GW150914: advanced interferometric detectors at the dawn of the gravitational wave astronomy

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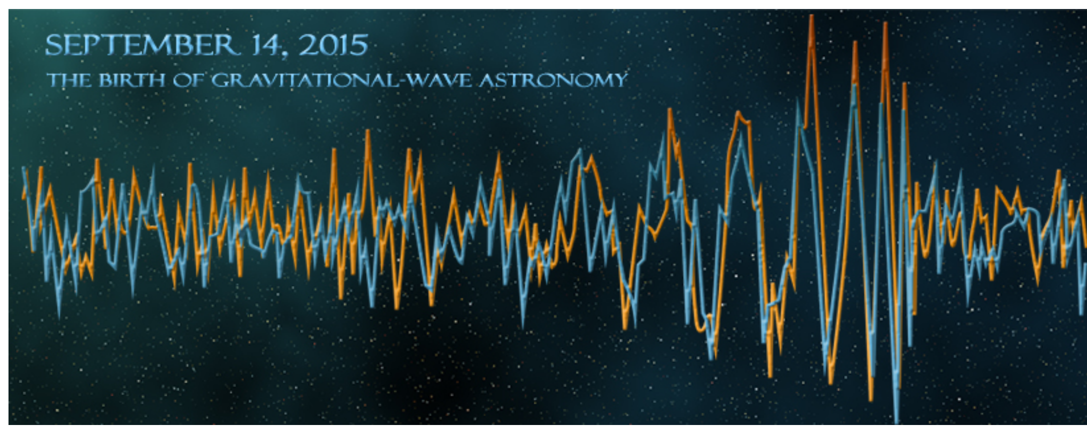
Nicolas Arnaud (narnaud@lal.in2p3.fr)
Laboratoire de l'Accélérateur Linéaire (CNRS/IN2P3 & Université Paris-Sud)
Pour la Collaboration Virgo et la Collaboration Scientifique LIGO



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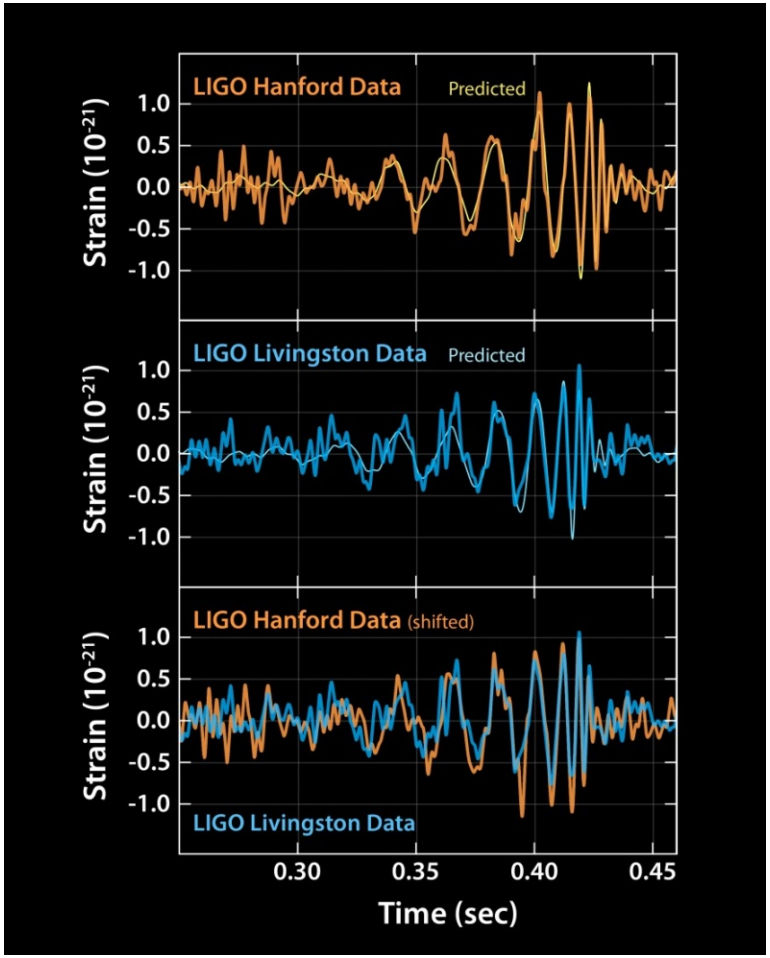
Outline

- See Tania Regimbau's plenary talk this morning
- Gravitational waves in a nutshell
  - Sources and properties
- Gravitational wave interferometric detectors
  - Principle and main characteristics
  - Advanced detectors
  - A worldwide network of detectors
- GW150914
  - The Advanced LIGO « Observation 1 » Run: September 2015 – January 2016
  - First direct detection 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 wich I borrowed ideas and material for this talk

Gravitational waves: sources and properties

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 ($g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$, $|h_{\mu\nu}| << 1$) 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

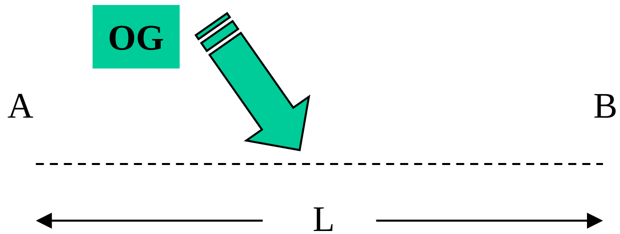
- Quadrupolar radiation
  - Need to deviate from axisymmetry to emit GW
  - No dipolar radiation – contrary to electromagnetism

- 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

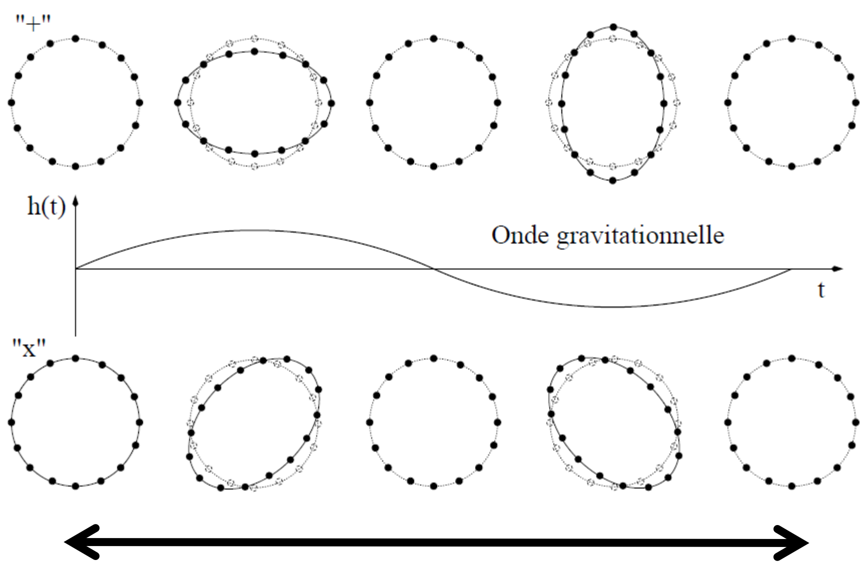
- GW: propagating perturbation of the spacetime metric
  - Acts on distance measurement between test masses (free falling)



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

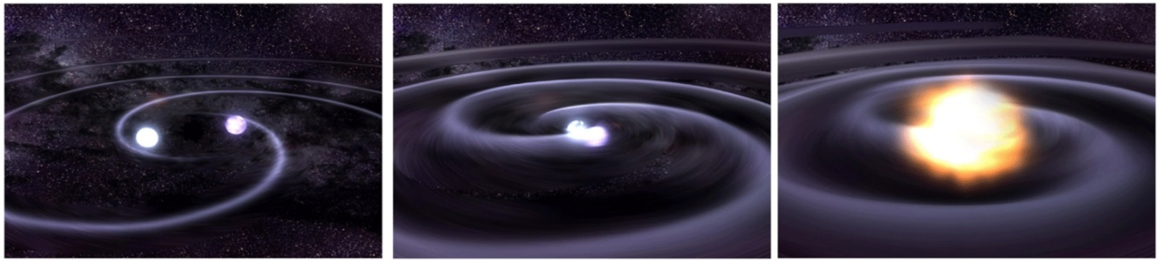
Variation doubled for an interferometer with arms of equal length L: $\delta L_{IFO} = hL$

- Effect of the two GW polarizations on a ring of free masses
  - « + » polarization
  - « × » polarization



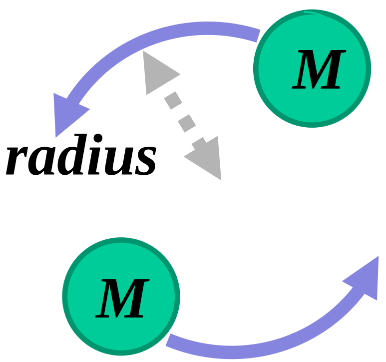
One period

A diversity of sources



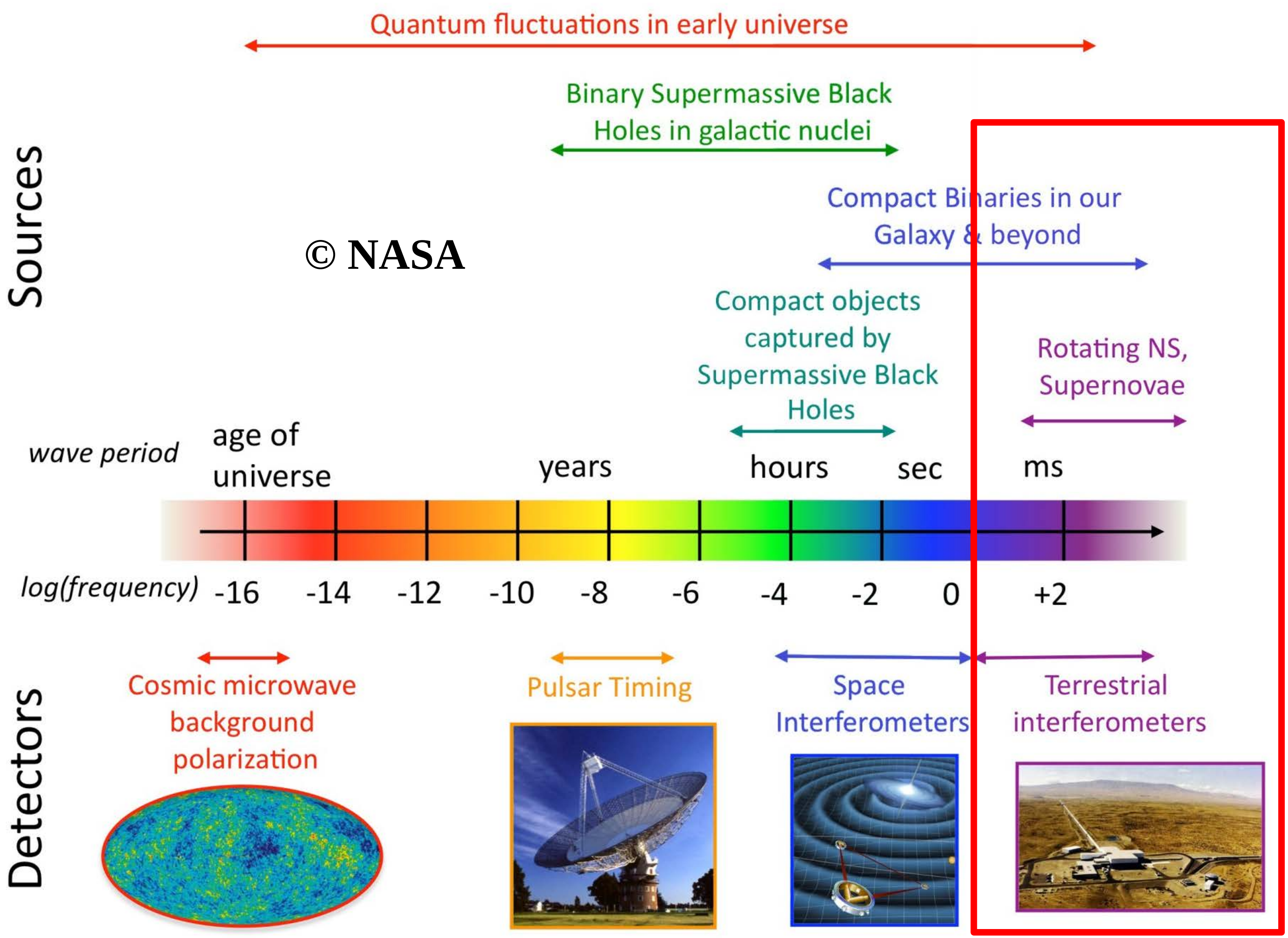
- Rough classification
  - Signal duration
  - Frequency range
  - Known/unknown waveform
  - Any counterpart (E.M., neutrinos, etc.) expected?
- Compact binary coalescence
  - Last stages of the evolution of a system like PSRB 1913+16
    $\rightarrow$ Compact stars get closer and closer while loosing energy through GW
  - Three phases: inspiral, merger and ringdown
    $\rightarrow$ Modeled via analytical computation and numerical simulations
  - Example: two masses M in circular orbit ($f_{GW} = 2\ f_{Orbital}$)

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



- Transient sources (« bursts »)
  - Example: core collapses (supernovae)
- Permanent sources
  - Pulsars, Stochastic backgrounds

Gravitational wave spectrum



LIGO, Virgo, etc.

Gravitational wave interferometric detectors

1916-2016: a century of progress

Theoretical developments

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

1957 Chapel Hill Conference (Bondi, Feynman, Pirani, etc.)

- **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.)**

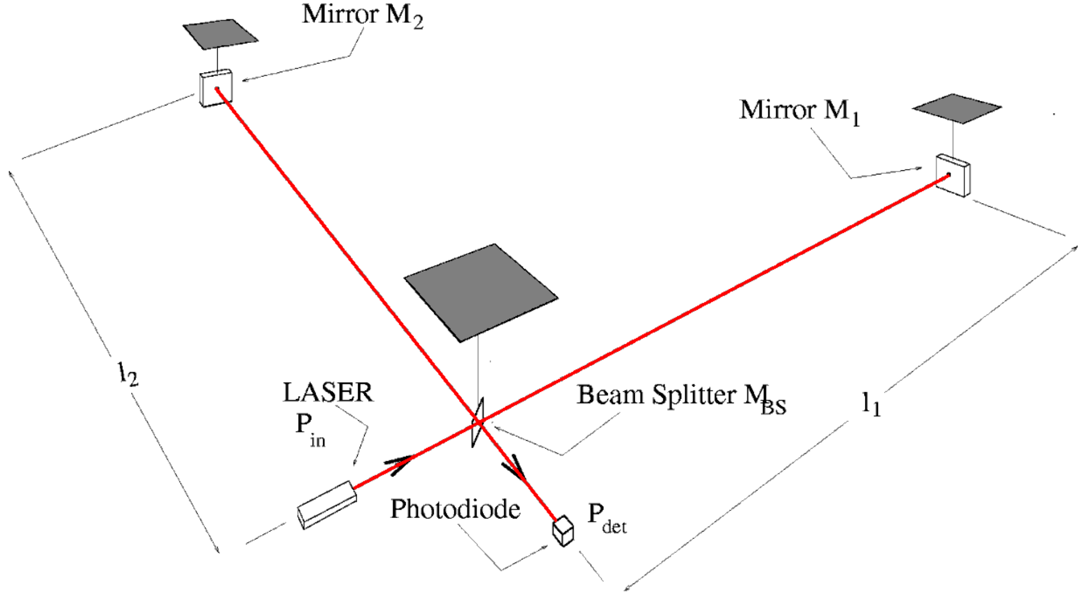
Experiments

- **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**

Gravitational wave interferometric detectors

- Instructions to build a GW detector
  - Use free test masses
  - Locate them far apart
  - Measure their relative displacement
  - Make sure their motion is not perturbated by any external source

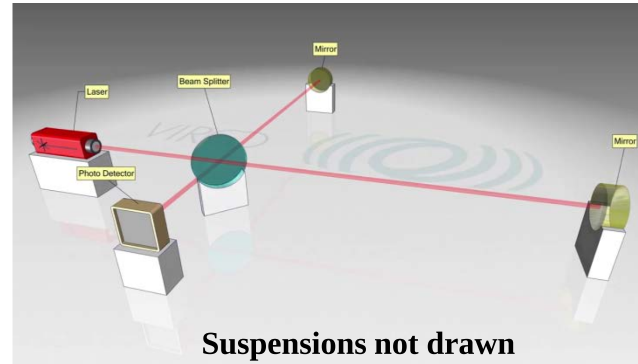
- Solution: a Michelson interferometer
  → Suspended mirrors
  → Kilometer-long arms
  → Get rid of common mode noise
  → Design + active control
  + noise mitigation/monitoring



- Incident GW
  ⇒ Optical path changes
  ⇒ Output power variation

- Best sensitivity around the dark fringe

Interferometer sensitivity



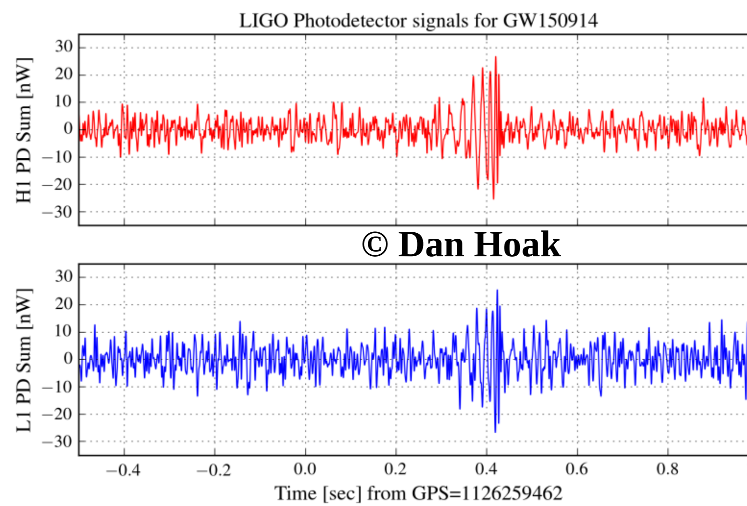
- Output power: $\delta P_{det} \propto P_{in}\, L\, h$
- Shot noise
  - A fundamental quantum noise
  - Fluctuation of the number of photons detected during a duration Δt

$$\delta P_{shot\ noise} \propto \sqrt{\frac{P_{in}}{\Delta t}}$$

$$\delta P_{det} = \delta P_{shot\ noise}$$

- Minimum detectable GW amplitude such that

$$\rightarrow \boxed{h_{min} \propto \frac{1}{\sqrt{P_{in}}\, L \sqrt{\Delta t}}}$$



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- Improving the sensitivity
  - Increase incident power on the beamsplitter
  - Increase length of the interferometer arms

Bandpass and notch filtering
25 nW offset subtracted
500 W incident on the beamsplitter

- Reaching $h_{min} \sim 10^{-22}$ or below requires
  - Kilowatts of laser power and
  - Arms about a hundred kilometer long

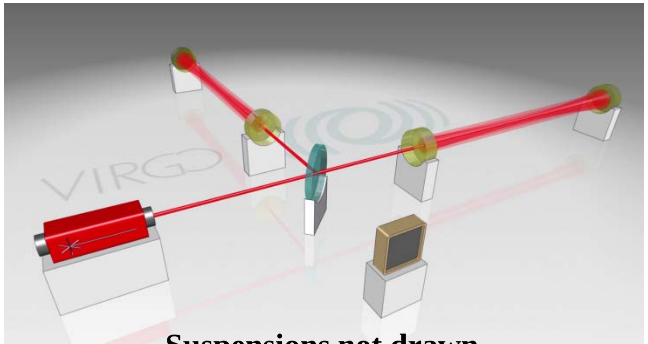
} Virgo/LIGO design

Improving the interferometer sensitivity

- Reminder: Interferometer (IFO) sensitivity $\propto \frac{1}{(\text{Arm length}) \times \sqrt{\text{Light power}}}$

→ Use high power laser, power- and frequency-stabilized
  - Tens to hundreds of watts

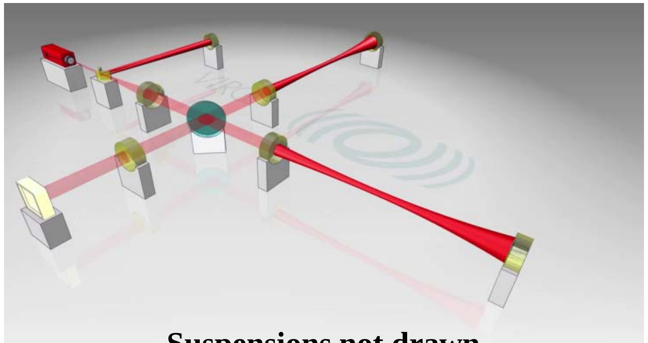
→ Kilometric arms (Virgo: 3km; LIGO: 4km)
→ Add Fabry-Perot cavities in the kilometric arms
  - Light path length increased: $L \rightarrow L \times G_{FP}$
    $G_{FP} \sim 300$ for Advanced Virgo
  - Low-pass filter on the IFO frequency response: processes faster than the light storage time are filtered



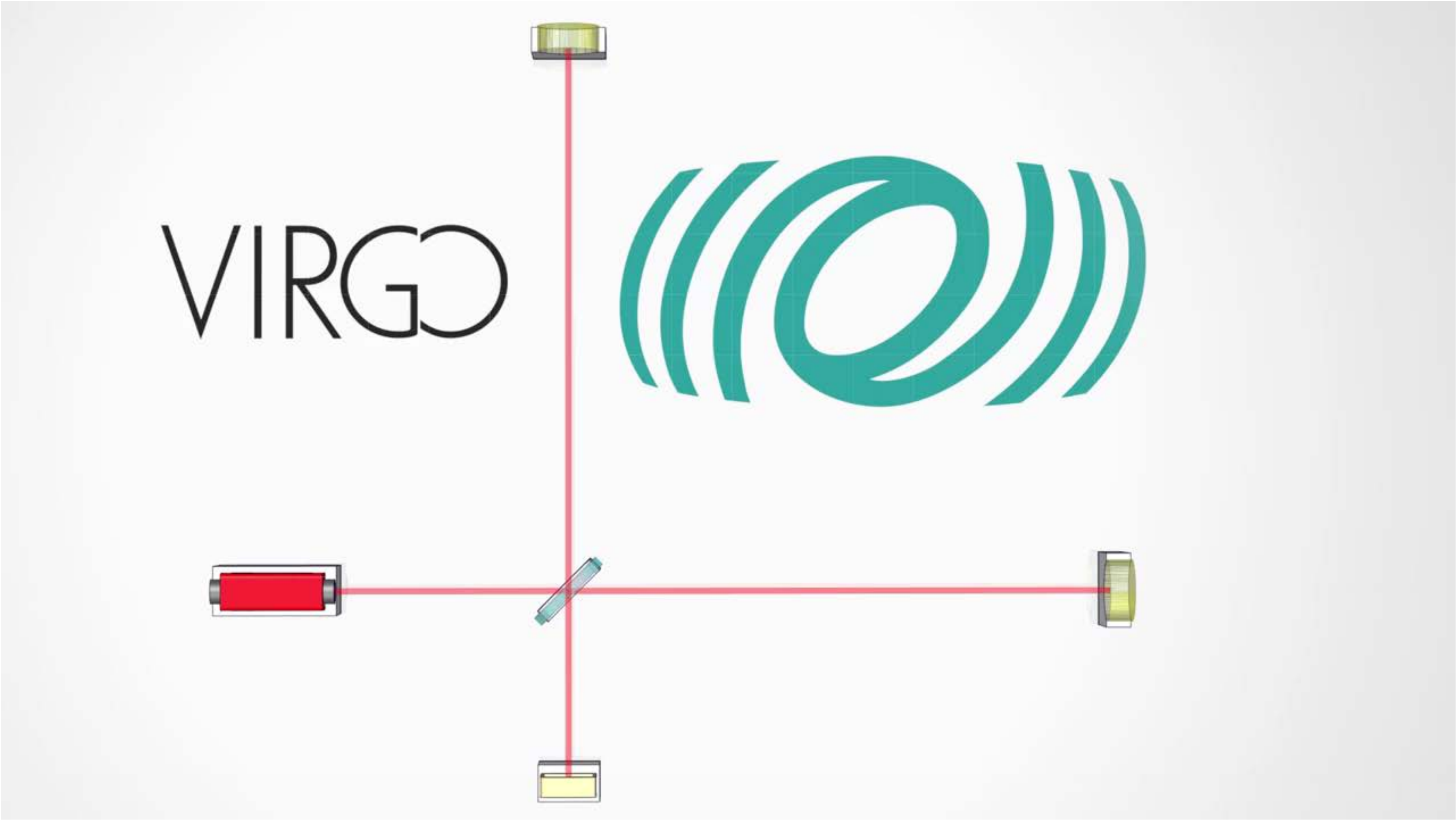
Suspensions not drawn

→ Add recycling mirror between the input laser and the beamsplitter
  - IFO set to the dark fringe + highly reflecting mirrors } All power reflected back to the laser!
    $P_{in} \rightarrow P_{in} \times G_{rec}$, $G_{rec} \sim 40$ for Advanced Virgo

→ Minimize transmission and losses for all mirrors
  - Set the gains of the interferometer cavities


Suspensions not drawn

Improving the interferometer sensitivity



Noise & sensitivity

- Noise: any kind of disturbance which pollutes the dark fringe output signal
- Detecting a GW of frequency f ↔ amplitude h « larger » 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

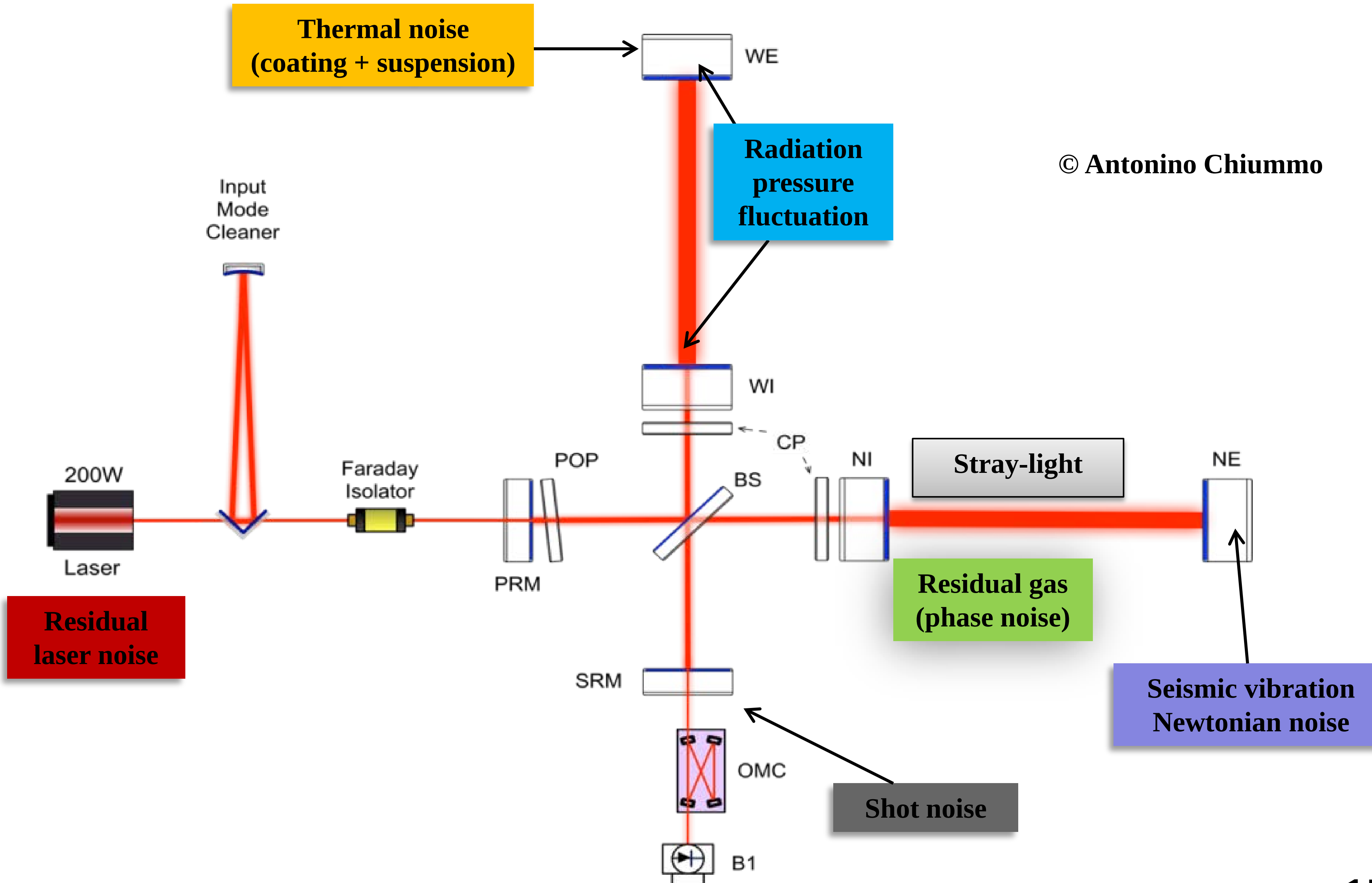
    → Cannot be avoided; optimize design to minimize these contributions
  - Instrumental

    → 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 power spectrum density (PSD, unit: $1/\sqrt{\text{Hz}}$)
  - Noise RMS in the frequency band $[f_{min};f_{max}] = \sqrt{\int_{f_{min}}^{f_{fmax}} \mathbf{PSD}^2(\mathbf{f})\,\mathbf{df}}$

Main interferometer noises

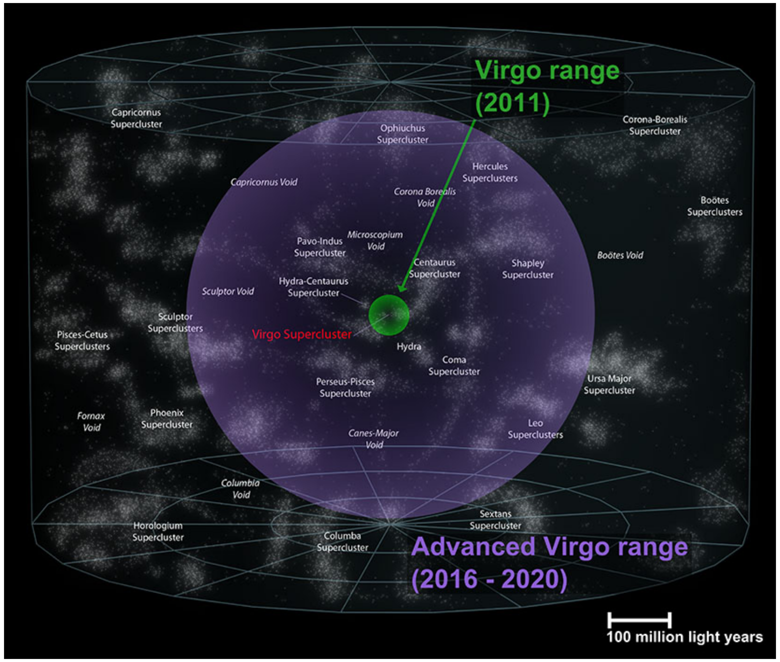


From initial to advanced detectors

- Goal: to improve the sensitivity by one order of magnitude
  - Volume of observable Universe multiplied by a factor 1,000
  - Rate should scale accordingly

    → Assuming uniform distribution of sources (true at large scale)

- A wide range of improvements
  - Increase the input laser power
  - Mirrors twice heavier
  - Increase the beamspot size on the end mirrors
  - Fused silica bonding to suspend the mirrors
  - Improve vacuum in the km-long pipes
  - Cryotraps at the Fabry-Perot ends
  - Instrumentation & optical benches under vacuum



- Advanced LIGO (aLIGO) funded a year or so before Advanced Virgo (AdV)
  - Financial crisis in 2008-2010…

  → aLIGO ready for its first « observation run » in September 2015
  - AdV upgrade still in progress

A worldwide network of gravitational wave interferometric detectors

Interferometer angular response

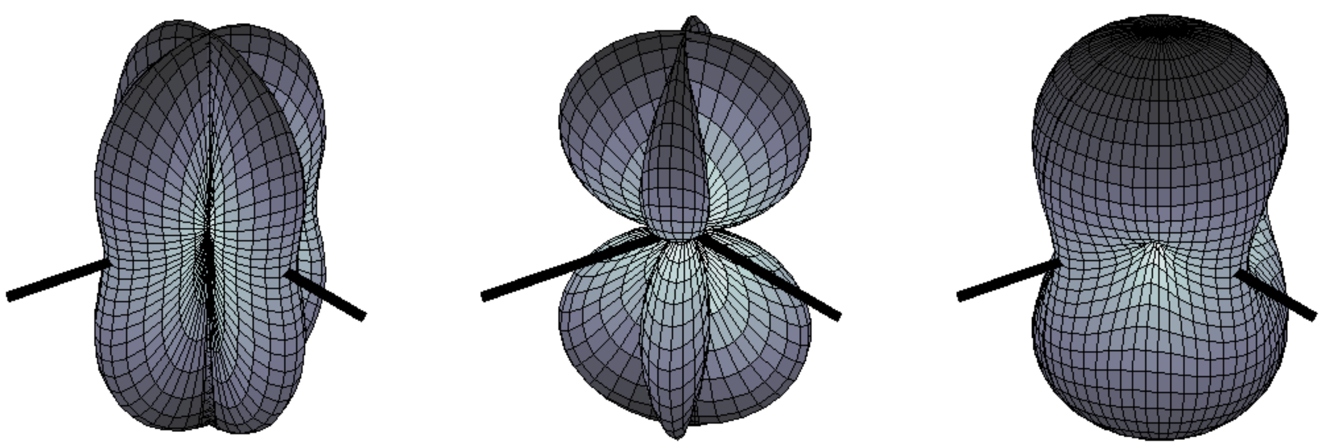
- An interferometer is not directional: it probes most of the sky at any time
  - More a microphone than a telescope!

- 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
    $\rightarrow$ Maximal when perpendicular to this plane
    $\rightarrow$ Blind spots along the arm bisector (and at 90 degres from it)

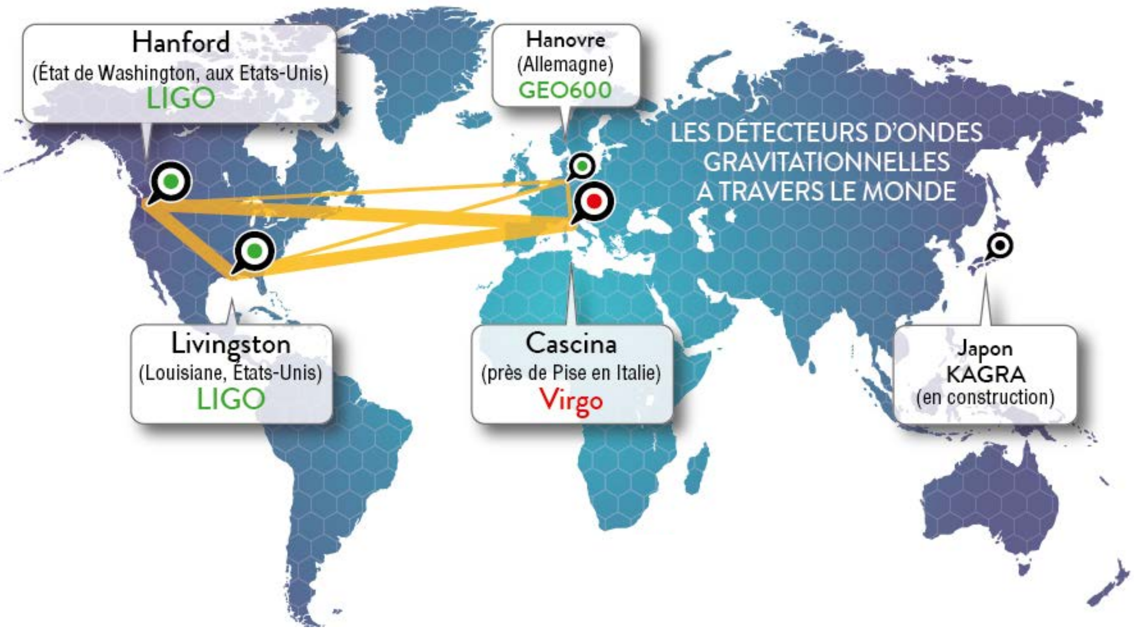
+ polarization × polarization unpolarized



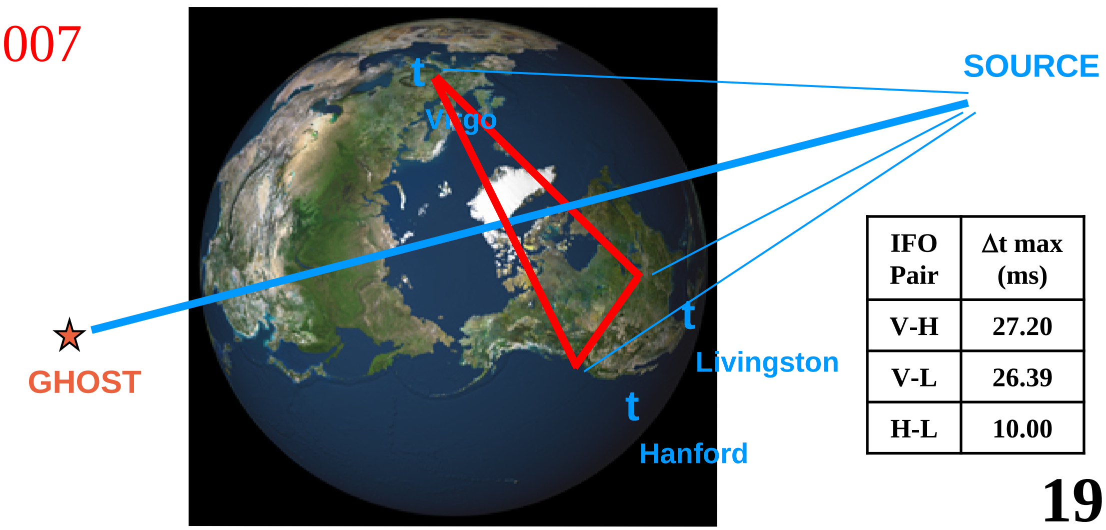
A network of interferometric detectors

- 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



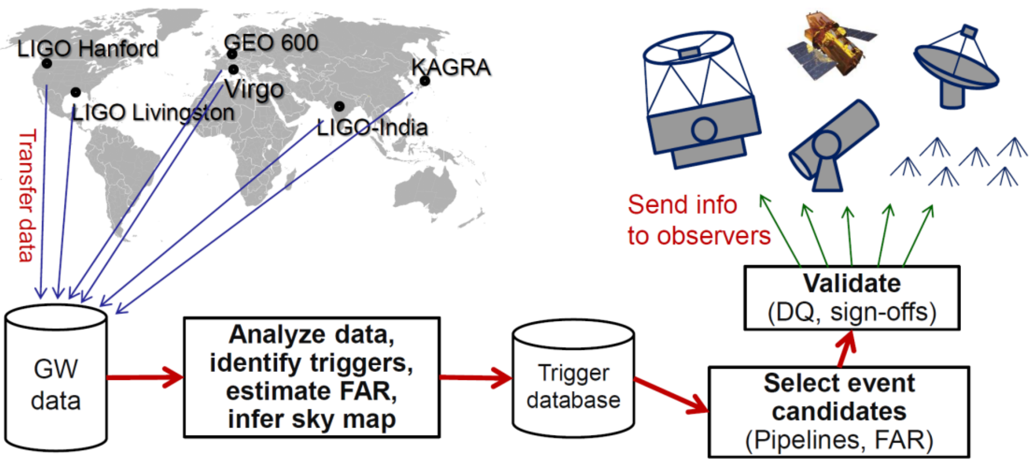
IFO Pair	Δt max (ms)
V-H	27.20
V-L	26.39
H-L	10.00

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



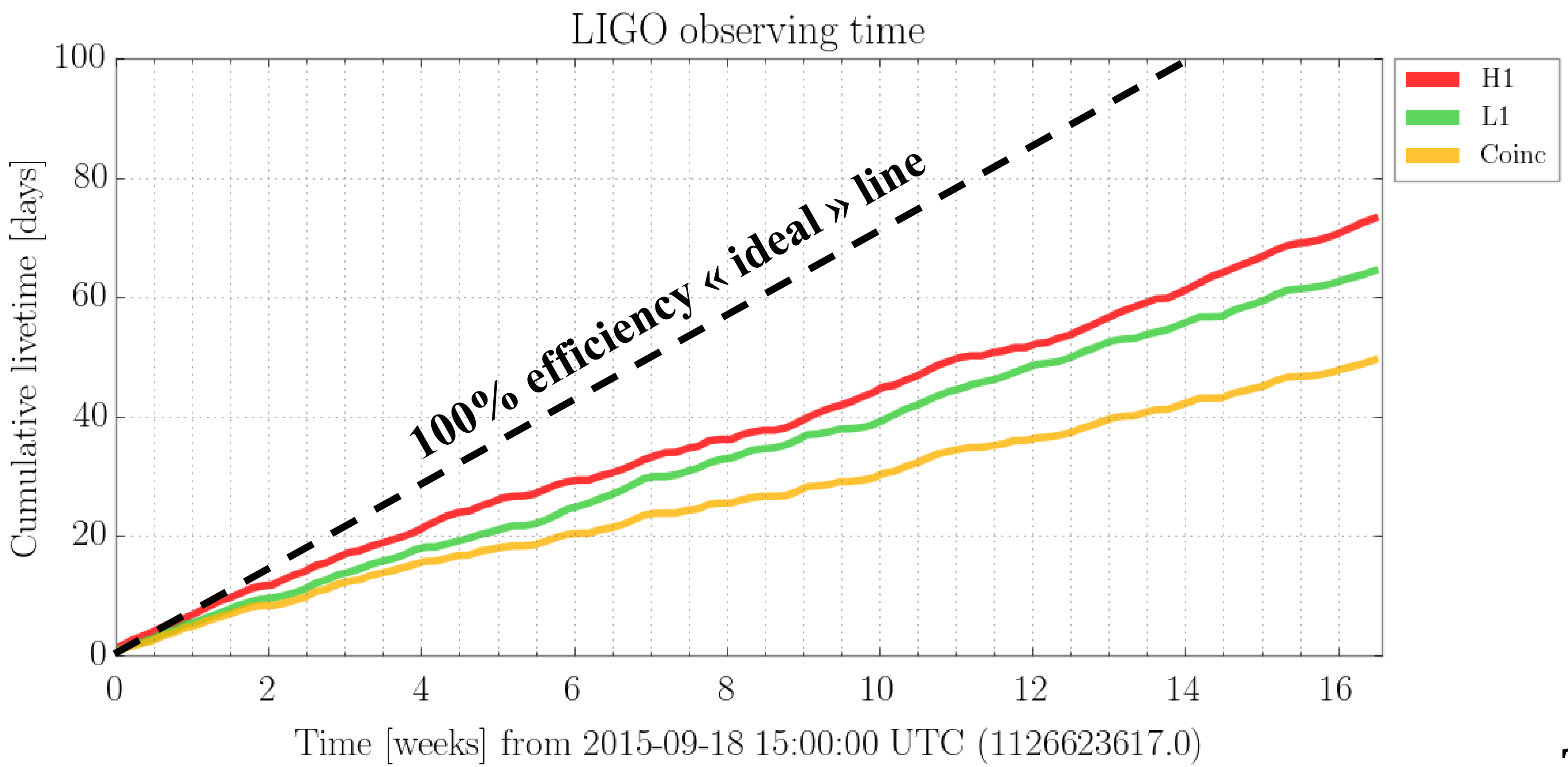
- Low latency h-reconstruction and data transfer between sites
  - Online GW searches for burst and compact binary coalescences

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

aLIGO O1 Run: Observing time

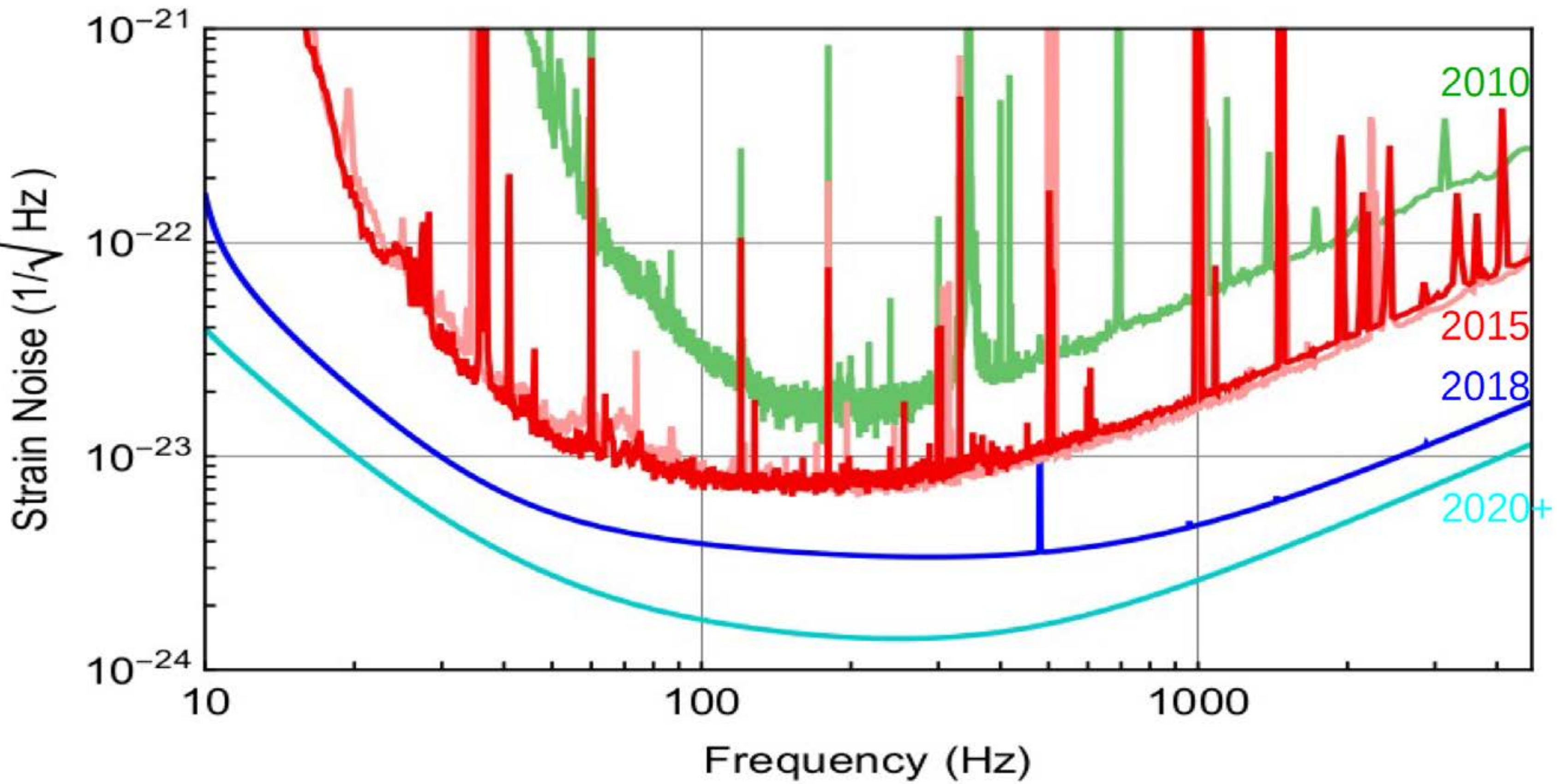
- September 2015 – January 2016
  - GW150914 showed up a few days before the official start of O1, during the « Engineering Run 8 »

→ Both interferometers were already working nominally



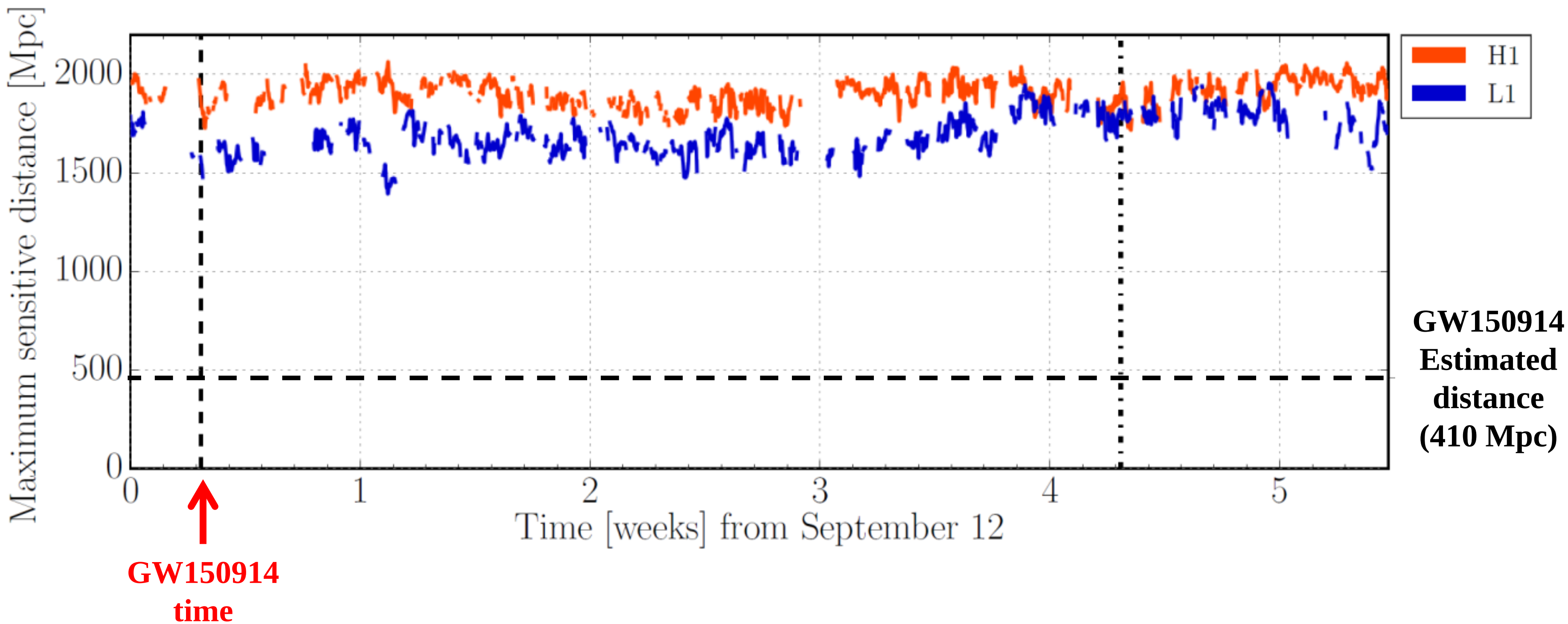
aLIGO O1 Run: Sensitivity

- Sensitiviy 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 the signal GW150914 is 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

GW 150914

Compact binary coalescence search

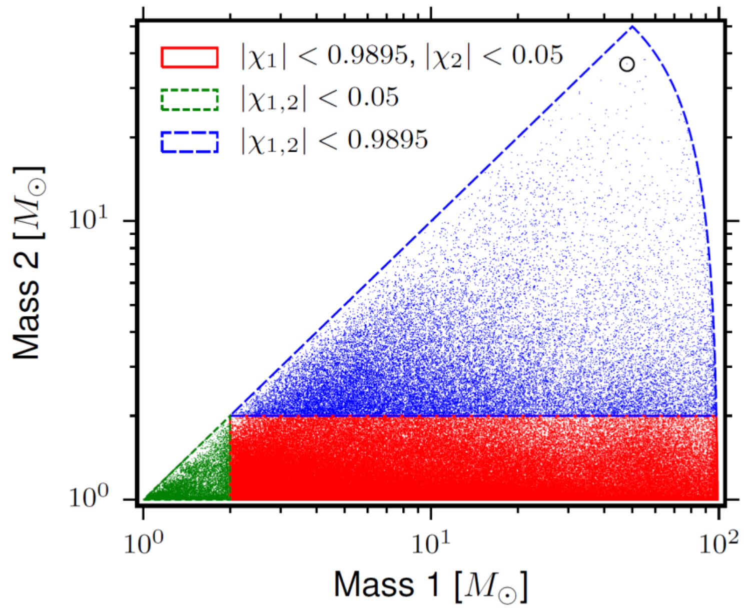
- Well-predicted waveform
  → Matched-filtering technique (optimal)
  - Noise-weighted cross-correlation of data with a template (expected signal)

FT of the data **Signal template**

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

Noise power spectral density

- 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

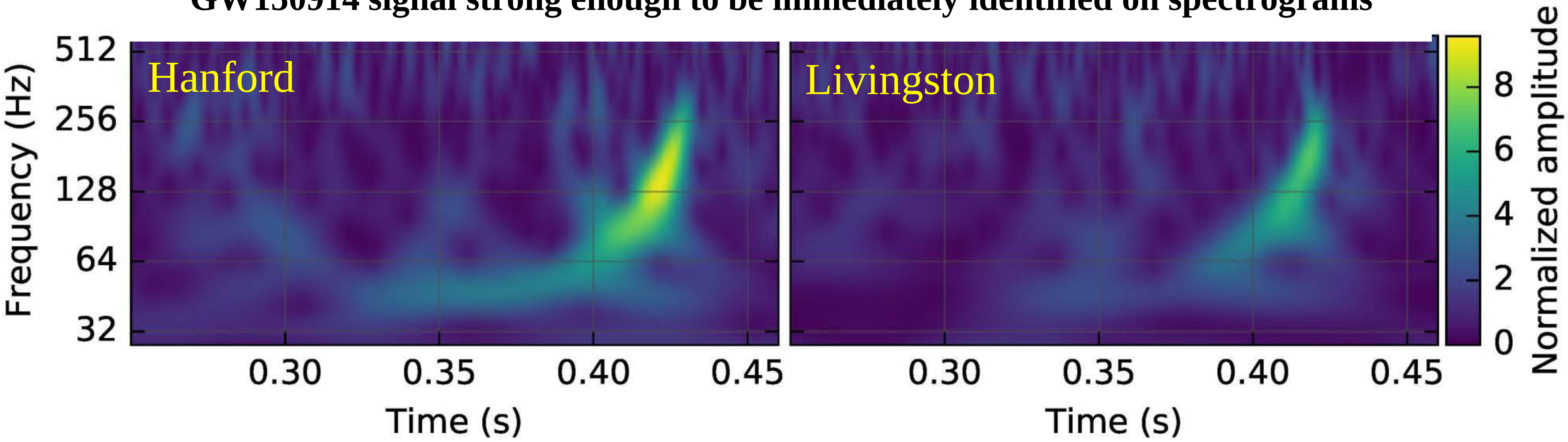


- Look for triggers from the two IFOs using the same template and coincident in time
  - Check matching between signal and template
- Offline search
  - Part of the parameter space searched online
  - Two independent offline pipelines

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

Data quality

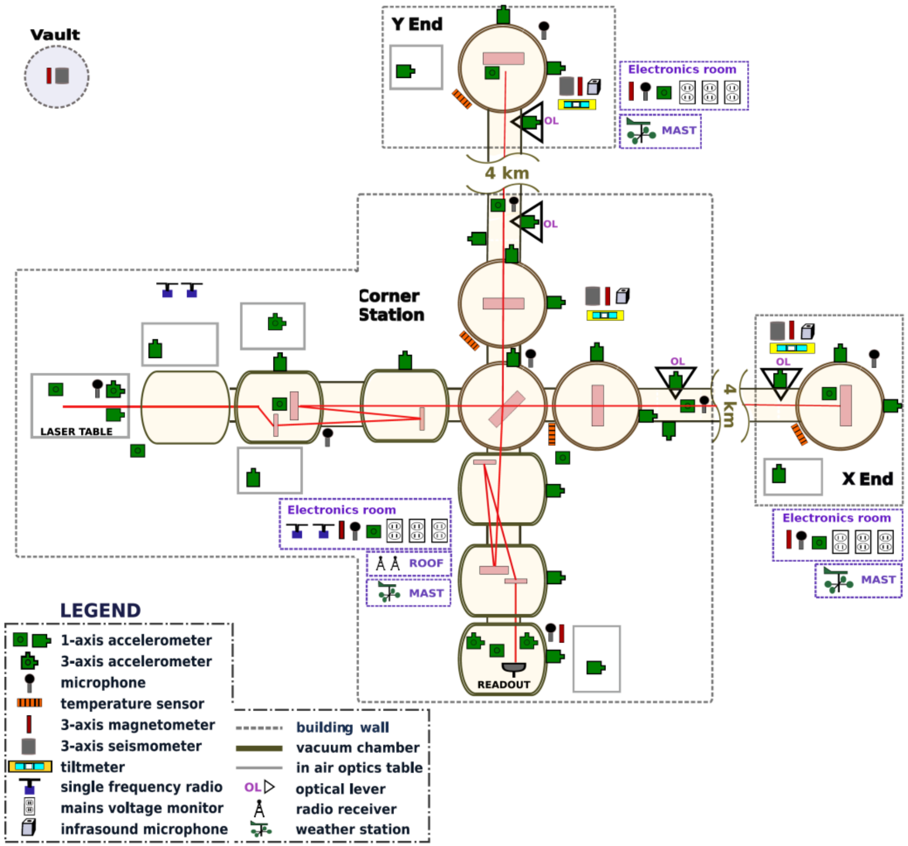
- Detector configuration frozen to integrate enough data for background studies
  - ~40 days (until end of October) corresponding to 16 days of coincidence data

  → Steady performances over that period

- Tens of thousands of probes monitor the interferometer status and the environment
  - Virgo: h(t) ~ 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

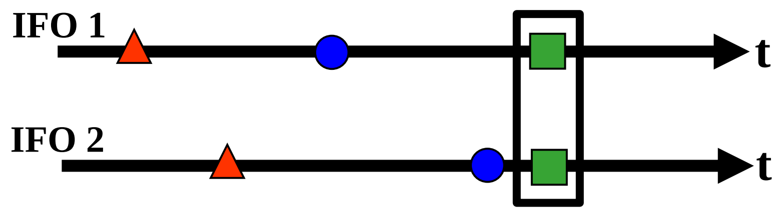
- Studies show that GW150914 is not due to issues with the interferometer running, nor the reflection of environmental disturbances (correlated or not)
  → How likely is it to be due to « expected » noise fluctuations?
    - Assess signal significance!

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

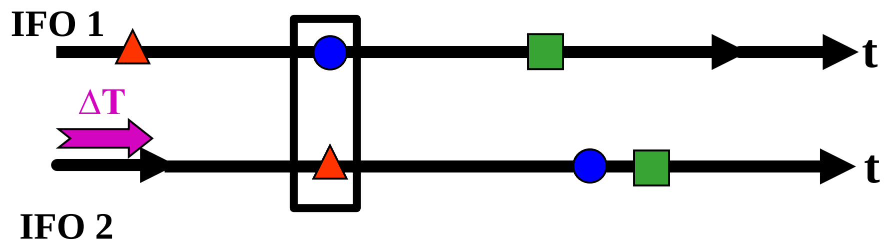
- Reminder: real GW events are shifted by 10 ms at most between IFOs
  - Light travel time over 3,000 km

- 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 »

A “zero-lag” trigger (true coincidence)



A “time-lag” trigger (accidental coincidence)

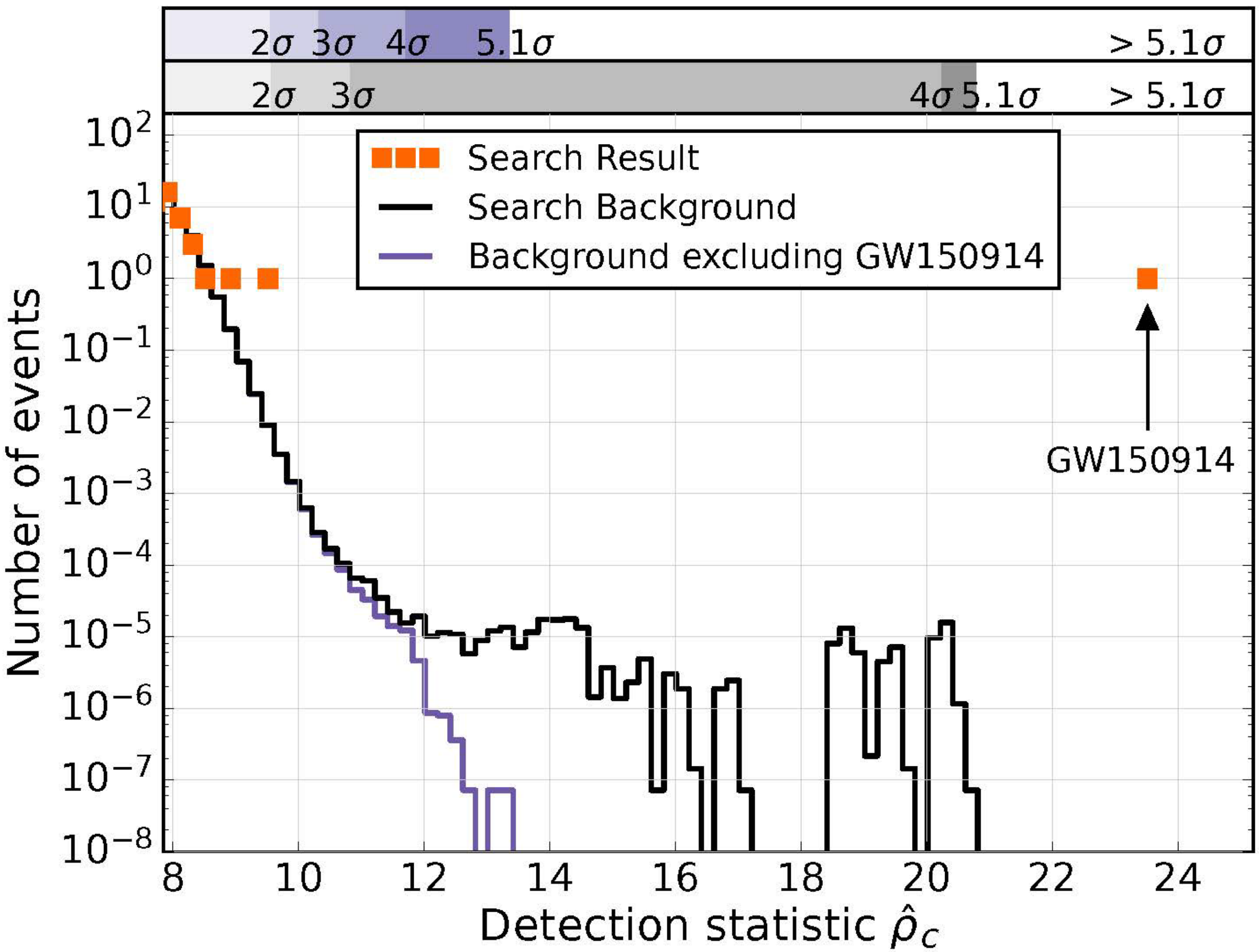


Signal significance – CBC analysis

- 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)



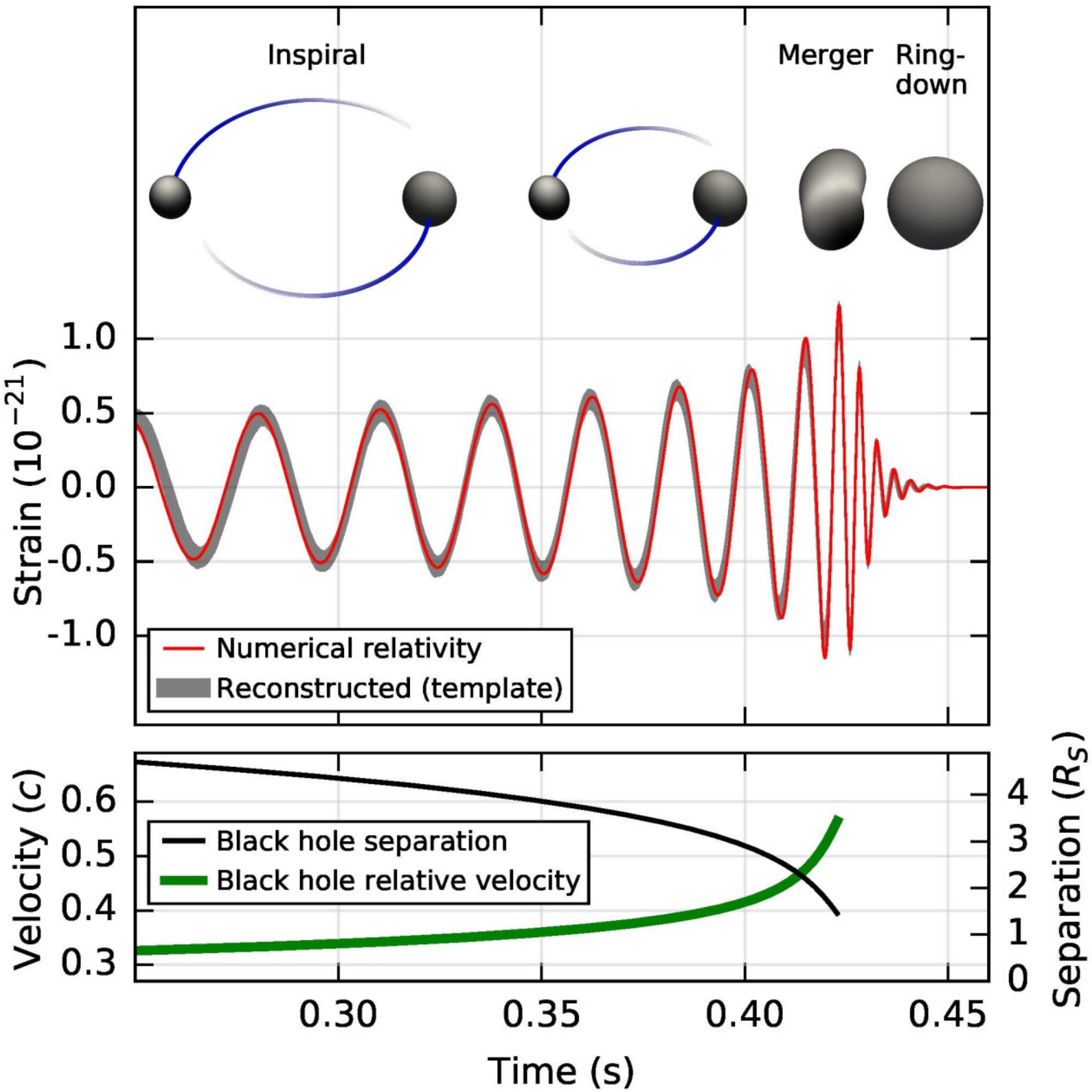
- SNR ~ 23.6; false alarm rate < 1 event / 203,000 years
  false alarm probability < 2×10^{-7} (> 5.1 σ)

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_{Sun} radiated in GW

- The « brighest » 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

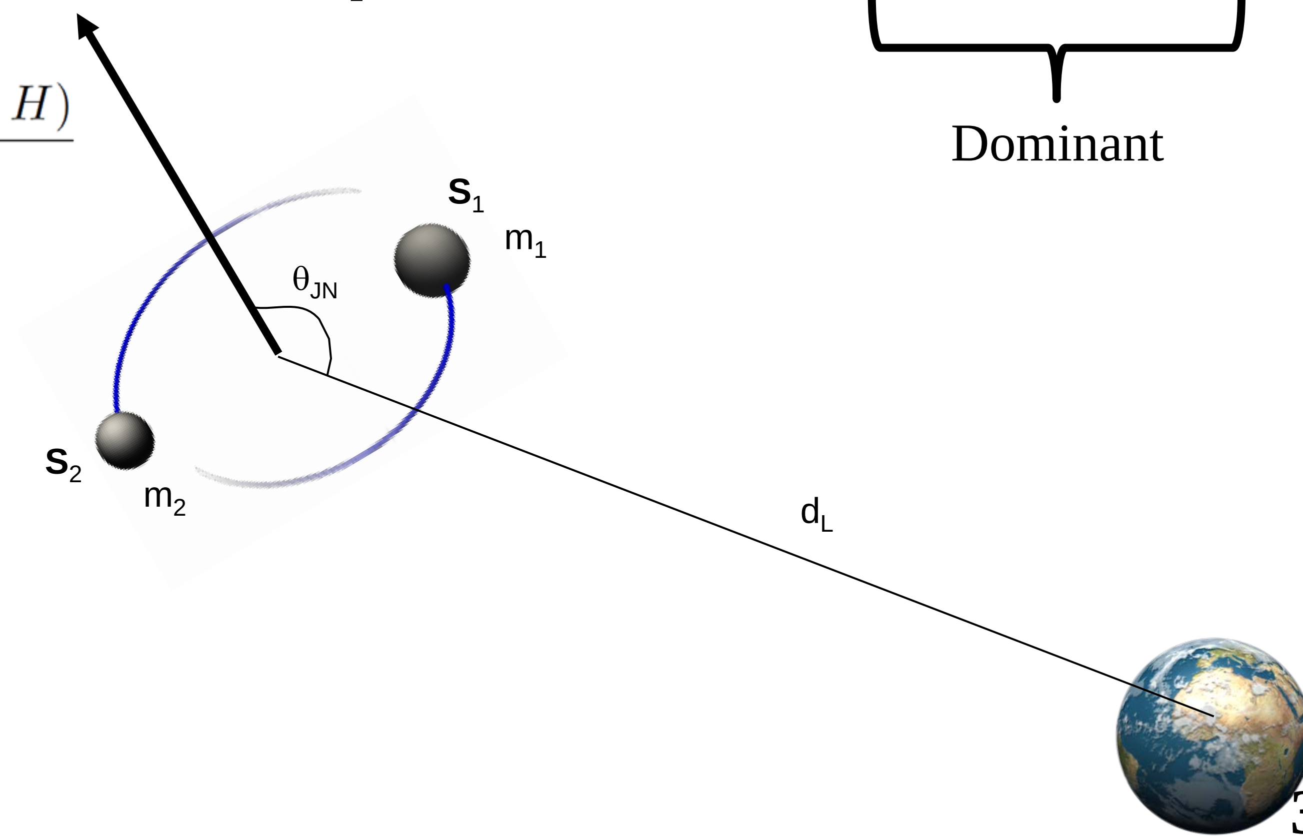
Parameter estimation

- 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

Dominant

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



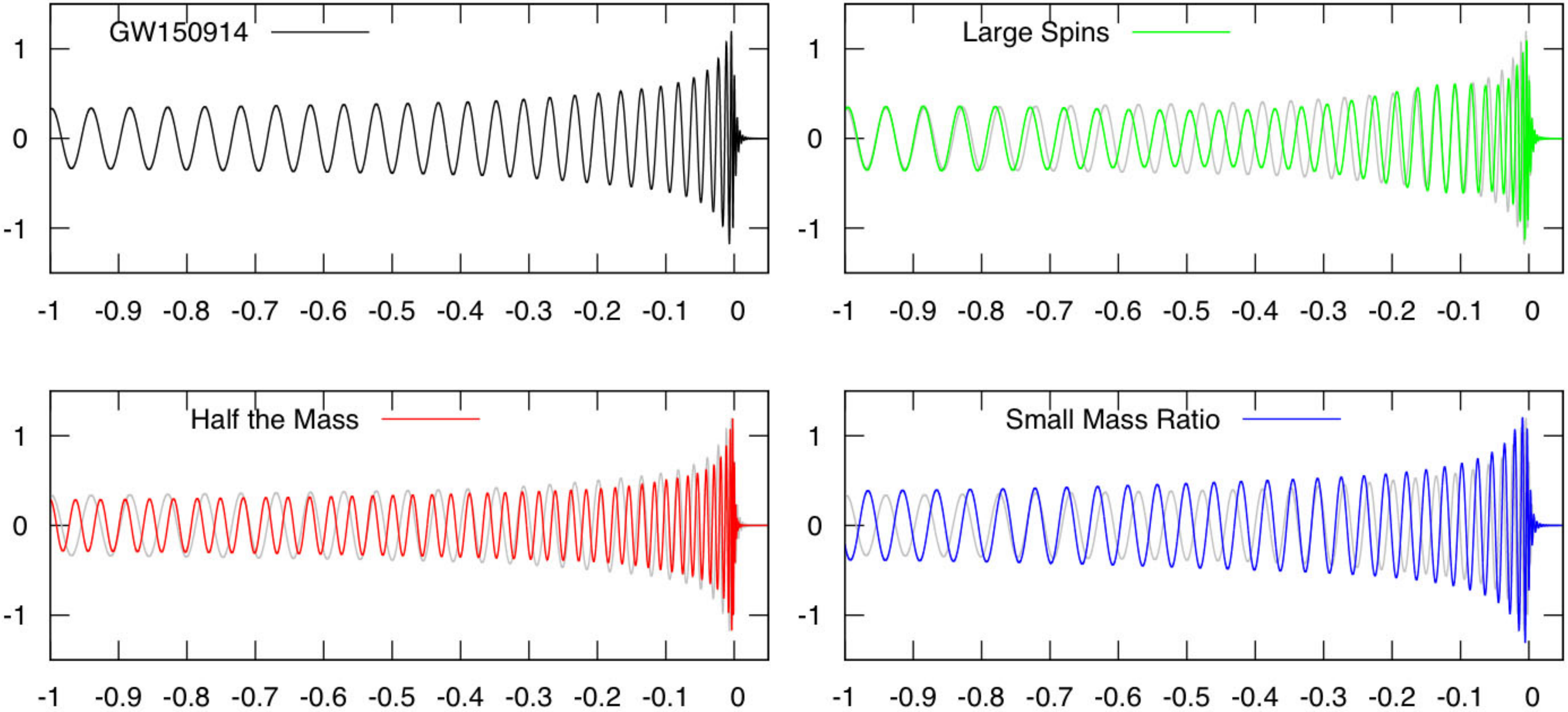
- θ: Parameters
- d: Data
- H: Model

- 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



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

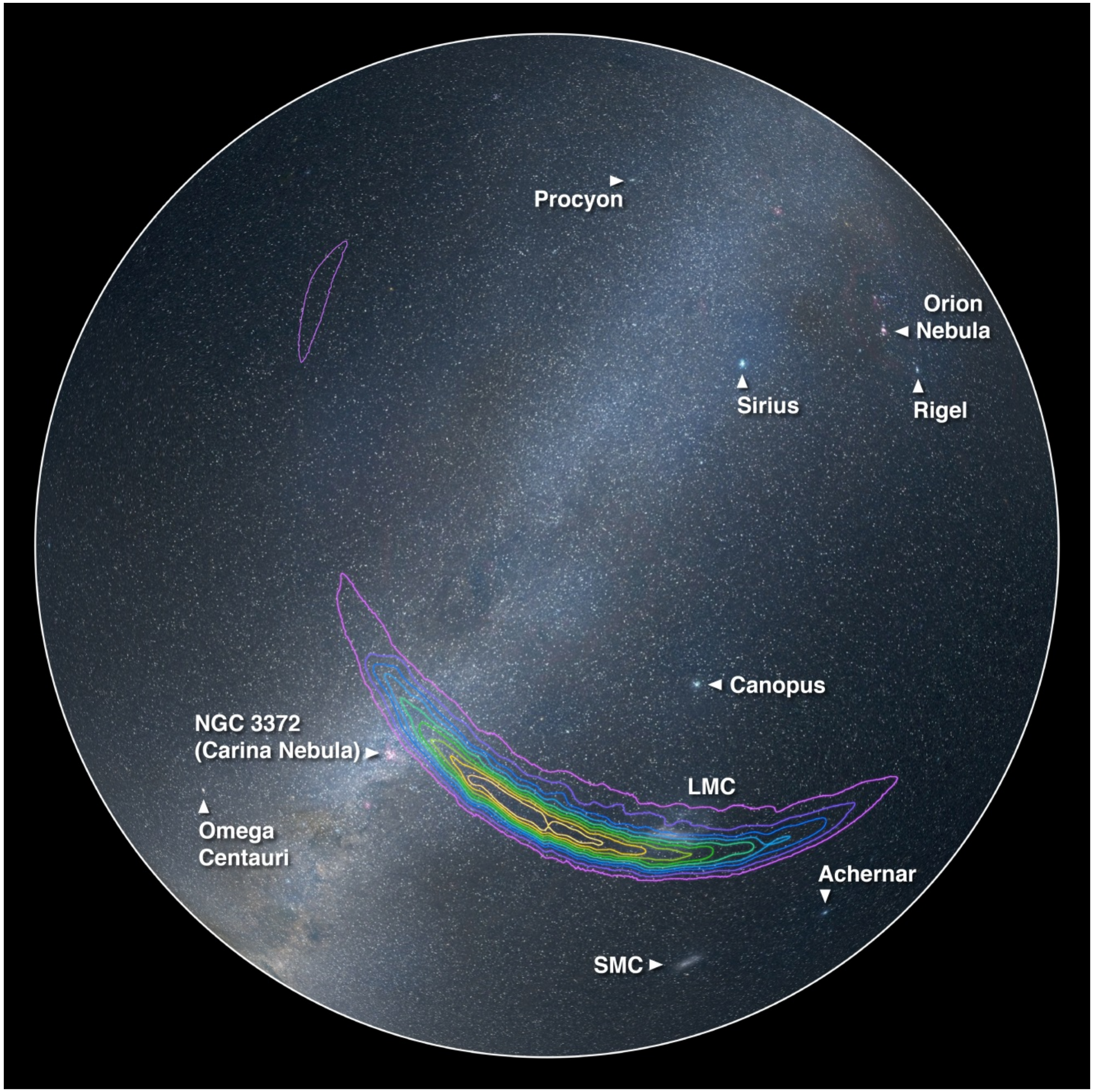
observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc
redshift	0.054 to 0.136
signal-to-noise ratio	24
false alarm prob.	< 1 in 5 million
false alarm rate	< 1 in 200,000 yr
Source Masses	M⊙
total mass	60 to 70
primary BH	32 to 41
secondary BH	25 to 33
remnant BH	58 to 67
mass ratio	0.6 to 1
primary BH spin	< 0.7
secondary BH spin	< 0.9
remnant BH spin	0.57 to 0.72
signal arrival time delay	arrived in L1 7 ms before H1
likely sky position	Southern Hemisphere
likely orientation	face-on/off
resolved to	~600 sq. deg.

duration from 30 Hz	~ 200 ms
# cycles from 30 Hz	~10
peak GW strain	1×10^{-21}
peak displacement of interferometers arms	±0.002 fm
frequency/wavelength at peak GW strain	150 Hz, 2000 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	3.6×10^{56} erg s^{-1}
radiated GW energy	2.5-3.5 M⊙
remnant ringdown freq.	~ 250 Hz
remnant damping time	~ 4 ms
remnant size, area	180 km, 3.5×10^5 km^2
consistent with general relativity?	passes all tests performed
graviton mass bound	$< 1.2 \times 10^{-22}$ eV
coalescence rate of binary black holes	2 to 400 Gpc^{-3} yr^{-1}
online trigger latency	~ 3 min
# offline analysis pipelines	5
CPU hours consumed	~ 50 million (=20,000 PCs run for 100 days)
papers on Feb 11, 2016	13
# researchers	~1000, 80 institutions in 15 countries

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

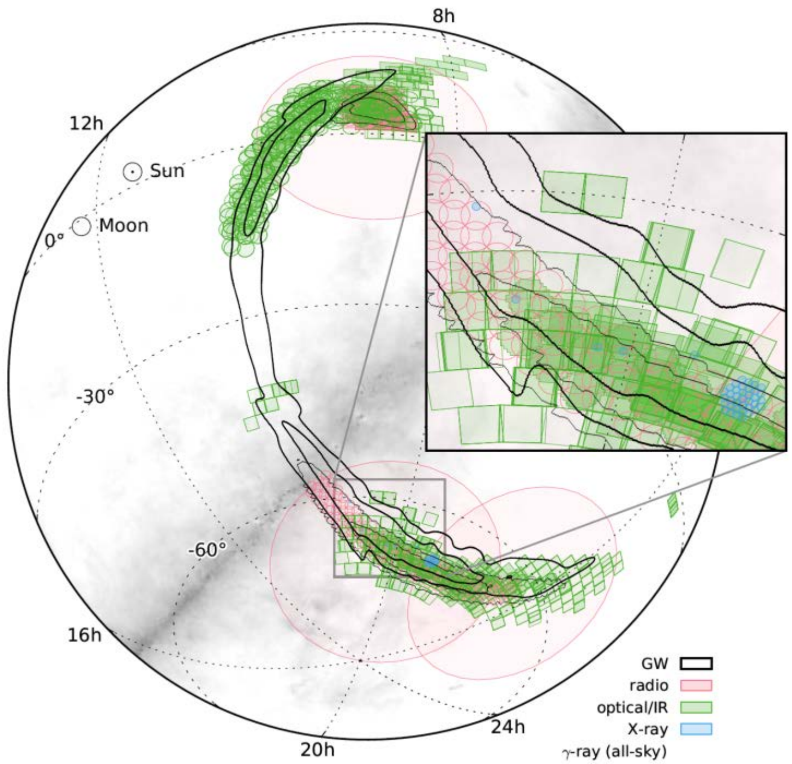
Skymap

- Sky at the time of the event
- Skymap contoured in deciles of probability
- 90% contour : ~ 590 degres^2
  - Full Moon: 0.5 degres^2
- View is from the South Atlantic Ocean, North at the top, with the Sun rising and the Milky Way diagonally from NW to SE

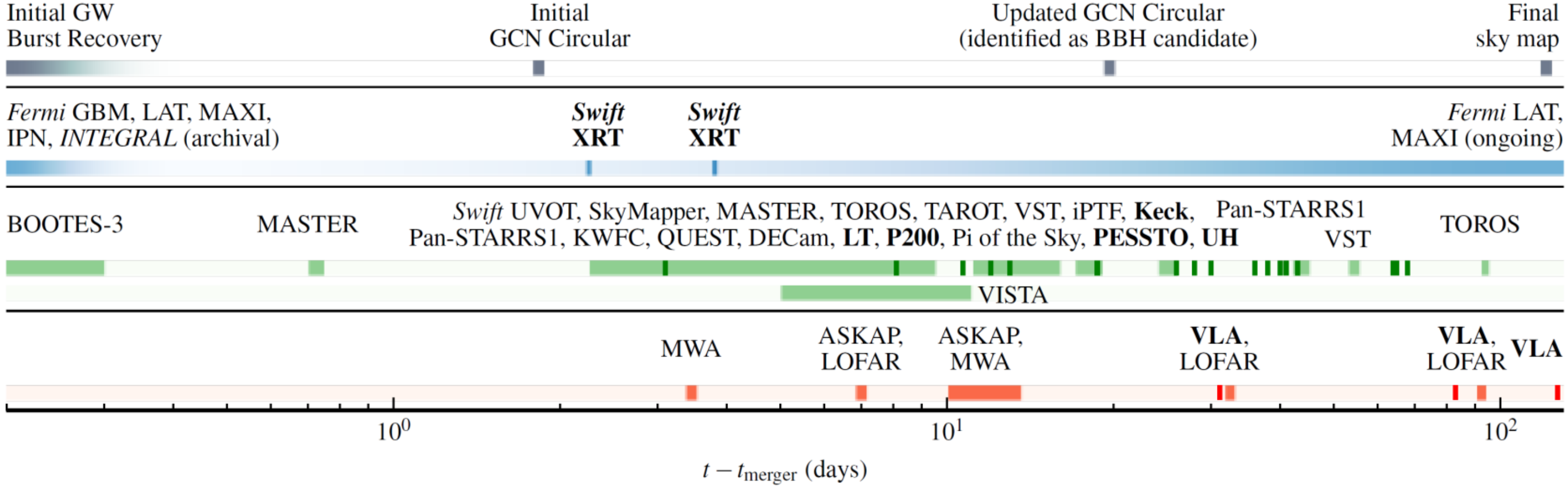


Looking for GW150914 counterparts

- Sky coverage



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

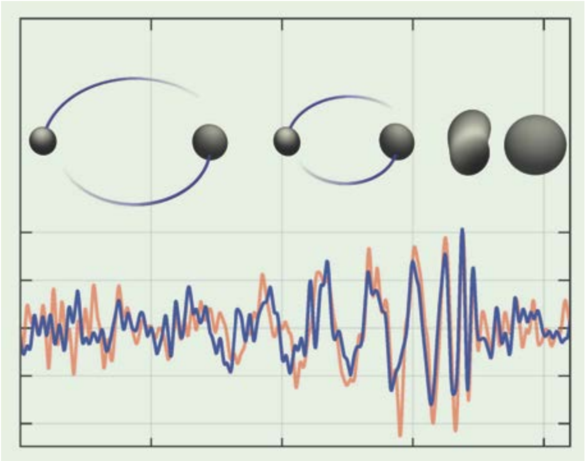


Conclusions

Outlook

- The network of advanced gravitational wave interferometers is taking shape
  - The two aLIGO detectors started taking data last September and detected the first direct gravitational wave signal (GW150914)
  - Virgo is completing its upgrade and is fully committed to joining LIGO asap
    → The right time for new groups to join the collaboration…
  - 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



Outlook

https://aas.org/meetings/aas228

- The [obscured] erferometers is taking shape
  - T[obscured] ast September and detected th[obscured] 50914)
  - V[obscured] mmitted to joining LIGO asap
    - [obscured] ollaboration…
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  - A[obscured] dia) some years later
- Ser[obscured] ational waves
  - In
  - R[obscured] tion instruments

[] Wednesday, 15 June, 10:15 am PDT

Latest News from the LIGO Scientific Collaboration

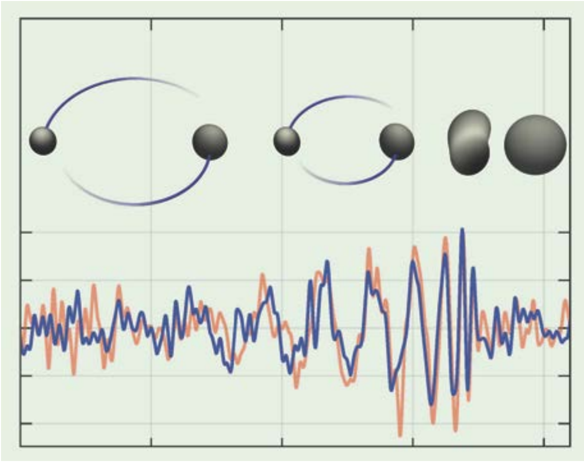
Gabriela González
LIGO Scientific Collaboration Spokesperson
(Louisiana State University)
[305.01]

Fulvio Ricci
Virgo Spokesperson
(University of Rome Sapienza & INFN Rome)

Dave Reitze
Executive Director of LIGO
(Caltech)

https://aas.org/aas-briefing-webcast

- LIGO and Virgo will release results from the full « Observation 1 » run analysis tomorrow night
  - Stay tuned…



GW detector peak sensitivity evolution vs. time