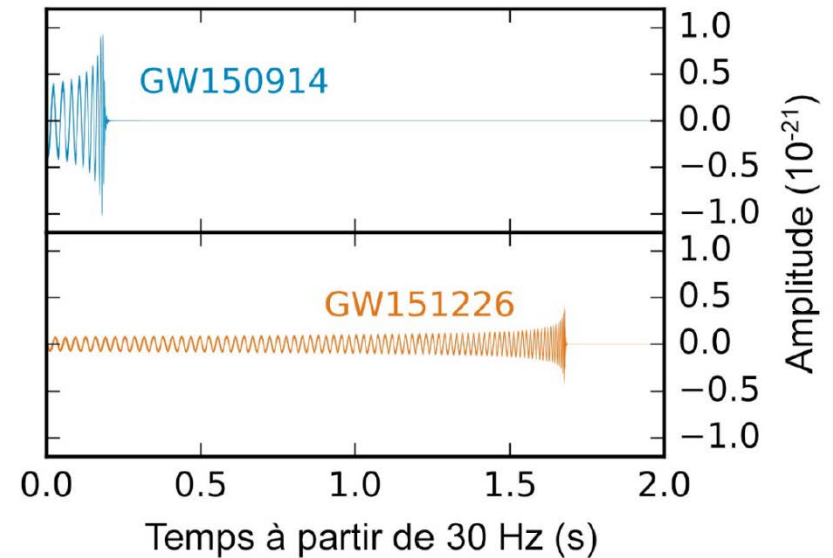


GW150914 & GW151226: the first direct detections of gravitational waves

M2 P3TMA (Marseille) Visit, October 28 2016

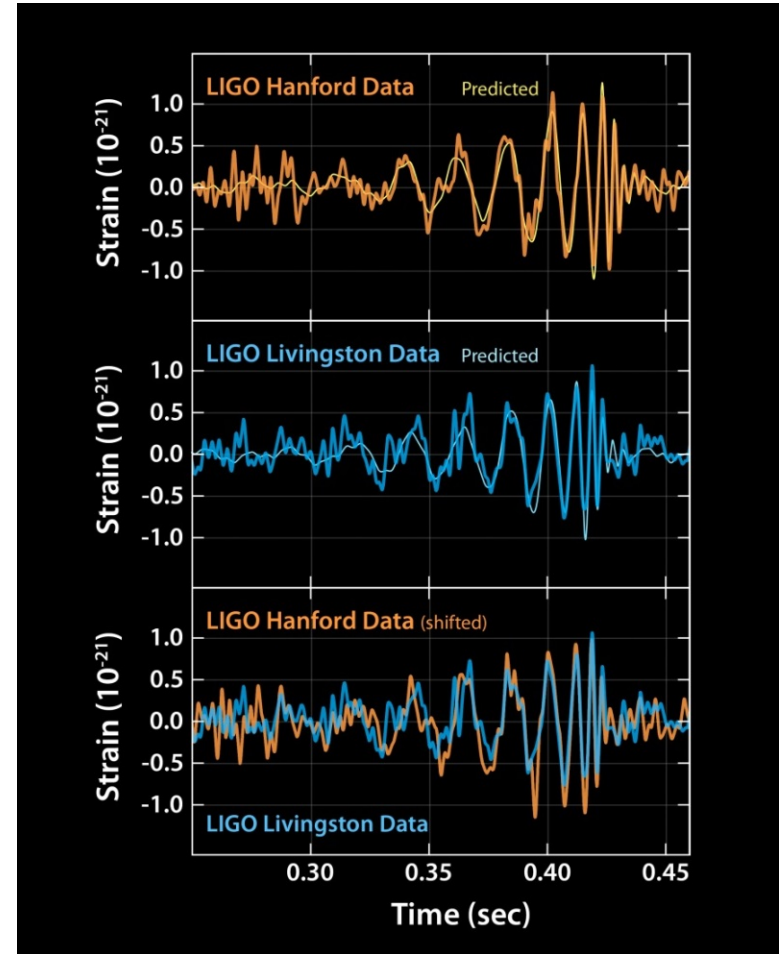
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European Gravitation Observatory (Consortium, CNRS & INFN)



Outline

- **Gravitational waves** in a nutshell
 - Sources and properties
- Gravitational wave **interferometric detectors**
 - Principle and main characteristics
 - Advanced detectors
 - A worldwide network of detectors
- **GW150914 & GW151226**
 - The **Advanced LIGO** « Observation 1 »
Run: September 2015 – January 2016
 - **First direct detections** of gravitational waves from a **black hole binary merger**
 - Physics results
- Outlook



*Thanks to the many colleagues
from the LAL Virgo group, from Virgo and LIGO
from which I borrowed ideas and material for this talk*

Gravitational waves: sources and properties

General relativity in a nutshell

- “Spacetime tells matter how to move; matter tells spacetime how to curve”

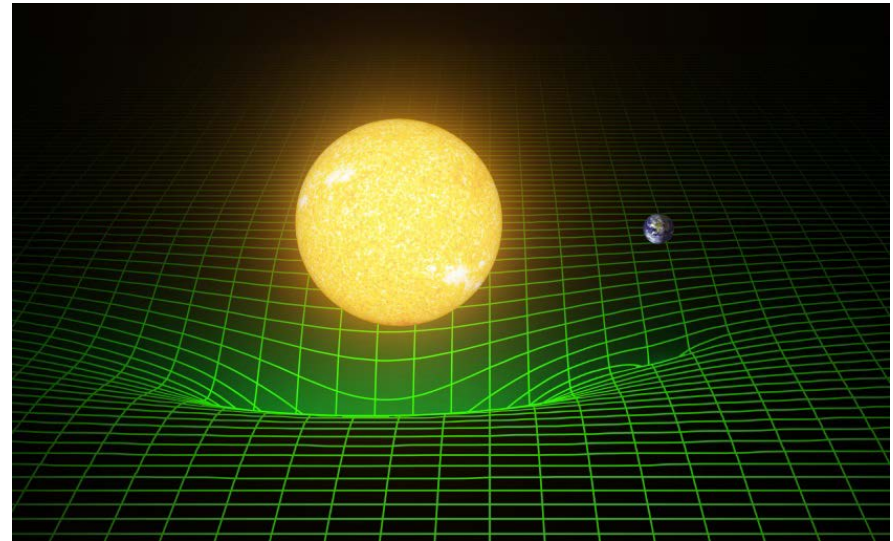
John Archibald Wheeler (1990)

- A massive body warps the spacetime fabric
- Objects (including light) move along paths determined by the spacetime geometry

- Einstein's equations

$$\mathbf{G}_{\mu\nu} = \frac{8\pi\mathbf{G}}{c^4} \mathbf{T}_{\mu\nu}$$

→ In words: **Curvature = Matter**



- Einstein tensor $\mathbf{G}_{\mu\nu}$: manifold curvature
- Stress-energy tensor $\mathbf{T}_{\mu\nu}$: density and flux of energy and momentum in spacetime
- Equality between two tensors
 - Covariant equations
- Need to match Newton's theory for weak and slowly variable gravitational fields
 - Very small coupling constant: the spacetime is very rigid
- Non linear equations: gravitational field present in both sides

Newtonian gravitation and black holes

- Newton 1687: **Law of universal gravitation**
 - Apply both on Earth and to celestial objects
 - Demonstrate Kepler laws
 - For centuries, predictions match very well the observations
 - Neptune discovery (1846):
Urbain Le Verrier (mathematical computation)
& Gottfried Galle (observation)
 - **Escape velocity**, in case one mass is much larger than the other one ($M \gg m$)
$$v_e = \sqrt{\frac{2GM}{r}}$$
 (independent from m)
 - **What if $v_e = c$?**
 - Stars with a gravitational field so strong that their light would be trapped
 - Context: the corpuscular theory of light
 - John Mitchell (1783)
 - Pierre-Simon de Laplace (1796)
- Issue forgotten until the publication of Einstein's general relativity (1915)

Schwartzschild Radius

- Newtonian escape velocity: $v_e = \sqrt{\frac{2GM}{r}}$
- **Schwartzschild radius R_s** (1916): $R_s = \frac{2GM}{c^2} \approx 3\text{km} \left(\frac{M}{M_{\text{Sun}}} \right)$
 - $R_s(M)$ such as $v_e = c$
 - Very small for « usual » celestial objects
 - Planets, stars

- **Compacity $C = \frac{R_s}{\text{radius}} \leq 1$**

Object	Earth	Sun	White dwarf	Neutron star	Black hole
Compacity	$1.4 \cdot 10^{-9}$	$4.3 \cdot 10^{-6}$	10^{-4}	0.3	1

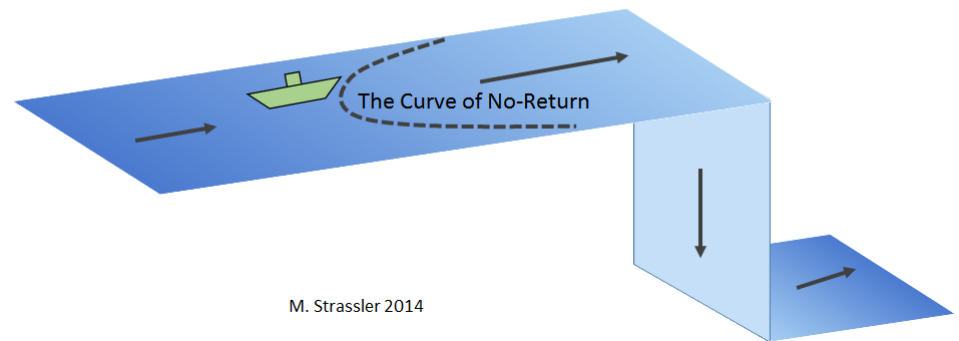
- **Beware: compact and dense are two different things!**
 - Black hole « density »

$$\rho = \frac{\text{"Mass"}}{\text{"Volume"}} \approx 1.8 \times 10^{16} \text{ g/cm}^3 \left(\frac{M_{\text{Sun}}}{M} \right)^2$$

Black holes

- Spacetime region in which gravitation is so strong that nothing, not even light, can escape from inside its horizon
- Formed by the collapse of massive stars running out of fuel
- Can grow by accreting matter
 - Supermassive black holes are thought to exist inside most galaxies
→ E.g. **Sagittarius A*** in the center of the Milky Way
- Characterized by three numbers (Kerr, 1963)
 - Mass
 - Spin
 - Electric charge
- Black hole horizon
 - Once crossed there's no way back
 - Can only grow with time

A Person In a Boat that Crosses the Curve of No-Return Will Notice Nothing at the Time, But is Doomed To Go Over The Waterfall

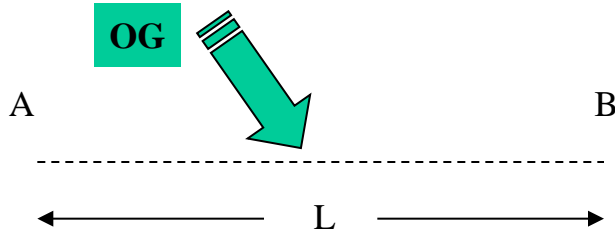


Gravitational waves (GW)

- One of the first predictions of general relativity (1916)
 - Accelerated masses induce perturbations of the spacetime which propagate at the speed of light
 - Linearization of the Einstein equations ($g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$, $|h_{\mu\nu}| \ll 1$) leads to a propagation equation far from the sources
- Traceless and transverse (tensor) waves
 - 2 polarizations: « + » and « × »
→ See next slide for the interpretation of these names
- Quadrupolar radiation
 - Need to deviate from axisymmetry to emit GW
 - No dipolar radiation – contrary to electromagnetism
- GW amplitude h is dimensionless
 - Scales with the inverse of the distance from the source
 - GW detectors sensitive to amplitude ($h \propto 1/d$) and not intensity ($h^2 \propto 1/d^2$)
→ Important to define the Universe volume a given detector is sensitive to

Effect of gravitational waves on test masses

- **GW: propagating perturbation of the spacetime metric**
 - Acts on distance measurement between test masses (free falling)

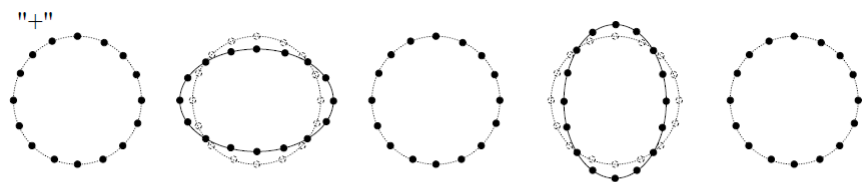


$$\delta L_{\max} = \frac{hL}{2}$$

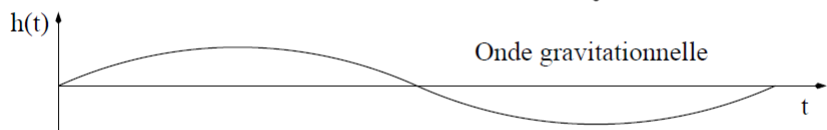
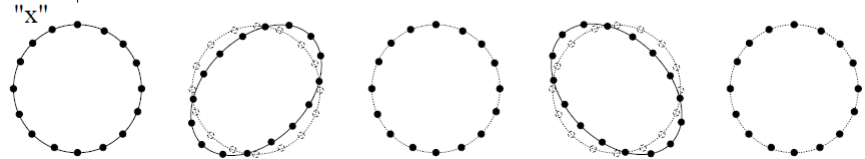
Variation doubled for an interferometer with arms of equal length L:
 $\delta L_{\text{IFO}} = hL$

- Effect of the two GW polarizations on a ring of free masses

▪ « + » polarization



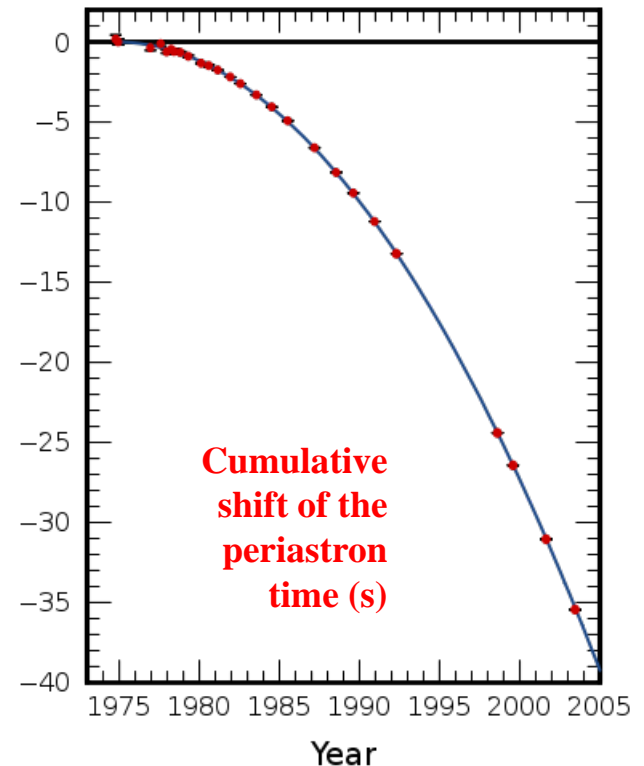
▪ « x » polarization



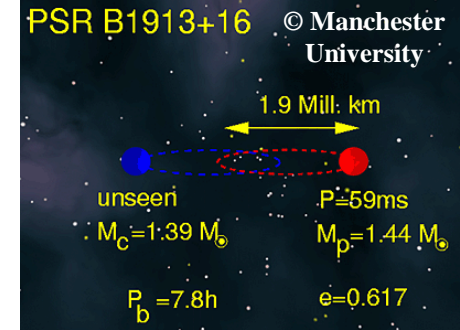
One period

Do gravitational waves exist?

- Question (officially) solved since February 11 2016!
 - But was very relevant beforehand ... and long-standing in the community
- Controversy for decades
 - Eddington, 1922: « *GW propagate at the speed of thought* »
 - 1950's: general relativity is mathematically consistent (Choquet-Buhat)
- Indirect evidence of the GW existence:
long-term study of **PSR B1913+16** – see next slide
 - Galactic (6.4 kpc away) binary system
 - Two neutron stars, one being a pulsar
- Discovered by Hulse and Taylor in 1974
 - Nobel prize 1993
- Laboratory for gravitation study
 - GW in particular
→ Taylor & Weisberg, Damour



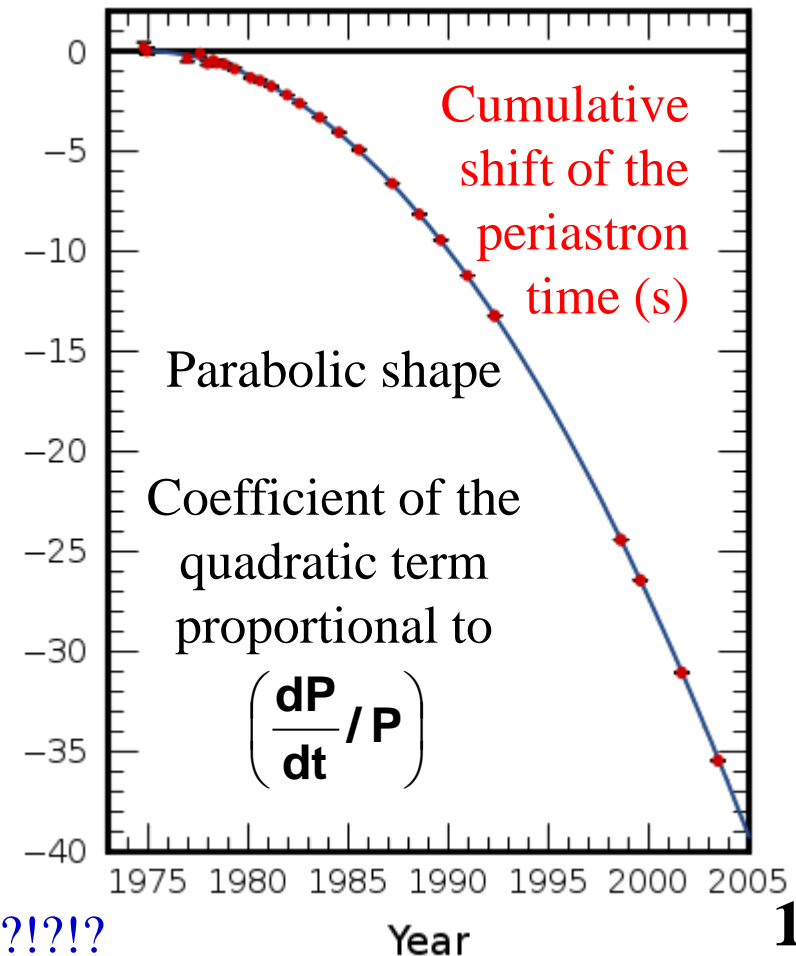
PSR B1913+16



- Galactic (6.4 kpc away) binary system
 - Two neutron stars, one being a pulsar
- Discovered by Hulse and Taylor in 1974
 - Nobel prize 1993 – for the discovery
- System parameters and orbital motion measured accurately
 - Laboratory for gravitation studies
- GW: long-term studies of the orbital motion
 - Taylor & Weisberg, Damour
- System slowly losing energy due to GW
 - Orbital motion “accelerates” accordingly
 - 76.5 μs / year – current period: $P = 7.75$ h
 - Compact stars get “closer”: 3.5 m / year
 - Coalescence in... 300 000 000 years
 - Virgo and LIGO « could » see that final part!?!?!?

Beware: not a fit!

Predictions and data overlaid



Sources of gravitational waves

Very small: 10^{-53} W^{-1}

- **Einstein quadrupole formula** (1916)

- Power radiated into gravitational waves
- Q: reduced quadrupole momenta

$$\mathbf{P} = \left(\frac{\mathbf{G}}{5\mathbf{c}^5} \right) \left\langle \ddot{\mathbf{Q}}_{\mu\nu} \ddot{\mathbf{Q}}^{\mu\nu} \right\rangle$$

- Let's rewrite this equation introducing some **typical parameters of the source**

- Mass M , dimension R , frequency $\omega/2\pi$ and asymmetry factor a

- One gets $\frac{d^3\mathbf{Q}}{dt^3} \sim (aMR^2)\omega^3$ and $\mathbf{P} \sim \frac{\mathbf{G}}{\mathbf{c}^5} a^2 M^2 R^4 \omega^6$

- Using $\omega \sim v/R$ and introducing R_s , one gets:

$$\mathbf{P} \sim \left(\frac{\mathbf{c}^5}{\mathbf{G}} \right) a^2 \mathbf{c}^2 \left(\frac{\mathbf{v}}{\mathbf{c}} \right)^6$$

Huge: 10^{53} W

© Joe Weber, 1974

→ A good GW source must be

- **Asymmetric**
- As **compact** as possible
- **Relativistic**

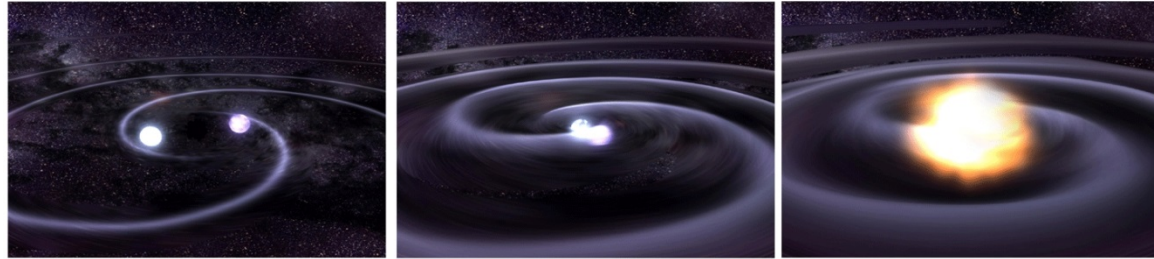
- Although all accelerated masses emit GW, no terrestrial source can be detected

→ Need to look for astrophysical sources (typically: $h \sim 10^{-22} \div 10^{-21}$)

A diversity of sources

- **Rough classification**

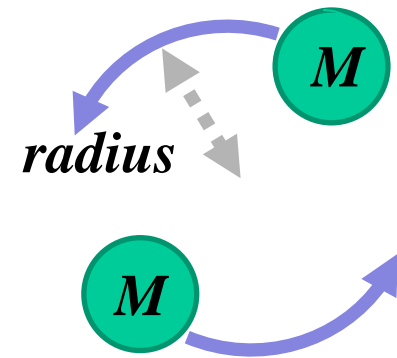
- **Signal duration**
- **Frequency range**
- **Known/unknown waveform**
- **Any counterpart** (E.M., neutrinos, etc.) expected?



- **Compact binary coalescence**

- Last stages of the evolution of a system like PSRB 1913+16
→ **Compact stars get closer and closer while losing energy through GW**
- Three phases: **inspiral**, **merger** and **ringdown**
→ Modeled via analytical computation and numerical simulations
- Example: **two masses M in circular orbit** ($f_{\text{GW}} = 2 f_{\text{Orbital}}$)

$$h \approx 10^{-21} \left(\frac{500 \text{ Mpc}}{\text{Distance}} \right) \left(\frac{\text{Mass}}{30 M_{\text{Sun}}} \right) \left(\frac{\text{Orbital radius}}{100 \text{ km}} \right)^2 \left(\frac{\text{Frequency}}{100 \text{ Hz}} \right)^2$$



- **Transient sources** (« bursts »)

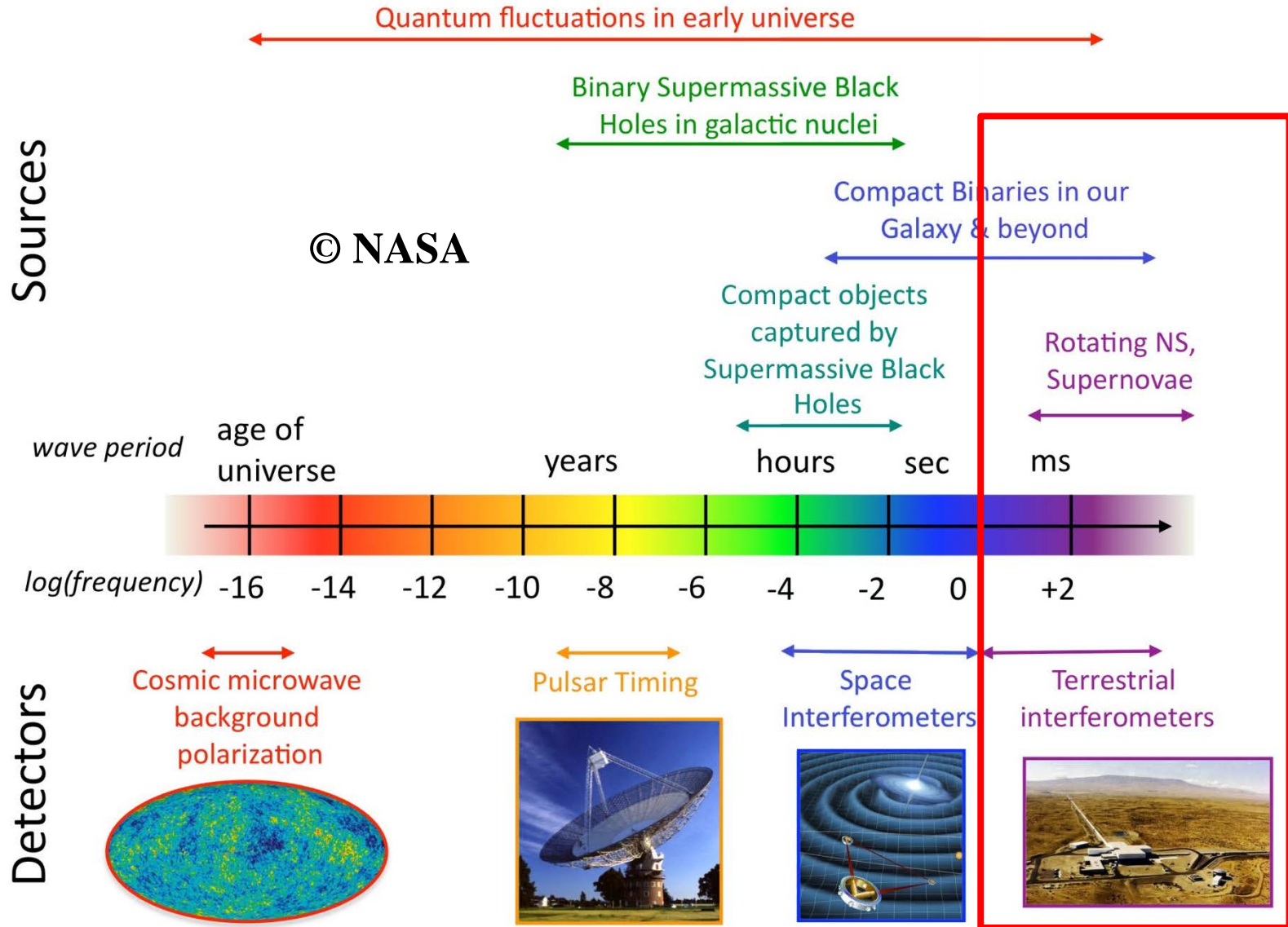
- Example: core collapses (supernovae)



- **Permanent sources**

- Pulsars, Stochastic backgrounds

Gravitational wave spectrum



LIGO, Virgo, etc.

Gravitational wave detectors

- **Ground-based**

- **Resonant bars** (**Joe Weber**'s pioneering work)

→ Narrow band, limited sensitivity: not used anymore

- **Interferometric detectors**

→ **LIGO**, **Virgo** and others

→ 2nd generation (« advanced ») detectors started operation

Design studies have started for 3rd generation detectors (Einstein Telescope)

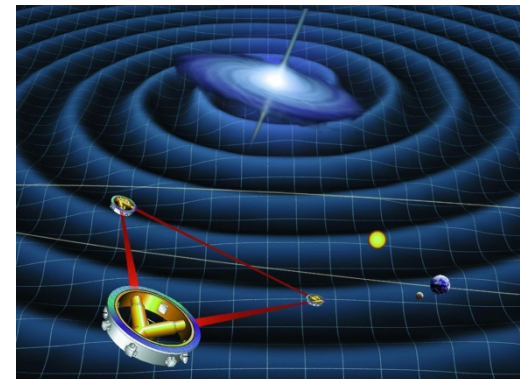
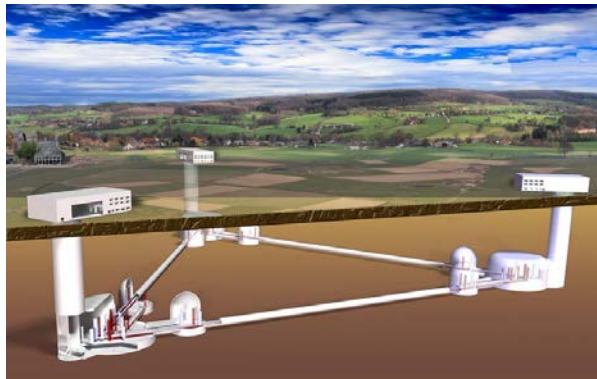
- **Pulsar Timing Array** (<http://www.ipta4gw.org>)

→ GW would vary the time of arrival pulses emitted by millisecond pulsars

- **In space**

- Future mission **eLISA** (<https://www.elisascience.org>, 2030's)

- Technologies tested by the **LISA pathfinder** mission, sent to space last December



Gravitational wave interferometric detectors

1916-2016: a century of progress

- **1916: GW prediction (Einstein)**

1957 Chapel Hill Conference

- **1963: rotating BH solution (Kerr)**

- **1990's: CBC PN expansion (Blanchet, Damour, Deruelle, Iyer, Will, Wiseman, etc.)**
- **2000: BBH effective one-body approach (Buonanno, Damour)**
- **2006: BBH merger simulation (Baker, Lousto, Pretorius, etc.)**

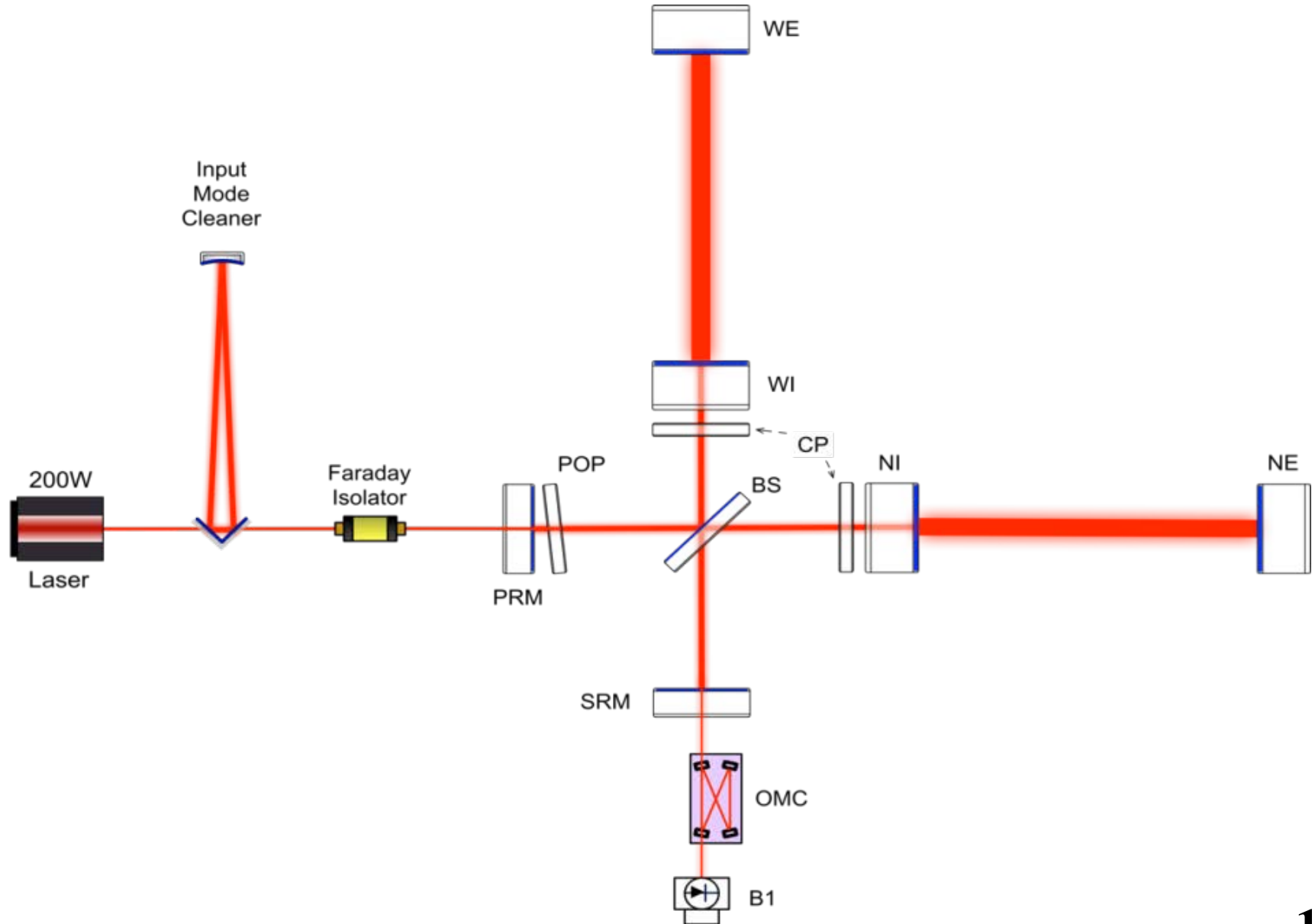
Theoretical developments

Experiments

(Bondi, Feynman, Pirani, etc.)

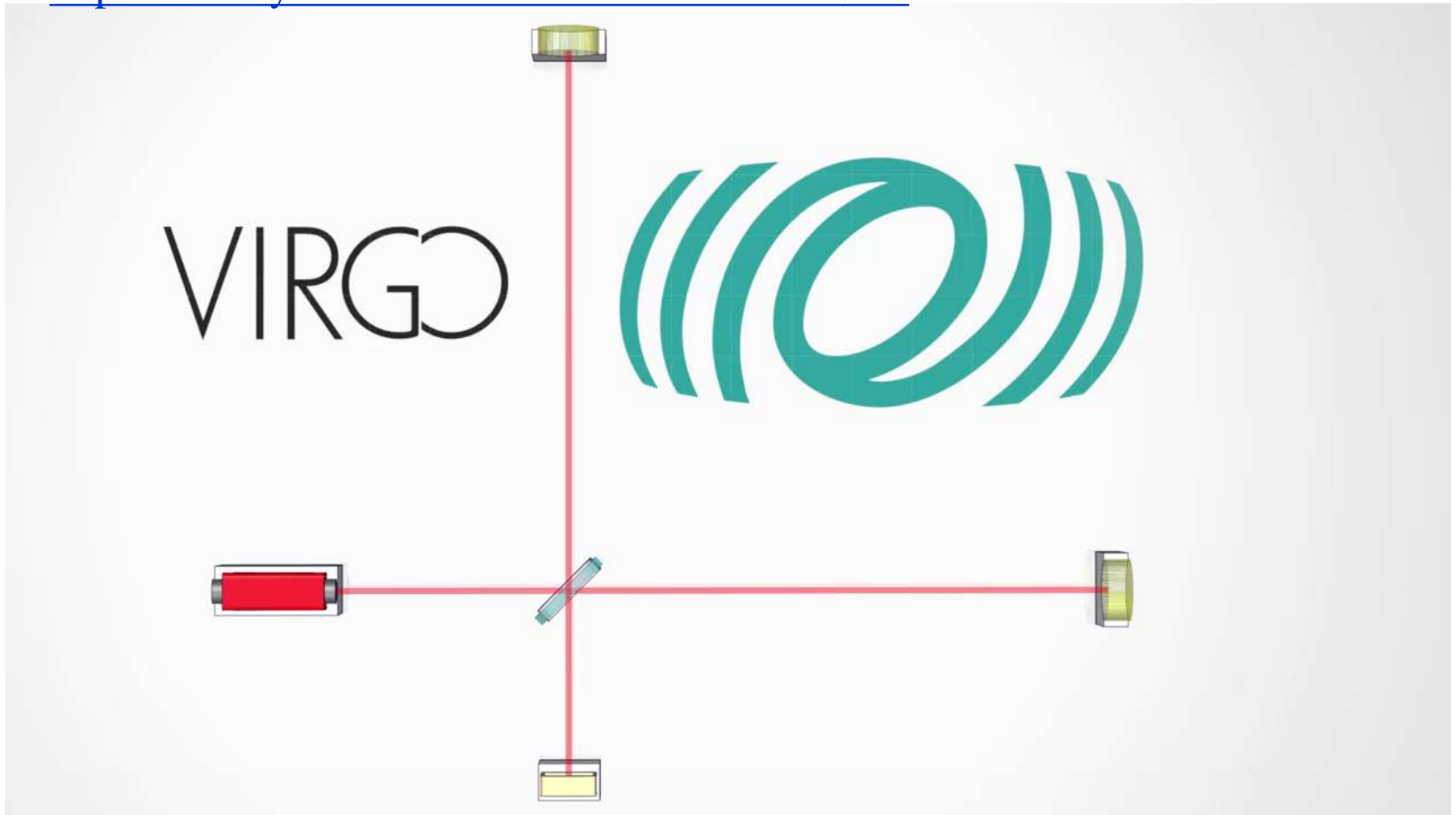
- **1960's: first Weber bars**
- **1970: first IFO prototype (Forward)**
- **1972: IFO design studies (Weiss)**
- **1974: PSRB 1913+16 (Hulse & Taylor)**
- **1980's: IFO prototypes (10m-long) (Caltech, Garching, Glasgow, Orsay)**
- **End of 1980's: Virgo and LIGO proposals**
- **1990's: LIGO and Virgo funded**
- **2005-2011: initial IFO « science » » runs**
- **2007: LIGO-Virgo Memorandum Of Understanding**
- **2012 : Advanced detectors funded**
- **2015: First Advanced LIGO science run**

The Advanced Virgo detector scheme



The Advanced Virgo detector revealed

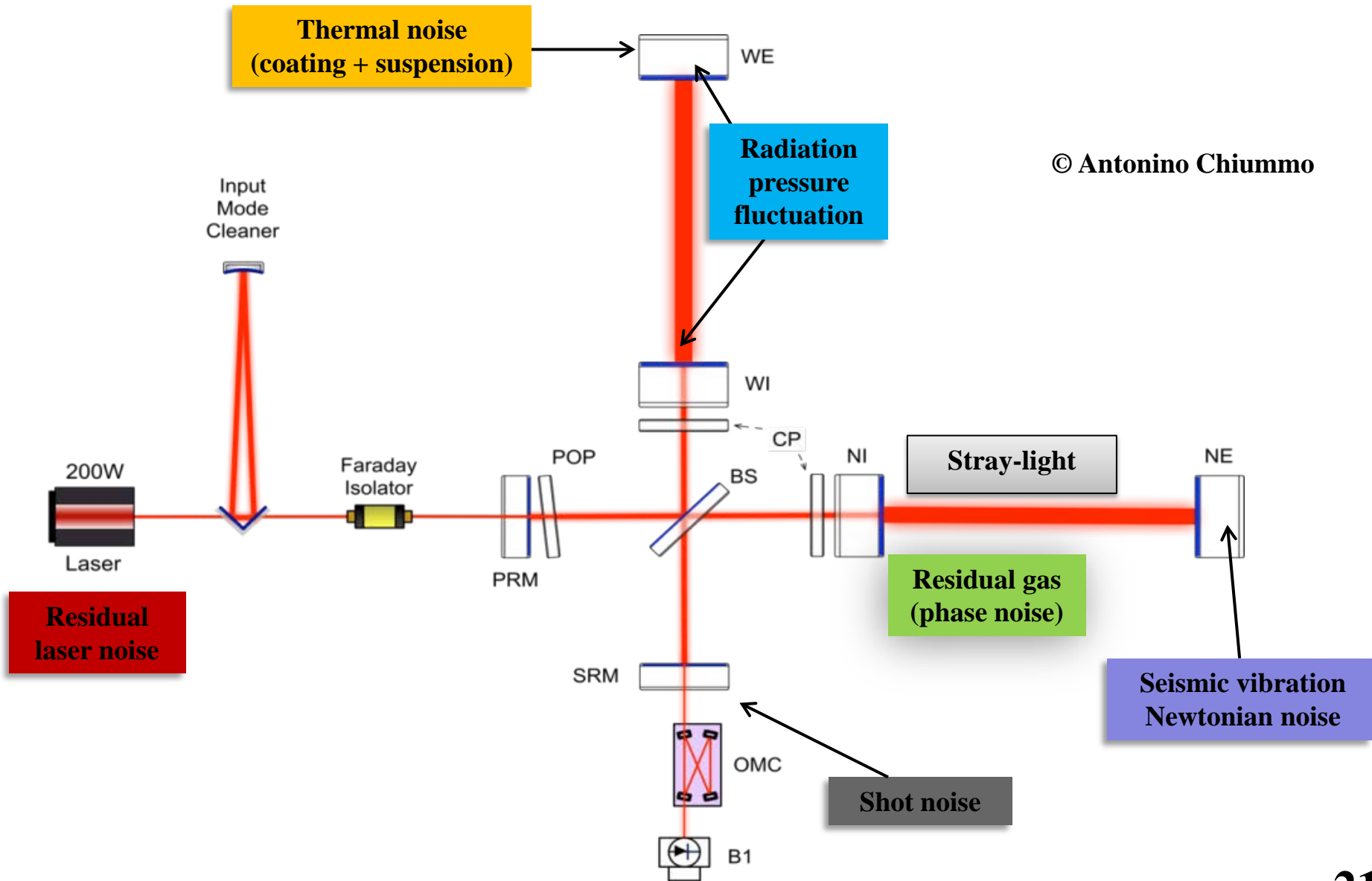
- Animation by Marco Kraan, NIKHEF
 - <https://www.youtube.com/watch?v=6raomYII9P4>



Noise & sensitivity

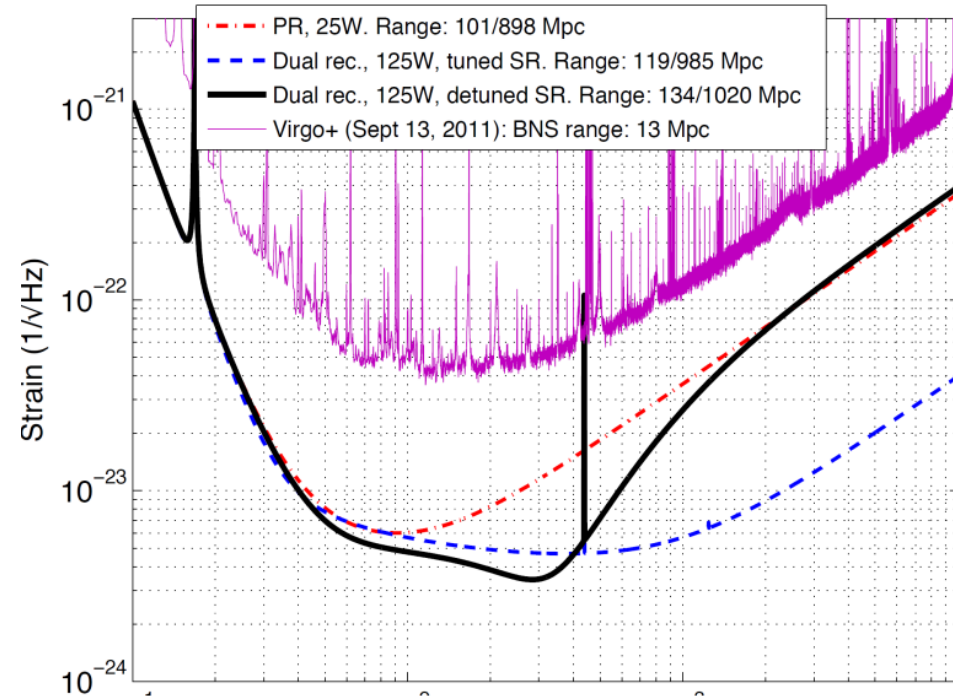
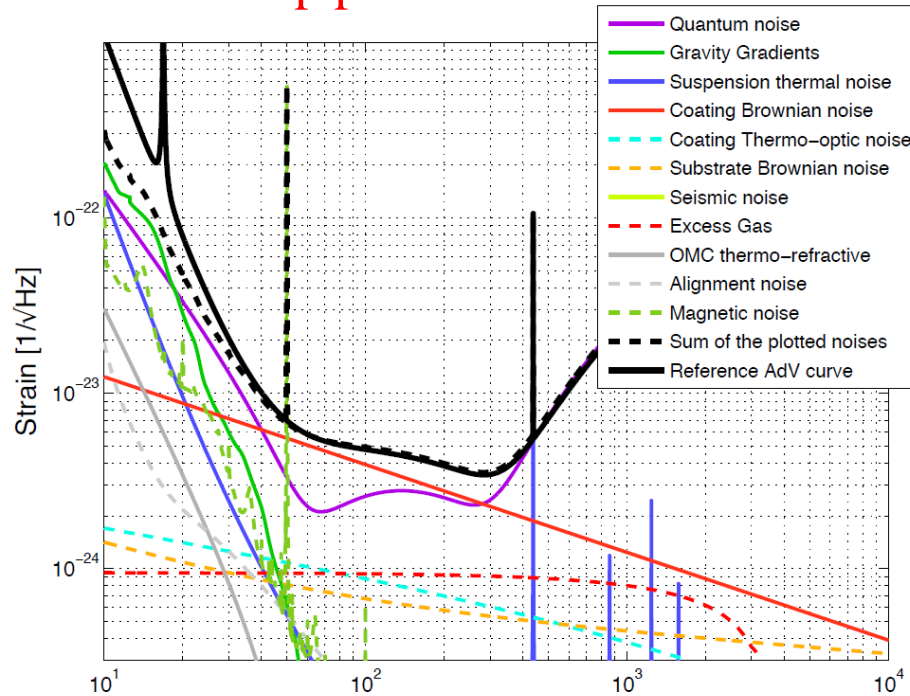
- **Noise**: any kind of disturbance which pollutes the dark fringe output signal
- Detecting a GW of frequency $f \leftrightarrow$ amplitude $h \ll \text{larger} \gg$ than noise at that frequency
- Interferometers are wide-band detectors
 - GW can span a wide frequency range
 - **Frequency evolution with time is a key feature of some GW signals**
→ Compact binary coalescences for instance
- Numerous sources of noise
 - **Fundamental**
→ Cannot be avoided; optimize design to minimize these contributions
 - **Instrumental**
→ For each noise, identify the source; then fix or mitigate
→ Then move to the next dominant noise; iterate...
 - **Environmental**
→ Isolate the instrument as much as possible; monitor external noises
- IFO sensitivity characterized by its **amplitude spectrum density (ASD, unit: $1/\sqrt{\text{Hz}}$)**
 - **Noise RMS** in the frequency band $[f_{\min}; f_{\max}] = \sqrt{\int_{f_{\min}}^{f_{\max}} \text{ASD}^2(f) df}$

Main interferometer noises



Sensitivity improvement

- A multi-step process



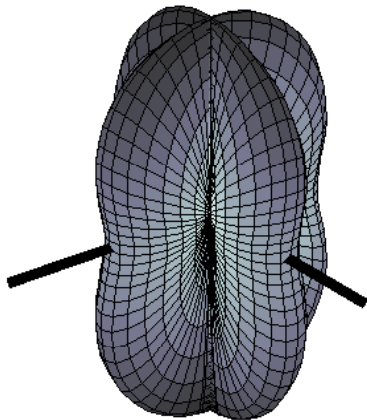
- Quantum noise dominant at low (radiation pressure) & high (shot noise) frequencies
→ R&D ongoing on frequency-dependent light squeezing
- Coating thermal noise dominant in between
- Low frequency sensitivity ultimately limited by Newtonian noise
 - Stochastic gravitational field induced by surface seismic waves
→ Either active cancellation or go underground

**A worldwide network
of gravitational wave
interferometric detectors**

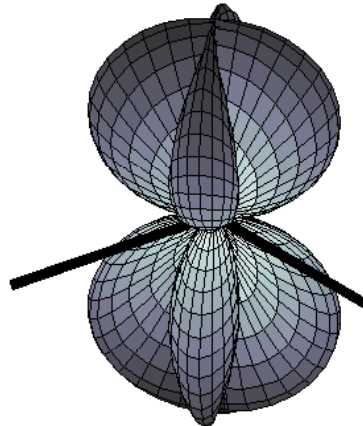
Interferometer angular response

- **An interferometer is not directional**: it probes most of the sky at any time
 - More a microphone than a telescope!
- **The GW signal is a linear combination of its two polarisations**
$$h(t) = F_+(t) \times h_+(t) + F_\times(t) \times h_\times(t)$$
 - F_+ and F_\times are antenna pattern functions which depend on the source direction in the sky w.r.t. the interferometer plane
 - Maximal when perpendicular to this plane
 - Blind spots along the arm bisector (and at 90 degrees from it)

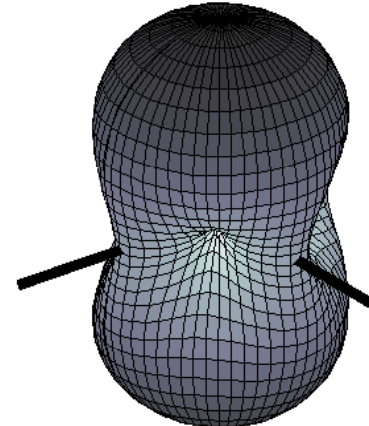
+ polarization



× polarization



unpolarized

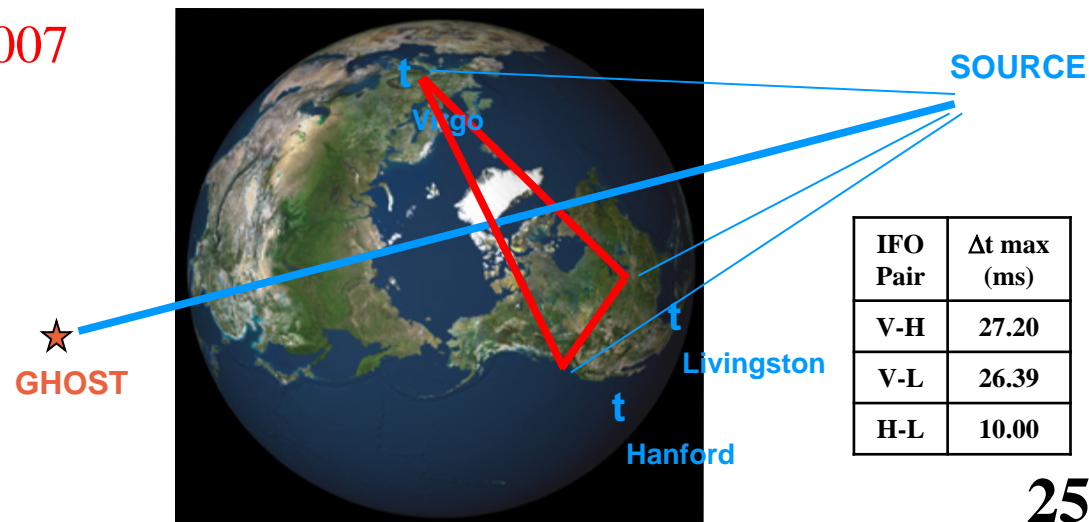
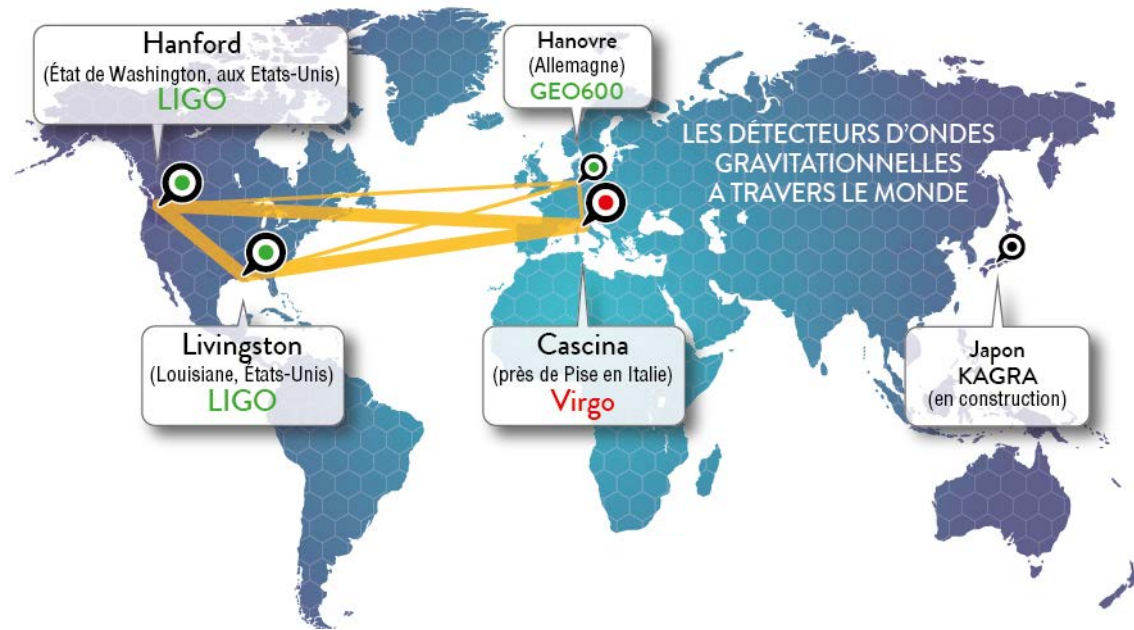


A network of interferometric detectors

- A single interferometer is not enough to detect GW
 - Difficult to separate a signal from noise confidently
 - There have been unconfirmed claims of GW detection

→ Need to use a network of interferometers

- Agreements (MOUs) between the different projects – Virgo/LIGO: 2007
 - Share data, common analysis, publish together
- IFO: non-directional detectors; non-uniform response in the sky
- Threefold detection: reconstruct source location in the sky

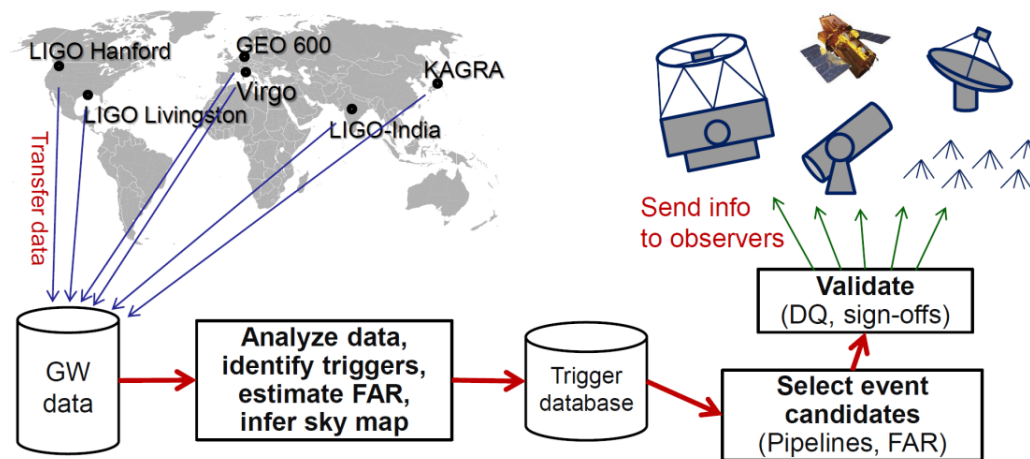


A network of interferometric detectors



Exploiting multi-messenger information

- Transient GW events are energetic
 - Only (a small) part of the released energy is converted into GW
 - **Other types of radiation released:** electromagnetic waves and neutrinos
- **Astrophysical alerts** ⇒ tailored GW searches
 - **Time and source location known** ; possibly the waveform
 - Examples: gamma-ray burst, type-II supernova
- **GW detectors are also releasing alerts to a worldwide network of telescopes**
 - Agreements signed with **~75 groups** – 150 instruments, 10 space observatories

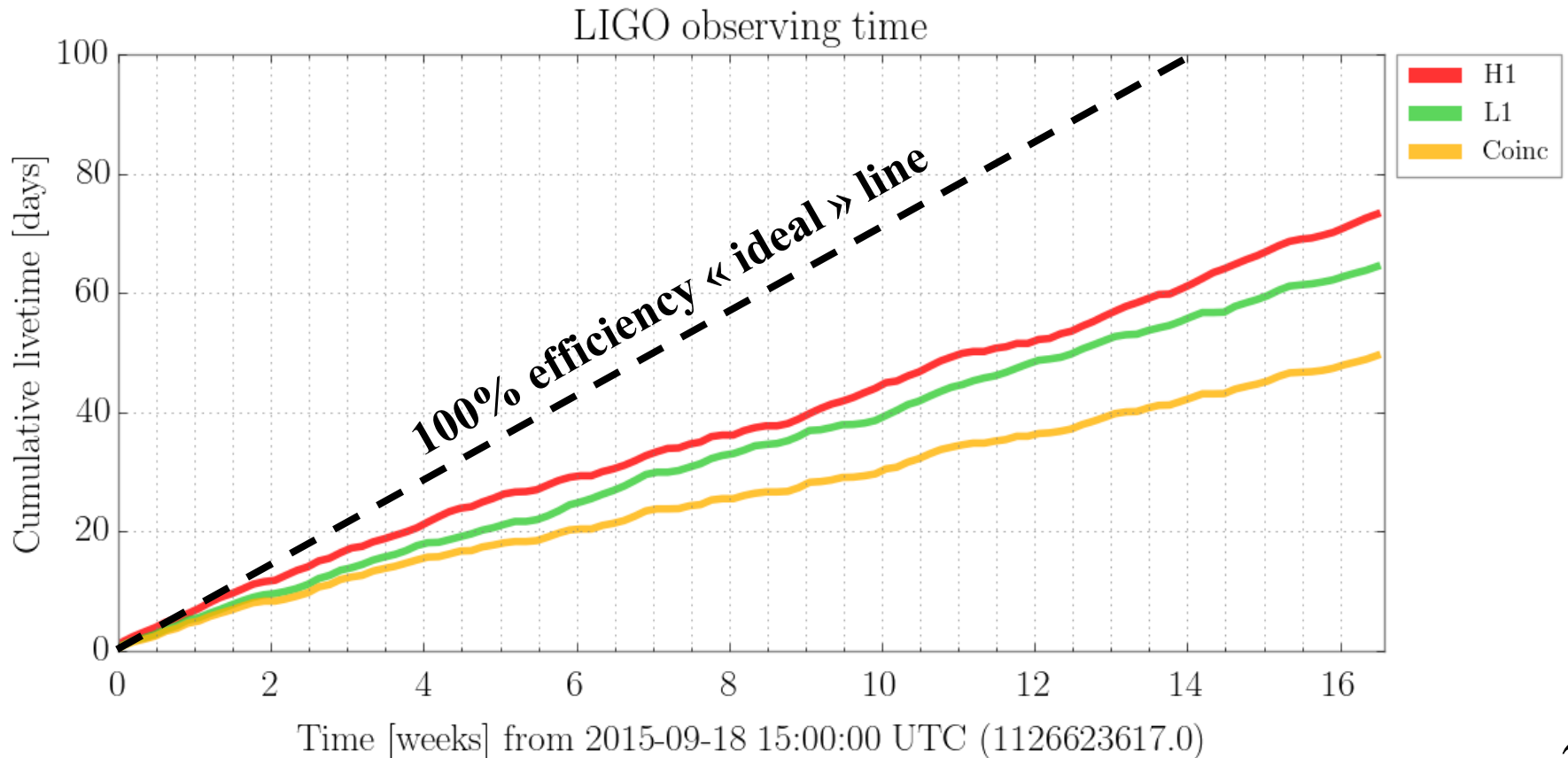


- **Low latency h-reconstruction and data transfer between sites**
 - **Online GW searches for burst and compact binary coalescences**

**The Advanced LIGO
«Observation 1» Run
(2015/09 – 2016/01)**

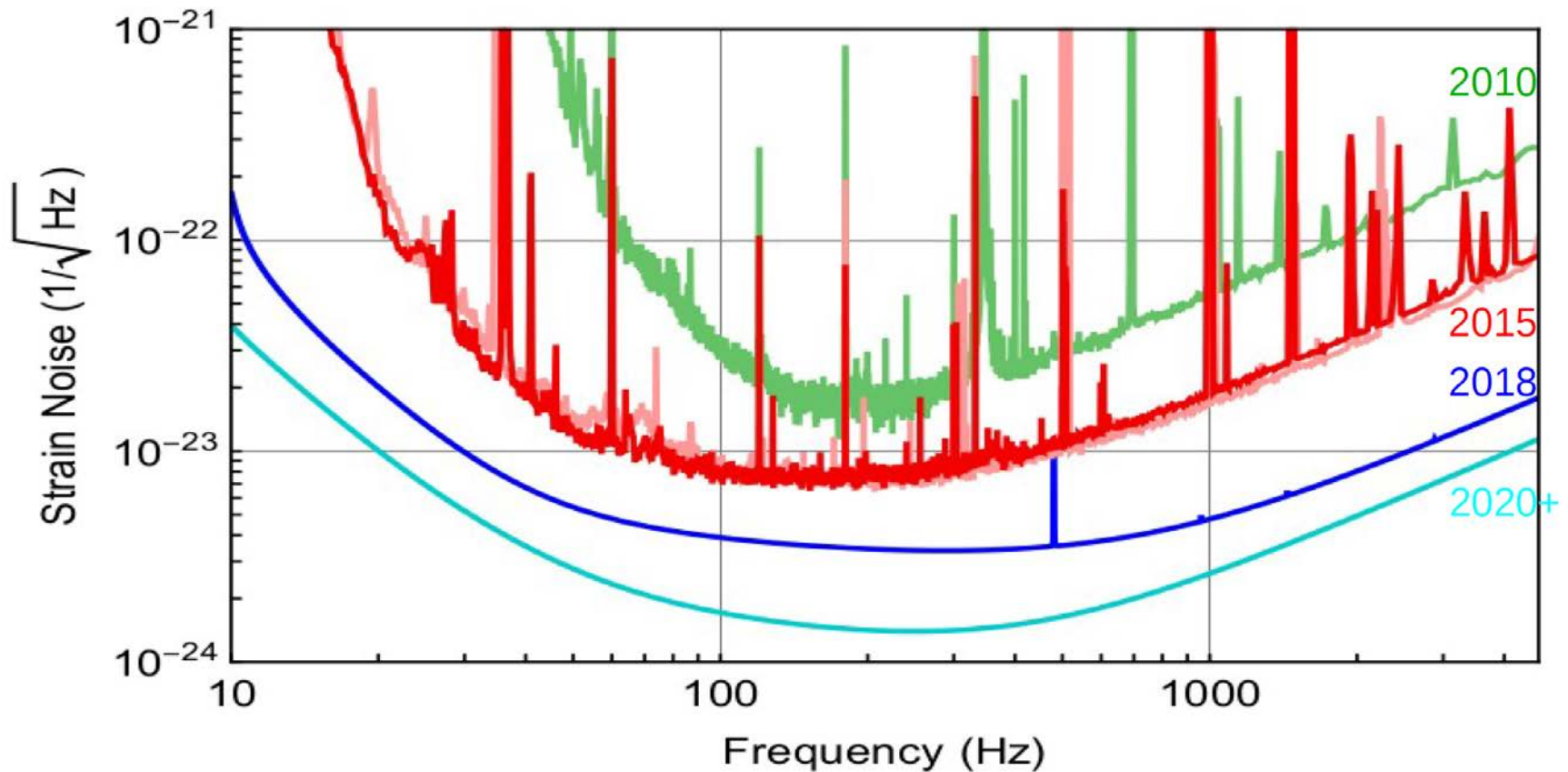
aLIGO O1 Run: Observing time

- **September 2015 – January 2016**
 - GW150914 showed up a few days before the official start of O1, during the « Engineering Run 8 »
- **Both interferometers were already working nominally**



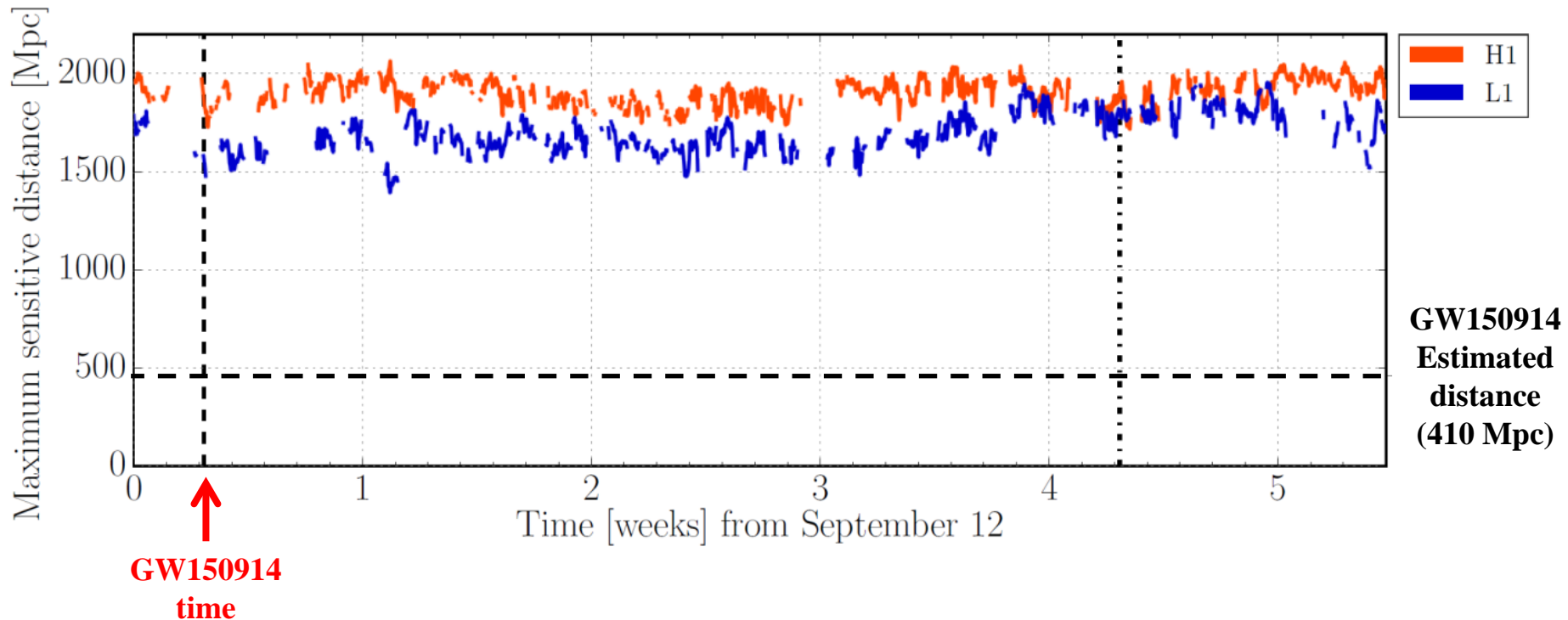
aLIGO O1 Run: Sensitivity

- Sensitivity much improved with respect to the initial detectors
 - Factor 3-4 in strain
 - Factor 30-60 in volume probed
- Gain impressive at low frequency – where both signals are located



aLIGO O1 Run: GW150914-like horizon

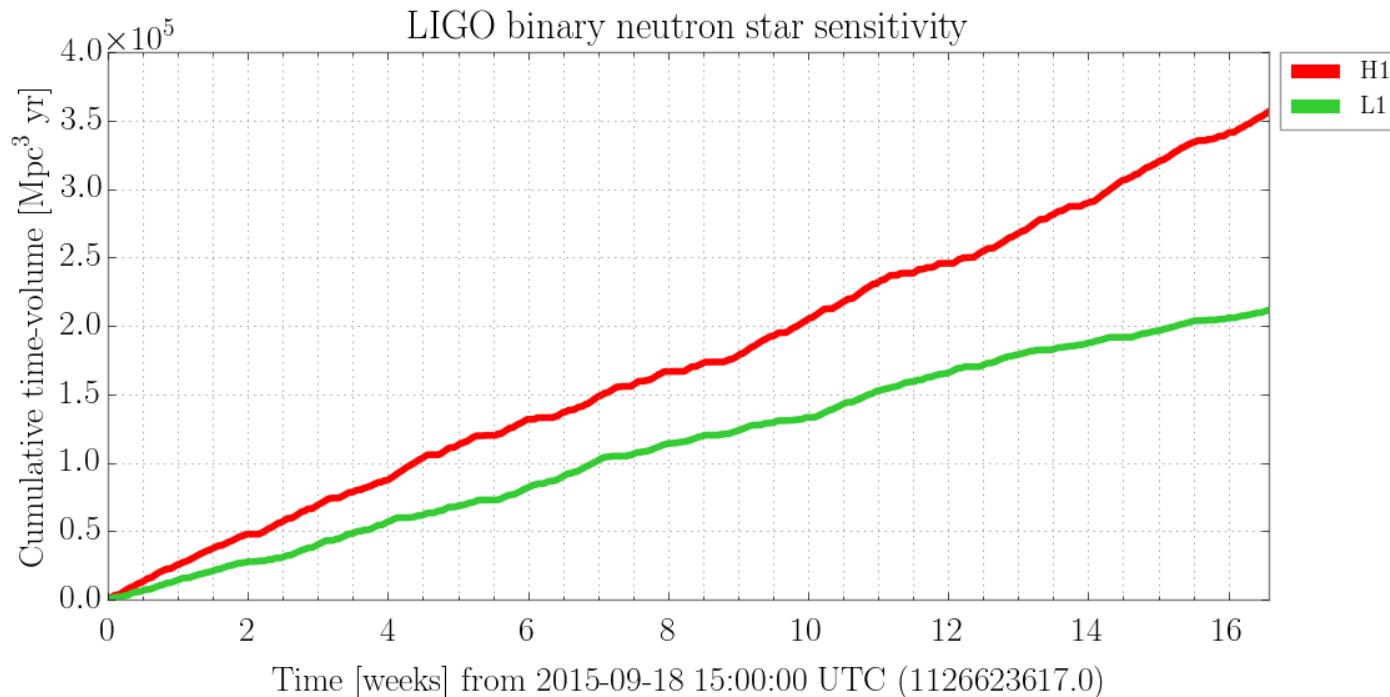
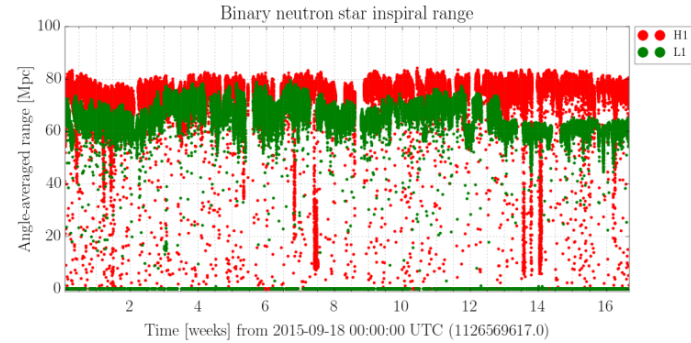
- Sky-averaged distance up to which a given signal can be detected
 - In this case a binary black hole system with the measured GW150914 parameters



- Only depends on the actual sensitivity of the interferometer
 - Online monitoring tool used during data taking

aLIGO O1 Run: “VT” figure of merit

- **Cumulative time-volume probed by the instruments**
 - Expected number of sources (given a model)
 - Unit: $\text{Mpc}^3 \cdot \text{year}$
 - This slide: $1.4\text{-}1.4 M_{\odot}$ « standard » binary neutron star system case
- **Mixes sensitivity and duty cycle information**

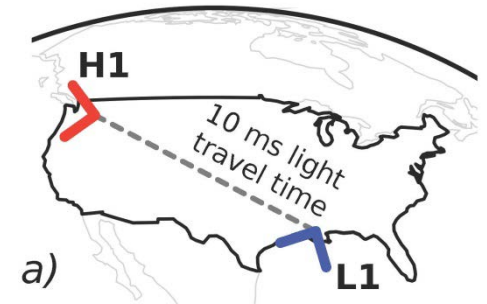
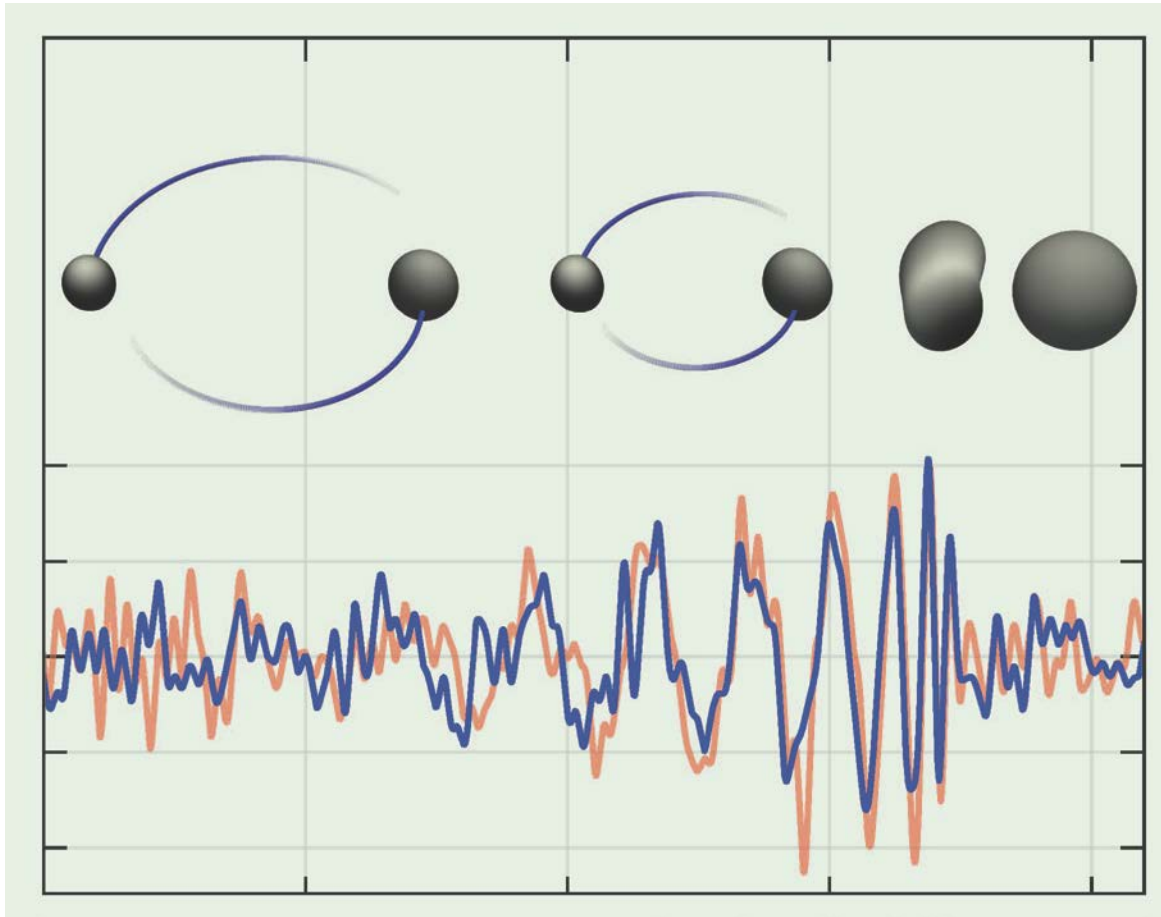


GW150914

September 14 2015, 11:51 CET

- Signal detected in both LIGO detectors, with a 7 ms delay
 - Short (< 1 s)
 - Very strong/significant
 - Signal expected from a binary black hole coalescence

Event labelled
GW150914



February 11 2016, 16:30 CET



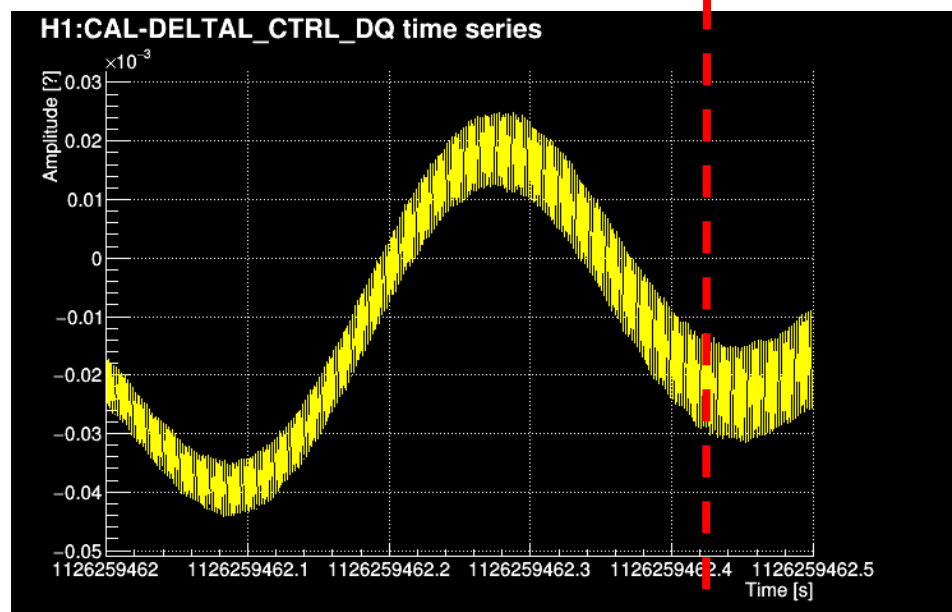
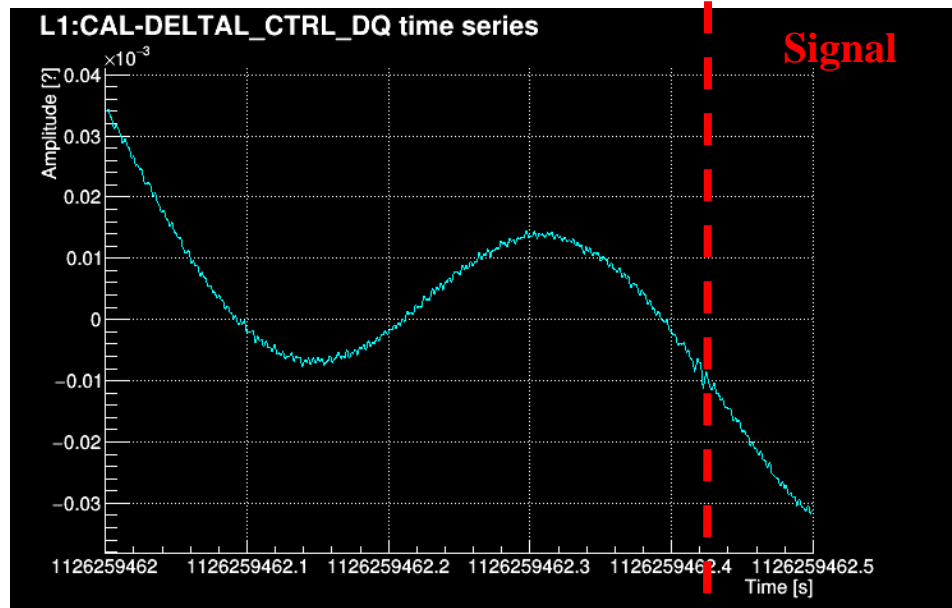
- Simultaneous press conferences in Washington DC, Cascina (Virgo site, Italy), Paris, Amsterdam, etc.
- Detection paper, accepted on PRL, made available online
 - Published by the LIGO and Virgo collaborations
 - <http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.061102>
- Several « companion » papers online at the same time – or shortly thereafter
 - See full list at <https://www.ligo.caltech.edu/page/detection-companion-papers>

In between these two dates...

- **Make sure that the signal was not a simulated waveform**
 - For instance a « blind » injection – or someone hacking LIGO!
- **Check the detector status** at/around the time of the event
- **« Freeze » the detector configuration**
 - To accumulate enough data to assess the signal significance
- **Rule out the possibility of environmental disturbances producing that signal**
- **Run offline analysis to confirm/improve the online results**
- **Extract all possible science** from this first/ unique (so far) event
- **Write detection paper and the associated « companion » papers**
 - Detection paper had to be accepted prior to making the result public
- **Keep GW150914 secret**, hope for the best
 - Any of the items above could have been a showstopper

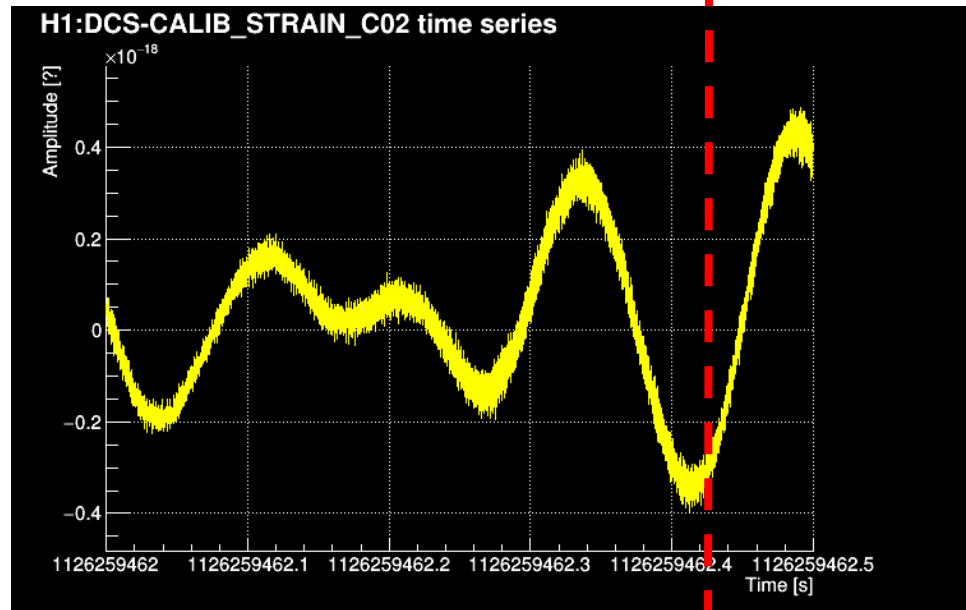
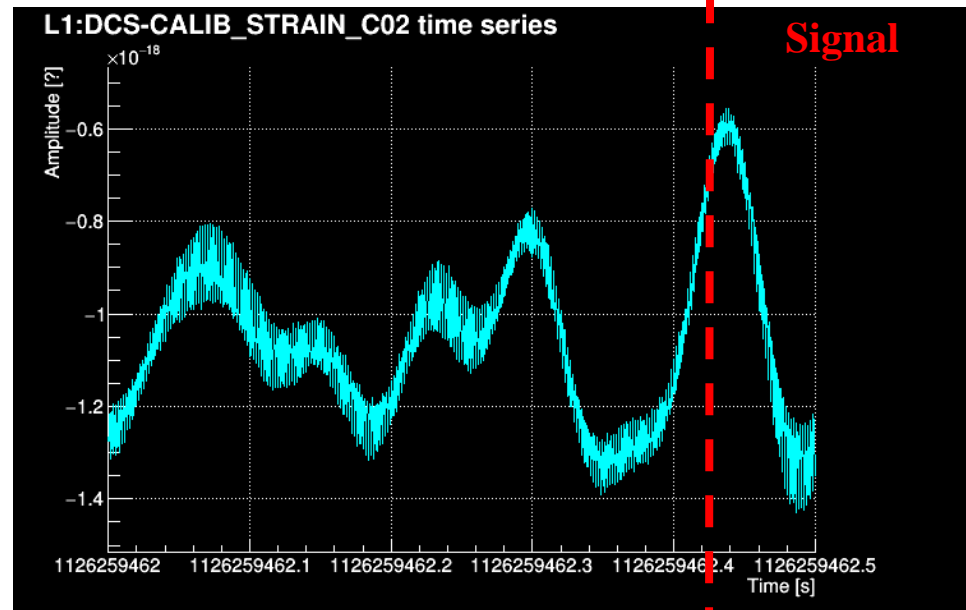
GW150914: raw power

- Blue: aLIGO Livingston
- Yellow: aLIGO Hanford



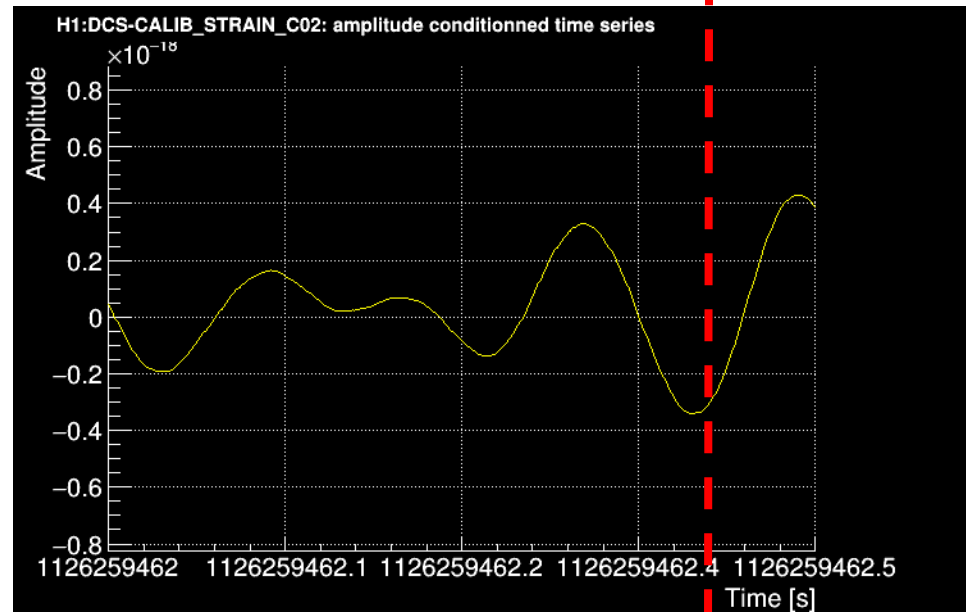
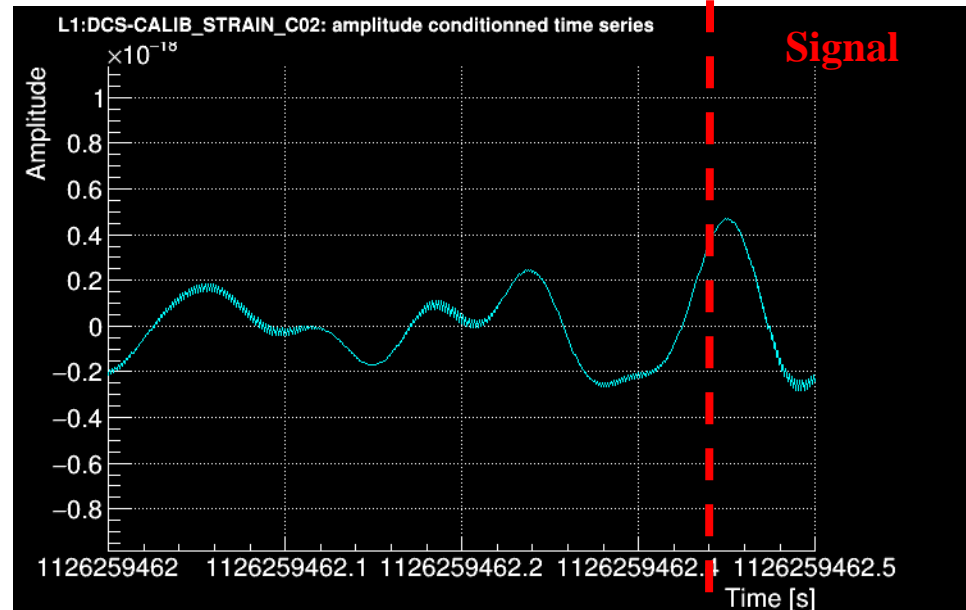
GW150914: calibrated $h(t)$

- Control signals used to recover the strain signal



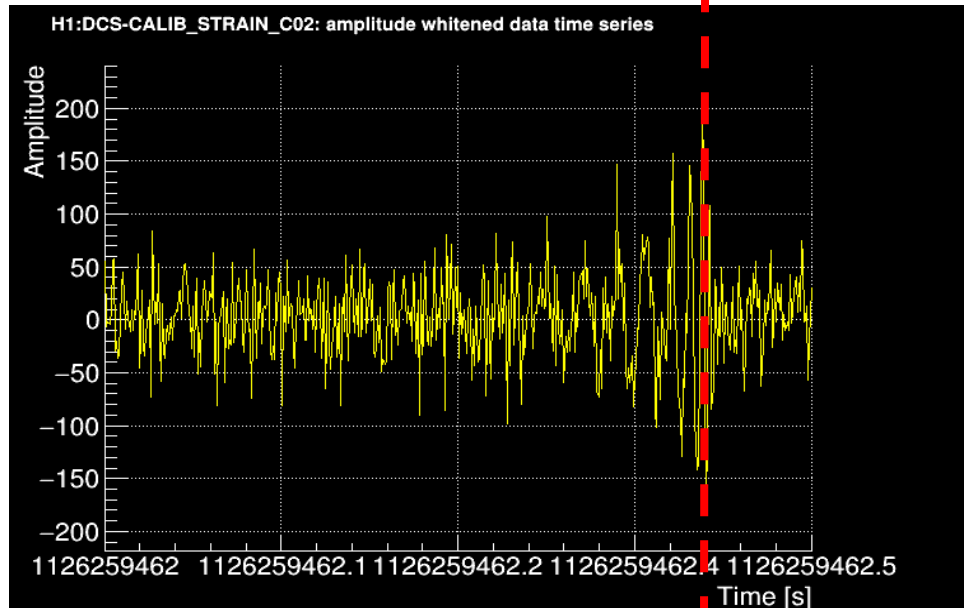
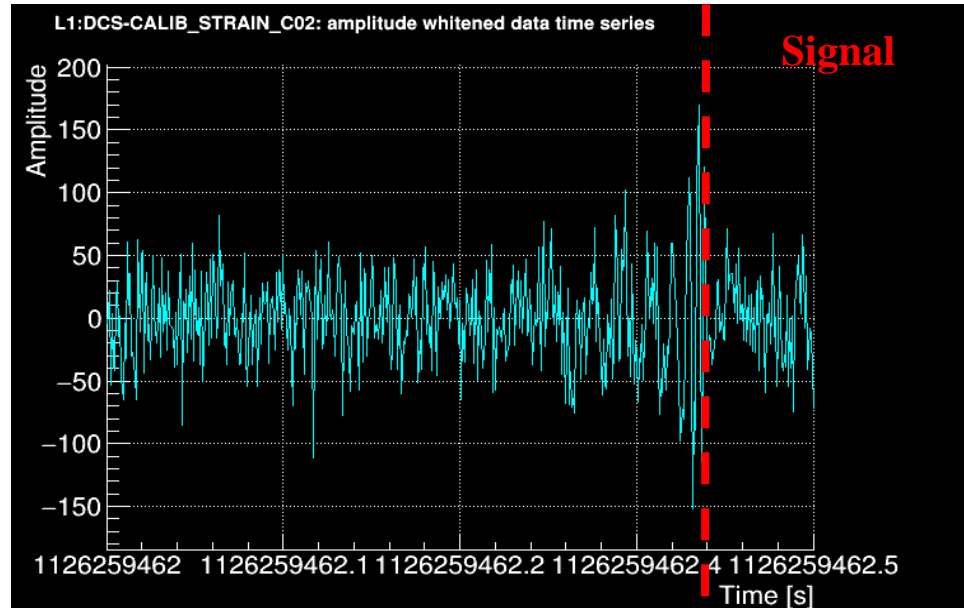
GW150914: band-pass filtering

- 20 Hz \rightarrow 500 Hz



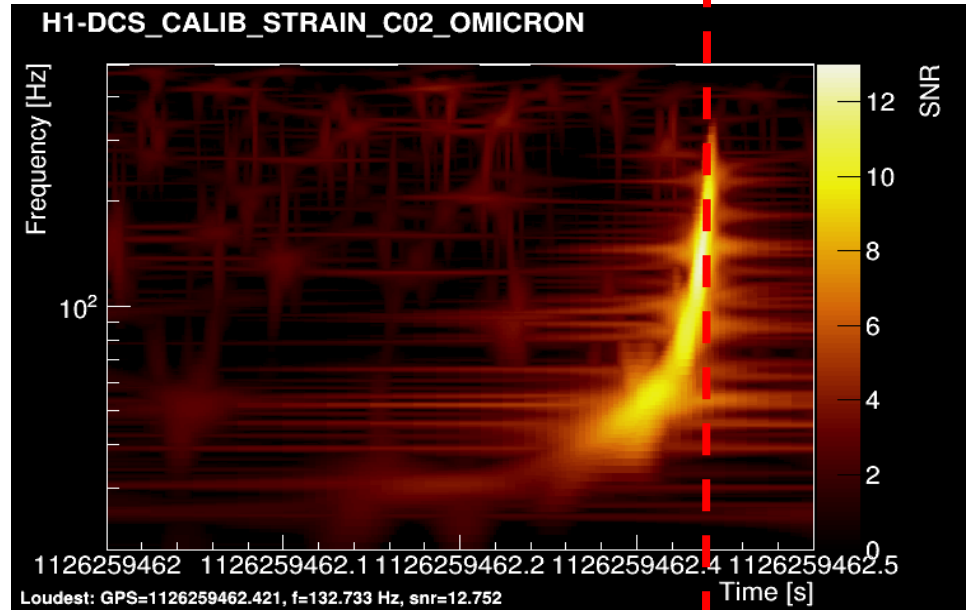
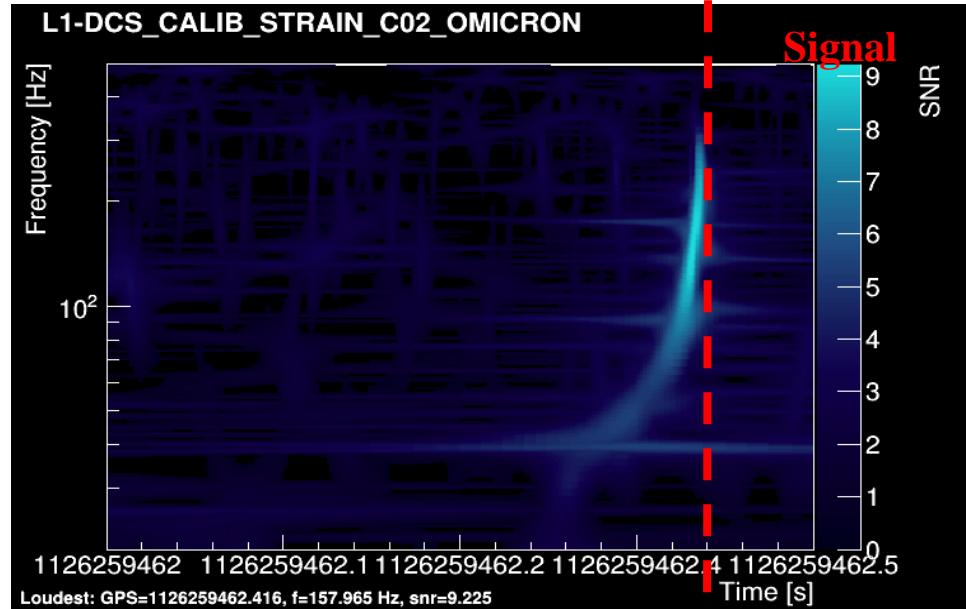
GW150914: whitened data

- Data weighted by the noise level in frequency space
→ Whitenened data have a flat PSD



GW150914: spectrograms

- Time-frequency maps



Compact binary coalescence search

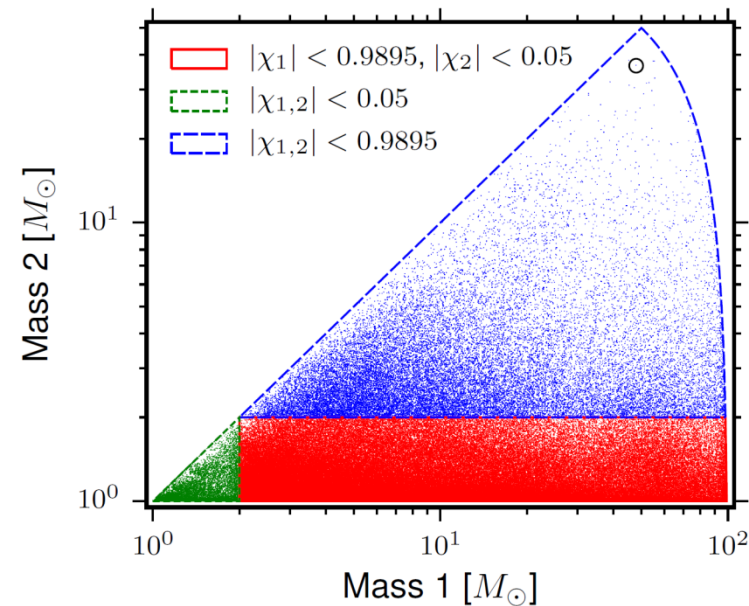
- Well-predicted waveform
 - Matched-filtering technique (optimal)
 - Noise-weighted cross-correlation of data with a template (expected signal)
- Parameter space covered by a template bank
 - Analytical for NS-NS, BH-NS
 - Analytical + numerical for BH-BH
 - Parameters: mass and spin of the initial black holes
 - ~250,000 templates in total
- Look for triggers from the two IFOs using the same template and coincident in time
 - Check matching between signal and template
- Offline search
 - Part of the parameter space searched online
 - Two independent offline pipelines

FT of the data

Signal template

$$C(t) = \int_{-\infty}^{\infty} \frac{\tilde{x}(f)\tilde{h}^*(f)}{S_n(f)} e^{2\pi ift} df$$

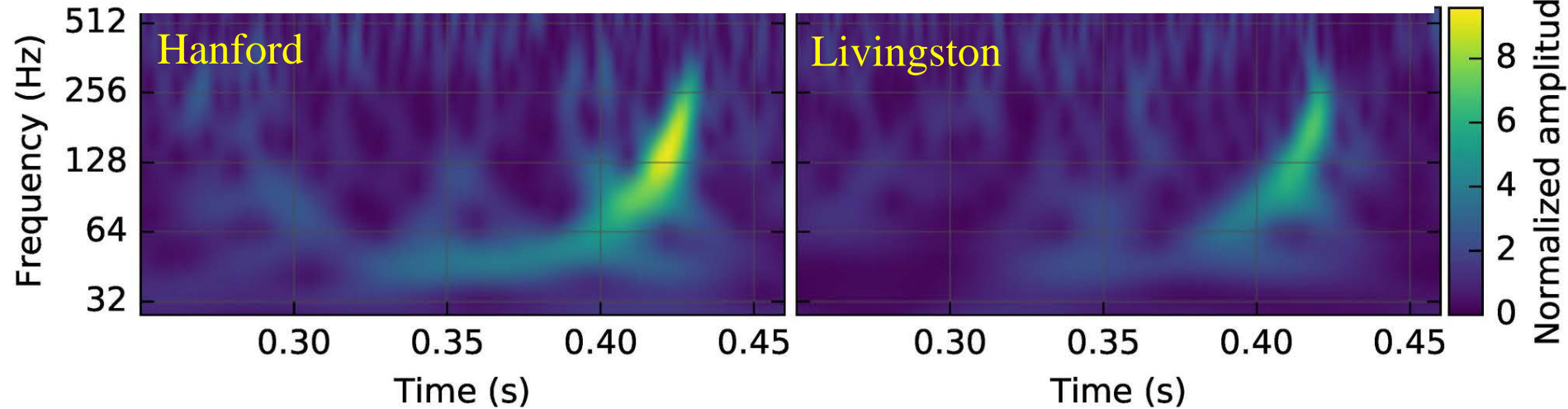
Noise power spectral density



Burst search

- Search for **clusters of excess power** (above detector noise) in **time-frequency plane**
 - **Wavelets**

GW150914 signal strong enough to be immediately identified on spectrograms



- **Chirp**-like shape: frequency and amplitude increasing with time
- **Coherent excess in the two interferometers**
 - Reconstructed signals required to be similar
- Efficiency similar to (optimal) matched filtering for binary black hole – short signal
 - **Online last September for O1**

Rapid response to GW150914

- 2015/09/14 11:51 CET: **event recorded** – first in Livingston, 7 ms later in Hanford
- 3 minutes later : **event flagged**, entry added to database, contacts notified
 - Online triggers important in particular for searches of counterparts
- 1 hour later: **e-mails started flowing** within the LIGO-Virgo collaboration

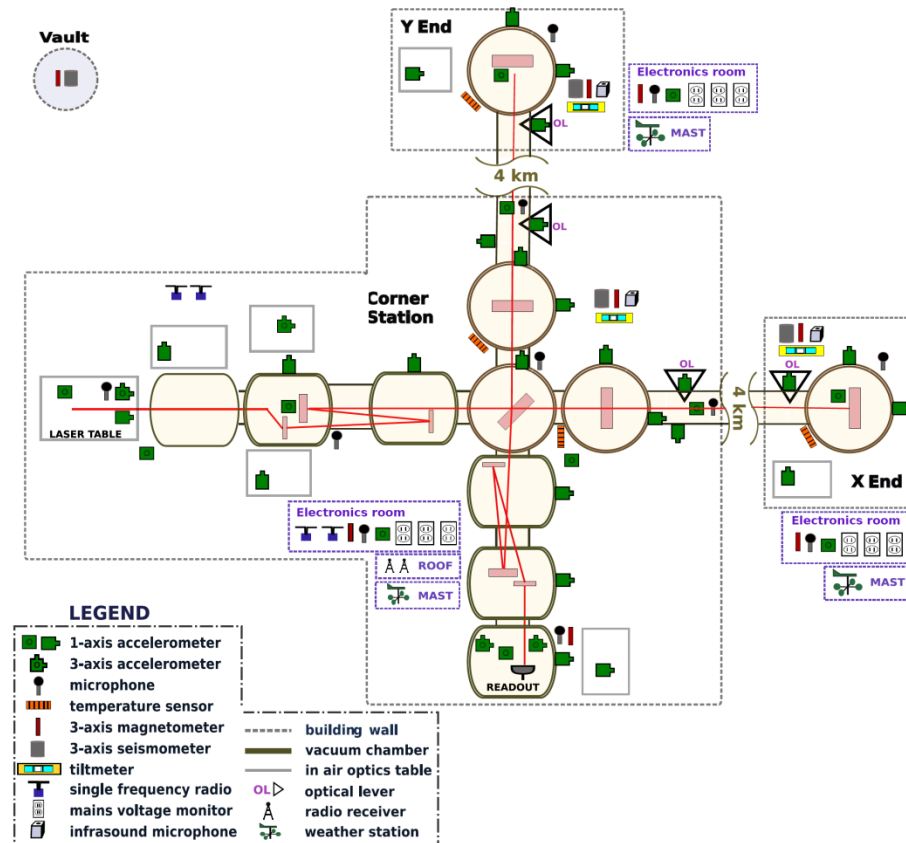
From Marco Drago★
Subject **[CBC] Very interesting event on ER8**

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

- 20 minutes later: **no signal injected** at that time
 - Confirmed officially at 17:59 that day – blind injections useful to test pipelines
- 10 minutes later: **binary black hole** candidate
- 25 minutes later: **data quality** looks OK in both IFOs at the time of the event
- 15 minutes later: **preliminary estimates of the signal parameters**
 - False alarm rate $< 1 / 300$ years: a significant event!
- Two days later (09/16, 14:39 CET): **alert circular sent to follow-up partners**

Data quality

- Detector configuration frozen to integrate enough data for background studies
 - ~40 days (until end of October) corresponding to 16 days of coincidence data
 - Steady performances over that period
- Tens of thousands of probes monitor the interferometer status and the environment
 - Virgo: $h(t) \sim 100$ kB/s
DAQ ~ 30 MB/s
- Help identifying couplings with GW channel
 - Quantify how big a disturbance should be to produce such a large signal
 - Not to mention the distinctive shape of the GW150914 signal
- Extensive studies performed
 - Uncorrelated and correlated noises
 - Bad data quality periods identified and vetoed
 - Clear conclusions: nominal running, no significant environmental disturbance



Background estimation

- Studies show that GW150914 is not due to issues with the interferometer running, nor the reflection of environmental disturbances (correlated or not)
 - How likely is it to be due to « expected » noise fluctuations?
 - Assess signal significance!

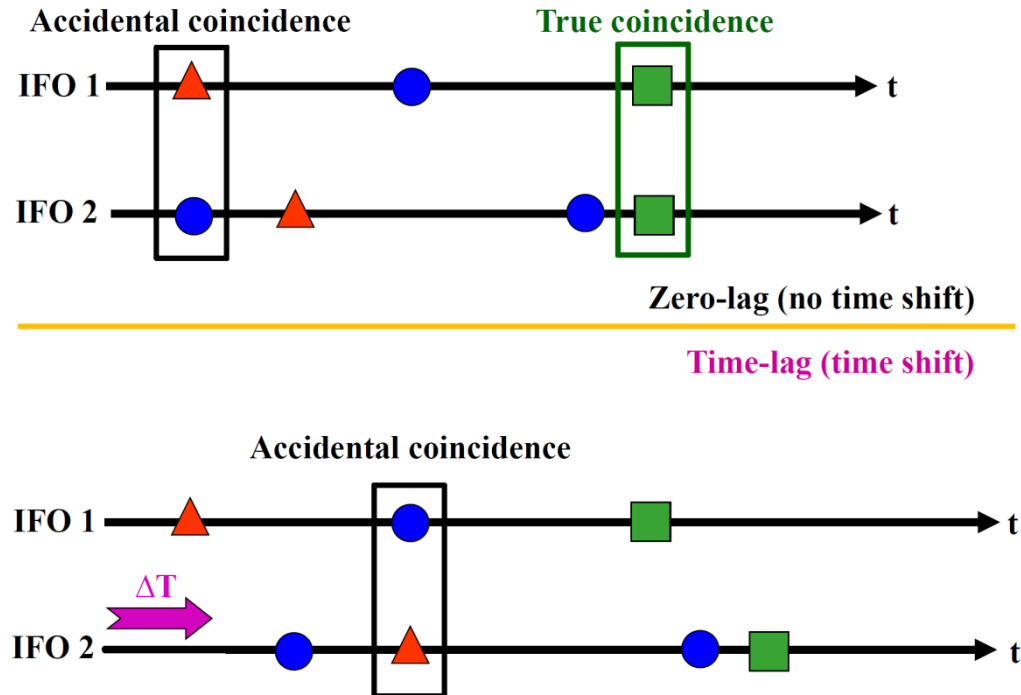
- Input: 16 days of coincidence data
 - Time shift method to generate a much larger background dataset

- Reminder: real GW events are shifted by 10 ms at most between IFOs

- Light travel time over 3,000 km

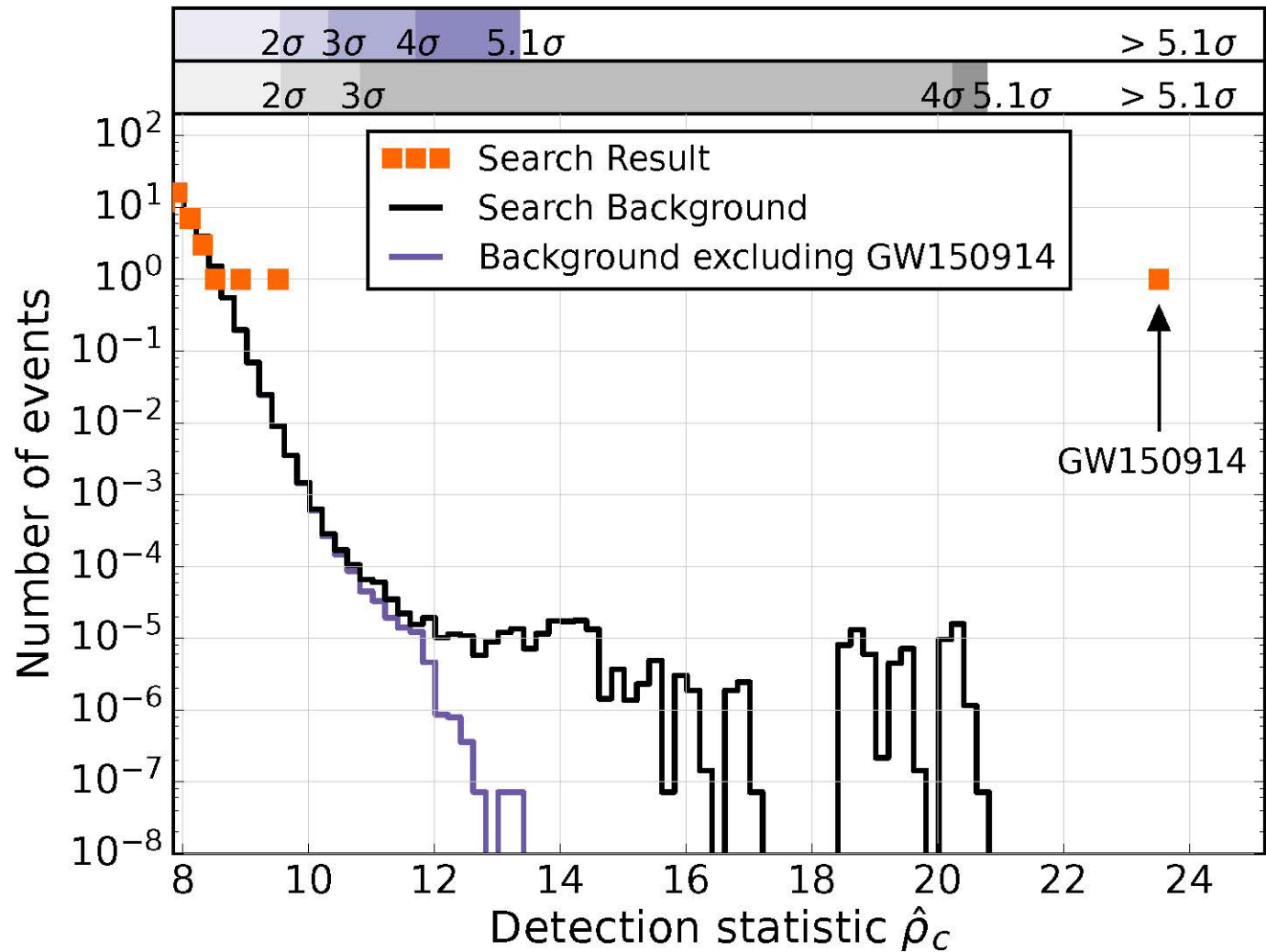
- By shifting one IFO datastream by a (much) larger time, one gets new datastreams in which « time » coincidence are necessarily due to noise

- 16 days of coincident data → tens of thousands years of background « data »



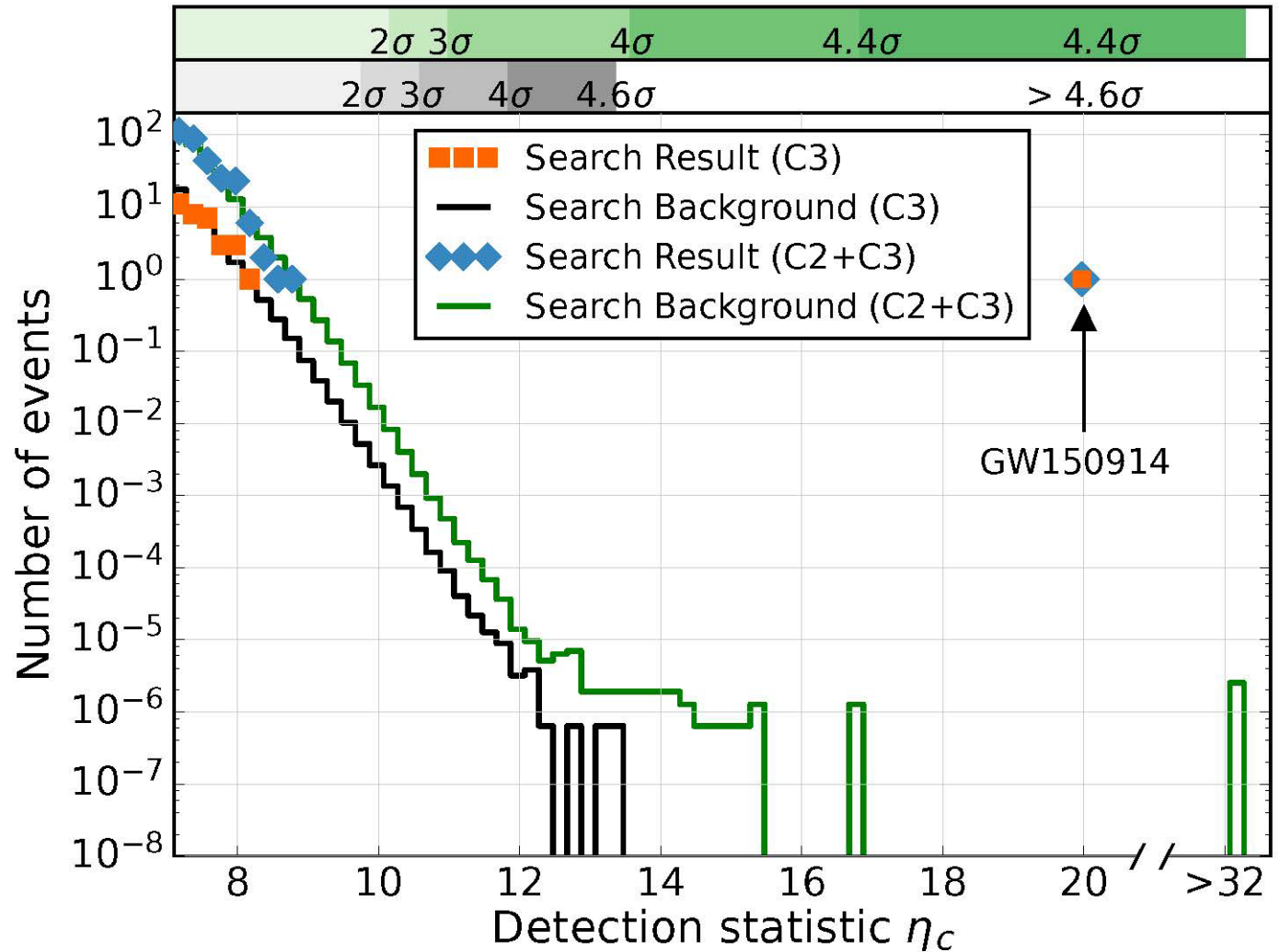
Signal significance – CBC analysis

- **x-axis: detection statistic used to rank events (the « SNR »)**
 - **GW150914: strongest event (true in both IFOs)**
- **Observed (zero-lag) events**
- **Solid lines: 2 background estimations (from time-lag)**
- **SNR ~ 23.6 ; false alarm rate < 1 event / 203,000 years
false alarm probability $< 2 \times 10^{-7}$ ($> 5.1 \sigma$)**



Signal significance – Burst analysis

- Similar plot



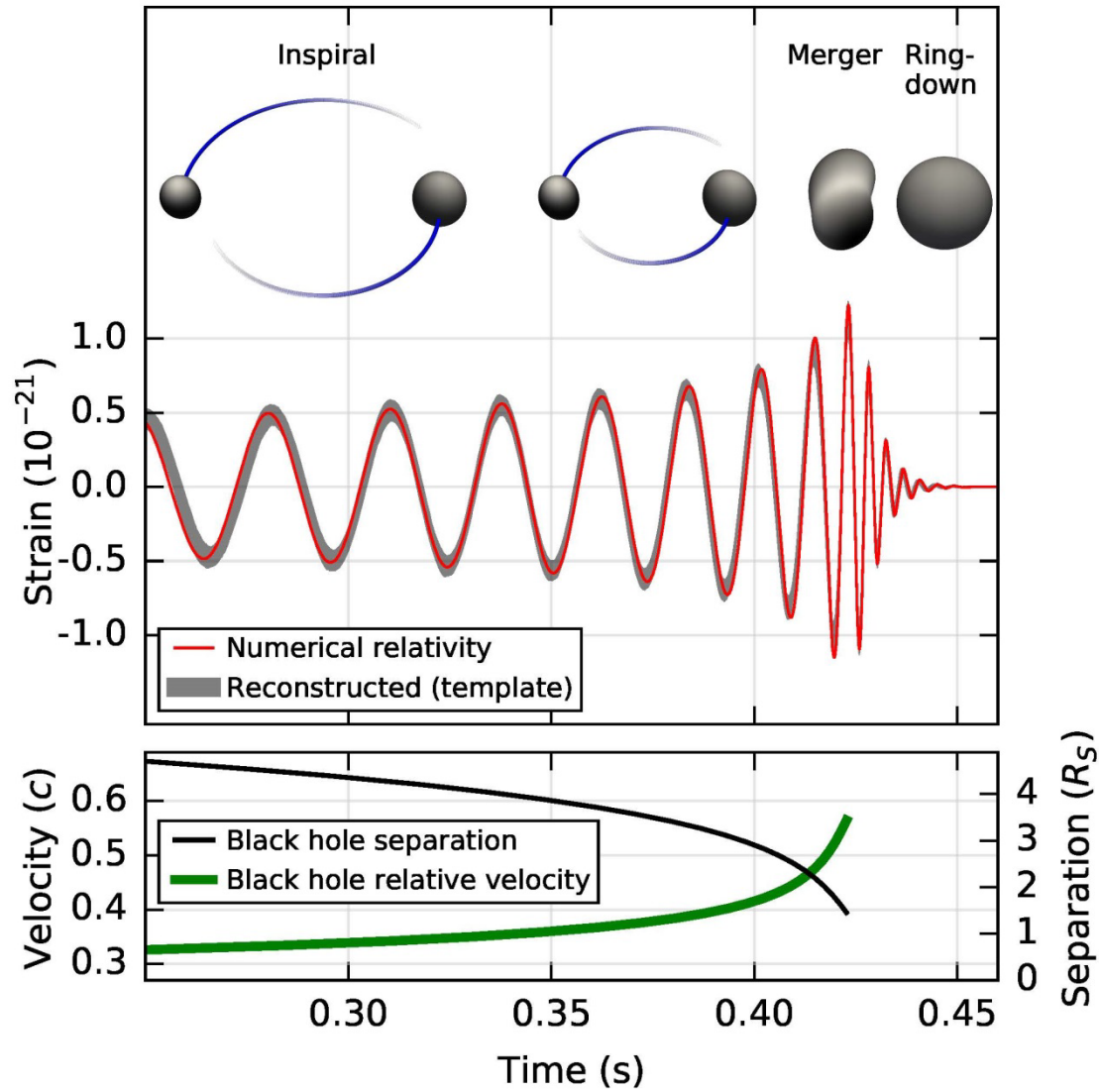
- False alarm rate < 1 event / 67,400 years
False alarm probability $< 2 \times 10^{-6}$ ($> 4.6 \sigma$)

Why two black holes?

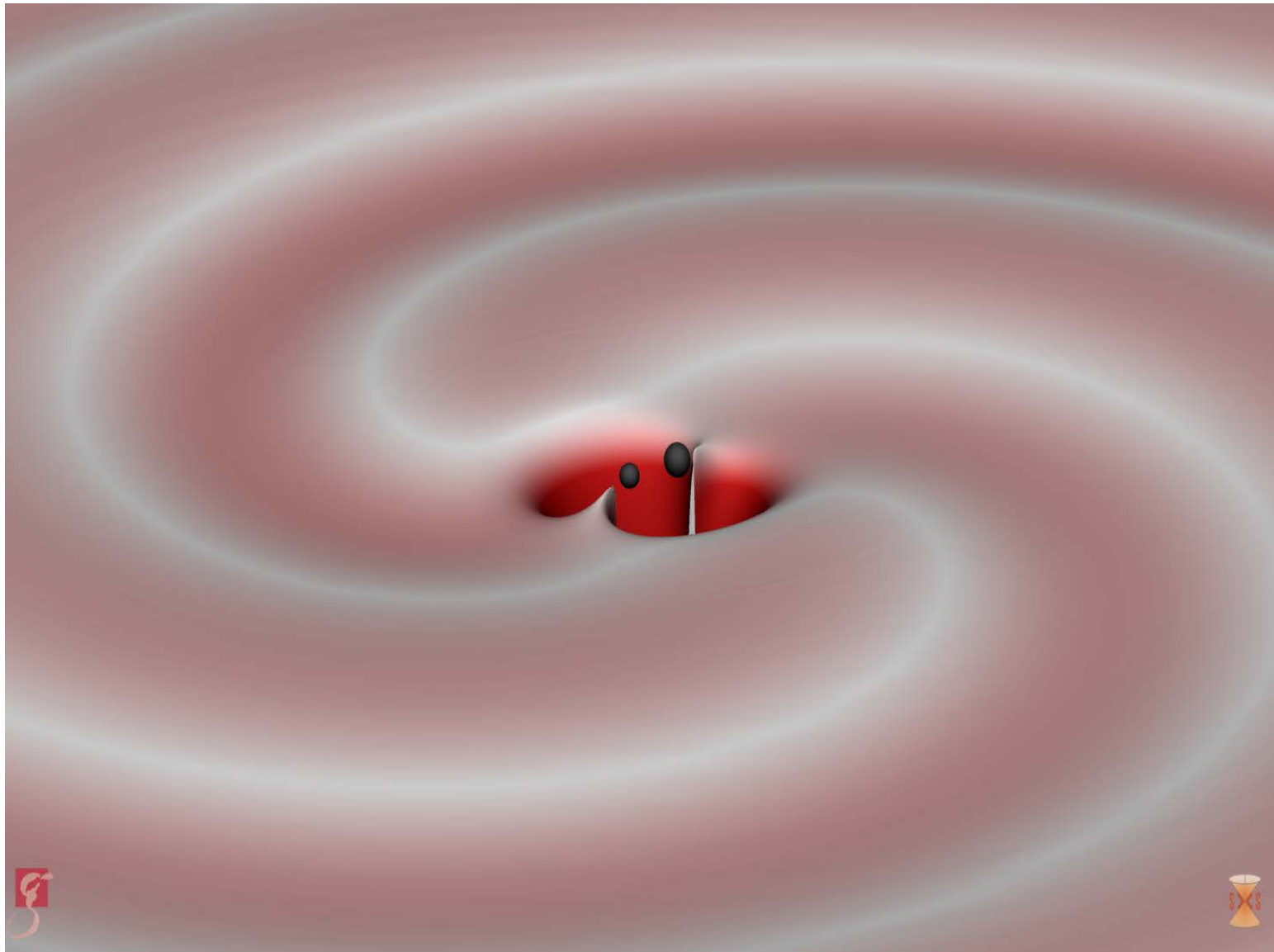
- **Result of matched filtering!**
 - Excellent match between the best template and the measured signal
- Two massive compact objects orbiting around each other at 75 Hz (half the GW frequency), hence at **relativistic speed**, and getting **very close** before the merging: only a few R_S away!

→ Black holes are the only known objects which can fit this picture

- **About $3 M_{\text{Sun}}$ radiated in GW**
- **The « brightest » event ever seen**
 - More powerful than any gamma-ray burst detected so far
 - Peak power larger than 10 times the power emitted by the visible Universe



Simulation of the coalescence

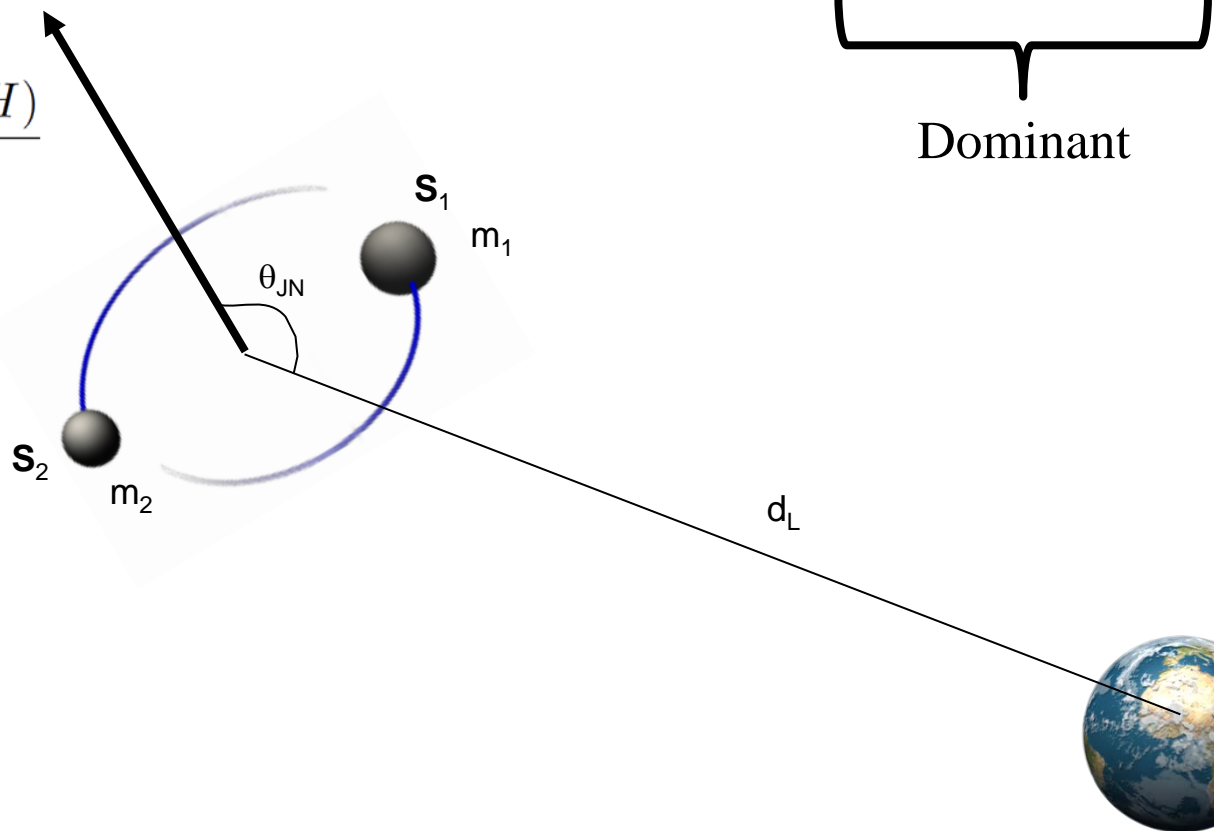


Parameter estimation

- **15 parameters total**
 - Initial masses, initial spins, final mass, final spin, distance, inclination angle + precession angle (if exists)
- **Bayesian inference**
 - Probability density function for each parameter: mean value + **statistical errors**

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

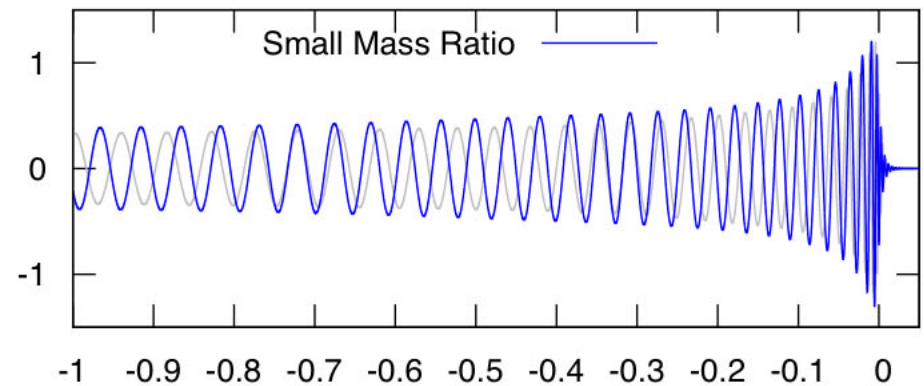
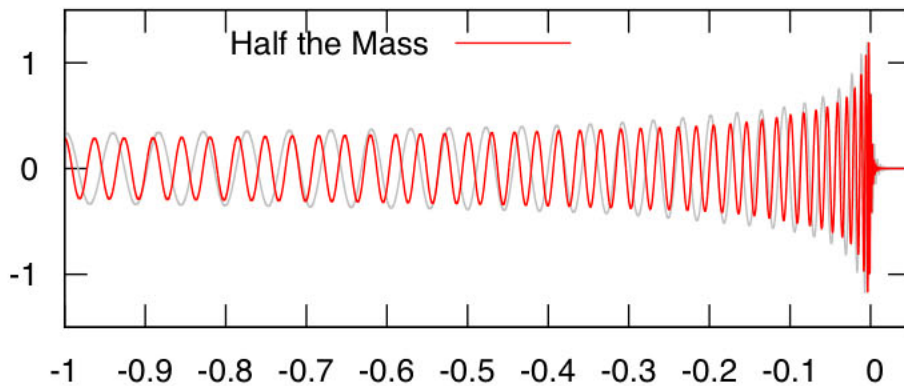
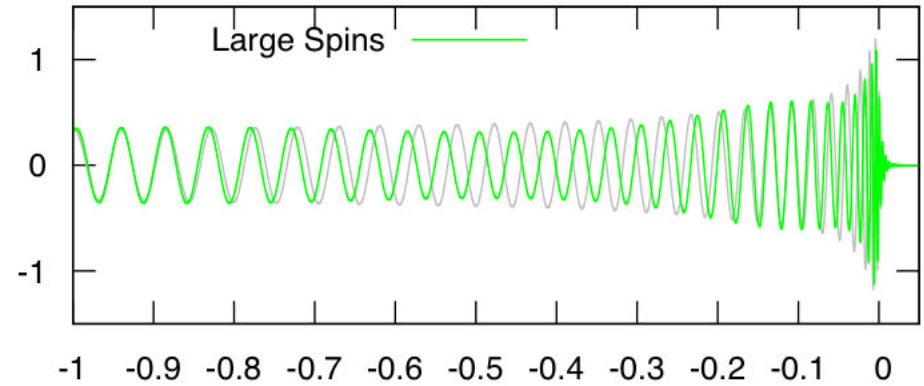
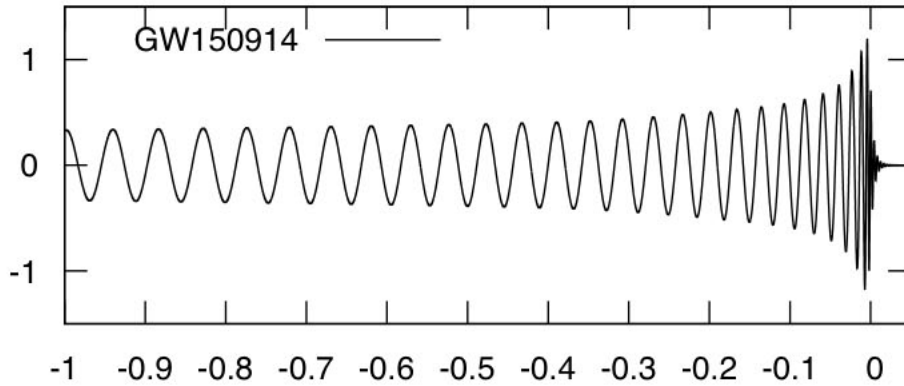
- θ : Parameters
- d : Data
- H : Model
- Compare results from two models
→ **Systematic errors**



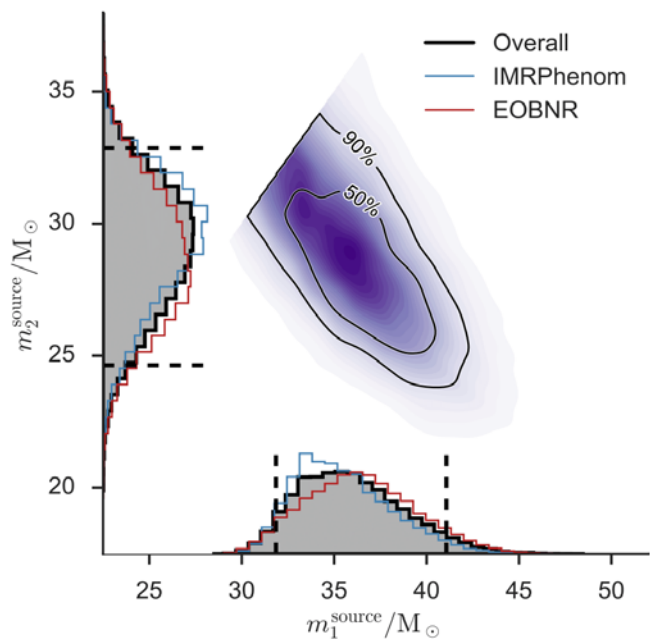
$$O_{ij} = \frac{P(H_i|d)}{P(H_j|d)}$$

Parameter estimation

- Impact of the black hole parameters on the waveform

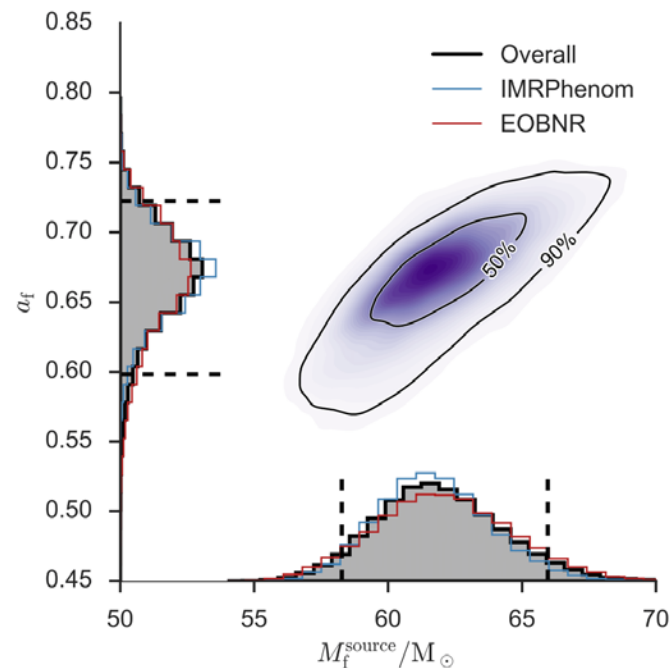


Main results



Individual masses

$$\begin{cases} m_1 = 36^{+5}_{-4} M_\odot \\ m_2 = 29^{+4}_{-4} M_\odot \end{cases}$$



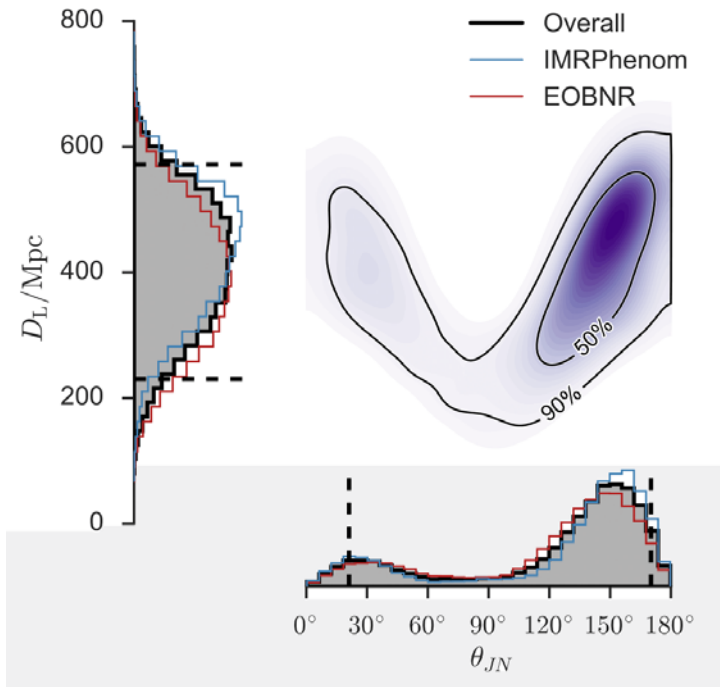
Final BH mass and spin

$$\begin{aligned} M_f &= 62^{+4}_{-4} M_\odot \\ a_f &= 0.67^{+0.05}_{-0.07} \end{aligned}$$

Final black hole has about
 the area of Iceland



Main results

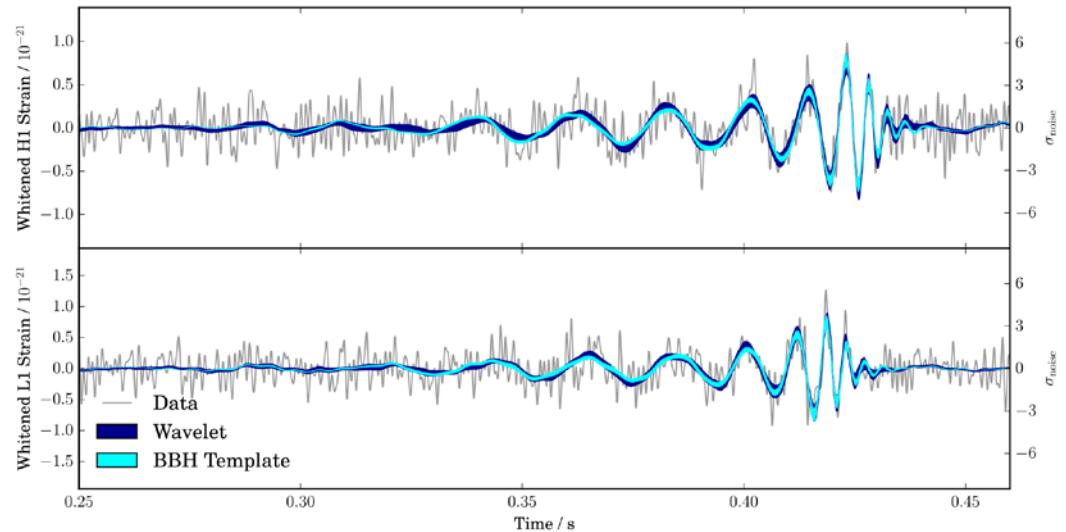


Degeneracy luminosity distance / inclination angle

- Face-on binary favored
- Luminosity distance ~ 400 Mpc – large error bar

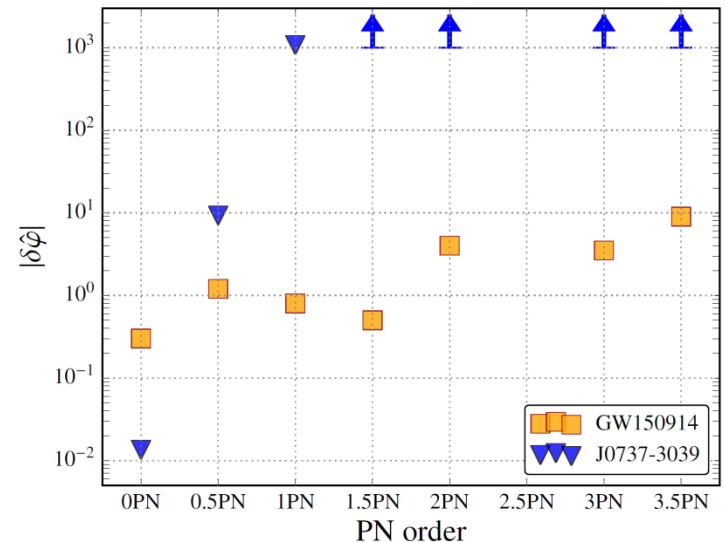
Waveform reconstruction

→ Excellent agreement between matched filtering (BBH template) and wavelet (burst reconstruction)



Testing general relativity

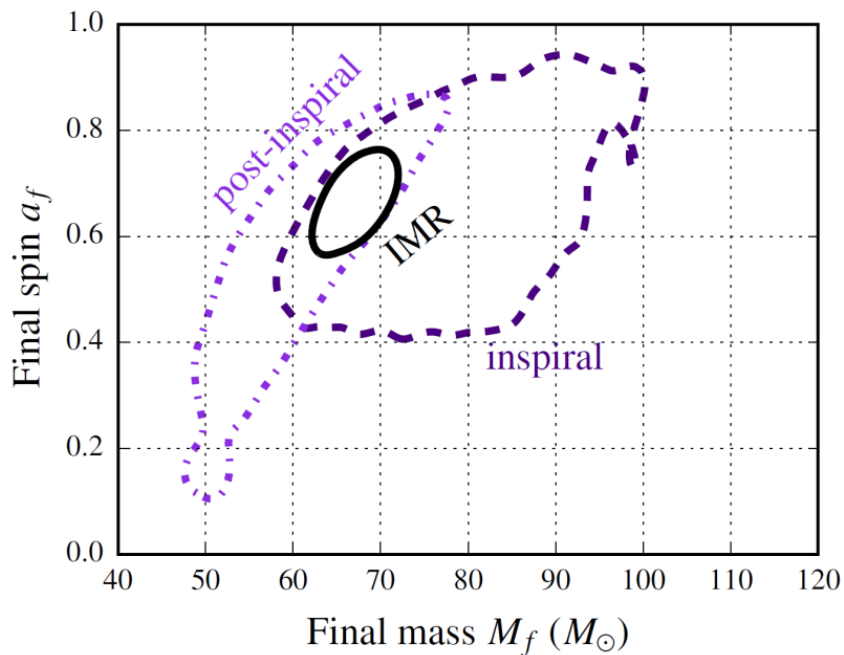
- Previous tests : solar system, binary pulsars, cosmology
 - Weak fields, linear regime ...
- With GW150914 : strong field, non-linear regime, relativistic velocities
 - New tests !
- Simplest test : data subtracted with closest predicted waveform
 - Residuals are compatible with Gaussian noise within measurement accuracy
 - Deviations from GR constrained to be less than 4%
- Search for deviations from GR prediction for PN expansion of the inspiral signal phase ($x\text{PN} \Leftrightarrow (v/c)^{2x}$)
 - Weak constraints but the best up to now except lowest order (few number of cycles)



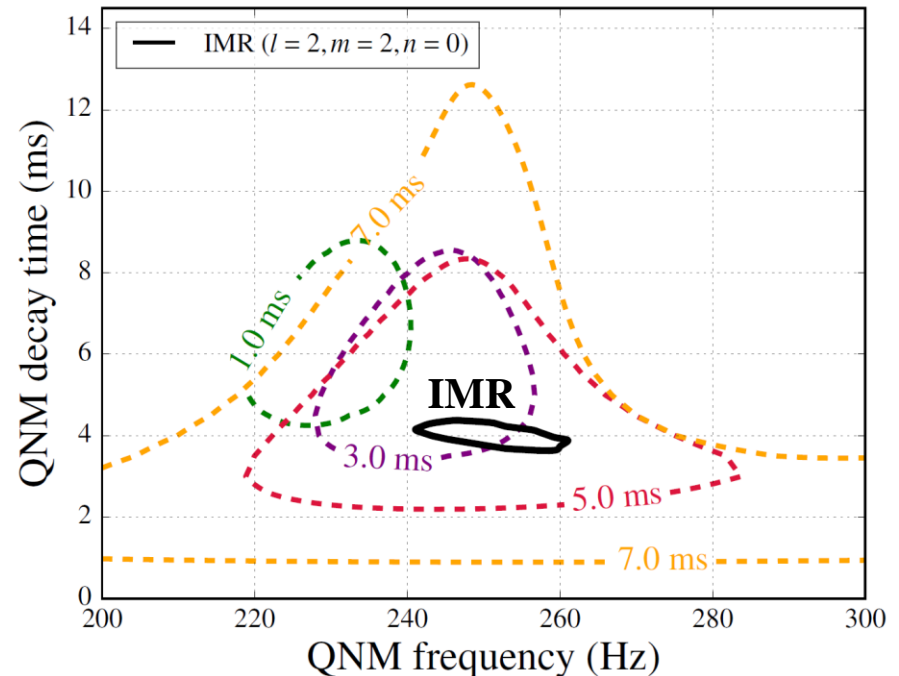
Testing general relativity

- Consistency tests

- The reconstructed waveform has 3 distinct regimes:
inspiral + merger + ringdown (IMR)



Consistency of parameters
from different regimes
(90% confidence region)



Best ringdown parameters
 $f \sim 250$ Hz, $\tau \sim 4$ ms
(Damped sinusoid model)
(4 different start times – offsets
from the merging time)

Bound on the graviton mass

- If the graviton were massive

- Dispersion relation

- Propagation velocity would depend on energy $v_g^2 = c^2 \left(1 - \frac{m_g^2 c^4}{2E^2} \right)$

→ Additional terms in the phase of the inspiral signal

where D is the distance, z the redshift and

$$\delta\phi(f) = \frac{\pi D c}{(1+z)\lambda_g^2} \frac{1}{f}$$

$\lambda_g = \frac{h}{m_g c}$ is the graviton Compton wavelength

- GW150914 data: $\lambda_g > 10^{13} \text{ km}$ or equivalently $m_g < 10^{-22} \text{ eV}$
 - Best limit!

- Best previous limit in solar system tests (Mars) : $\lambda_g > 3 \times 10^{12} \text{ km}$
 - Yukawa correction to the Newtonian potential

$$V(r) = \frac{GM}{r} \exp\left(-\frac{r}{\lambda_g}\right)$$

- Binary pulsars tests: not competitive $\lambda_g > 10^9 - 10^{10} \text{ km}$

GW150914: FACTSHEET

BACKGROUND IMAGES: TIME-FREQUENCY TRACE (TOP) AND TIME-SERIES (BOTTOM) IN THE TWO LIGO DETECTORS; SIMULATION OF BLACK HOLE HORIZONS (MIDDLE-TOP), BEST FIT WAVEFORM (MIDDLE-BOTTOM)

first direct detection of gravitational waves (GW) and first direct observation of a black hole binary

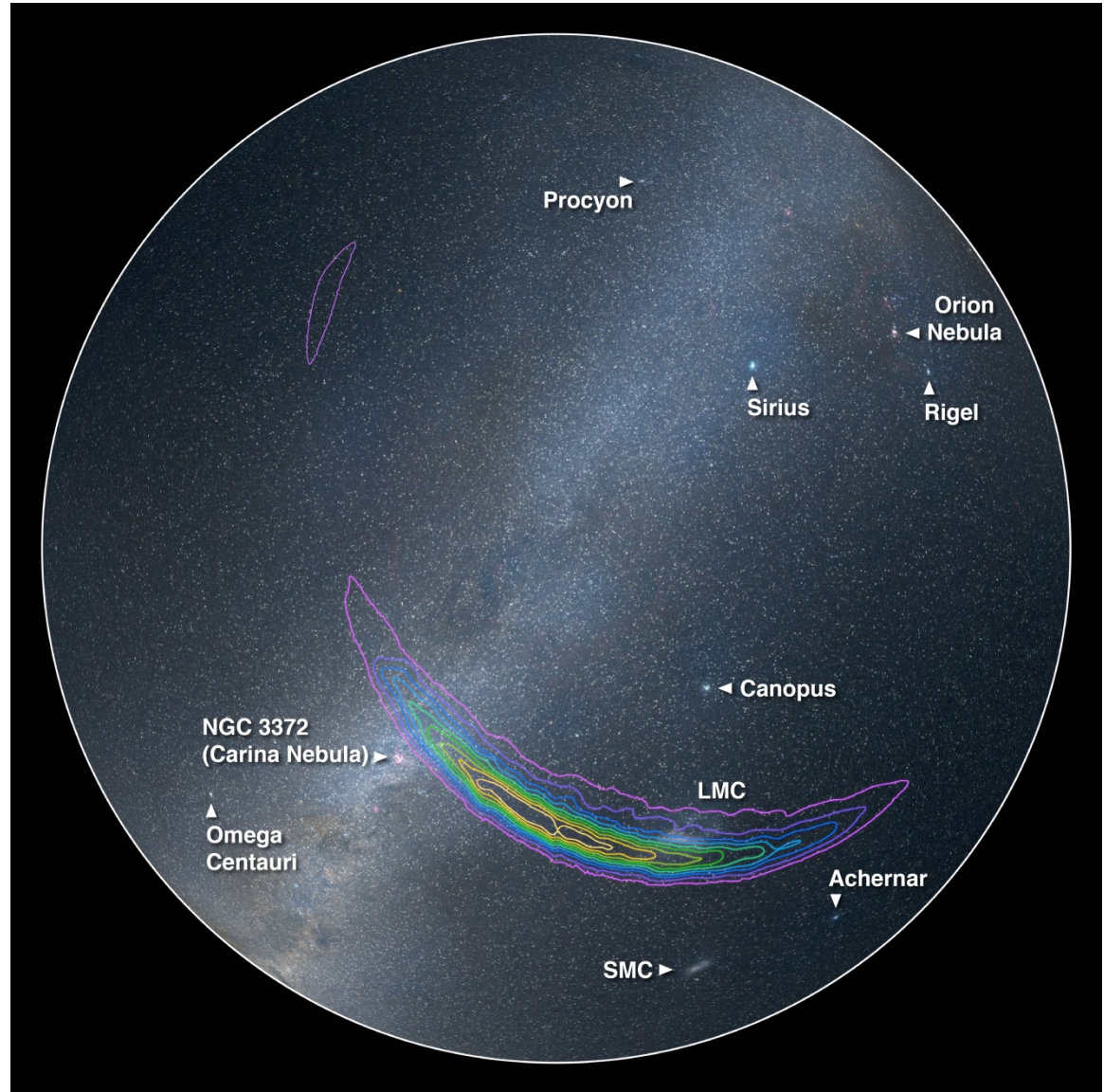
observed by	LIGO L1, H1	duration from 30 Hz	~ 200 ms
source type	black hole (BH) binary	# cycles from 30 Hz	~10
date	14 Sept 2015	peak GW strain	1×10^{-21}
time	09:50:45 UTC	peak displacement of interferometers arms	± 0.002 fm
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc	frequency/wavelength at peak GW strain	150 Hz, 2000 km
redshift	0.054 to 0.136	peak speed of BHs	~ 0.6 c
signal-to-noise ratio	24	peak GW luminosity	3.6×10^{56} erg s ⁻¹
false alarm prob.	< 1 in 5 million	radiated GW energy	2.5-3.5 M _⊙
false alarm rate	< 1 in 200,000 yr	remnant ringdown freq.	~ 250 Hz
Source Masses	M _⊙	remnant damping time	~ 4 ms
total mass	60 to 70	remnant size, area	180 km, 3.5×10^5 km ²
primary BH	32 to 41	consistent with general relativity?	passes all tests performed
secondary BH	25 to 33	graviton mass bound	< 1.2×10^{-22} eV
remnant BH	58 to 67	coalescence rate of binary black holes	2 to 400 Gpc ⁻³ yr ⁻¹
mass ratio	0.6 to 1	online trigger latency	~ 3 min
primary BH spin	< 0.7	# offline analysis pipelines	5
secondary BH spin	< 0.9	CPU hours consumed	~ 50 million (=20,000 PCs run for 100 days)
remnant BH spin	0.57 to 0.72	papers on Feb 11, 2016	13
signal arrival time delay	arrived in L1 7 ms before H1	# researchers	~1000, 80 institutions in 15 countries
likely sky position	Southern Hemisphere		
likely orientation resolved to	face-on/off ~600 sq. deg.		

Detector noise introduces errors in measurement. Parameter ranges correspond to 90% credible bounds.

Acronyms: L1=LIGO Livingston, H1=LIGO Hanford; Gly=giga lightyear= 9.46×10^{12} km; Mpc=mega parsec=3.2 million lightyear, Gpc= 10^3 Mpc, fm=femtometer= 10^{-15} m, M_⊙=1 solar mass= 2×10^{30} kg

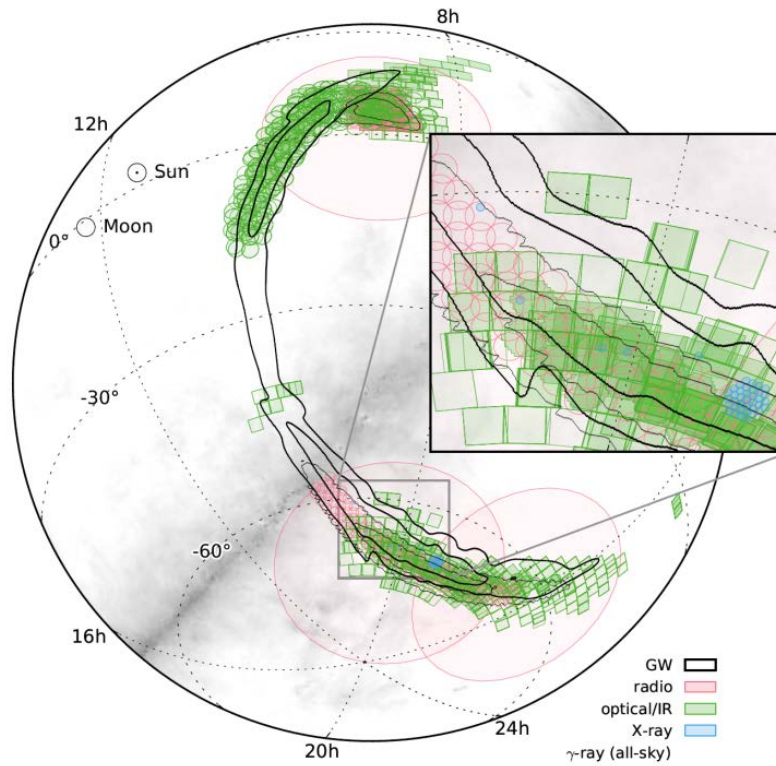
Skymap

- Sky at the time of the event
- Skymap contoured in deciles of probability
- 90% contour :
~ 590 degrees²
 - Full Moon: 0.5 degrees²
- View is from the South Atlantic Ocean, North at the top, with the Sun rising and the Milky Way diagonally from NW to SE

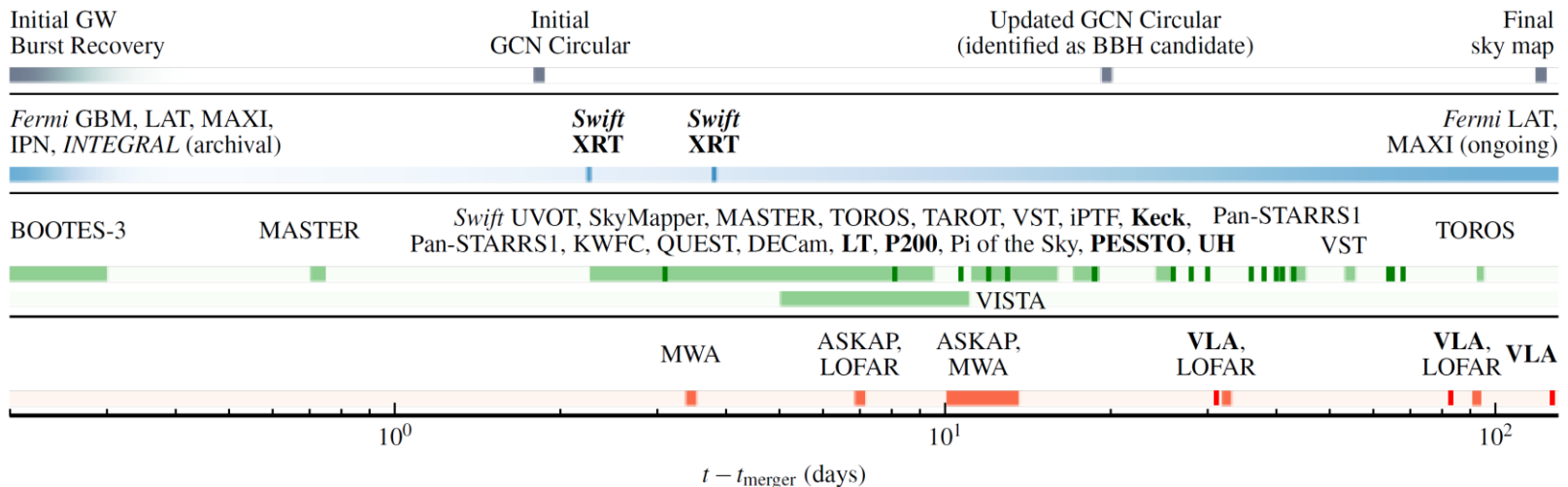


Looking for GW150914 counterparts

- Sky coverage



- Observation timeline: **no counterpart found** – none expected for a binary black hole



GW151226

GW151226

- Observed on ‘Boxing Day’
 - Online trigger from the matched filtering analysis
 - Not detected by the burst online search
 - Detailed studies delayed by the completion of the GW150914 analyses

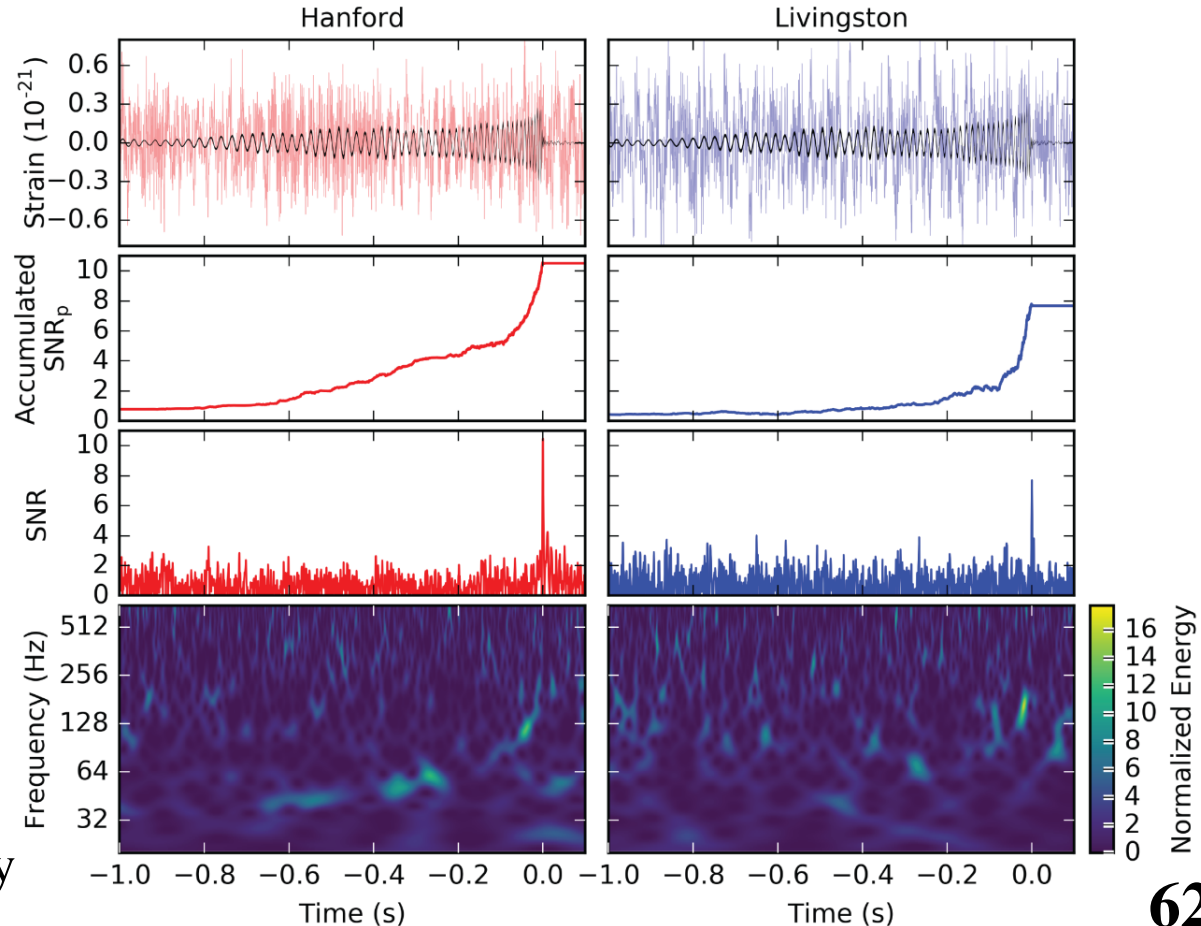
- Not all GW signals visible to the naked eye!

- Another binary black hole coalescence

- Lighter black holes
 - 14 and 8 M_{\odot}

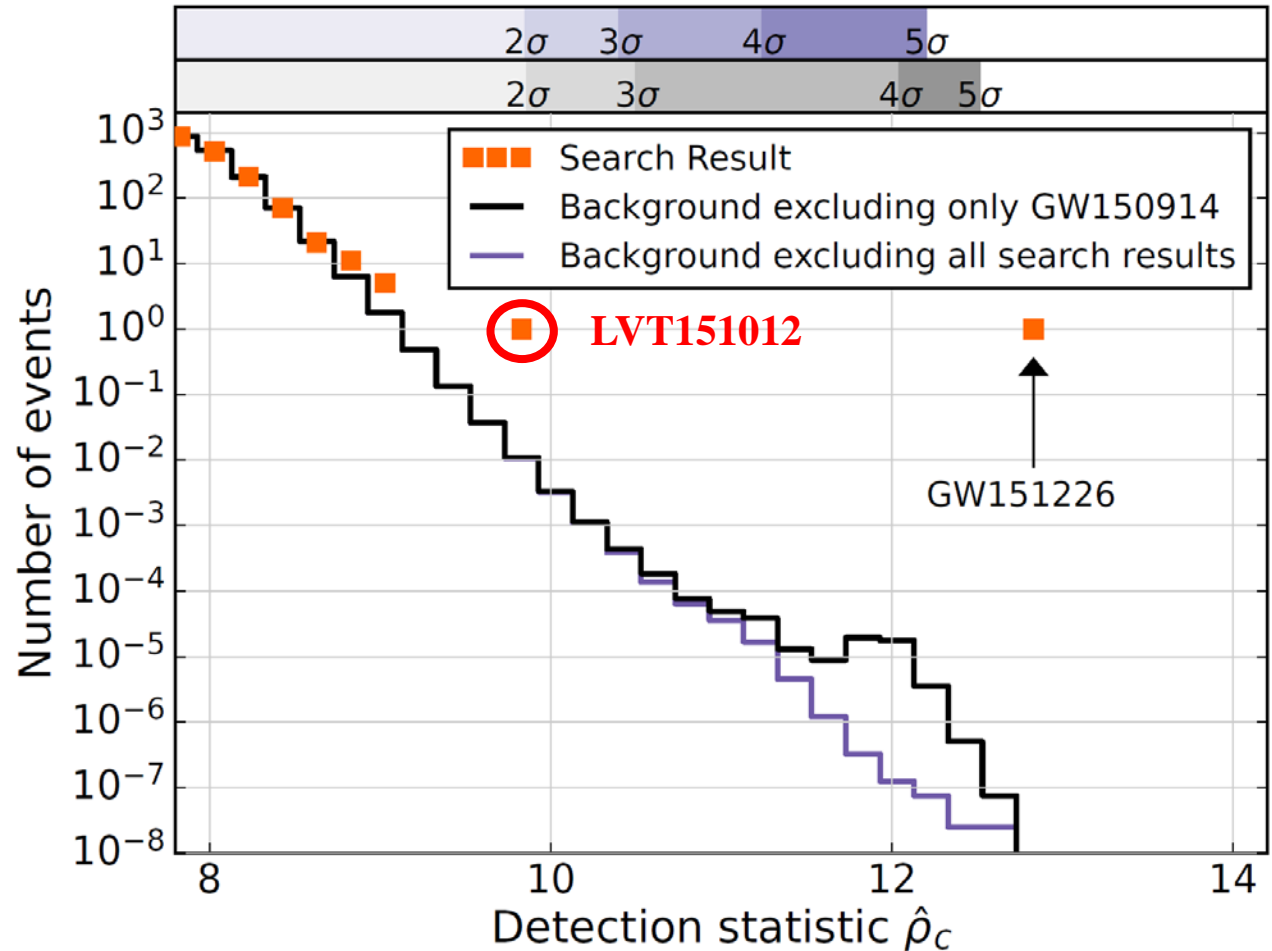
- Smaller amplitude
- More cycles in the detector bandwidth

→ Matched filtering mandatory



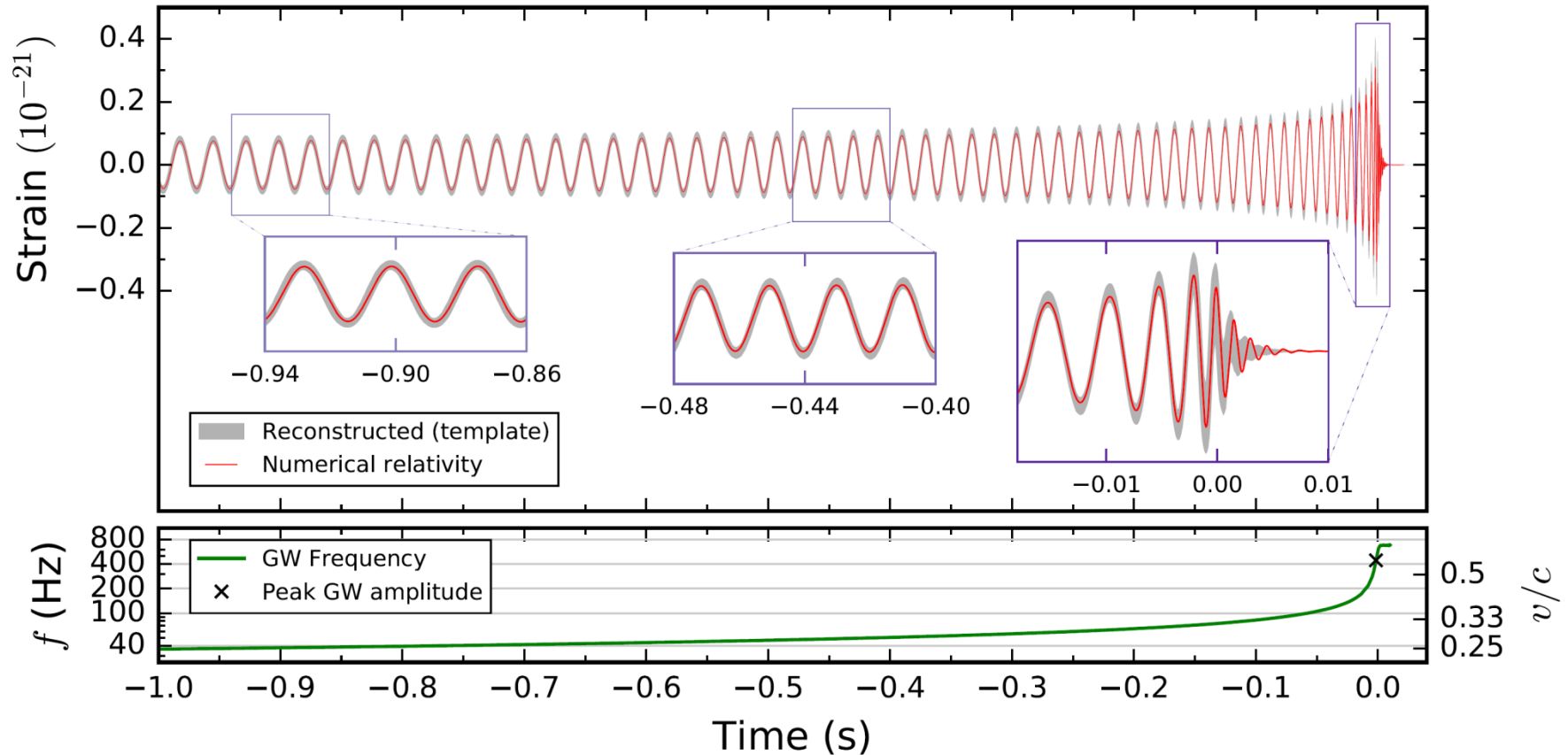
GW151226

- **2nd largest event recorded**
 - After GW150914
- **A third candidate:**
LVT151012
 - Lower statistical significance
→ « Source »
much further away (~1 Gpc)
- In this plot, GW150914 has been removed to estimate the bkg as it is a true signal



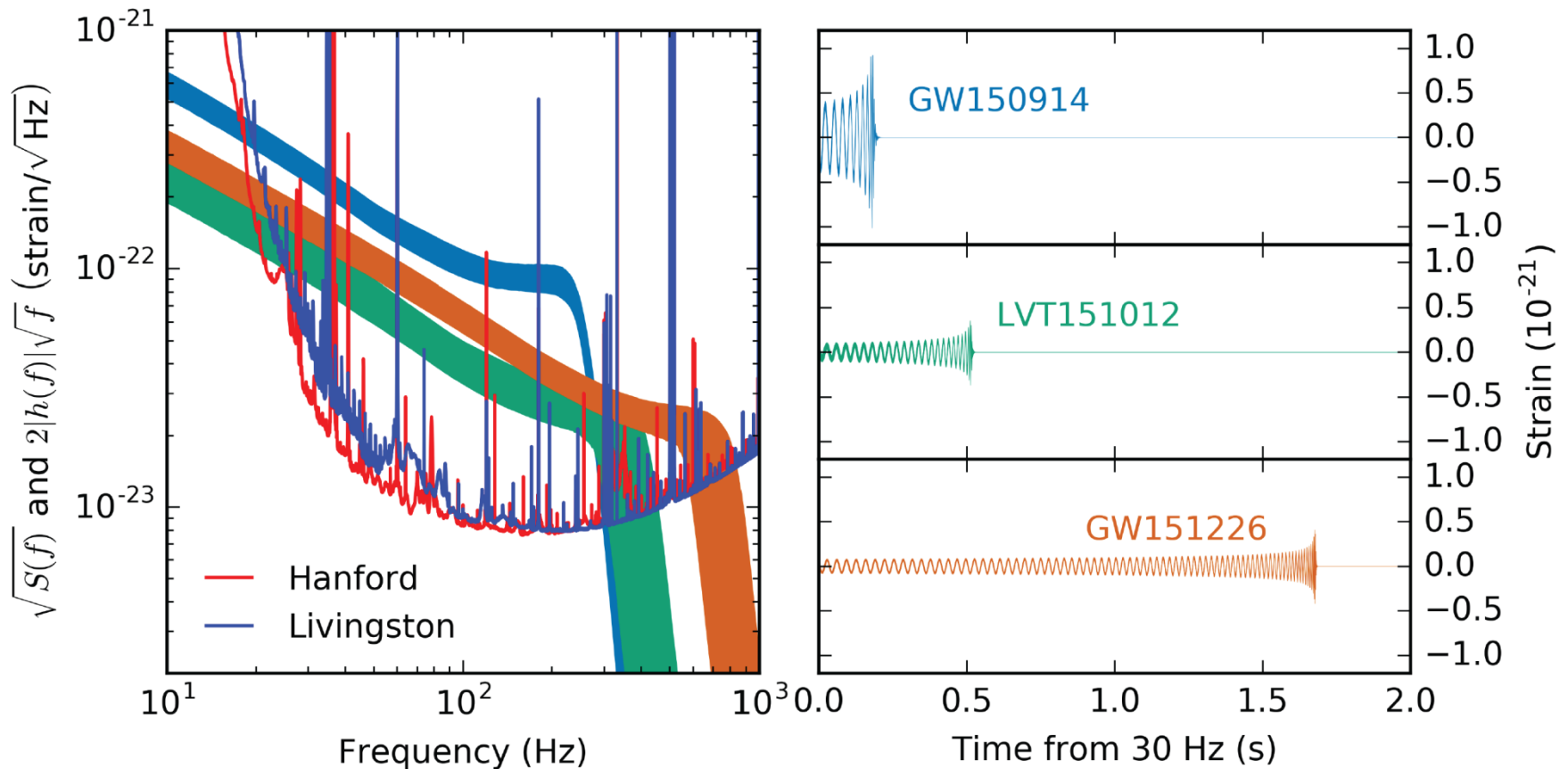
GW151226

- **Excellent agreement** between the different reconstructed waveforms
 - **analytical computation** (post-Newtonian expansion, in grey)
 - **numerical relativity** (in red)



In summary: two events, one candidate

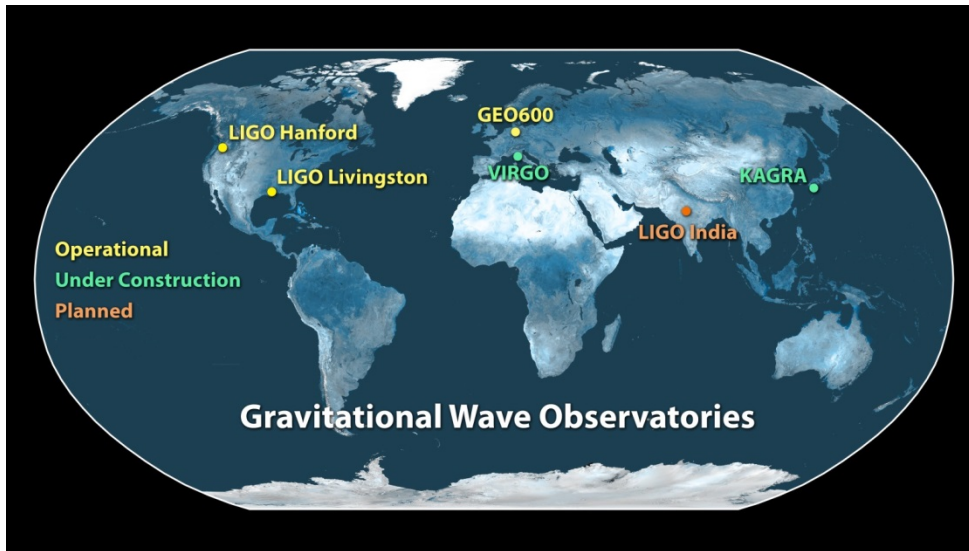
- Black hole binary systems
- No other GW source observed so far



Conclusions

Prospects

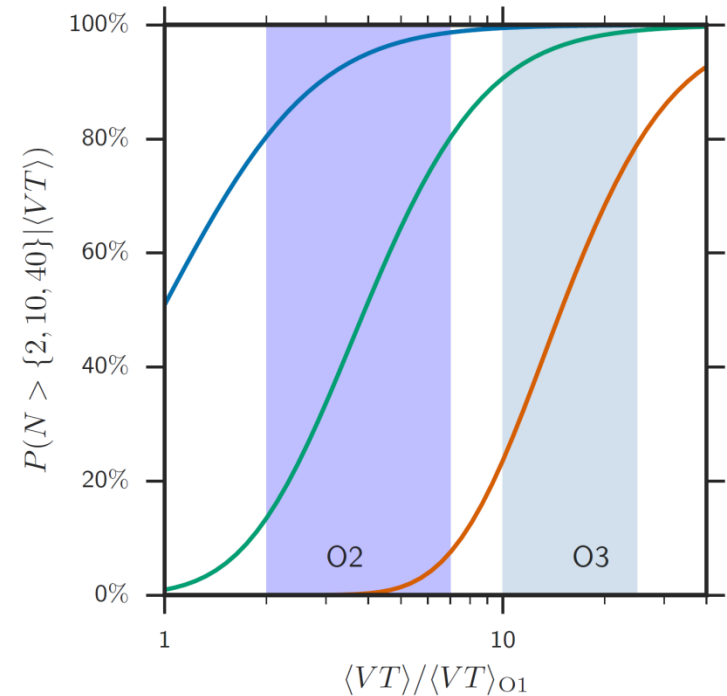
- Soon: a **ground-based detector network**
 - **larger** and
 - **more sensitive**



→ On can expect to detect (much) more GW signals soon

Probabilities that the number of detections exceeds

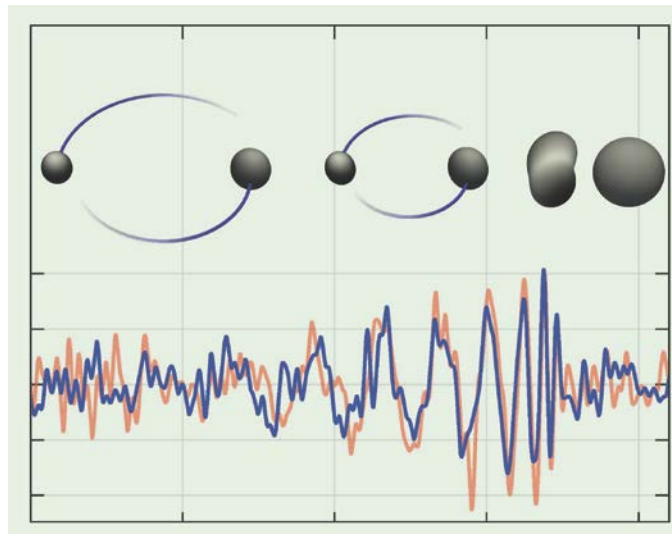
- **2**
- **10**
- **40**



OX : « **Observation** »
Run number **X**

Outlook

- The network of advanced gravitational wave interferometers is taking shape
 - The two aLIGO detectors started taking data last September and detected the first two gravitational wave signals (GW150914 and GW151226)
 - Virgo is completing its upgrade and is fully committed to joining LIGO asap
 - KAGRA should then join the network in 2018
 - And possibly a third LIGO detector (LIGO-India) some years later
- Sensitivity already good enough to detect gravitational waves
 - Improvements expected in the coming years
 - R&D activities already ongoing for 3rd generation instruments



GW detector peak sensitivity evolution vs. time

