

EGO/Virgo Visit

07 February 2023

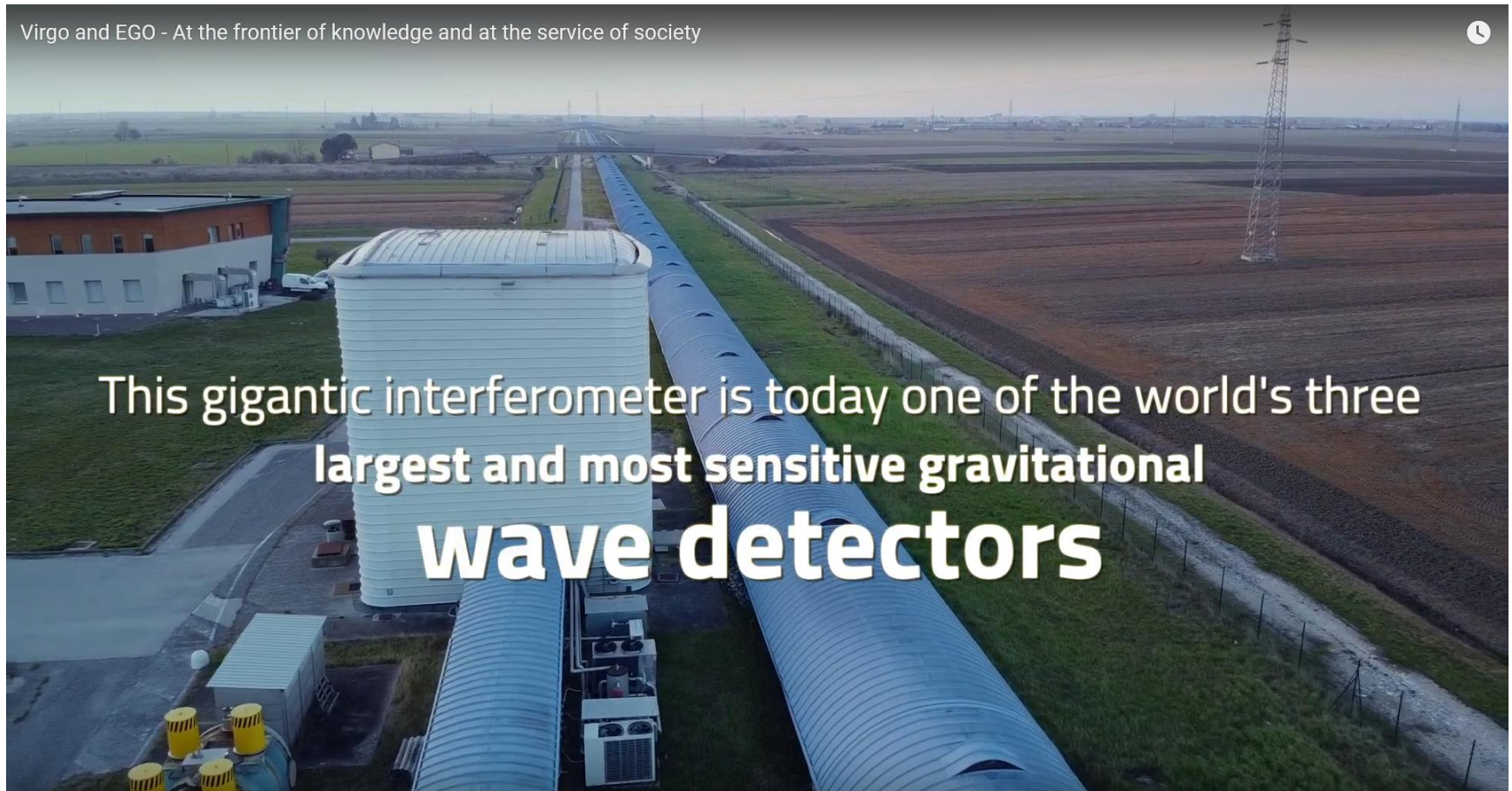
Nicolas Arnaud (nicolas.arnaud@ijclab.in2p3.fr)

Laboratoire de Physique des Deux Infinis Irène Joliot-Curie (Université Paris-Saclay & CNRS/IN2P3)
European Gravitational Observatory (CNRS, INFN & NIKHEF Consortium)



Visit teaser

- “**Virgo** and **EGO** - **At the frontier of knowledge** and at the service of society”
 - <https://www.youtube.com/watch?v=HeiyXXsTOD0>



EGO: the Virgo site

Leaning Tower of Pisa

Pisa airport
Runway length: 3 km

Zoom

Virgo

European Gravitational Observatory

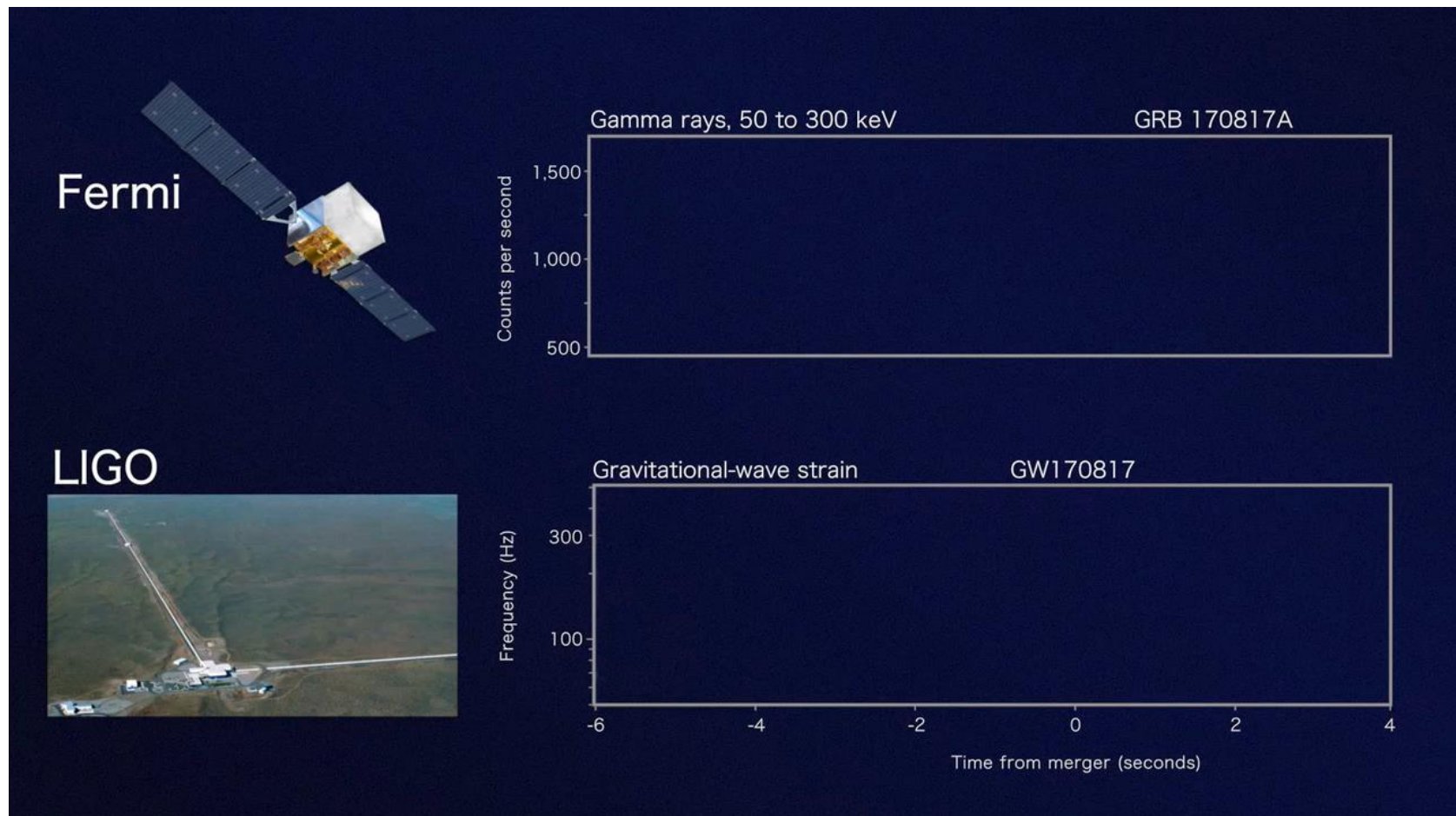
17-18 August 2017:

12 quite extraordinary hours

A long time ago in a galaxy far,
far away....

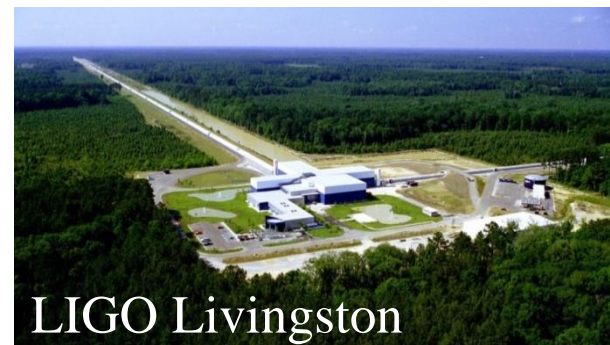
Thursday August 17, 2017 – 14:41 CEST

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



Later the same day...

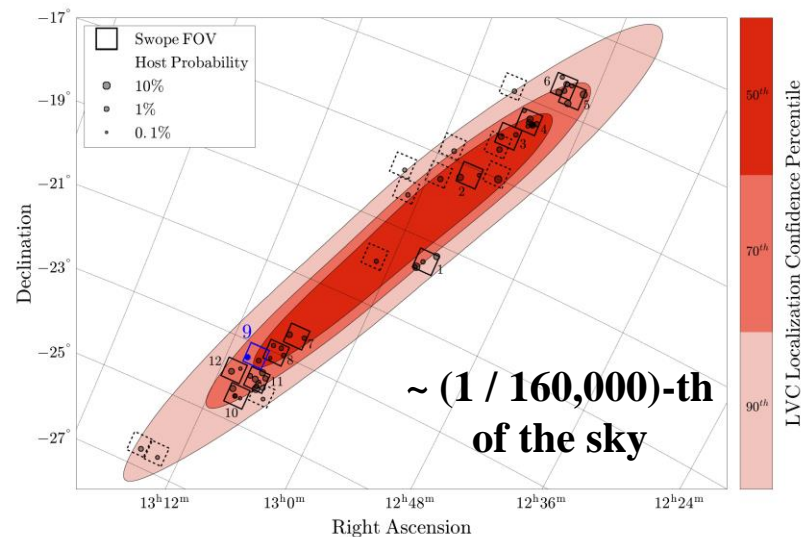
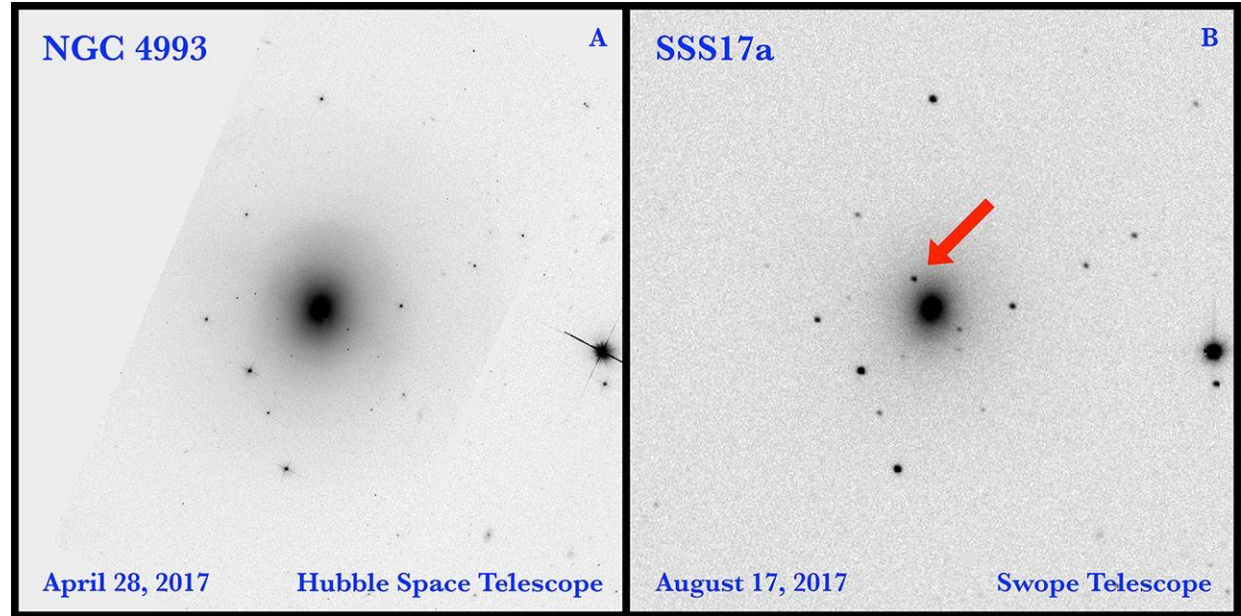
- 19:55 CEST
 - 5 hours later...
- LIGO-Virgo localisation
 - Position in the sky:
28 square degrees
 - Estimation of the
distance to the source



The following night...

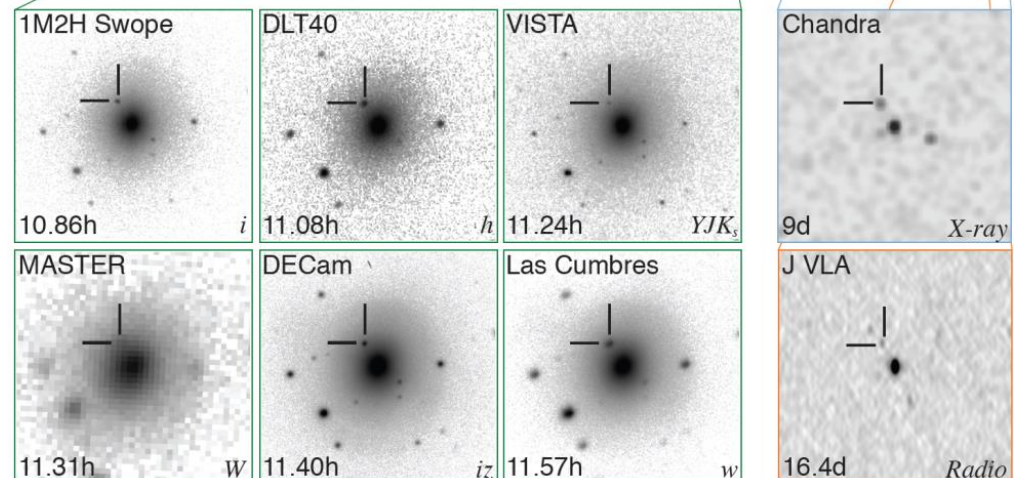
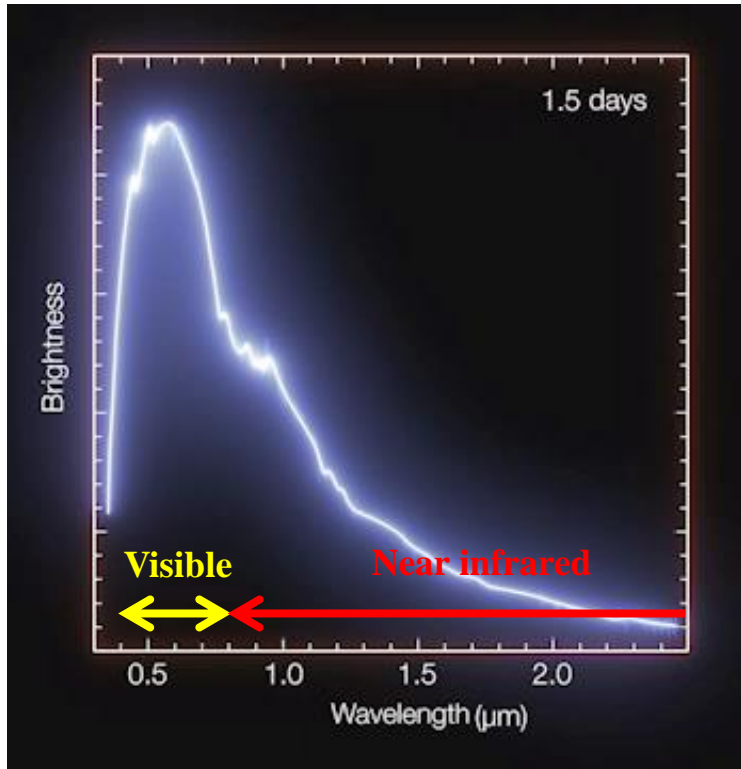
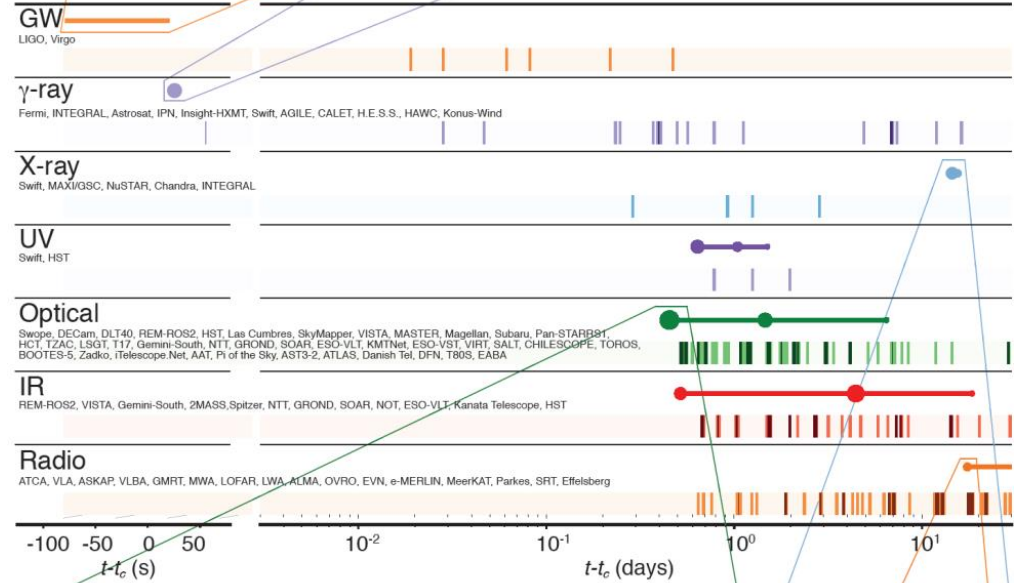
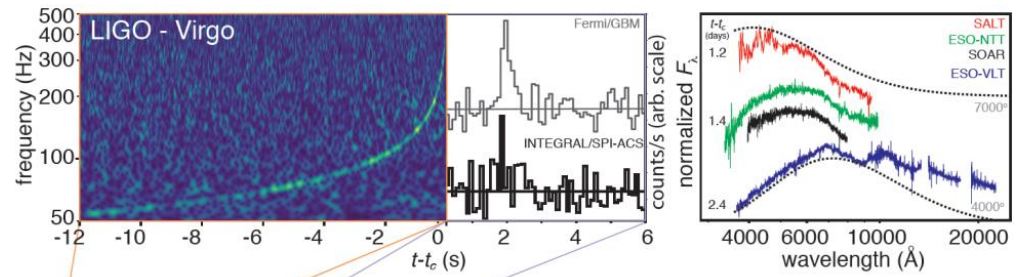
- 2017/08/18
01:33 CEST

→ Discovery of the optical counterpart by the SWOPE telescope in Chile



Multi-messenger Astronomy

- Gravitational waves,
- gamma-ray burst,
- the whole electromagnetic spectrum

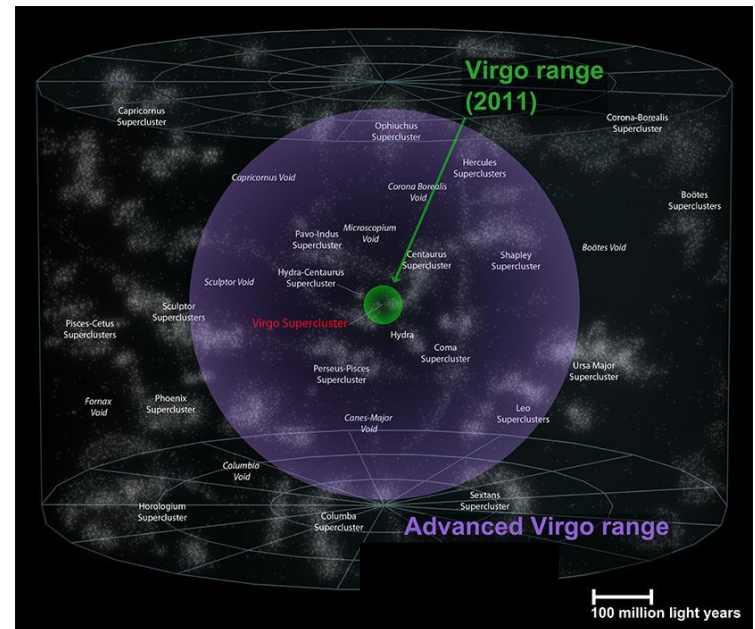
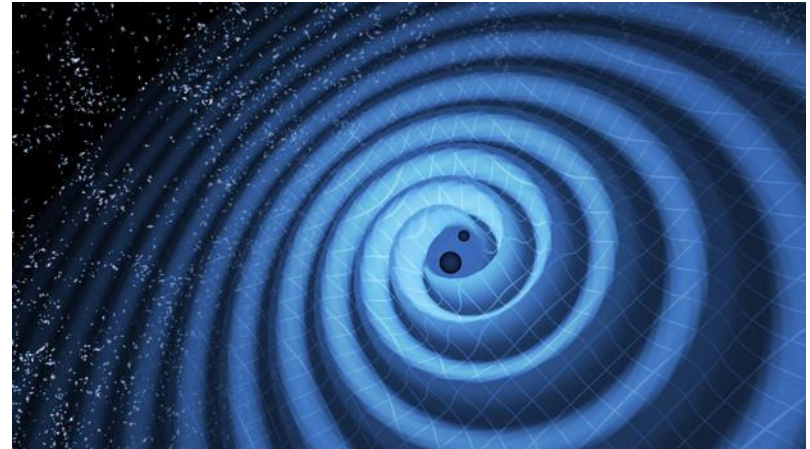


Detecting gravitational waves

*Thanks to the many colleagues from the LAL (now IJCLab) Virgo group,
Virgo and LIGO, from which I borrowed ideas and material for this talk*

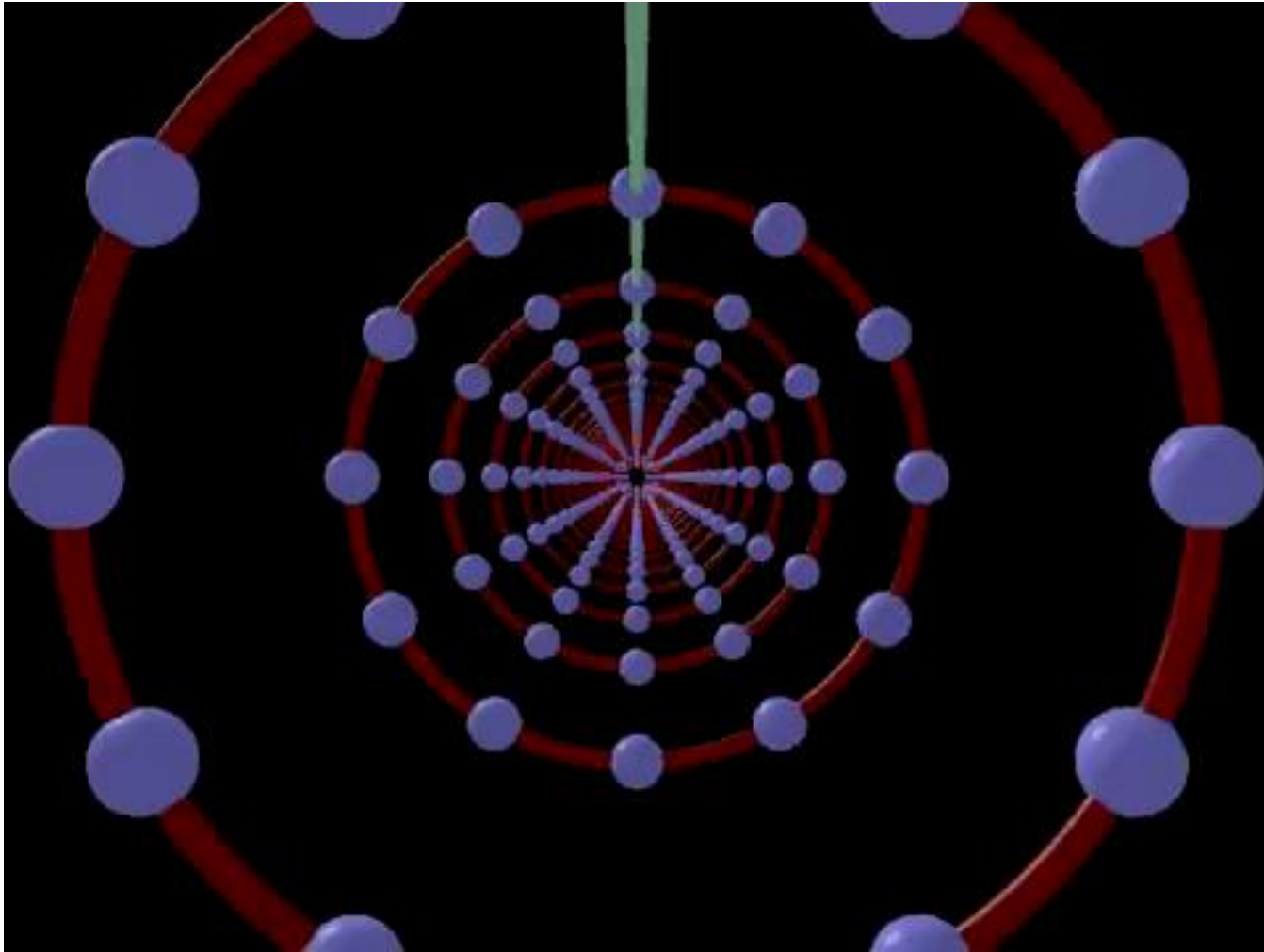
Gravitational waves

- One of the first predictions (1916) of general relativity (1915)
 - Accelerated masses induce perturbations of the spacetime that propagate at the speed of light
 - No gravitational wave (GW) emission if the source is axisymmetrical
 - A « good » source must have an asymmetrical mass distribution
 - GW amplitude h
 - Dimensionless
 - Scales down like $1/(\text{distance to source})$
 - Detectors are directly sensitive to h
- Factor 2 (10) gain in sensitivity
⇔ Gain of a factor 2 (10) in distance
⇔ Observable Universe volume scales by a factor 8 (1000)

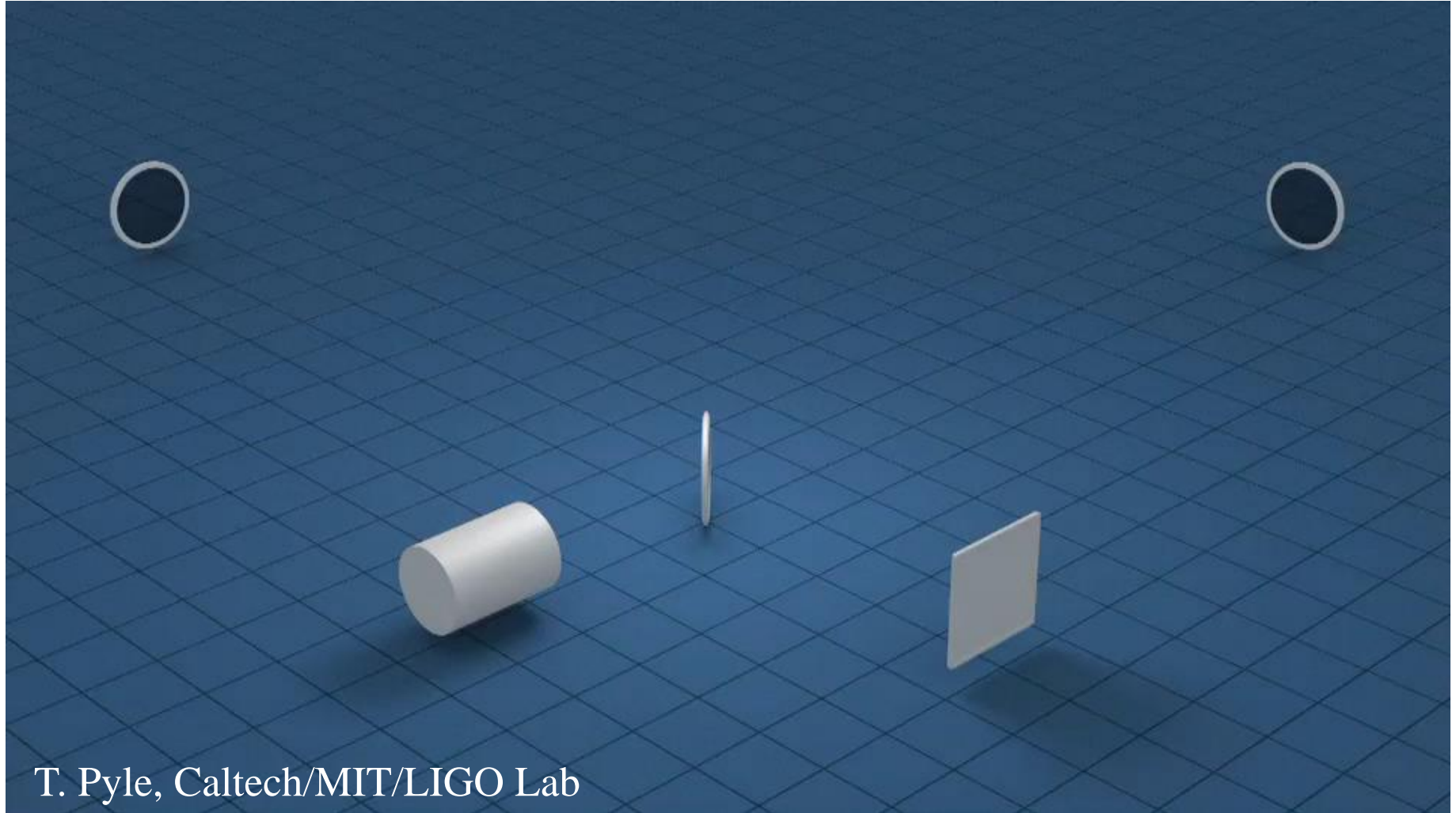


Effect of gravitational waves on test masses

- In 3D



An interferometer in a nutshell



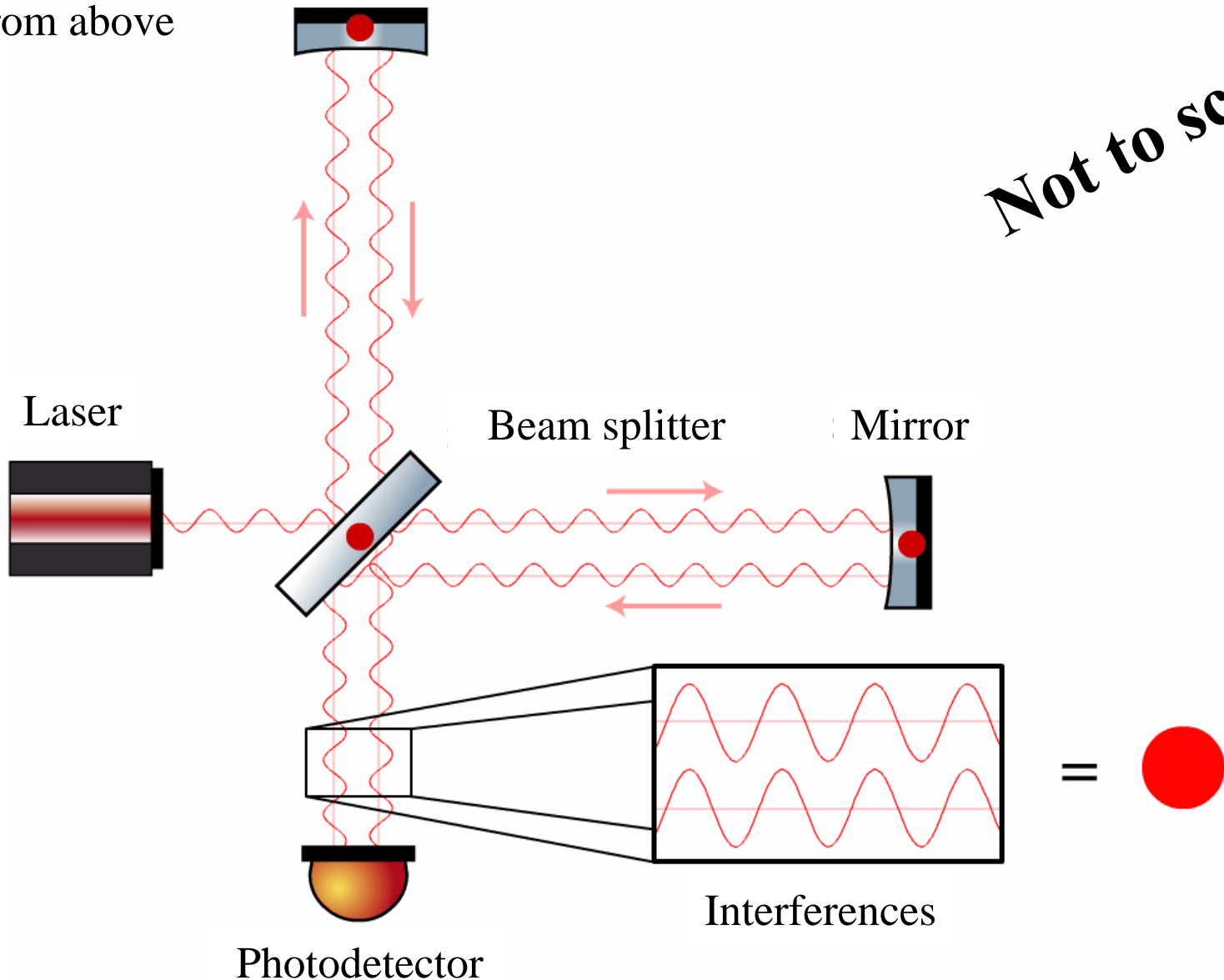
T. Pyle, Caltech/MIT/LIGO Lab

Sensitivity $\propto 1 / (\text{arm length}) / \sqrt{(\text{laser power})}$

As small as possible

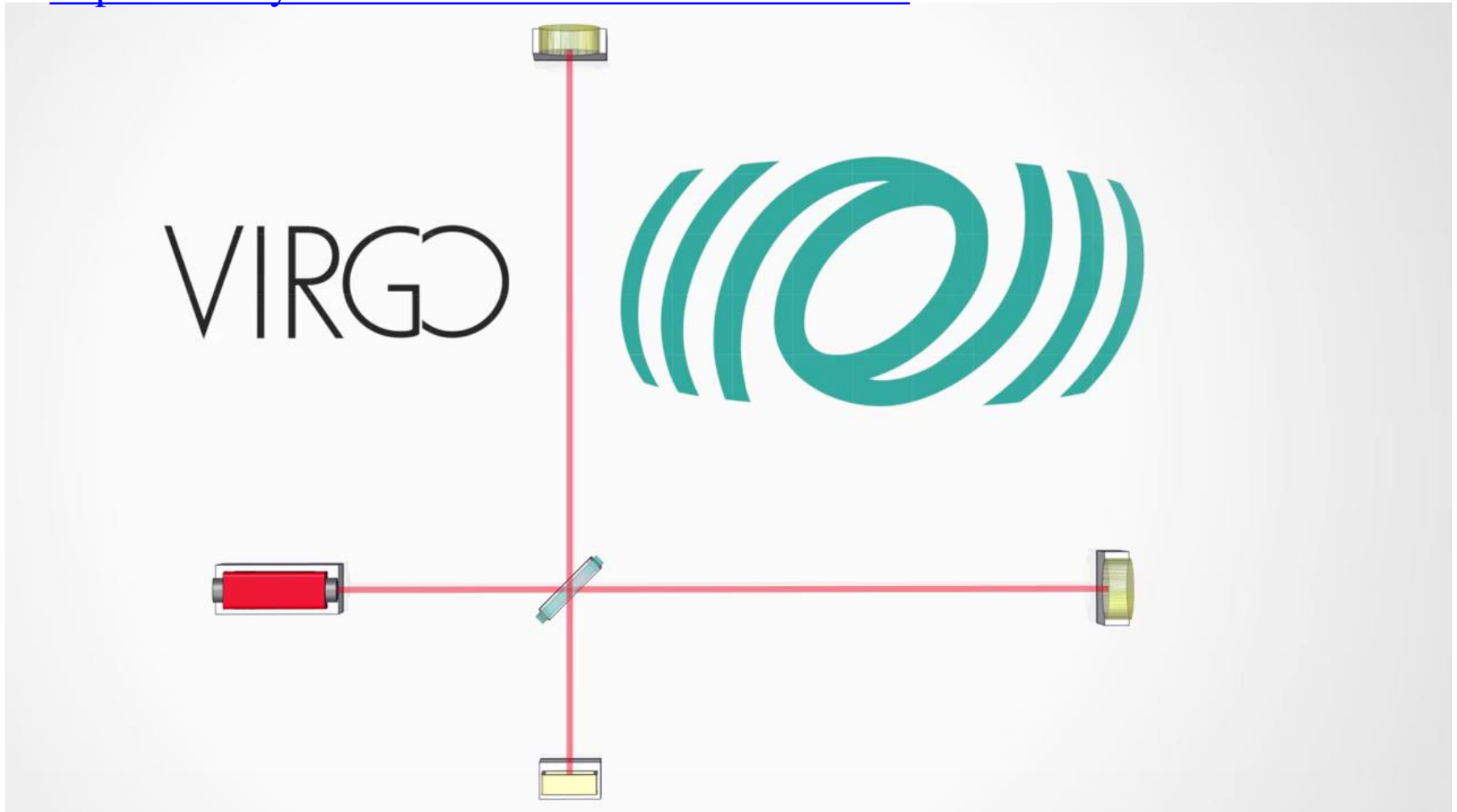
An interferometer in a nutshell

- From above



The Advanced Virgo detector revealed

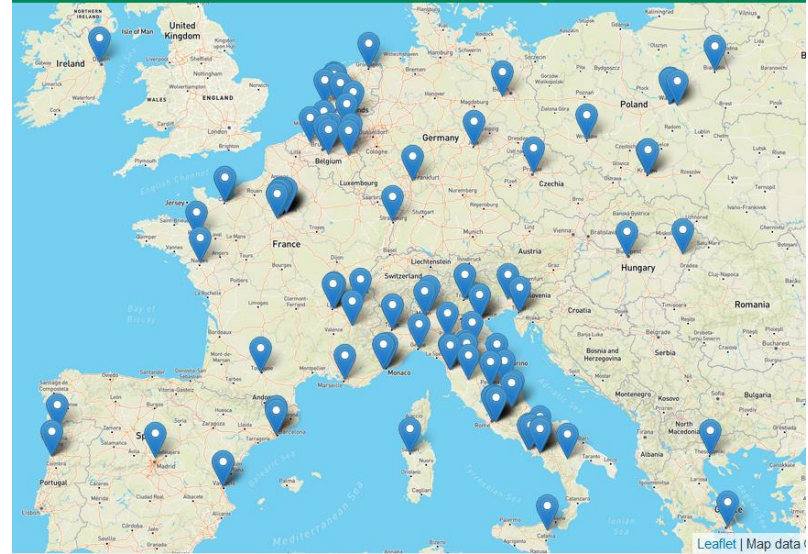
- Animation by Marco Kraan, NIKHEF
 - <https://www.youtube.com/watch?v=6raomYII9P4>



Virgo, LIGO and co.

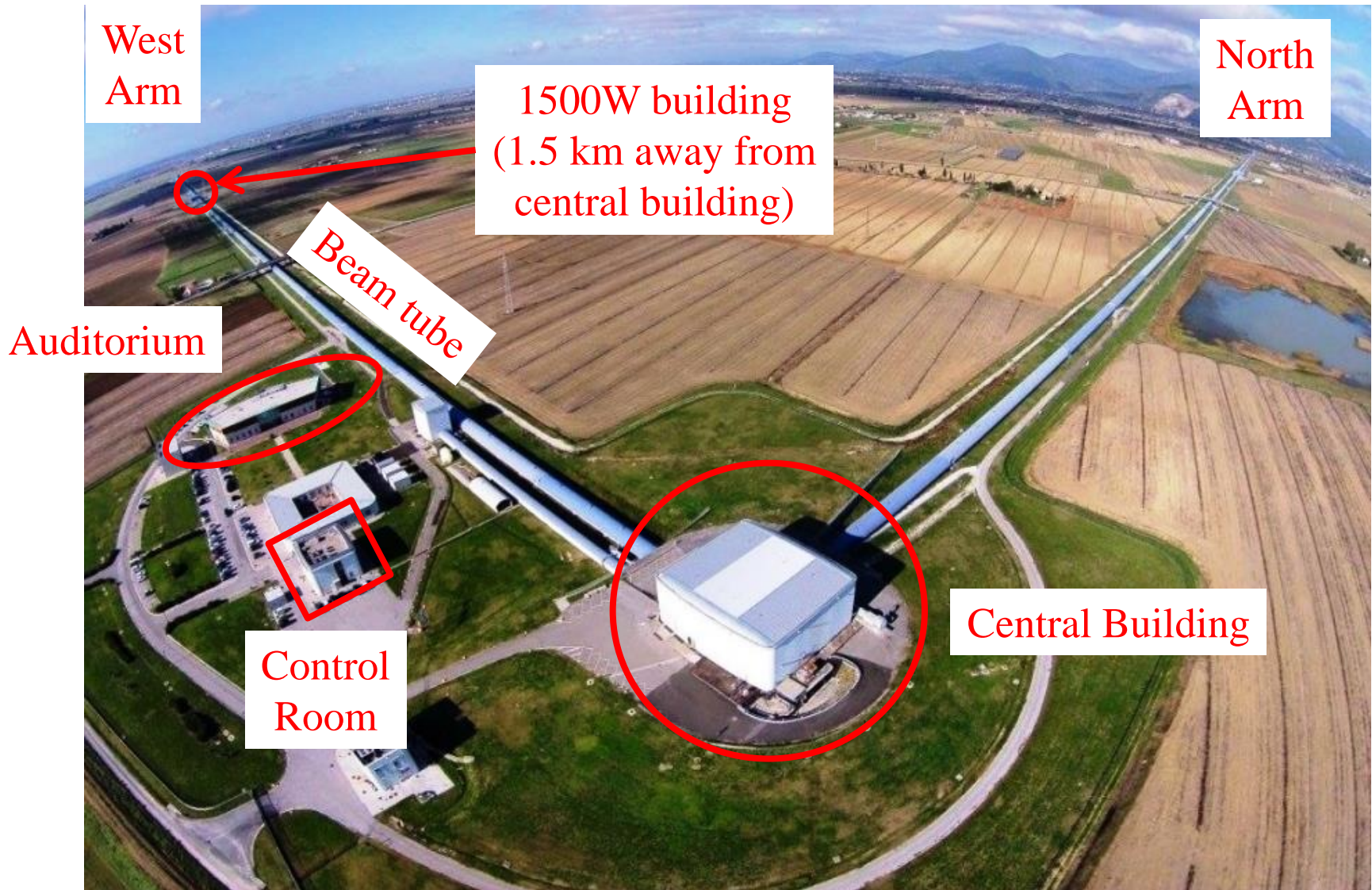
The Virgo Collaboration

- A **recent snapshot**
 - Possibly (slightly) outdated
- ~800 members
 - Among which ~450 authors
- Representing ~140 institutions from 15 countries
- **9 countries** represented in the Virgo governance board
 - ~35 groups total

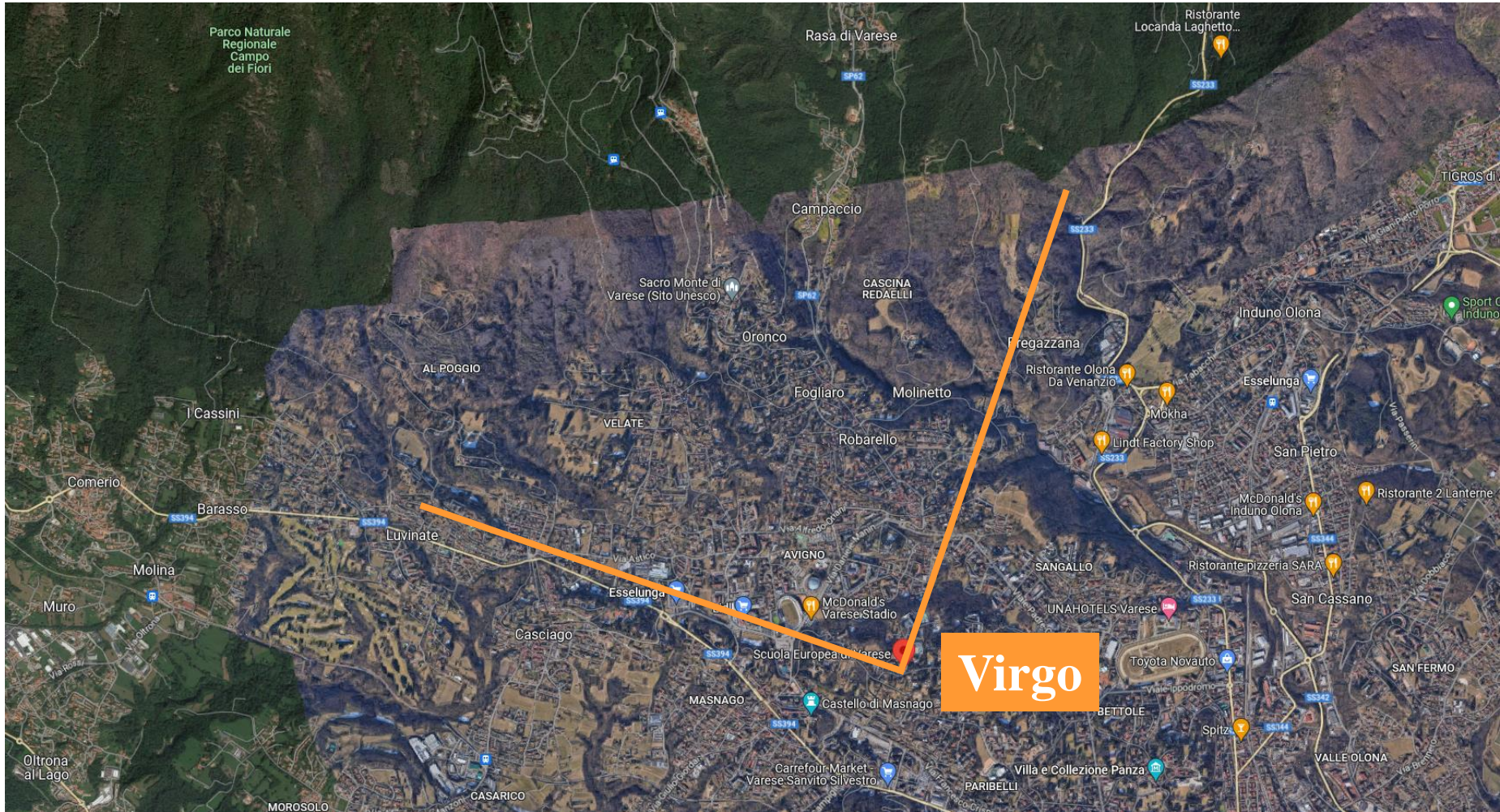


Pre 1st discovery announcement (2016/02/11): about half of the Virgo collaboration (~ 250 people at the time, from 18 groups in 5 countries)

Virgo from the sky



If Virgo were located in Varese...



A network of interferometric detectors

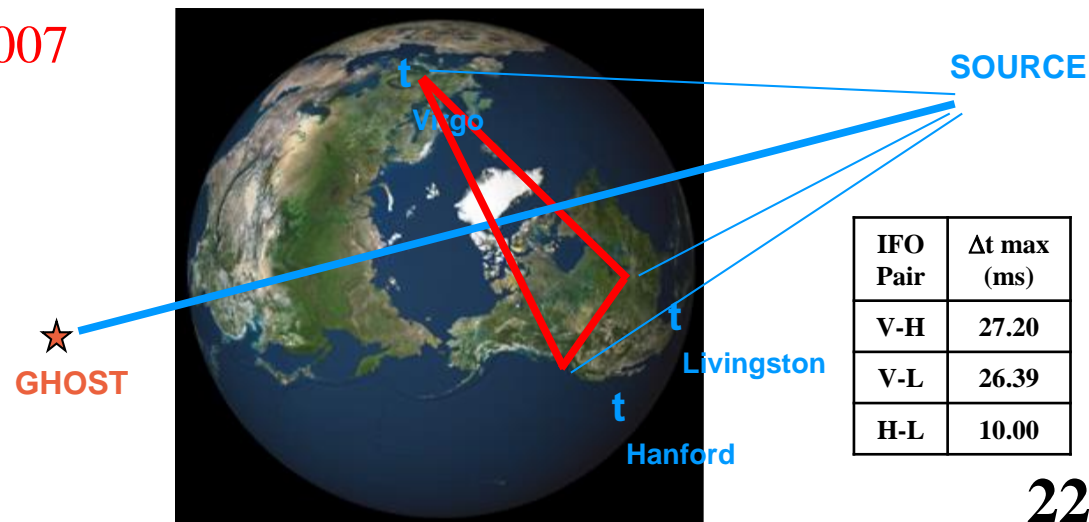
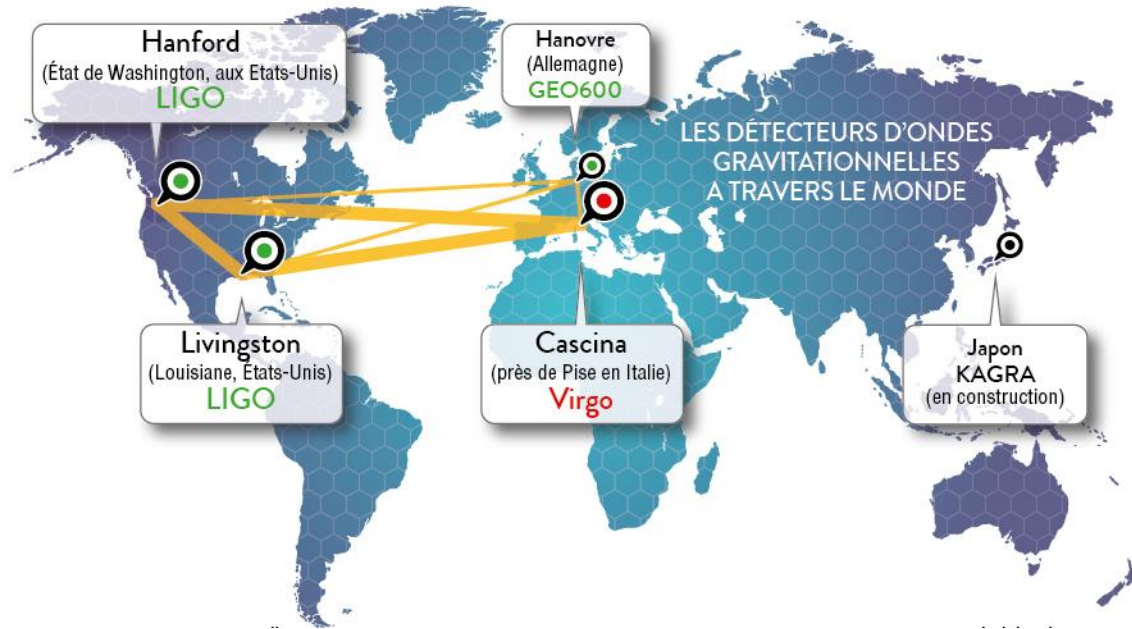


A network of interferometric detectors

- 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

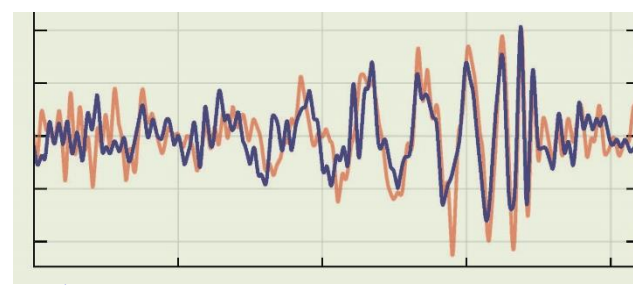
→ Need to use a network of interferometers

- 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**



September 14, 2015, 11:51 CEST

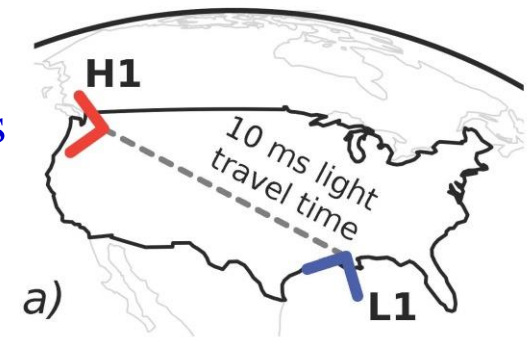
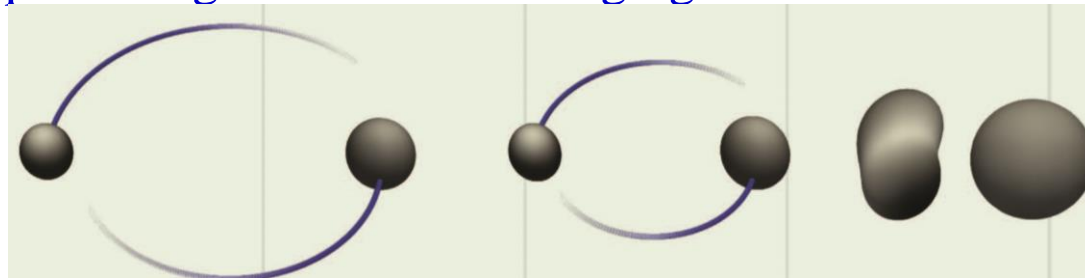
- Signal observed in the two LIGO detectors with a 7 ms delay
 - Extremely short (< 1 s)
 - Very strong
 - With respect to the instrumental noise
 - Very weak in absolute terms
- Expected signature for the merging of 2 stellar black holes



Event called

GW150914:

- Gravitational wave
- 2015
- September
- 14



**LIGO Hanford
Washington State, USA**



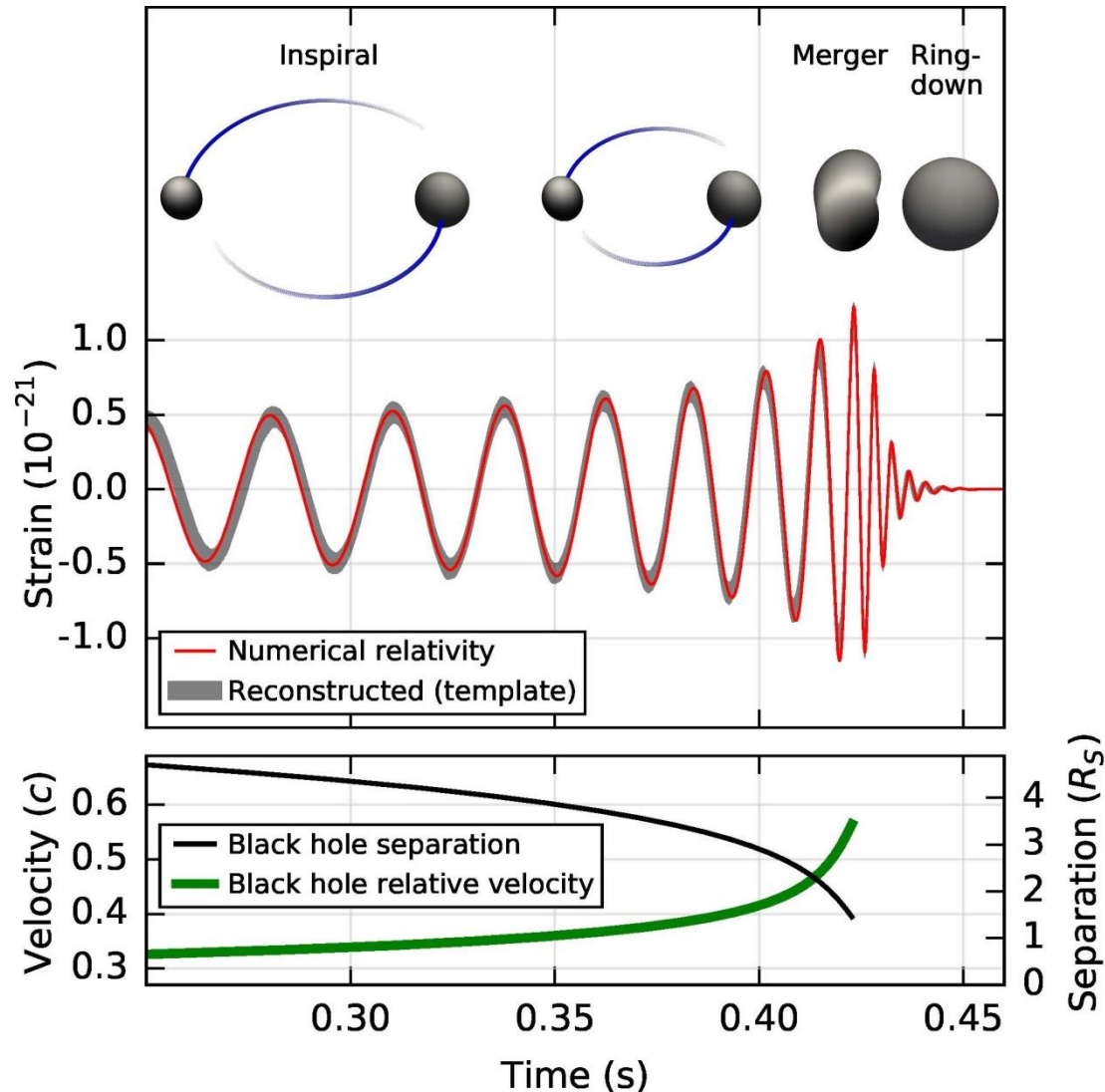
LIGO Livingston Louisiana, USA

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!

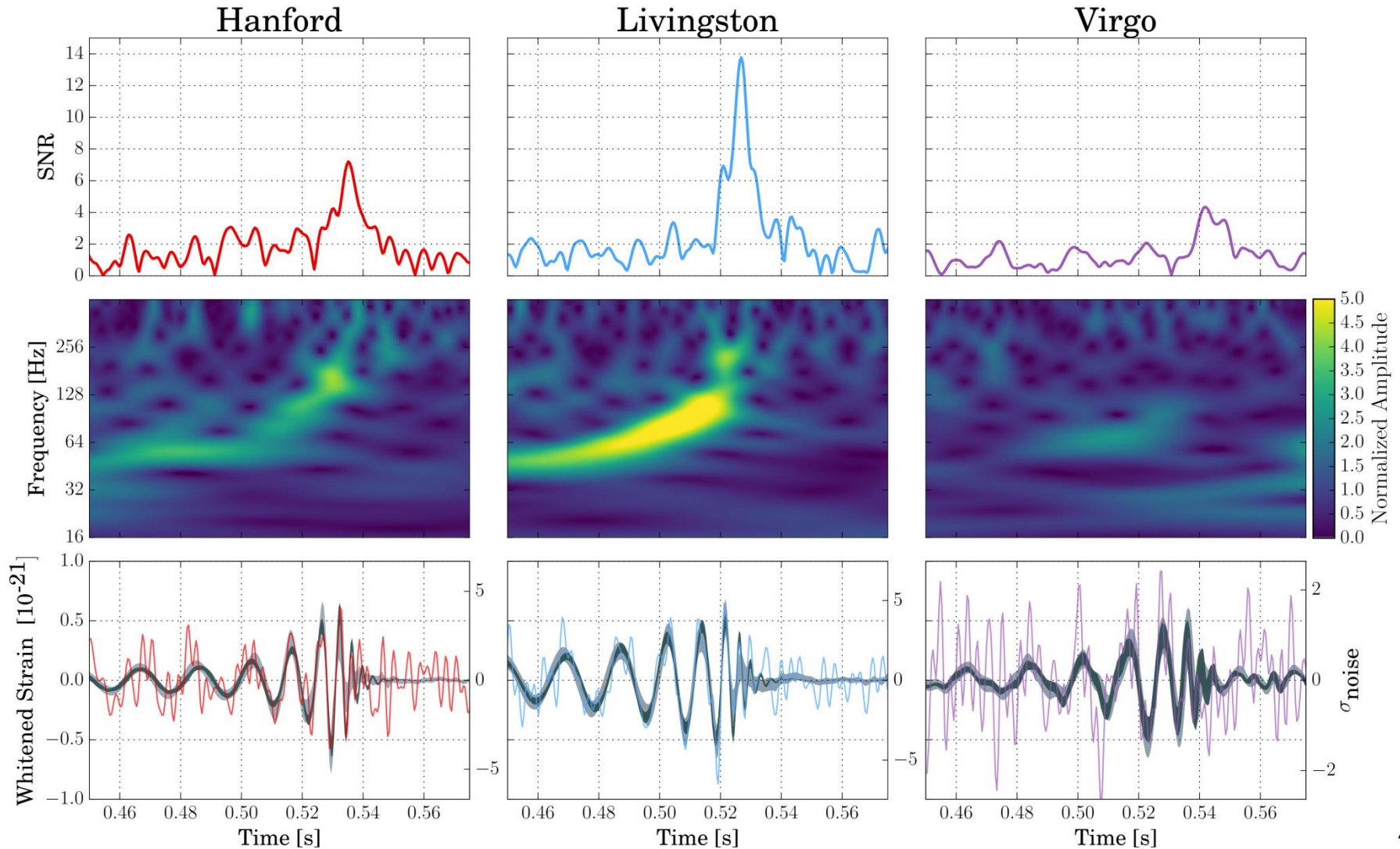
→ Black holes are the only known objects which can fit this picture

- **About $3 M_{\text{Sun}}$ radiated in GW**
- **The « brightest » 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



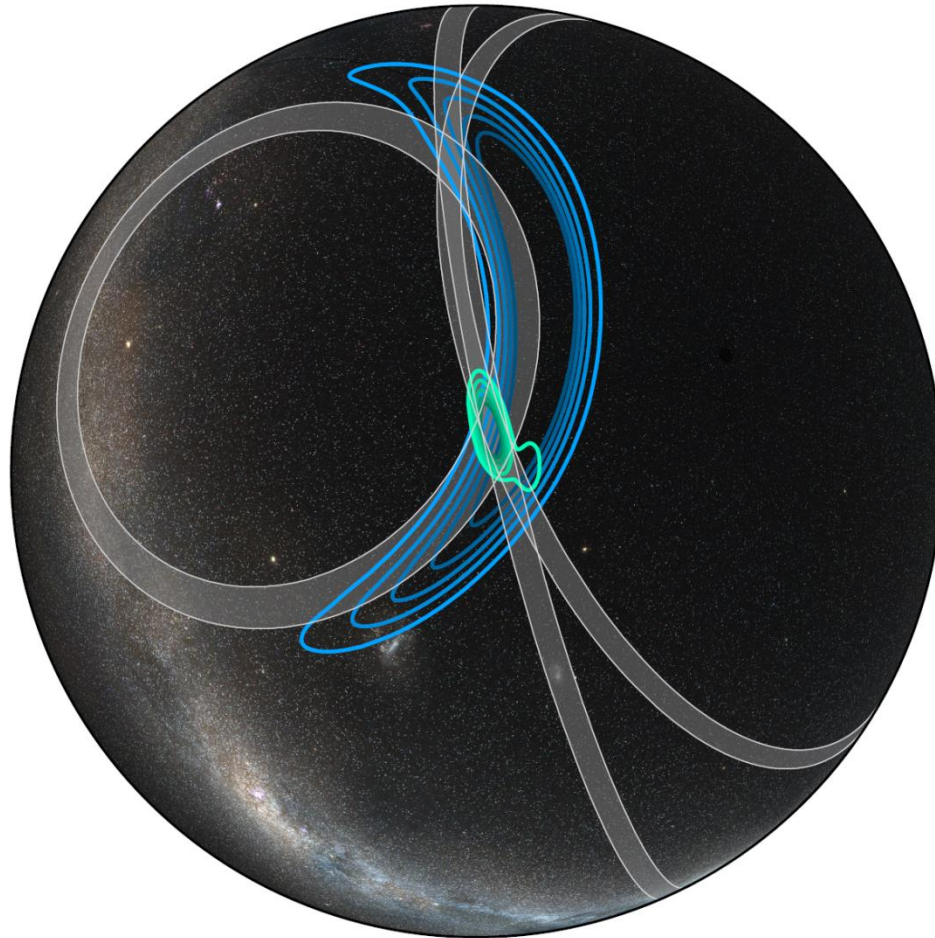
GW170814: first 3-detector signal

- Detailed studies confirm **evidence of a signal in the Virgo detector**



GW170814: LIGO-Virgo sky localization

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

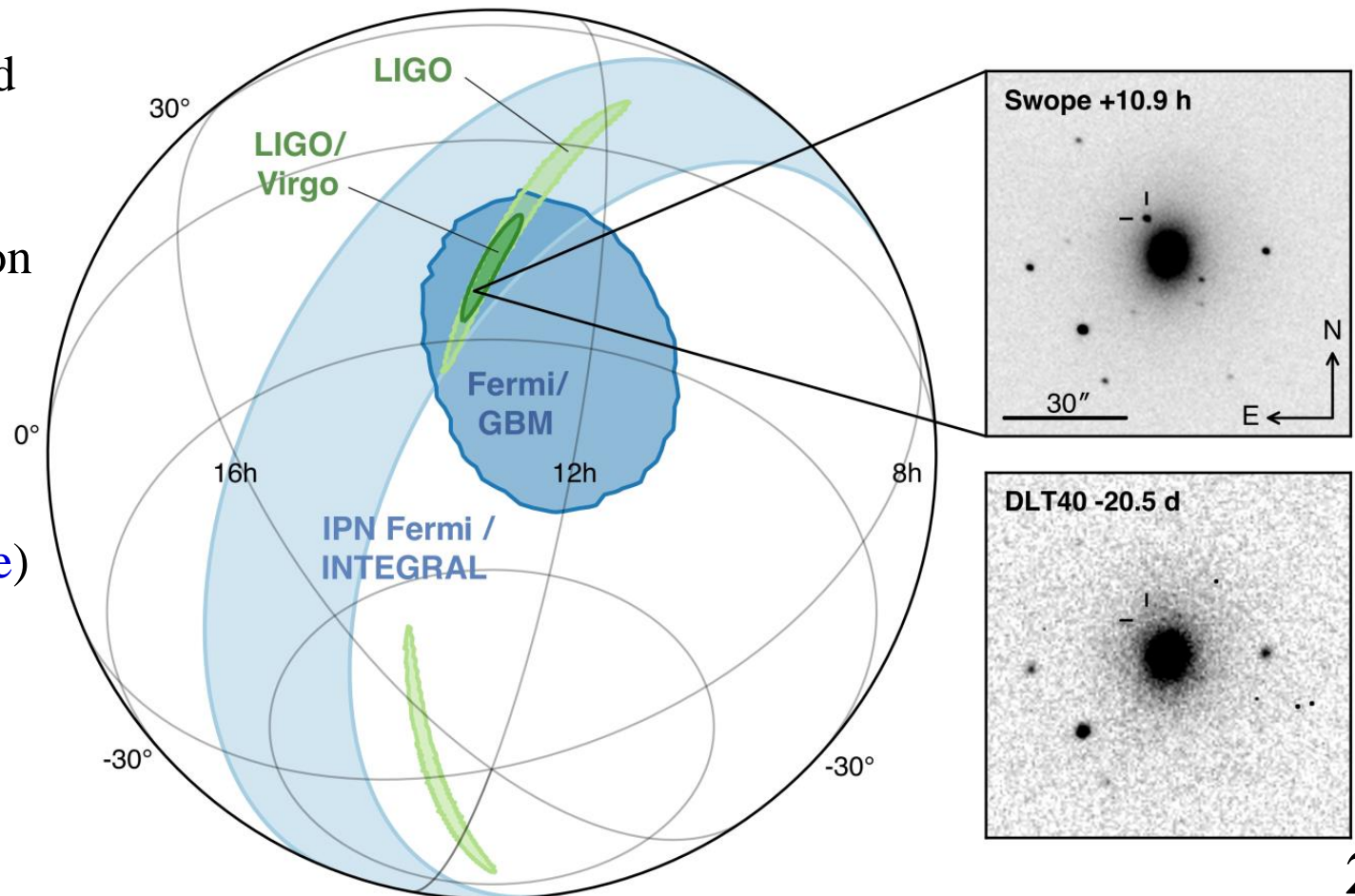


Sky localizations & source position

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

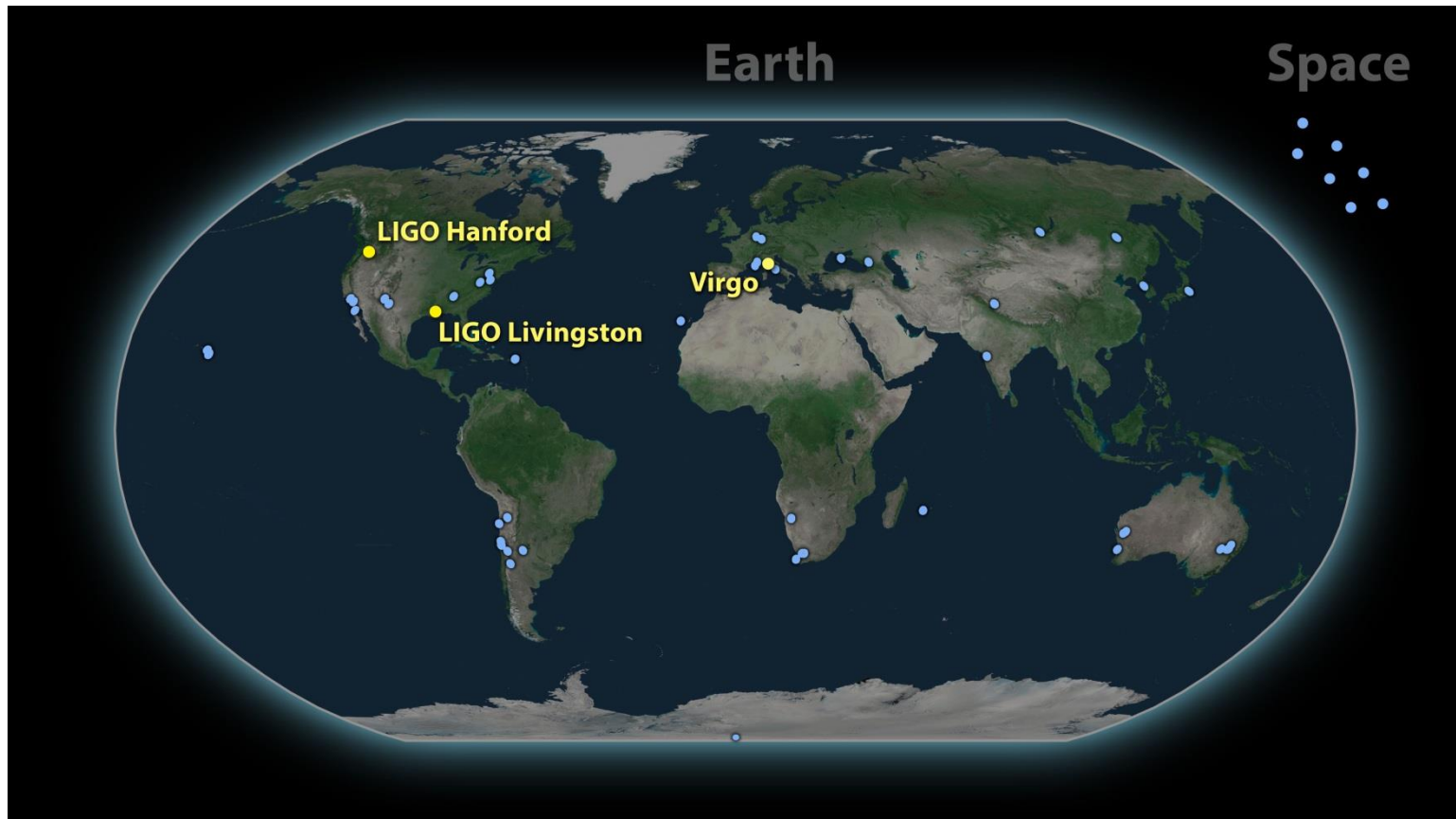
→ Accurate sky localization sent at 19:55 CEST (+ 05:14 after GW was recorded)

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



Worldwide astronomy

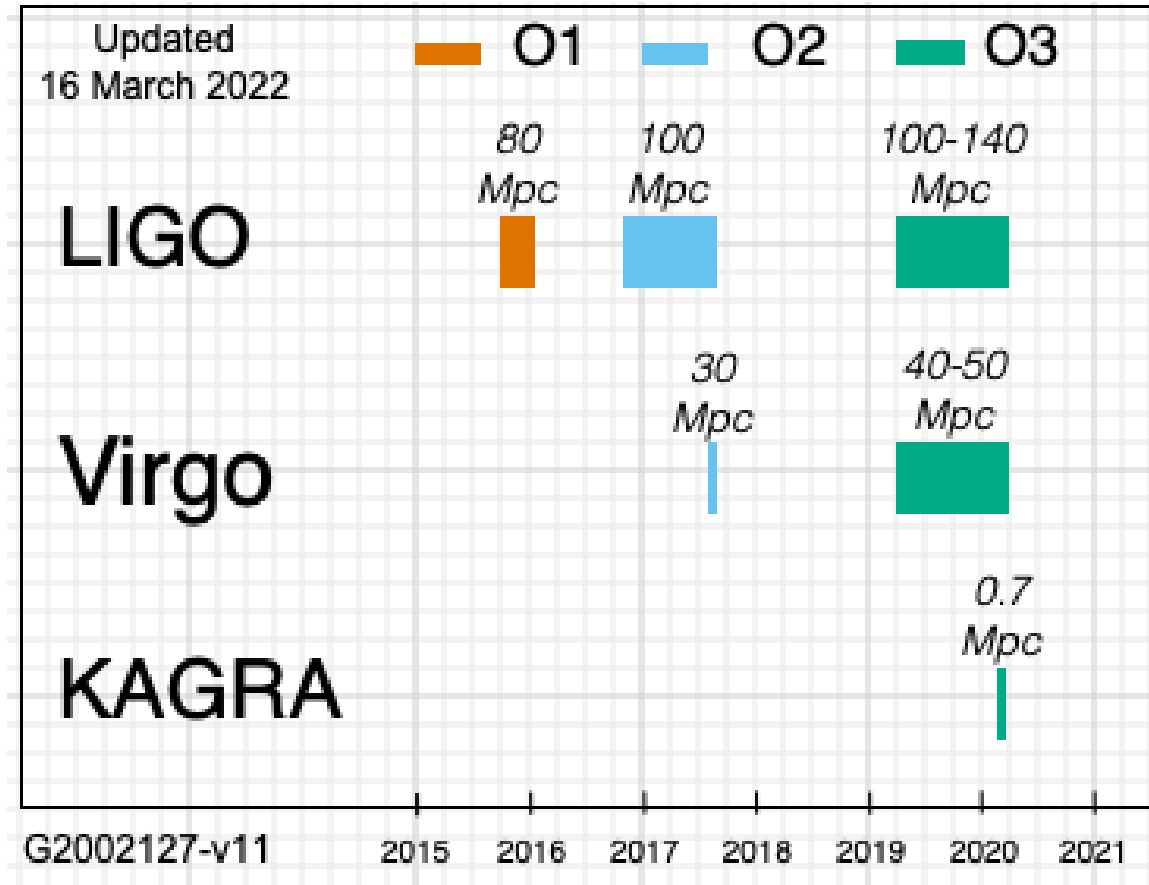
- **Three gravitational-wave detectors**
- **Tens of partner observatories**



The LIGO-Virgo O3 run

- **01 April 2019** → **27 March 2020**
 - 1 month commissioning break: **October 2019**
- Ended 1 month earlier than anticipated due to the **covid-19 pandemic**

- **O_x**: Observing Run *x*
 - **O₁**: LIGO detectors
 - **O₂**: Mostly LIGO, Virgo in August'17
 - **O₃**: LIGO-Virgo



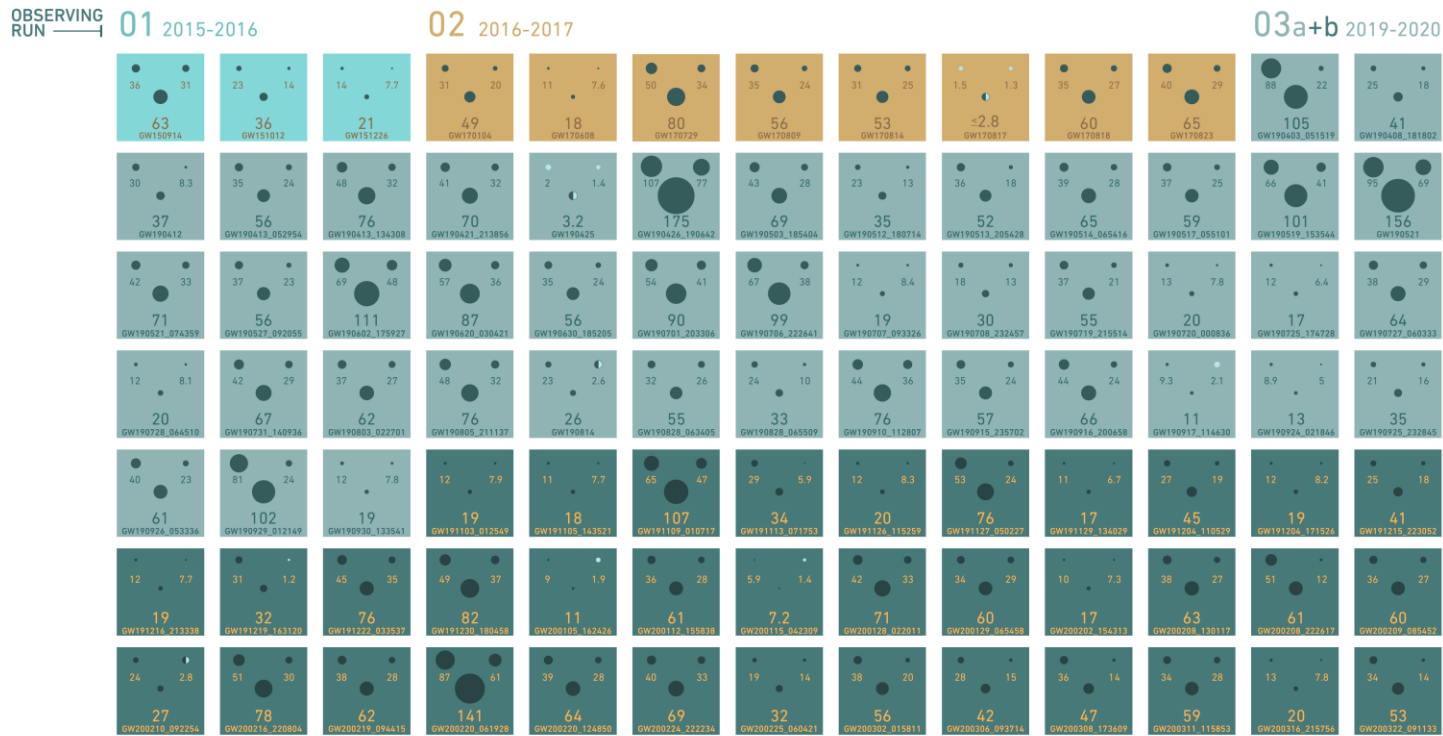
-
- **O₄**: Should be **LIGO** + **Virgo** + **KAGRA**
 - **2020-2023**: **upgrades**
 - **Improve all detectors**
 - **Better sensitivity**
 - **More detections** when **data taking restarts**

A harvest of detections

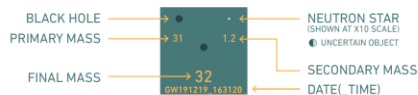
- 90 signals in the latest edition of the LIGO-Virgo-KAGRA catalog: **GWTC-3**

GRAVITATIONAL WAVE **MERGER** DETECTIONS

→ SINCE 2015



KEY



UNITS ARE SOLAR MASSES
1 SOLAR MASS = 1.989×10^{30} kg

Note that the mass estimates shown here do not include uncertainties, which is why the final mass is sometimes larger than the sum of the primary and secondary masses. In actuality, the final mass is smaller than the primary plus the secondary mass.

The events listed here pass one of two thresholds for detection. They either have a probability of being astrophysical of at least 50%, or they pass a false alarm rate threshold of less than 1 per 3 years.



To be continued...

- **Observing plans:** <https://observing.docs.ligo.org/plan>

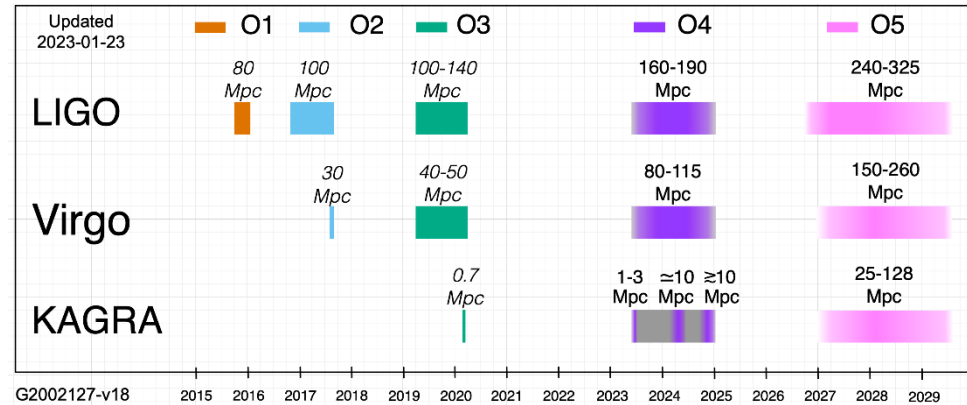
LIGO, VIRGO AND KAGRA OBSERVING RUN PLANS

(19 January 2023 update; next update 15 April 2023 or sooner)

With this update on the timing of the O4 LIGO-Virgo-KAGRA observing run, we wish to indicate two changes to the planning from previous announcements.

On the timing of the start of O4, the detectors continue to present challenges to reach the level of stability and sensitivity that we hold as pre-requisites for the start of the run. All of the detectors need further work to advance to the O4 starting sensitivity goals. **We now plan to start the observing run on 24 May**; this will be preceded by a one-month engineering period.

In addition, **we now plan on 18 calendar months of observing for O4** (as a change from the previous 12-month duration). This change is motivated by upgrade plans for the O5 observing run. The sensitivity improvement



- **Projects of third-generation detectors**

