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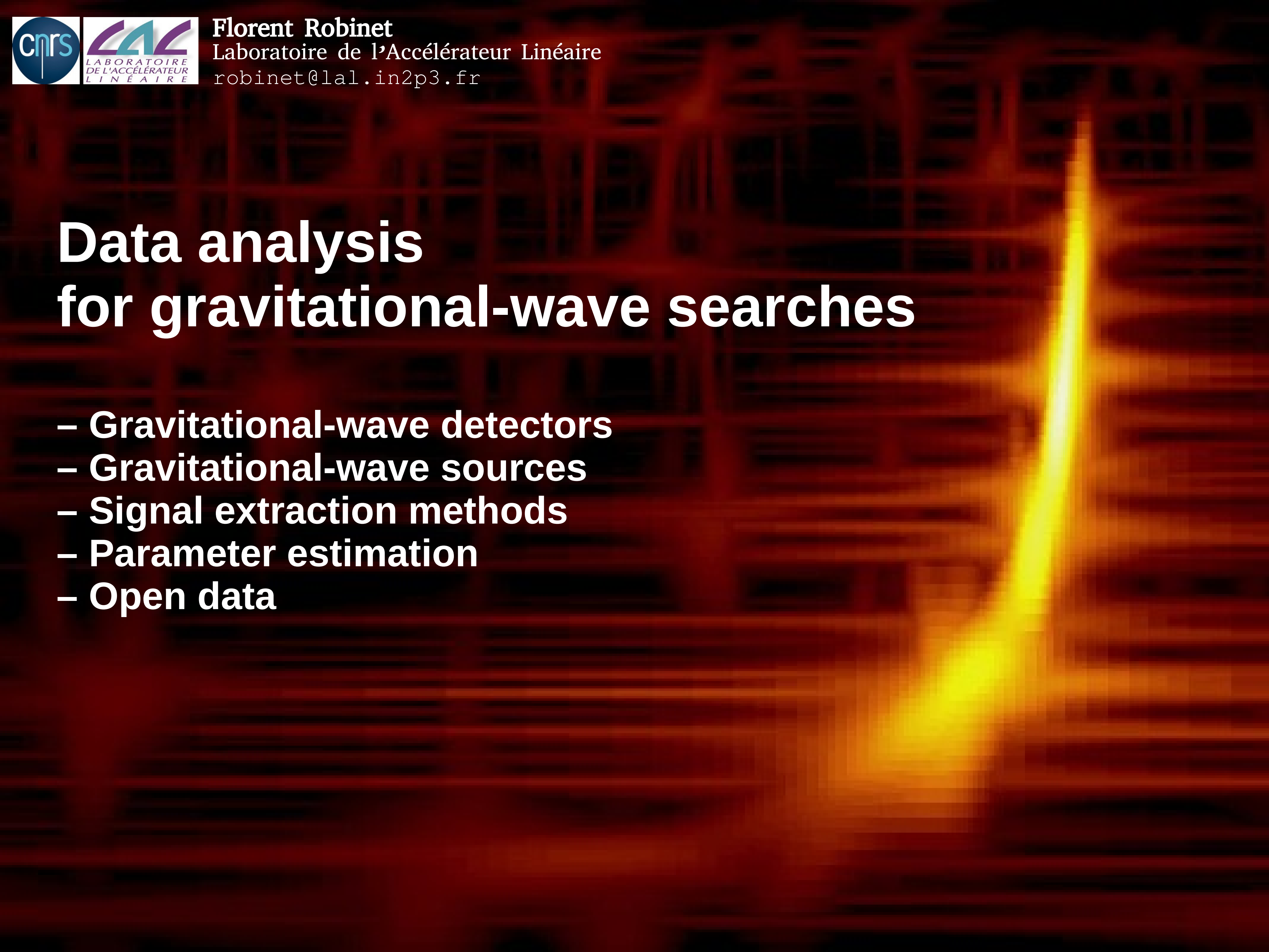
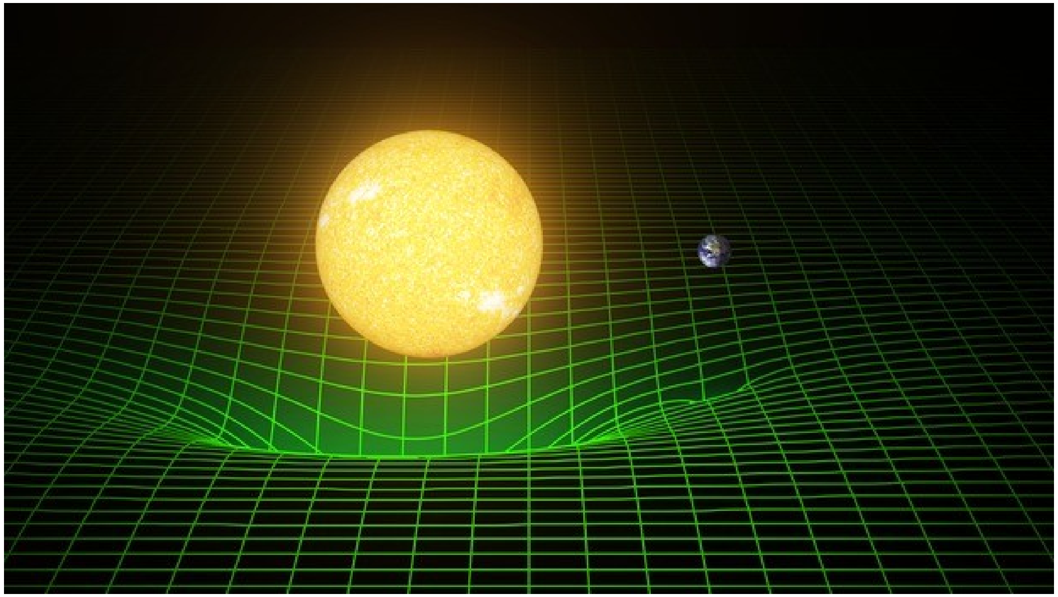


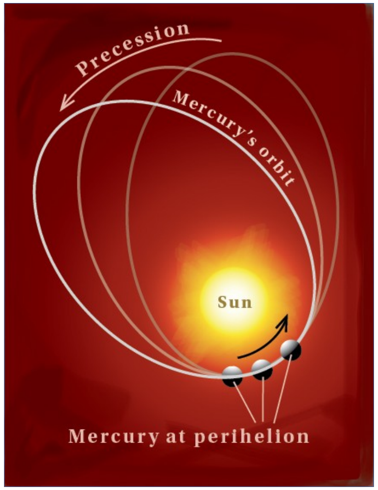
Data analysis
for gravitational-wave searches

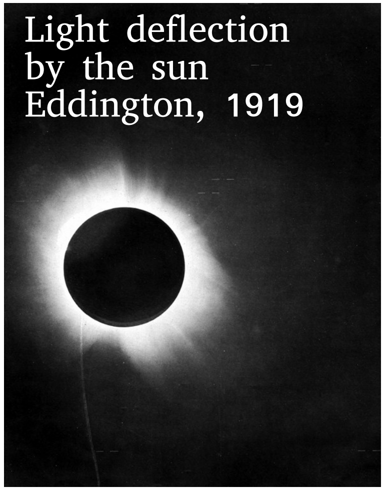
- – Gravitational-wave detectors
- – Gravitational-wave sources
- – Signal extraction methods
- – Parameter estimation
- – Open data

General Relativity

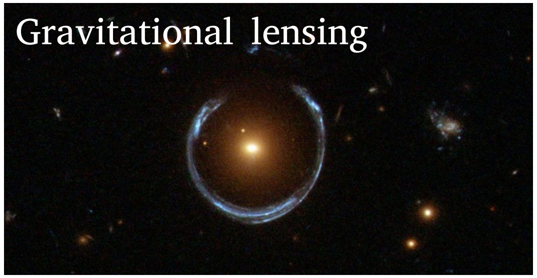
- Gravity is no longer a force (Newton)
- Gravity = geometric property of space and time (Einstein)
- Space-time curvature dictated by the mass distribution and/or energy radiation
- Einstein's equation: $G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$







Light deflection by the sun Eddington, 1919



Gravitational lensing

Specific predictions:

☑ Fine description of orbiting bodies (Mercury anomalous perihelion shift)

☑ Light propagation affected by gravity (gravitational lensing, gravitational redshift, Shapiro delay...)

☑ Black holes

☐ Gravitational waves

Gravitational waves

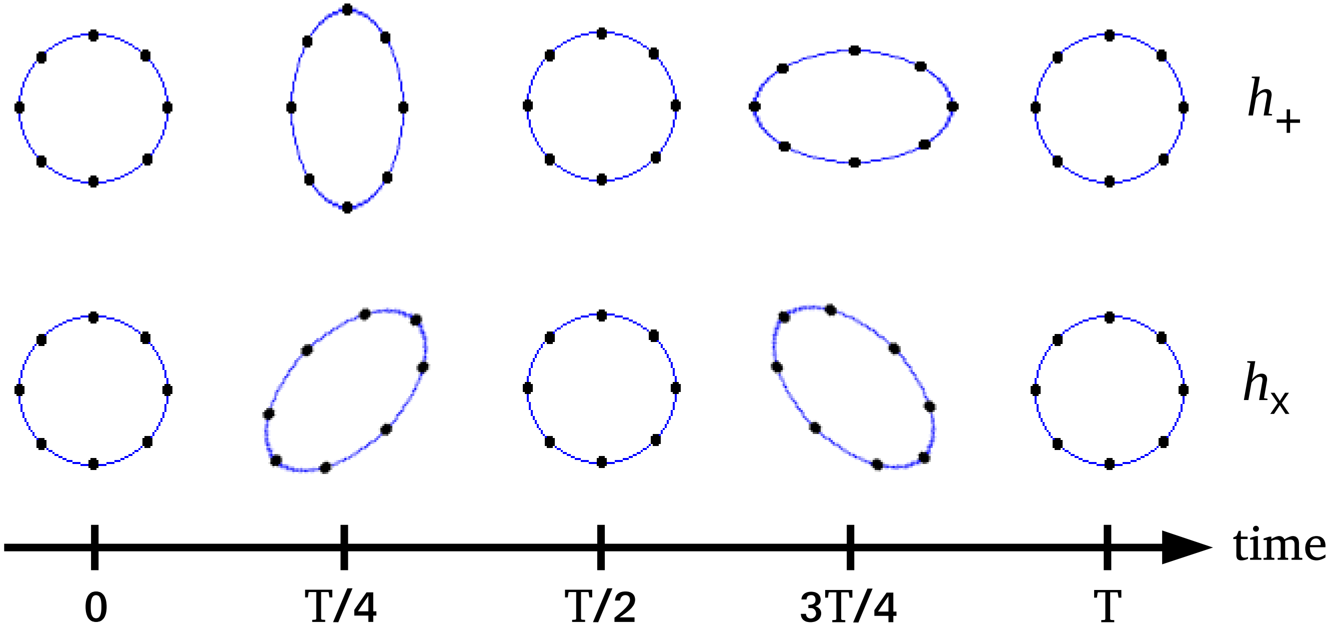
Add a small perturbation to the Minkowski metric: $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ $|h_{\mu\nu}| \ll 1$

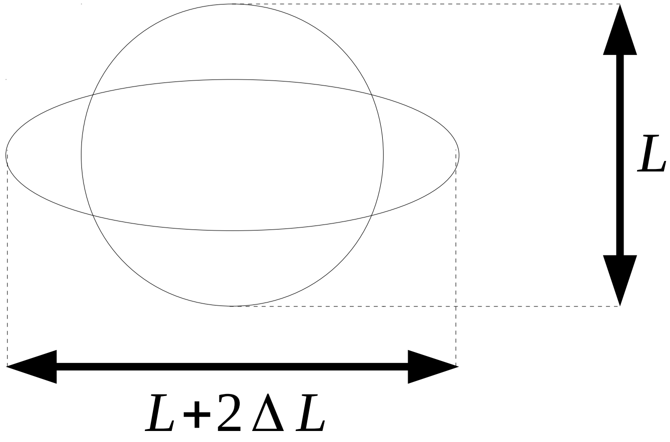
– h obeys a plane-wave equation

– the wave propagates at the speed of light

– 2 degrees of freedom: h_+ and $h_\times$

→ Gravitational waves



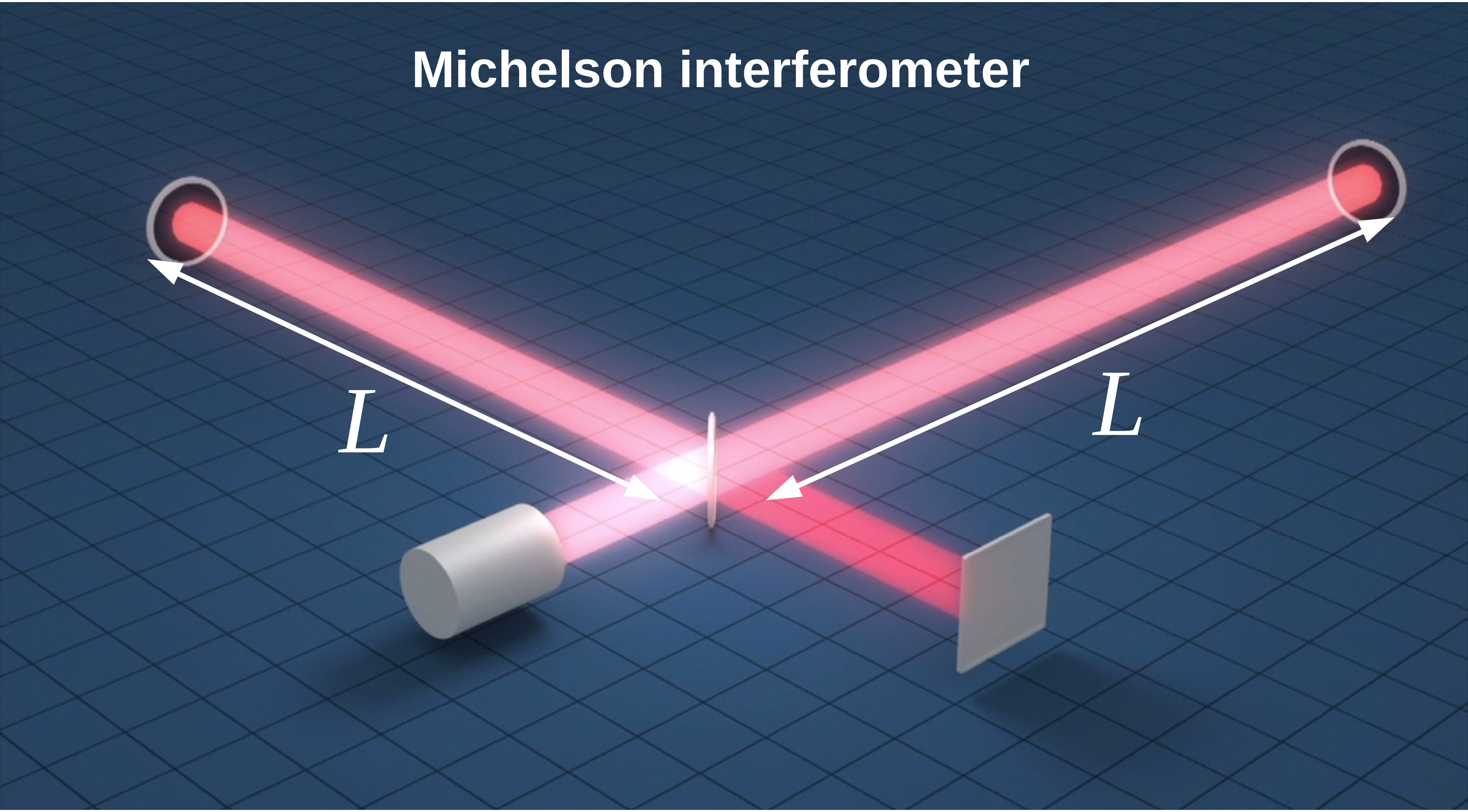


$$h = 2\frac{\Delta L}{L}$$

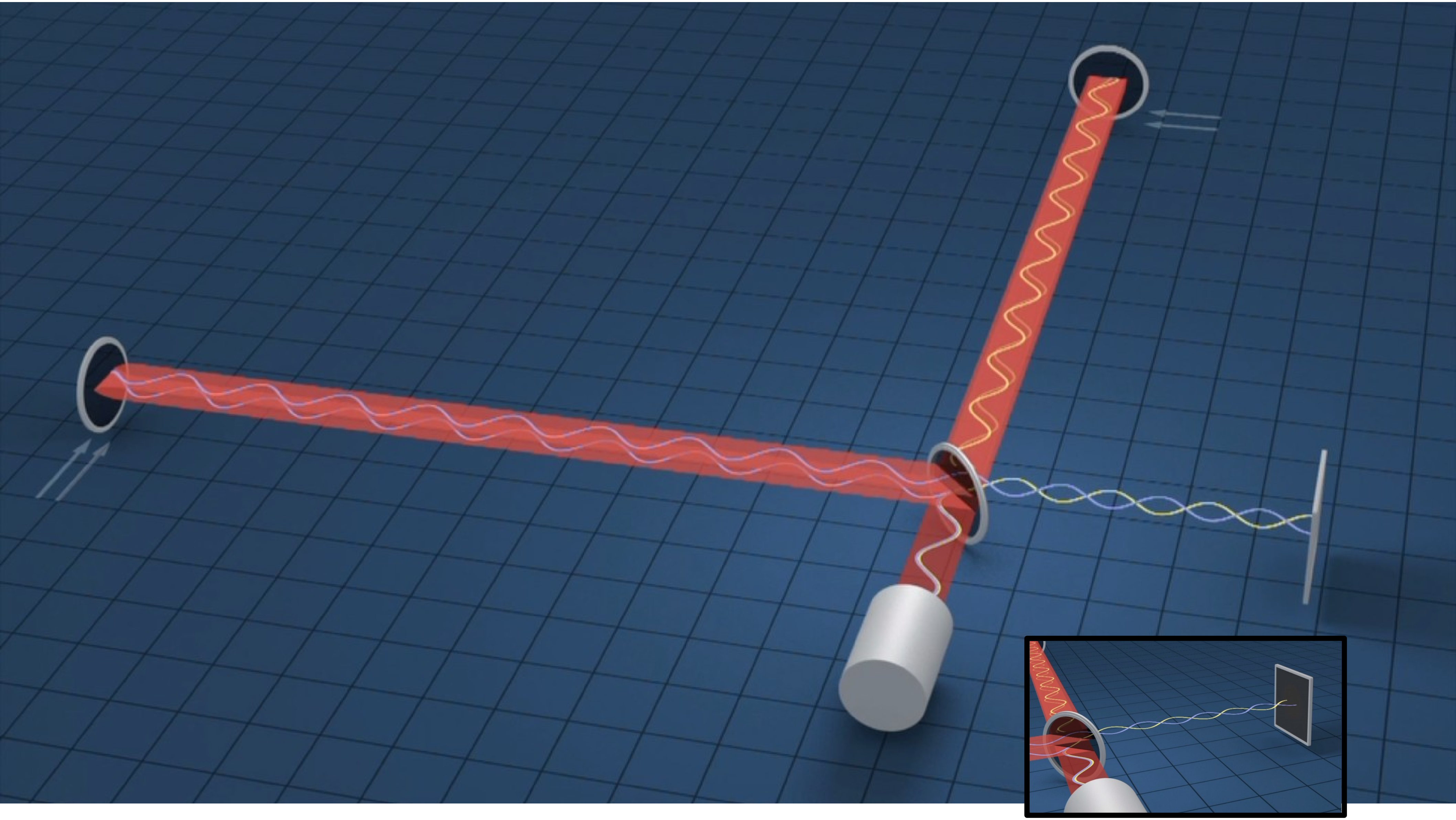
When they propagate, gravitational waves
– do not interact with matter
– are attenuated by 1/r

→ Gravitational waves are the perfect probe!
→ BUT... h~10^{-21}

Gravitational-wave detection: interferometry

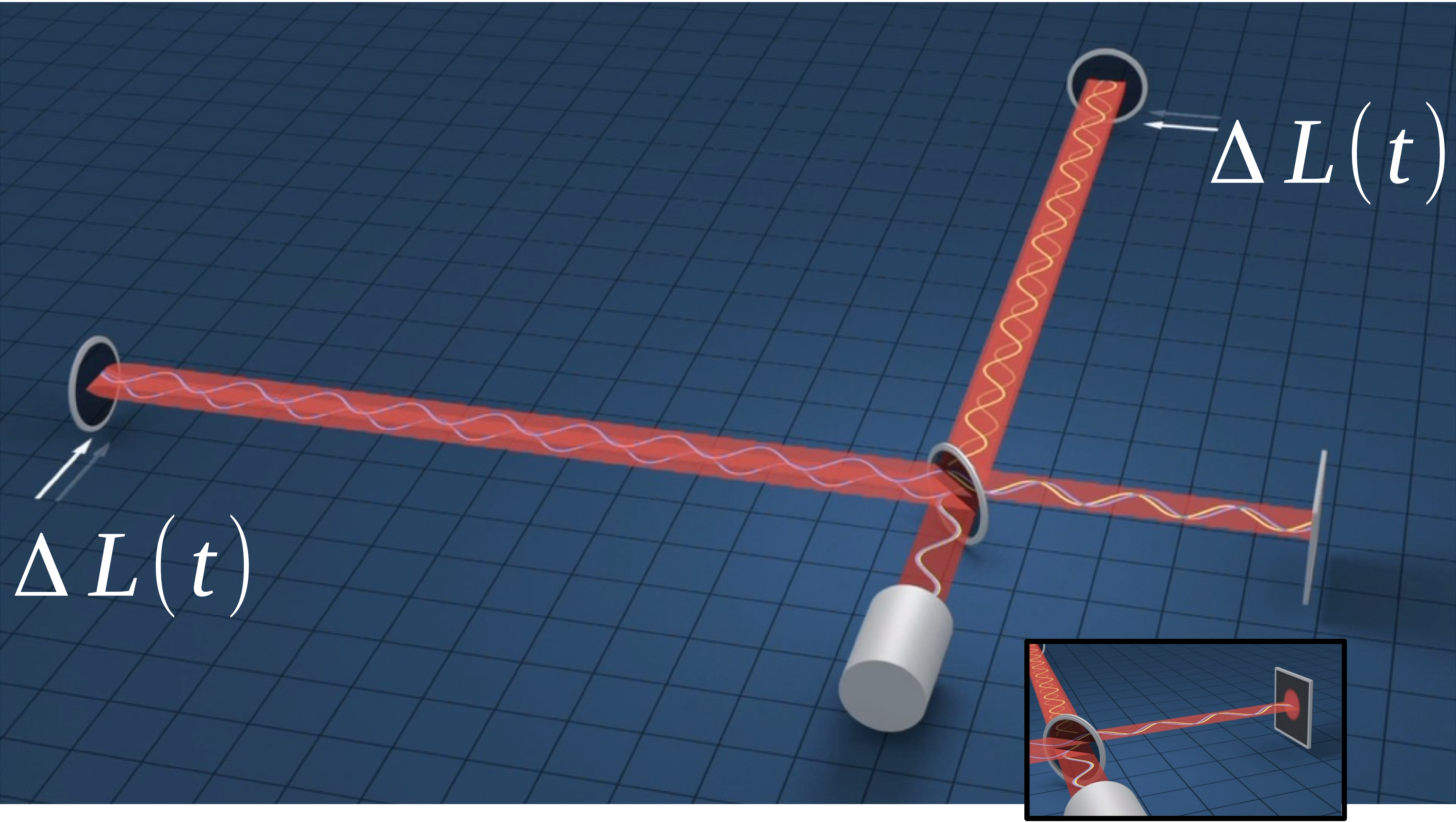


Gravitational-wave detection: interferometry



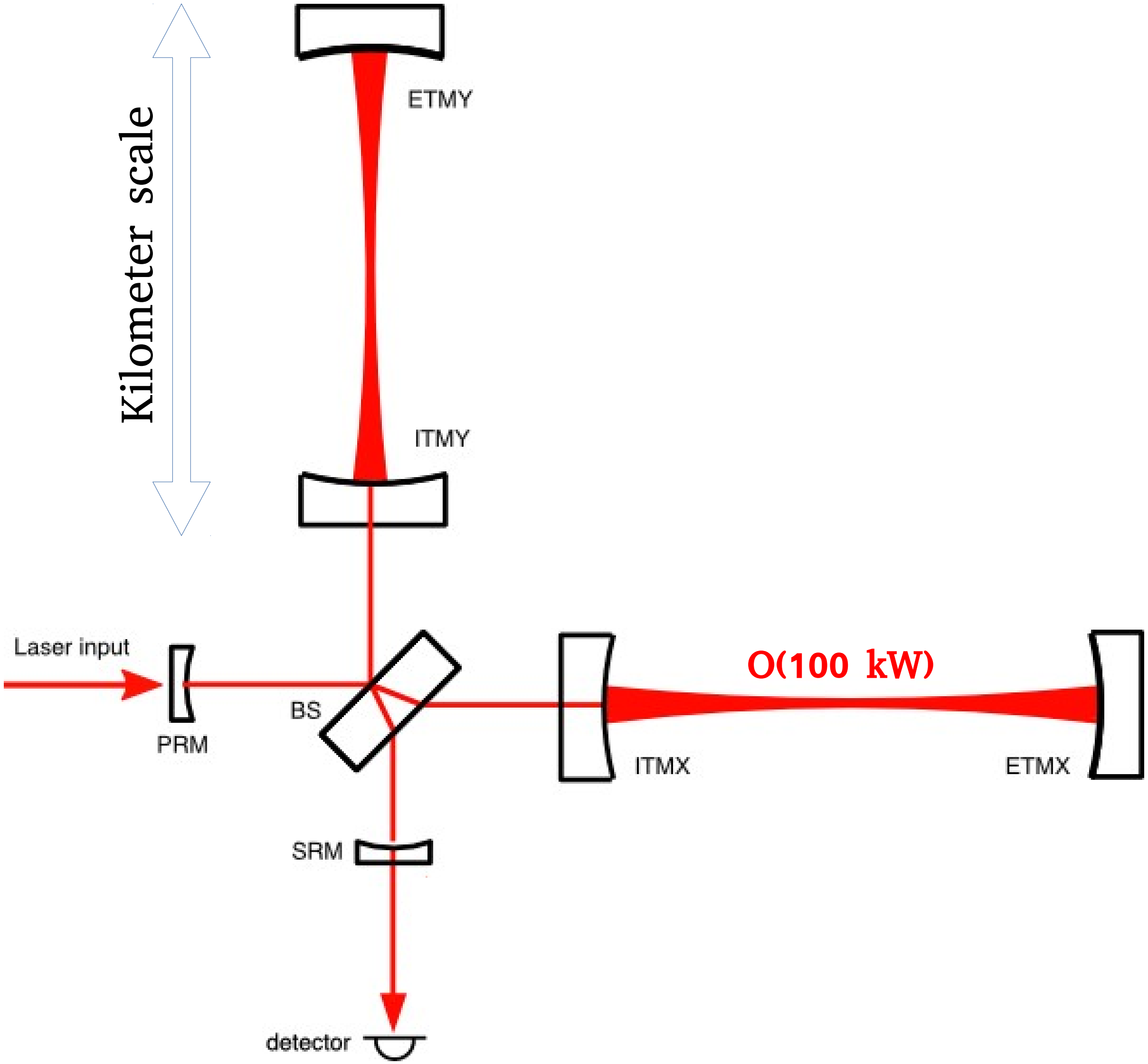
Destructive interference
→ no light

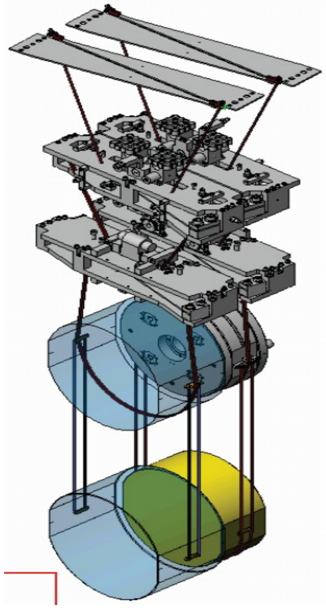
Gravitational-wave detection: interferometry

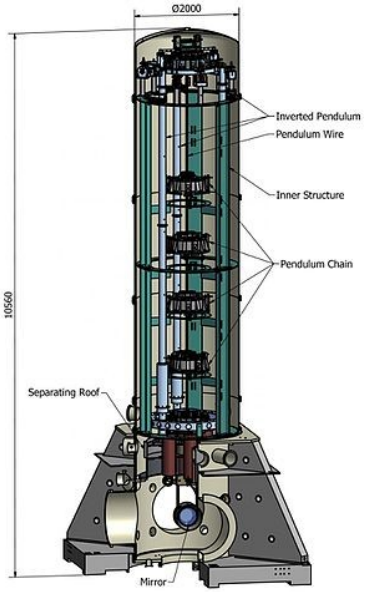


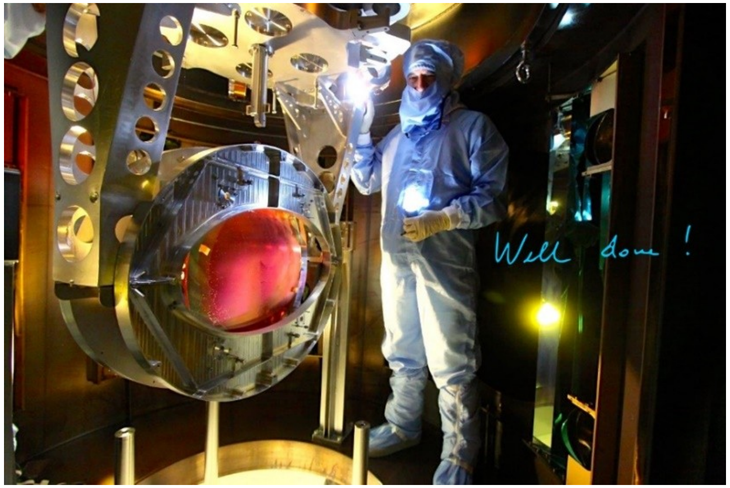
Constructive interference
→ bright light

Gravitational-wave detection: ground-based interferometers





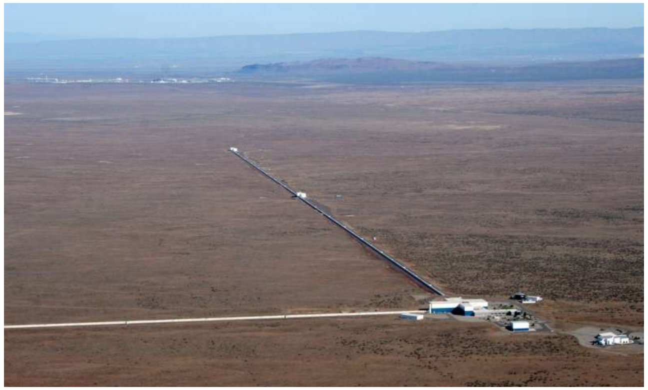




Gravitational-wave detection: ground-based interferometers

LIGO Linvingston (USA)

LIGO Hanford (USA)



Virgo (Italy)

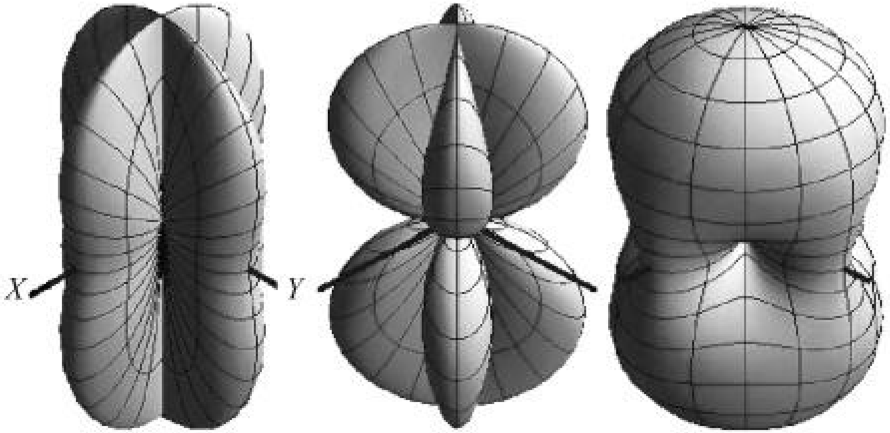
Kagra (Japan)

LIGO India

LIGO
INDIA

Gravitational-wave detection: ground-based interferometers

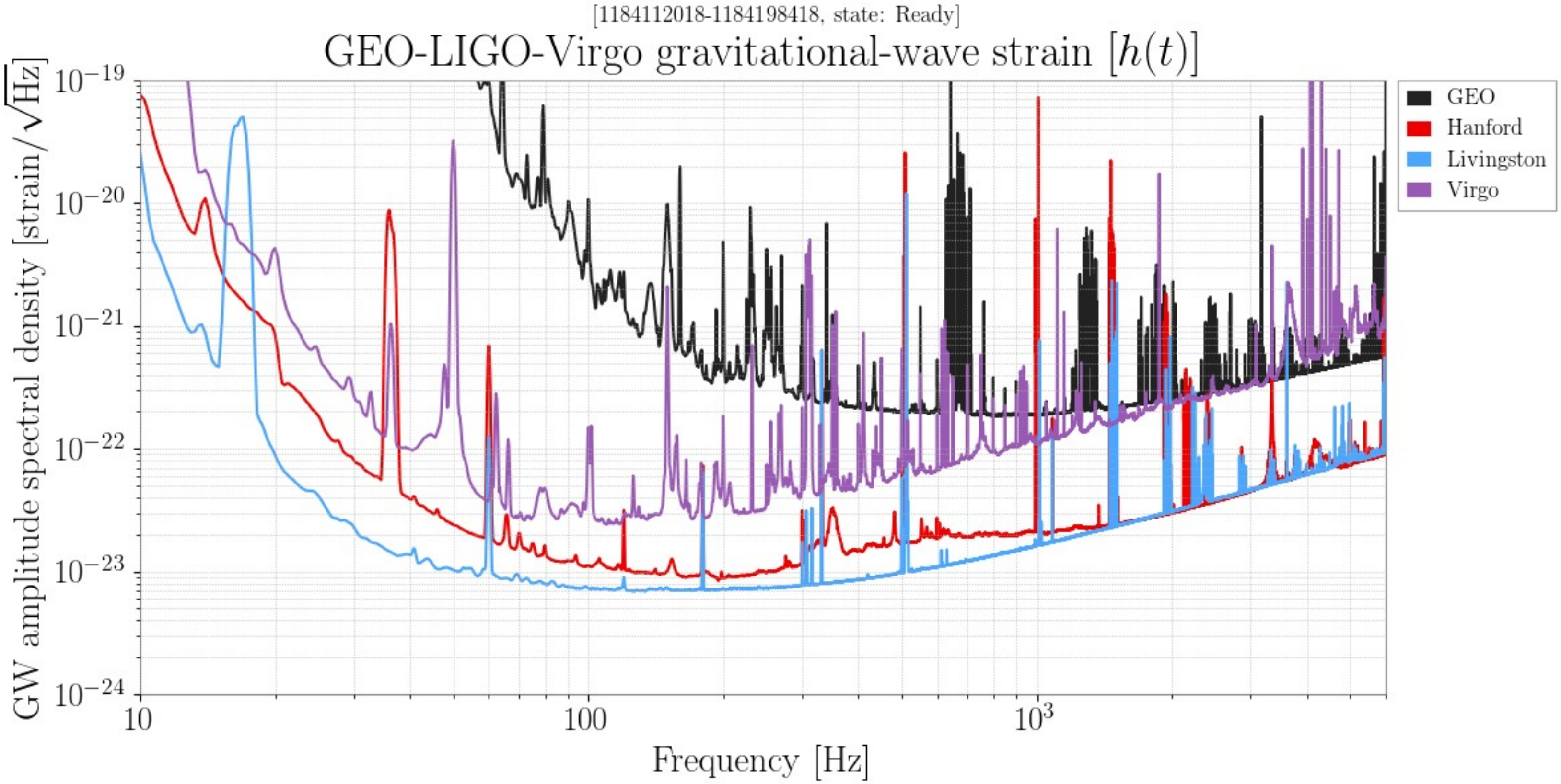
The sensitivity of the detector is not uniform over the sky



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

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

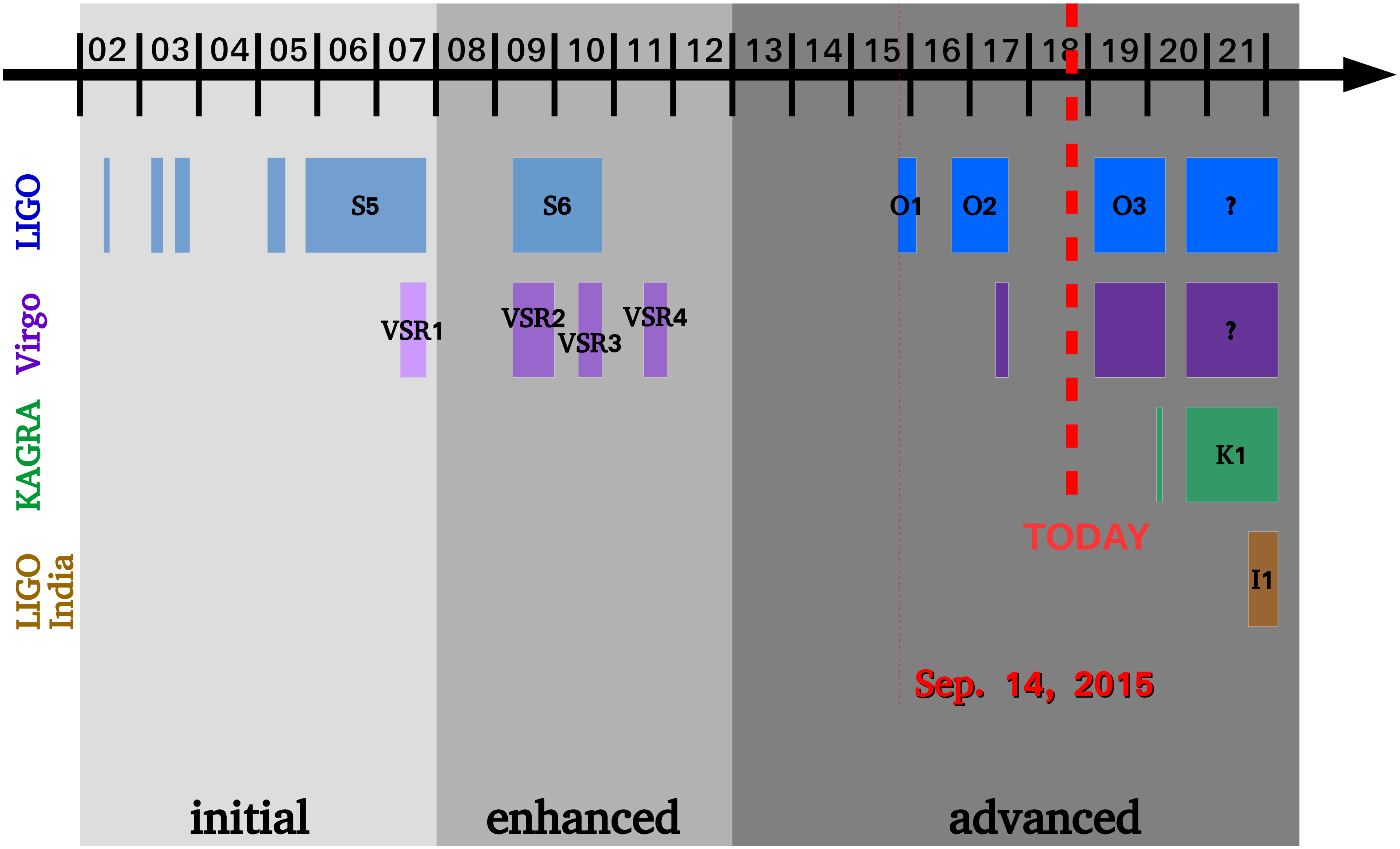
Gravitational-wave detection: ground-based interferometers



The sensitivity of ground-based interferometers is limited by

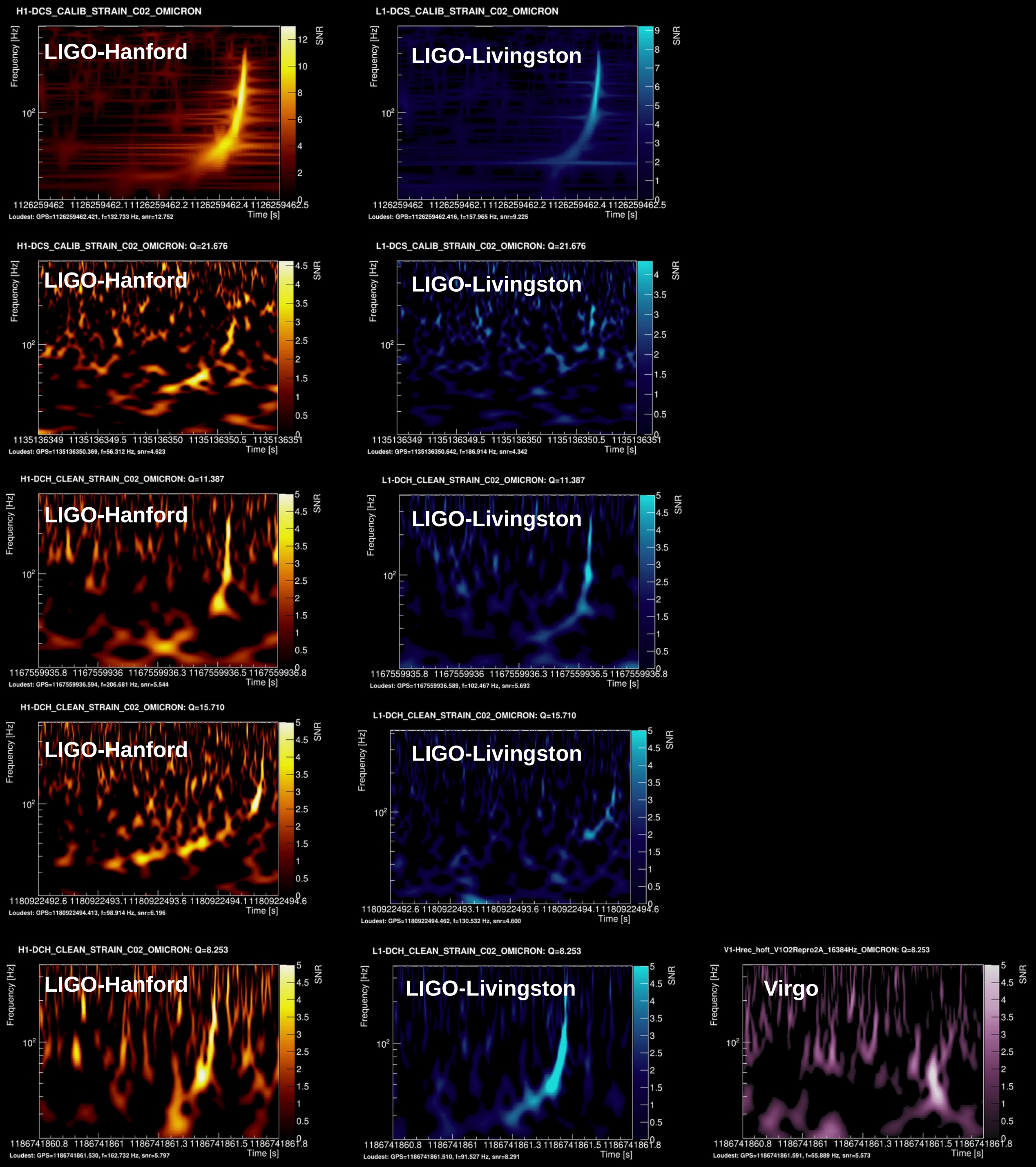
- 3 fundamental noise sources
  - → seismic noise (< 10 Hz)
  - → thermal noise (10 → 100 Hz)
  - → quantum noise (>100 Hz)
- Technical noise
  - → control noise
  - → scattered light
  - → electronic noise
  - → frequency noise
  - → ...

Gravitational-wave detection: ground-based interferometers



Data analysis :
– O1 : ~50 days of data, 2 detectors
– O2 : ~100 days of data, 2 detectors
– O3 : ~200 days of data, 3 detectors

O1 & O2 detections



GW150914

GW151226

GW170104

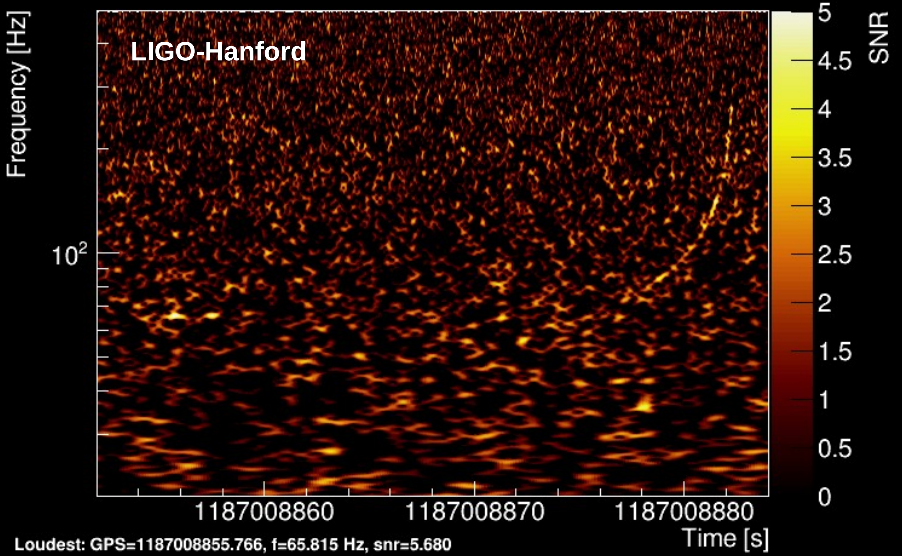
GW170608

GW170814

O1 & O2 detections

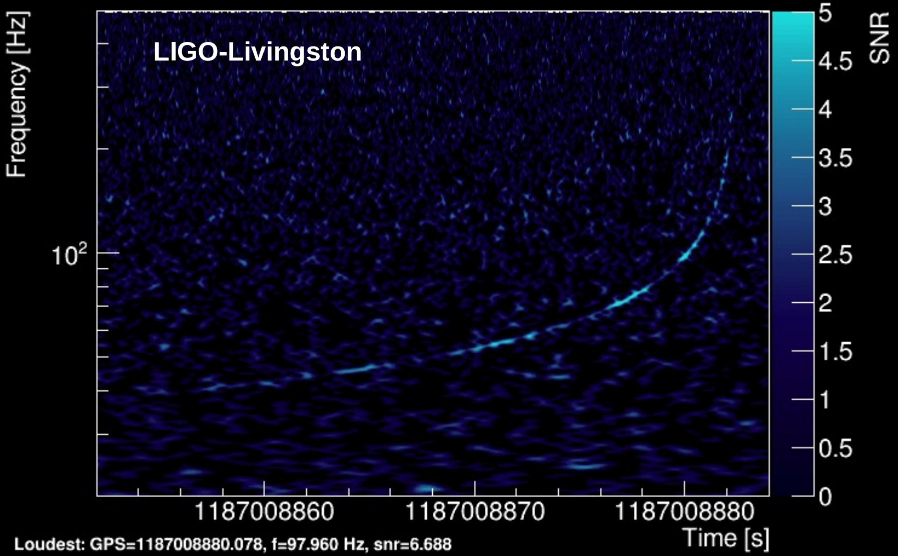
GW170817

H1-DCH_CLEAN_STRAIN_C02_OMICRON: Q=99.459



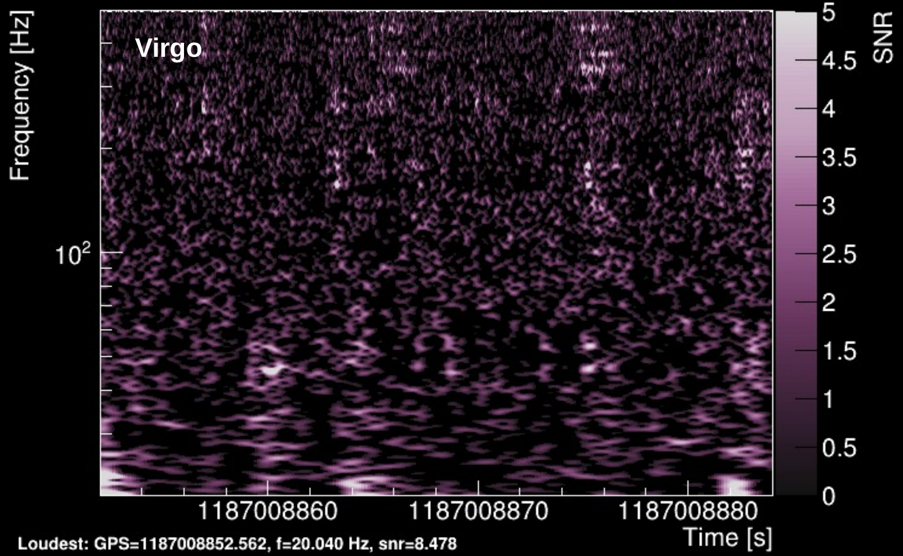
Loudest: GPS=1187008855.766, f=65.815 Hz, snr=5.680

L1-DCH_CLEAN_STRAIN_C02_T1700406_v3_OMICRON: Q=99.459



Loudest: GPS=1187008880.078, f=97.960 Hz, snr=6.688

V1-Hrec_hoft_V1O2Repro2A_16384Hz_OMICRON: Q=99.459



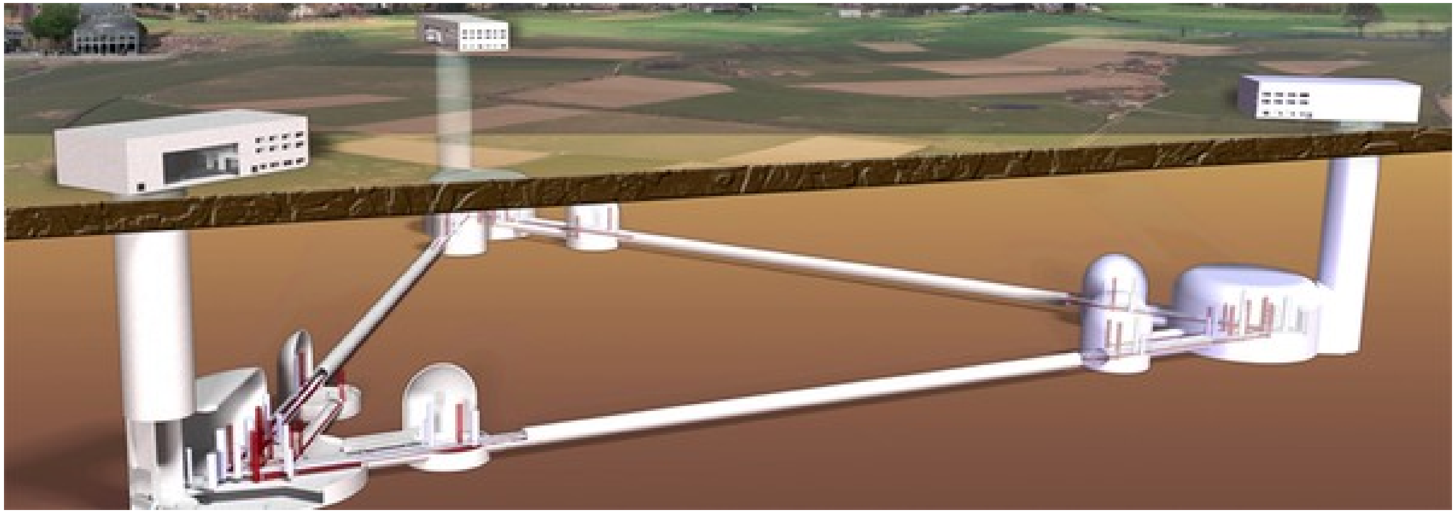
Loudest: GPS=1187008852.562, f=20.040 Hz, snr=8.478

What’s next ?

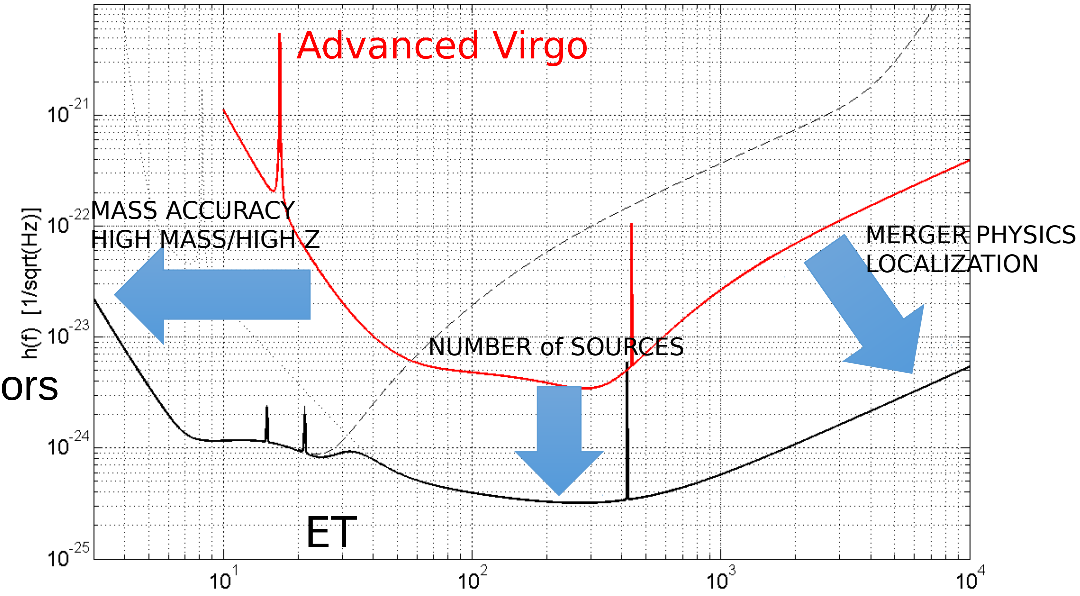
Gravitational-wave detection: Advanced Virgo +

– Use Virgo infrastructure → push further technologies (laser power, mirror size, coatings...)
– Improve sensitivity by a factor of a few
– Widening the frequency band

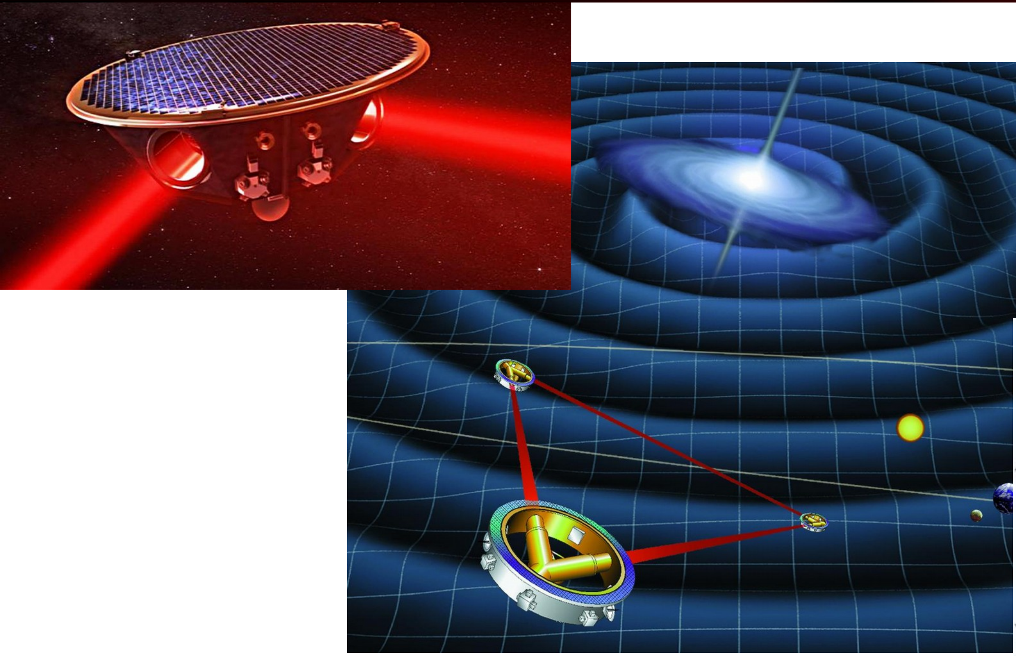
Gravitational-wave detection: Einstein telescope

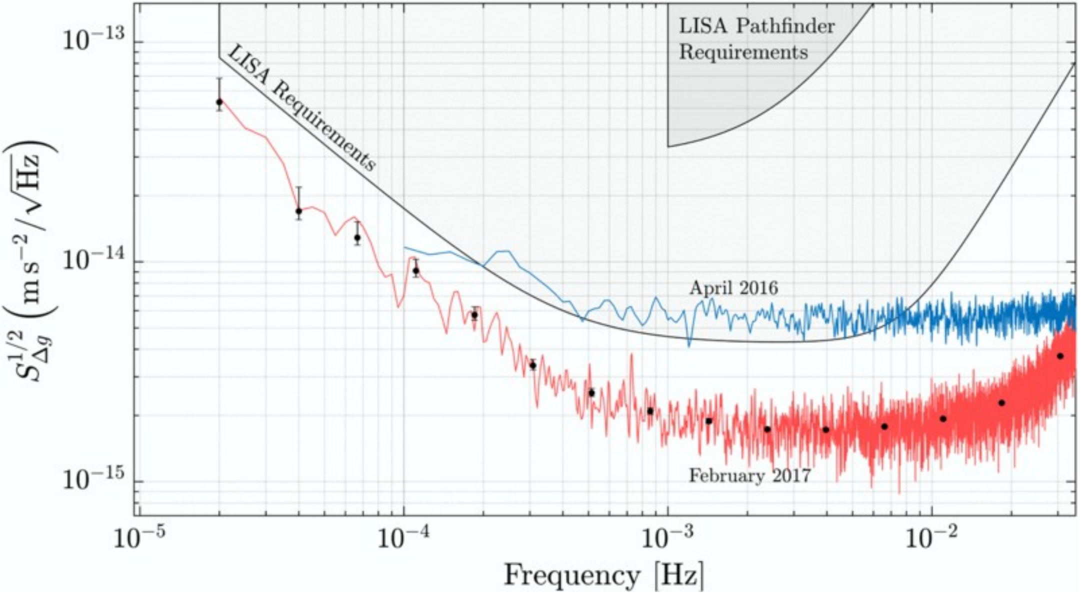


- → Underground to reduce seismic noise
- → 10 km arms
- → Cryogenic mirrors
- → Lower frequency limit – 1 Hz
- → 10 x better sensitivity than 2nd generation detectors
- → Farther back in the universe



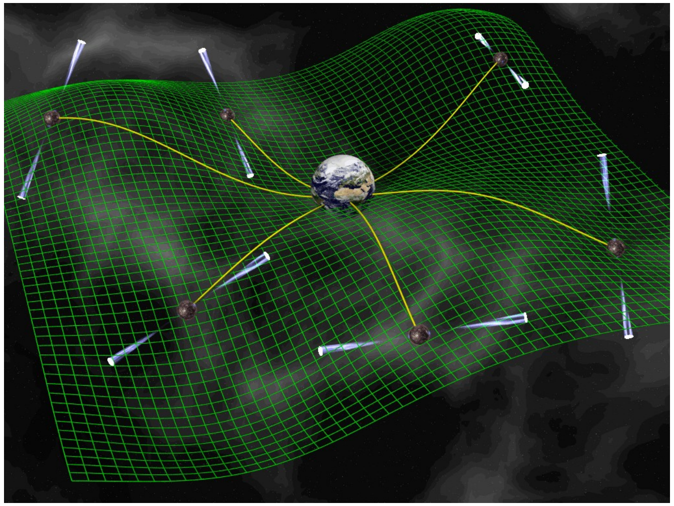
Gravitational-wave detection: LISA





- → ESA – All Systems GO!
- → NASA coming back
- → LIGO GW events and Lisa Pathfinder success have helped significantly
- → Tremendous activity at present
- → Planned launch 2034
- → Earlier launch? 2030?
- → 4 year mission → 10 years?

Gravitational-wave detection: pulsar timing



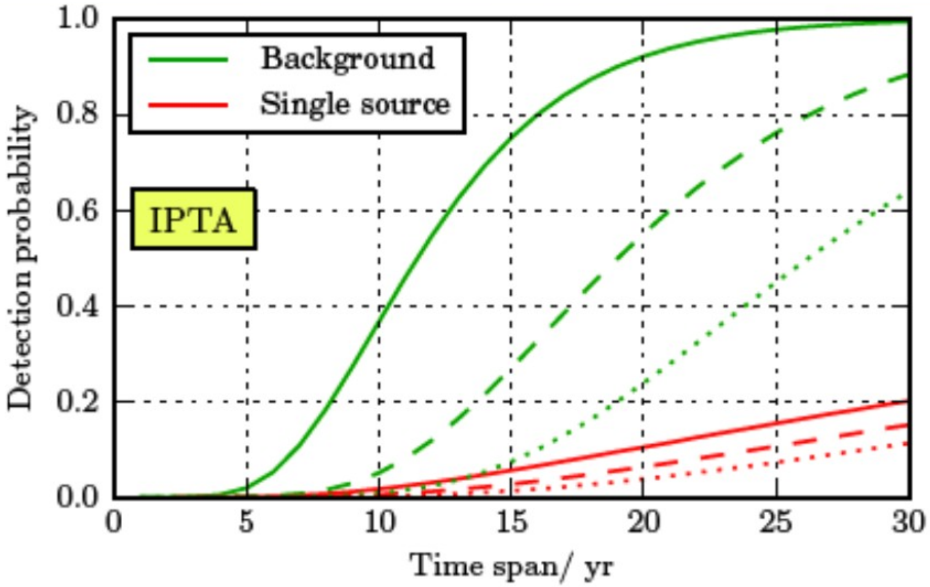
Distant pulsars send regular radio pulses

→ highly accurate clocks.

A passing gravitational wave would change the arrival time of the pulse.

Numerous collaborations around the world. Interesting upper limits and likely detections in the near future.

European pulsar timing array



Gravitational-wave sources

~~Monopole~~

$$\cancel{m=\int \rho\, d^3\vec{r}}$$

~~Dipole~~

$$\cancel{P_i=\int \rho\, x_i\, d^3\vec{r}}$$

Quadrupole (traceless)

$$Q_{ij}=\int \rho\left(x_i x_j-\frac{1}{3}r^2\delta_{ij}\right)d^3\vec{r}$$

Einstein quadrupole formula (radiated power)

$$\frac{dE}{dt}=-\frac{G}{5c^5}\left\langle\frac{d^3Q^{ij}}{dt^3}\frac{d^3Q_{ij}}{dt^3}\right\rangle$$

Estimate using the source parameters

$$Q\sim\varepsilon M R^2$$

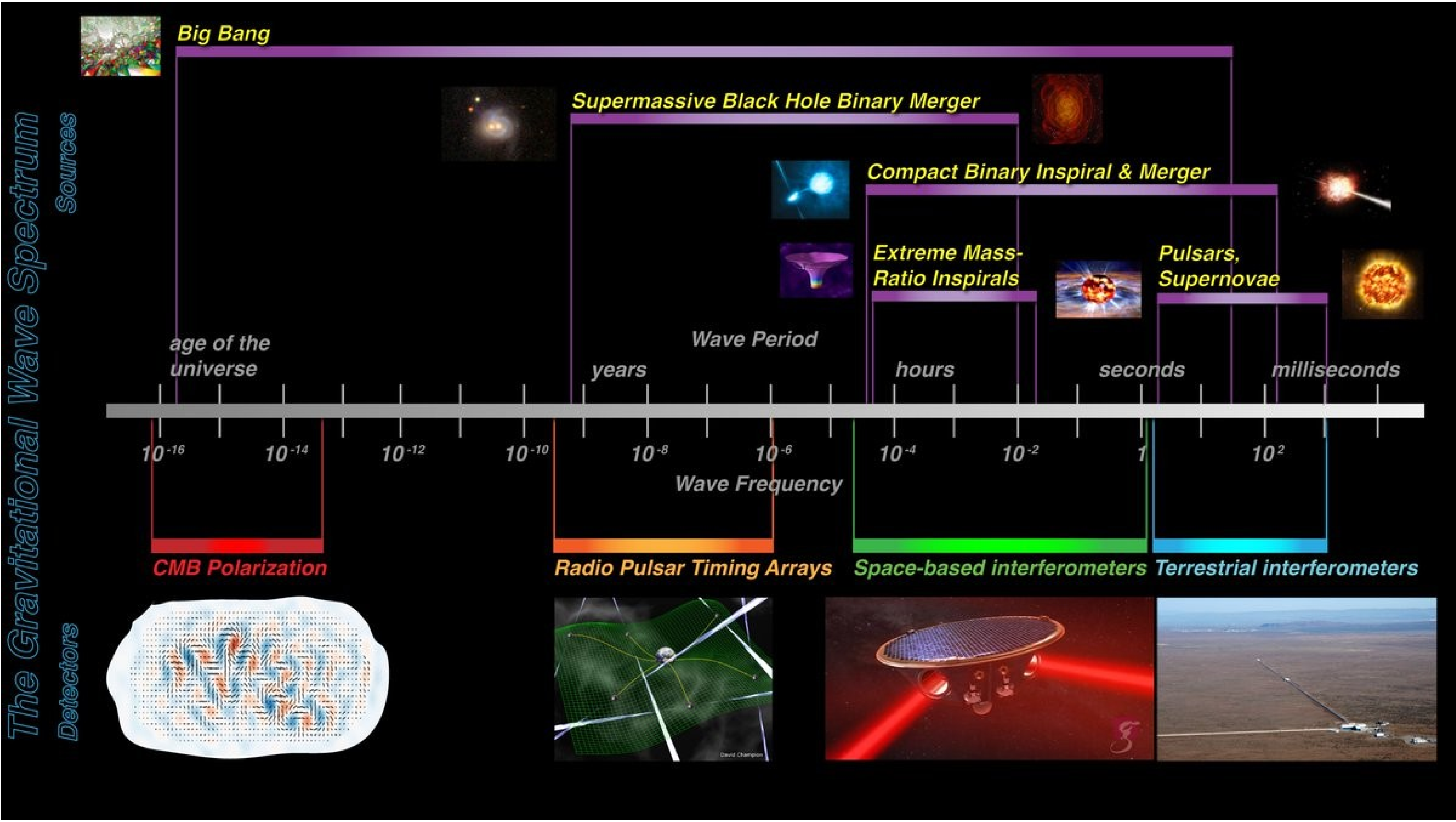
$$\frac{d^3Q}{dt^3}\sim\varepsilon M R^2\omega^3$$

$$\frac{dE}{dt}\sim-\frac{G}{c^5}\varepsilon^2M^2R^4\omega^6\sim-\boxed{\frac{c^5}{G}}\varepsilon^2\left(\frac{R_s}{R}\right)^2\left(\frac{v}{c}\right)^6$$

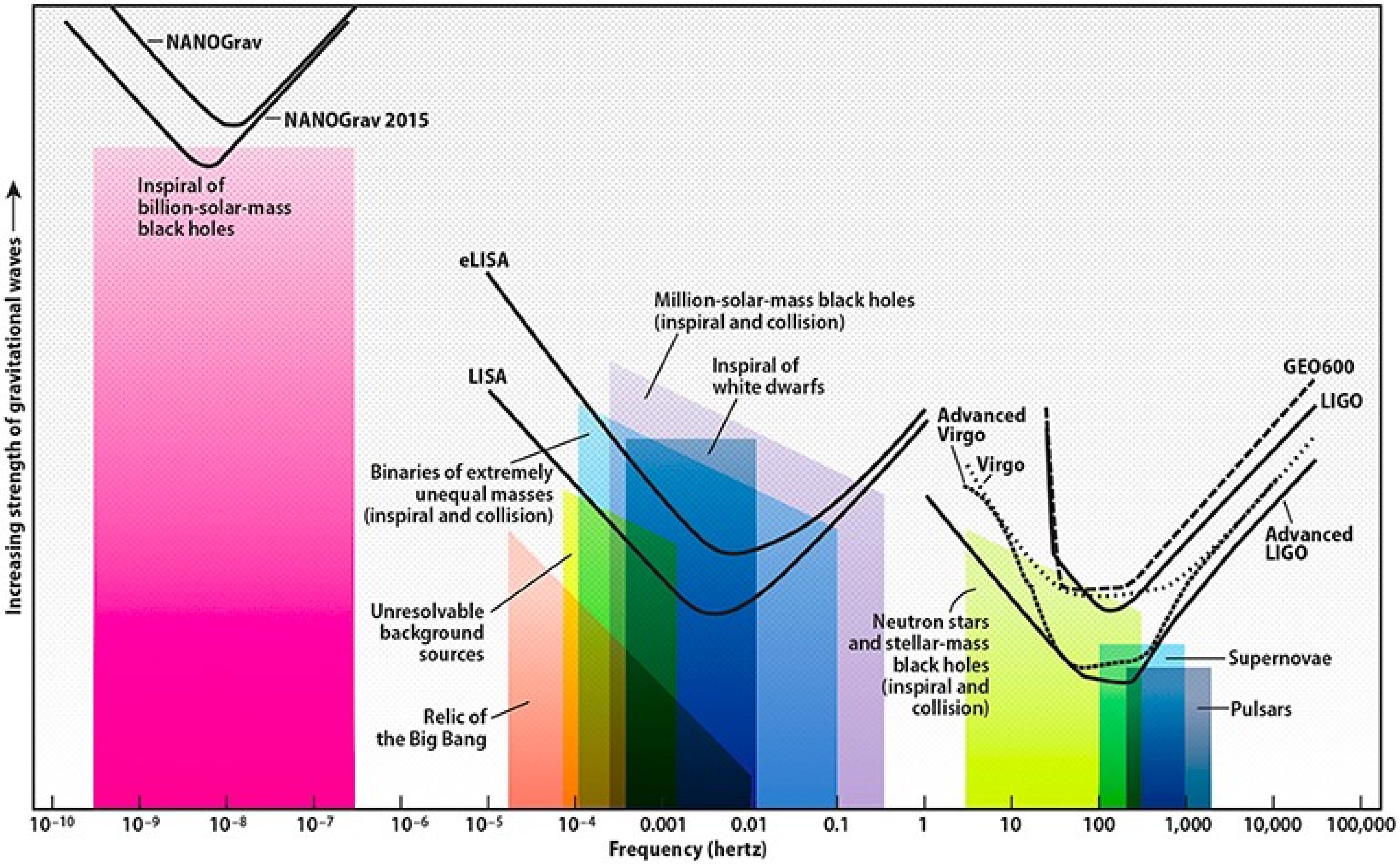
$$\simeq 10^{52}\,W$$

→ Important source characteristics:
- asymmetric
- compact
- relativistic

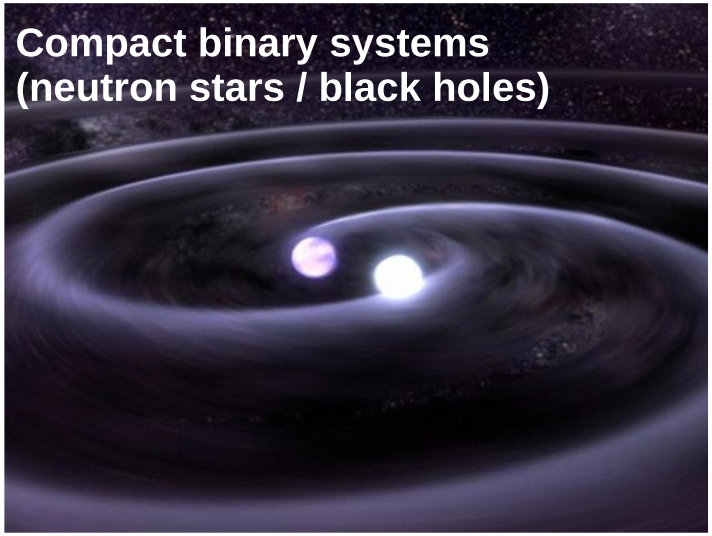
Gravitational-wave sources



Gravitational-wave sources

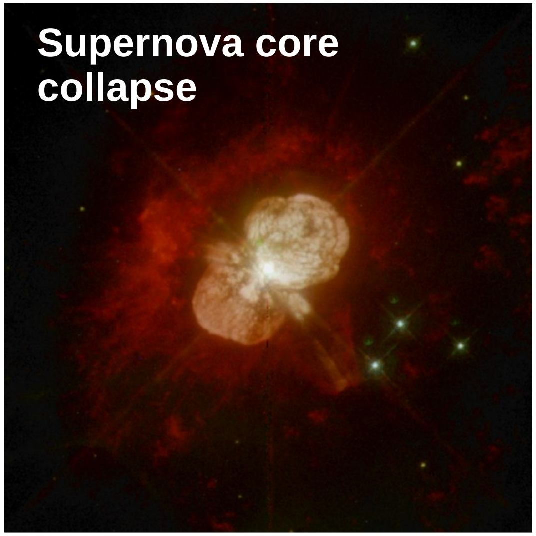


Relevant gravitational-wave sources (> 10 Hz)



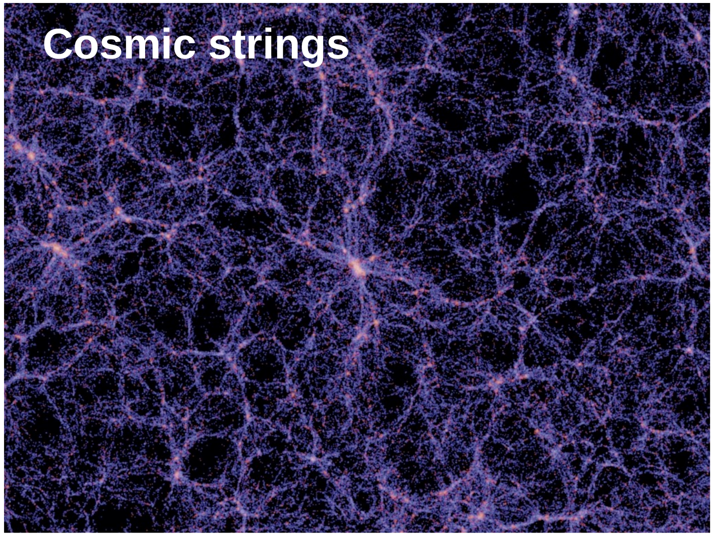
Compact binary systems
(neutron stars / black holes)

newly-formed black holes

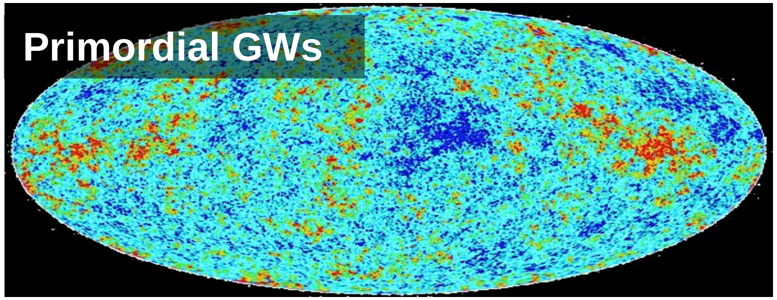


Supernova core collapse

Isolated neutron stars



Cosmic strings

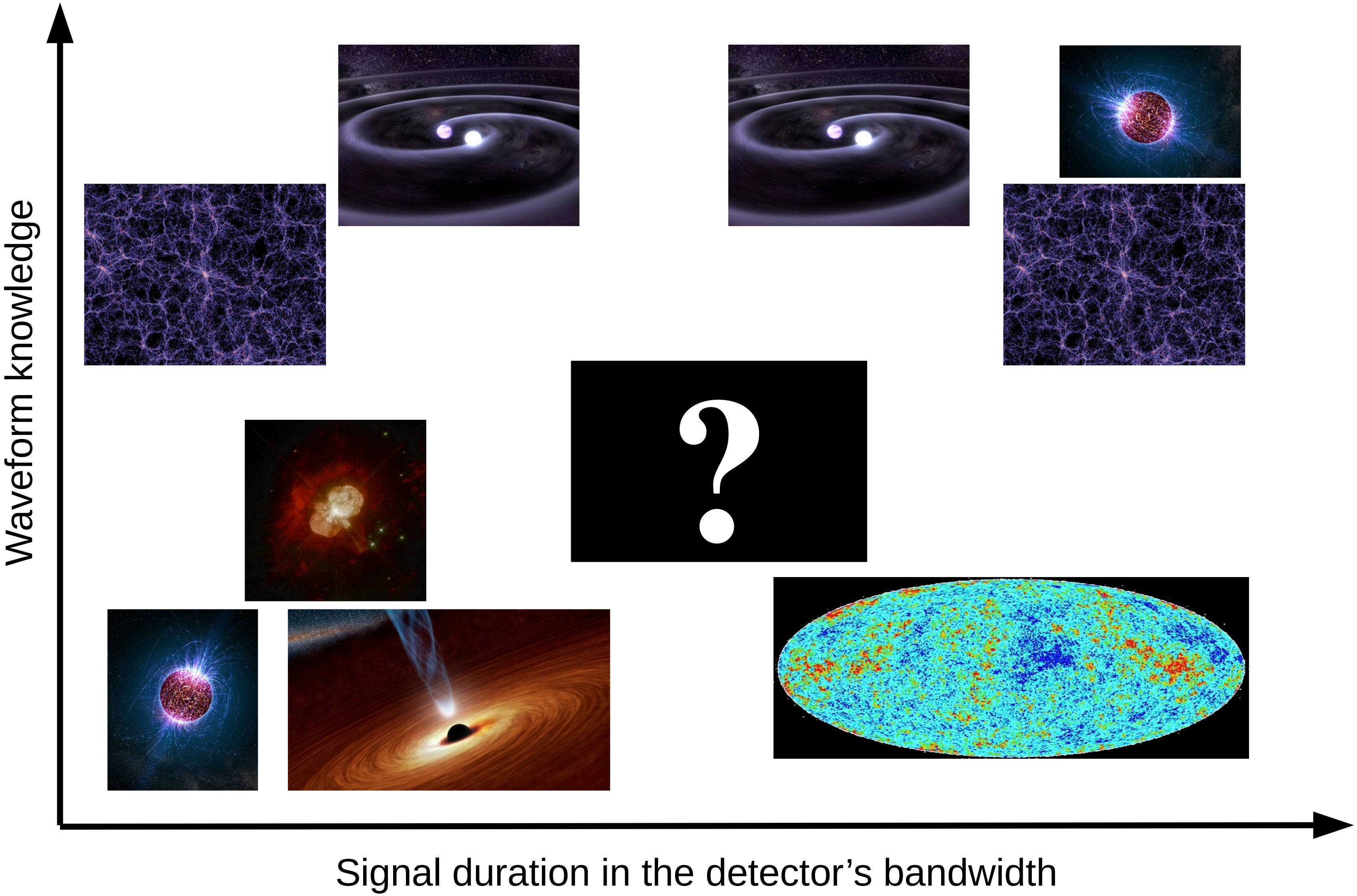


Primordial GWs

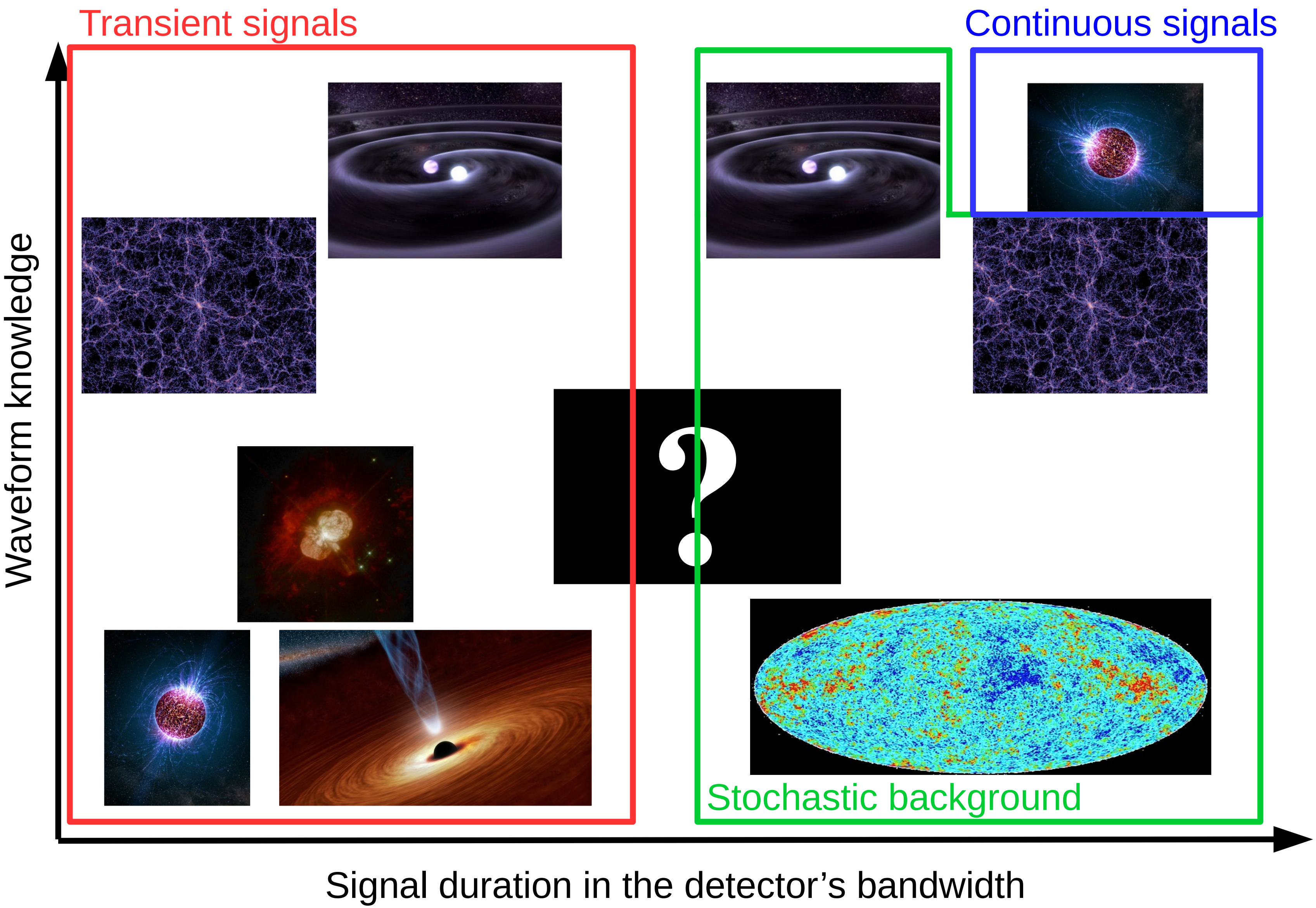
Unknown sources

?

Source classification : analysis methods



Source classification : analysis methods



Transient signals

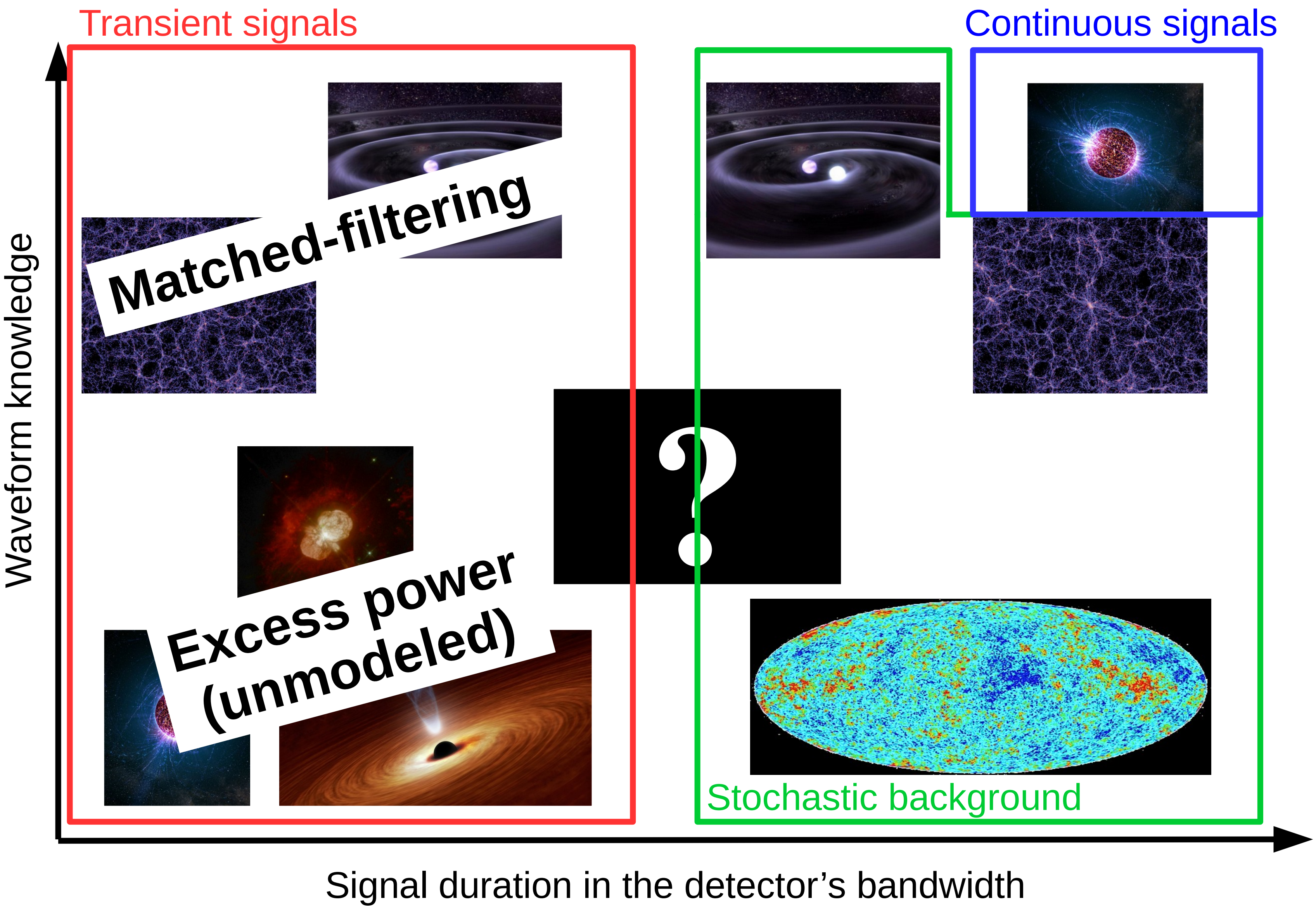
Continuous signals

Stochastic background

Waveform knowledge

Signal duration in the detector’s bandwidth

Source classification : analysis methods



Transient signals

Continuous signals

Matched-filtering

Excess power (unmodeled)

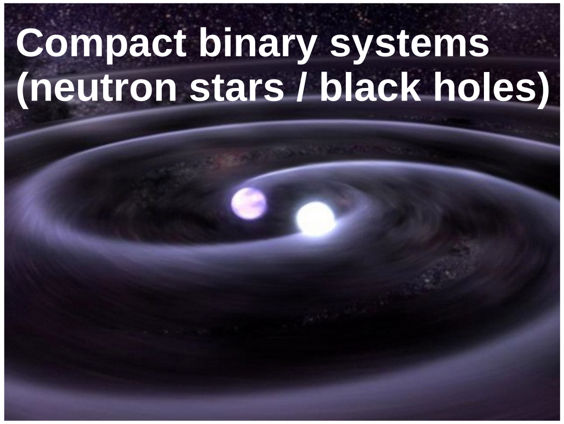
?

Stochastic background

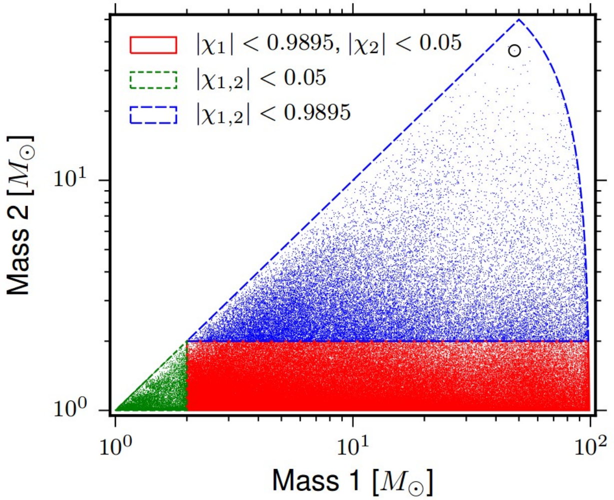
Waveform knowledge

Signal duration in the detector’s bandwidth

CBC searches

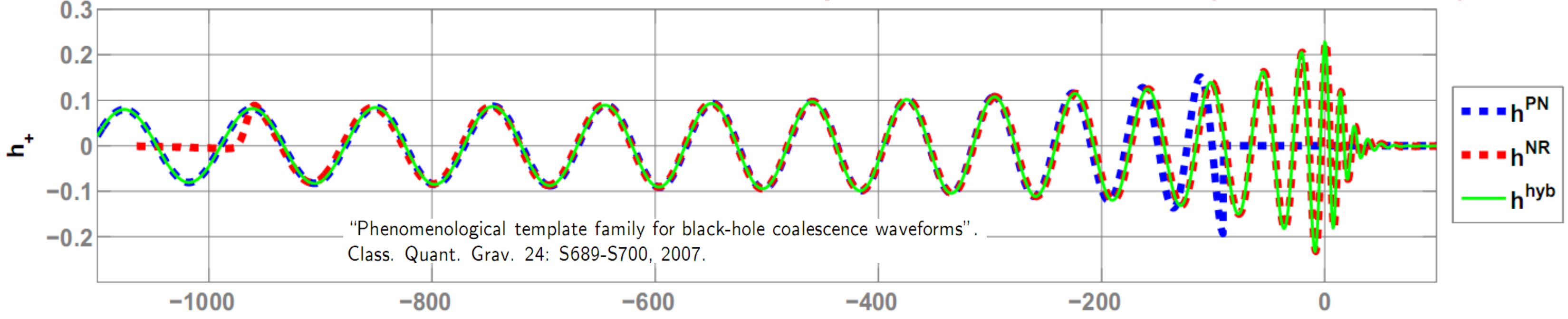


Compact binary systems (neutron stars / black holes)



- 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-filtering template searches (~250,000 templates).
- Unique way to study strong field gravity and the structure of the nuclear matter in the most extreme conditions

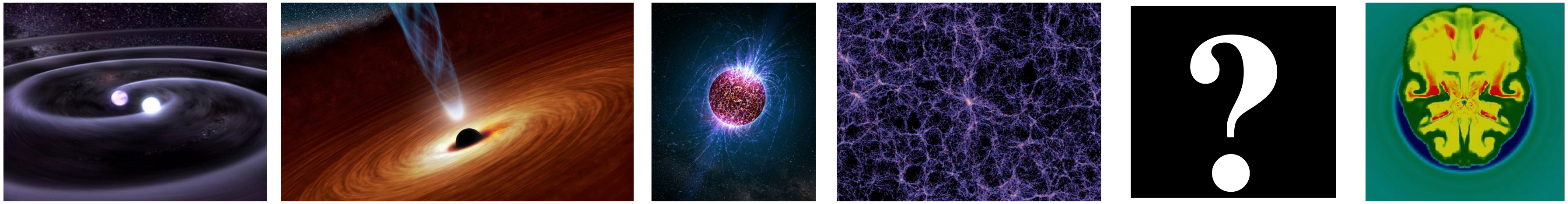
Gravitational waveform: inspiral merger BH-ringdown



"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, ...

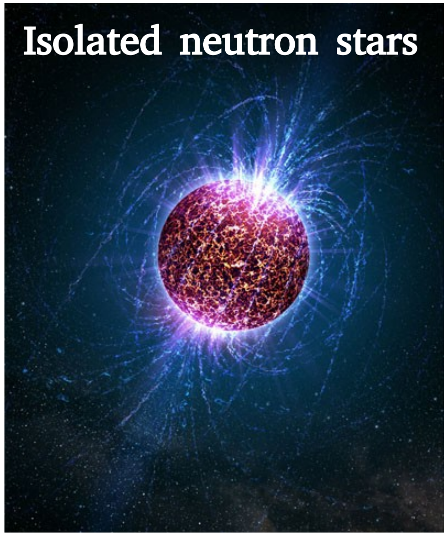
Burst searches

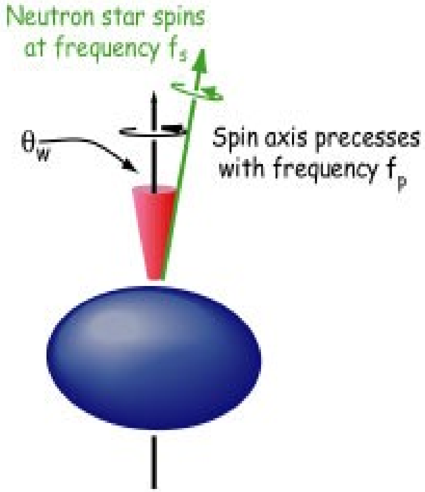


- Many transient sources:
  - CBC
  - Supernovae: probe the explosion mechanisms.
  - Gamma Ray Bursts: collapse of rapidly rotating massive stars or neutron star mergers.
  - Pulsar glitches.
  - Cosmic strings cusps and kinks.

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

Continuous-wave searches





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

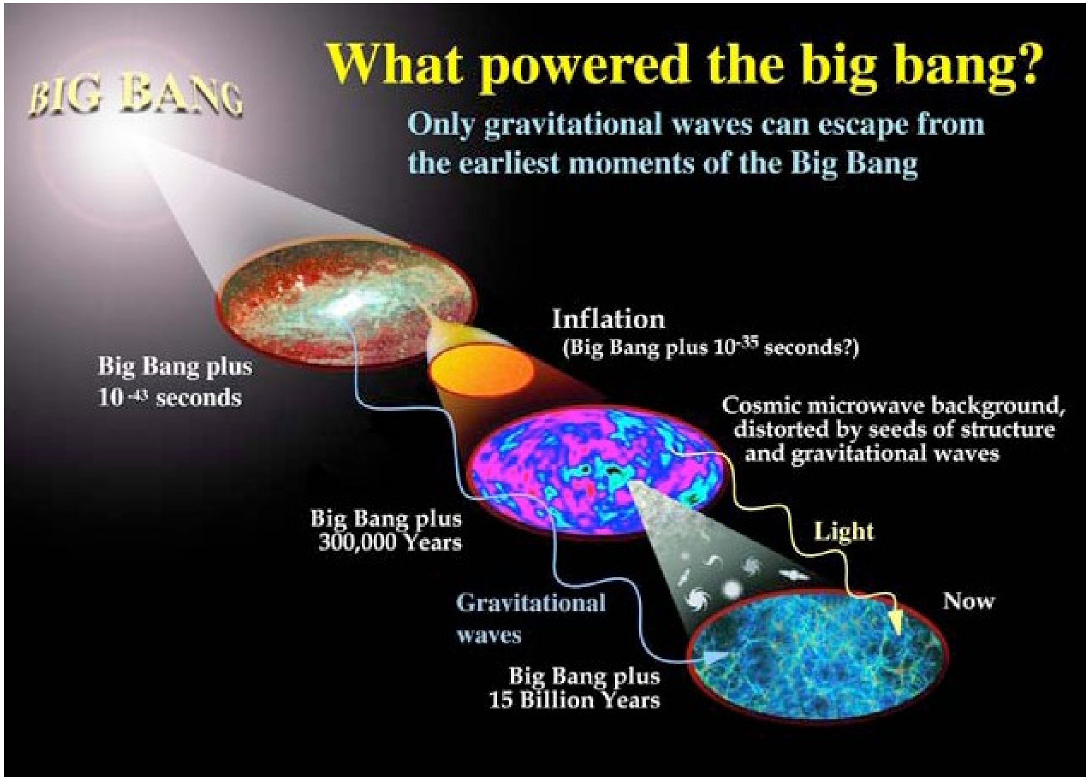
- Pulsars with mass non-uniformity:
  - distortion due to elastic stresses or magnetic field
  - distortion due to matter accretion
  - free precession around rotation axis
  - excitation of long-lasting oscillations (e.g. r-modes)
- Produce gravitational-waves, often at twice the rotational frequency.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

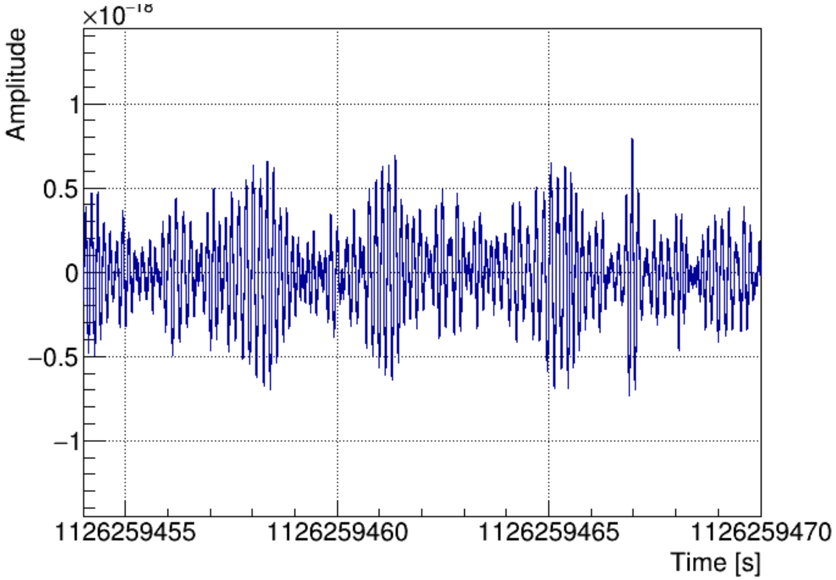


$$\Omega_{GW}(f) = \frac{f}{\rho_c}\frac{d\rho_{GW}}{df}$$

Gravitational-wave 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

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

The detector’s noise

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

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

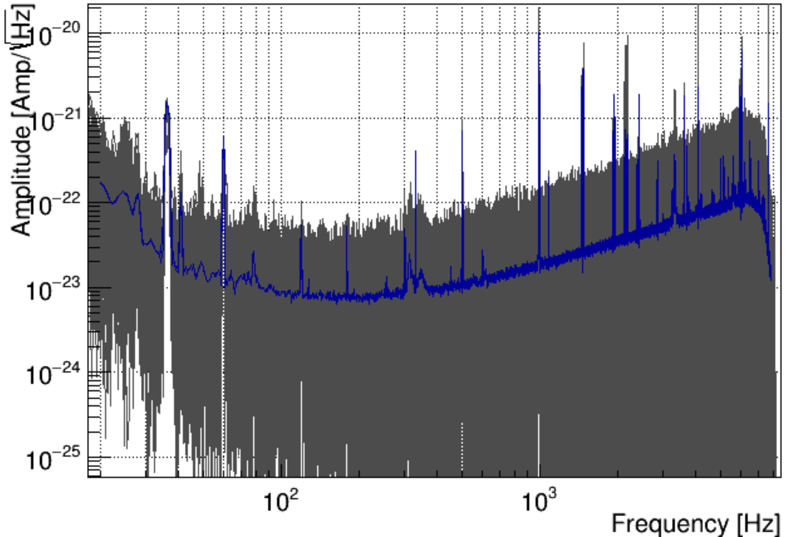
Sensitivity measured using the noise power spectral density :

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

+ median-to-mean correction

One-sided / Two sided PSDs

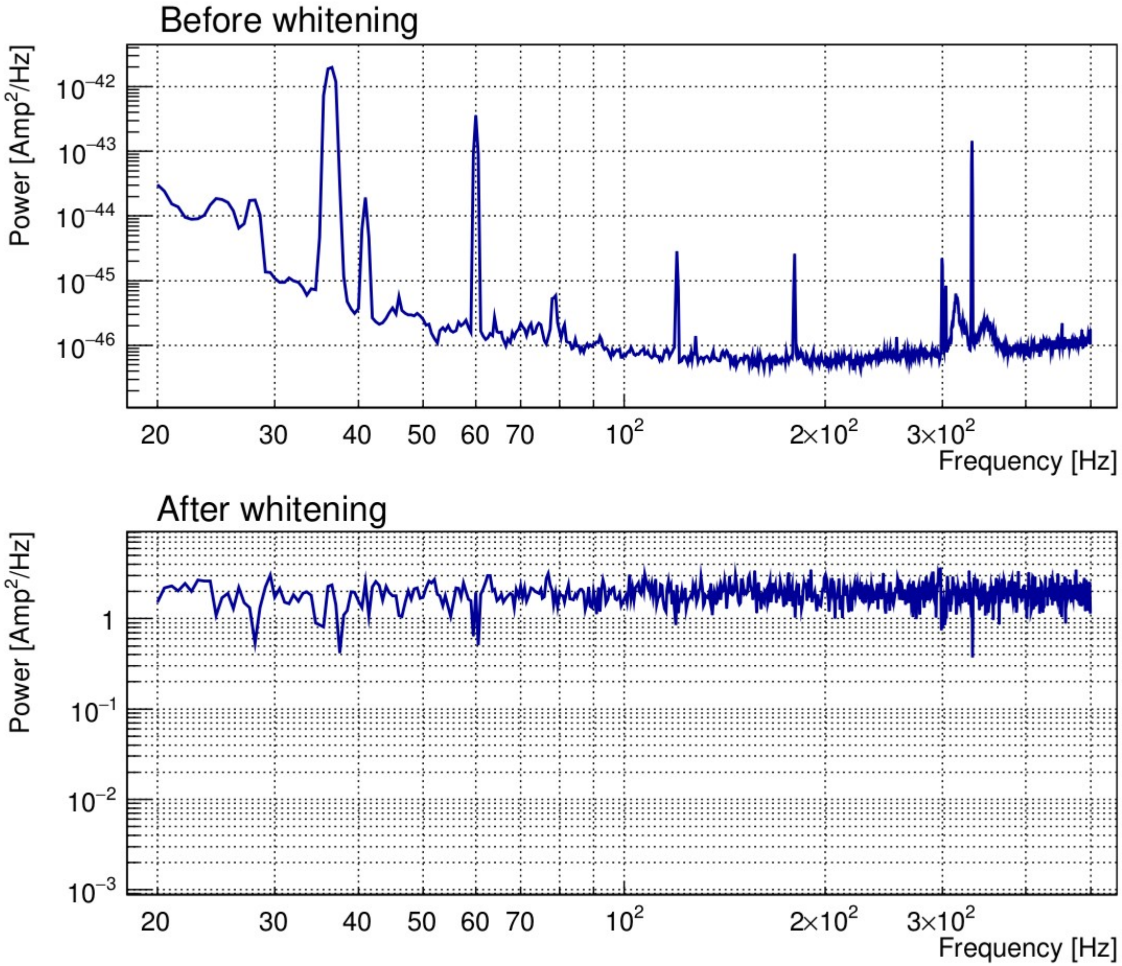
Amplitude power spectral density: $\sqrt{S_n(k)}$



Data whitening

GW data must be whitened. Several methods are used :
- reweighting of frequency bins
- linear prediction

→ white noise is mandatory for statistical interpretation of the data



Stochastic background of gravitational waves

Assumption : stationary, unpolarized, and Gaussian stochastic background

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

$$h_i = n_i + {\color{red}GW_i}$$

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

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

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

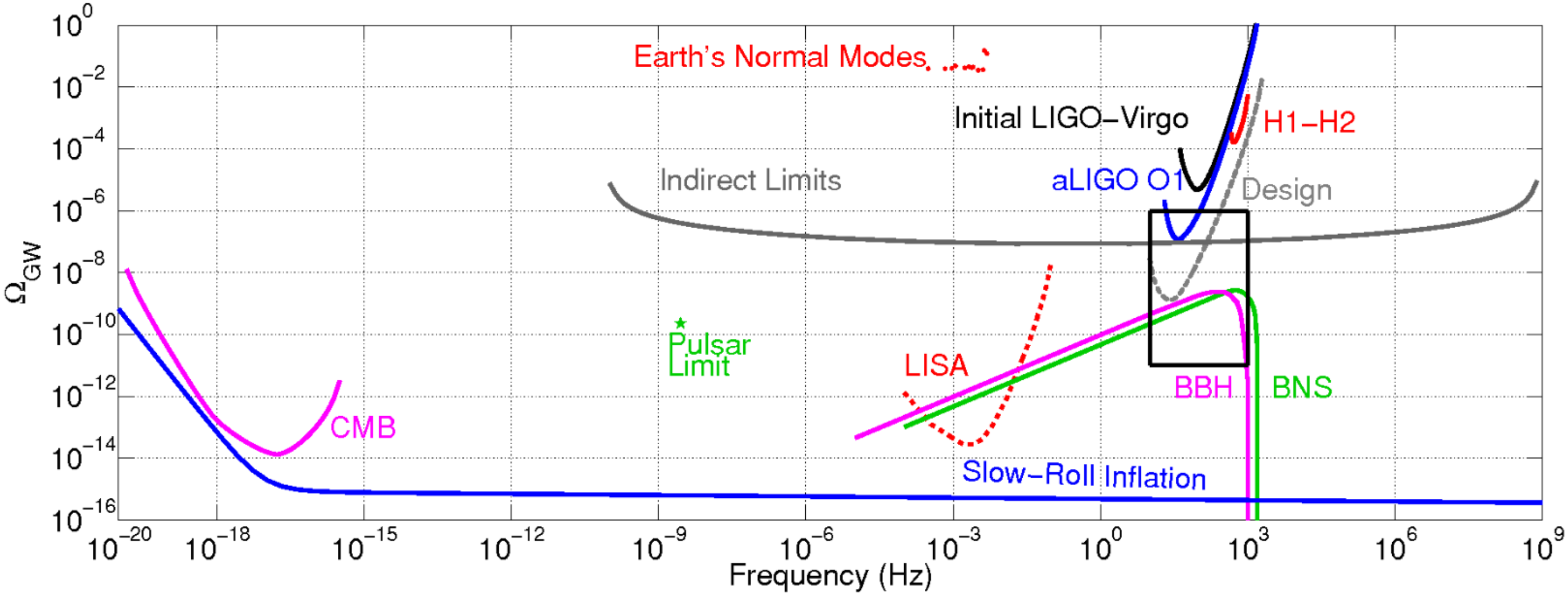
$$\tilde{Q}(f) \propto \frac{\gamma(f)\,\Omega_{GW}(f)}{f^3 S_{n,1}(f)\, S_{n,2}(f)}$$

Detector PSDs

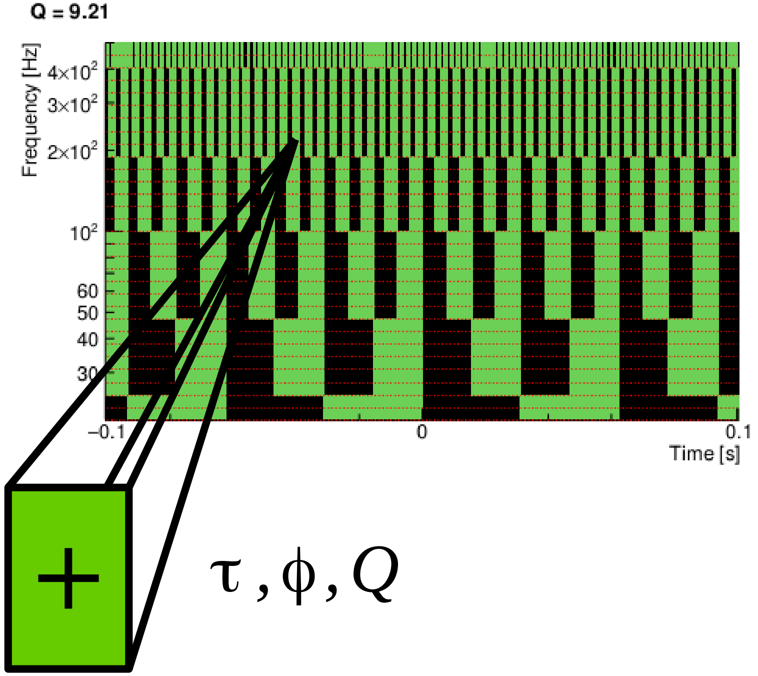
O1 isotropic search, for $\alpha = 0$: $\Omega_{GW}(25\,Hz) < 1.7 \times 10^{-7}$

PRL.118.121101 (2017)

Stochastic background of gravitational waves



Transient searches : excess power



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

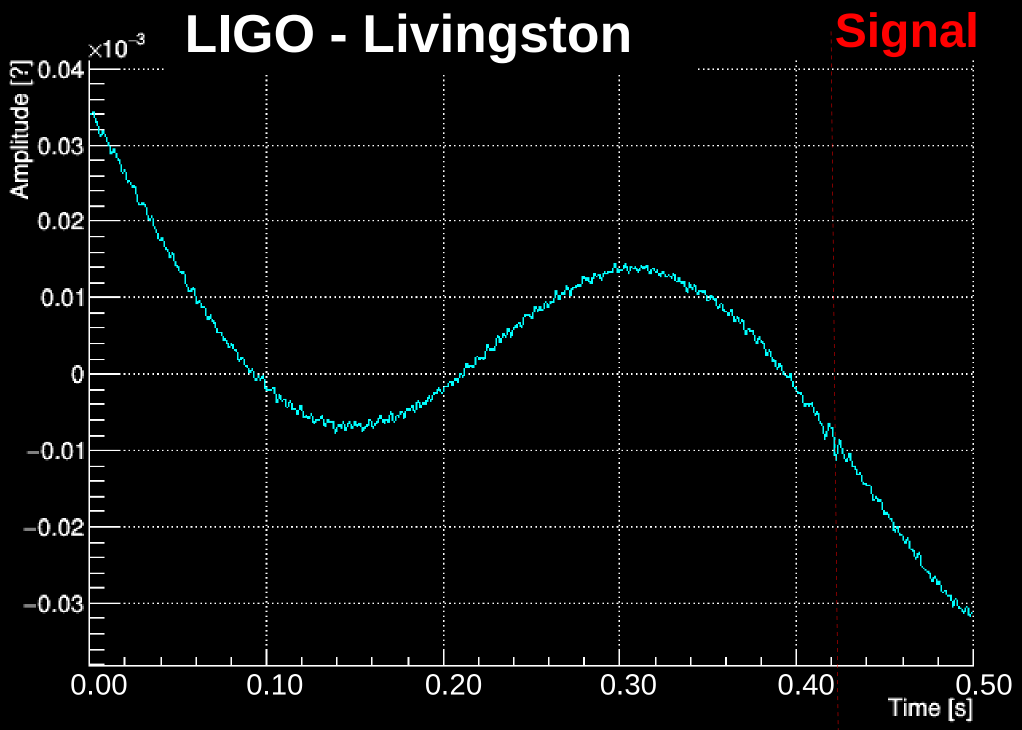
$$\hat{\rho}^2(\tau,\phi,Q)=|X^w(\tau,\phi,Q)|^2-\langle|N^w(\tau,\phi,Q)|^2\rangle=|X^w(\tau,\phi,Q)|^2-1$$

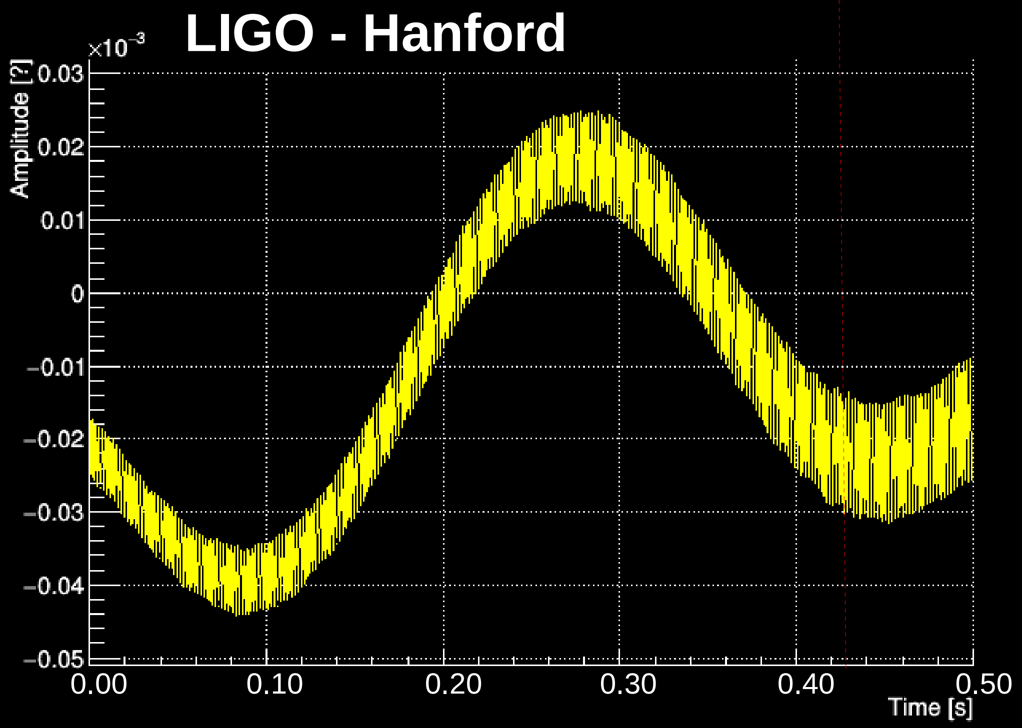
Statistical interpretation: noise is Gaussian-distributed with unit variance

GW150914

Output power

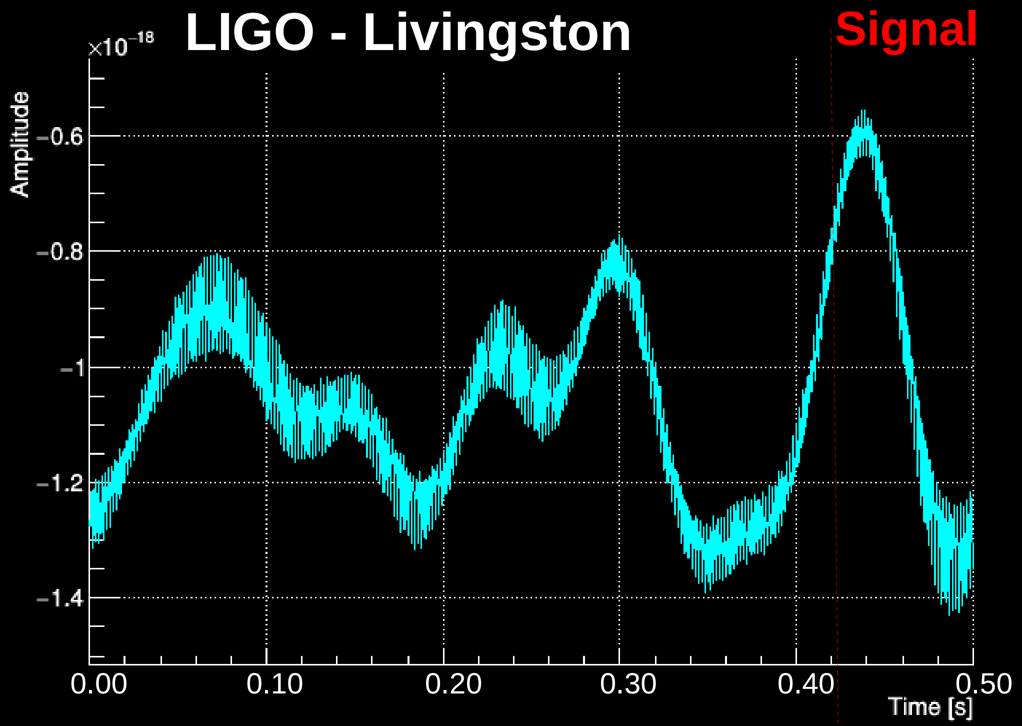
Output power





GW150914

$h(t)$

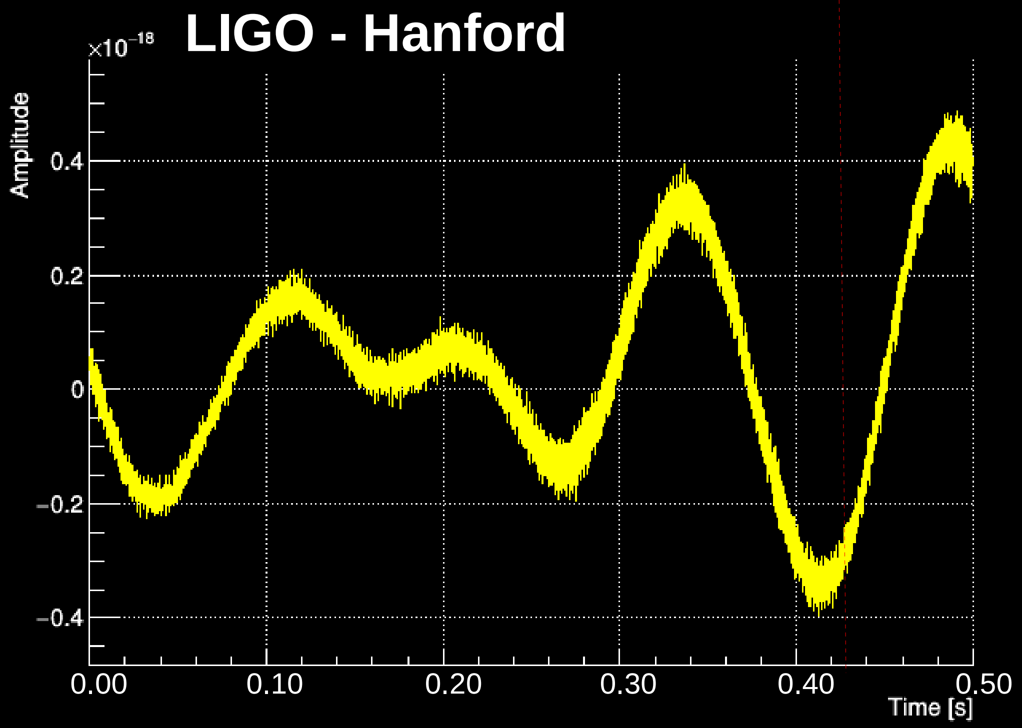

LIGO - Livingston

Data is calibrated

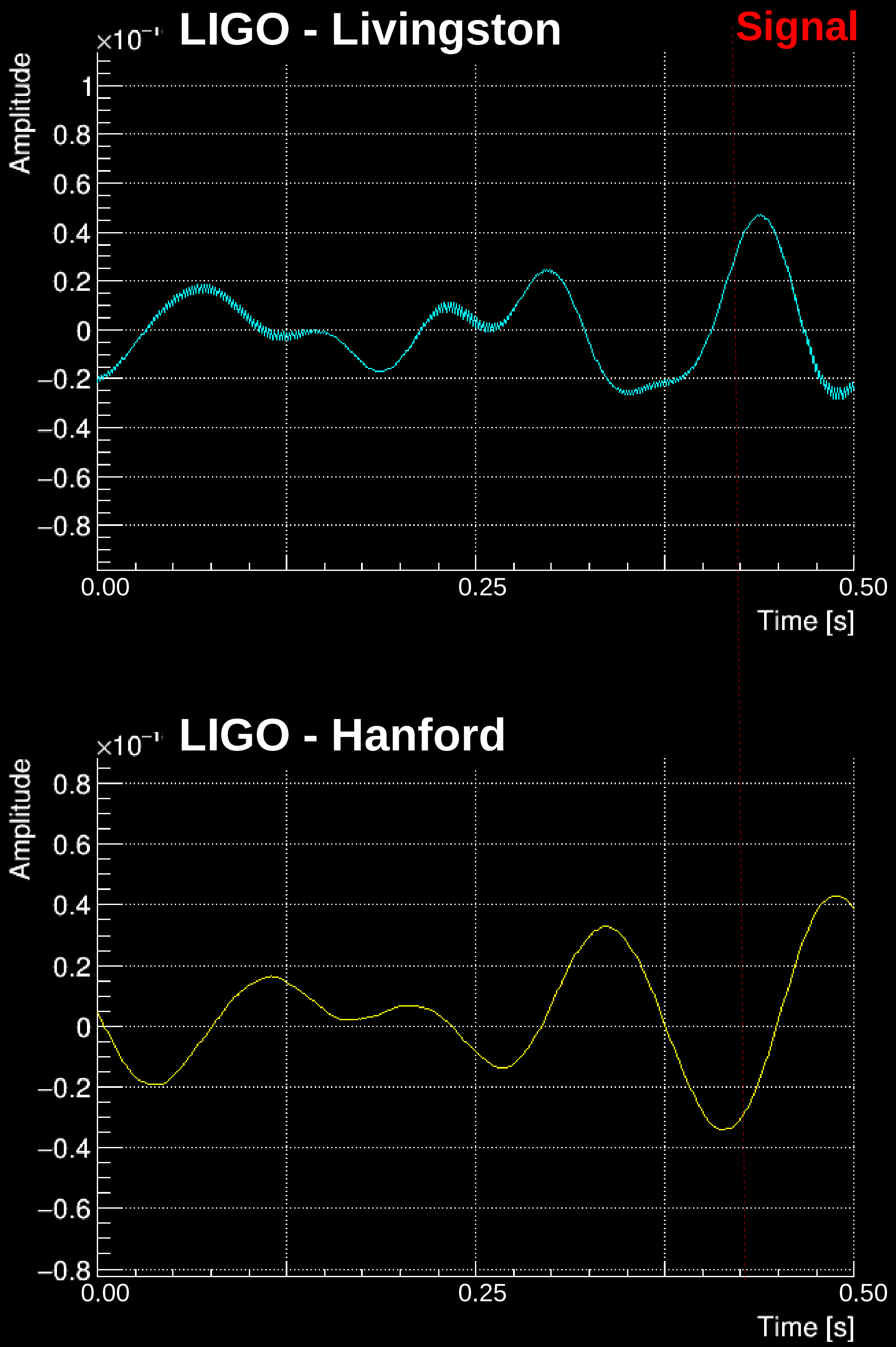
→ GW strain amplitude *h(t)*

(including high-pass filter f > 10 Hz)

$h(t)$

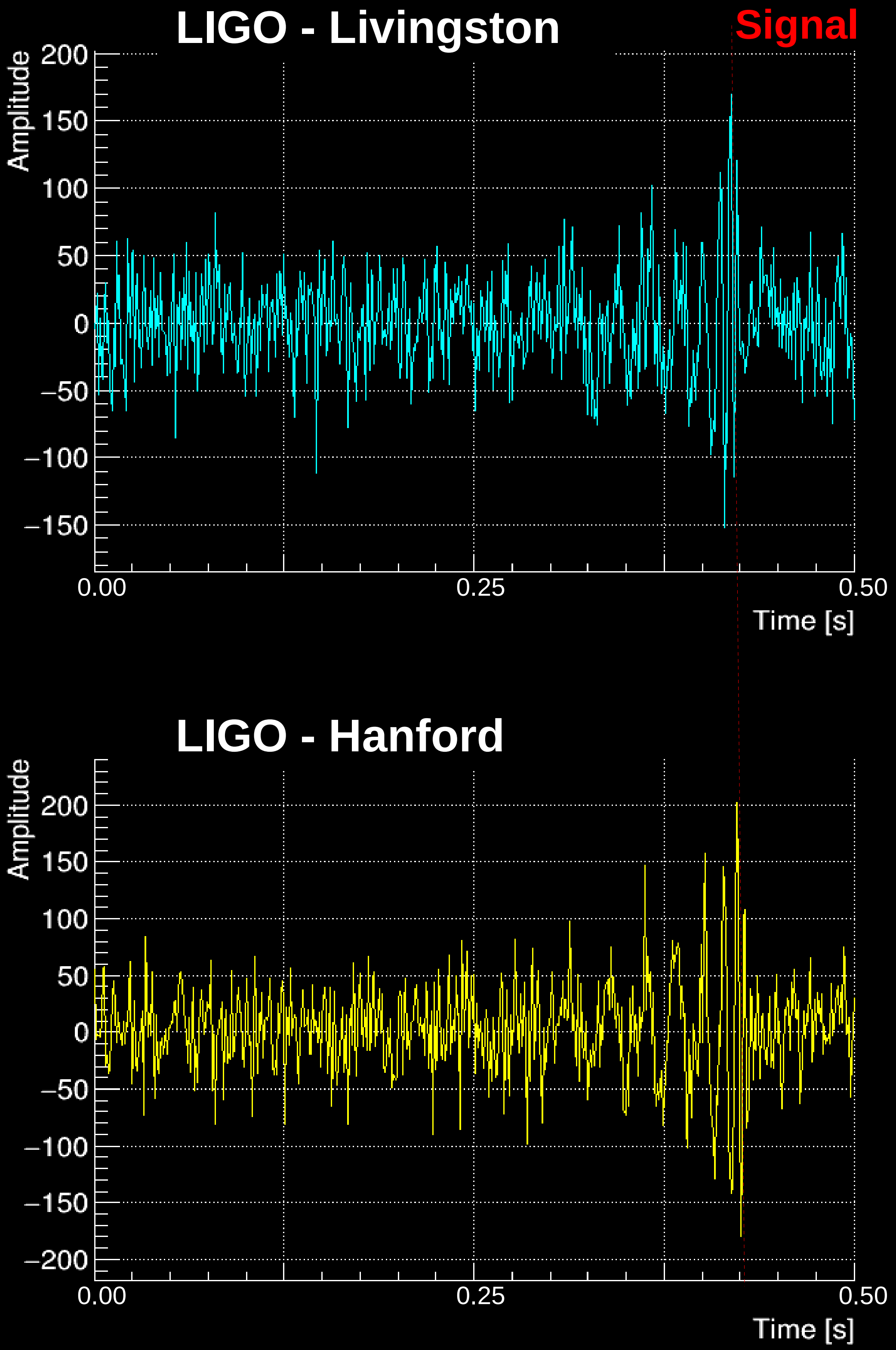

LIGO - Hanford

GW150914



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

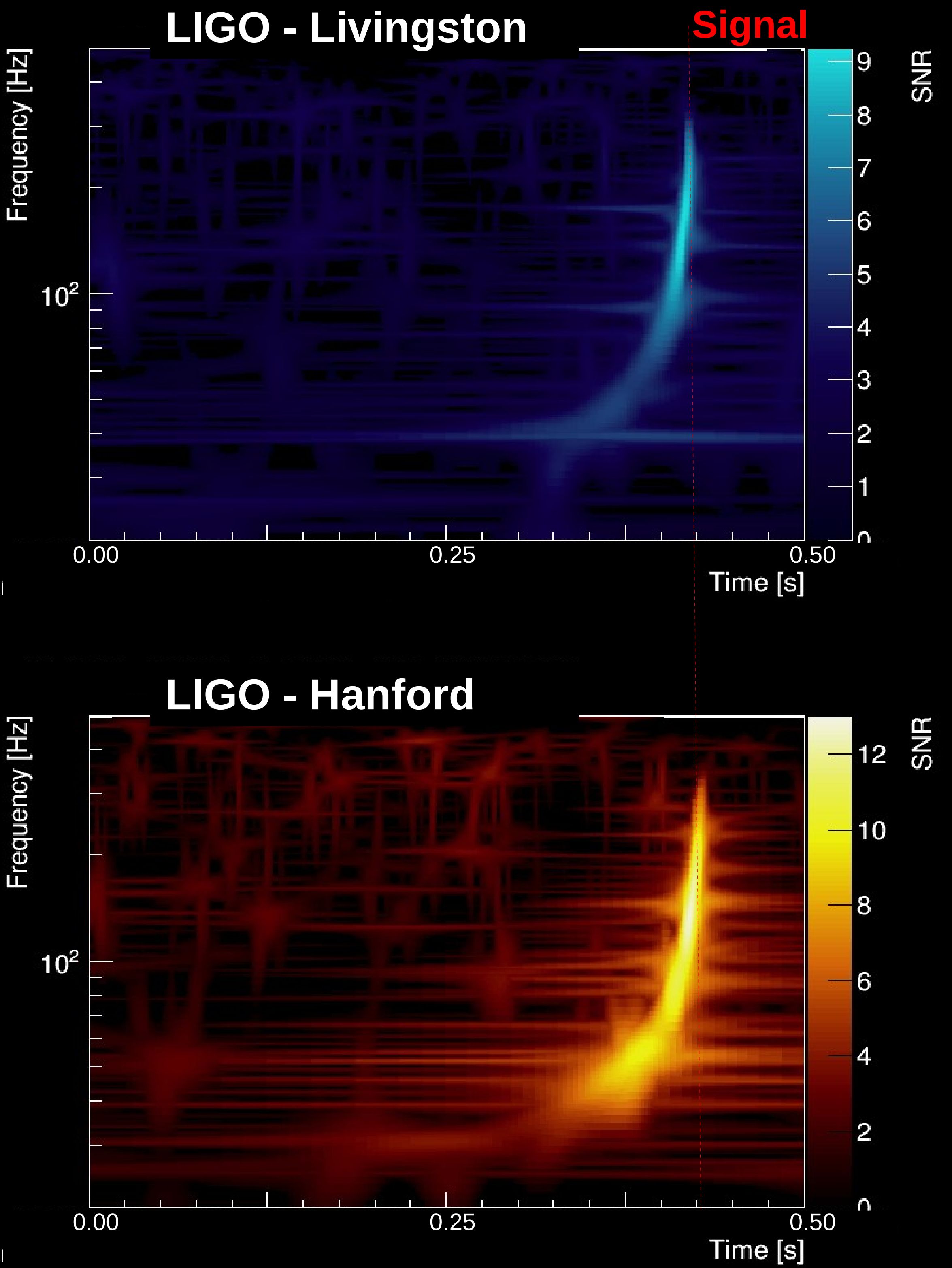
GW150914



Data are whitened

GW150914

Time-frequency decomposition
(Short Fourier transforms)



Match-filtering

Known waveform → matched-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 : $h_{det}(t) = \delta(t) \Rightarrow C(t) = k(t)$

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

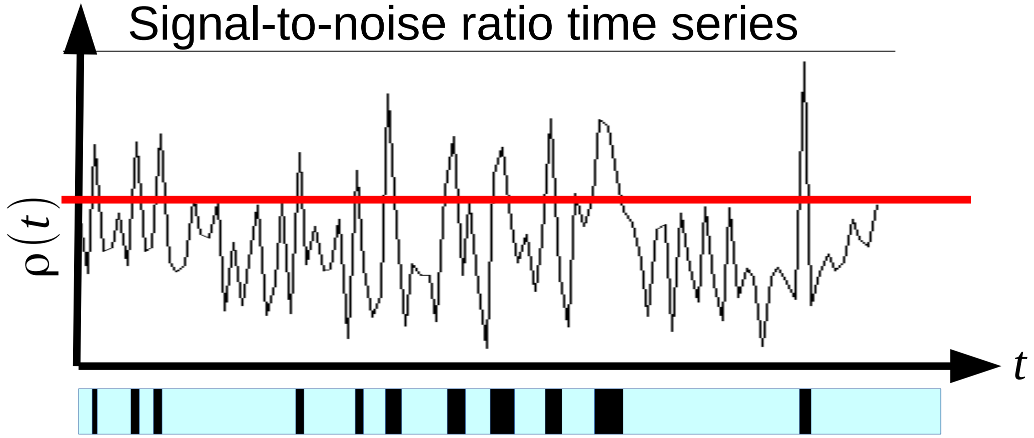
$$h_{det}(t) = n(t) + GW(t)$$

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

The SNR is maximized if $\tilde{k}(f) \propto \frac{\tilde{GW}^*(f)}{S_n(f)}$

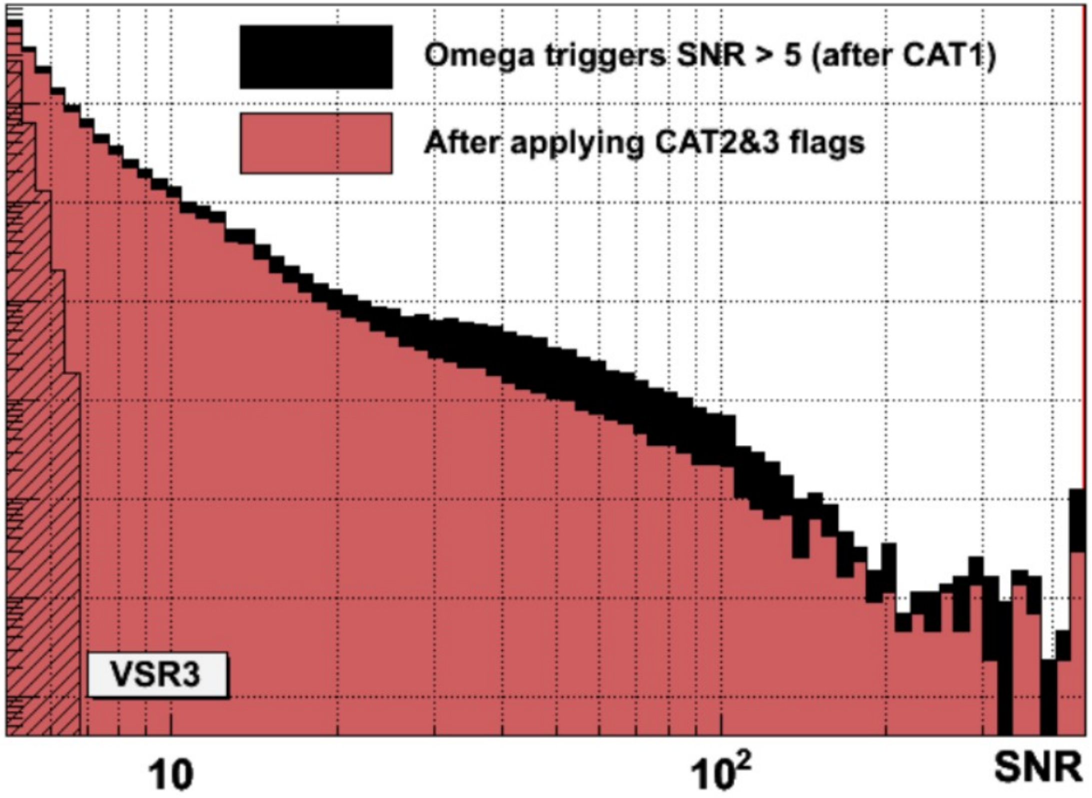
$$\rho(t) = \int_{-\infty}^{+\infty} \frac{\tilde{GW}^*(f)\tilde{h}_{det}(f)}{S_n(f)} e^{2i\pi ft}df$$

Transient searches : triggers



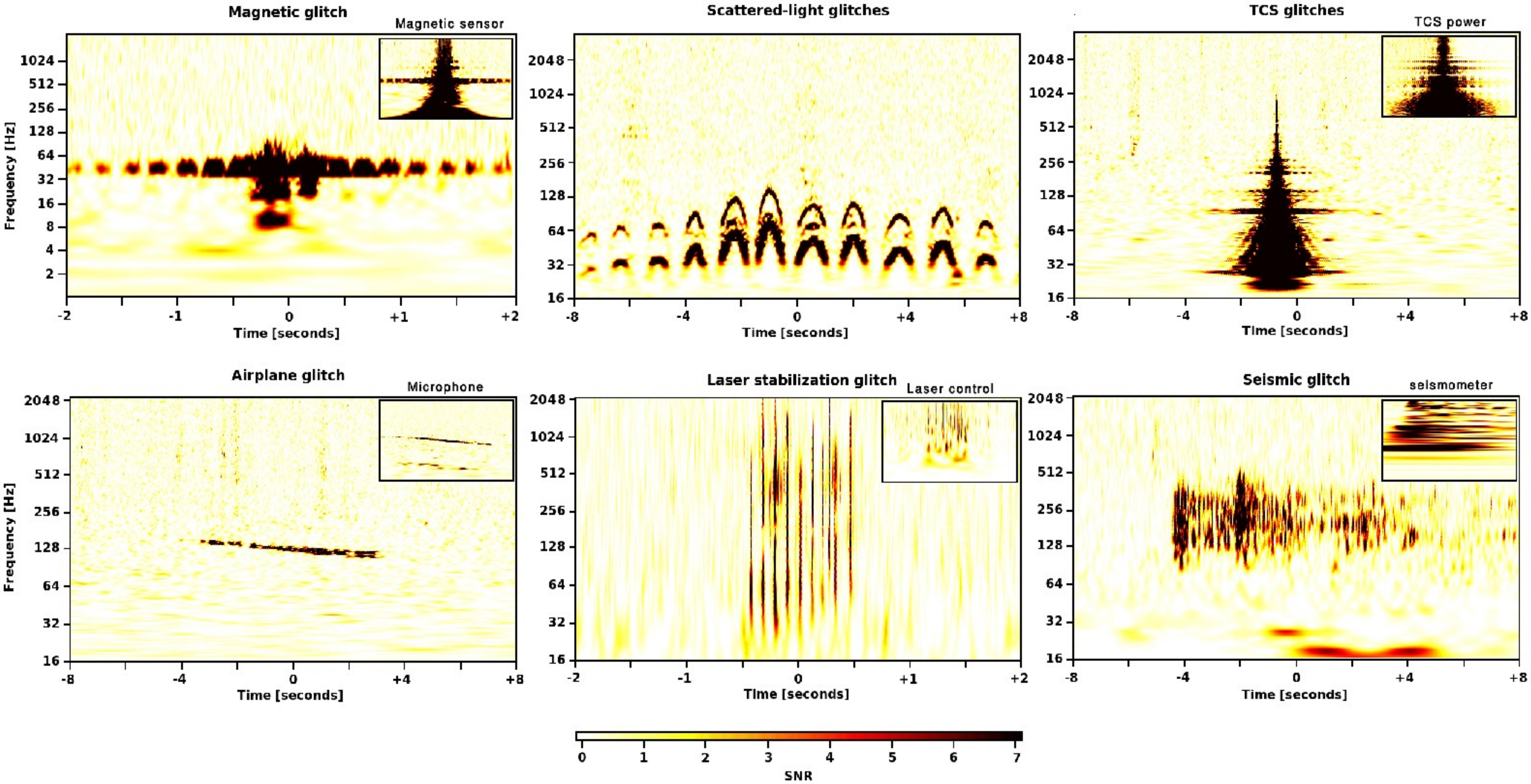
A list of events is produced:
– start/end/peak times
– SNR
– template parameters (masses, spins)

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

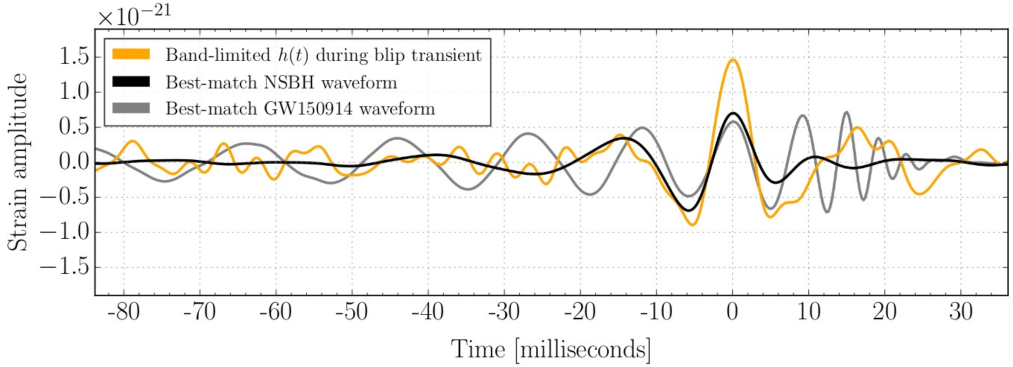


The noise distribution is highly non-Gaussian !

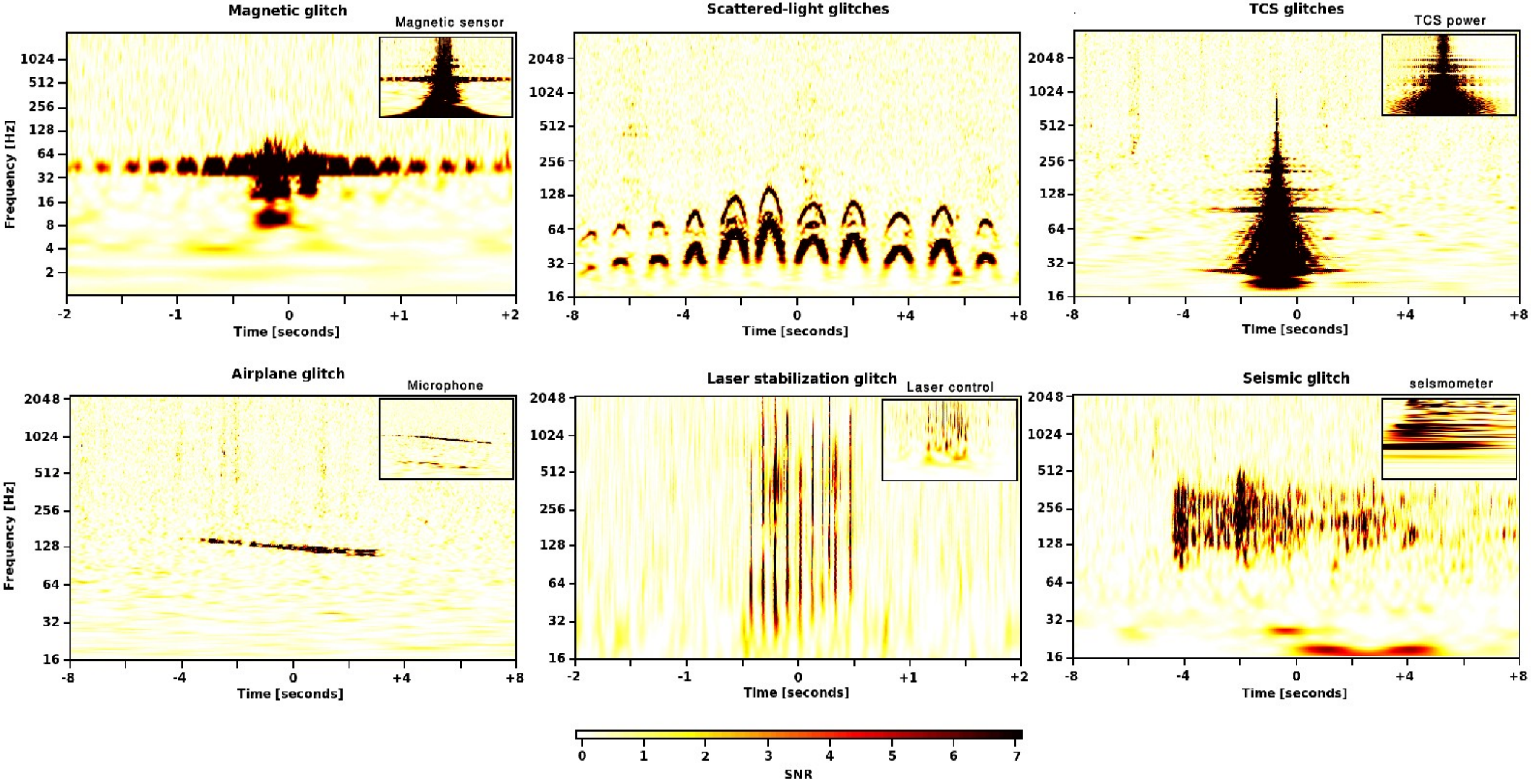
Transient searches : “glitches”



Glitches can mimic the characteristics of a true signal



Transient searches : “glitches”



Thousands of auxiliary channels are used to monitor the instruments and witness glitches

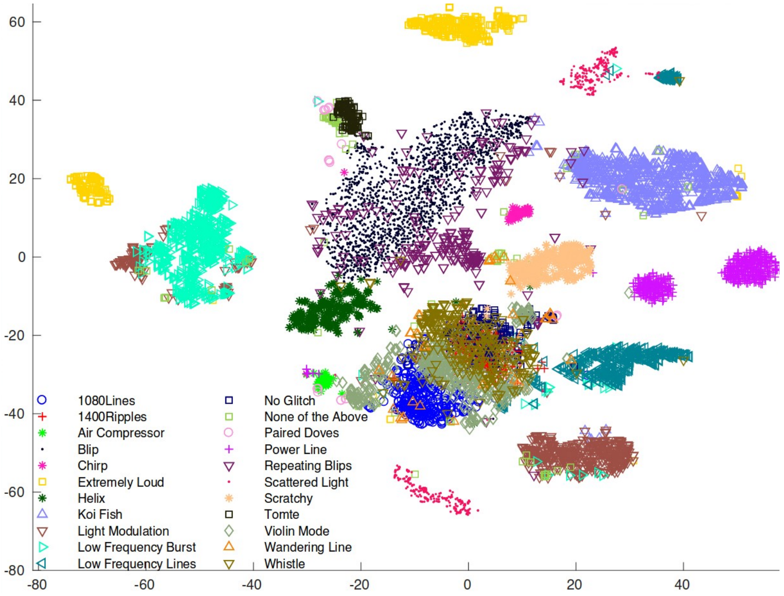
– environmental sensors

– detector sub-systems

– detector control

→ Data quality flags to veto glitches

Transient searches : glitch classification



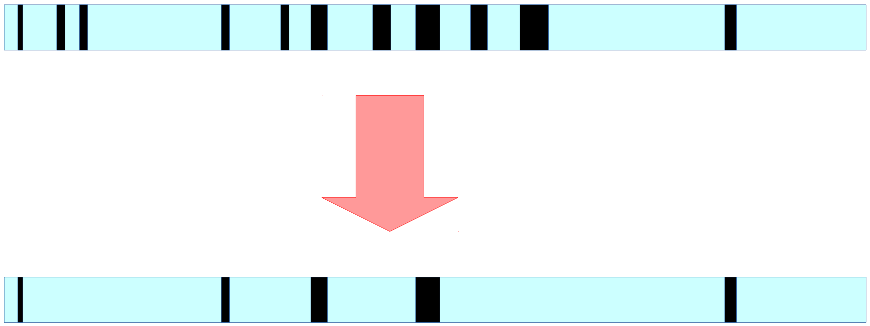
→ t-distributed stochastic neighbor embedding (t-SNE) for reducing high-dimensional data into a space of two or three dimensions

→ Identifies clustering of glitches based on morphology, and similarity between differing glitch types

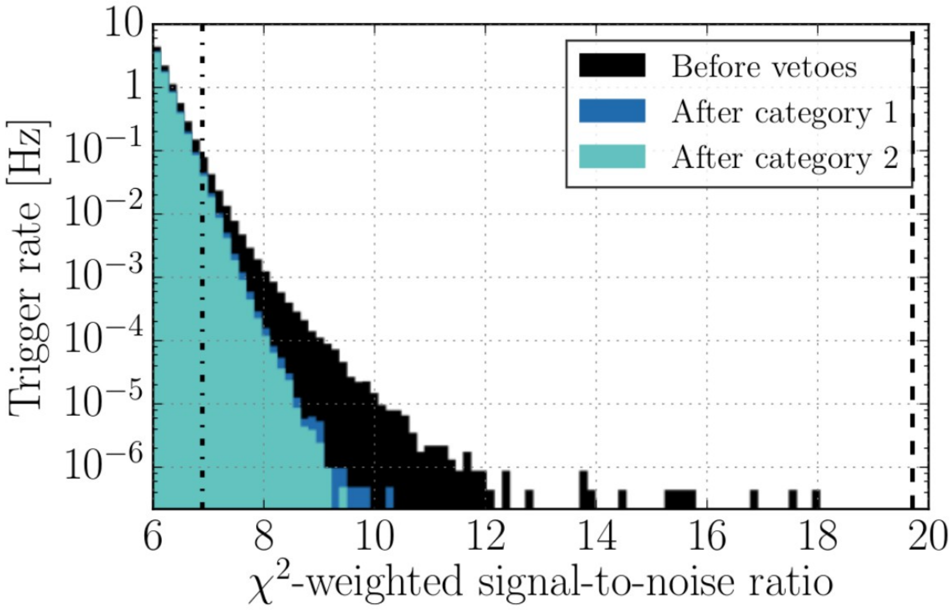
Citizen project ”GravitySpy”
(https://www.zooniverse.org/projects/zooniverse/gravity-spy)

Ongoing efforts of MLA to classify and reject glitches
→ See Agata Trovato’s talk

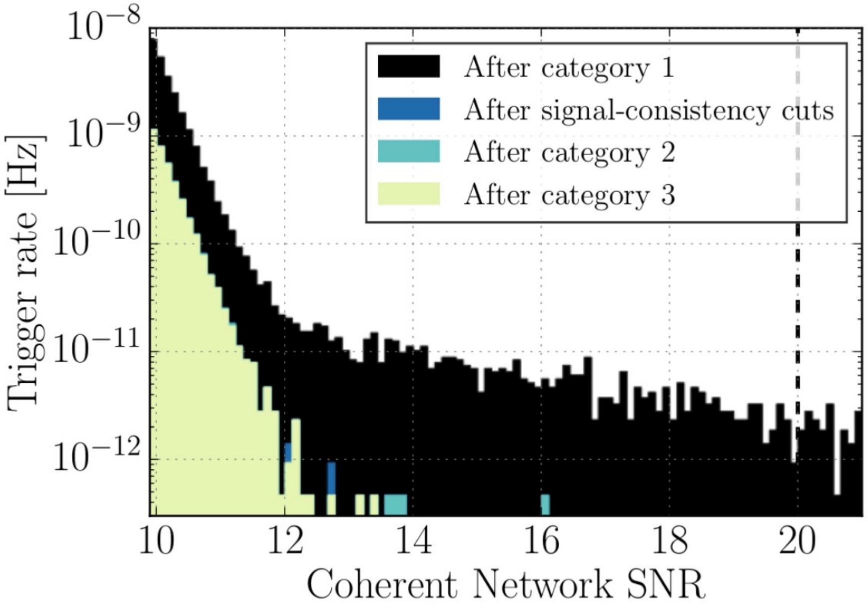
Transient searches : vetoes



CBC search



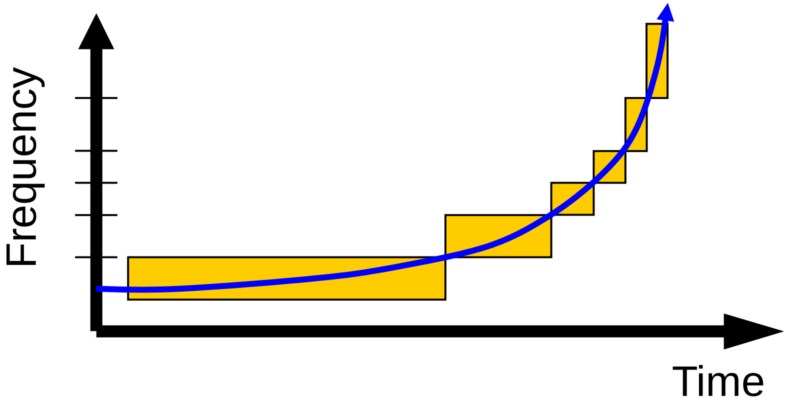
Burst search



CBC searches : waveform consistency test

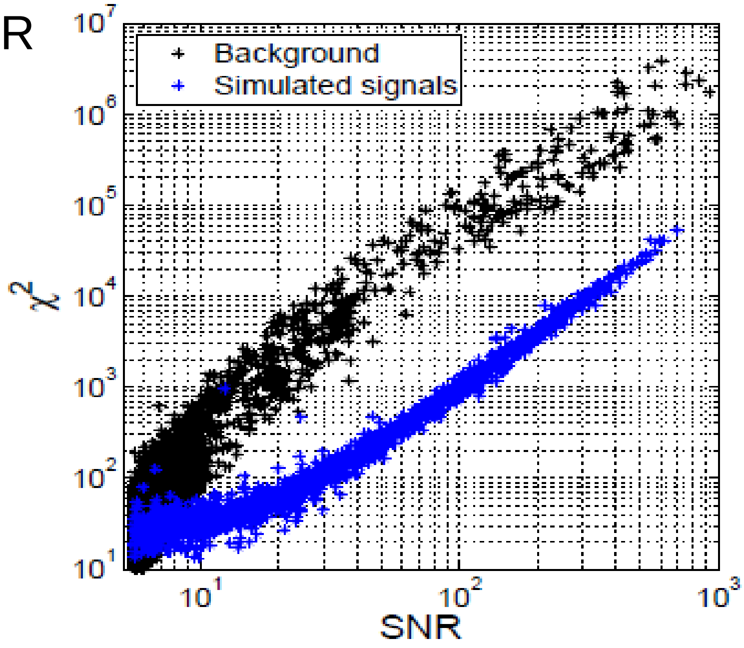
- Divide the “selected” template into p parts
- The frequency intervals are chosen so that for a true signal, the SNR is uniformly shared among the frequency bands.

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



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

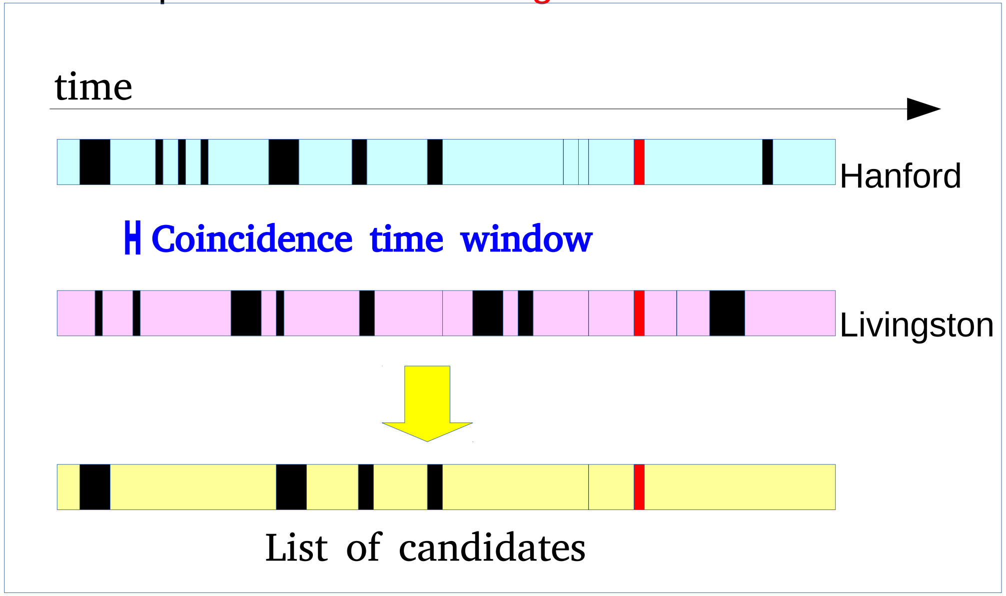
$$\rho_{\rm new} = \begin{cases} \rho, & \chi^2 \leq n_{\rm dof} \\ \dfrac{\rho}{\left[\left(1 + \frac{\chi^2}{n_{dof}}^{4/3}\right)/2\right]^{1/4}}, & \chi^2 > n_{\rm dof} \end{cases}$$



Coincidence between detectors

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

True experiment = noise + signal



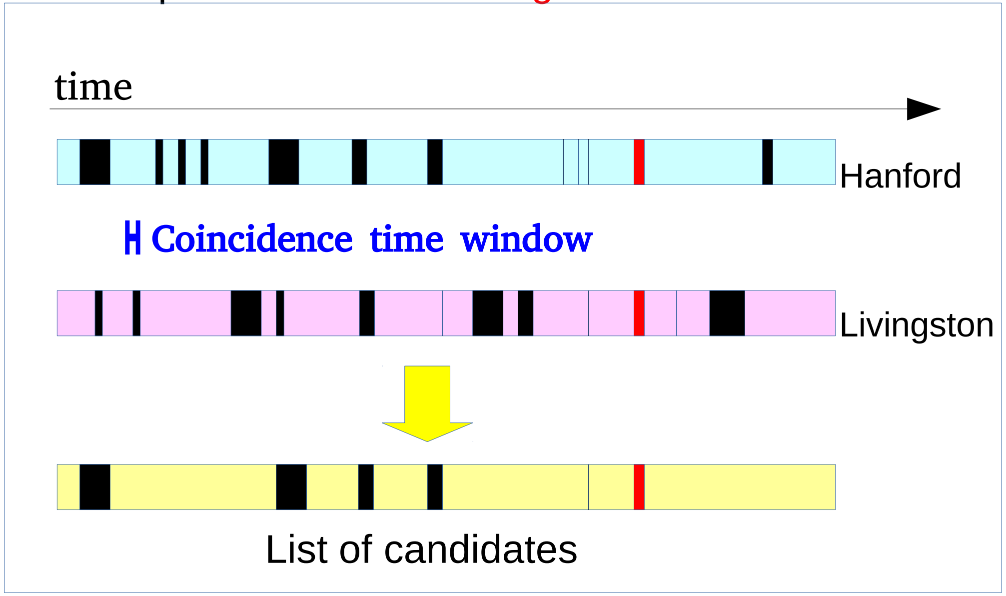
Coincidence rate:

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

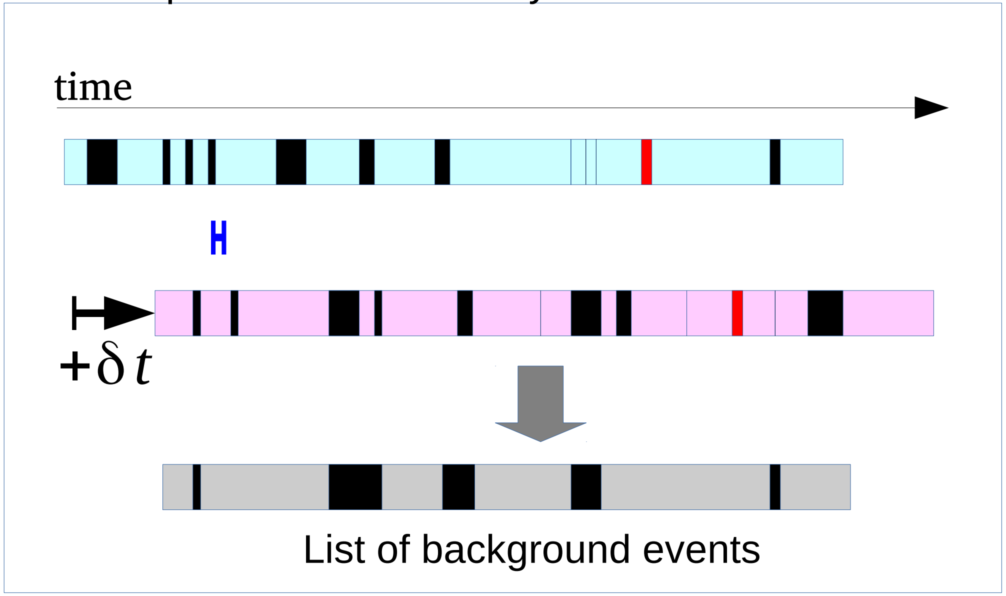
Background estimation

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

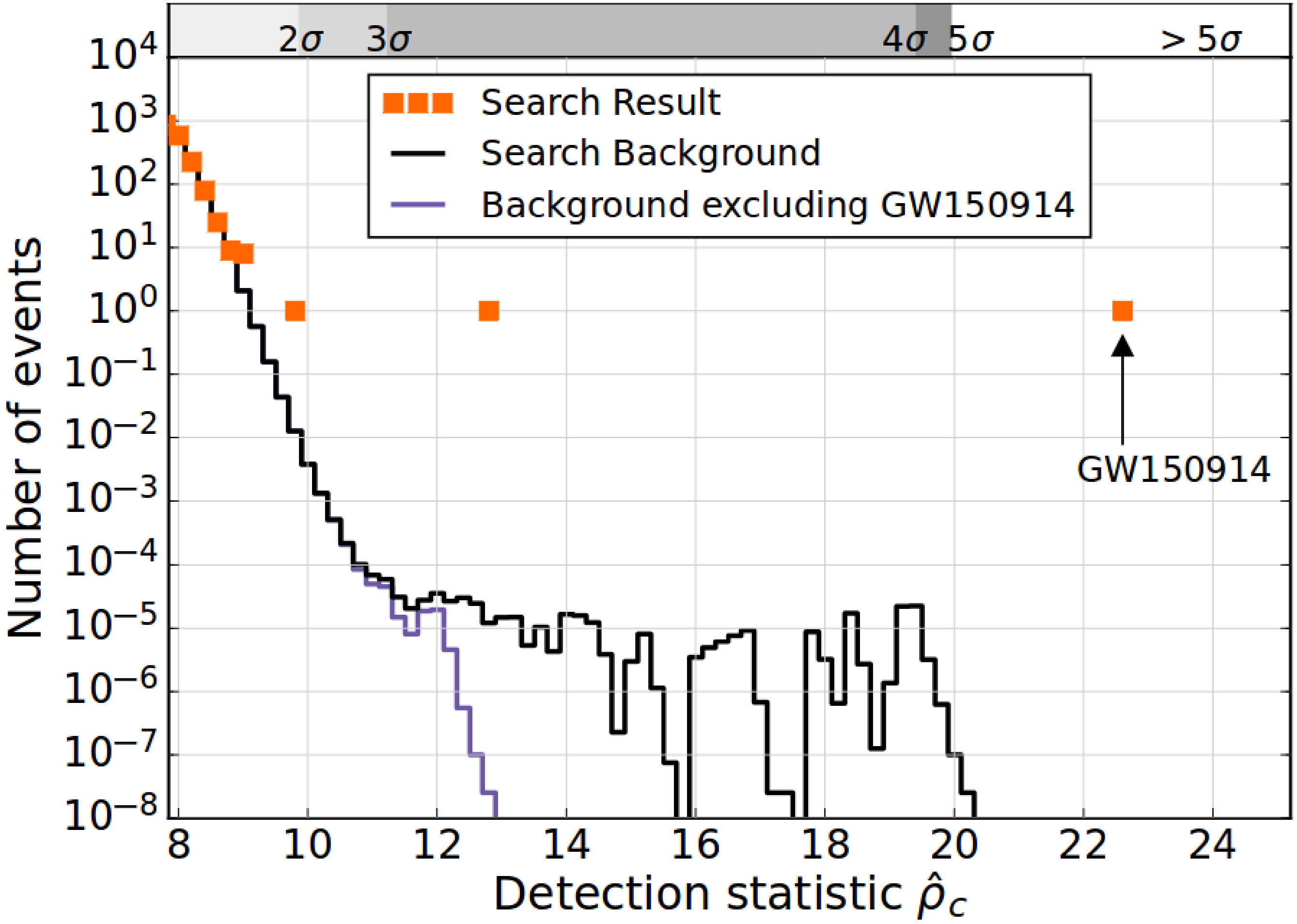


A very large number of fake experiments can be simulated using multiple offsets

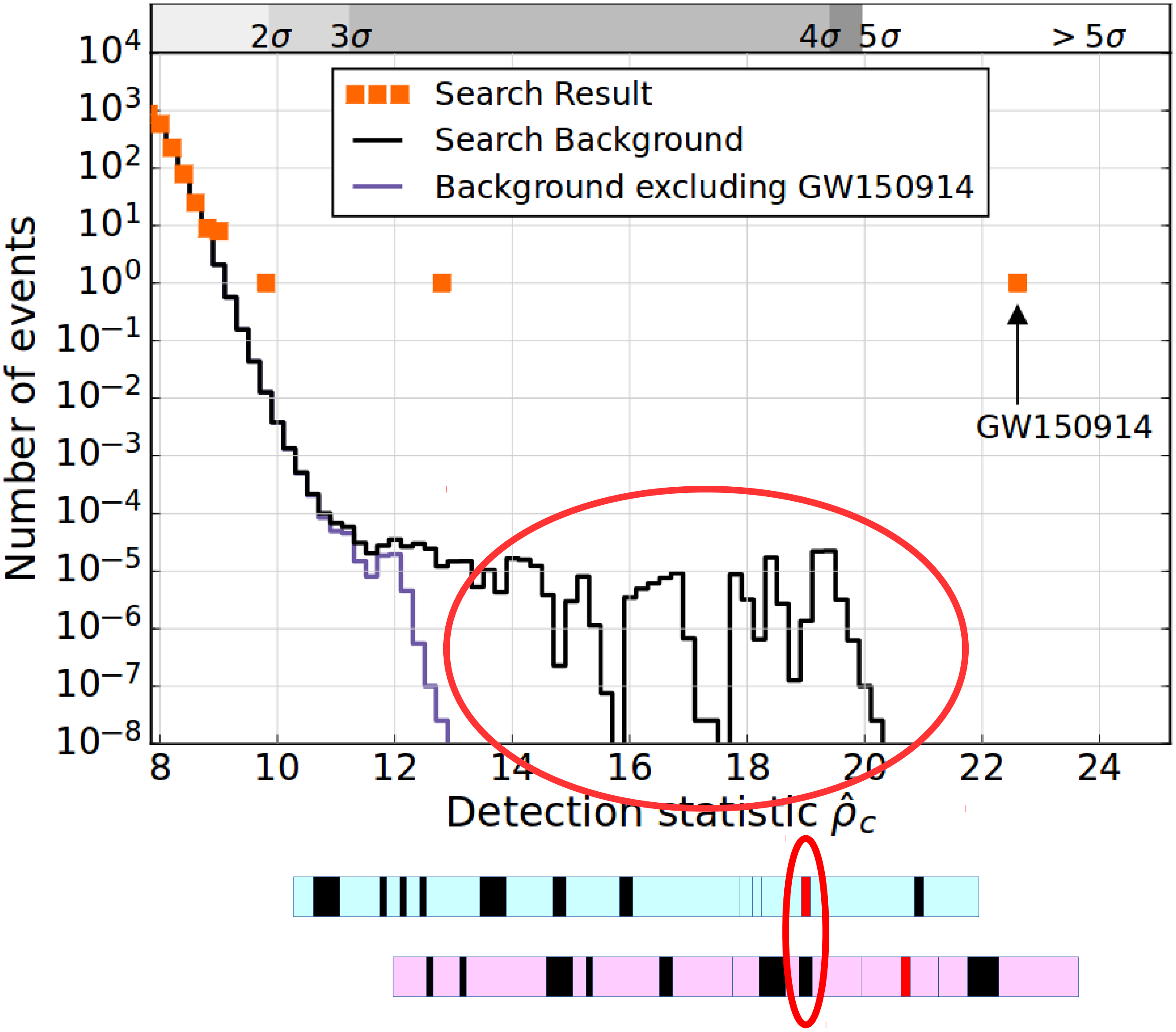
LIGO O1 analysis:
– O(10^6) time offsets

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

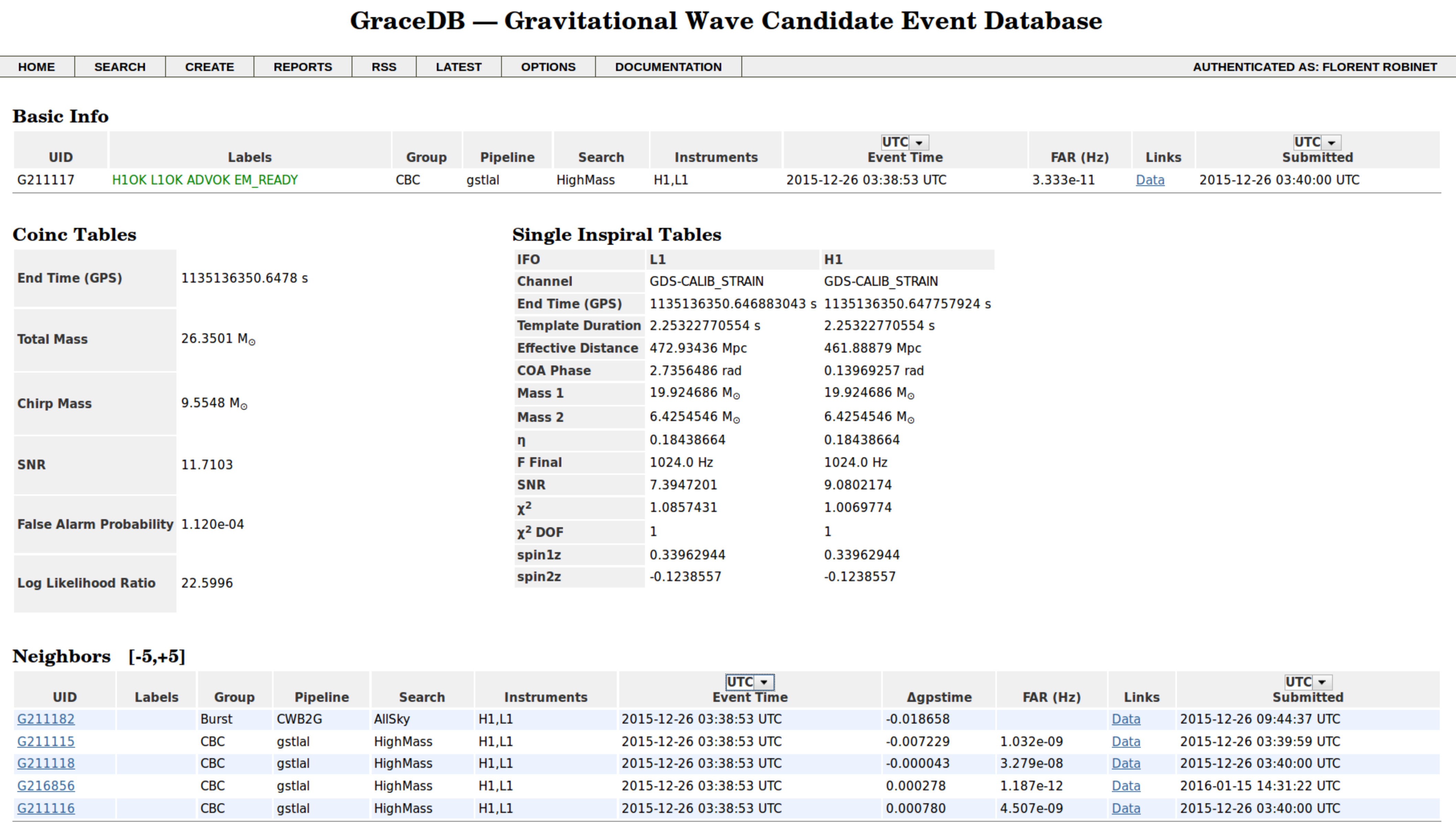
Event significance



Event significance



Online searches



GraceDB — Gravitational Wave Candidate Event Database

Basic Info

UID	Labels	Group	Pipeline	Search	Instruments	UTC ▾ Event Time	FAR (Hz)	Links	UTC ▾ Submitted
G211117	H1OK L1OK ADVOK EM_READY	CBC	gstlal	HighMass	H1,L1	2015-12-26 03:38:53 UTC	3.333e-11	Data	2015-12-26 03:40:00 UTC

Coinc Tables

End Time (GPS)	1135136350.6478 s
Total Mass	26.3501 $M_{\odot}$
Chirp Mass	9.5548 $M_{\odot}$
SNR	11.7103
False Alarm Probability	1.120e-04
Log Likelihood Ratio	22.5996

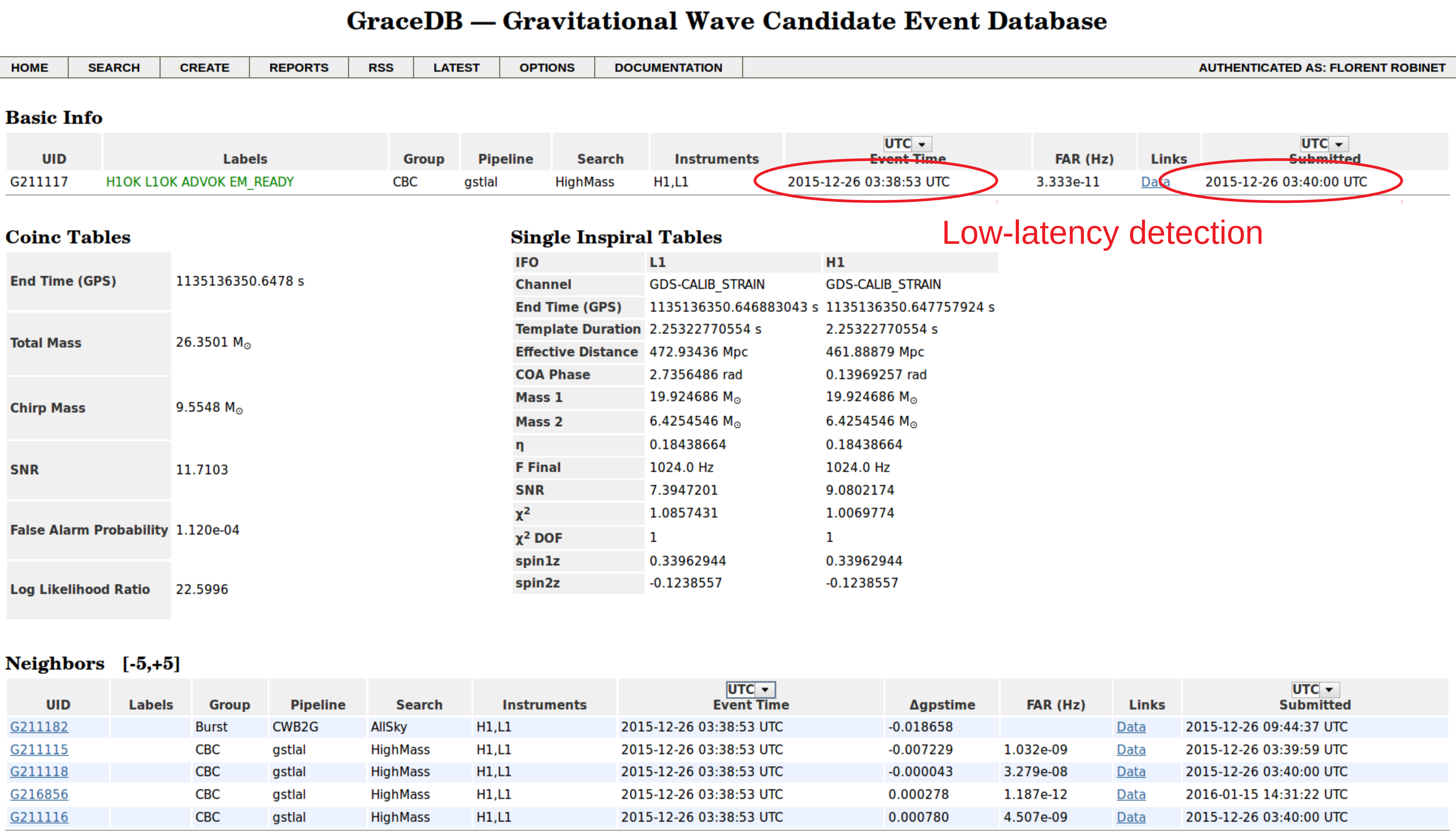
Single Inspiral Tables

IFO	L1	H1
Channel	GDS-CALIB_STRAIN	GDS-CALIB_STRAIN
End Time (GPS)	1135136350.646883043 s	1135136350.647757924 s
Template Duration	2.25322770554 s	2.25322770554 s
Effective Distance	472.93436 Mpc	461.88879 Mpc
COA Phase	2.7356486 rad	0.13969257 rad
Mass 1	19.924686 $M_{\odot}$	19.924686 $M_{\odot}$
Mass 2	6.4254546 $M_{\odot}$	6.4254546 $M_{\odot}$
η	0.18438664	0.18438664
F Final	1024.0 Hz	1024.0 Hz
SNR	7.3947201	9.0802174
χ^2	1.0857431	1.0069774
χ^2 DOF	1	1
spin1z	0.33962944	0.33962944
spin2z	-0.1238557	-0.1238557

Neighbors [-5,+5]

UID	Labels	Group	Pipeline	Search	Instruments	UTC ▾ Event Time	Δgpstime	FAR (Hz)	Links	UTC ▾ Submitted
G211182		Burst	CWB2G	AllSky	H1,L1	2015-12-26 03:38:53 UTC	-0.018658		Data	2015-12-26 09:44:37 UTC
G211115		CBC	gstlal	HighMass	H1,L1	2015-12-26 03:38:53 UTC	-0.007229	1.032e-09	Data	2015-12-26 03:39:59 UTC
G211118		CBC	gstlal	HighMass	H1,L1	2015-12-26 03:38:53 UTC	-0.000043	3.279e-08	Data	2015-12-26 03:40:00 UTC
G216856		CBC	gstlal	HighMass	H1,L1	2015-12-26 03:38:53 UTC	0.000278	1.187e-12	Data	2016-01-15 14:31:22 UTC
G211116		CBC	gstlal	HighMass	H1,L1	2015-12-26 03:38:53 UTC	0.000780	4.507e-09	Data	2015-12-26 03:40:00 UTC

Online searches



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G211118		CBC	gstlal	HighMass	H1,L1	2015-12-26 03:38:53 UTC	-0.000043	3.279e-08	Data	2015-12-26 03:40:00 UTC
G216856		CBC	gstlal	HighMass	H1,L1	2015-12-26 03:38:53 UTC	0.000278	1.187e-12	Data	2016-01-15 14:31:22 UTC
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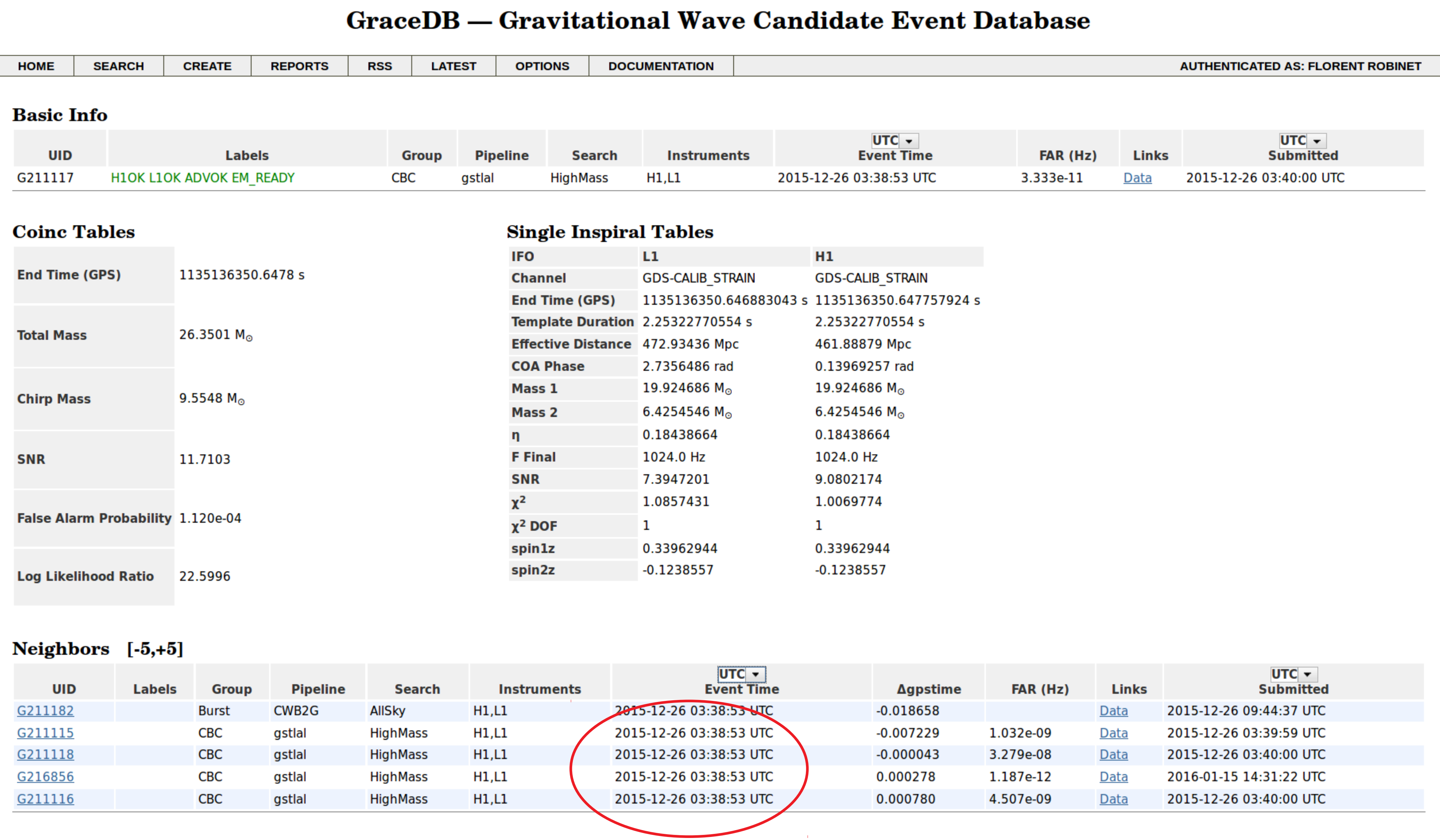
Online searches



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G211116		CBC	gstlal	HighMass	H1,L1	2015-12-26 03:38:53 UTC	0.000780	4.507e-09	Data	2015-12-26 03:40:00 UTC

Multiple triggers

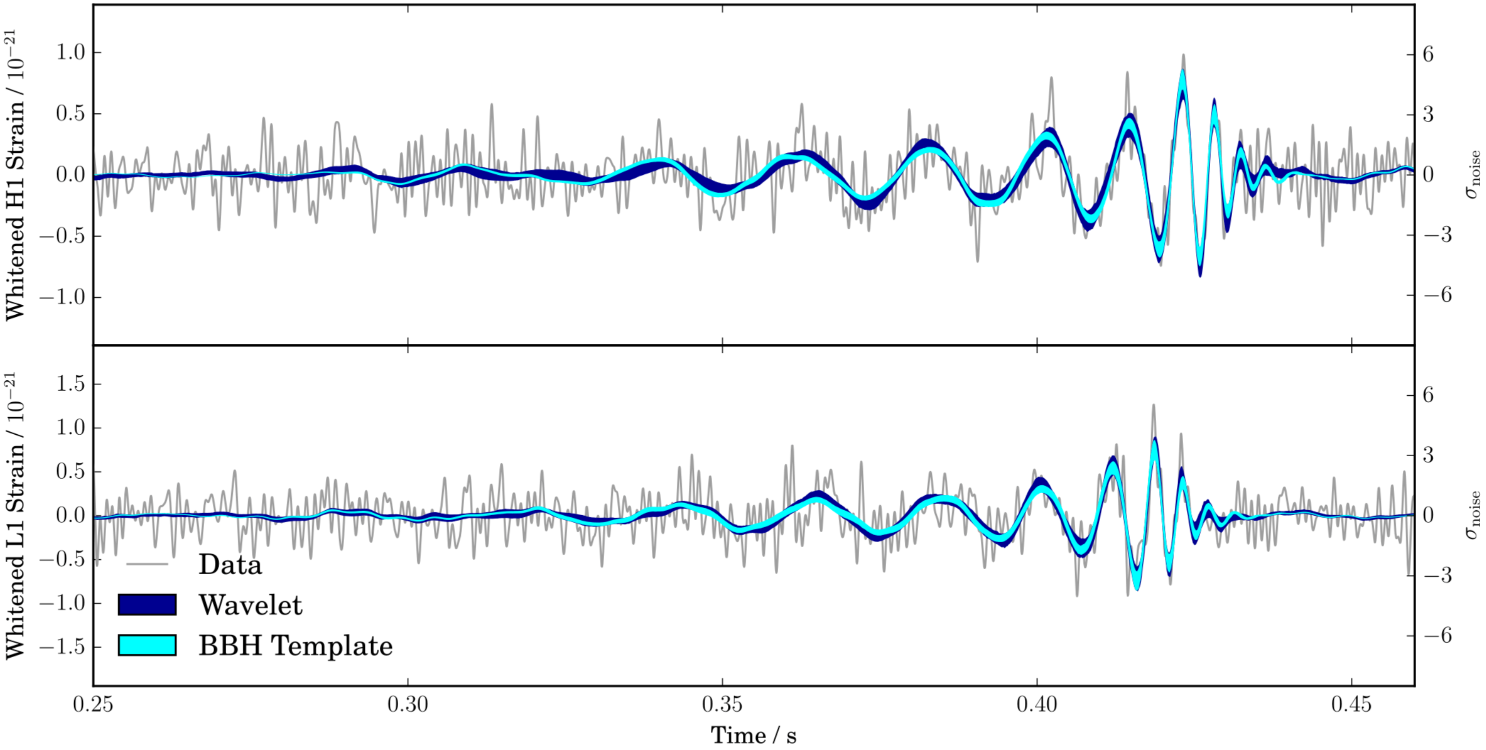
Parameter estimation

Full analysis of the data surrounding the event
→ only input from searches: time of the event
→ fully explore the parameter space
→ fully coherent search
→ 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)



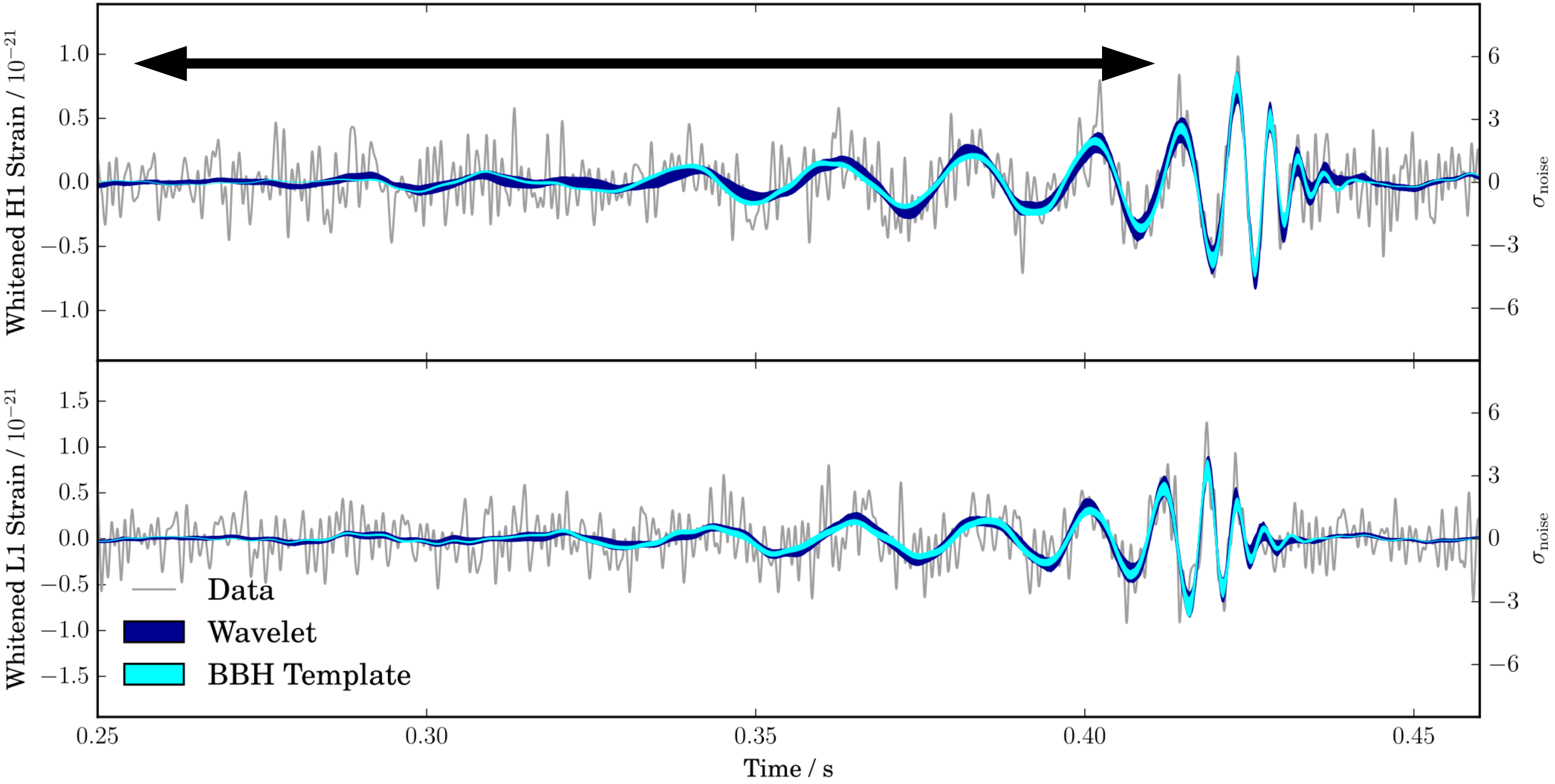
Parameter estimation

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

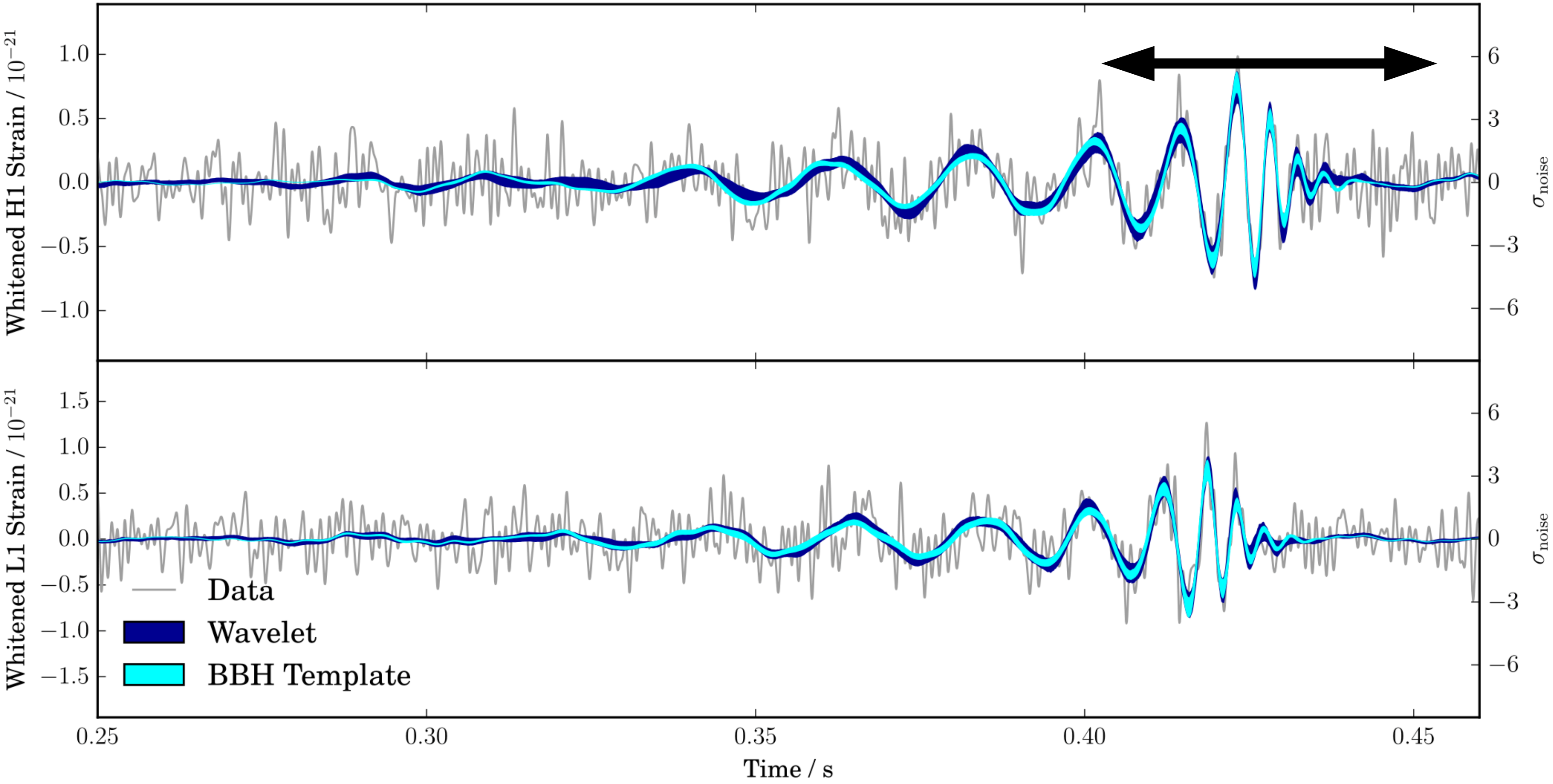


Parameter estimation

Late inspiral – merger – ringdown: numerical relativity waveforms

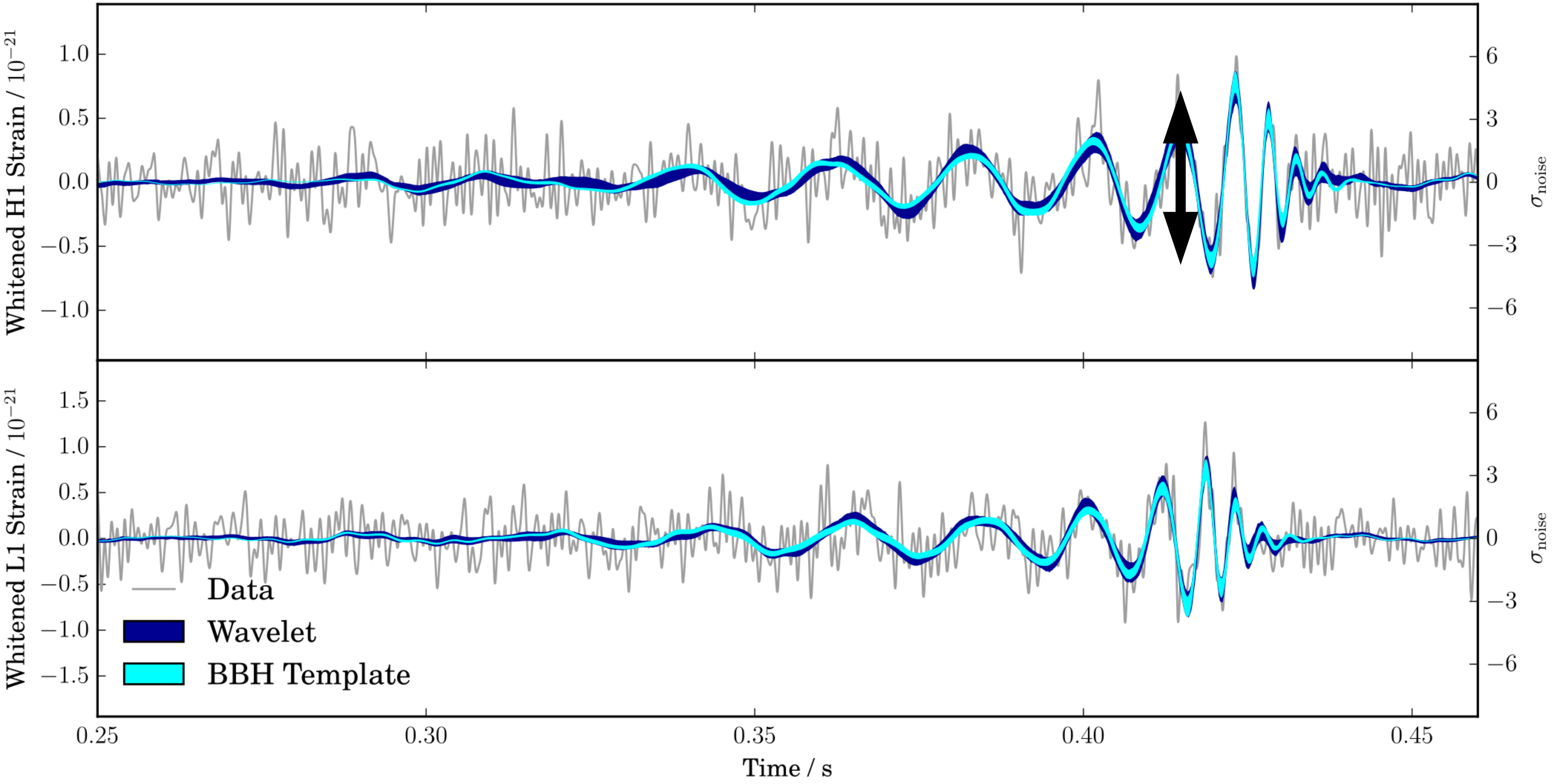
Late inspiral → total mass (+chirp mass + m1/m2) → individual masses

Ringdown → final BH mass and spin



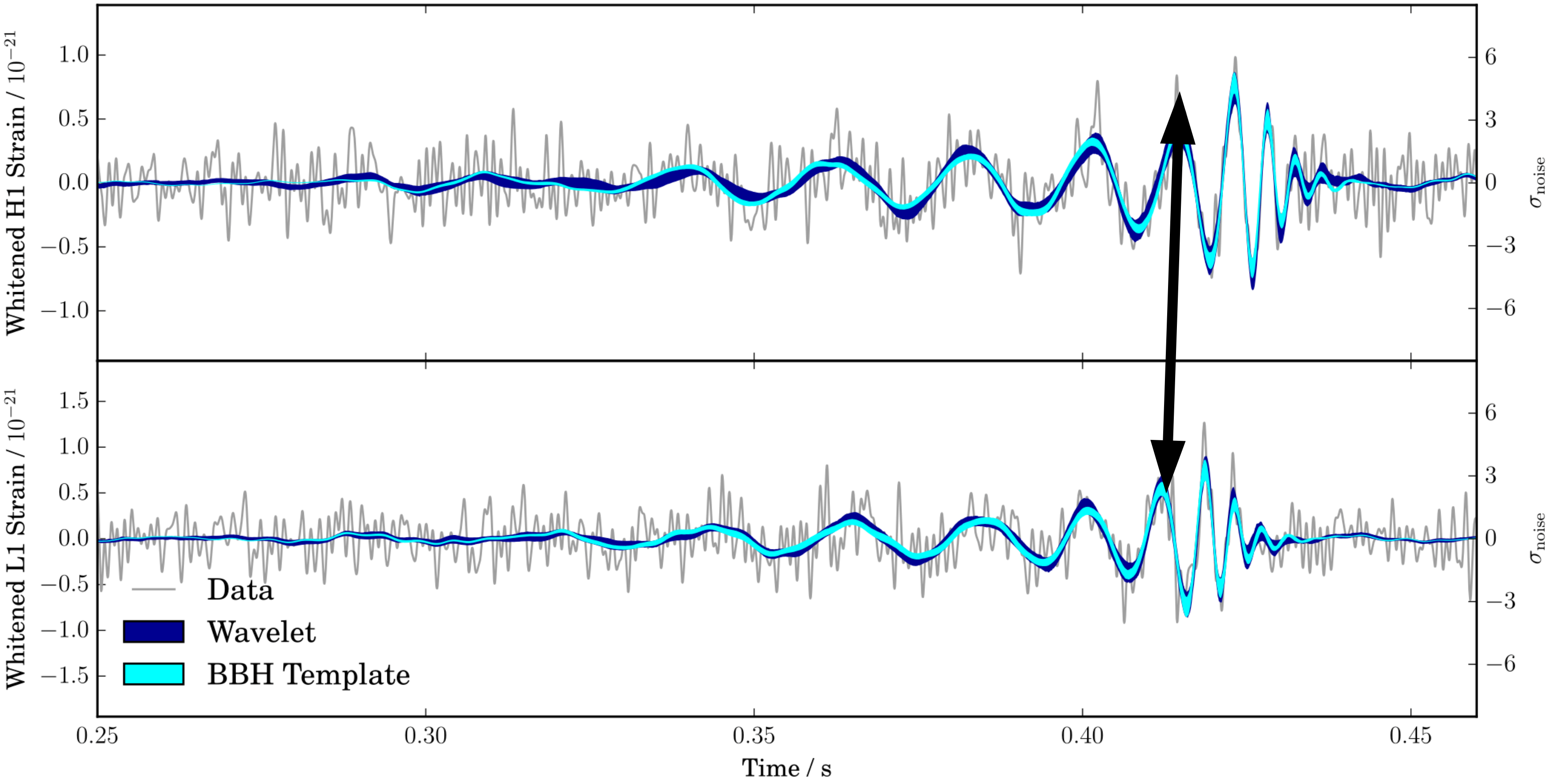
Parameter estimation

Amplitude: inversely proportional to the distance

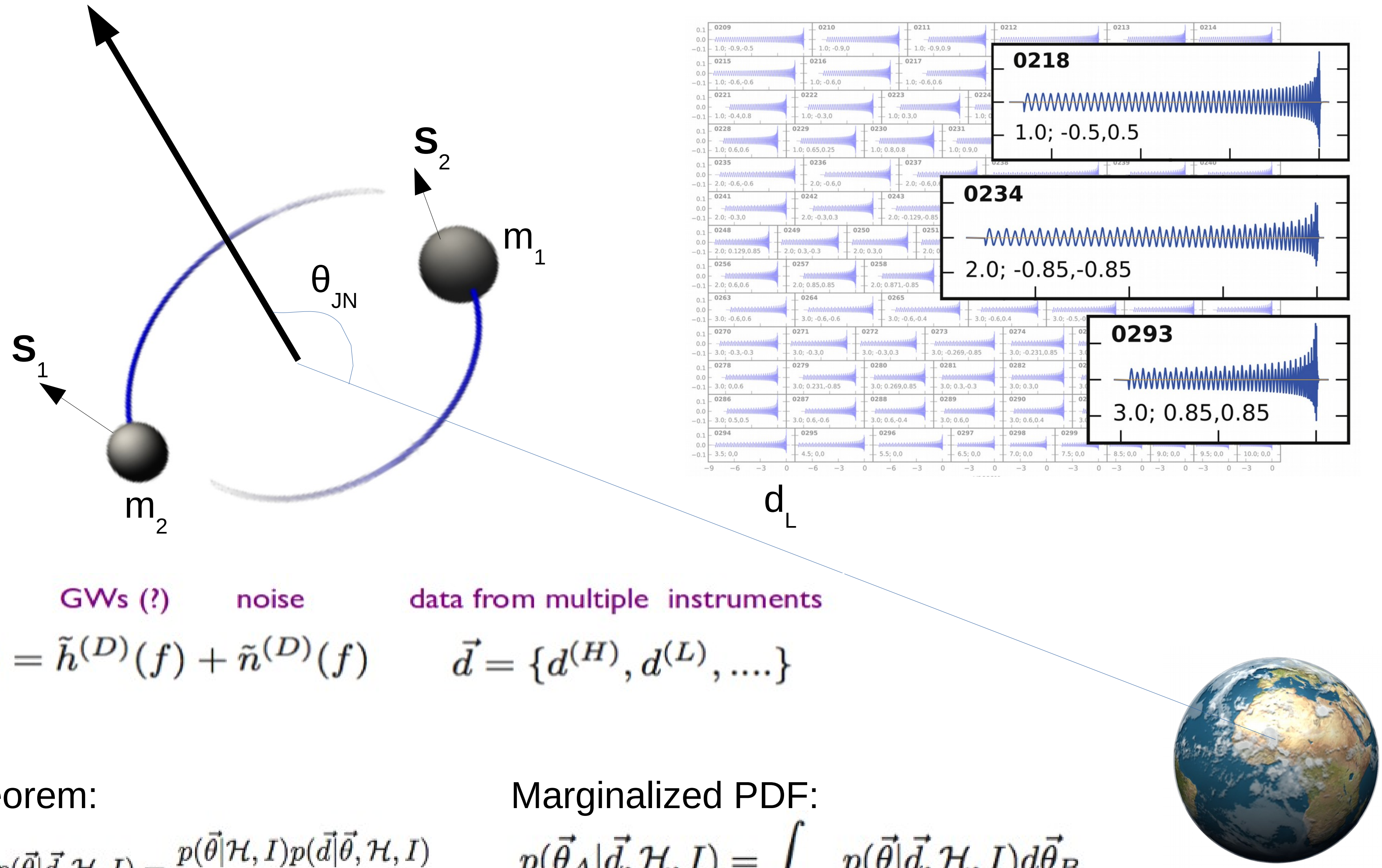


Parameter estimation

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



Parameter estimation



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:

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

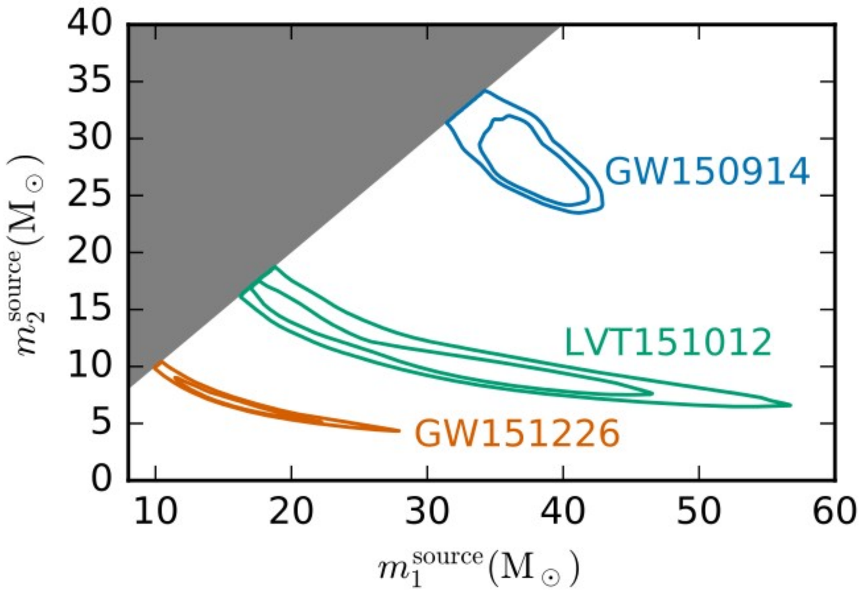
posterior prior likelihood

Marginalized PDF:

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

→ Marc Arène’s talk

Parameter estimation : ex. masses



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

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

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

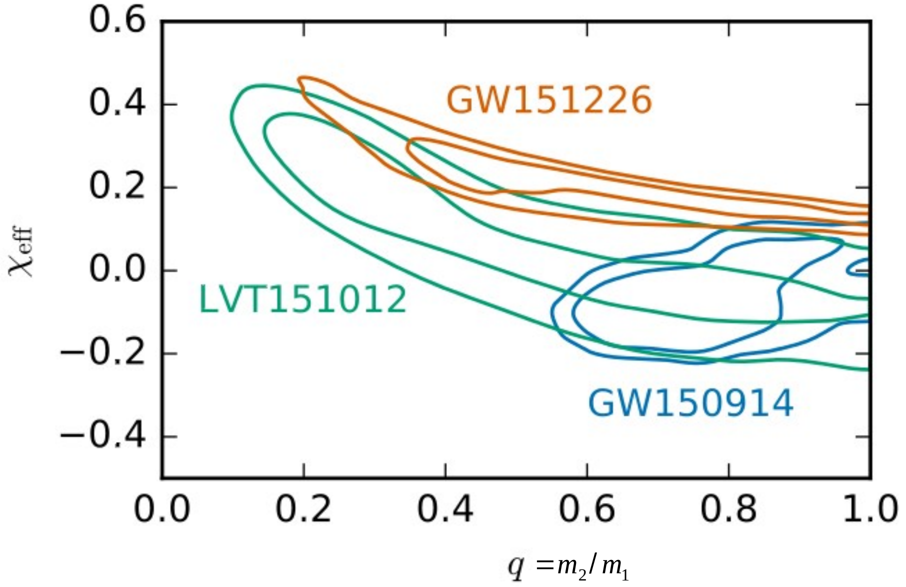
GW151226

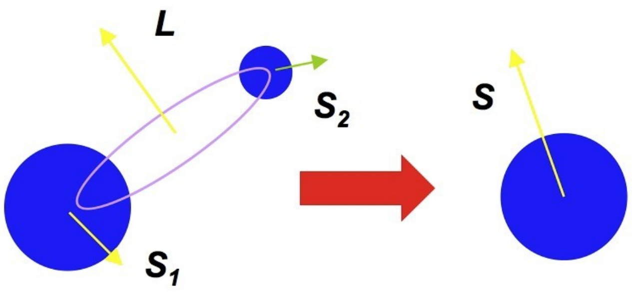
$$m_1 = 14.2^{\%+8.3}_{-3.7} M_{sun}$$

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

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

Parameter estimation : ex. spins





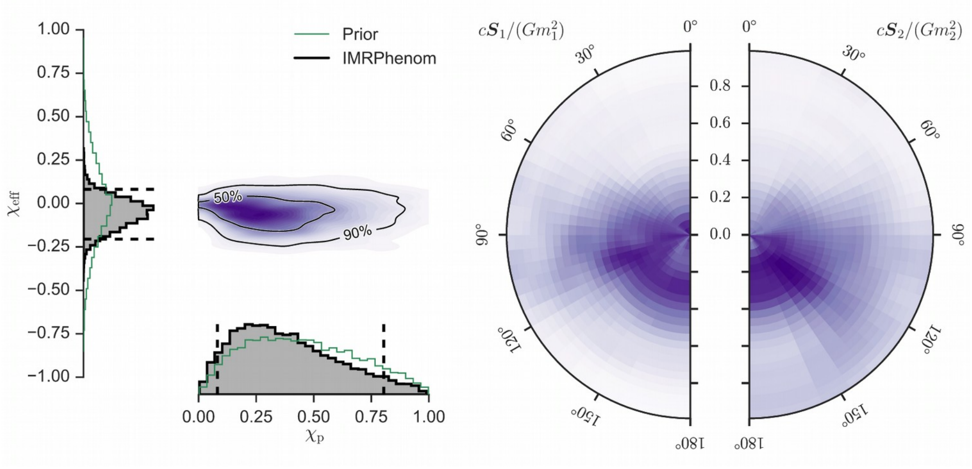
$$\chi_{eff}=\frac{m_1 a_{1z}+m_2 a_{2z}}{m_1+m_2}$$

→ not well constrained

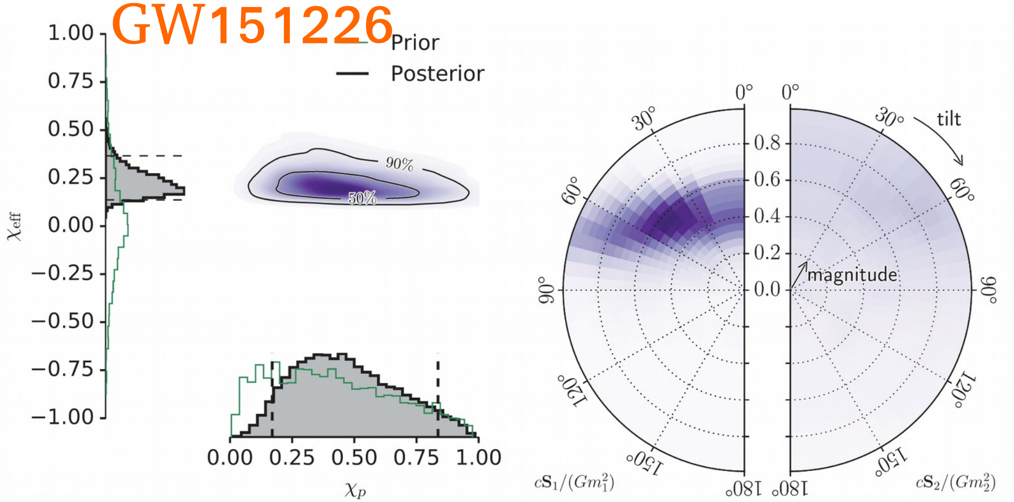
GW151226: at least one black hole is a Kerr black hole
spin >**0.2**

Uninformative about precession

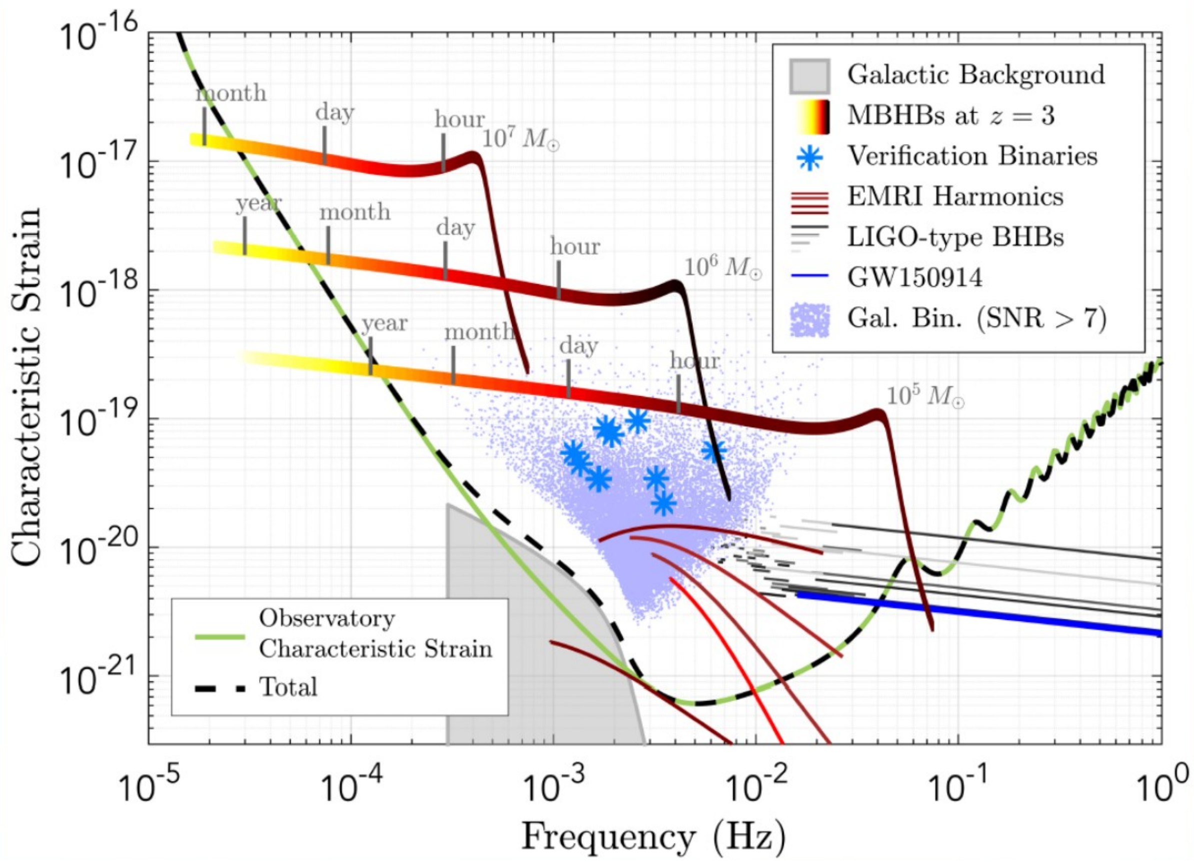
GW150914



GW151226



Signal-dominated analysis → LISA



→ 6 x10^7 galactic binaries

→ 10-100/year super-massive black hole binaries

→ 10-1000/year extreme mass ratio inspirals

→ large number of stellar origin black hole binaries (LIGO/Virgo)

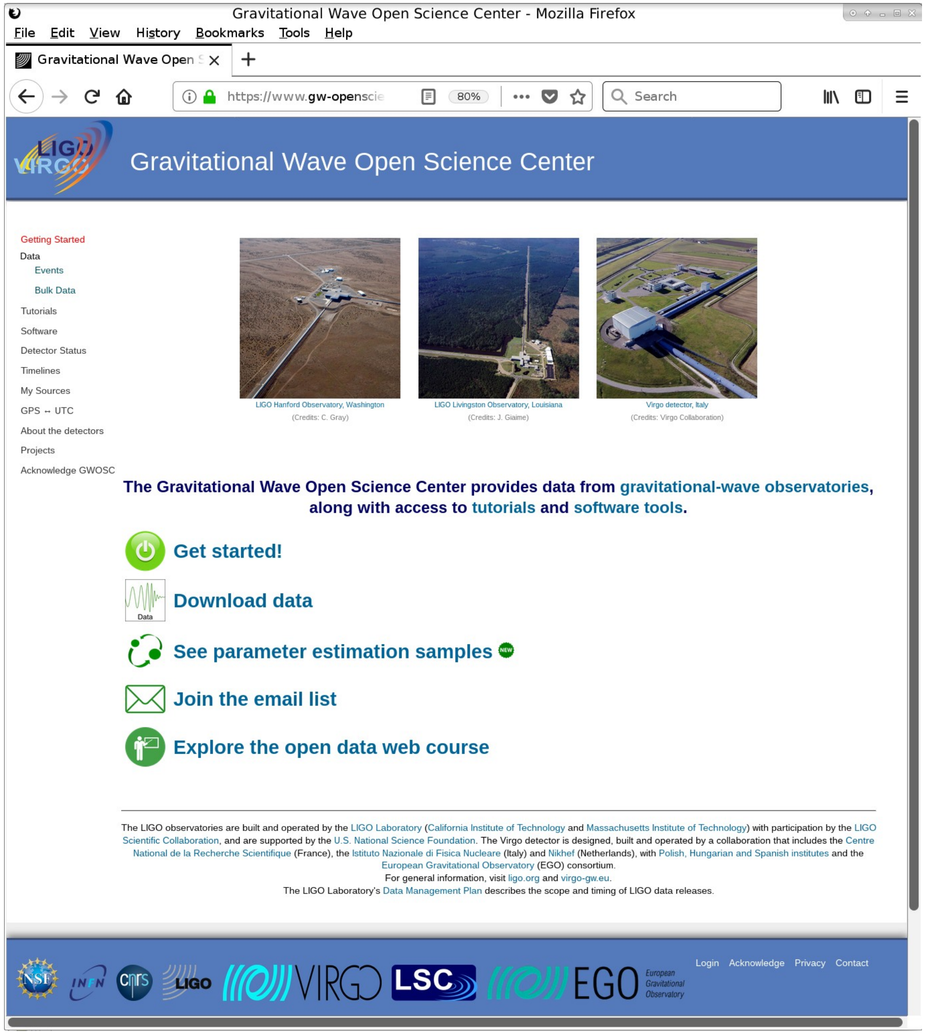
→ cosmological backgrounds

Challenge: physical background

→ See Nikolaos Karnesis’s talk

LIGO-Virgo open data

https://www.gw-openscience.org



Gravitational Wave Open Science Center - Mozilla Firefox

Gravitational Wave Open Science Center

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LIGO Hanford Observatory, Washington (Credits: C. Gray)

LIGO Livingston Observatory, Louisiana (Credits: J. Giaime)

Virgo detector, Italy (Credits: Virgo Collaboration)

The Gravitational Wave Open Science Center provides data from gravitational-wave observatories, along with access to tutorials and software tools.

- **Get started!**
- **Download data**
- **See parameter estimation samples** NEW
- **Join the email list**
- **Explore the open data web course**

The LIGO observatories are built and operated by the LIGO Laboratory (California Institute of Technology and Massachusetts Institute of Technology) with participation by the LIGO Scientific Collaboration, and are supported by the U.S. National Science Foundation. The Virgo detector is designed, built and operated by a collaboration that includes the Centre National de la Recherche Scientifique (France), the Istituto Nazionale di Fisica Nucleare (Italy) and Nikhef (Netherlands), with Polish, Hungarian and Spanish institutes and the European Gravitational Observatory (EGO) consortium.
For general information, visit ligo.org and virgo-gw.eu.
The LIGO Laboratory's Data Management Plan describes the scope and timing of LIGO data releases.

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LIGO Open Science Center

LIGO is operated by California Institute of Technology and Massachusetts Institute of Technology and supported by the U.S. National Science Foundation.

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Data Releases for Observed Transients

Data Releases: Compact Object Mergers

Click icons below for data and documentation:

Audio files

Listen to audio files from LIGO detections.

Rapid Triggers from LIGO Data

During O1 and O2, information about detected transients was shared [illegible] interested astronomers as GCN notices. This exchange is archived:

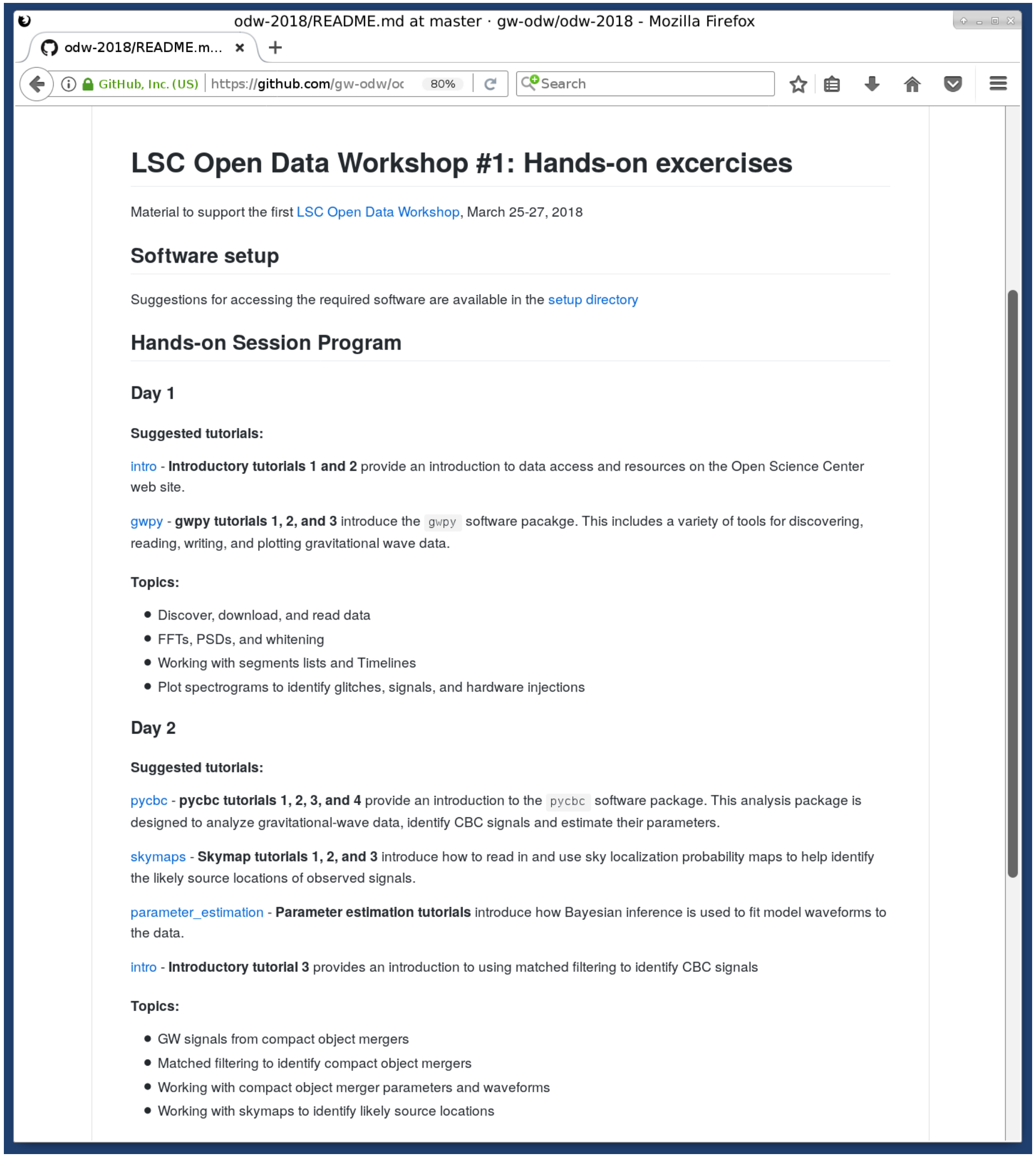
- GW150914
- LVT151012
- GW151226
- GW170104
- GW170608
- GW170814
- GW170817

~1 heure autour de
chaque événement
publié

LIGO-Virgo open data

https://www.gw-openscience.org

Online tutorials and hands-on exercises



LSC Open Data Workshop #1: Hands-on excercises

Material to support the first LSC Open Data Workshop, March 25-27, 2018

Software setup

Suggestions for accessing the required software are available in the setup directory

Hands-on Session Program

Day 1

Suggested tutorials:

intro - **Introductory tutorials 1 and 2** provide an introduction to data access and resources on the Open Science Center web site.

gwpy - **gwpy tutorials 1, 2, and 3** introduce the `gwpy` software pacakge. This includes a variety of tools for discovering, reading, writing, and plotting gravitational wave data.

Topics:

- Discover, download, and read data
- FFTs, PSDs, and whitening
- Working with segments lists and Timelines
- Plot spectrograms to identify glitches, signals, and hardware injections

Day 2

Suggested tutorials:

pycbc - **pycbc tutorials 1, 2, 3, and 4** provide an introduction to the `pycbc` software package. This analysis package is designed to analyze gravitational-wave data, identify CBC signals and estimate their parameters.

skymaps - **Skymap tutorials 1, 2, and 3** introduce how to read in and use sky localization probability maps to help identify the likely source locations of observed signals.

parameter_estimation - **Parameter estimation tutorials** introduce how Bayesian inference is used to fit model waveforms to the data.

intro - **Introductory tutorial 3** provides an introduction to using matched filtering to identify CBC signals

Topics:

- GW signals from compact object mergers
- Matched filtering to identify compact object mergers
- Working with compact object merger parameters and waveforms
- Working with skymaps to identify likely source locations

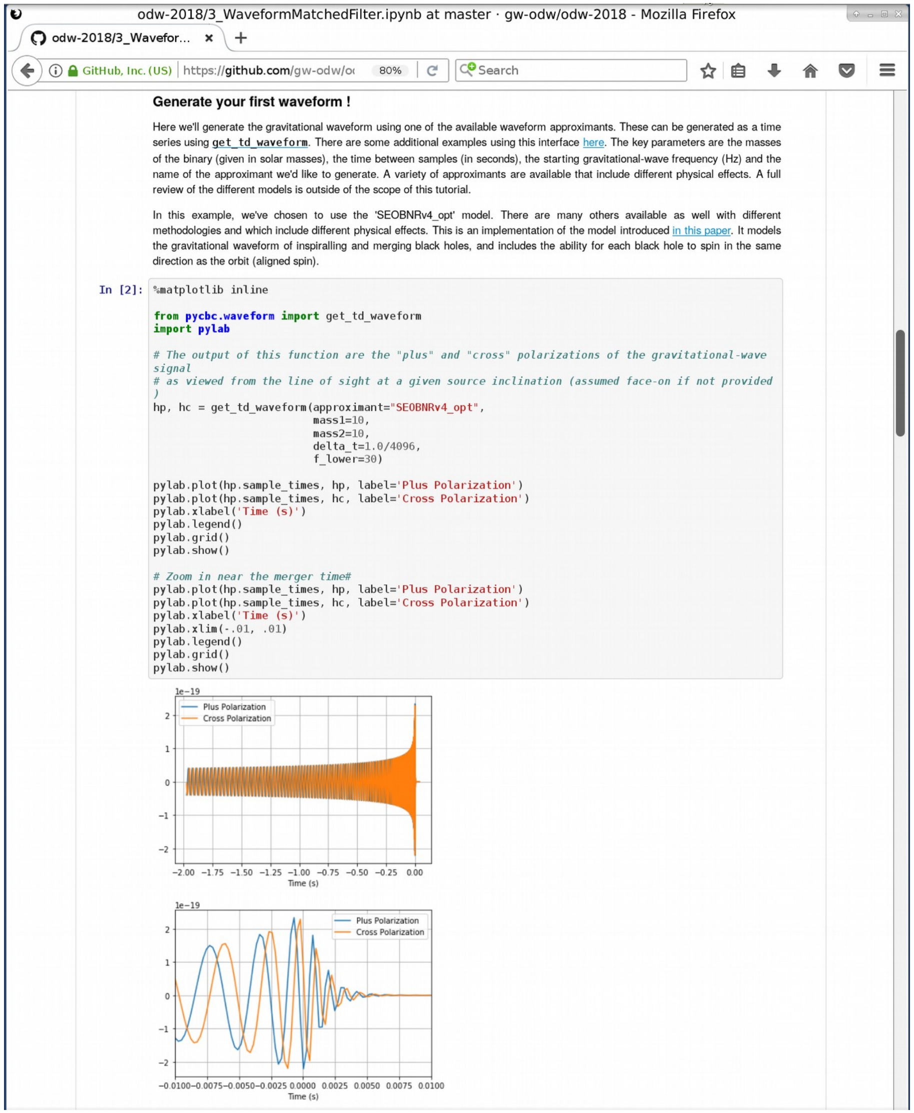
LIGO-Virgo open data

https://www.gw-openscience.org

Jupyter notebook
Software libraries

pip install gwpy
pip install lalsuite
pip install pycbc

Data access,
Waveform generation
Filtering, pre-processing
And more...



Generate your first waveform !

Here we'll generate the gravitational waveform using one of the available waveform approximants. These can be generated as a time series using `get_td_waveform`. There are some additional examples using this interface here. The key parameters are the masses of the binary (given in solar masses), the time between samples (in seconds), the starting gravitational-wave frequency (Hz) and the name of the approximant we'd like to generate. A variety of approximants are available that include different physical effects. A full review of the different models is outside of the scope of this tutorial.

In this example, we've chosen to use the 'SEOBNRv4_opt' model. There are many others available as well with different methodologies and which include different physical effects. This is an implementation of the model introduced in this paper. It models the gravitational waveform of inspiralling and merging black holes, and includes the ability for each black hole to spin in the same direction as the orbit (aligned spin).

In [2]:

```
%matplotlib inline

from pycbc.waveform import get_td_waveform
import pylab

# The output of this function are the "plus" and "cross" polarizations of the gravitational-wave
signal
# as viewed from the line of sight at a given source inclination (assumed face-on if not provided
)
hp, hc = get_td_waveform(approximant="SEOBNRv4_opt",
                         mass1=10,
                         mass2=10,
                         delta_t=1.0/4096,
                         f_lower=30)

pylab.plot(hp.sample_times, hp, label='Plus Polarization')
pylab.plot(hp.sample_times, hc, label='Cross Polarization')
pylab.xlabel('Time (s)')
pylab.legend()
pylab.grid()
pylab.show()

# Zoom in near the merger time#
pylab.plot(hp.sample_times, hp, label='Plus Polarization')
pylab.plot(hp.sample_times, hc, label='Cross Polarization')
pylab.xlabel('Time (s)')
pylab.xlim(-.01, .01)
pylab.legend()
pylab.grid()
pylab.show()
```

Conclusion

Data analysis challenge and open questions:

→ rare signals buried in detectors' noise

→ highly non-Gaussian noise distribution (glitches)

→ no model to describe the noise components

→ Noise subtraction

→ Detect gravitational-waves with a single detector

→ a full coherent CBC analysis is computing demanding

→ simplifications must be used for spins and orbit eccentricity of binaries

→ low-latency analysis (parameter estimation) for multi-messenger follow-up

→ source rate not well constrained

→ physical background (ex. galactic binaries for LISA)

→ control systematic effects (pulsar timing)