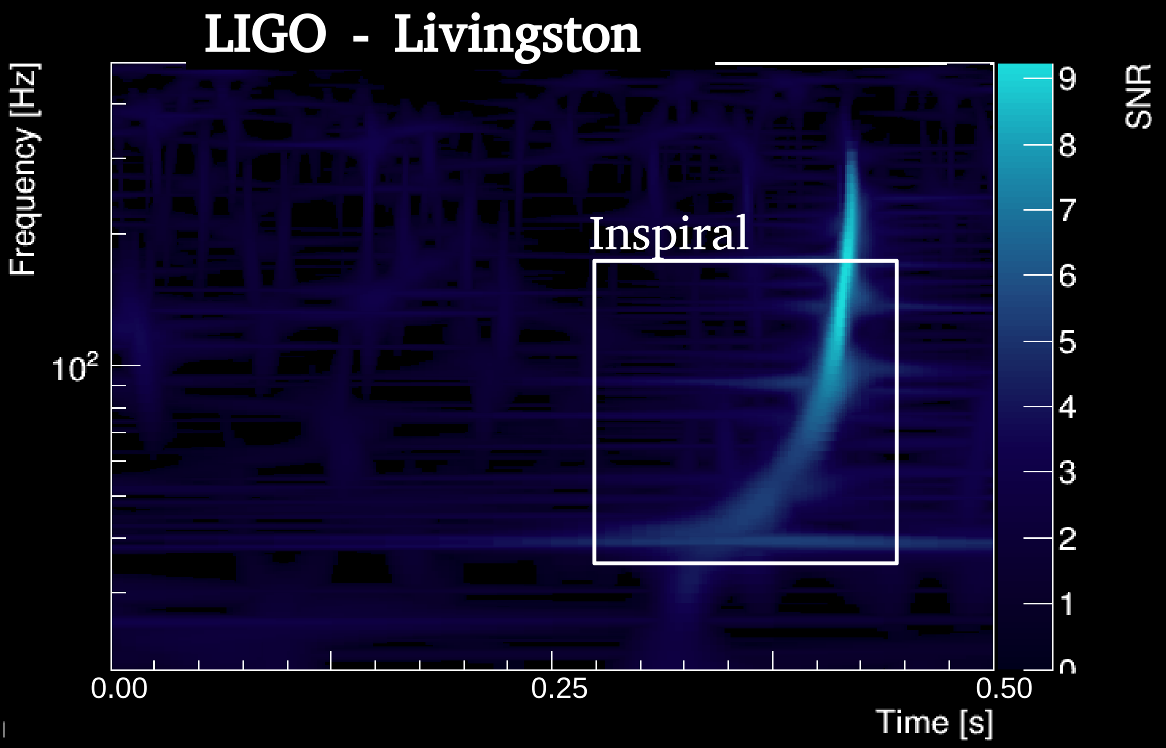
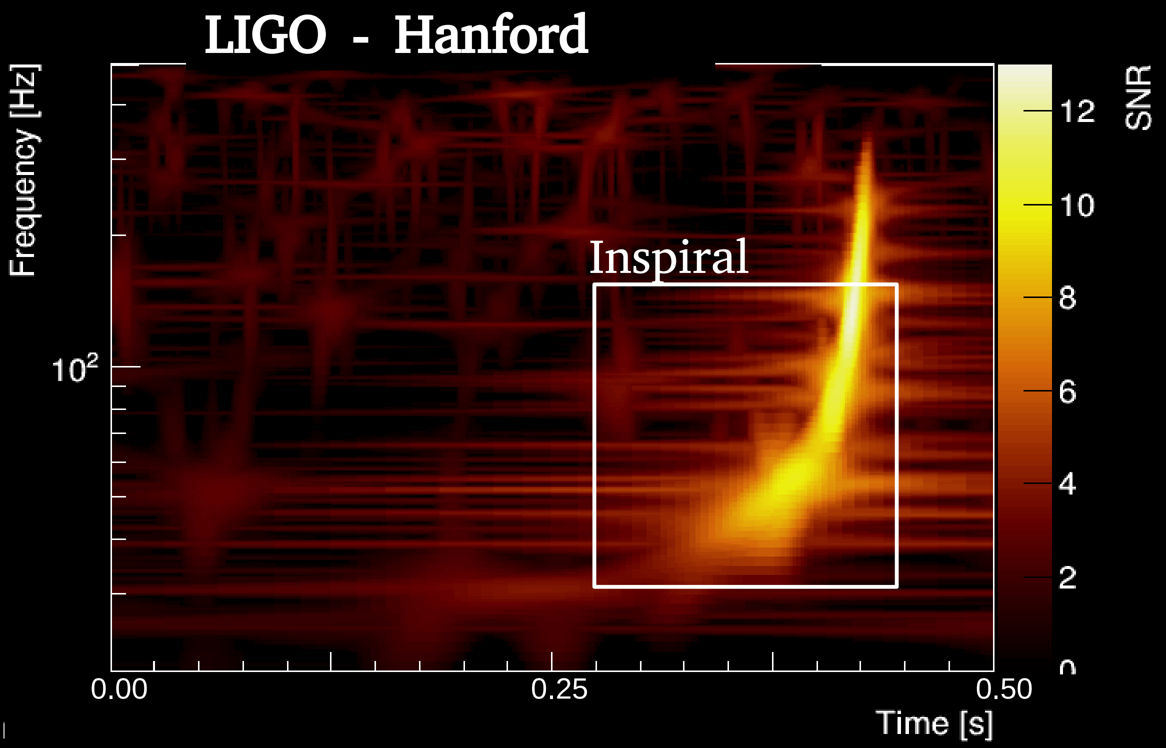


Time-frequency decomposition (Short Fourier transforms)





LIGO - Livingston



LIGO - Hanford

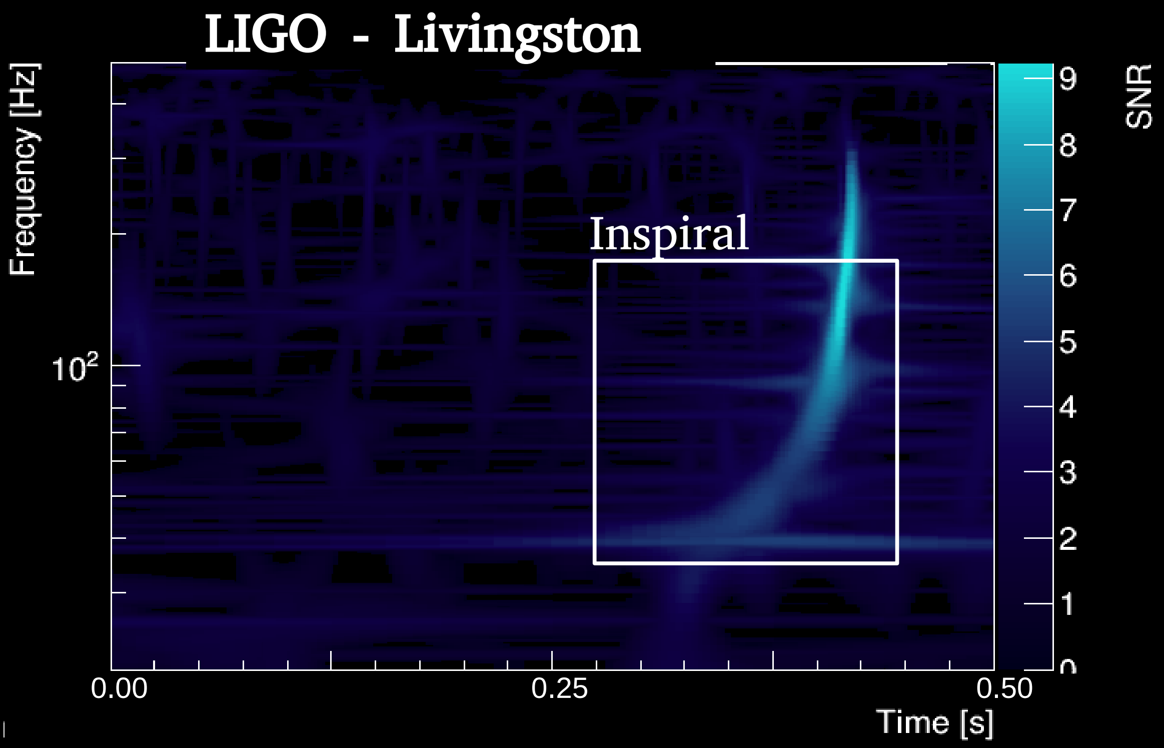
Phase evolution dictated by the chirp mass:

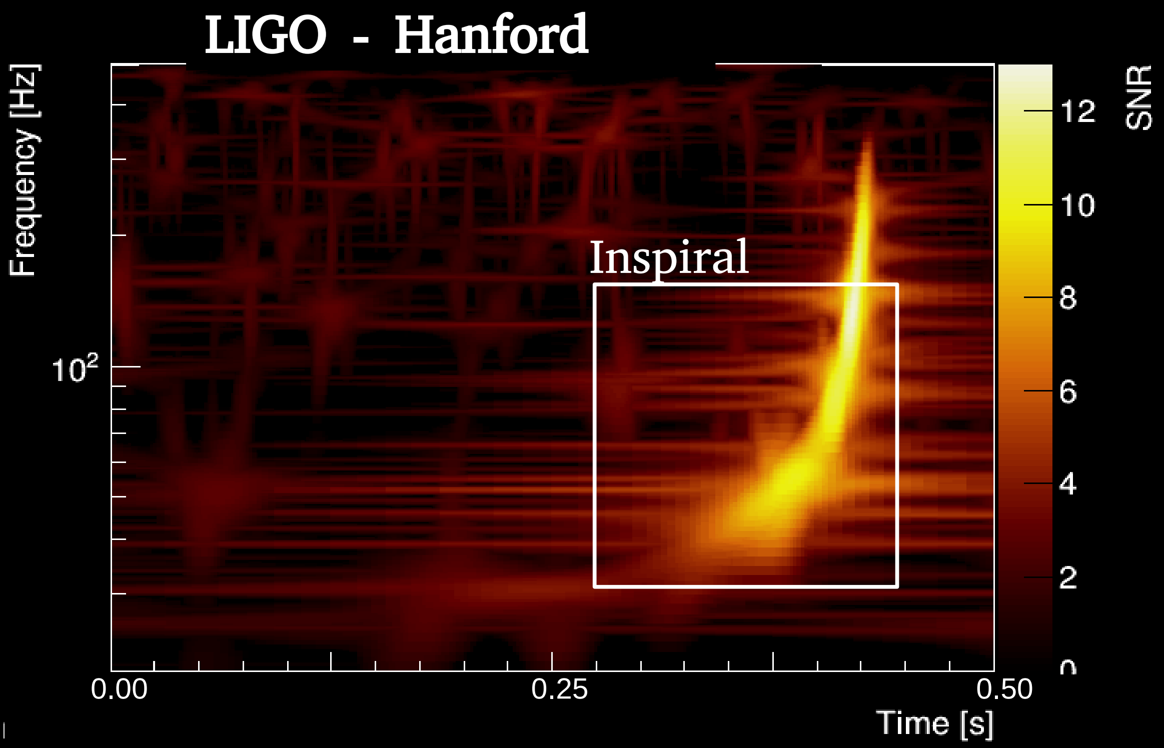
$$M_{chirp} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3}\dot{f}\right]^{3/5}$$

$$M_{chirp} \simeq 30\ M_{sun}$$

→ Total mass:

$$M_{tot} = m_1 + m_2 \geqslant 70\ M_{sun}$$





Phase evolution dictated by the chirp mass:

$$M_{chirp} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3}\dot{f}\right]^{3/5}$$

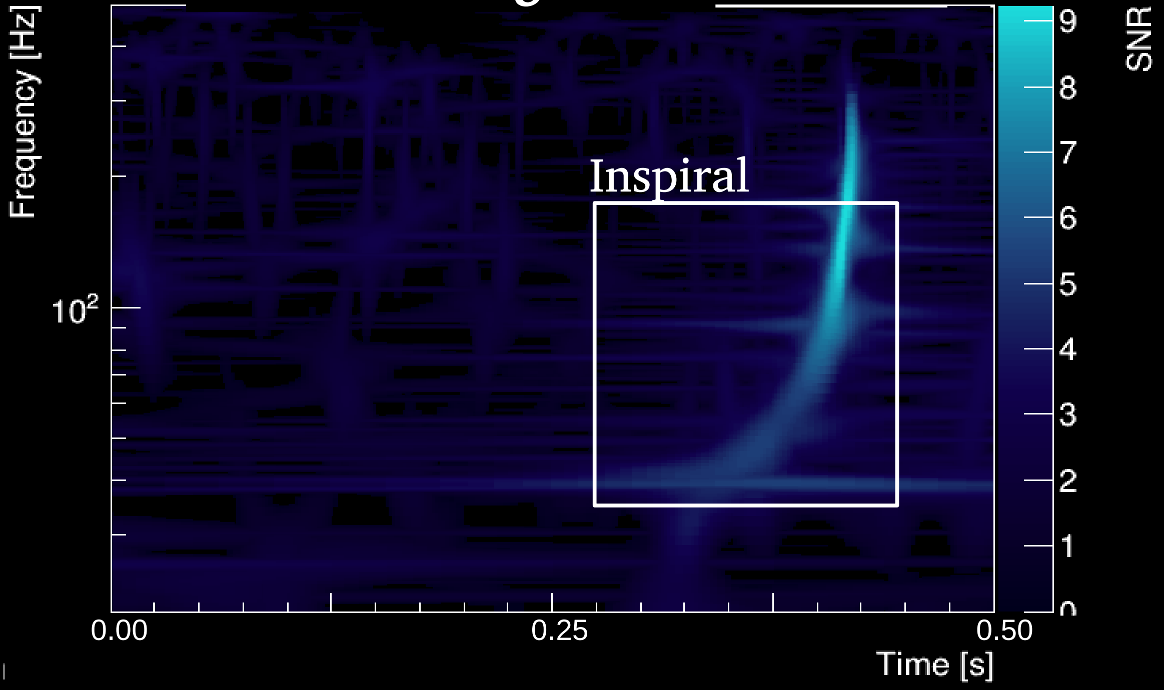
$$M_{chirp} \simeq 30\, M_{sun}$$

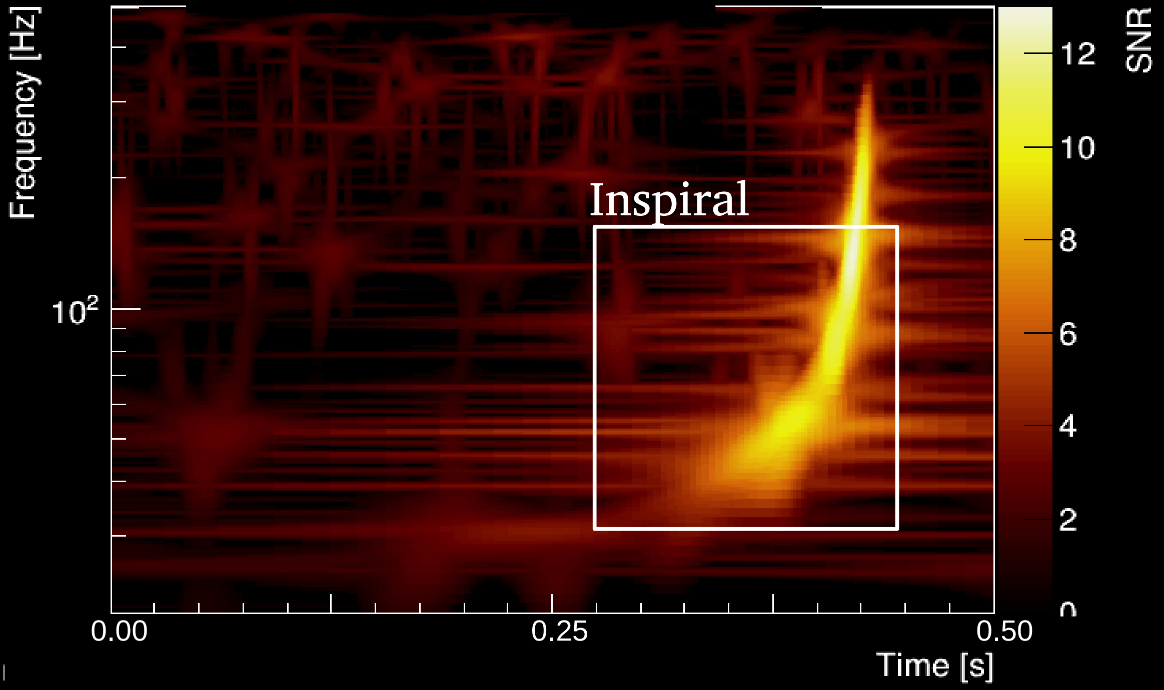
→ Total mass:

$$M_{tot} = m_1 + m_2 \geqslant 70\, M_{sun}$$

Schwarschild radius:

$$\frac{2GM_{tot}}{c^2} \geqslant 210\, km$$


LIGO - Livingston


LIGO - Hanford

Phase evolution dictated by the chirp mass:

$$M_{chirp} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5}$$

$$M_{chirp} \simeq 30\ M_{sun}$$

→ Total mass:

$$M_{tot} = m_1 + m_2 \geqslant 70\ M_{sun}$$

Schwarschild radius:

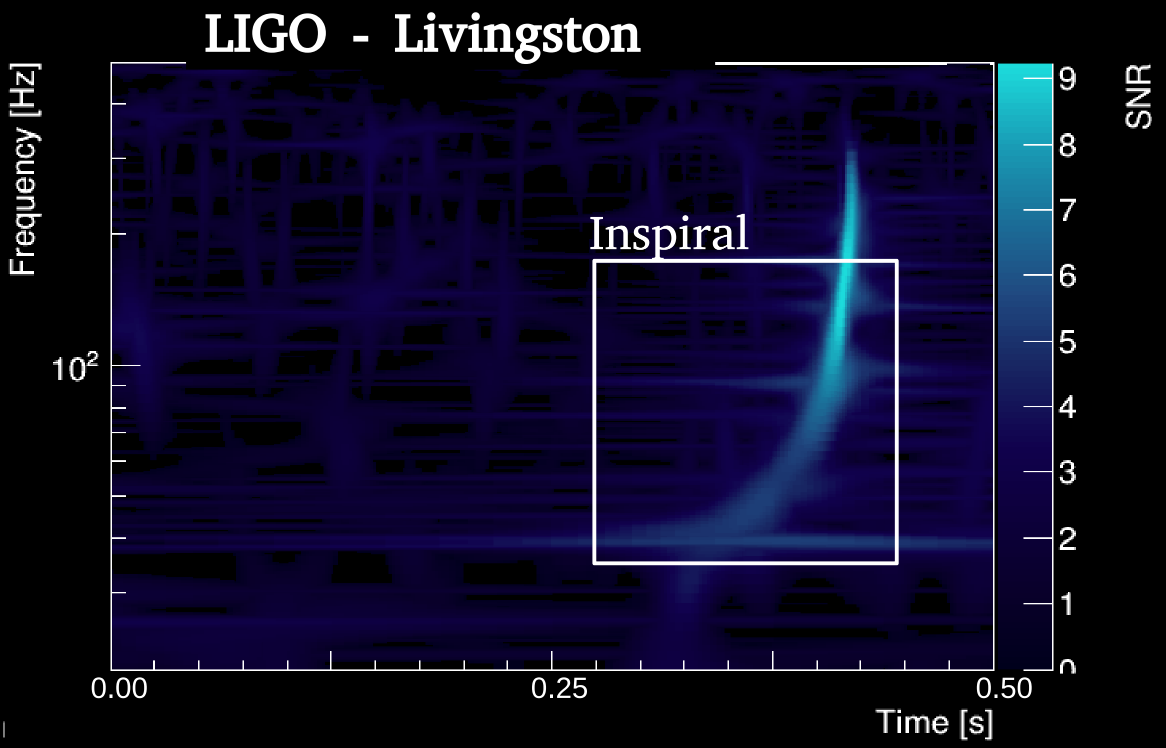
$$\frac{2GM_{tot}}{c^2} \geqslant 210\,km$$

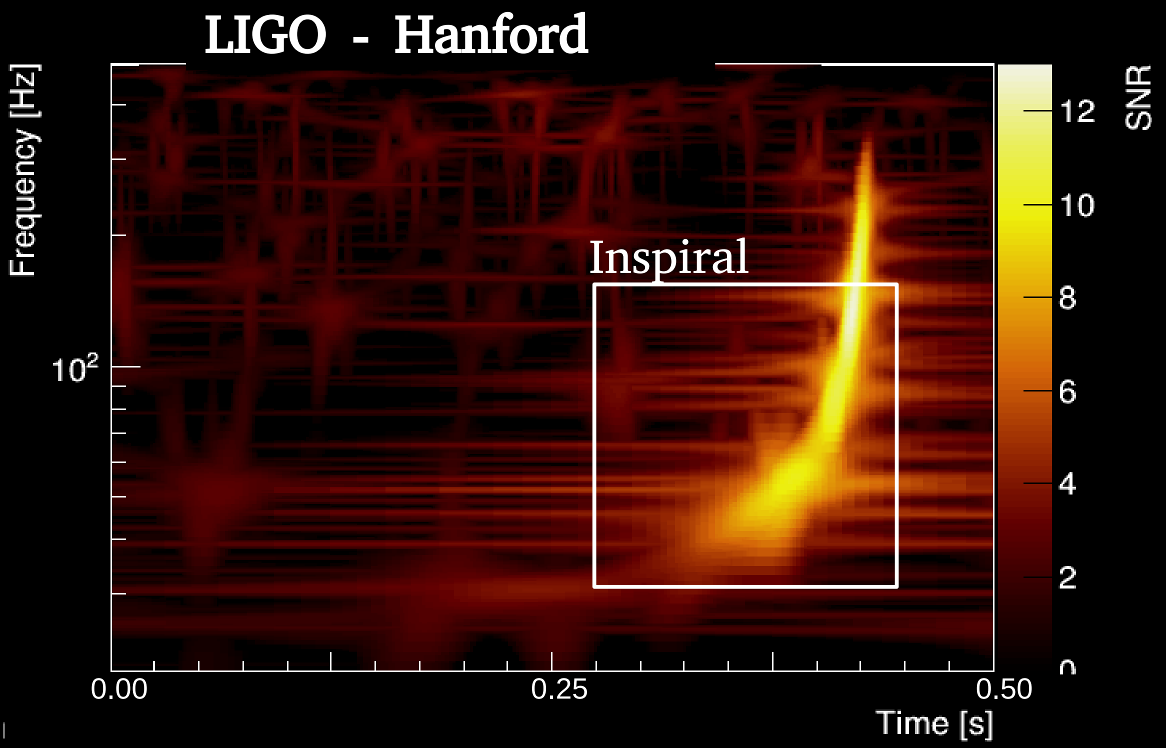
Orbital frequency:

$$f_{orbit} = f/2 \simeq 75\ Hz$$

Equal Newtonian point masses orbit:

$$d \simeq 350\,km$$


LIGO - Livingston


LIGO - Hanford

Phase evolution dictated by the chirp mass:

$$M_{chirp} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = \frac{c^3}{G} \left[\frac{5}{96} \pi^{-8/3} f^{-11/3} \dot{f} \right]^{3/5}$$

$$M_{chirp} \simeq 30\, M_{sun}$$

→ Total mass:

$$M_{tot} = m_1 + m_2 \geqslant 70\, M_{sun}$$

Schwarschild radius:

$$\frac{2GM_{tot}}{c^2} \geqslant 210\, km$$

Orbital frequency:

$$f_{orbit} = f/2 \simeq 75\ Hz$$

Equal Newtonian point masses orbit:

$$d \simeq 350\, km$$

→ Black hole binary

Match-filtering

Known waveform → match-filtering technique

Simplest linear filter: correlation $C(t)=\int_{-\infty}^{+\infty} h_{det}(t')k(t-t')\,dt=\int_{-\infty}^{+\infty} \tilde{h}_{det}(f)\,\tilde{k}^*(f)\,e^{2i\pi ft}\,df$

k(t) is the impulse response function of the filter : $h_{det}(t)=\delta(t)\Rightarrow C(t)=k(t)$

Match-filter: optimal filter maximizing the SNR in presence of additive noise

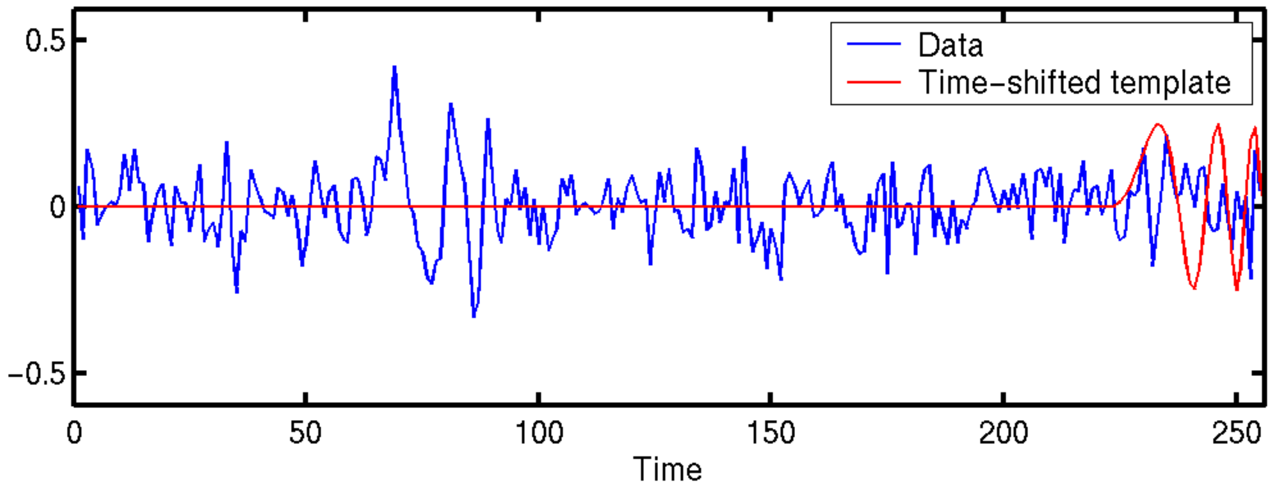
$$h_{det}(t)=n(t)+GW(t)$$

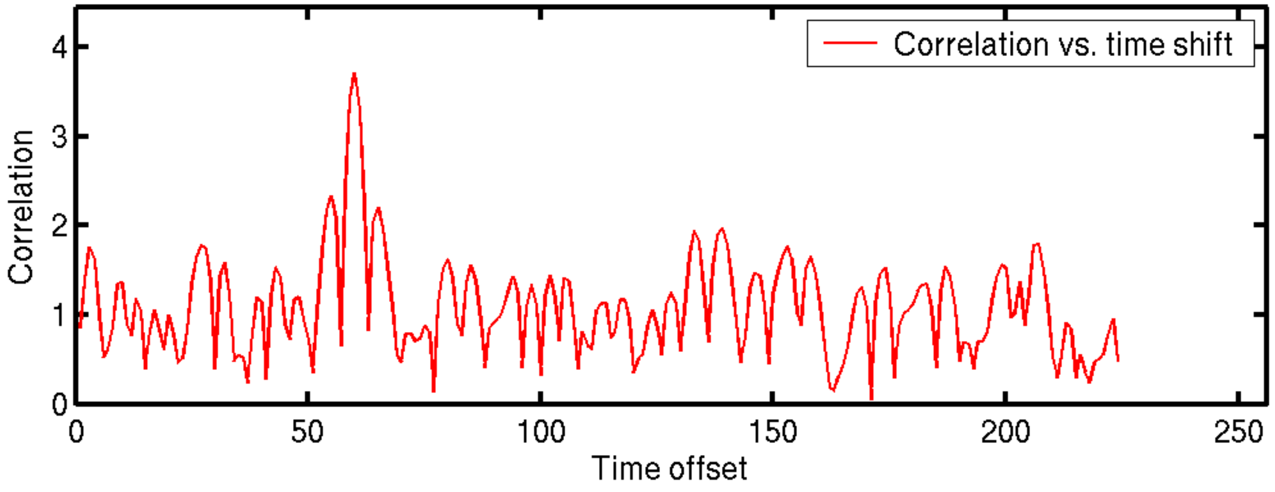
$\rho(t)=\dfrac{C(t)}{\sqrt{\langle N^2(t)\rangle}}$ with $\langle N^2(t)\rangle=\int_{-\infty}^{+\infty} |\tilde{k}(f)|^2 S_n(f)\,df$

The SNR is maximized if $\tilde{k}(f)\propto\dfrac{G\tilde{W}^*(f)}{S_n(f)}$

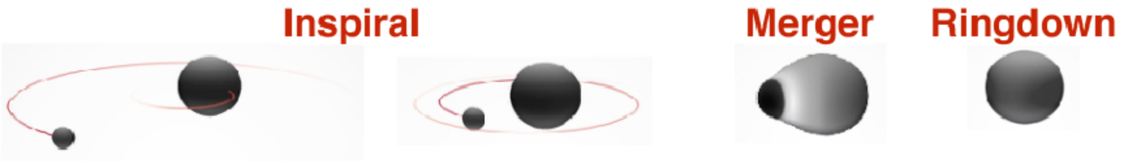
$$\rho(t)=\int_{-\infty}^{+\infty}\frac{G\tilde{W}^*(f)\,\tilde{h}_{det}(f)}{S_n(f)}\,e^{2i\pi ft}\,df$$

Match-filtering

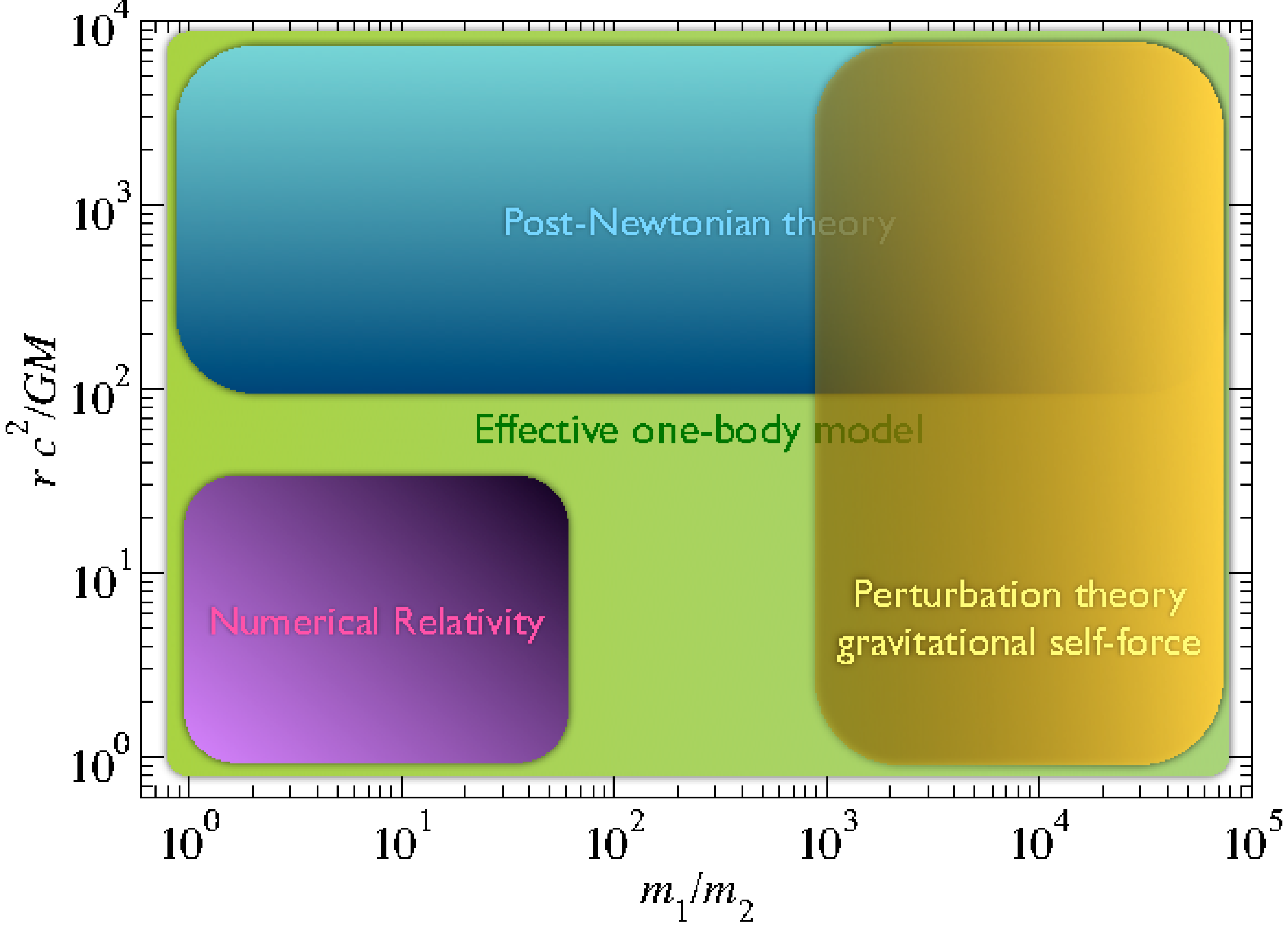




The CBC search



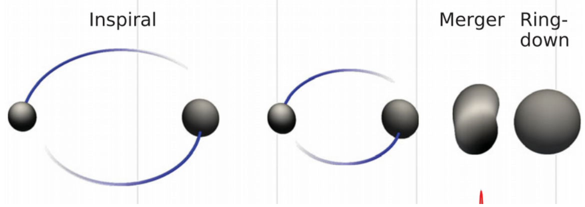
[arXiv 1410.7832]



The CBC 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)



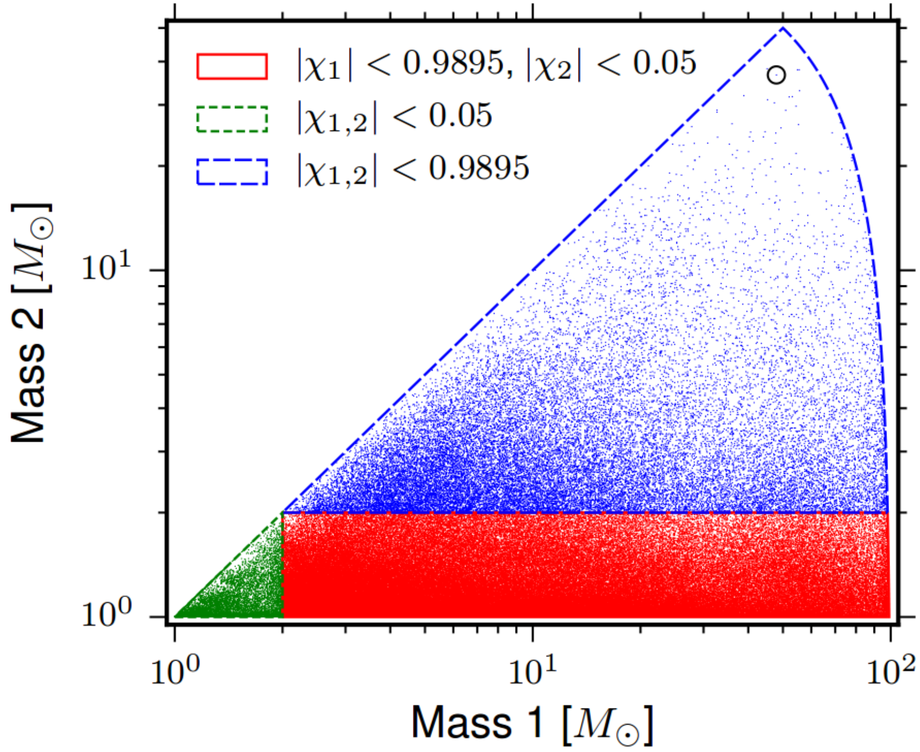
The intrinsic waveform parameters:

- Masses (2 dofs):

$$M_{tot} = M_1 + M_2$$

- Spins and orbital angular momentum (6 do

$$\vec{S}_{tot} = \vec{S}_1 + \vec{S}_2 + \vec{J}$$

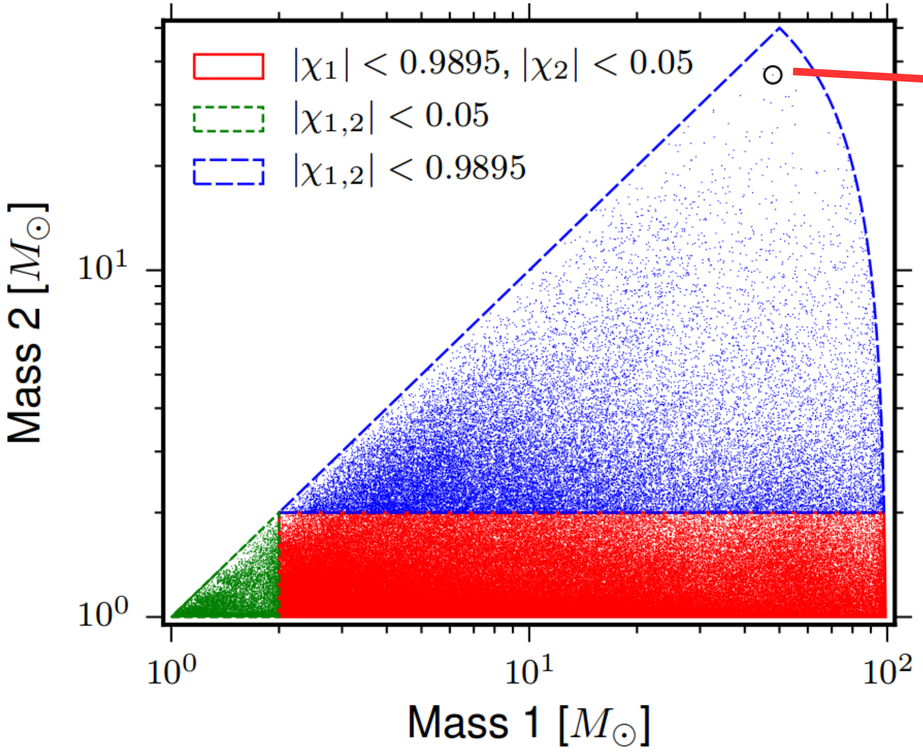


The waveform models used for the search:

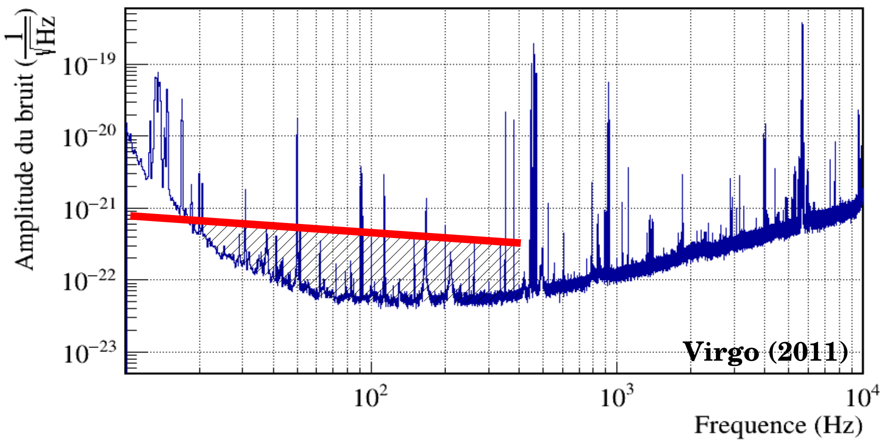
- Inspiral, PN3.5 for $M_{tot} < 4\, M_{sun}$
- Inspiral/Merger/Ringdown EOB + numerical relativity for $M_{tot} > 4\, M_{sun}$
- Spins and orbital angular momentum are aligned

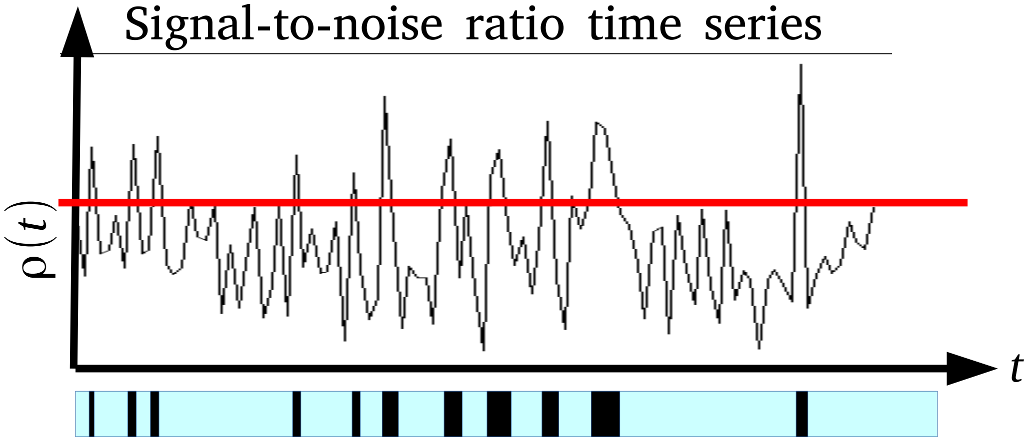
Template bank → match-filtering technique

The CBC search



$$\rho(t) = \int_{-\infty}^{+\infty} \frac{\widetilde{GW}^*(f)\,\tilde{h}_{det}(f)}{S_n(f)} e^{2i\pi ft}\, df$$

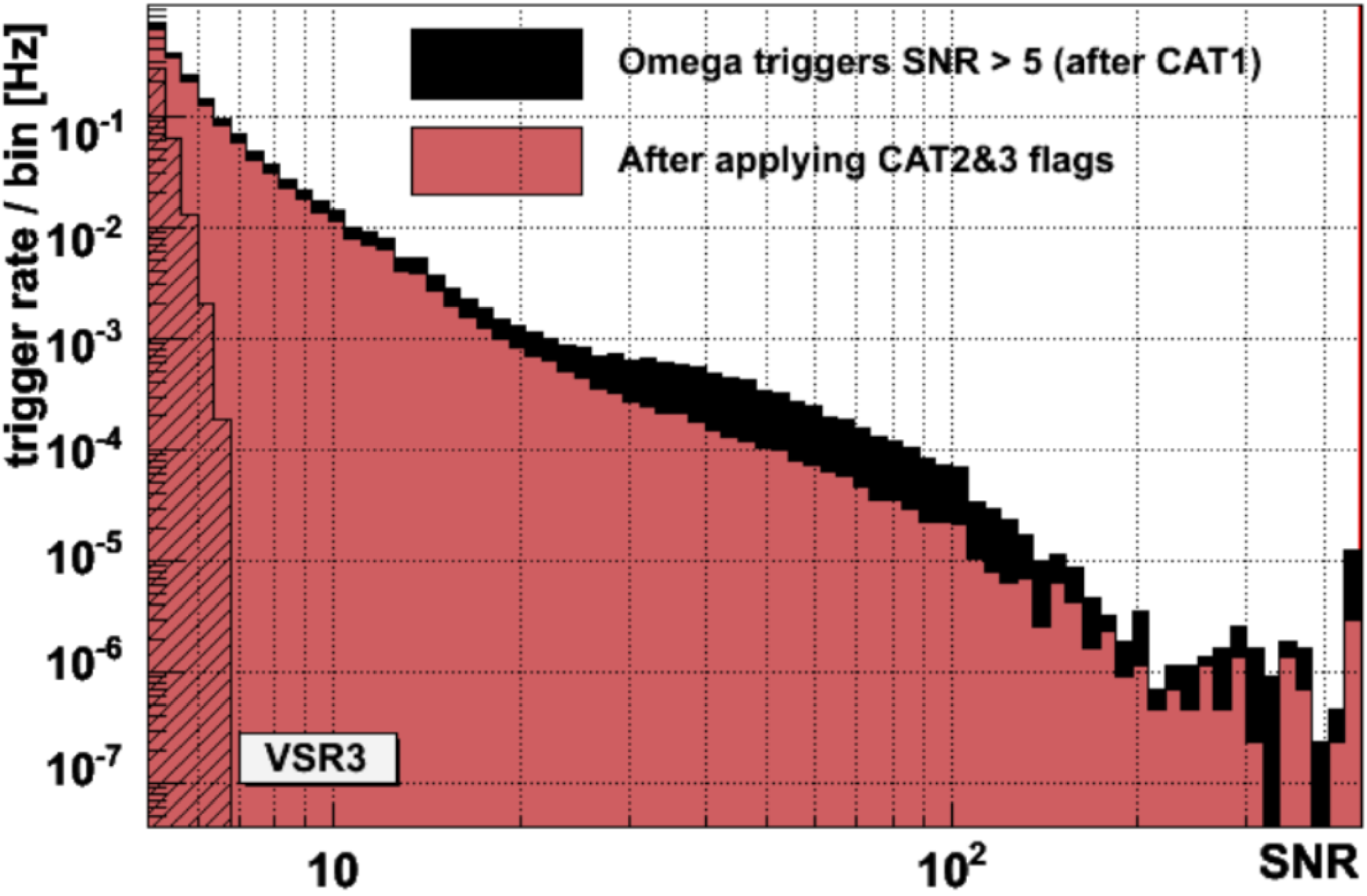




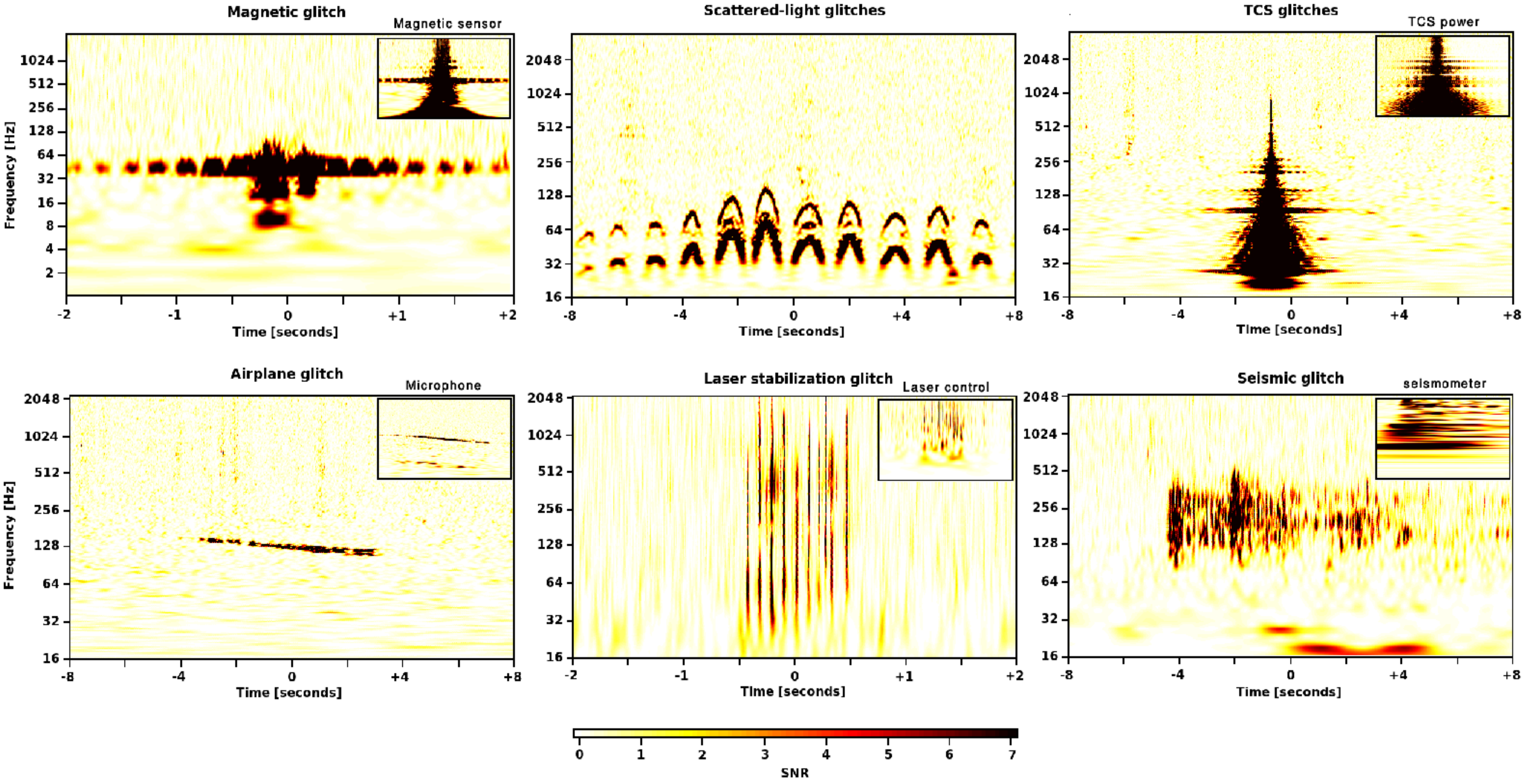
A list of events is produced:
- start/end/peak times
- SNR
- template parameters (masses, spins)

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

Non-Gaussian noise



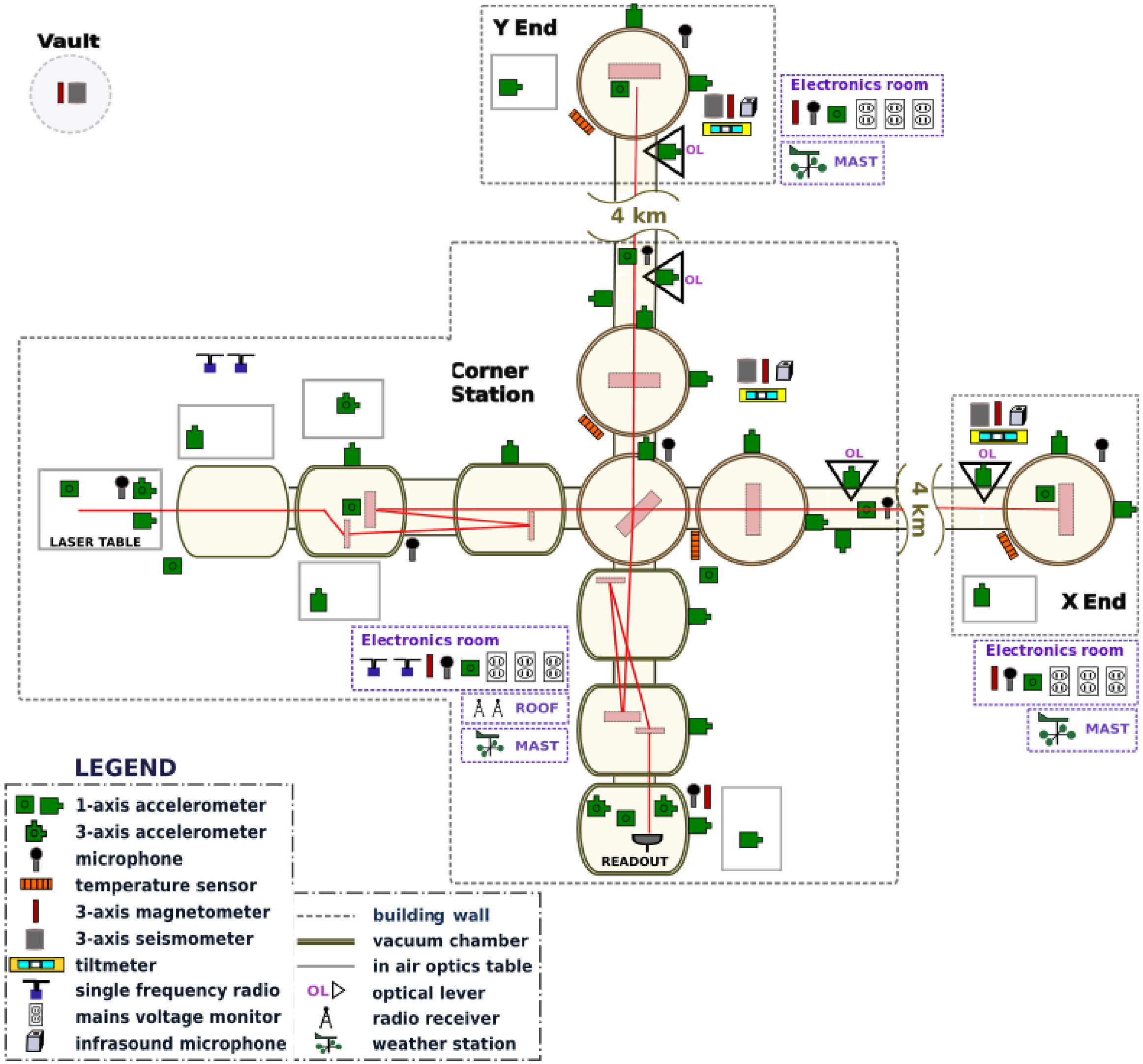
« Glitches »


Magnetic glitch
Magnetic sensor
Frequency [Hz]
1024
512
256
128
64
32
16
8
4
2
-2
-1
0
+1
+2
Time [seconds]
Scattered-light glitches
2048
1024
512
256
128
64
32
16
-8
-4
0
+4
+8
Time [seconds]
TCS glitches
TCS power
2048
1024
512
256
128
64
32
16
-8
-4
0
+4
+8
Time [seconds]
Airplane glitch
Microphone
Frequency [Hz]
2048
1024
512
256
128
64
32
16
-8
-4
0
+4
+8
Time [seconds]
Laser stabilization glitch
Laser control
2048
1024
512
256
128
64
32
16
-2
-1
0
+1
+2
Time [seconds]
Seismic glitch
seismometer
2048
1024
512
256
128
64
32
16
-8
-4
0
+4
+8
Time [seconds]
0
1
2
3
4
5
6
7
SNR

Monitoring the noise

Thousands of auxiliary channels are used to monitor the instruments

- environmental sensors
- detector sub-systems
- detector control



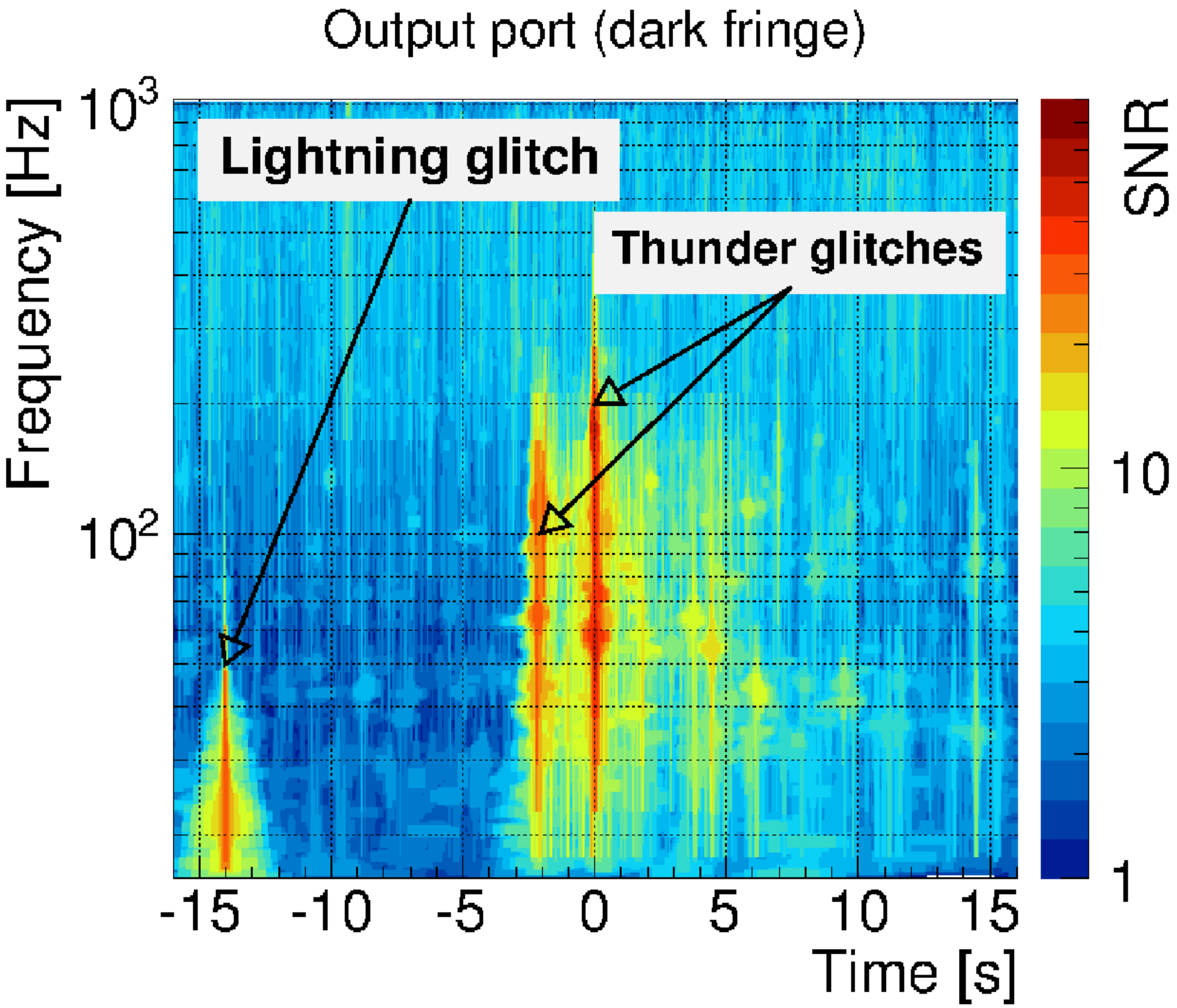
Noise injection campaigns are conducted to identify the detector's response to different noise stimulation

Multiple transient noises were identified during the run

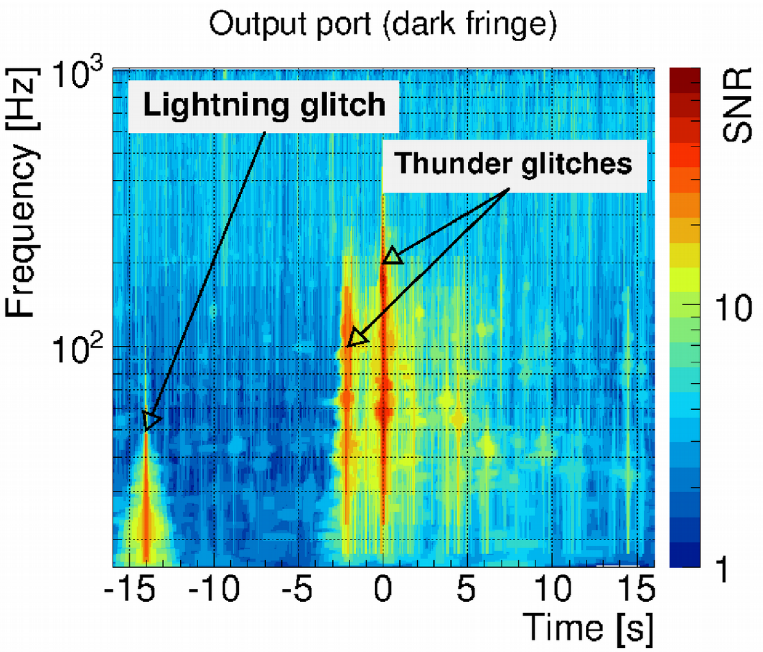
→ Anthropogenic noise
→ Earthquakes
→ Radio-frequency modulation
→ …

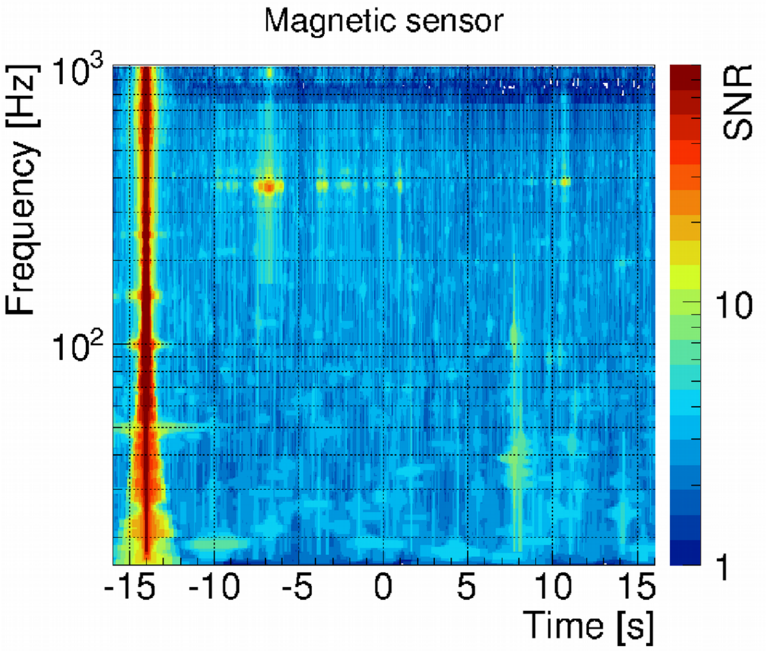
Option #1: fix the detector
Option #2: remove transient events in the data

Example : thunderstorm



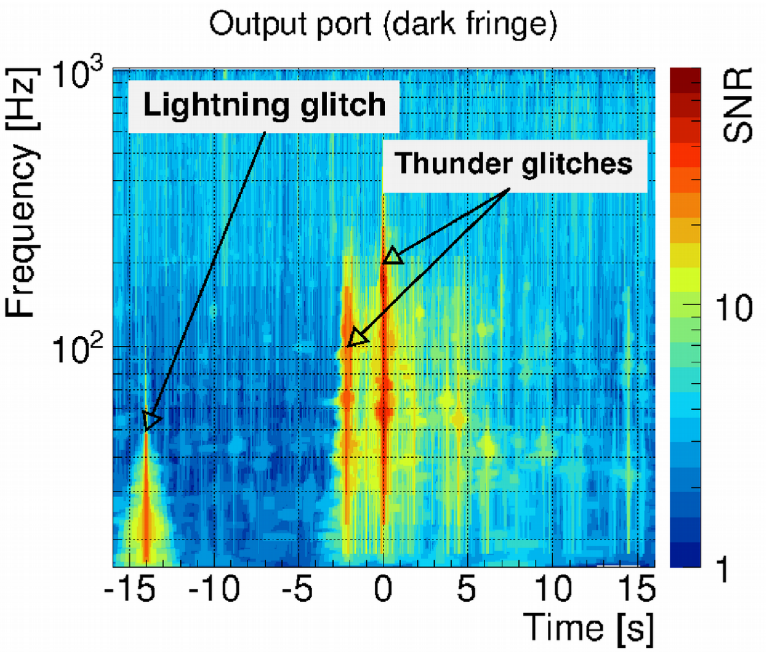
Example : thunderstorm


Output port (dark fringe)

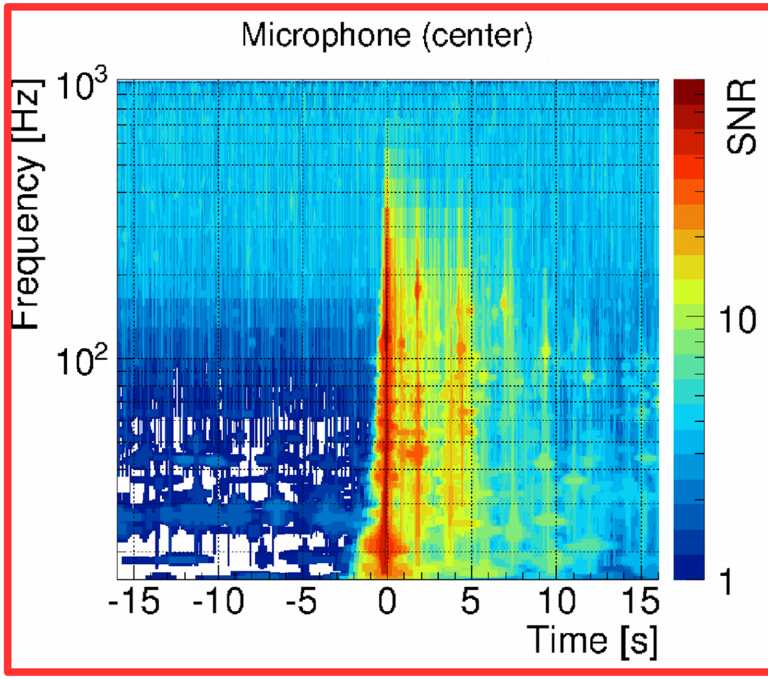

Magnetic sensor

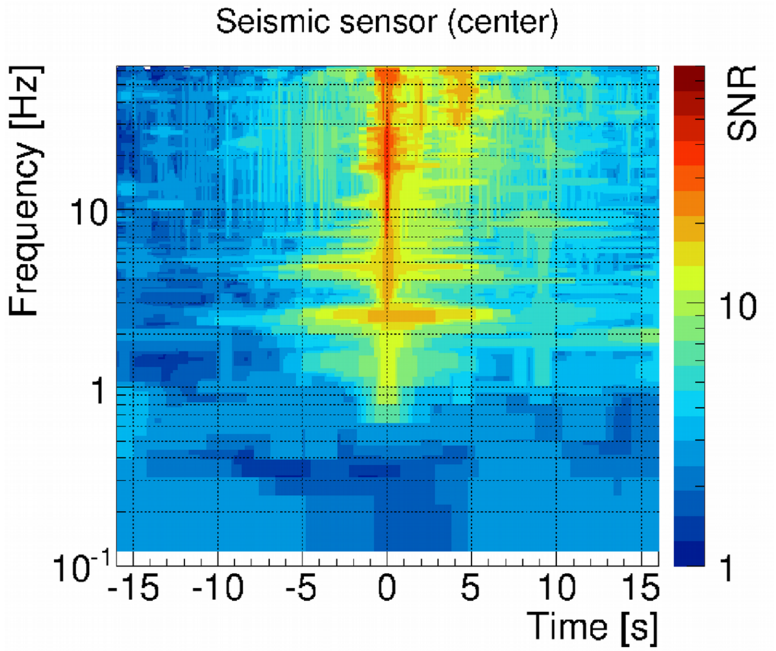
The lightnings are detected in magnetic sensors

Example : thunderstorm



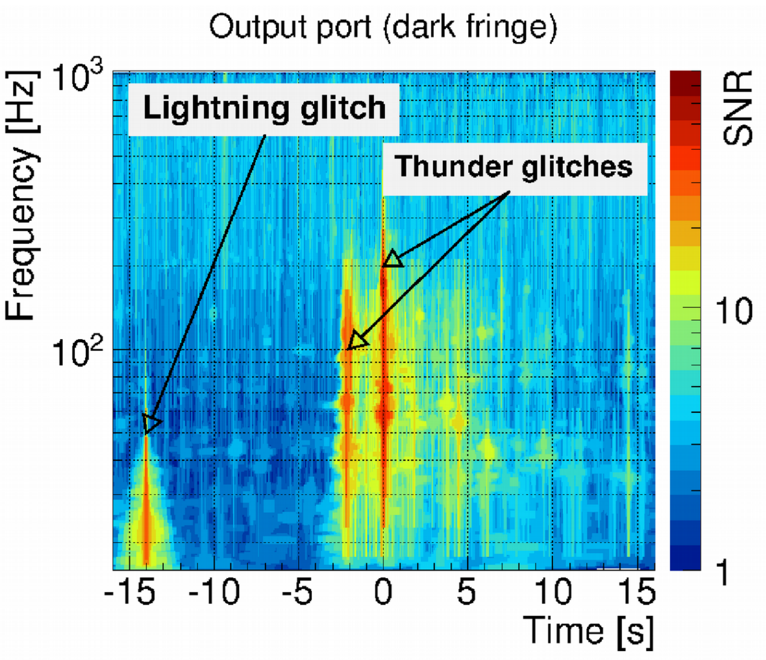
The thunder is detected in seismic sensors and microphones

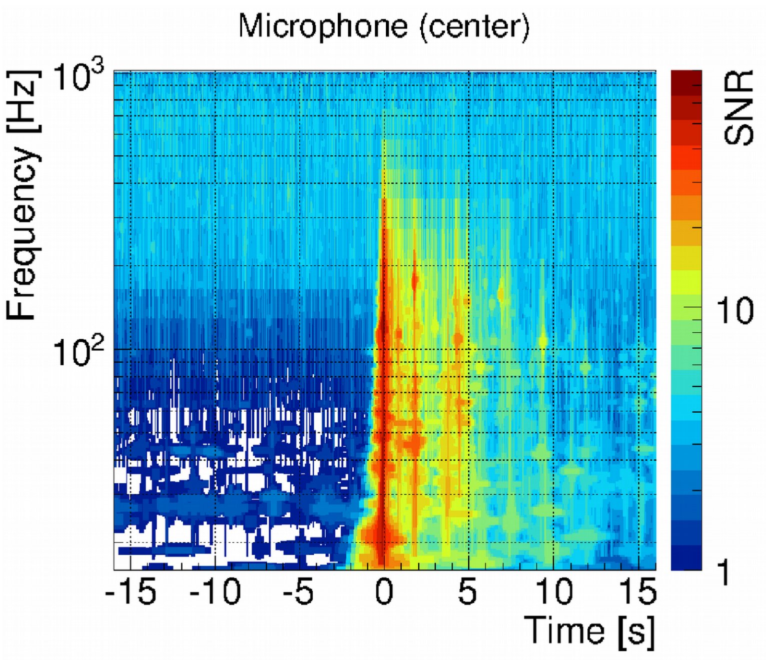




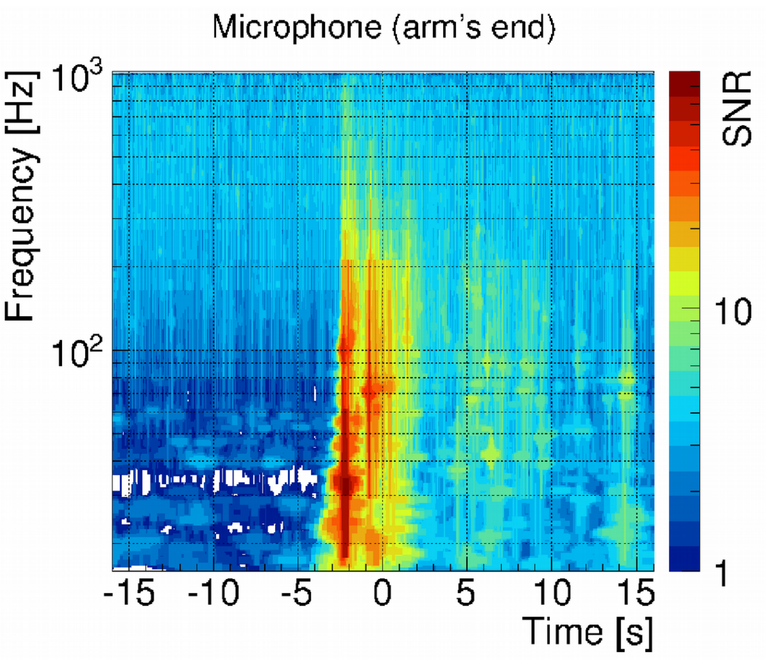
Central building

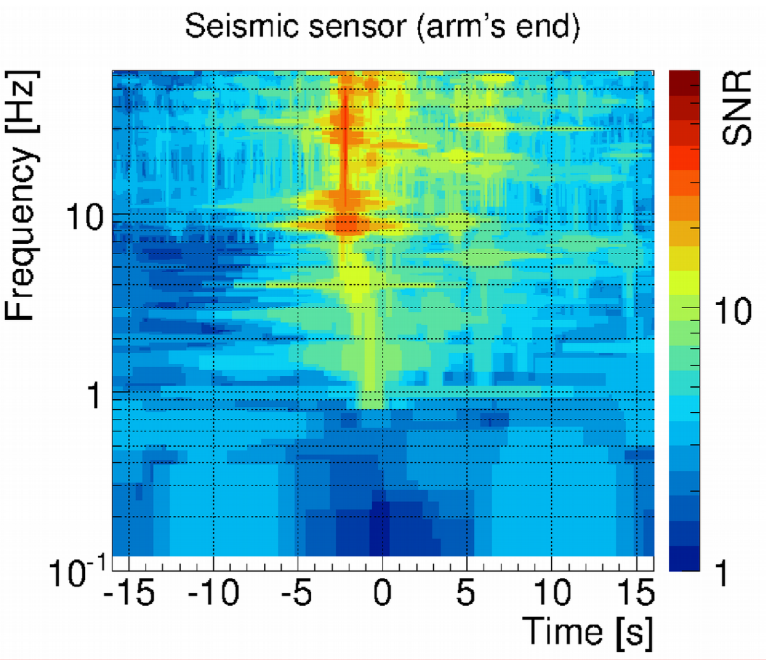
Example : thunderstorm


Output port (dark fringe)

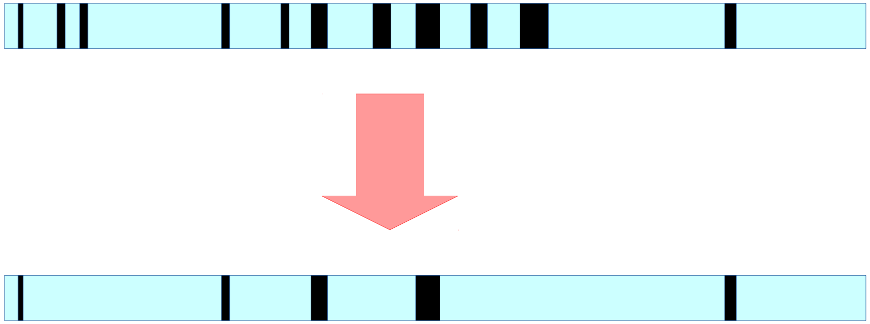

Microphone (center)

Arm's end


Microphone (arm's end)


Seismic sensor (arm's end)

Analysis vetoes



Analysis vetoes are created to remove transient noise events from known origins

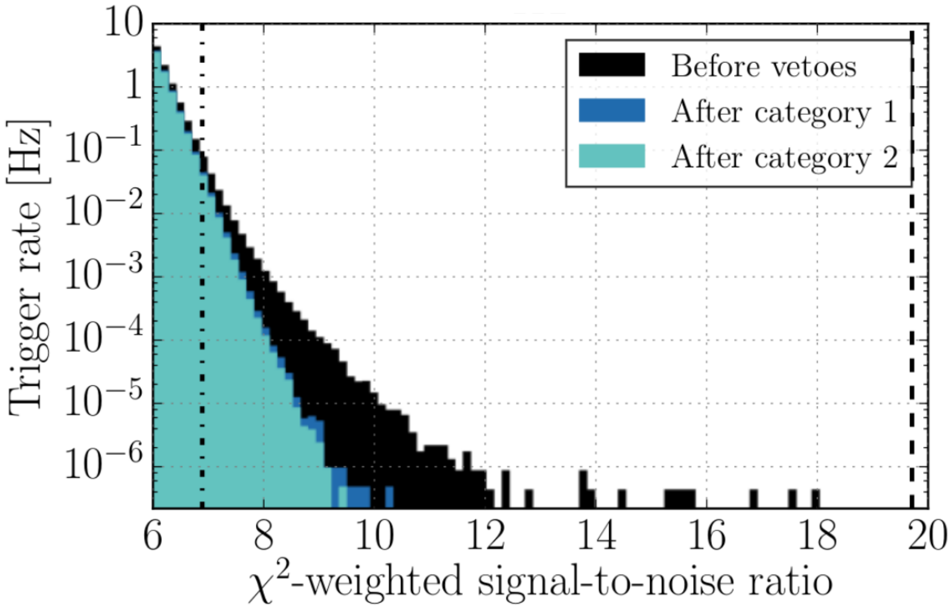
– environment

– detector glitches (laser, control loops…)

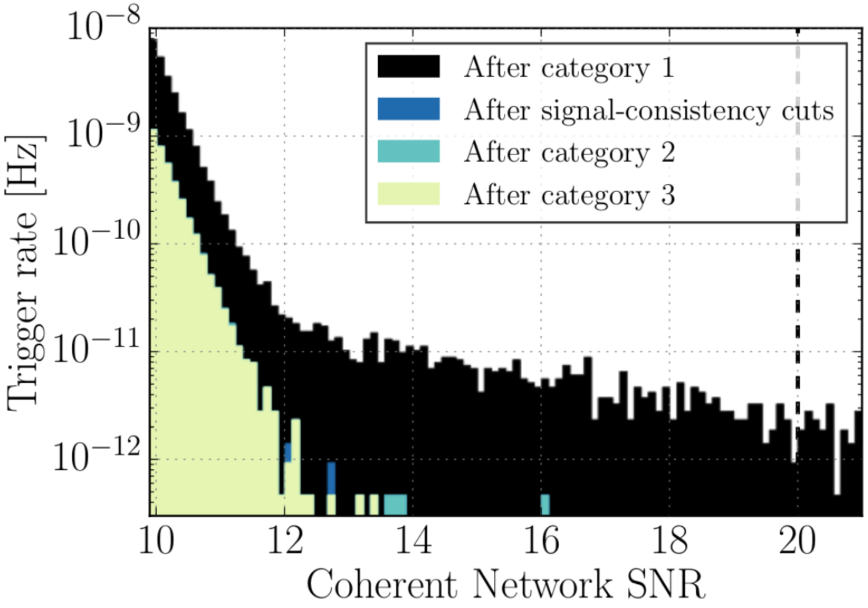
– scattered light

– …

CBC search

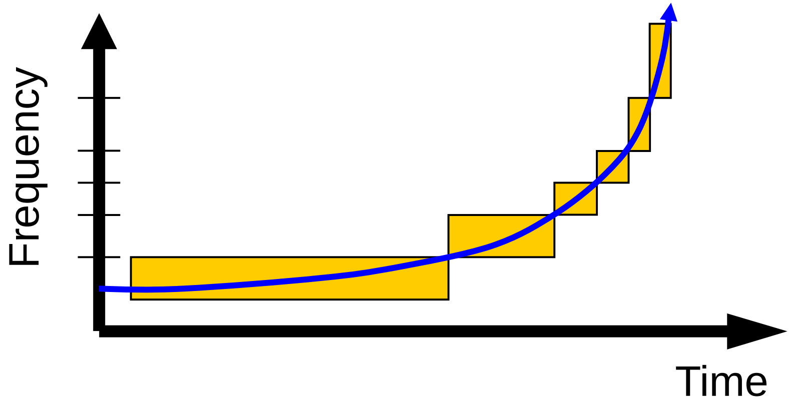


Burst search



Waveform consistency test

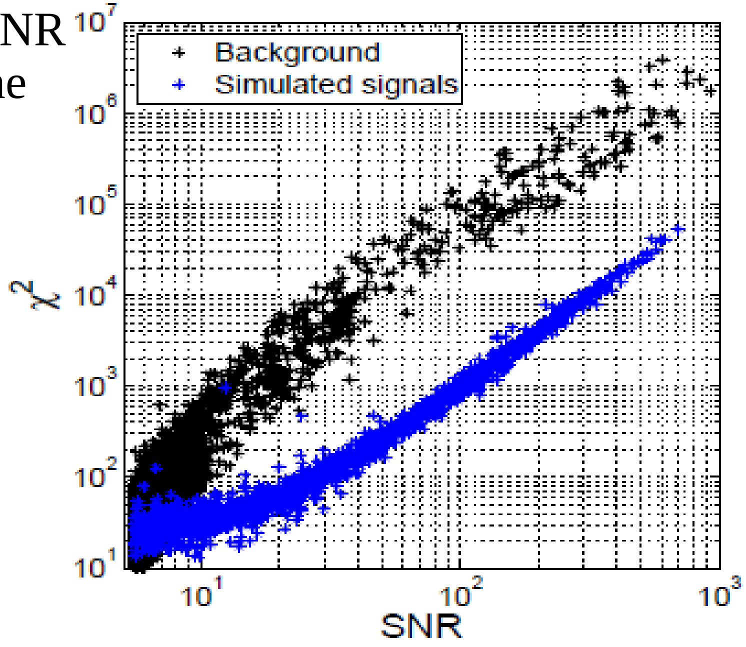
- Divide the “selected” template into p parts
- The frequency intervals are chosen so that for a true signal, the SNR is uniformly shared among the frequency bands.



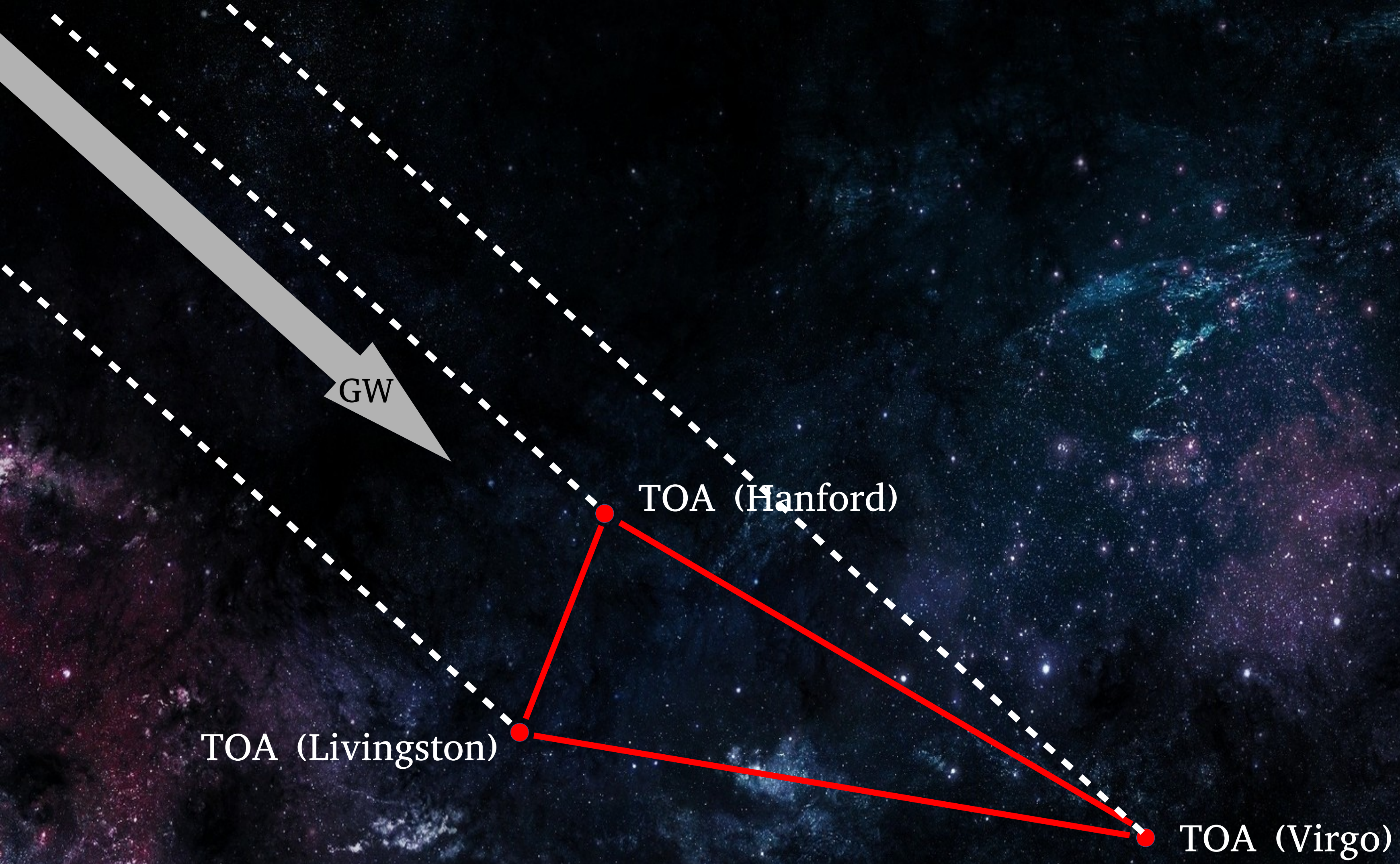
$$\chi^2(t) = p \sum_{j=1}^{p} |\rho_j - \frac{\rho}{p}|^2$$

- For a stationary and Gaussian noise χ^2 has an expectation value: $< \chi^2 >= p - 1$
- In practise χ^2 values are larger than expected for large SNR (discrete template banks effect) → cut in (SNR, χ^2) plane
- Weighted SNR

$$\rho_{\rm new} = \begin{cases} \rho, & \chi^2 \le n_{\rm dof} \\ \dfrac{\rho}{\left[\left(1 + \frac{\chi^2}{n_{dof}}^{4/3}\right)/2\right]^{1/4}}, & \chi^2 > n_{\rm dof} \end{cases}$$



Coincidence between detectors



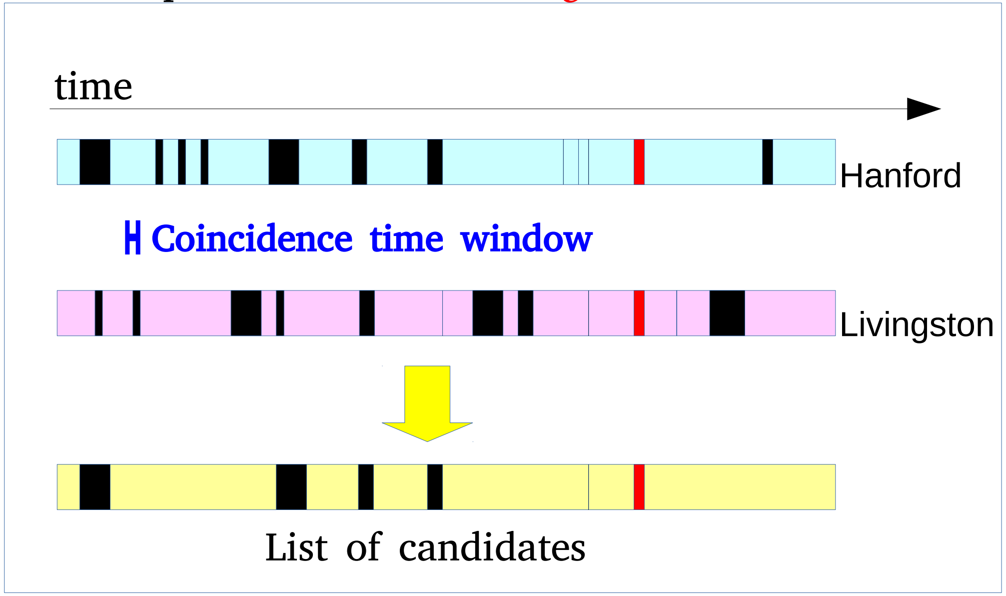
- The GW signal must be detected almost simultaneously across the network $\delta t \leqslant Max\ light\ travel\ time$

- The noise in the detectors is uncorrelated

Coincidence between detectors

A gravitational-wave signal is detected by multiple detectors almost simultaneously

True experiment = noise + signal



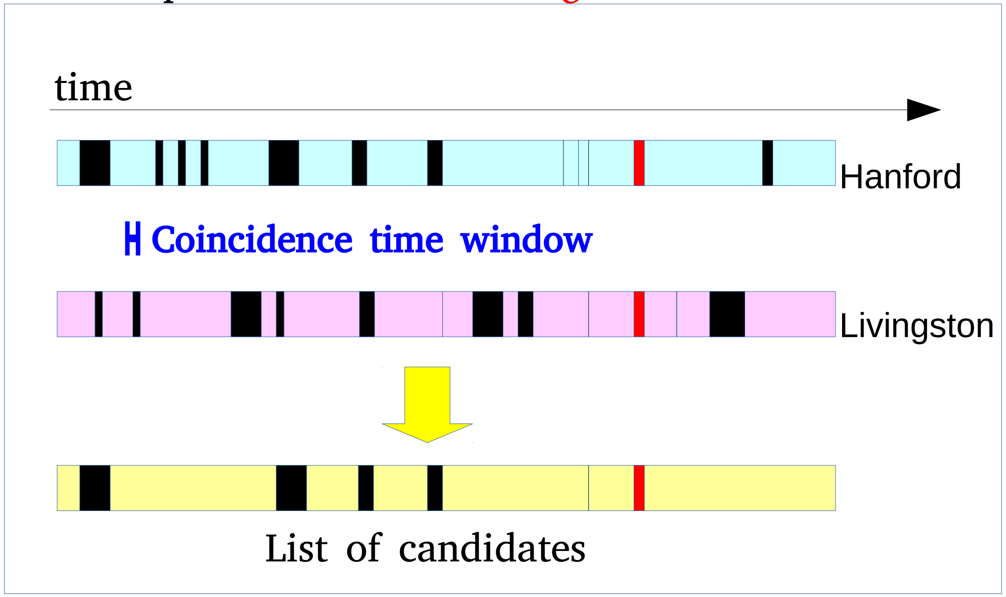
Coincidence rate:

$$R_{coinc} \sim R_H R_L \Delta t_{win}$$
$$\sim (1\,Hz) \times (1\,Hz) \times (10^{-2}\,s) = 10^{-2}\,Hz$$

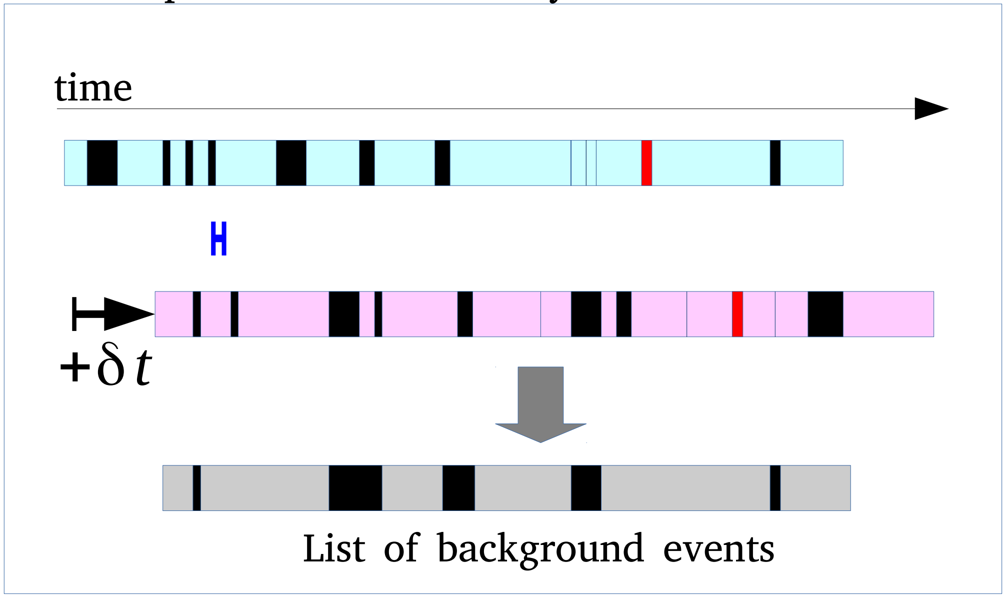
Event significance

The background of a gravitational-wave search is estimated using the time-slide technique
Assumption = uncorrelated noise between detectors

True experiment = noise + signal



Fake experiment = noise only

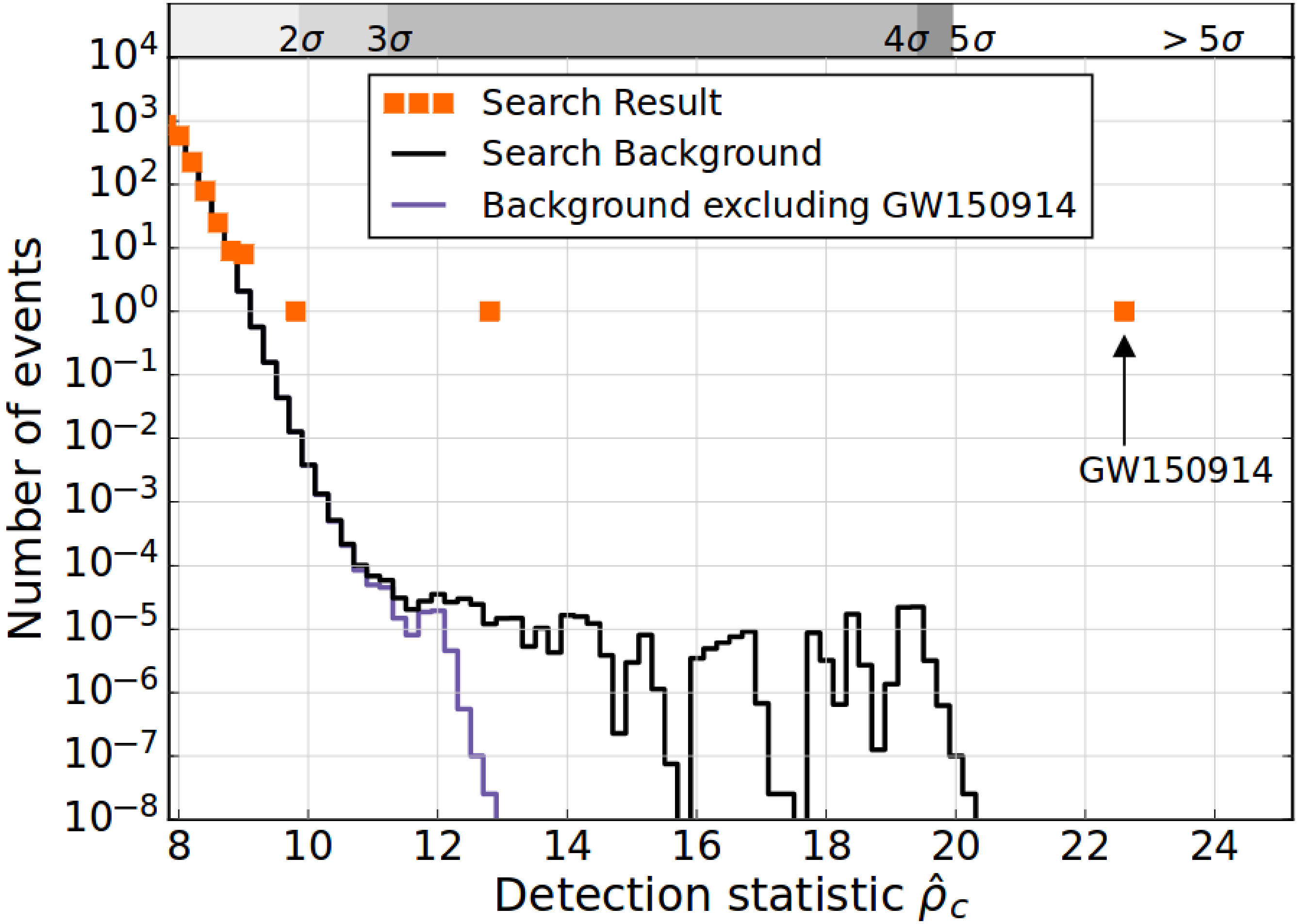


A very large number of fake experiments can be simulated using multiple offsets

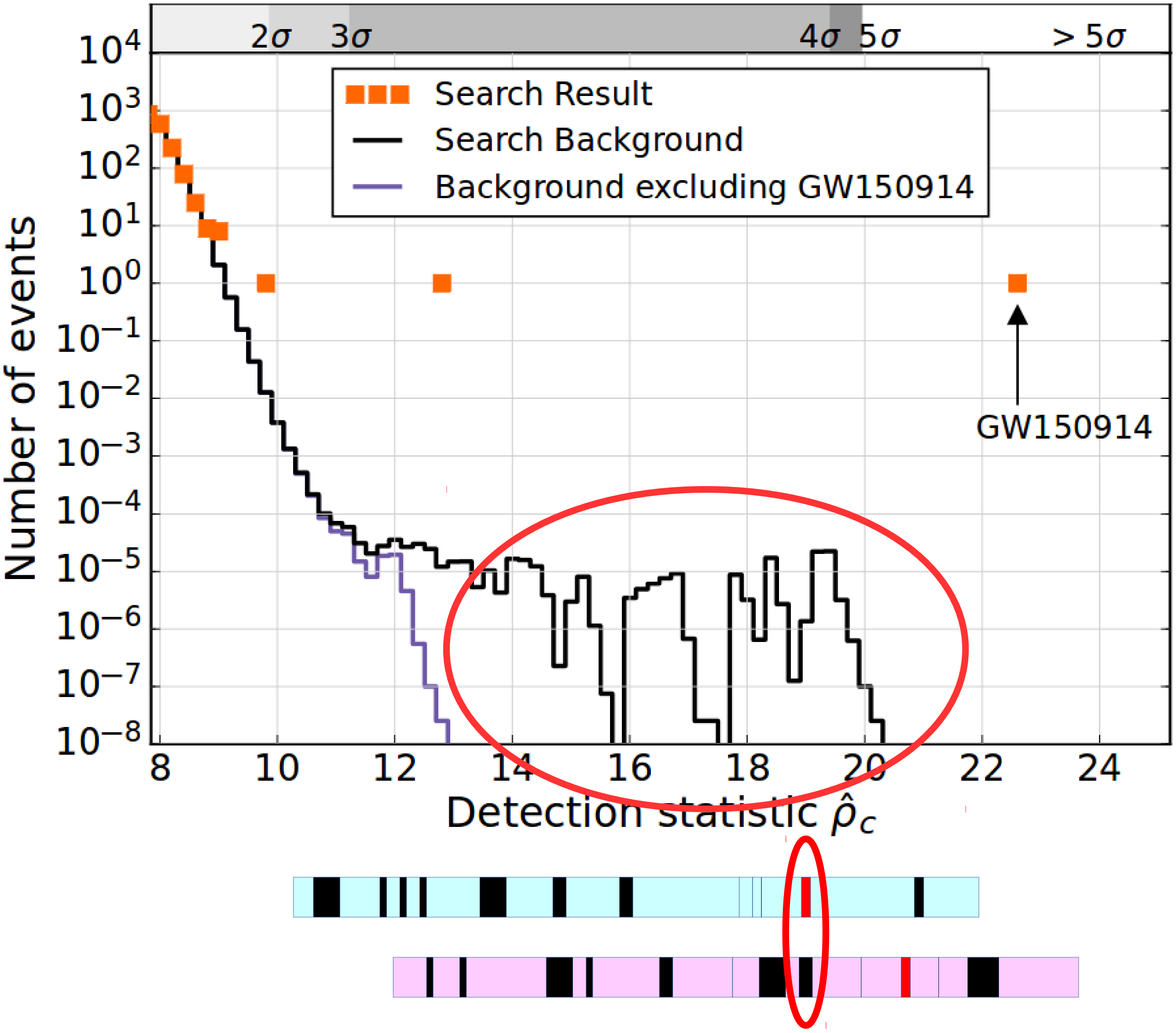
LIGO O1 analysis:
– O(10^6) time offsets

→ background estimated using a fake experiment of O(100,000 years)

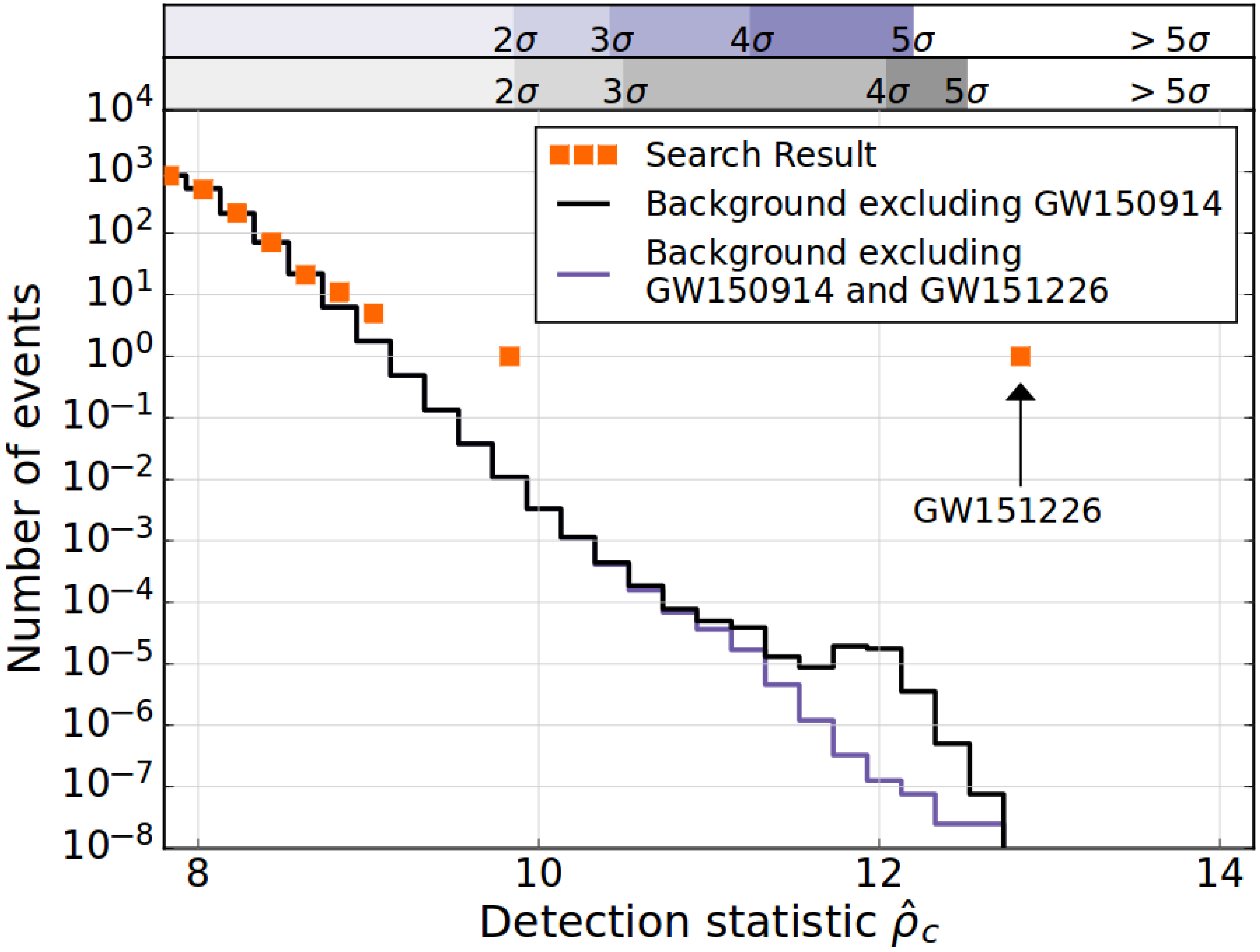
Event significance



Event significance



Event significance



Monday September 14, 2015 09:50:45 UTC

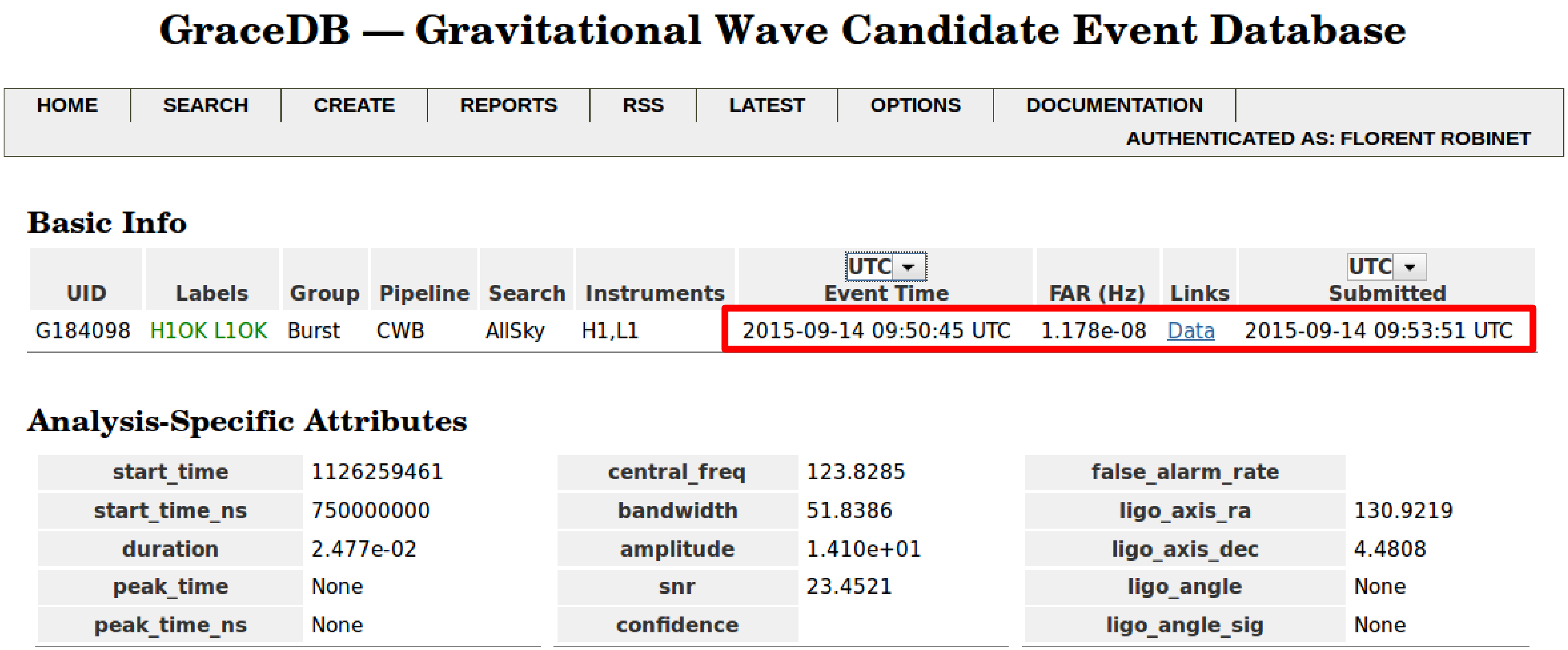
The LIGO detectors are both operational and stable (O1)

Virgo is off (upgrade in progress)

It is daytime in Europe,
the middle of the night in the US

Online analysis

GW150914 was detected within 3 minutes by a burst search



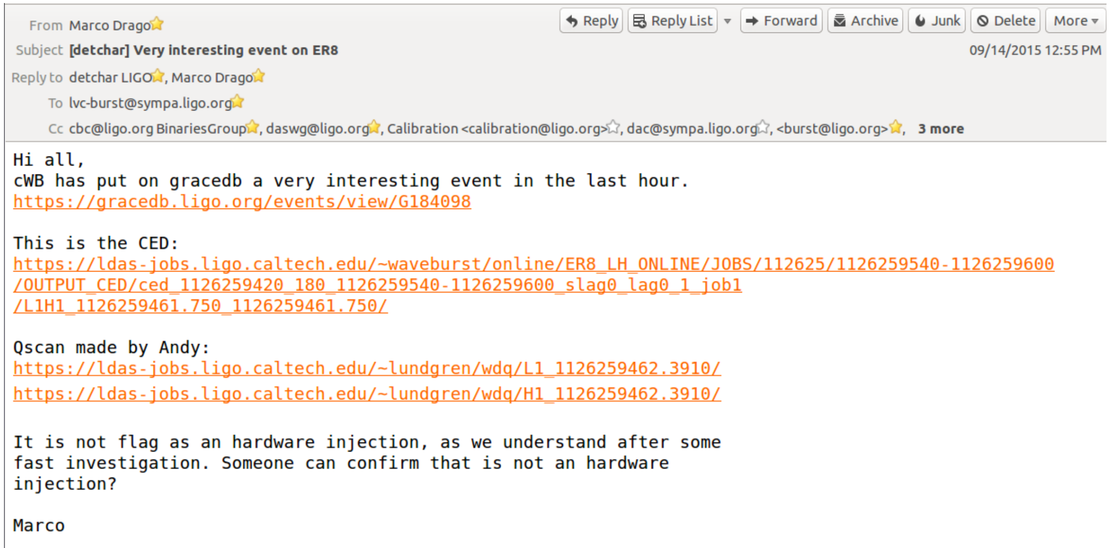
GraceDB — Gravitational Wave Candidate Event Database

Basic Info

UID	Labels	Group	Pipeline	Search	Instruments	UTC Event Time	FAR (Hz)	Links	UTC Submitted
G184098	H1OK L1OK	Burst	CWB	AllSky	H1,L1	2015-09-14 09:50:45 UTC	1.178e-08	Data	2015-09-14 09:53:51 UTC

Analysis-Specific Attributes

start_time	1126259461	**central_freq**	123.8285	**false_alarm_rate**	
start_time_ns	750000000	**bandwidth**	51.8386	**ligo_axis_ra**	130.9219
duration	2.477e-02	**amplitude**	1.410e+01	**ligo_axis_dec**	4.4808
peak_time	None	**snr**	23.4521	**ligo_angle**	None
peak_time_ns	None	**confidence**		**ligo_angle_sig**	None



From Marco Drago
Subject **[detchar] Very interesting event on ER8**
09/14/2015 12:55 PM
Reply to detchar LIGO, Marco Drago
To lvc-burst@sympa.ligo.org
Cc cbc@ligo.org BinariesGroup, daswg@ligo.org, Calibration <calibration@ligo.org>, dac@sympa.ligo.org, <burst@ligo.org>, **3 more**

Hi all,
cWB has put on gracedb a very interesting event in the last hour.
https://gracedb.ligo.org/events/view/G184098

This is the CED:
https://ldas-jobs.ligo.caltech.edu/~waveburst/online/ER8_LH_ONLINE/JOBS/112625/1126259540-1126259600/OUTPUT_CED/ced_1126259420_180_1126259540-1126259600_slag0_lag0_1_job1/L1H1_1126259461.750_1126259461.750/

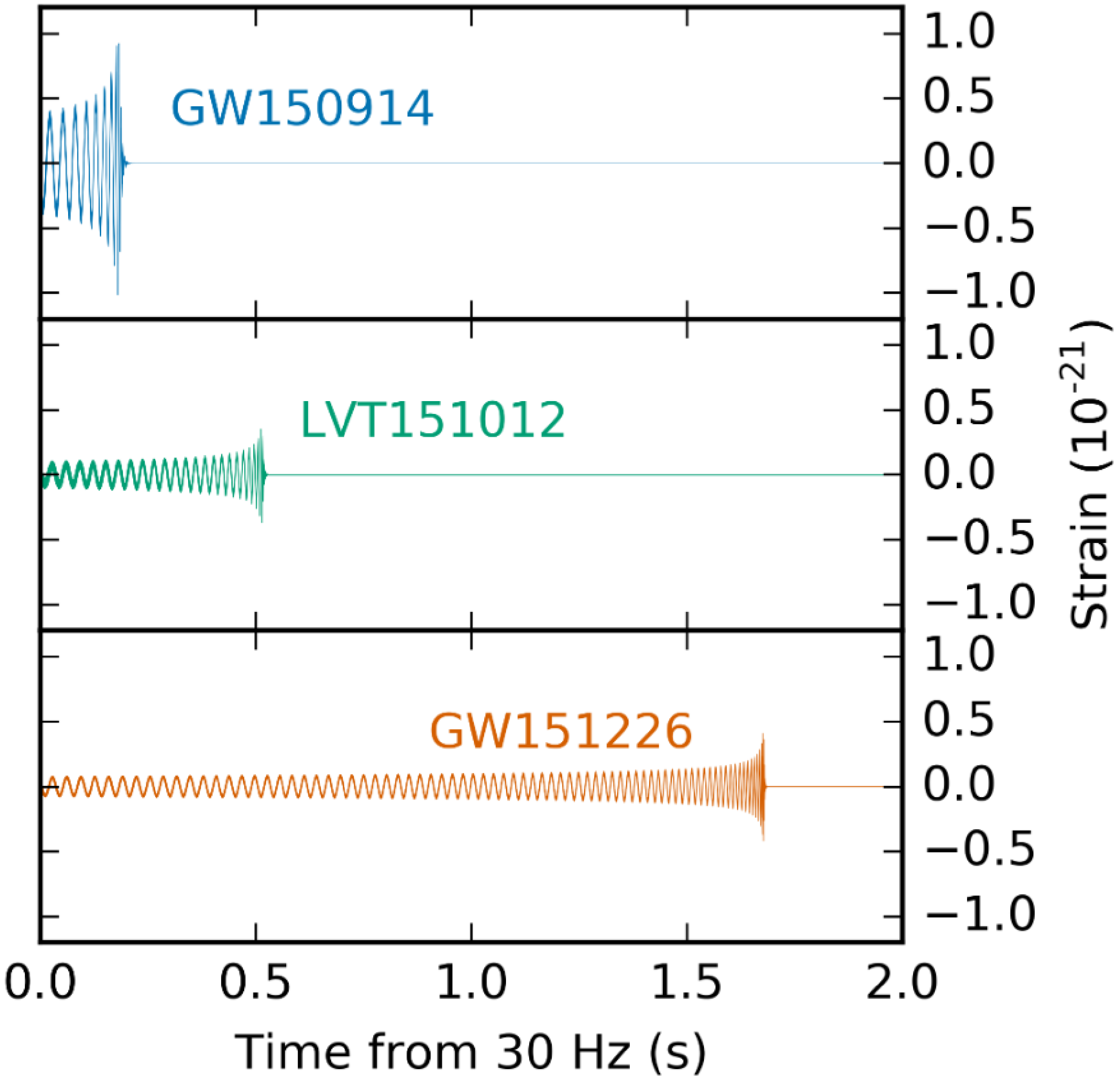
Qscan made by Andy:
https://ldas-jobs.ligo.caltech.edu/~lundgren/wdq/L1_1126259462.3910/
https://ldas-jobs.ligo.caltech.edu/~lundgren/wdq/H1_1126259462.3910/

It is not flag as an hardware injection, as we understand after some fast investigation. Someone can confirm that is not an hardware injection?

Marco

O1 gravitational-wave events

2+1 events associated to the coalescence of a black hole binary system



Short-duration and high-amplitude event

Event with low significance

Long-duration and low-amplitude event

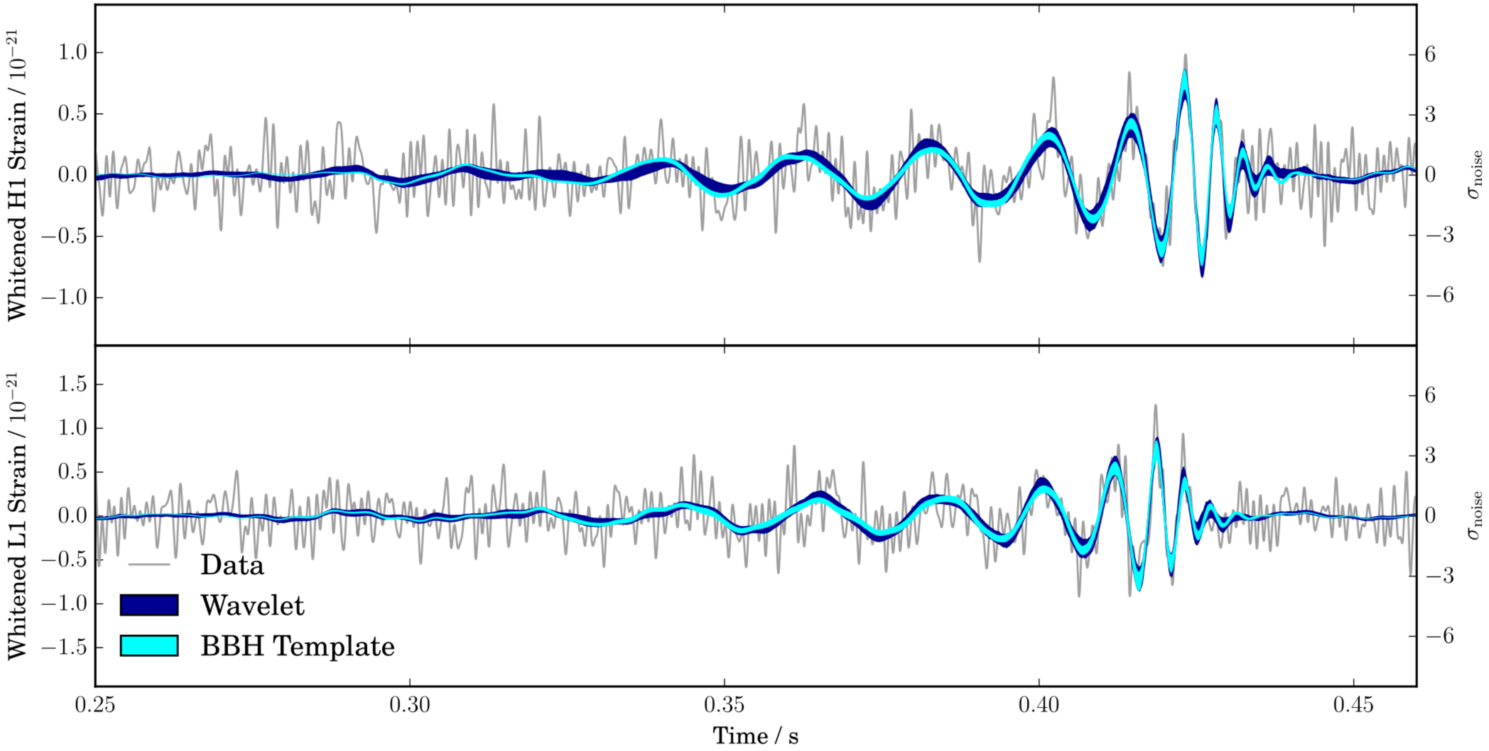
Parameter estimation

Full analysis of the data surrounding the event
→ only input from searches: time of the event
→ fully explore the parameter space
→ include calibration uncertainty

8 intrinsic parameters (masses and spins)
9 extrinsic parameters (distance, position, orientation, coalescence time and phase)
Orbital ellipticity is neglected

Dimensionless spin: $a = \frac{c|\vec{S}|}{Gm^2} \leq 1$

Frequency is redshifted → masses must be rescaled by a factor (1+z)



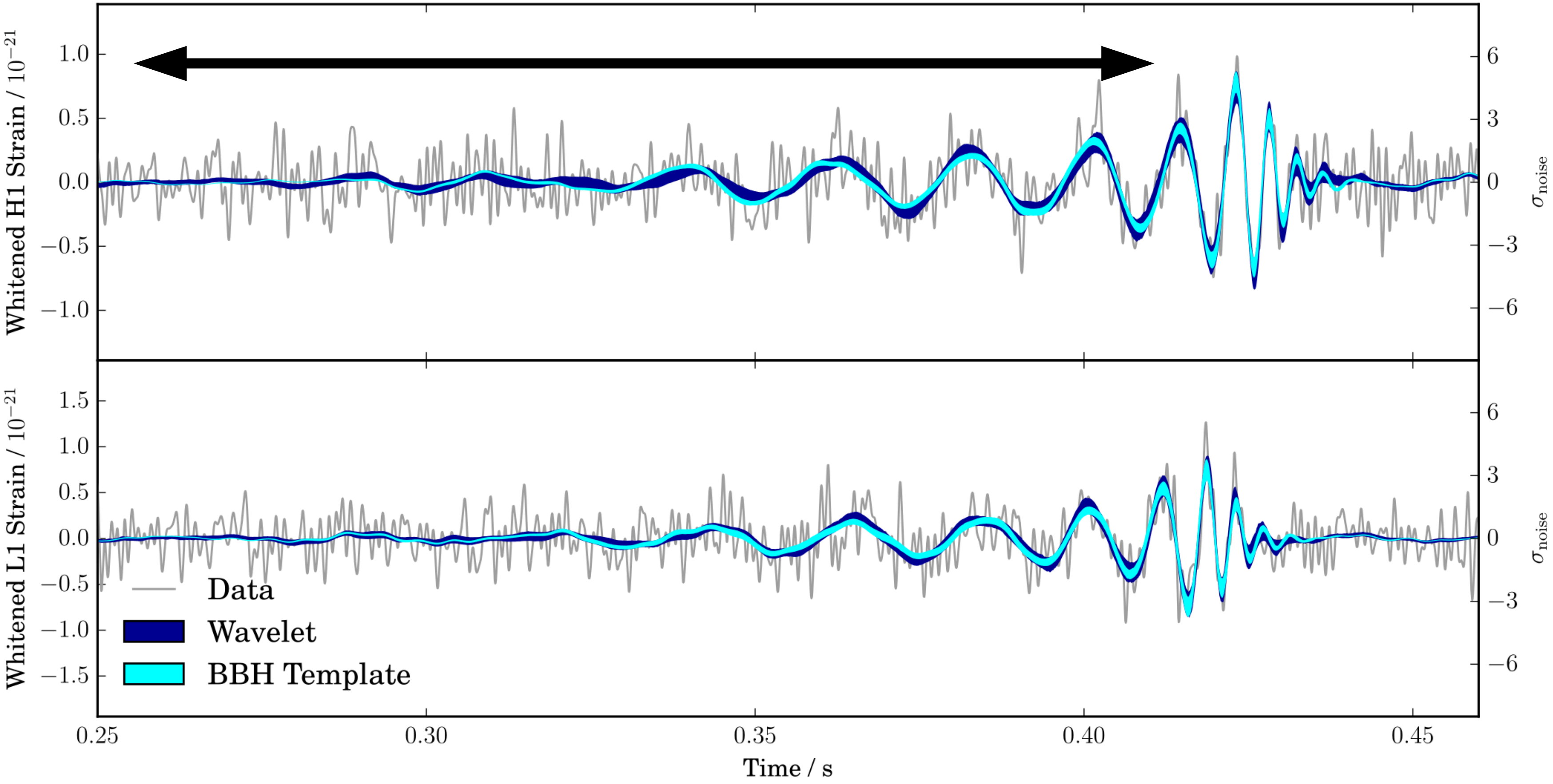
Parameter estimation

Inspiral phase: PN perturbative expansion (v/c)

Leading order → phase evolution driven by the chirp mass (tight constraints)

Next order → m2/m1 and spins // **L**

Next orders → full spins

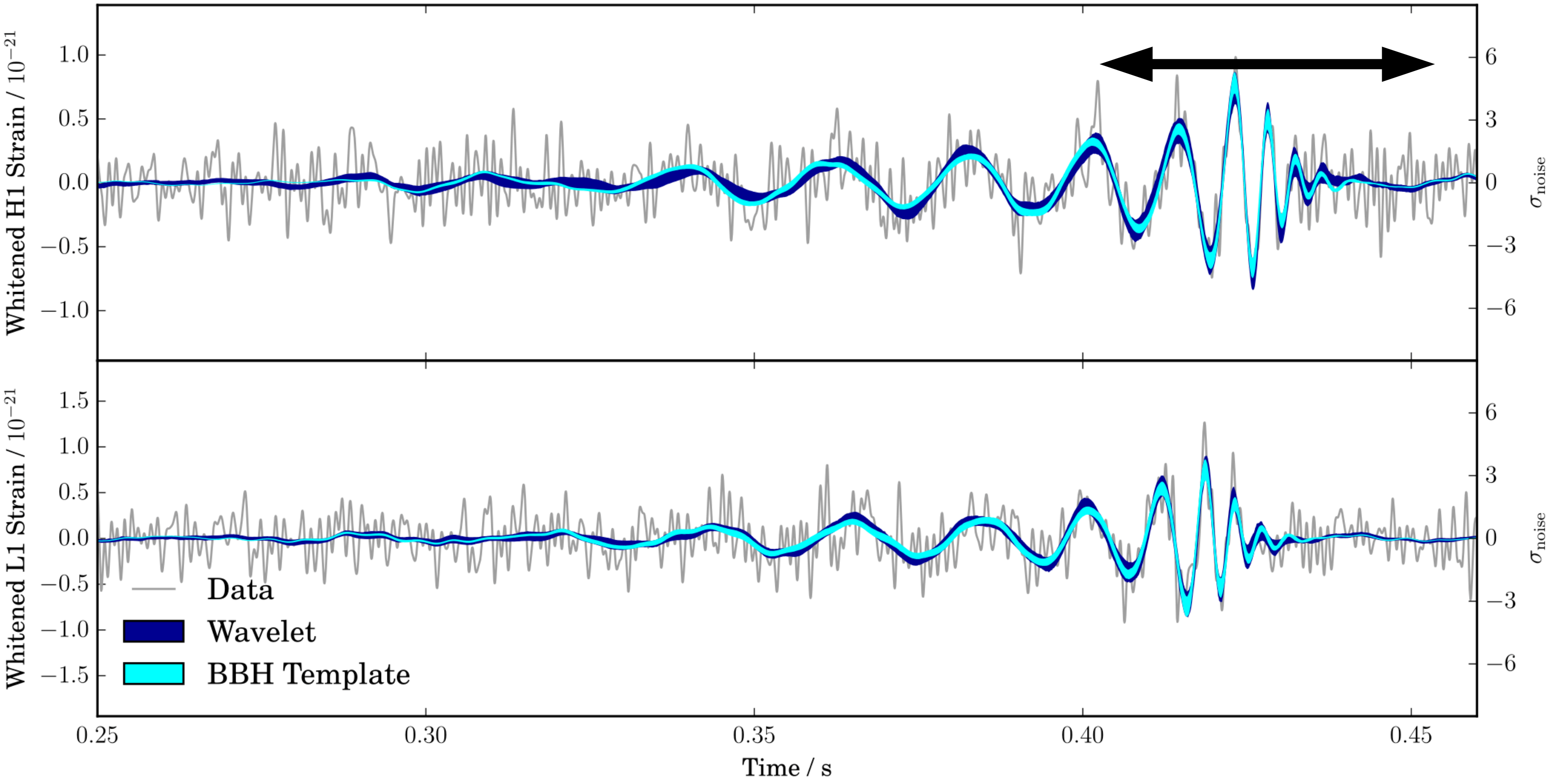


Parameter estimation

Late inspiral – merger – ringdown: numerical relativity waveforms

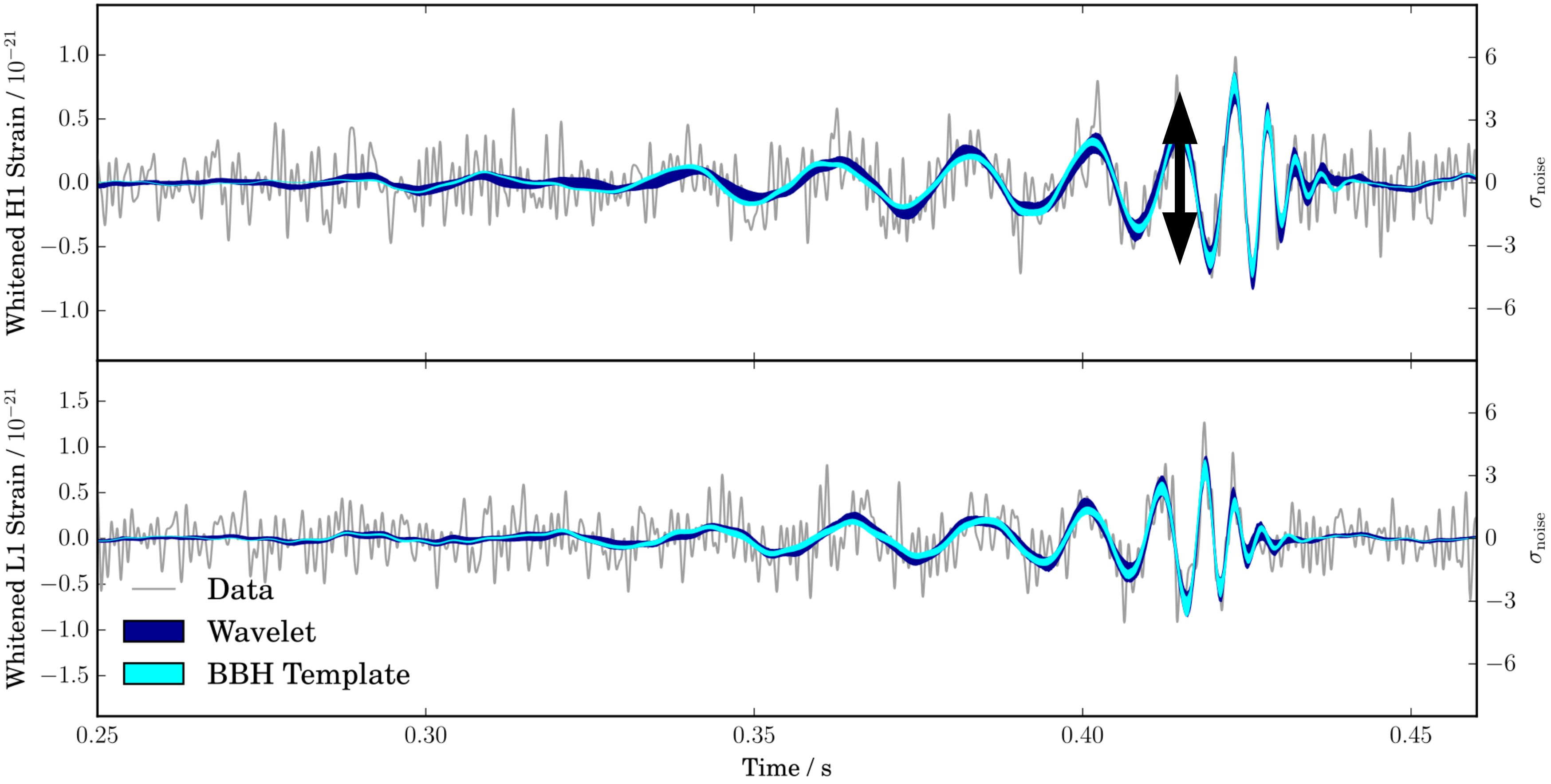
Late inspiral → total mass (+chirp mass + m1/m²) → individual masses

Ringdown → final BH mass and spin



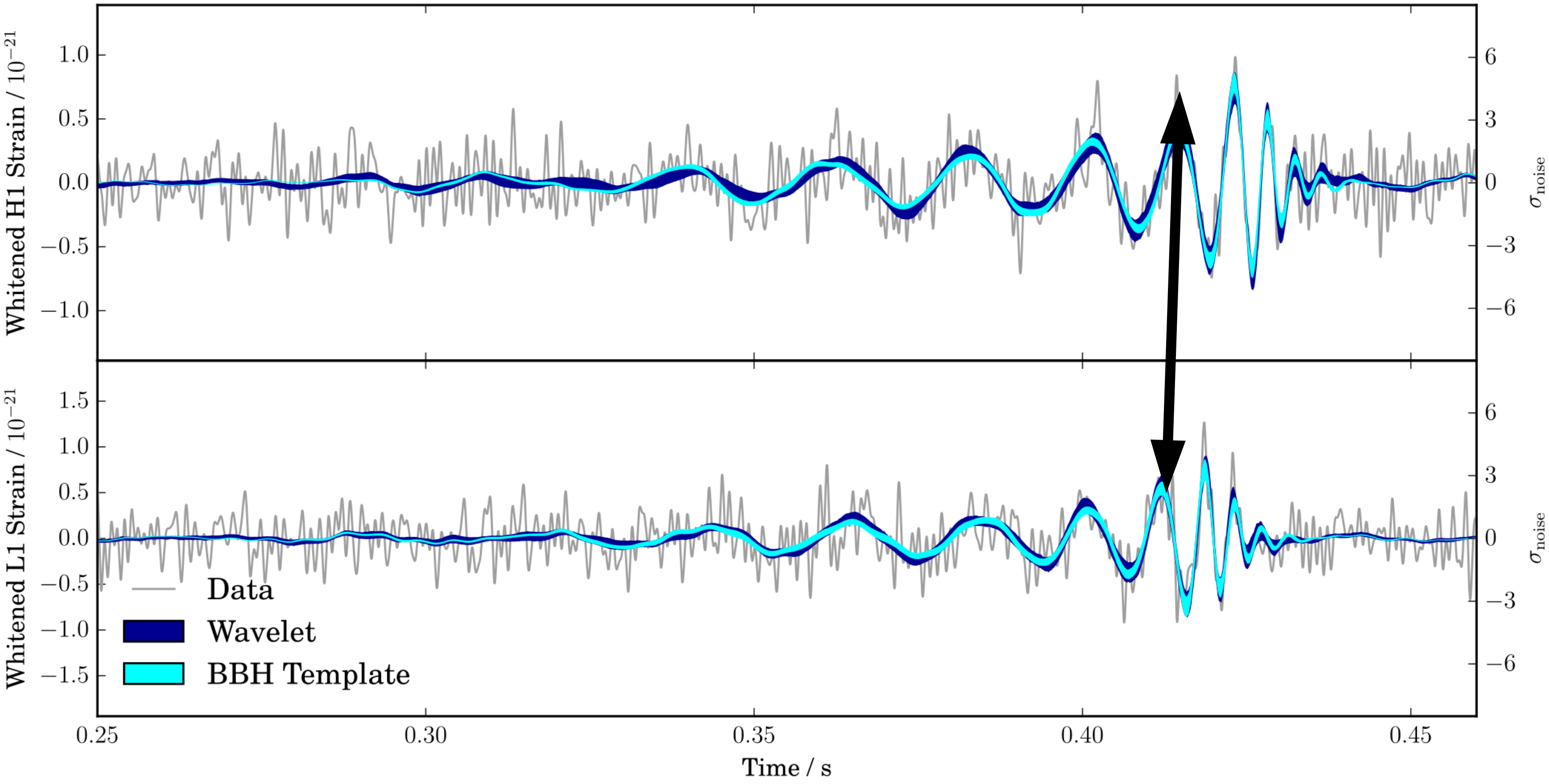
Parameter estimation

Amplitude: inversely proportional to the distance

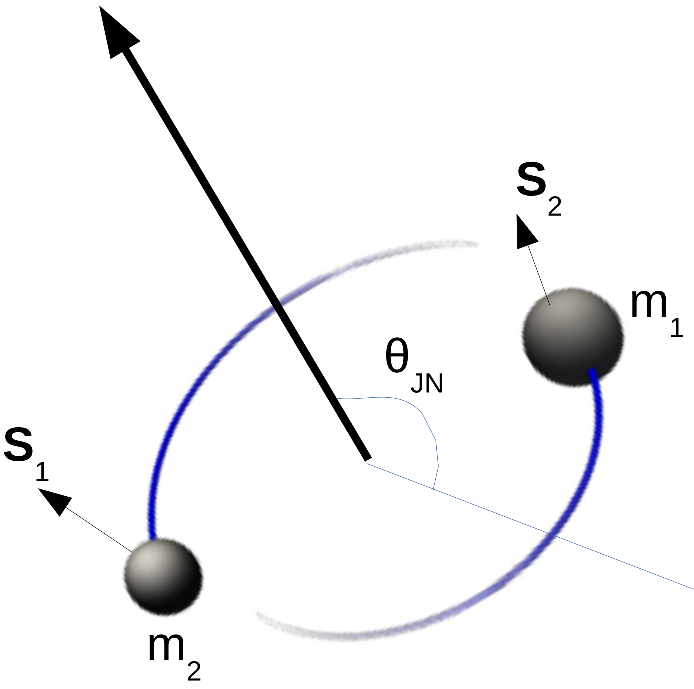


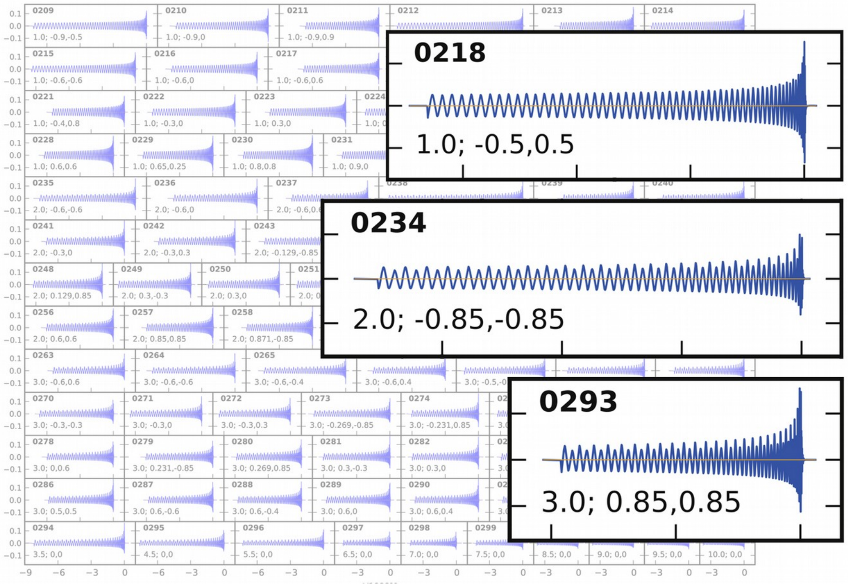
Parameter estimation

Amplitude and phase difference between sites → sky location
+ Amplitude and phase consistency



Parameter estimation





d_L

GWs (?) noise data from multiple instruments

$$\tilde{d}^{(D)}(f) = \tilde{h}^{(D)}(f) + \tilde{n}^{(D)}(f) \qquad \vec{d} = \{d^{(H)}, d^{(L)}, \dots\}$$

Bayes theorem:

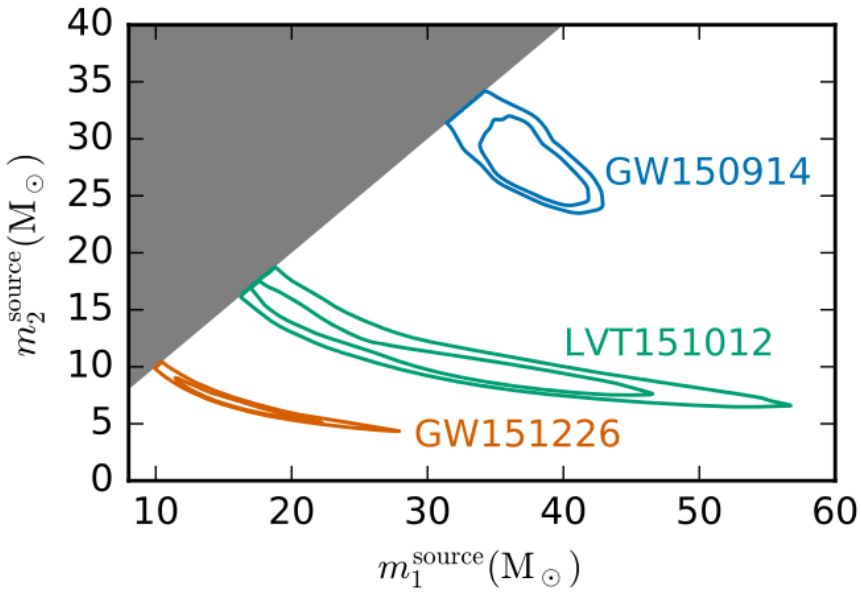
$$p(\vec{\theta}|\vec{d},\mathcal{H},I) = \frac{p(\vec{\theta}|\mathcal{H},I)\,p(\vec{d}|\vec{\theta},\mathcal{H},I)}{p(\vec{d}|\mathcal{H},I)}$$

posterior prior likelihood

Marginalized PDF:

$$p(\vec{\theta}_A|\vec{d},\mathcal{H},I) = \int_{\Theta_B} p(\vec{\theta}|\vec{d},\mathcal{H},I)\,d\vec{\theta}_B$$

Parameter estimation



Mostly sensitive to the chirp mass
→ m_1, m_2 degeneracy

$$M_c = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

GW150914

$$m_1 = 36.2^{+5.2}_{-3.2}\, M_{sun}$$

$$m_2 = 29.1^{+3.7}_{-4.4}\, M_{sun}$$

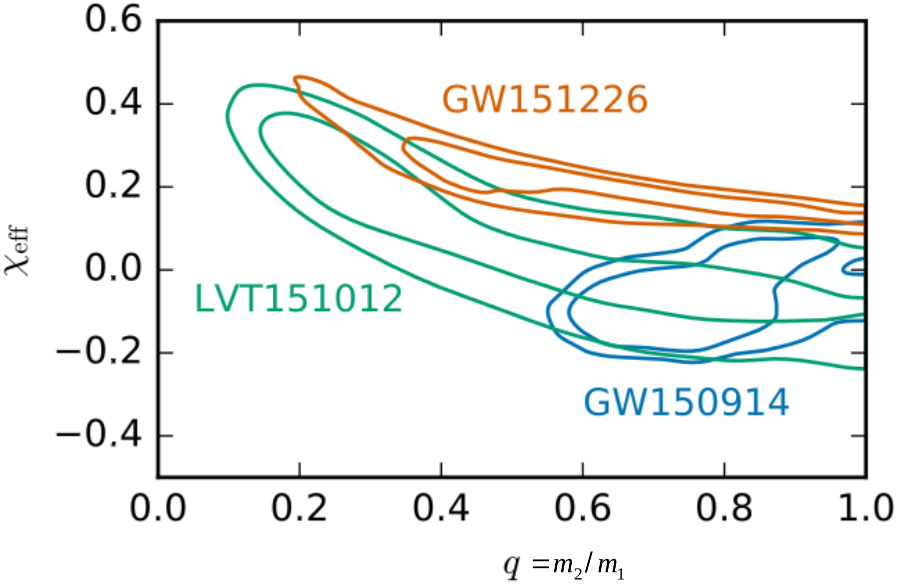
GW151226

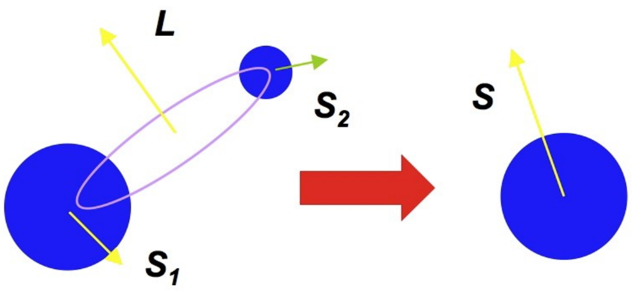
$$m_1 = 14.2^{+8.3}_{-3.7}\, M_{sun}$$

$$m_2 = 7.5^{+2.3}_{-2.3}\, M_{sun}$$

→ All the components are black holes
→ Very high masses for GW150914

Parameter estimation





$$\chi_{eff} = \frac{m_1 a_{1z} + m_2 a_{2z}}{m_1 + m_2}$$

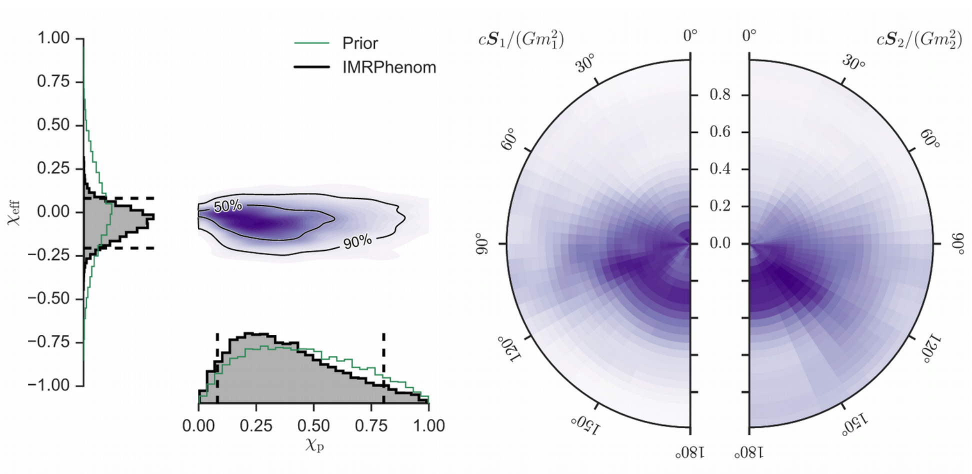
→ not well constrained

GW151226: at least one black hole is a Kerr black hole

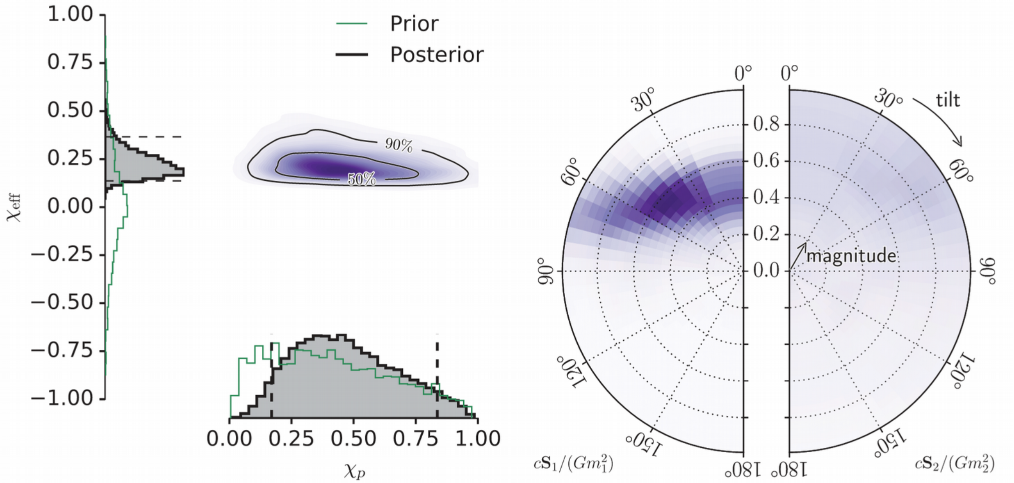
spin $>$**0.2**

Uninformative about precession

GW150914

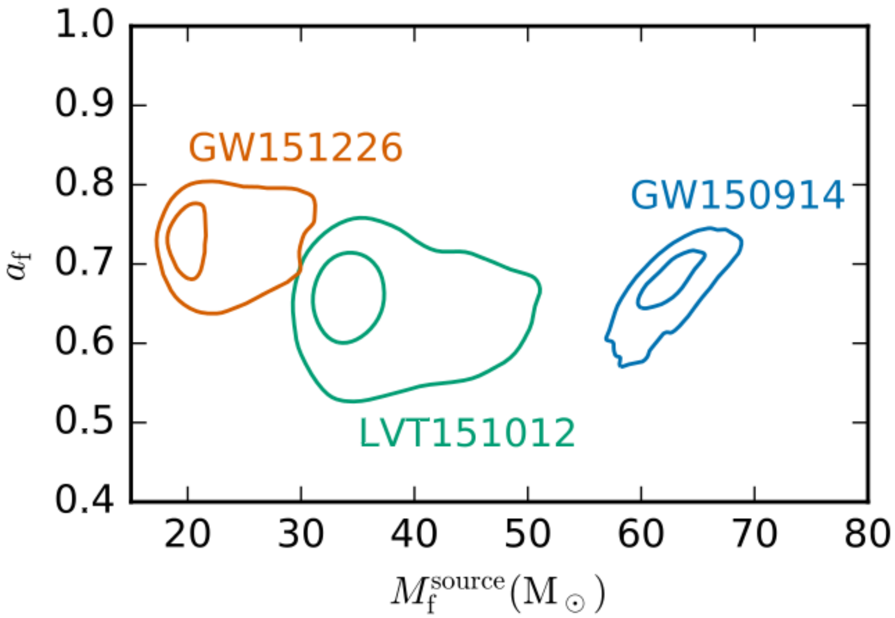


GW151226



Parameter estimation

Final mass & spin



GW150914

$$M_f = 62.3^{+3.7}_{-3.1}\, M_{sun}$$

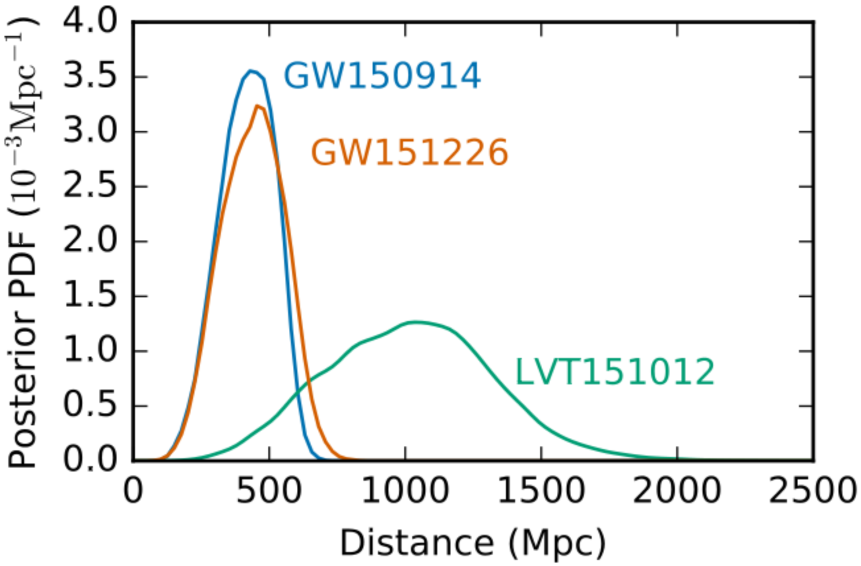
$$a_f = 0.68^{+0.05}_{-0.06}$$

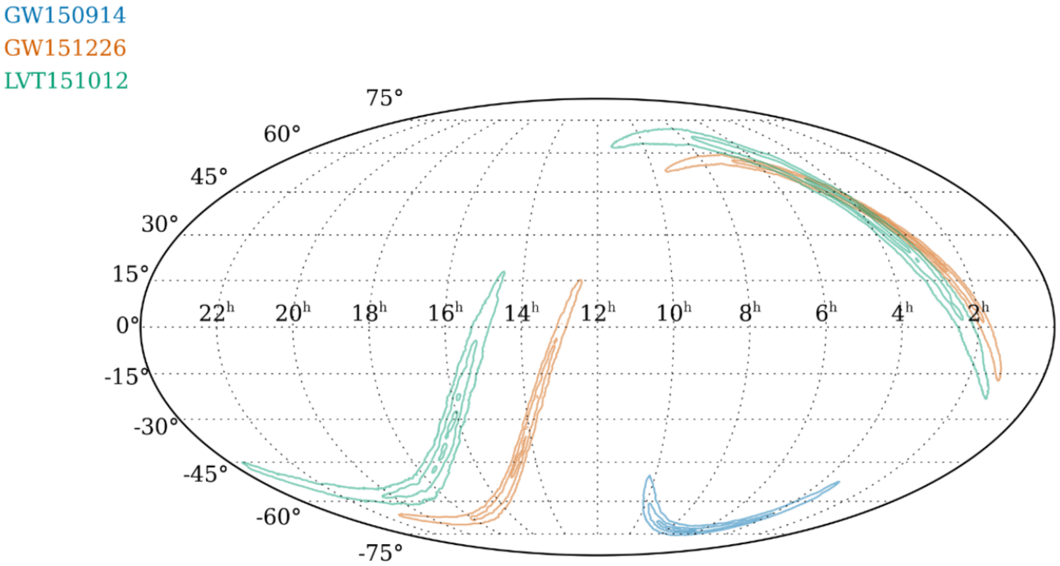
GW151226

$$M_f = 20.8^{+6.1}_{-1.7}\, M_{sun}$$

$$a_f = 0.74^{+0.06}_{-0.06}$$

Parameter estimation





GW150914

$$D_L = 420^{+150}_{-180}\,Mpc \qquad z = 0.09^{+0.03}_{-0.04}$$

GW151226

$$D_L = 440^{+180}_{-190}\,Mpc \qquad z = 0.09^{+0.03}_{-0.04}$$

(Lambda-CDM cosmology)

90% credible region for sky location:

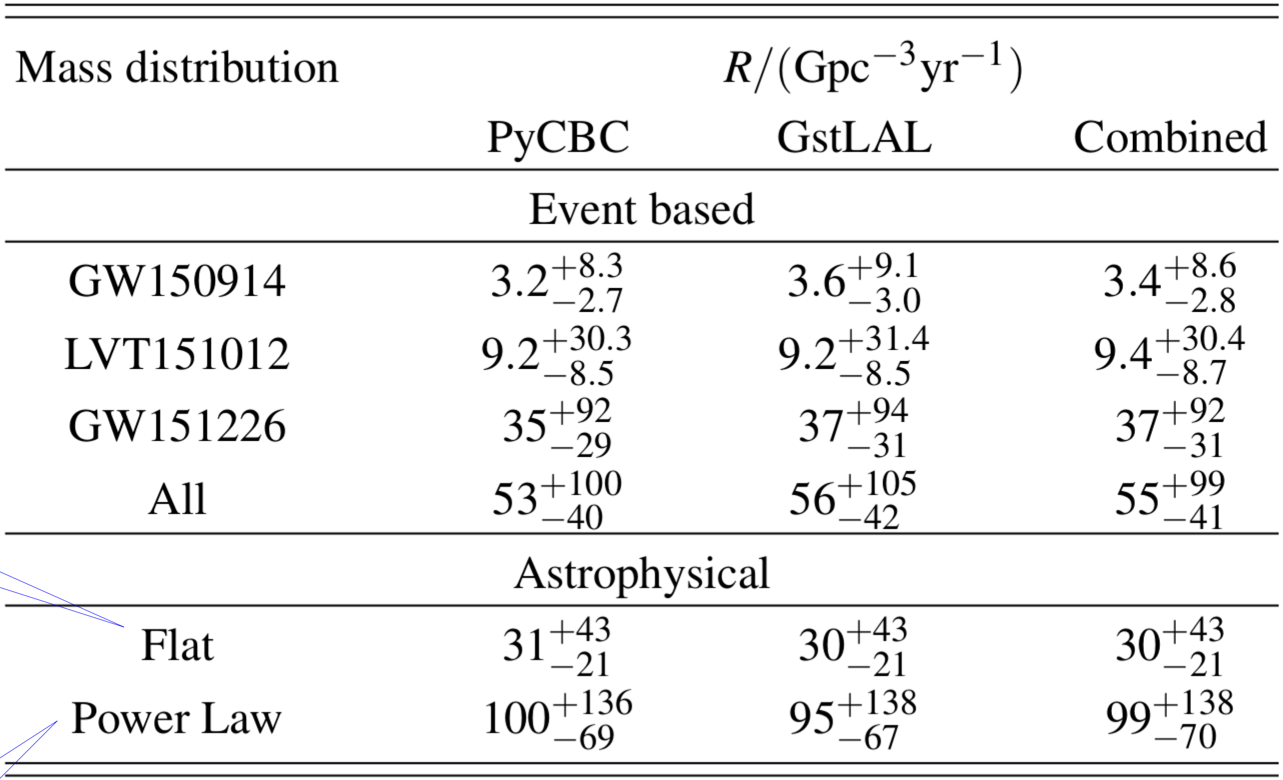
→ **GW150914 = 230** deg²

→ **GW151226 = 850** deg²

Limited accuracy with **2** detectors
→ will be improved with a **3**rd detector (a few deg²)

Parameter estimation

- Simulated signals with parameters drawn from astrophysical populations
- Noise distribution from GW searches



Mass distribution	$R/(\mathrm{Gpc}^{-3}\mathrm{yr}^{-1})$		
	PyCBC	GstLAL	Combined
	Event based		
GW150914	$3.2^{+8.3}_{-2.7}$	$3.6^{+9.1}_{-3.0}$	$3.4^{+8.6}_{-2.8}$
LVT151012	$9.2^{+30.3}_{-8.5}$	$9.2^{+31.4}_{-8.5}$	$9.4^{+30.4}_{-8.7}$
GW151226	35^{+92}_{-29}	37^{+94}_{-31}	37^{+92}_{-31}
All	53^{+100}_{-40}	56^{+105}_{-42}	55^{+99}_{-41}
	Astrophysical		
Flat	31^{+43}_{-21}	30^{+43}_{-21}	30^{+43}_{-21}
Power Law	100^{+136}_{-69}	95^{+138}_{-67}	99^{+138}_{-70}

$p(m_1, m_2) \propto m_1^{-1} m_2^{-1}$

$\sim$*underestimates the rate*

$p(m_1) \propto m_1^{-2.35}$

$p(m_2) = cte$

$\sim$*overestimates the rate*

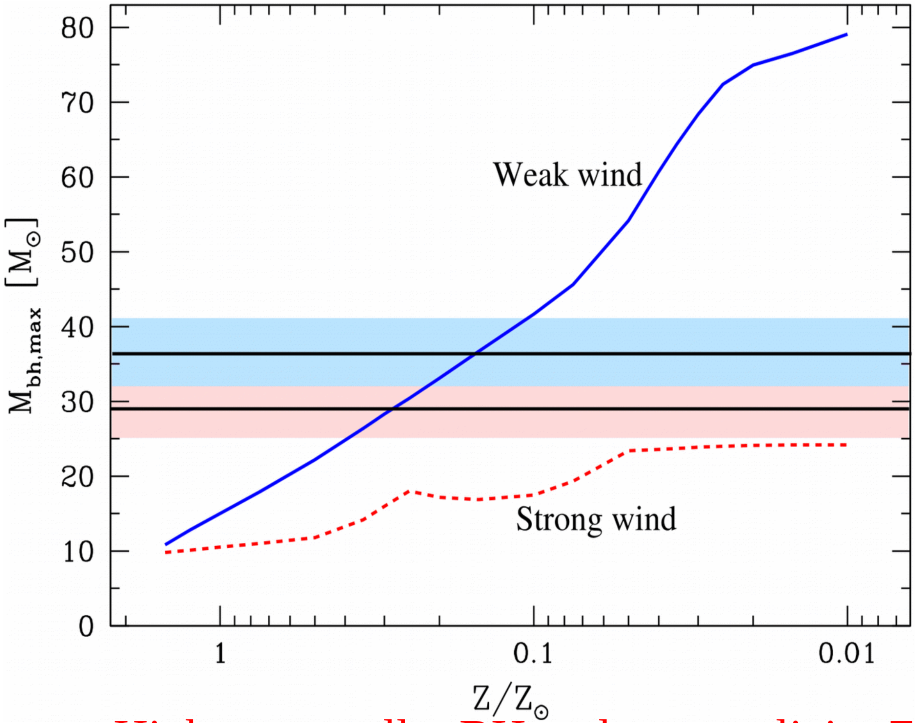
$$R = 9 - 240\, Gpc^{-3}\, yr^{-1}$$

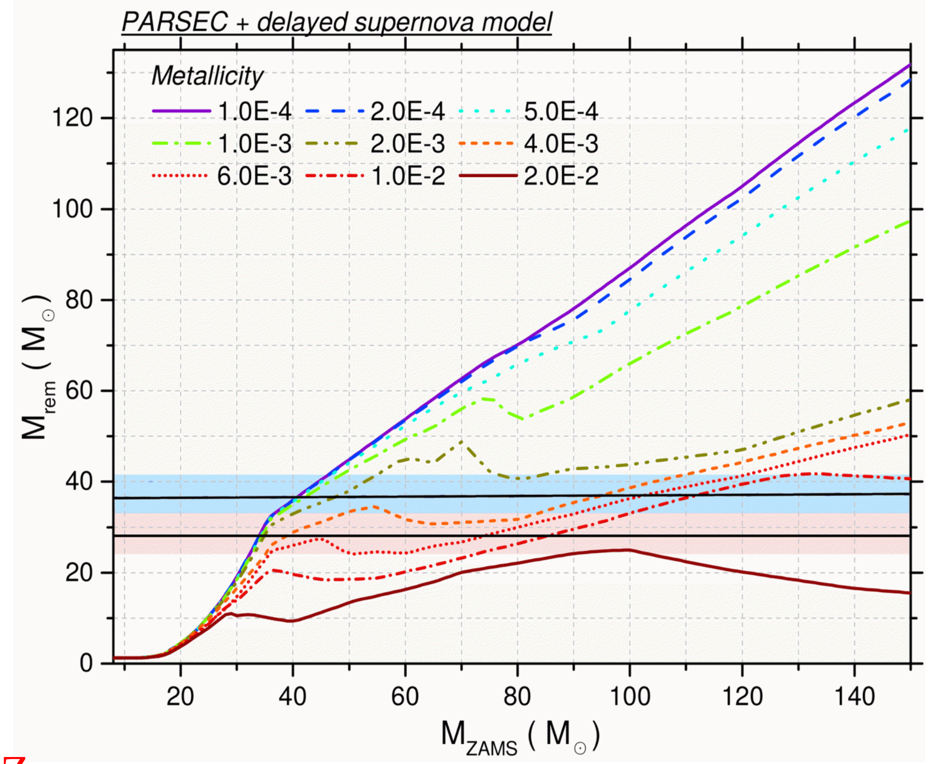
GW astronomy

- Better understand BH and BBH formation scenarios.
- Testing GR in strong field.
- Core collapse supernovae explosion mechanisms.
- New standard sirens to measure the Universe expansion.
- Fundamental physics test:
  - EOS in neutron stars
  - Graviton mass, neutrino masses, …
  - Primordial BH as dark matter
  - Primordial GWs and inflation

Star formation astrophysics

- First BBH system ever observed & heaviest stellar mass black holes (>25 Msun).





High mass stellar BH → low metalicity Z < ½ Zsun
→ weak massive-star winds

- BBH formation: isolated binaries (low-Z to popIII) vs capture in dense clusters (globular clusters, galactic centers, …): no way to discriminate between the 2 scenarios with 4 BBHs.

Testing GR

First opportunity to study GR in a strong-field regime

Test #1 → signal waveform/GR consistency: residual compatible with noise

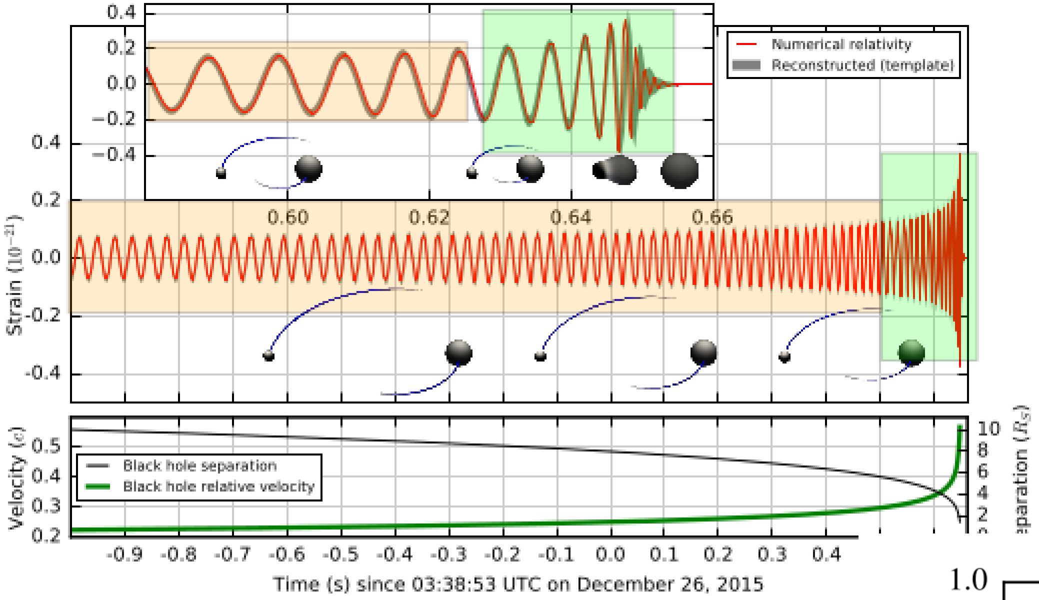
Test #2 → BBH parameter consistency before/after merger: excellent

Test #3 → deviation from PN waveforms: constraints on PN coefficients

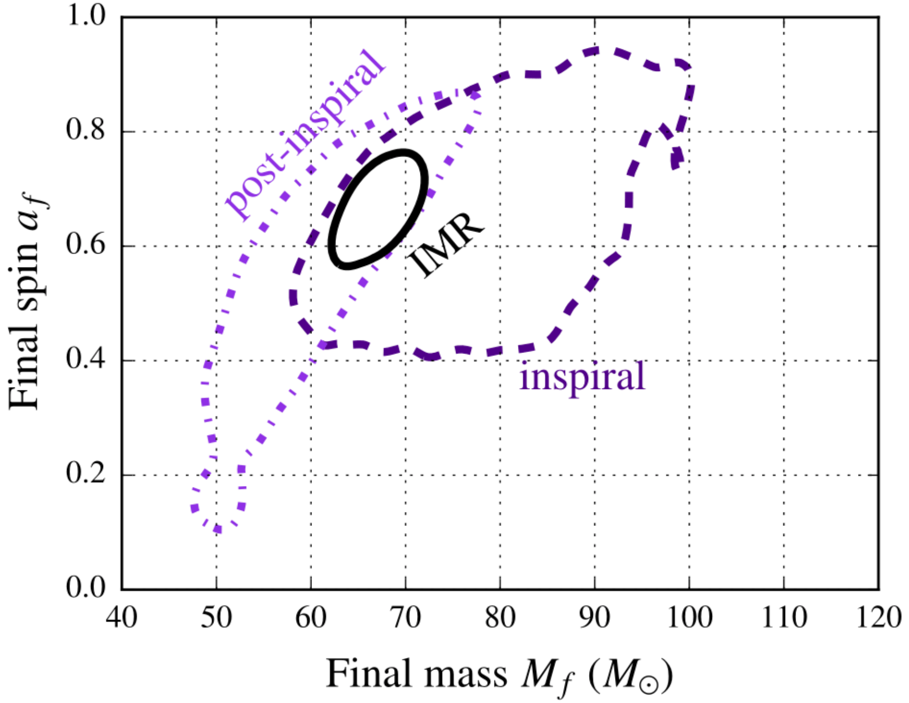
Test #4 → consistency with the least-damped quasi-normal-mode of the remnant black hole

Test #5 → theory with massive graviton: best constraints on the graviton mass

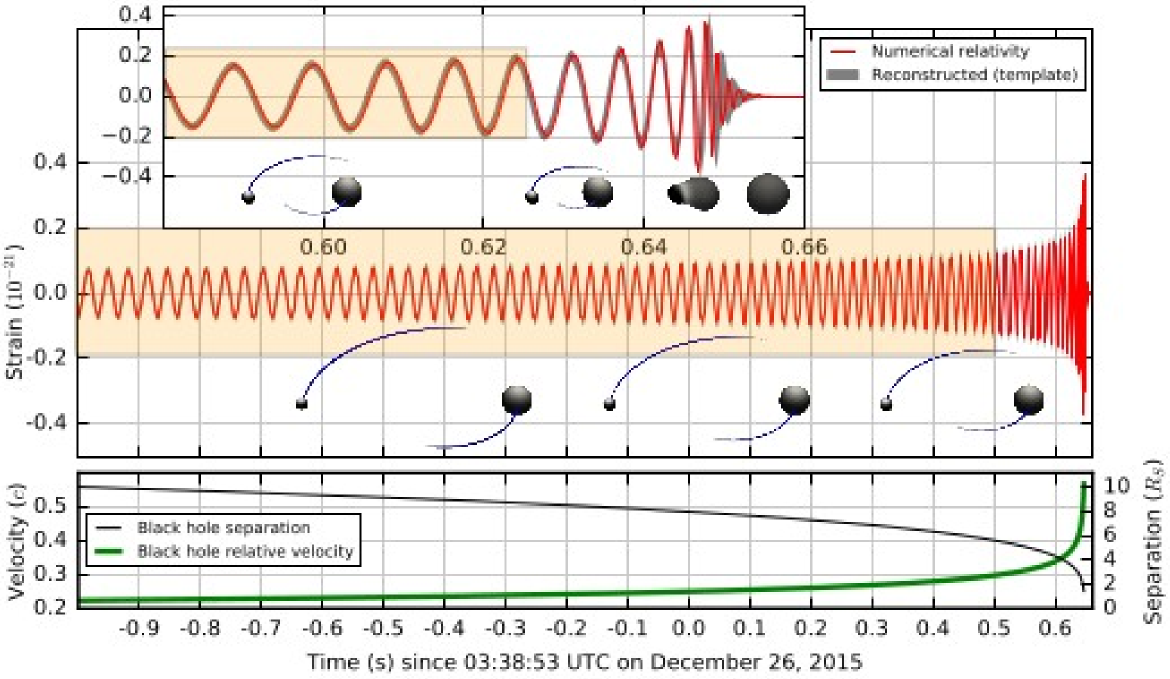
Testing GR



Verify self-consistency by comparing final mass and spin predicted from the “inspiral” and from the “post-inspiral”
[Ghosh+, 2016]
[LVC PRL(2016)]

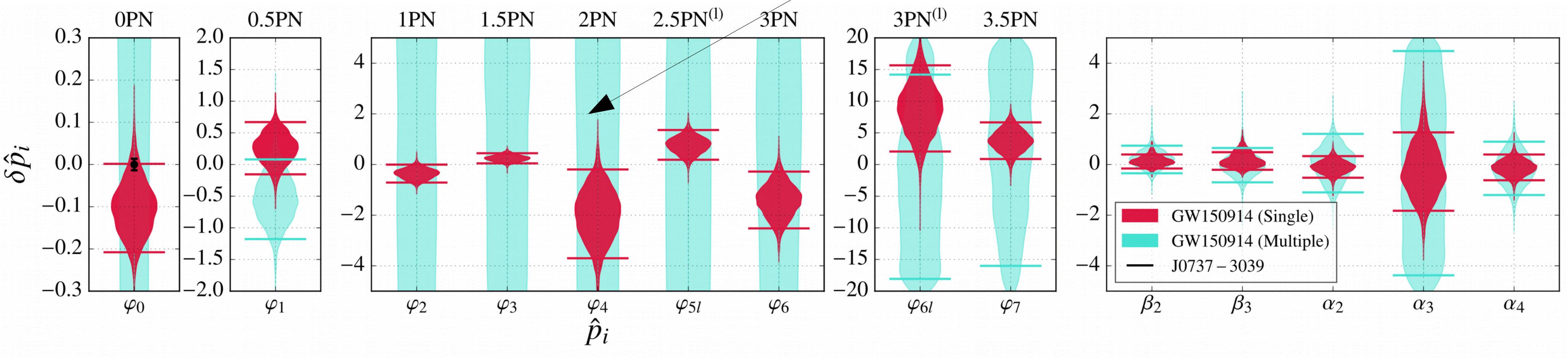


Testing GR

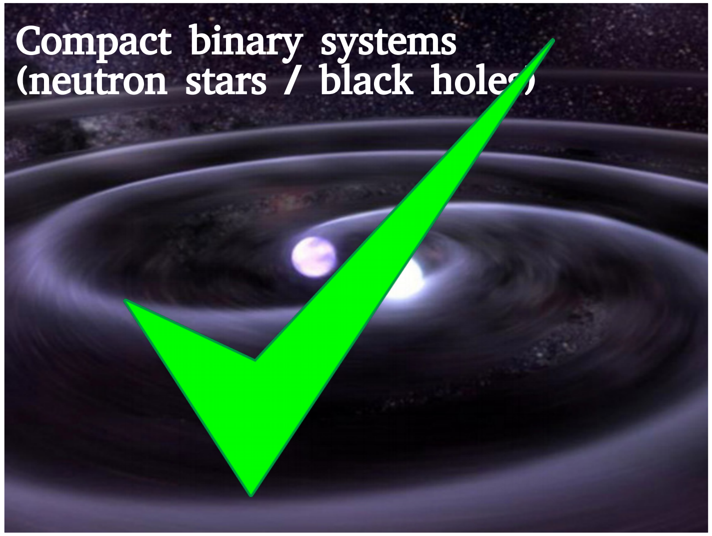


- Waveform:
  $h(f,\theta) = A(f;\theta)e^{i\phi(f;\theta)}$,
- $\phi = \phi_o + \sum \phi_k(\theta)(\pi M f)^{(k-5)}$
  $\theta = \{m_1, m_2, \mathbf{s_1}, \mathbf{s_2}\}$
- $\phi_k = \phi_k^{GR}(1 + \delta\phi_k)$

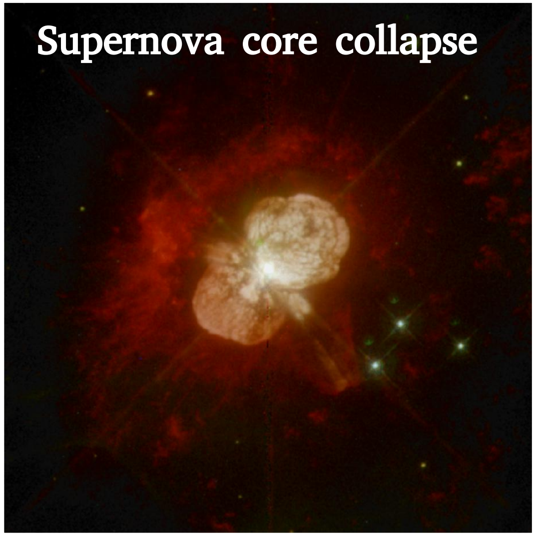
[LVC PRL(2016), PRX(2016), PRL(2017)]

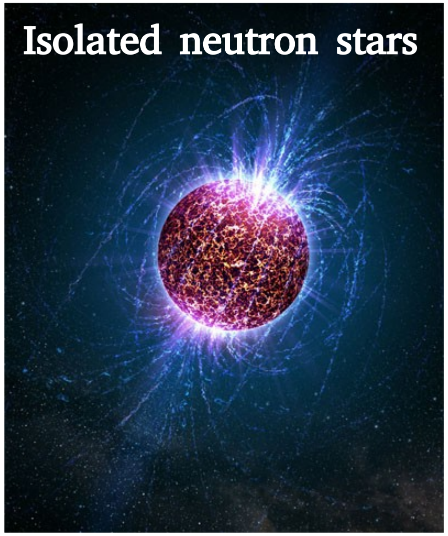


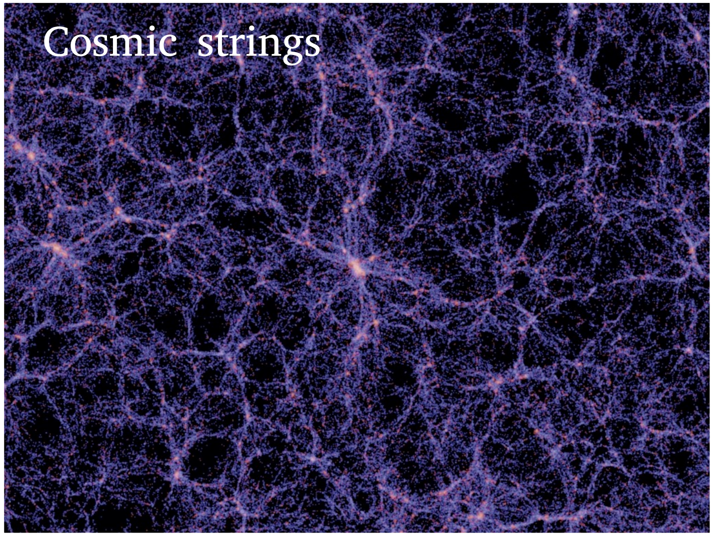
Relevant GW Sources

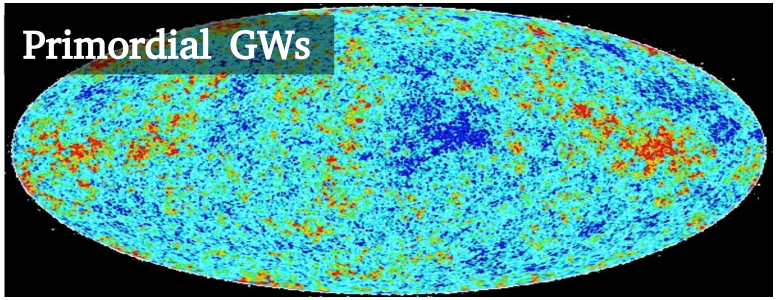

Compact binary systems
(neutron stars / black holes)


newly-formed black holes


Supernova core collapse


Isolated neutron stars


Cosmic strings


Primordial GWs

Unknown sources

?

Unmodeled burst search

Target : transient signals with duration ranging from milliseconds to seconds over the frequency band of 32 to 4096 Hz

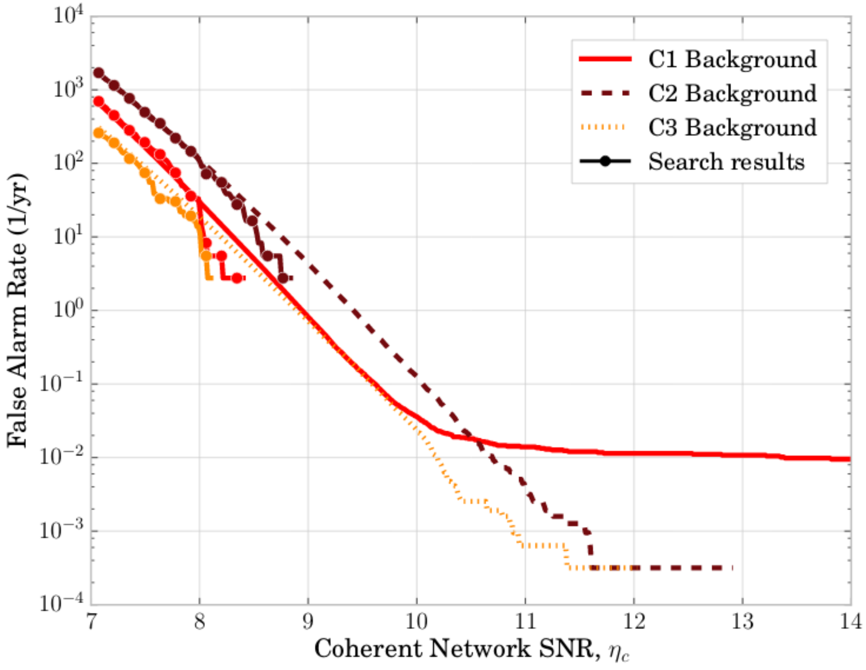
→ compact binary mergers

→ core-collapse supernovae

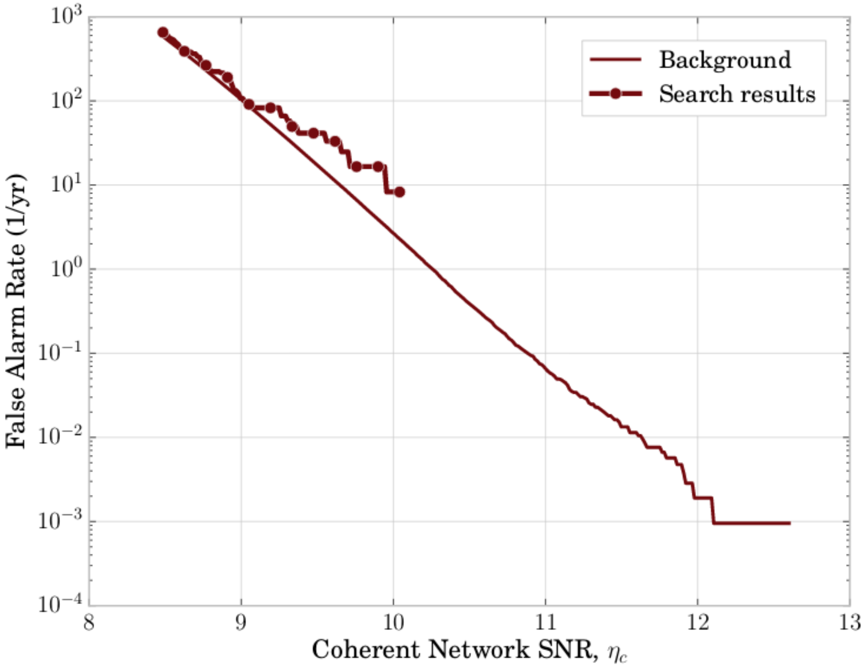
→ neutron stars collapsing to form black holes

→ pulsar glitches

→ cosmic string cusps



(a) **cWB** 32-1024 Hz search classes: $C1$ (red), $C2$ (brown), $C3$ (yellow).



(b) **cWB** 1024-4096 Hz search class.

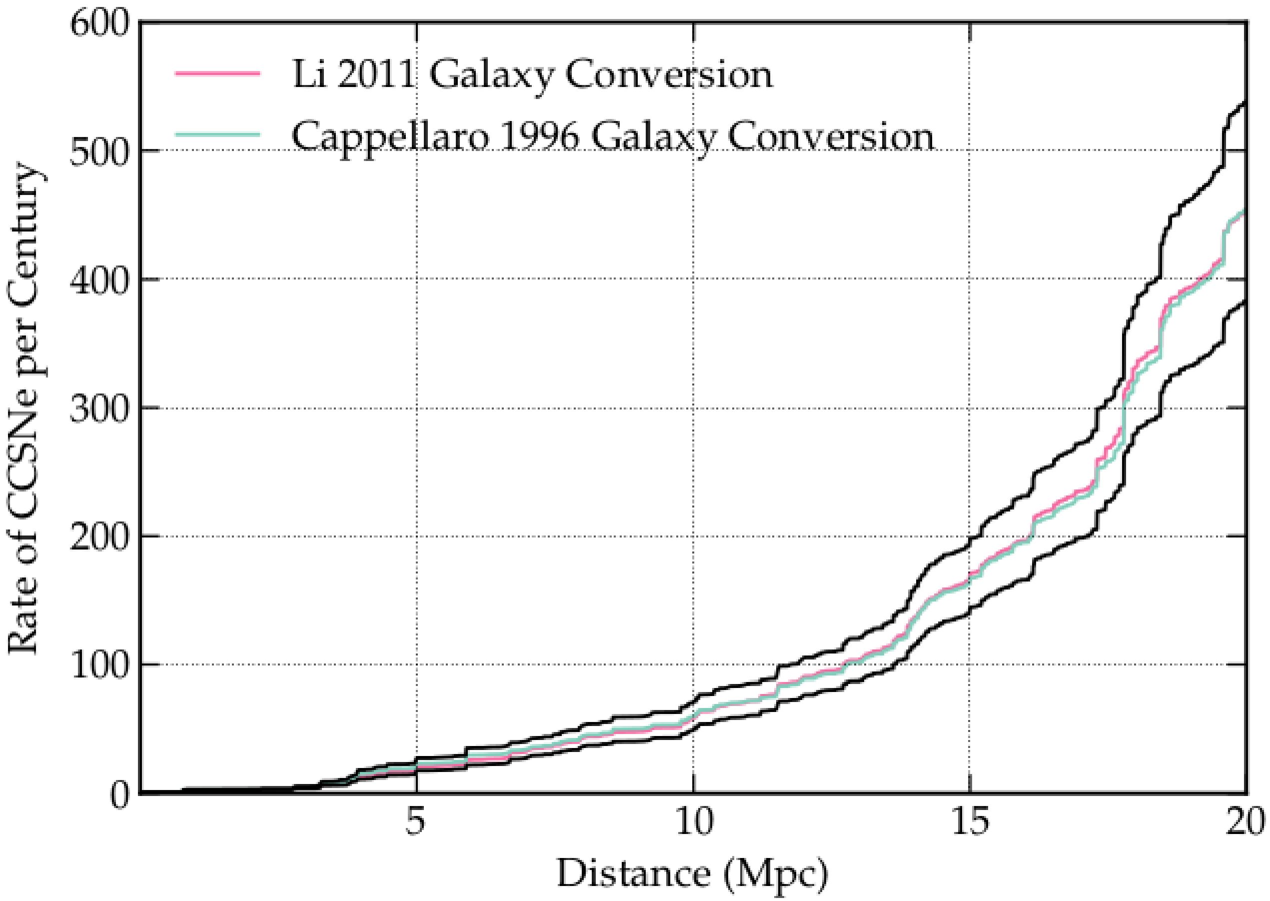
→ the search results are consistent with the expectations of accidental noise coincidences

GW from core-collapse supernovae

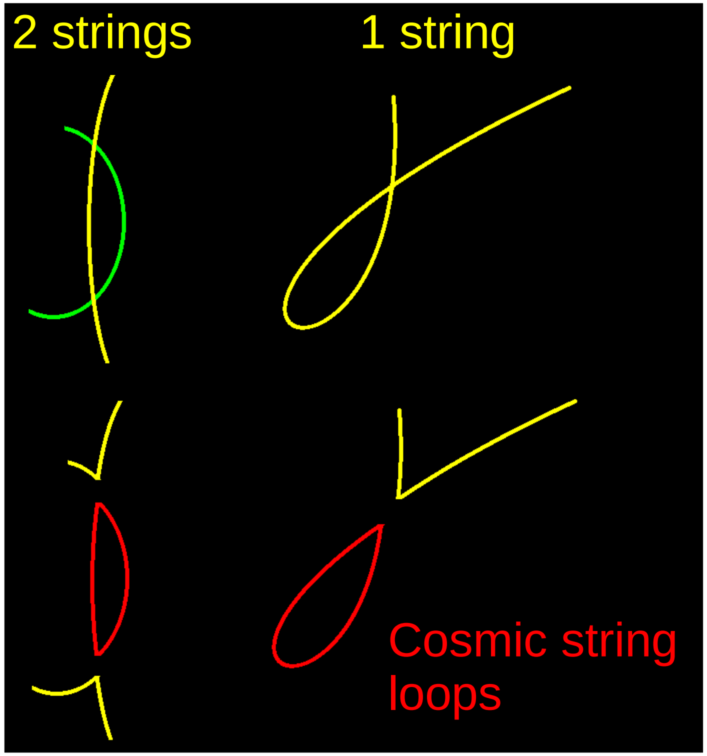
With advanced LIGO and advanced Virgo:

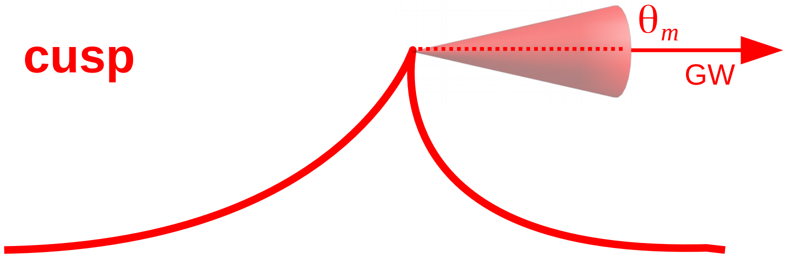
Distance: between 100 kpc (SASI and MHD) and 20 Mpc (extreme model like disk fragmentation and bar mode) [Gossan et al arxiv:1511.02836]

Rate : [J. Gill et al in preparation]



GW from cosmic strings





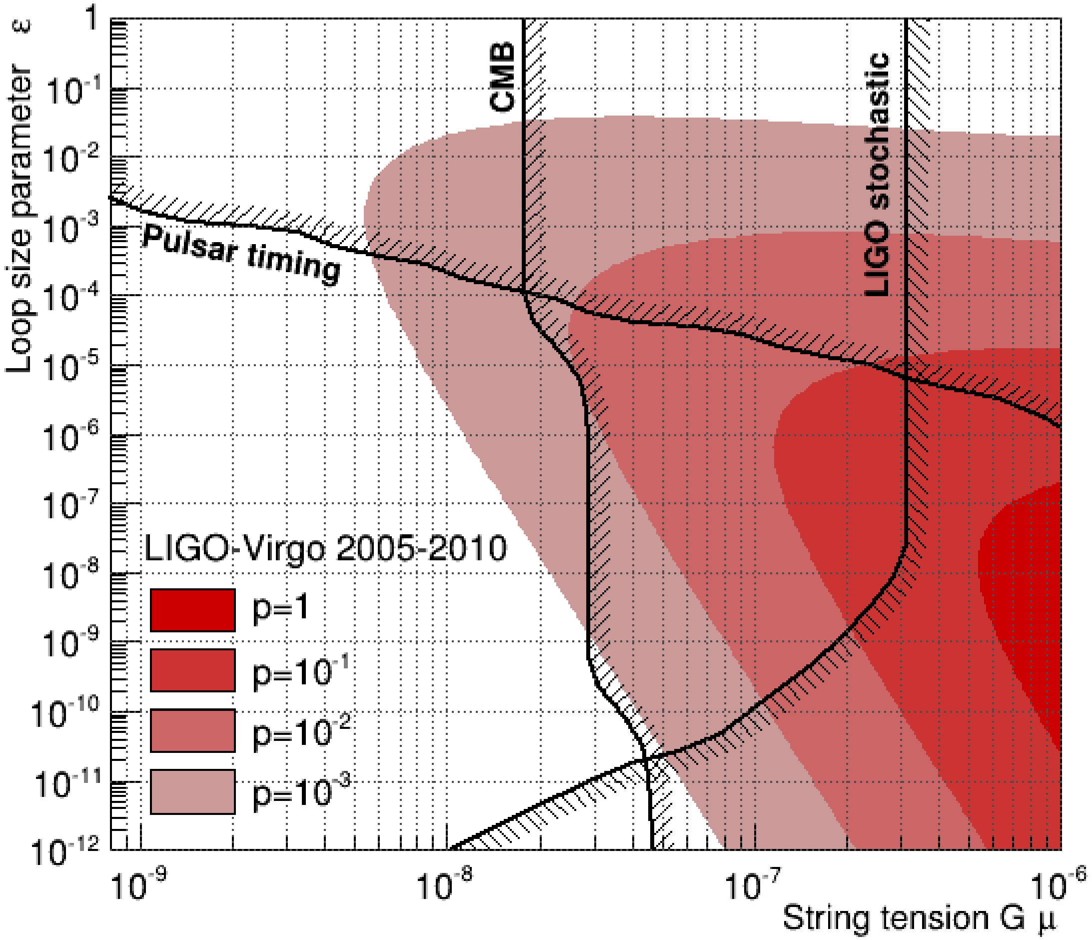
GW waveform:

$$h(\ell, z, f) = A_q(\ell, z) f^{-q} \Theta(f_h - f)$$

$$A_q(\ell, z) = g_1 \frac{G\mu \ell^{2-q}}{(1+z)^{q-1} r(z)}$$

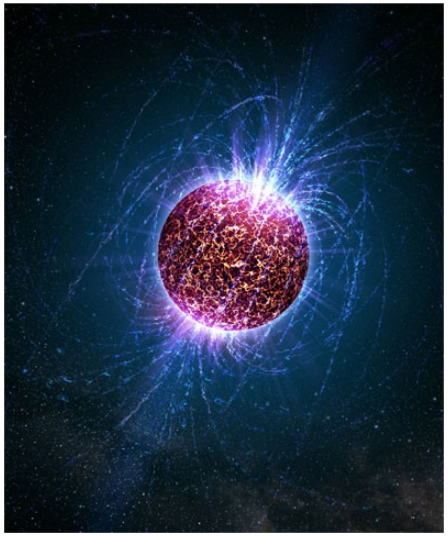
q = 4/3 for cusps, q = 5/3 for kinks

+ model for loop distribution



[Enhanced LIGO/Virgo results]

Pulsar searches



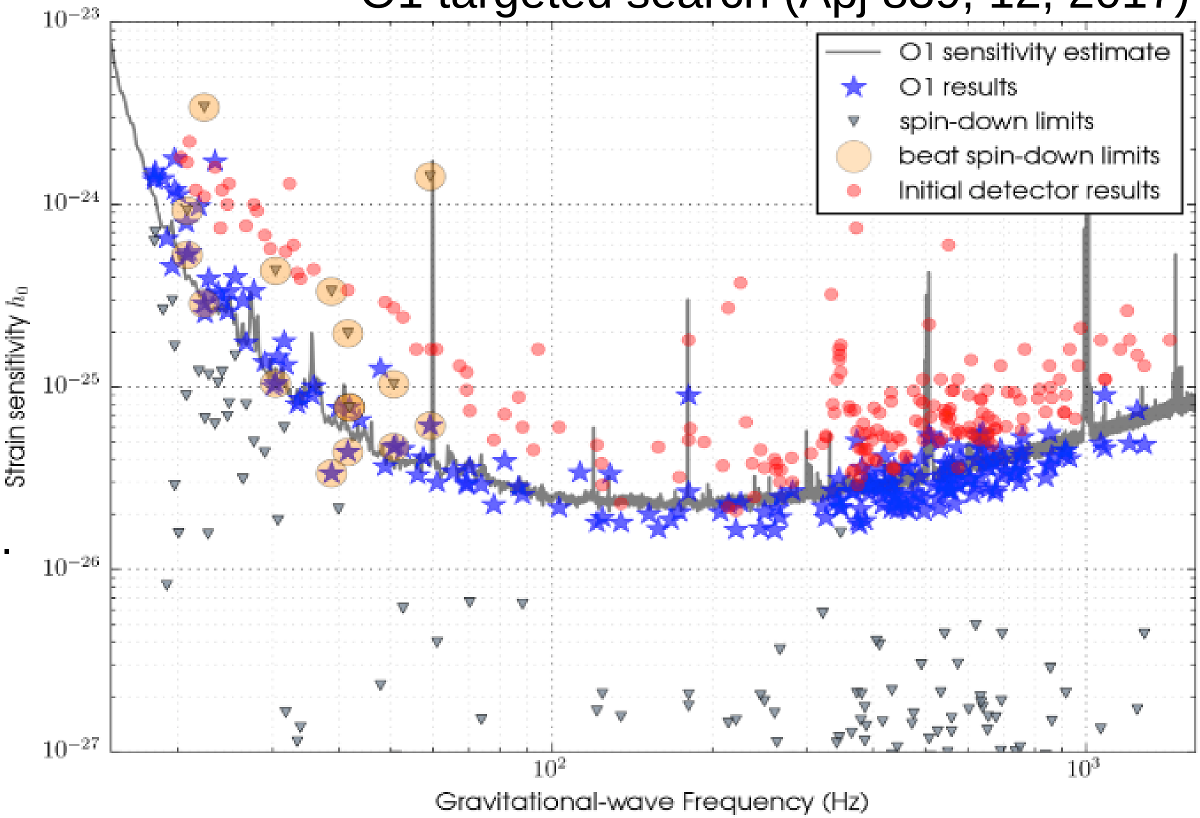
Signal amplitude: $h_0 \cong 10^{-27}\left(\frac{I_{zz}}{10^{38}\,kg\cdot m^2}\right)\left(\frac{10kpc}{r}\right)\left(\frac{f}{100Hz}\right)^2\left(\frac{\varepsilon}{10^{-6}}\right)$

ε : ellipticity (adimensional number measuring the star's degree of asymmetry)

f : signal frequency, proportional to star rotation frequency

- Persistant signals.
- Weak amplitudes (ellipticity unknown).
- Known sources in the galaxy.
- Multi-messenger analysis with radio telescope inputs.
- All-sky/targeted searches
- 8 known pulsars spin down limit beaten.

O1 targeted search (Apj 839, 12, 2017)



Stochastic background of GWs

Assumption : stationary, unpolarized, and Gaussian stochastic background

→ Cross correlate the output of detector pairs to eliminate the noise

$$h_i = n_i + GW_i$$

$$\langle h_1, h_2 \rangle = \langle GW_1, GW_2 \rangle + \underbrace{\langle n_1, GW_2 \rangle}_{0} + \underbrace{\langle GW_1, n_2 \rangle}_{0} + \underbrace{\langle n_1, n_2 \rangle}_{0}$$

With $\langle x_1, x_2 \rangle = \int_{-\infty}^{+\infty} \tilde{x}_1^*(f) \tilde{Q}(f) \tilde{x}_2(f) \, df$

Optimal filter:

overlap of antenna pattern

GW spectrum

$\Omega_{GW}(f) = \Omega_\alpha f^\alpha$

$$\tilde{Q}(f) \propto \frac{\gamma(f) \Omega_{GW}(f)}{f^3 S_{n,1}(f) S_{n,2}(f)}$$

Detector PSDs

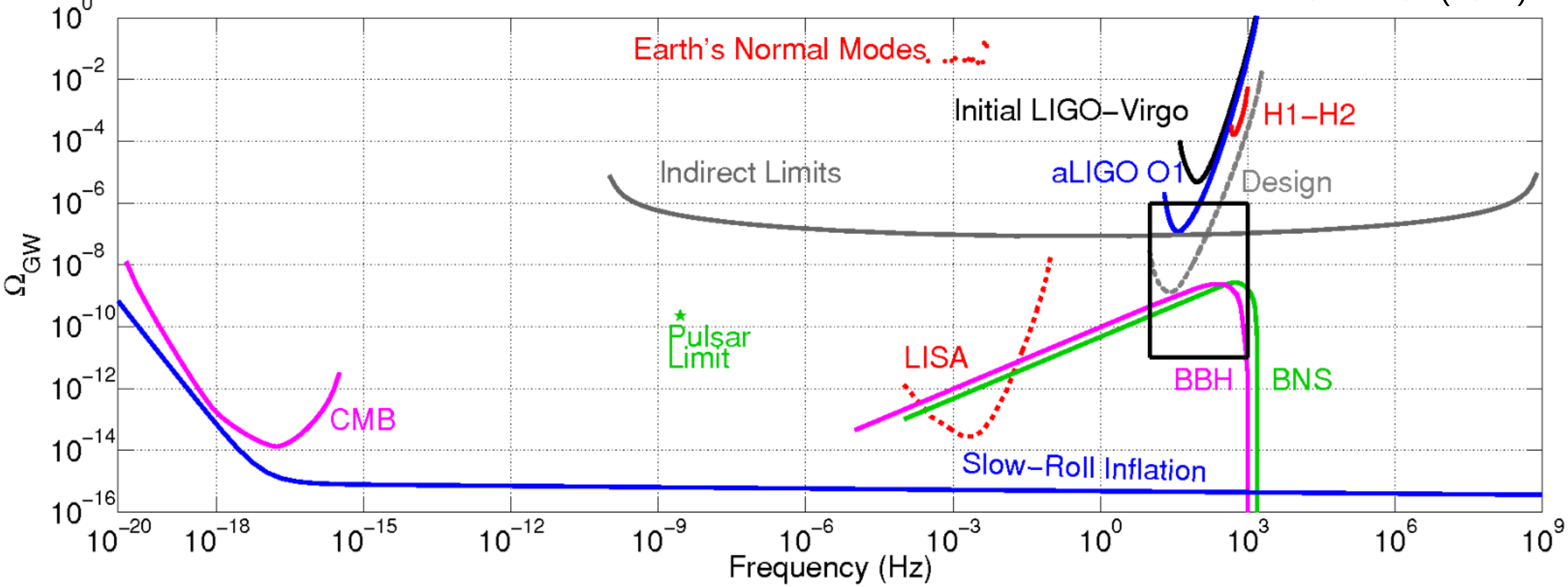
O1 isotropic search, for $\alpha = 0$: $\Omega_{GW}(25\,Hz) < 1.7 \times 10^{-7}$

PRL.118.121101 (2017)

Stochastic background of GWs

O1 isotropic search, for $\alpha = 0$: $\Omega_{GW}(25\,Hz) < 1.7 \times 10^{-7}$

PRL.118.121101 (2017)



Stochastic background of BBH mergers

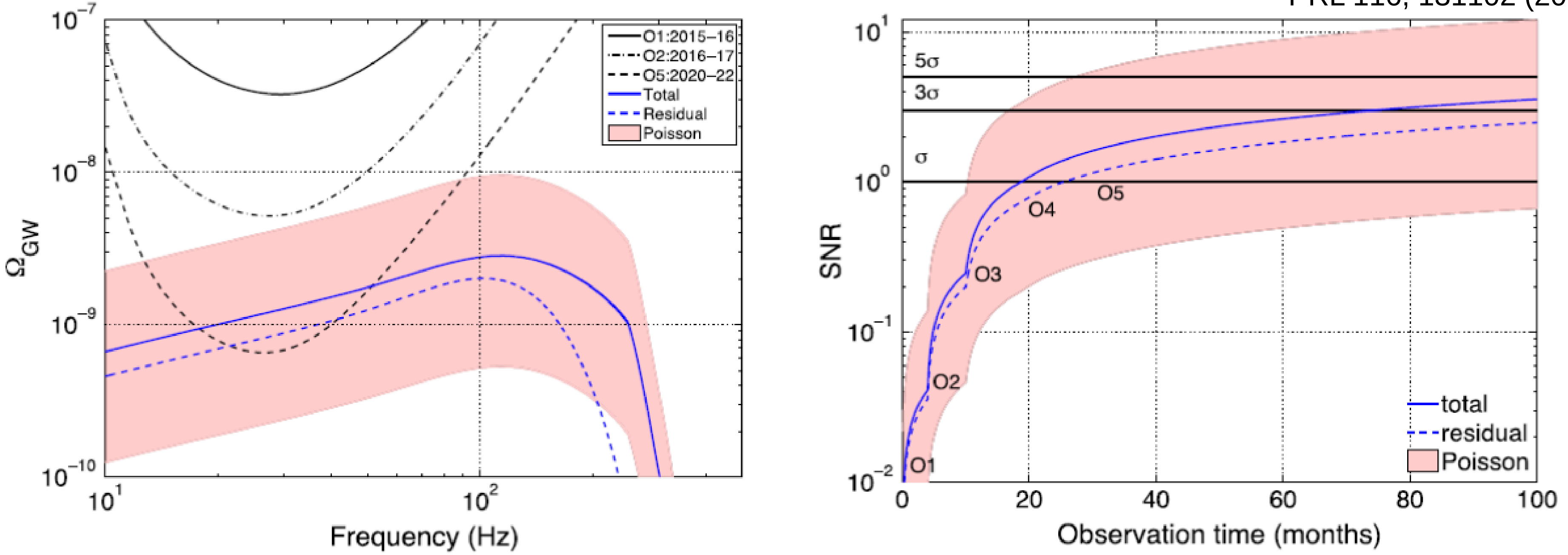
Merger Rate

Source Energy Spectrum

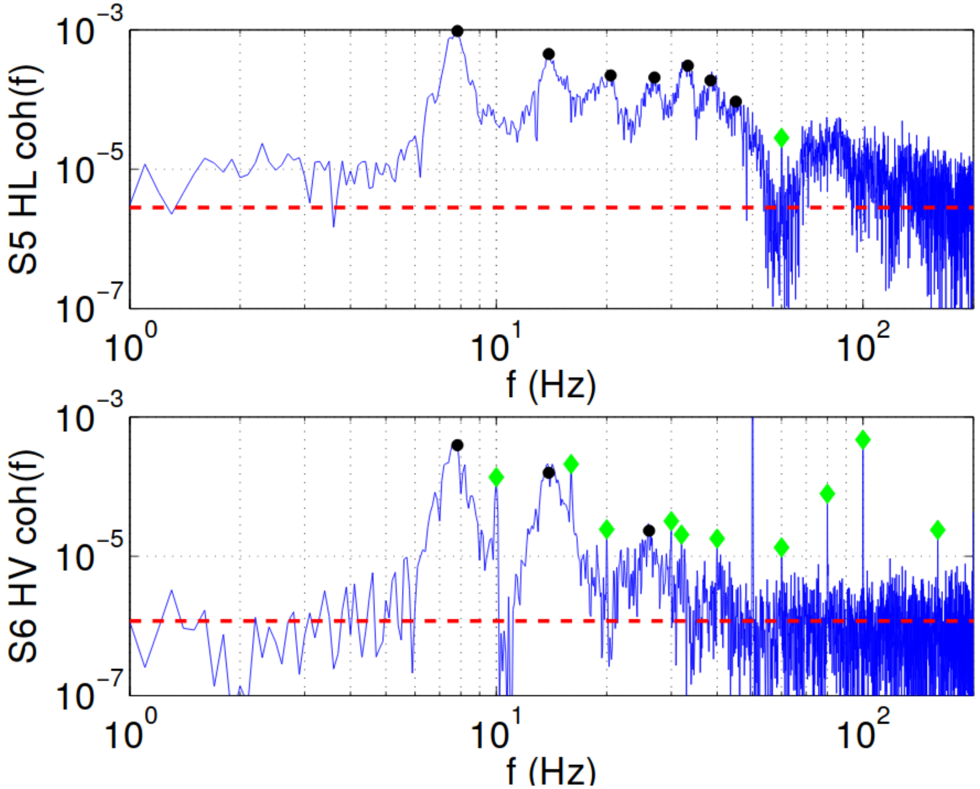
$$\Omega_{\rm GW}(f;\theta_k) = \frac{f}{\rho_c H_0}\int_0^{z_{\max}} dz \frac{R_m(z,\theta_k)\frac{dE_{\rm GW}}{df_s}(f_s,\theta_k)}{(1+z)E(\Omega_{\rm M},\Omega_\Lambda,z)}$$

Cosmology

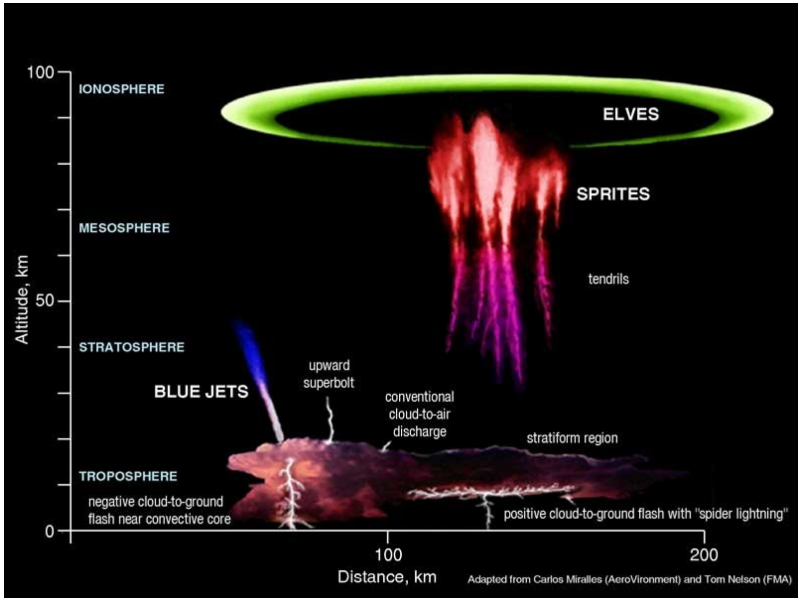
PRL 116, 131102 (2016)



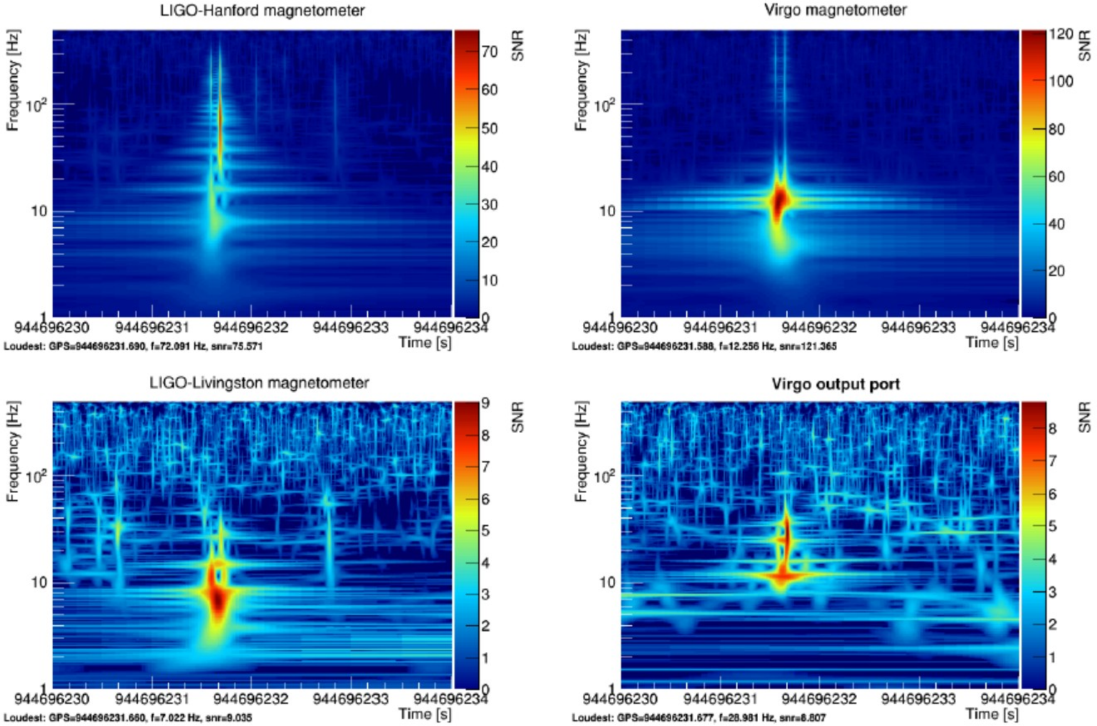
Correlated noise



Schumann resonance



Adapted from Carlos Miralles (AeroVironment) and Tom Nelson (FMA)



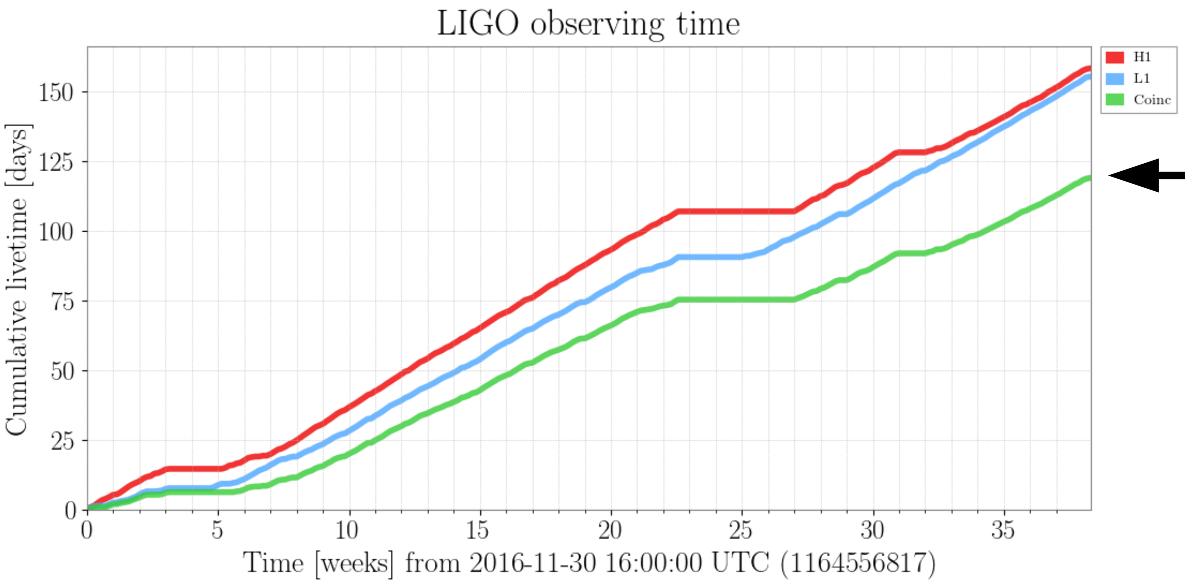
Loudest: GPS=944696231.690, f=72.091 Hz, snr=75.571

Loudest: GPS=944696231.588, f=12.256 Hz, snr=121.365

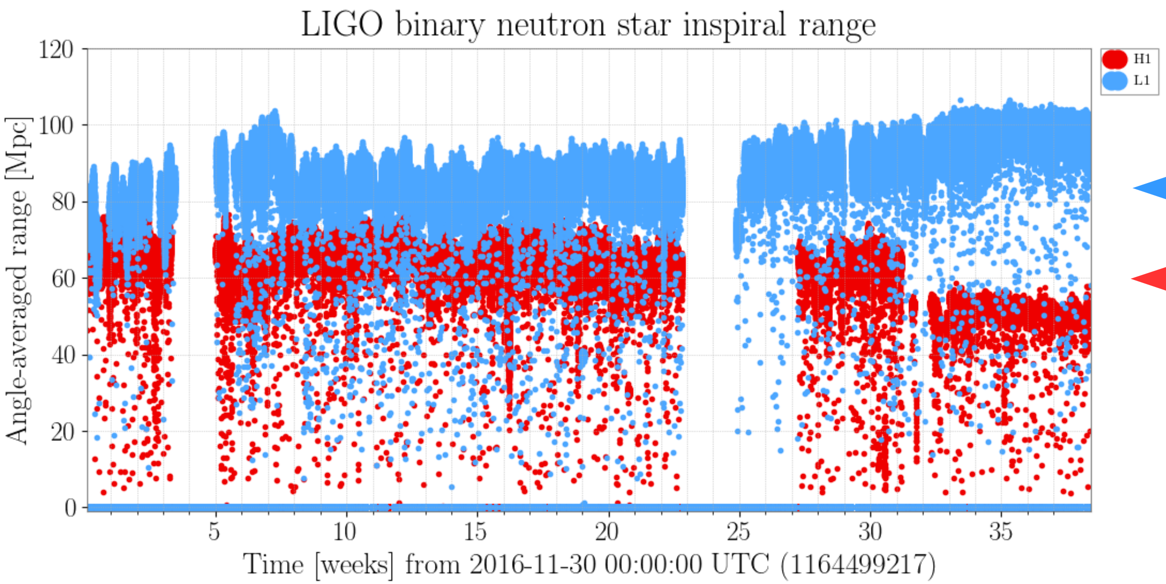
Loudest: GPS=944696231.660, f=7.022 Hz, snr=9.035

Loudest: GPS=944696231.677, f=28.981 Hz, snr=8.807

Status of O2



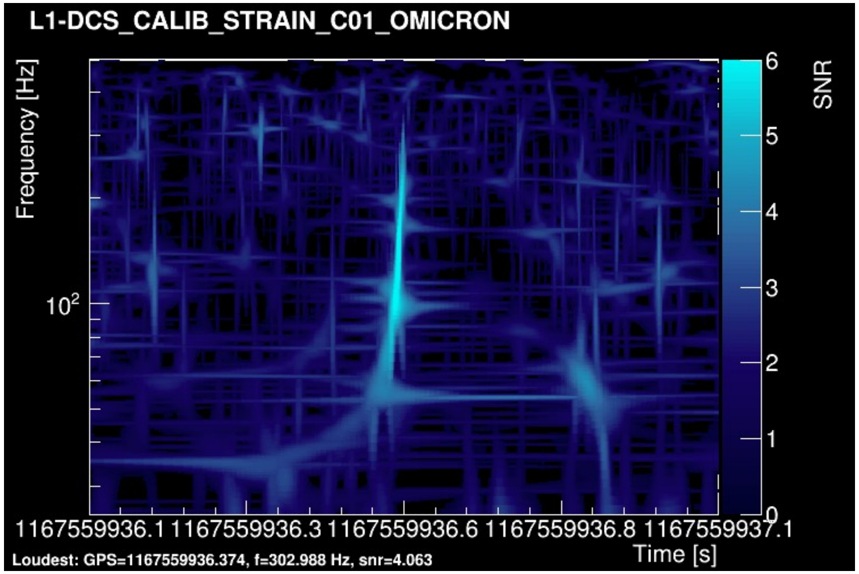
Livetime x 2.5 /O1

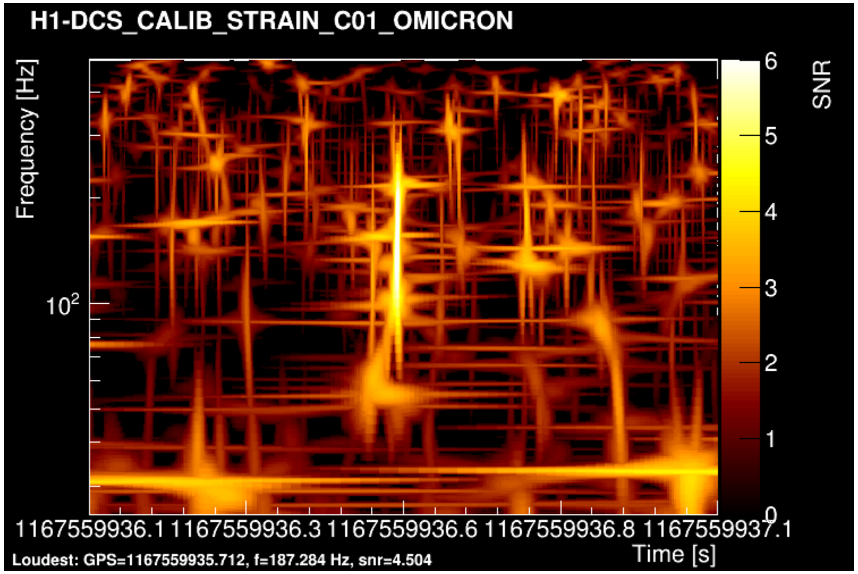


L1 sensitivity x 1.3 /O1

H1 sensitivity x 0.8 /O1

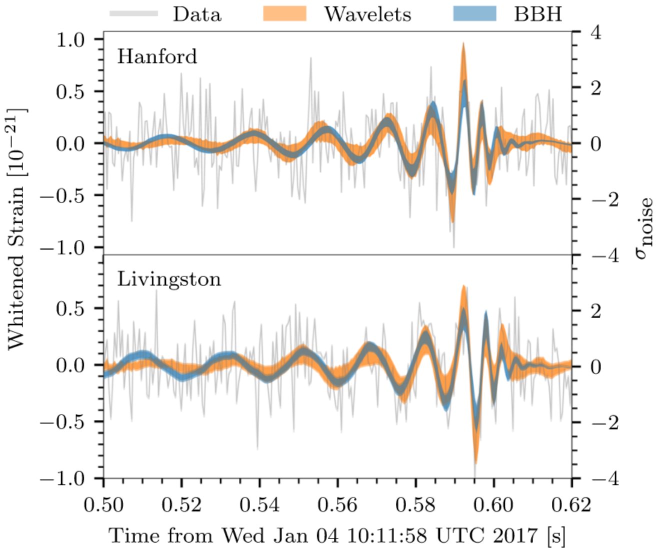
First O2 event





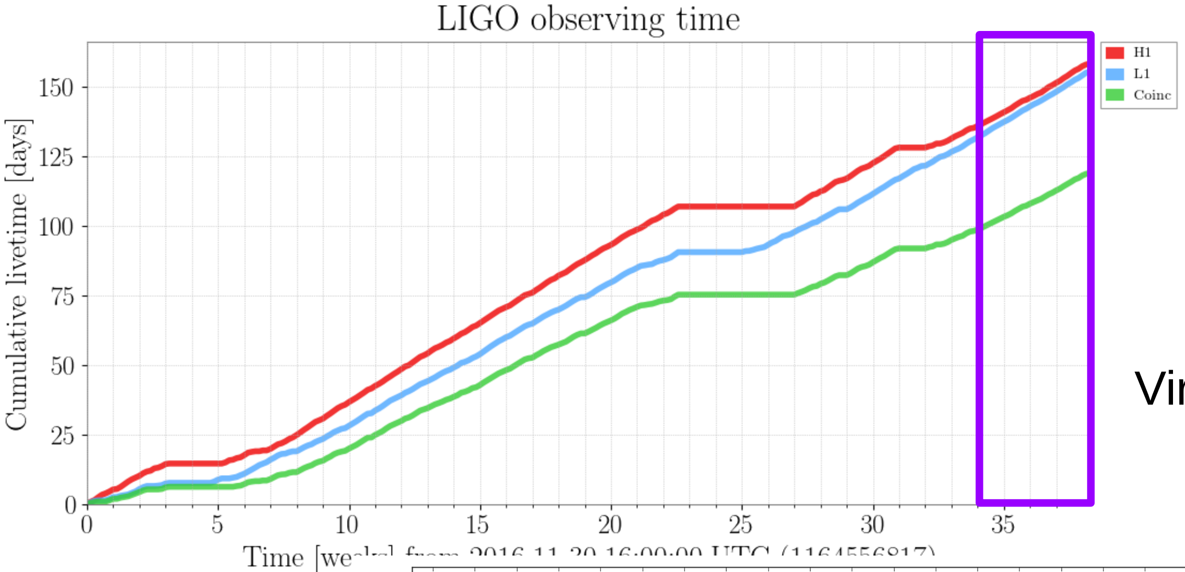
GW170104

Primary black hole mass m_1	$31.2^{+8.4}_{-6.0} M_\odot$
Secondary black hole mass m_2	$19.4^{+5.3}_{-5.9} M_\odot$
Chirp mass $\mathcal{M}$	$21.1^{+2.4}_{-2.7} M_\odot$
Total mass M	$50.7^{+5.9}_{-5.0} M_\odot$
Final black hole mass M_f	$48.7^{+5.7}_{-4.6} M_\odot$
Radiated energy $E_{\rm rad}$	$2.0^{+0.6}_{-0.7} M_\odot c^2$
Peak luminosity $\ell_{\rm peak}$	$3.1^{+0.7}_{-1.3} \times 10^{56} \mathrm{erg\,s^{-1}}$
Effective inspiral spin parameter $\chi_{\rm eff}$	$-0.12^{+0.21}_{-0.30}$
Final black hole spin a_f	$0.64^{+0.09}_{-0.20}$
Luminosity distance D_L	880^{+450}_{-390} Mpc
Source redshift z	$0.18^{+0.08}_{-0.07}$

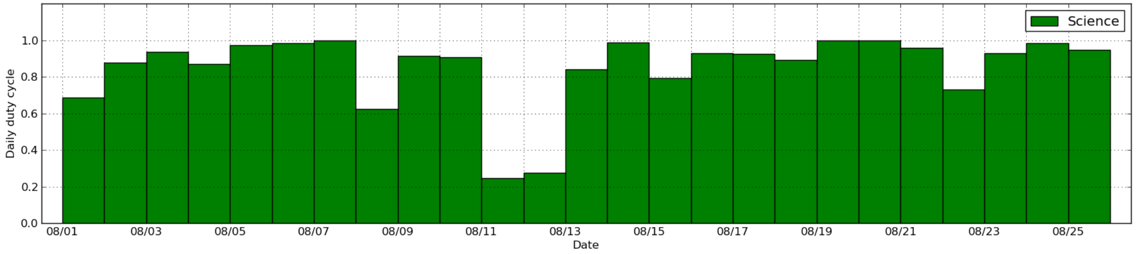


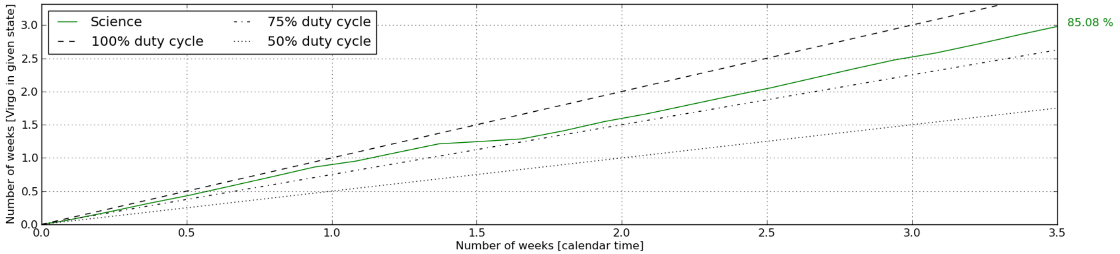
PRL118,221101 (2017)

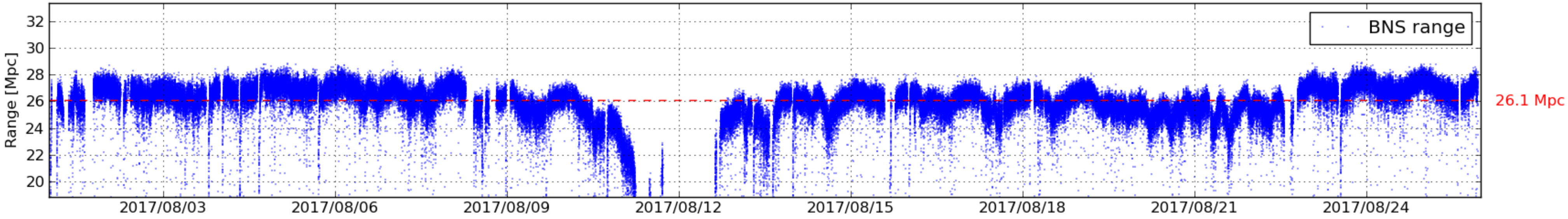
Status of O2



Virgo joined O2







O2 run

The Virgo and LIGO Scientific Collaborations have been observing since November 30, 2016 in the second Advanced Detector Observing Run ‘O2’, searching for gravitational-wave signals, first with the two LIGO detectors, then with both LIGO and Virgo instruments operating together since August 1, 2017. **Some promising gravitational-wave candidates have been identified in data from both LIGO and Virgo during our preliminary analysis, and we have shared what we currently know with astronomical observing partners**. We are working hard to assure that the candidates are valid gravitational-wave events, and it will require time to establish the level of confidence needed to bring any results to the scientific community and the greater public. We will let you know as soon we have information ready to share.