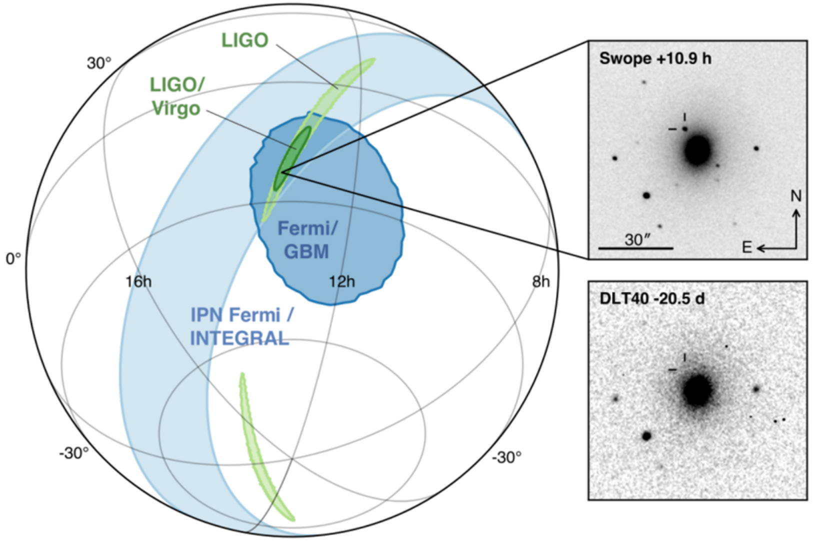
The detection of gravitational waves

EGO/Virgo Visit, May 30th, 2018

Nicolas Arnaud (narnaud@lal.in2p3.fr)
Laboratoire de l'Accélérateur Linéaire (CNRS/IN2P3 & Université Paris-Sud)
European Gravitational Observatory (Consortium, CNRS & INFN)



EGO EUROPEAN GRAVITATIONAL OBSERVATORY

cnrs dépasser les frontières

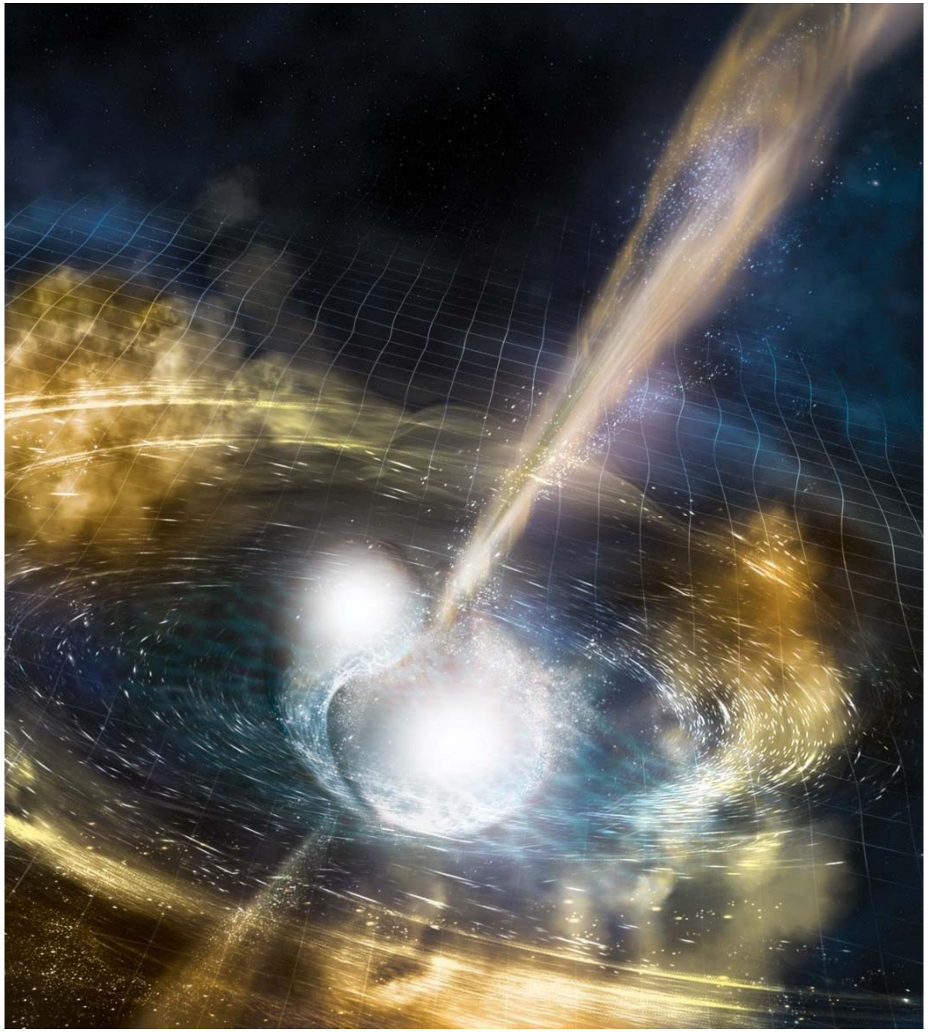
LAL LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

UNIVERSITÉ PARIS SUD

université PARIS-SACLAY

Outline

- Sources of gravitational waves
- The Virgo Collaboration
- The LIGO-Virgo network of detectors
- The August 2017 data taking period
- 2015-2017: the first detections of gravitational waves



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

Gravitational waves: sources and properties

Gravitational waves (GW)

- One of the first predictions of general relativity (1916)
  - Accelerated masses induce perturbations of the spacetime which propagate at the speed of light
  - Linearization of the Einstein equations ($g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$, $|h_{\mu\nu}| << 1$) leads to a propagation equation at the speed of ~~light~~ gravity far from the source

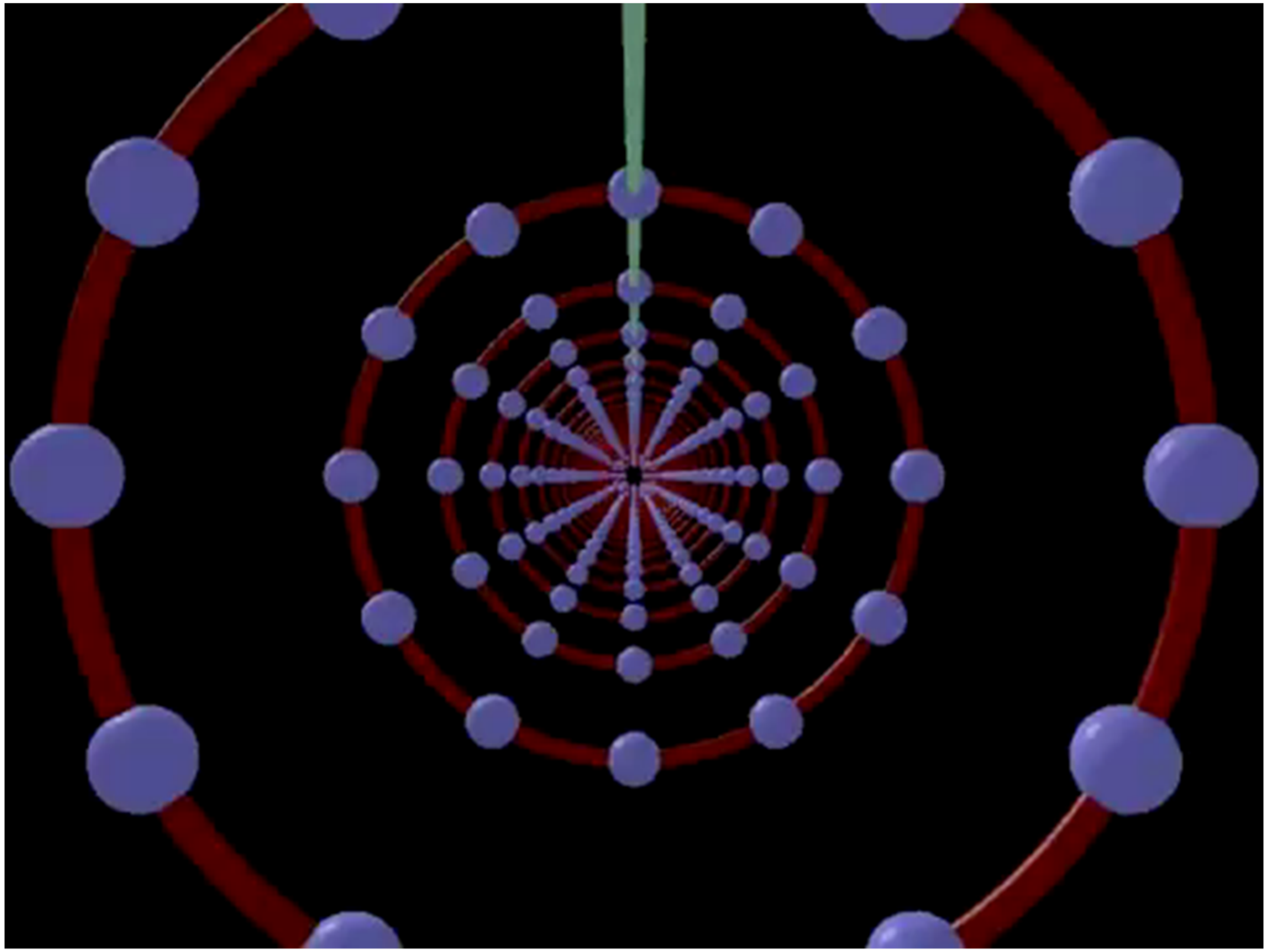
- Traceless and transverse (tensor) waves
  - 2 polarizations: « + » and « × »

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

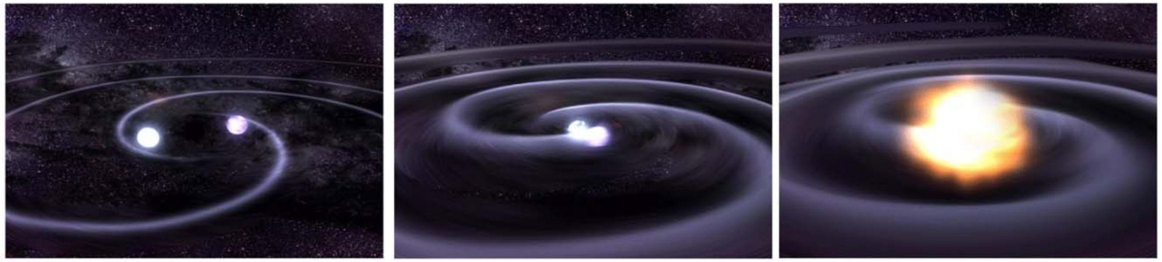
- GW amplitude h is dimensionless
  - Scales with the inverse of the distance from the source
  - GW detectors sensitive to amplitude ($h \propto 1/d$) and not intensity ($h^2 \propto 1/d^2$)
    $\rightarrow$ Important to define the Universe volume a given detector is sensitive to

Effect of gravitational waves on test masses

- In 3D

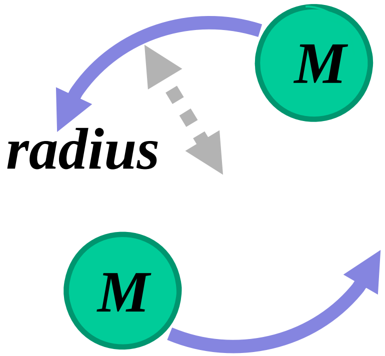


A diversity of sources

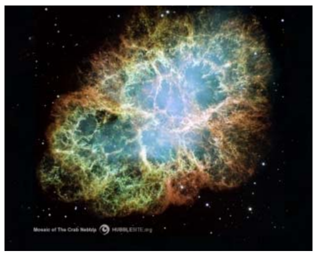


- Rough classification
  - Signal duration
  - Frequency range
  - Known/unknown waveform
  - Any counterpart (E.M., neutrinos, etc.) expected?
- Compact binary coalescence
  - Last stages of the evolution of a system like PSRB 1913+16
    → Compact stars get closer and closer while loosing energy through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

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

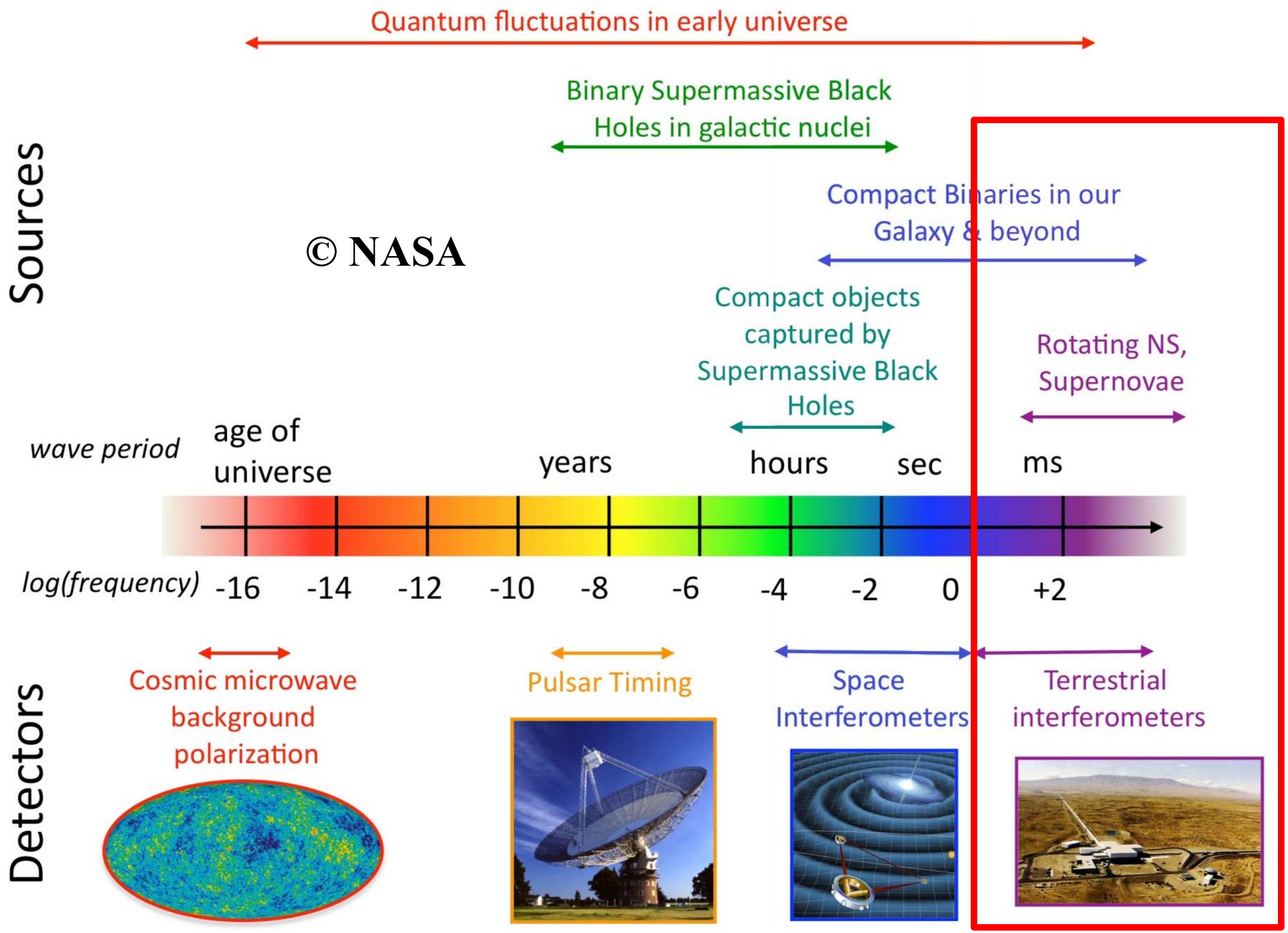


- Transient sources (« bursts »)
  - Example: core collapses (supernovae)



- Permanent sources
  - Pulsars, Stochastic backgrounds

Gravitational wave spectrum



LIGO, Virgo, etc.

Gravitational wave detectors

- Ground-based
  - Resonant bars (Joe Weber's pioneering work)

    → Narrow band, limited sensitivity: not used anymore
  - Interferometric detectors

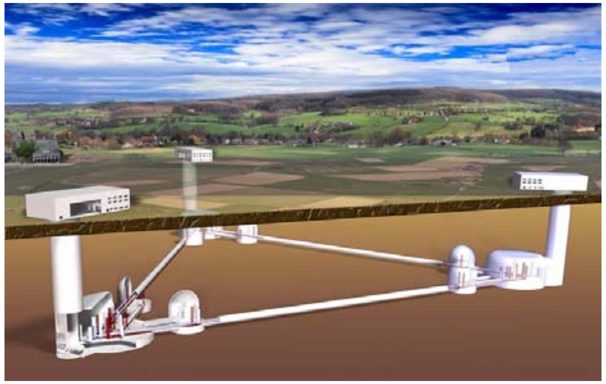
    → LIGO, Virgo and others

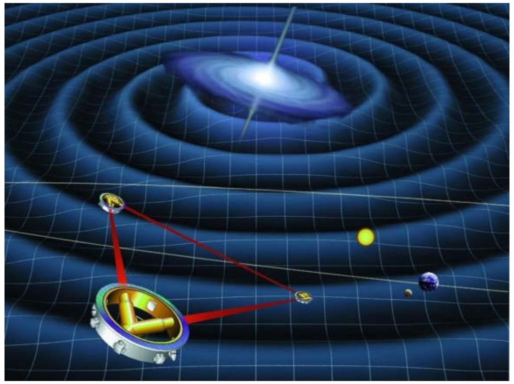
    → 2nd generation (« advanced ») detectors started operation

    Design studies have started for 3rd generation detectors (Einstein Telescope)
  - Pulsar Timing Array (http://www.ipta4gw.org)

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

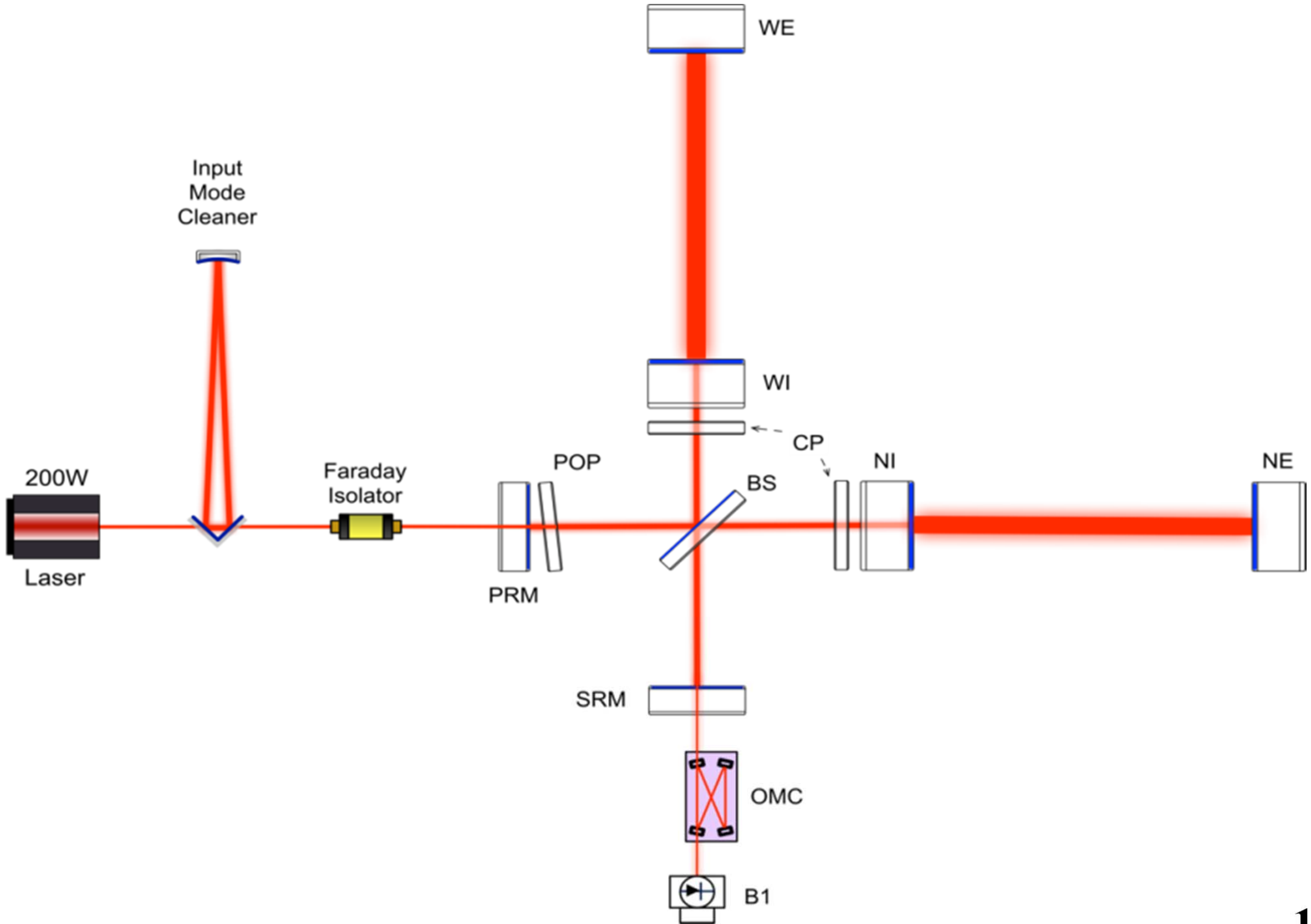
- In space
  - Future mission eLISA (https://www.elisascience.org, 2030's)
  - Technologies tested by the LISA pathfinder mission, sent to space last December



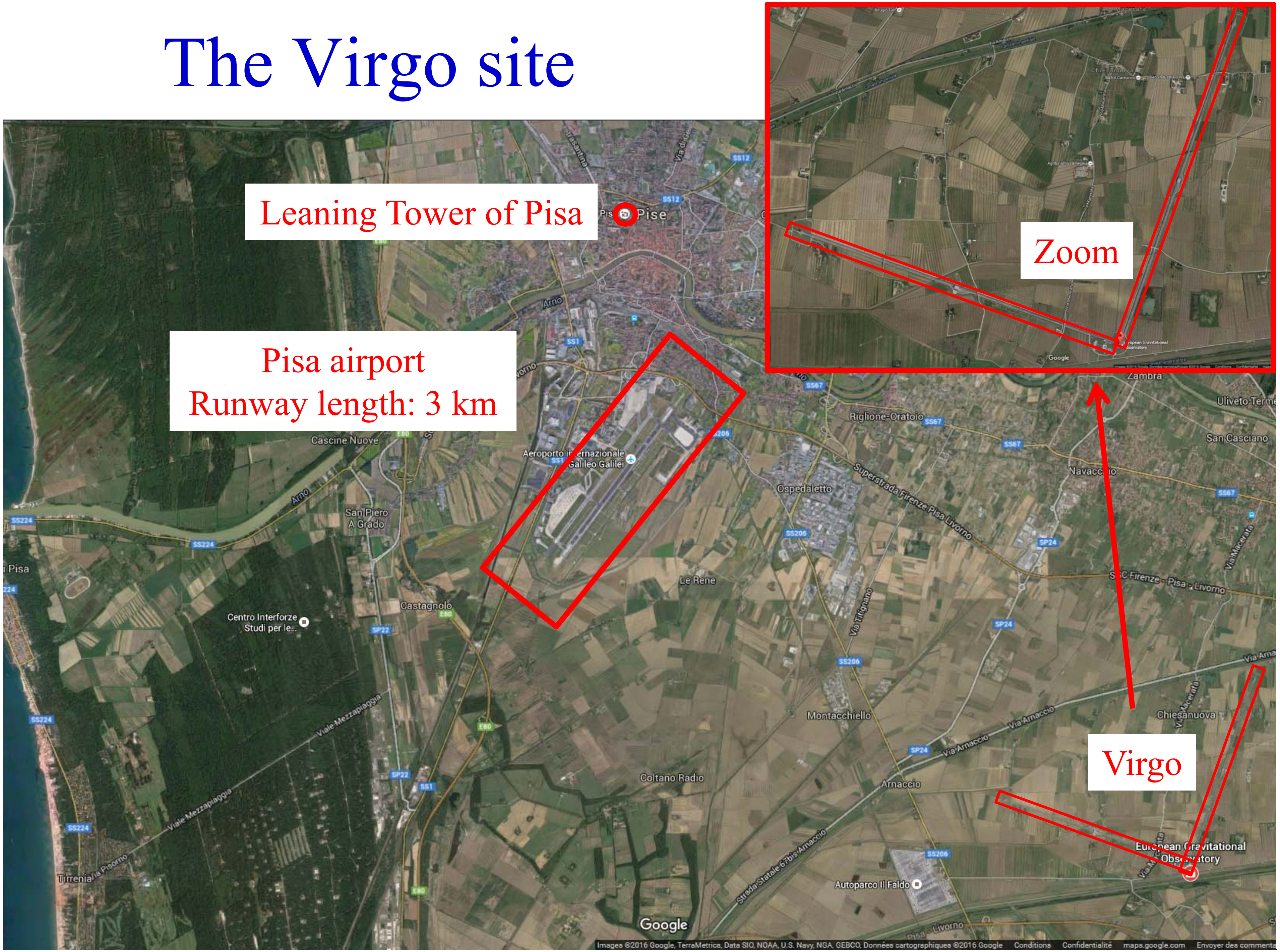


The Virgo collaboration

The Advanced Virgo detector scheme



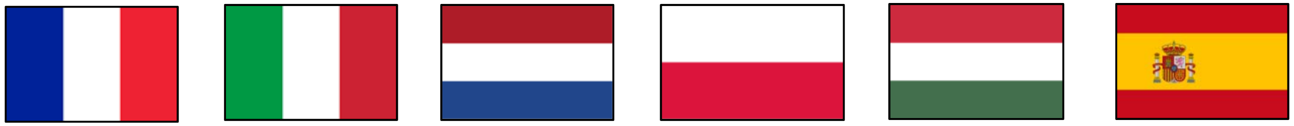
The Virgo site



If Virgo were located in Linköping…

The Virgo Collaboration

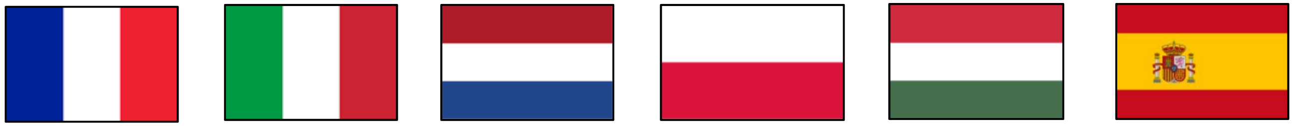
- 6 European countries



- 21 laboratories
- About 300 members (LIGO : 750)

The Virgo Collaboration

- 6 European countries



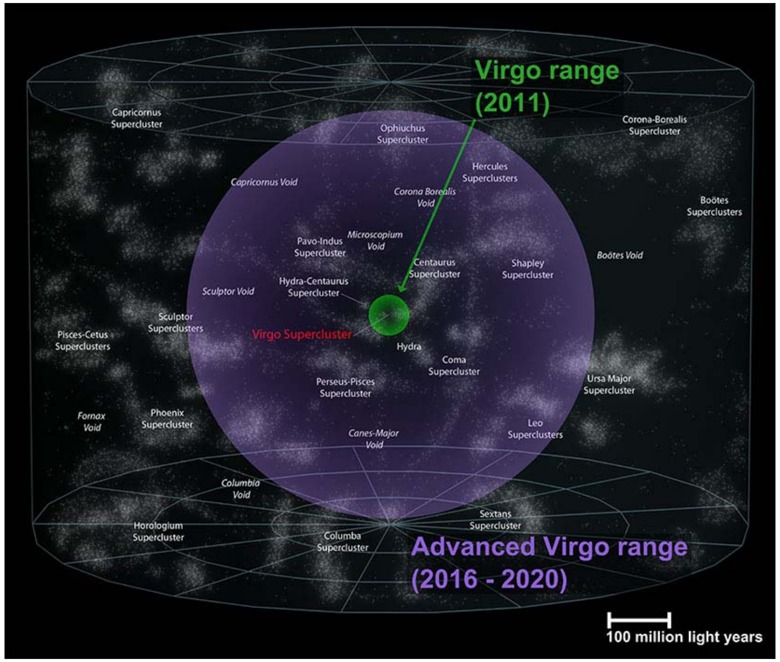
- 21 laboratories
- About 300 members (LIGO: 750)
- Virgo was built by 11 CNRS (France) and INFN (Italy) laboratories
  - Budget: ~150 M€
  - Groups from the Netherlands, Poland, Hungary and Spain joined later the project
- Advanced Virgo funding: ~20 M€
  - Plus in-kind contribution from NIKHEF
- The EGO (European Gravitational Observatory) consortium is managing the Virgo site in Cascina. It provides the infrastructures and ressources to ensure the detector construction and operation

APC Paris
ARTEMIS Nice
EGO Cascina
INFN Firenze-Urbino
INFN Genova
INFN Napoli
INFN Perugia
INFN Pisa
INFN Roma La Sapienza
INFN Roma Tor Vergata
INFN Padova
INFN TIFPA
LAL Orsay – ESPCI Paris
LAPP Annecy
LKB Paris
LMA Lyon
NIKHEF Amsterdam
POLGRAW (Poland)
RADBOUD Uni. Nijmegen
RMKI Budapest
Valence University

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 completed mid-2017

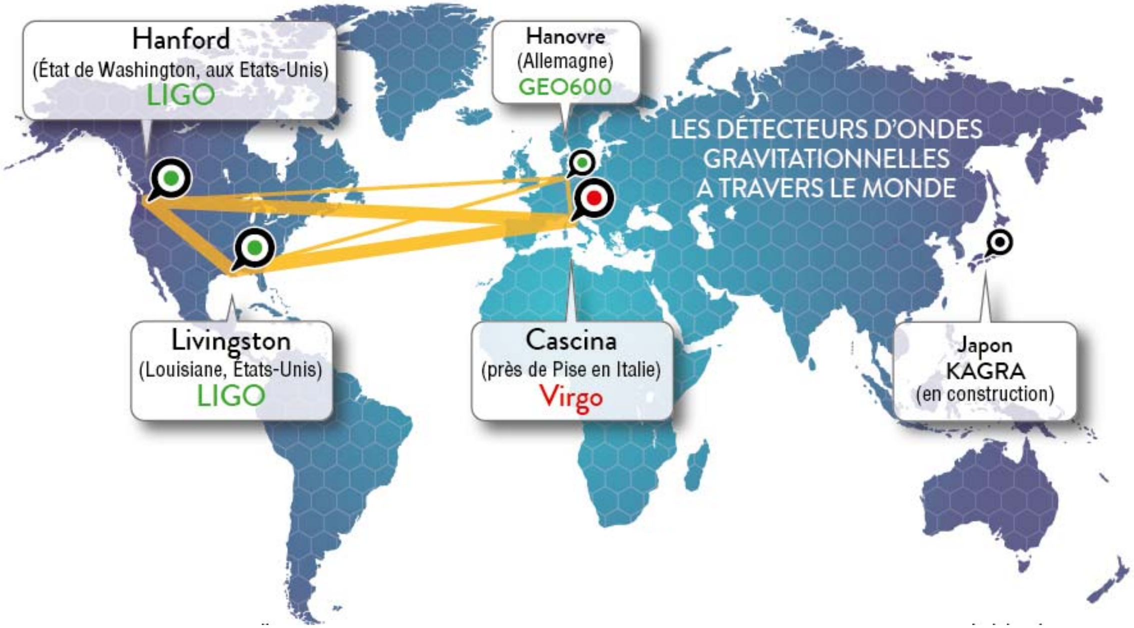
A global network of gravitational-wave interferometric detectors

A network of interferometric detectors

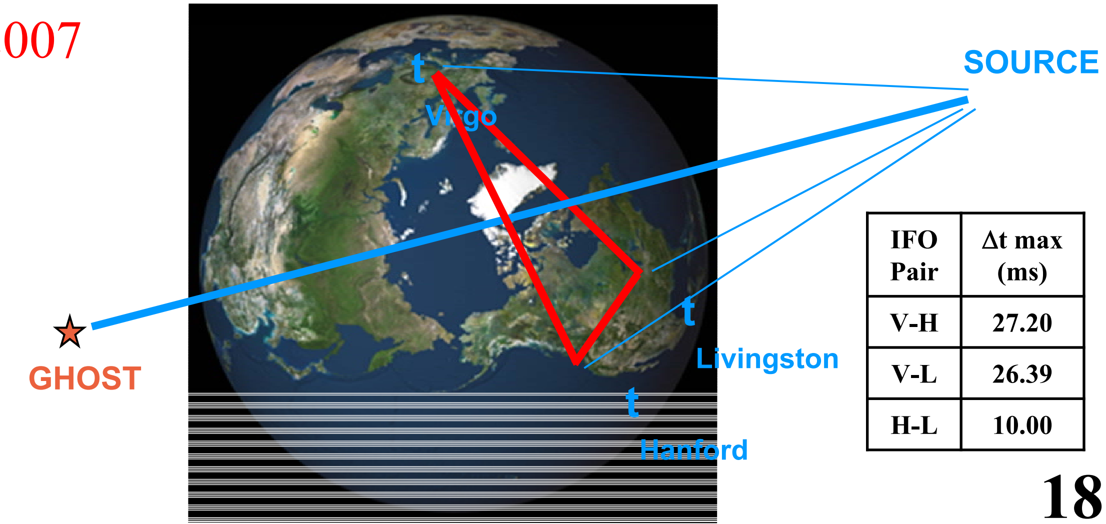
A network of interferometric detectors

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

→ Need to use a network of interferometers



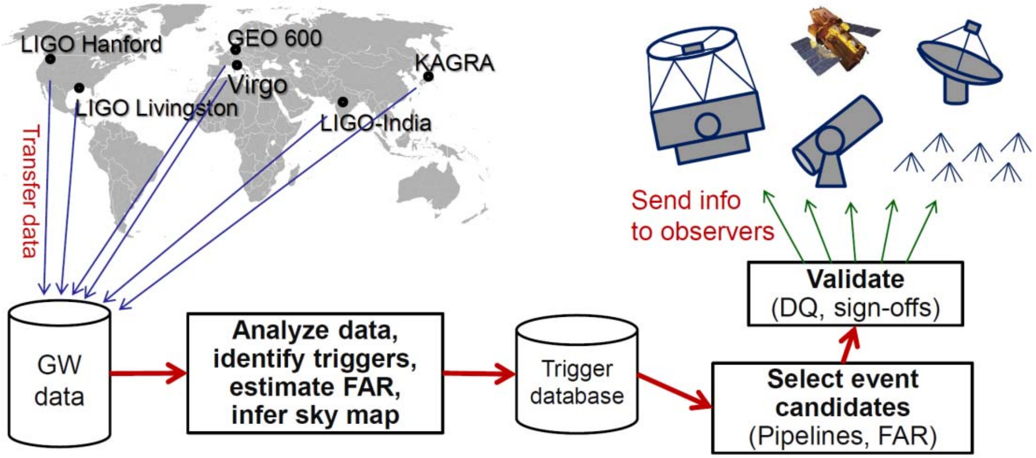
- Agreements (MOUs) between the different projects – Virgo/LIGO: 2007
  - Share data, common analysis, publish together
- IFO: non-directional detectors; non-uniform response in the sky
- Threefold detection: reconstruct source location in the sky



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

Exploiting multi-messenger information

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



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

Interferometer angular response

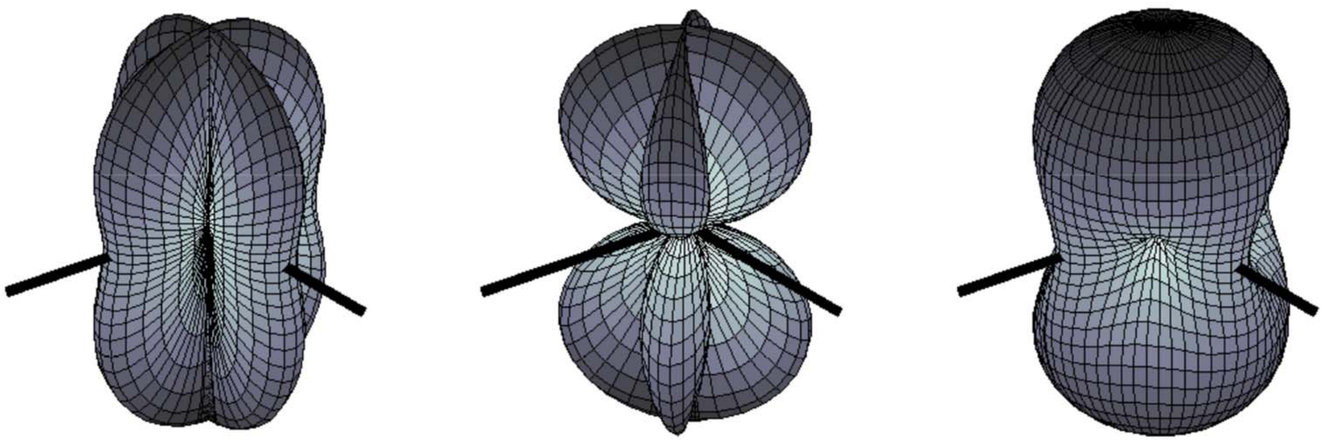
- An interferometer is not directional: it probes most of the sky at any time
  - More a microphone than a telescope!

- 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)

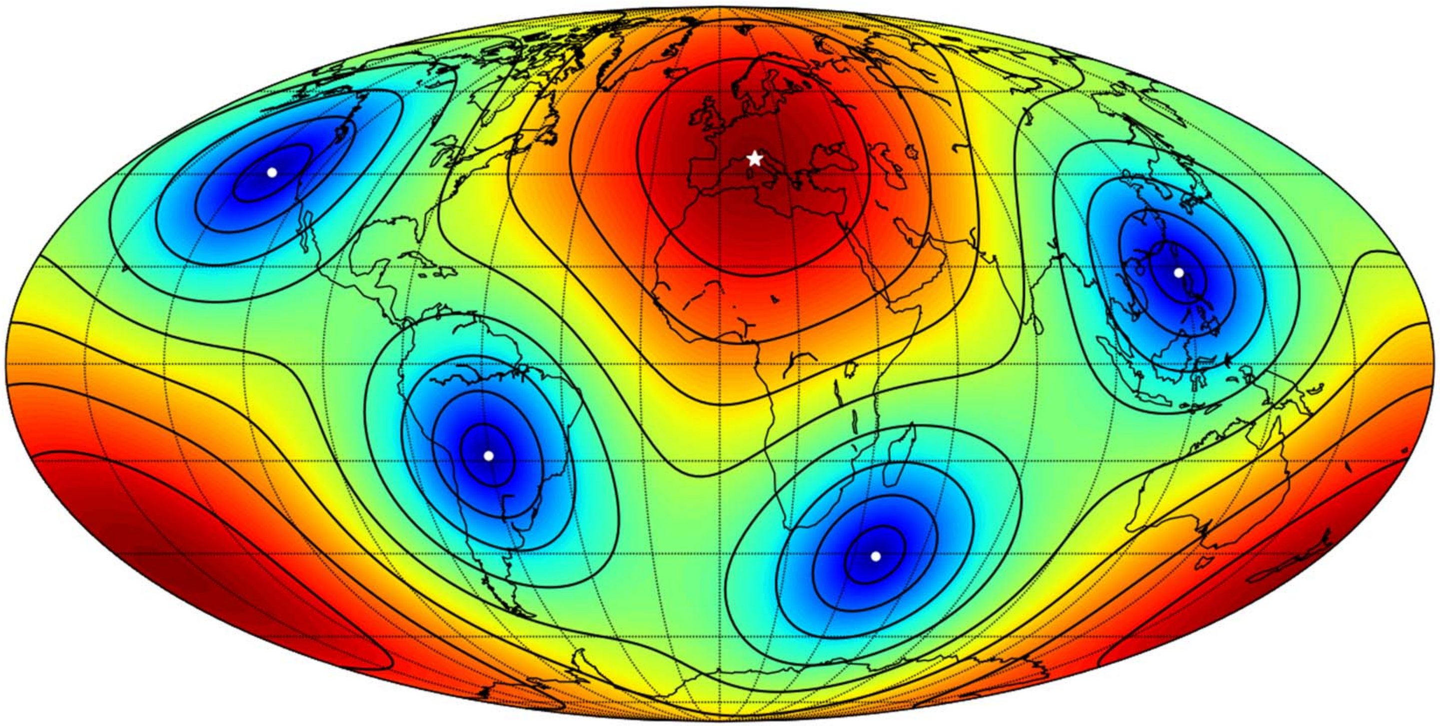
+ polarization   × polarization   unpolarized



Virgo antenna pattern

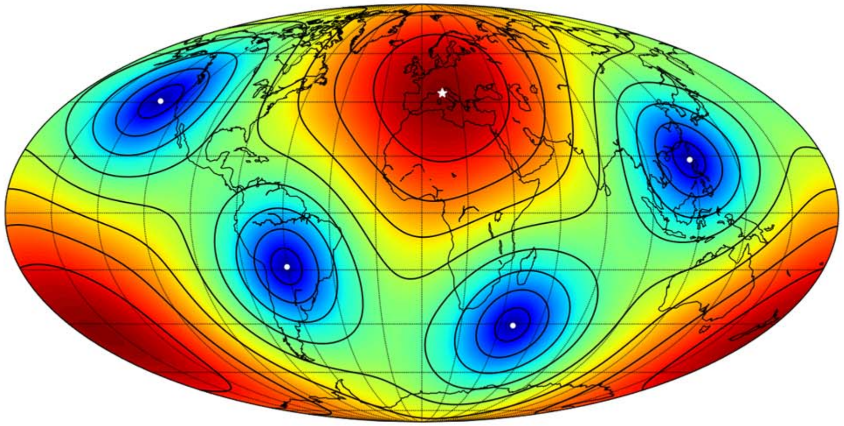
- Two optimal directions
  - Zenith and nadir

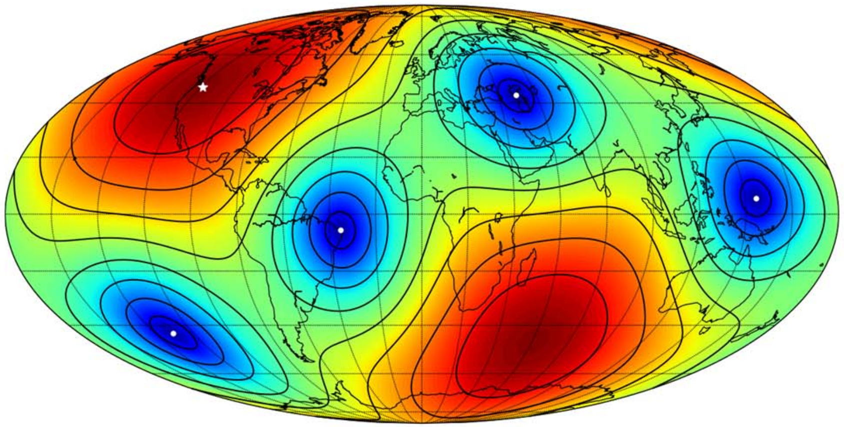
- Four blind spots
  - All in the detector plane
  - Along the arm bissector and at 90 degrees from that

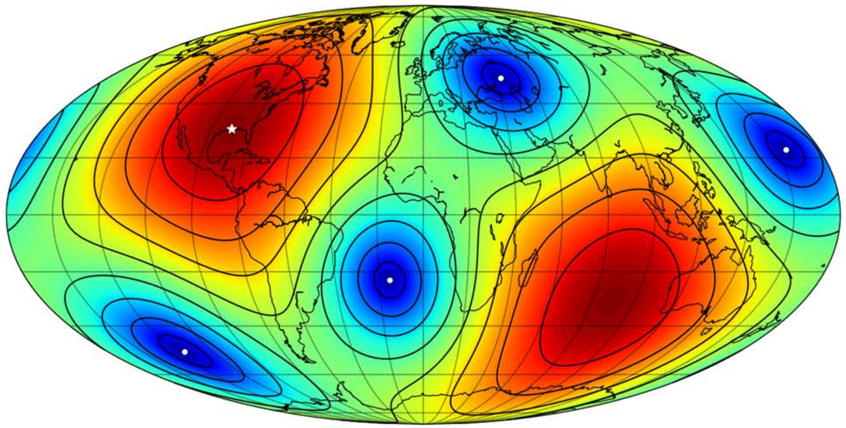


LIGO-Virgo antenna patterns

- LIGO detectors ≈ co-aligned
- Virgo has a different orientation



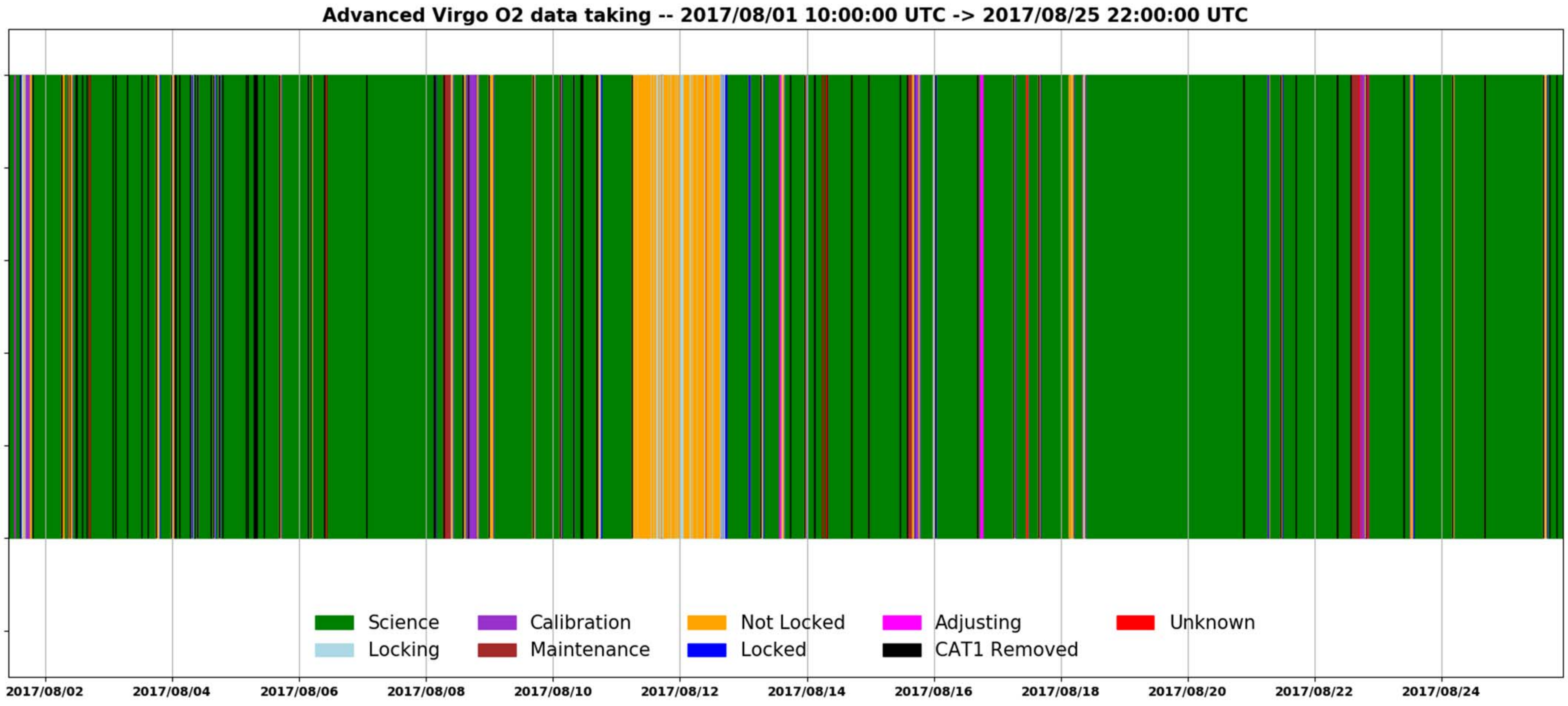




Virgo O2 data taking August 1 – August 25 2017

4 weeks of Virgo data taking in a nutshell

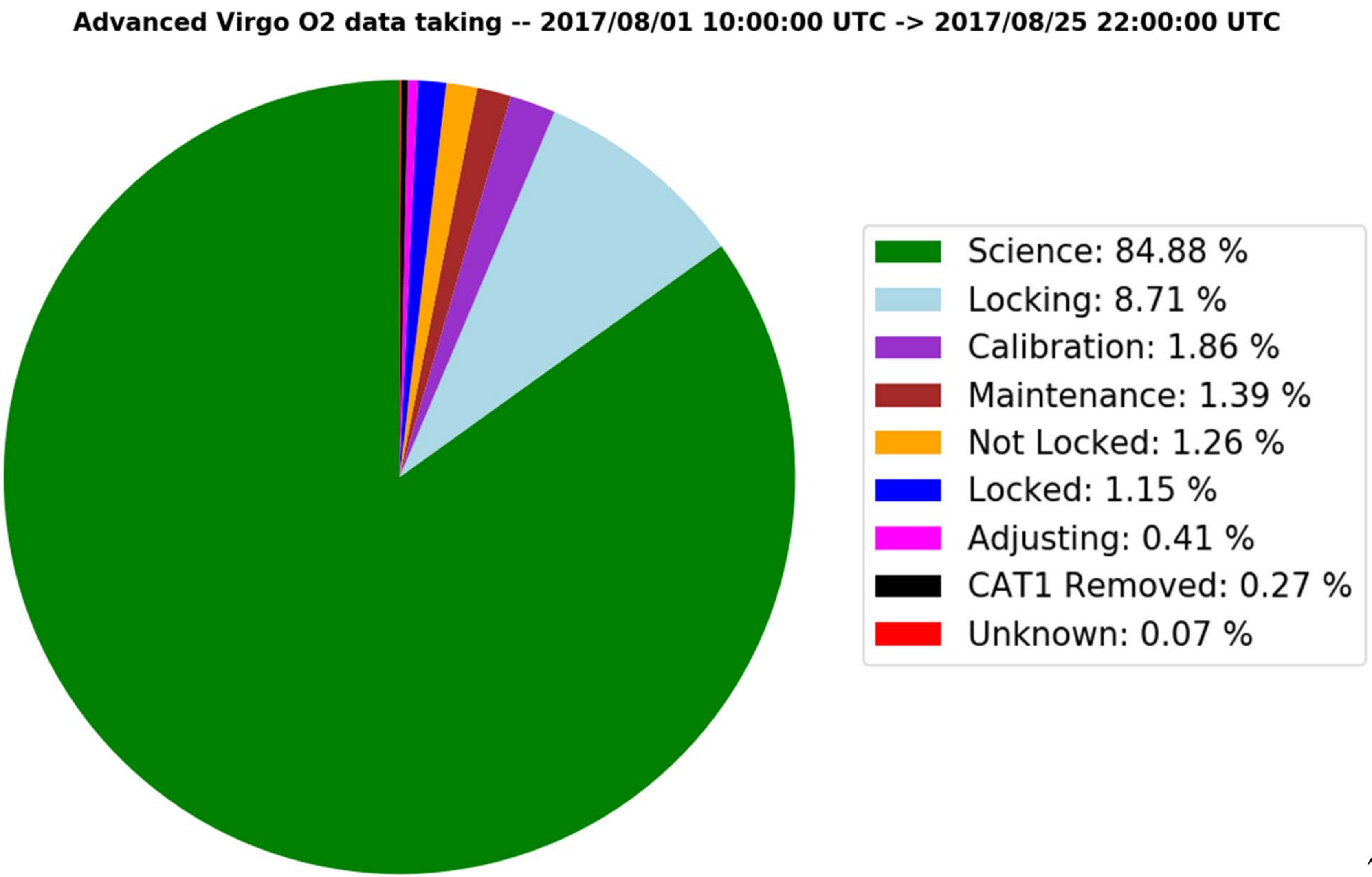
- Duty cycle stripchart
  - Green ↔ Data taking in science mode



- 'Segments' (vertical colored bands) are drawn from the longest to the shortest
  → Short segments look more visible than their actual weight in the dataset

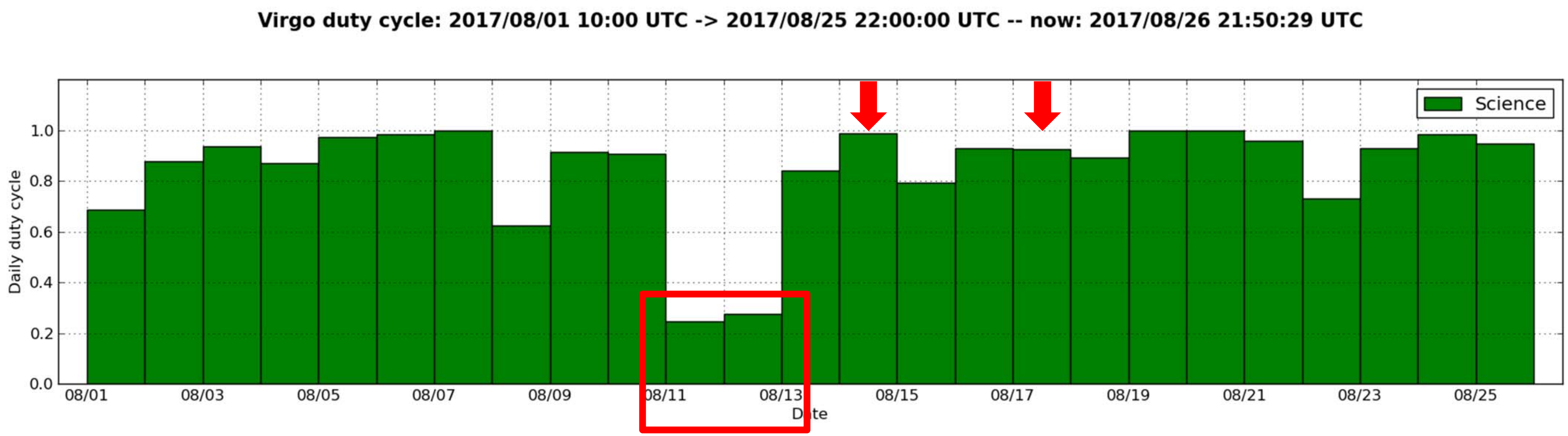
4 weeks of Virgo data taking in a nutshell

- Duty cycle pie chart



4 weeks of Virgo data taking in a nutshell

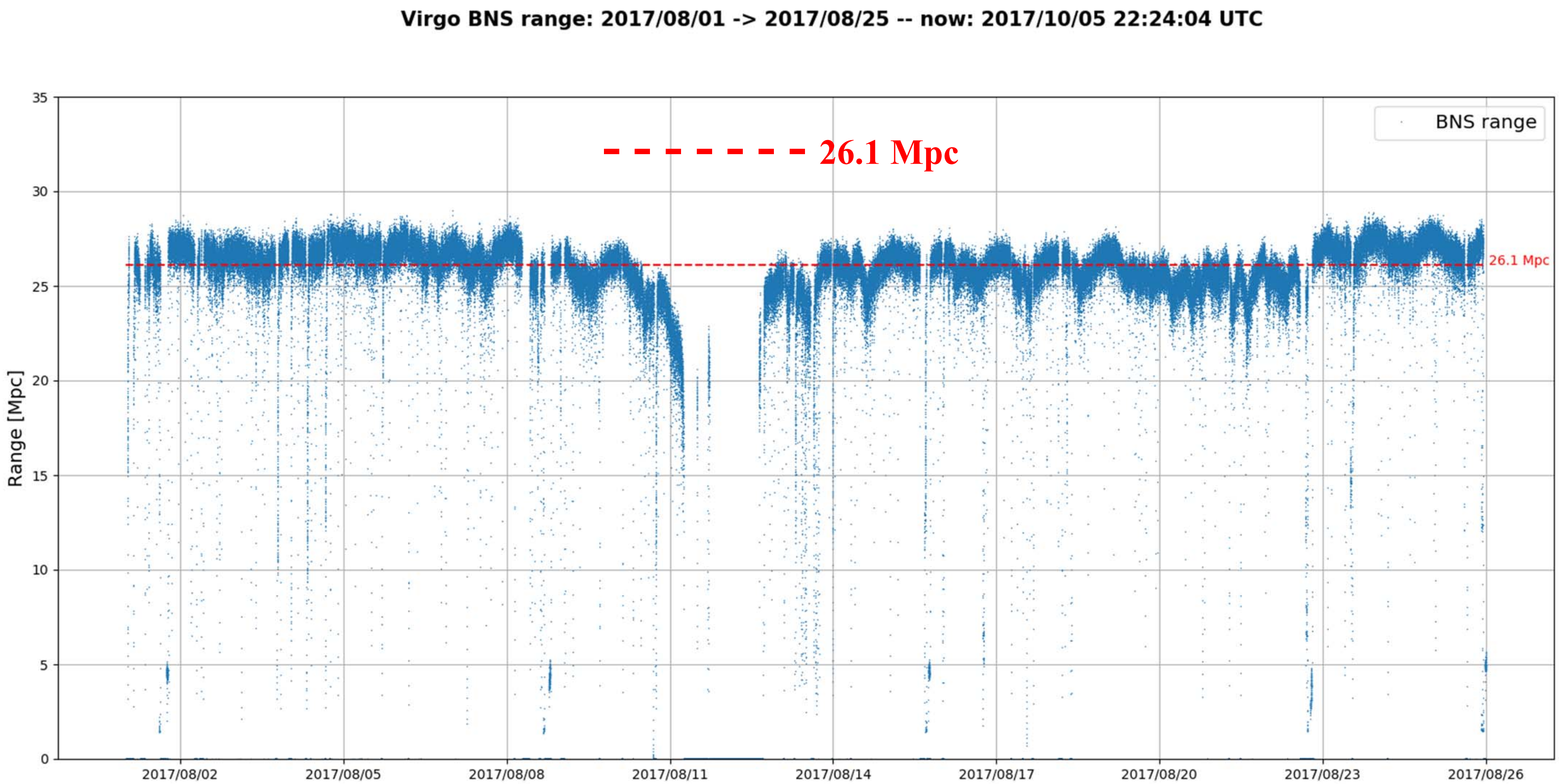
- Daily duty cycle



Bad weather conditions
→ High seismic activity

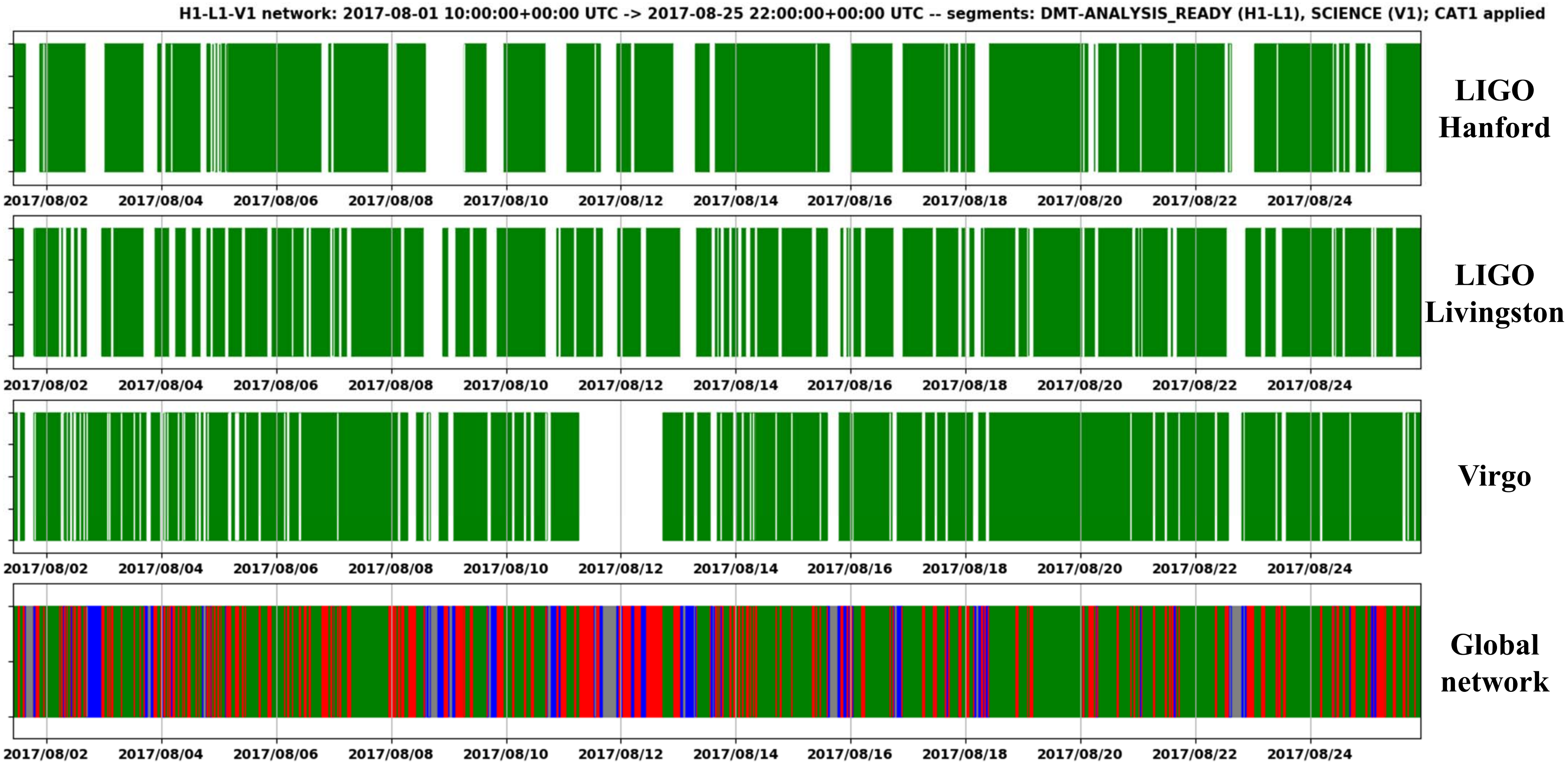
4 weeks of Virgo data taking in a nutshell

- Binary neutron star (BNS) range
  - Figure of merit summarizing the detector sensitivity



Global network data taking

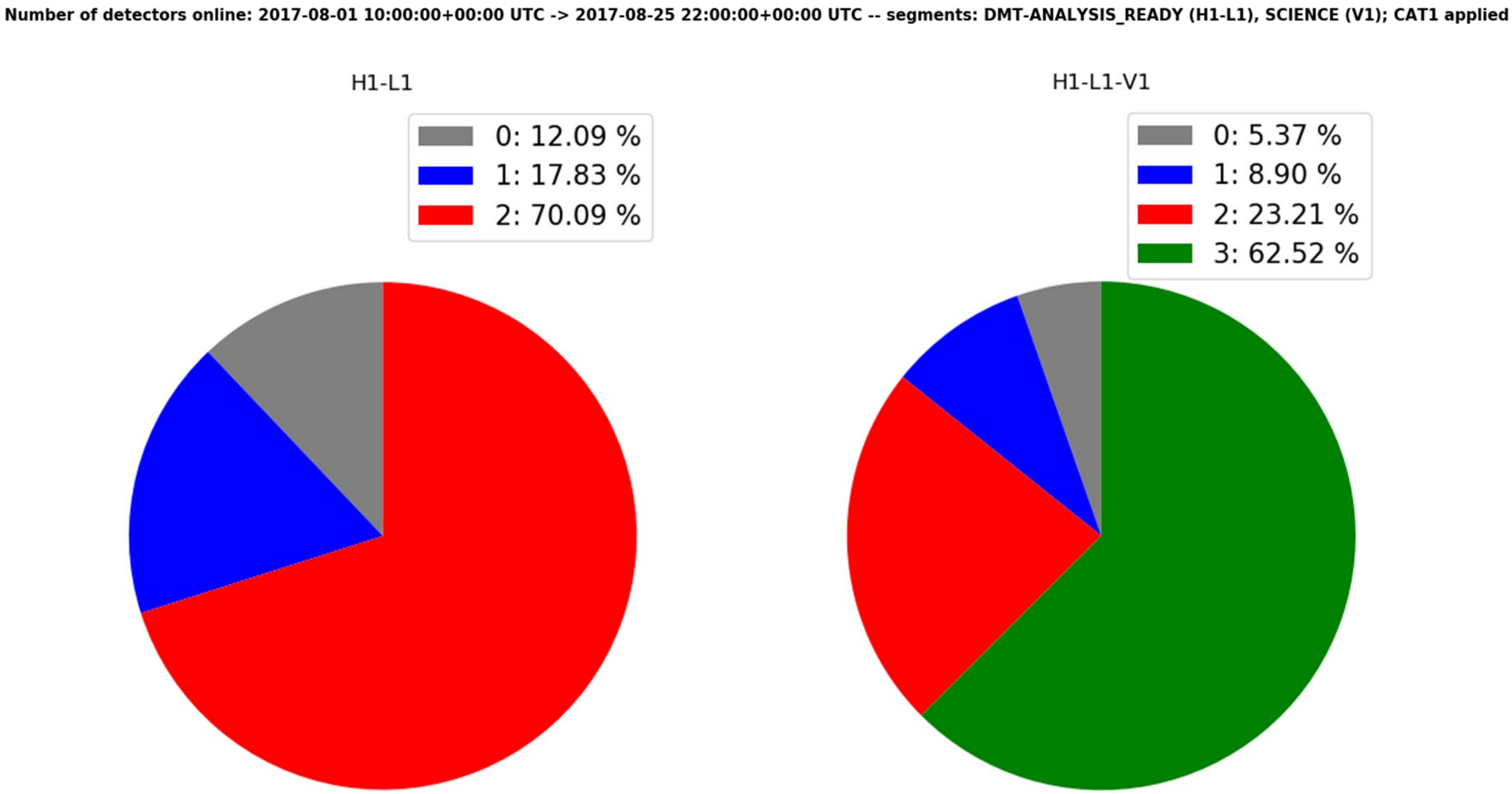
- Network duty cycle
  - Single detectors: Green ↔ Good science data
  - Network: 0/3 2/3 1/3 3/3



- Synchronized maintenance periods clearly visible

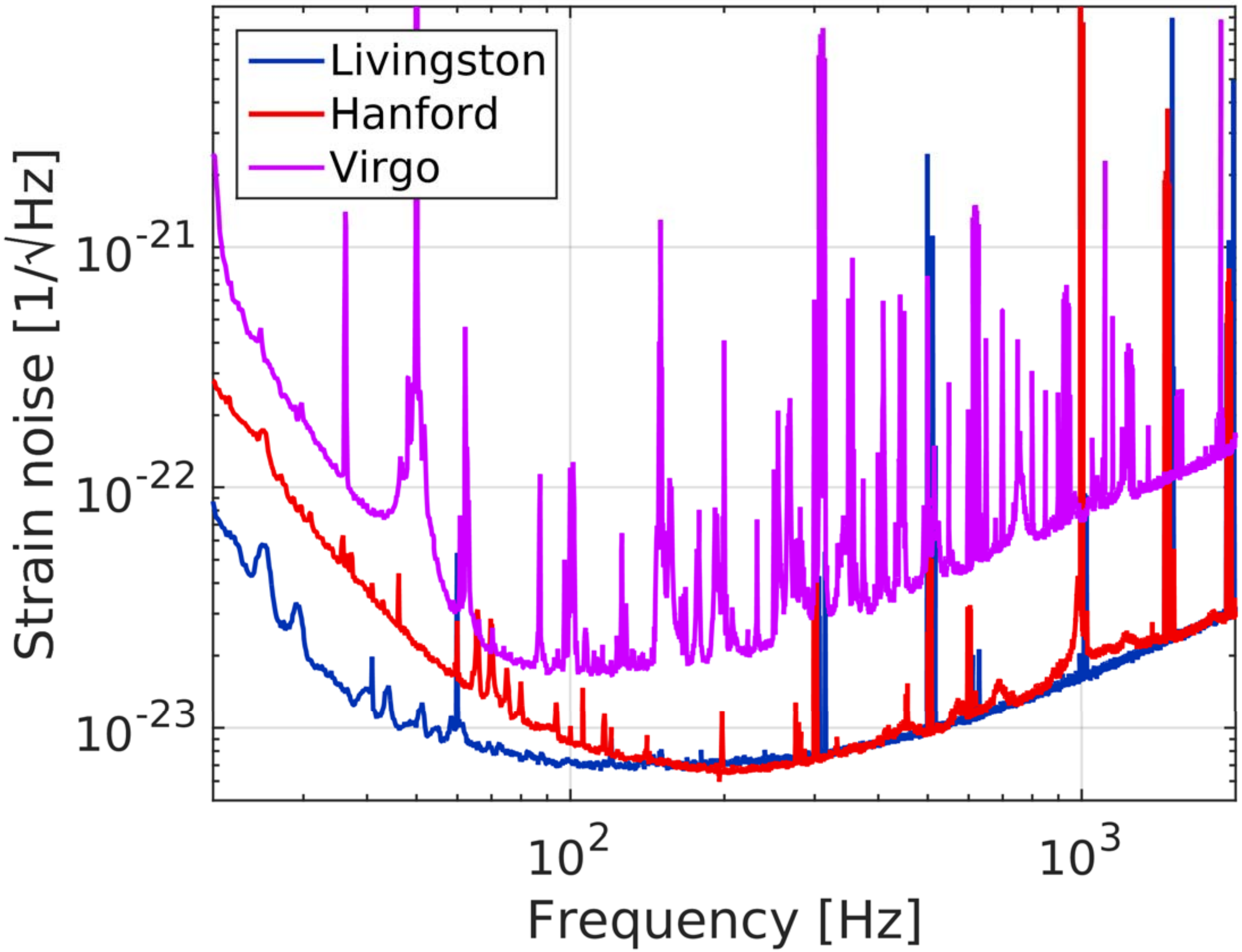
Global network data taking

- Pie charts comparing the LIGO and LIGO-Virgo network performances



Global network data taking

- Comparing typical August 2017 sensitivities



2015-2017:
the first detections
of gravitational waves

1916-2018: 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 (Brillet, Giazotto) and LIGO proposals
- **1990's: LIGO and Virgo funded**
- **2005-2011: initial IFO « science » » runs**
- **2007: LIGO-Virgo MoU**
- **First half of the 2010's: Upgrades**
- **2015: First Advanced LIGO run**
- **2017: First Advanced Virgo run**

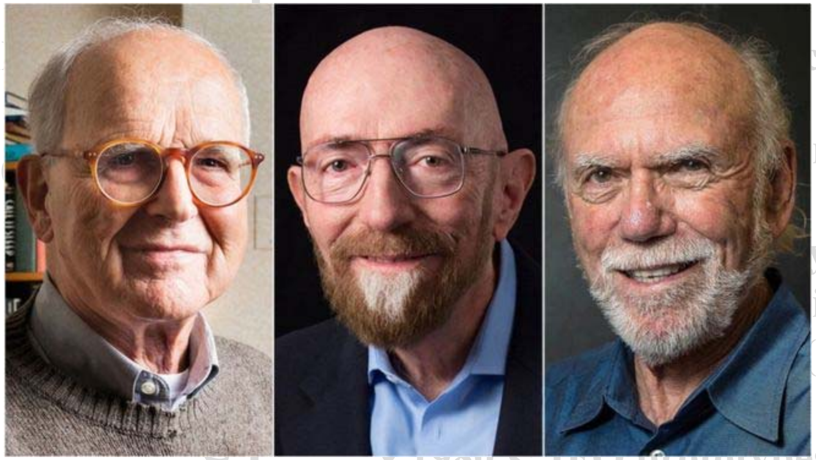
} **First GW Detections**

1916-2018: a century of progress

- 1916: GW prediction (Einstein)

1957: Chapel Hil … .)

- 1963: rotating BH solution … rs



… ype (Forward)
… ies (Weiss)
… (Hulse & Taylor)

- 1980's: IFO prototypes (10m-long)
(Caltech, Garching, Glasgow, Orsay)
→ End c …

90's: I …

05-20 …

07: LI …

rst hal …

(Baker, Lousto, Pretorius, etc.)

- 2015: First Advanced LIGO run
- 2017: First Advanced Virgo run

} First GW Detections

LIGO and Virgo data taking periods

- Pluriannual upgrade program of the LIGO and Virgo detectors
  - Ultimate goal: to increase the instrument sensitivity by one order of magnitude
    → Increase the volume of Universe probed by a factor 1,000

- Observation Run 1 (« O1 »): September 2015 → January 2016
  - LIGO detectors only

  → First two detections of gravitational-wave (GW) signals
    - GW150914 (detected on 2015/09/14) and GW151226
    - In both cases the coalescence of two stellar-mass black holes

- Observation Run 2 (« O2 »): November 30, 2016 – August 25, 2017
  - Maintenance and upgrade in between O1 and O2 for the LIGO detectors
  - First the two LIGO detectors, then LIGO and Virgo from August 1st
  - More binary black hole mergers: GW170104, GW170608, GW170814
  - First binary neutron star merger: GW170817

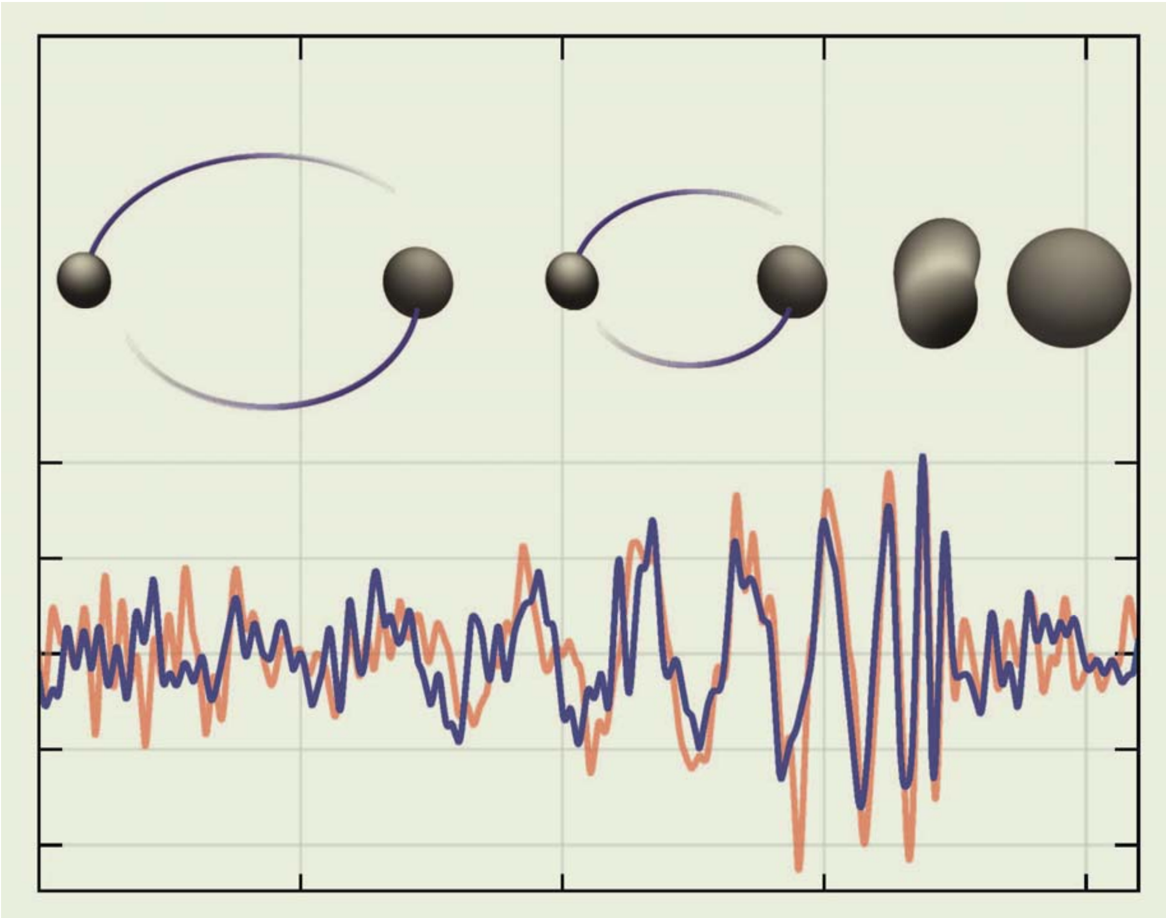
- Then, one year of upgrade before starting the Observation Run 3 (« O3 »)
  - In Fall 2018, for about one year

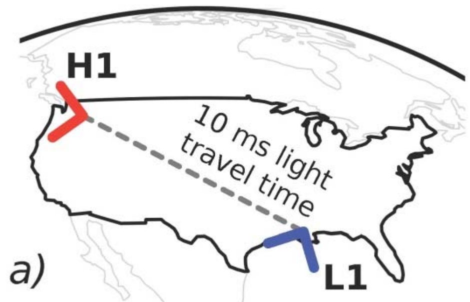
GW150914

September 14 2015, 11:51 CET

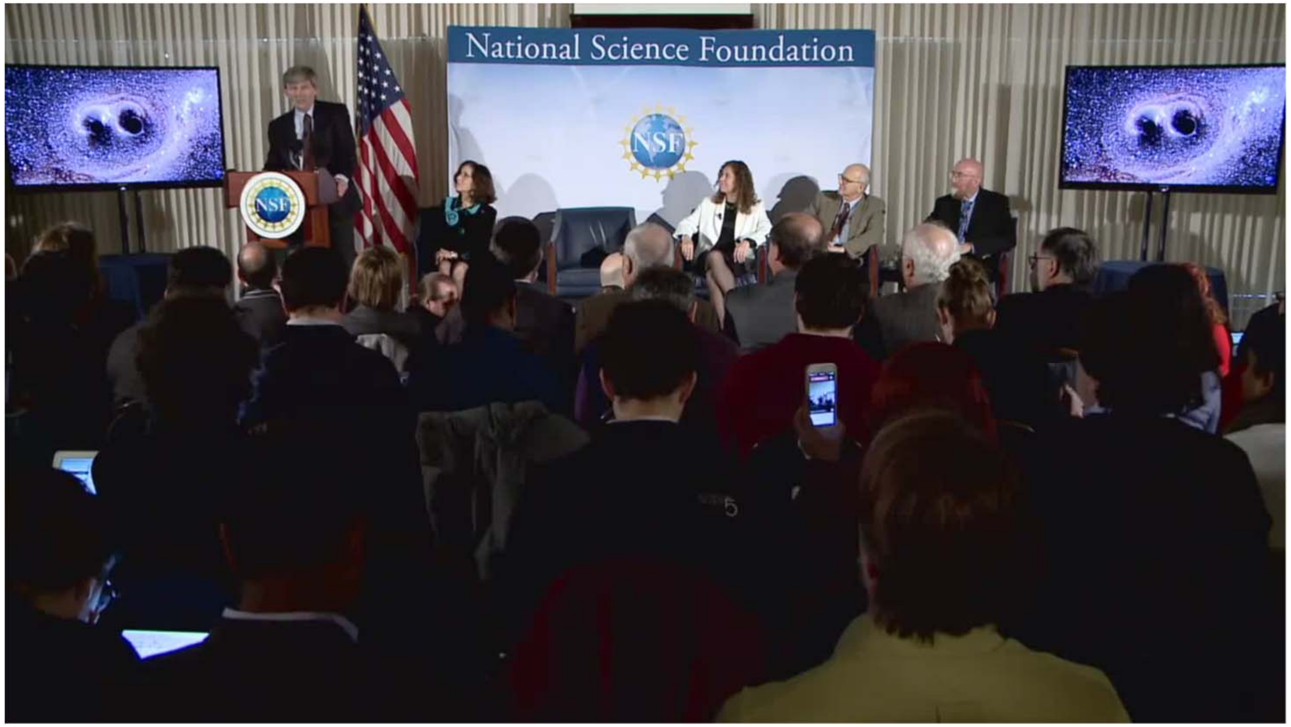
- Signal detected in both LIGO detectors, with a 7 ms delay
  - Short (< 1 s)
  - Very strong/significant
  - Signal expected from a binary black hole coalescence

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

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**

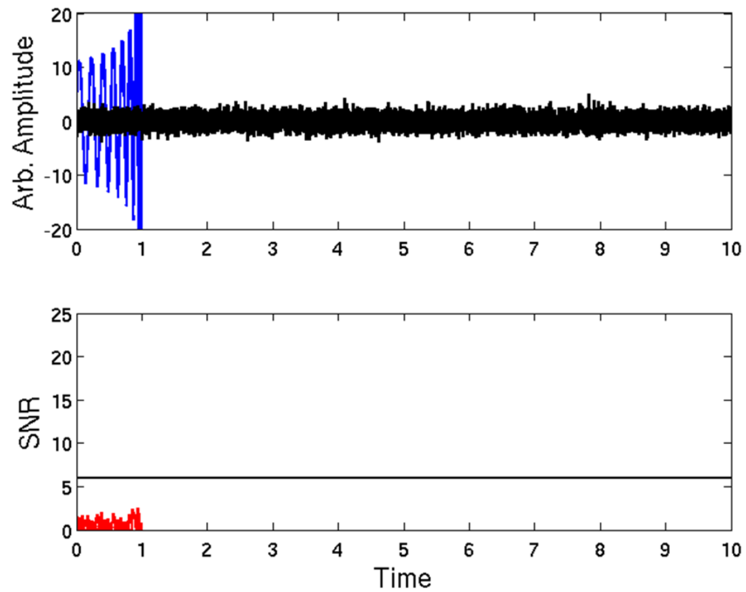
$$\mathcal{C}(t) = \int_{-\infty}^{\infty} \frac{\tilde{x}(f)\tilde{h}^*(f)}{S_n(f)} e^{2\pi i f t} df$$

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



Compact binary coalescence search

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

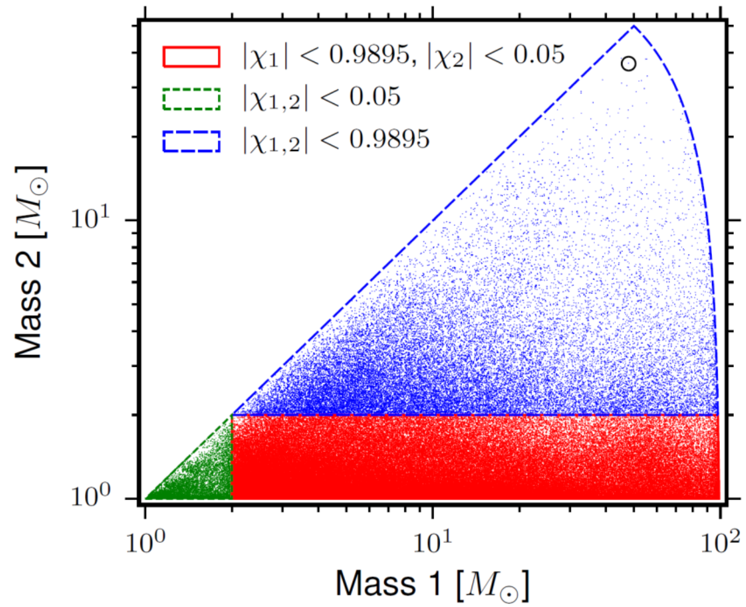
FT of the data

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



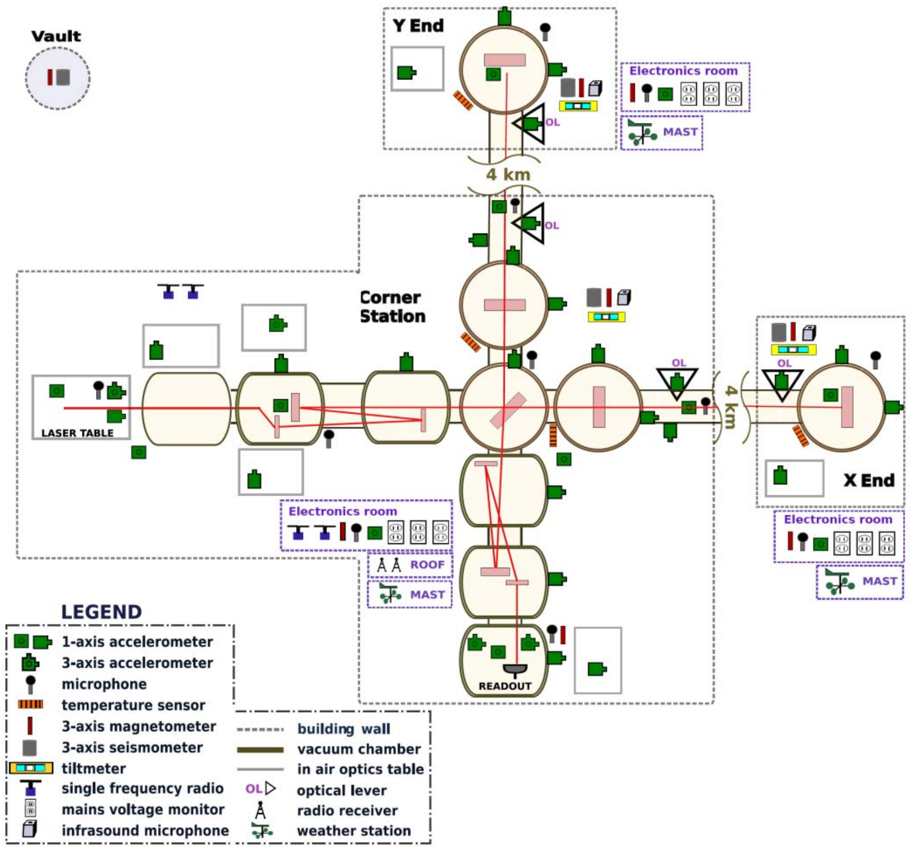
- Look for triggers from the two IFOs using the same template and coincident in time
  - Check matching between signal and template
- Offline search
  - Part of the parameter space searched online
  - Two independent offline pipelines

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

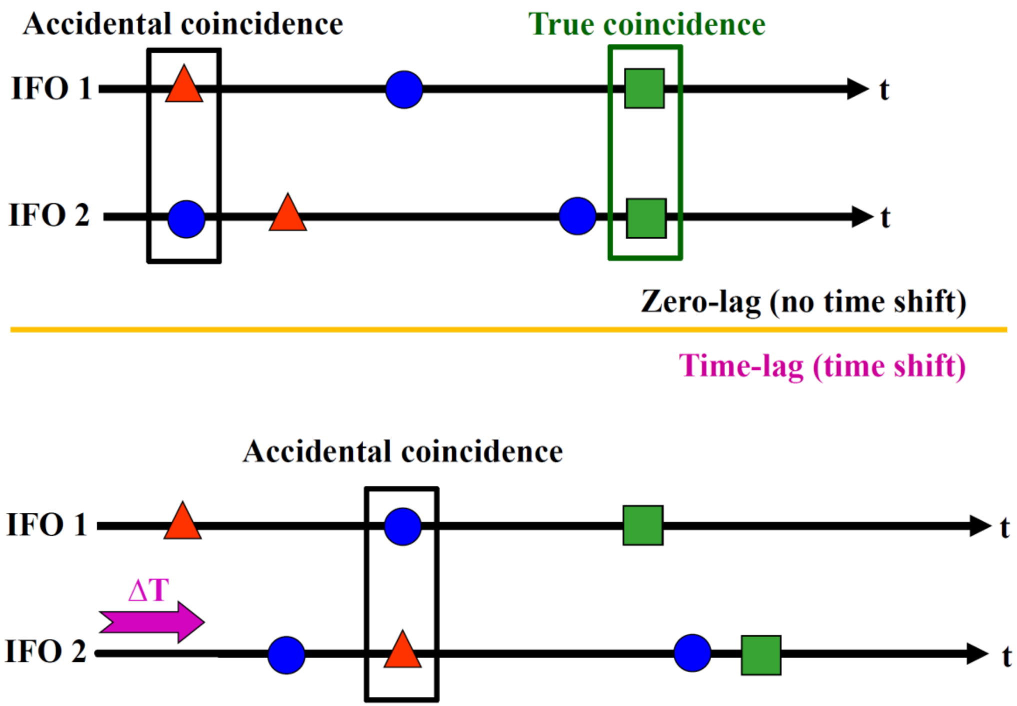
- Extensive studies performed
  - Uncorrelated and correlated noises
  - Bad data quality periods identified and vetoed

  → 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

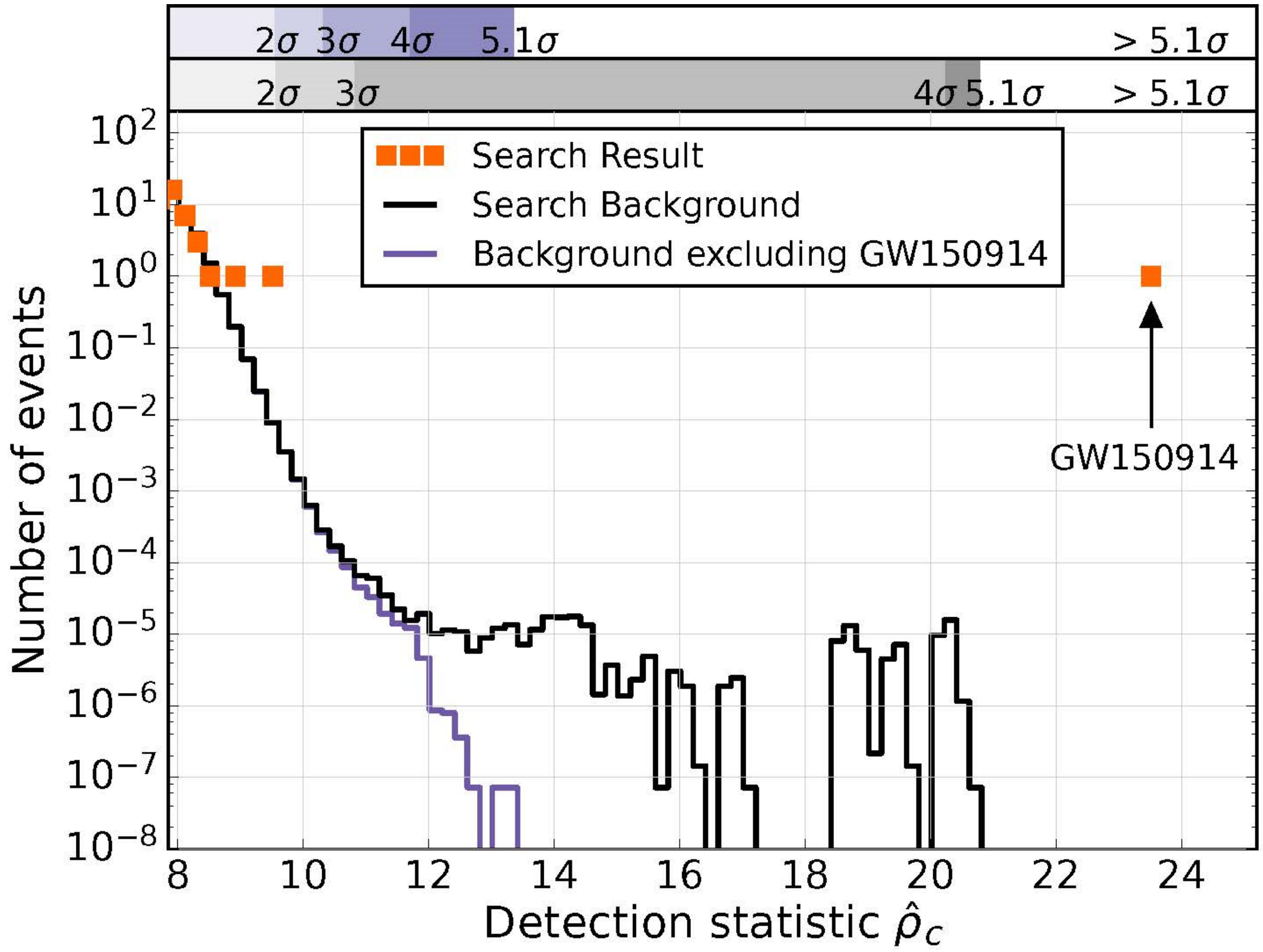


- Reminder: real GW events are shifted by 10 ms at most between IFOs
  - Light travel time over 3,000 km

- 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)

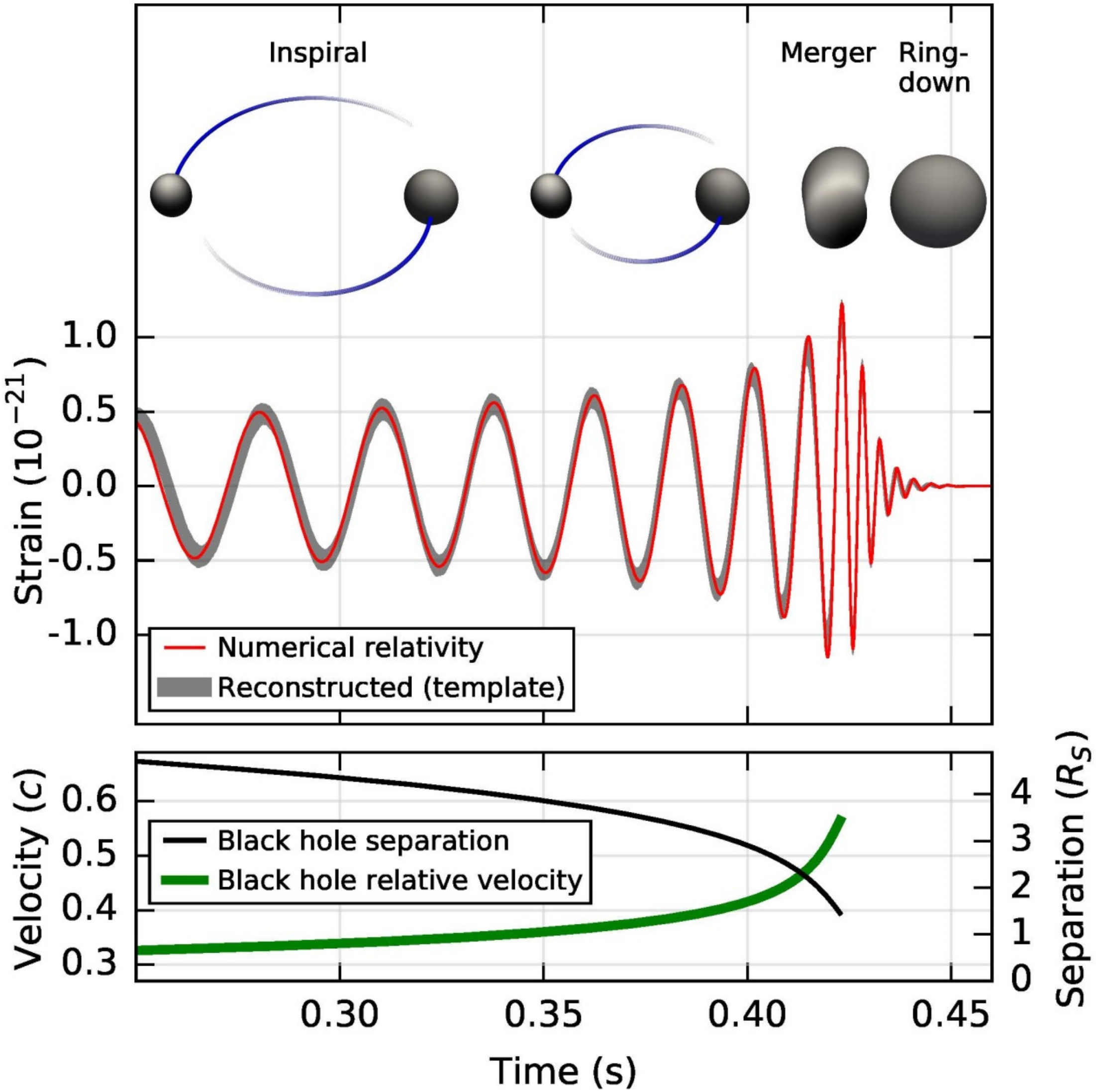


- SNR ~ 23.6; false alarm rate < 1 event / 203,000 years
  false alarm probability $< 2\times10^{-7}$ (> 5.1 σ)

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

GW151226

GW151226

- Observed on 'Boxing Day' 2015
  - Online trigger from the matched filtering analysis
  - Not detected by the burst online search
  - Detailed studies delayed by the completion of the GW150914 analyses

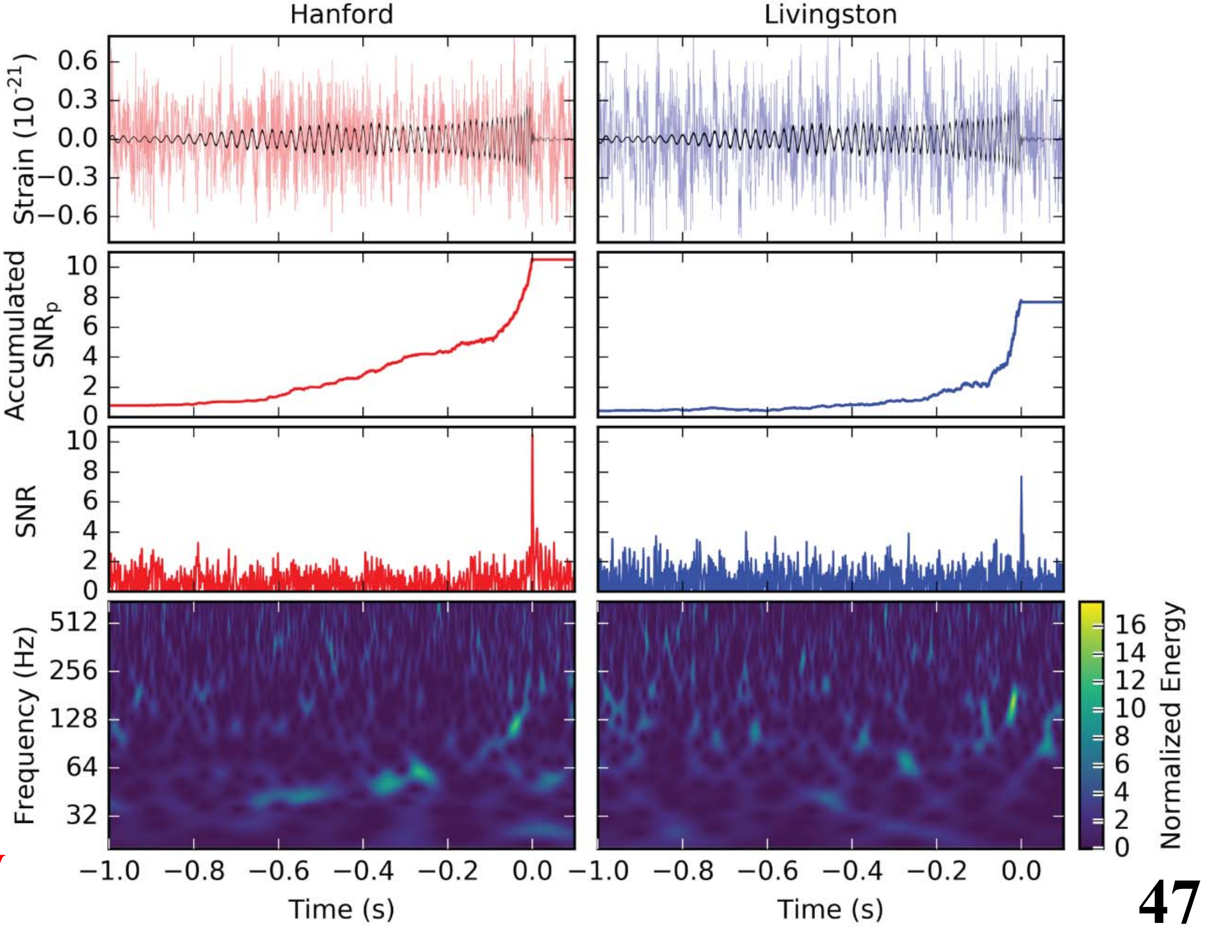
- Not all GW signals visible to the naked eye!

- Another binary black hole coalescence

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

- Smaller amplitude
- More cycles in the detector bandwidth

→ Matched filtering mandatory



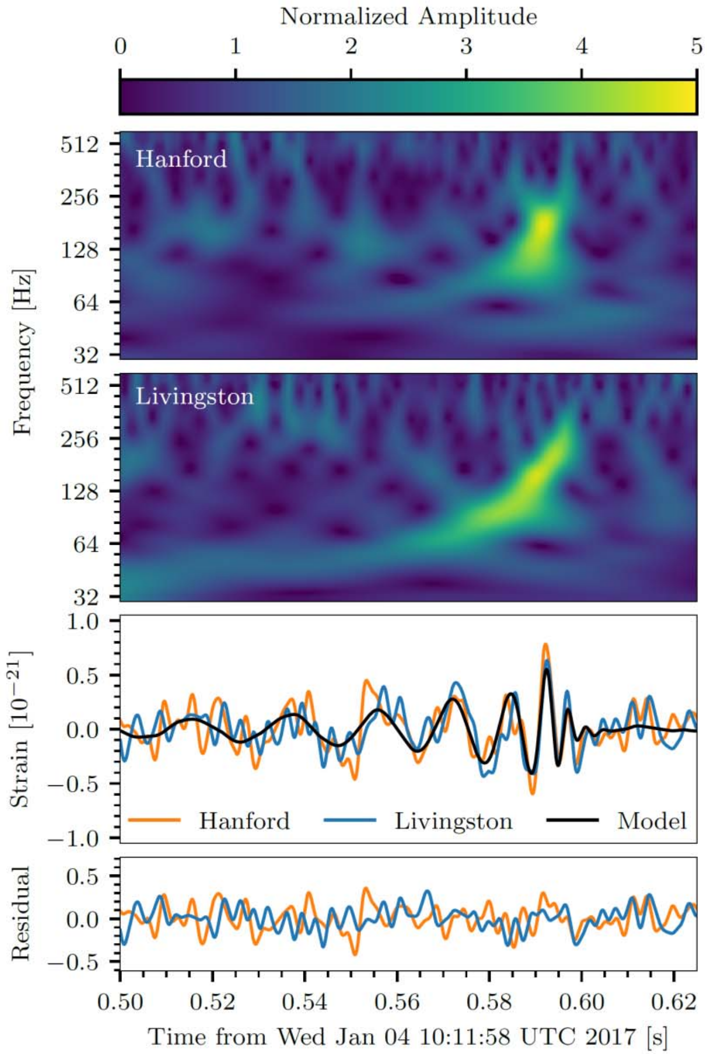
GW170104

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



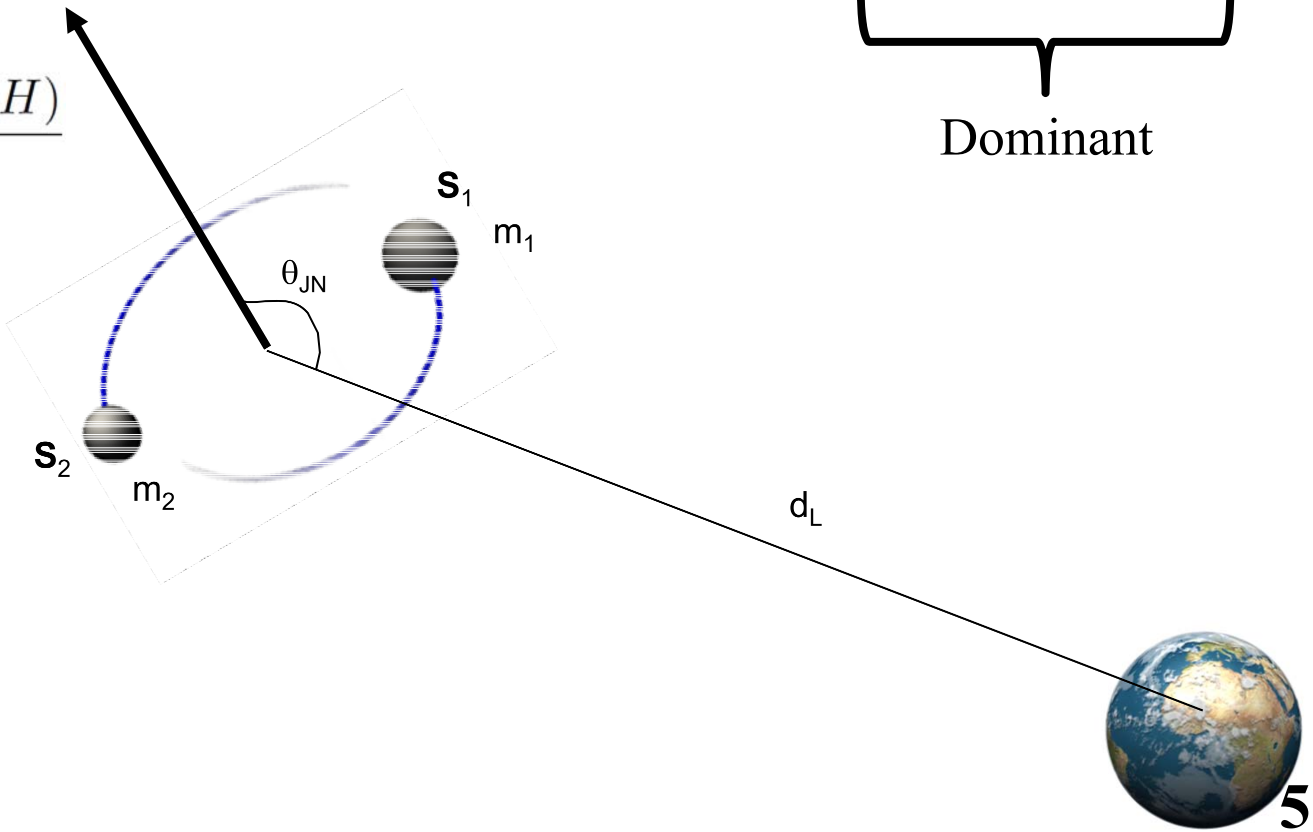
Parameter estimation

- 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

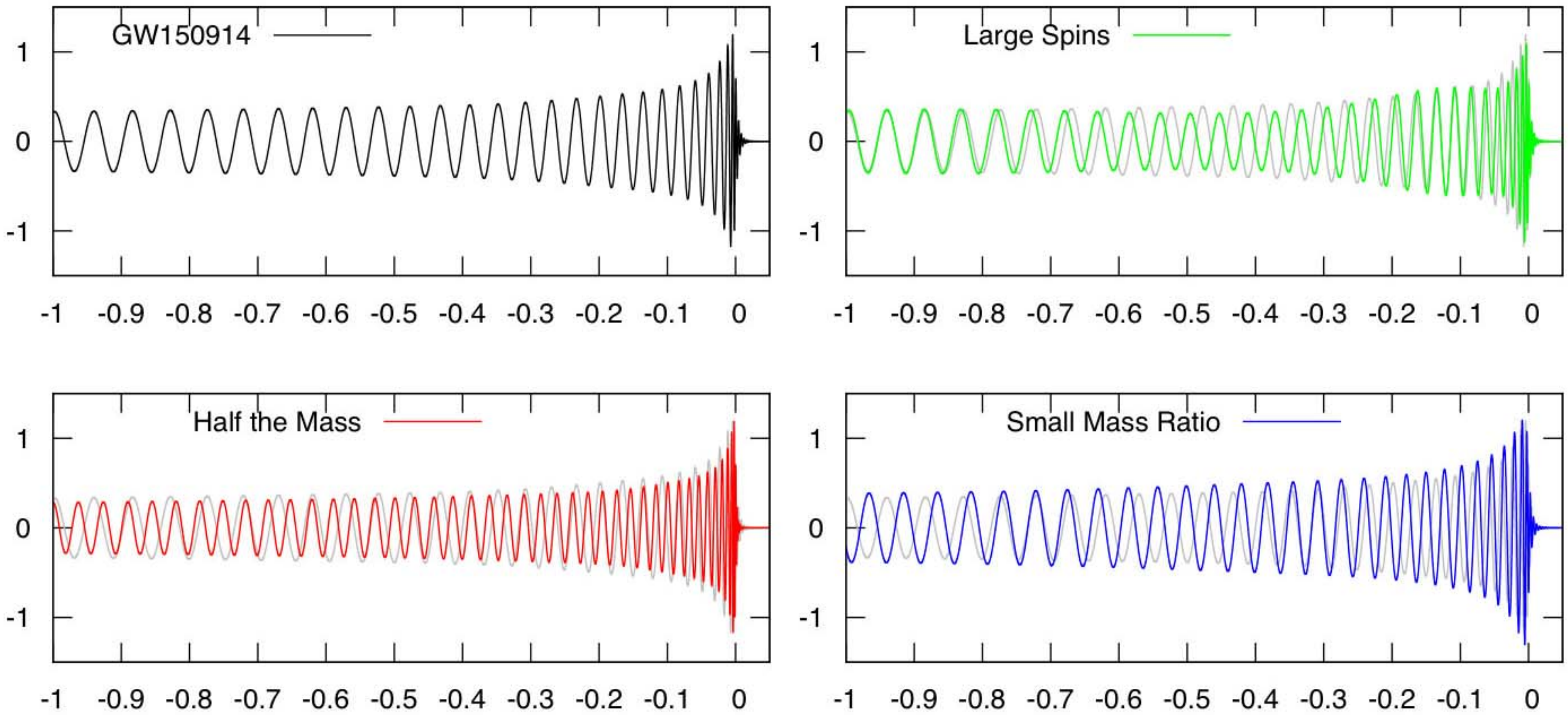


- Compare results from different models → Systematic errors

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

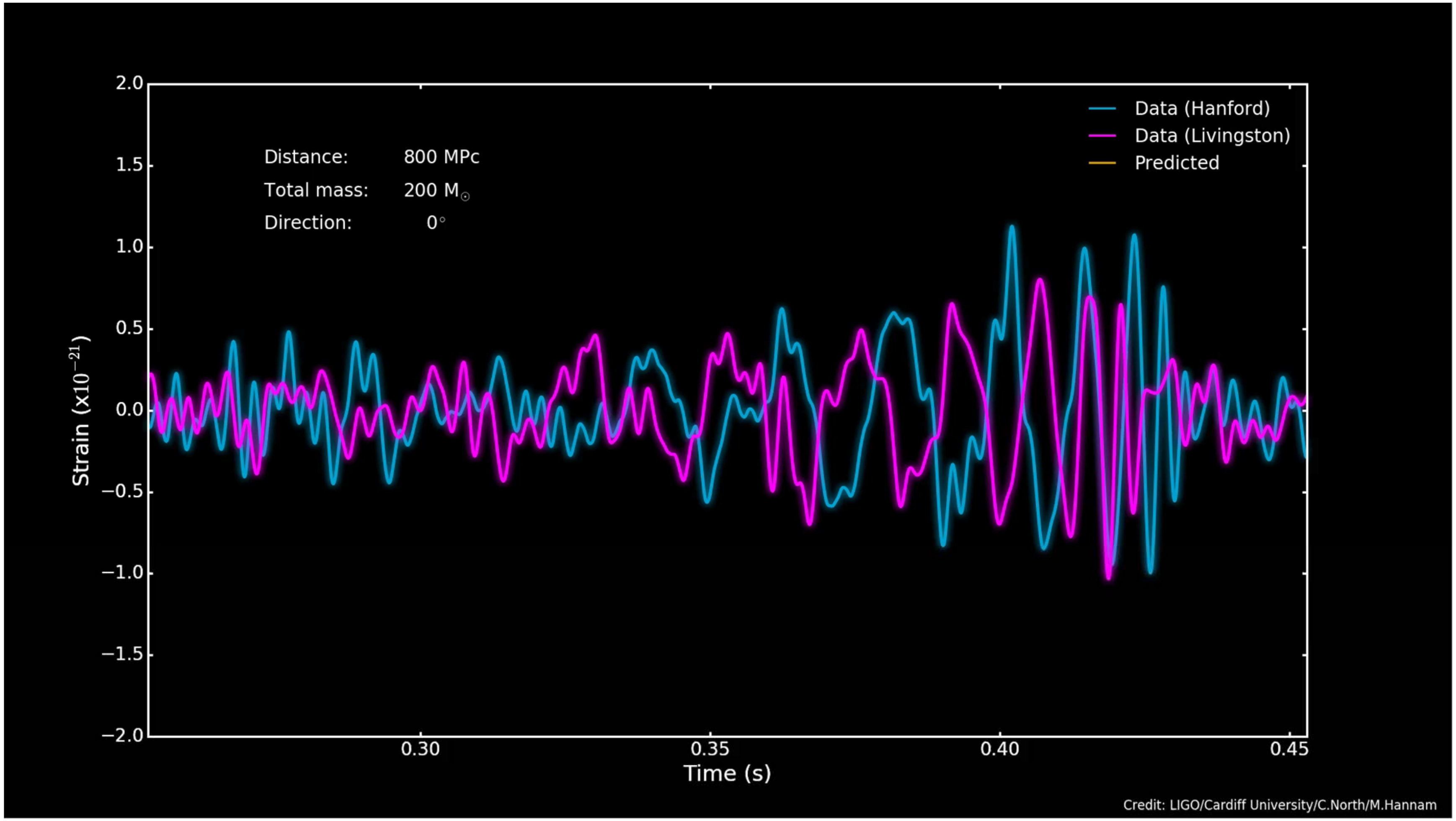
Parameter estimation

- Impact of the black hole parameters on the waveform



Parameter fitting

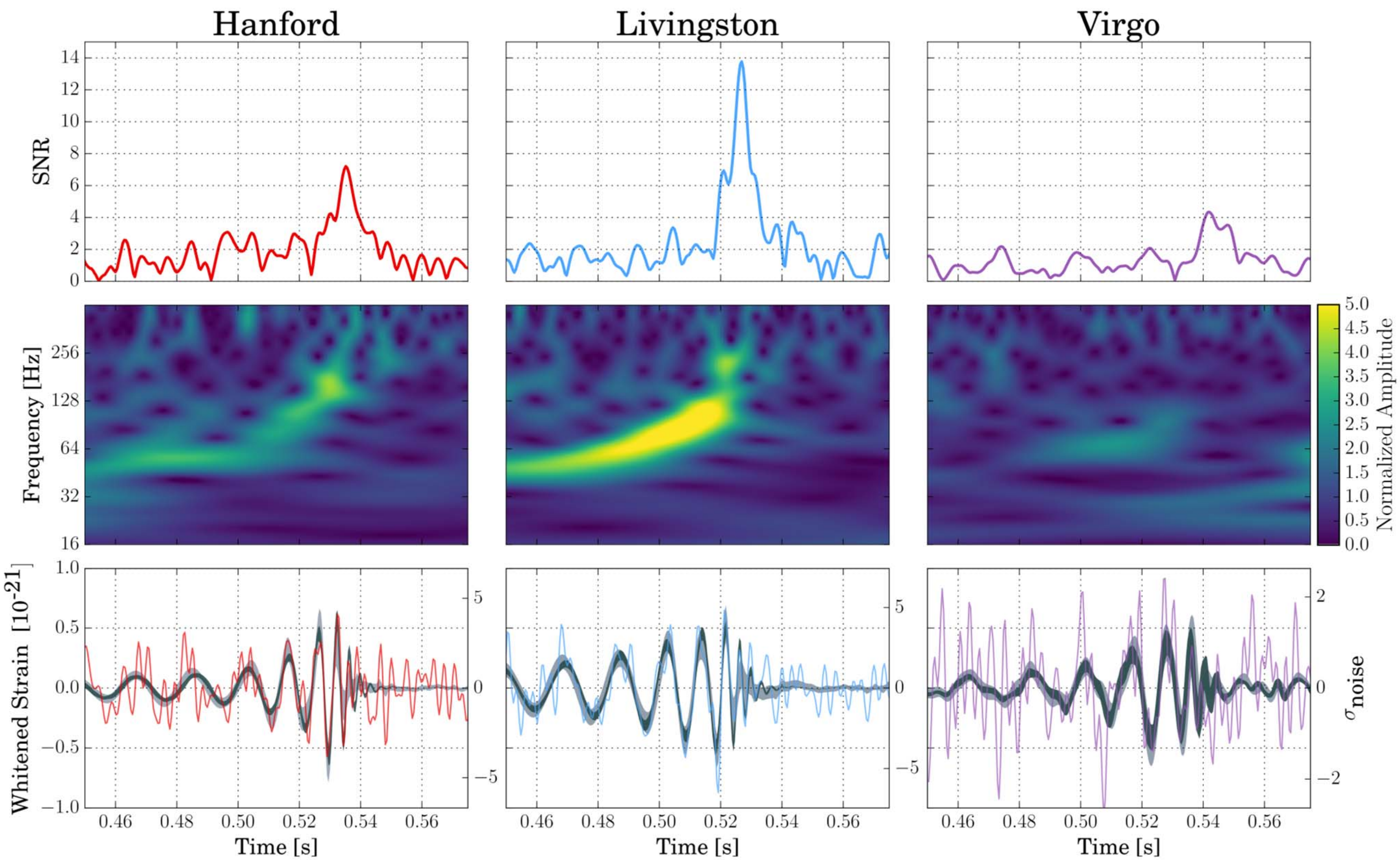
- Animation based on GW170104 data



GW170814

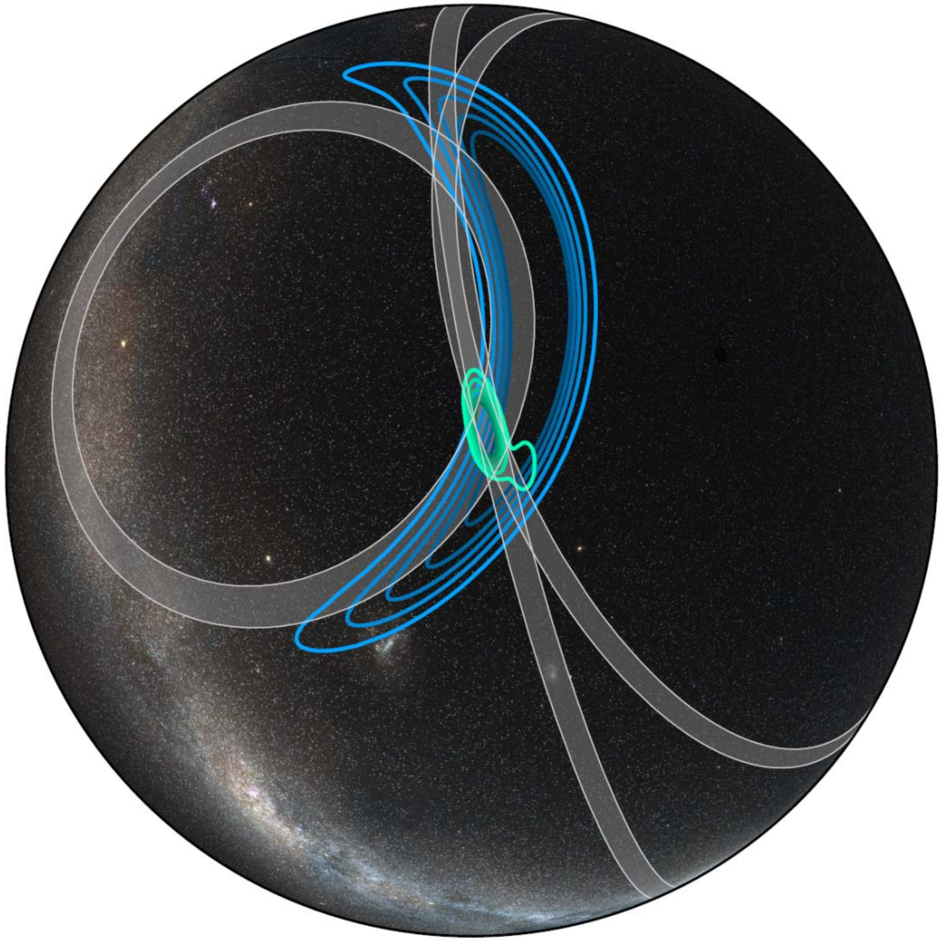
GW170814 detected signals

- Detailled studies confirm evidence of a signal in the Virgo detector



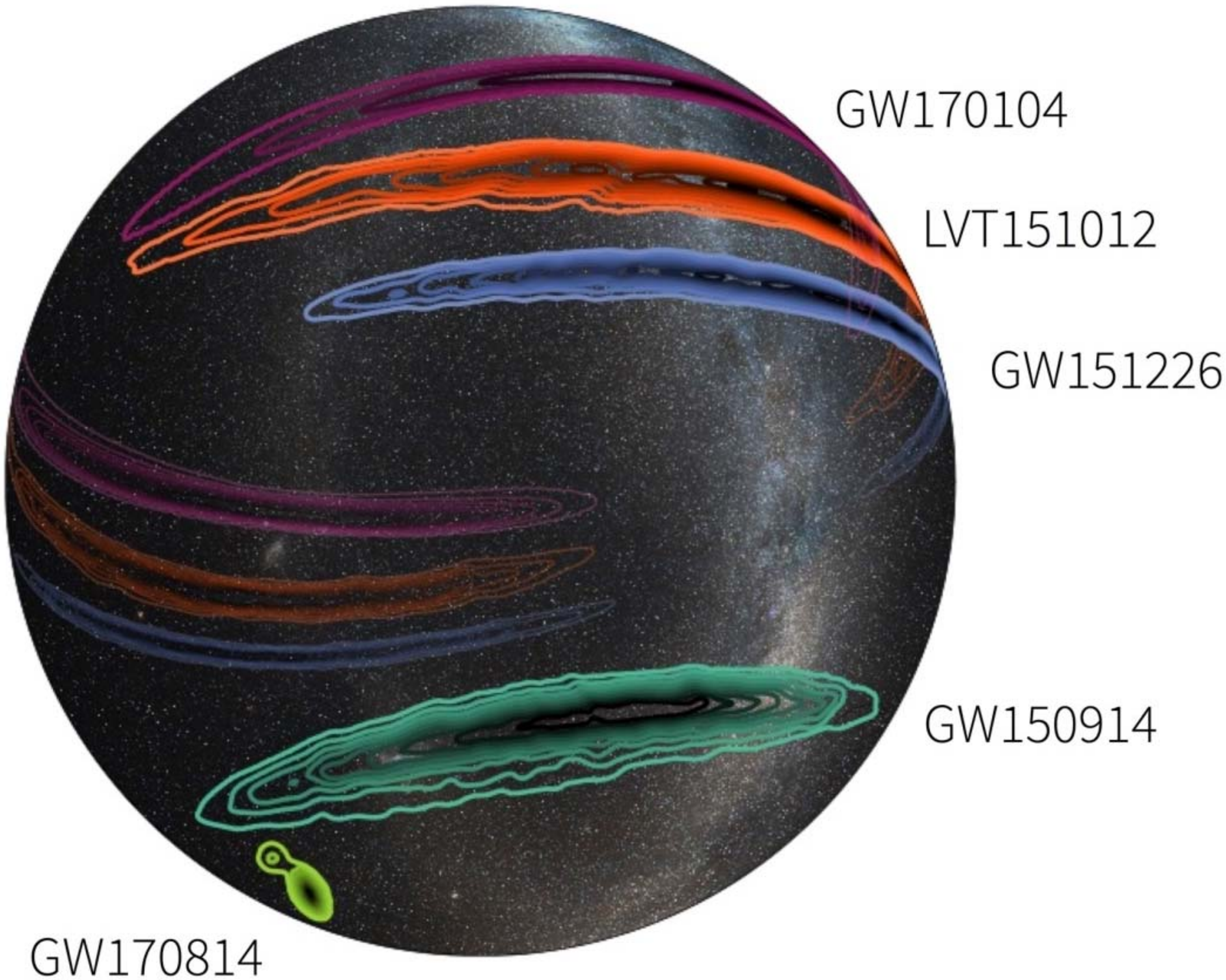
LIGO-Virgo sky localization

- Triangulation
  - Delays in the signal arrival time between detectors
  - Difference in shape and amplitude for the detected signals



LIGO-Virgo sky localization

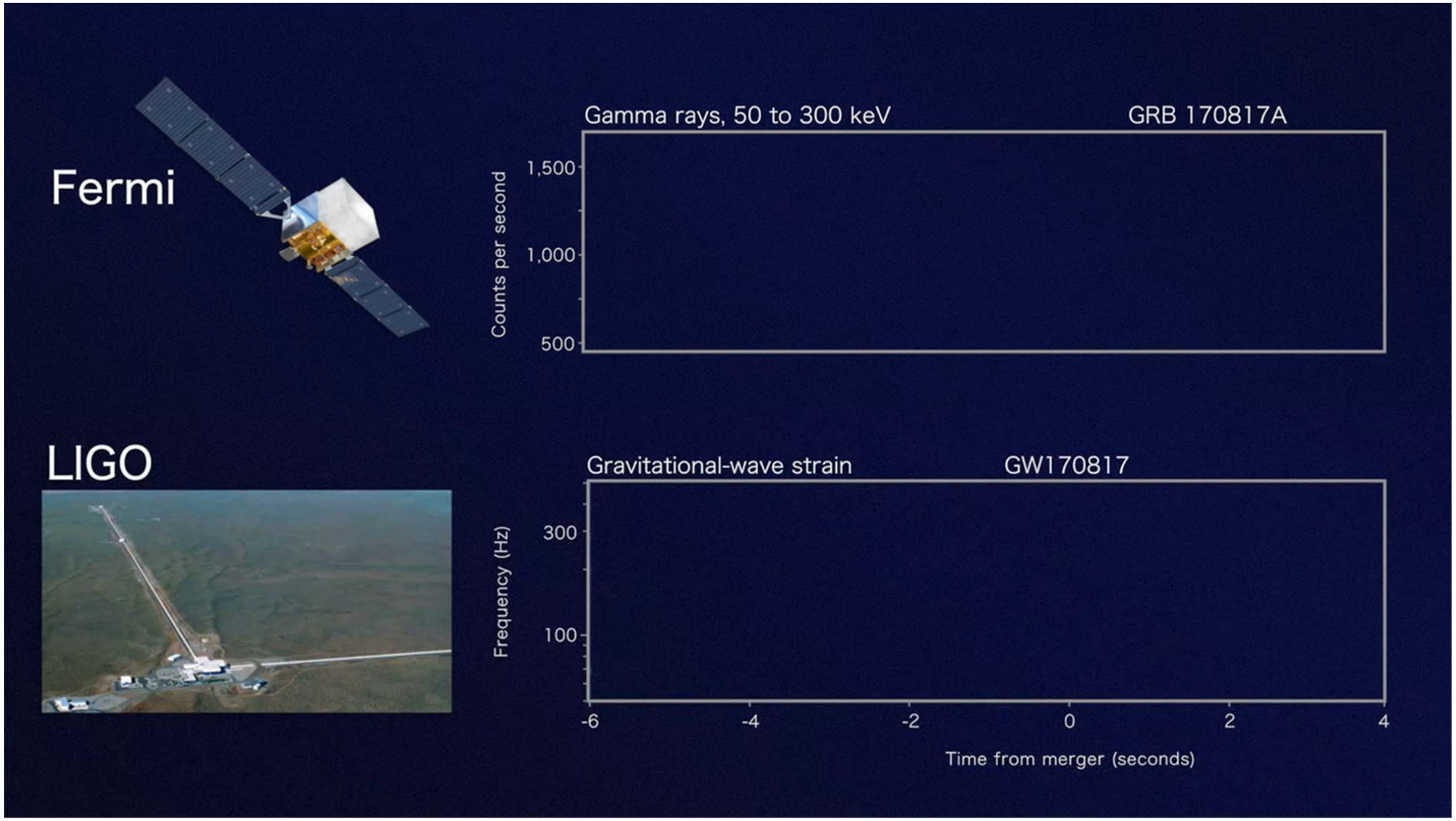
- Global 3-detector network: much-improved sky localization



GW170817

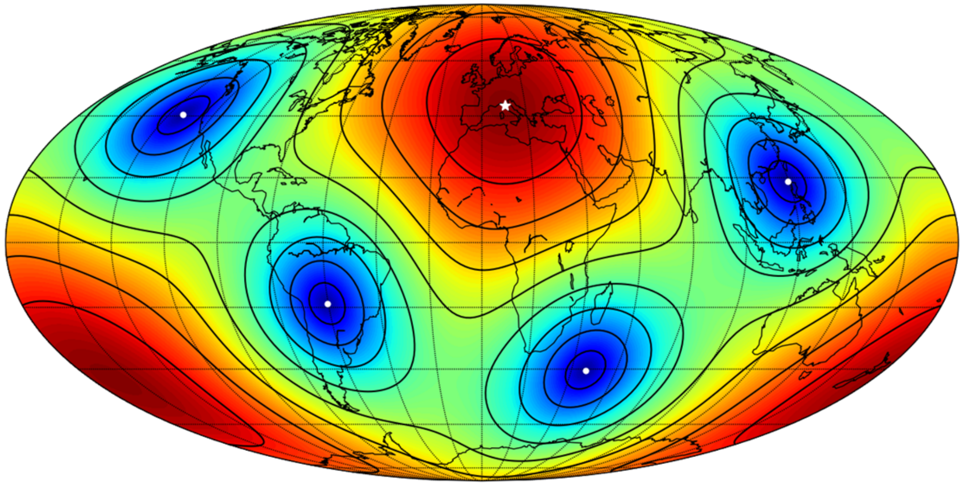
Thursday August 17, 2017 – 14:41 CEST

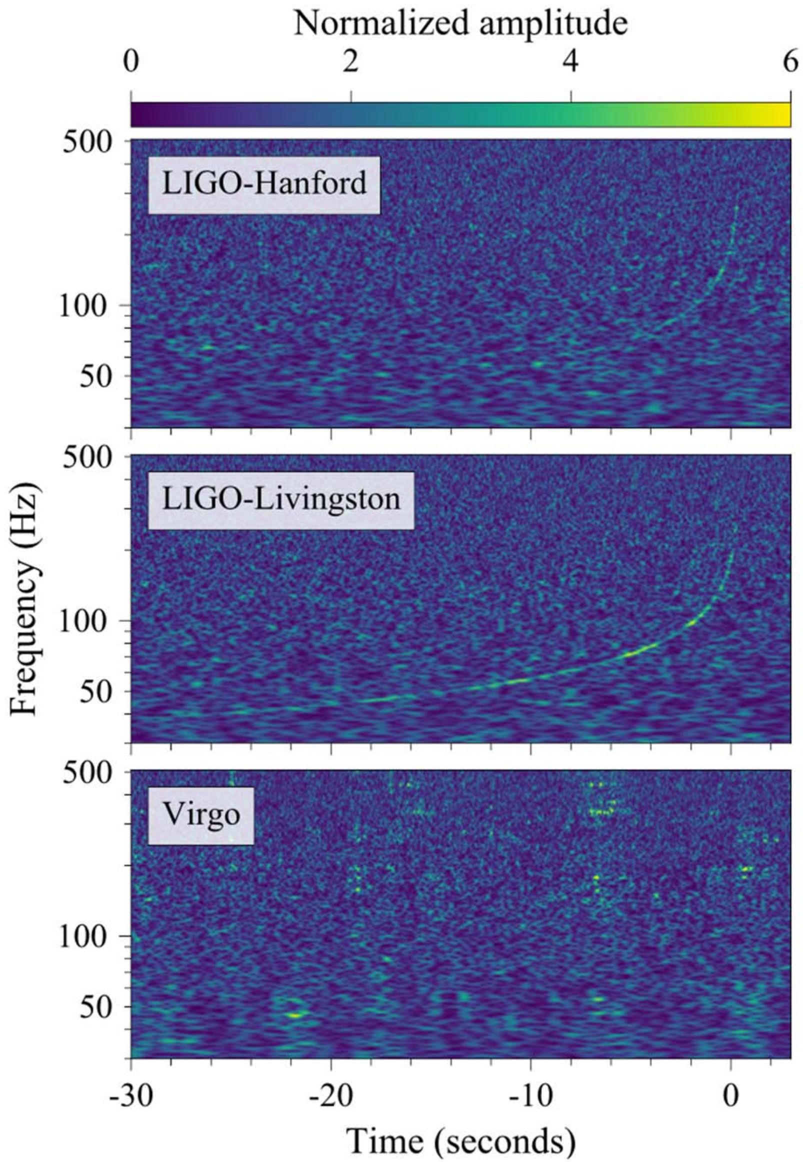
- Signals recorded within 1.7 second
  - LIGO (gravitational waves) first
  - Then the GBM instrument (gamma ray burst) on board the Fermi satellite



Gravitational waves from GW170817

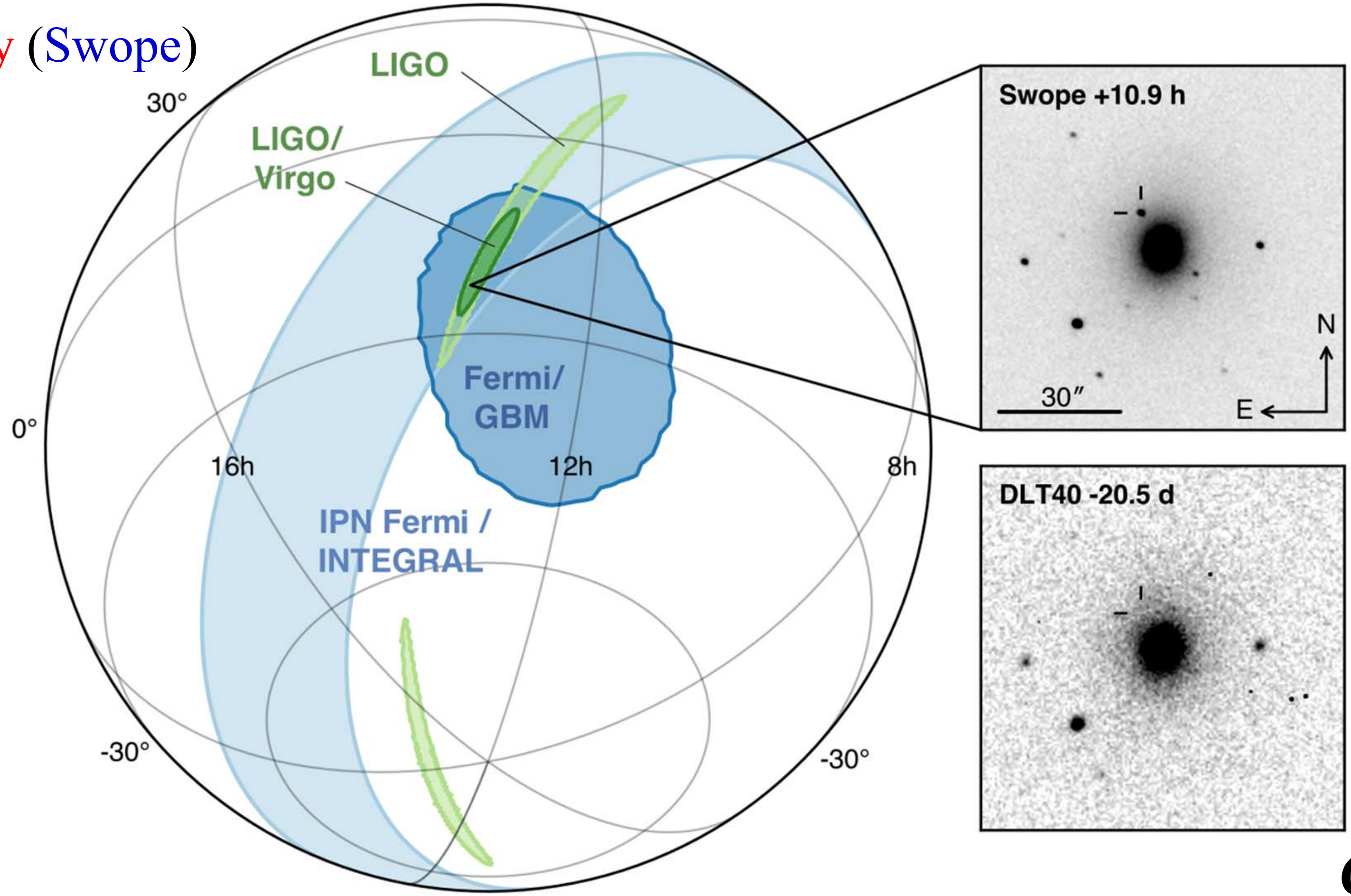
- Lower sensitivity + antenna pattern!





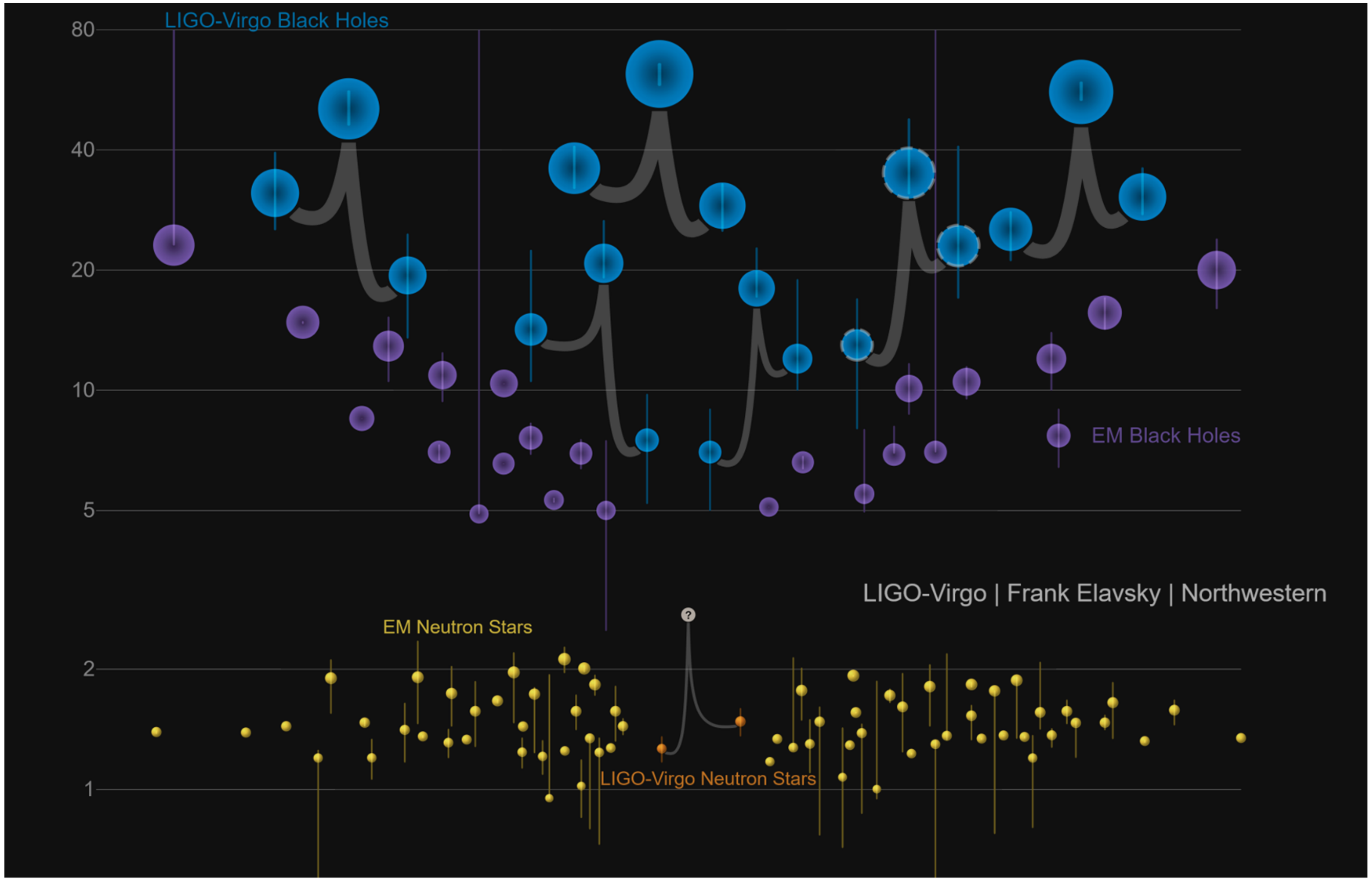
Sky localizations & source position

- Green: LIGO and LIGO + Virgo
- Blue : information from gamma ray burst satellites
- Optical discovery (Swope)



Detections

- Five binary black hole coalescences
  - GW150914, GW151226, GW170104, GW170814, GW170608
- One neutron star coalescence: GW170817



Detections

- Five binary black hole coalescences
  - GW150914, GW151226, GW170104, GW170814, GW170608
- One neutron star coalescence: GW170817