Detecting gravitational waves

Virgo/EGO visit, June 13th 2017

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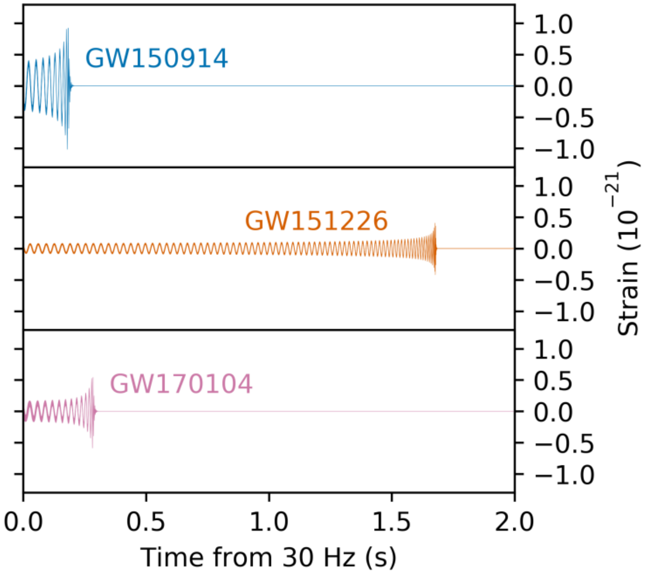

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Outline

- Gravitational waves in a nutshell
  - Sources and properties

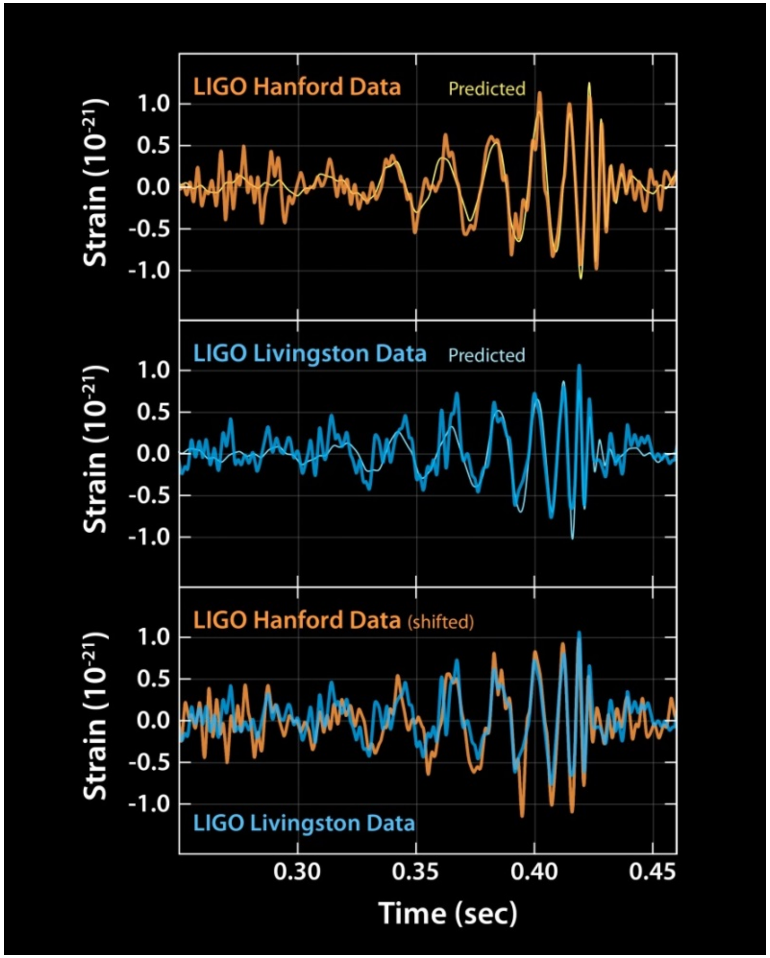
- Gravitational wave interferometric detectors
  - Principle and main characteristics
  - Advanced detectors
  - A worldwide network of detectors

- GW150914, GW151226 & GW170104
  - 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

GW150914



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

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)
  - 11.2 km/s (42.1 km/s) to escape from the Earth (Sun) gravitational field

$$v_e = \sqrt{\frac{2GM}{r}}$$

(independent from m)

- What if $v_e = c$?
  - Stars with a gravitational field so strong that their light would be trapped
  - Context: the corpuscular theory of light

    → John Mitchell (1783)
    → Pierre-Simon de Laplace (1796)

→ Issue forgotten until the publication of Einstein’s general relativity (1915)

Schwartzschild Radius

- Newtonian escape velocity: $v_e = \sqrt{\frac{2GM}{r}}$
- Schwartzschild radius R_S (1916): $R_S = \frac{2GM}{c^2} \approx 3\text{km}\left(\frac{M}{M_{Sun}}\right)$
  - $R_S(M)$ such as $v_e = c$

→ Very small for « usual » celestial objects

  - Planets, stars

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

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

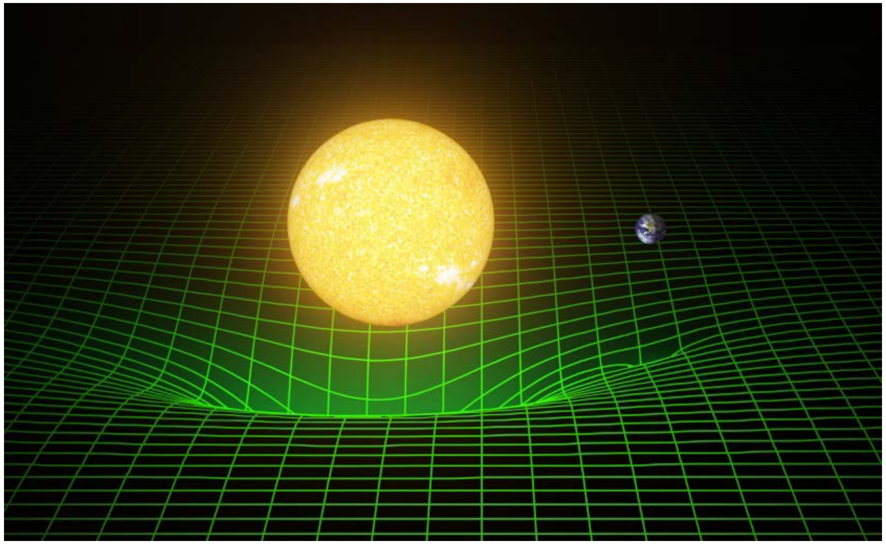
- Beware: compact and dense are two different things!
  - Black hole « density »

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

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

Black holes

- Spacetime region in which gravitation is so strong that nothing, not even light, can escape from inside its horizon

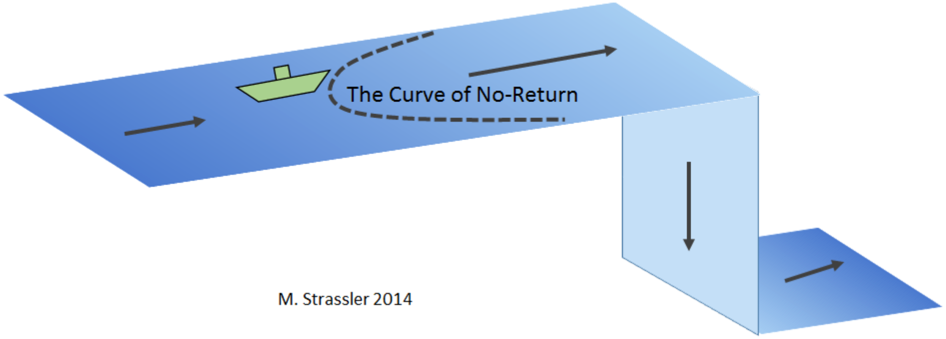
- Formed by the collapse of massive stars running out of fuel

- 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

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



M. Strassler 2014

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

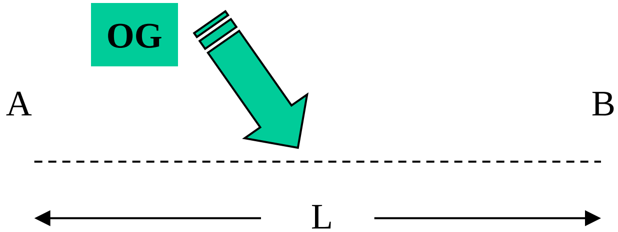
- Quadrupolar radiation
  - Need to deviate from axisymmetry to emit GW
  - No dipolar radiation – contrary to electromagnetism

- 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

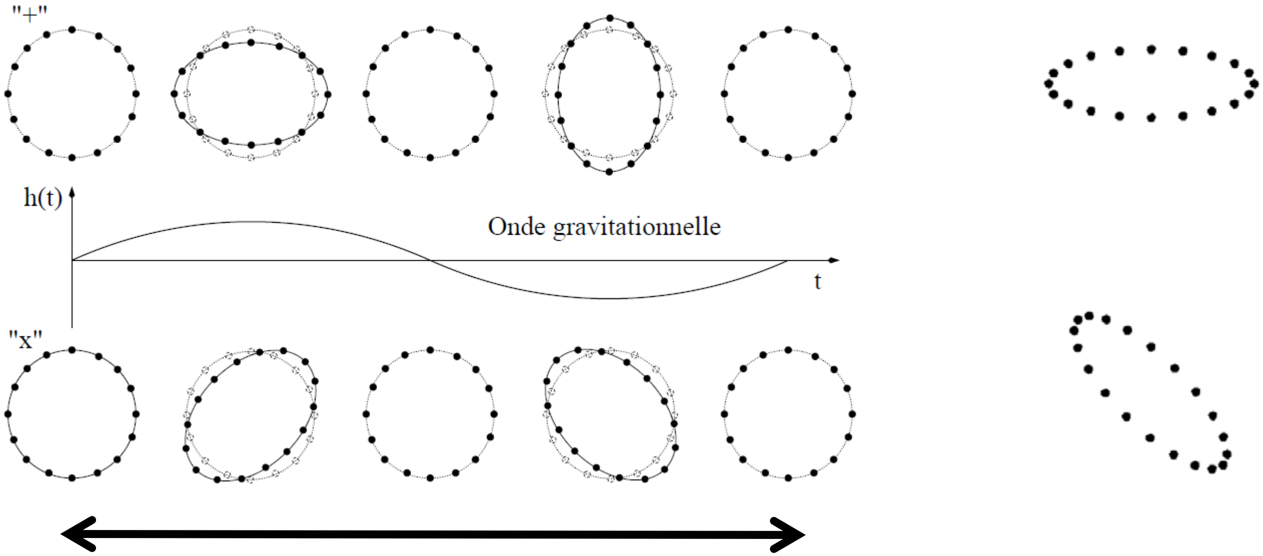
- GW: propagating perturbation of the spacetime metric
  - Acts on distance measurement between test masses (free falling)



$$\delta \mathbf{L}_{\mathbf{max}} = \frac{\mathbf{hL}}{\mathbf{2}}$$

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

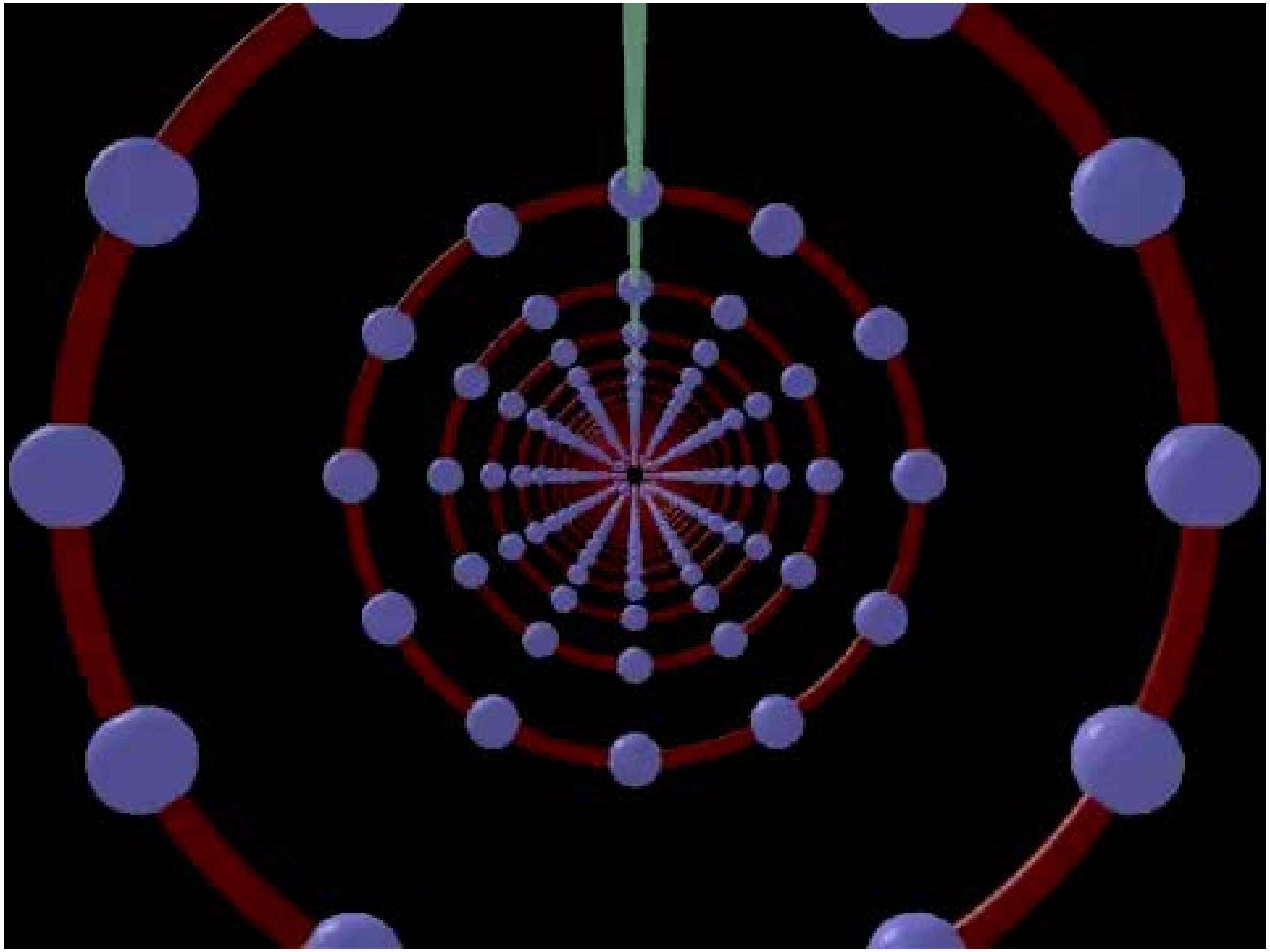
- Effect of the two GW polarizations on a ring of free masses
  - « + » polarization
  - « × » polarization



One period

Effect of gravitational waves on test masses

- In 3D



Do gravitational waves exist?

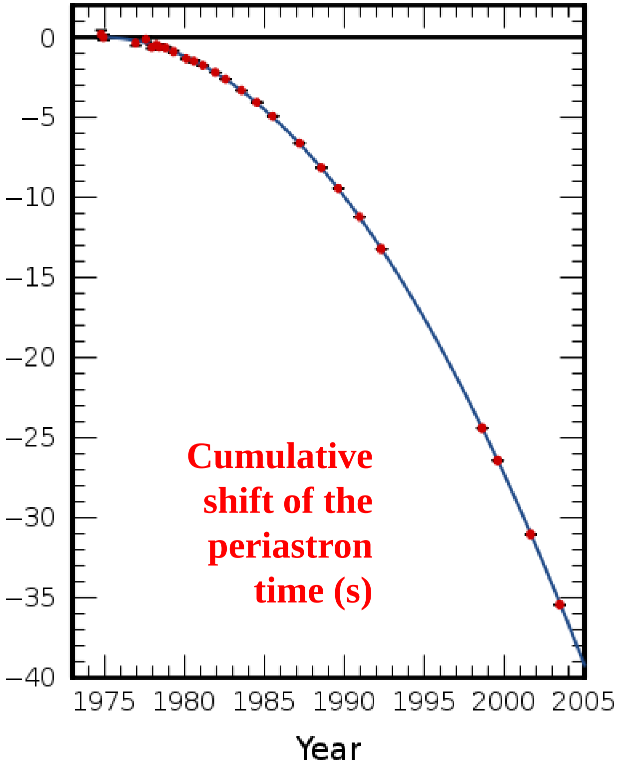
- Question (officially) solved since February 11 2016!
  - But was very relevant beforehand … and long-standing in the community

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

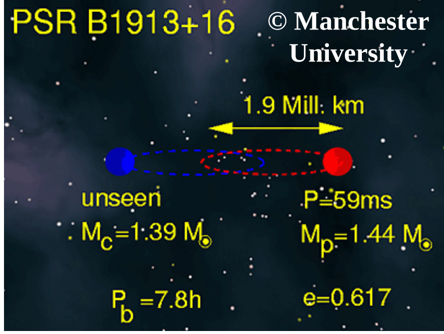
- Indirect evidence of the GW existence: long-term study of PSR B1913+16 – see next slide
  - Galactic (6.4 kpc away) binary system
  - Two neutron stars, one being a pulsar

- Discovered by Hulse and Taylor in 1974
  - Nobel prize 1993

- Laboratory for gravitation study
  - GW in particular
    → Taylor & Weisberg, Damour

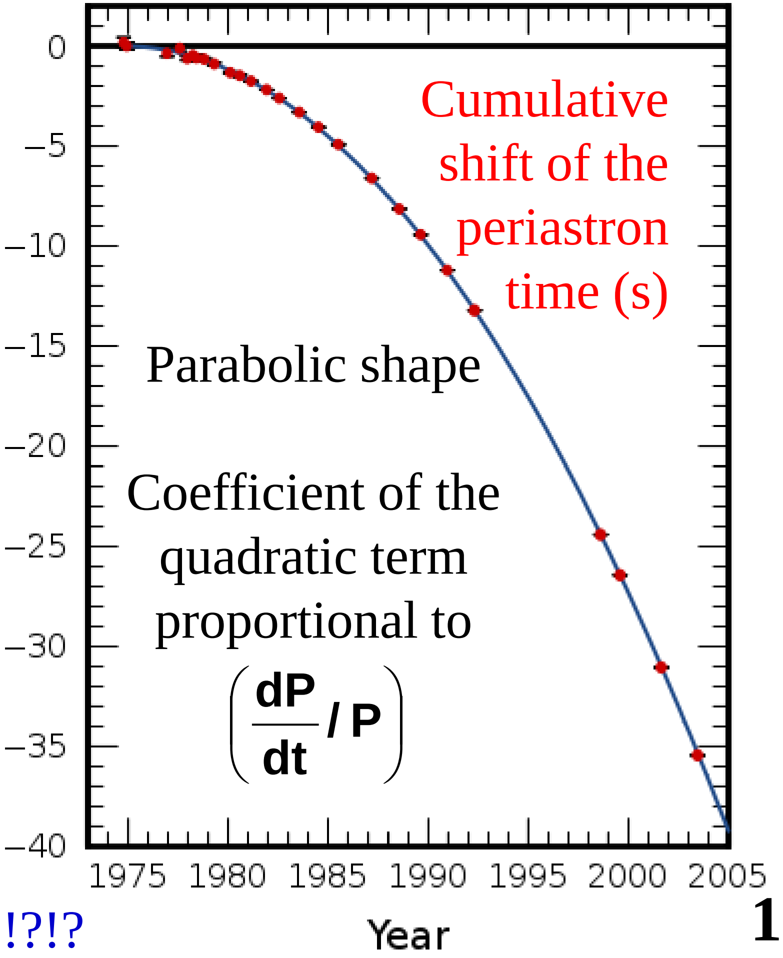


PSR B1913+16



- 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



Cumulative shift of the periastron time (s)

Parabolic shape

Coefficient of the quadratic term proportional to

$$\left(\frac{dP}{dt}/P\right)$$

Sources of gravitational waves

- Einstein quadrupole formula (1916)
  - Power radiated into gravitational waves

    Q: reduced quadrupole momenta

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

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

- Let’s rewrite this equation introducing some typical parameters of the source
  - Mass M, dimension R, frequency $\omega/2\pi$ 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:

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

Huge: 10^{53} W

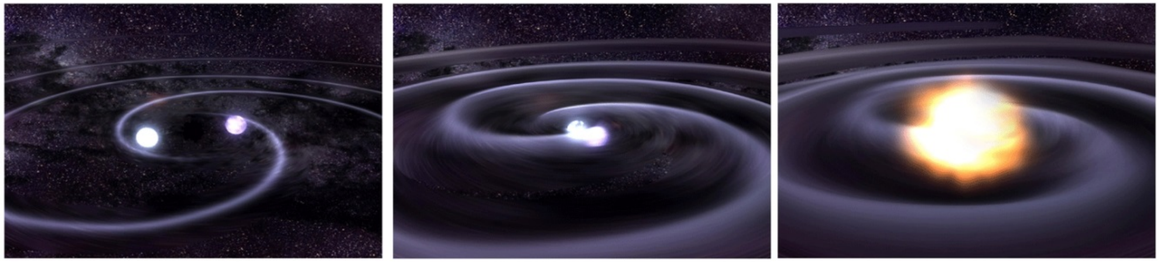
© Joe Weber, 1974

→ 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



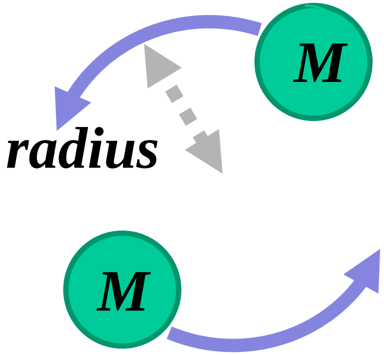
- Rough classification
  - Signal duration
  - Frequency range
  - Known/unknown waveform
  - Any counterpart (E.M., neutrinos, etc.) expected?

- 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 ($f_{GW} = 2\ f_{Orbital}$)

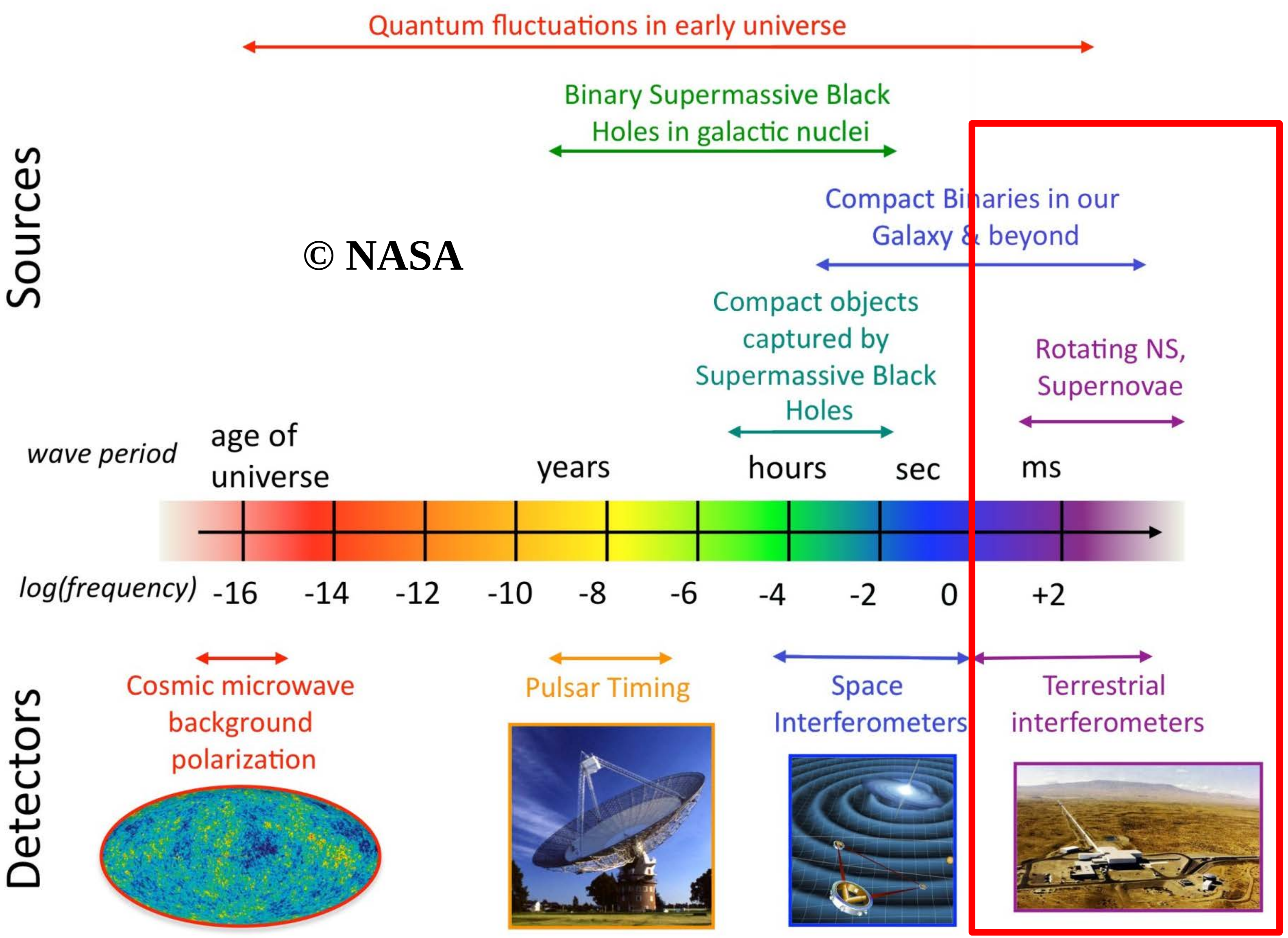
$$h \approx 10^{-21} \left(\frac{500\ \text{Mpc}}{\text{Distance}}\right)\left(\frac{\text{Mass}}{30\ \text{M}_{\text{Sun}}}\right)\left(\frac{\text{Orbital radius}}{100\ \text{km}}\right)^2\left(\frac{\text{Frequency}}{100\ \text{Hz}}\right)^2$$



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

- Permanent sources
  - Pulsars, Stochastic backgrounds

Gravitational wave spectrum



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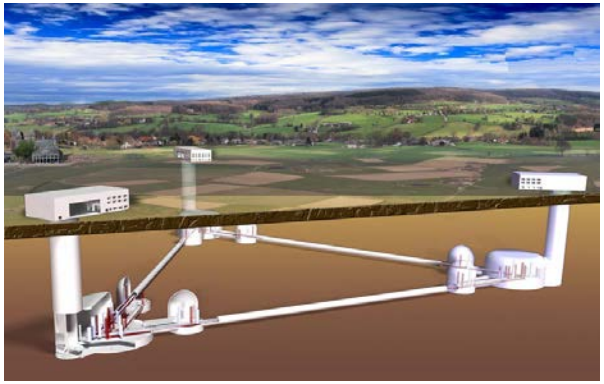
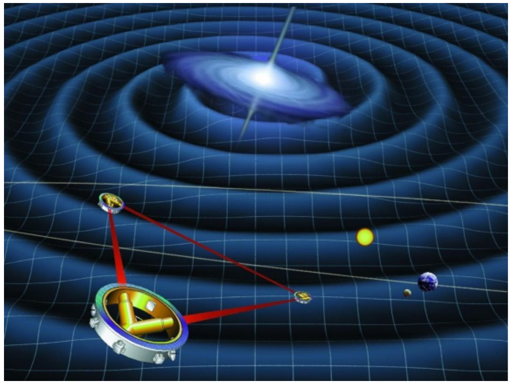
LIGO, Virgo, etc.

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

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

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

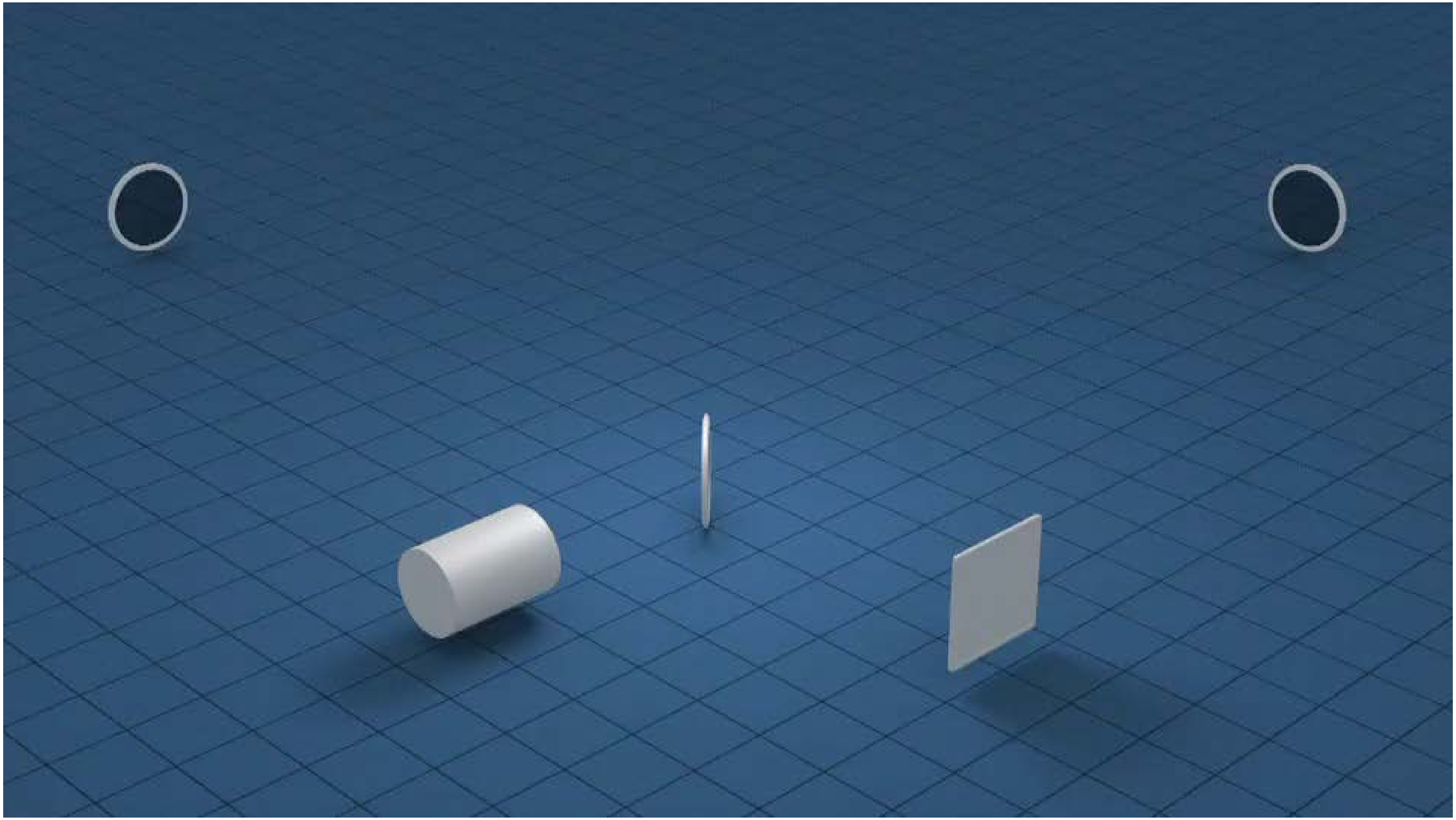
Theoretical developments

- **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.)**

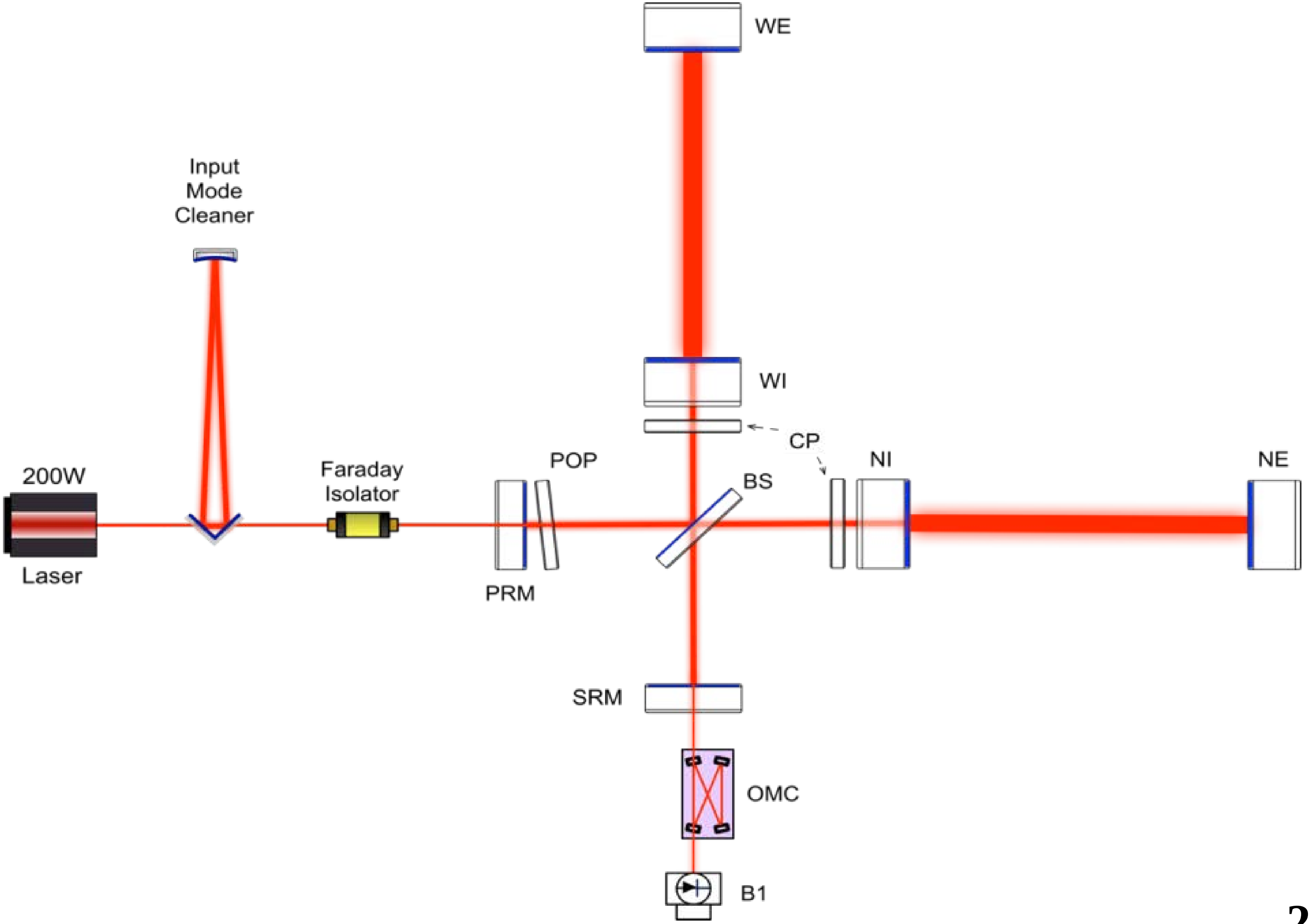
Experiments

- **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

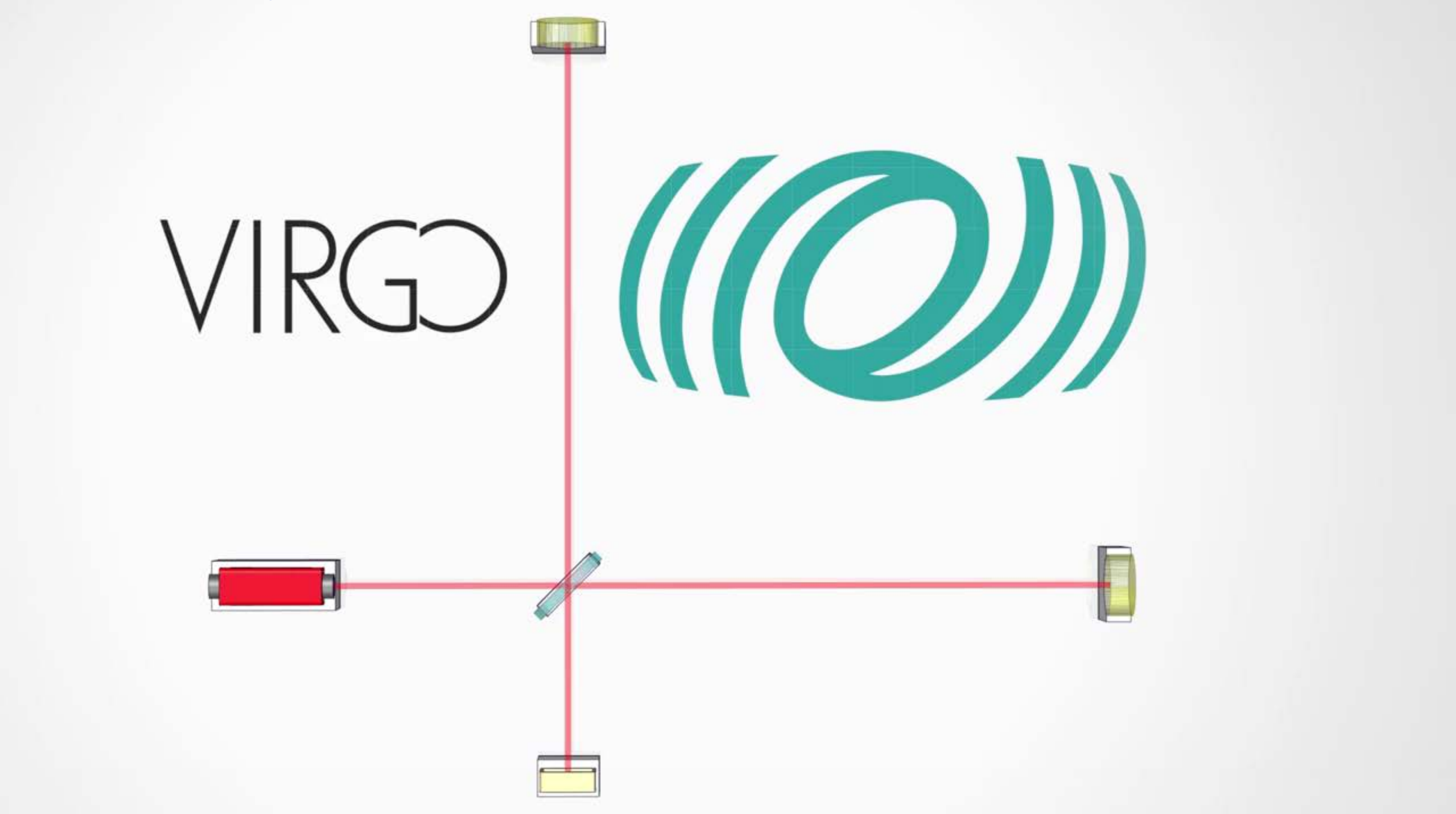


The Advanced Virgo detector scheme



The Advanced Virgo detector revealed

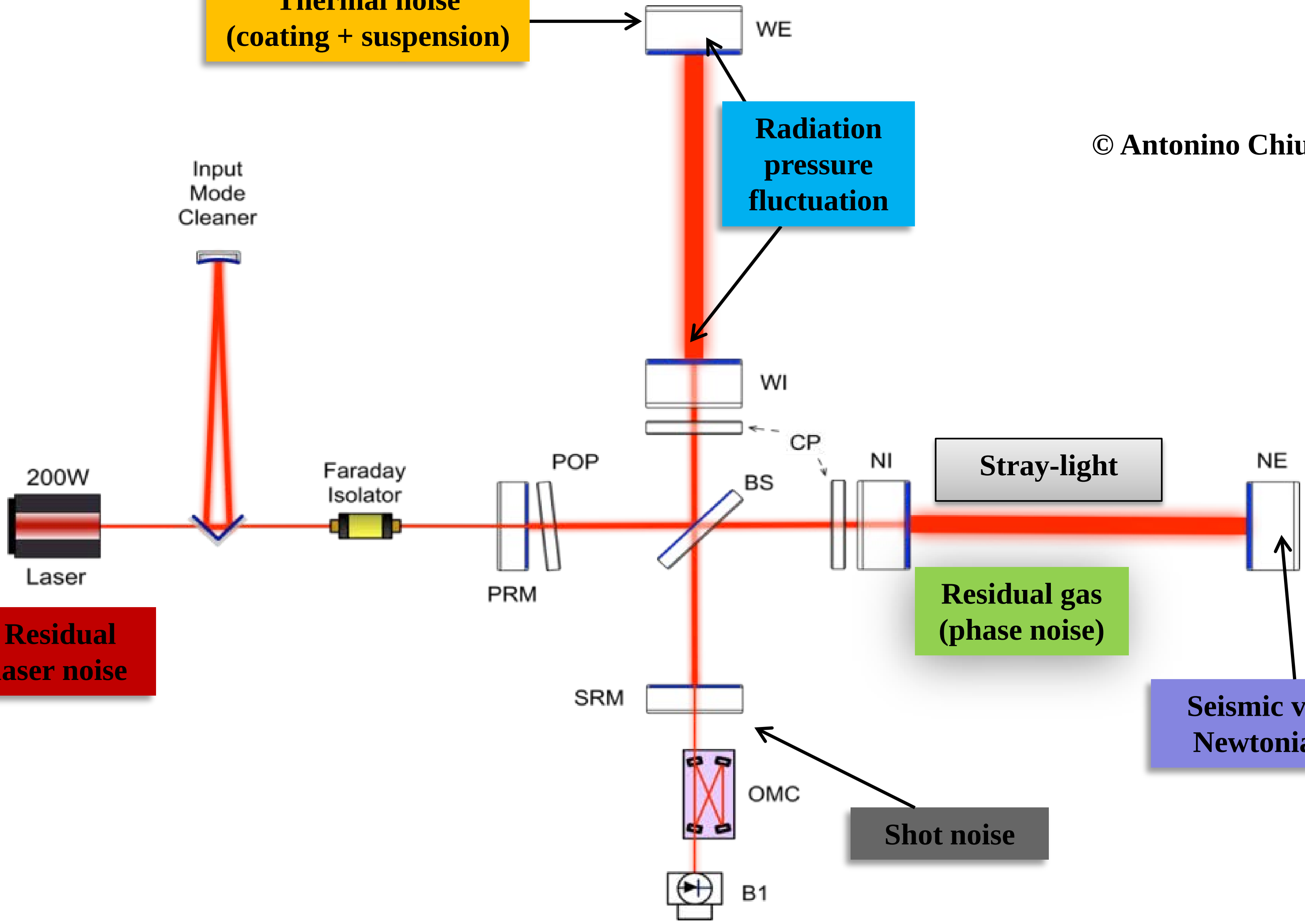
- Animation by Marco Kraan, NIKHEF
  - https://www.youtube.com/watch?v=6raomYII9P4



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 $[f_{min};f_{max}] = \sqrt{\int_{f_{min}}^{f_{fmax}} \mathrm{ASD}^2(f)\,df}$

Main interferometer noises



Thermal noise (coating + suspension)

Radiation pressure fluctuation

© Antonino Chiummo

Stray-light

Residual laser noise

Residual gas (phase noise)

Seismic vibration Newtonian noise

Shot noise

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

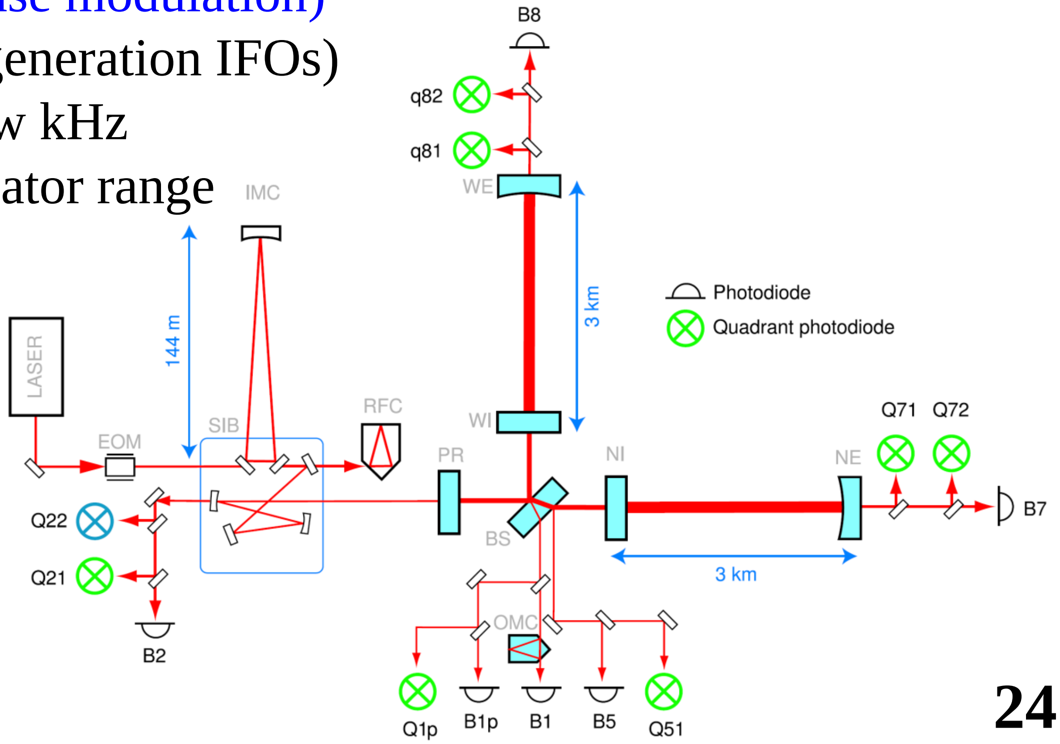
Free mirrors

↓

Local control

↓

Global control

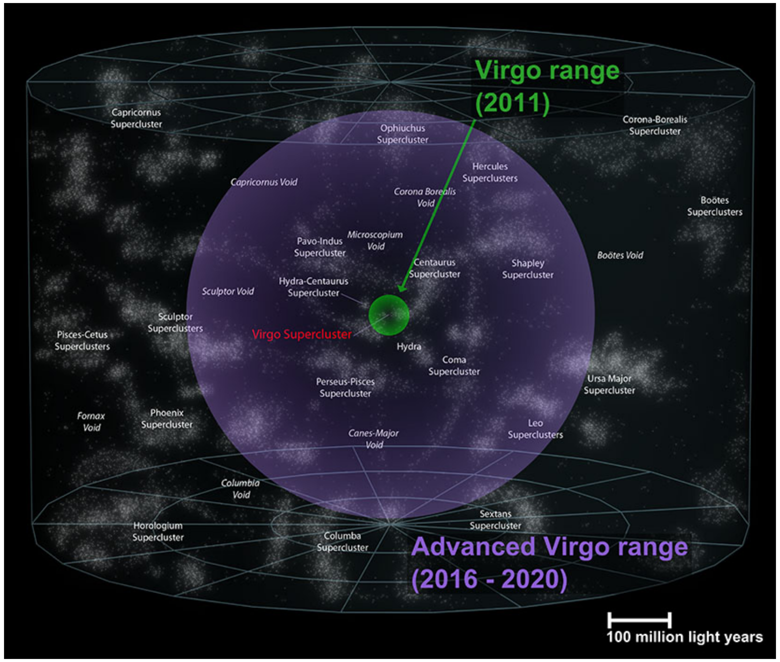


From initial to advanced detectors

- 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

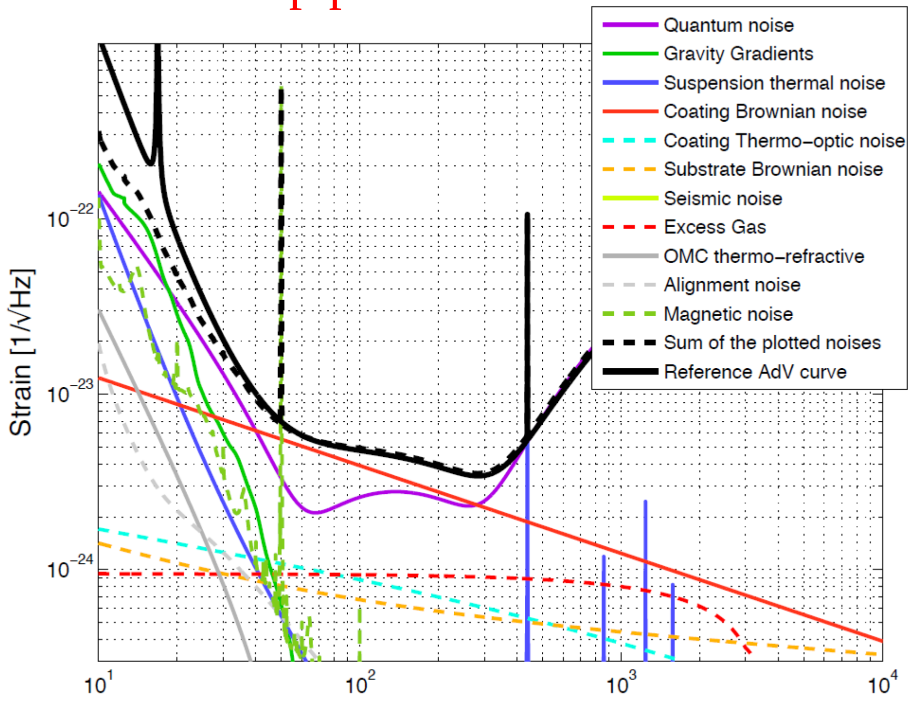


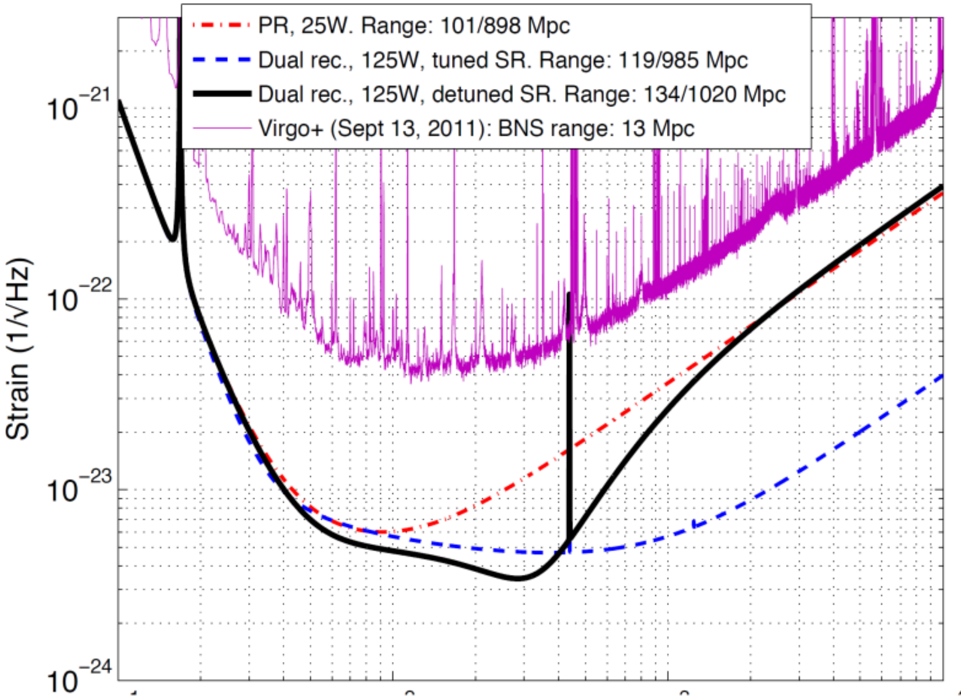
- Advanced LIGO (aLIGO) funded a year or so before Advanced Virgo (AdV)
  - Financial crisis in 2008-2010…

  → 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

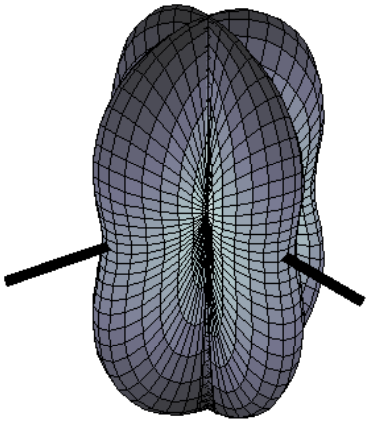
Interferometer angular response

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

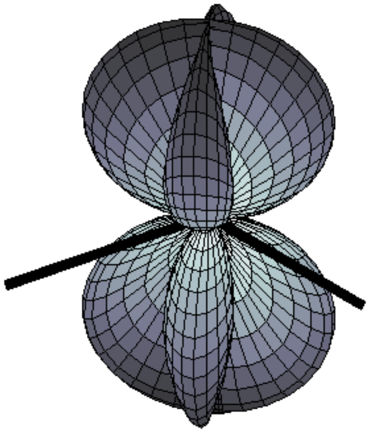
- The GW signal is a linear combination of its two polarisations

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

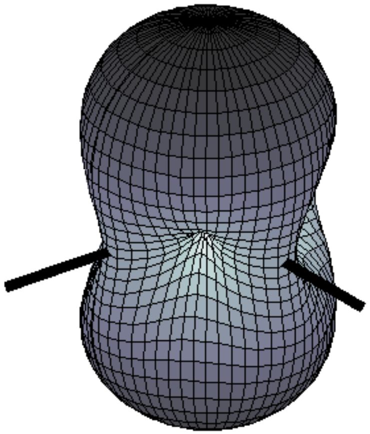
  - F_+ and $F_\times$ are antenna pattern functions which depend on the source direction in the sky w.r.t. the interferometer plane
    → Maximal when perpendicular to this plane
    → Blind spots along the arm bisector (and at 90 degres from it)



+ polarization



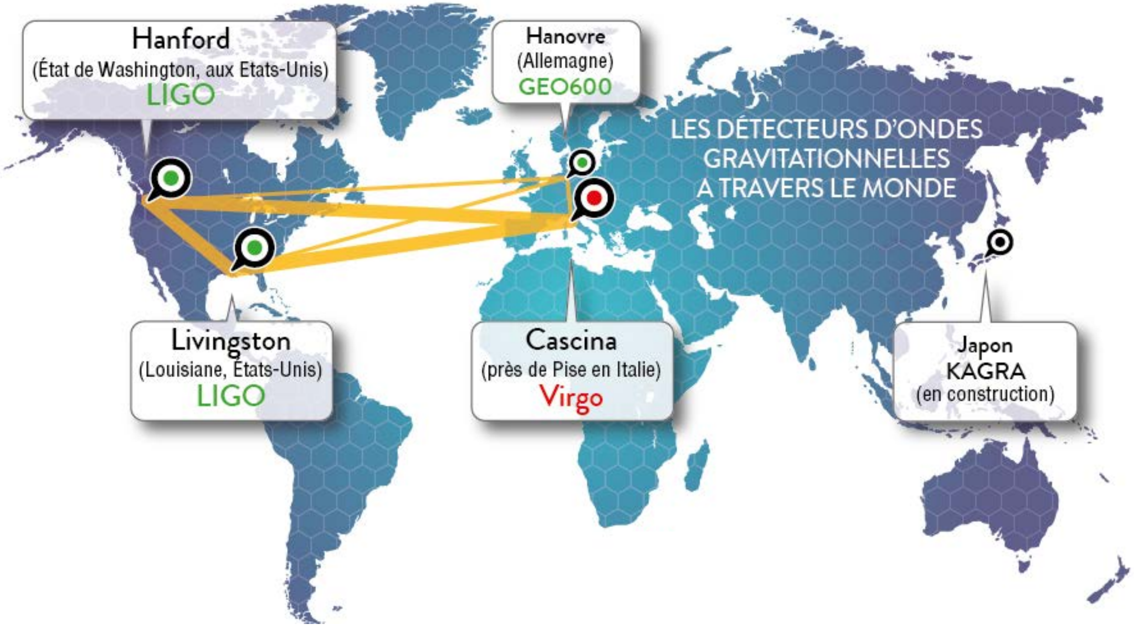
× polarization



unpolarized

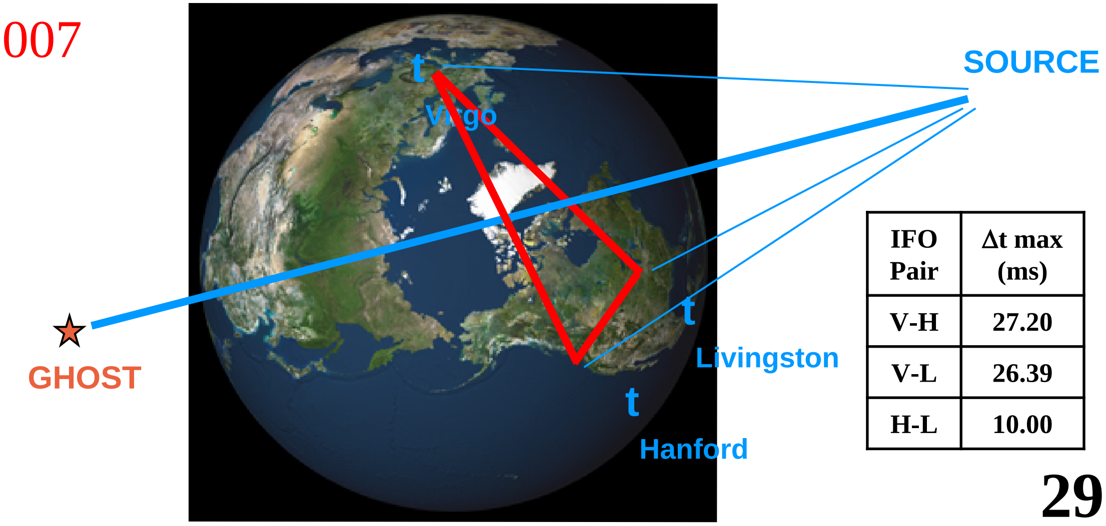
A network of interferometric detectors

- 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

A network of interferometric detectors


LIGO Hanford
Washington State, USA


LIGO Livingston
Louisiana, USA

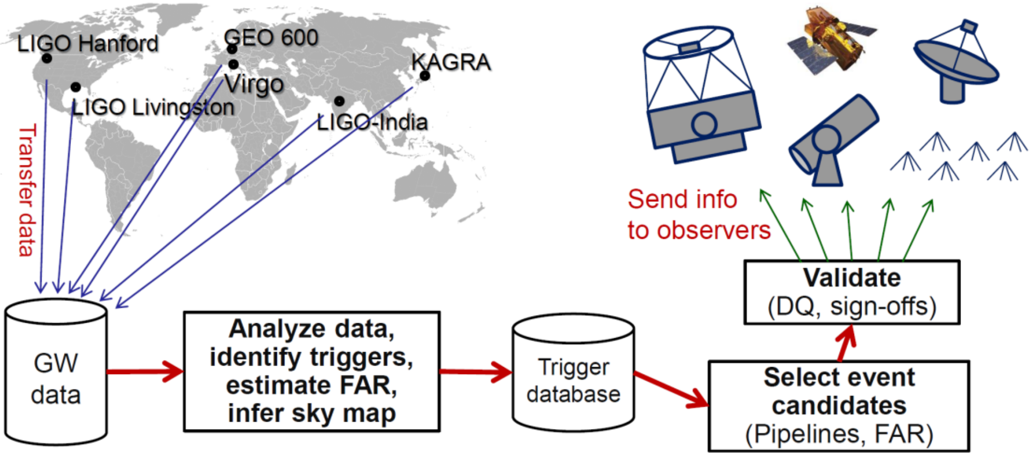

Virgo Cascina (near Pisa), Italy

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



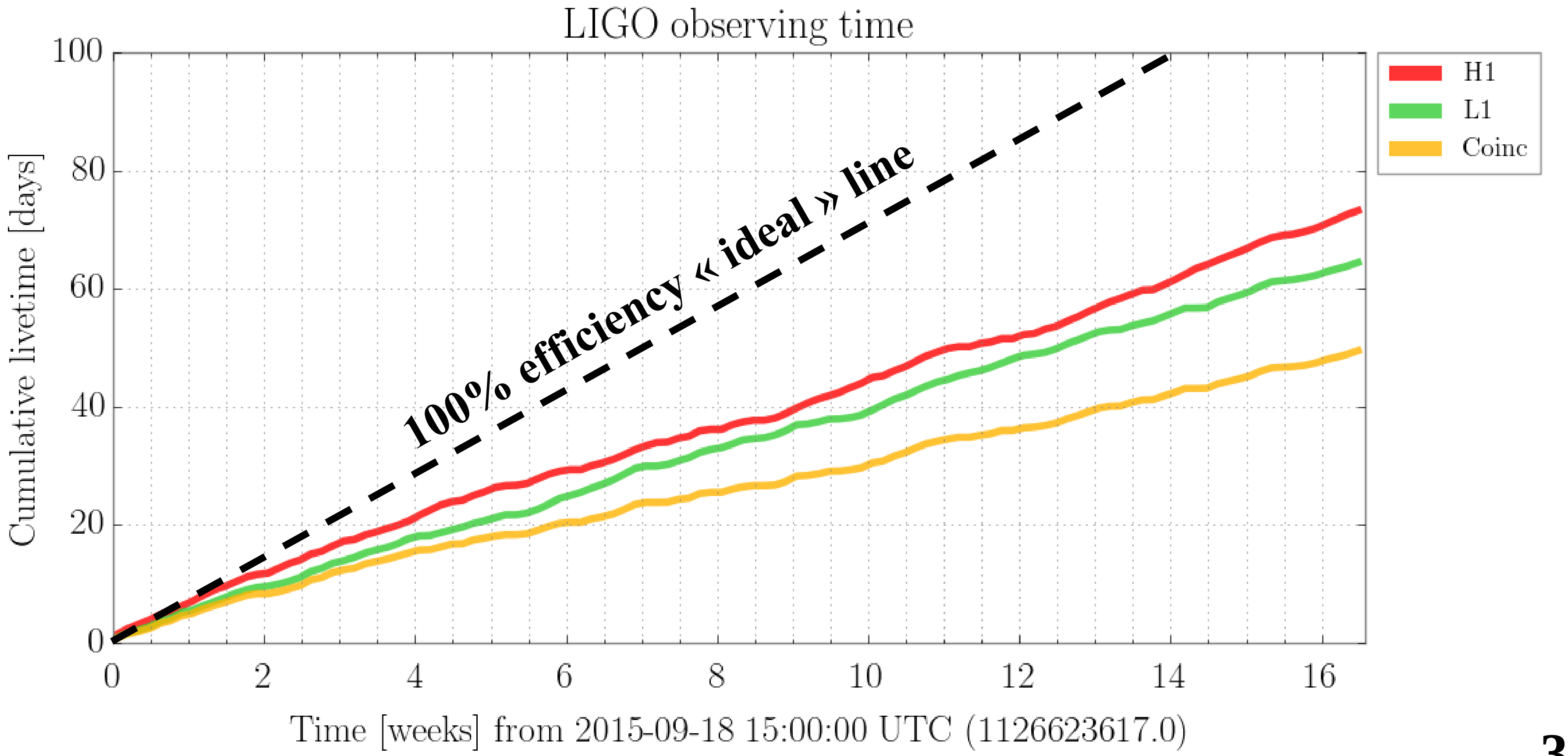
- Low latency h-reconstruction and data transfer between sites
  - Online GW searches for burst and compact binary coalescences

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 »

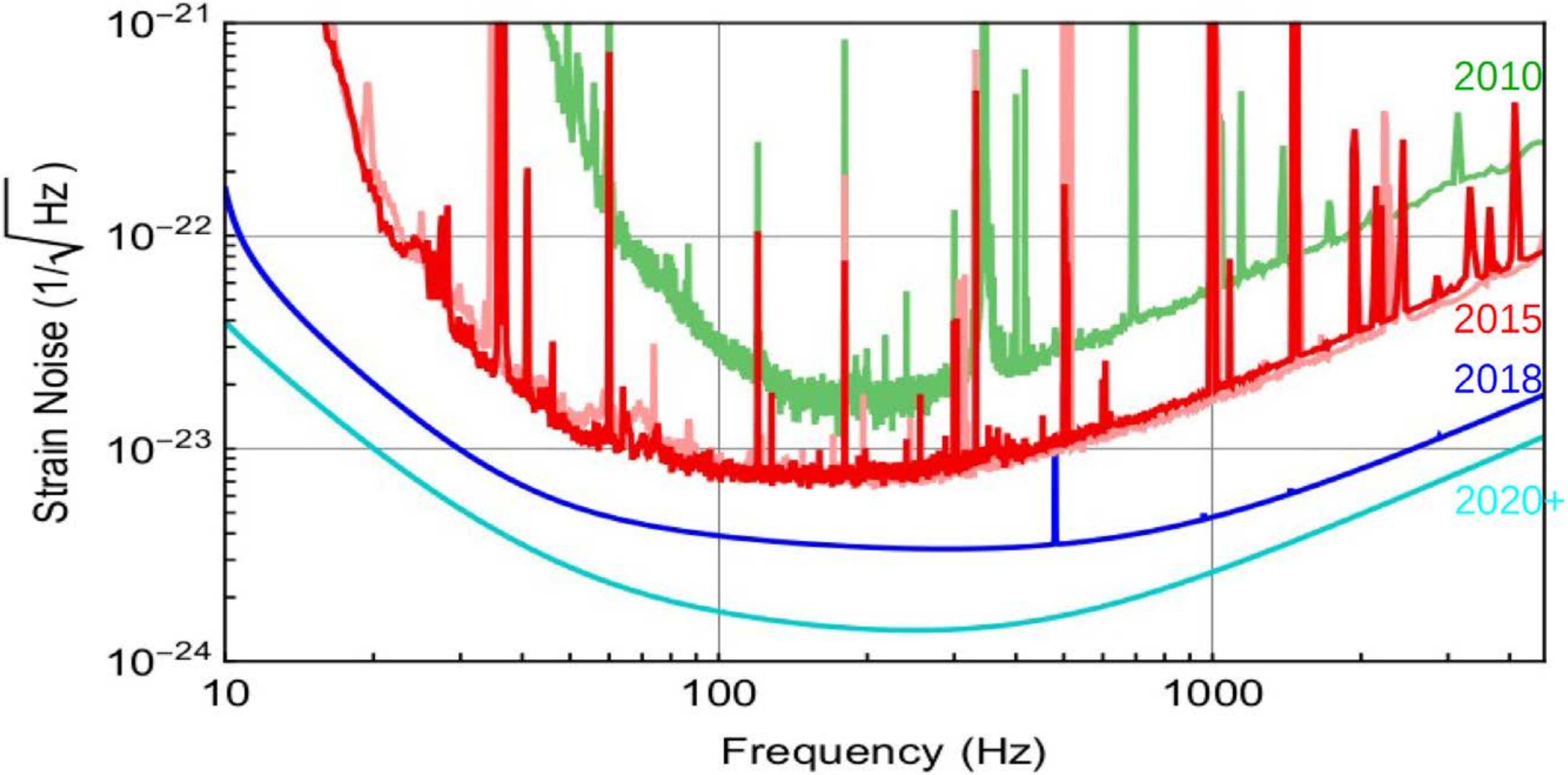
→ Both interferometers were already working nominally



aLIGO O1 Run: Sensitivity

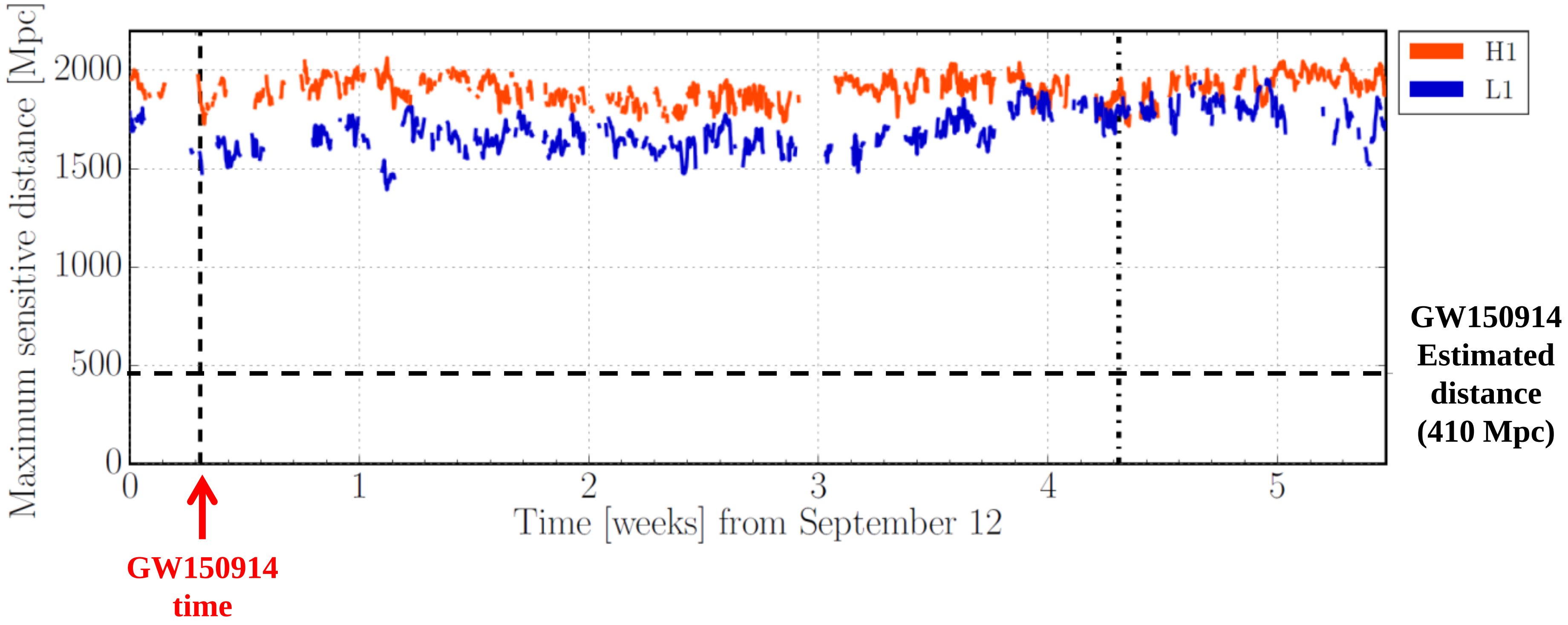
- Sensitiviy much improved with respect to the initial detectors
  - Factor 3-4 in strain

    → 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



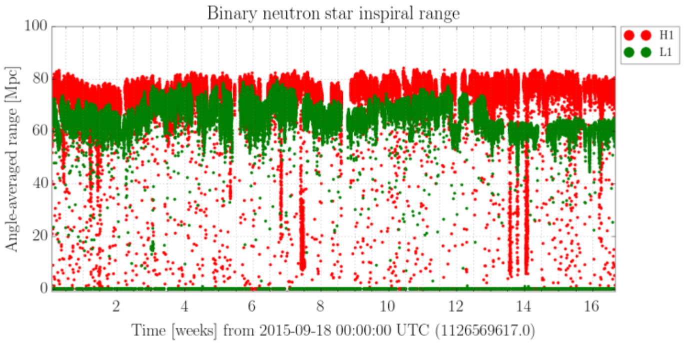
GW150914 Estimated distance (410 Mpc)

GW150914 time

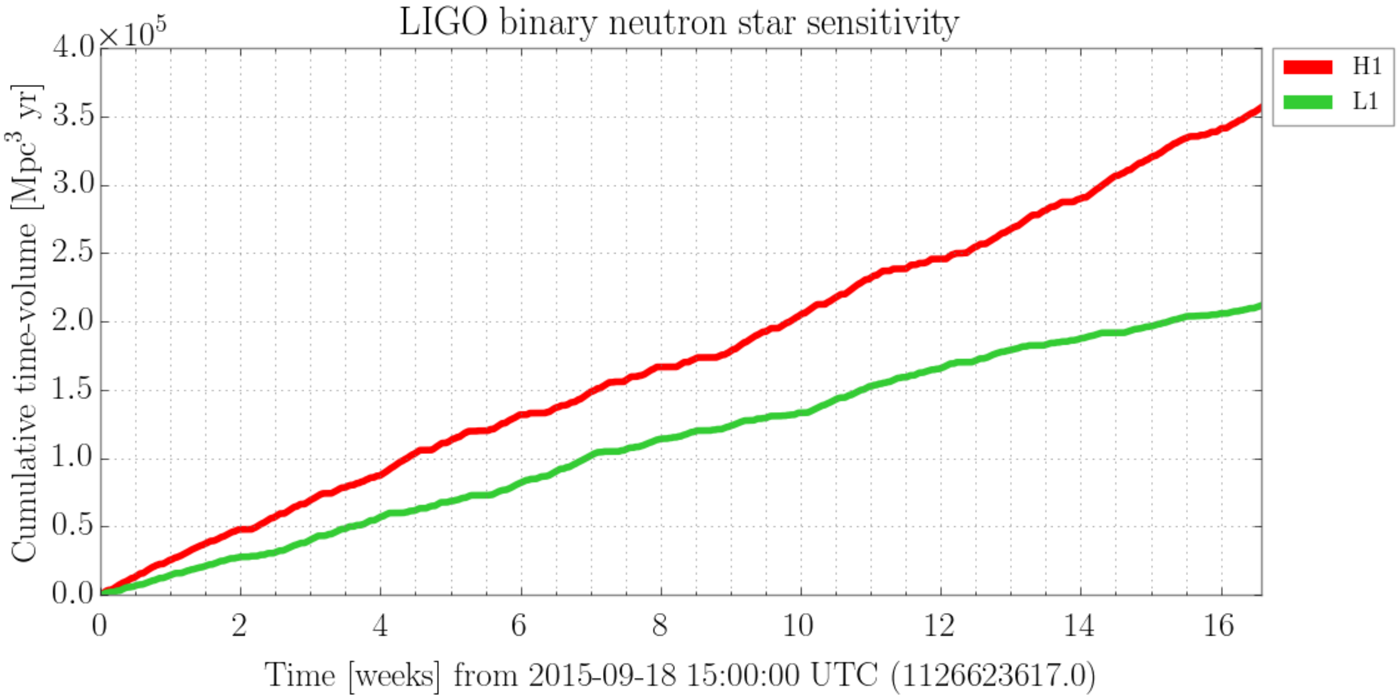
- Only depends on the actual sensitivity of the interferometer
  - Online monitoring tool used during data taking

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

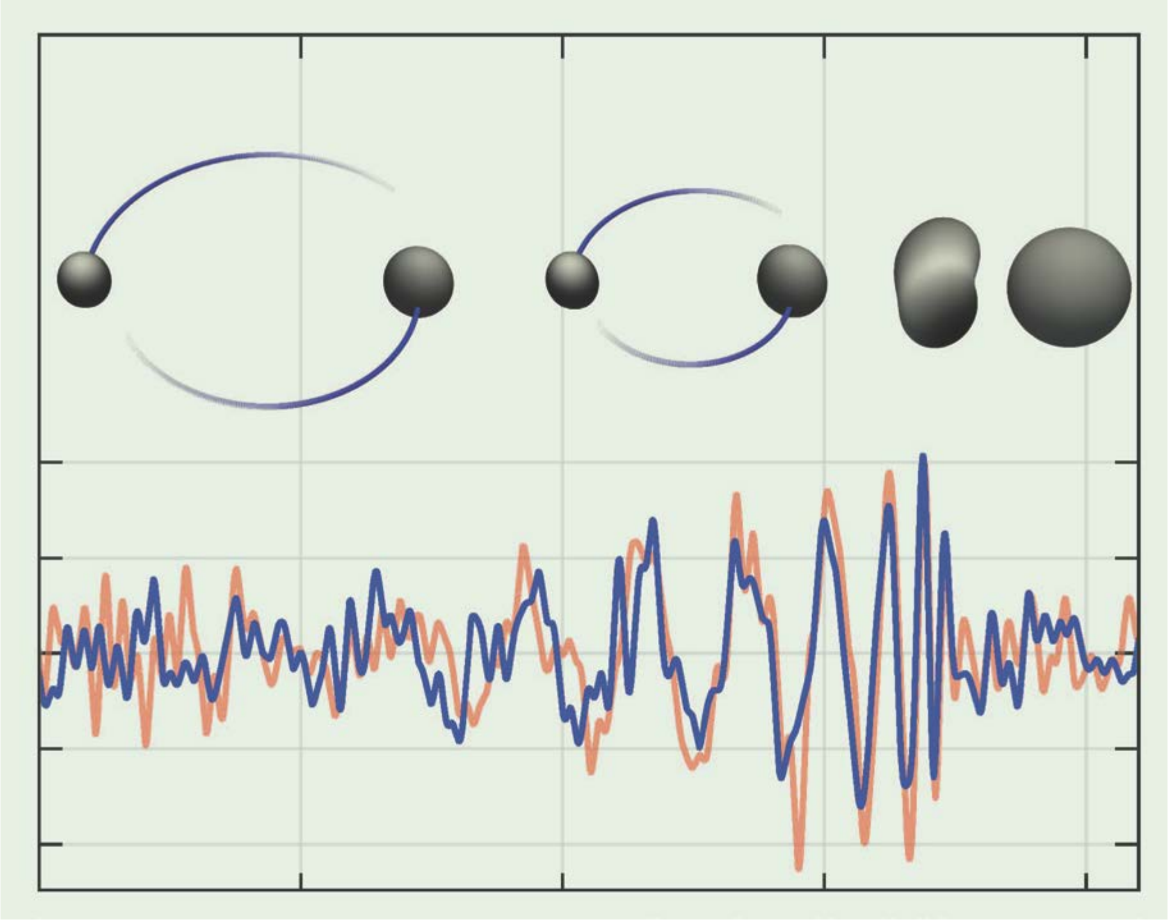


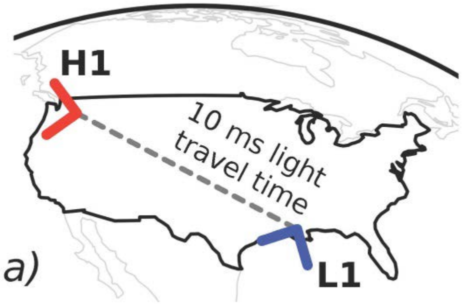
GW150914

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

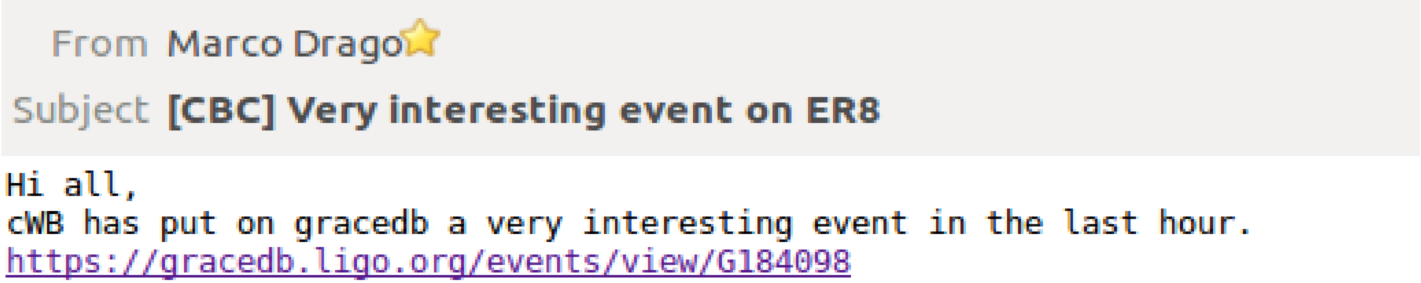
- Extract all possible science from this first/ unique (so far) event

- 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**

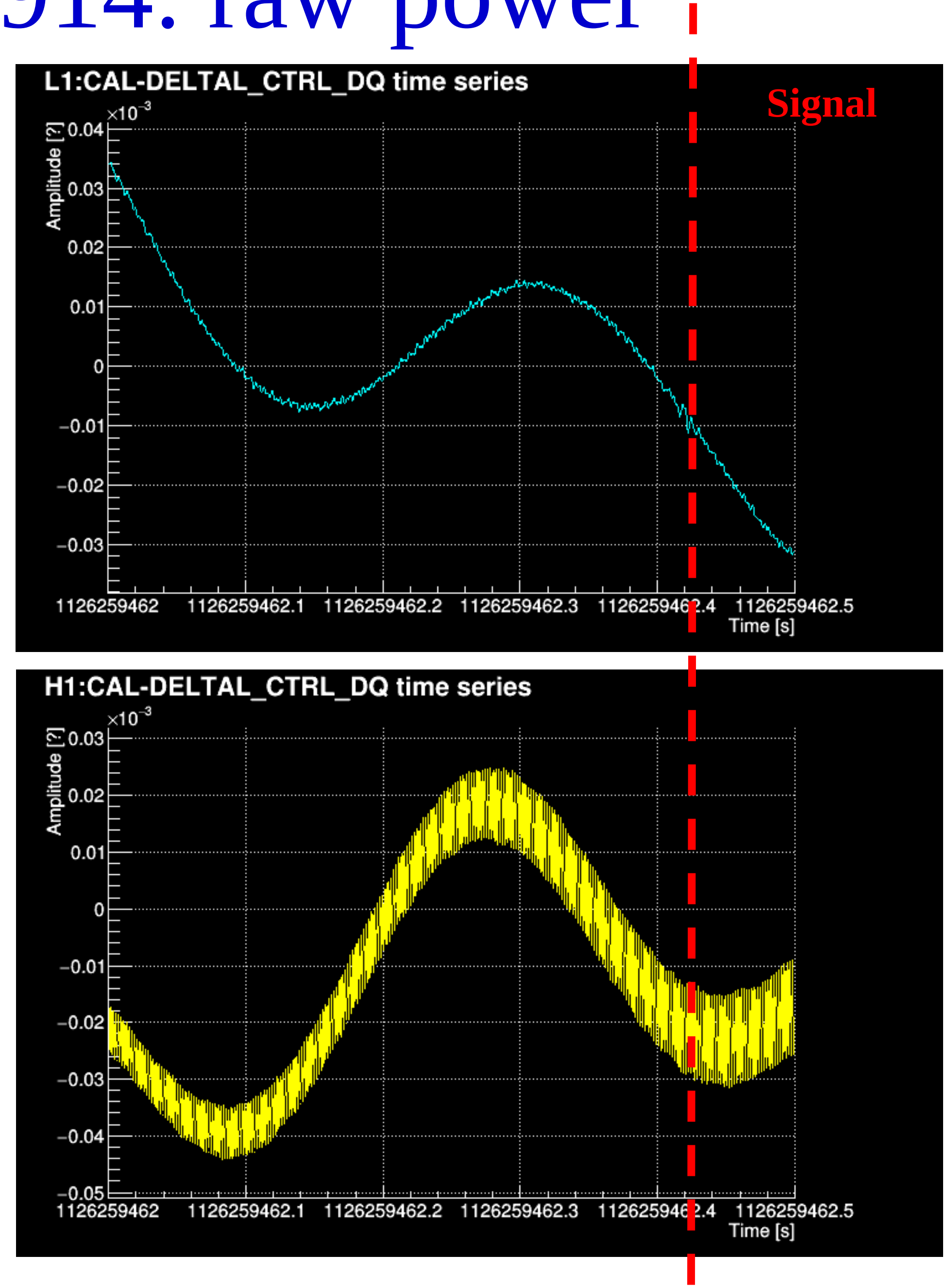
Subject **[CBC] Very interesting event on ER8**

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

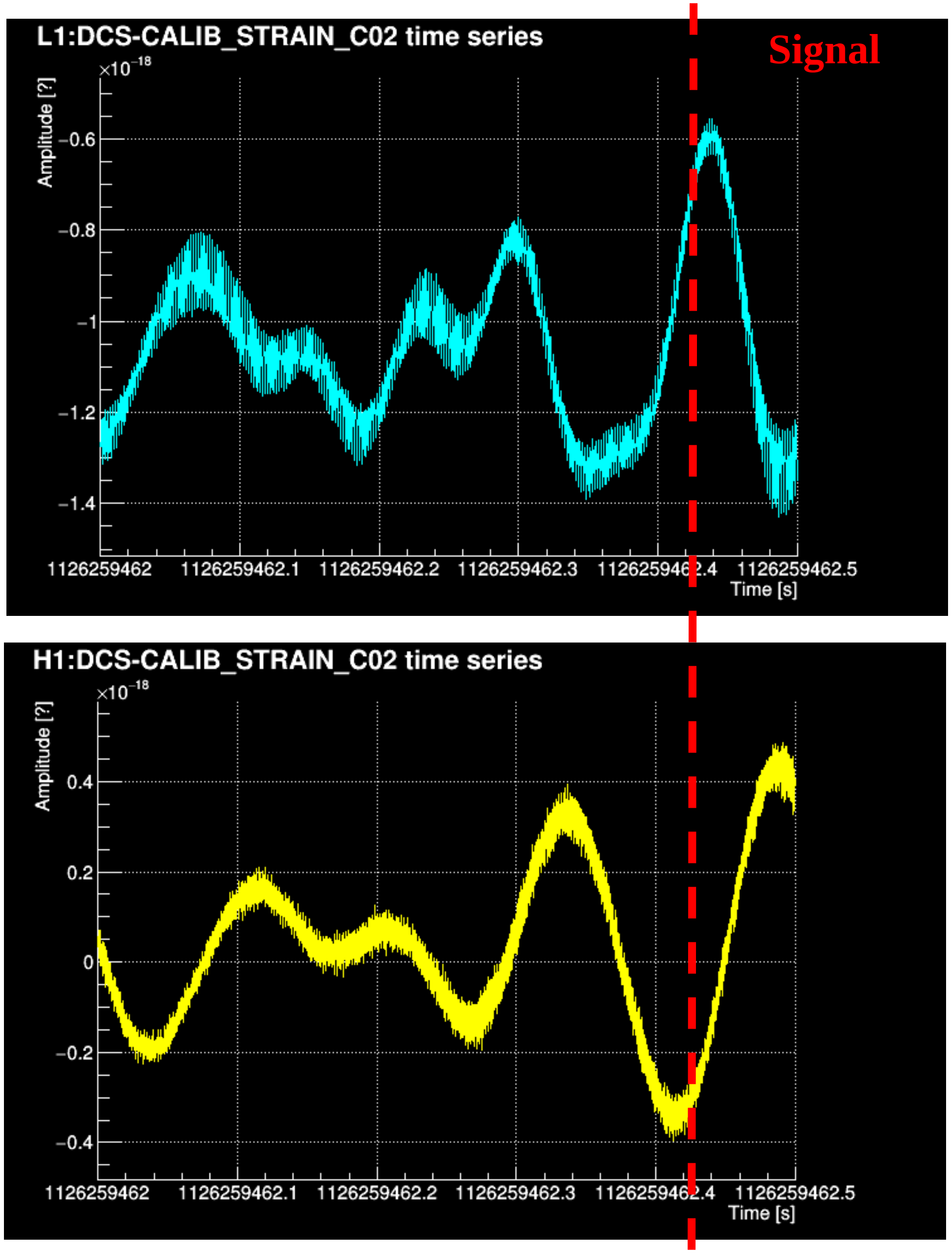
GW150914: raw power

- Blue: aLIGO Livingston
  Yellow: aLIGO Hanford



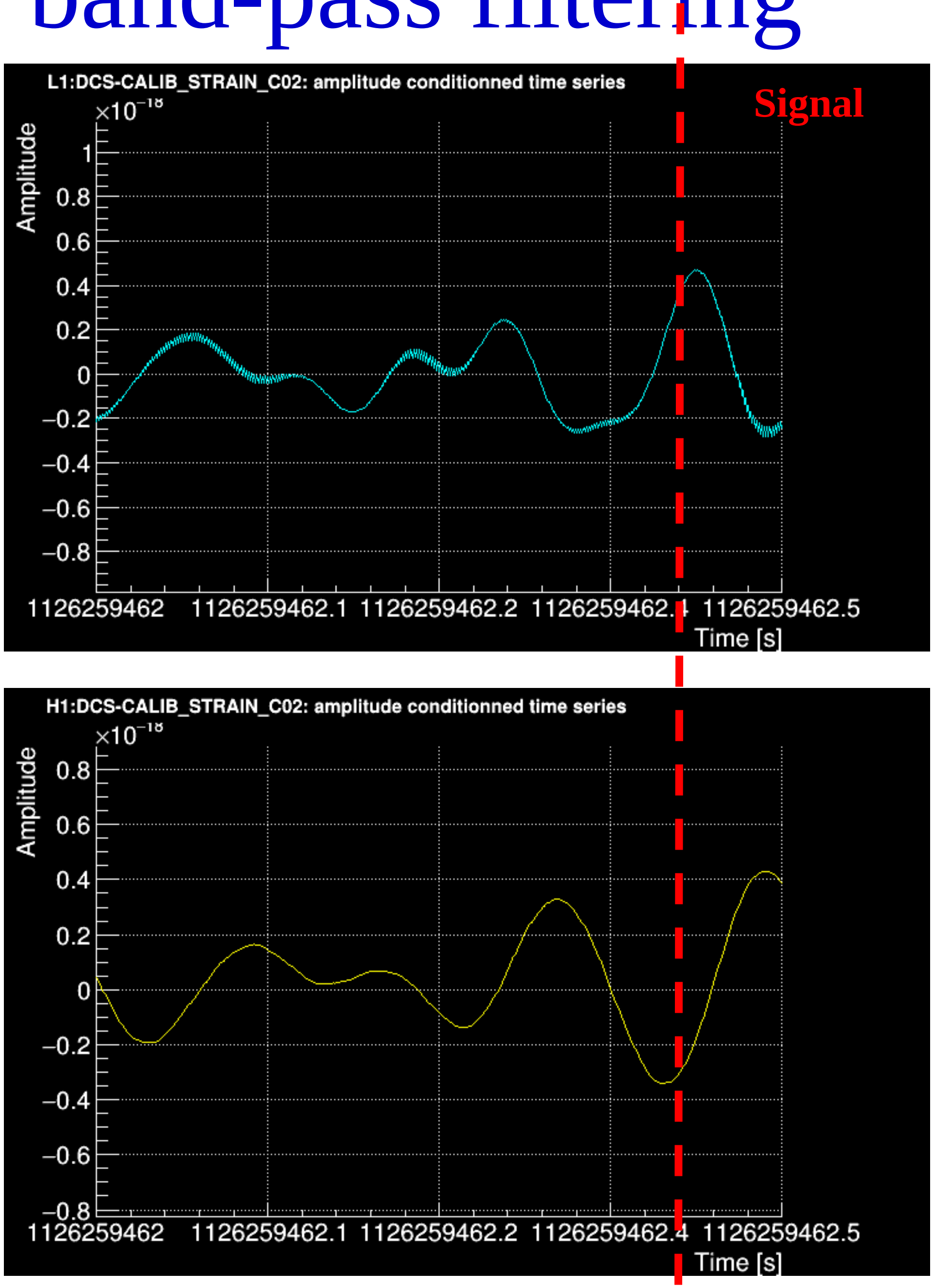
GW150914: calibrated h(t)

- Control signals used to recover the strain signal



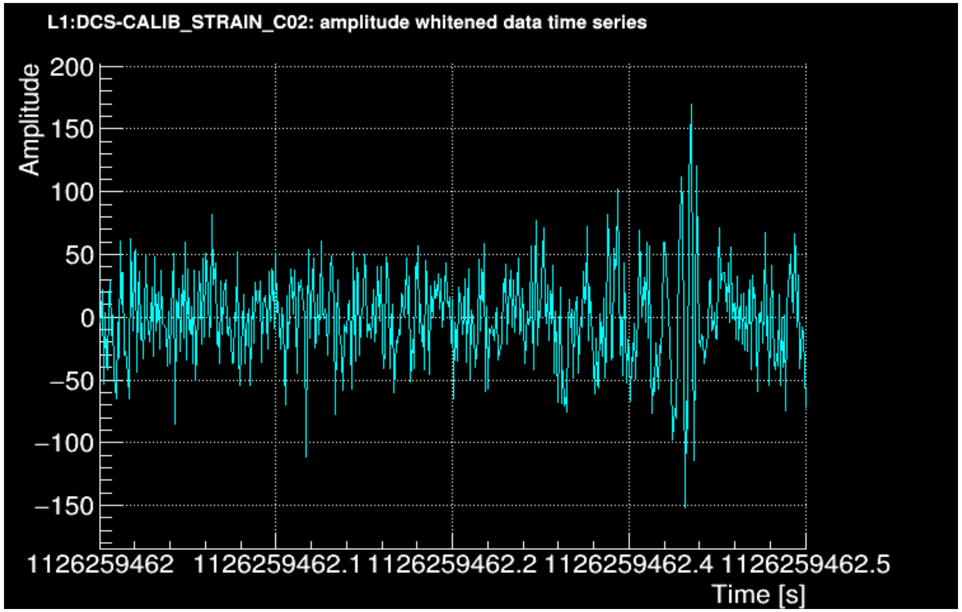
GW150914: band-pass filtering

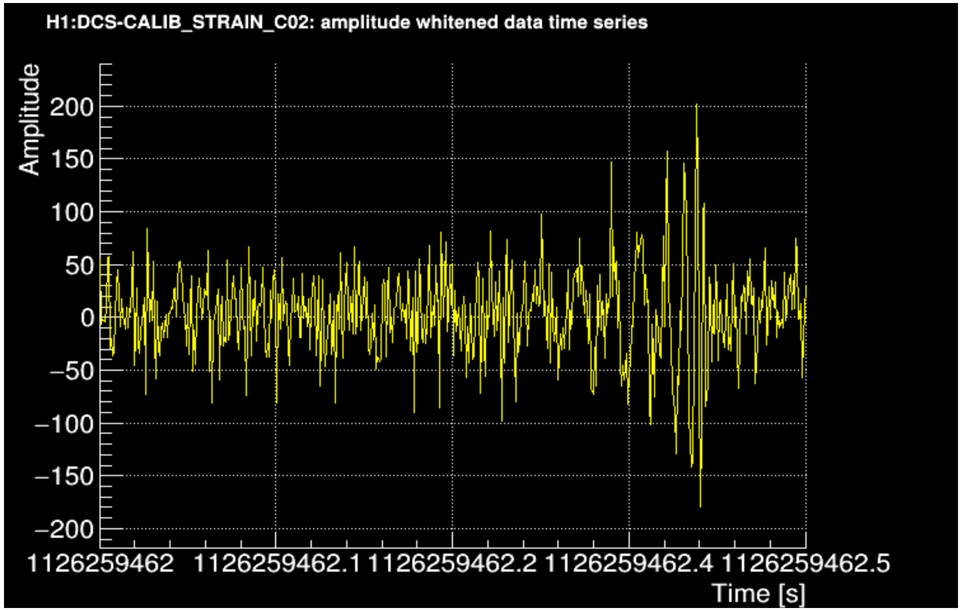
- 20 Hz → 500 Hz



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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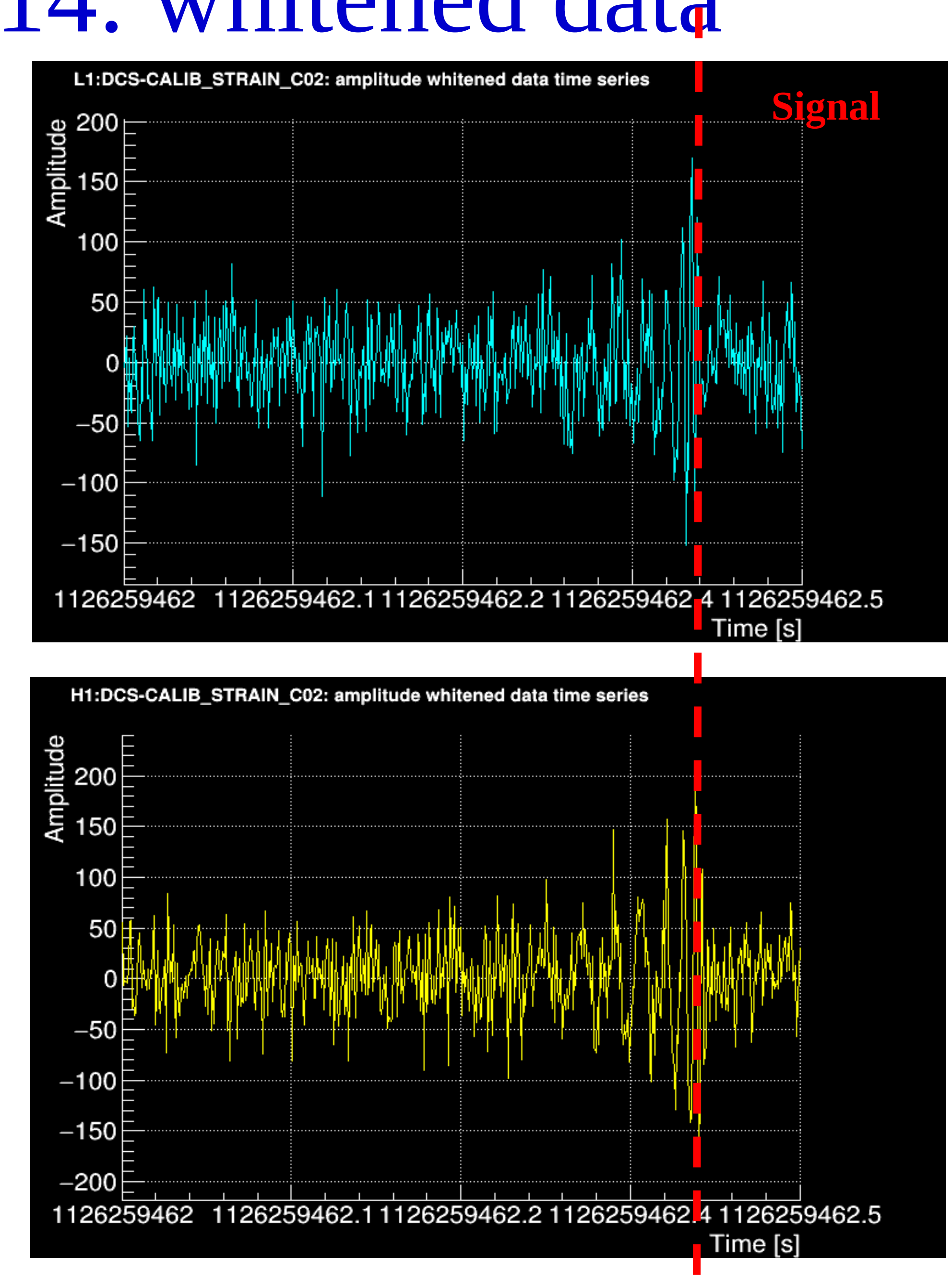

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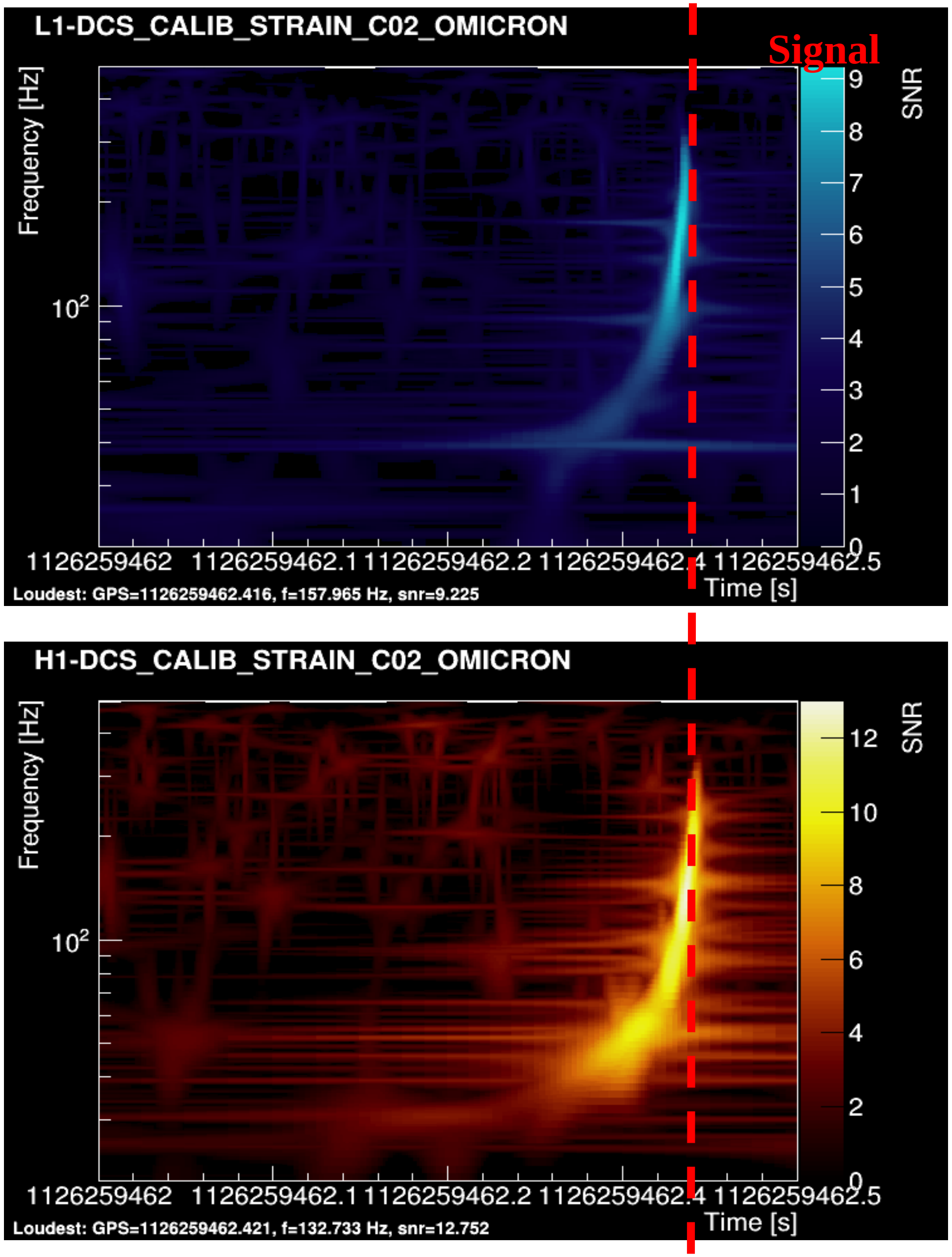
GW150914: spectrograms

- Time-frequency maps



Compact binary coalescence search

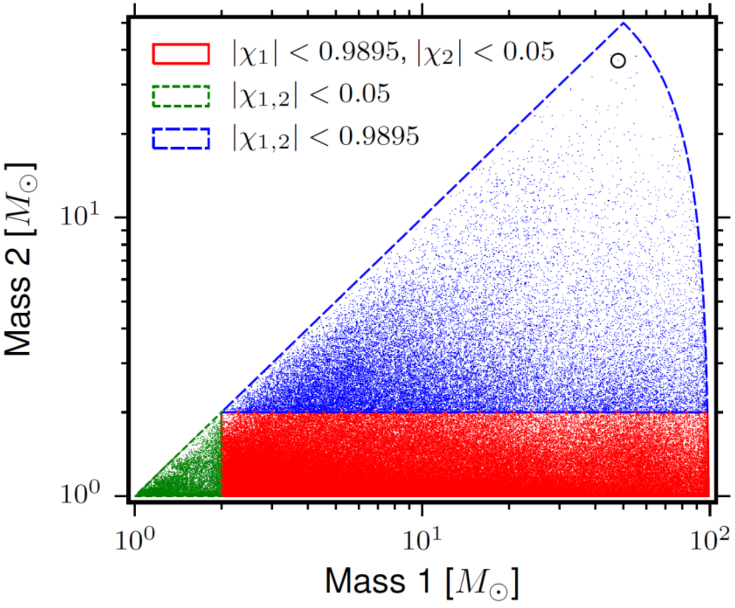
- Well-predicted waveform
  → Matched-filtering technique (optimal)
  - Noise-weighted cross-correlation of data with a template (expected signal)
- Parameter space covered by a template bank
  - Analytical for NS-NS, BH-NS
  - Analytical + numerical for BH-BH
  - Parameters: mass and spin of the initial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

FT of the data

Signal template

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

Noise power spectral density



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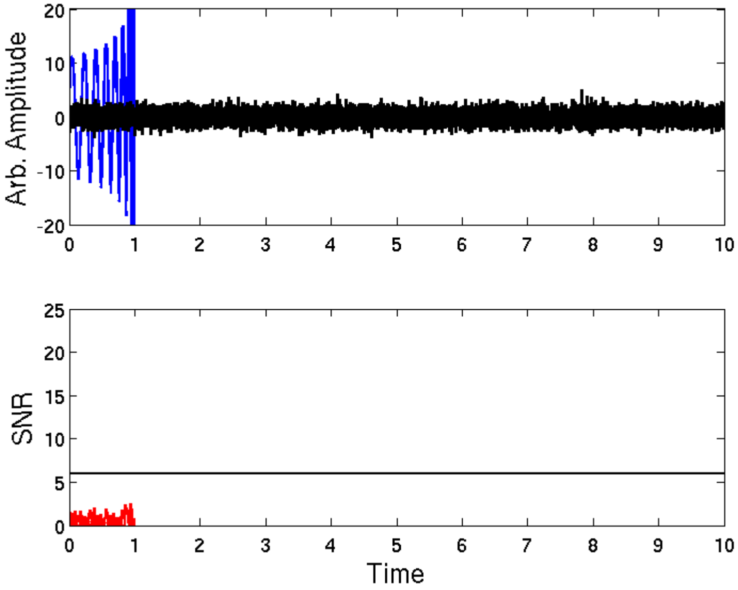

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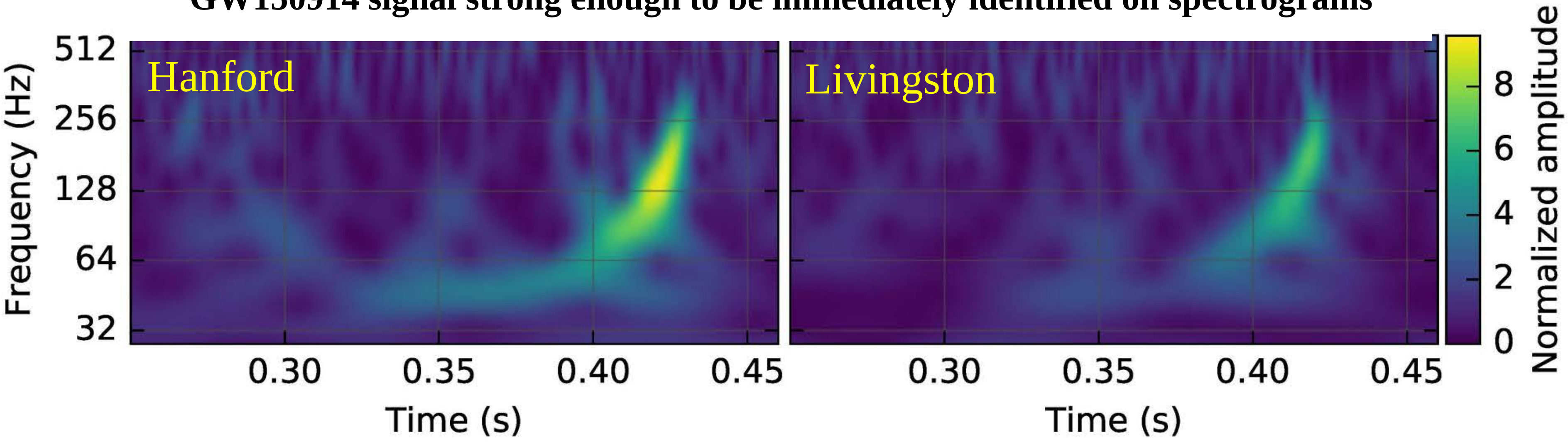
  - Part of the parameter space searched online
  - Two independent offline pipelines

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

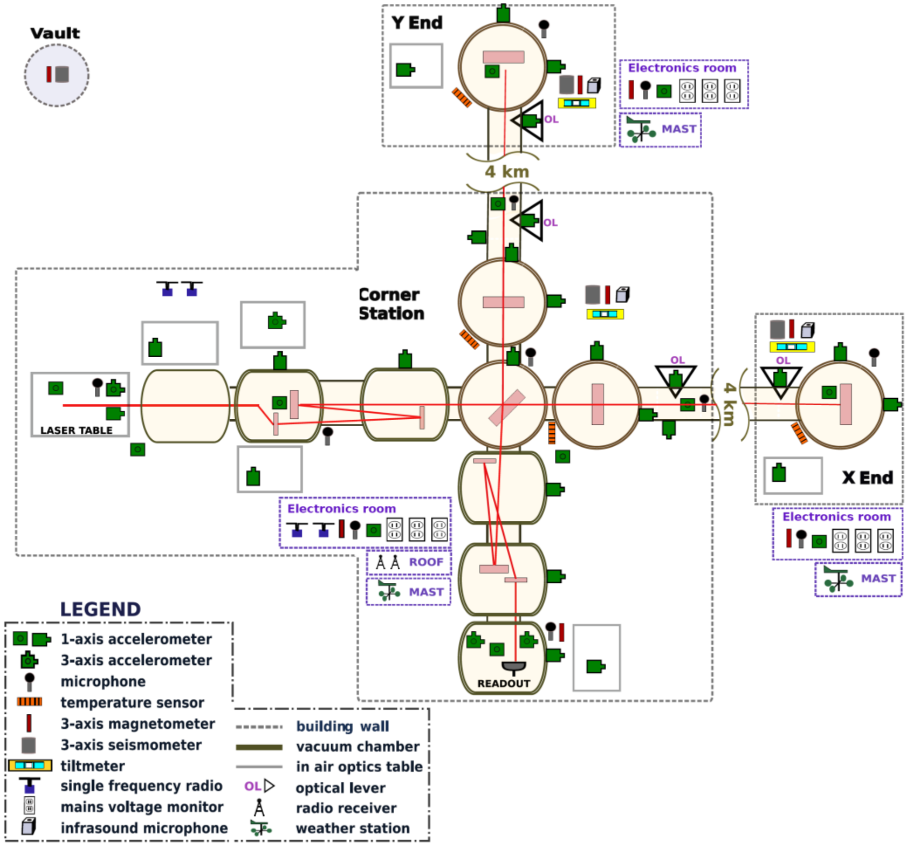
- Efficiency similar to (optimal) matched filtering for binary black hole – short signal
  - Online last September for O1

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

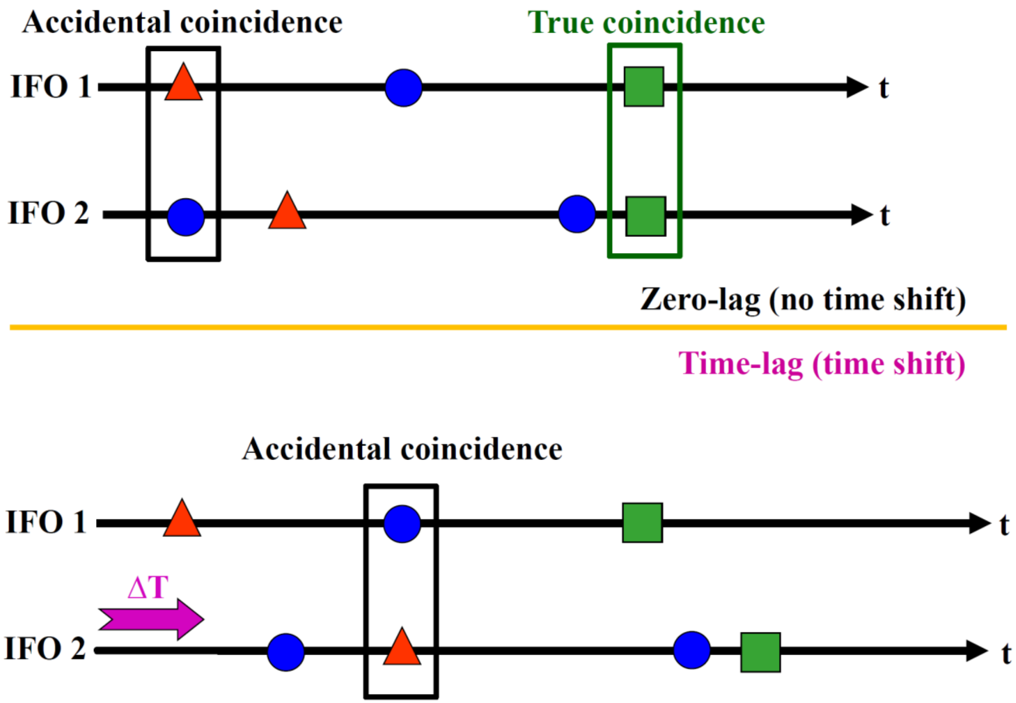


- Extensive studies performed
  - Uncorrelated and correlated noises
  - Bad data quality periods identified and vetoed

→ 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!



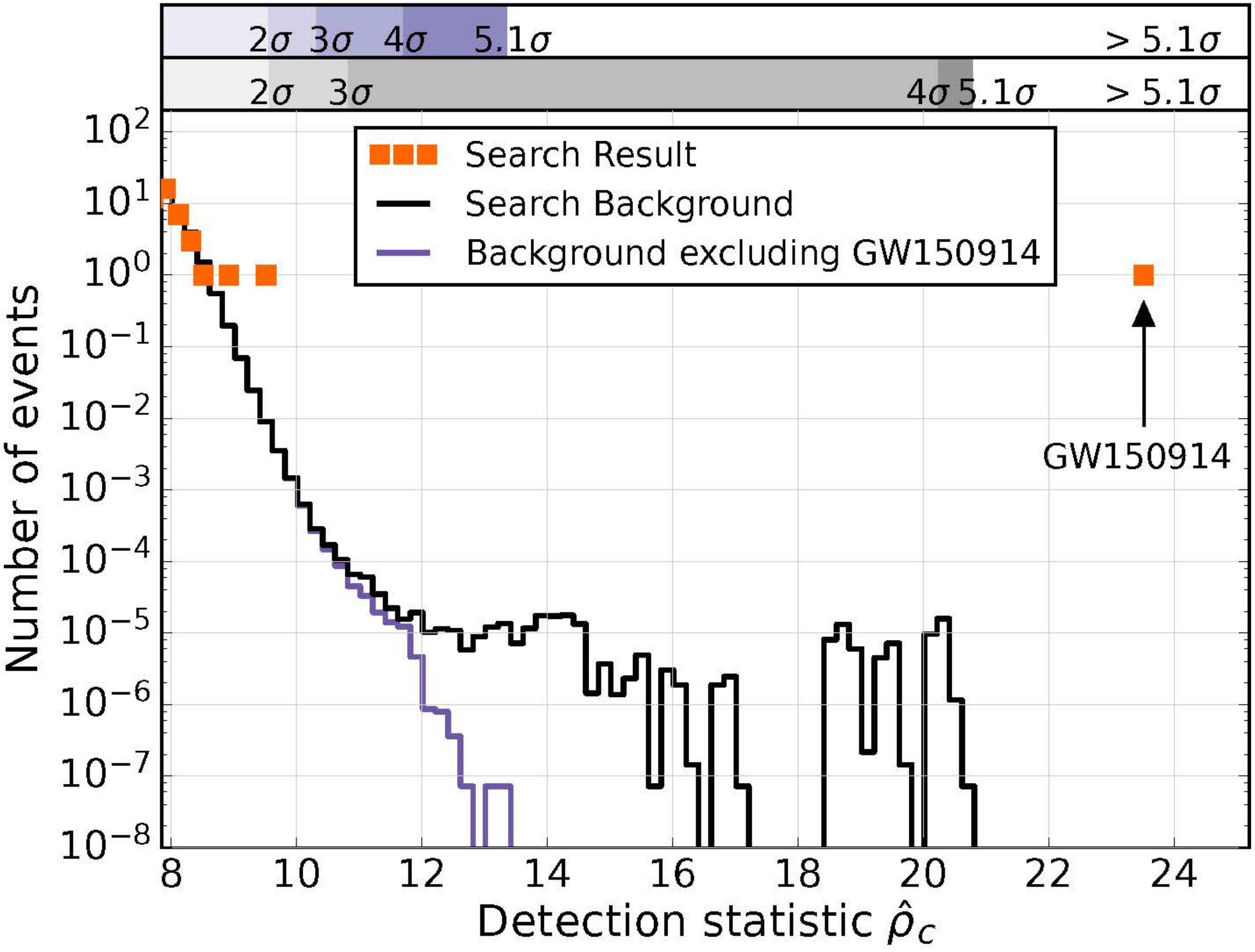
- Input: 16 days of coincidence data
  → Time shift method to generate a much larger background dataset
- Reminder: real GW events are shifted by 10 ms at most between IFOs
  - Light travel time over 3,000 km
- By shifting one IFO datastream by a (much) larger time, one gets new datastreams in which « 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**

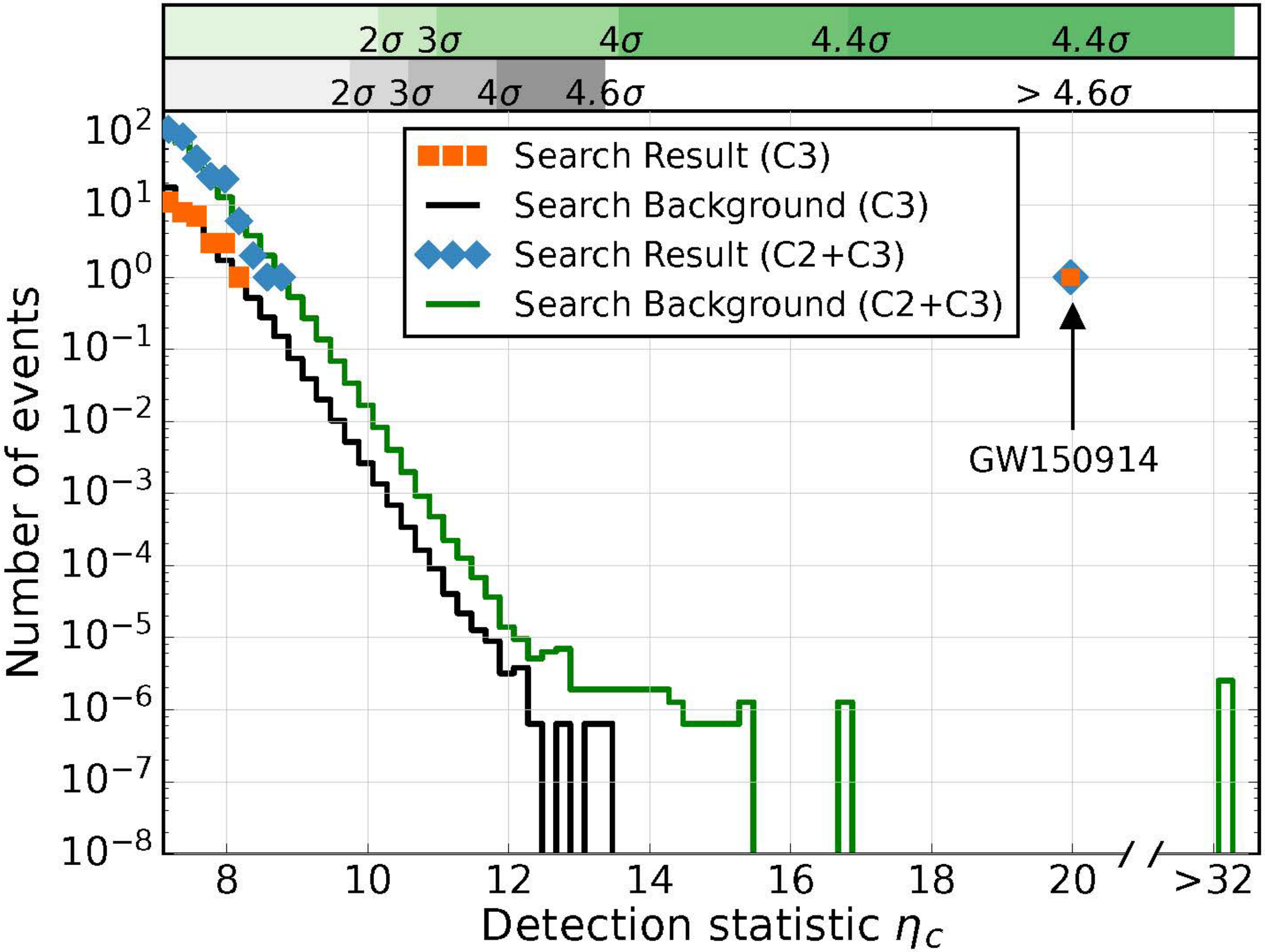
- Solid lines: 2 background estimations (from time-lag)



- SNR ~ 23.6; false alarm rate < 1 event / 203,000 years
  false alarm probability $< 2\times10^{-7}$ (> 5.1 σ)

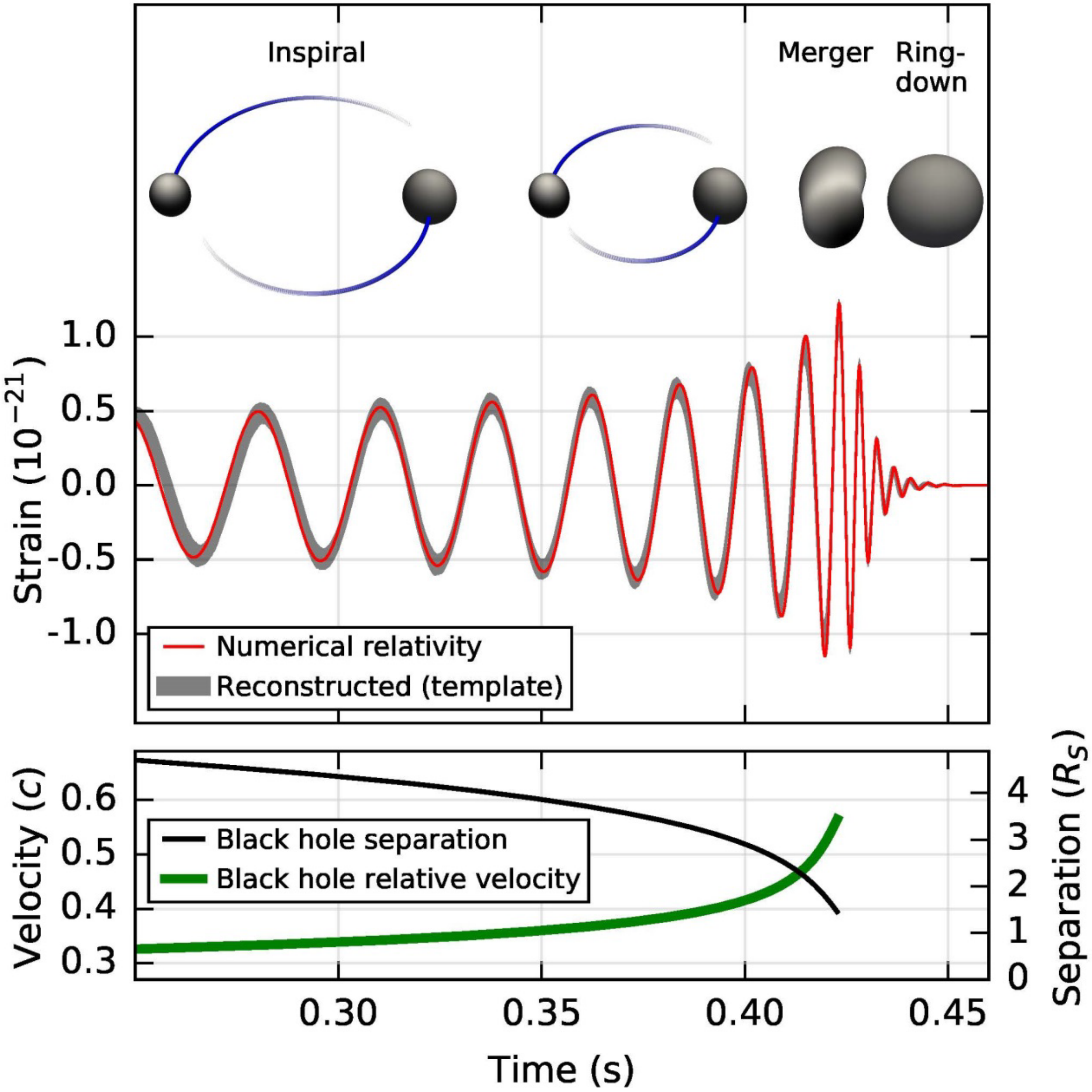
Signal significance – Burst analysis

- Similar plot



- False alarm rate < 1 event / 67,400 years
  False alarm probability $< 2\times10^{-6}$ (> 4.6 σ)

Why two black holes?

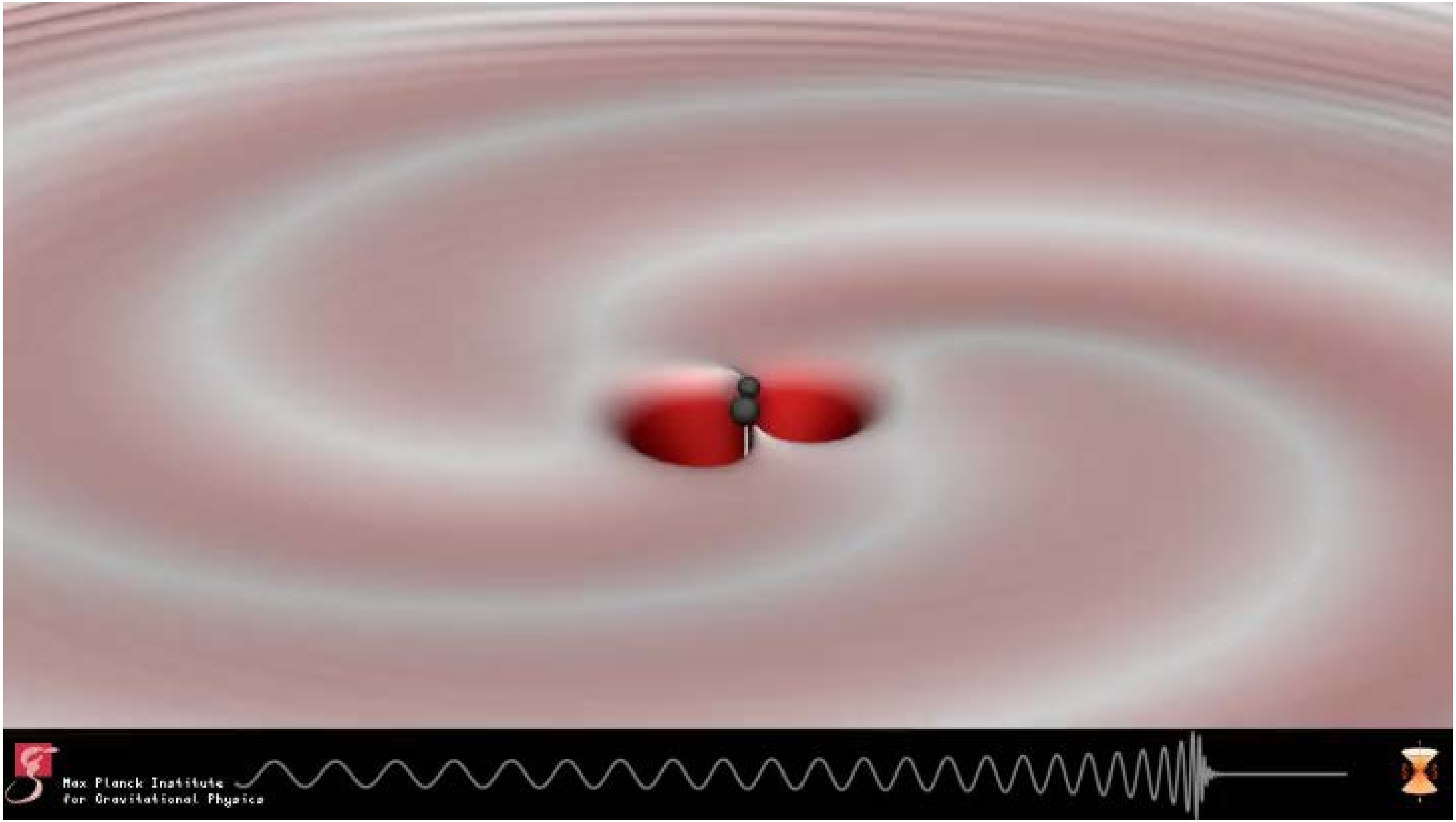


- Result of matched filtering!
  - Excellent match between the best template and the measured signal
- Two massive compact objects orbiting around each other at 75 Hz (half the GW frequency), hence at relativistic speed, and getting very close before the merging: only a few R_S away!

→ 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

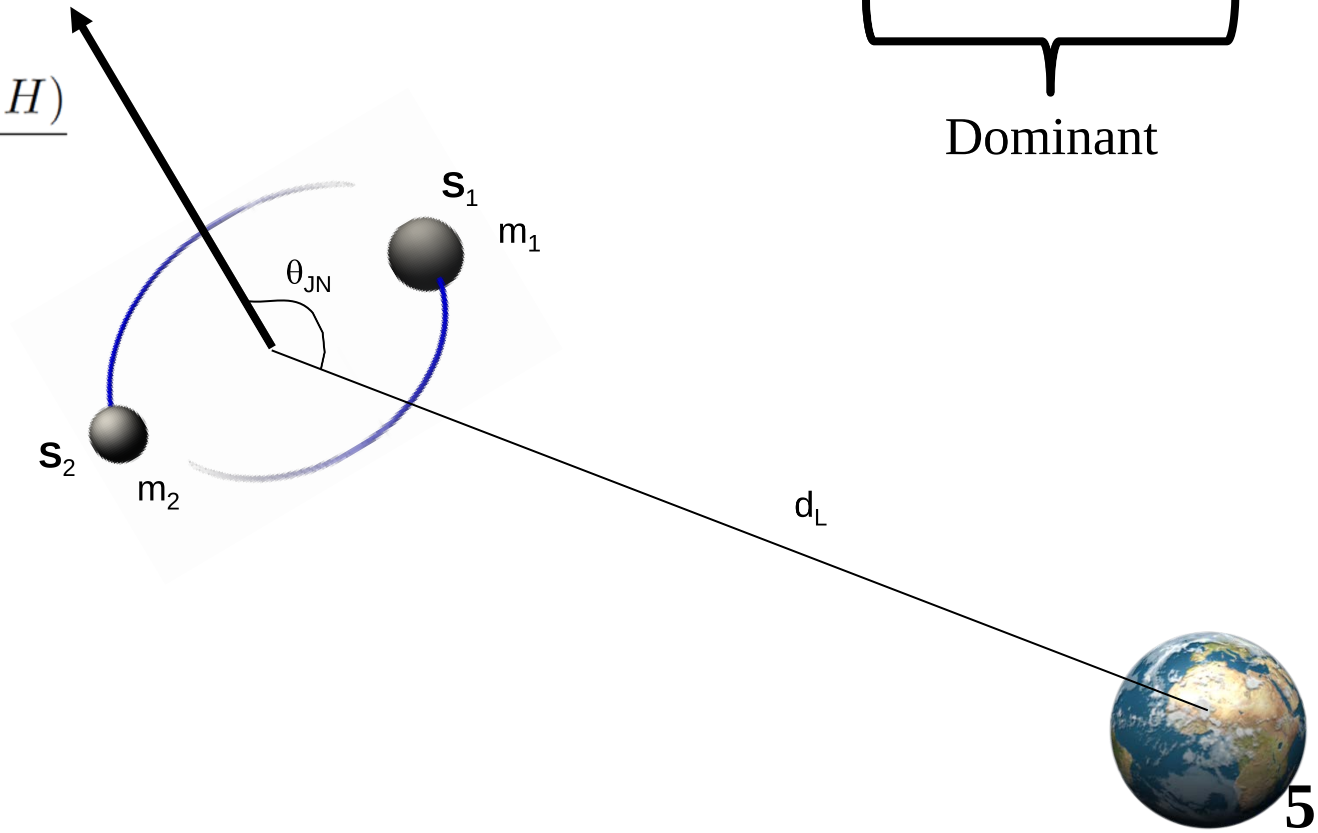
Simulation of the coalescence



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 + $\underbrace{\text{statistical errors}}_{\text{Dominant}}$



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

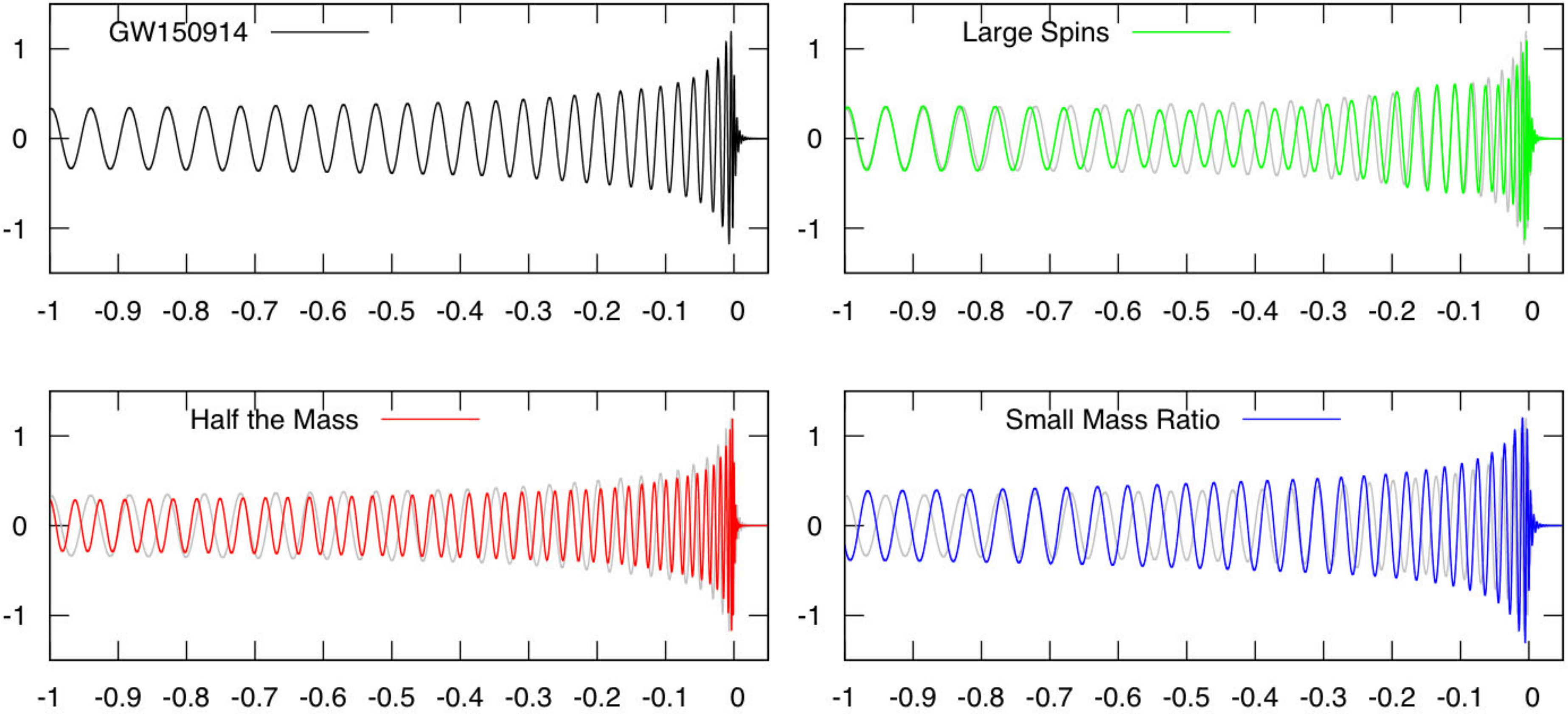
- θ: Parameters
- d: Data
- H: Model

- Compare results from two models → Systematic errors

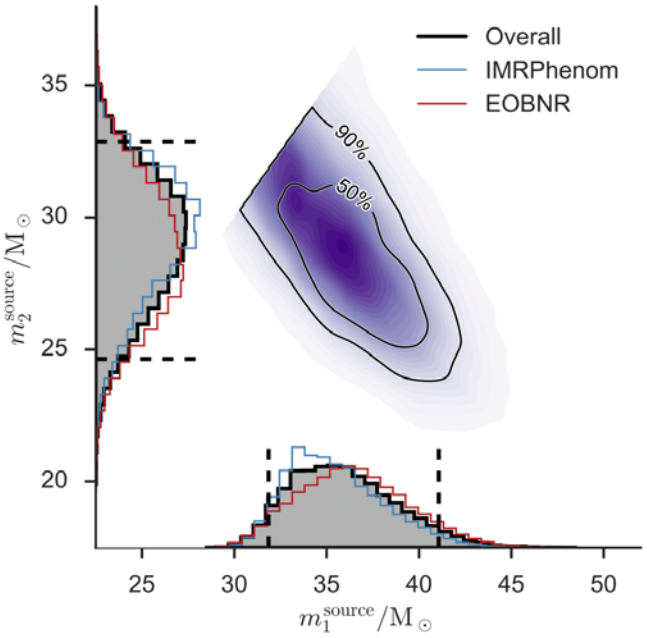
$$O_{ij} = \frac{P(H_i|d)}{P(H_j|d)}$$

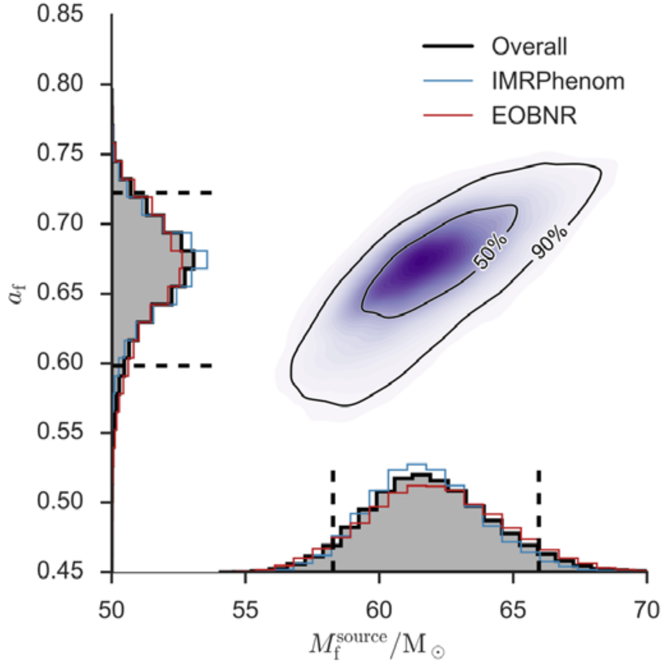
Parameter estimation

- Impact of the black hole parameters on the waveform



Main results





Individual masses

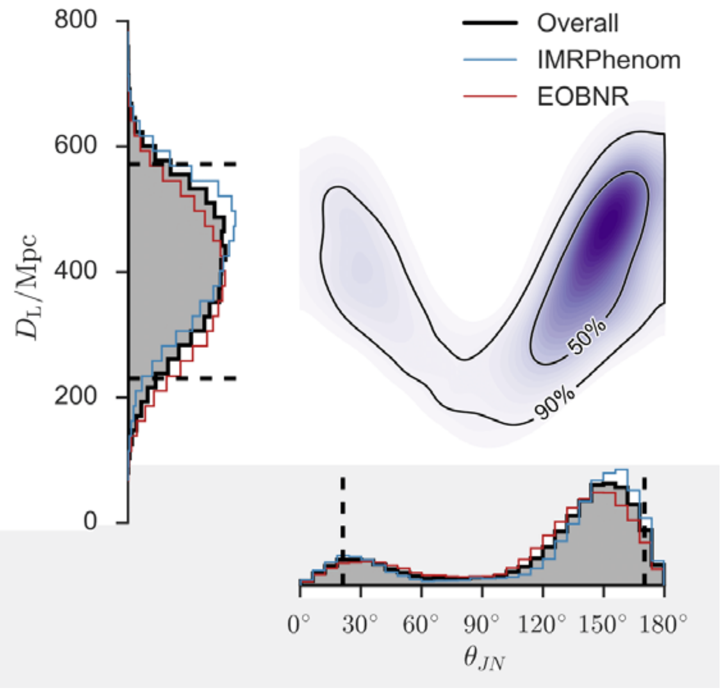
$m_1 = 36^{+5}_{-4}\, M_\odot$
$m_2 = 29^{+4}_{-4}\, M_\odot$

Final BH mass and spin

$M_\mathrm{f} = 62^{+4}_{-4}\, M_\odot$
$a_\mathrm{f} = 0.67^{+0.05}_{-0.07}$

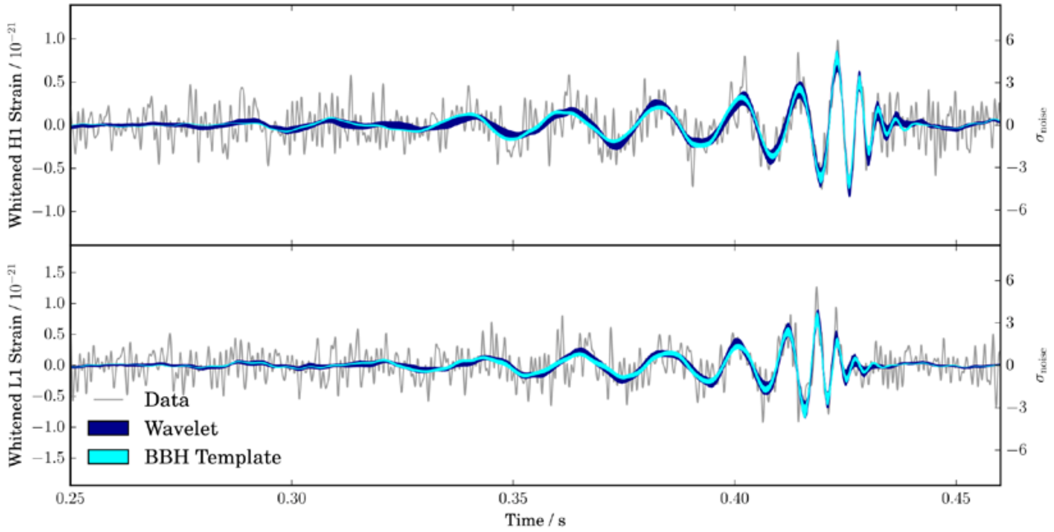
Final black hole has about the area of Iceland

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)

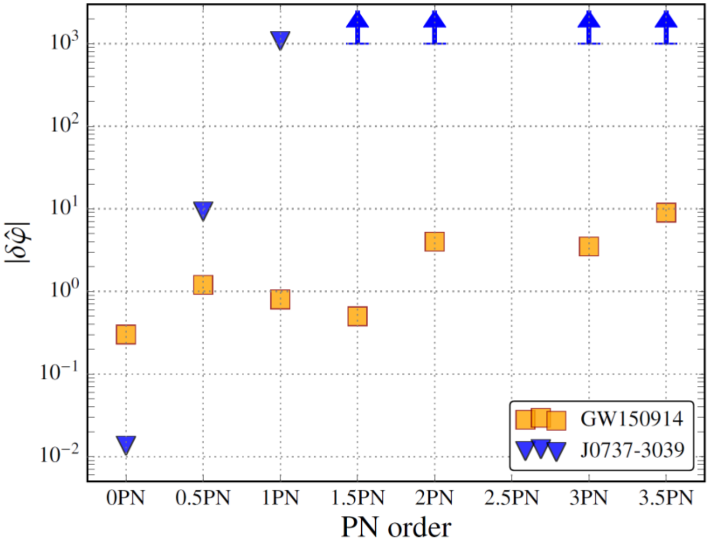
Testing general relativity

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

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

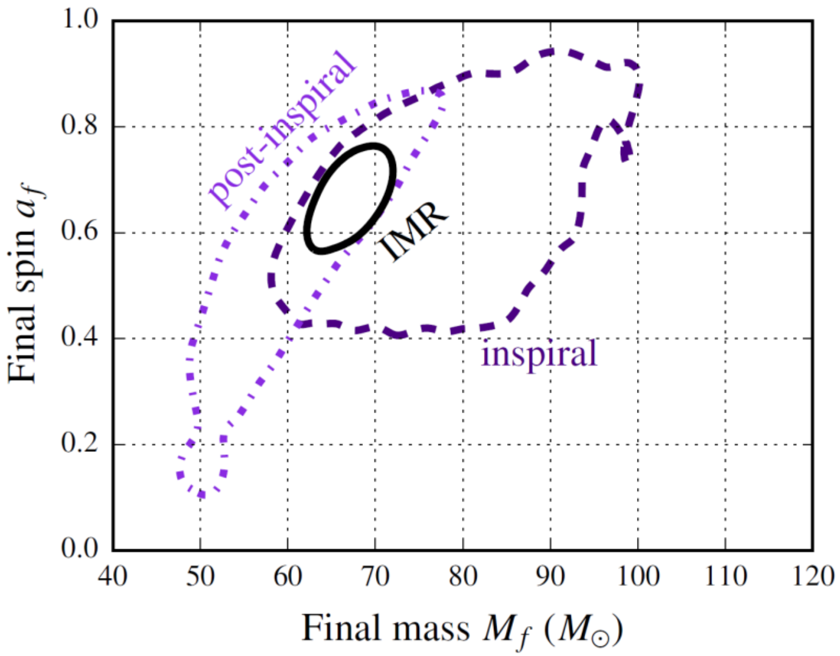
- Simplest test : data substracted with closest predicted waveform
  - Residuals are compatible with Gaussian noise within measurement accuracy
    → Deviations from GR constrained to be less than 4%

- 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)

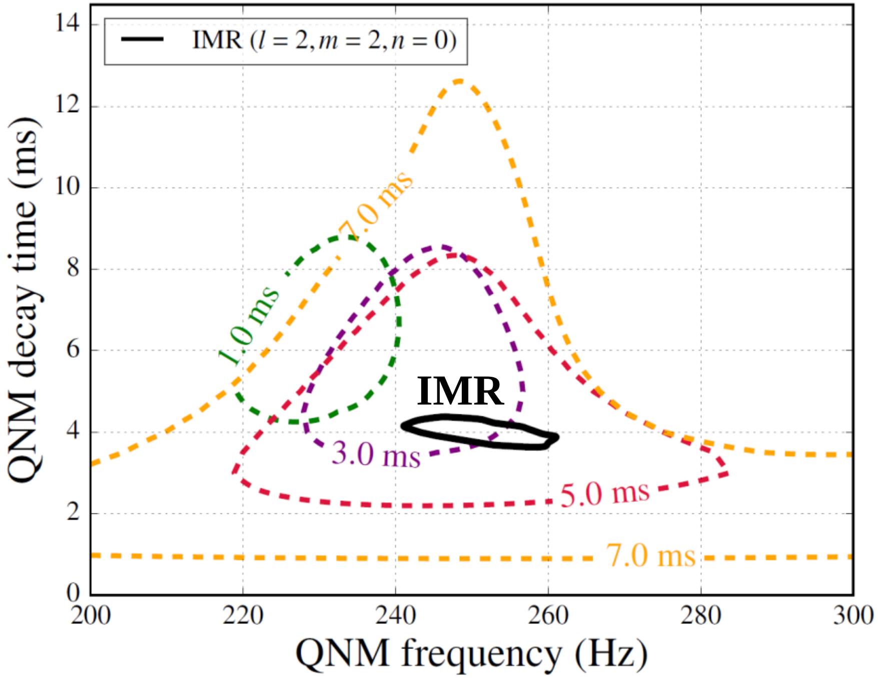


Testing general relativity

- 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 $$v_g^2 = c^2\left(1-\frac{m_g^2c^4}{2E^2}\right)$$

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

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

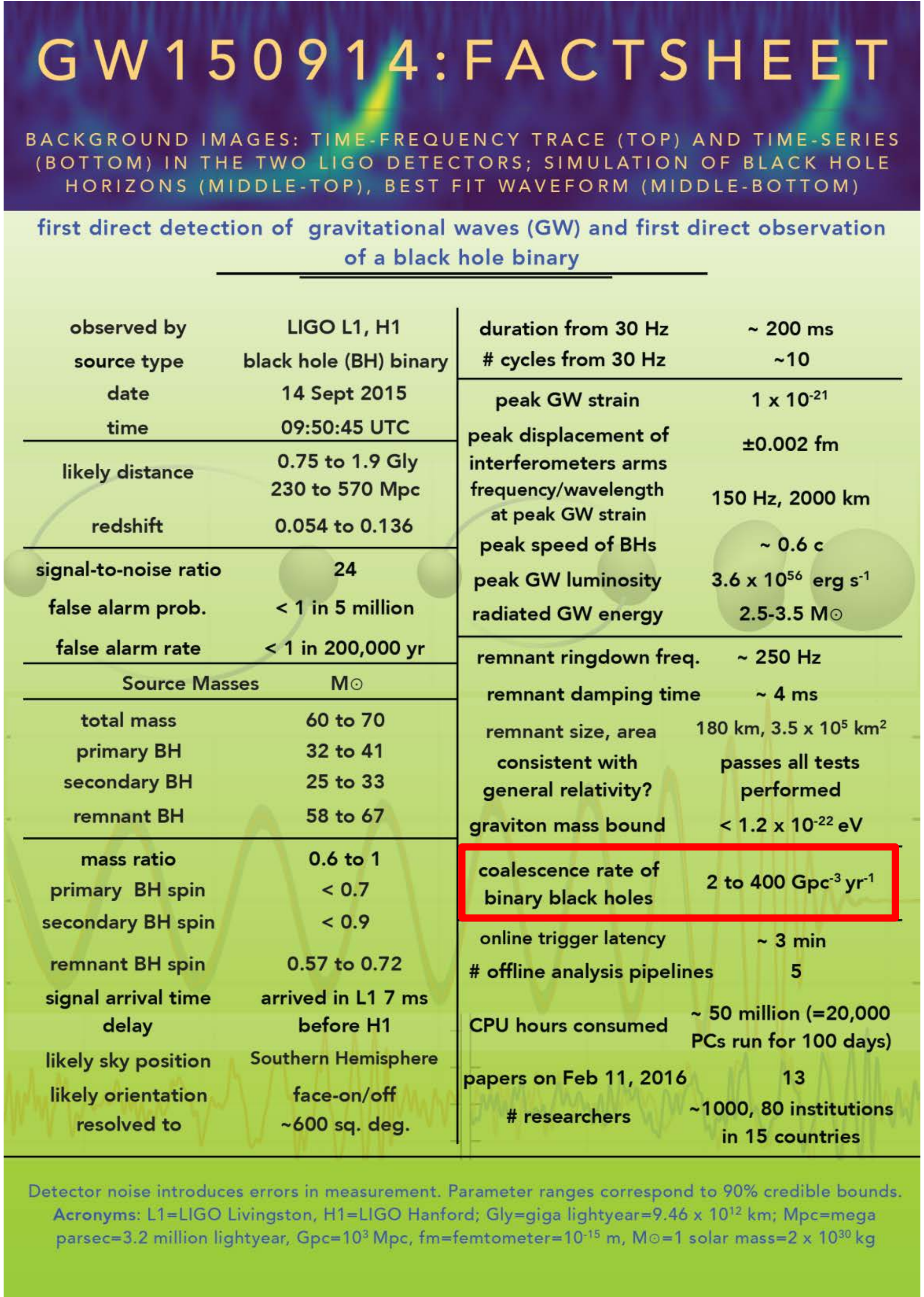
$\lambda_g = \frac{h}{m_g c}$ is the graviton Compton wavelength

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

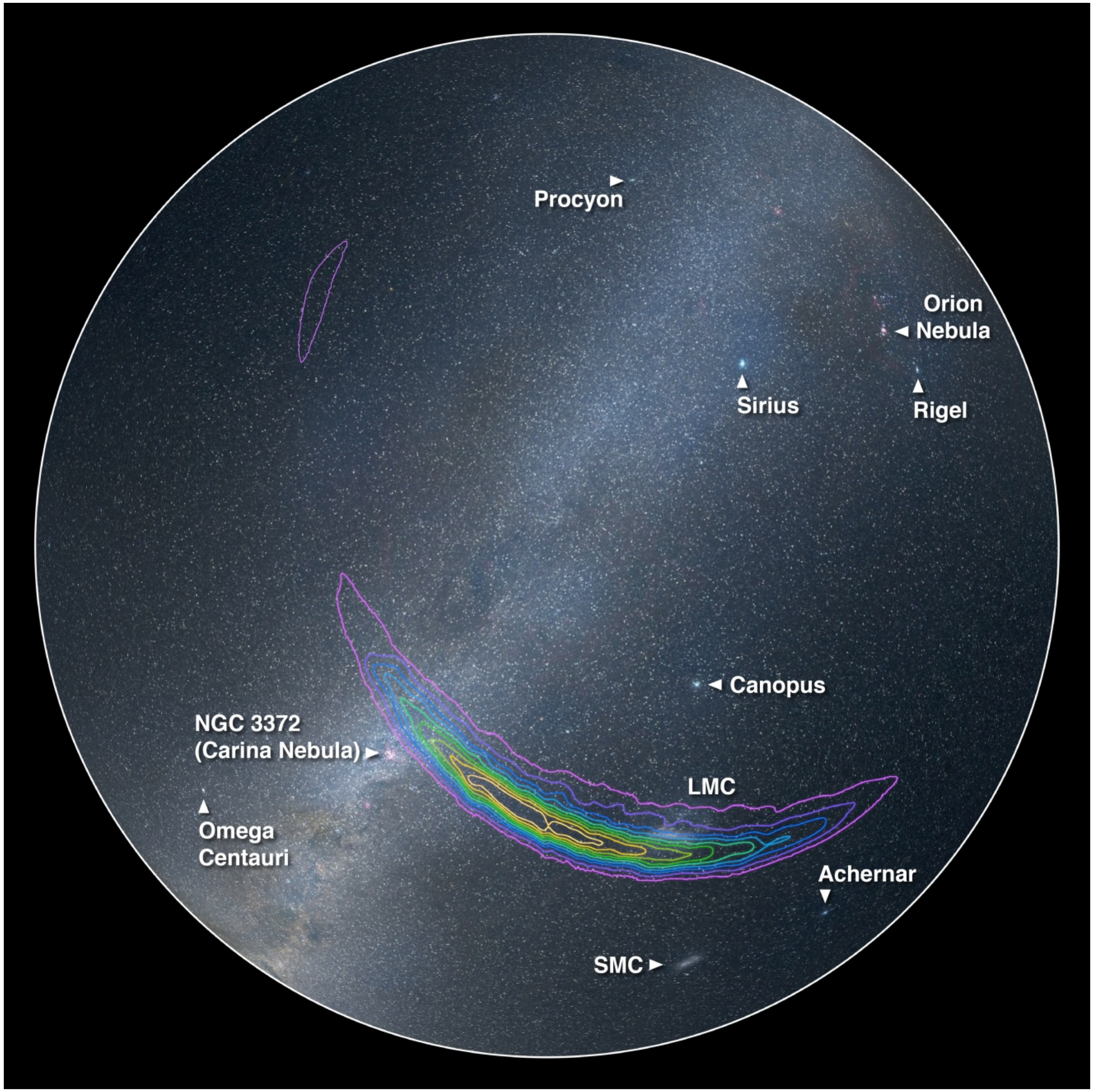
observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc
redshift	0.054 to 0.136
signal-to-noise ratio	24
false alarm prob.	< 1 in 5 million
false alarm rate	< 1 in 200,000 yr
Source Masses	**M⊙**
total mass	60 to 70
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	< 1.2×10^{-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 x 10^{12} km; Mpc=mega parsec=3.2 million lightyear, Gpc=10^3 Mpc, fm=femtometer=10^{-15} m, M⊙=1 solar mass=2 x 10^{30} kg

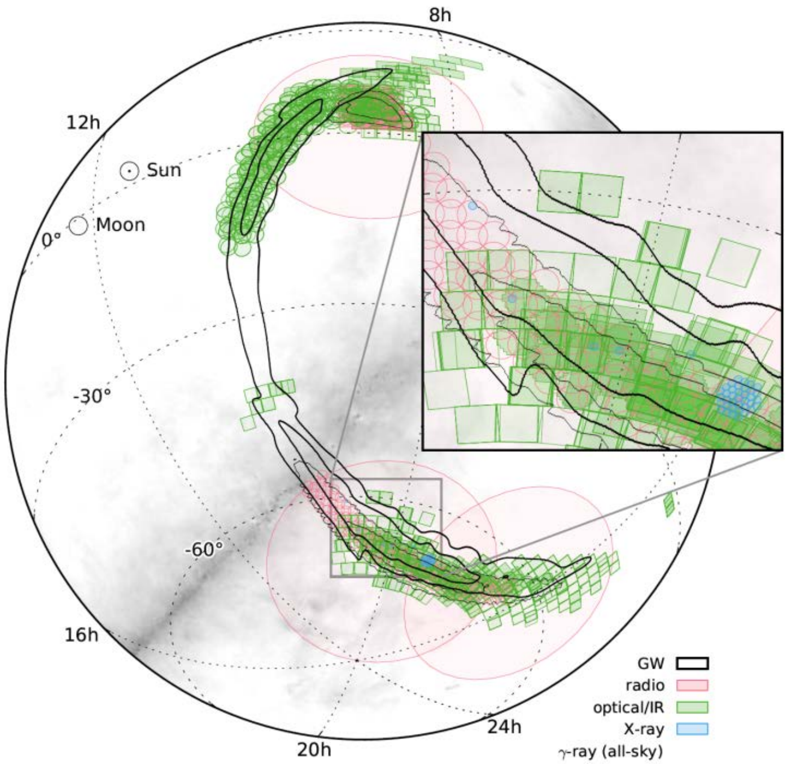
Skymap

- 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

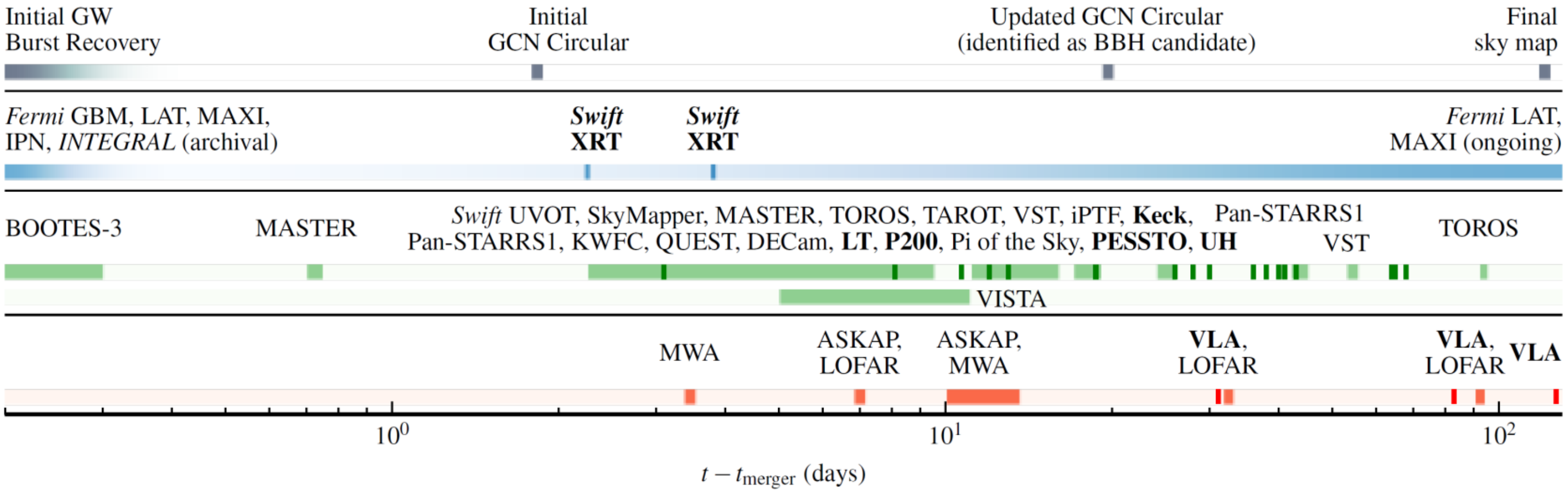


Looking for GW150914 counterparts

- 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

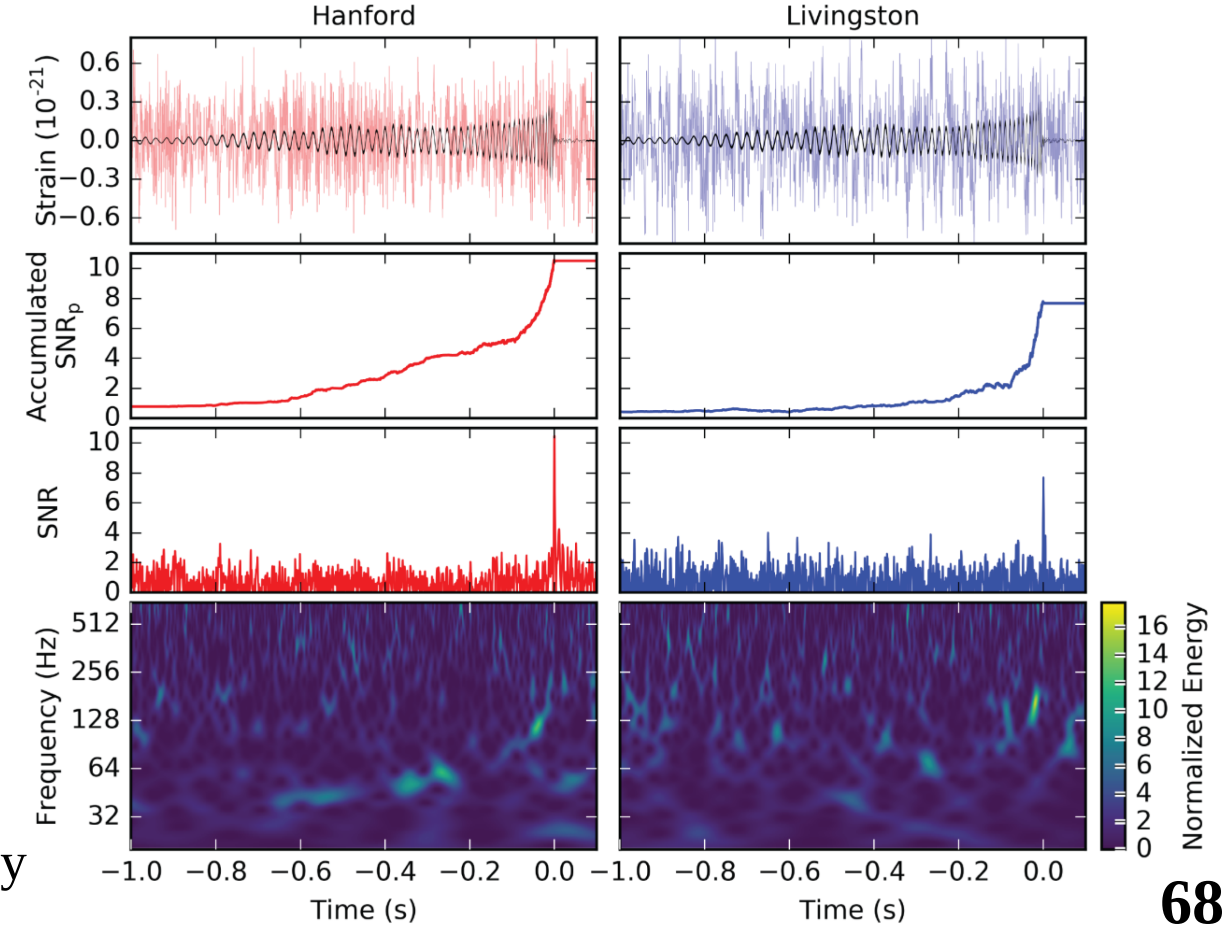
- Not all GW signals visible to the naked eye!

- Another binary black hole coalescence

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

- Smaller amplitude
- More cycles in the detector bandwidth

→ Matched filtering mandatory



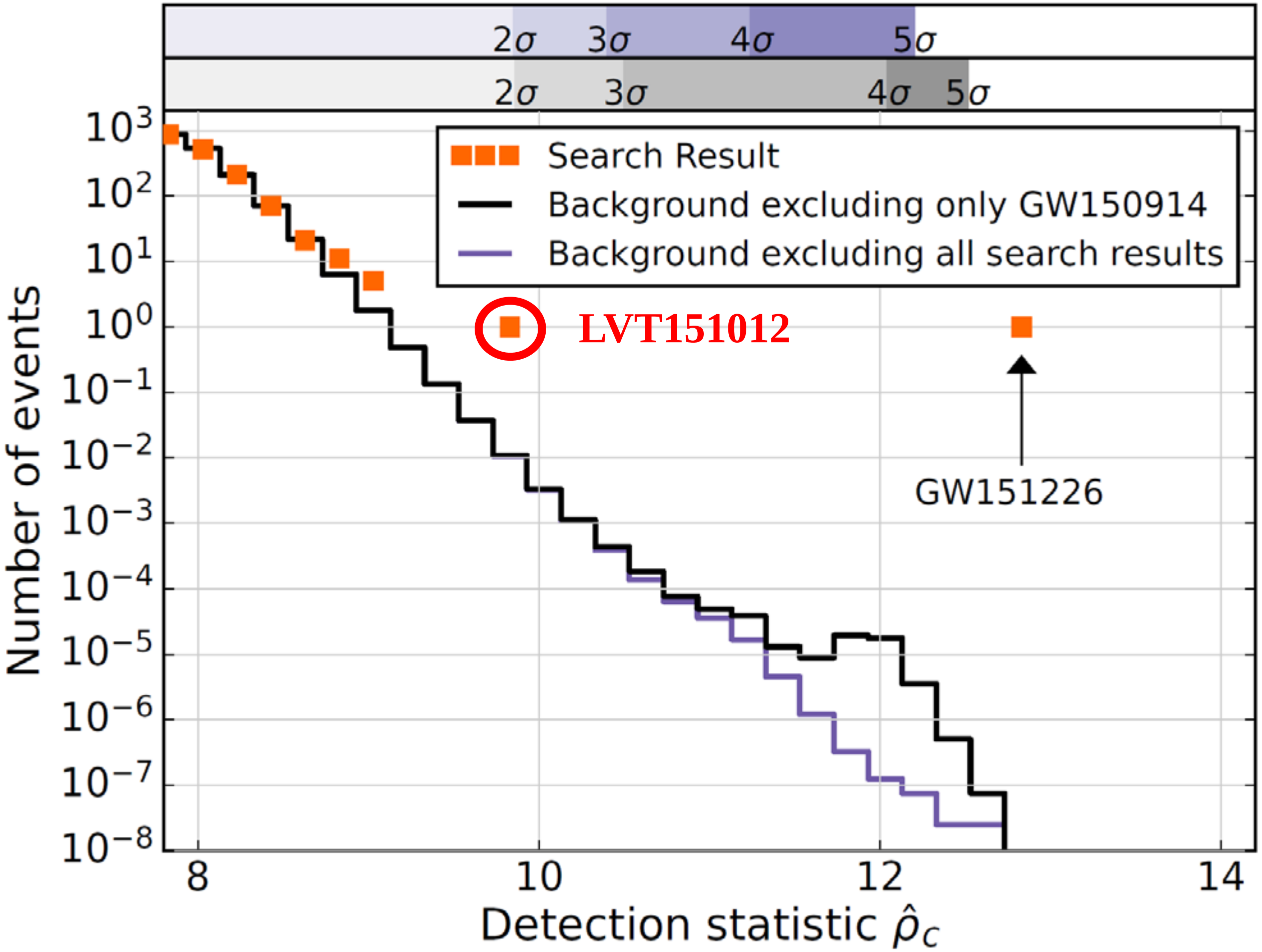
GW151226

- 2nd largest event recorded
  - After GW150914

- A third candidate: LVT151012
  - Lower statistical significance

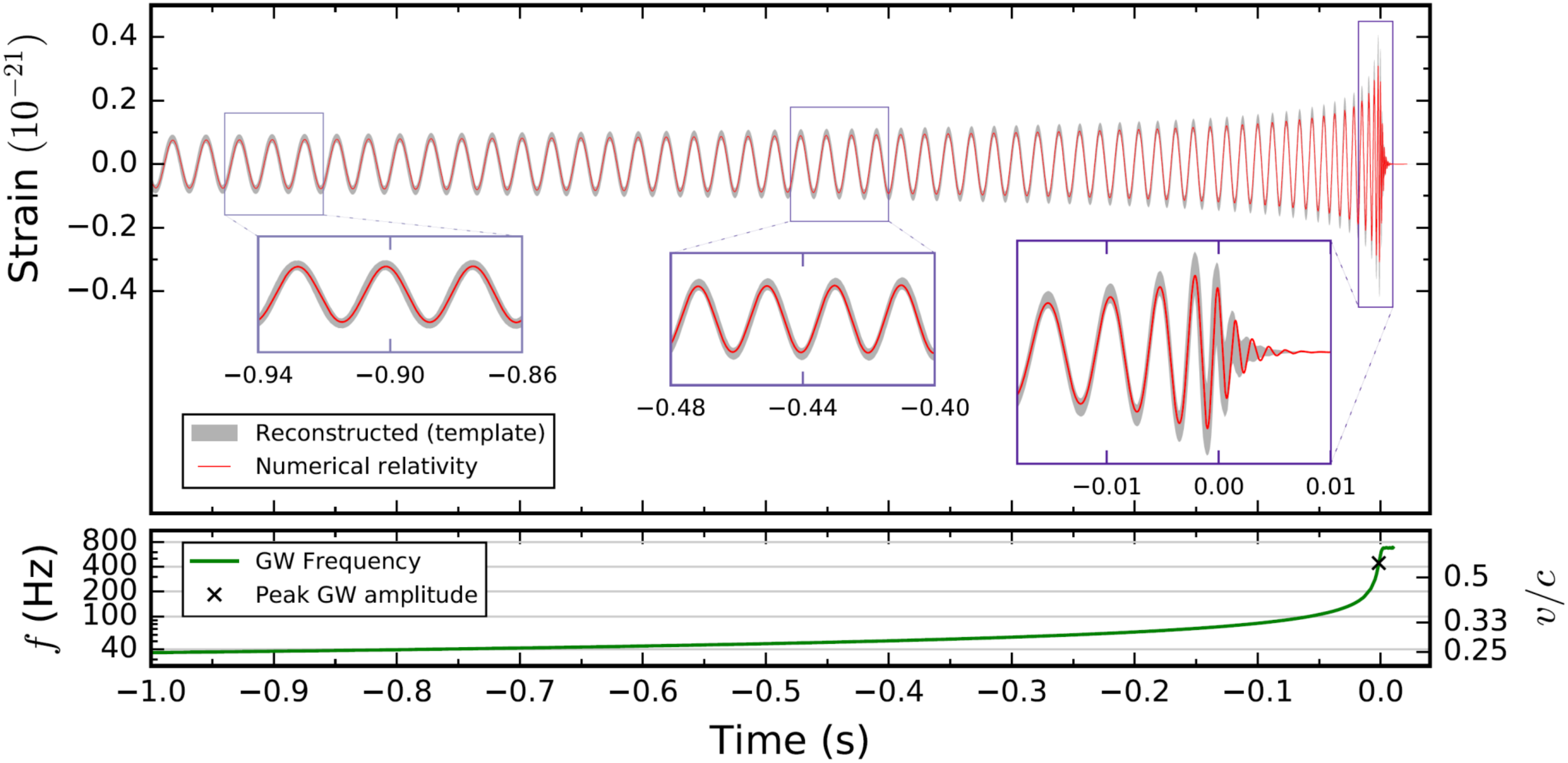
  → « Source » much further away (~1 Gpc)

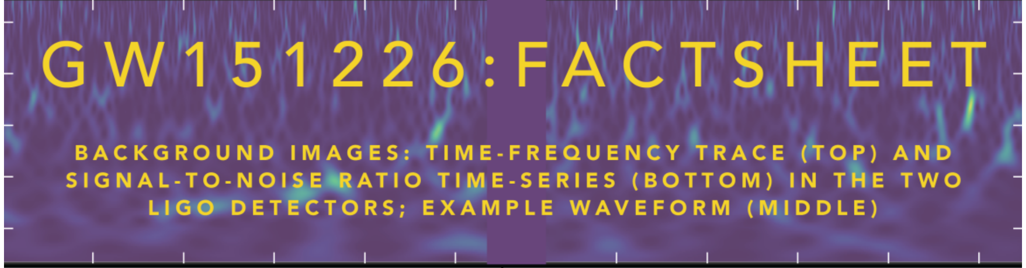
- In this plot, GW150914 has been removed to estimate the bkg as it is a true signal



GW151226

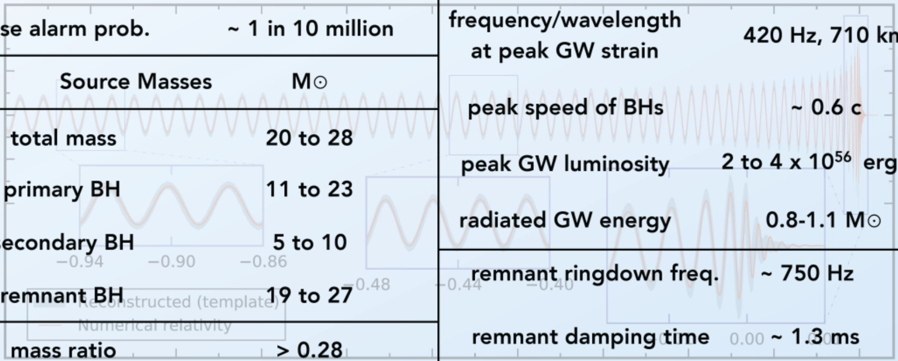
- Excellent agreement between the different reconstructed waveforms
  - analytical computation (post-Newtonian expansion, in grey)
  - numerical relativity (in red)





GW151226: FACTSHEET

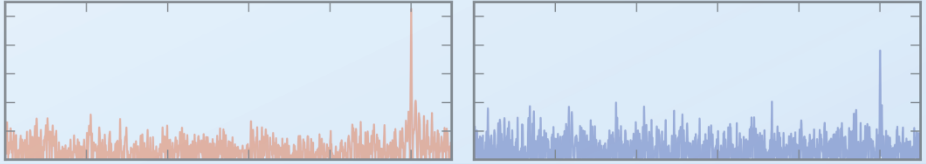
BACKGROUND IMAGES: TIME-FREQUENCY TRACE (TOP) AND SIGNAL-TO-NOISE RATIO TIME-SERIES (BOTTOM) IN THE TWO LIGO DETECTORS; EXAMPLE WAVEFORM (MIDDLE)



observed by	LIGO L1, H1
source type	black hole (BH) binary
date	26 Dec 2015
time	03:38:53 UTC
distance	250 to 620 Mpc
redshift	0.05 to 0.13
signal-to-noise ratio	13
false alarm prob.	~ 1 in 10 million
Source Masses	M⊙
total mass	20 to 28
primary BH	11 to 23
secondary BH	5 to 10
remnant BH	19 to 27
mass ratio	> 0.28
spin of one of the black holes	> 0.2
remnant BH spin	0.7 to 0.8
resolved to	~850 sq. deg.

duration from 35 Hz	~1 s
# cycles from 35 Hz	~55
signal arrival time delay	arrived in H1 1 ms after L1
peak GW strain	~ 3.4 x 10^{-22}
peak displacement of interferometers arms	~ ±0.7 am
frequency/wavelength at peak GW strain	420 Hz, 710 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	2 to 4 x 10^{56} erg s^{-1}
radiated GW energy	0.8-1.1 M⊙
remnant ringdown freq.	~ 750 Hz
remnant damping time	~ 1.3 ms
remnant size, area	60 km, 3.5 x 10^4 km^2
online trigger latency	~ 67 s
# offline analysis pipelines	2

Parameter ranges correspond to 90% credible bounds. **Acronyms:** L1/H1=LIGO Livingston/Hanford; Mpc=mega parsec=3.2 million lightyear, am=attometer=10^{-18} m, M⊙=1 solar mass=2 x 10^{30} kg



GW170104

GW170104

- Second « Observation Run » (O2)
  - Started on November 30th 2016

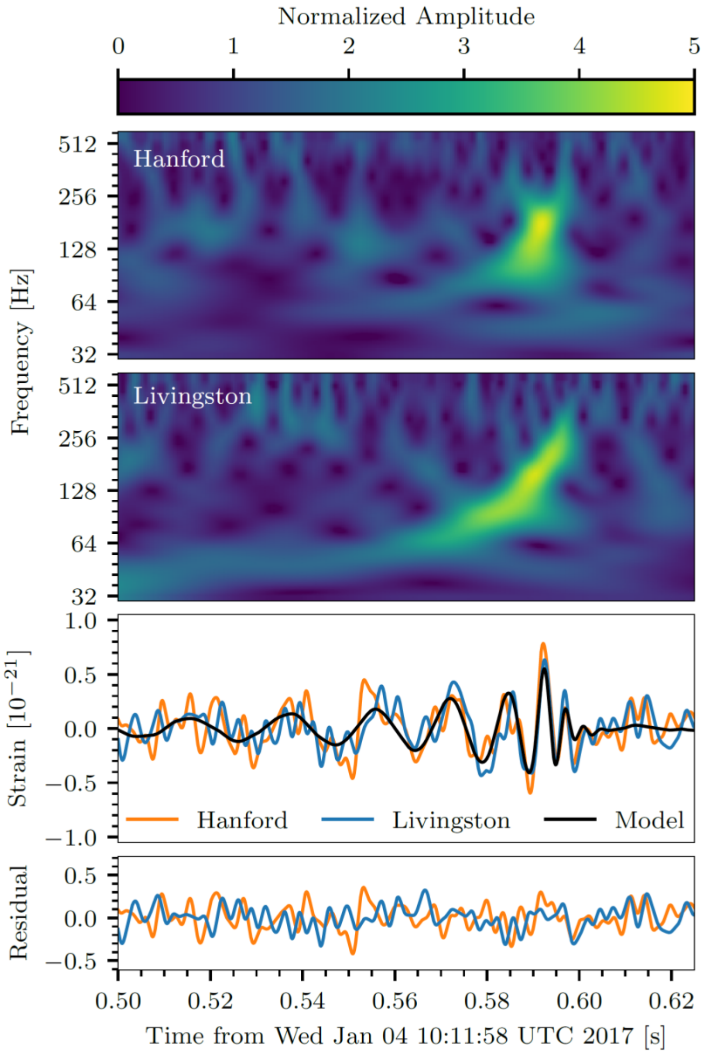
    → After a ~10 month-long break
    for maintenance and upgrade
  - End date scheduled for the end of August

    → Then there will be a 12-18 month-long stop
    before the start of O3 for LIGO and Virgo

- A third binary black hole coalescence
  - Primary black holes: about 31 and
    19 solar masses
  - Final black hole: about 49 solar masses
  - Source located about 3 billion light-years away

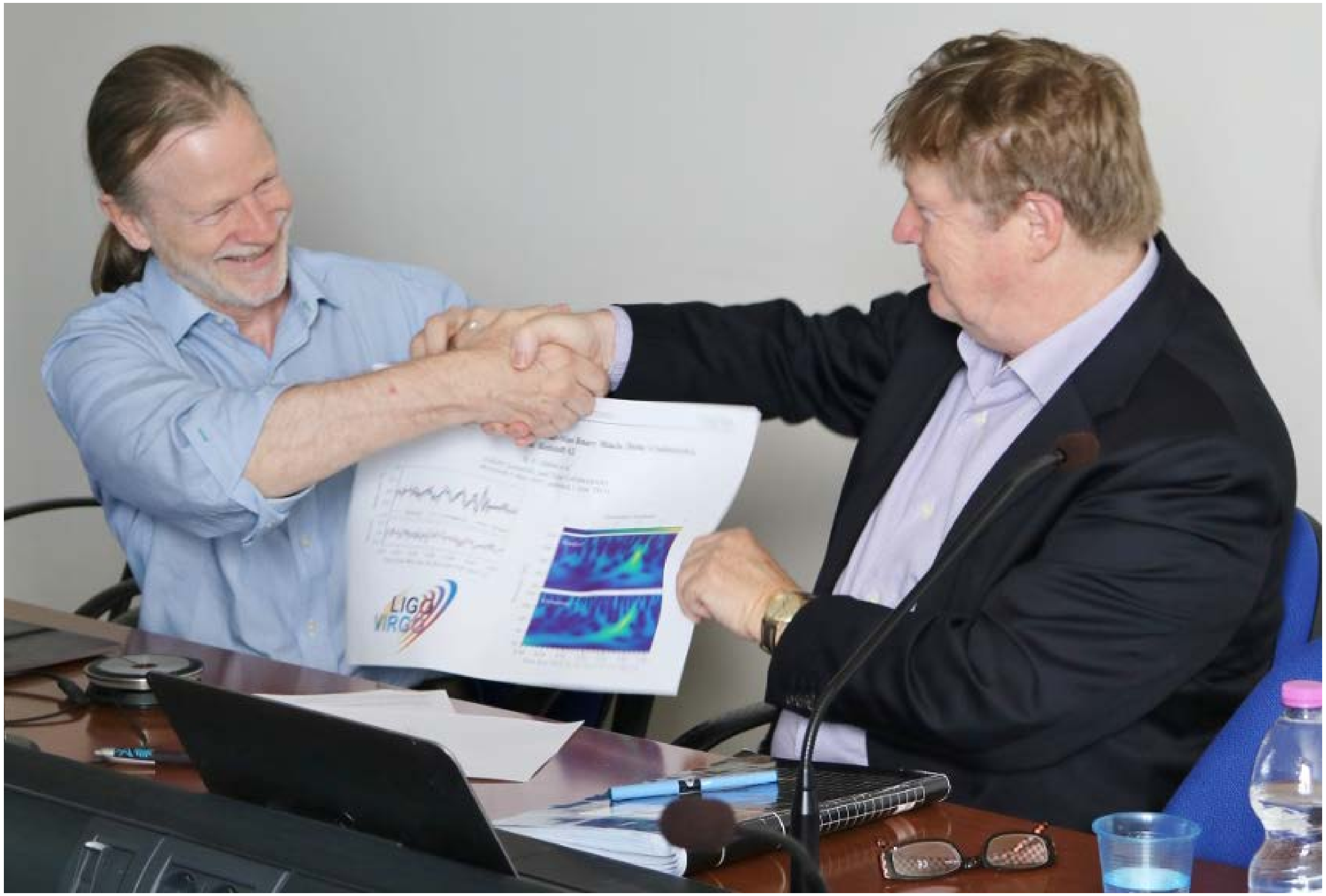
    → Twice as far as the first two events

- First detection during O2
  - January 04th 2017 at 11:11:59 CET
    10:11:59 UTC

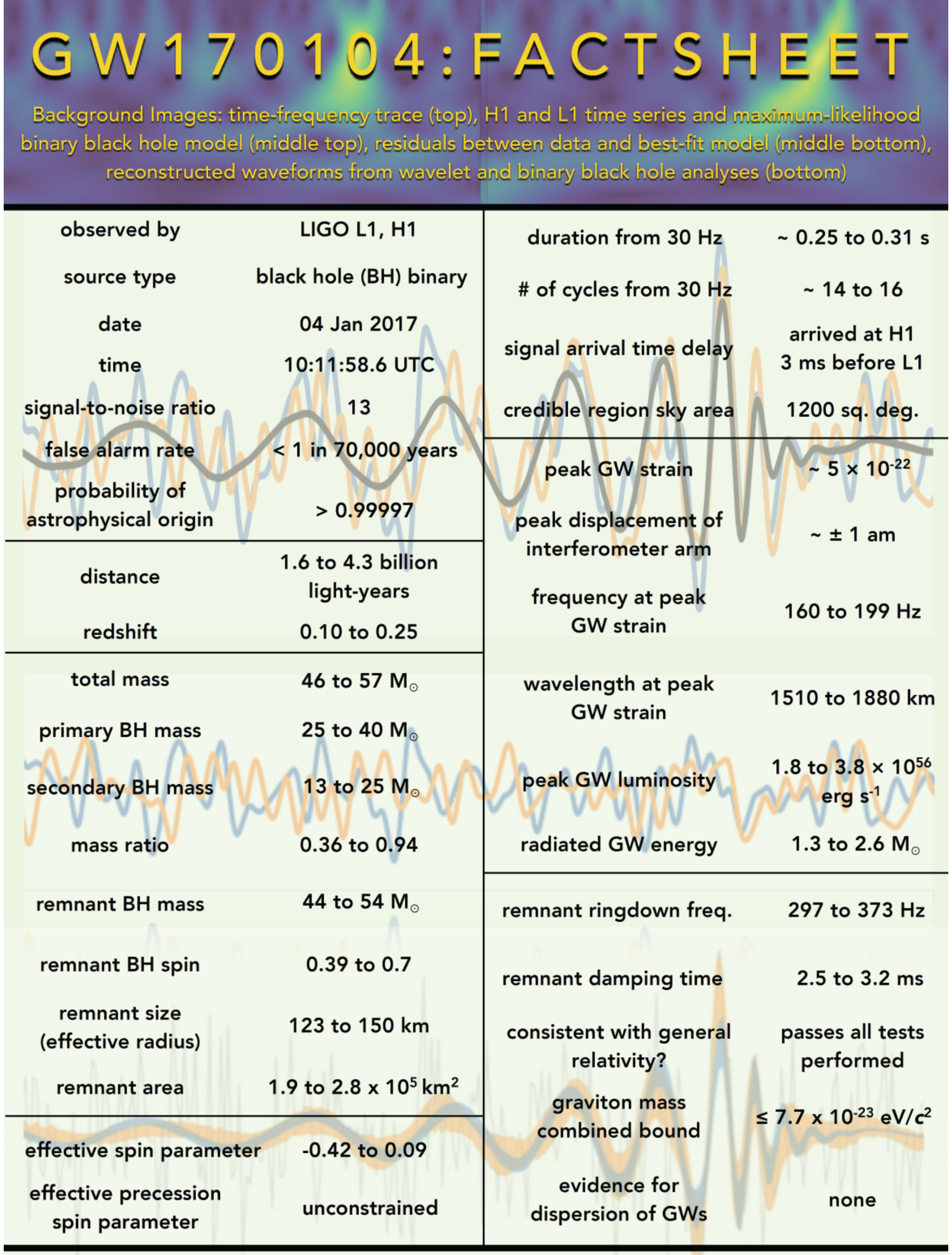


GW170104

- A human adventure after all!
  - LIGO (left) and Virgo (right) spokespersons shaking hands on May 31^{rst} 2017 prior to the press briefing announcing the discovery to journalists



GW170104: FACTSHEET



Background Images: time-frequency trace (top), H1 and L1 time series and maximum-likelihood binary black hole model (middle top), residuals between data and best-fit model (middle bottom), reconstructed waveforms from wavelet and binary black hole analyses (bottom)

observed by	LIGO L1, H1
source type	black hole (BH) binary
date	04 Jan 2017
time	10:11:58.6 UTC
signal-to-noise ratio	13
false alarm rate	< 1 in 70,000 years
probability of astrophysical origin	> 0.99997
distance	1.6 to 4.3 billion light-years
redshift	0.10 to 0.25
total mass	46 to 57 $M_\odot$
primary BH mass	25 to 40 $M_\odot$
secondary BH mass	13 to 25 $M_\odot$
mass ratio	0.36 to 0.94
remnant BH mass	44 to 54 $M_\odot$
remnant BH spin	0.39 to 0.7
remnant size (effective radius)	123 to 150 km
remnant area	1.9 to 2.8 x 10^5 km^2
effective spin parameter	-0.42 to 0.09
effective precession spin parameter	unconstrained

duration from 30 Hz	~ 0.25 to 0.31 s
# of cycles from 30 Hz	~ 14 to 16
signal arrival time delay	arrived at H1 3 ms before L1
credible region sky area	1200 sq. deg.
peak GW strain	~ 5 x 10^{-22}
peak displacement of interferometer arm	~ ± 1 am
frequency at peak GW strain	160 to 199 Hz
wavelength at peak GW strain	1510 to 1880 km
peak GW luminosity	1.8 to 3.8 x 10^{56} erg s^{-1}
radiated GW energy	1.3 to 2.6 $M_\odot$
remnant ringdown freq.	297 to 373 Hz
remnant damping time	2.5 to 3.2 ms
consistent with general relativity?	passes all tests performed
graviton mass combined bound	≤ 7.7 x 10^{-23} eV/c^2
evidence for dispersion of GWs	none

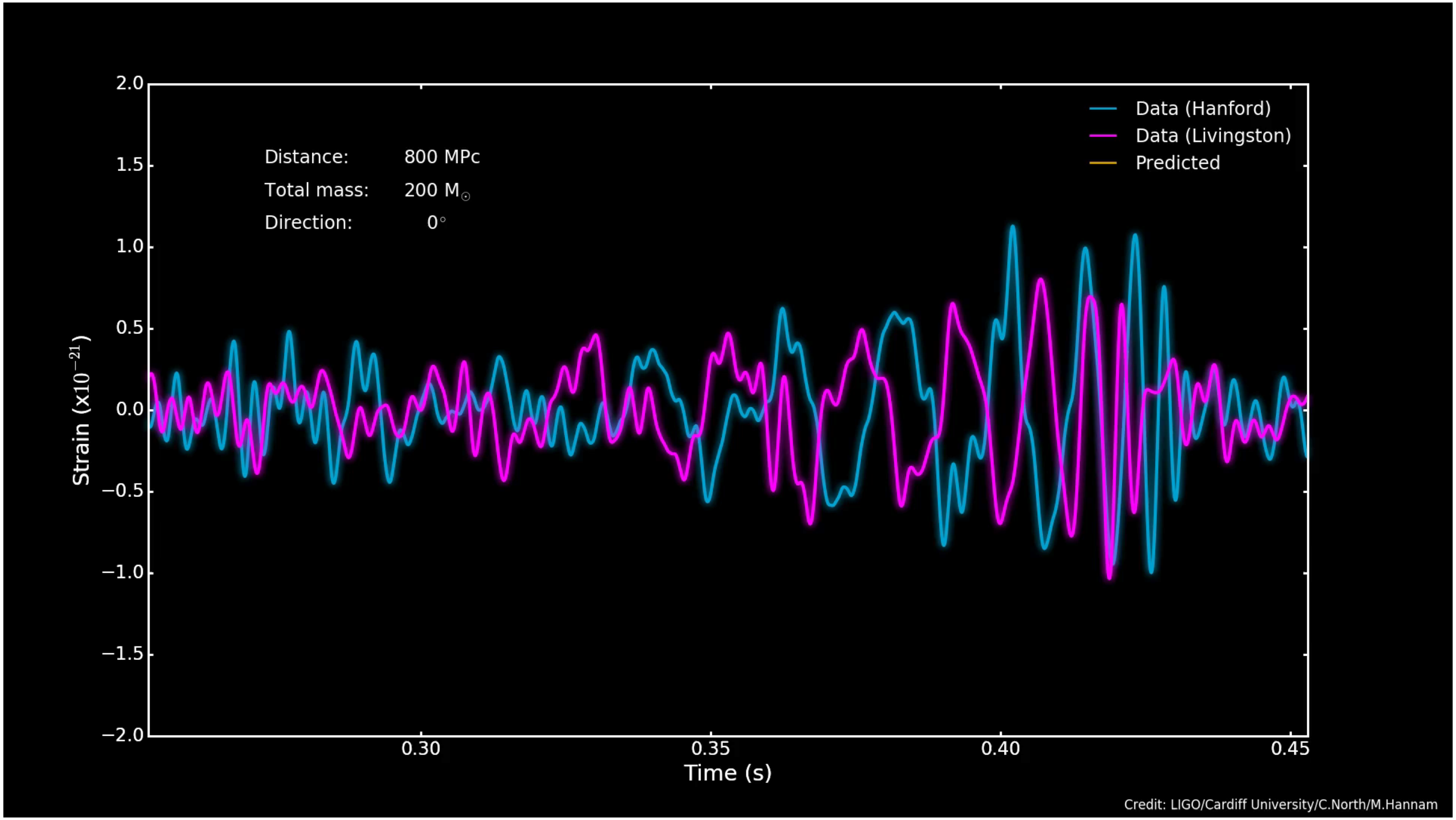
Parameter ranges correspond to 90% credible intervals.

Acronyms:

L1/H1=LIGO Livingston/Hanford, am=attometer=10^{-18} m, $M_\odot$=1 solar mass=2 x 10^{30} kg

GW170104

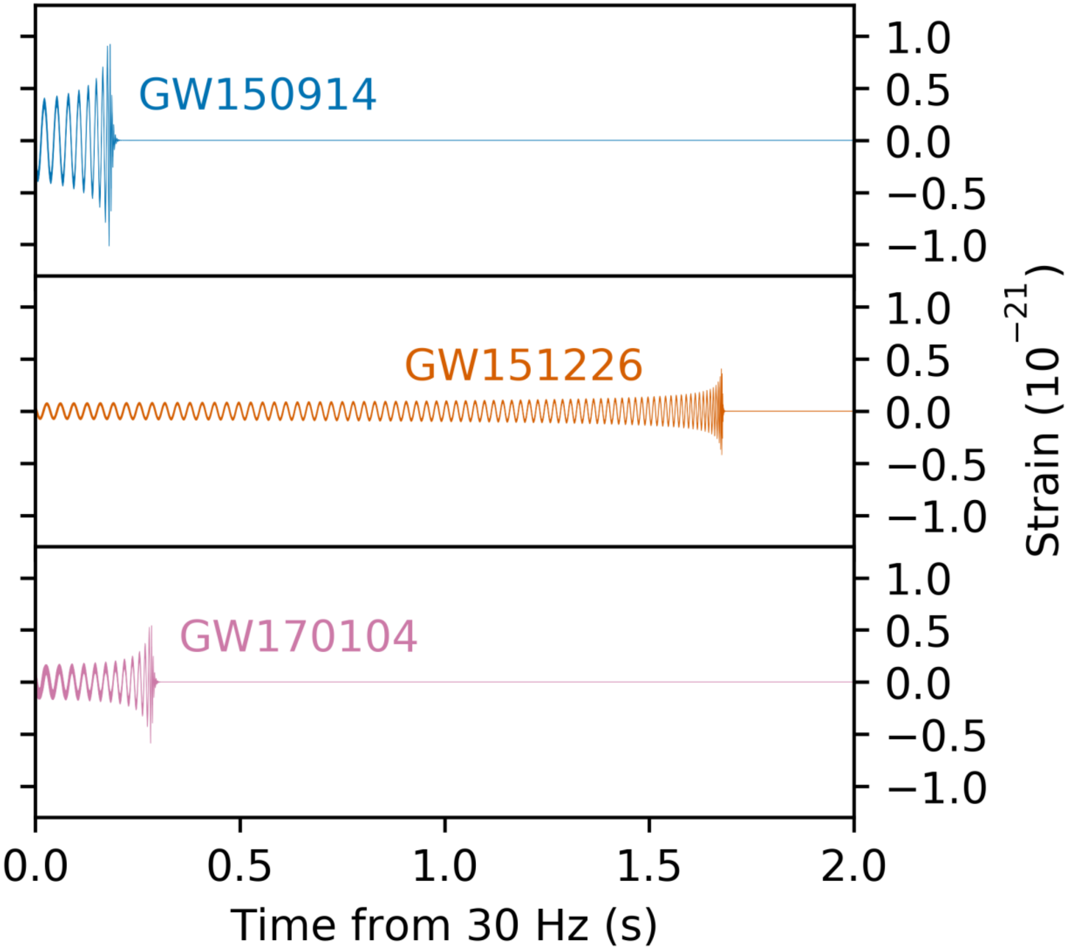
- Parameter fitting



Credit: LIGO/Cardiff University/C.North/M.Hannam

In summary: three events

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



And now!?

Current status of the detectors

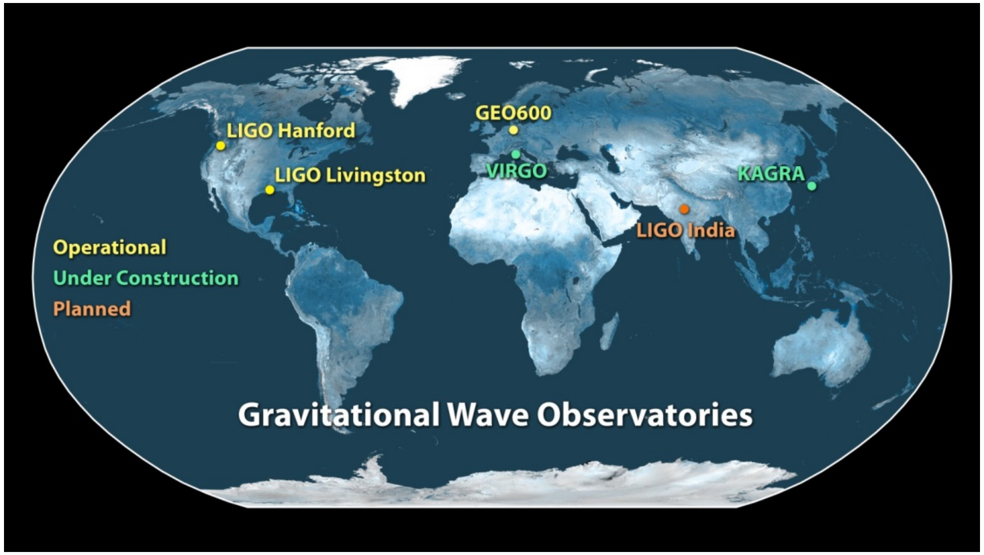
- Advanced LIGO detectors
  - Second data taking period started on November 30 2016
  - Early March review : 74 days of coincidence data as of May 8 2017
    7 candidates identified (1 was GW17014); partners notified
    → Data analysis in progress

- Advanced Virgo
  - Detector fully controlled: commissioning phase nearing its end
  - Current goals: sensitivity improvement ↔ « noise hunting »
    → Advanced Virgo is a « brand new » detector
  - Goal : to join LIGO's O2 data taking period within a few weeks
    → In the home stretch after a lot of work

Conclusions

Prospects

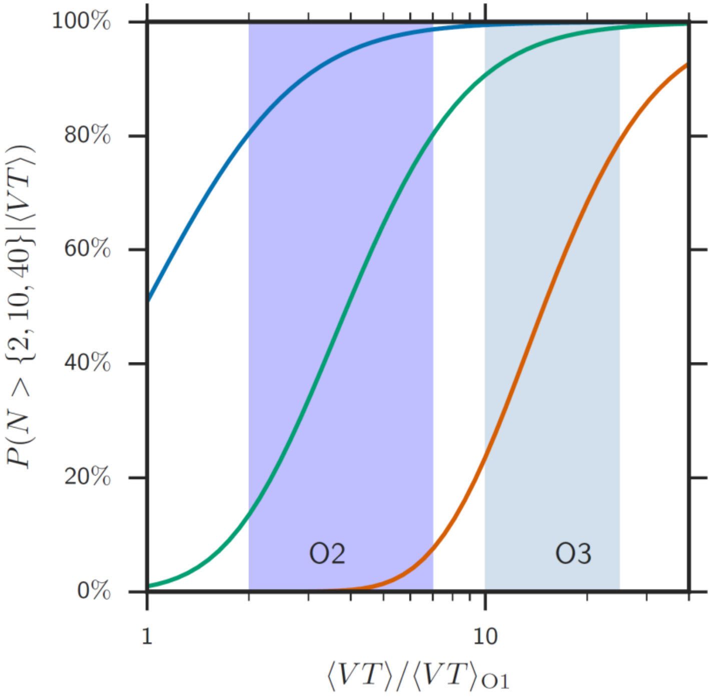
- Soon: a ground-based detector network
  - larger and
  - more sensitive



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

Probabilities that the number of detections exceeds

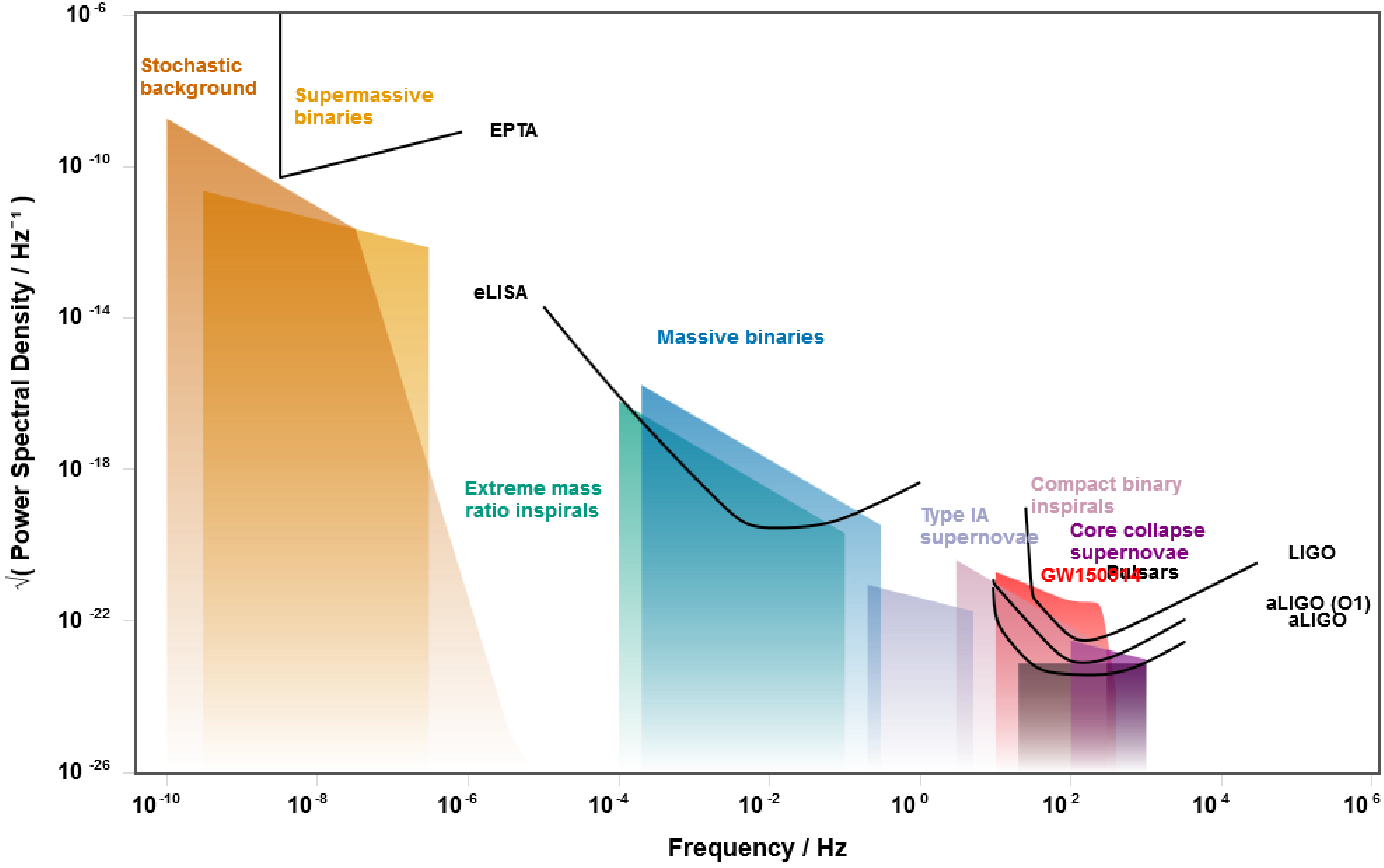
- **2**
- **10**
- **40**



OX : « Observation »
Run number X

Detectors and sources: a summary plot

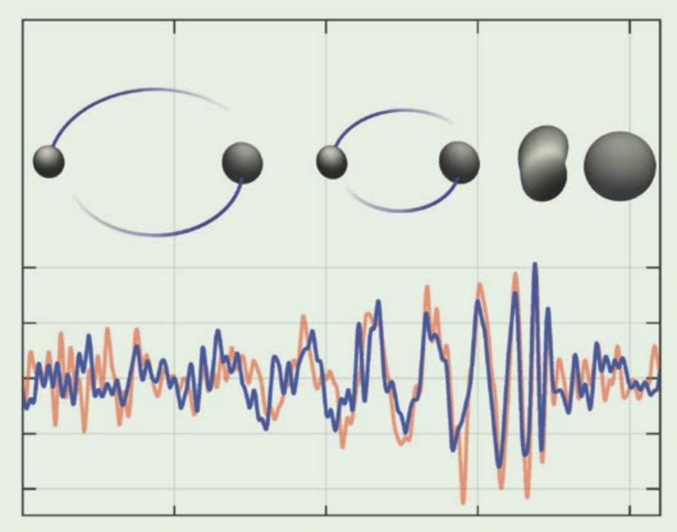
- From http://rhcole.com/apps/GWplotter



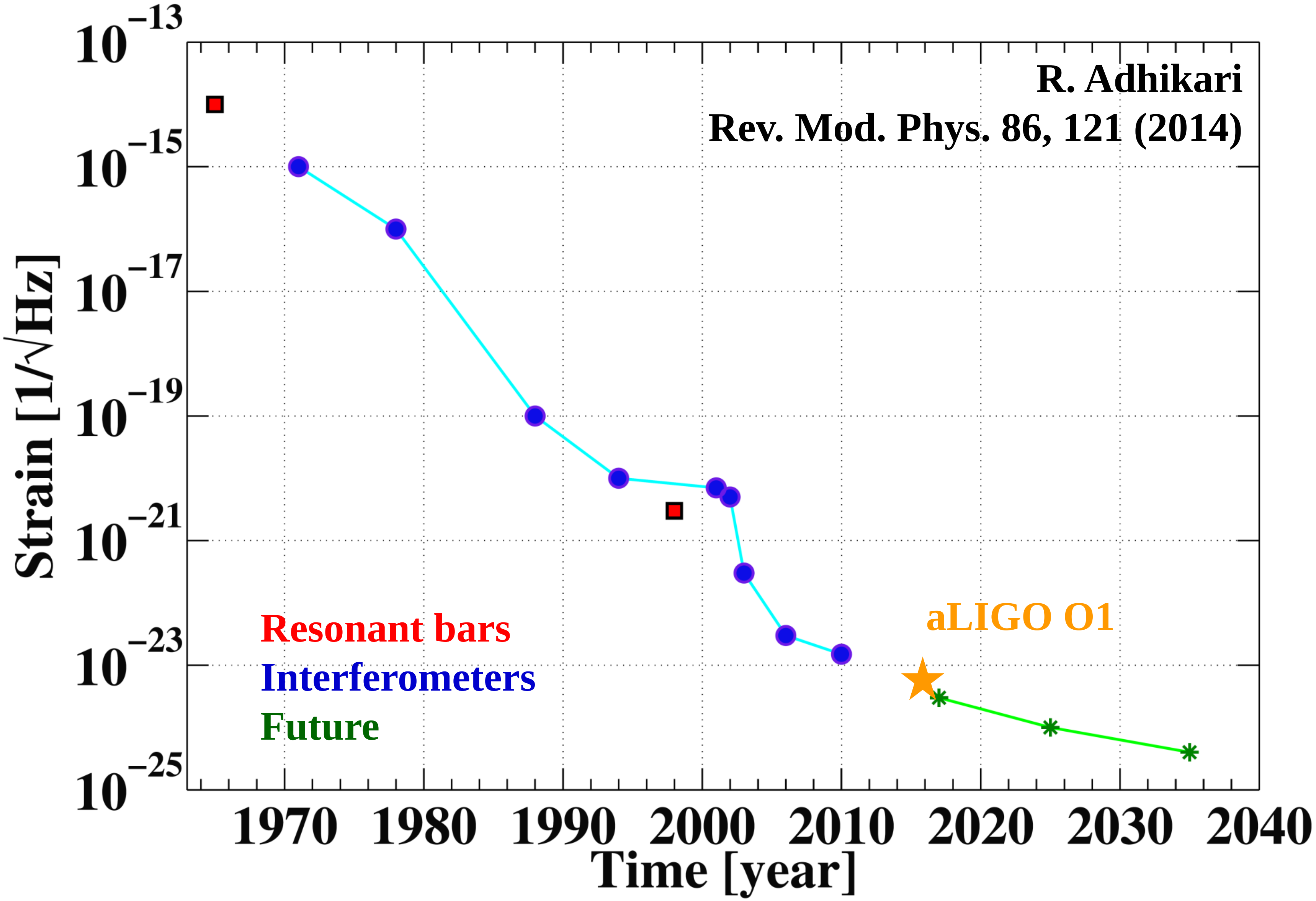
Outlook

- The network of advanced gravitational wave interferometers is taking shape
  - The two aLIGO detectors started taking data in September 2015 and detected the first three gravitational wave signals (GW150914, GW151226 & GW170104)
  - 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



For more information in Polish

- https://polgraw.camk.edu.pl

VIRGO-POLGRAW BADANIA Q&A POLSKI ENGLISH

Virgo–POLGRAW

Fale grawitacyjne: astrofizyka i modelowanie źródeł, analiza danych, budowa detektora Virgo

GW170104: Trzecia bezpośrednia detekcja fal grawitacyjnych

- http://users.camk.edu.pl/bejger/outreach
- http://users.camk.edu.pl/bejger/talks/fg_afterO1.pdf

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