The first direct detections of gravitational waves

Group from Marlborough College Blackett Observatory
EGO visit, April 3rd 2017

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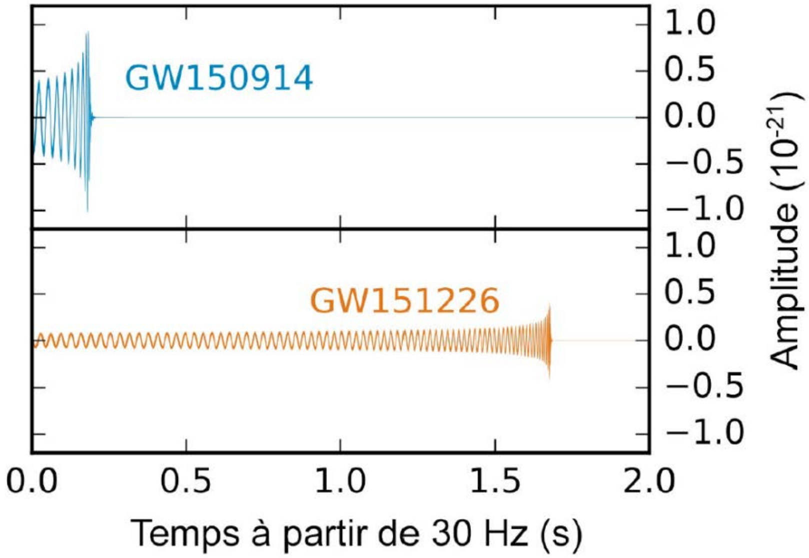

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Outline

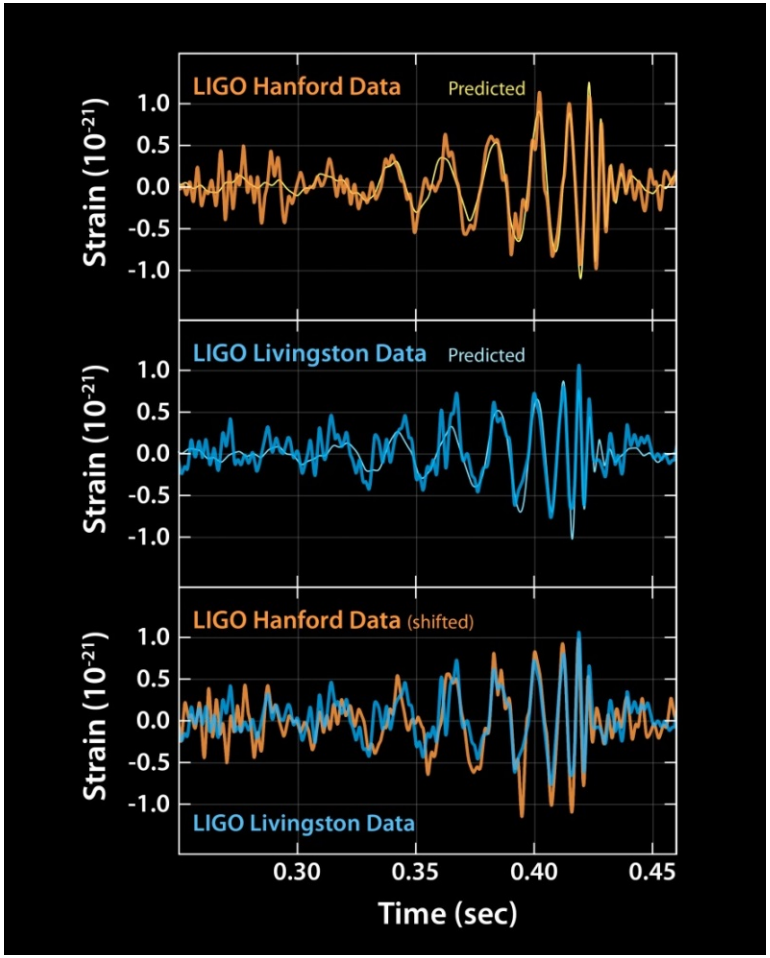
- Gravitational waves in a nutshell
  - Sources and properties

- 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

- LIGO & Virgo current status

- Outlook

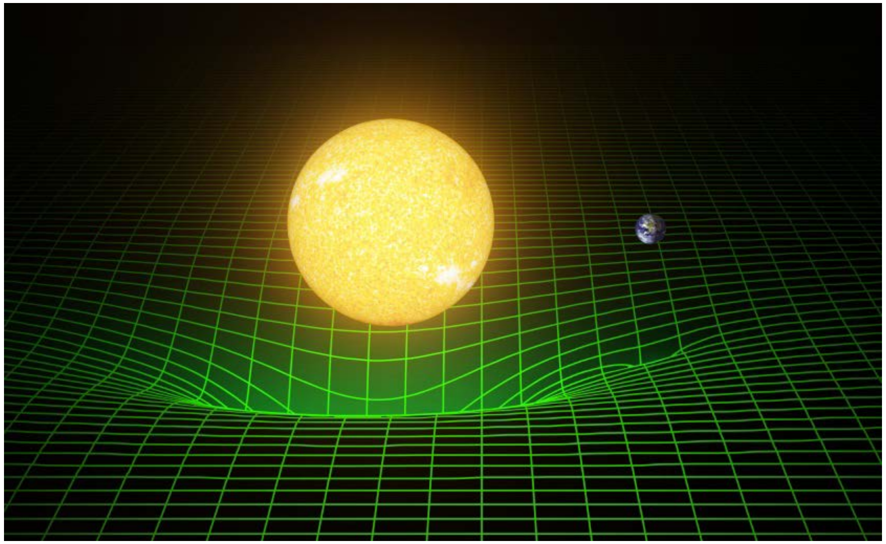


Thanks to the many colleagues from the LAL Virgo group, from Virgo and LIGO from wich I borrowed ideas and material for this talk

Gravitational waves: sources and properties

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

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$\rightarrow$ In words: Curvature = Matter

- Einstein tensor $G_{\mu\nu}$: manifold curvature
- Stress-energy tensor $T_{\mu\nu}$: density and flux of energy and momentum in spacetime
- Equality between two tensors
  $\rightarrow$ Covariant equations
- Need to match Newton's theory for weak and slowly variable gravitational fields
  $\rightarrow$ 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)

$$F_{M \to m} = F_{m \to M} = \frac{GmM}{r^2}$$

- Escape velocity, in case one mass is much larger than the other one (M>>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: $v_e = \sqrt{\dfrac{2GM}{r}}$
- Schwartzschild radius R_S (1916): $R_S = \dfrac{2GM}{c^2} \approx 3\text{km}\left(\dfrac{M}{M_{Sun}}\right)$
  - $R_S(M)$ such as $v_e = c$

  → Very small for « usual » celestial objects
    - Planets, stars
- Compactity $C = \dfrac{R_S}{\text{radius}} \leq 1$

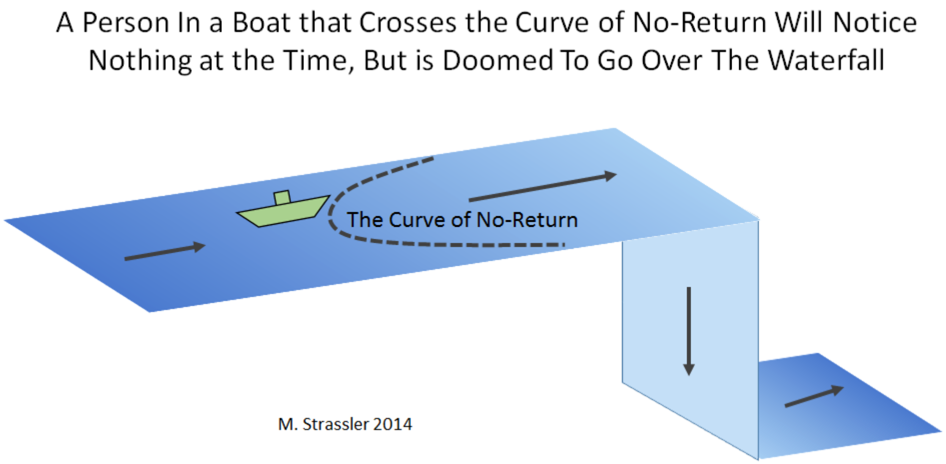
Object	Earth	Sun	White dwarf	Neutron star	Black hole
Compacity	$1.4\ 10^{-9}$	$4.3\ 10^{-6}$	10^{-4}	0.3	1

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

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

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 though 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



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

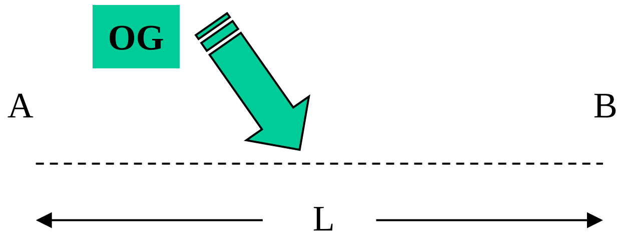
- Traceless and transverse (tensor) waves
  - 2 polarizations: « + » and « × »
    $\rightarrow$ See next slide for the interpretation of these names

- 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 ($h^2 \propto 1/d^2$)
    $\rightarrow$ Important to define the Universe volume a given detector is sensitive to

Effect of gravitational waves on test masses

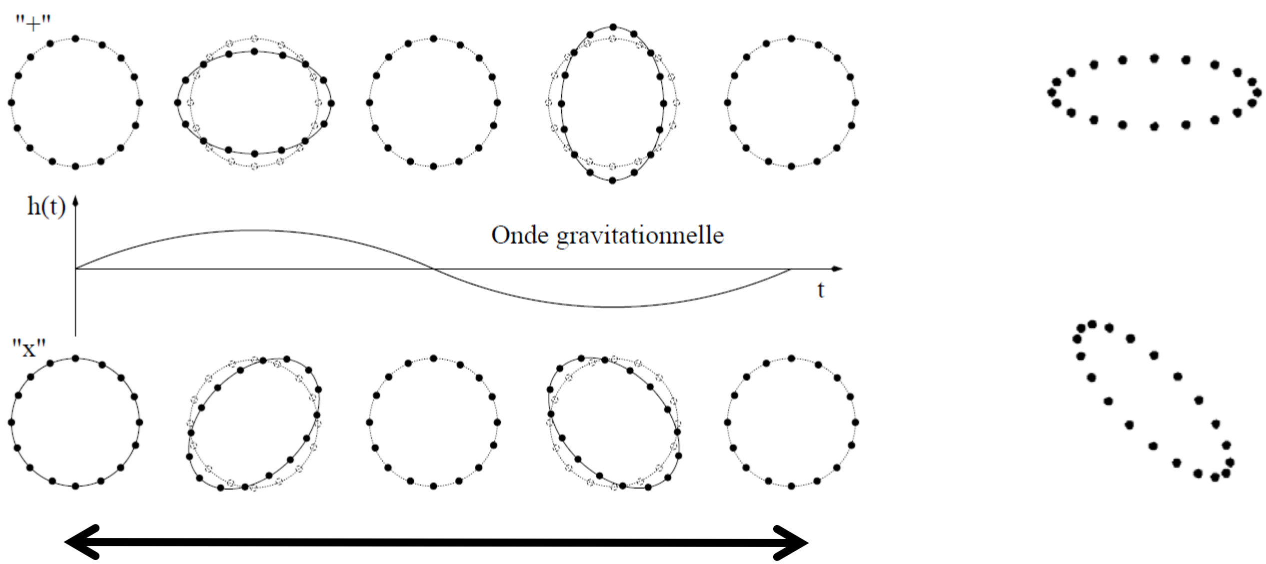
- GW: propagating perturbation of the spacetime metric
  - Acts on distance measurement between test masses (free falling)



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

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

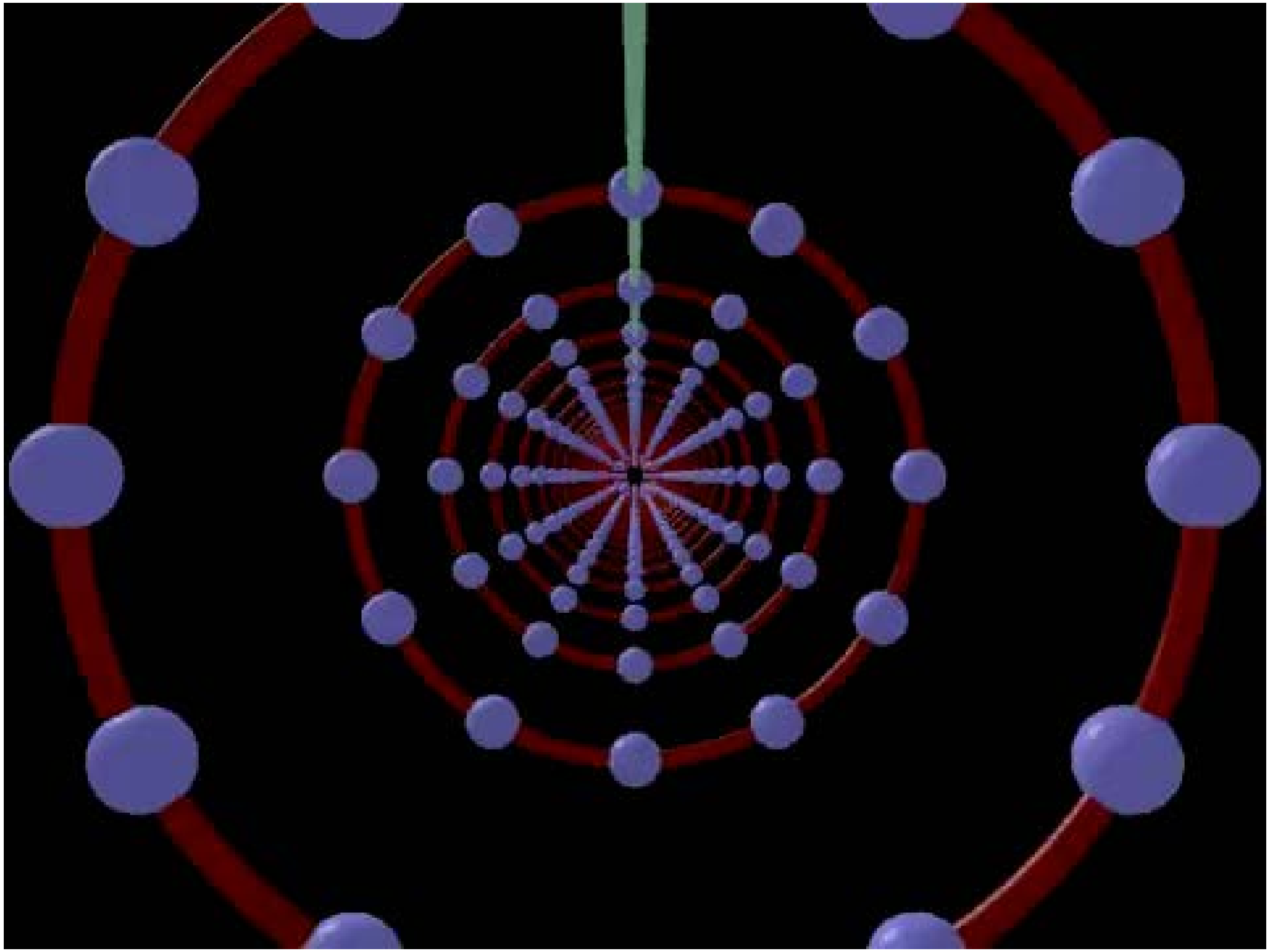
- Effect of the two GW polarizations on a ring of free masses
  - « + » polarization
  - « × » polarization



One period

Effect of gravitational waves on test masses

- In 3D



Do gravitational waves exist?

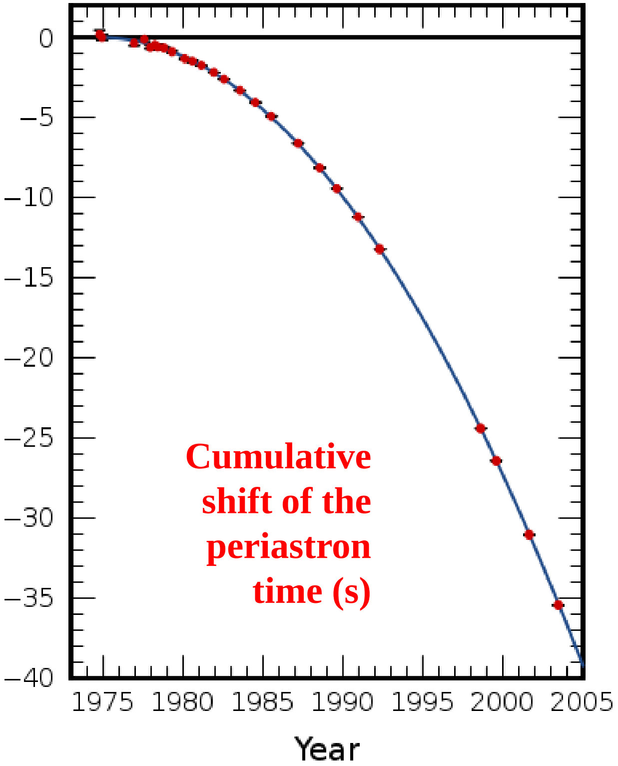
- Question (officially) solved since February 11 2016!
  - But was very relevant beforehand … and long-standing in the community

- Controversy for decades
  - Eddington, 1922: « *GW propagate at the speed of thought* »
  - 1950's: general relativity is mathematically consistent (Choquet-Buhat)

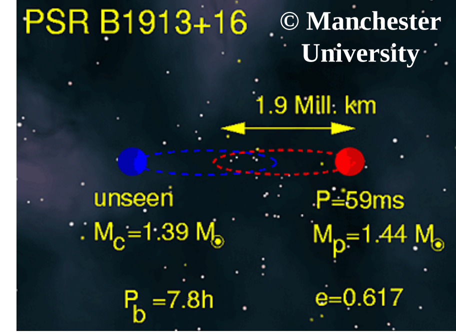
- Indirect evidence of the GW existence:
  long-term study of PSR B1913+16 – see next slide
  - Galactic (6.4 kpc away) binary system
  - Two neutron stars, one being a pulsar

- 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

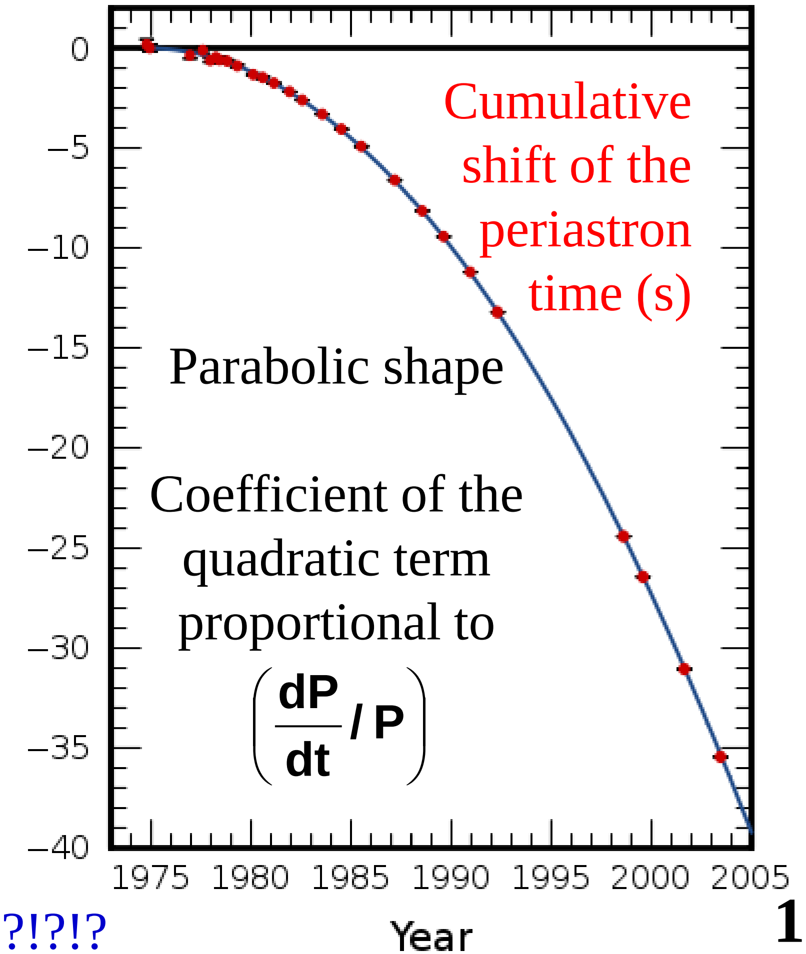
- Discovered by Hulse and Taylor in 1974
  - Nobel prize 1993 – for the discovery

- System parameters and orbital motion measured accurately
  → Laboratory for gravitation studies

- GW: long-term studies of the orbital motion
  - Taylor & Weisberg, Damour

- System slowly loosing 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

$$P = \frac{G}{5c^5}\left\langle \dddot{Q}_{\mu\nu} \dddot{Q}^{\mu\nu} \right\rangle$$

- Let's rewrite this equation introducing some typical parameters of the source
  - Mass M, dimension R, frequency ω/2π and asymmetry factor a
  - One gets $\frac{d^3Q}{dt^3} \sim \left(aMR^2\right)\omega^3$ and $P \sim \frac{G}{c^5} a^2 M^2 R^4 \omega^6$

- Using $\omega \sim v/R$ and introducing R_S, one gets: $P \sim \frac{c^5}{G} a^2\ C^2 \left(\frac{v}{c}\right)^6$

Huge: 10^{53} W

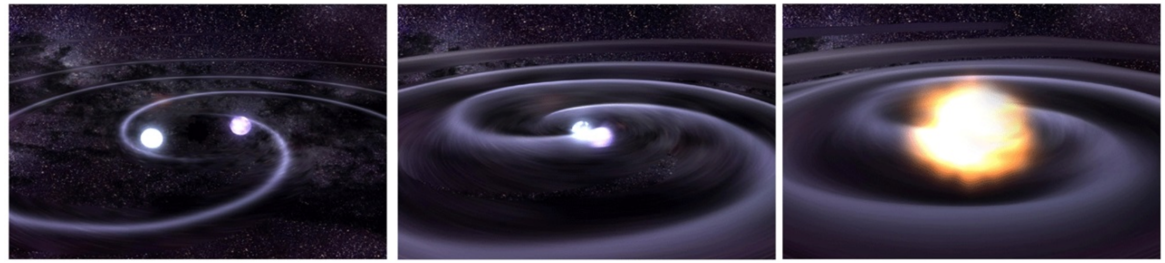
© Joe Weber, 1974

→ A good GW source must be
  - Asymmetric
  - As compact as possible
  - Relativistic

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

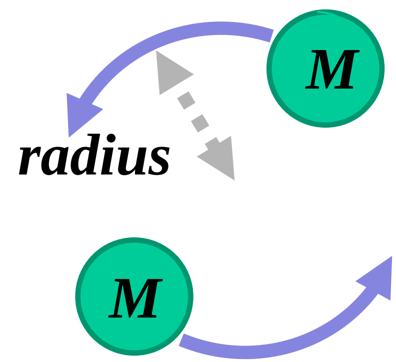
  → Need to look for astrophysical sources (typically: $h \sim 10^{-22} \div 10^{-21}$)

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 loosing energy through GW
  - Three phases: inspiral, merger and ringdown
    → Modeled via analytical computation and numerical simulations
  - Example: two masses M in circular orbit ($f_{GW} = 2\ f_{Orbital}$)

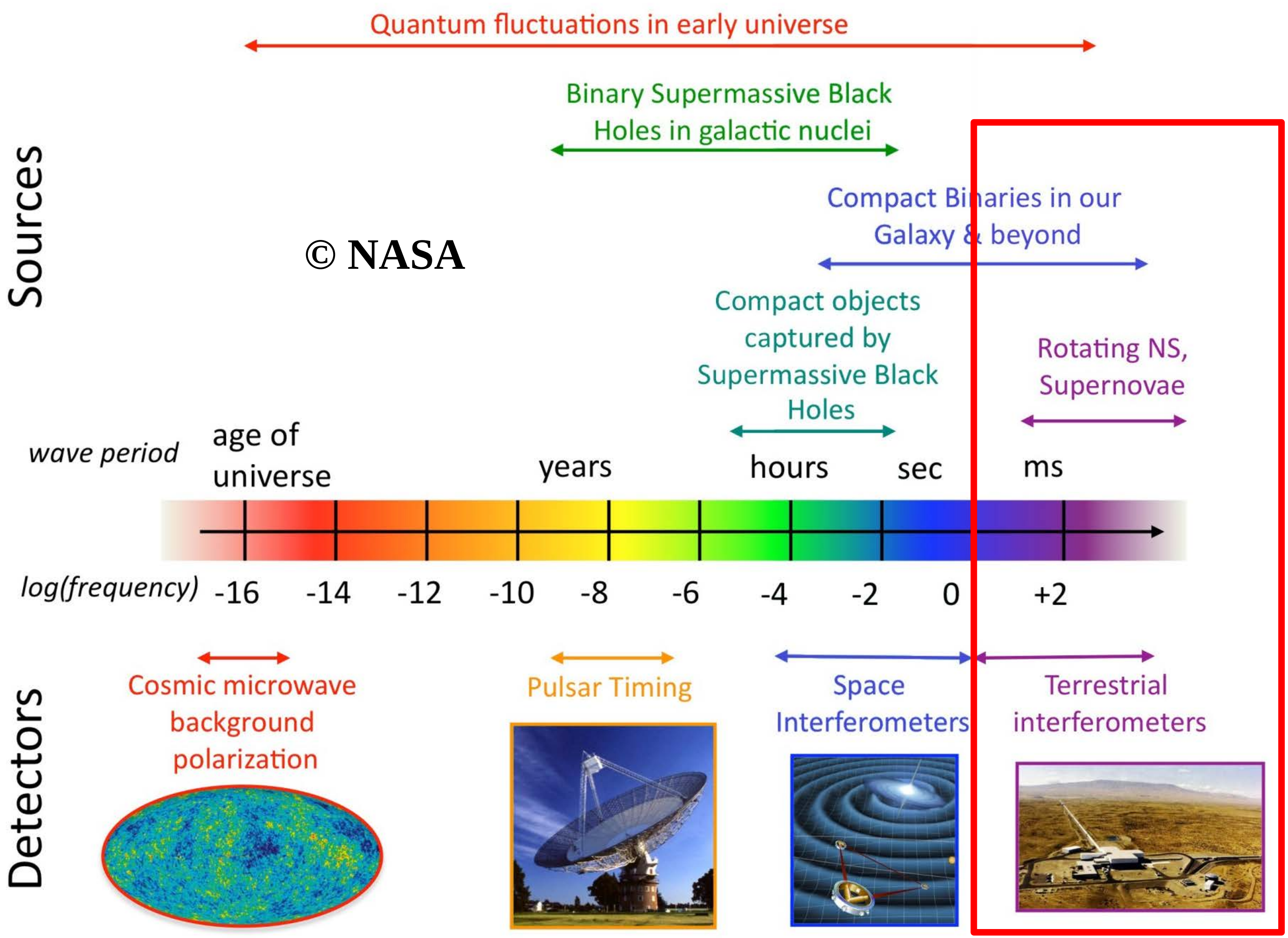
$$h \approx 10^{-21} \left(\frac{500\ \text{Mpc}}{\text{Distance}}\right)\left(\frac{\text{Mass}}{30\ M_{\text{Sun}}}\right)\left(\frac{\text{Orbital radius}}{100\ \text{km}}\right)^2\left(\frac{\text{Frequency}}{100\ \text{Hz}}\right)^2$$



- Transient sources (« bursts »)
  - Example: core collapses (supernovae)

- Permanent sources
  - Pulsars, Stochastic backgrounds

Gravitational wave spectrum



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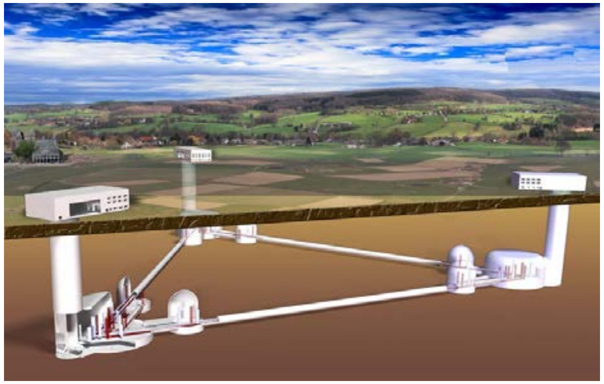
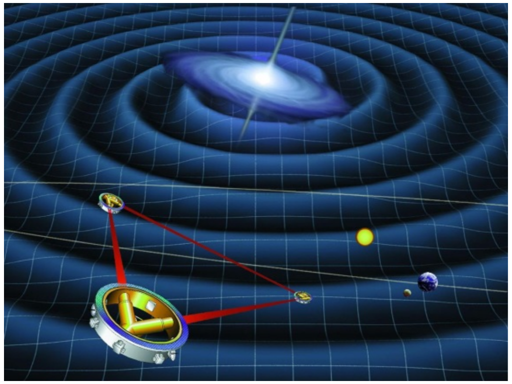
LIGO, Virgo, etc.

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

Theoretical developments

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

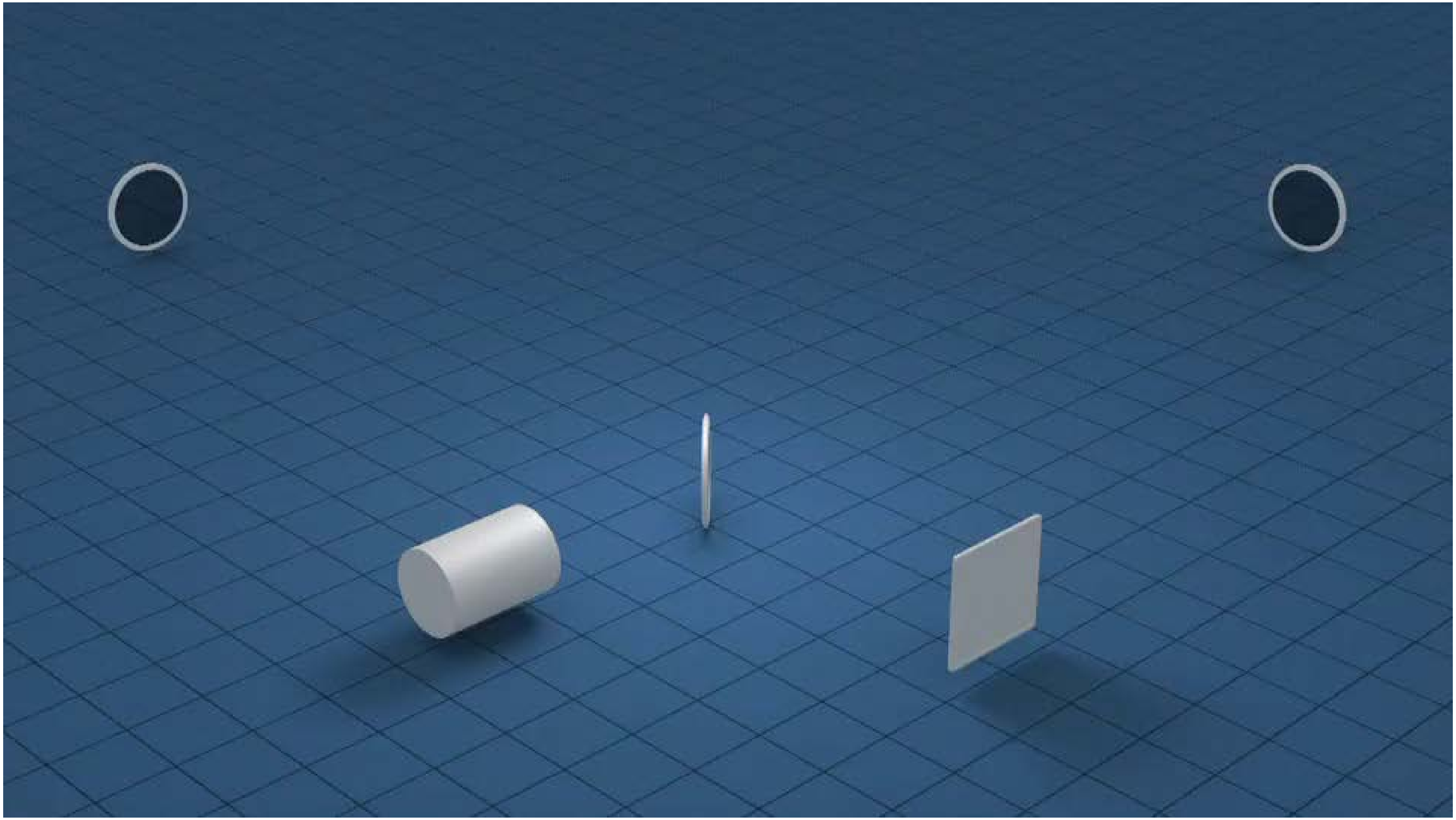
1957 Chapel Hill Conference (Bondi, Feynman, Pirani, etc.)

- **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.)**

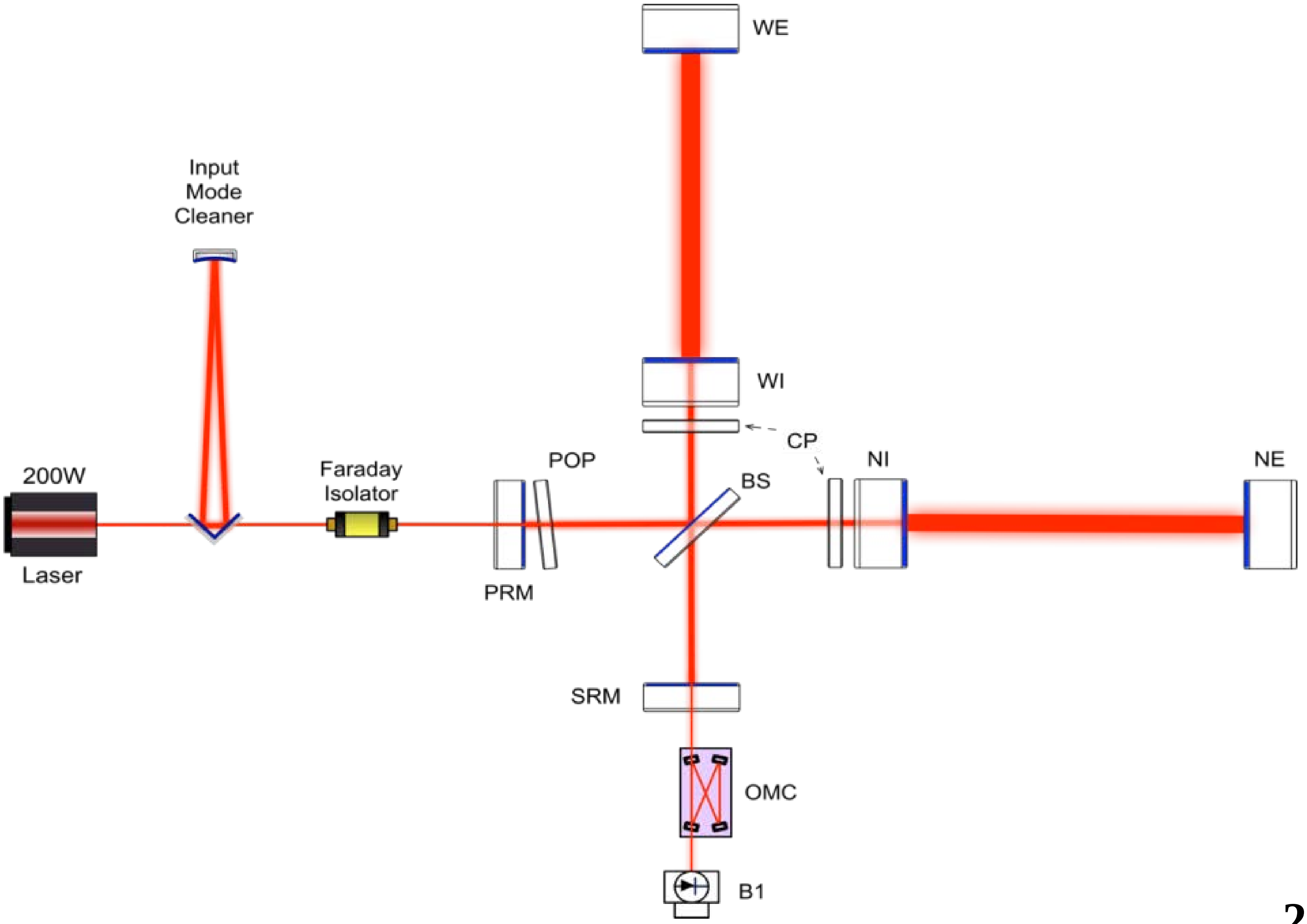
Experiments

- **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**

An interferometer in a nutshell

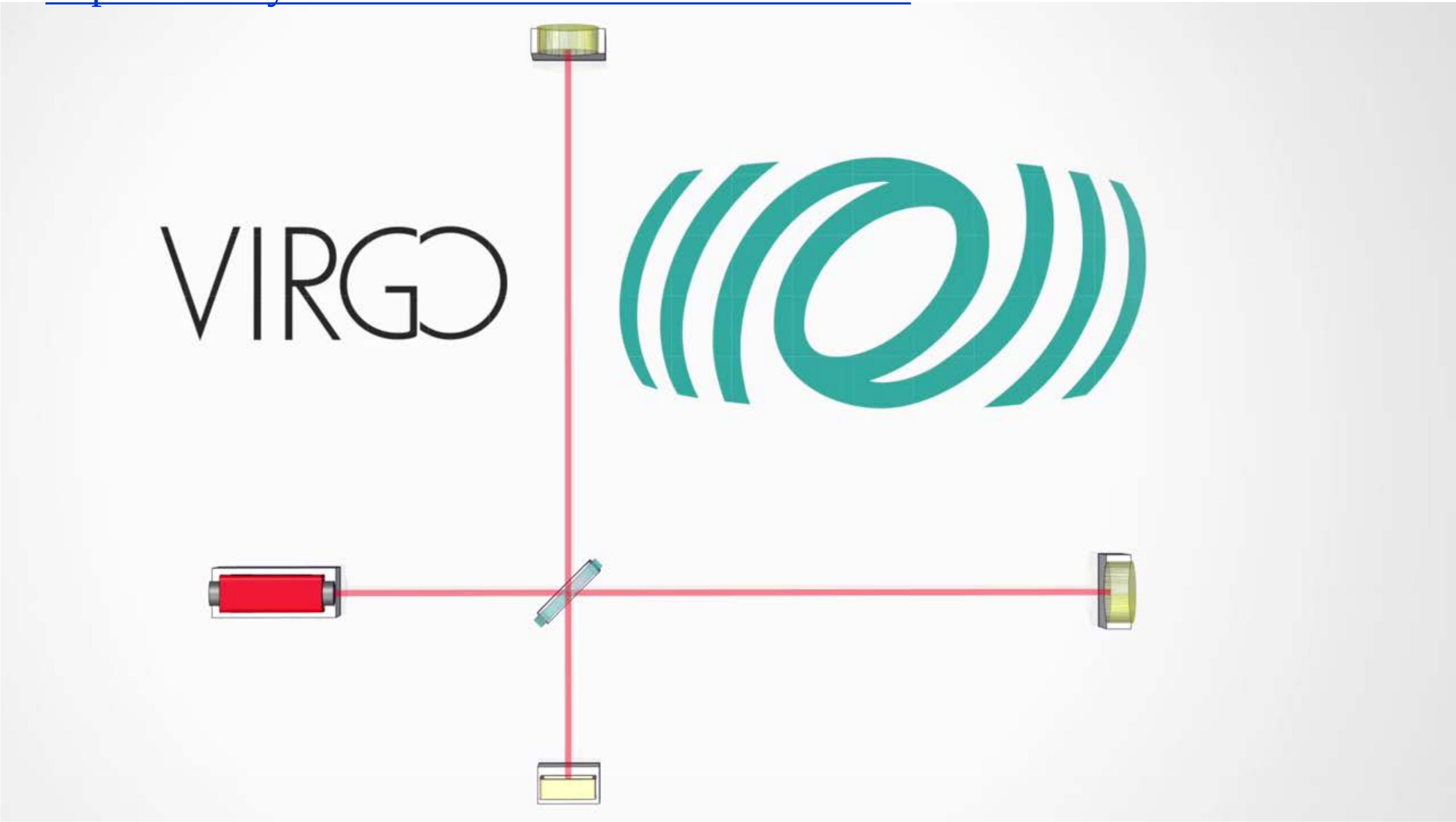


The Advanced Virgo detector scheme



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 ↔ 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

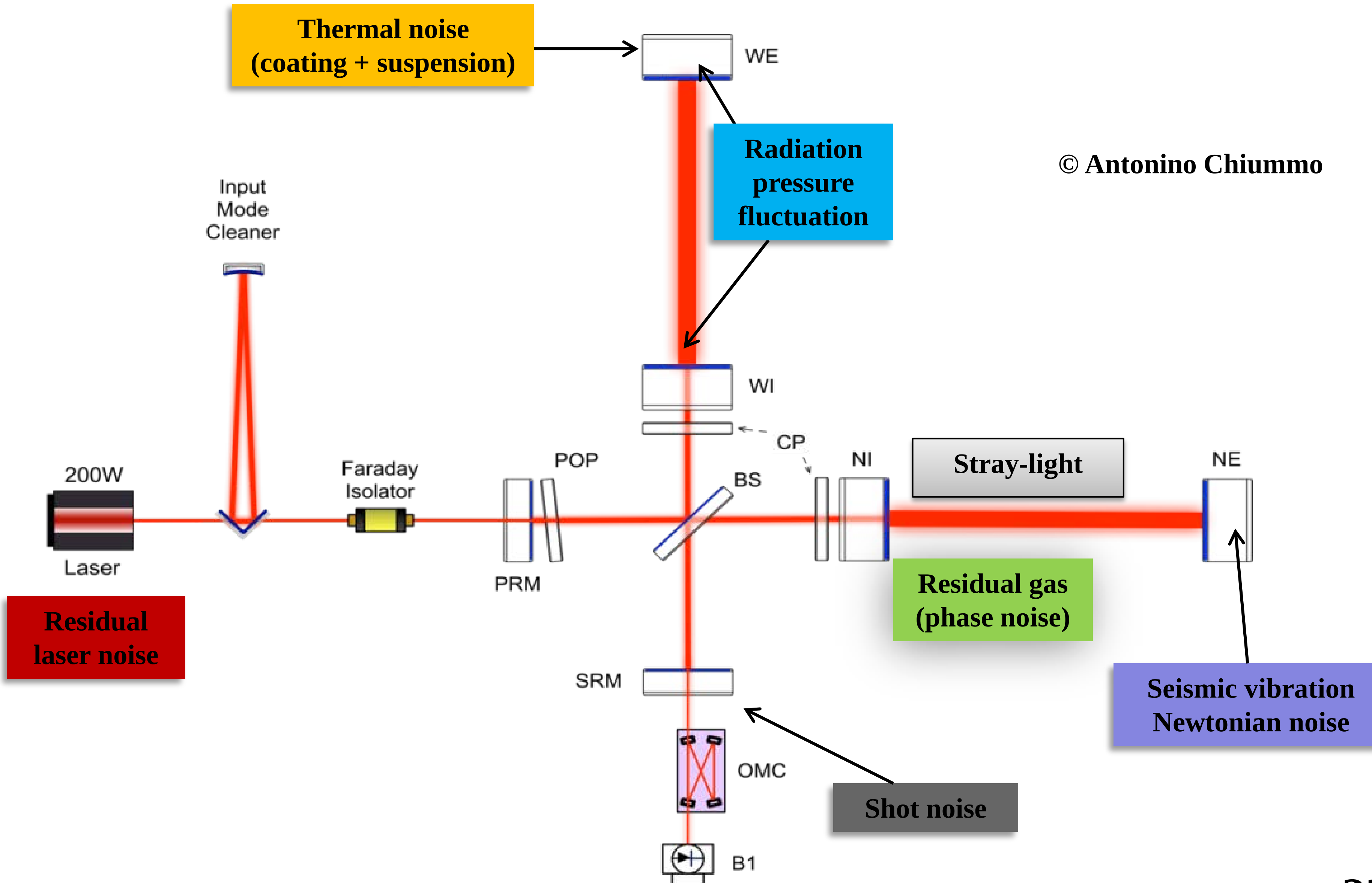
    → Cannot be avoided; optimize design to minimize these contributions
  - Instrumental

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

Main interferometer noises



Interferometer control

- A complex working point
  - Resonant Fabry-Perot and recycling cavities + IFO on the dark fringe
  - Arm length difference controled with an accuracy better than 10^{-15} m
  - The better the optical configuration, the narrower the working point

- « Locking » the IFO is a non-trivial engineering problem
  - Use several error signals to apply corrections on mirror positions and angles
    - → Pound-Drever-Hall signals (phase modulation)
    - → Auxiliary green lasers (for 2nd generation IFOs)
  - Feedback loops from few Hz to few kHz
  - Cope with filter bandwith and actuator range

- Multi-step lock acquisition procedure

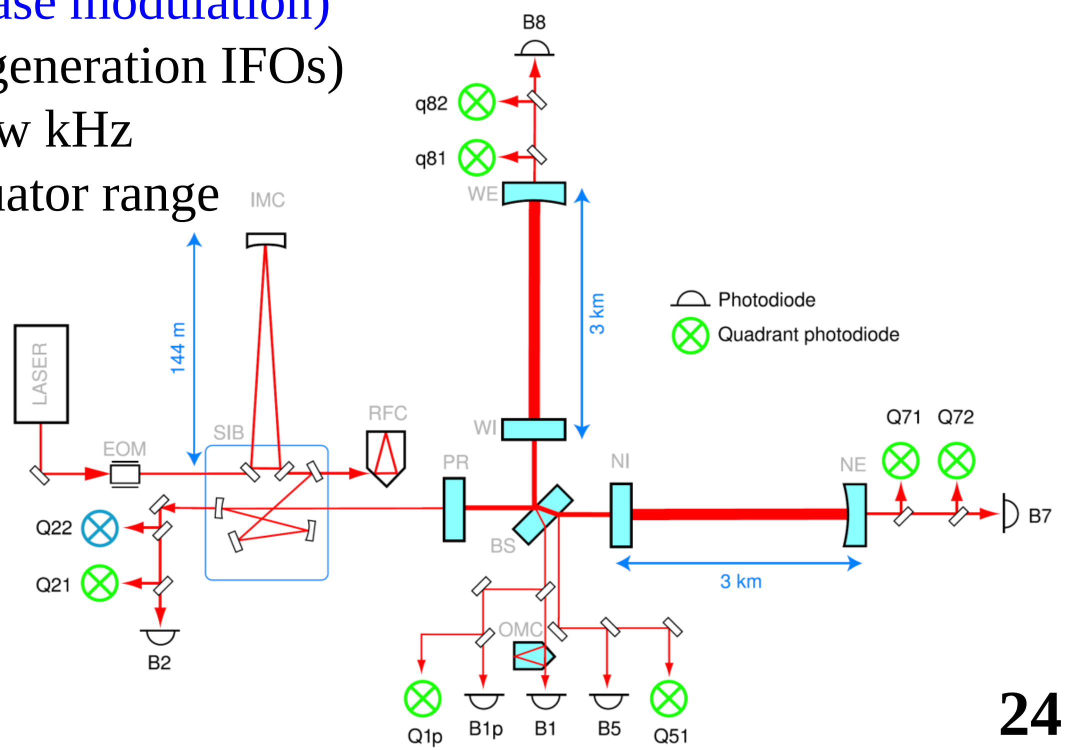
Free mirrors

↓

Local control

↓

Global control

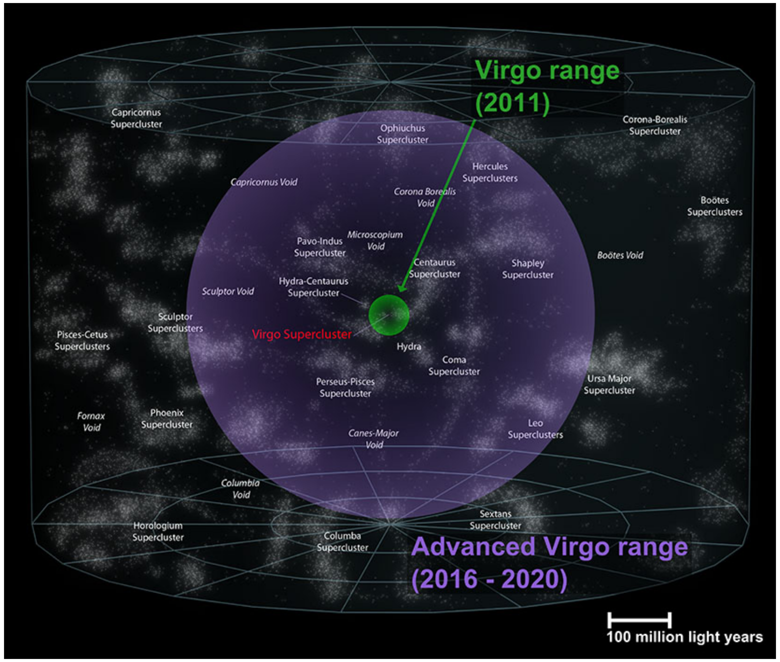


From initial to advanced detectors

- 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

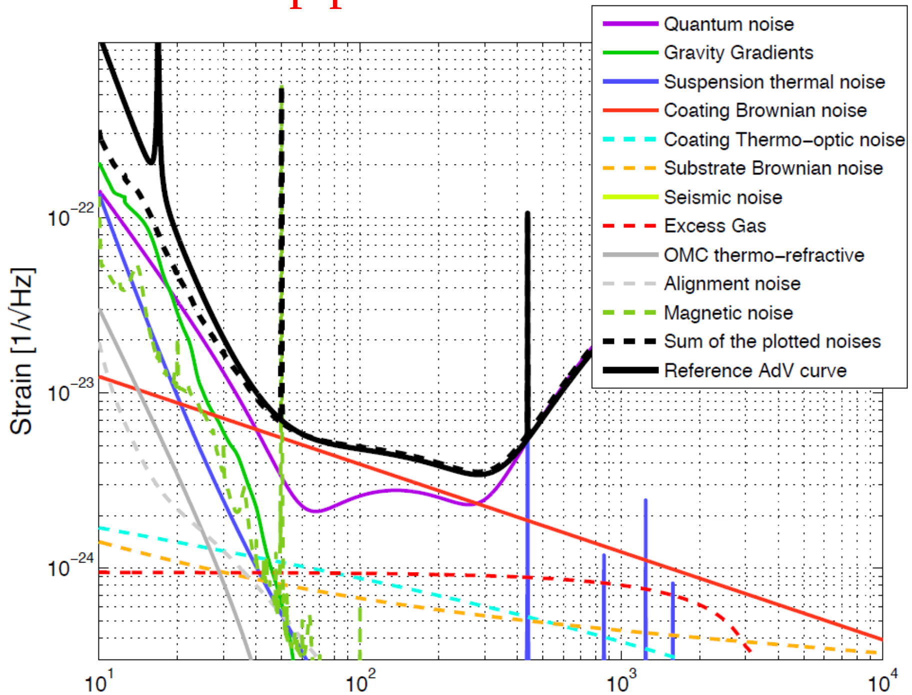


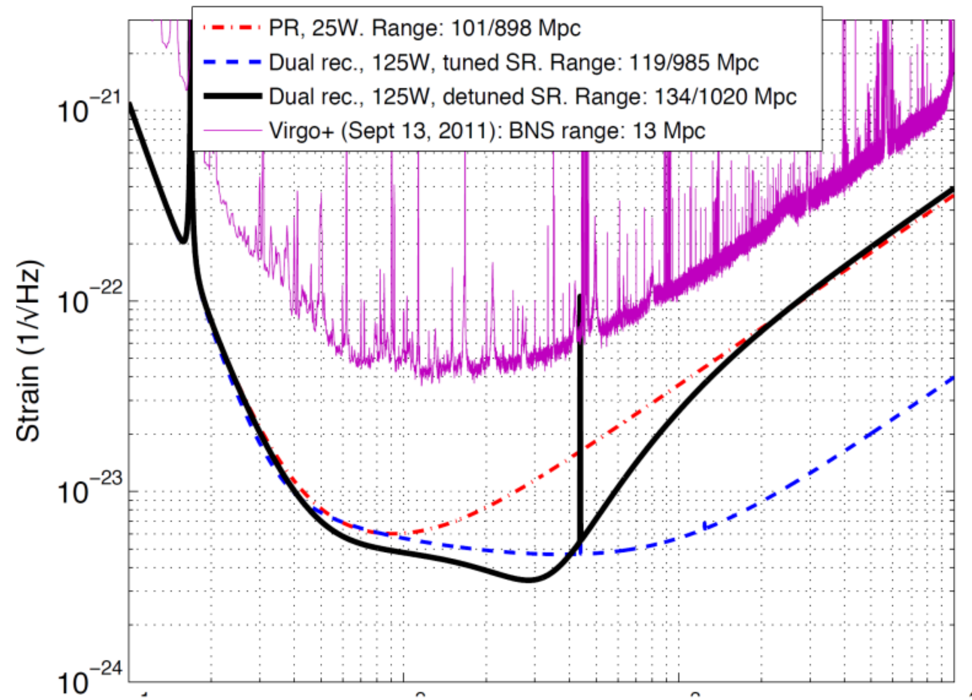
- Advanced LIGO (aLIGO) funded a year or so before Advanced Virgo (AdV)
  - Financial crisis in 2008-2010…

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

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

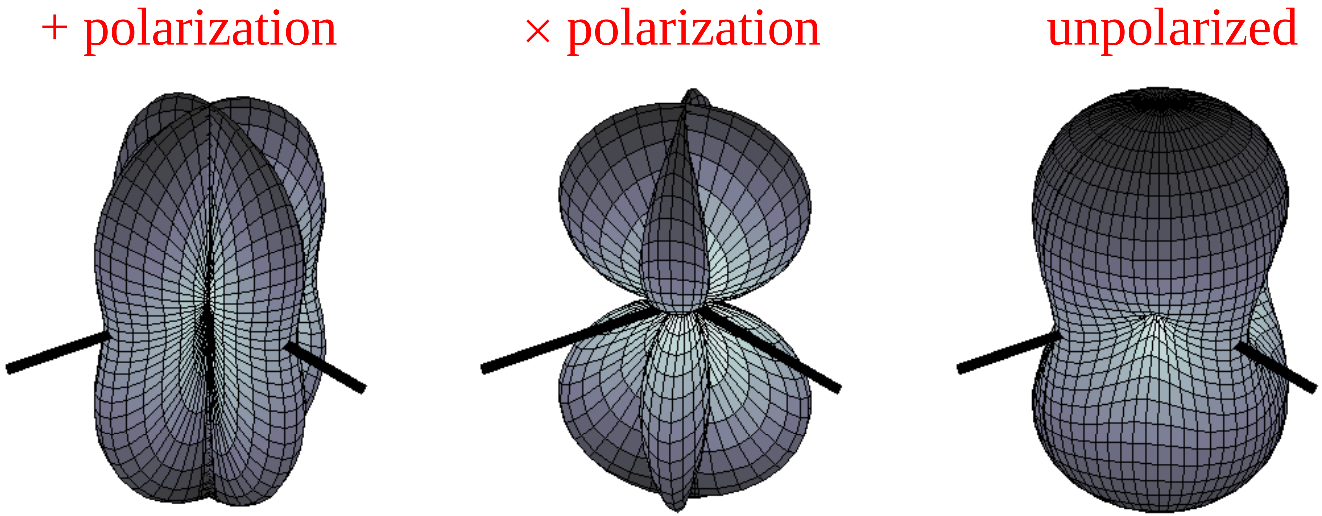
Interferometer angular response

- 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

$$h(t) = F_+(t) \times h_+(t) + F_\times(t) \times h_\times(t)$$

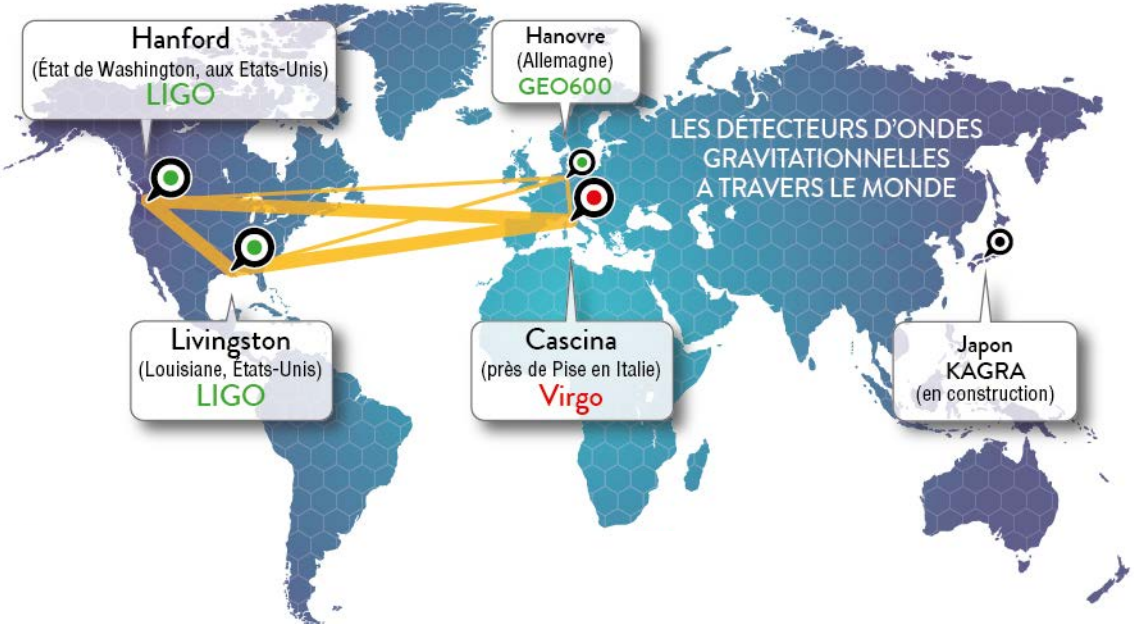
  - F_+ and $F_\times$ are antenna pattern functions which depend on the source direction in the sky w.r.t. the interferometer plane
    → Maximal when perpendicular to this plane
    → Blind spots along the arm bisector (and at 90 degres from it)



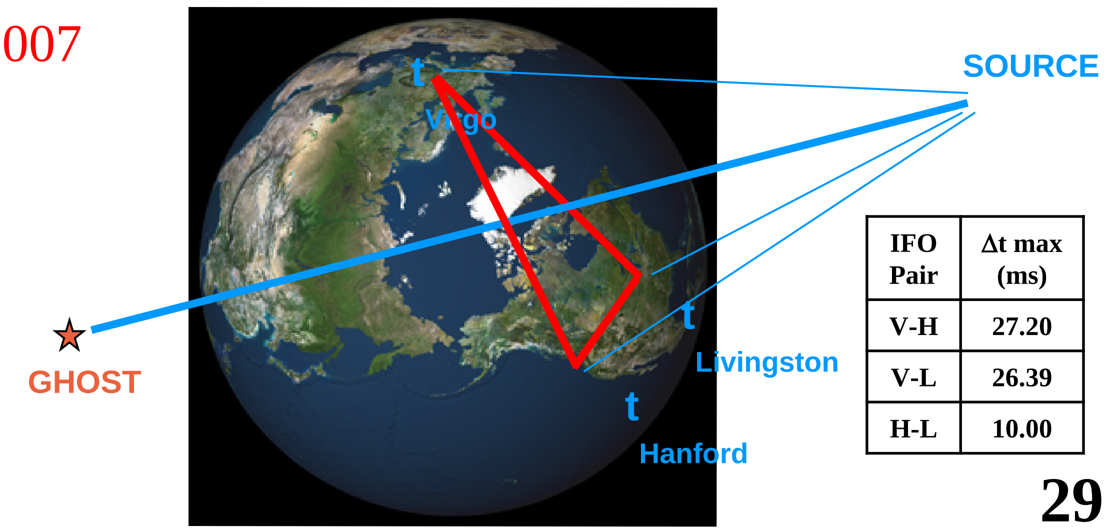
A network of interferometric detectors

- 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

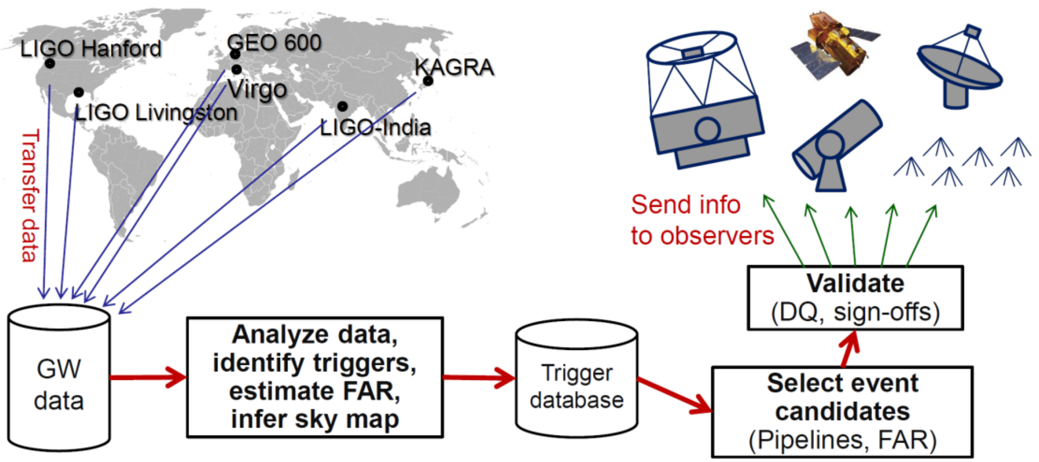


IFO Pair	Δt max (ms)
V-H	27.20
V-L	26.39
H-L	10.00

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



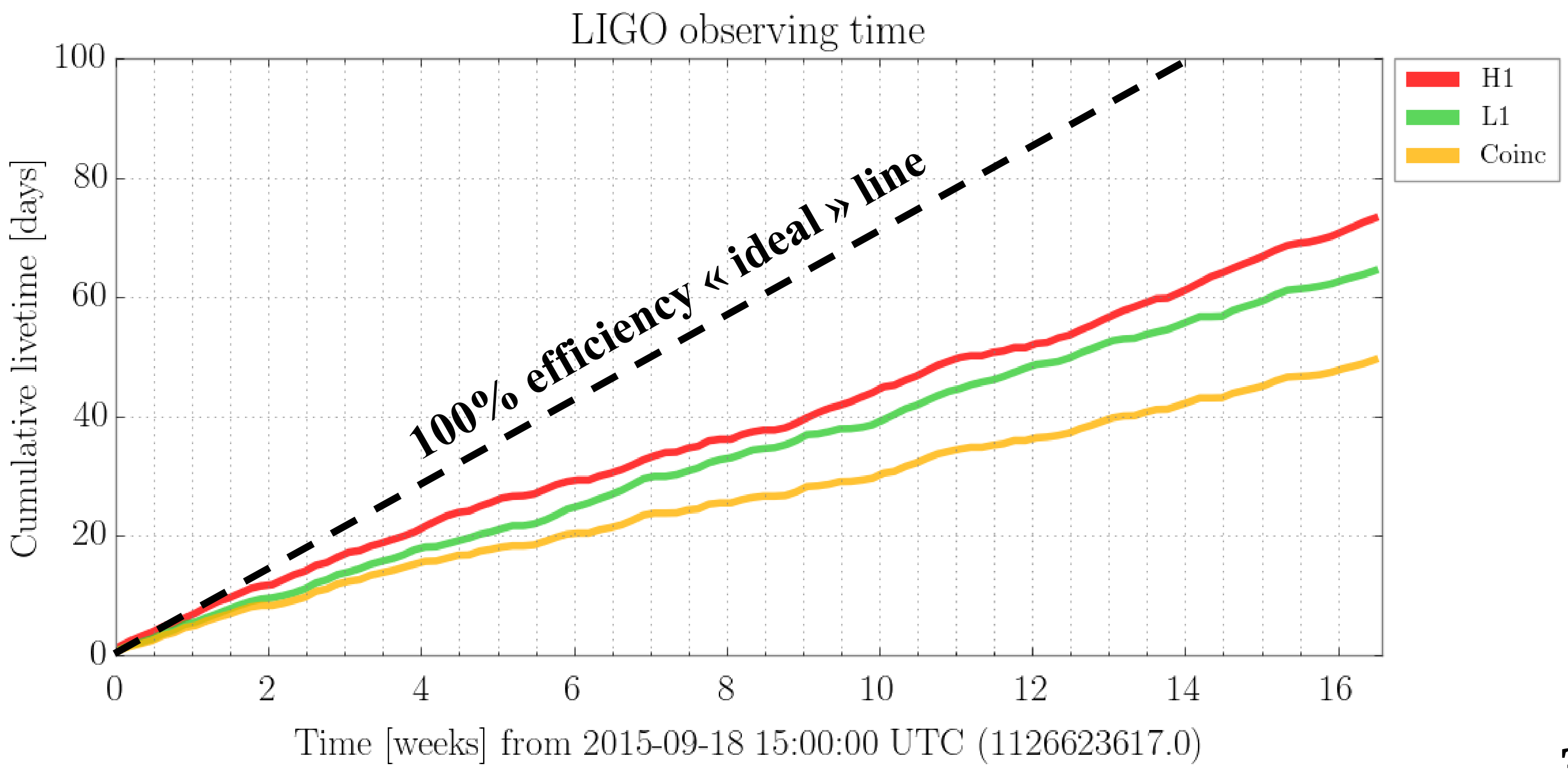
- Low latency h-reconstruction and data transfer between sites
  - Online GW searches for burst and compact binary coalescences

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 »

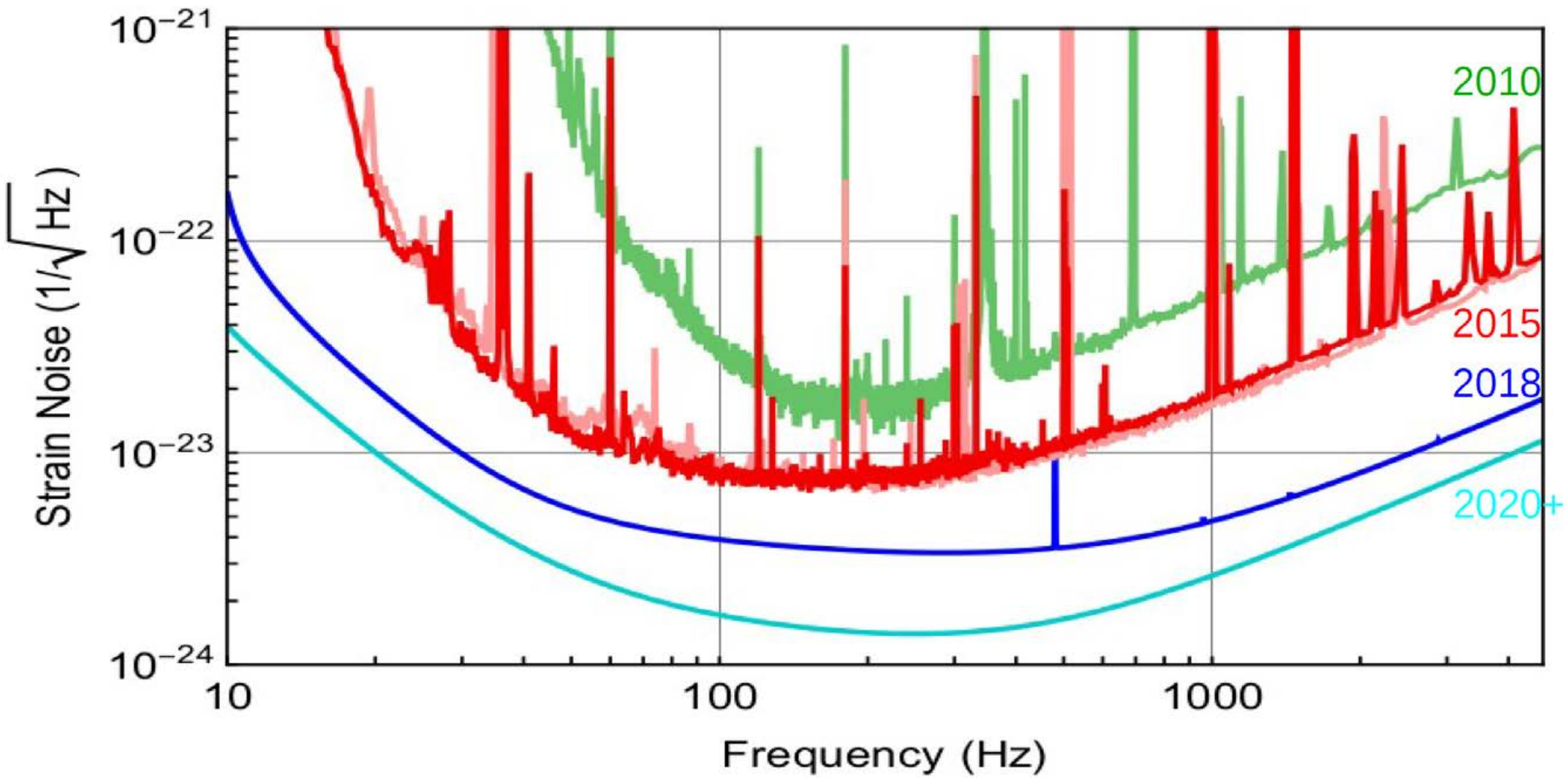
→ Both interferometers were already working nominally



aLIGO O1 Run: Sensitivity

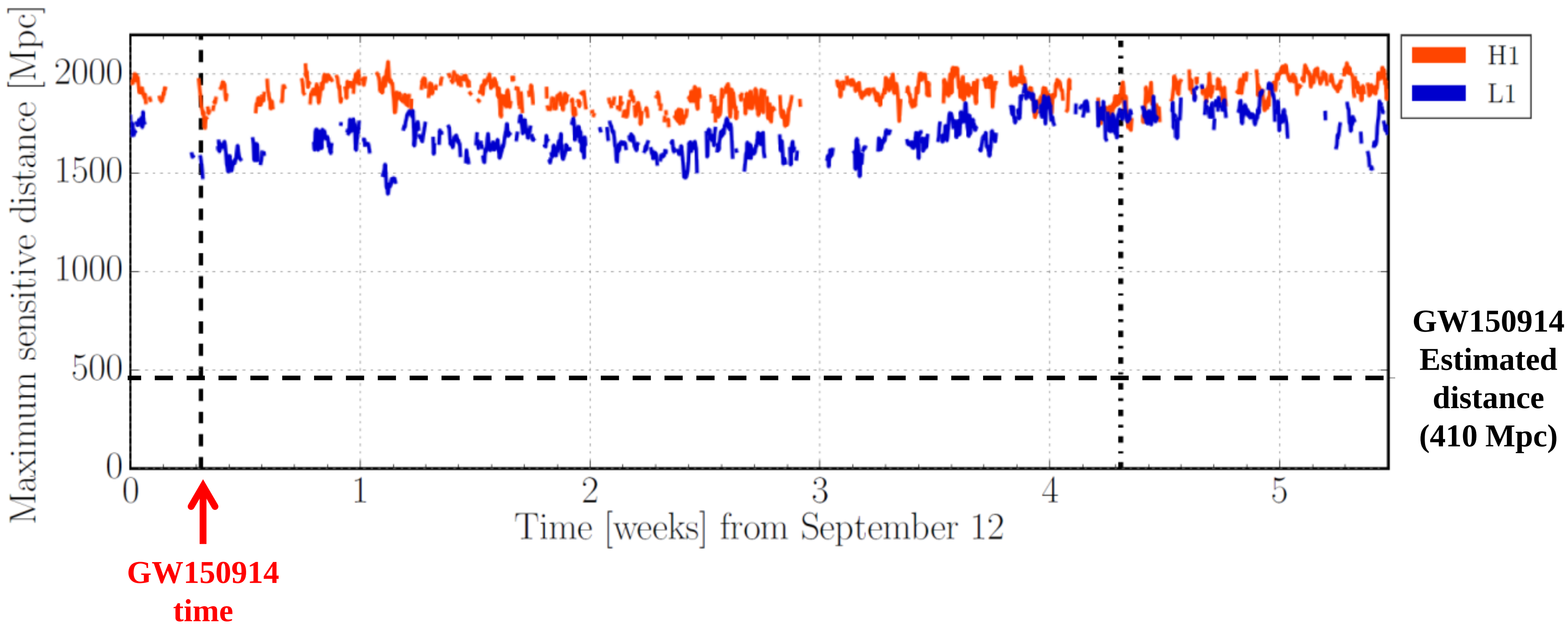
- Sensitiviy much improved with respect to the initial detectors
  - Factor 3-4 in strain

    → Factor 30-60 in volume probed
- Gain impressive at low frequency – where both signals are located



aLIGO O1 Run: GW150914-like horizon

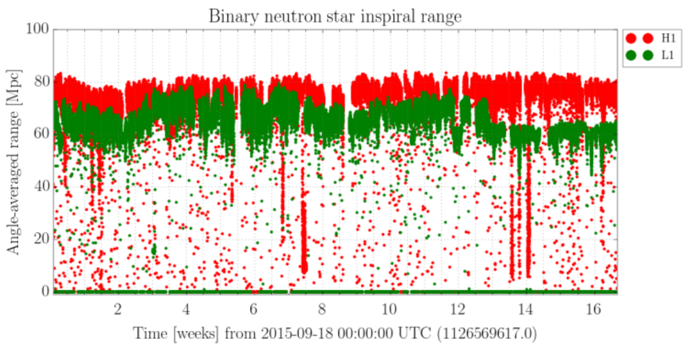
- Sky-averaged distance up to which a given signal can be detected
  - In this case a binary black hole system with the measured GW150914 parameters



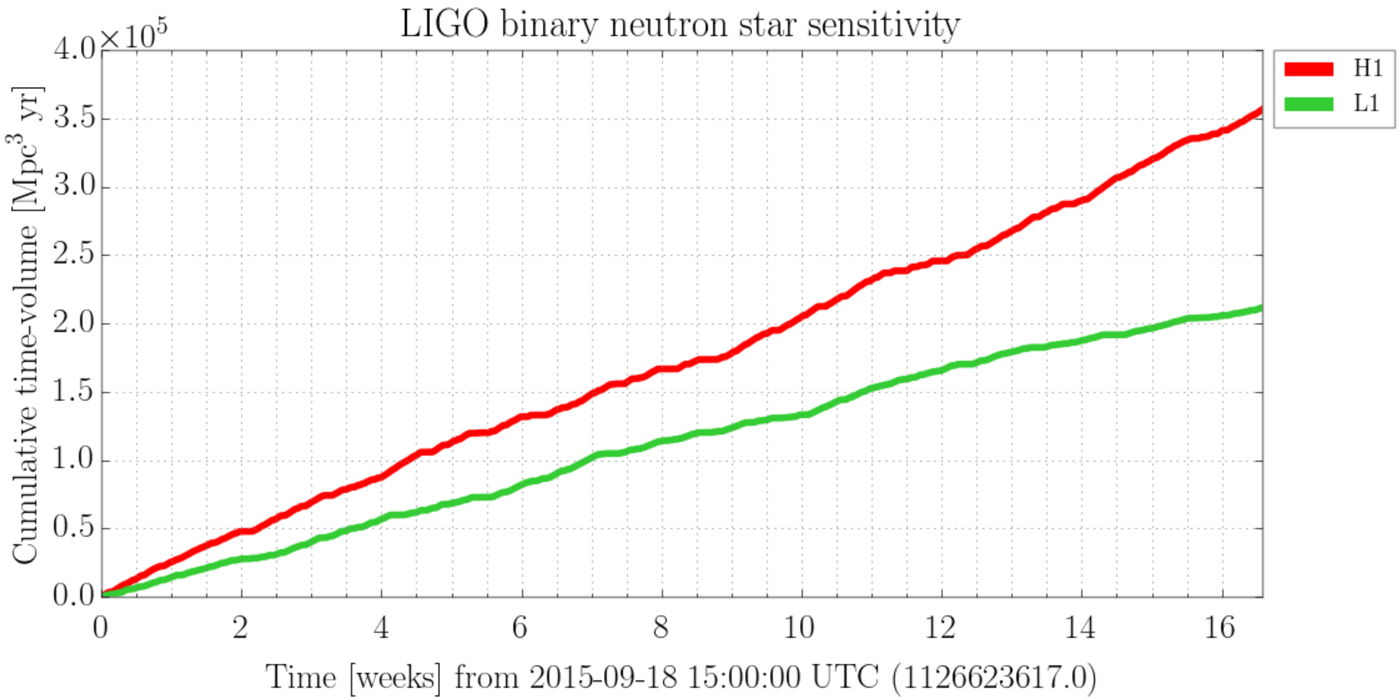
- Only depends on the actual sensitivity of the interferometer
  - Online monitoring tool used during data taking

aLIGO O1 Run: "VT" figure of merit

- Cumulative time-volume probed by the instruments
  → Expected number of sources (given a model)
  - Unit: Mpc^3.year
  - This slide: 1.4-1.4 $M_\odot$ « standard » binary neutron star system case



- Mixes sensitivity and duty cycle information

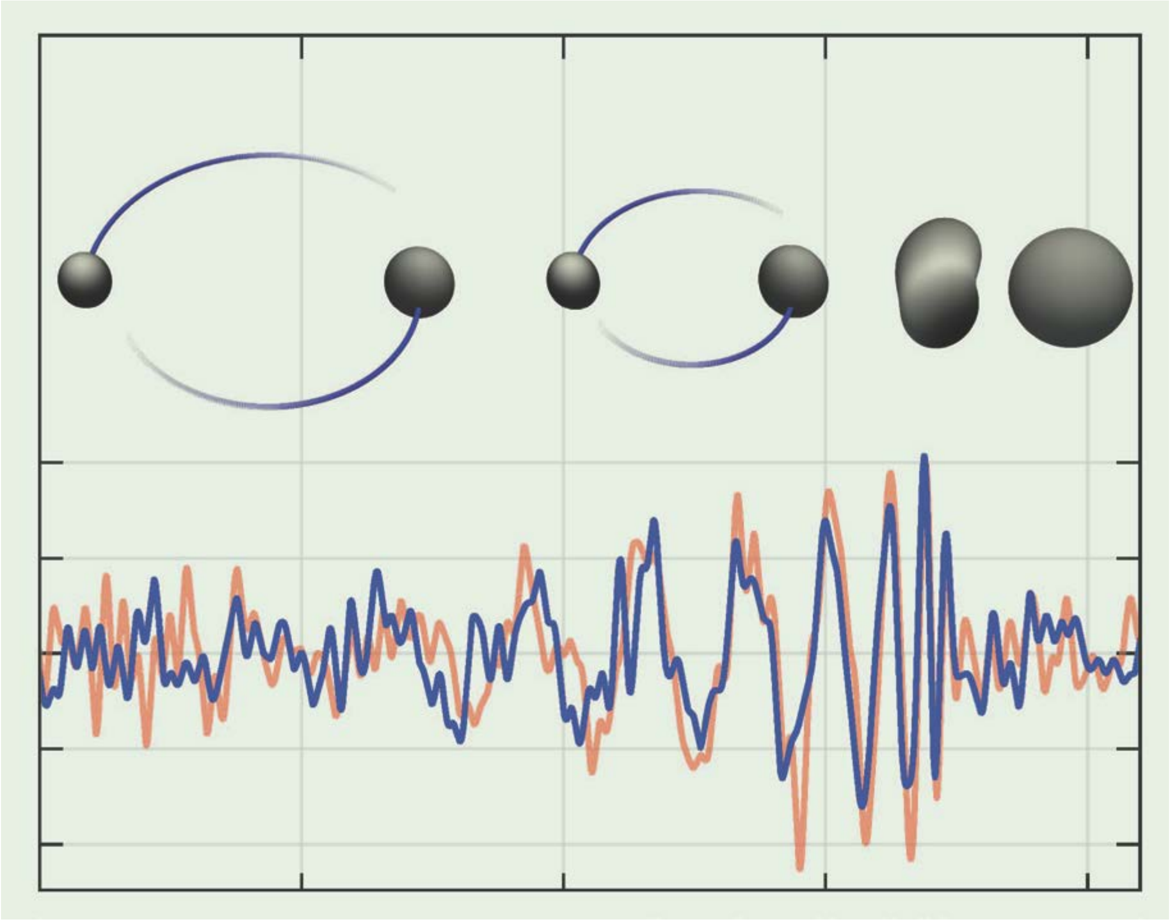


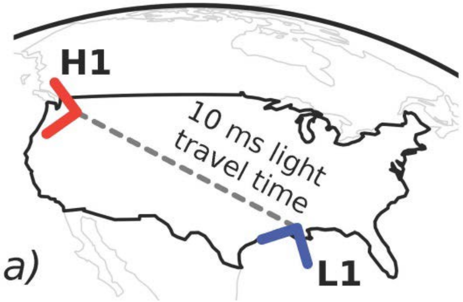
GW150914

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

Rapid response to GW150914

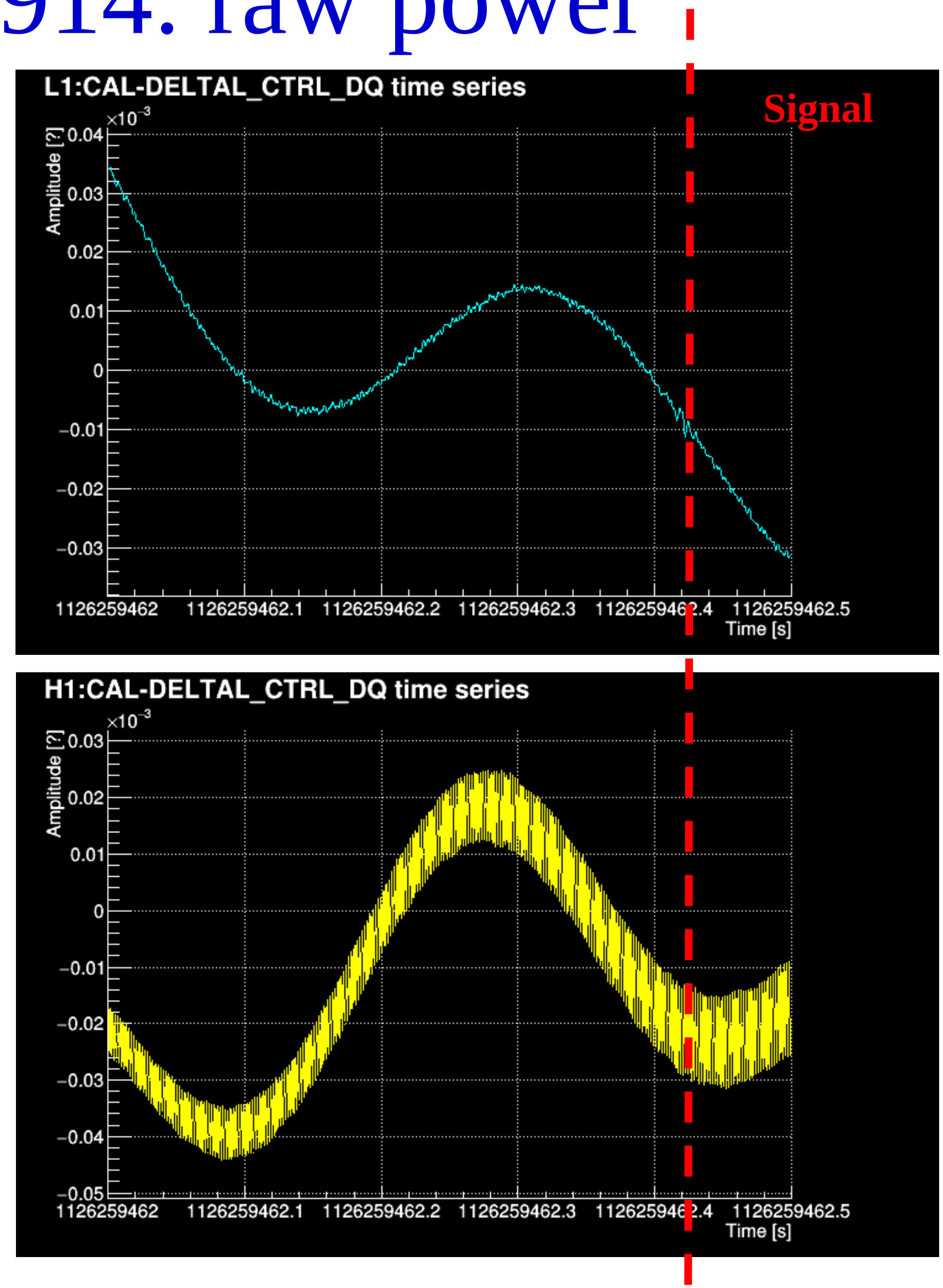
- 2015/09/14 11:51 CET: event recorded – first in Livingston, 7 ms later in Hanford
- 3 minutes later : event flagged, entry added to database, contacts notified
  - Online triggers important in particular for searches of counterparts
- 1 hour later: e-mails started flowing within the LIGO-Virgo collaboration

> 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

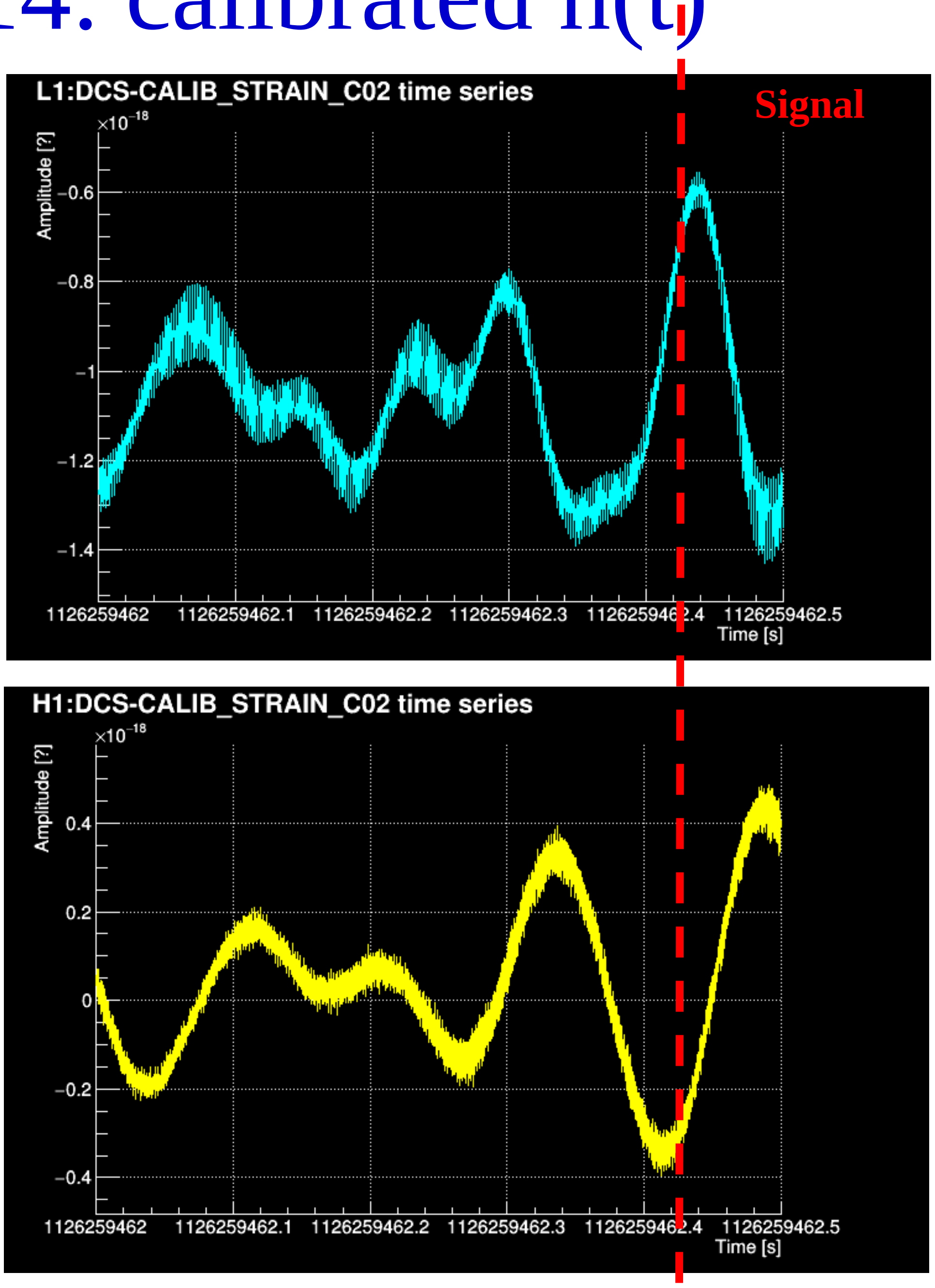
GW150914: raw power

- Blue: aLIGO Livingston
  Yellow: aLIGO Hanford



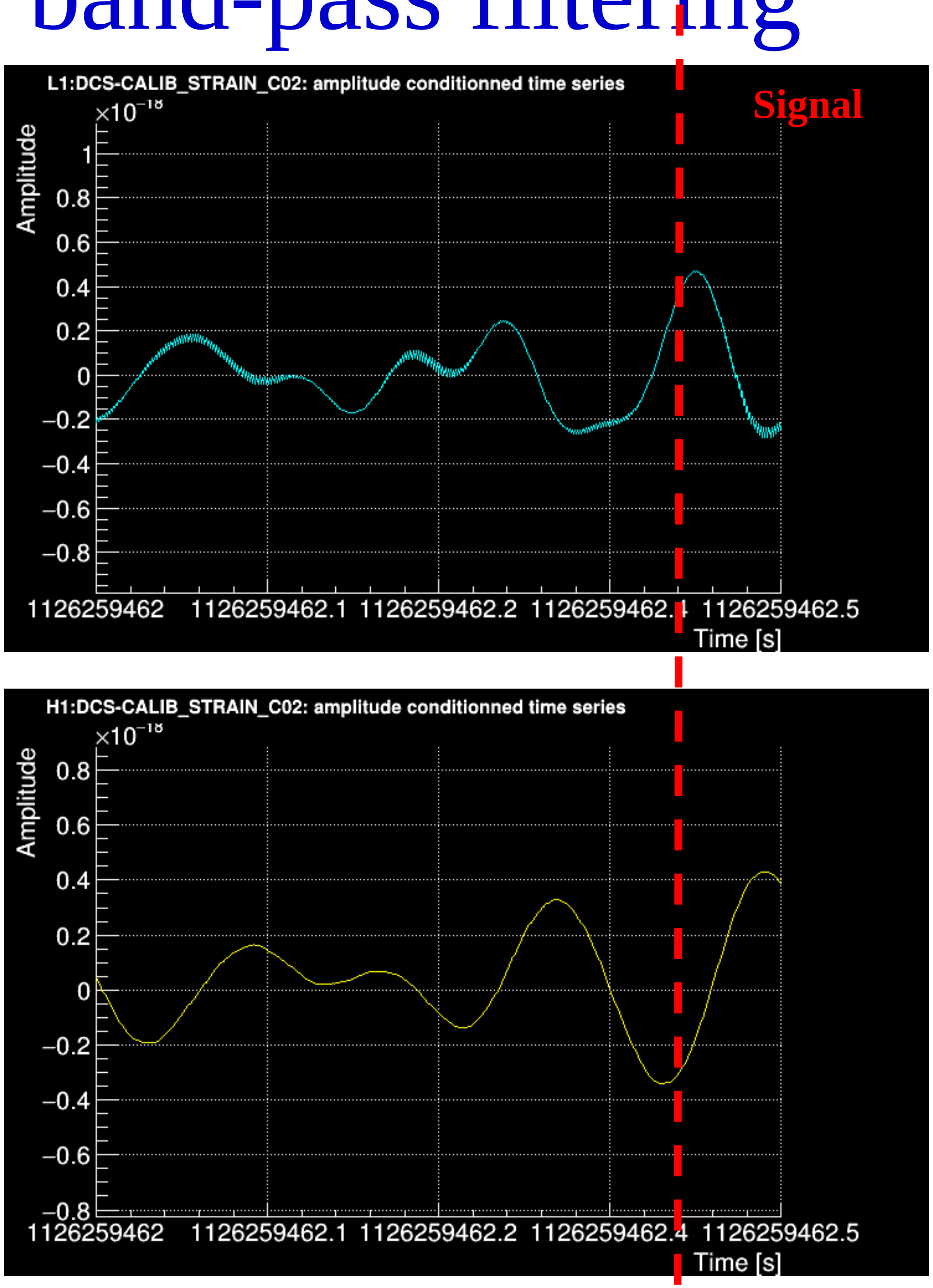
GW150914: calibrated h(t)

- Control signals used to recover the strain signal



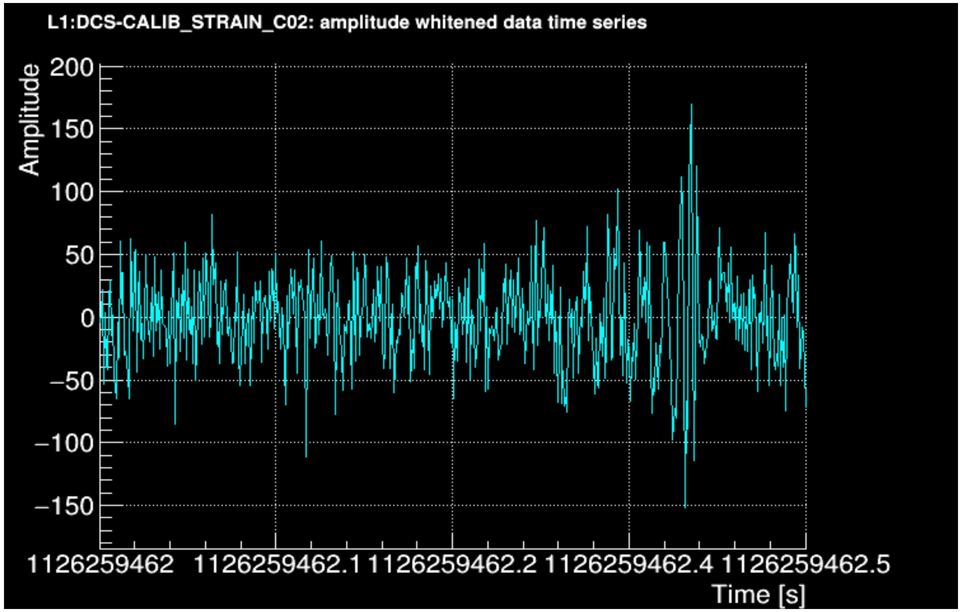
GW150914: band-pass filtering

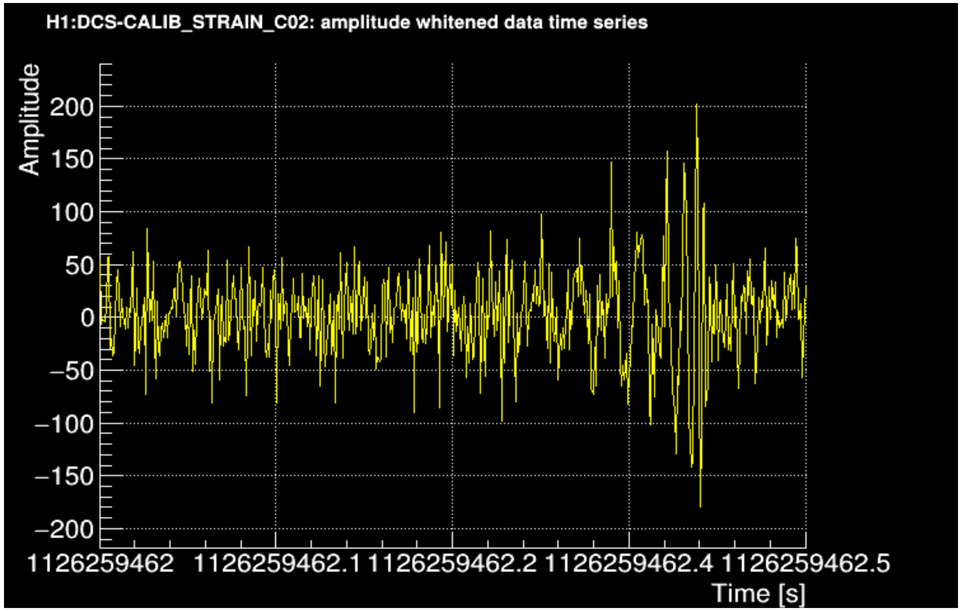
- 20 Hz → 500 Hz



GW150914: whitened data

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





- ± 20 nW peak-to-peak at the interferometer output port
  - To be compared with the incident power on the beamsplitter: ~500 W

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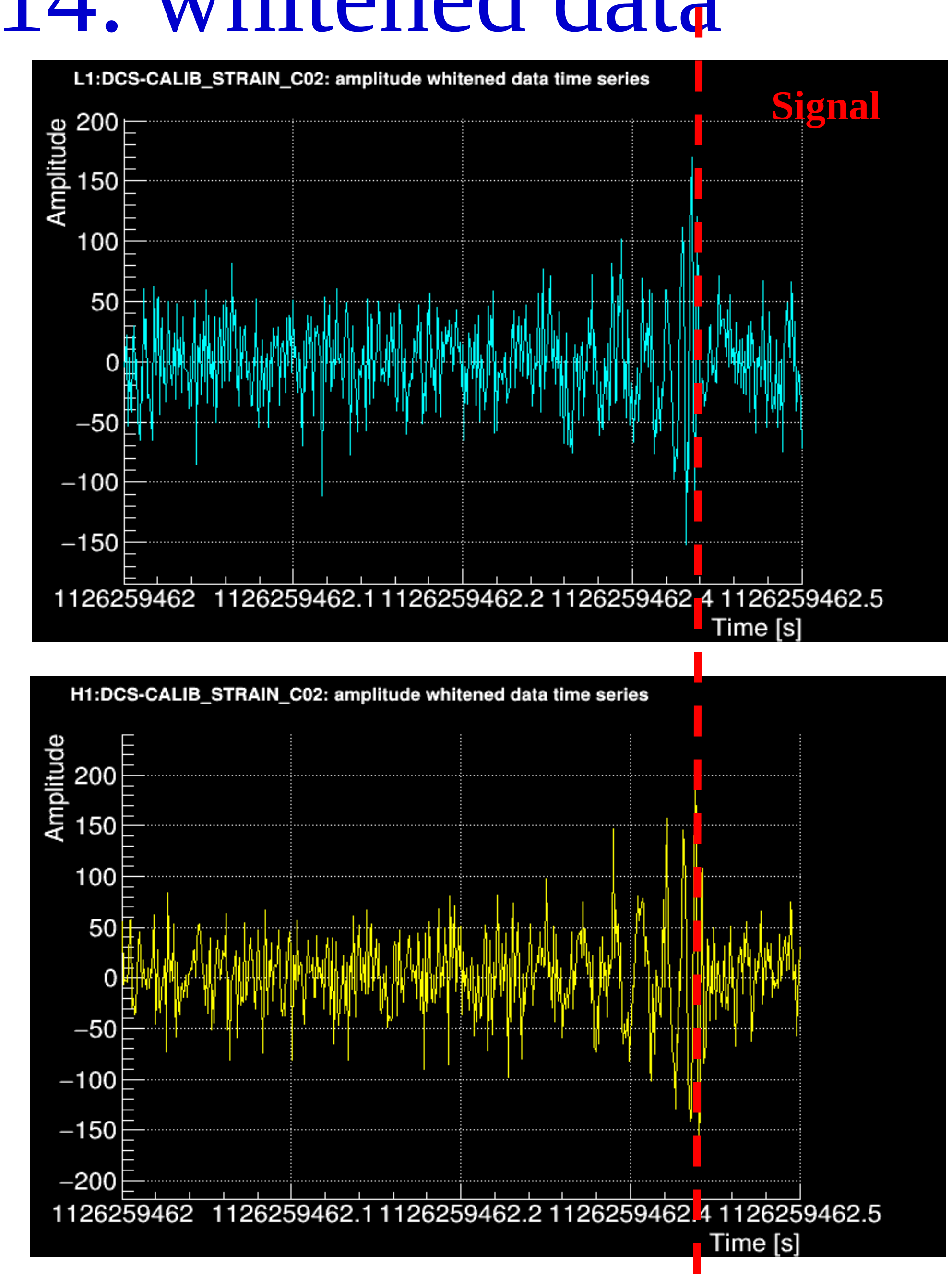

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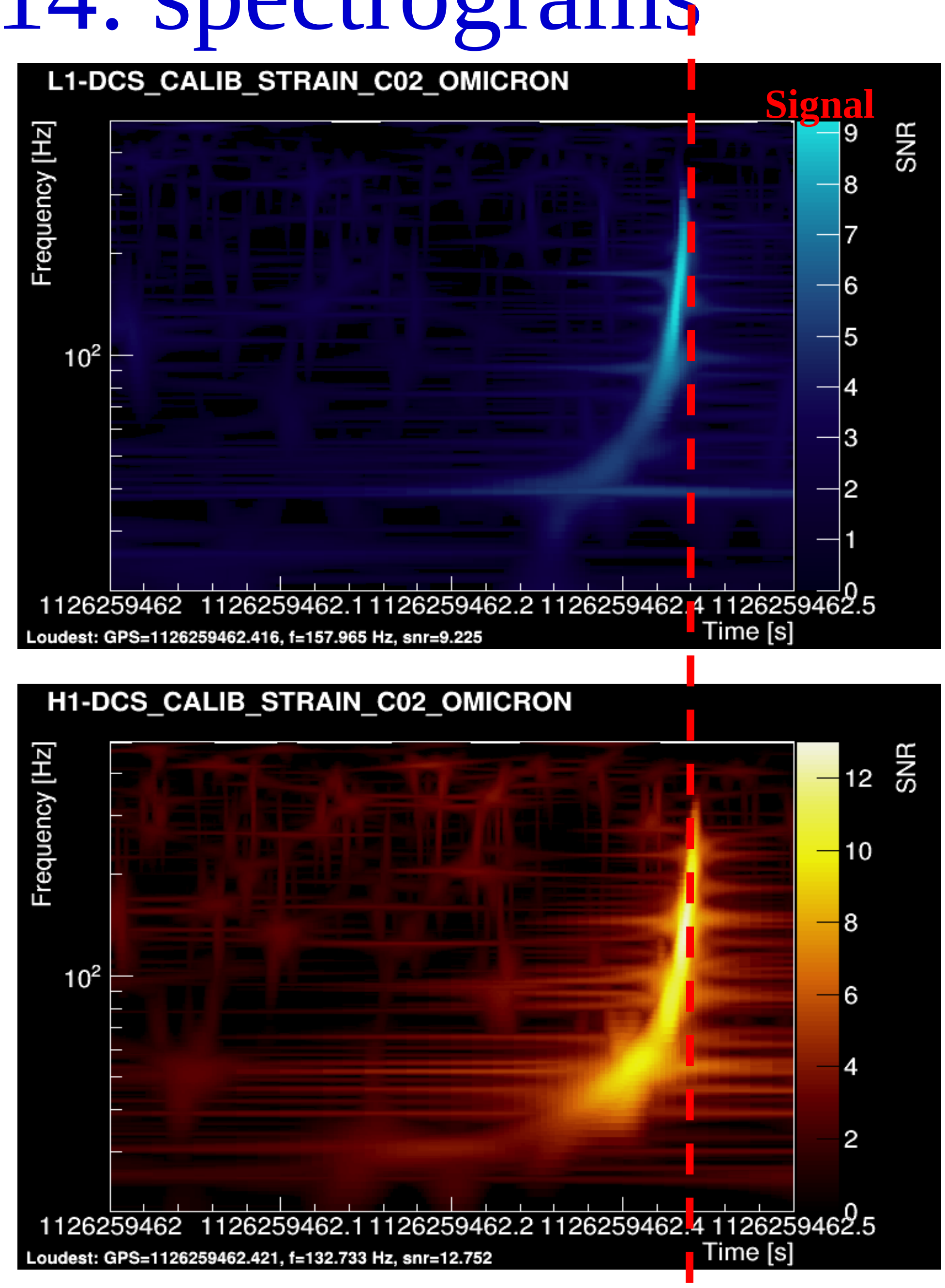
GW150914: spectrograms

- Time-frequency maps



Compact binary coalescence search

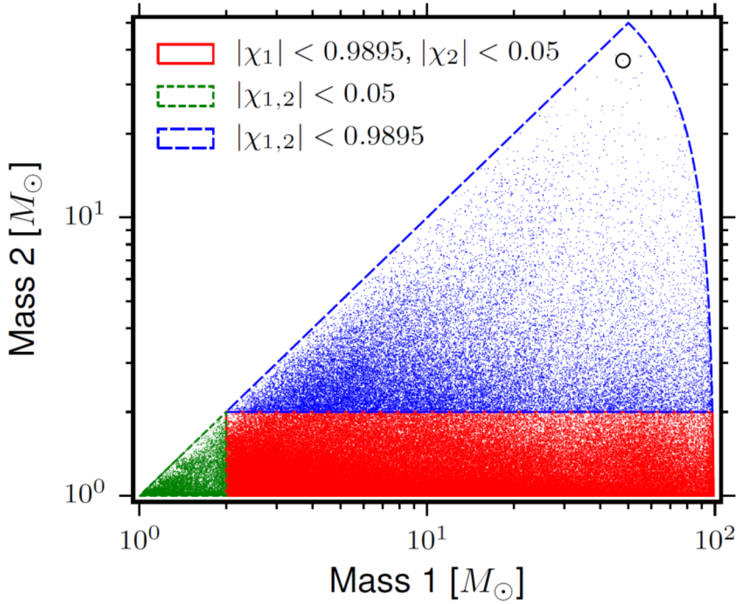
- Well-predicted waveform
  → Matched-filtering technique (optimal)
    - Noise-weighted cross-correlation of data with a template (expected signal)

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



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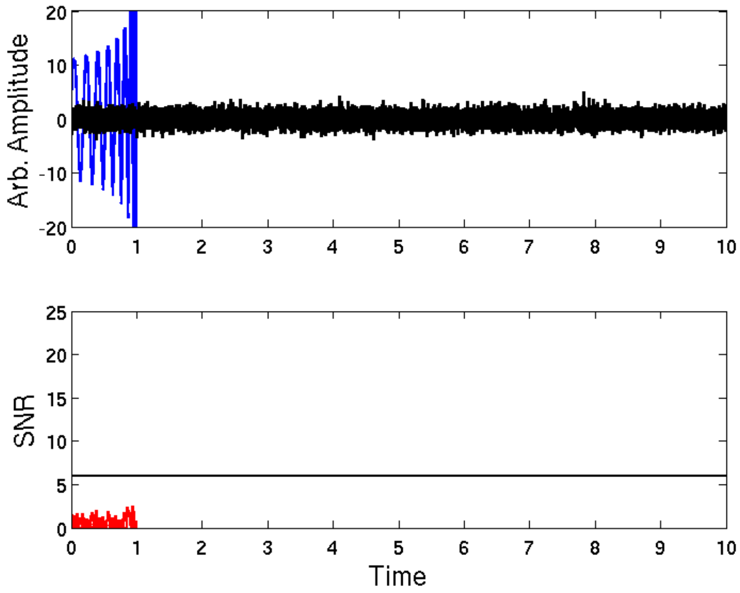

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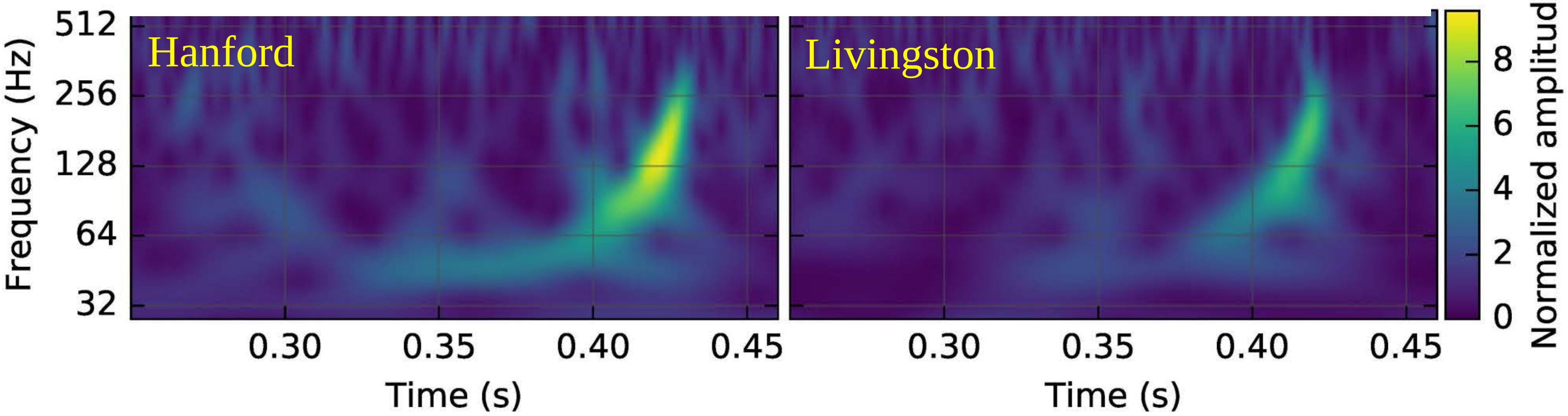
  - Check matching between signal and template

- 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

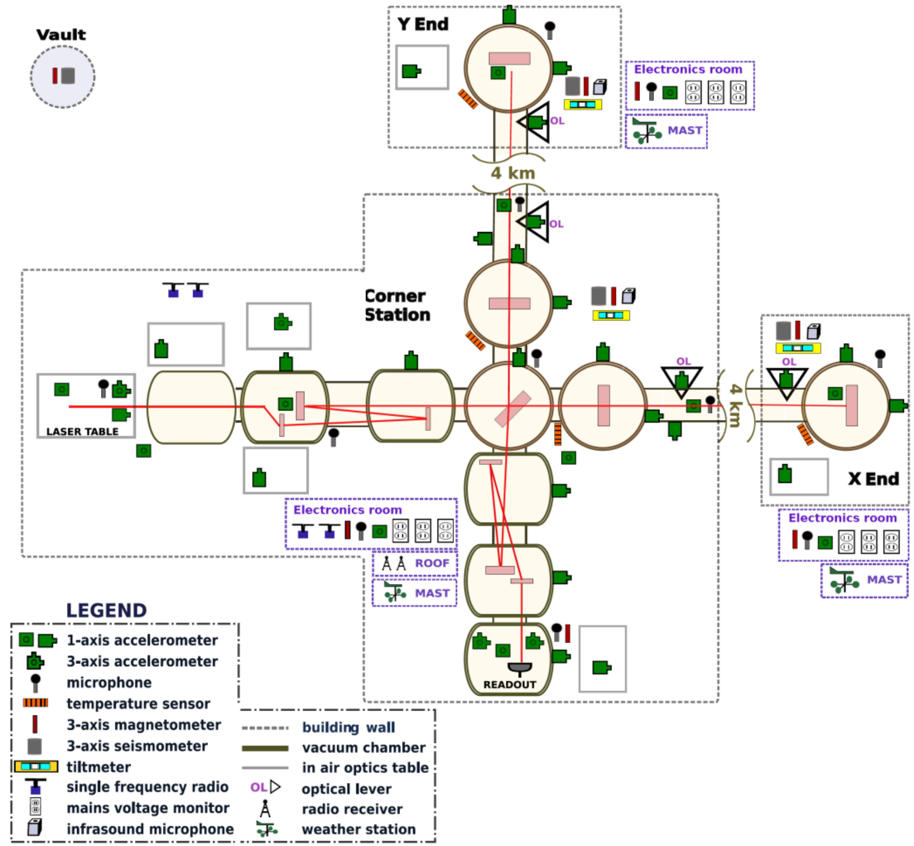
- Detector configuration frozen to integrate enough data for background studies
  - ~40 days (until end of October) corresponding to 16 days of coincidence data

  → 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



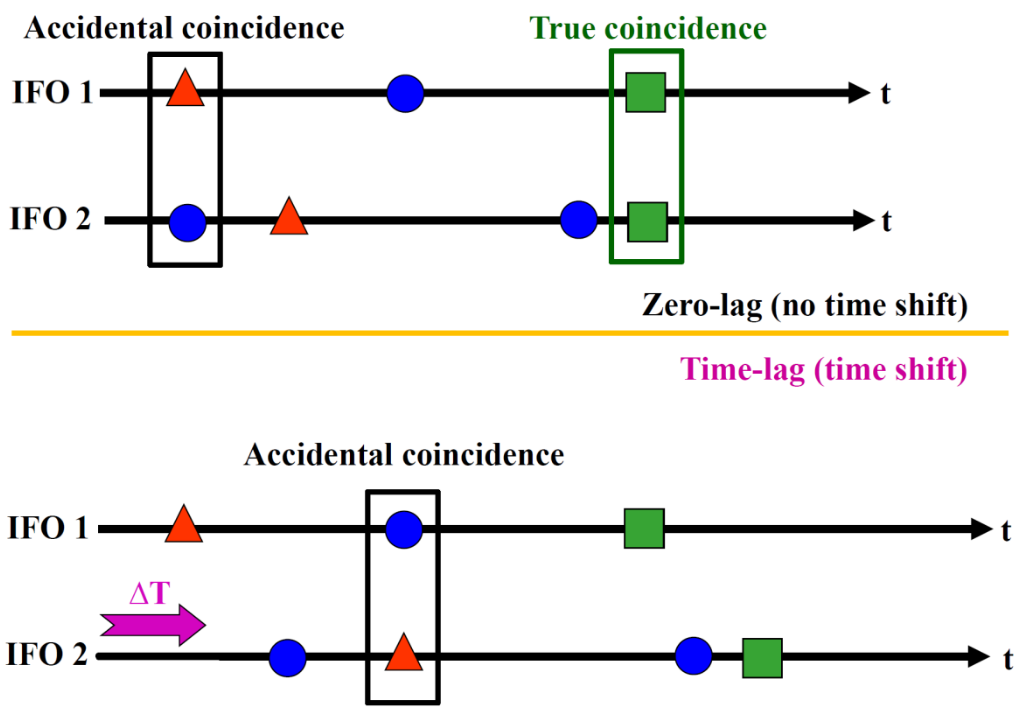
- Extensive studies performed
  - Uncorrelated and correlated noises
  - Bad data quality periods identified and vetoed

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

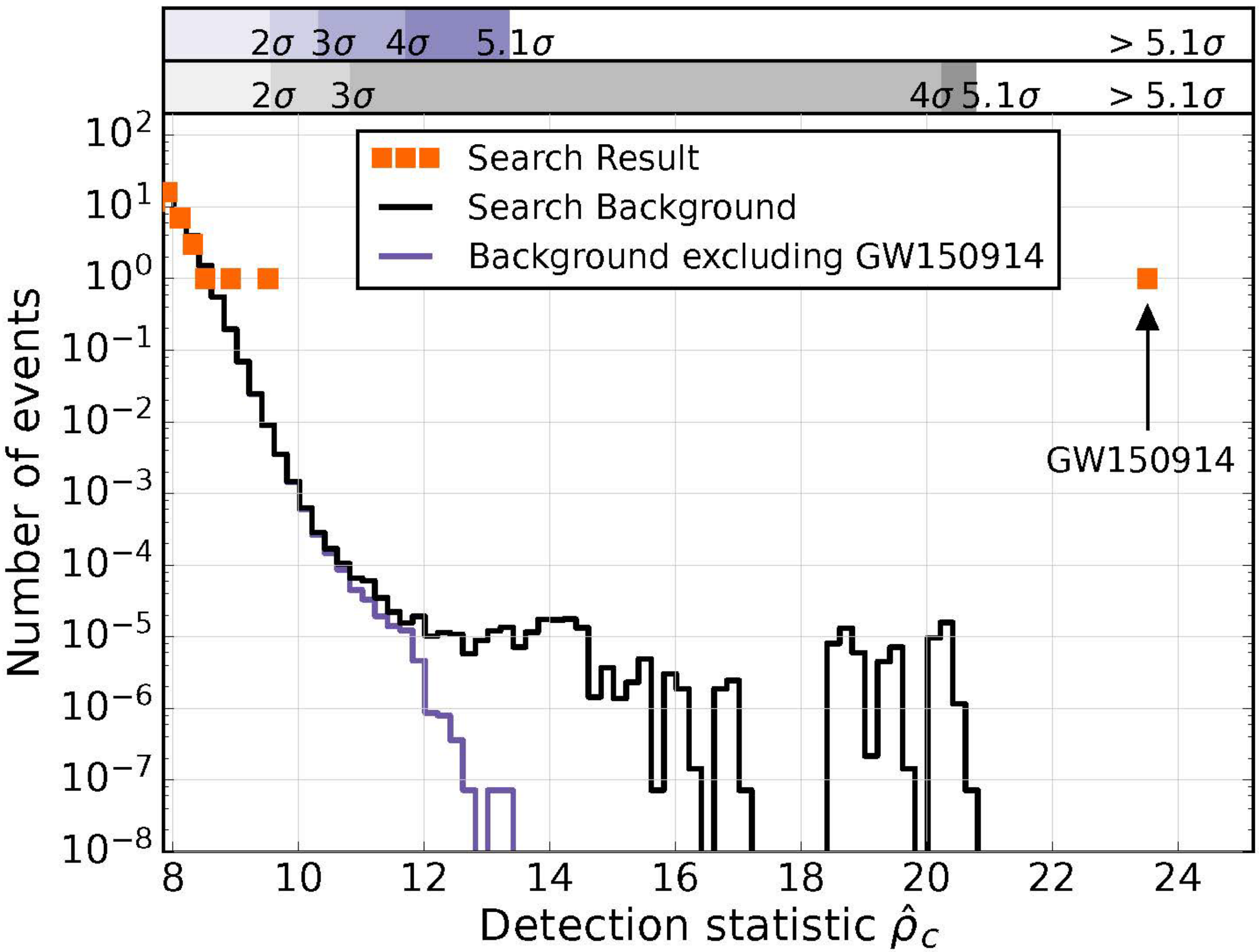


- Reminder: real GW events are shifted by 10 ms at most between IFOs
  - Light travel time over 3,000 km

- 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

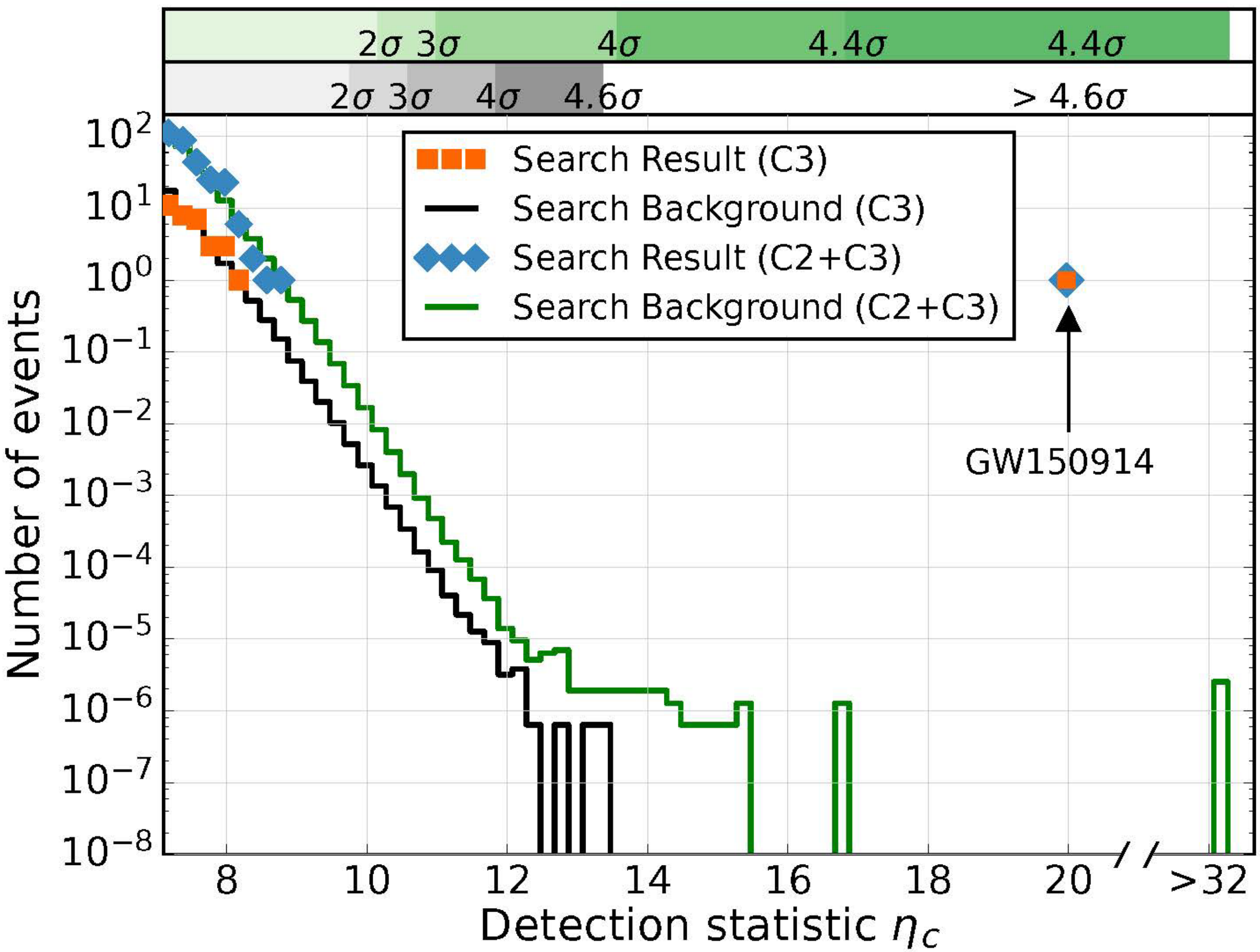
- x-axis: detection statistic used to rank events (the « SNR »)
  - GW150914: strongest event (true in both IFOs)
- Observed (zero-lag) events
- Solid lines: 2 background estimations (from time-lag)



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

Signal significance – Burst analysis

- Similar plot



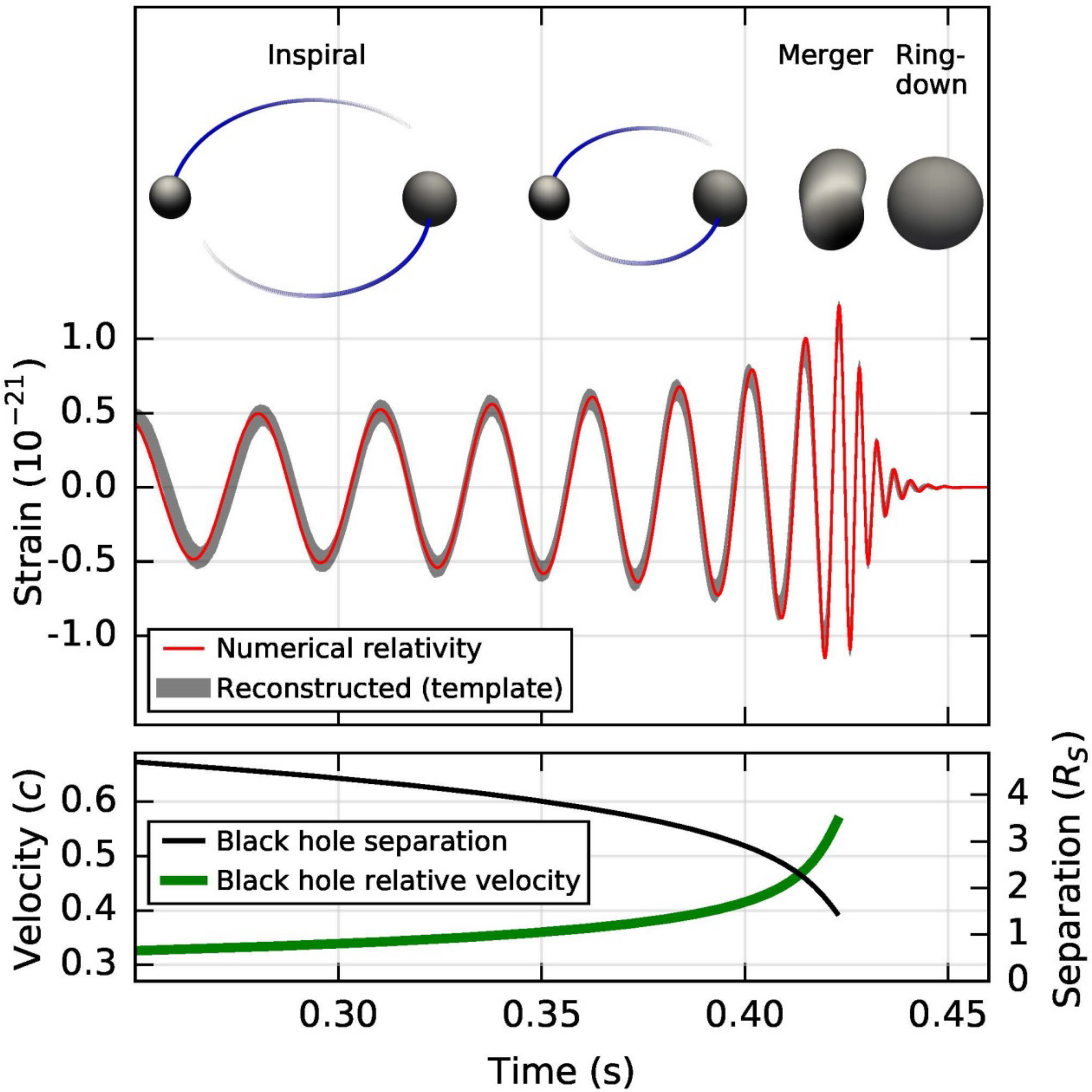
- False alarm rate < 1 event / 67,400 years
  False alarm probability < 2×10^{-6} (> 4.6 σ)

Why two black holes?

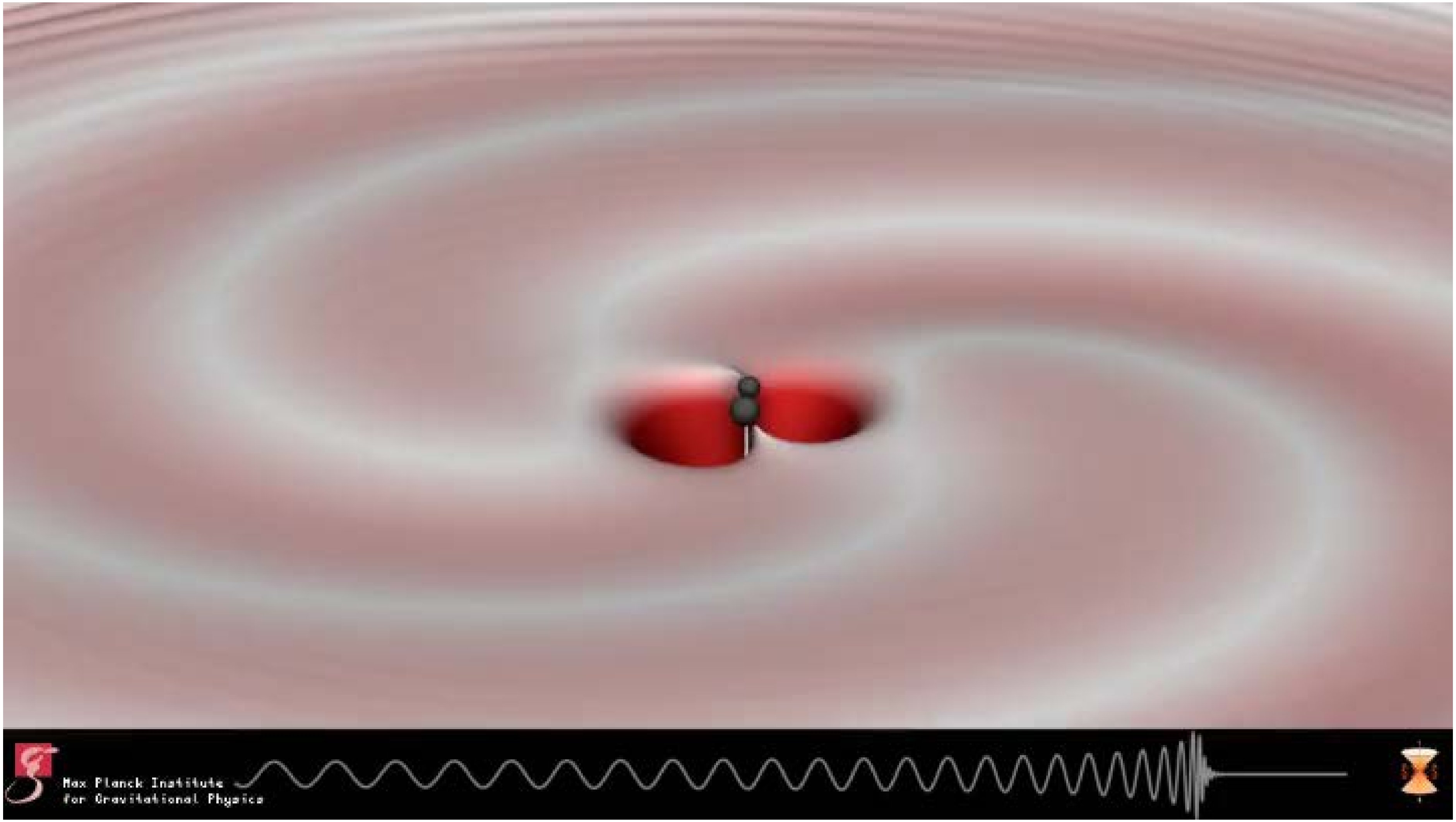
- Result of matched filtering!
  - Excellent match between the best template and the measured signal
- Two massive compact objects orbiting around each other at 75 Hz (half the GW frequency), hence at relativistic speed, and getting very close before the merging: only a few R_S away!

→ 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



Simulation of the coalescence



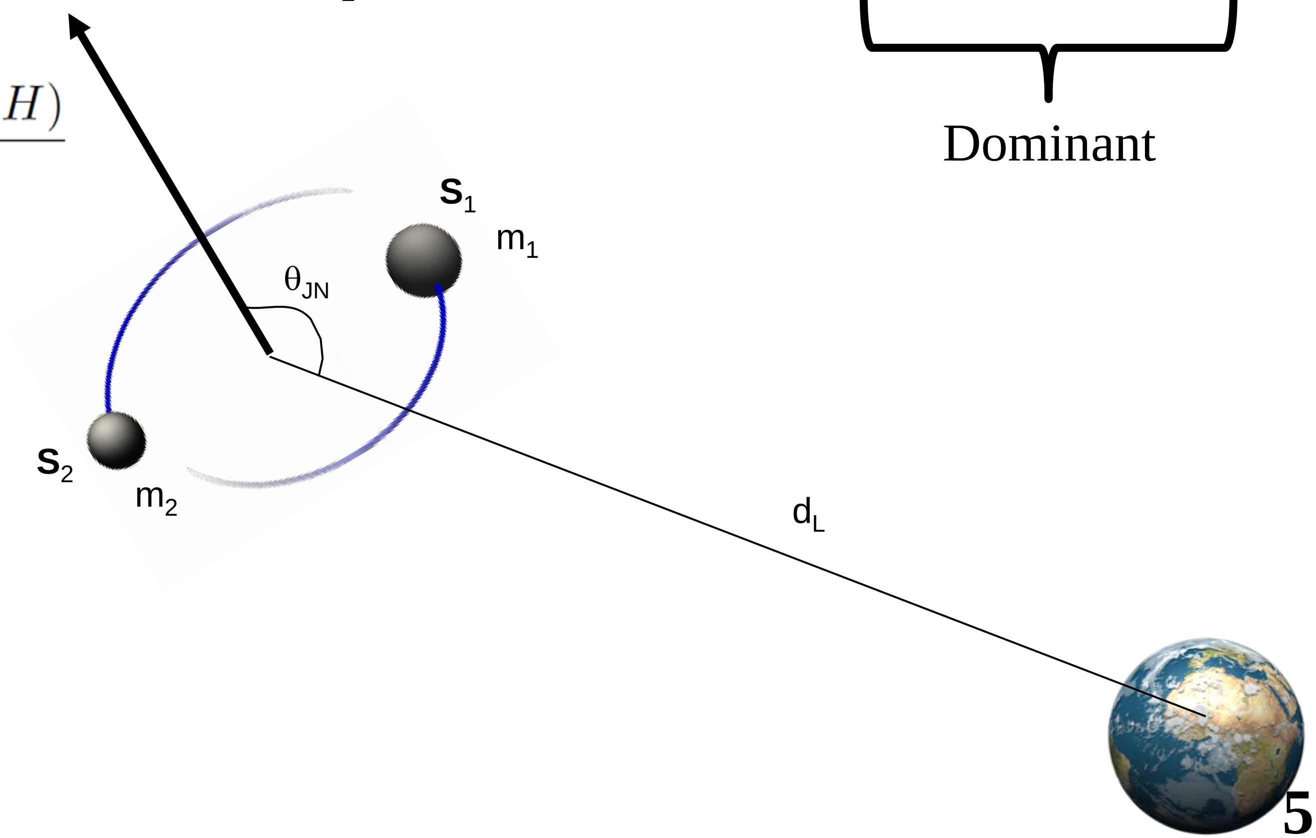
Parameter estimation

- 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

Dominant

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

- θ: Parameters
- d: Data
- H: Model

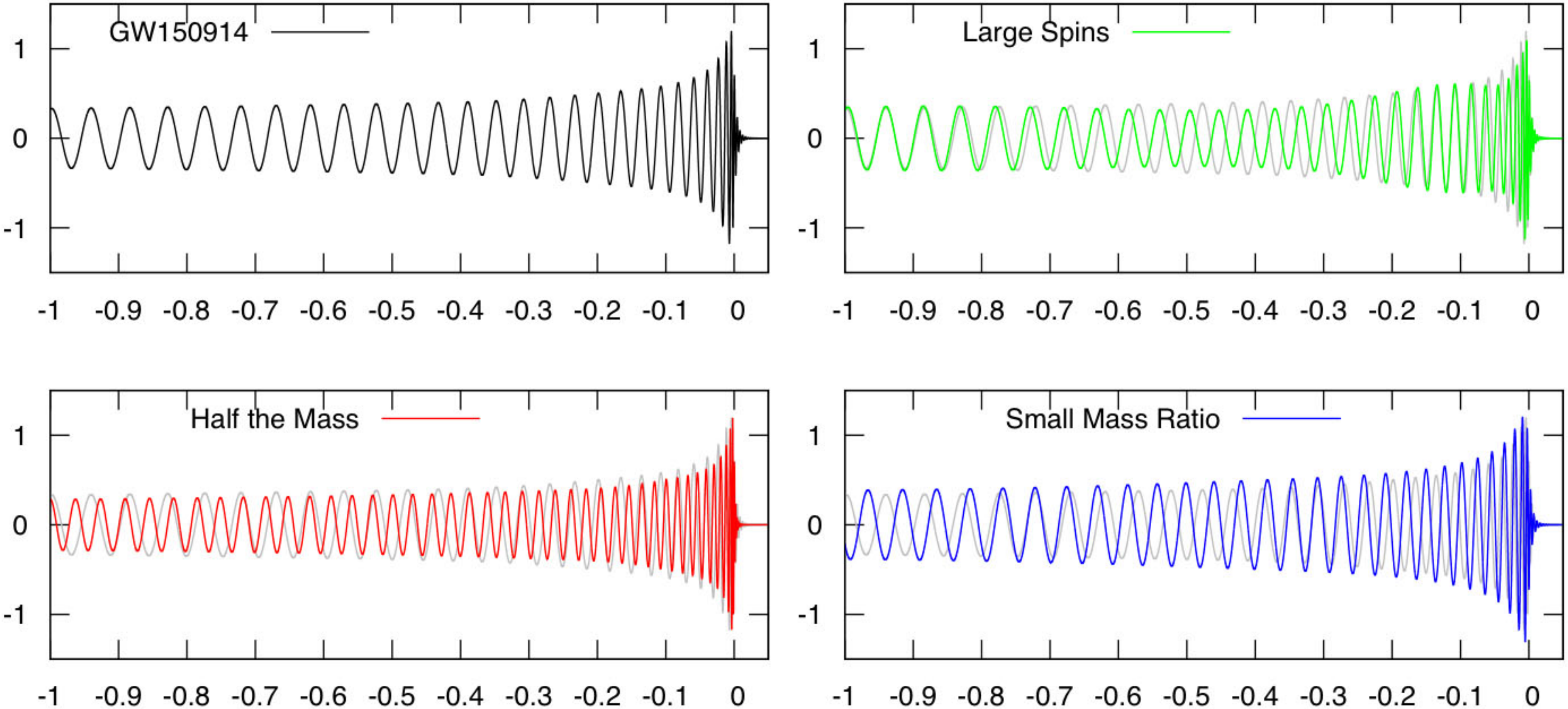


- Compare results from two models → Systematic errors

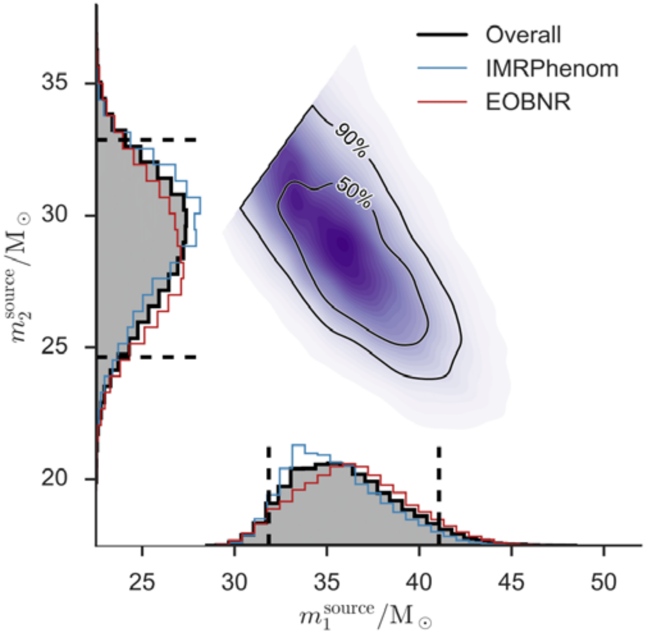
$$O_{ij} = \frac{P(H_i|d)}{P(H_j|d)}$$

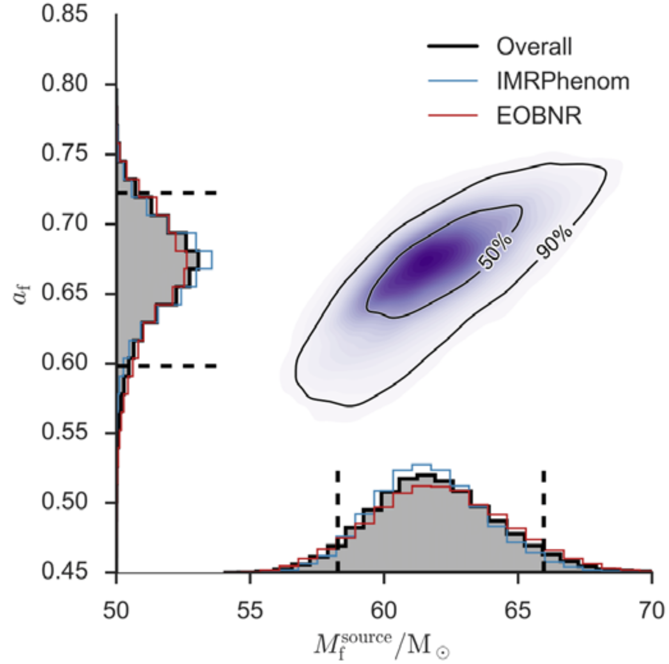
Parameter estimation

- Impact of the black hole parameters on the waveform



Main results





Individual masses

$m_1 = 36^{+5}_{-4}\,M_\odot$

$m_2 = 29^{+4}_{-4}\,M_\odot$

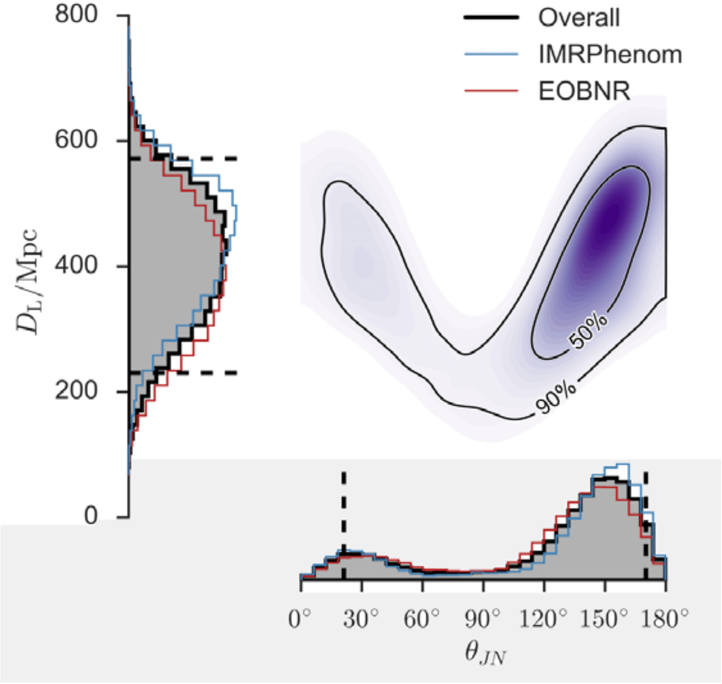
Final BH mass and spin

$M_f = 62^{+4}_{-4}\,M_\odot$

$a_f = 0.67^{+0.05}_{-0.07}$

Final black hole has about the area of Iceland

Main results

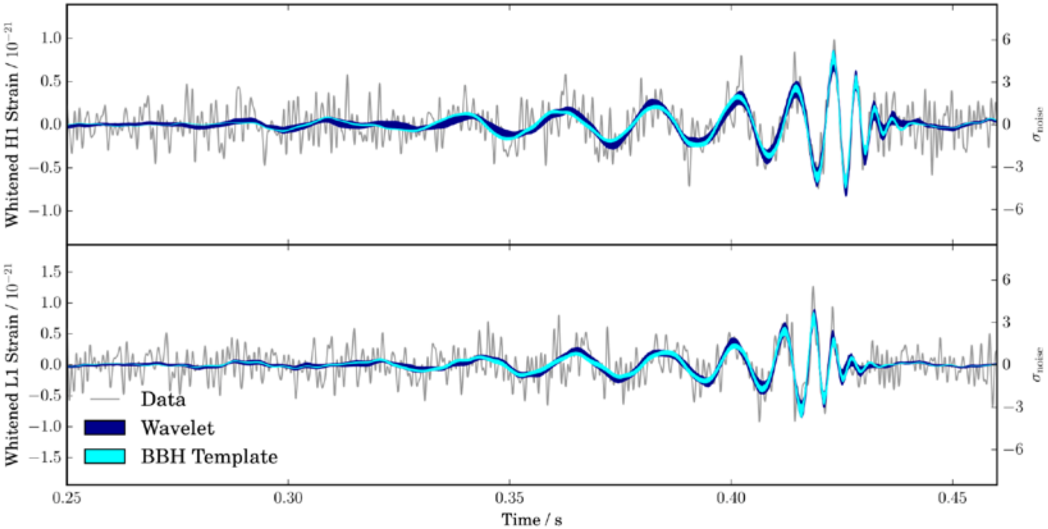


Degeneracy luminosity distance / inclination angle

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

Waveform reconstruction

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



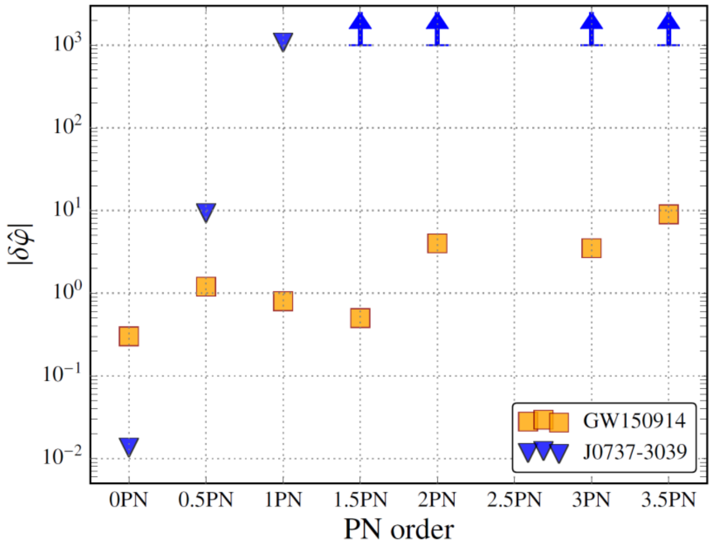
Testing general relativity

- Previous tests : solar system, binary pulsars, cosmology
  - Weak fields, linear regime …

- With GW150914 : strong field, non-linear regime, relativistic velocities
  → New tests !

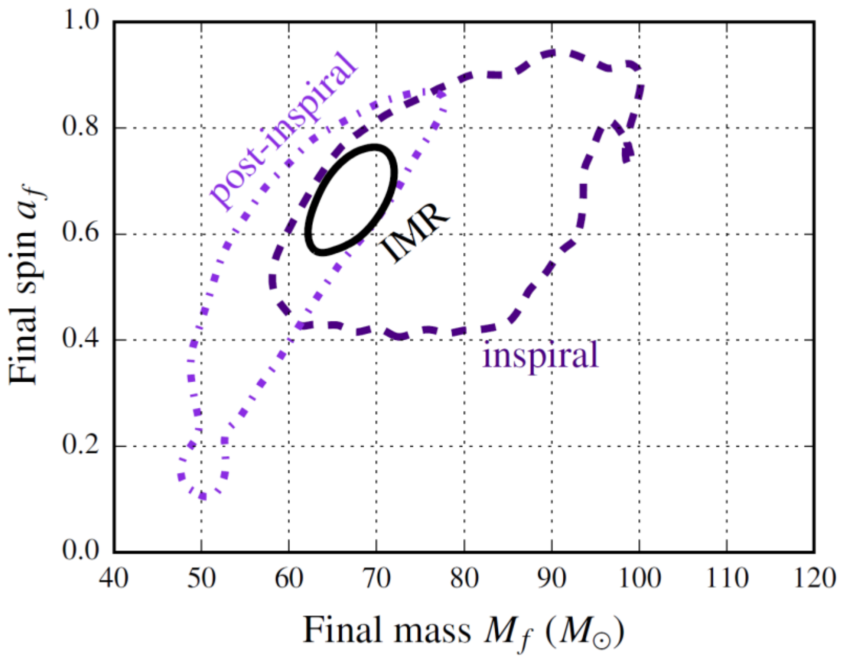
- Simplest test : data substracted with closest predicted waveform
  - Residuals are compatible with Gaussian noise within measurement accuracy
    → Deviations from GR constrained to be less than 4%

- Search for deviations from GR prediction for PN expansion of the inspiral signal phase (xPN ⇔ $(v/c)^{2x}$)
  - Weak constraints but the best up to now except lowest order (few number of cycles)

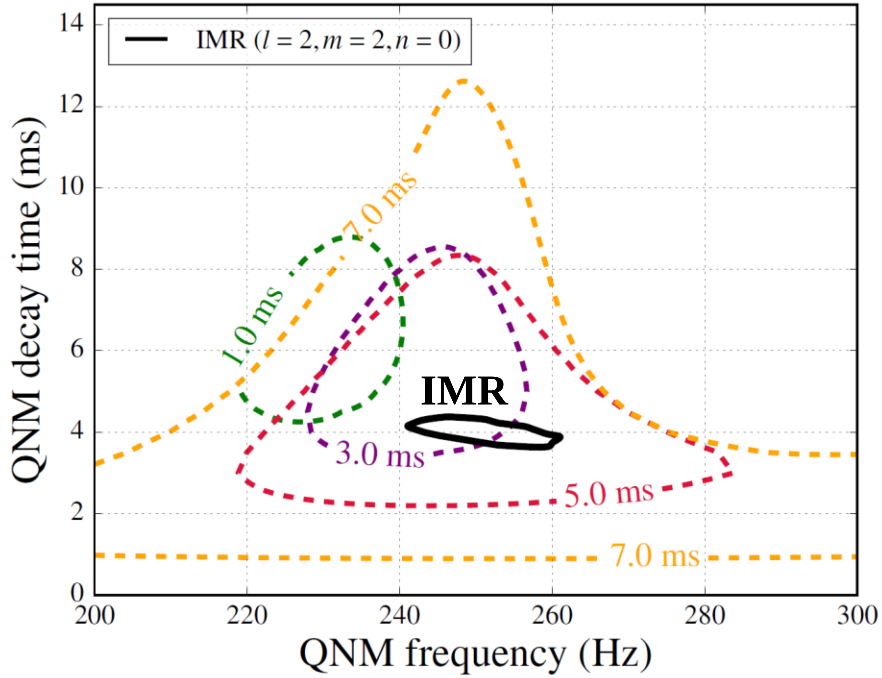


Testing general relativity

- 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~250Hz, τ~4ms
(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 $v_g^2 = c^2\left(1 - \frac{m_g^2 c^4}{2E^2}\right)$

$\rightarrow$ Additional terms in the phase of the inspiral signal

where D is the distance, z the redshift and $\delta\varphi(f) = \frac{\pi D c}{(1+z)\lambda_g^2}\frac{1}{f}$

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

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

- Best previous limit in solar system tests (Mars) : $\lambda_g > 3\times10^{12}\,\mathrm{km}$
  - Yukawa correction to the Newtonian potentiel

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

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

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

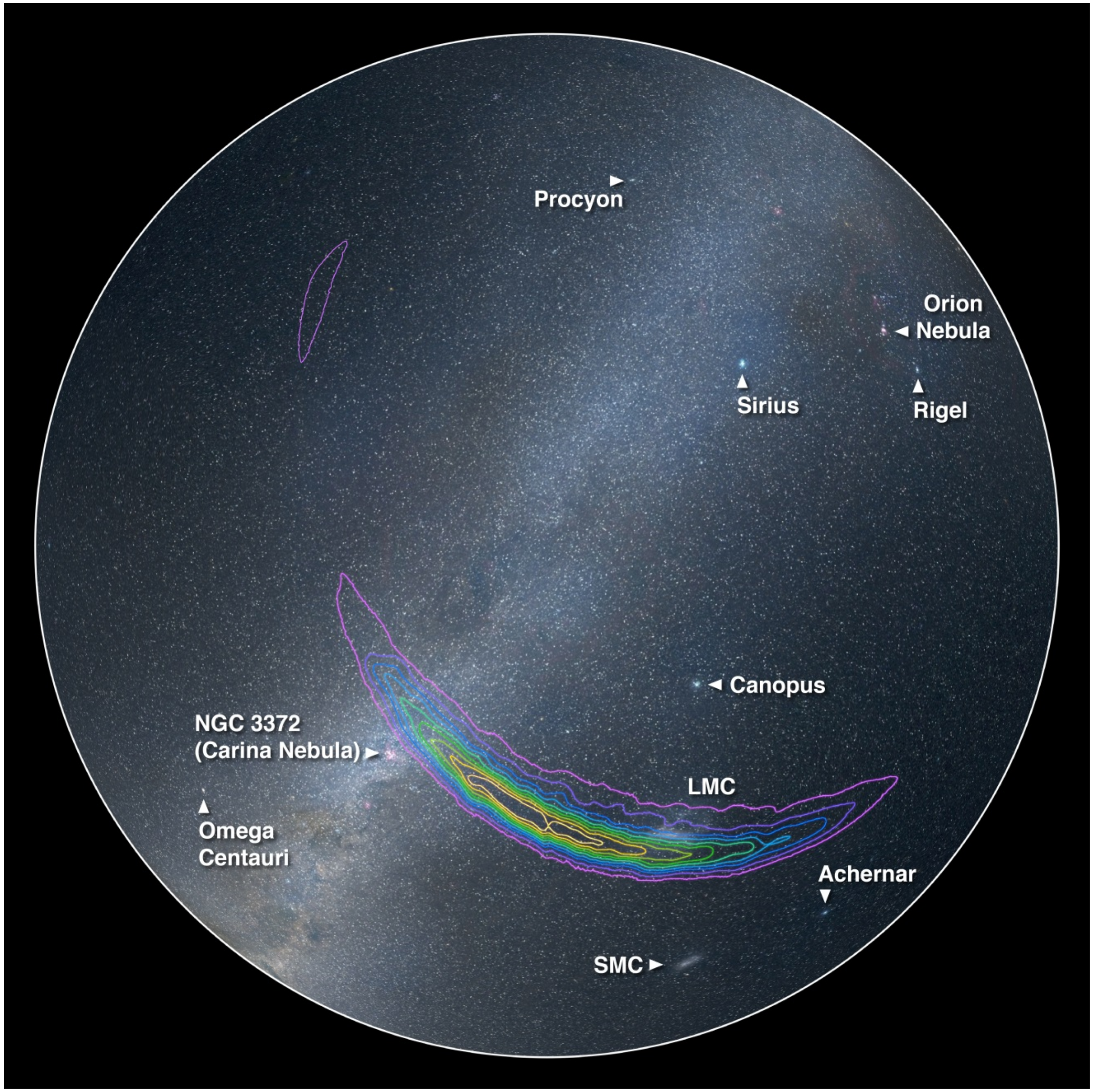
observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc
redshift	0.054 to 0.136
signal-to-noise ratio	24
false alarm prob.	< 1 in 5 million
false alarm rate	< 1 in 200,000 yr
Source Masses	**M⊙**
total mass	60 to 70
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

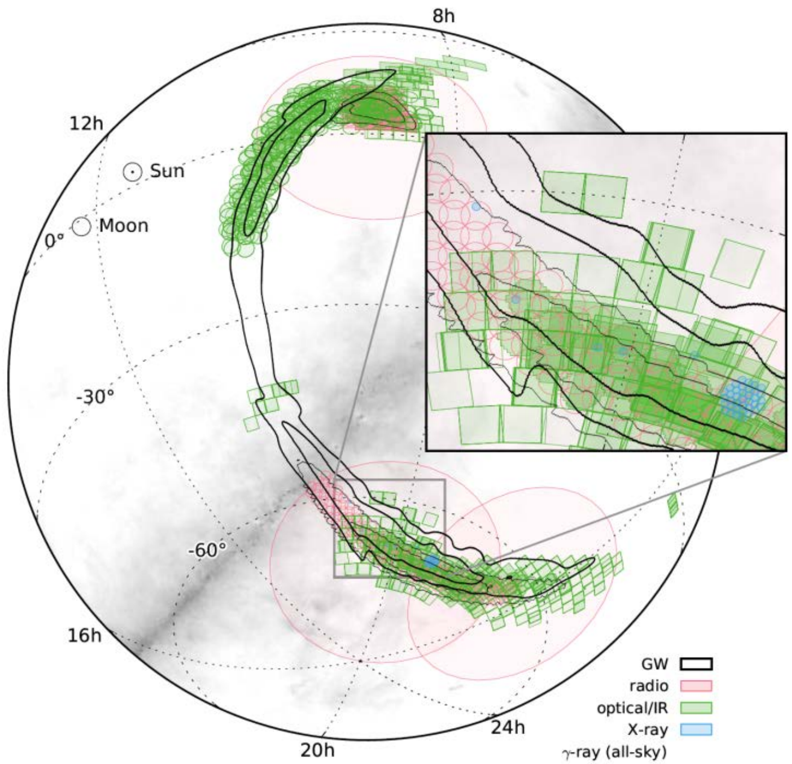
Skymap

- 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

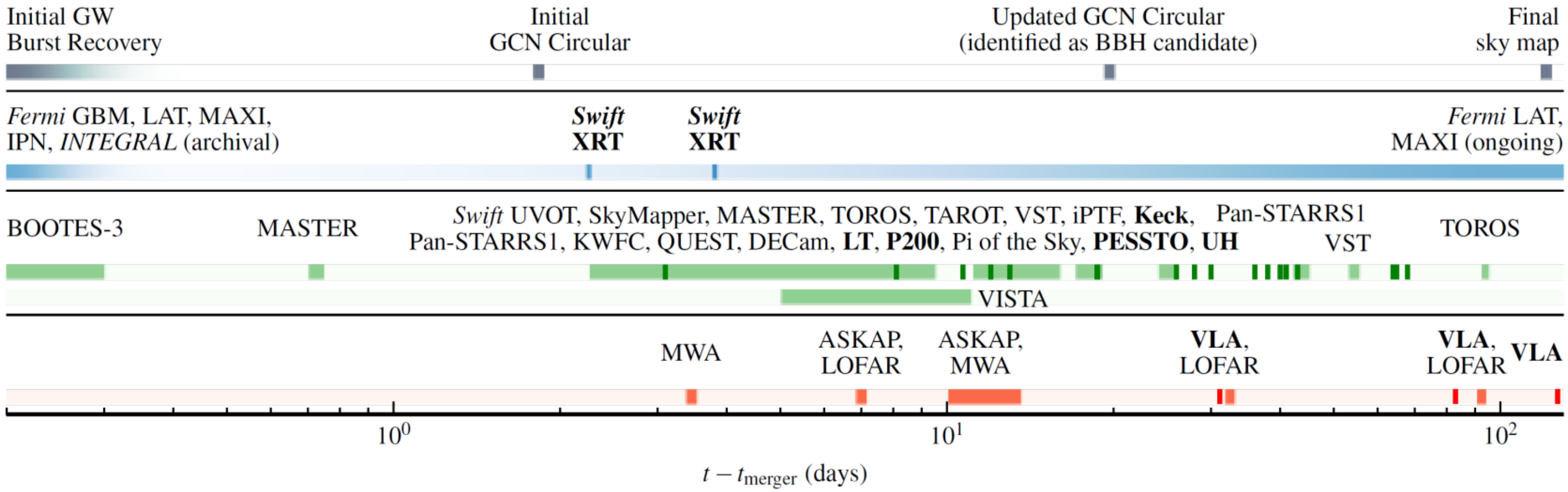


Looking for GW150914 counterparts

- Sky coverage



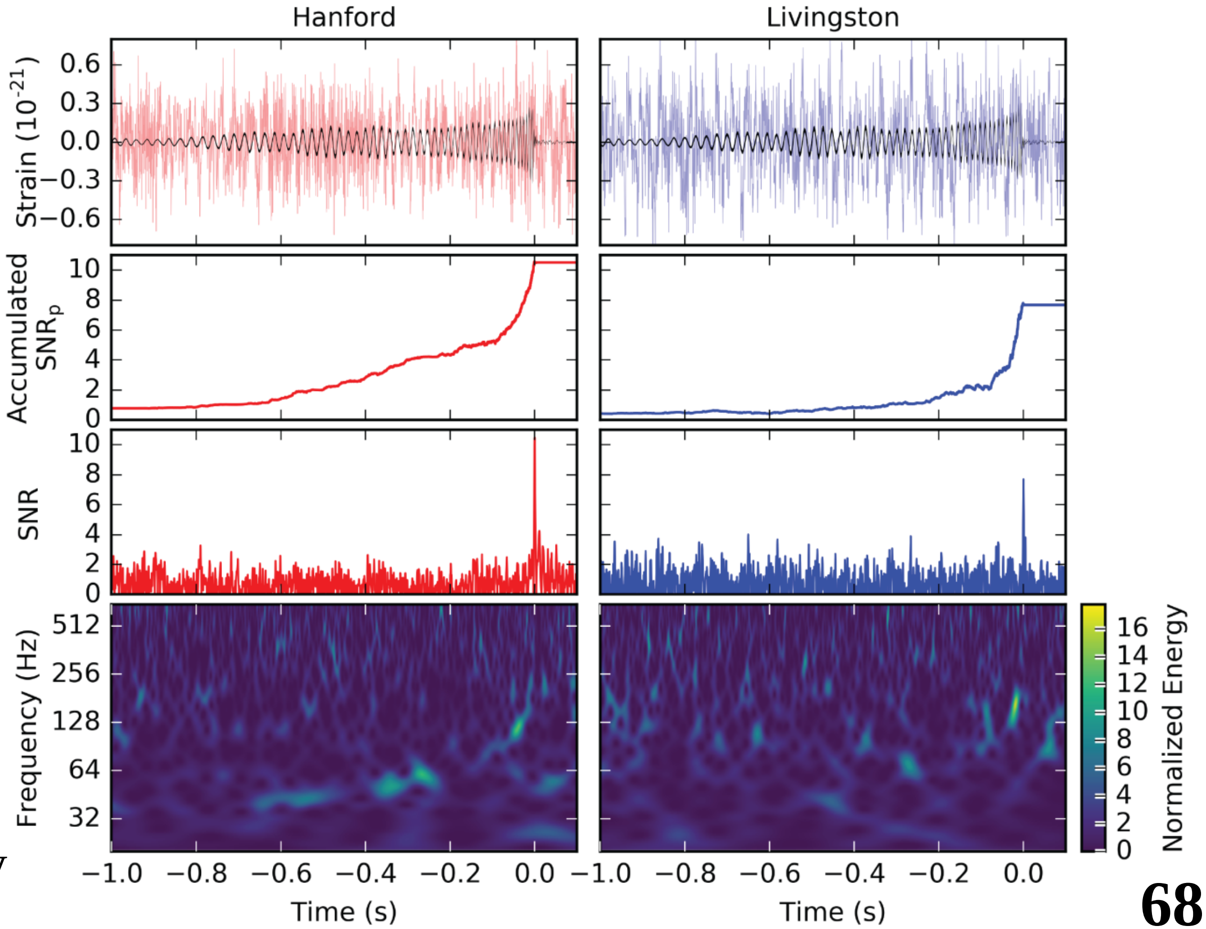
- Observation timeline: no counterpart found – none expected for a binary black hole



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

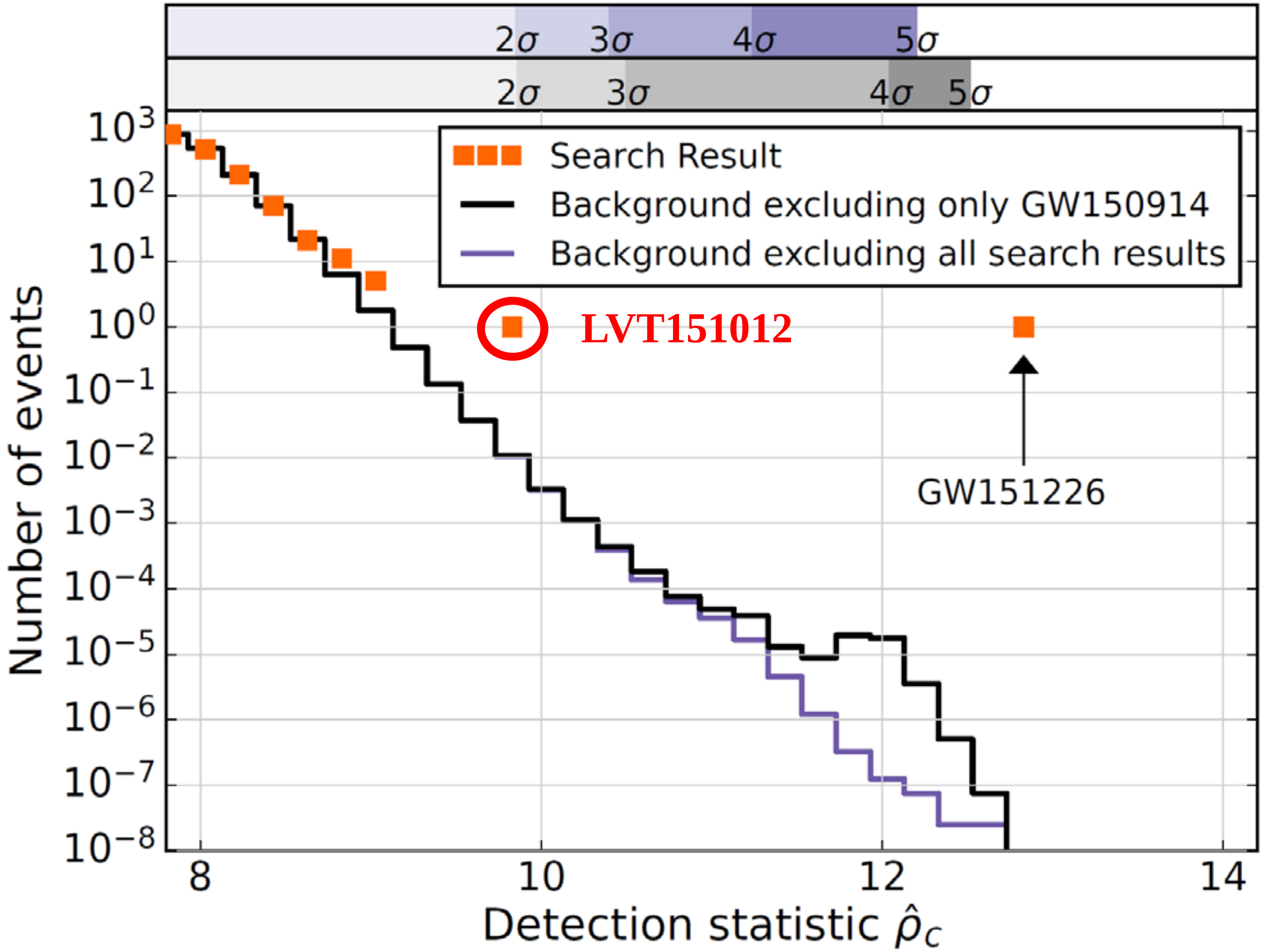
GW151226

- 2nd largest event recorded
  - After GW150914

- A third candidate: LVT151012
  - Lower statistical significance

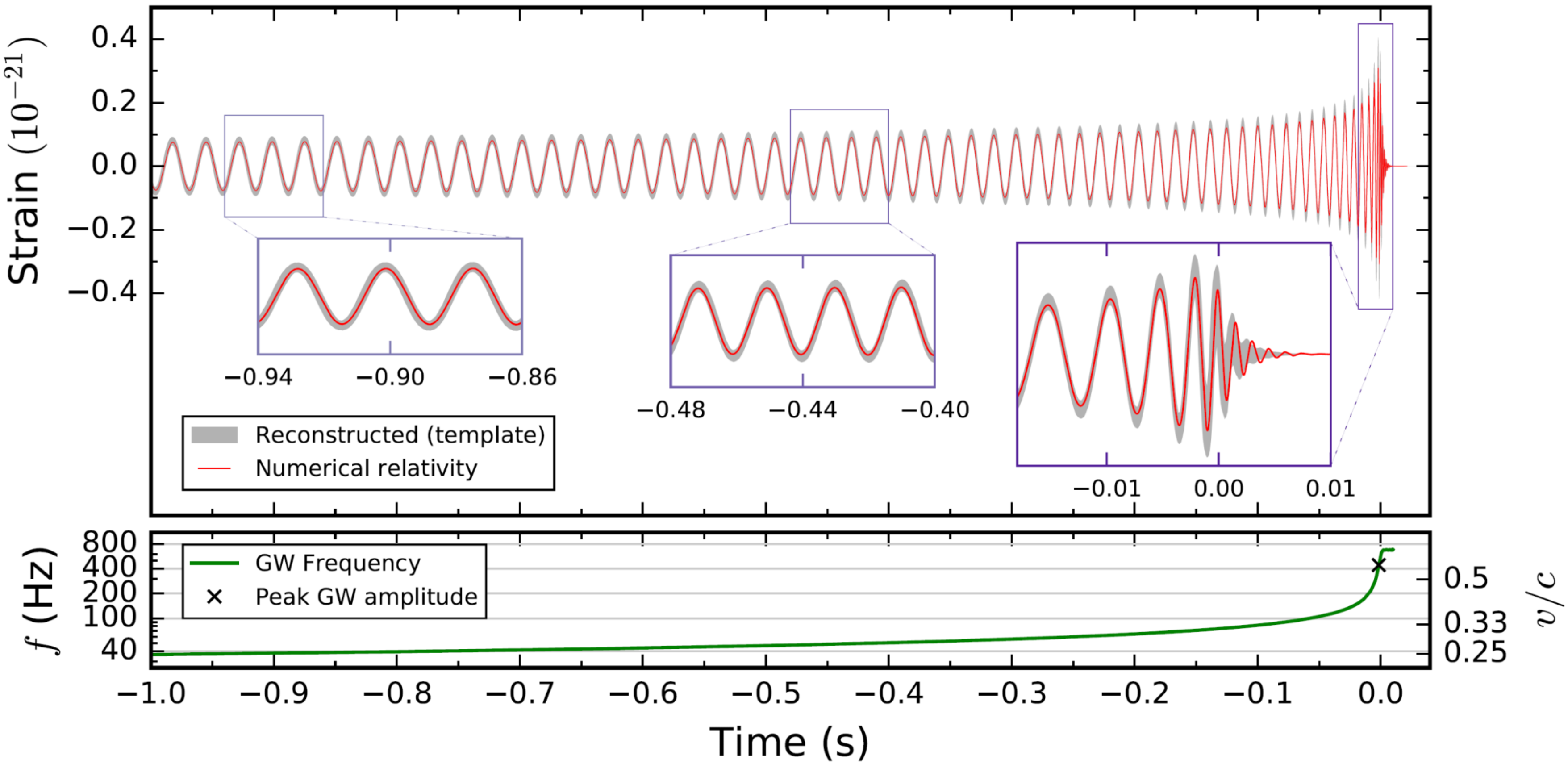
  → « Source » much further away (~1 Gpc)

- In this plot, GW150914 has been removed to estimate the bkg as it is a true signal



GW151226

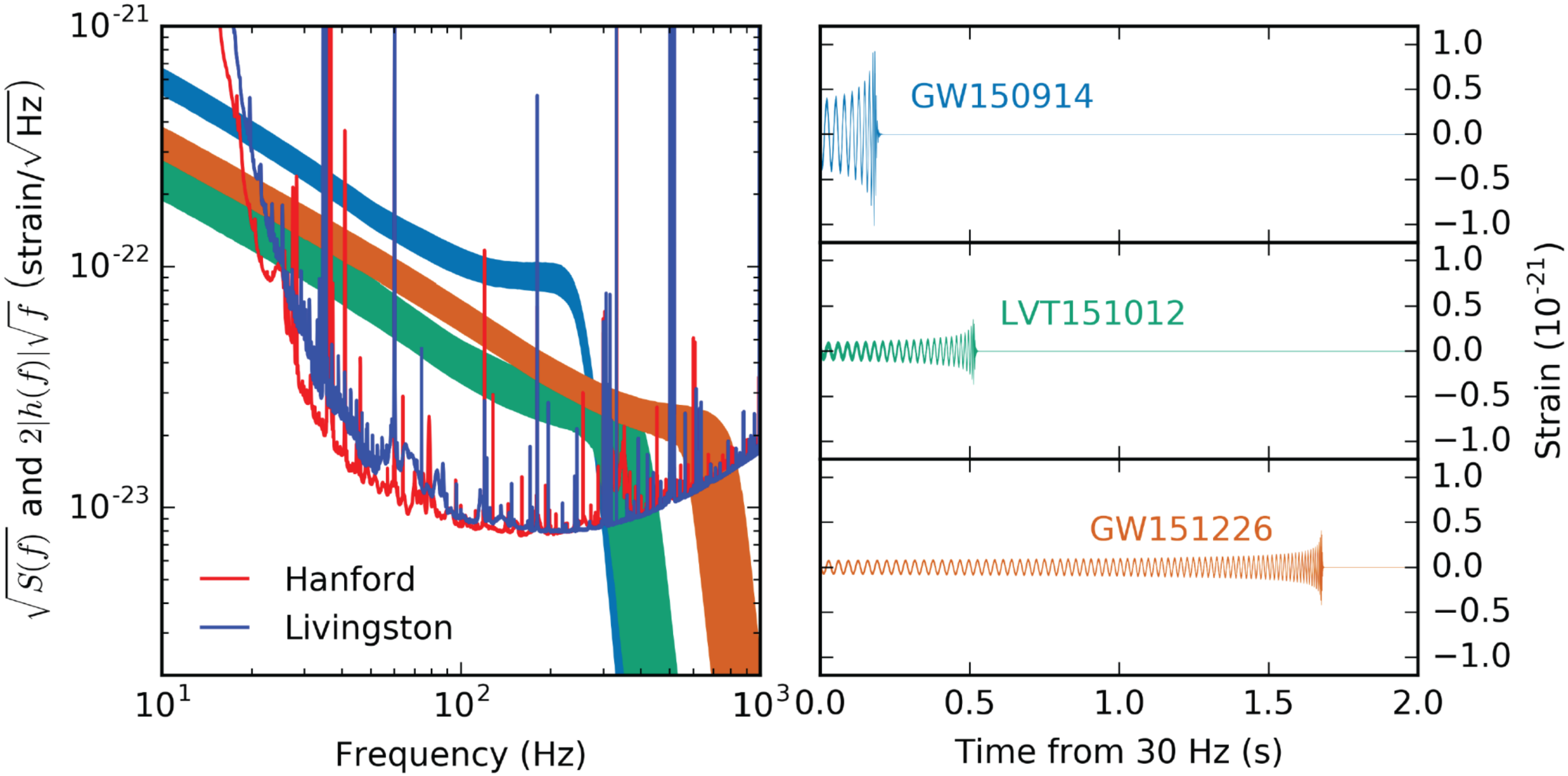
- Excellent agreement between the different reconstructed waveforms
  - analytical computation (post-Newtonian expansion, in grey)
  - numerical relativity (in red)



In summary: two events, one candidate

- Black hole binary systems

- No other GW source observed so far



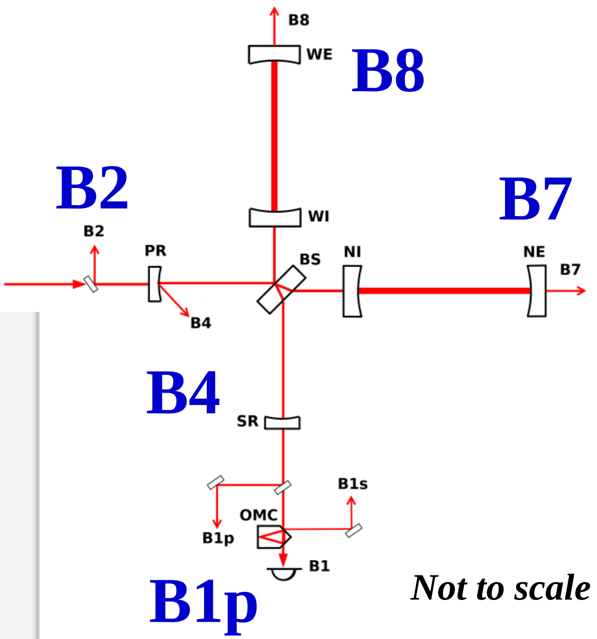
And now!?

Current status of the detectors

- Advanced LIGO detectors
  - Second data taking period started on November 30 2016
  - Early March review : 30 days of coincidence data as of February 23 2017
    3 candidates identified; partners notified
    → Data analysis in progress

- Advanced Virgo detector
  - Commissioning at full speed!
  - Significant milestones already reached – understanding + control of the instrument
    → Advanced Virgo is a « brand new » detector
  - Goal : to reach LIGO « as soon as possible »
    → A few more weeks of work required…

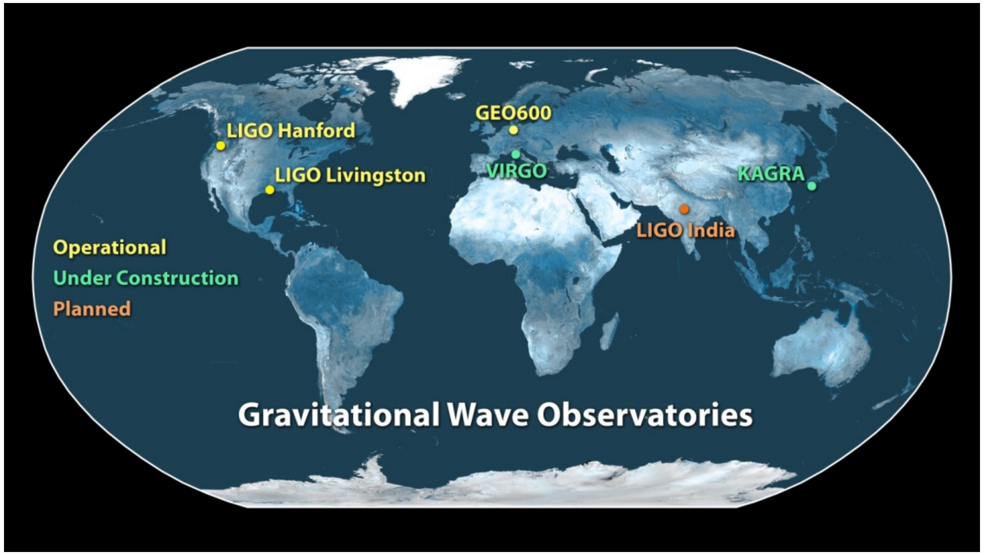
Controlling the Advanced Virgo detector



Conclusions

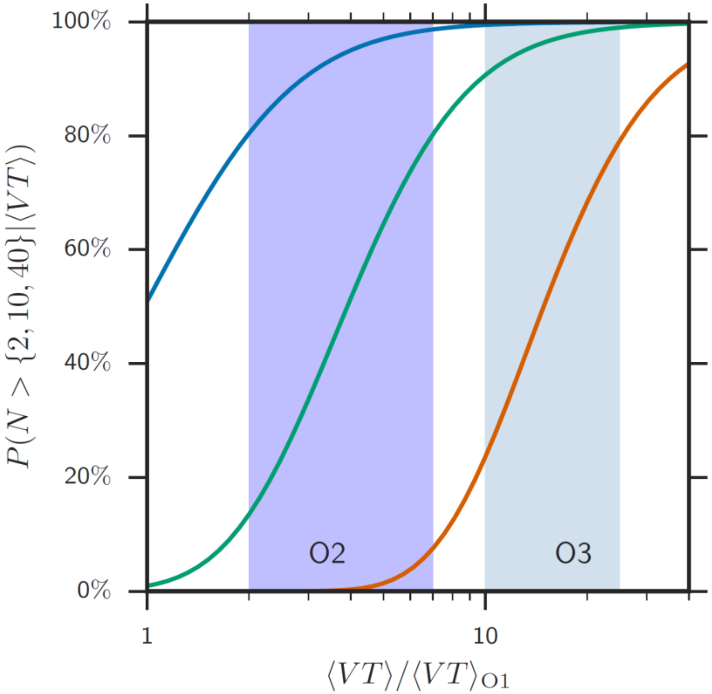
Prospects

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



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

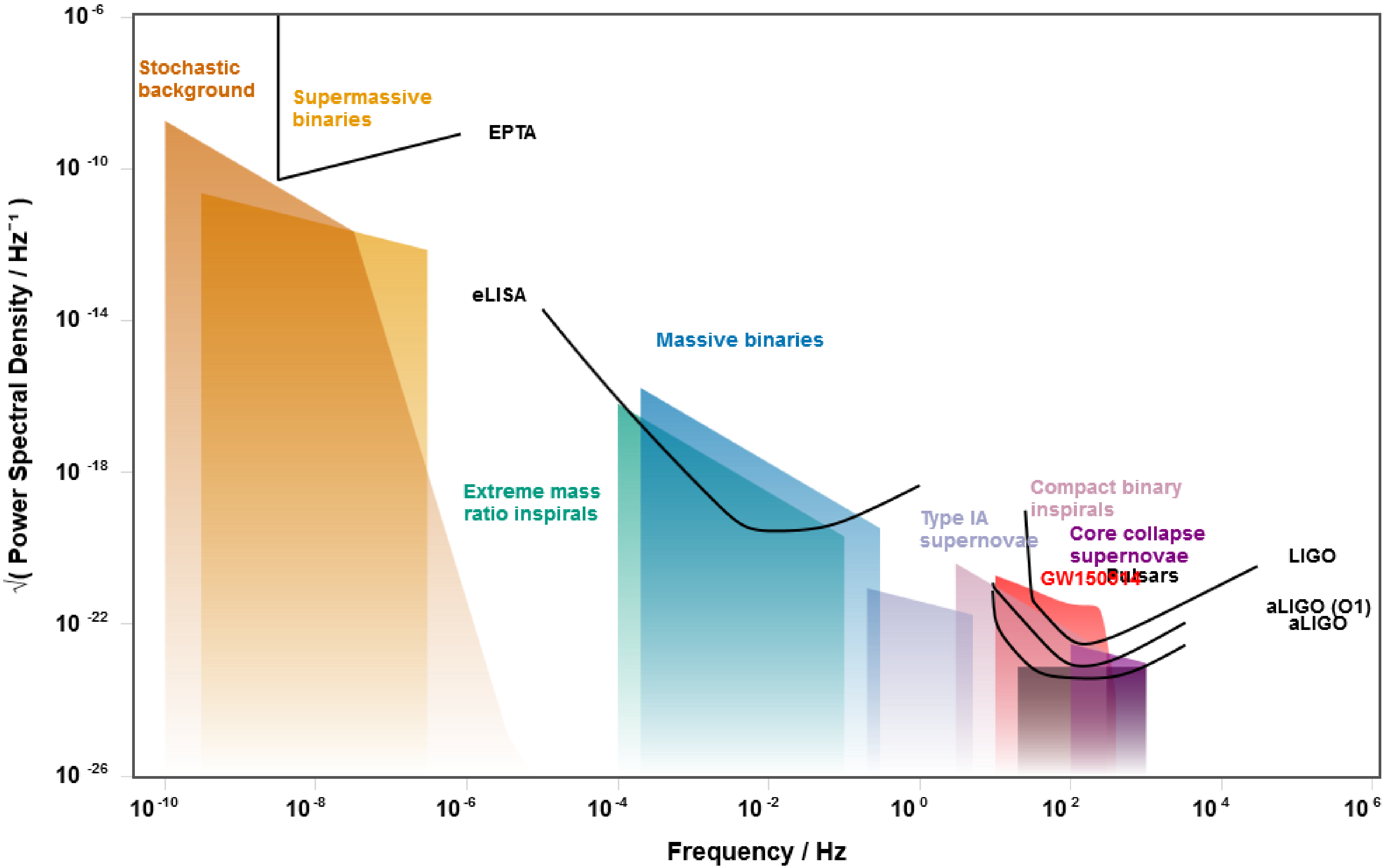
Probabilities that the number of detections exceeds
- **2**
- **10**
- **40**



OX : « Observation » Run number X

Detectors and sources: a summary plot

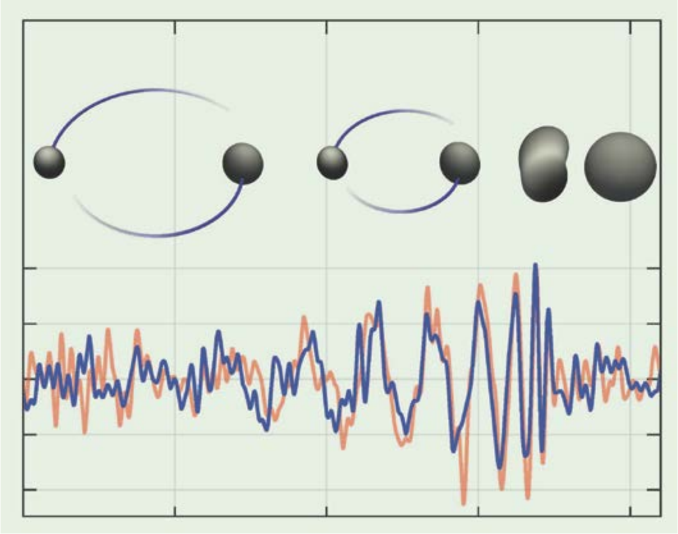
- From http://rhcole.com/apps/GWplotter



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