Gravitational waves don't go on holiday!

The week of the 15th of August seen from the perspective of the Virgo experiment

LPC Clermont-Ferrand, January 17 2018

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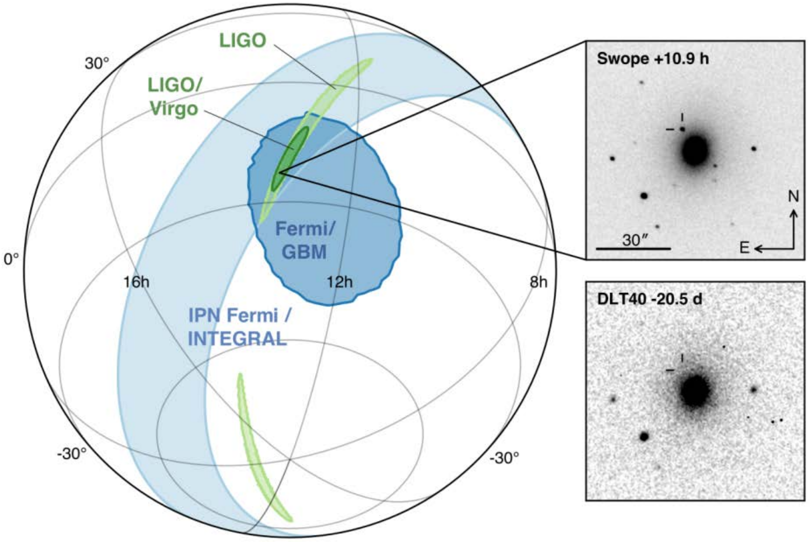

EGO EUROPEAN GRAVITATIONAL OBSERVATORY

cnrs dépasser les frontières

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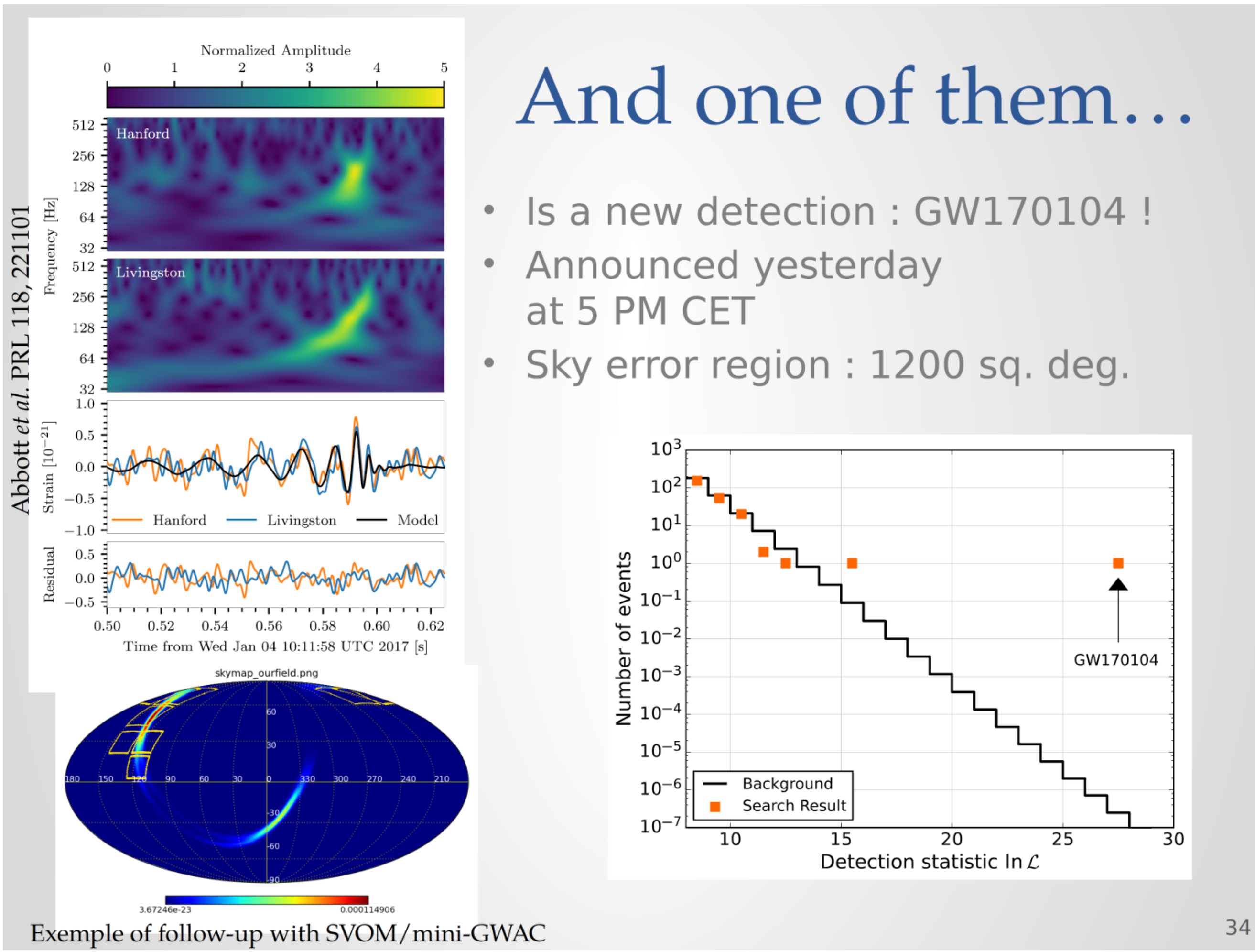
Summary of the previous episode

- June 2, 2017

Summary of the previous episode

- June 2, 2017
  - The day after the announcement of the GW170104 event



Summary of the previous episode

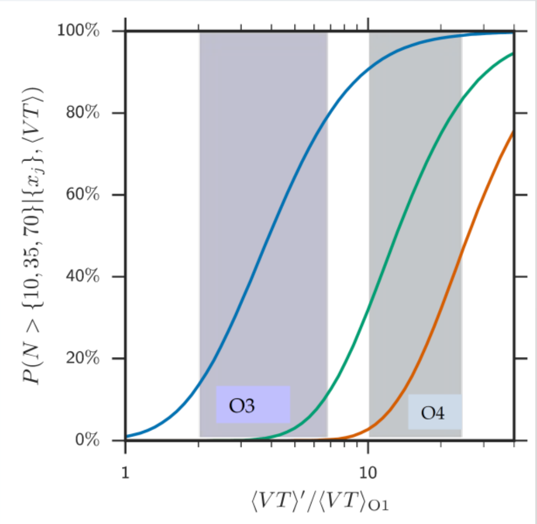
- June 2, 2017
  - Conclusion slide

At the end

- We have made the first direct detections of an astrophysical event with gravitational wave
- We have for the first time observed two binary black hole systems and their mergers
- We have observed several high mass binary systems

We are opening new ways to observe the Universe and its densest parts
We will also be able to test GR in new regimes

Time around 2020 will be very interesting for transient sky (including LSST) and tests for gravitation !



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Status on June 2, 2017

- 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
  - ✓ First phase of the upgrade completed by LIGO in 2015
  - ✗ Still ongoing for Virgo
    - Construction phase has ended, commissioning in progress
      → Goal: join LIGO asap

- Observation Run 1 (« O1 »): September 2015 → January 2016
  → 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 »): ongoing since November 30, 2016
  - Maintenance and upgrade in between O1 and O2 for the LIGO detectors
  - 3rd GW signal: GW170104 – yet another binary black hole merger
  - Data taking scheduled to end on August 25, 2017

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

What has happened since then?

- GW170608
  - Another stellar mass binary black hole coalescence
  - Observed by the two LIGO detectors
    $\rightarrow$ Virgo was still in commissioning phase with low sensitivity
  - Discovery announced on November 15, 2017
- August 1st, 2017: Virgo is finally joining the LIGO O2 data taking period
  - Lower sensitivity but good enough to have some impact in case of detection, in particular for the sky localization of the source
- August 25, 2017: O2 ends as planned
  - Quoting the corresponding press release:

    « *Some promising gravitational-wave candidates have been identified in data from both LIGO and Virgo during our preliminary analysis, and we have shared what we currently know with astronomical observing partners.* »
- September 27, 2017: announcement of the GW170814 event
  - First detection by the 3-detector global network: LIGO and Virgo together!
- October 16, 2017: announcement of the GW170817 event
  - First binary neutron star merger, accurately located in the sky by LIGO-Virgo
  - Source observed ~11 hours after the GW detection

Let’s focus on the recent events

Outline

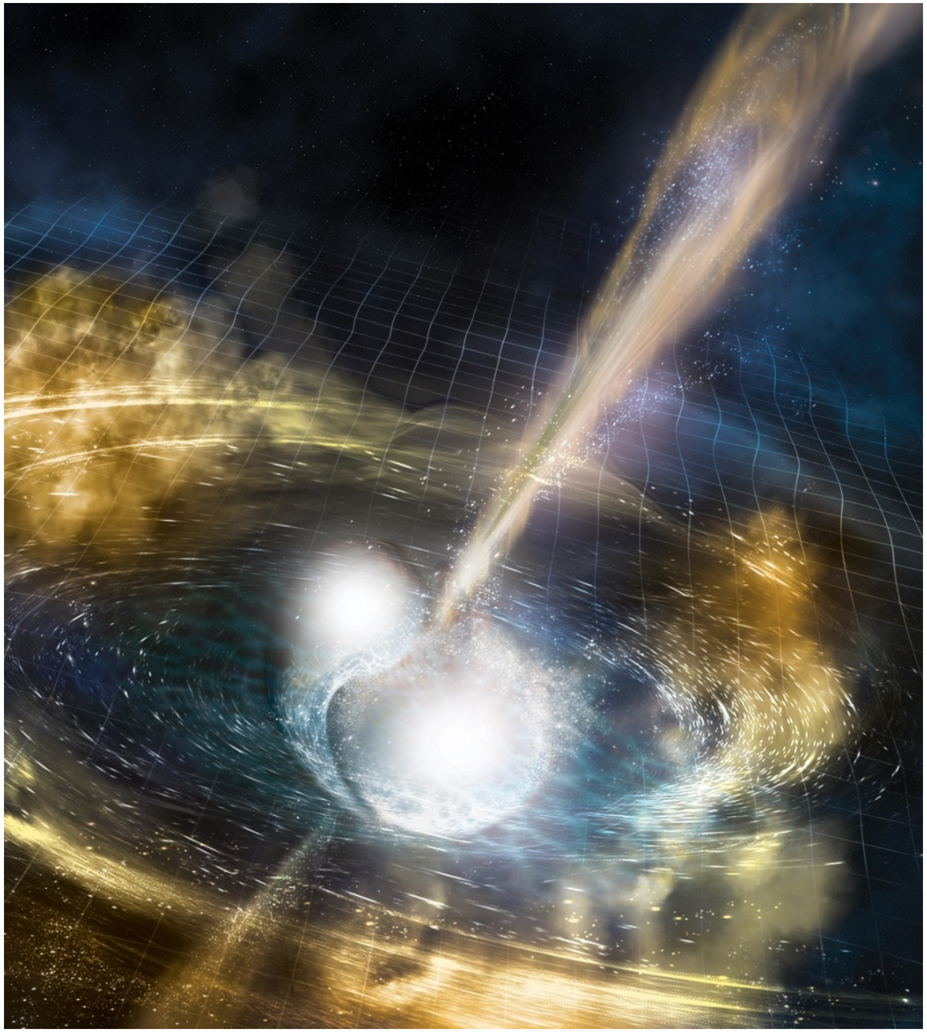
- In a nutshell
  - Gravitational waves (GW)
    → Sources and properties
  - Giant interferometric detectors
    → Principle and main characteristics

- A worldwide network of detectors
  - Multi-messenger astronomy

- Advanced Virgo
  - The road to O2
  - The O2 data taking period

- GW don't go on holiday!
  - GW170814
  - GW170817

- O2-O3 shutdown

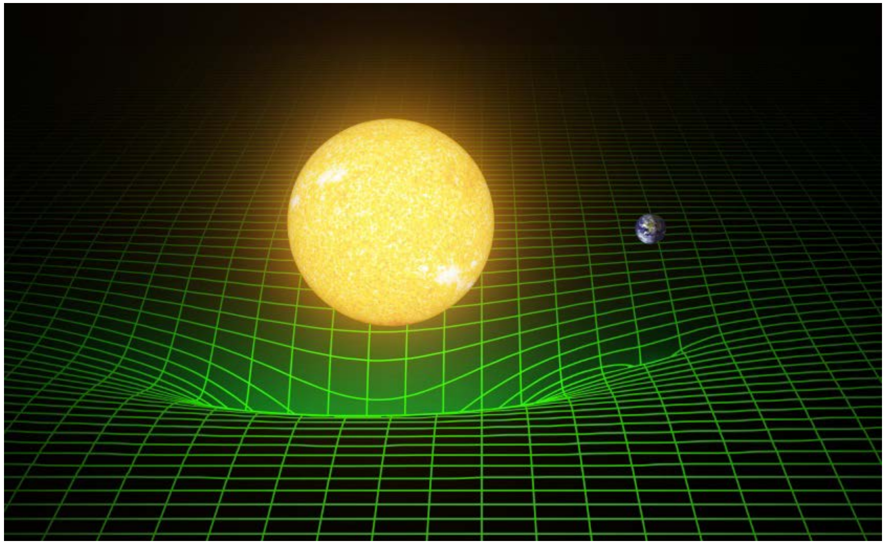


Thanks to the many colleagues from the LAL Virgo group, from Virgo and LIGO from wich I borrowed ideas and material for this talk

Gravitational waves: sources and properties

General relativity in a nutshell

- "Spacetime tells matter how to move; matter tells spacetime how to curve"
  John Archibald Wheeler (1990)
  - A massive body warps the spacetime fabric
  - Objects (including light) move along paths determined by the spacetime geometry



- Einstein's equations

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

$\rightarrow$ In words: Curvature = Matter

- Einstein tensor $G_{\mu\nu}$: manifold curvature
- Stress-energy tensor $T_{\mu\nu}$: density and flux of energy and momentum in spacetime
- Equality between two tensors
  $\rightarrow$ Covariant equations
- Need to match Newton's theory for weak and slowly variable gravitational fields
  $\rightarrow$ Very small coupling constant: the spacetime is very rigid
- Non linear equations: gravitational field present in both sides

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

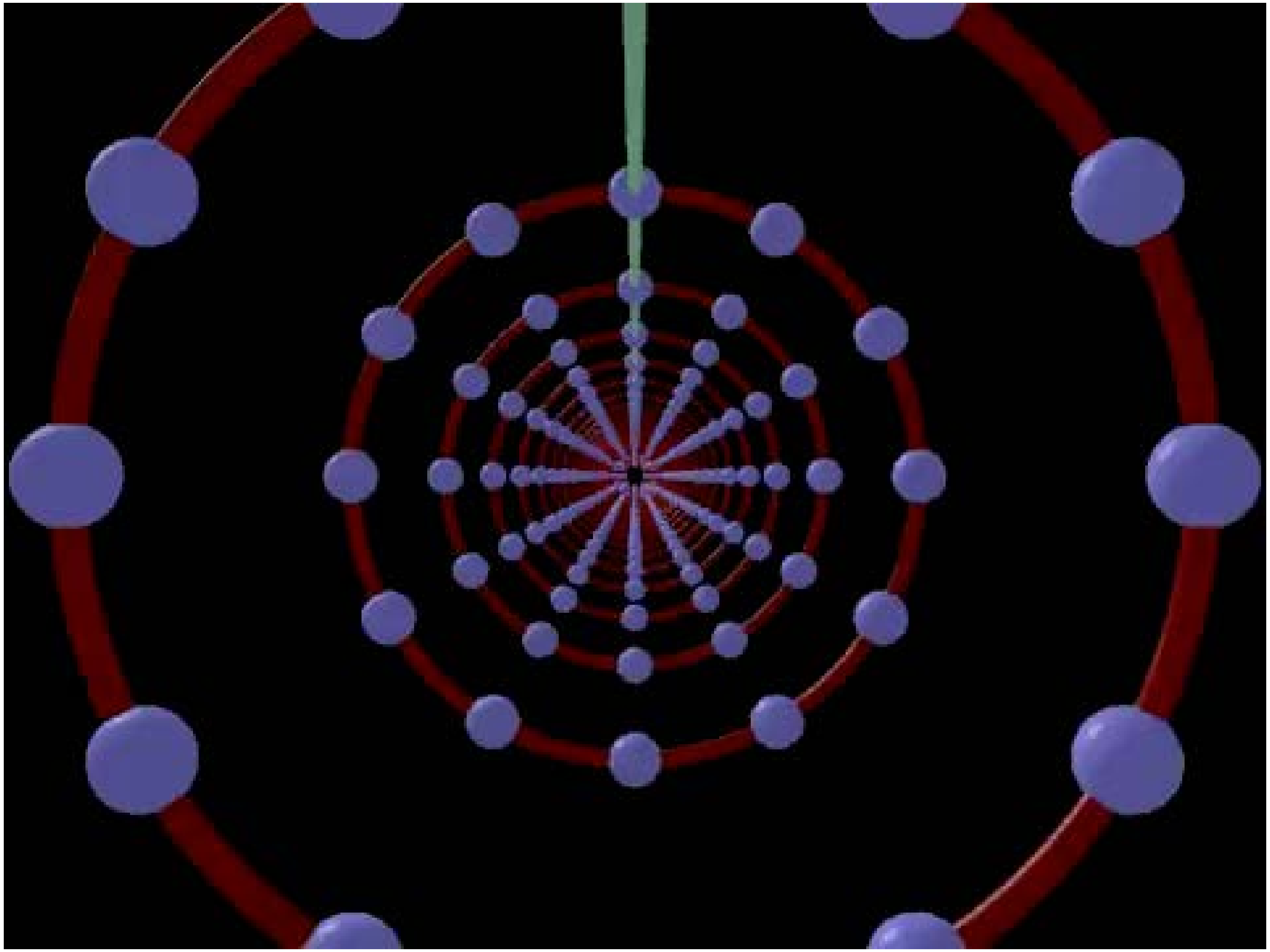
- Traceless and transverse (tensor) waves
  - 2 polarizations: « + » and « × »

- 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



Sources of gravitational waves

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

- Einstein quadrupole formula (1916)
  - Power radiated into gravitational waves
    Q: reduced quadrupole momenta

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

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

- Using $\omega \sim v/R$ and introducing R_S, one gets:

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

Huge: 10^{53} W

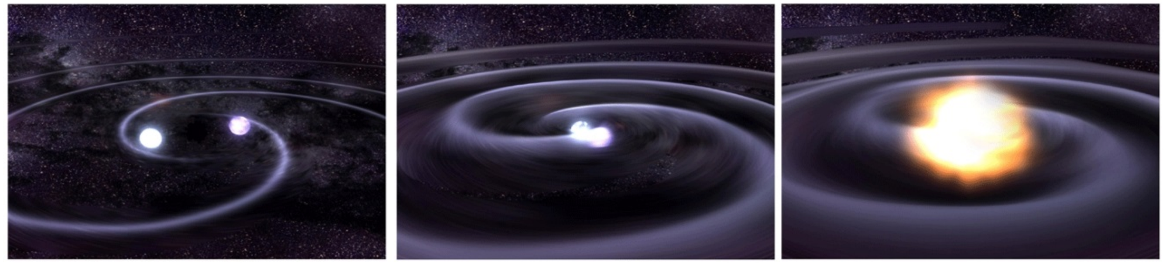
© Joe Weber, 1974

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

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

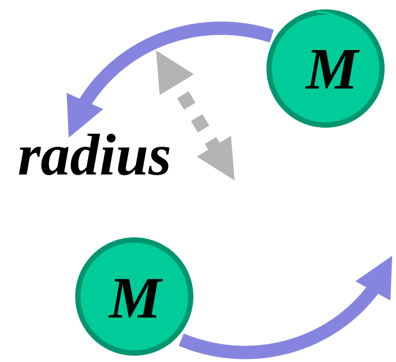
- Although all accelerated masses emit GW, no terrestrial source can be detected
  → Need to look for astrophysical sources (typically: $h \sim 10^{-22} \div 10^{-21}$)

A diversity of sources



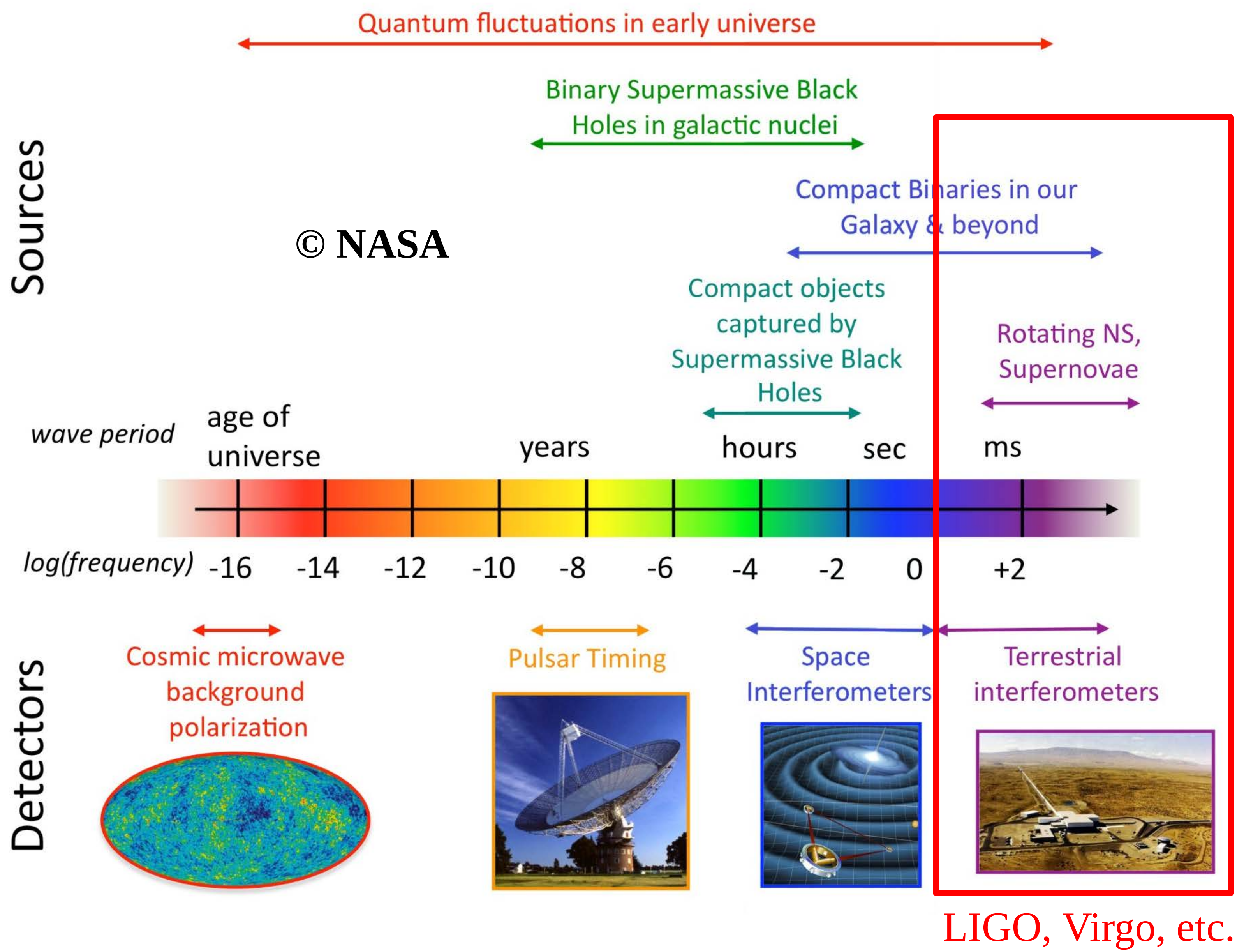
- Rough classification
  - Signal duration
  - Frequency range
  - Known/unknown waveform
  - Any counterpart (E.M., neutrinos, etc.) expected?
- Compact binary coalescence
  - Last stages of the evolution of a system like PSRB 1913+16
    $\rightarrow$ Compact stars get closer and closer while loosing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

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



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

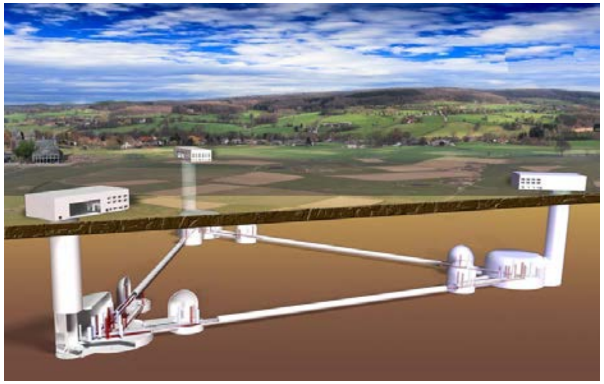
Gravitational wave spectrum

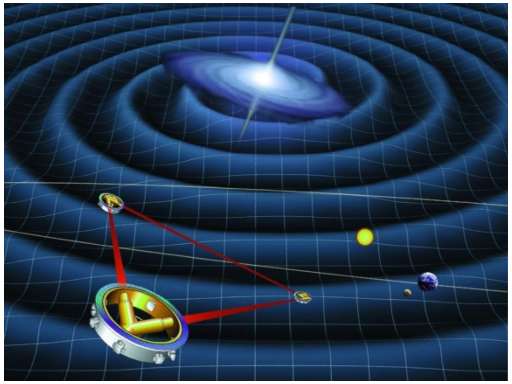


Gravitational wave detectors

- 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

1916-2017: a century of progress

Theoretical developments | *Experiments*

- **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.)**

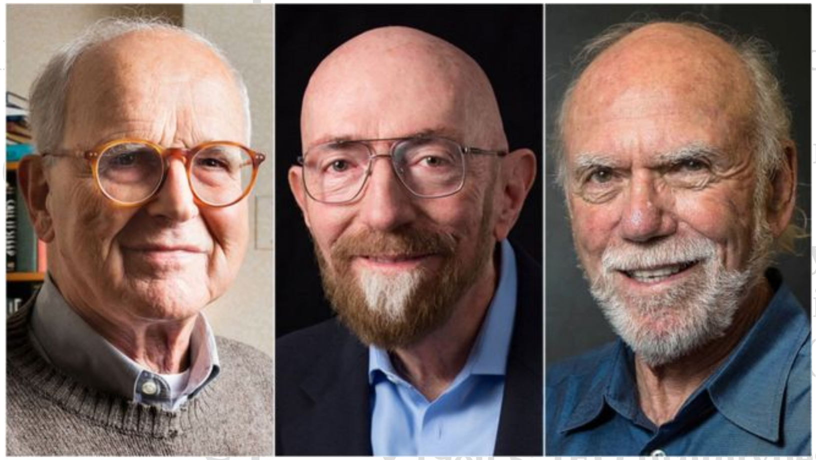
- **1960's: first Weber bars**
- **1970: first IFO prototype (Forward)**
- **1972: IFO design studies (Weiss)**
- **1974: PSRB 1913+16 (Hulse & Taylor)**
- **1980's: IFO prototypes (10m-long) (Caltech, Garching, Glasgow, Orsay)**
  → End of 1980's: Virgo (Brillet, Giazotto) and LIGO proposals
- **1990's: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

1916-2017: a century of progress

- 1916: GW prediction (Einstein)

1957: Chapel Hil



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- 1963: rotating BH solution

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

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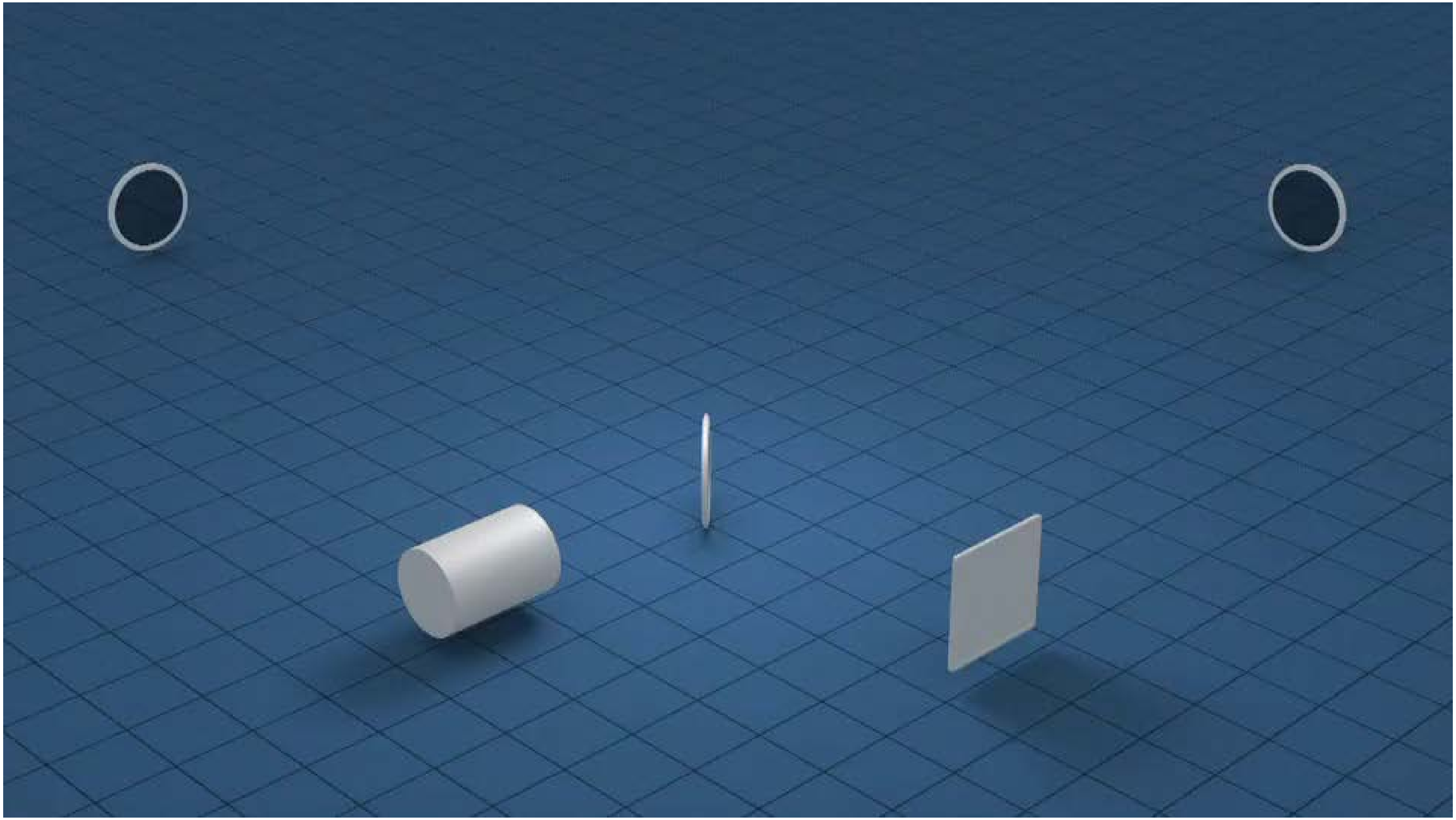
(Baker, Lousto, Pretorius, etc.)

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

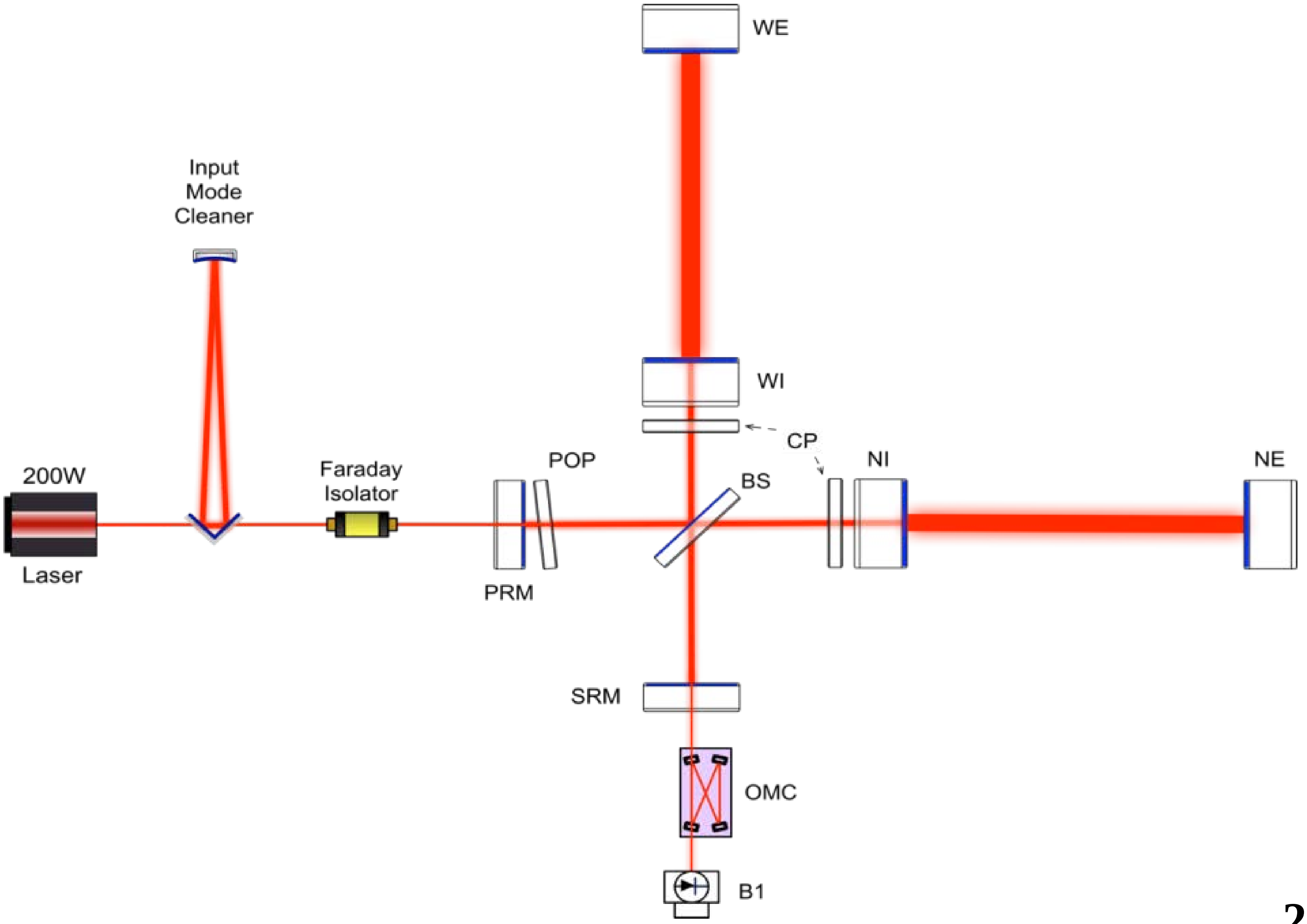
} First GW Detections

An interferometer in a nutshell



T. Pyle, Caltech/MIT/LIGO Lab

The Advanced Virgo detector scheme



Noise & sensitivity

- Noise: any kind of disturbance which pollutes the dark fringe output signal
- Detecting a GW of frequency f ↔ amplitude h « larger » than noise at that frequency
- Interferometers are wide-band detectors
  - GW can span a wide frequency range
  - Frequency evolution with time is a key feature of some GW signals

    → Compact binary coalescences for instance
- Numerous sources of noise
  - Fundamental

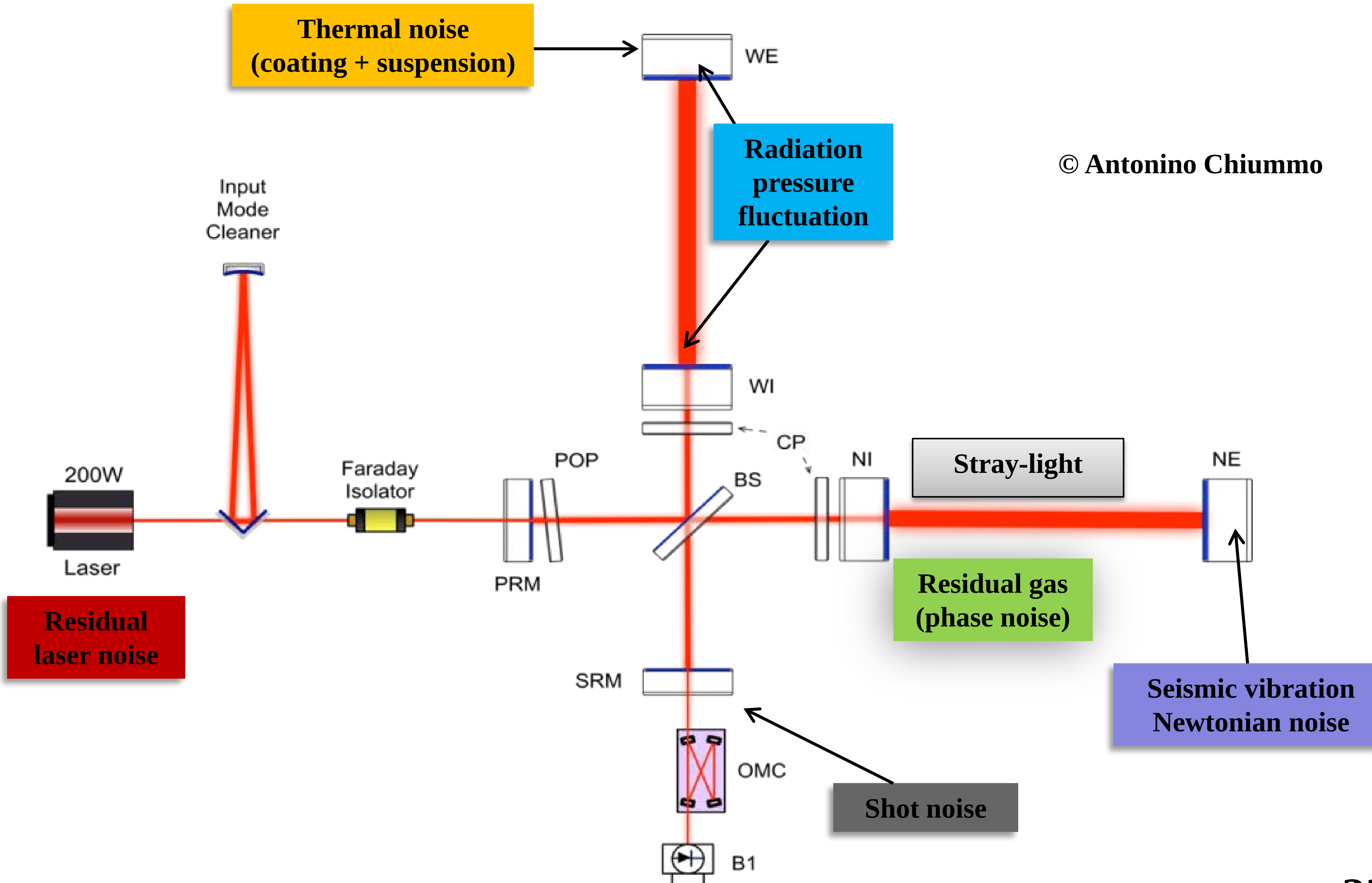
    → Cannot be avoided; optimize design to minimize these contributions
  - Instrumental

    → For each noise, identify the source; then fix or mitigate

    → Then move to the next dominant noise; iterate…
  - Environmental

    → Isolate the instrument as much as possible; monitor external noises
- IFO sensitivity characterized by its amplitude spectrum density (ASD, unit: 1/√Hz)
  - Noise RMS in the frequency band $[f_{min};f_{max}] = \sqrt{\int_{f_{min}}^{f_{fmax}} \mathbf{ASD}^2(\mathbf{f})\,\mathbf{df}}$

Main interferometer noises



Interferometer control

- A complex working point
  - Resonant Fabry-Perot and recycling cavities + IFO on the dark fringe
  - Arm length difference controled with an accuracy better than 10^{-15} m
  - The better the optical configuration, the narrower the working point
- « Locking » the IFO is a non-trivial engineering problem
  - Use several error signals to apply corrections on mirror positions and angles
    - → Pound-Drever-Hall signals (phase modulation)
    - → Auxiliary green lasers (for 2nd generation IFOs)
  - Feedback loops from few Hz to few kHz
  - Cope with filter bandwith and actuator range
- Multi-step lock acquisition procedure

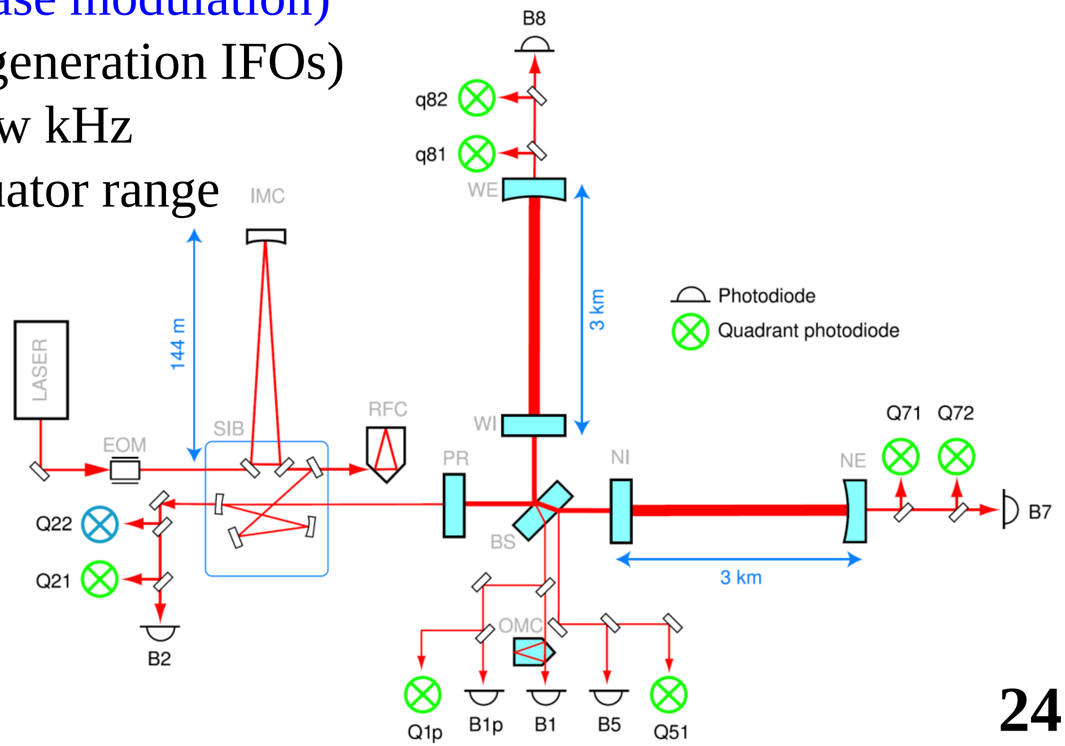
Free mirrors

↓

Local control

↓

Global control

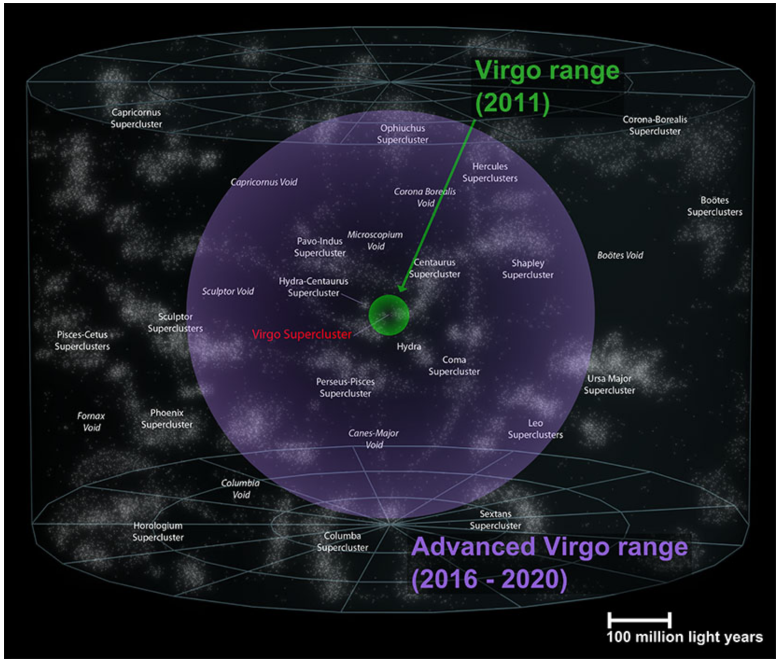


From initial to advanced detectors

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

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

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

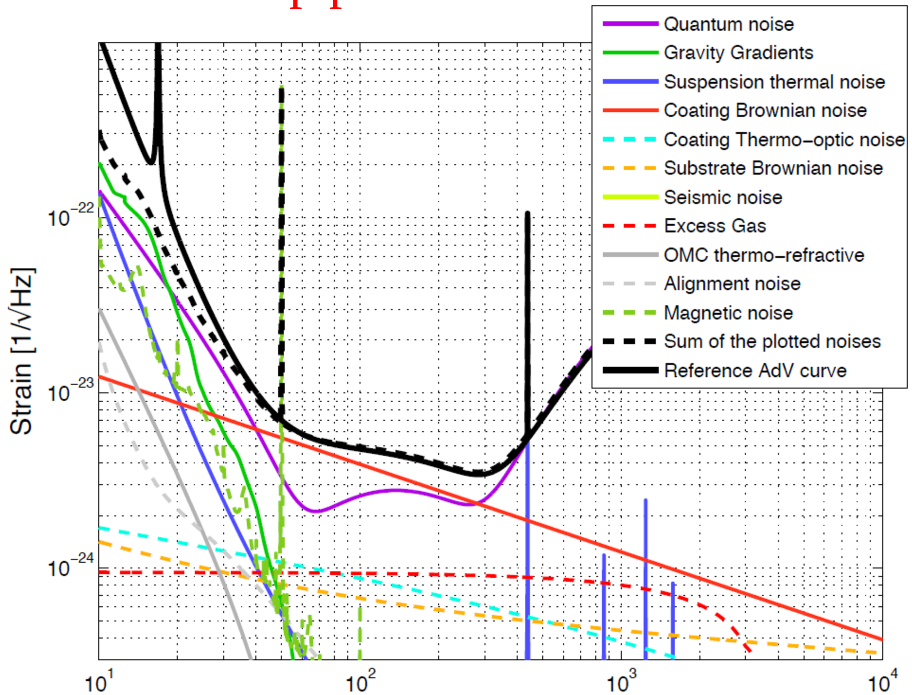


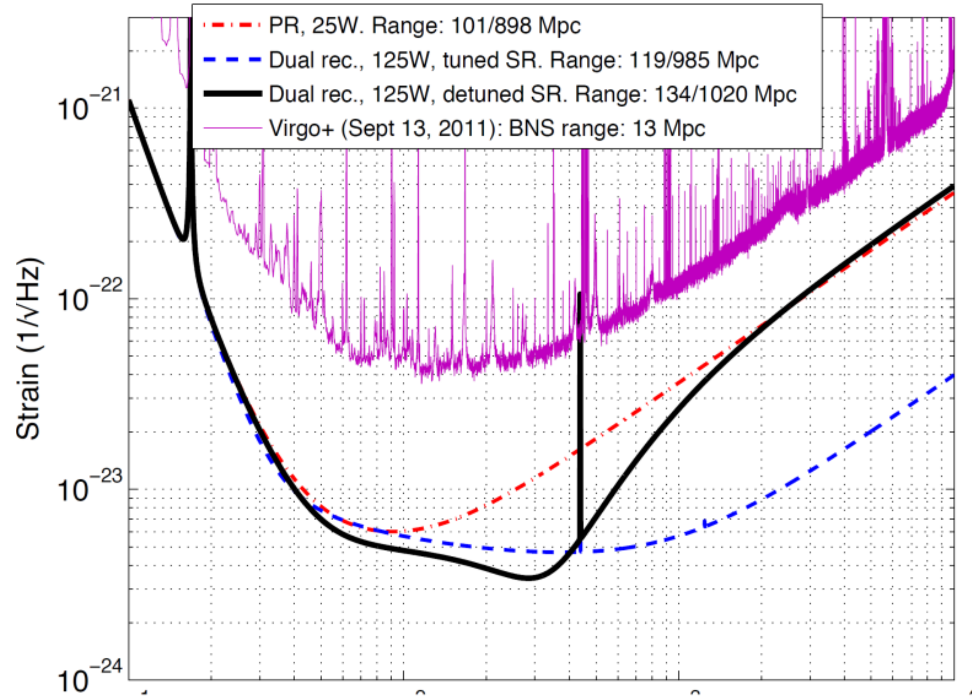
- Advanced LIGO (aLIGO) funded a year or so before Advanced Virgo (AdV)
  - Financial crisis in 2008-2010…

    → aLIGO ready for its first « observation run » in September 2015
  - AdV upgrade completed mid-2017

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

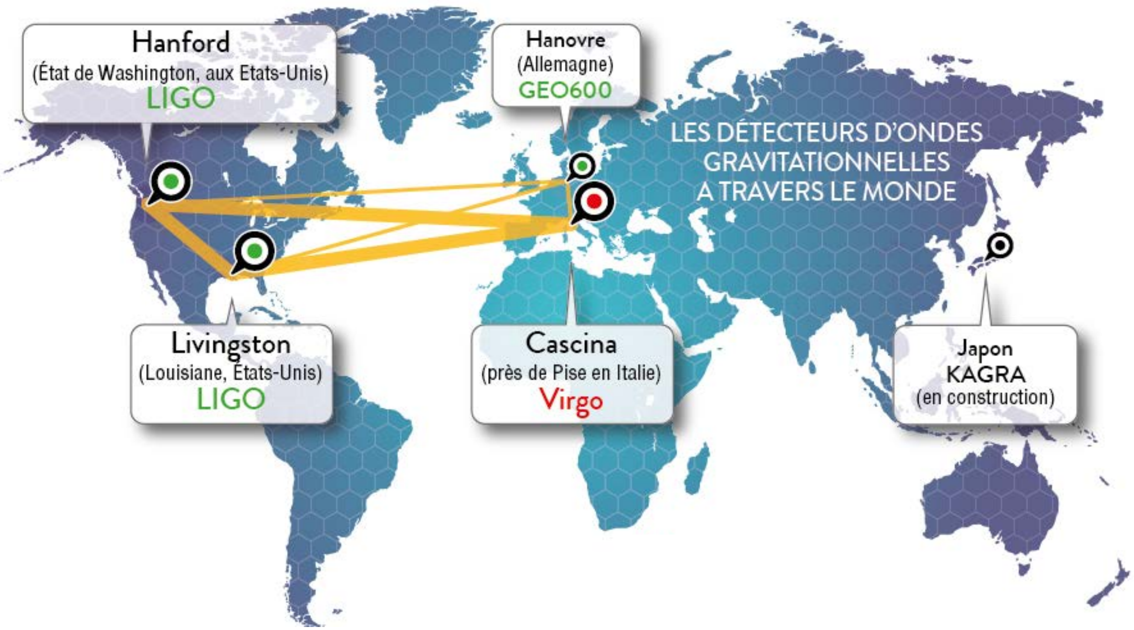
- Low frequency sensitivity ultimately limited by Newtonian noise
  - Stochastic gravitational field induced by surface seismic waves
    → Either active cancellation or go underground

A global network of gravitational-wave interferometric detectors

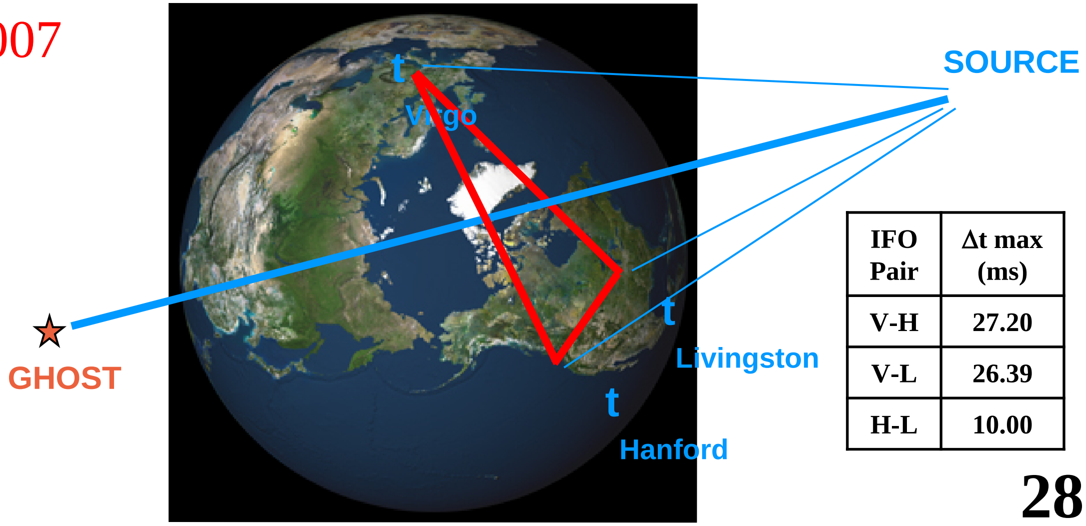
A network of interferometric detectors

- 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



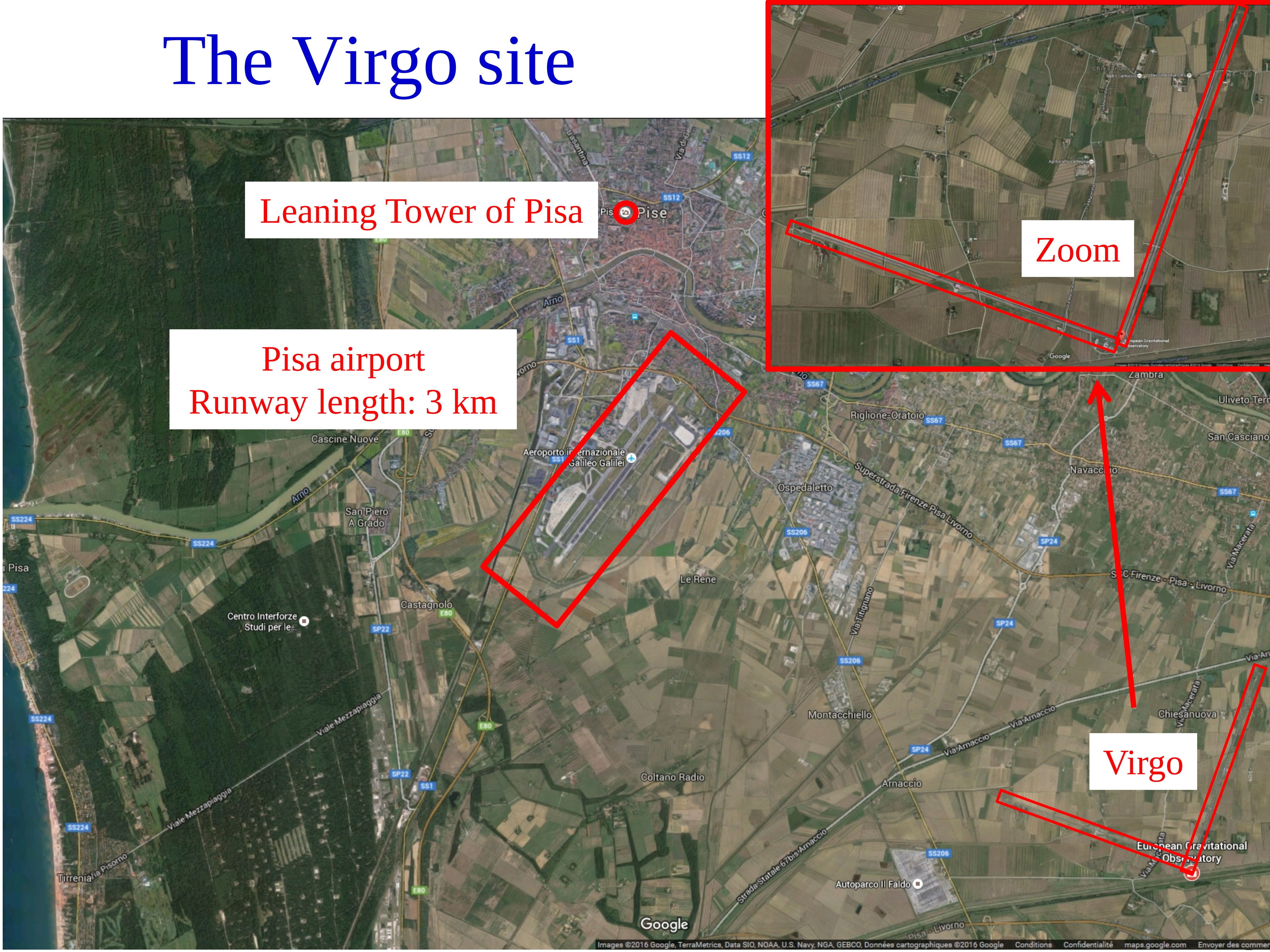
- Agreements (MOUs) between the different projects – Virgo/LIGO: 2007
  - Share data, common analysis, publish together
- IFO: non-directional detectors; non-uniform response in the sky
- Threefold detection: reconstruct source location in the sky



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

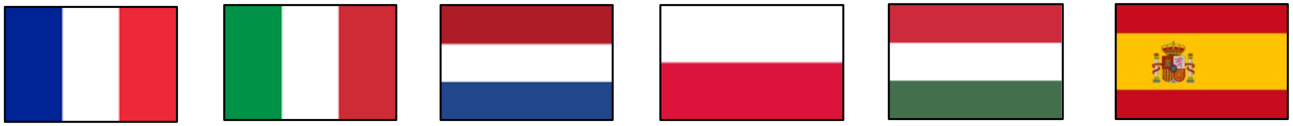
A network of interferometric detectors

The Virgo site



The Virgo Collaboration

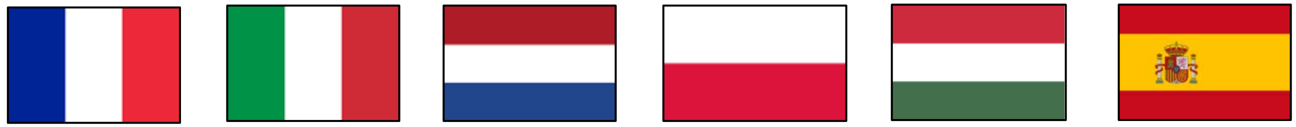
- 6 European countries



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

The Virgo Collaboration

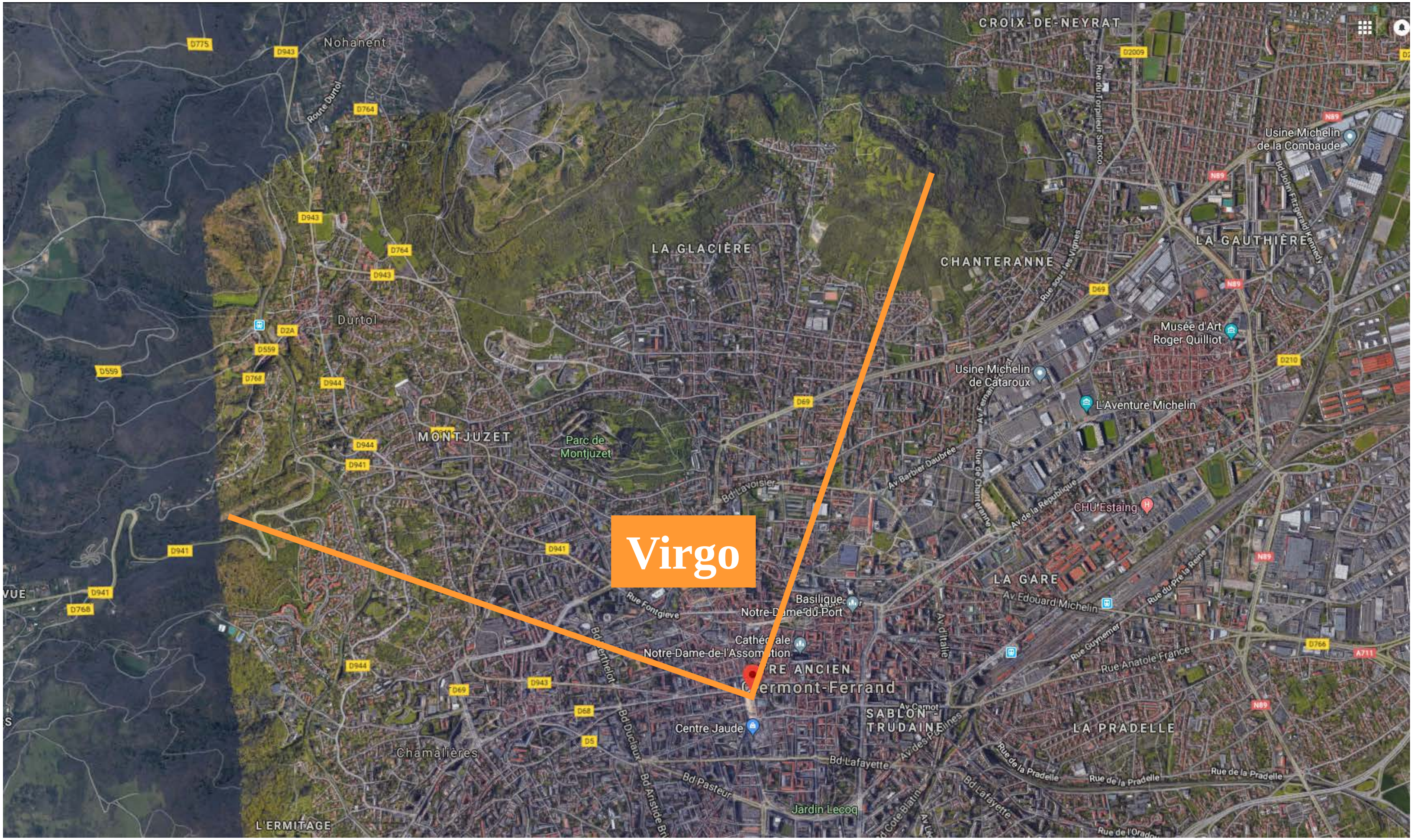
- 6 European countries



- 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

If Virgo were located in Clermont-Ferrand…

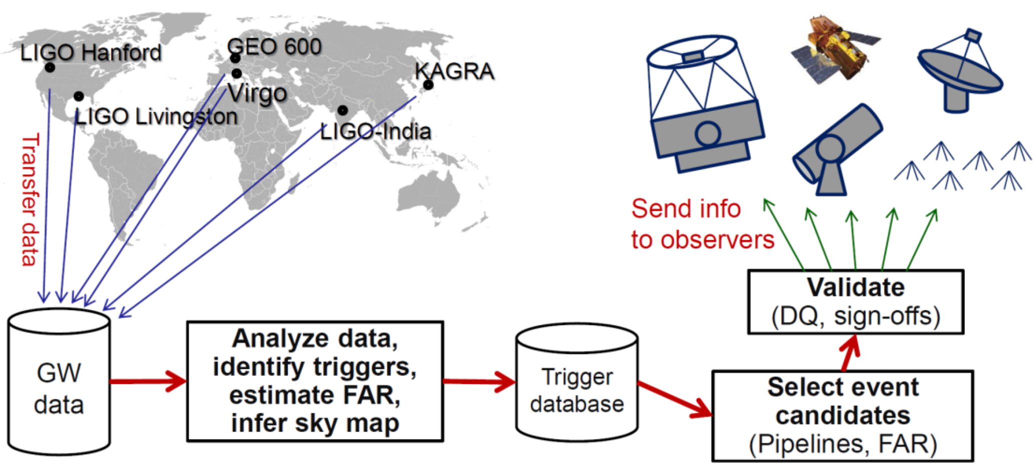


Exploiting multi-messenger information

- 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

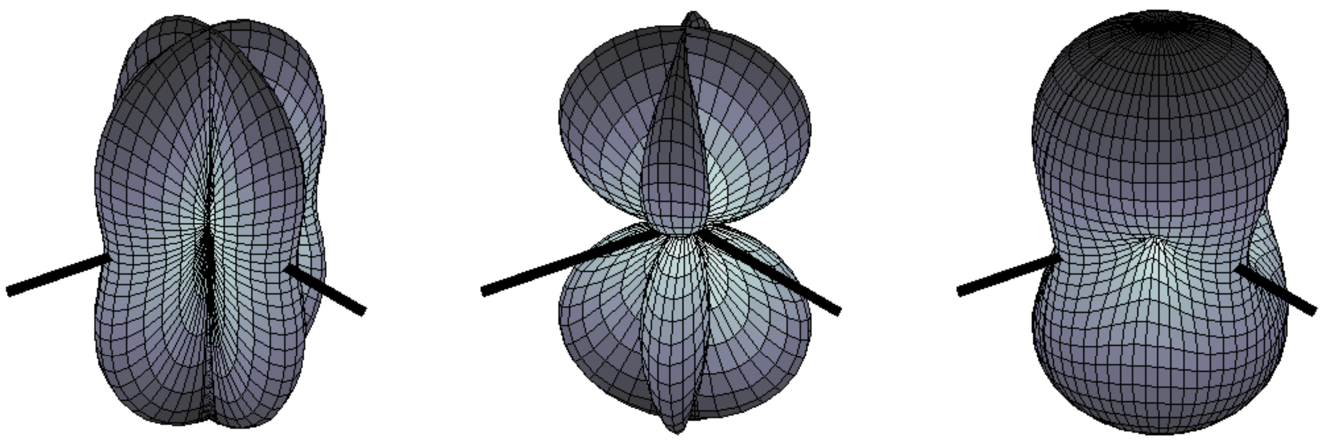
- An interferometer is not directional: it probes most of the sky at any time
  - More a microphone than a telescope!

- 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)

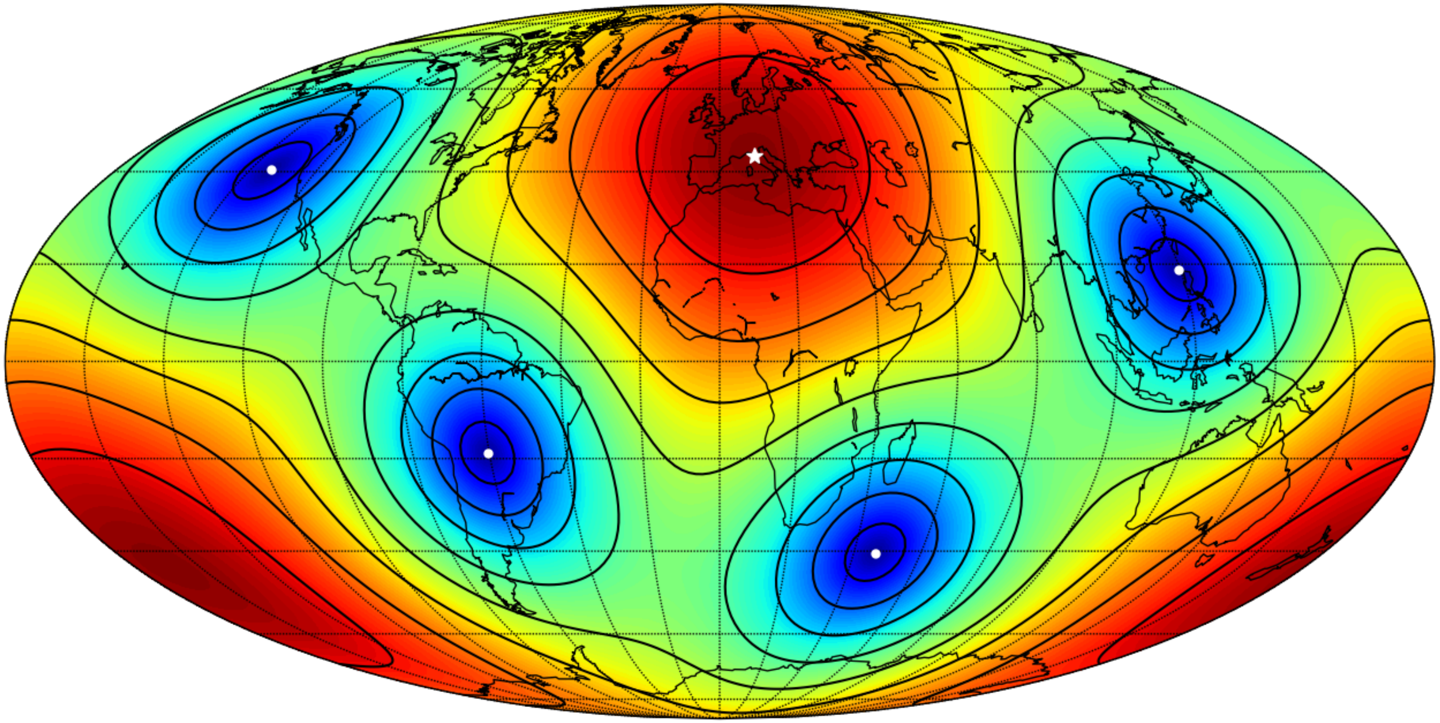
+ polarization | × polarization | unpolarized



Virgo antenna pattern

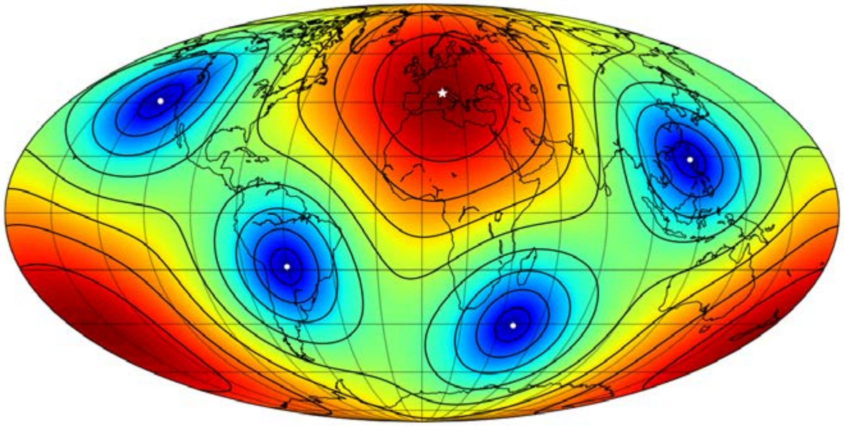
- Two optimal directions
  - Zenith and nadir

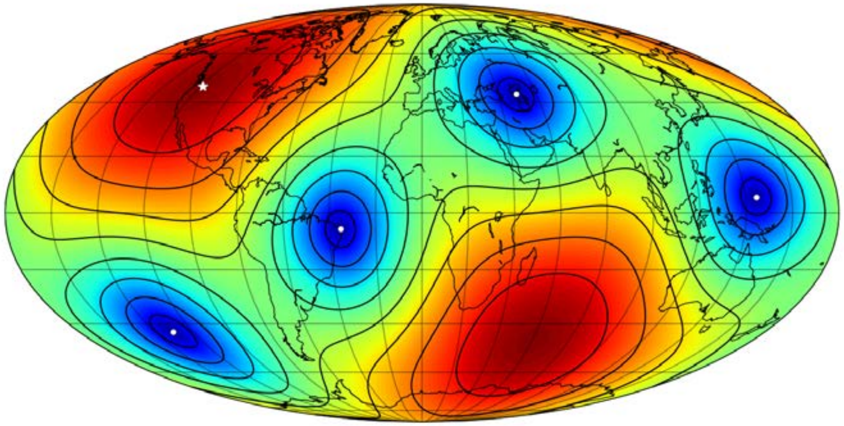
- Four blind spots
  - All in the detector plane
  - Along the arm bissector and at 90 degrees from that

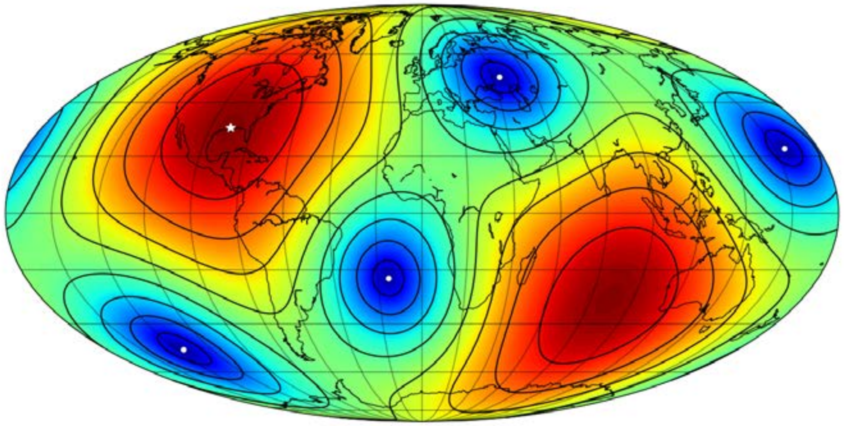


LIGO-Virgo antenna patterns

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



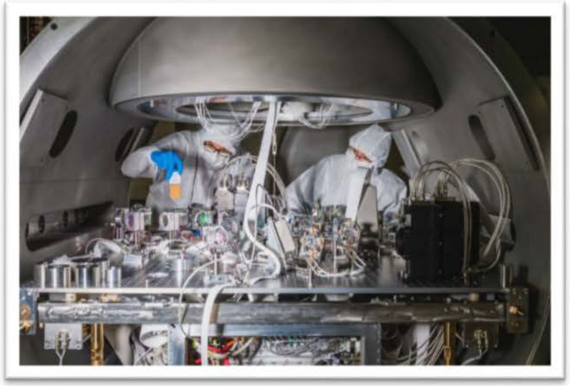




Virgo O2 data taking
August 1 – August 25 2017

Virgo to Advanced Virgo timeline

- October 2007: Advanced Virgo initial design completed
- November 2008-May 2009: Project reviewed by an international committee
- December 2009: Advanced Virgo project approved by the funding agencies
- October 2011: Virgo decommissioning starts



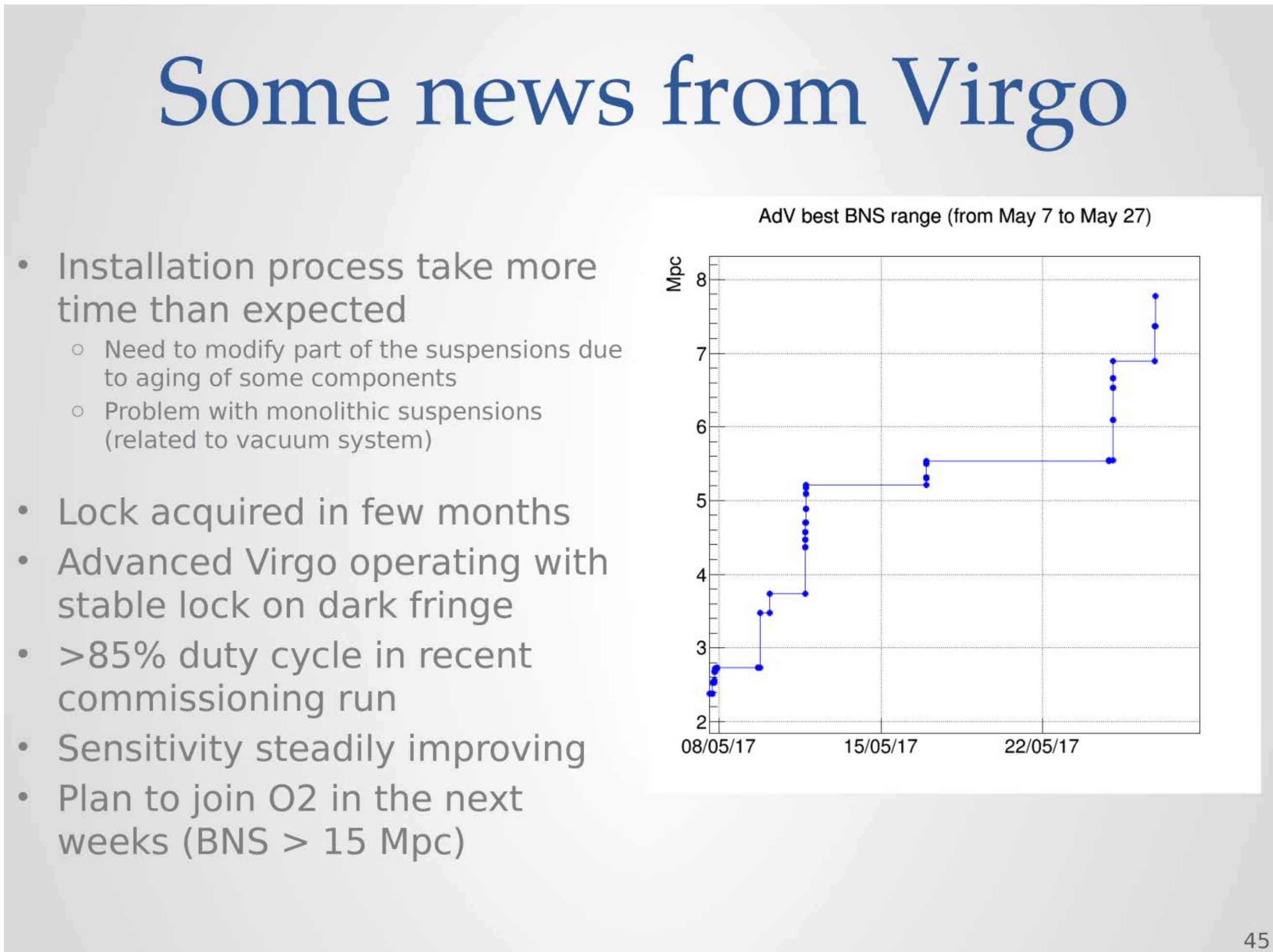
Physicists working on one of the suspended benches (Photo: © Cyril FRESILLON/Virgo/CNRS Photothèque)

- April 2012: Advanced Virgo final design
- August 2016: End of the integration phase: Advanced Virgo fully under vacuum
- February 2017: Advanced Virgo dedication ceremony
- August 2017: Virgo joins LIGO for four weeks of data-taking
- September 27, 2017: announcement of the first three detectors observation of gravitational waves

West arm of the Virgo interferometer (Photo: Virgo Collaboration/Maurizio Perciballi)

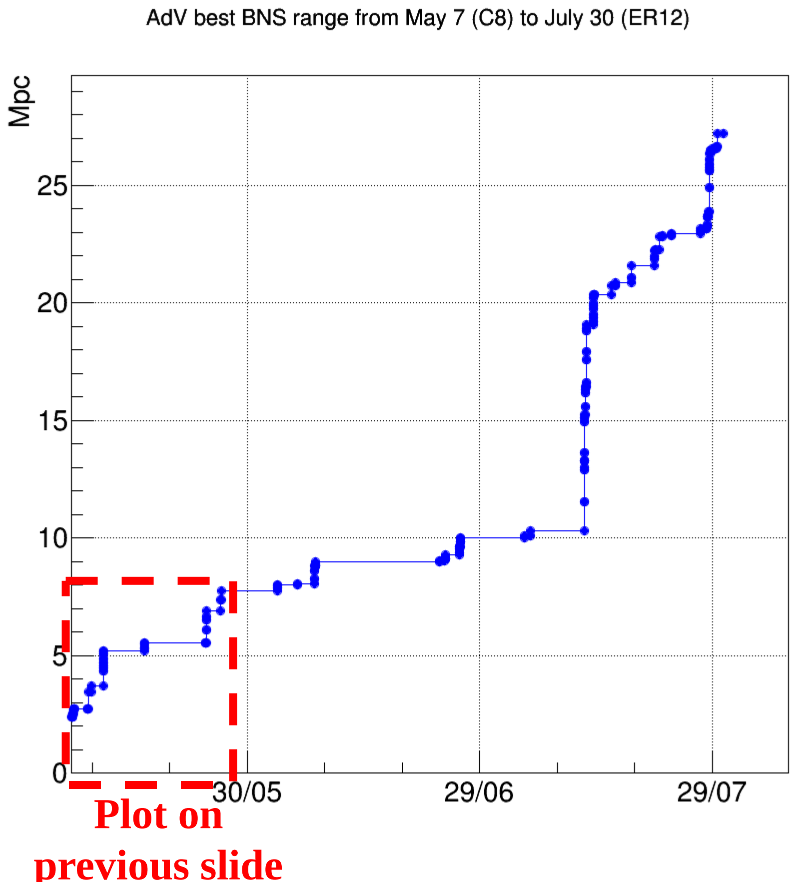
Long was the road…

- June 2, 2017



Advanced Virgo: joining O2

- Timeline covering the last year before joining the « O2 » data taking period
  - On August 1st, 2017



- 2016 August: End of integration: Advanced Virgo fully under vacuum
- November: Full detector available for commissioning
- December: Control of the power-recycled interferometer, Michelson degree of freedom controlled at half fringe
- 2017 February: Advanced Virgo dedication ceremony, full interferometer controlled for 15 minutes
- March: One hour stable control of the full detector
- April: Control of the final configuration
- May-July: Control performance and sensitivity improvements, noise hunting
- July: Best sensitivity achieved by the first generation Virgo detector exceeded
- August: Virgo joins LIGO for four weeks of data-taking
- **Fall 2017: Publication of the first gravitational-wave detection including Virgo data**

Mirror of Advanced Virgo
(Photo:©enrico sacchetti www.es-photography.com)

Last update: 27 September, 2017

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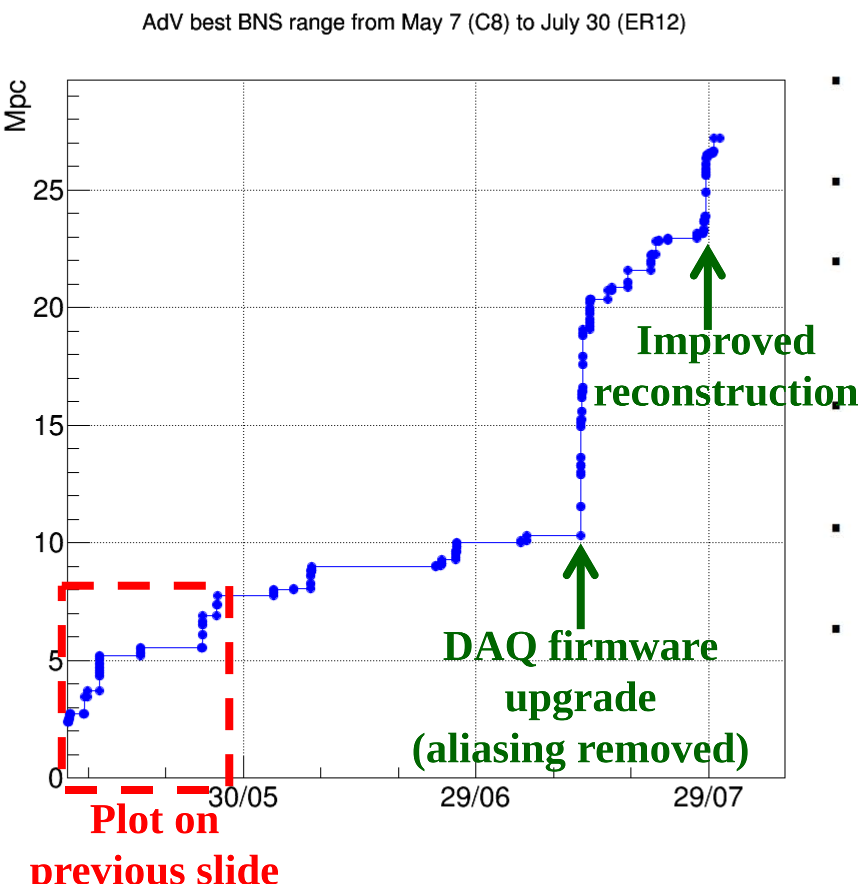

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Mirror of Advanced Virgo
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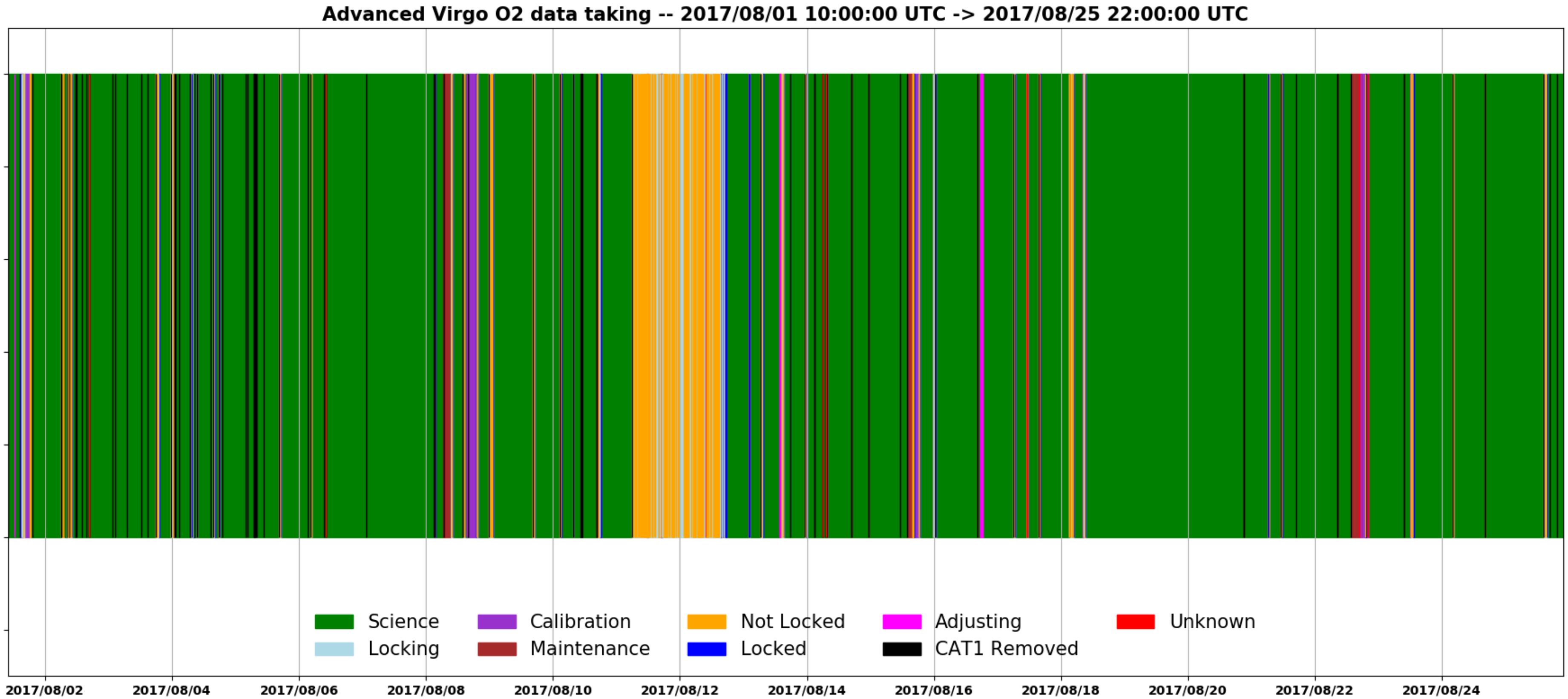
Last update: 27 September, 2017

4 weeks of Virgo data taking in a nutshell

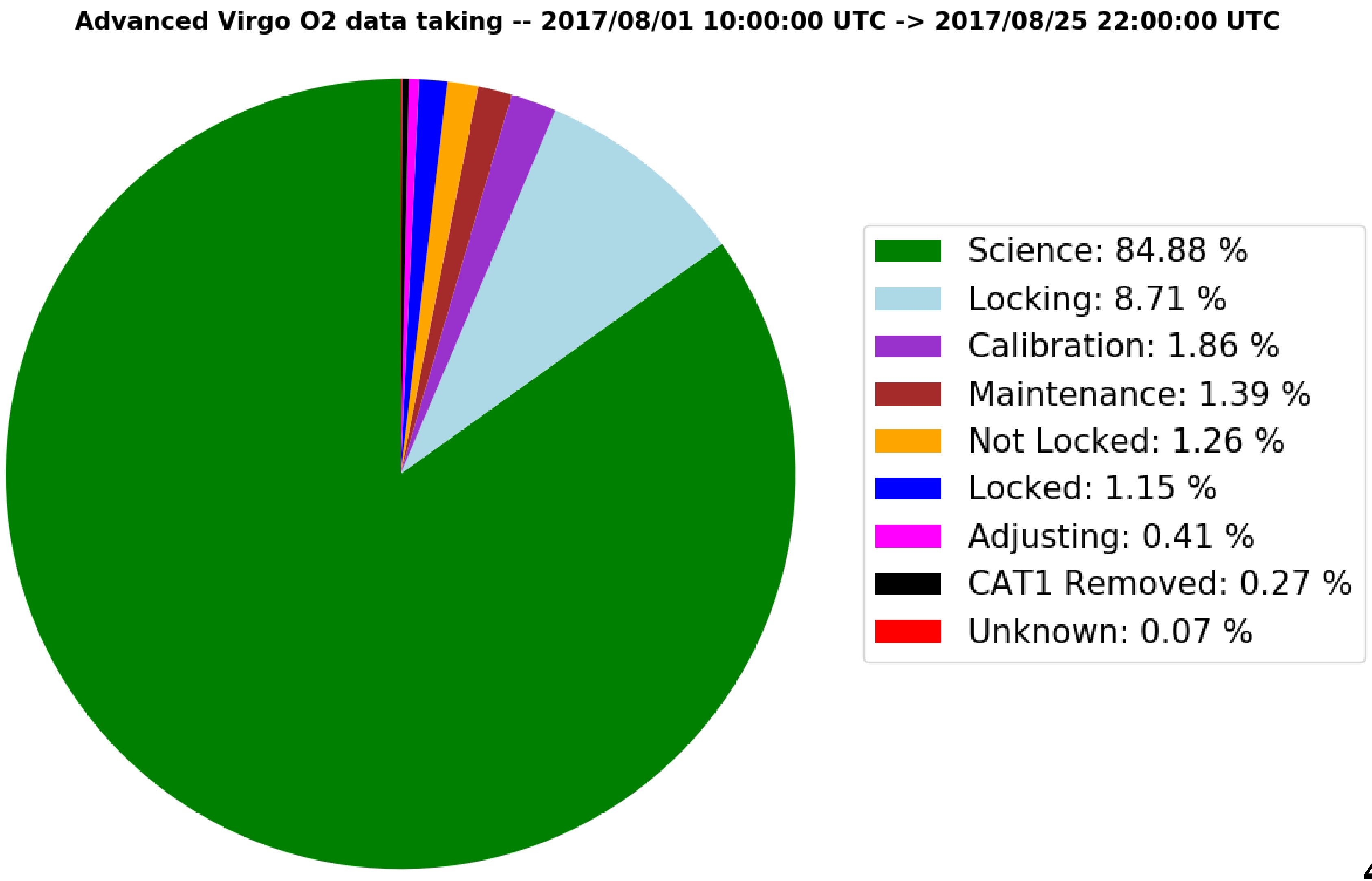
- Duty cycle stripchart
  - Green ↔ Data taking in science mode



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

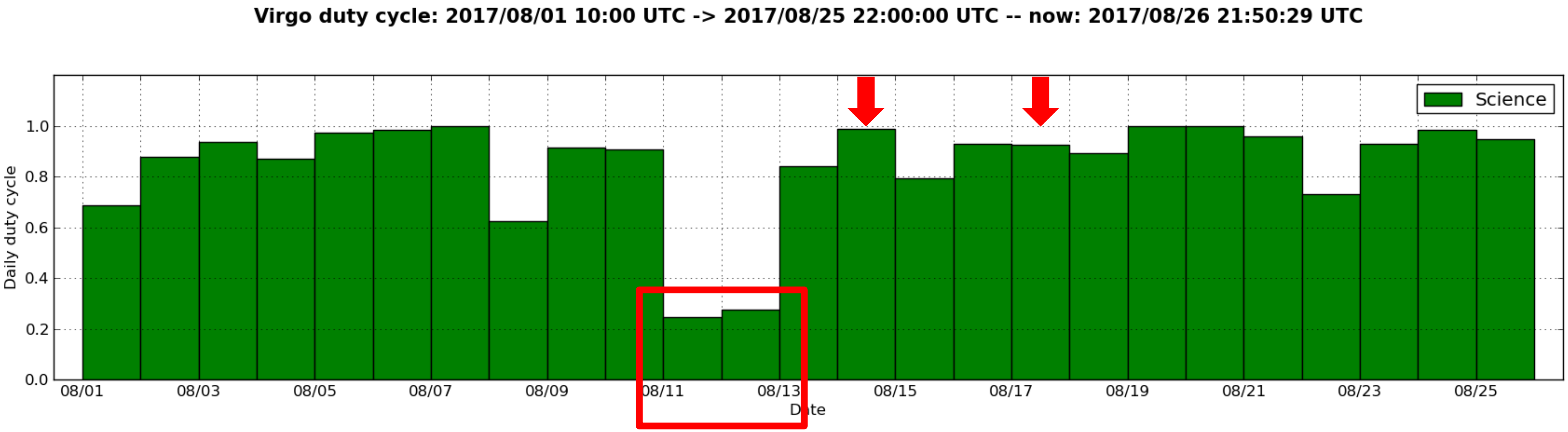
4 weeks of Virgo data taking in a nutshell

- Duty cycle pie chart



4 weeks of Virgo data taking in a nutshell

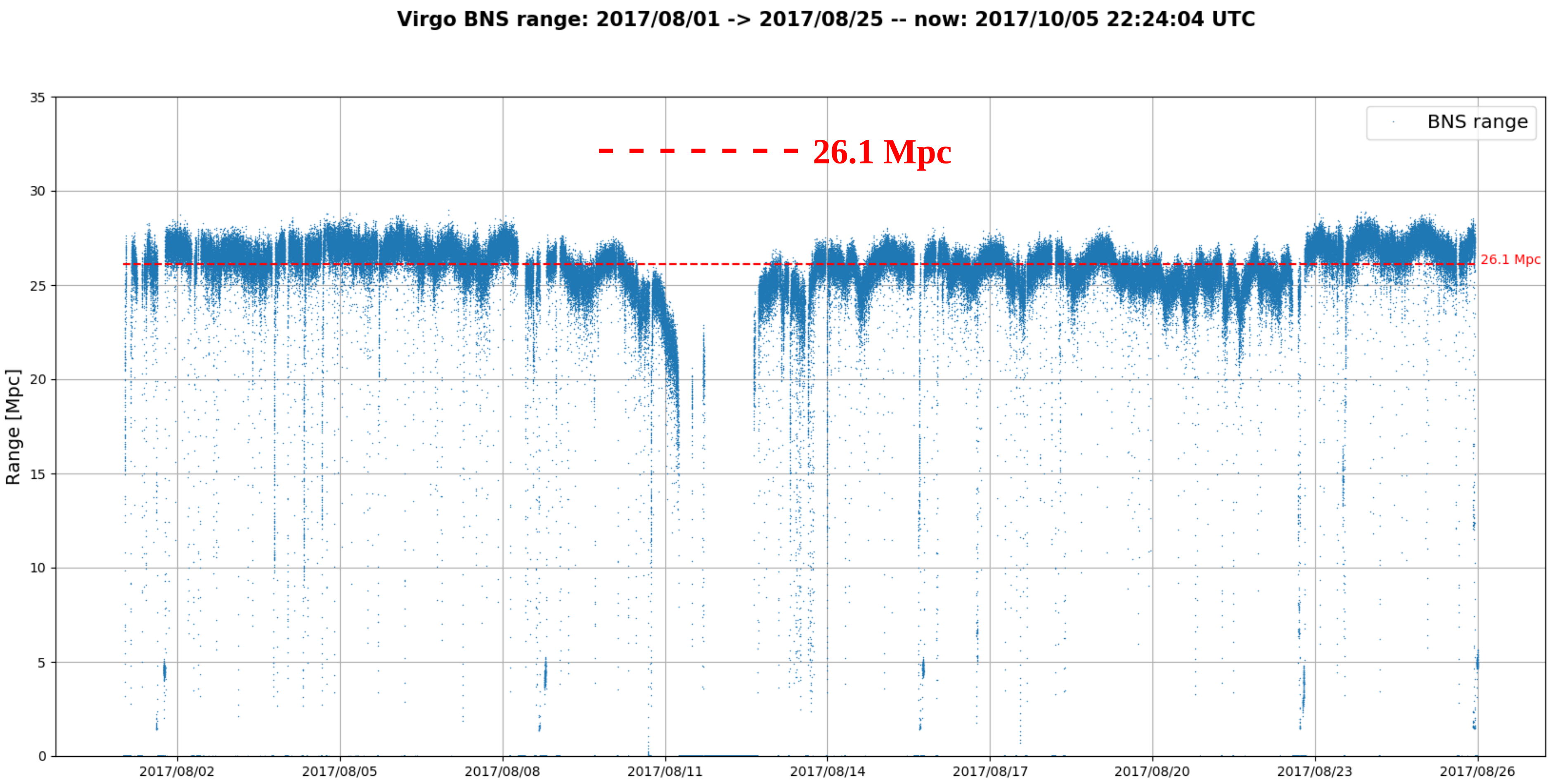
- Daily duty cycle



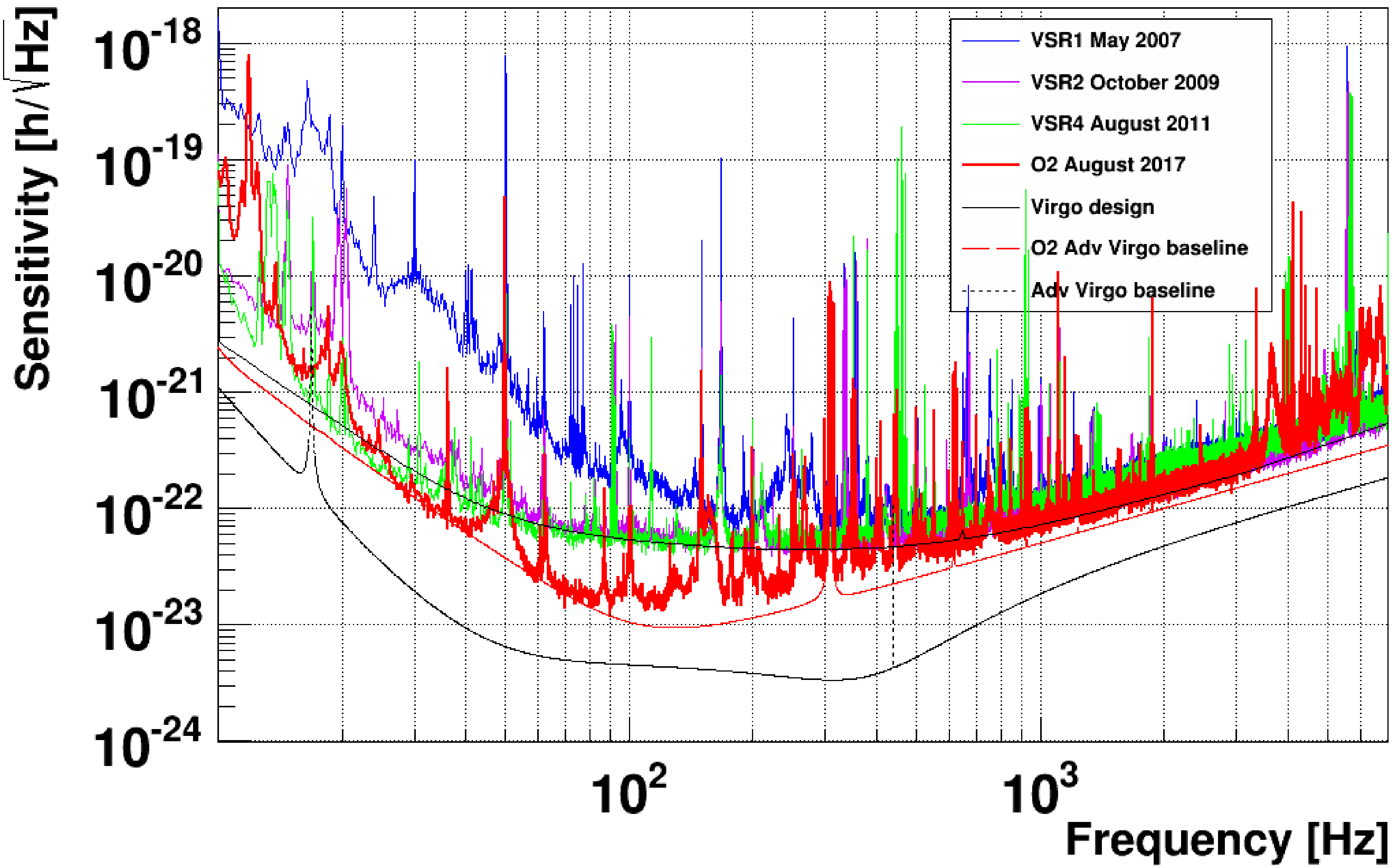
Bad weather conditions
→ High seismic activity

4 weeks of Virgo data taking in a nutshell

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

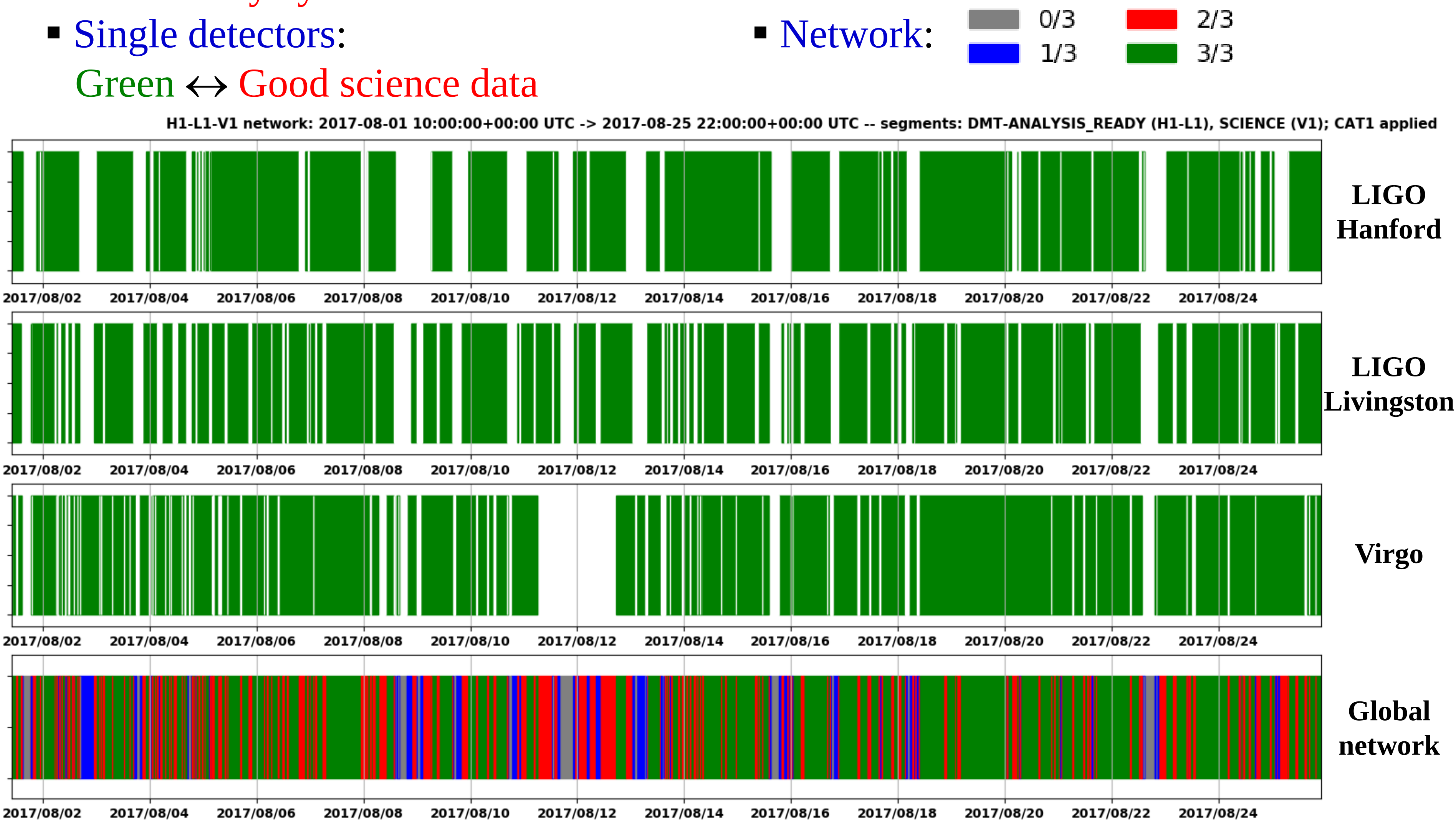


Evolution of the Virgo sensitivity



Global network data taking

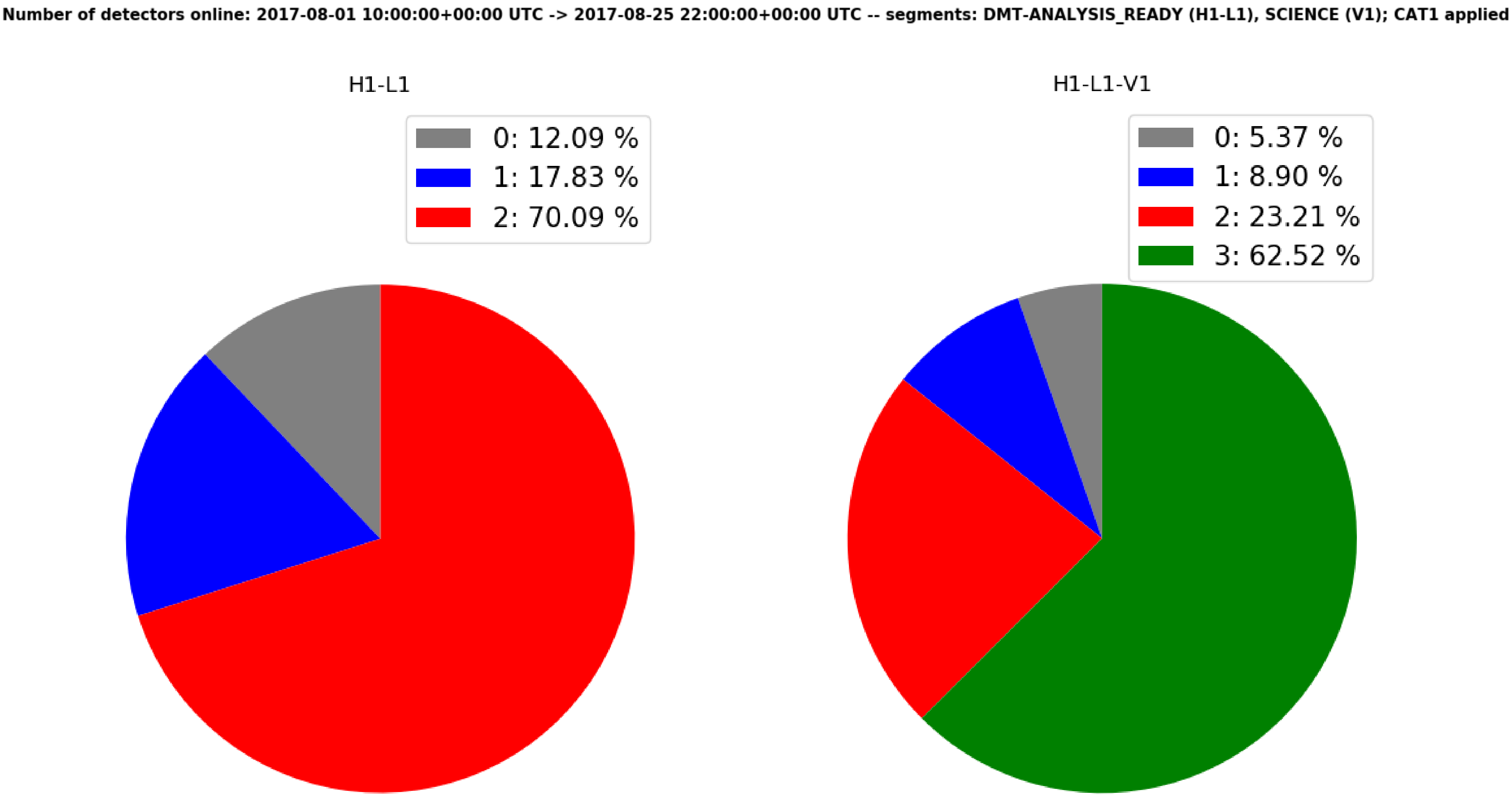
- Network duty cycle
  - Single detectors:
    Green ↔ Good science data
  - Network:



- Synchronized maintenance periods clearly visible

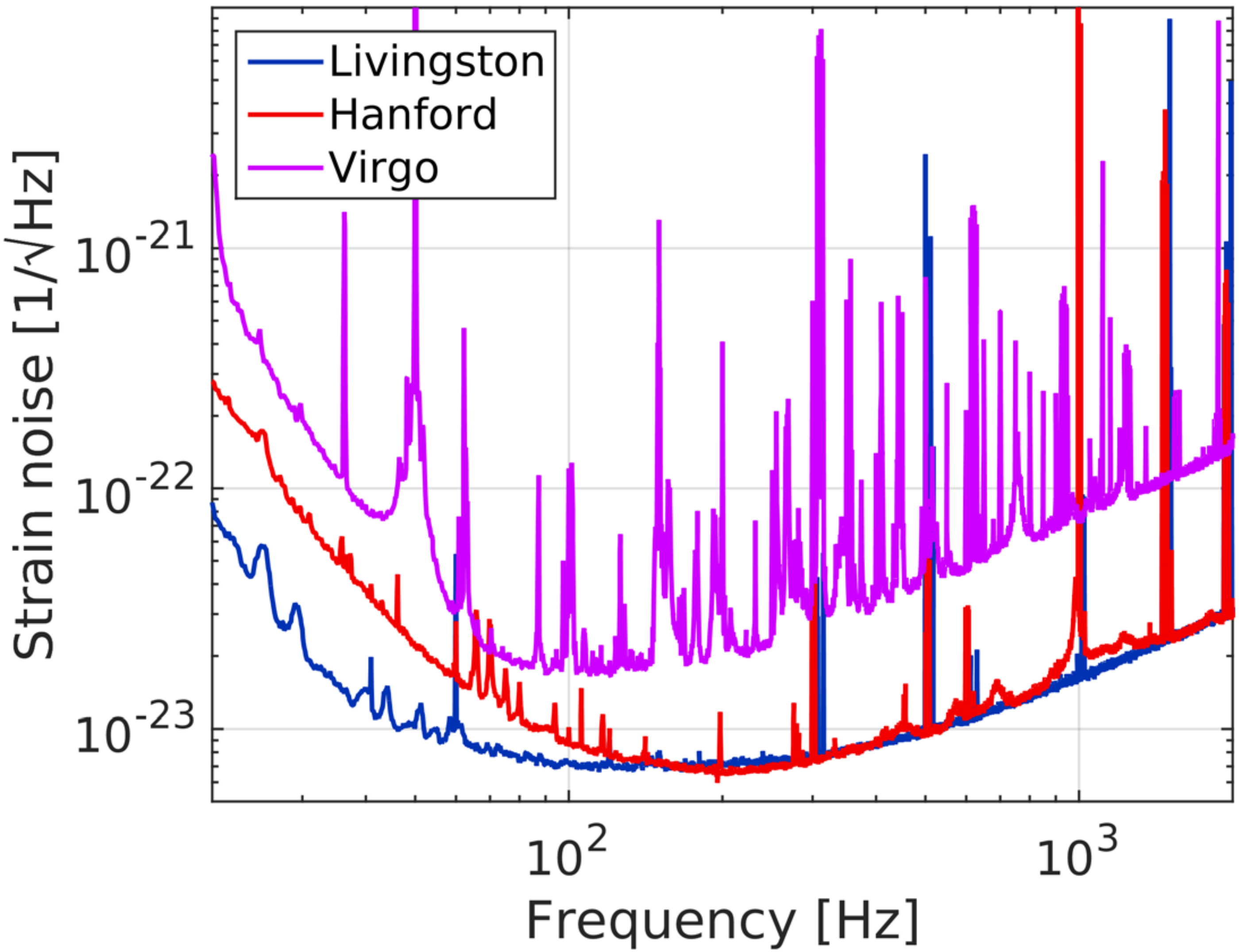
Global network data taking

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



Global network data taking

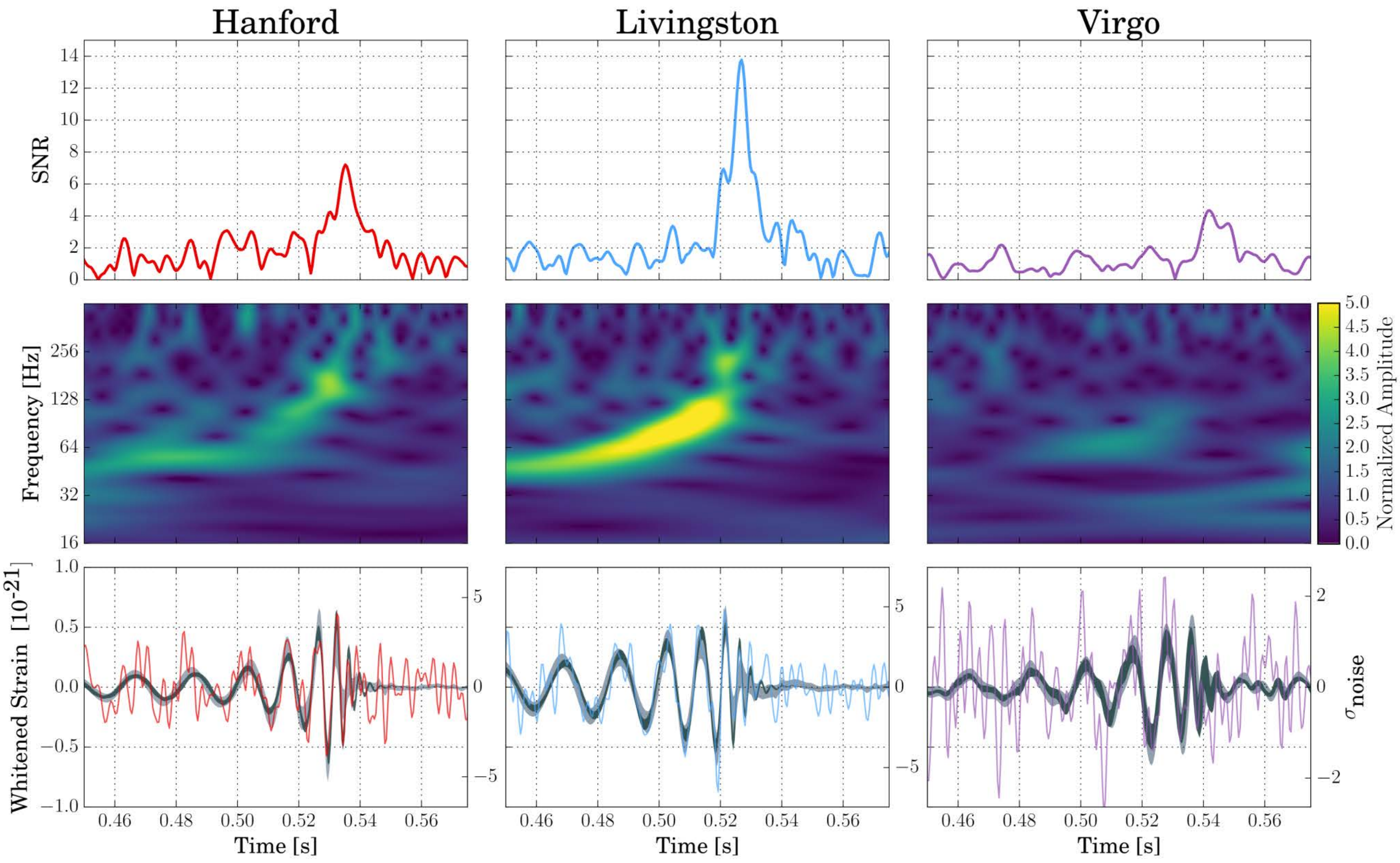
- Comparing typical August 2017 sensitivities



GW170814

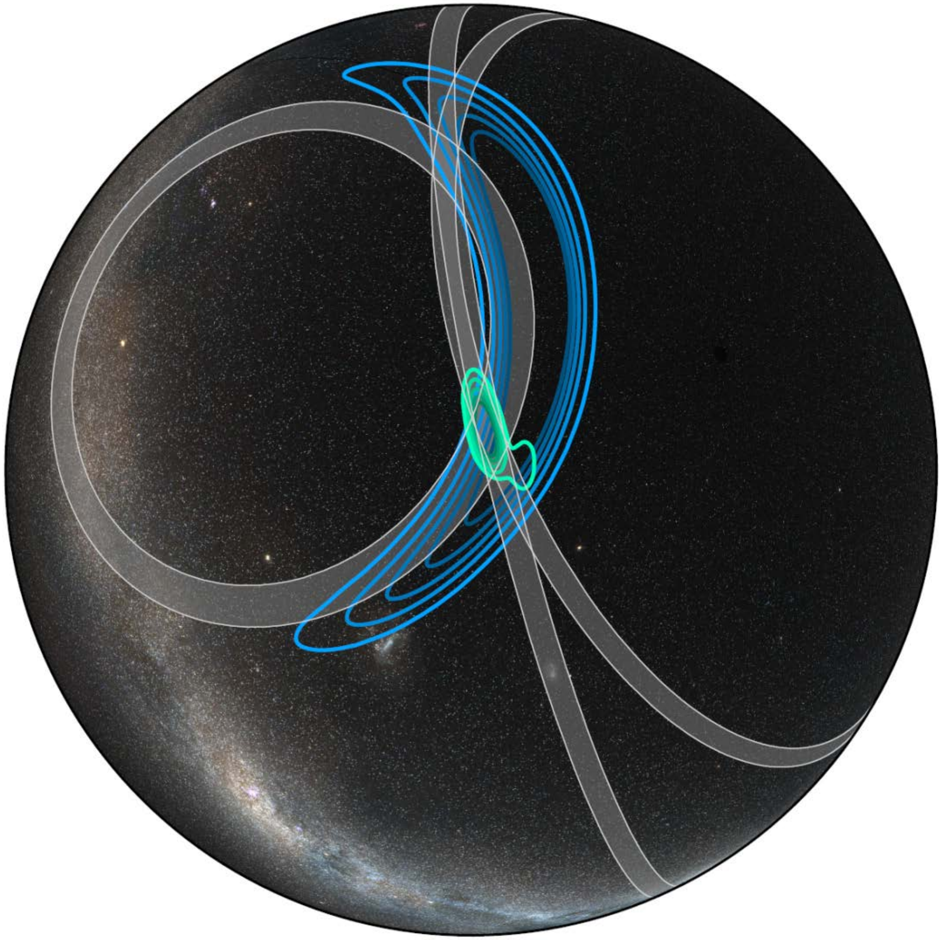
GW170814 detected signals

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



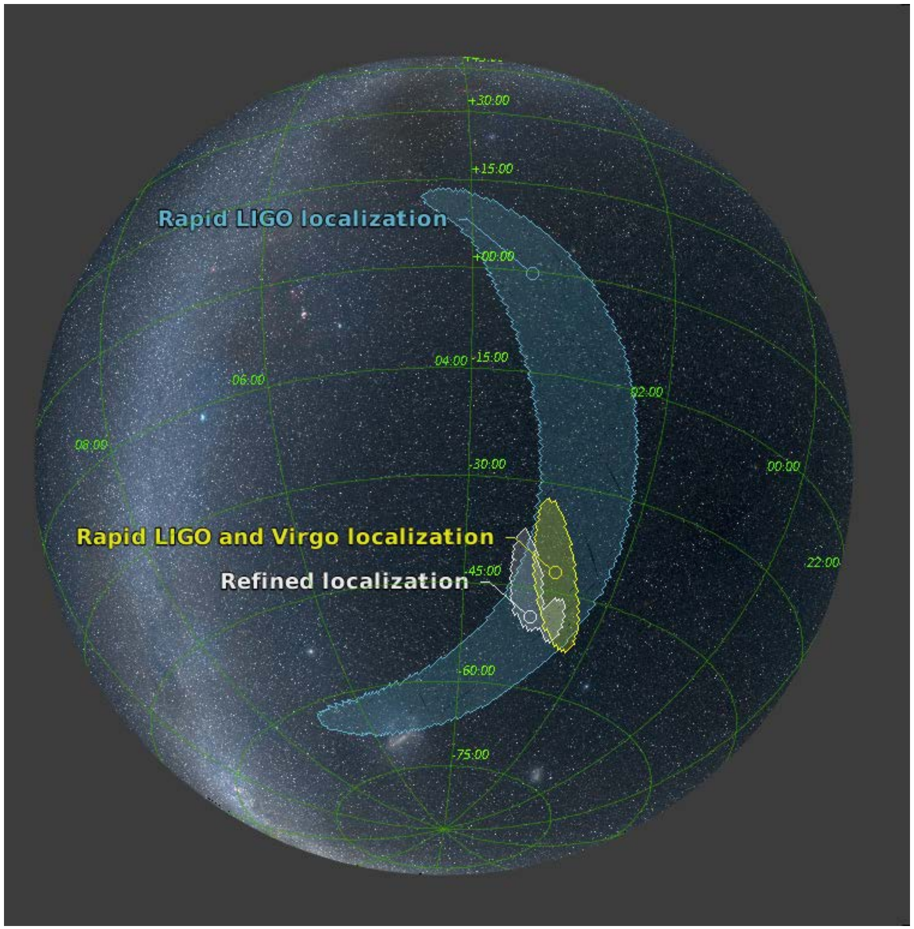
LIGO-Virgo sky localization

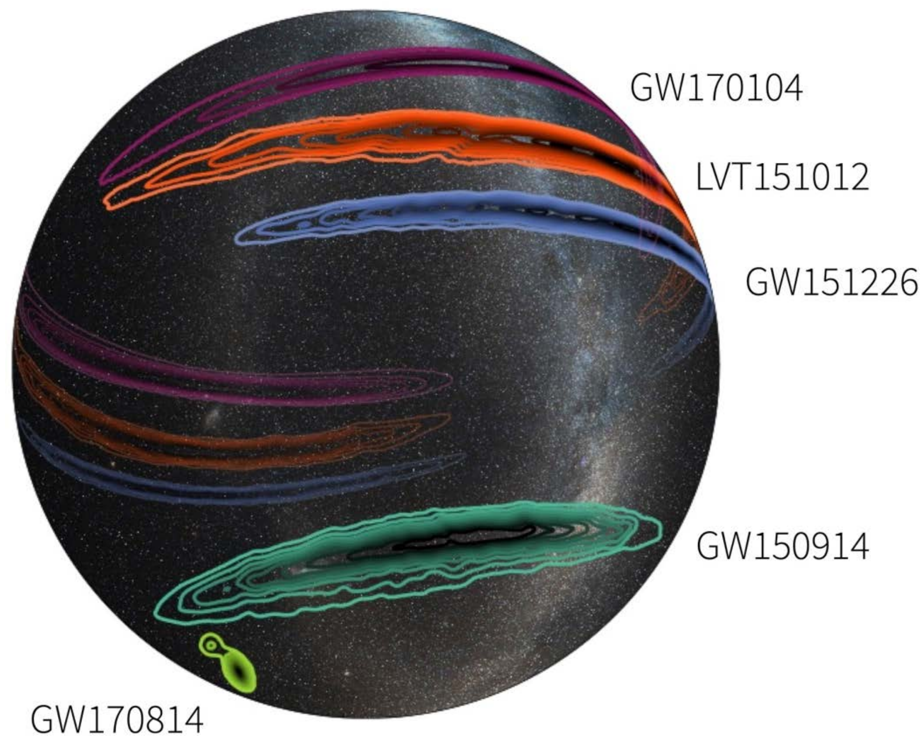
- Triangulation
  - Delays in the signal arrival time between detectors
  - Difference in shape and amplitude for the detected signals



LIGO-Virgo sky localization

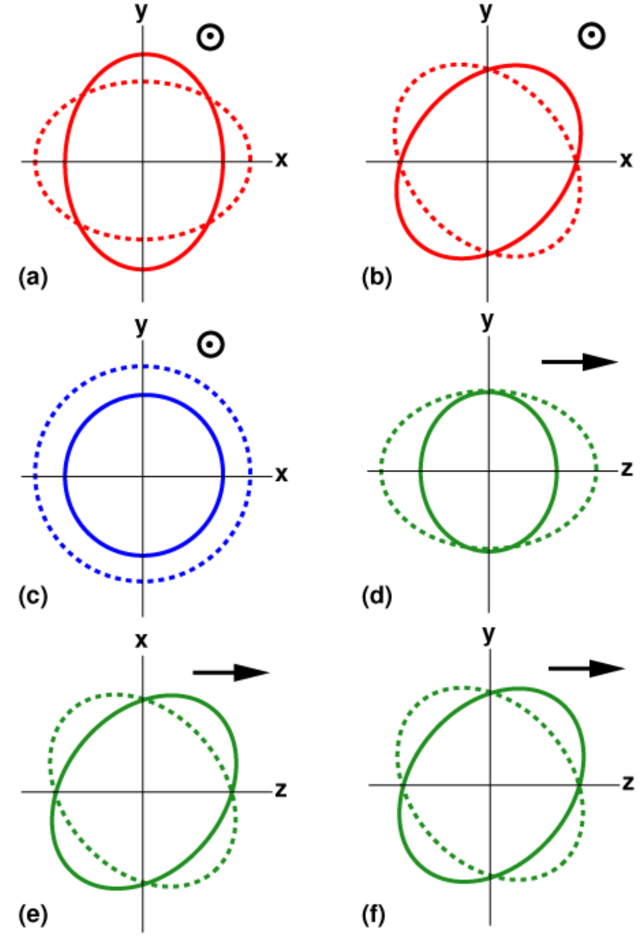
- Global 3-detector network: much-improved sky localization





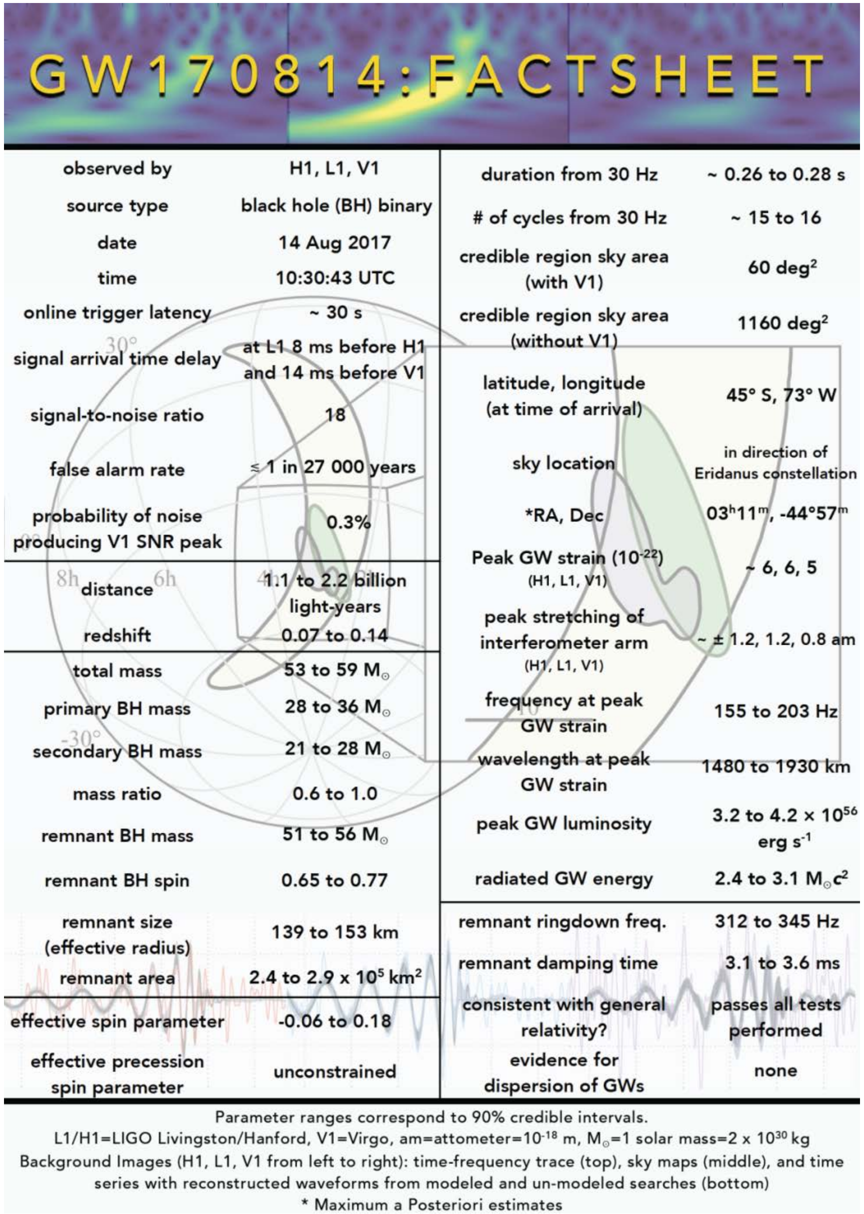
Gravitational-wave polarization

- Up to six polarisations allowed by the most generic metric theories of gravitation
  - General relativity (GR): only two (tensor) allowed
    $h(t) = F_+(t) \times h_+(t) + F_\times(t) \times h_\times(t)$
  - Additional scalar and vector polarizations
- LIGO detectors nearly coaligned
  → Record same combination of polarizations
- Network of five detectors needed to measure the gravitational-wave polarization
- First investigation with GW170814
  → Phenomenological model
  - Signal time series from GR
  - Compare three hypothesis: GR / scalar mode only / vector mode only
    → GW may be a mix of all three polarizations



→ GR polarization much more likely than
  - scalar mode only: Bayes factor ~1,000
  - vector mode only: Bayes factor ~200

Factsheet



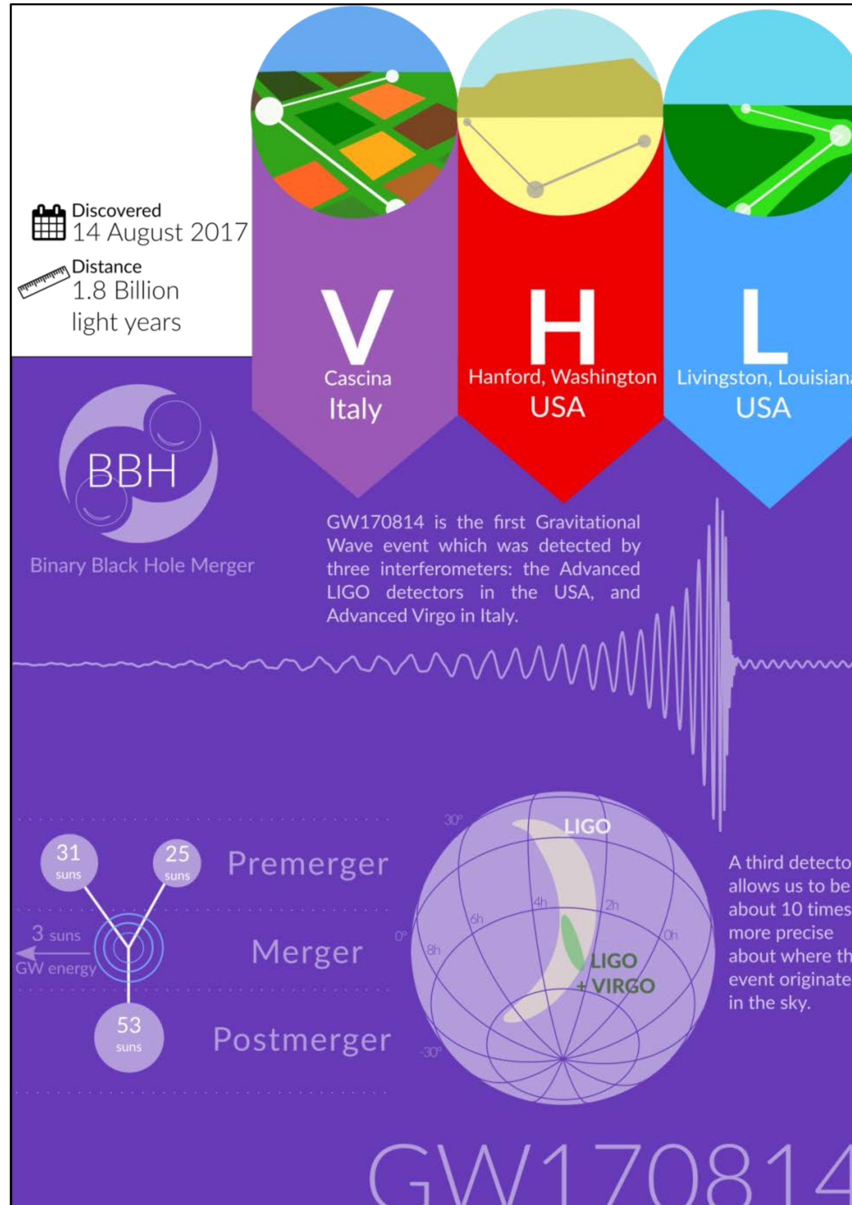
GW170814: FACTSHEET

observed by	H1, L1, V1
source type	black hole (BH) binary
date	14 Aug 2017
time	10:30:43 UTC
online trigger latency	~ 30 s
signal arrival time delay	at L1 8 ms before H1 and 14 ms before V1
signal-to-noise ratio	18
false alarm rate	≲ 1 in 27 000 years
probability of noise producing V1 SNR peak	0.3%
distance	1.1 to 2.2 billion light-years
redshift	0.07 to 0.14
total mass	53 to 59 $M_\odot$
primary BH mass	28 to 36 $M_\odot$
secondary BH mass	21 to 28 $M_\odot$
mass ratio	0.6 to 1.0
remnant BH mass	51 to 56 $M_\odot$
remnant BH spin	0.65 to 0.77
remnant size (effective radius)	139 to 153 km
remnant area	2.4 to 2.9 x 10^5 km^2
effective spin parameter	-0.06 to 0.18
effective precession spin parameter	unconstrained

duration from 30 Hz	~ 0.26 to 0.28 s
# of cycles from 30 Hz	~ 15 to 16
credible region sky area (with V1)	60 deg^2
credible region sky area (without V1)	1160 deg^2
latitude, longitude (at time of arrival)	45° S, 73° W
sky location	in direction of Eridanus constellation
*RA, Dec	03^h11^m, $-44°57^m$
Peak GW strain (10^{-22}) (H1, L1, V1)	~ 6, 6, 5
peak stretching of interferometer arm (H1, L1, V1)	~ ± 1.2, 1.2, 0.8 am
frequency at peak GW strain	155 to 203 Hz
wavelength at peak GW strain	1480 to 1930 km
peak GW luminosity	3.2 to 4.2 × 10^{56} erg s^{-1}
radiated GW energy	2.4 to 3.1 $M_\odot c^2$
remnant ringdown freq.	312 to 345 Hz
remnant damping time	3.1 to 3.6 ms
consistent with general relativity?	passes all tests performed
evidence for dispersion of GWs	none

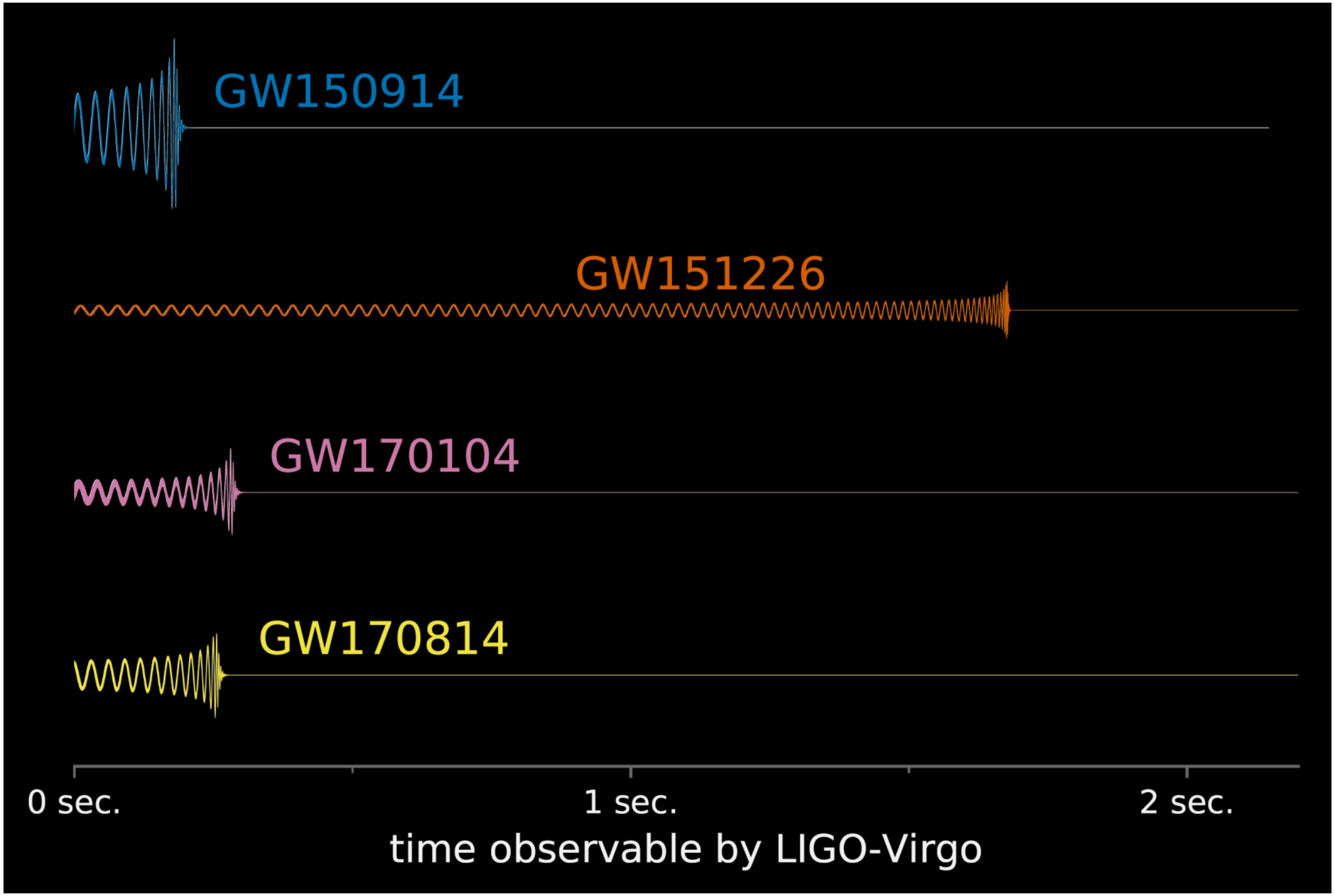
Parameter ranges correspond to 90% credible intervals.
L1/H1=LIGO Livingston/Hanford, V1=Virgo, am=attometer=10^{-18} m, $M_\odot$=1 solar mass=2 x 10^{30} kg
Background Images (H1, L1, V1 from left to right): time-frequency trace (top), sky maps (middle), and time series with reconstructed waveforms from modeled and un-modeled searches (bottom)
* Maximum a Posteriori estimates

Infographics



Binary black hole summary: four events

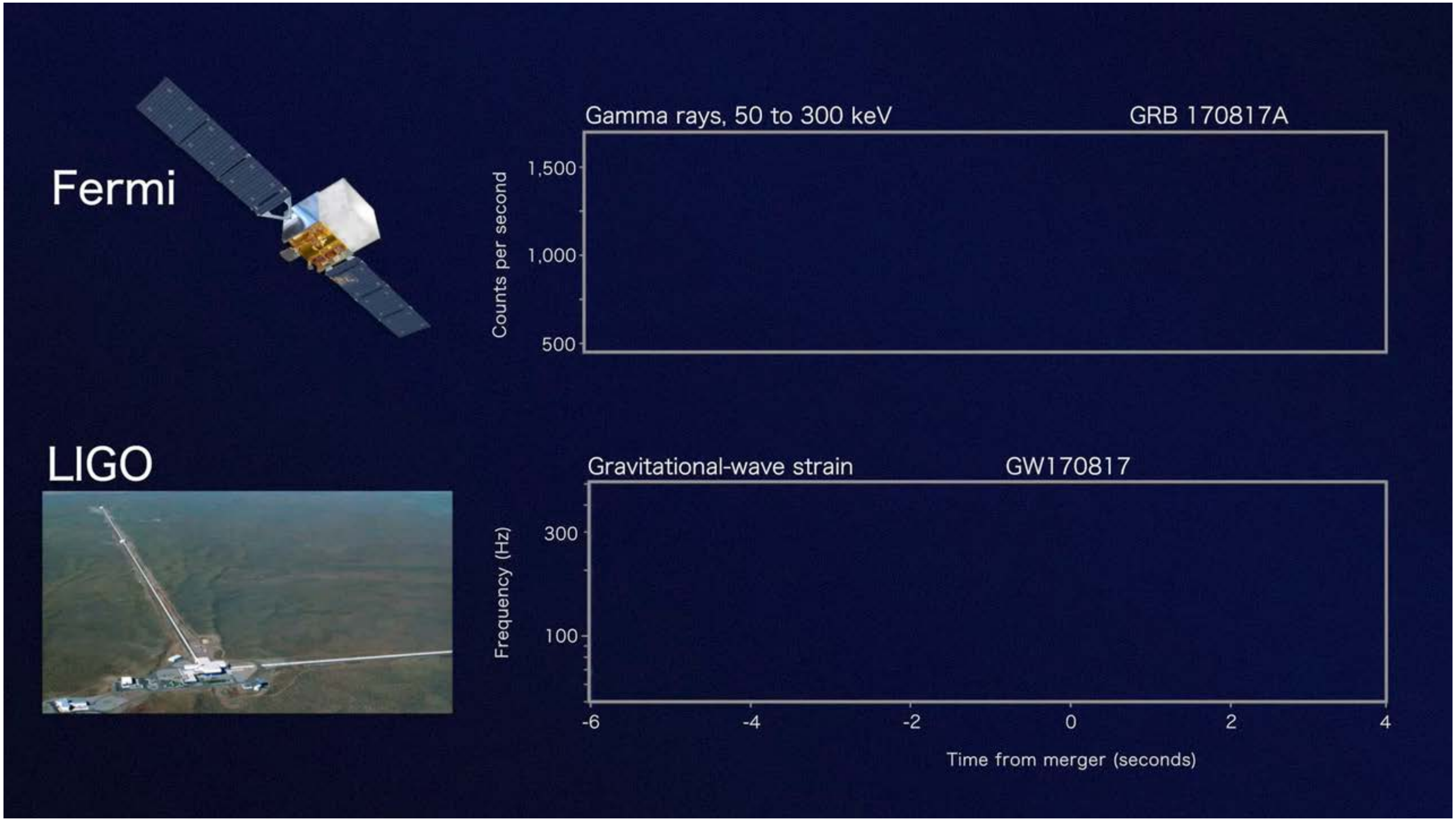
- Black hole binary systems



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

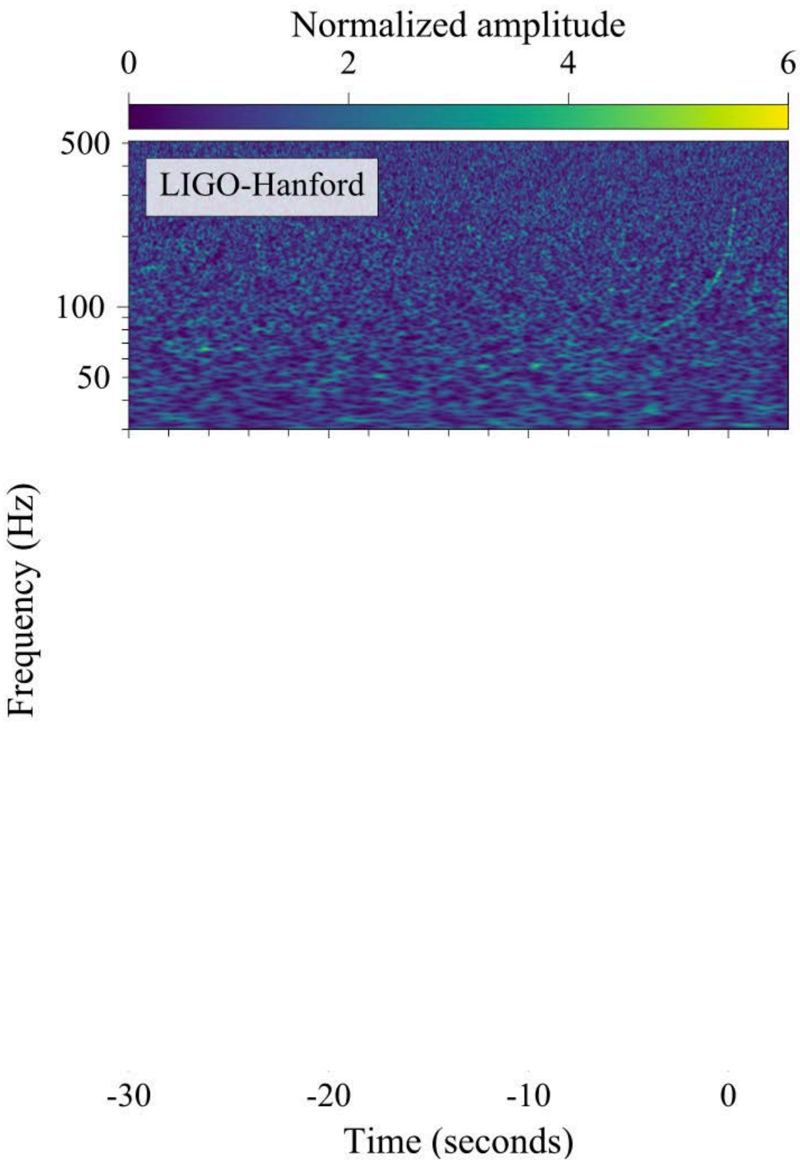


Gravitational waves from GW170817

- Initially: LIGO Hanford-only trigger
  - Chirp signal visible for a few seconds
    - → Low-mass binary
    - → Matter (neutron star(s))?
    - → Electromagnetic counterpart?

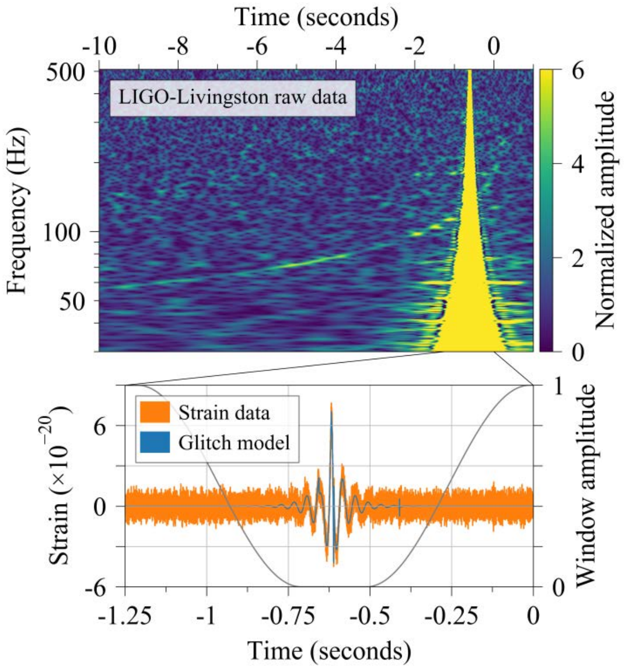
- Fermi-GBM trigger
  - Too close in time to be a coincidence!

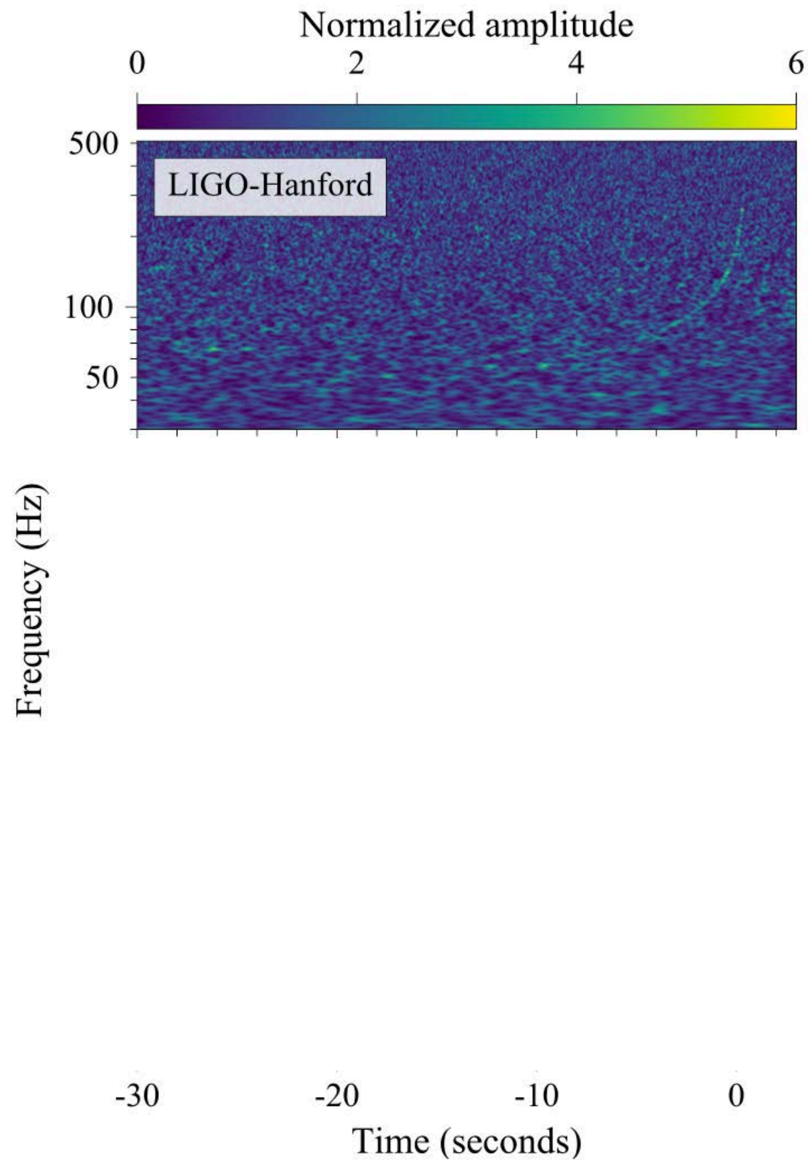
→ What did the other two interferometers record?
  - LIGO Livingston should be more sensitive than LIGO Hanford



Gravitational waves from GW170817

- Ooops: huge glitch in LIGO Livingston!
  → Reason why no trigger was released
  - Glitches like that one occur from time to time in both LIGO detectors





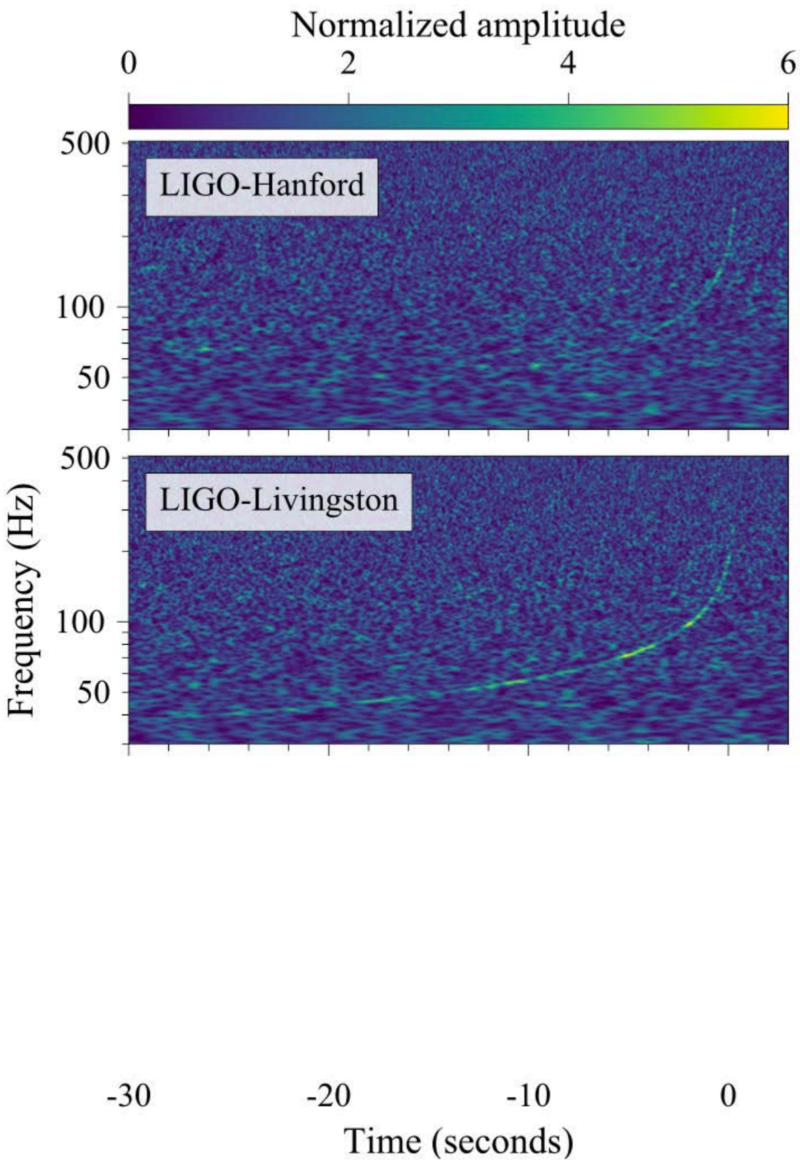
- Limited overlap with the GW signal in the time-frequency plane
  → Glitch can be excised

Gravitational waves from GW170817

- Impressive result from the glitch-removal procedure
  - Signal lasts more than 30 seconds in LIGO Livingston

→ Binary neutron star merger

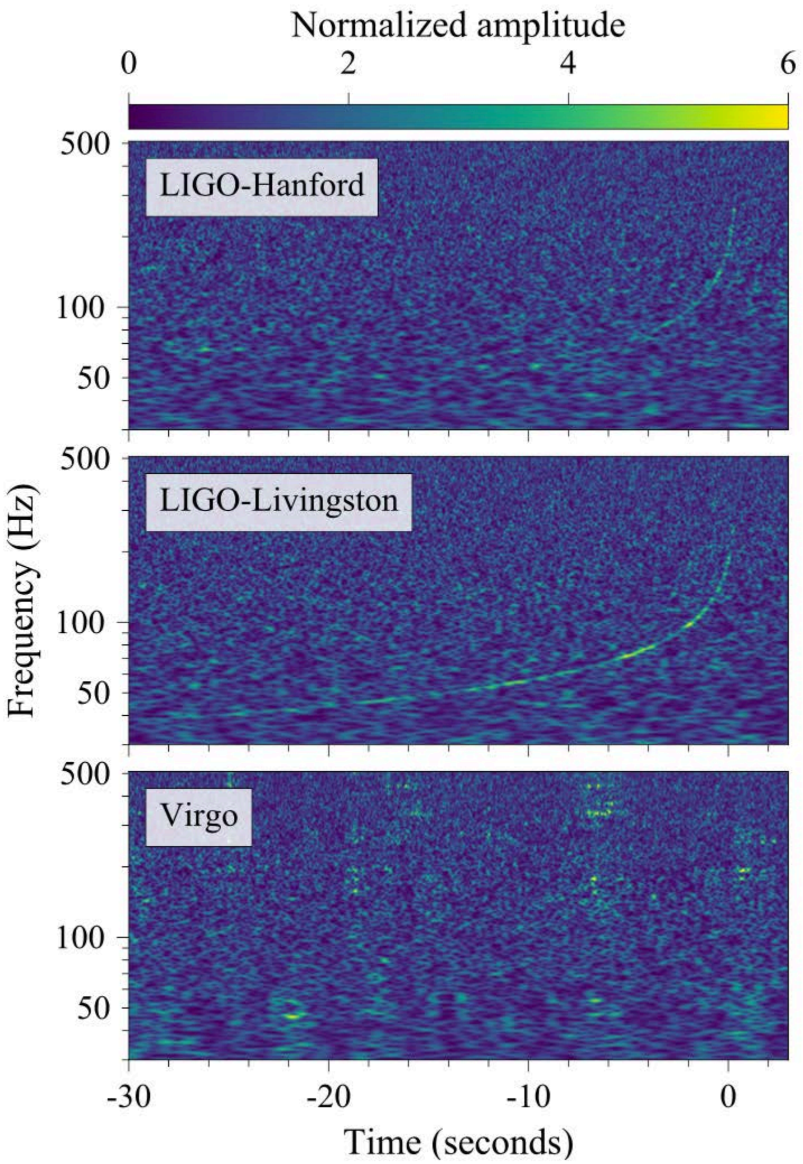
- And what about Virgo?



Gravitational waves from GW170817

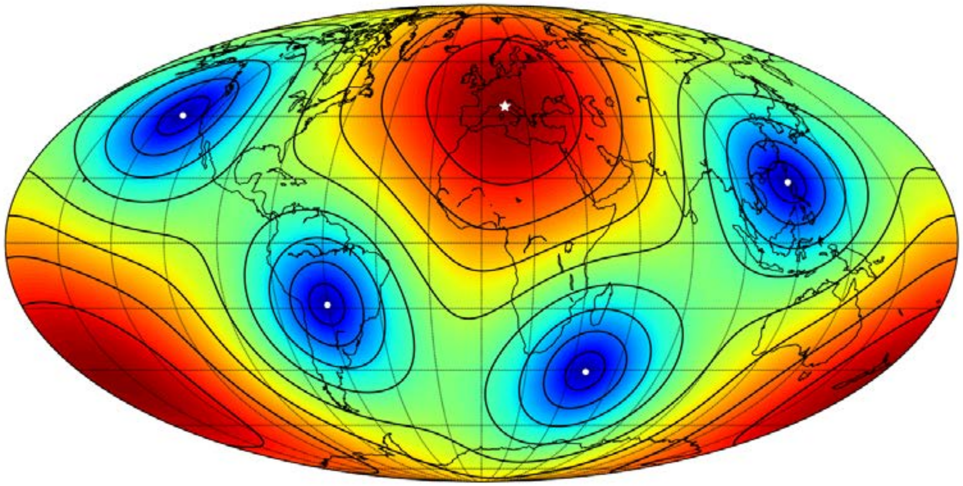
- Nothing in Virgo!

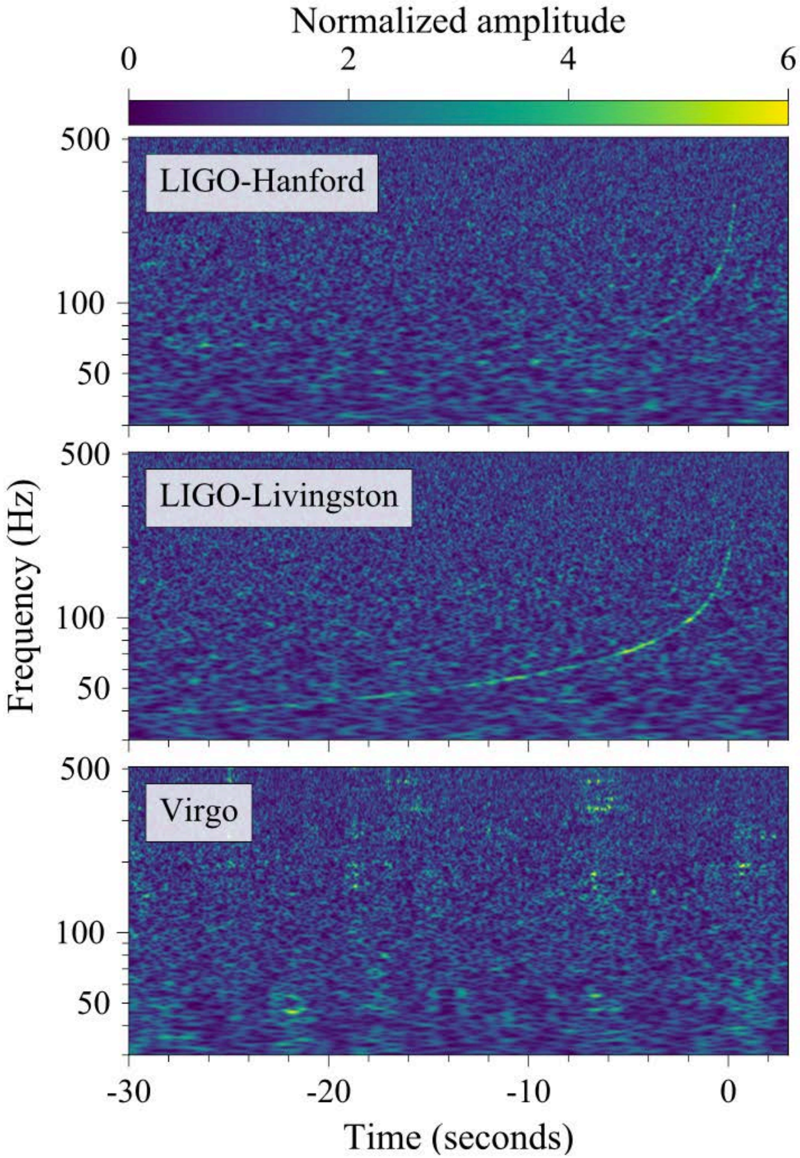
→ A tumbleweed moment…
[In French: « Un ange passe … »]



Gravitational waves from GW170817

- Lower sensitivity + antenna pattern!





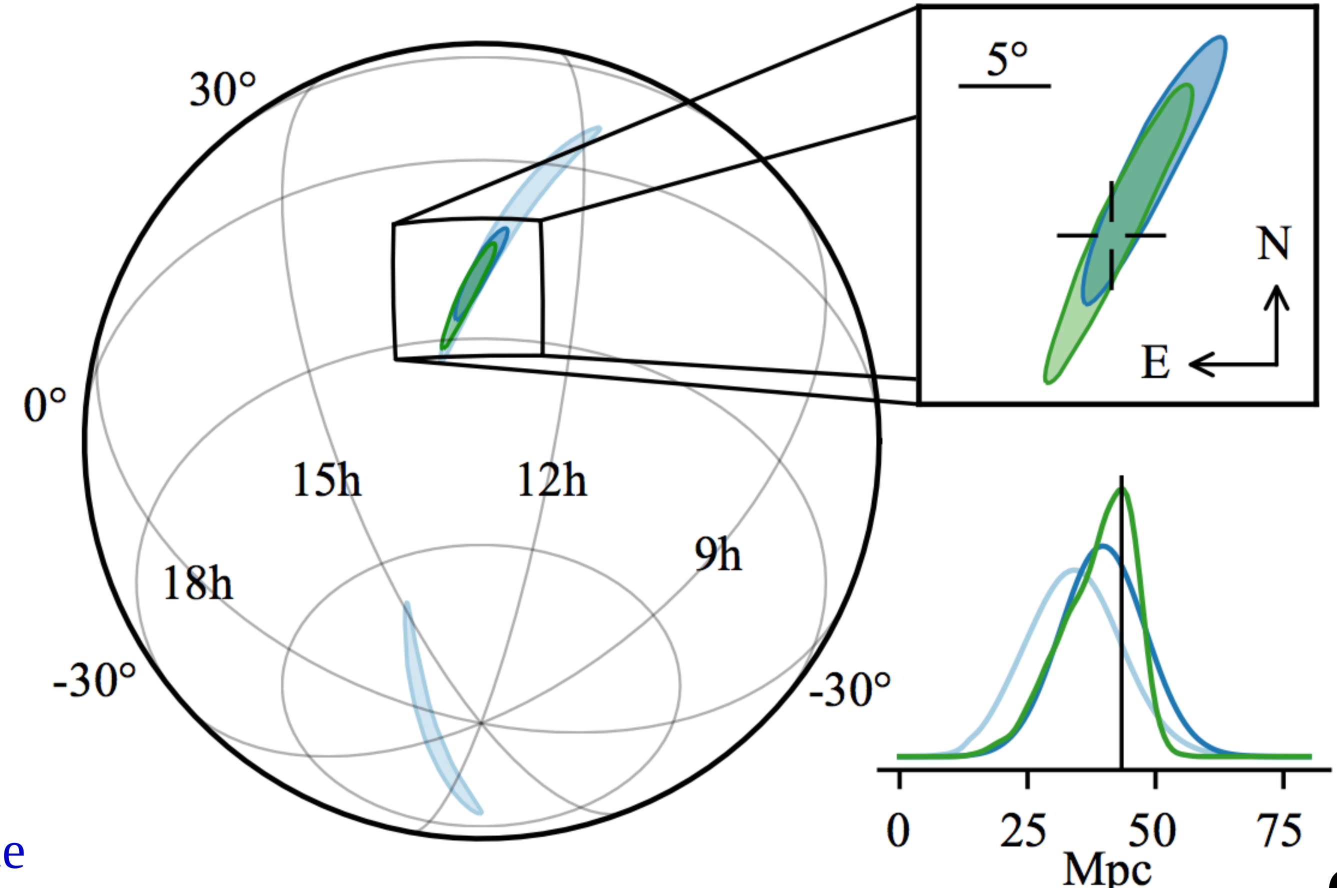
LIGO-Virgo sky localization

- Combined Signal / Noise Ratio of 32.4
- Source close to one of the Virgo blind spots

→ Accurate sky localization sent at 19:55 CEST (+ 05:14 after GW was recorded)

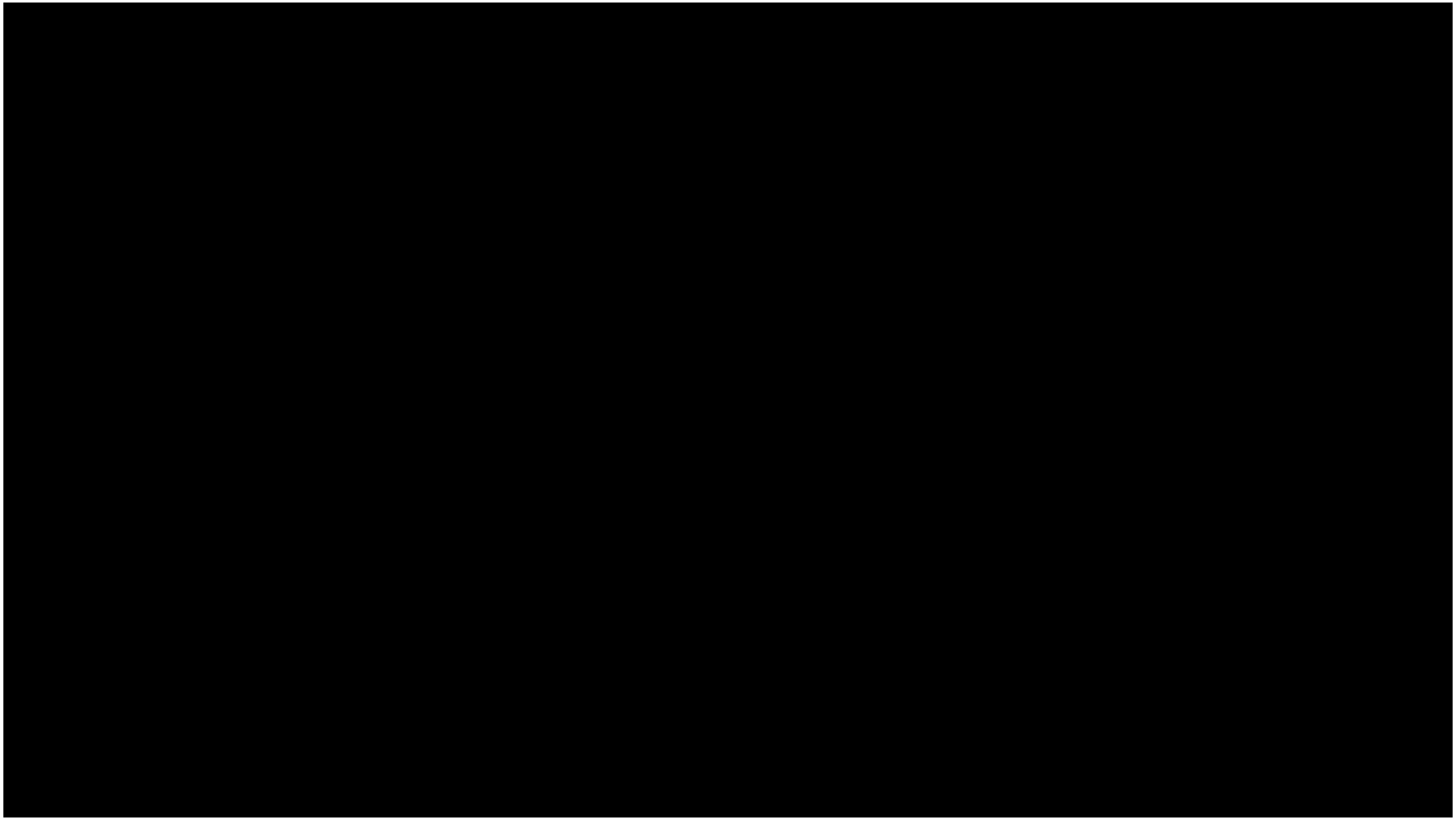
- Pale blue
  LIGO only
- Deep blue
  LIGO + Virgo
  initial map
- Green:
  LIGO + Virgo
  final map

→ 3D-localization
  - Position + distance



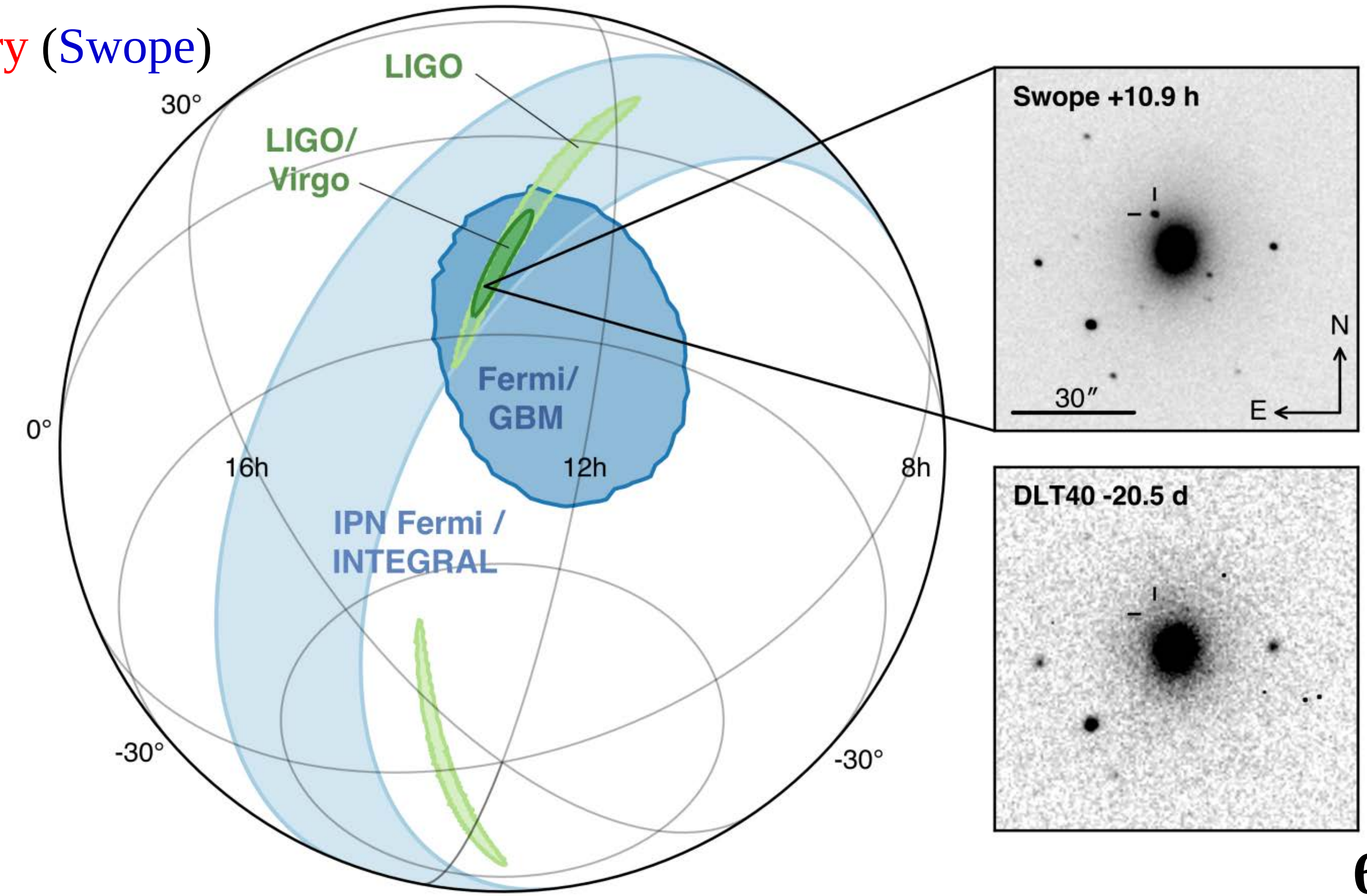
Search for GW170817 counterparts

- Alert sent to telescopes by LIGO-Virgo, including a skymap (@ 19:55 CEST)



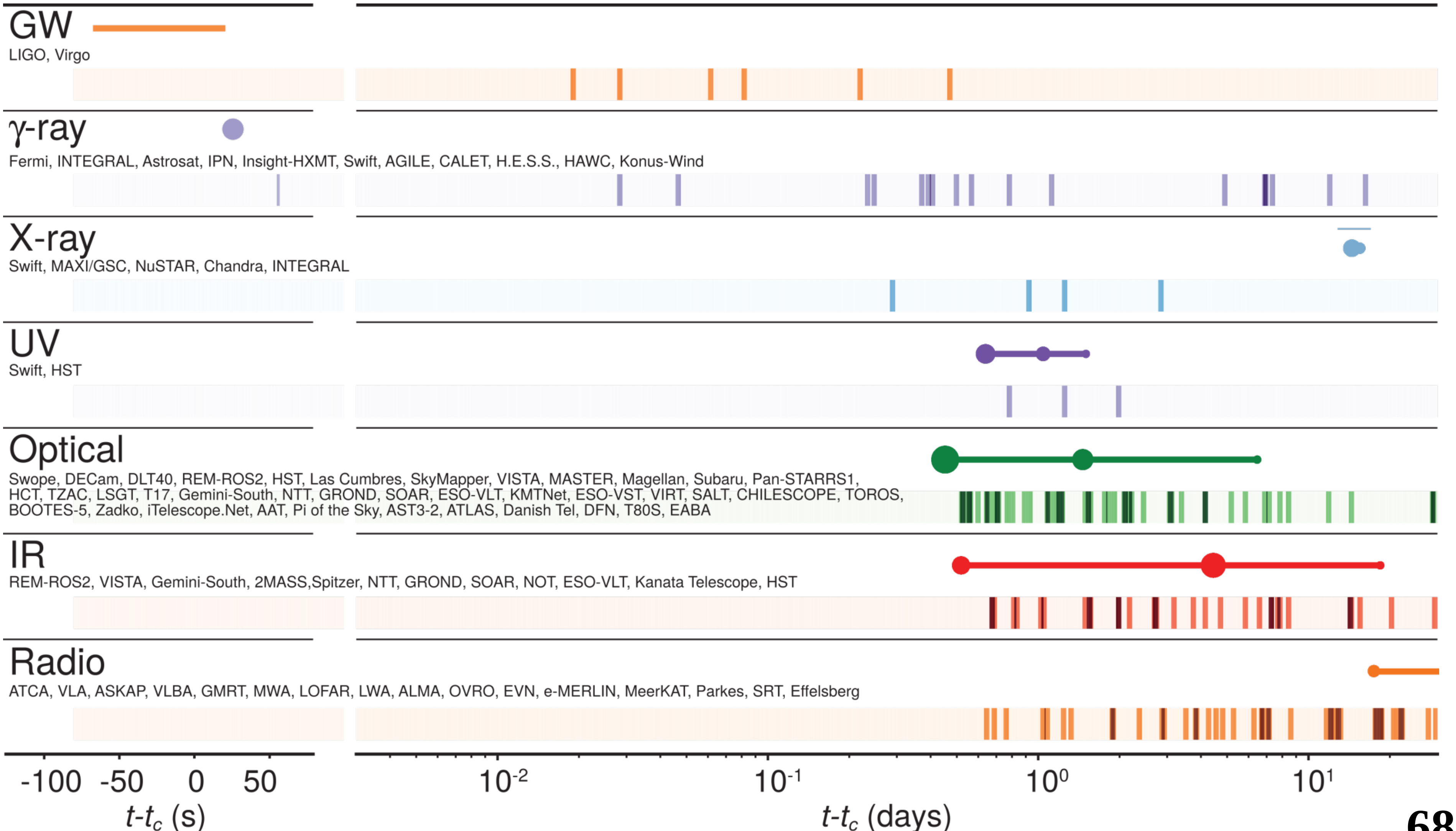
Sky localizations & source position

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



Multi-messenger astronomy

- Gravitational wave, gamma ray burst, whole electromagnetic spectrum



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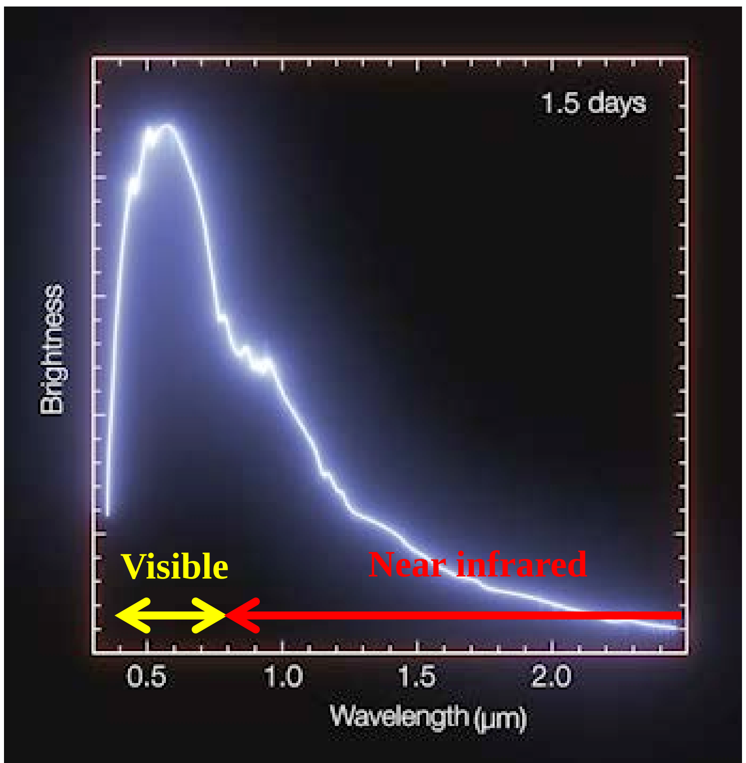
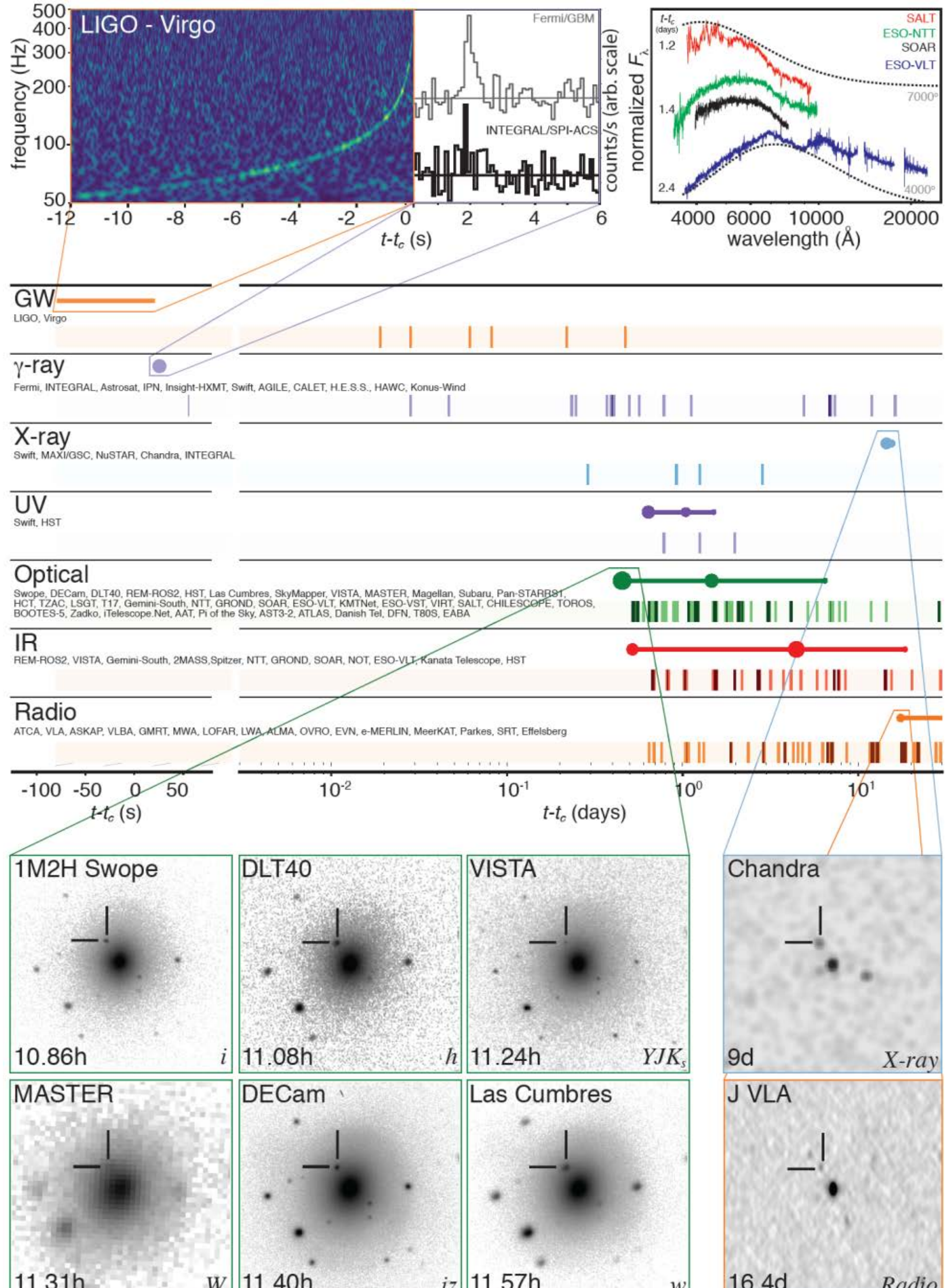
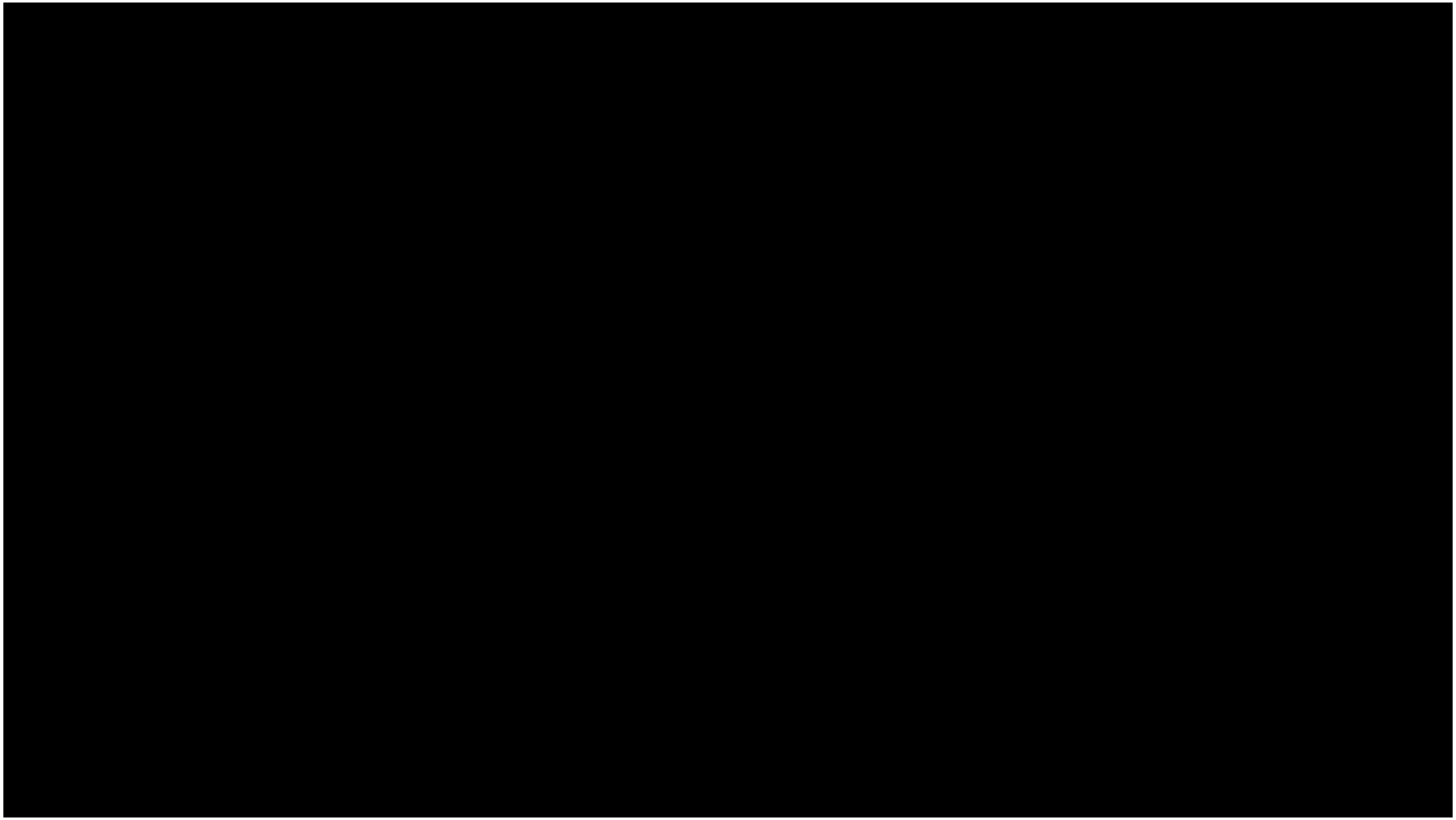




Binary neutron star merger

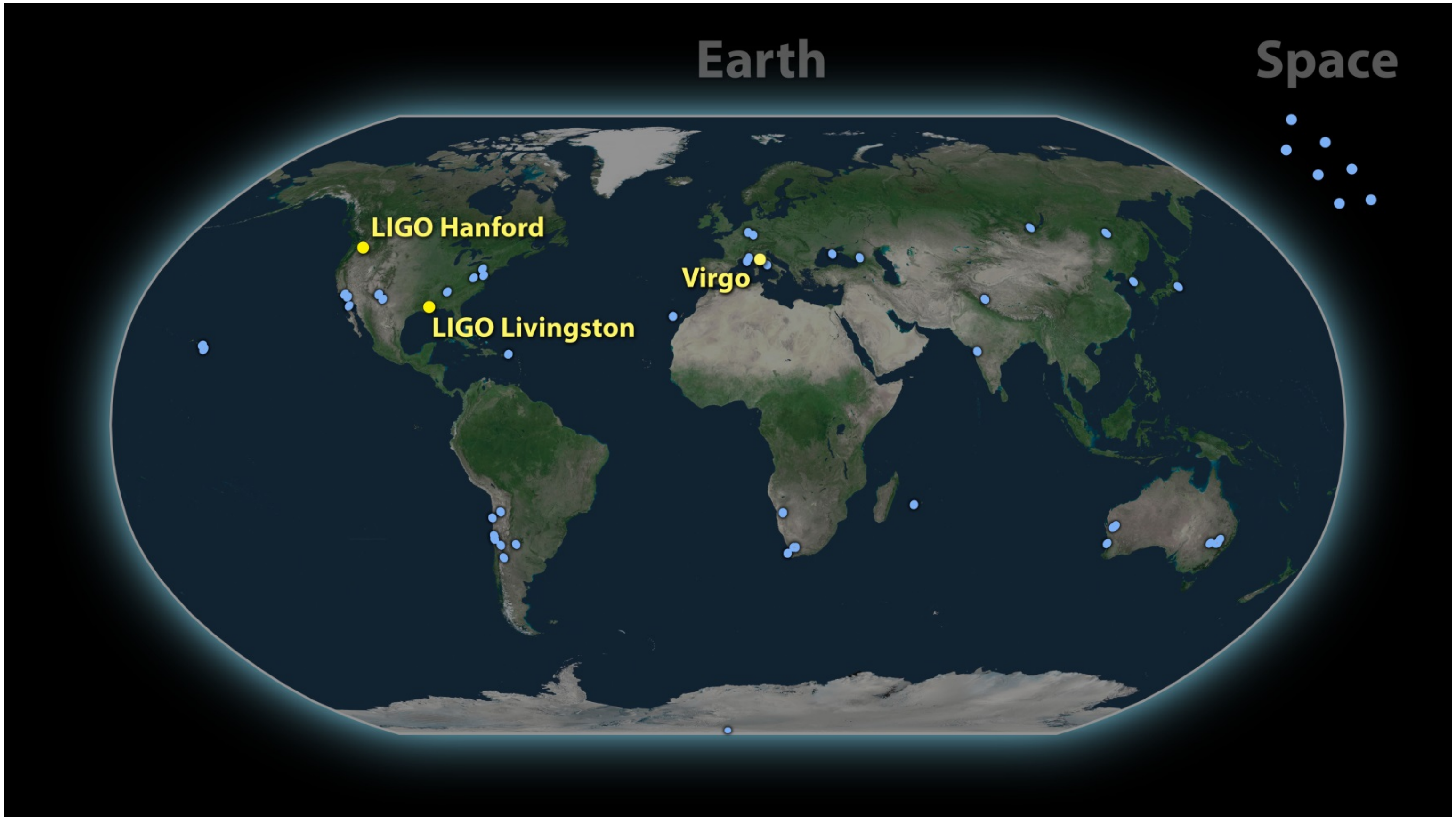
- Fusion of two neutron stars
  - Gravitational waves, gamma ray burst, kilonova, ???

NASA's Goddard
Space Flight Center



Worldwide astronomy

- Three gravitational-wave detectors
- Tens of partner observatories



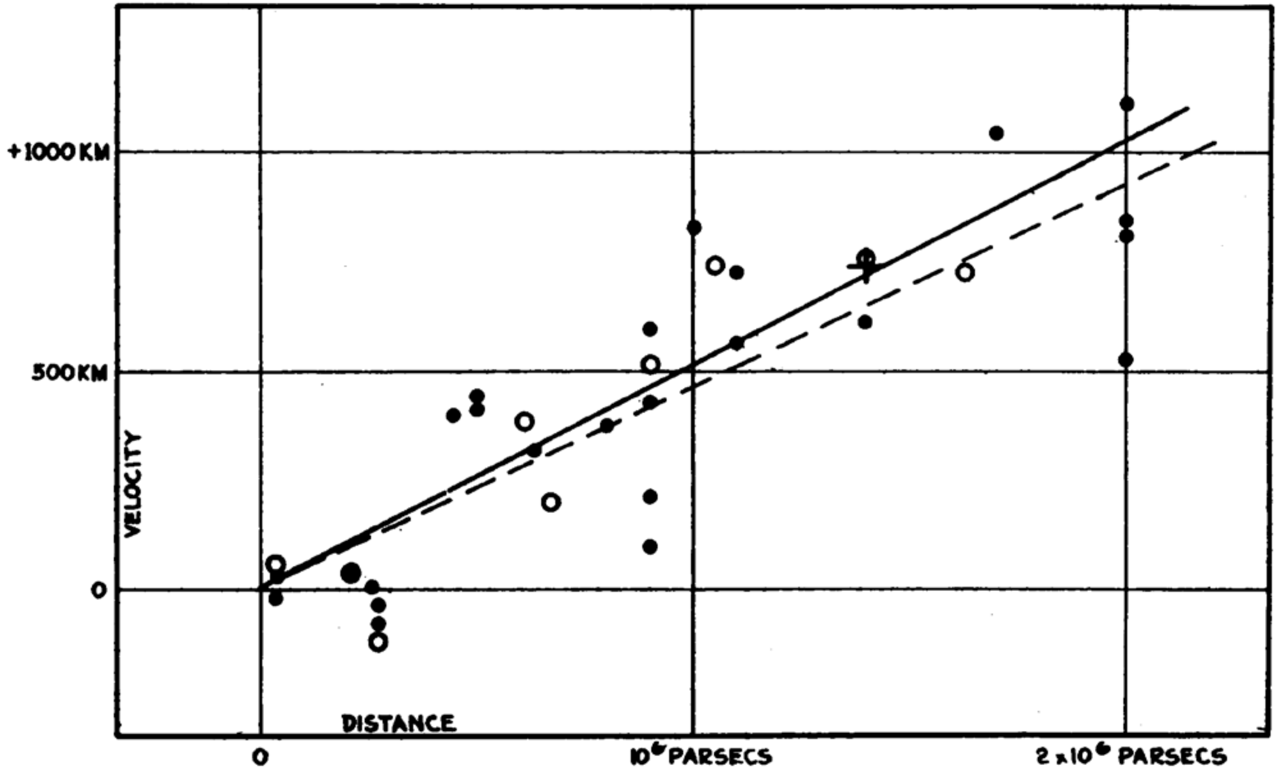
Hubble constant measurement

- $v_H = H_0 \times d$ for nearby sources (d≈ 50 Mpc at most)
  - v_H: Radial (recession) velocity
  - H_0: Hubble constant
  - d: Distance of the source

- Two techniques to measure H_0 so far
  - Type-I supernovae
  - CMB

- $H_0 \approx 70$ km / s / Mpc
  - Tension between results from the two methods

- Gravitational waves
  - New, independent measurement



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  - v_H: Radial (recession) velocity
  - H_0: Hubble constant
  - d: Distance of the source

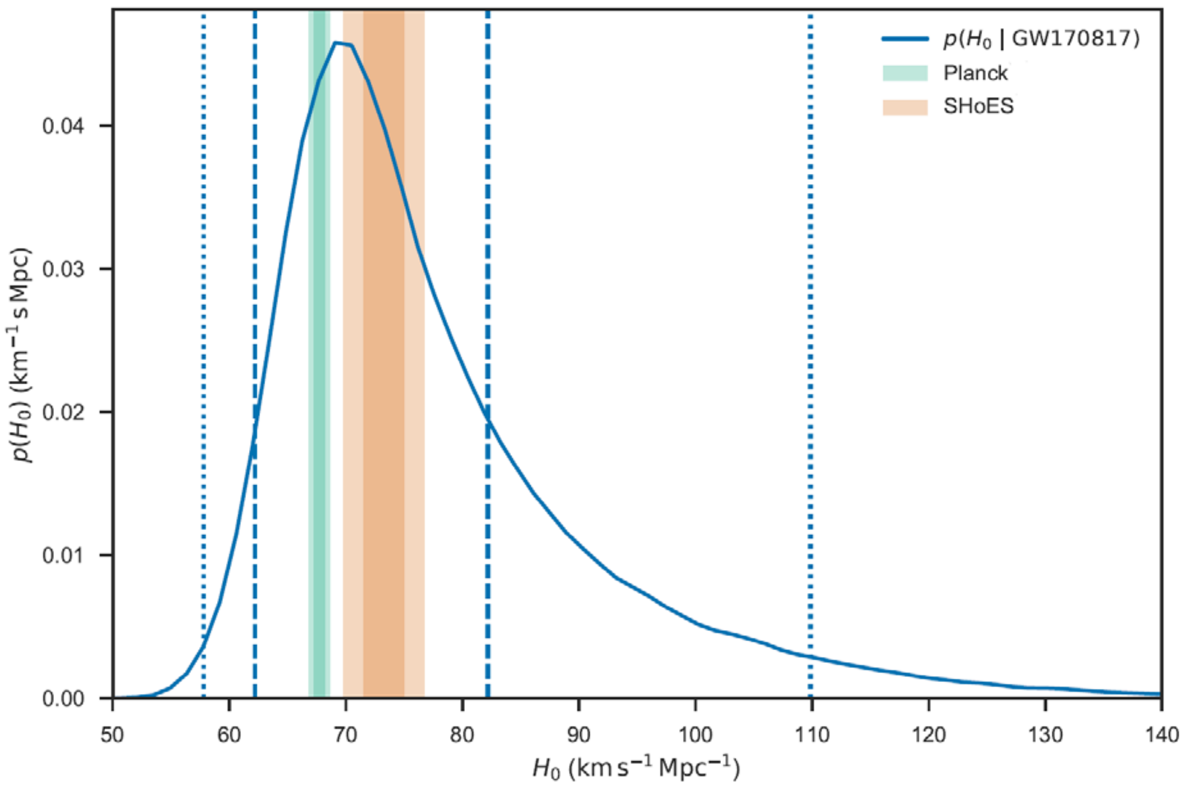
- Distance provided by gravitational waves
  - $h \propto 1 / d$

  $\rightarrow d \approx 44$ Mpc

- Radial velocity given by host galaxy identification
  - NGC 4993, Hydra constellation

  $\rightarrow v_H \approx 3000$ km / s

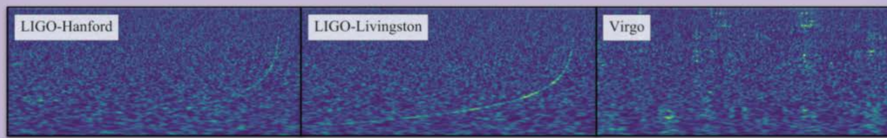
$\rightarrow H_0 = 70^{+10}_{-12}$ km / s / Mpc



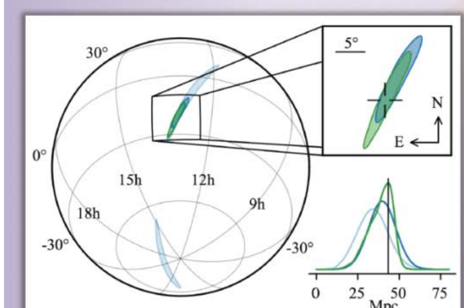
Factsheet

Infographics

GW170817 FACTSHEET



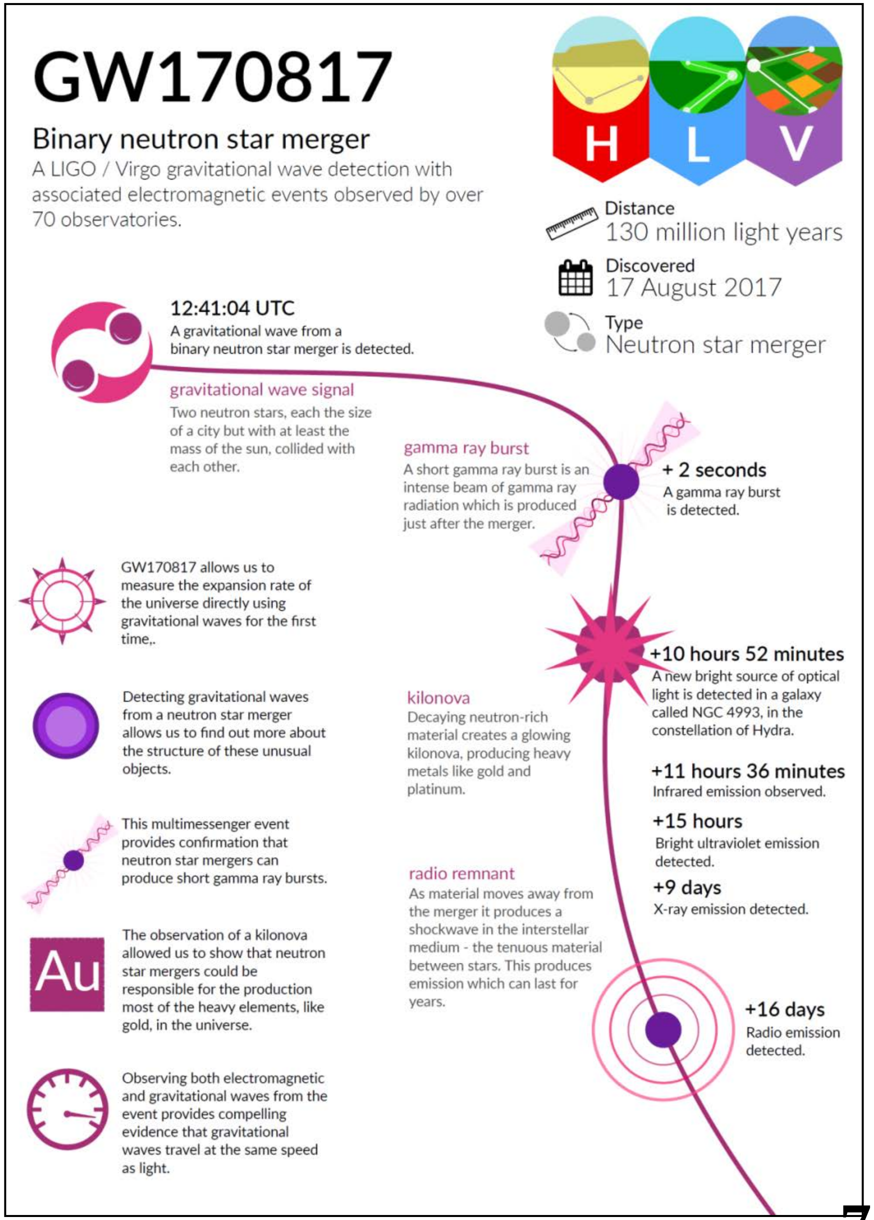
observed by	H, L, V
source type	binary neutron star (NS)
date	17 August 2017
time of merger	12:41:04 UTC
signal-to-noise ratio	32.4
false alarm rate	< 1 in 80 000 years
distance	85 to 160 million light-years
total mass	2.73 to 3.29 $M_\odot$
primary NS mass	1.36 to 2.26 $M_\odot$
secondary NS mass	0.86 to 1.36 $M_\odot$
mass ratio	0.4 to 1.0
radiated GW energy	> 0.025 $M_\odot c^2$
radius of a 1.4 $M_\odot$ NS	likely ≲ 14 km
effective spin parameter	-0.01 to 0.17
effective precession spin parameter	unconstrained
GW speed deviation from speed of light	< few parts in 10^{15}
inferred duration from 30 Hz to 2048 Hz**	~ 60 s
inferred # of GW cycles from 30 Hz to 2048 Hz**	~ 3000
initial astronomer alert latency*	27 min
HLV sky map alert latency*	5 hrs 14 min
HLV sky area†	28 deg^2
# of EM observatories that followed the trigger	~ 70
also observed in	gamma-ray, X-ray, ultraviolet, optical, infrared, radio
host galaxy	NGC 4993
source RA, Dec	$13^h09^m48^s$, -23°22'53"
sky location	in Hydra constellation
viewing angle (without and with host galaxy identification)	≤ 56° and ≤ 28°
Hubble constant inferred from host galaxy identification	62 to 107 km s^{-1} Mpc^{-1}



Images: time frequency traces (top), GW sky map (left, HL = light blue, HLV = dark blue, improved HLV = green, optical source location = cross-hair)

GW=gravitational wave, EM = electromagnetic, $M_\odot$=1 solar mass=2×10^{30} kg, H/L=LIGO Hanford/Livingston, V=Virgo

Parameter ranges are 90% credible intervals.
*referenced to the time of merger
**maximum likelihood estimate
†90% credible region



The significance of GW170817

- First binary neutron merger ever detected
  - Gravitational waves + electromagnetic spectrum
- First gravitational-wave signal whose source is located and observed by several telescopes worldwide
  - Kilonova
- At least part of the short gamma-ray burst are due to binary neutron star mergers
  - But the observed gamma-ray burst is much weaker than expected
- Neutron star fusions may play a key role in the formation of heavy chemical elements (beyond iron) in the Univers
- Independent measurement of the Hubble constant
  - Universe expansion rate
- Another experimental confirmation of the validity of the general relativity
  - Agreement predictions – measurements strongly constrainst alternative theories

O2-O3 « Long shutdown »

One year-long shutdown

- Hardware upgrades
  → Virgo
    - High-power laser (100 W)
    - Monolithic suspensions
    - Vacuum system
    - Frequency-independent squeezing
    - Installation of an array of seismic sensors to measure the Newtonian noise

- Technical and environmental noise hunting
  - Use experience gained during the commissioning and O2 data taking phases
  - Improve/tighten detector control

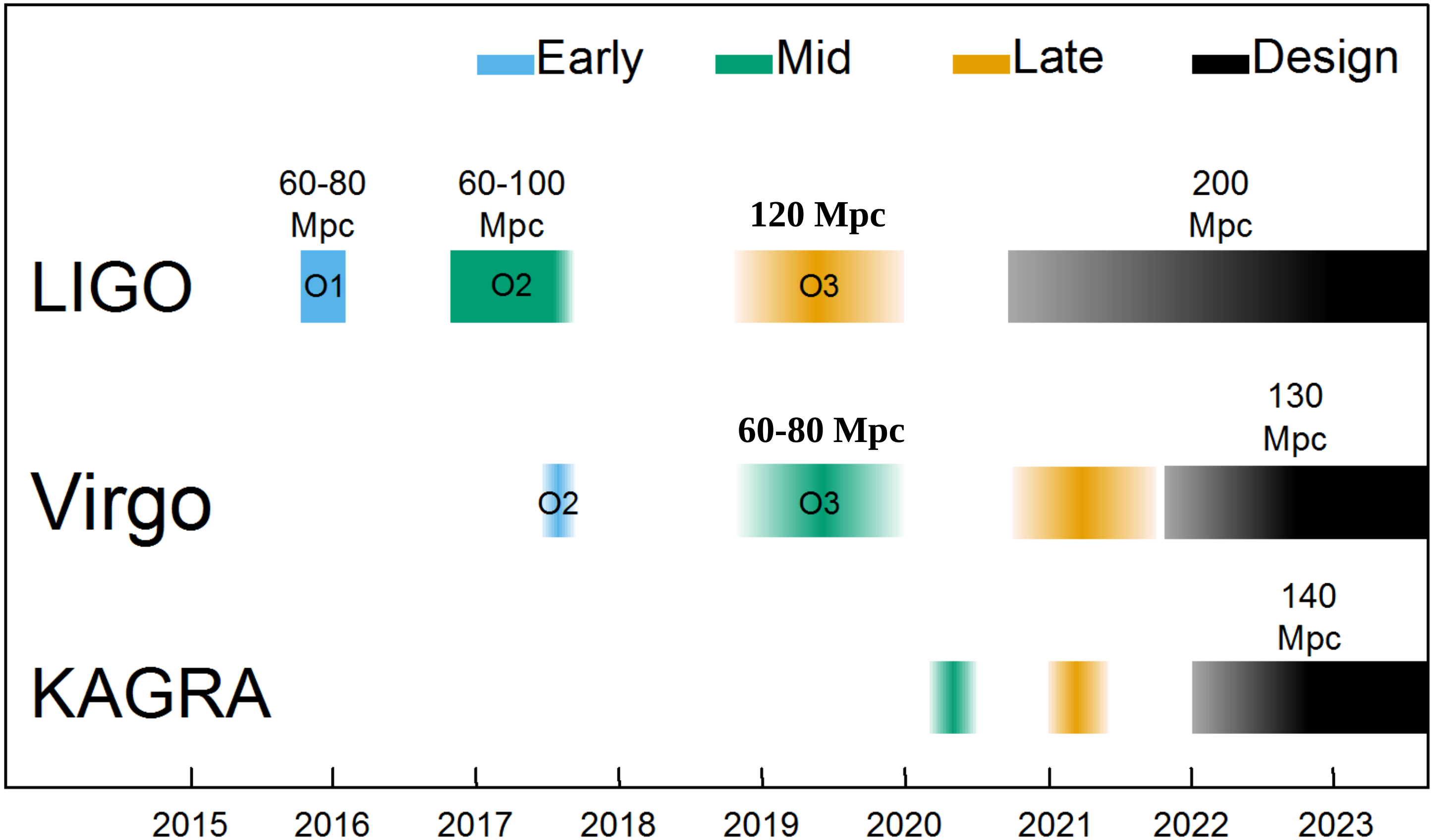
→ Virgo
  - Post-O2 commissioning phase until early December
  - Hardware upgrades until mid-Spring
  - Then back to commissioning

- Goal: start O3 (Fall 2018) with the LIGO detectors and with a decent sensitivity

Observing scenario

- Sensitivity improvement over time
  - Expressed in terms of « Binary Neutron Star (BNS) range »

  → Sky-averaged distance up to which one can detect a BNS merger @ SNR = 8



On the longer term

- Upgrades post-O3
  - Newtonian noise cancellation
  - Frequency-dependent squeezing
  - Signal recycling
  - Full-power laser (up to 200 W)

  → Sensitivity goal: ~160 Mpc

- After O4 (mid-2022): « Advanced Virgo + »

  → Make the best possible use of the existing infrastructure
  - Larger mirrors
  - Improved coating

  → Reduce thermal noise

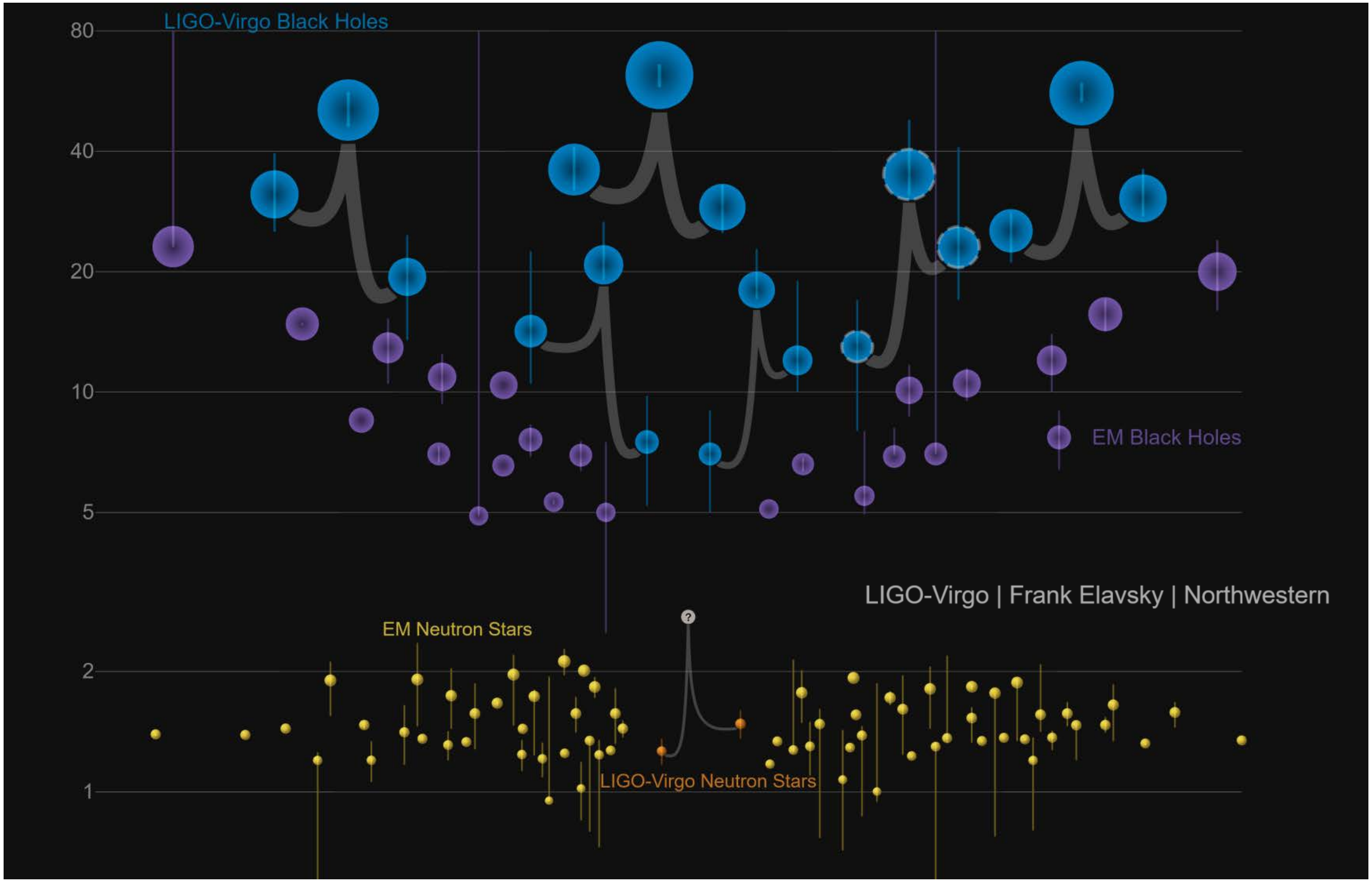
  → Sensitivity goal: ~300 Mpc

- Launch of the LISA space mission scheduled for 2034

Conclusions

Detections

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



Detections

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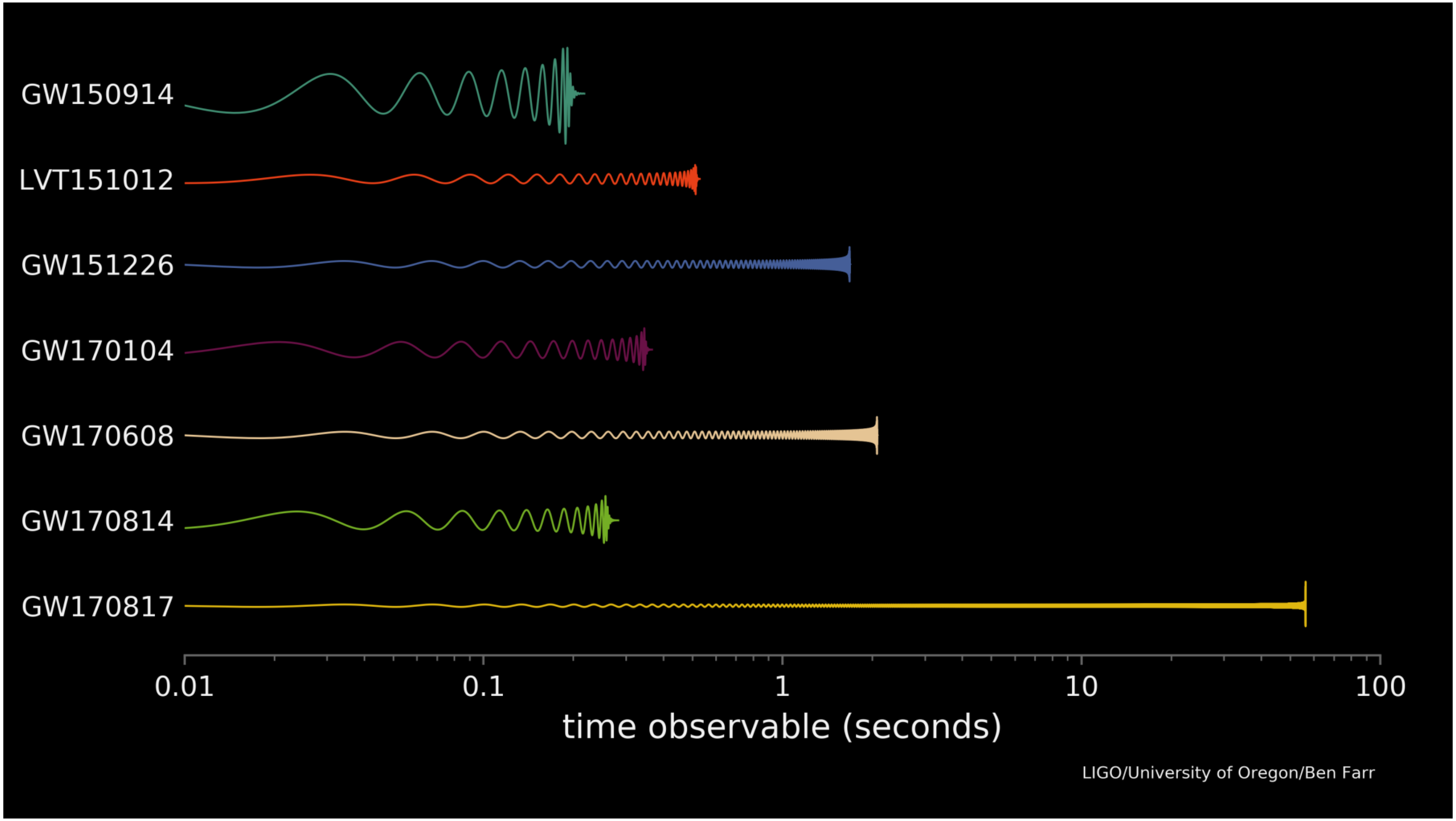

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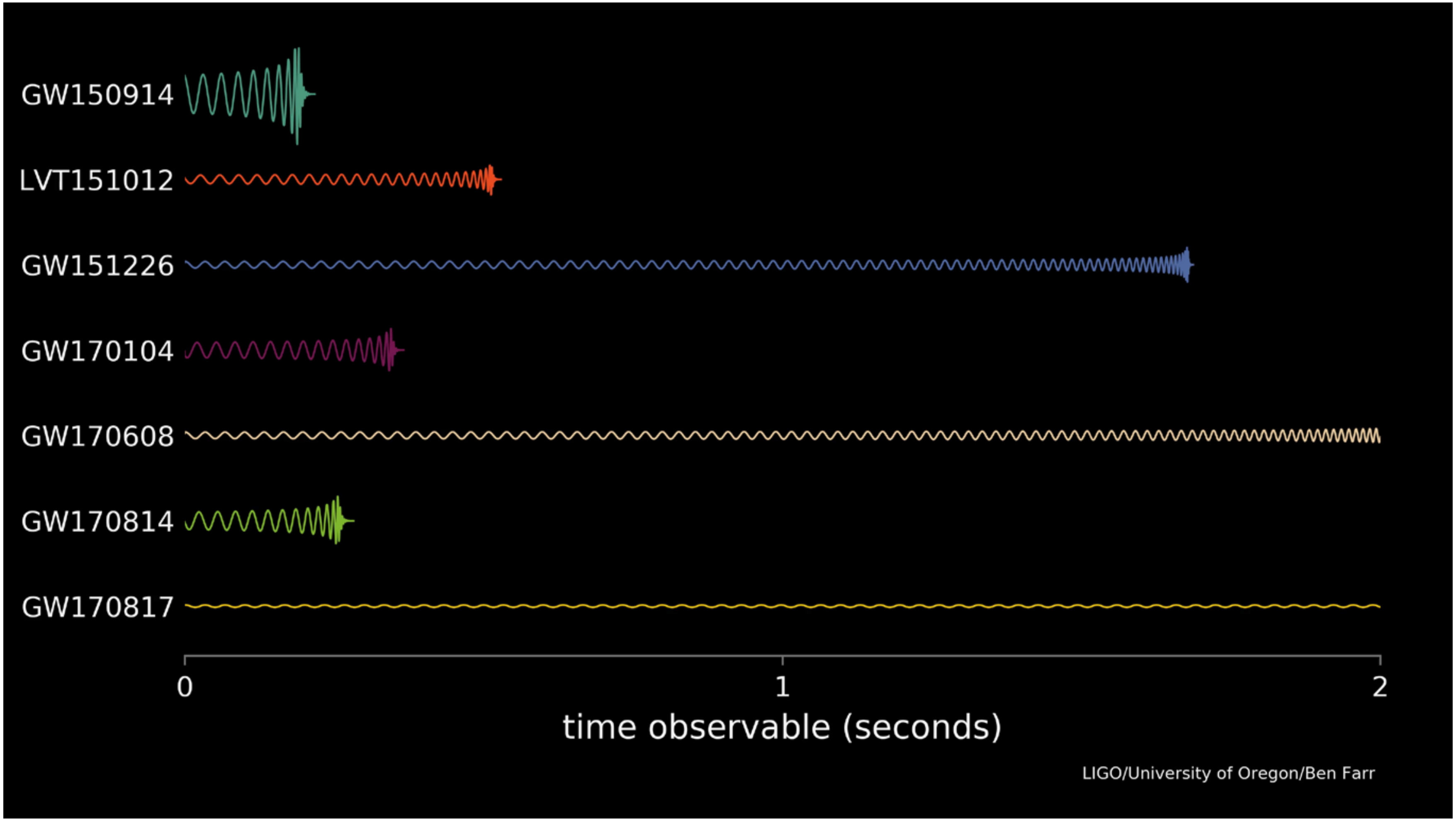

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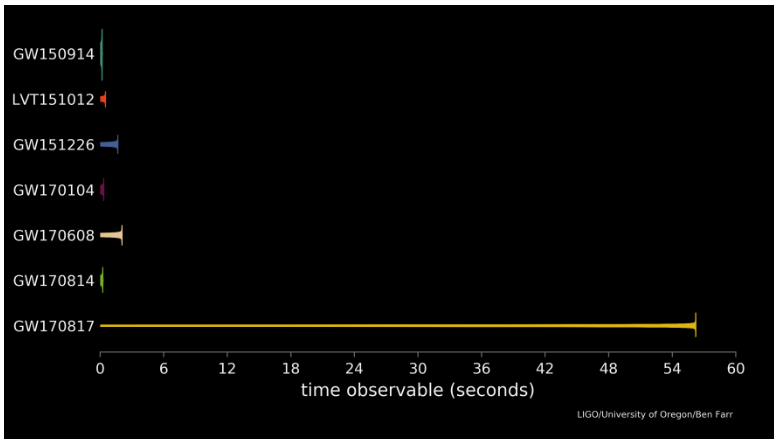

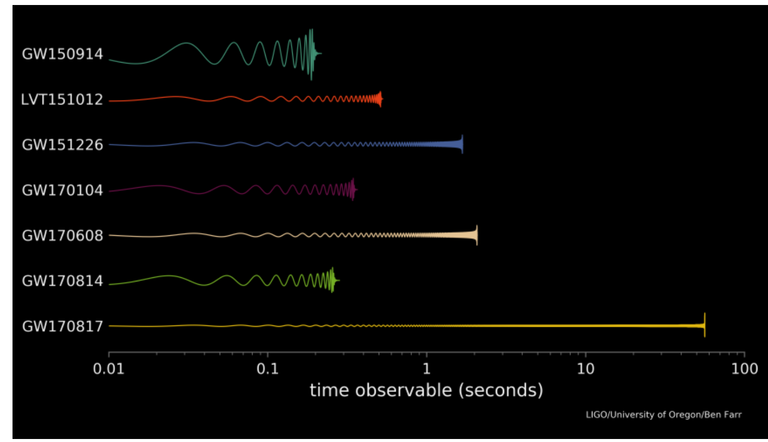

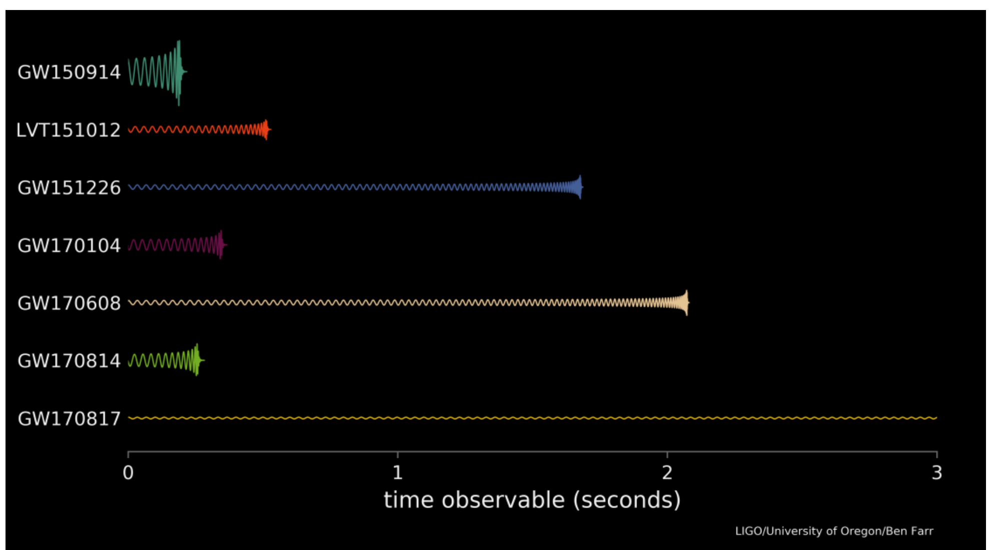

Outlook

- The global network of advanced gravitational-wave detectors is now a reality
  - The two aLIGO detectors started taking data in September 2015 and detected some gravitational-wave signals: GW150914, GW151226, GW170104, GW170608
  - Virgo completed its upgrade as well and joined LIGO on August 1st, 2017

    → Two more discoveries reported
    - GW170814: First triple detection published
    - GW170817: First binary neutron star merger + multi-messenger astronomy

- Towards a larger network
  - KAGRA (Japan) should join by the end of the decade
  - Possibly a third LIGO detector (LIGO-India) some years later

- Sensitivity already good enough to detect gravitational waves
  - Improvements expected in the near future

    → Upgrade program until Fall 2018 for both LIGO and Virgo
  - Roadmap document being written about the update of the Advanced detectors
  - R&D activities already ongoing for 3rd generation instruments

- There is room for new labs within the Virgo collaboration
  - Open meeting about « Advanced Virgo+ » in the coming months

GW detector peak sensitivity evolution vs. time