The first direct detections of gravitational waves

High-school students from Thessaloniki
EGO visit, April 5th 2017

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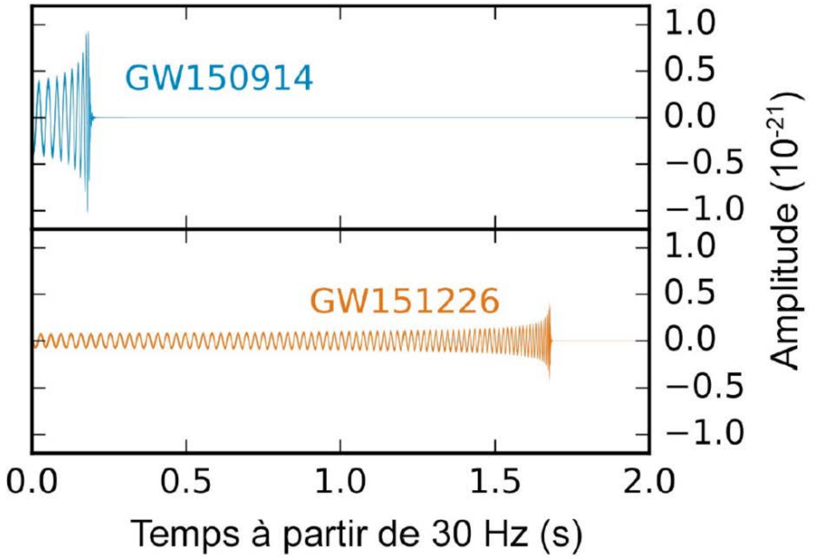

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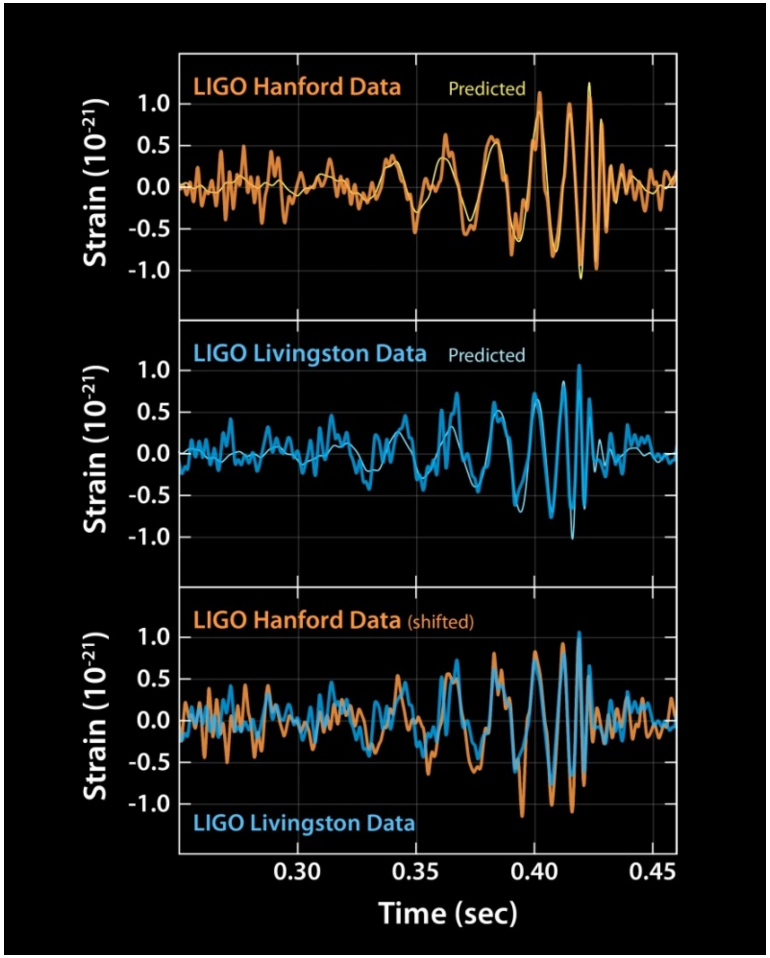
Outline

- The discovery in a nutshell: GW150914
- The gravitational wave saga
- How to detect gravitational waves?
  - Giant suspended interferometers
- GW150914 & GW151226
- And now?
  - Opening a new window onto the Universe

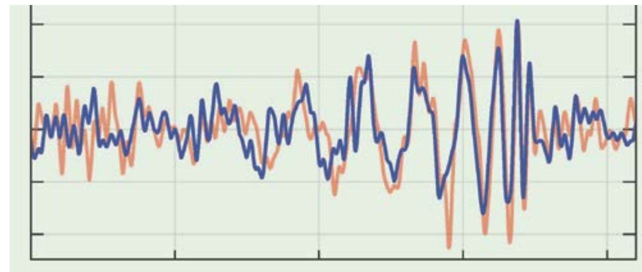


Thanks to the many colleagues
from the LAL Virgo group, from Virgo and LIGO
from wich I borrowed ideas and material for this talk

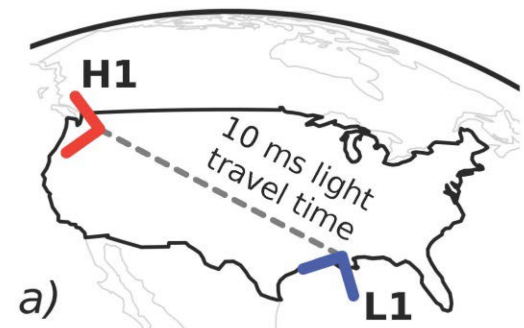
The discovery in a nutshell: GW150914

September 14 2015, 11:51 CET

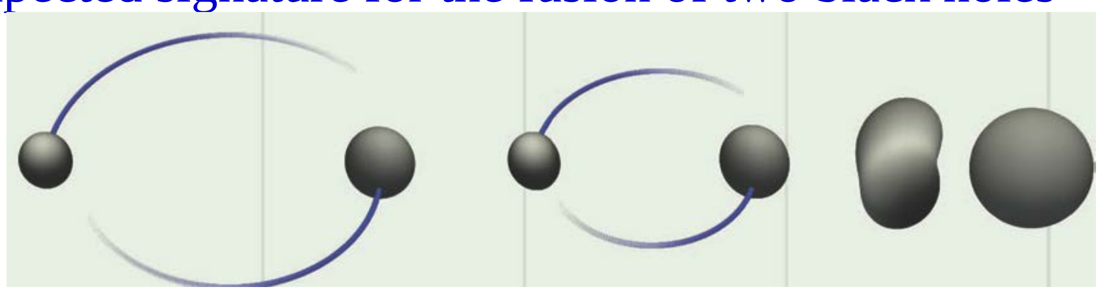
- Signal in both LIGO detectors
  with a 7 ms delay
  - Very short (< 1 s)
  - Very strong
    - With respect to the instrument noises
    - Very weak in absolute



Event labelled GW150914



- Expected signature for the fusion of two black holes



February 11 2016, 16:30 CET

« Ladies and gentlemen,
we have detected
gravitational waves,
we did it. »
David Reitze,
Executive Director of
the LIGO Laboratories

- 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?

- 5 months of deep analysis involving hundreds of scientists worldwide
  → Many open questions had to be answered accurately
  → While keeping secret the potential discovery
    - Any test not passed could have turned it into a noise fluctuation

- Does the observed event originate from the cosmos?
  - Neither an artificially simulated signal nor … a hacking of the LIGO observatories!
  - Not caused by an environmental phenomenon

- Were the two LIGO detectors running nominally at the time of the event?
  - Quality and accuracy of the data
  - Decision to « freeze » the detector configurations for a few weeks
    → In order to record enough « similar » data and assess the « reality » of the signal
      - How likely is it to come from the cosmos?

- Which are the scientific results one can extract from this unique (at the time) event?

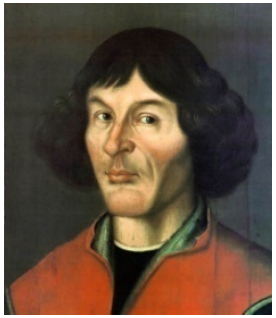
- Writing of the discovery article and of several companion papers
  - Discovery to be announced only when discovery article accepted by PRL

The gravitational wave saga

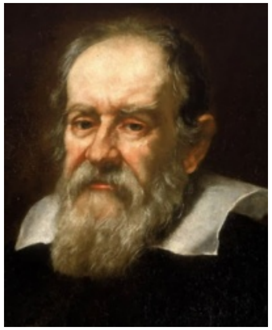
Celestial mechanics

Schema huius præmissæ diuisionis Sphærarum.

- Initially: geocentric model of the solar system (IInd century A.C.) from Ptolemy
  → Earth in the center
  → All the « wandering stars » orbit around it, moving on complex set of spheres



- First significant questioning: the heliocentric model from Copernic (1543)



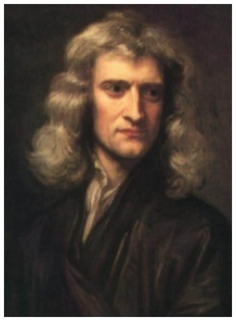
- Galileo : observations in contradiction with Ptolemy‘s model (1610)
  → Catholic church forces him to renounce to Copernic‘s « mistake »

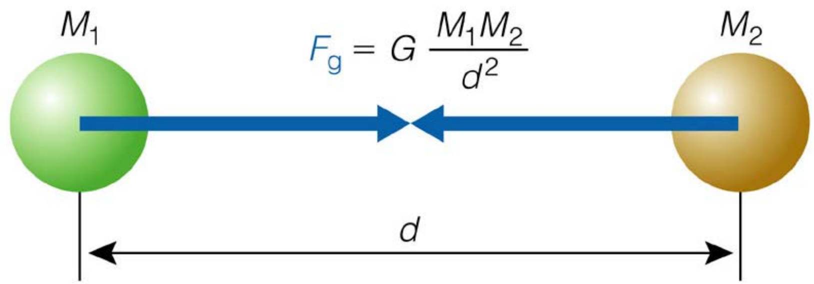
- Kepler (1609-1619) : assumes an heliocentric model & elliptical orbits
  → Deduces three empirical laws from which he makes predictions confirmed by observation

Law of universal gravitation

- Newton (1687) :

«Every point mass attracts every single other point mass by a force pointing along the line intersecting both points. The force is proportional to the product of the two masses and inversely proportional to the square of the distance between them»





- Simple and powerful
- Explains Kepler's laws
- Replaces the huge and complex set of spheres needed to make Ptolemy's mode still work

Rules on mechanics for more than two centuries

Still widely used today!

- Neptune discovery (1846)
  - Urbain Le Verrier (mathematical computations)
  - Gottfried Galle (astronomical observations)

Law of universal gravitation

- Special case: assumes that one mass is much stronger than the other: M >> m
  - Examples: Earth motion around the Sun
    A satellite orbiting around the Earth

  → Quasi-circular motion

- Minumun velocity of orbitation
  - Orbiting around the body of mass M at a distance r
    → 7,9 km / s on Earth

$$\mathbf{v_{orb}} = \sqrt{\frac{\mathbf{GM}}{\mathbf{r}}}$$

- Escape velocity
  - Speed needed to escape the attraction of the body of M
    → 11,2 km / s for the Earth
    → 42,1 km / s for the Sun
    (at the Sun-Earth distance)

$$\mathbf{v_{esc}} = \sqrt{\frac{\mathbf{2GM}}{\mathbf{r}}}$$

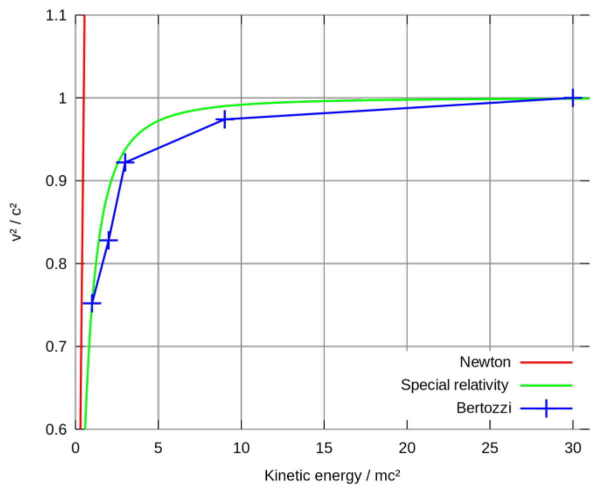
- v_{orb} and v_{esc} are independent from mass m and proportional

Black holes?

- Reminder: escape velocity
  - Scales like √M
    → The more massive the body, the stronger its attraction
  - Scales like 1/√r
    → The further away from the body, the weaker its attraction

$$v_{esc} = \sqrt{\frac{2GM}{r}}$$

- Limit speed: velocity of light in vacuum
  - Special relativity theory (Einstein, 1905)
  - c = 299 792 458 m / s



- Can one have $v_{esc} = c$?
  - Yes: take M very big and/or r very small
  - Situation already foreseen during XVIII[th] century
    → Mitchell (1783)
    → de Laplace (1796)
    } **Corpuscular theory of light**
  - Should such stars exist, their gravitional field would be strong that nothing, not even light, could espace from it

- XIX[th] century : light ⇔ wave
  → Issue put aside until the General relativity theory (1915)

Schwartzschild Radius

- Newtonian escape velocity: $v_{esc} = \sqrt{\dfrac{2GM}{r}}$
- 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
- Compacity $C = \dfrac{R_S}{\text{radius}} \leq 1$

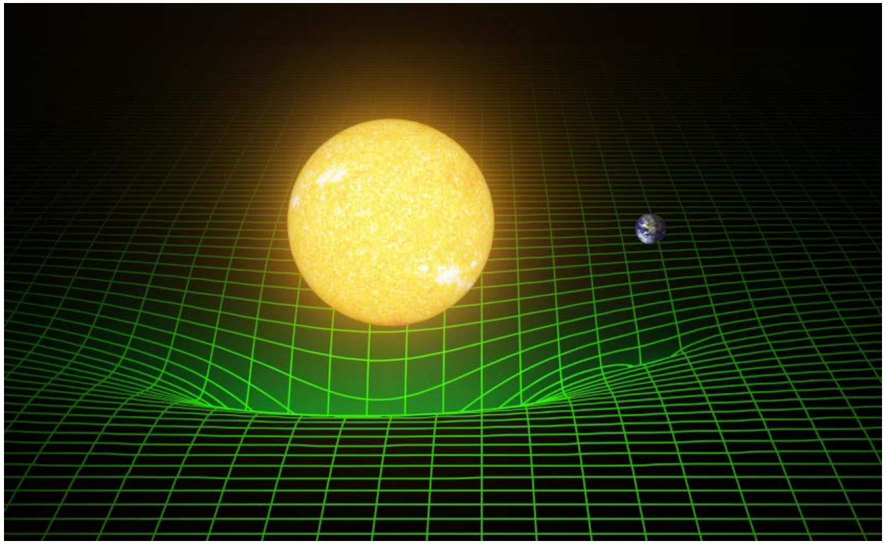
Object	Earth	Sun	White dwarf	Neutron star	Black hole
Compacity	$1.4\ 10^{-9}$	$4.3\ 10^{-6}$	10^{-4}	0.3	1

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

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

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

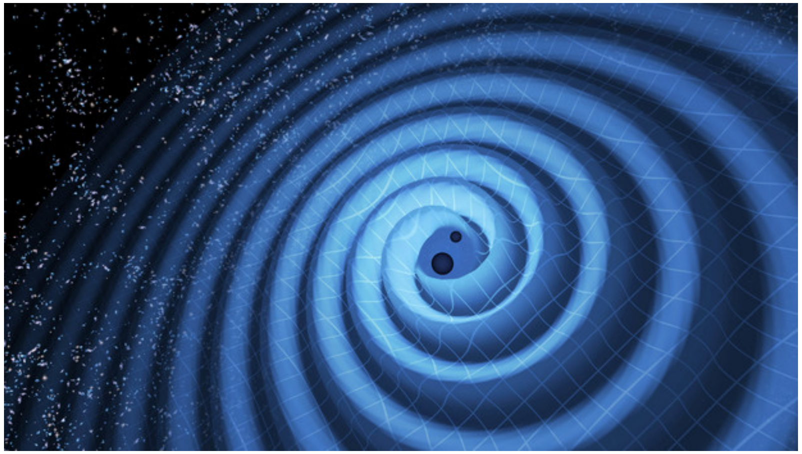
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

→ 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
  → 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

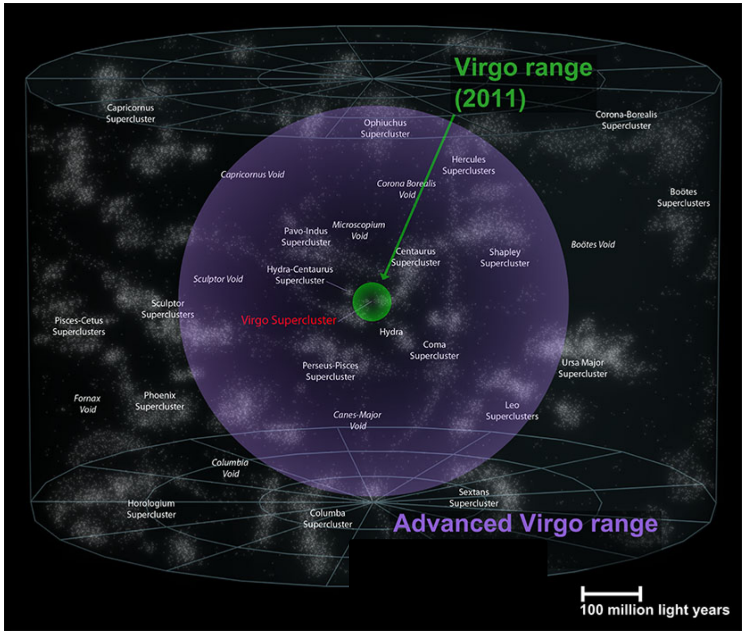
Gravitational waves

- One of the first predictions of General relativity (1916)
  - Accelerated masses induce ripples in the space-time which propagate at the speed of light



- No gravitational wave (GW) emission if the source is axisymetrical
  - A « powerful » GW source must have an asymetrical mass distribution

- GW amplitude h
  - Dimensionless
  - Scales like 1/(distance d to the source)
  - Detectors directly sensitive to h



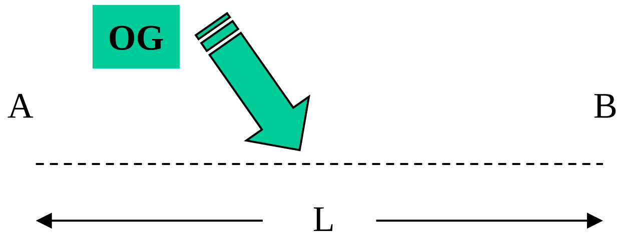
→ Gain of a factor 2 (10) in sensitivity

⇔ Gain of a factor 2 (10) in distance

⇔ Observable volume of the Universe increased by a factor 8 (1000)

Effect of gravitational waves on test masses

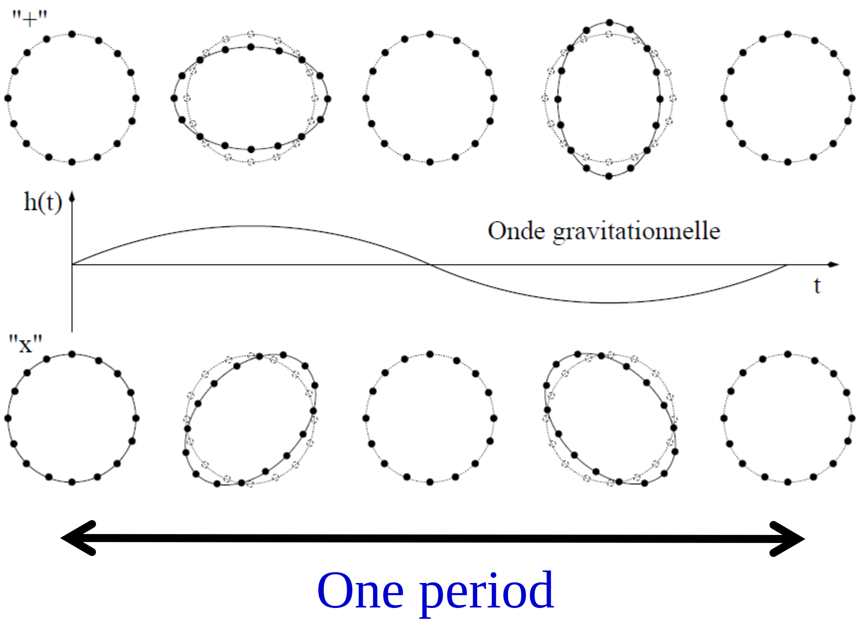
- GW: propagating perturbation of the spacetime metric
  - Acts on distance measurement between test masses (free falling)



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

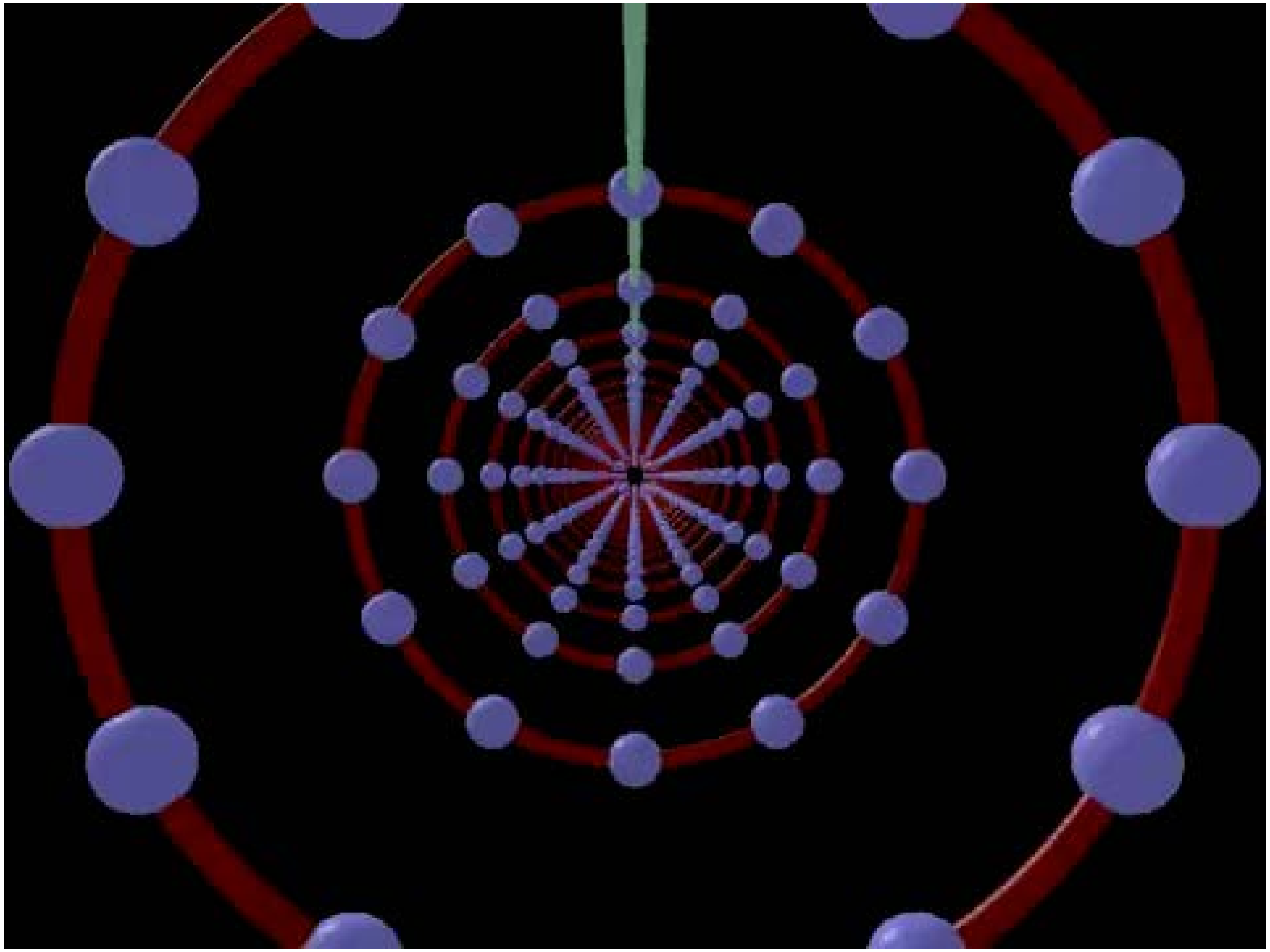
Variation doubled for an interferometer with arms of equal length L:
$\delta L_{IFO} = hL$

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

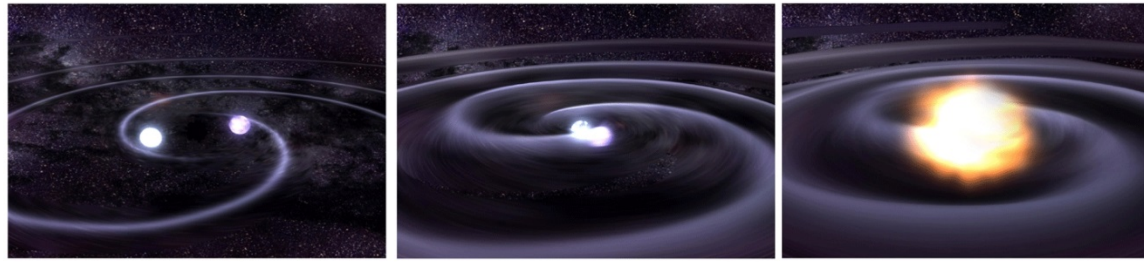


Effect of gravitational waves on test masses

- In 3D

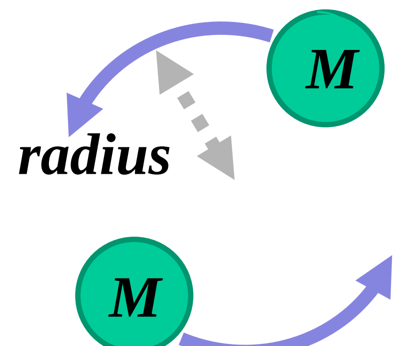


A diversity of sources



- Rough classification
  - Signal duration
  - Frequency range
  - Known/unknown waveform
  - Any counterpart (electromagntic spectrum, 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 ($f_{GW} = 2\ f_{Orbital}$)

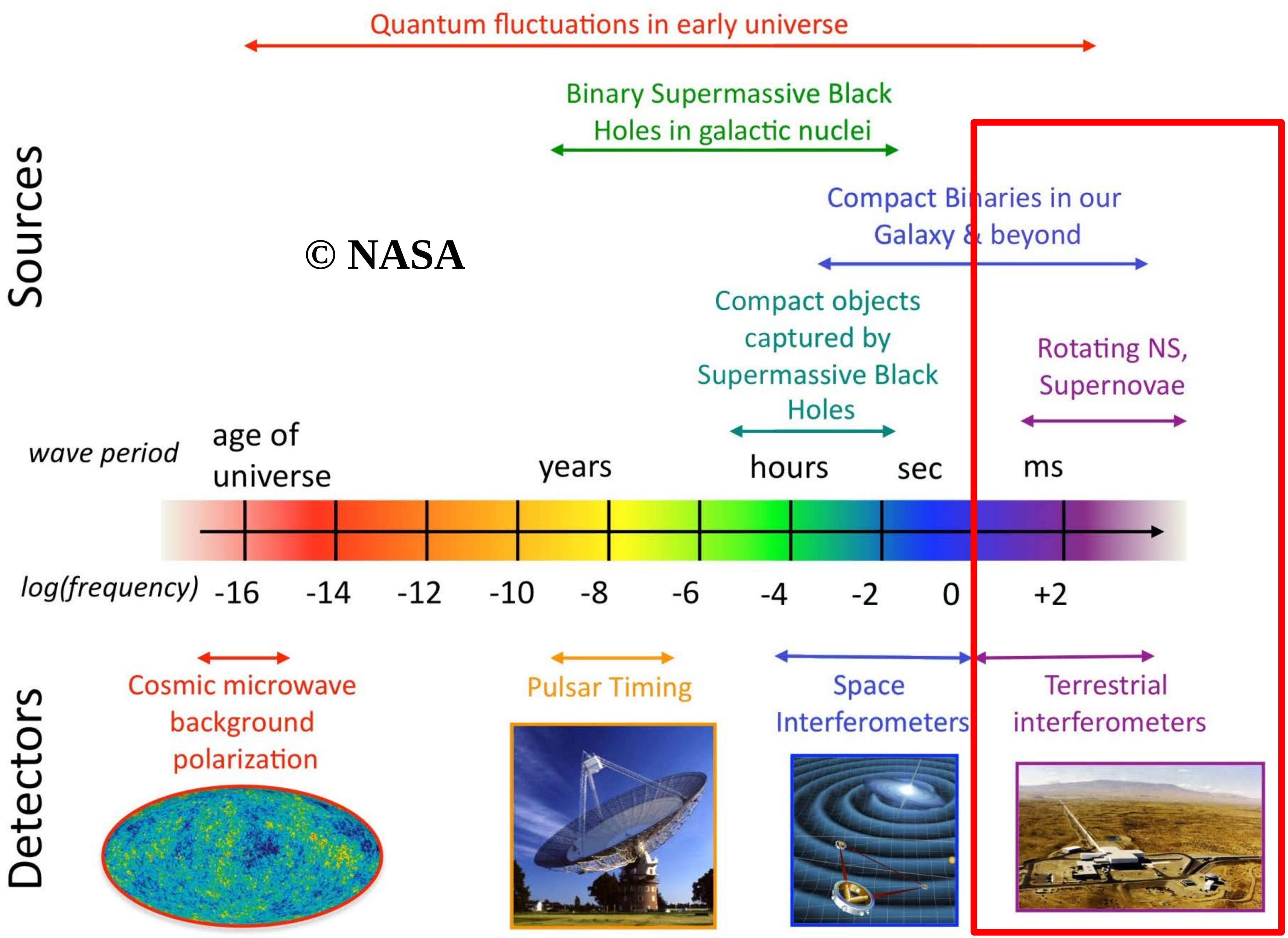
$$h \approx 10^{-21} \left(\frac{\text{500 Mpc}}{\text{Distance}}\right)\left(\frac{\text{Mass}}{30\ M_{Sun}}\right)\left(\frac{\text{Orbital radius}}{\text{100 km}}\right)^2\left(\frac{\text{Frequency}}{\text{100 Hz}}\right)^2$$



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

- Permanent sources
  - Pulsars, Stochastic backgrounds

Gravitational wave spectrum

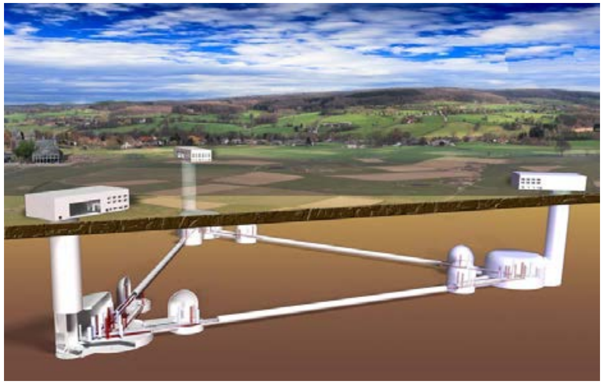


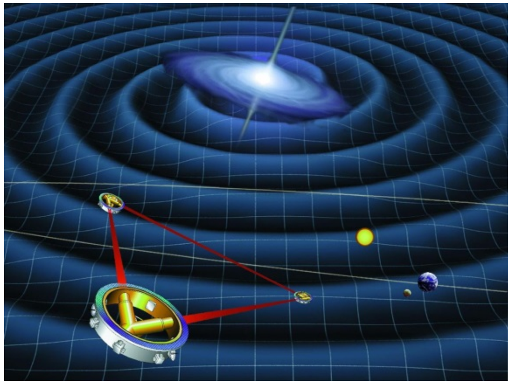
LIGO, Virgo, etc.

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, circa 2030)
  - Technology successfully tested by the recent LISA pathfinder space mission





Detecting gravitational waves

1916-2016: a century of progress

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

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

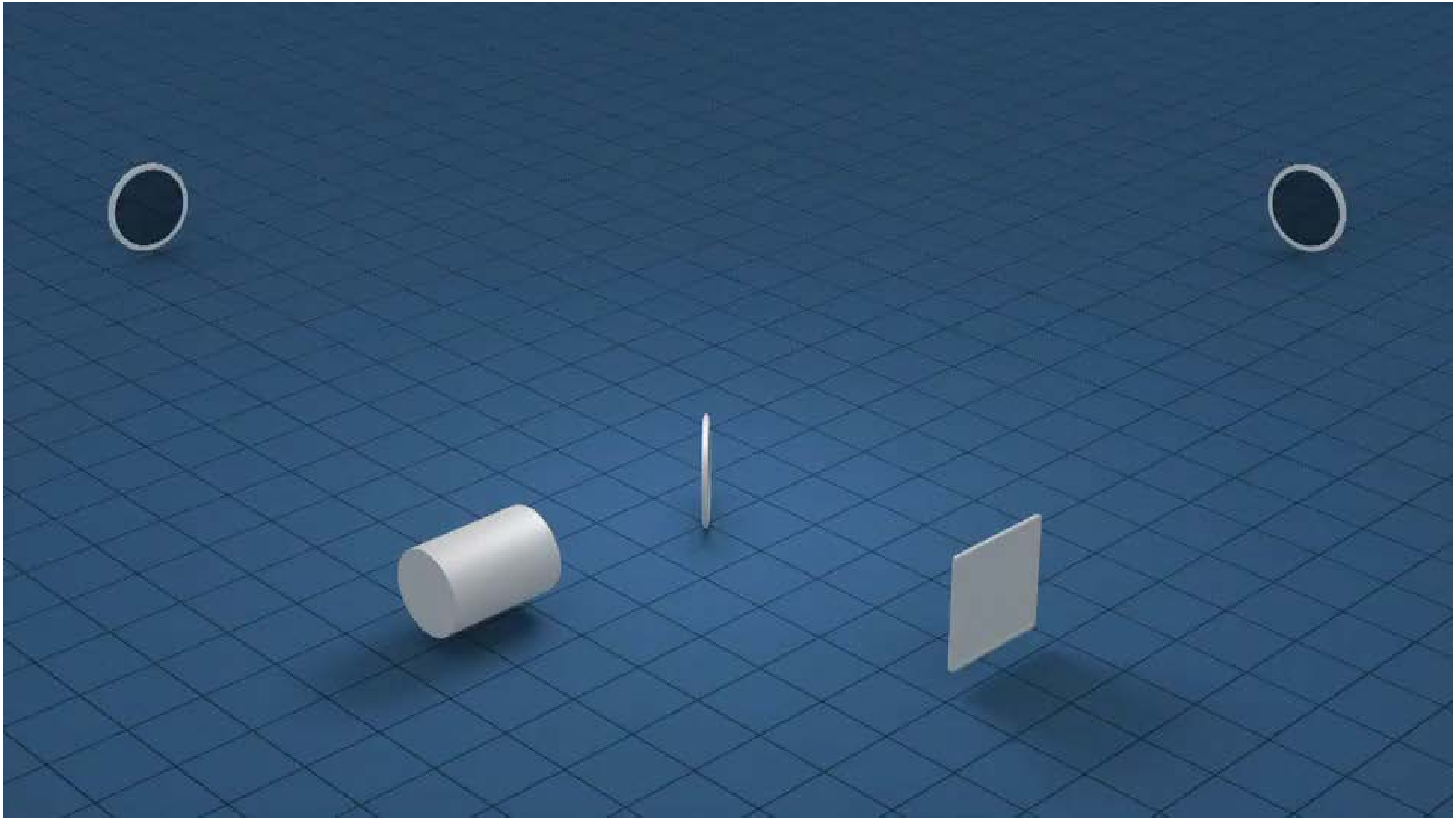
Theoretical developments

- **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

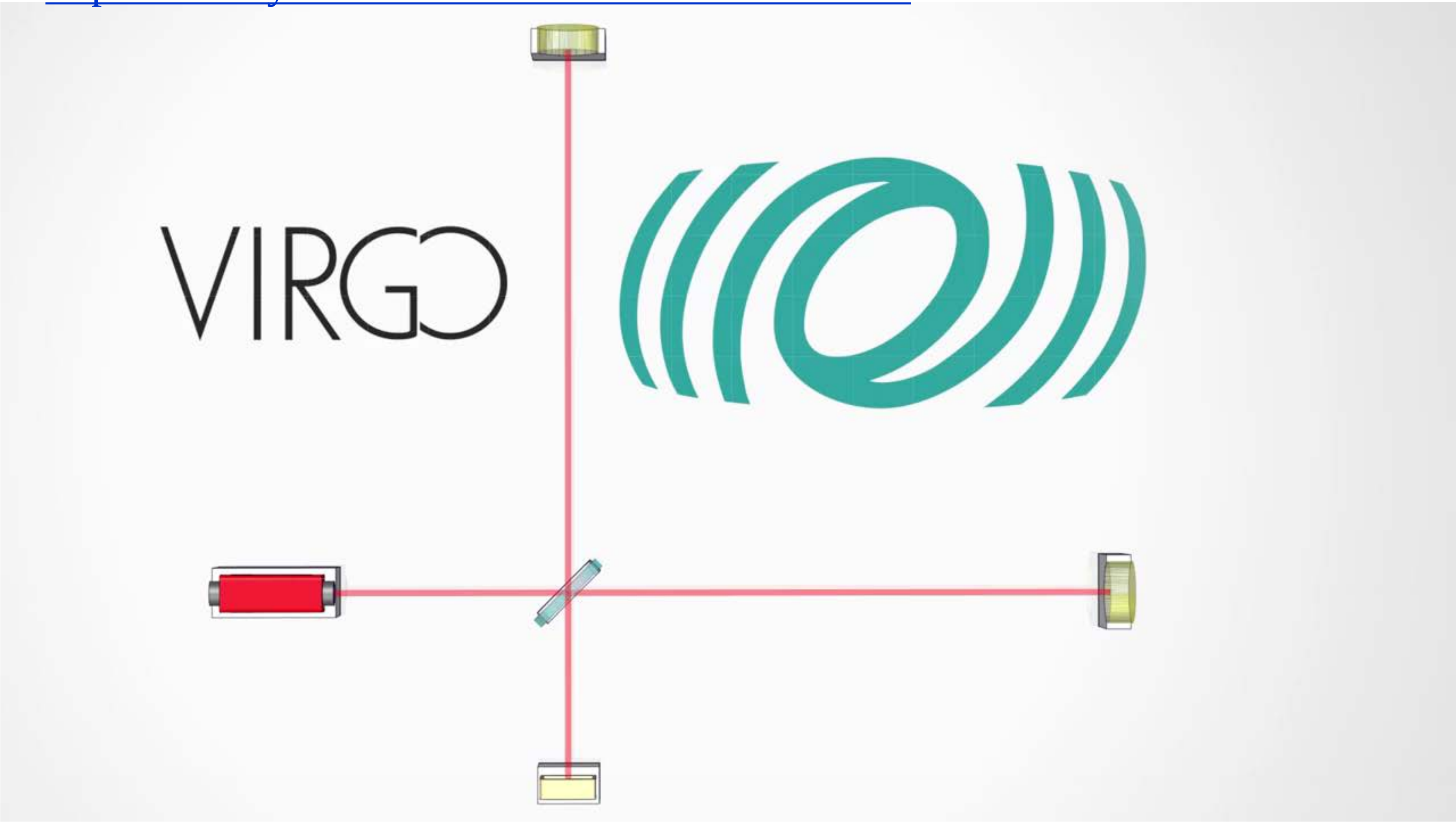
- **1960's: first Weber bars**
- **1970: first IFO prototype (Forward)**
- **1972: IFO design studies (Weiss)**
- **1974: PSRB 1913+16 (Hulse & Taylor)**
- **1980's: IFO prototypes (10m-long) (Caltech, Garching, Glasgow, Orsay)**
- **End of 1980's: Virgo and LIGO proposals**
- **1990's: LIGO and Virgo 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

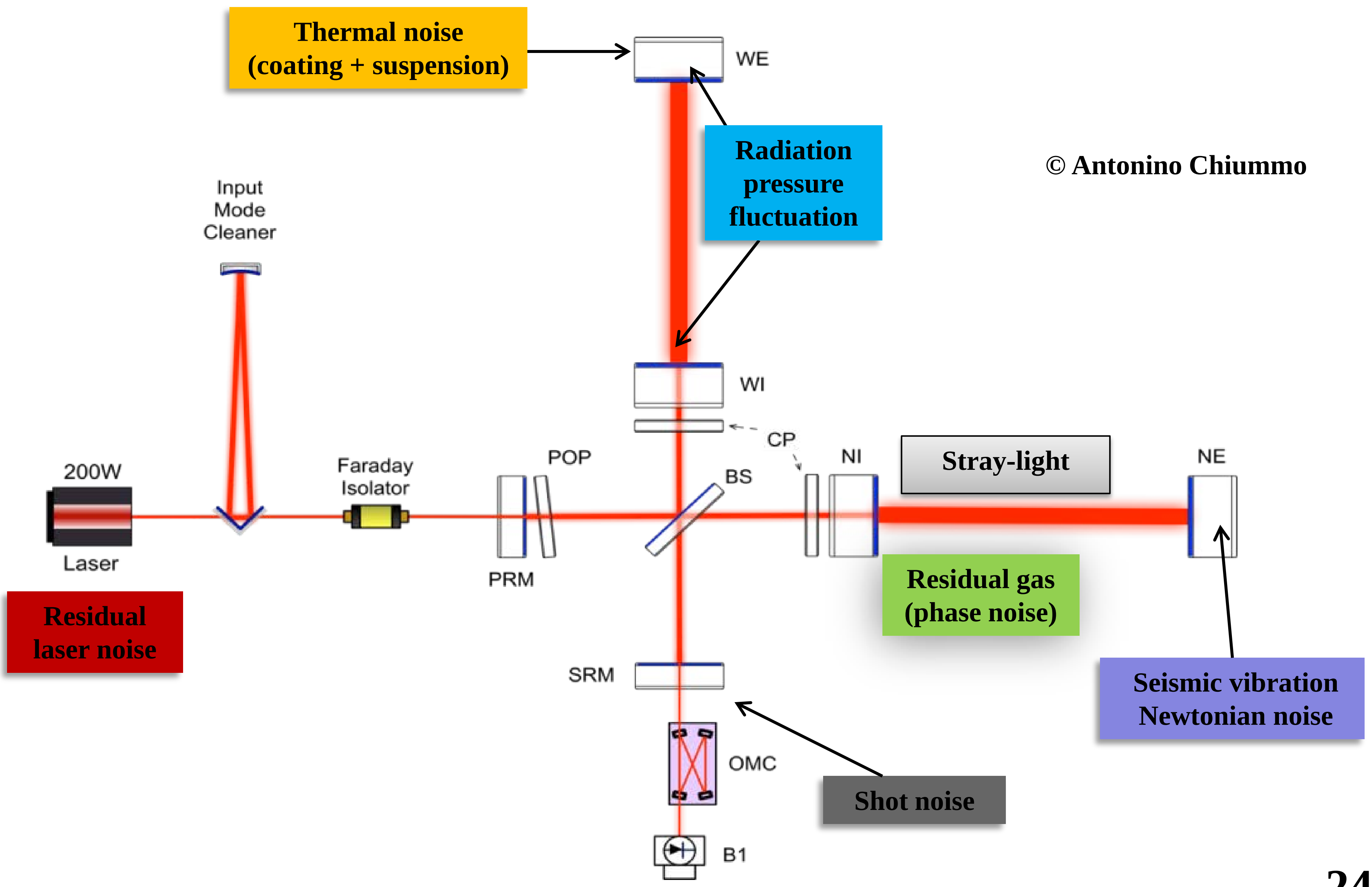


The Advanced Virgo detector revealed

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

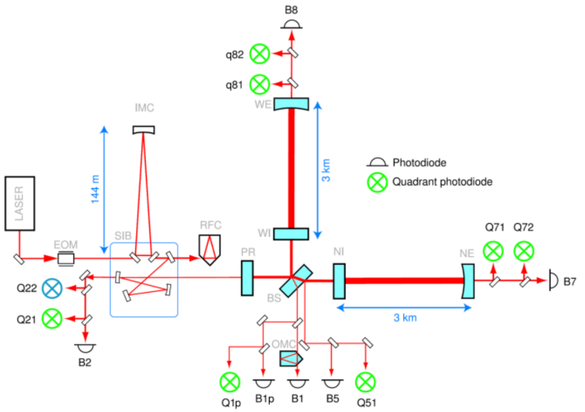


Main interferometer noises

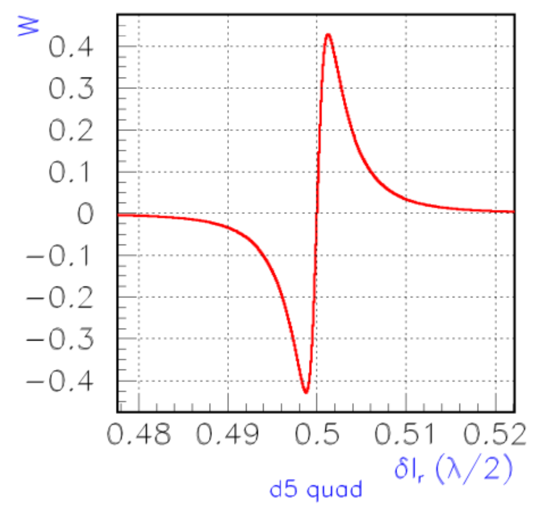


Interferometer control

- Sensitivity to OG ⇔ Interferometer kept at its working point
  - Resonant optical cavities + interferometer on the dark fringe
  - Accuracy of the length cavity control: down to 10^{-15} m
  - Accuracy of the mirror alignment control: 10^{-9} rad



- A complex engineering problem
  - Broken down in several successive steps
    Mirror free motion → Local control → Global control
  - Use of « error signals » to measure the difference between the detector current state and its working point
    → Corrections (positions, angles) are computed and applied onto the mirrors
  - Control loops: from a few Hz to a few kHz
  - Limitations: control bandwidth and performance of the actuators which apply the corrections to the mirror suspensions

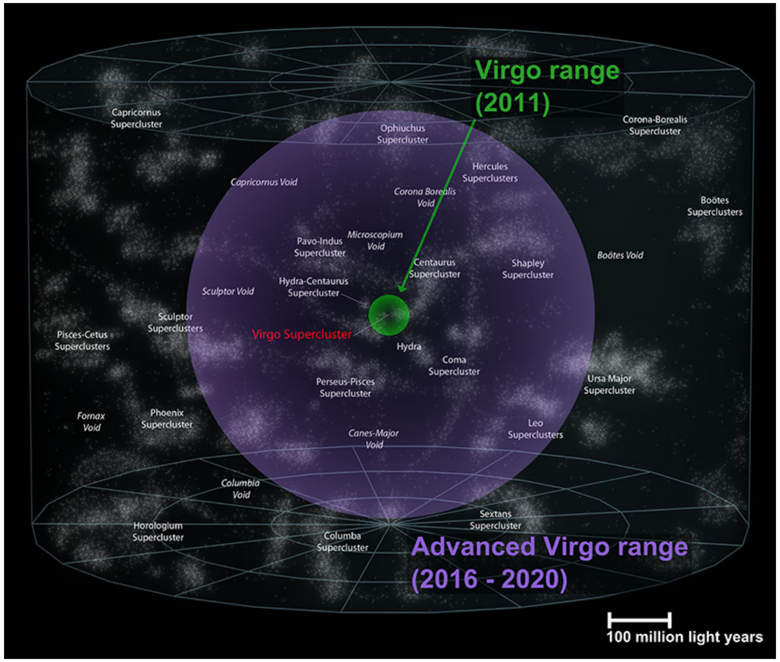


From initial to advanced detectors

- 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 and isotropic distribution of sources (true at large distance)

- 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



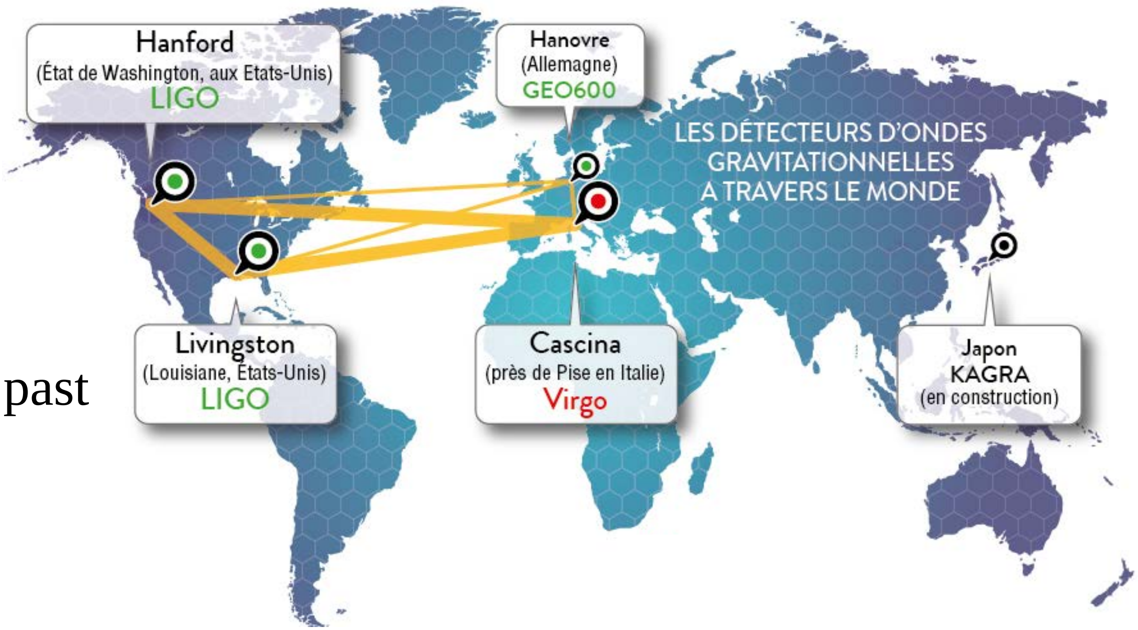
- Advanced LIGO (aLIGO) funded a year or so before Advanced Virgo (AdV)
  - Financial crisis in 2008-2010…

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

A network of interferometric detectors

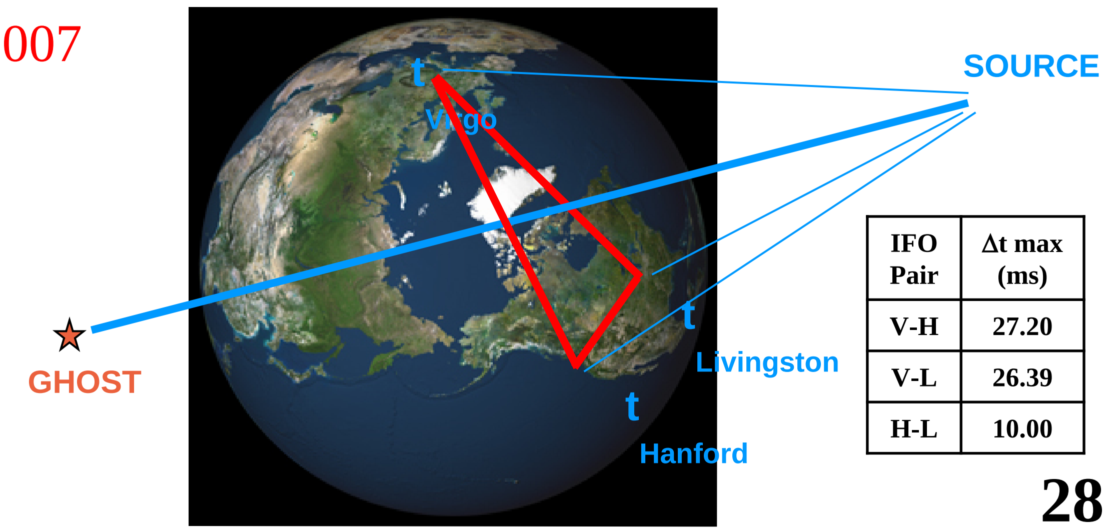
A network of interferometric detectors

- Single interferometer not enough to detect GW
  - Difficult to separate a signal from noise with confidence
  - There have been unconfirmed claims of GW detection in the past



→ 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

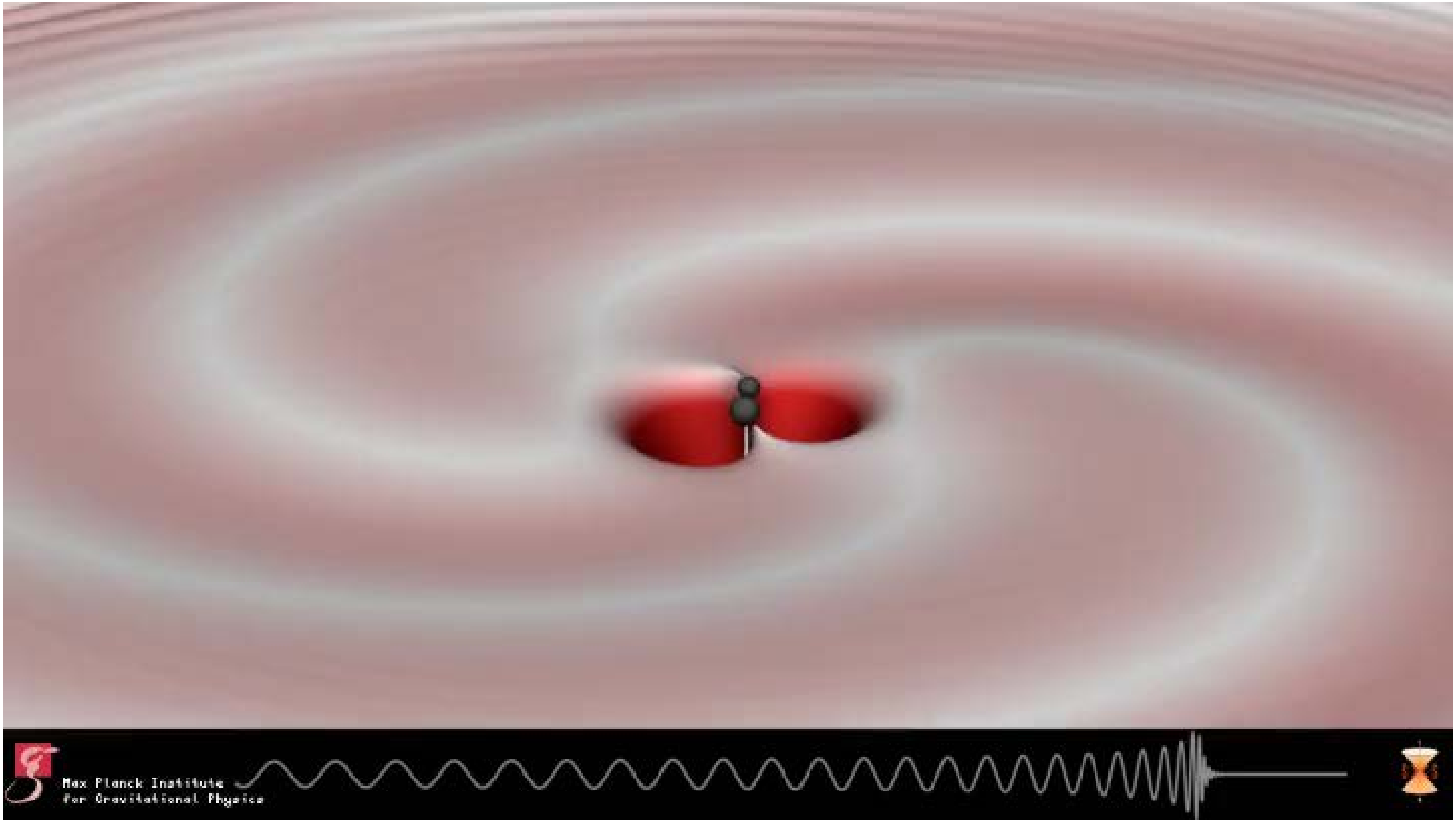


IFO Pair	Δt max (ms)
V-H	27.20
V-L	26.39
H-L	10.00

First detections

GW150914

Simulation of the coalescence



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

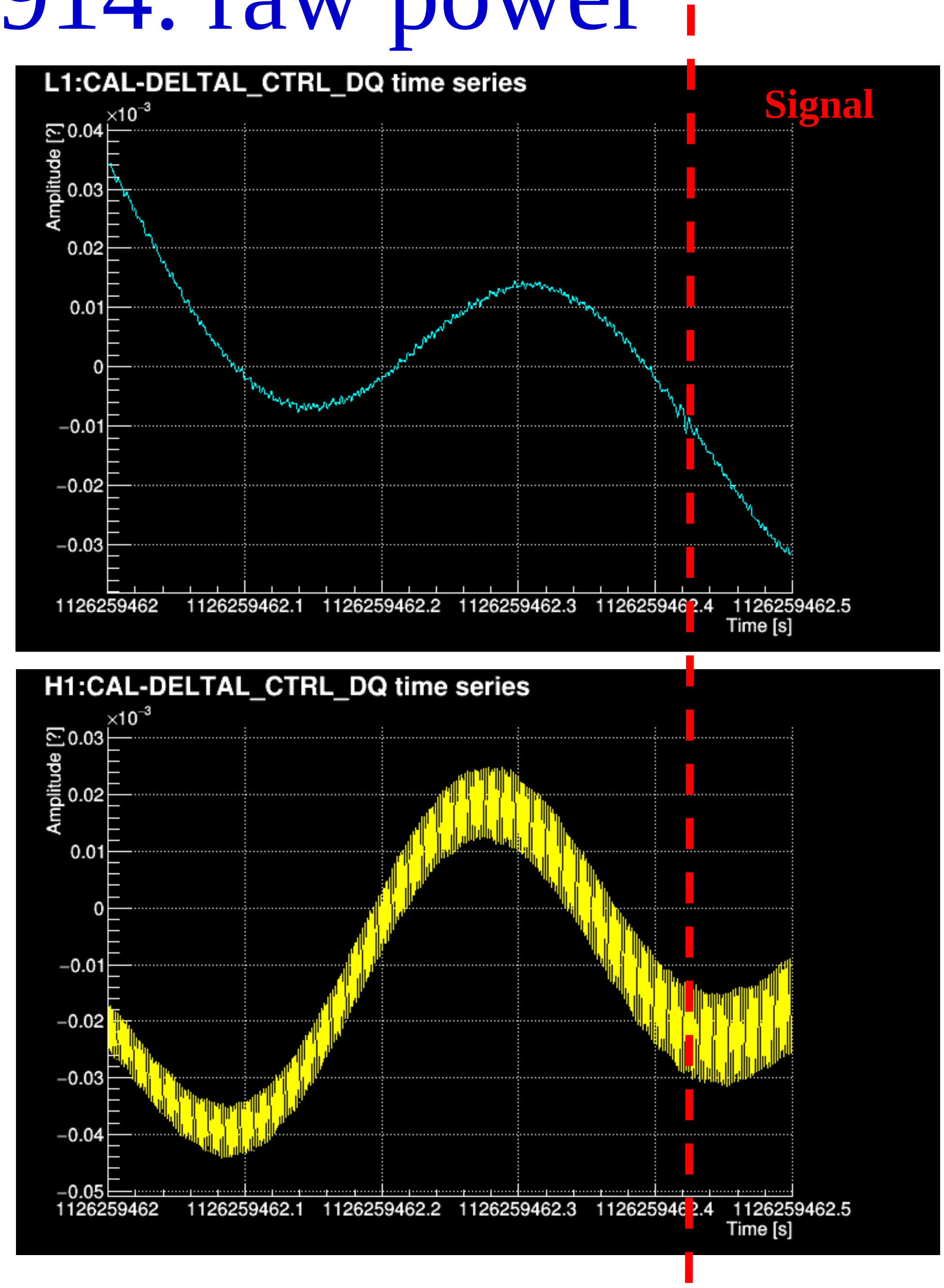
From Marco Drago
Subject **[CBC] Very interesting event on ER8**

```
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

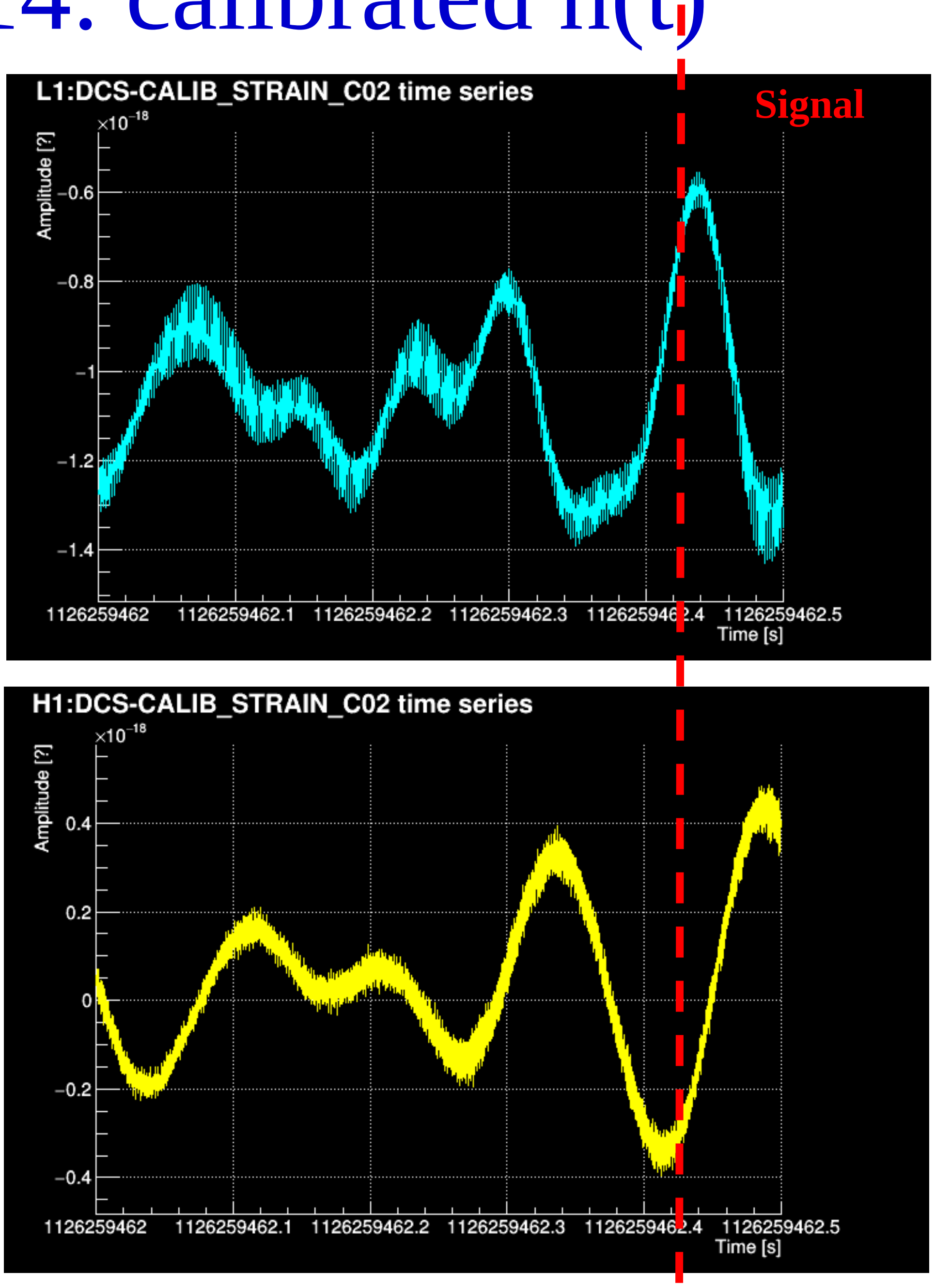
GW150914: raw power

- Blue: aLIGO Livingston
  Yellow: aLIGO Hanford



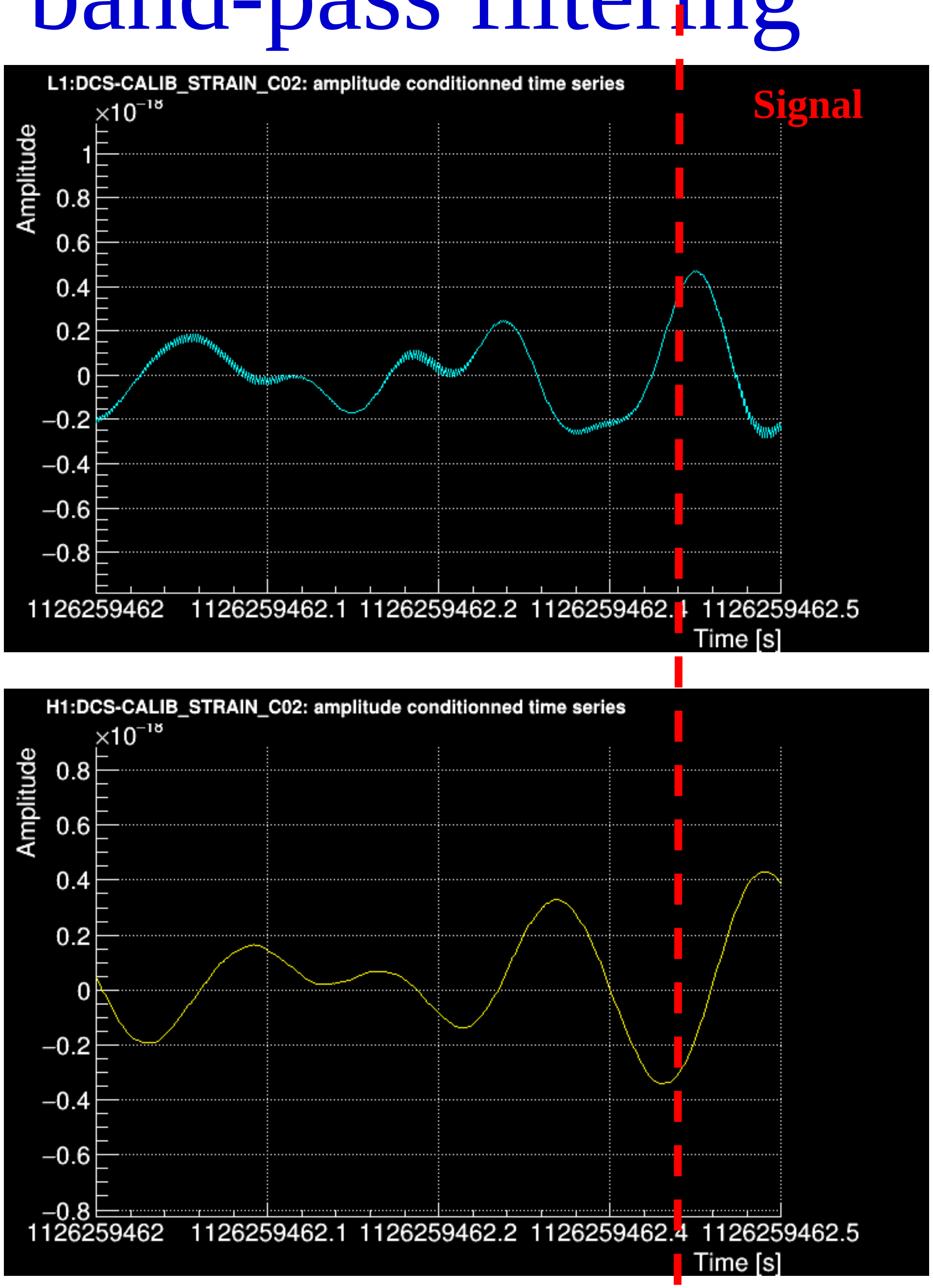
GW150914: calibrated h(t)

- Control signals used to recover the strain signal



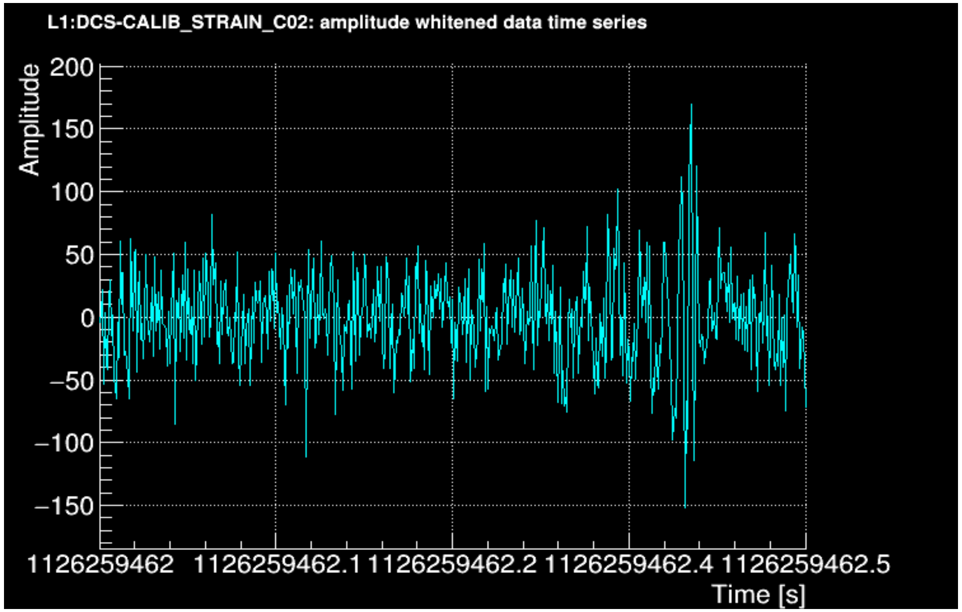
GW150914: band-pass filtering

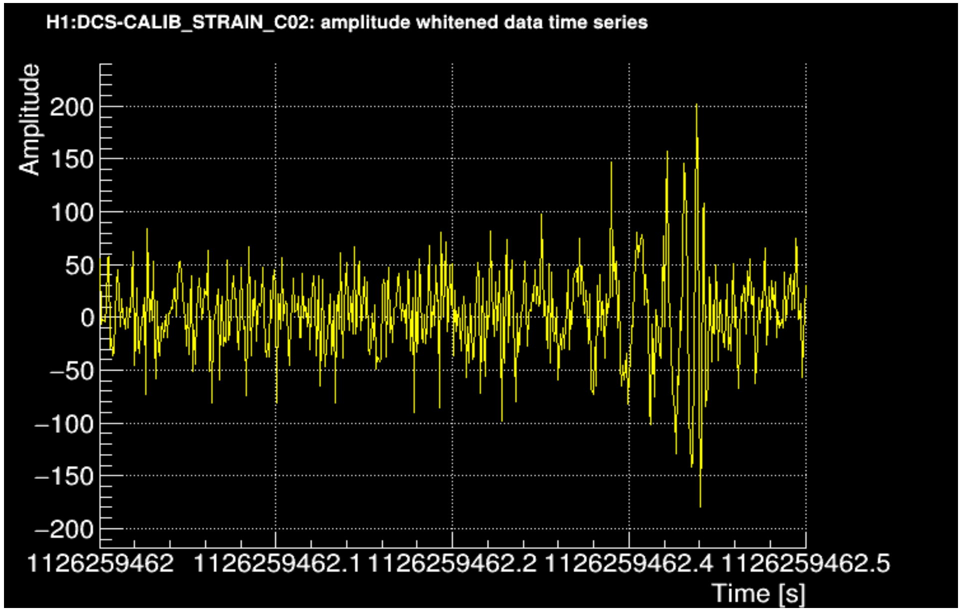
• 20 Hz → 500 Hz



GW150914: whitened data

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

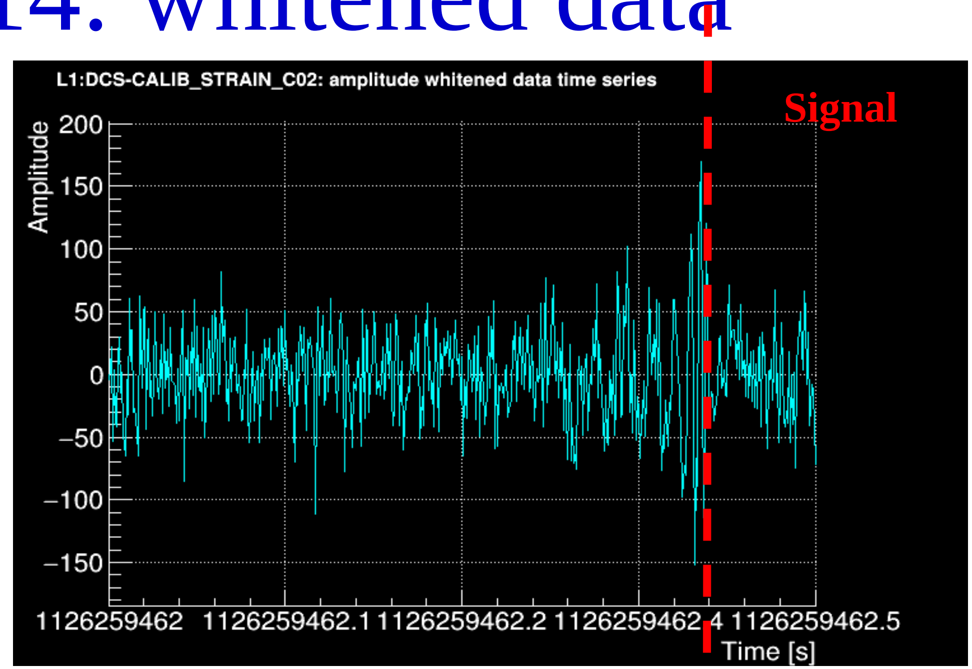


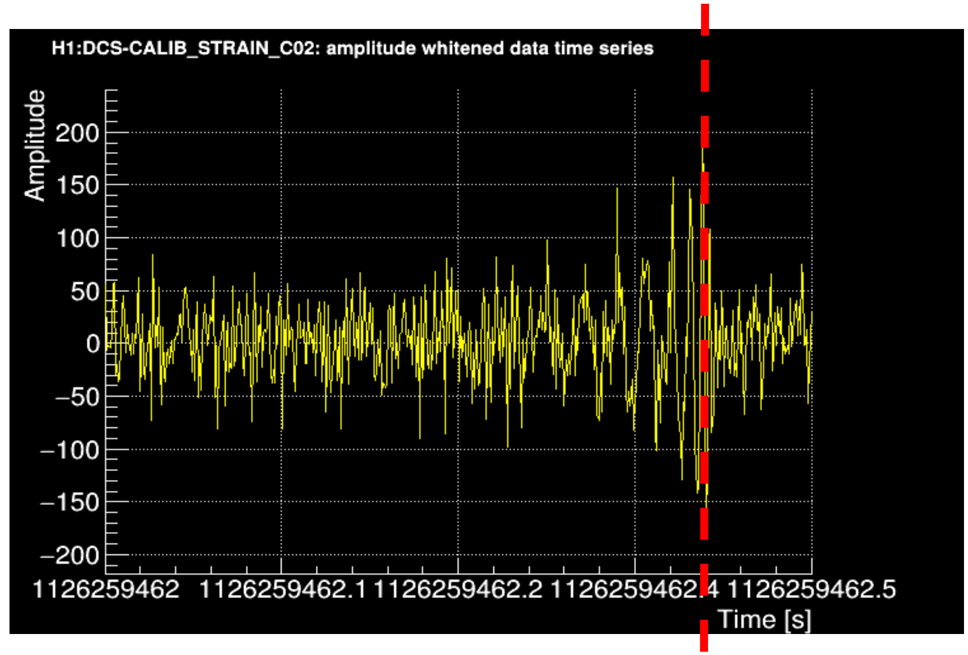


- ± 20 nW peak-to-peak at the interferometer output port
  - To be compared with the incident power on the beamsplitter: ~500 W

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
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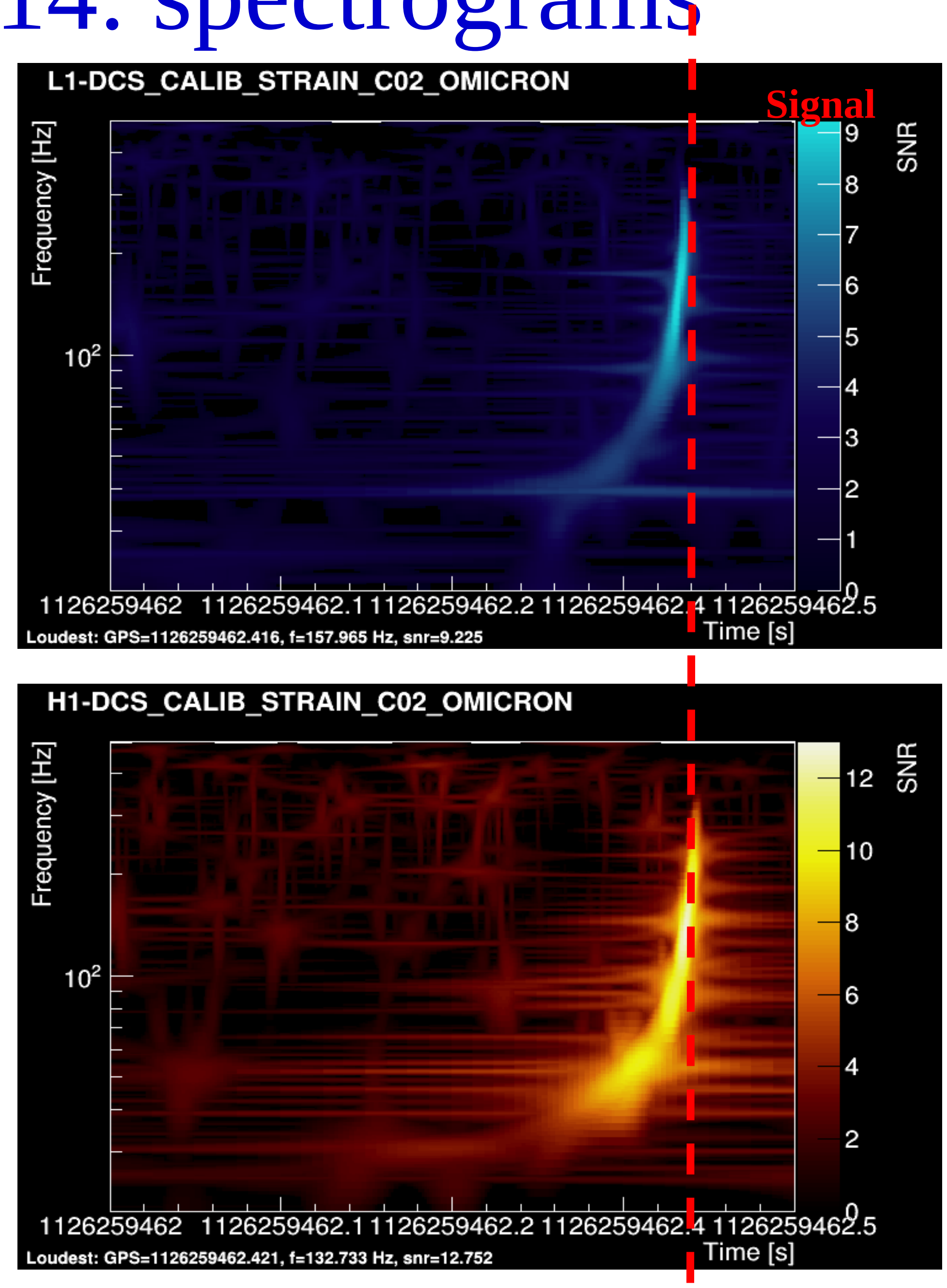
GW150914: spectrograms

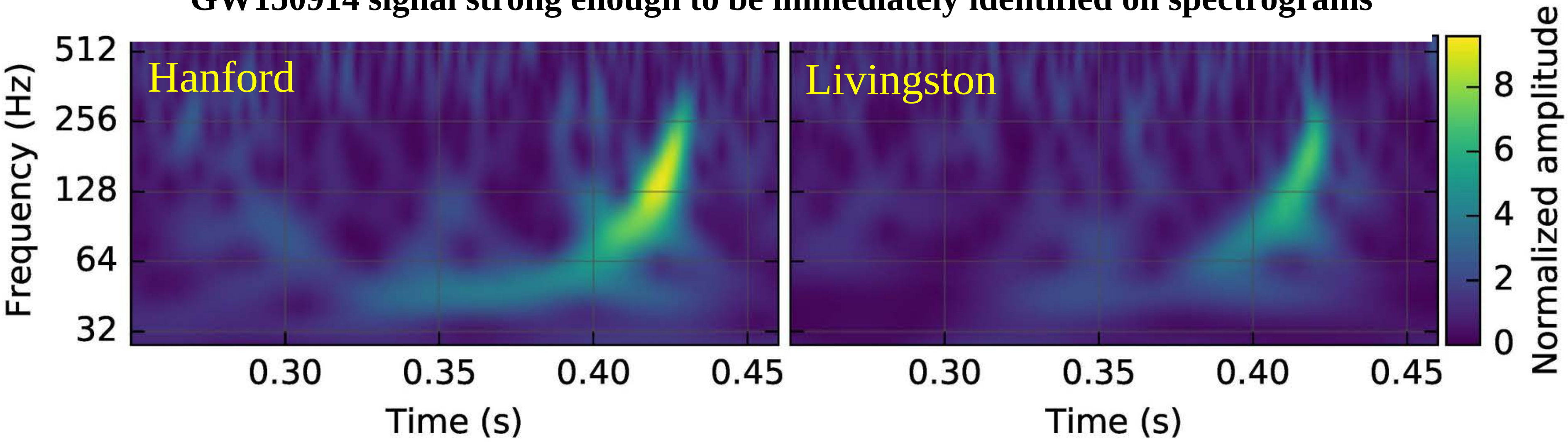
- Time-frequency maps



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

Compact binary coalescence search

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

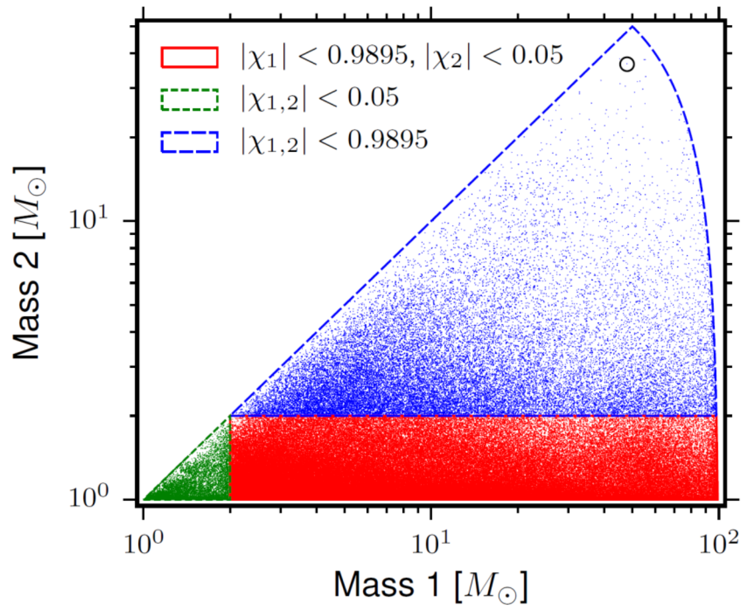
FT of the data

Signal template

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

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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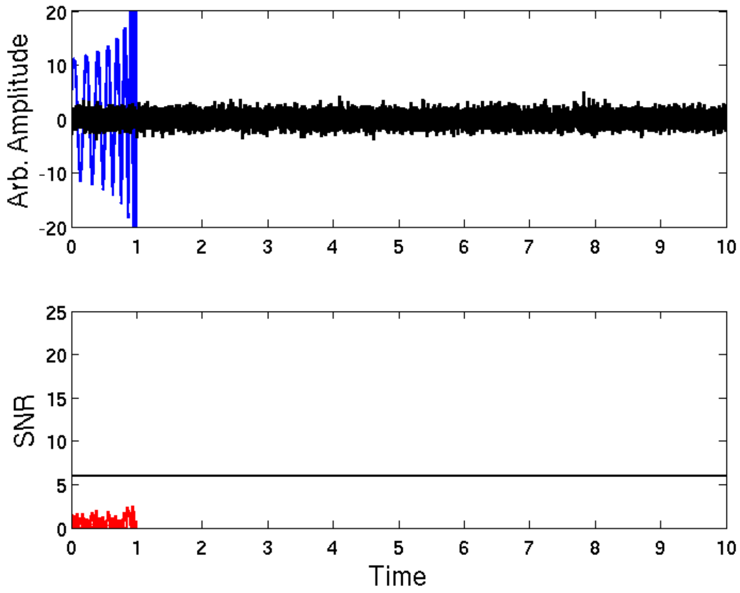


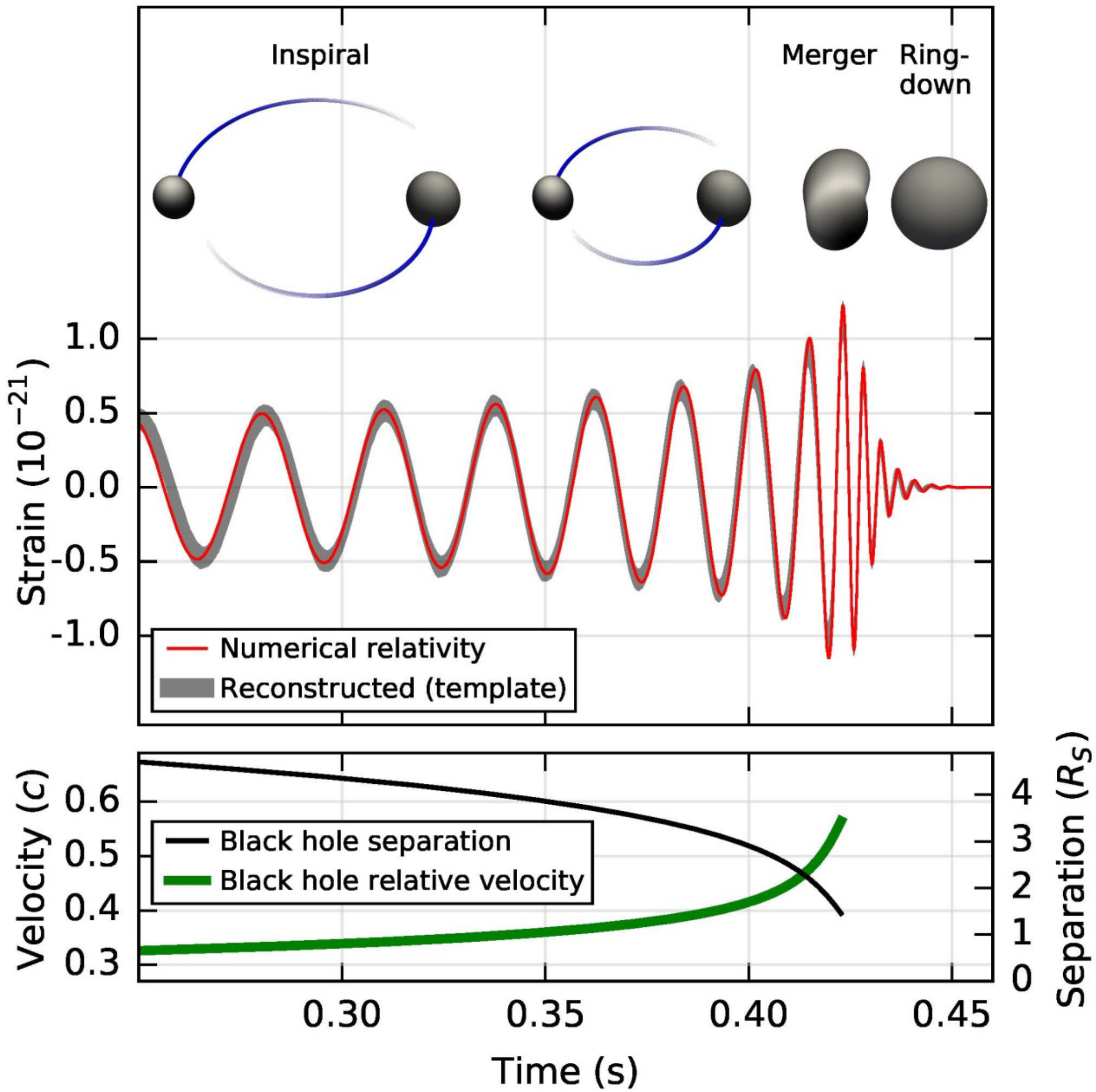
Earth shaken by GW150914

- Scale of effect vastly exaggerated
  - But animation faithful to the evolution over time of the signal

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!

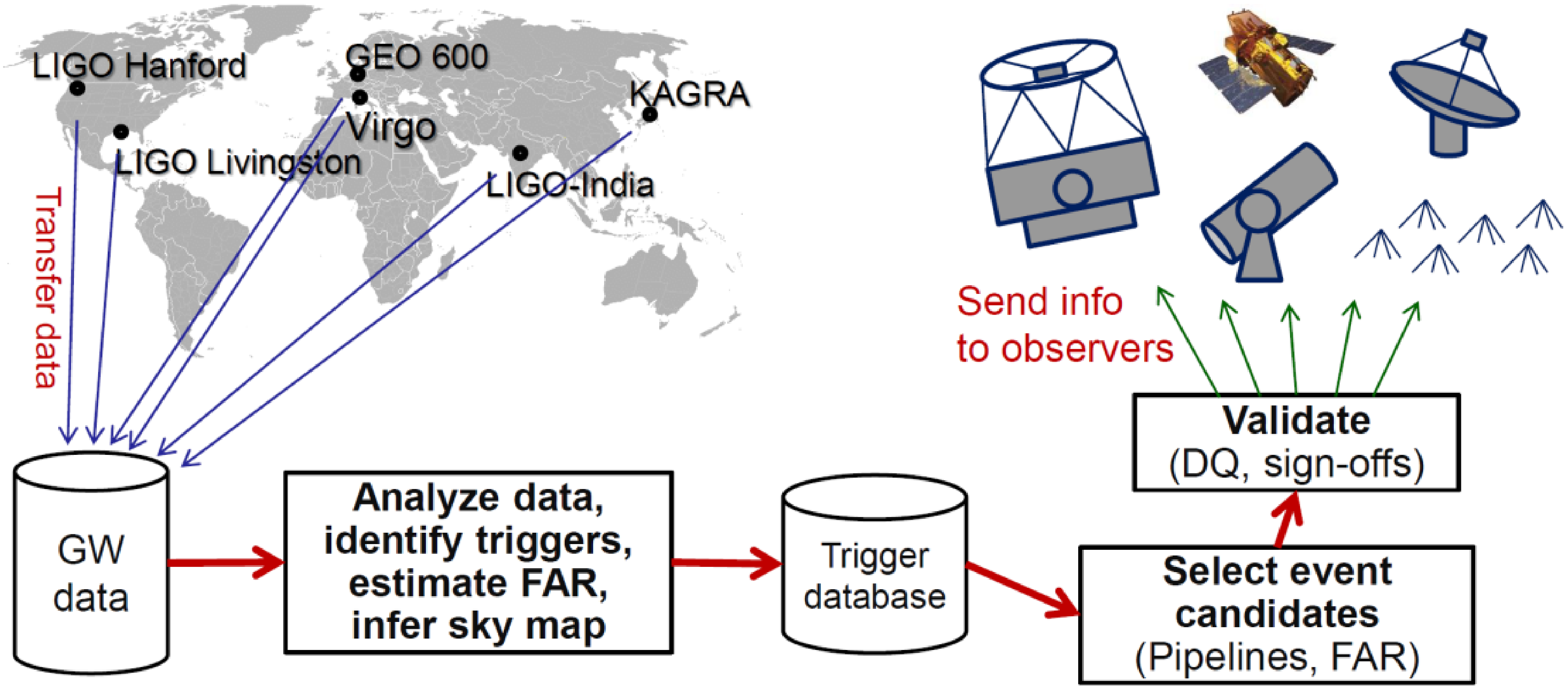
→ Black holes are the only known objects which can fit this picture



- 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

Exploiting multi-messenger information

- Method



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

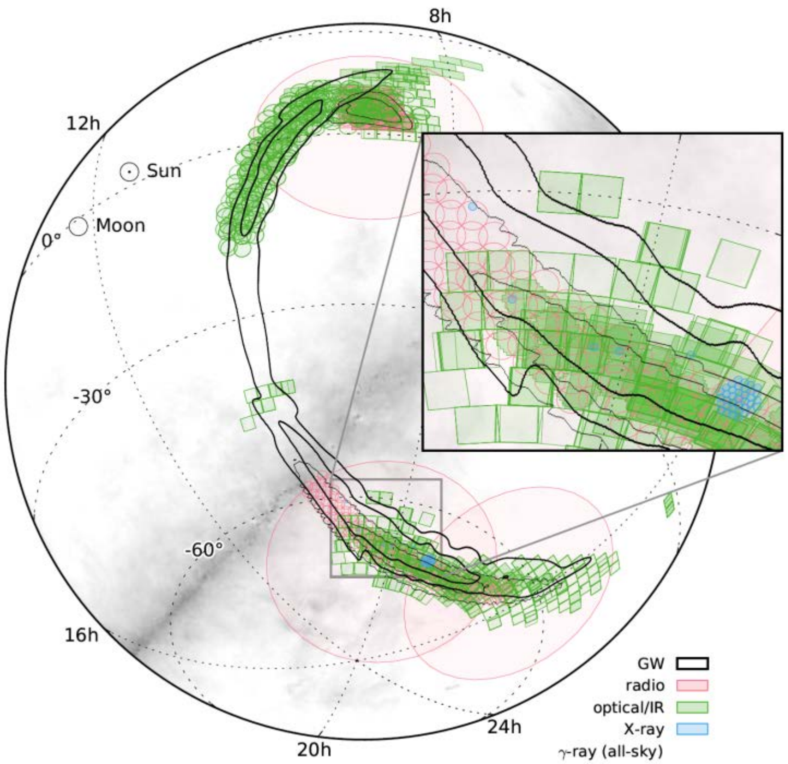
- Astrophysical alerts ⇒ tailored GW searches
  - Time and source location known
    Possibly the waveform as well
    → Examples: gamma-ray burst, type-II supernova

- GW detectors are also releasing alerts to a worldwide network of telescopes
  - Agreements signed with ~75 groups
    → 150 instruments, 10 space observatories

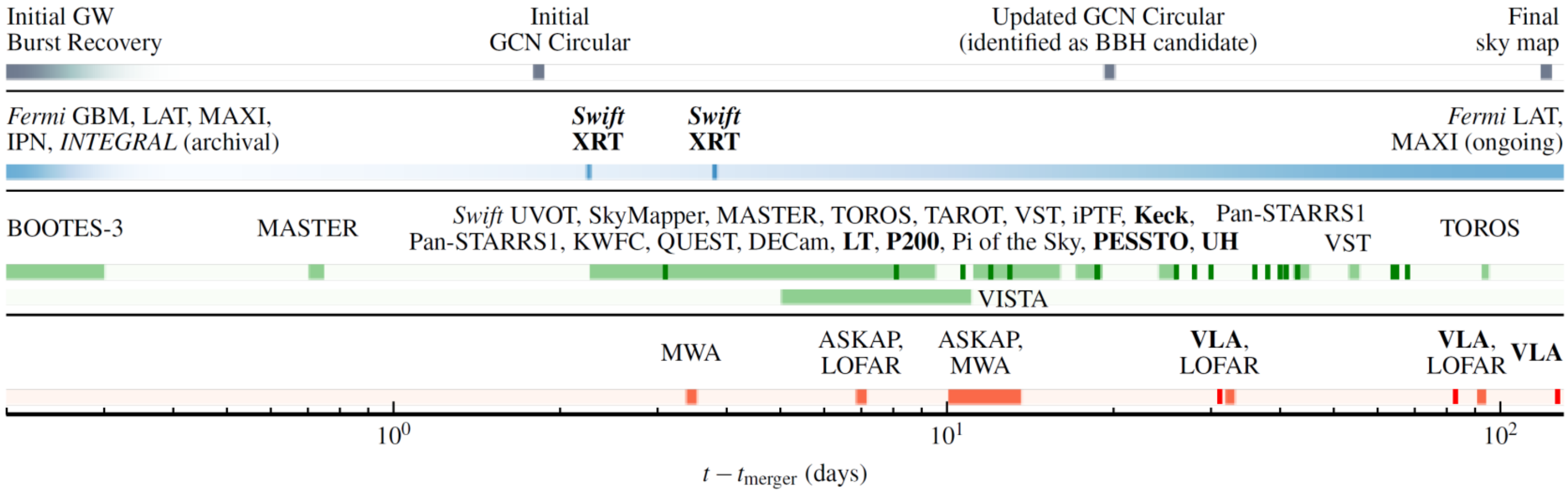
- Low latency h-reconstruction and data transfer between sites
  - Online GW searches for burst and compact binary coalescences

Looking for GW150914 counterparts

- Sky coverage



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



Measuring the signal parameters

- More than a dozen unknown parameters in total
  - Masses and spins of the two initial black holes and of the final black hole, distance to the source, etc.

- Use of statistical methods – bayesian inference to name it – in order to
  - estimate the value of each parameter and the associated error
  - compare waveform models

- Astrophysical results
  - Rate of events similar to GW150914

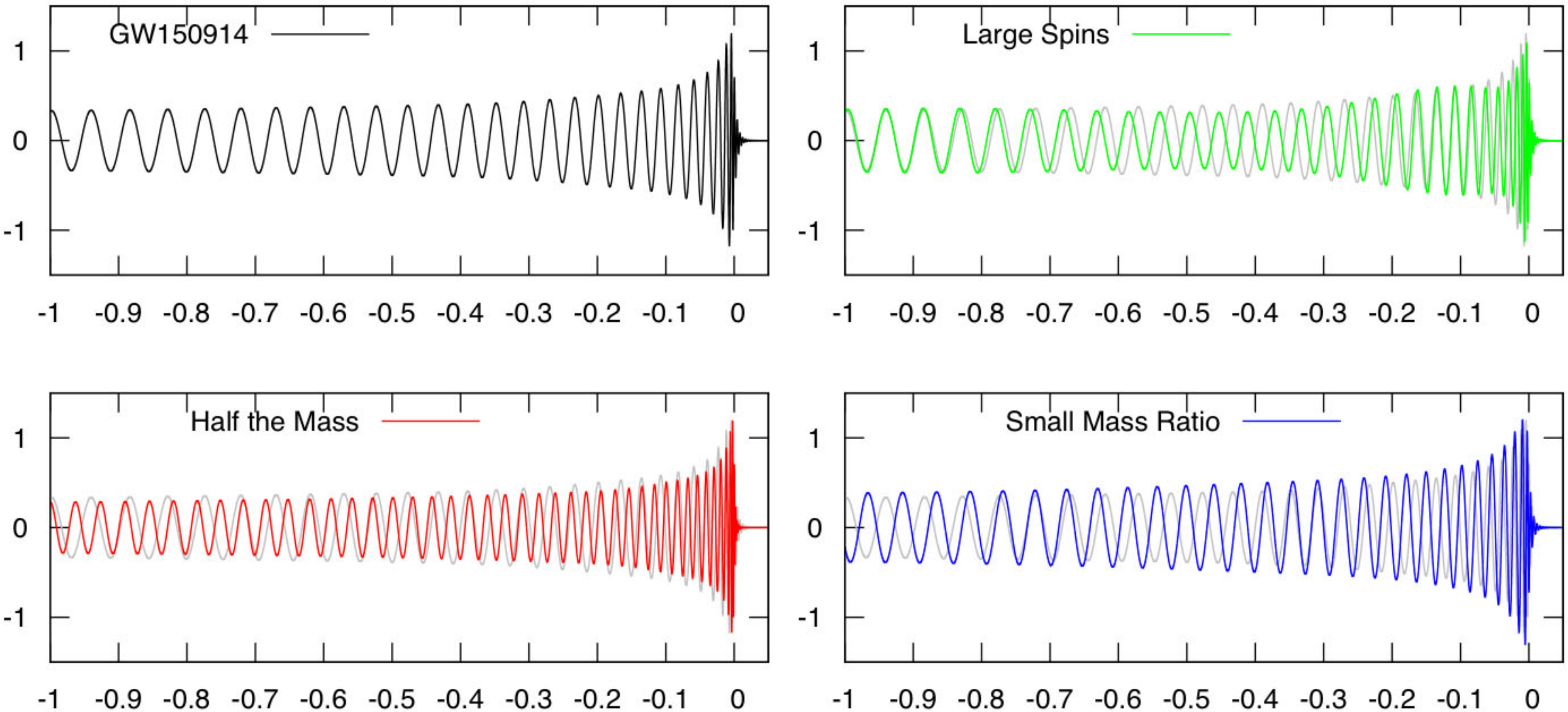
    $\rightarrow$ More events needed to compute the rate accurately
  - Learn more about how stellar mass binary black holes get formed

- General relativity tests
  - No significant deviation observed with respect to the predictions
  - Best limit on the mass of an hypothetical graviton

    $\rightarrow$ $< 10^{-22}$ eV/c^2

Parameter estimation

- Impact of the black hole parameters on the waveform



To sum up

GW150914: FACTSHEET

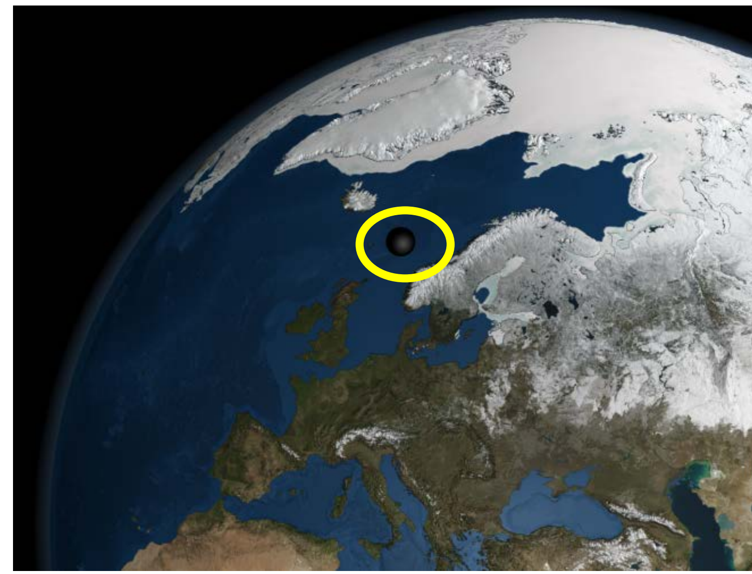
BACKGROUND IMAGES: TIME-FREQUENCY TRACE (TOP) AND TIME-SERIES (BOTTOM) IN THE TWO LIGO DETECTORS; SIMULATION OF BLACK HOLE HORIZONS (MIDDLE-TOP), BEST FIT WAVEFORM (MIDDLE-BOTTOM)

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



The final black hole has about the size of Iceland

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

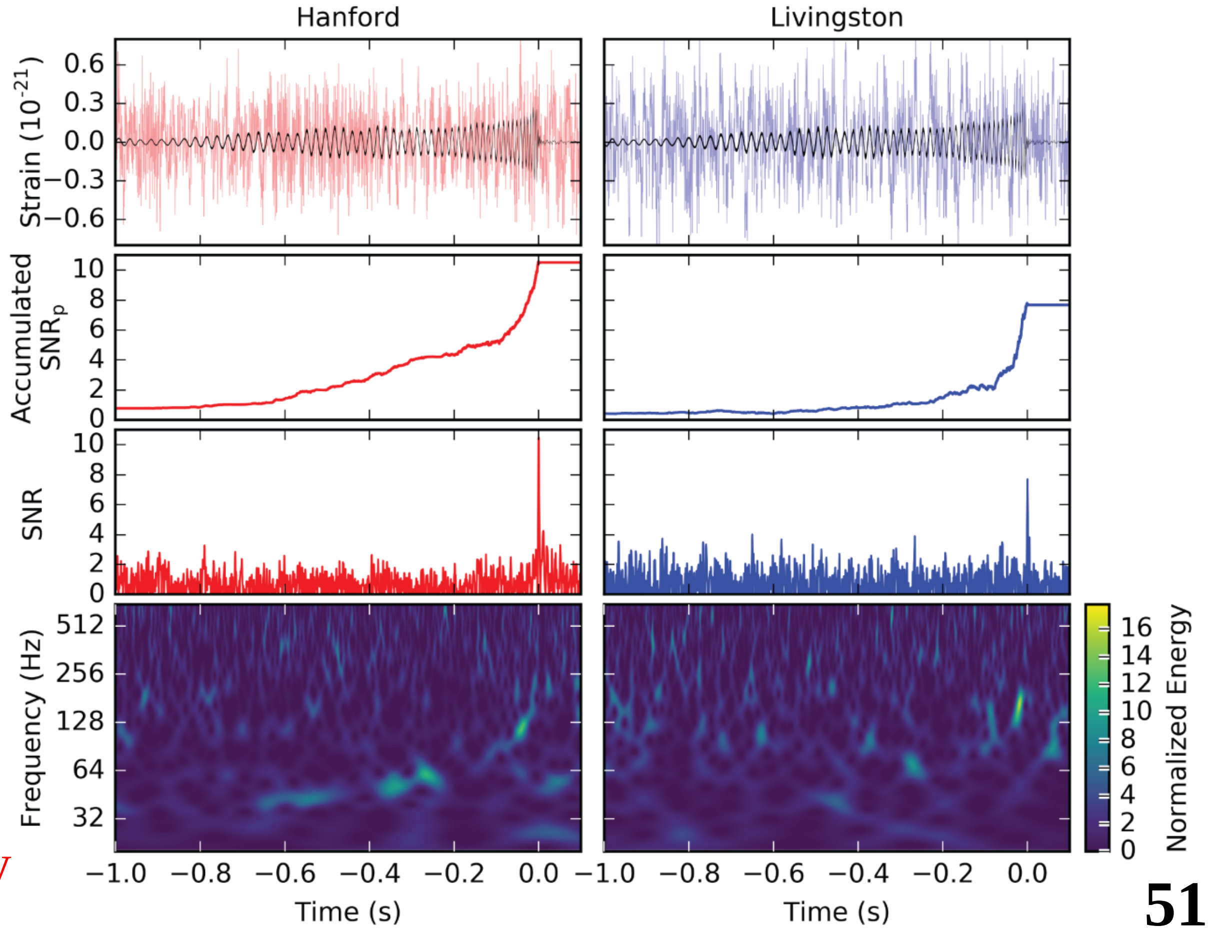
- Not all GW signals visible to the naked eye!

- Another binary black hole coalescence

- Lighter black holes
  - 14 and 8 $M_\odot$

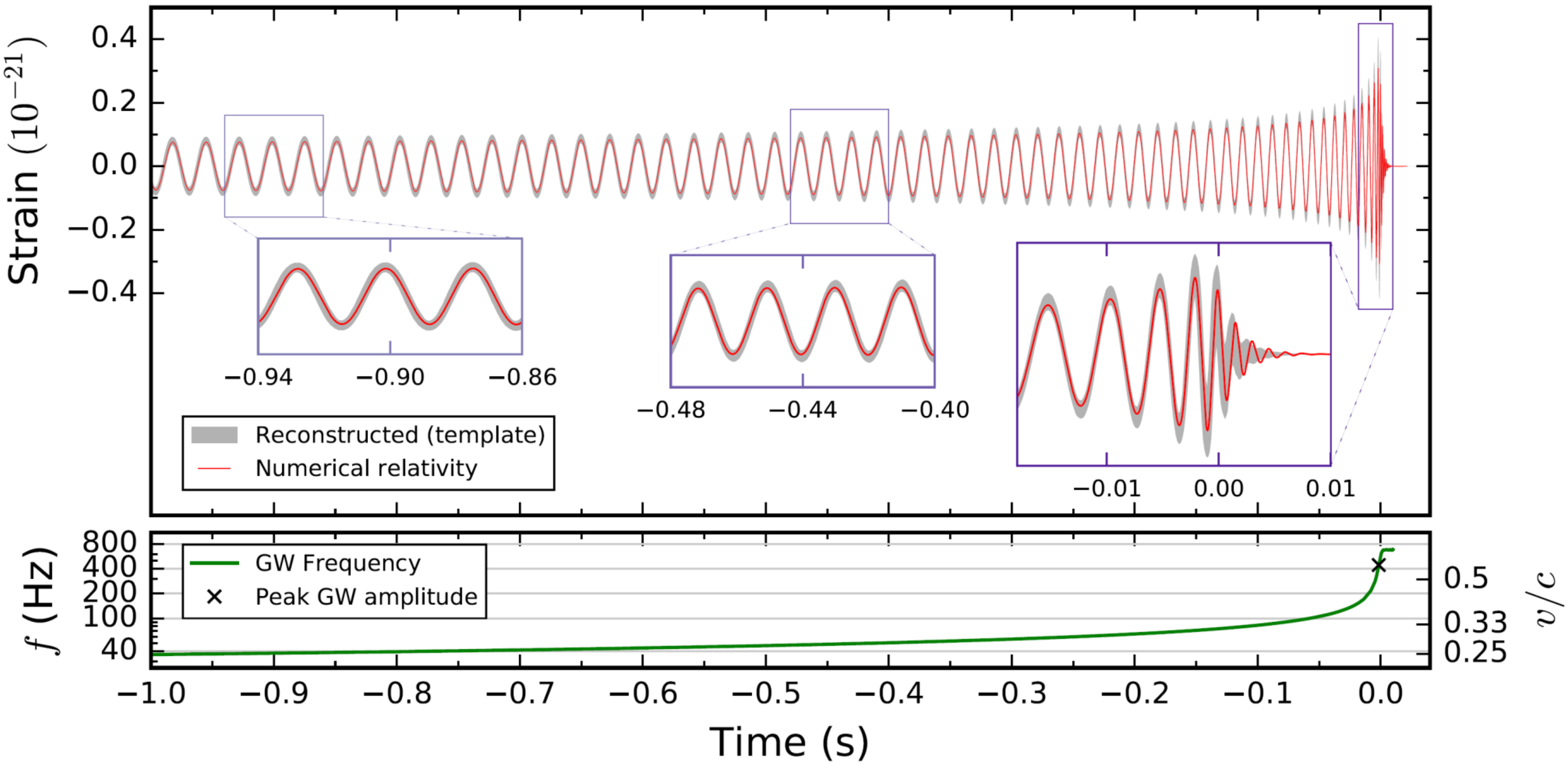
- Smaller amplitude
- More cycles in the detector bandwidth

→ Matched filtering mandatory



GW151226

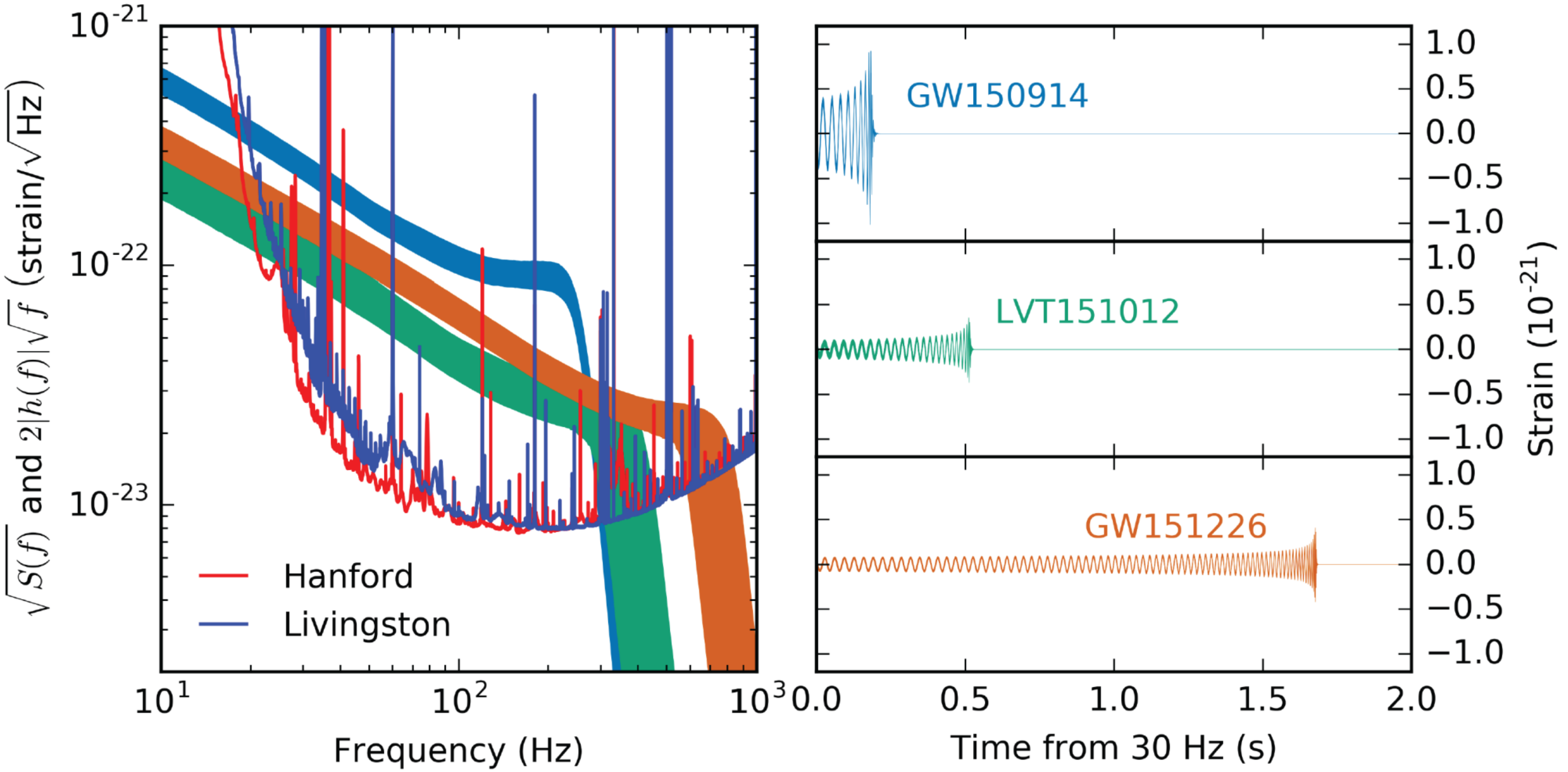
- Excellent agreement between the different reconstructed waveforms
  - analytical computation (post-Newtonian expansion, in grey)
  - numerical relativity (in red)



Summing up: two events, one candidate

- Only black hole binary systems

- No other GW source observed so far



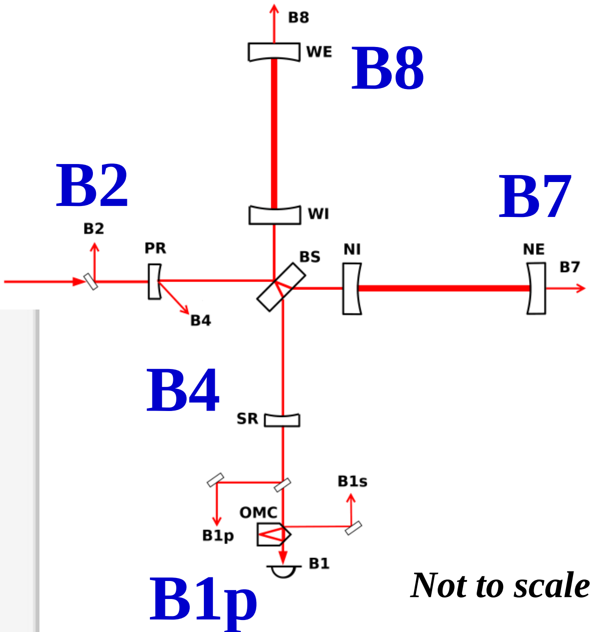
And now!?

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

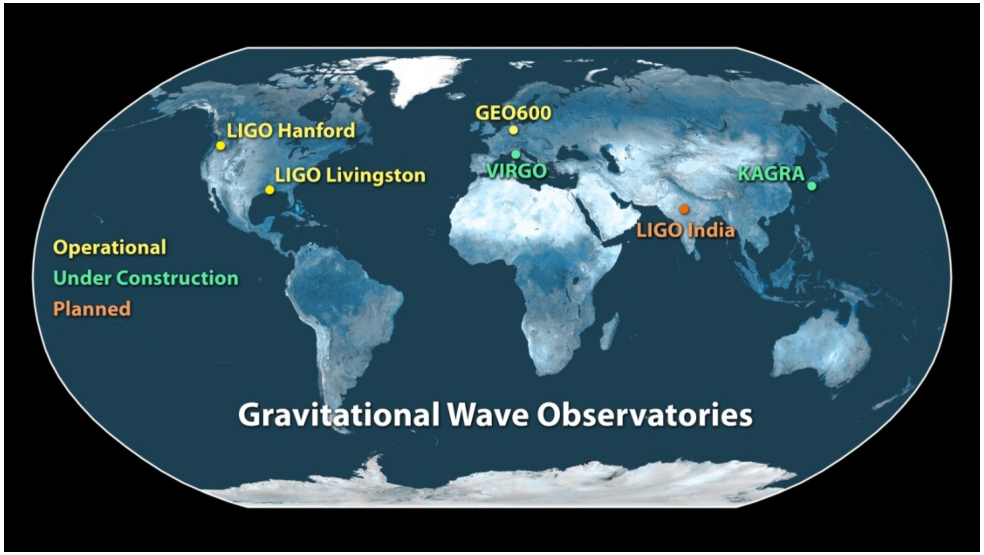


Not to scale

Conclusions

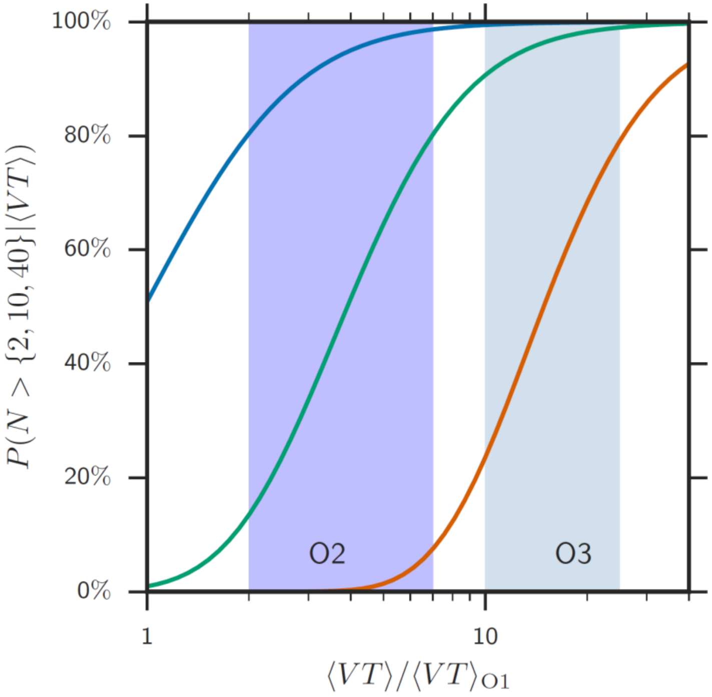
Prospects

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



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

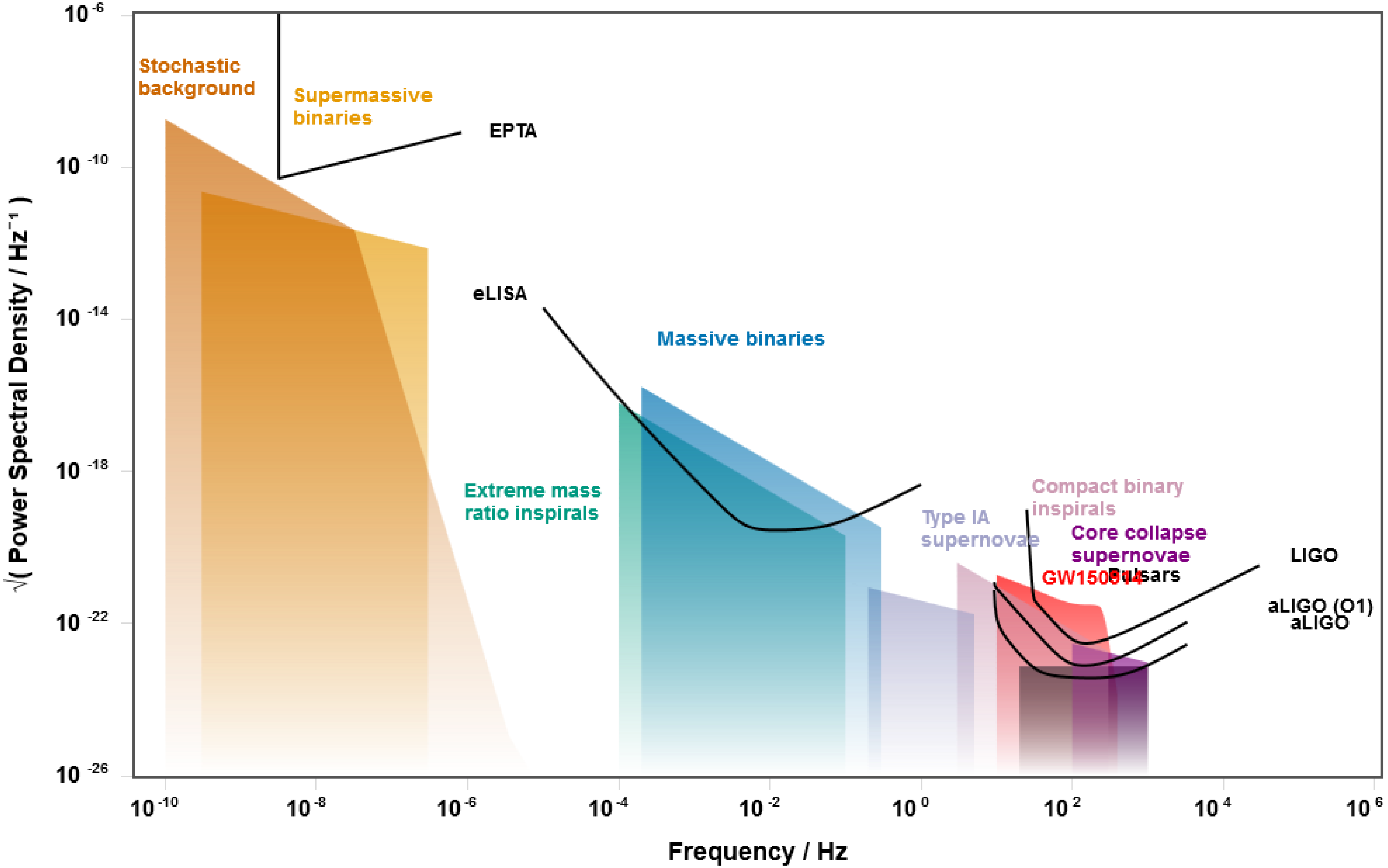
Probabilities that the number of detections exceeds
- **2**
- **10**
- **40**



OX : « Observation » Run number X

Detectors and sources: a summary plot

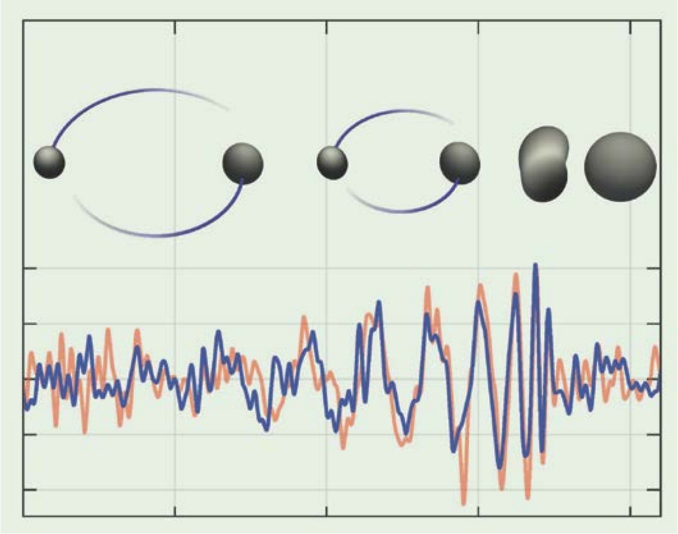
- From http://rhcole.com/apps/GWplotter



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