An introduction to gravitational-wave astronomy

Matteo Barsuglia

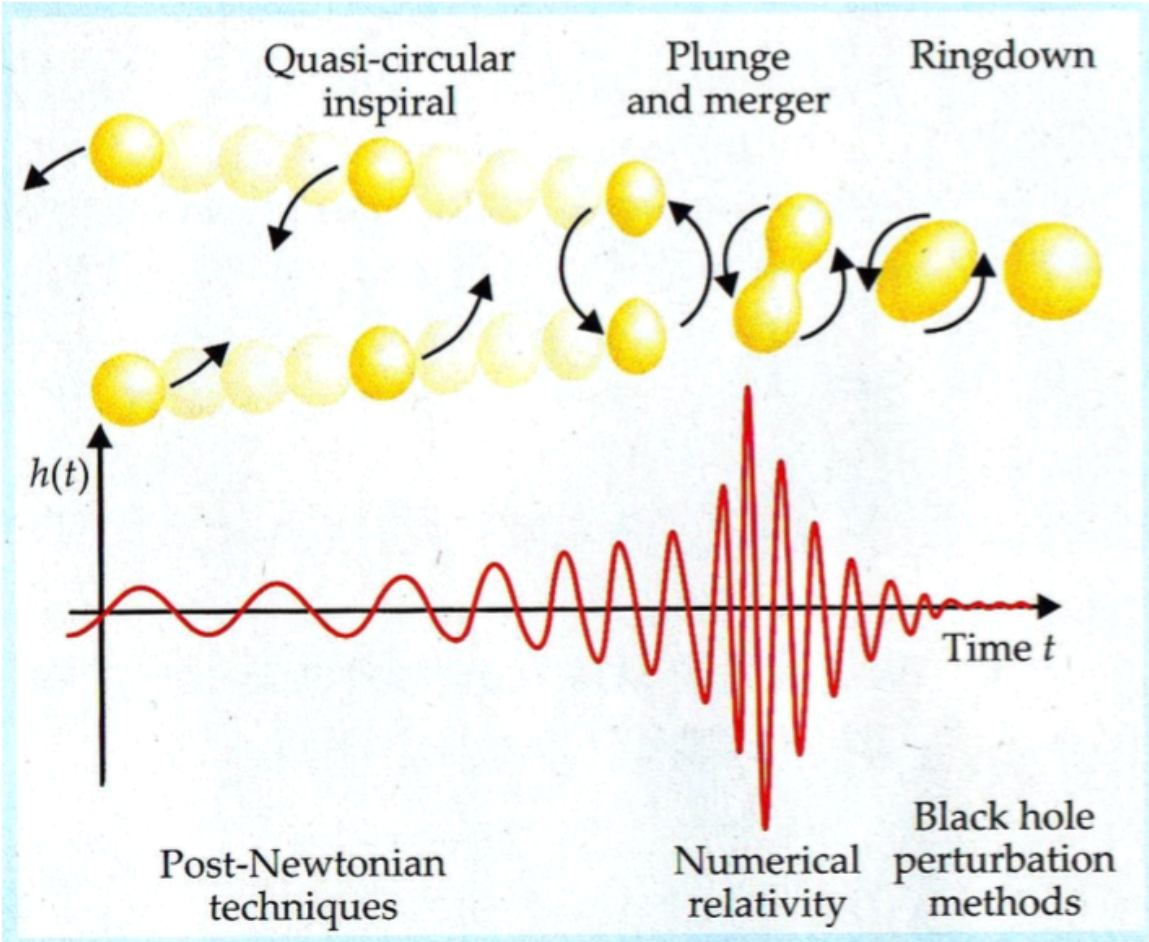
barsu@apc.in2p3.fr

Gravitational-waves

- Consequence of general relativity (1916)
- Perturbation of the metric propagating as a wave
- Speed of light
- 2 transverse polarizations
- Produced by acceleration of the mass quadrupole moment

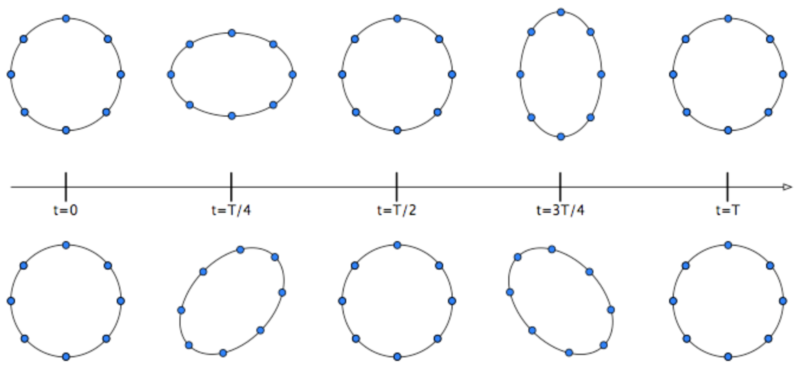
$$h_{ij}(t) = \frac{2}{r}\frac{G}{c^4}\ddot{Q}_{ij}(t - r/c)$$

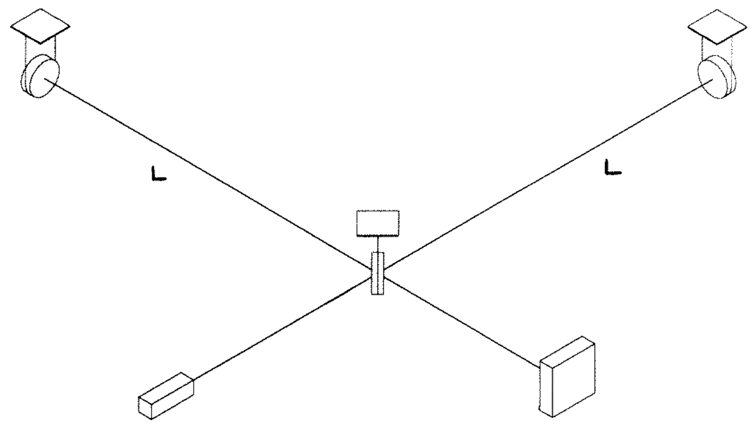
GW from compact objects



$h \sim 10^{-21}$ for a realistic source at a realistic distance

Interferometric detectors





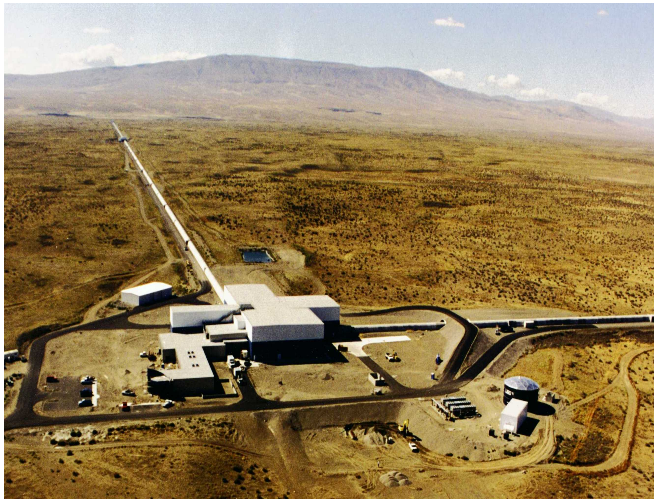
- Concept: Gertsenshtein and V. I. Pustovoit (1962)

- E. Moss, L. R. Miller, and R. L. Forward (1971) – 10^{-14} $\mathrm{m\,Hz^{-1/2}}$
- R. Weiss (1972) – study of the noises
- R.Drever ideas to improve interferometric detectors

Proposal for km scale projects (1980) Virgo, GEO, LIGO

Virgo/LIGO/GEO ~ 2000

LIGO Hanford

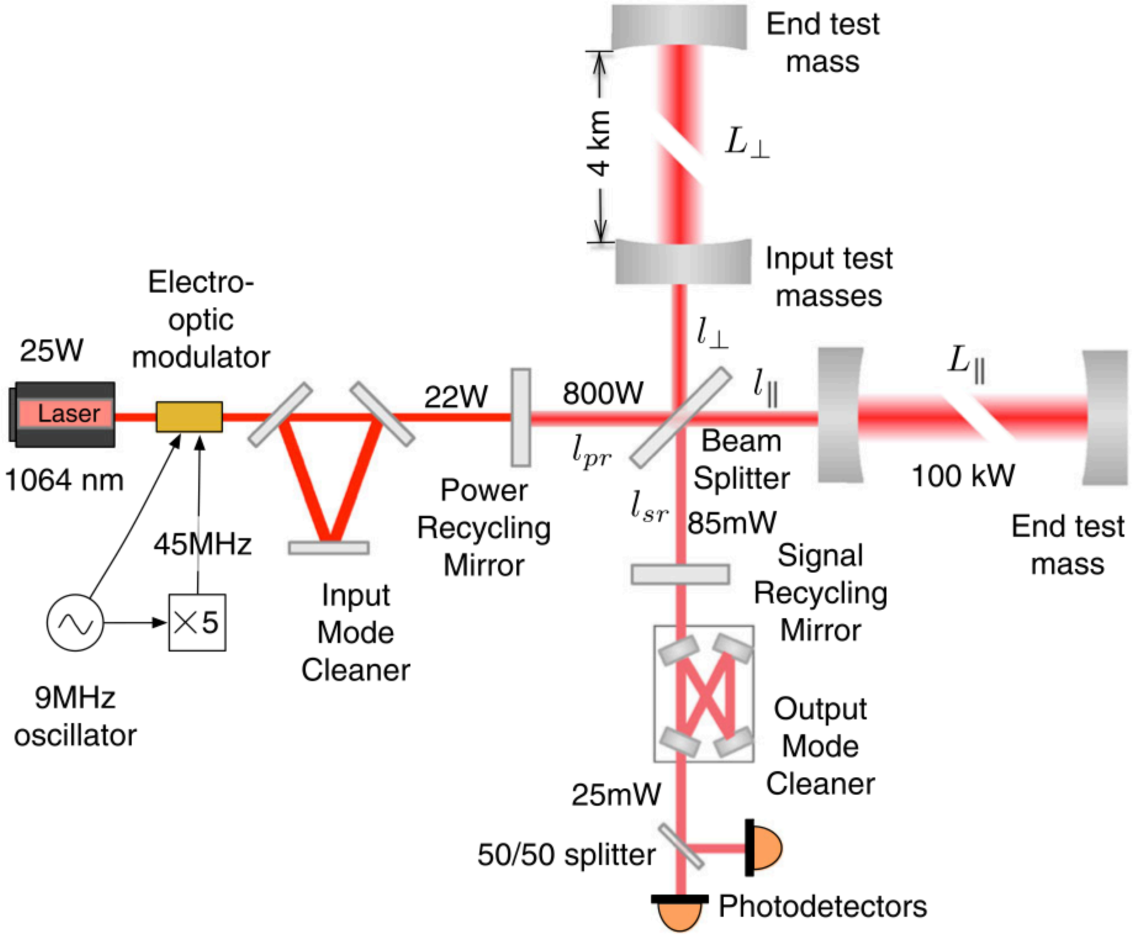


LIGO Livingston

GEO

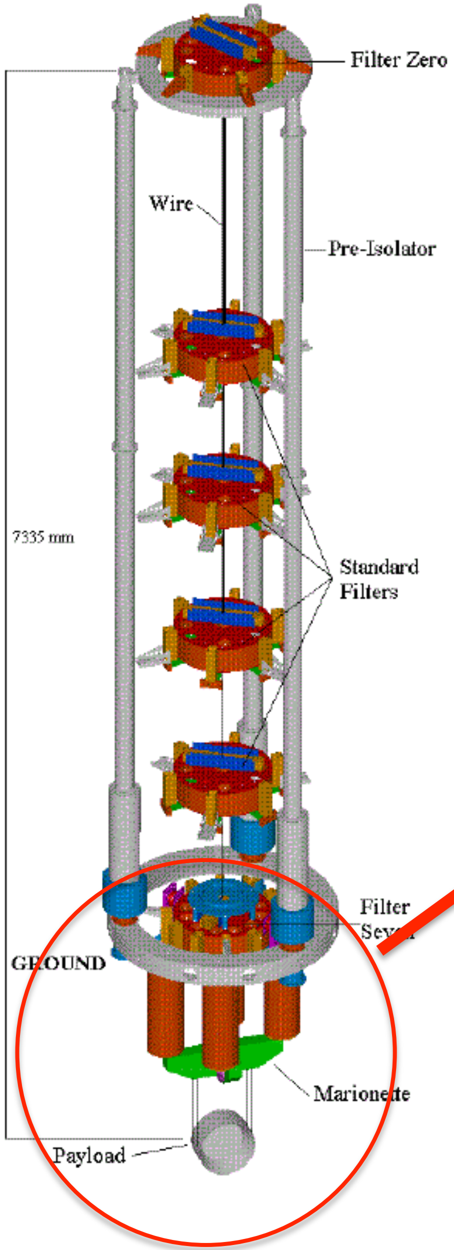
TAMA

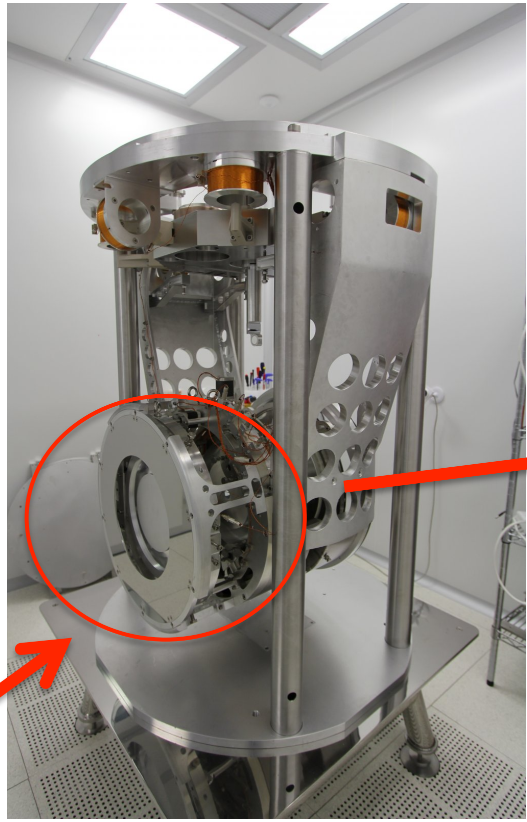
From the Michelson interferometer to LIGO and Virgo



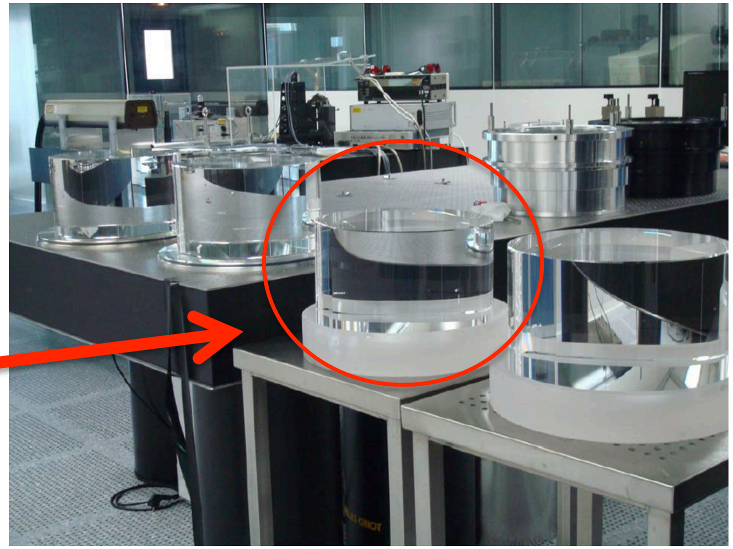
Sensitivity of the Advanced LIGO detectors at the beginning of gravitational wave astronomy
D. V. Martynov *et al.* Phys. Rev. D **93**, 112004 – (2016)

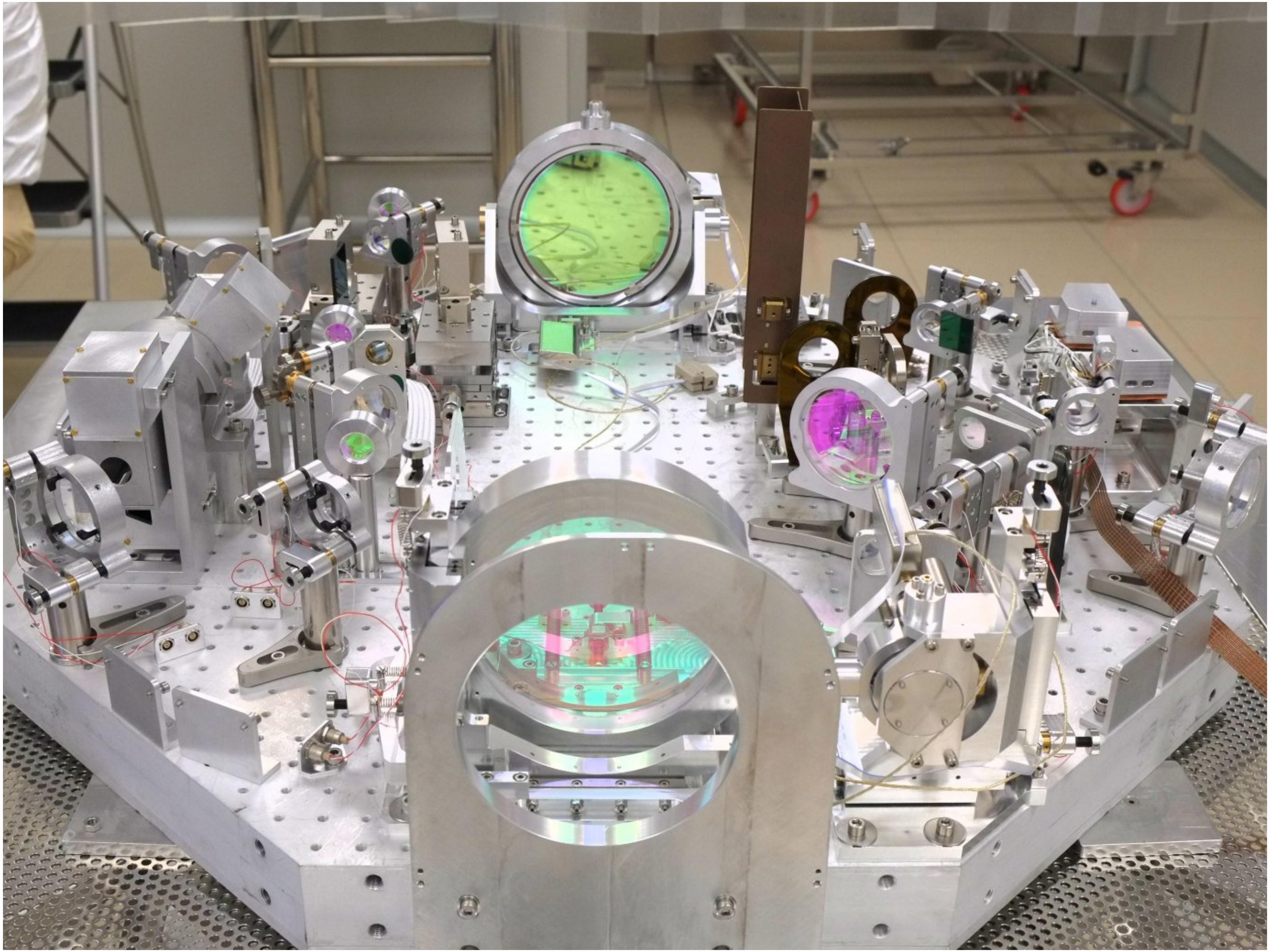
Suspensions and mirrors





Credit Virgo

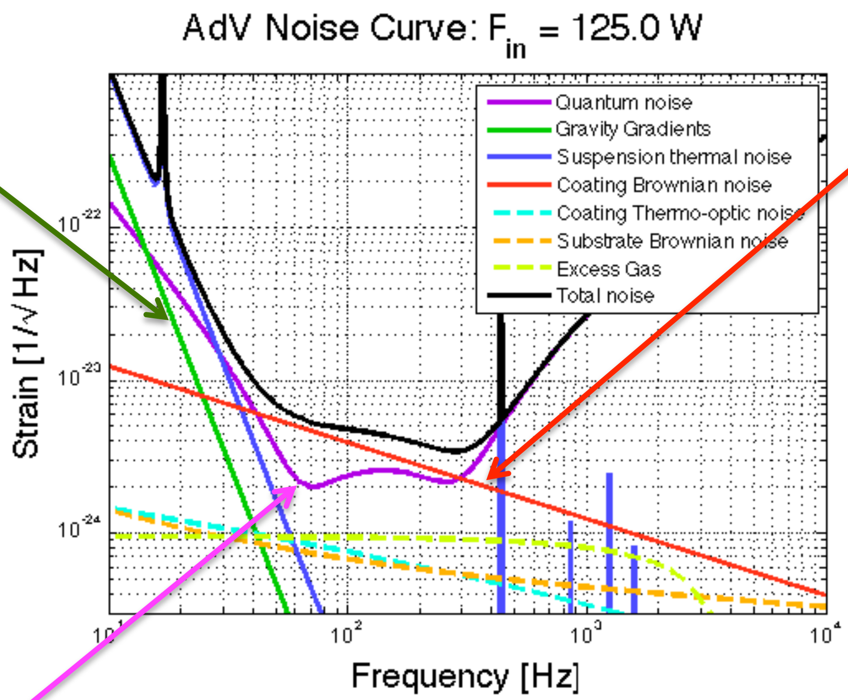




Main noises limiting the detector's sensitivity

Seismic and gravity gradient noise

Thermal noise



Quantum noise

From 1916 to 2015: The path to the first detection

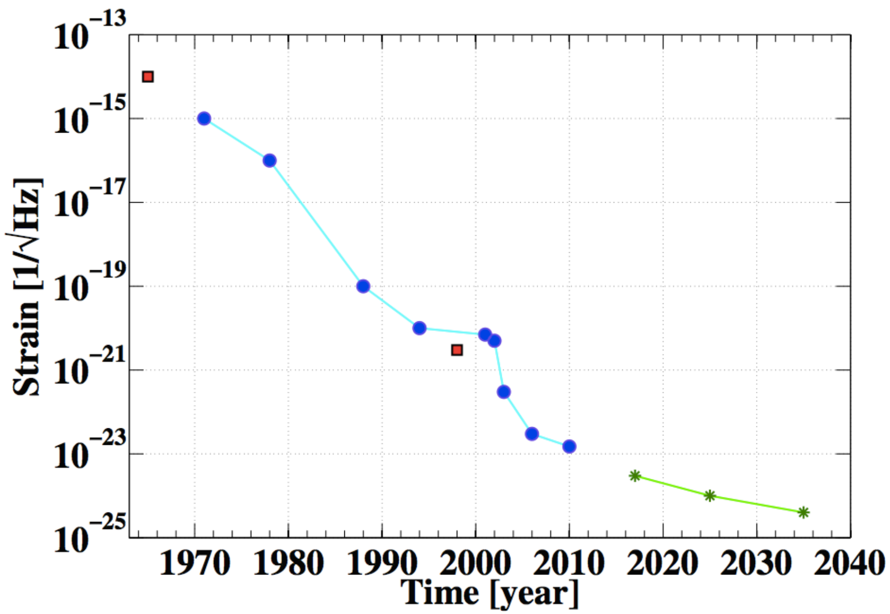
Discovery of black-holes and neutron stars

Hulse and Taylor binary pulsar (GWs exist)

Technology (lasers, control systems)

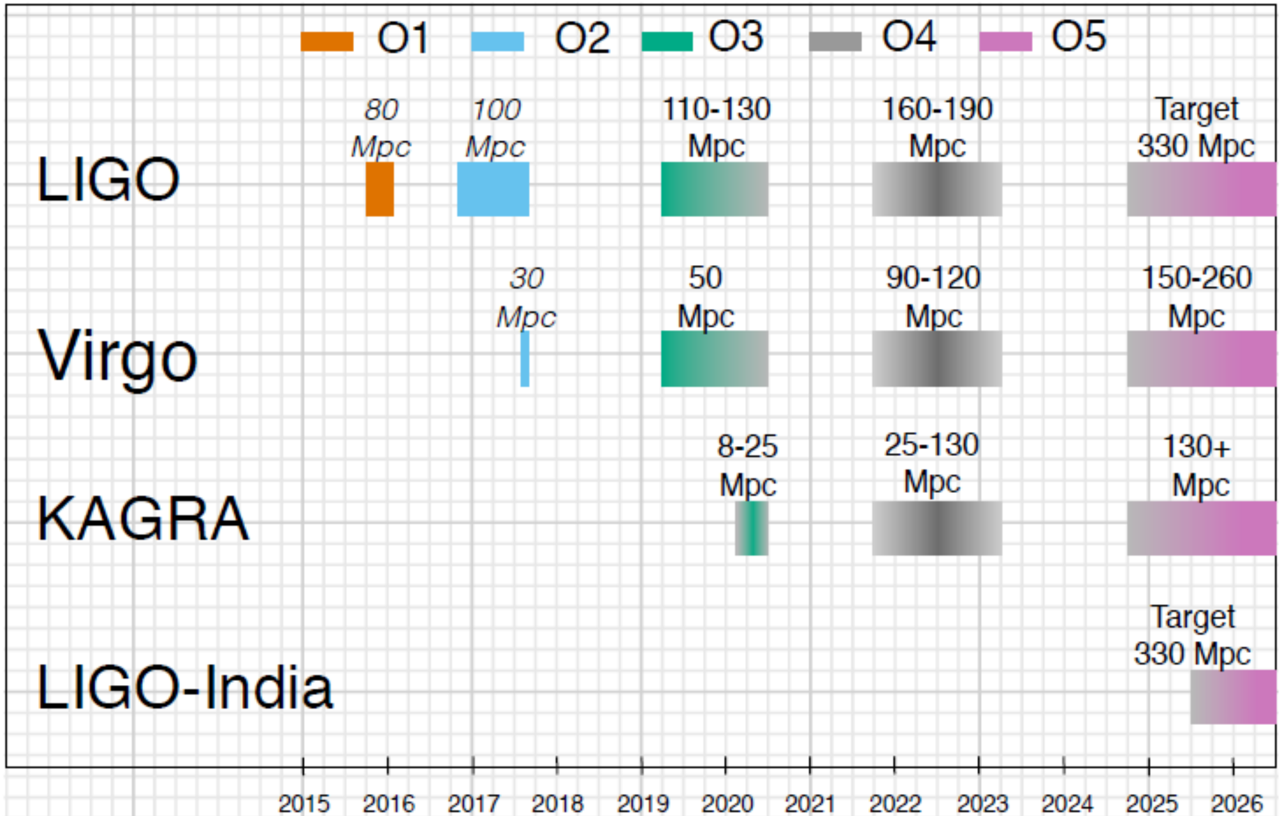
Theoretical developments (waveforms, estimation of the amplitudes)

Perseverance and collaborative work to reach $h=10^{-21}$



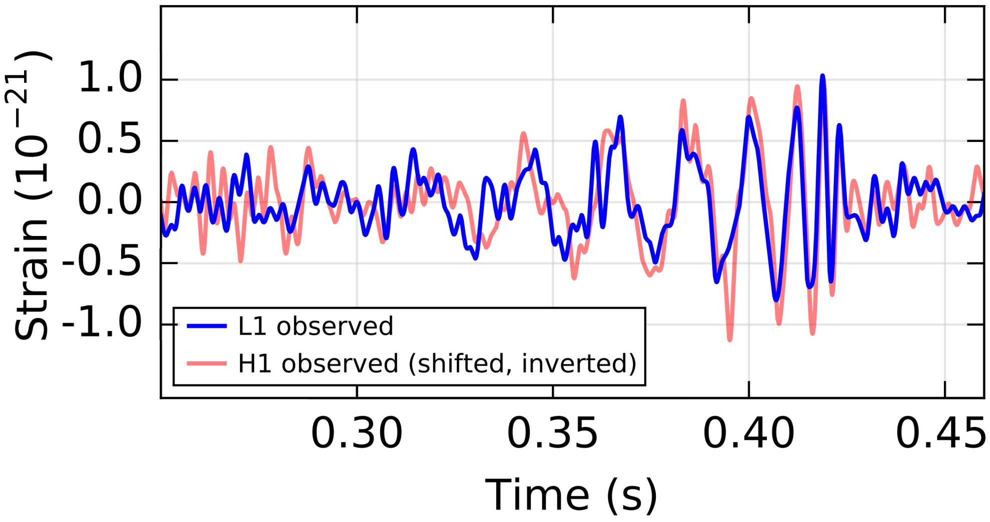
R.Adhikari, Gravitational Radiation Detection with Laser Interferometry, arXiv:1305.5188, 2013

LIGO-Virgo observing runs



Prospects for Observing and Localizing Gravitational-WaveTransients with Advanced LIGO, Advanced Virgo andKAGRA
Abbott, B. P. et al. (KAGRA Collaboration,LIGO Scientific Collaboration, and VirgoCollaboration), arXiv:1304.0670

The first detection: GW150914



Checks:

1) Same waveform in the two LIGOs (with a propagation delay)
2) Not coincident with environmental sensors and with auxiliary channels
3) Not a malicious injection (not an hacker)
4) High statistical significance
5) Matching with general relativity

Observation of Gravitational Waves from a Binary Black Hole Merger, B. P. Abbott et al. (LIGO and Virgo Collaborations), Phys. Rev. Lett., Vol. 116, 061102, (2016).

The announcement: 12 February 2016

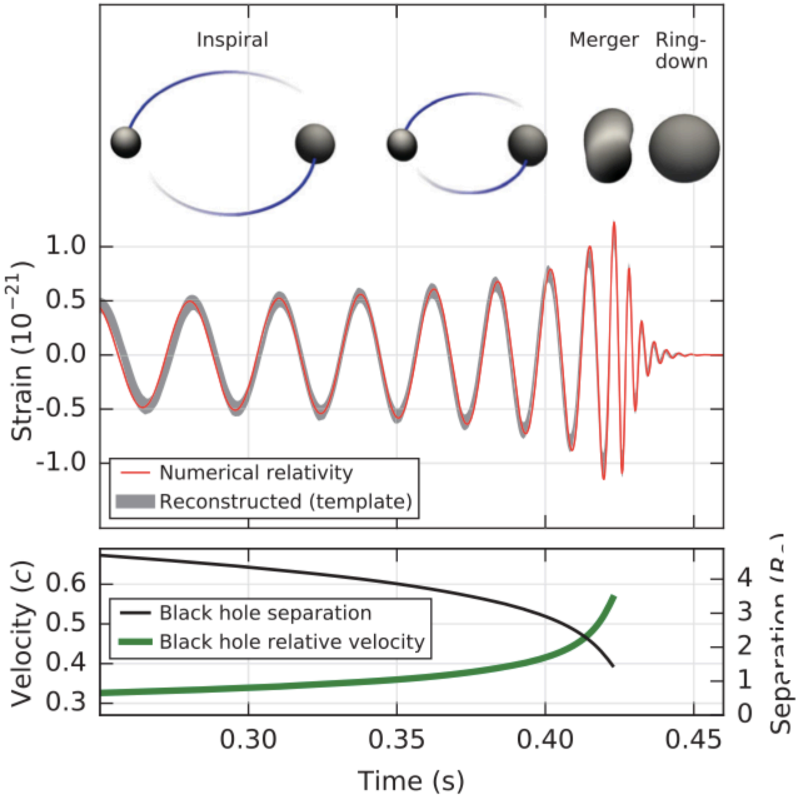
Selected for a Viewpoint in *Physics*
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

GW150914: a binary black-hole system

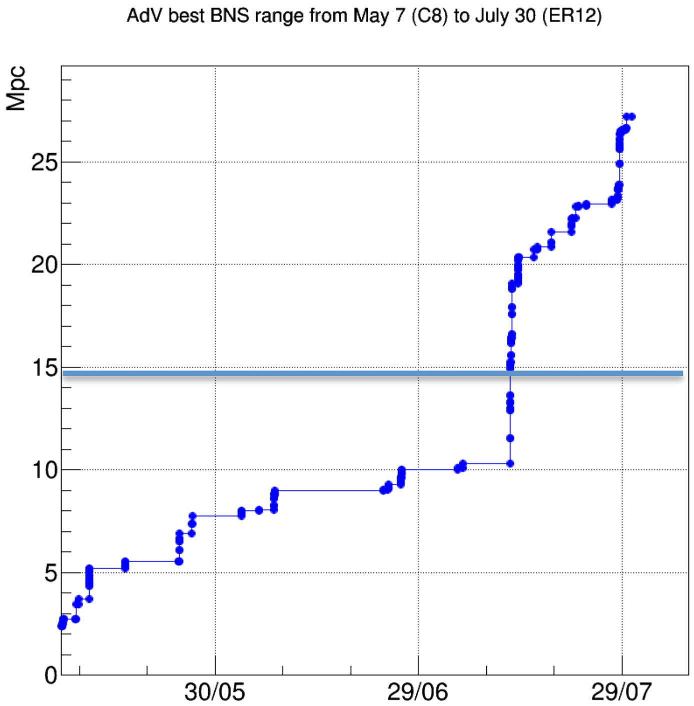


Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

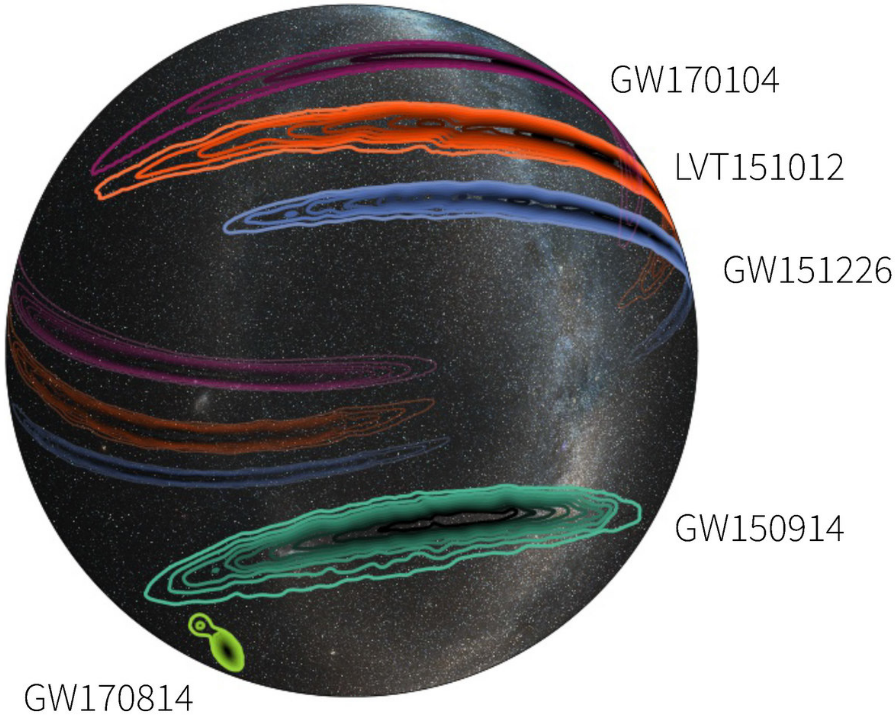
Energy in GW $3.0^{+0.5}_{-0.5} M_\odot c^2$

Luminosity $3.6^{+0.5}_{-0.4} \times 10^{56}$ erg/s

Virgo enters in the network: August 2017



First triple detection: GW170814

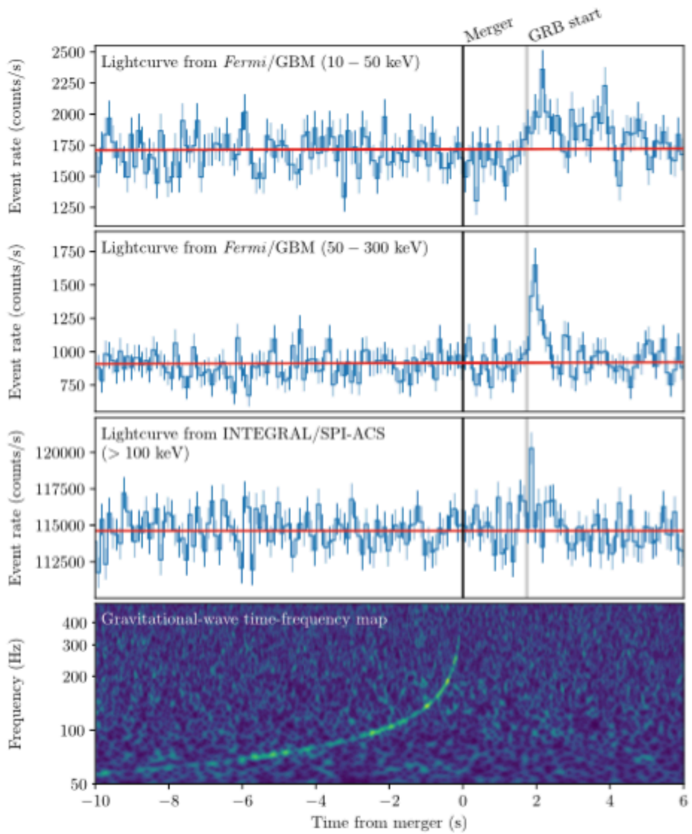


GW170814: A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence, B.P. Abbott et al, Phys. Rev. Lett. 119, 141101 (2017)

~ 60 deg^2

- ~ x 10 better localization
- first tests of GW polarization

First binary neutron star merger: GW170817



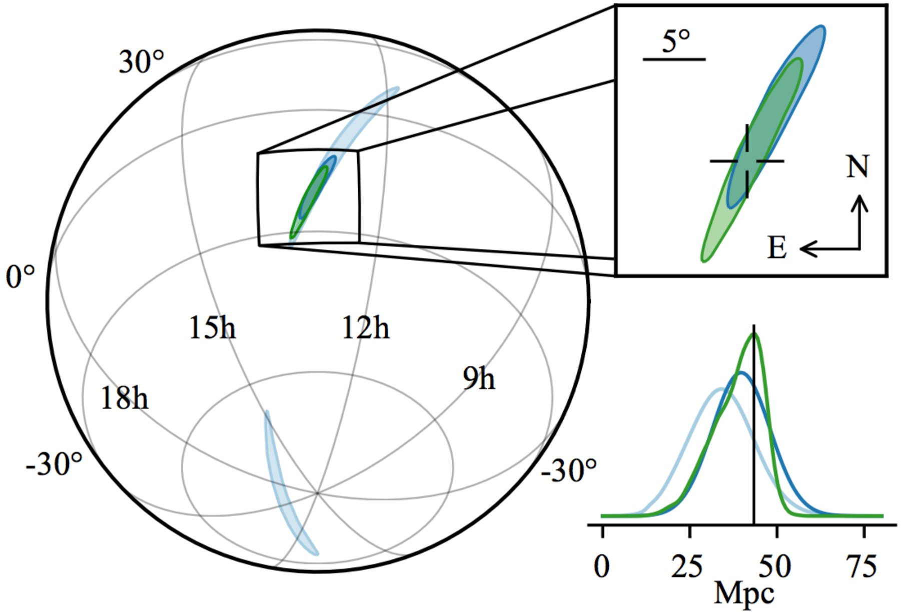
Measurement of gravitational-waves speed

$$-3 \times 10^{-15} \leqslant \frac{\Delta v}{v_{\rm EM}} \leqslant +7 \times 10^{-16}$$

Photons emitted 10 seconds after

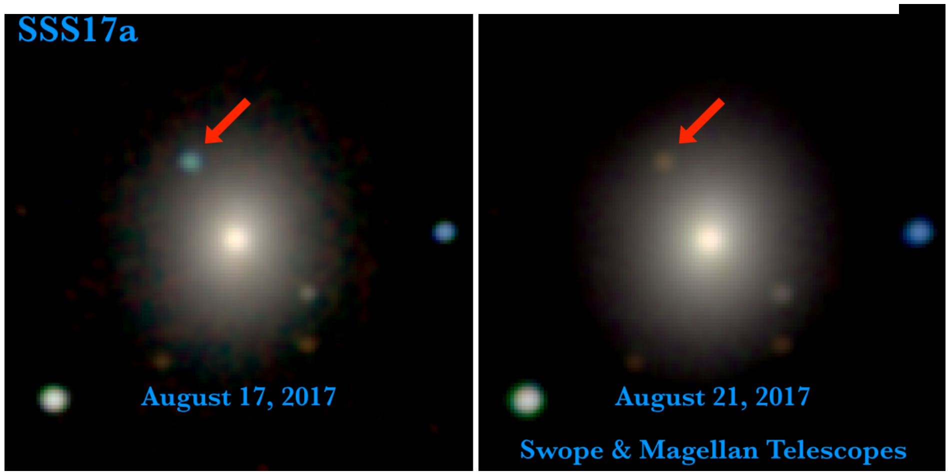
GW and photons emitted at the same time

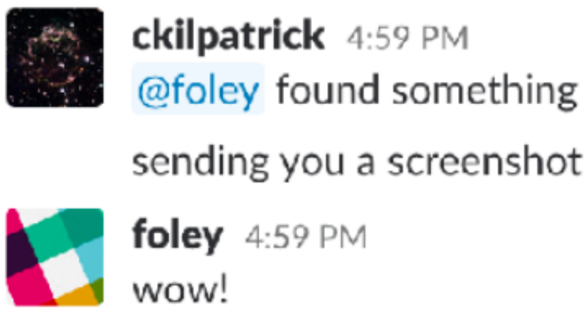
The galaxy identification and the kilonova



GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral, B.P.Abbott, Phys. Rev. Lett. 119, 161101 (2017)

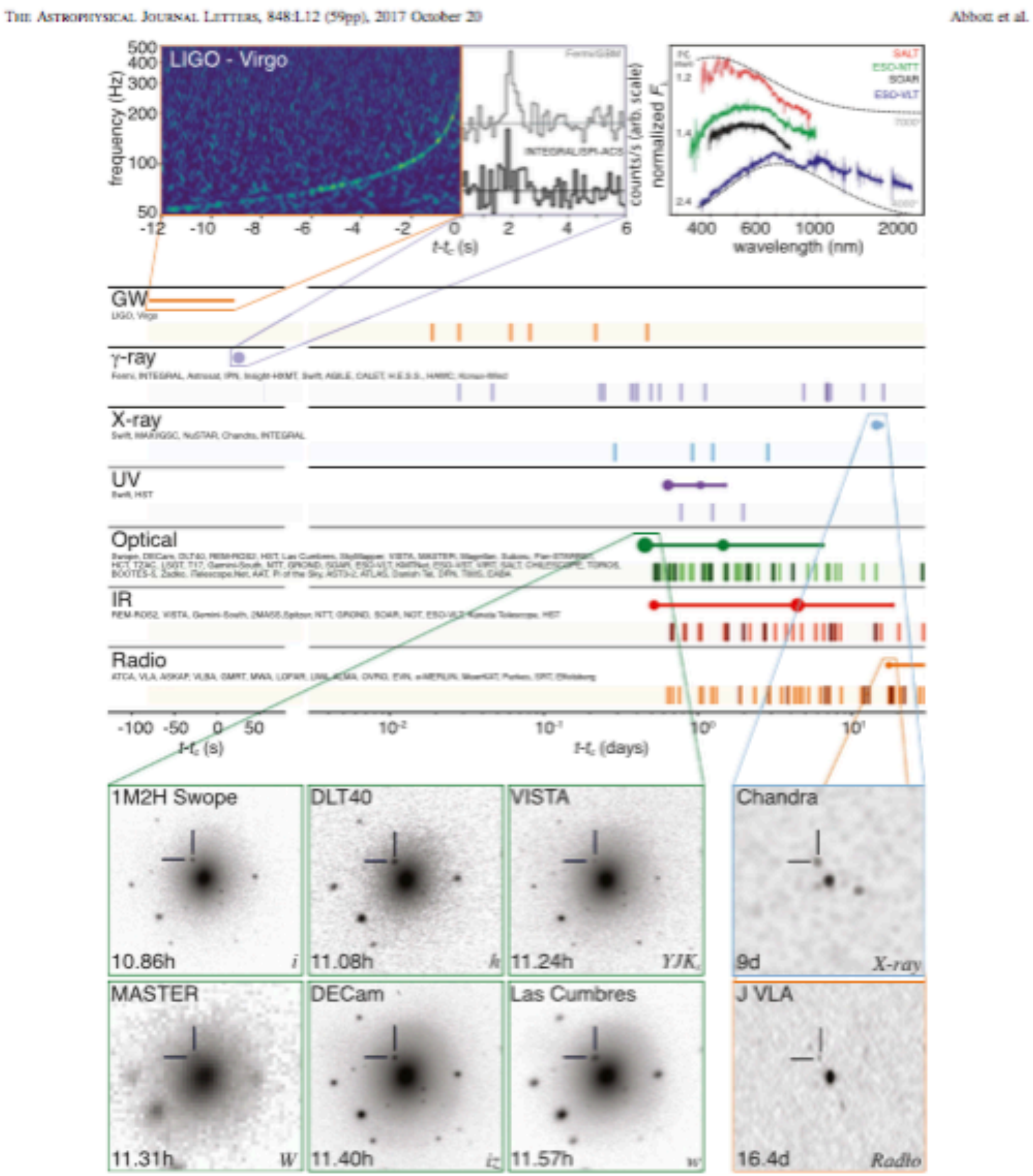
Properties of the Binary Neutron Star Merger GW170817, B. P. Abbott et al., Phys. Rev. X 9, 011001 (2019)





https://ziggy.ucolick.org/sss17a/

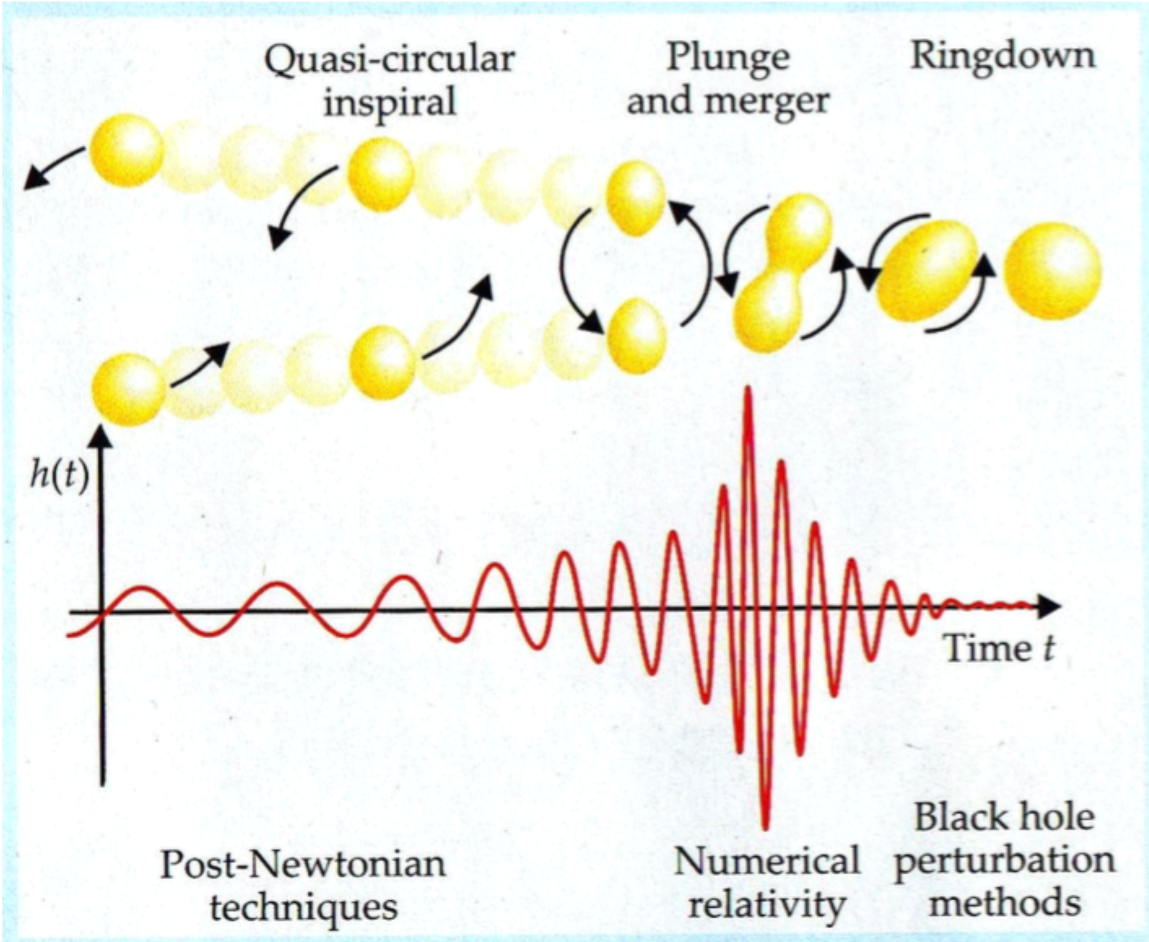
A planetary observation



Multi-Messenger Observations of a Binary Neutron Star Merger, B.P.Abbott, et al. (Virgo and LIGO and other astrophysics group) Astrophys. J. Lett. 848, L12 (2017)

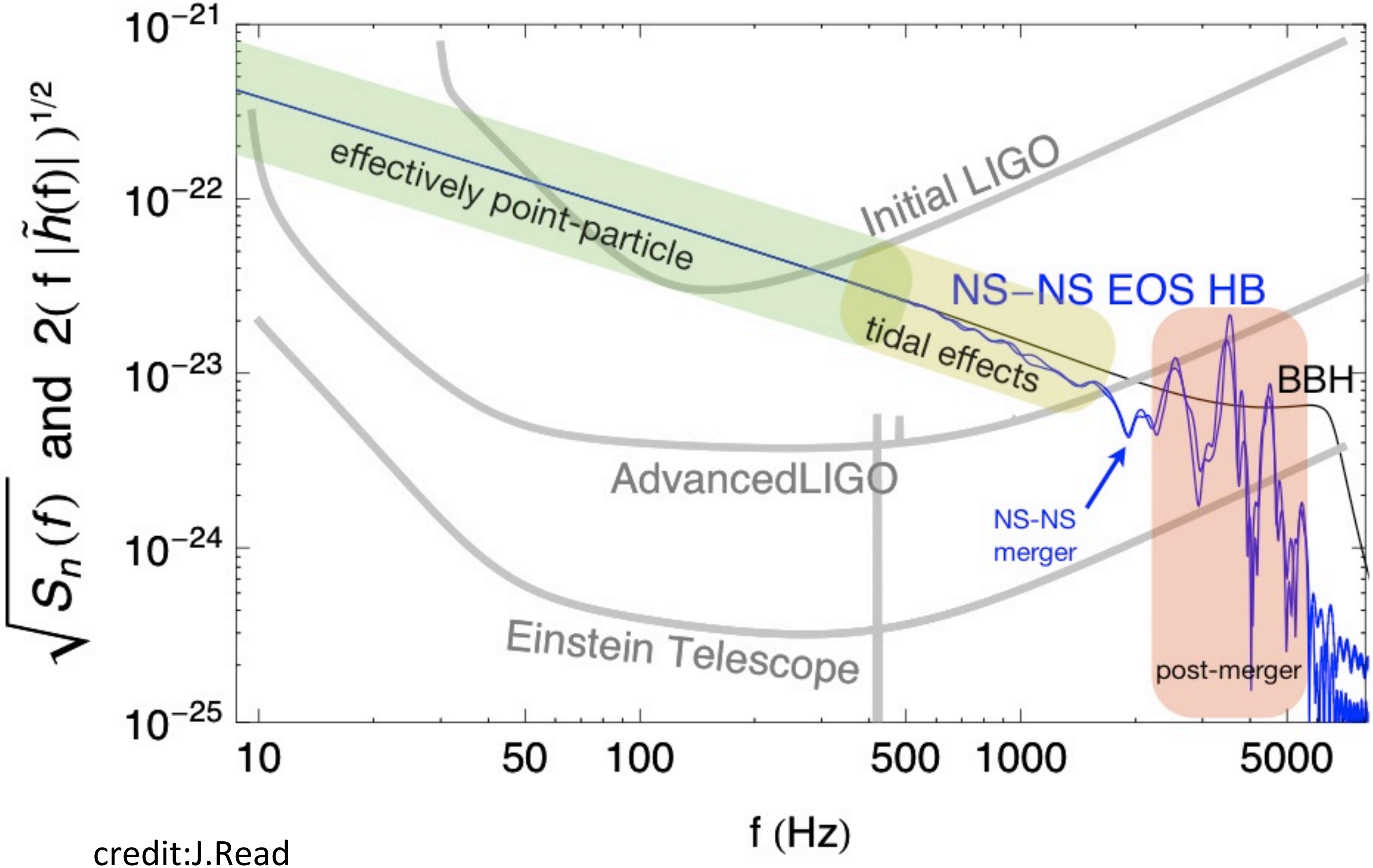
56 teams and collaborations, 3600 authors

GW from compact objects



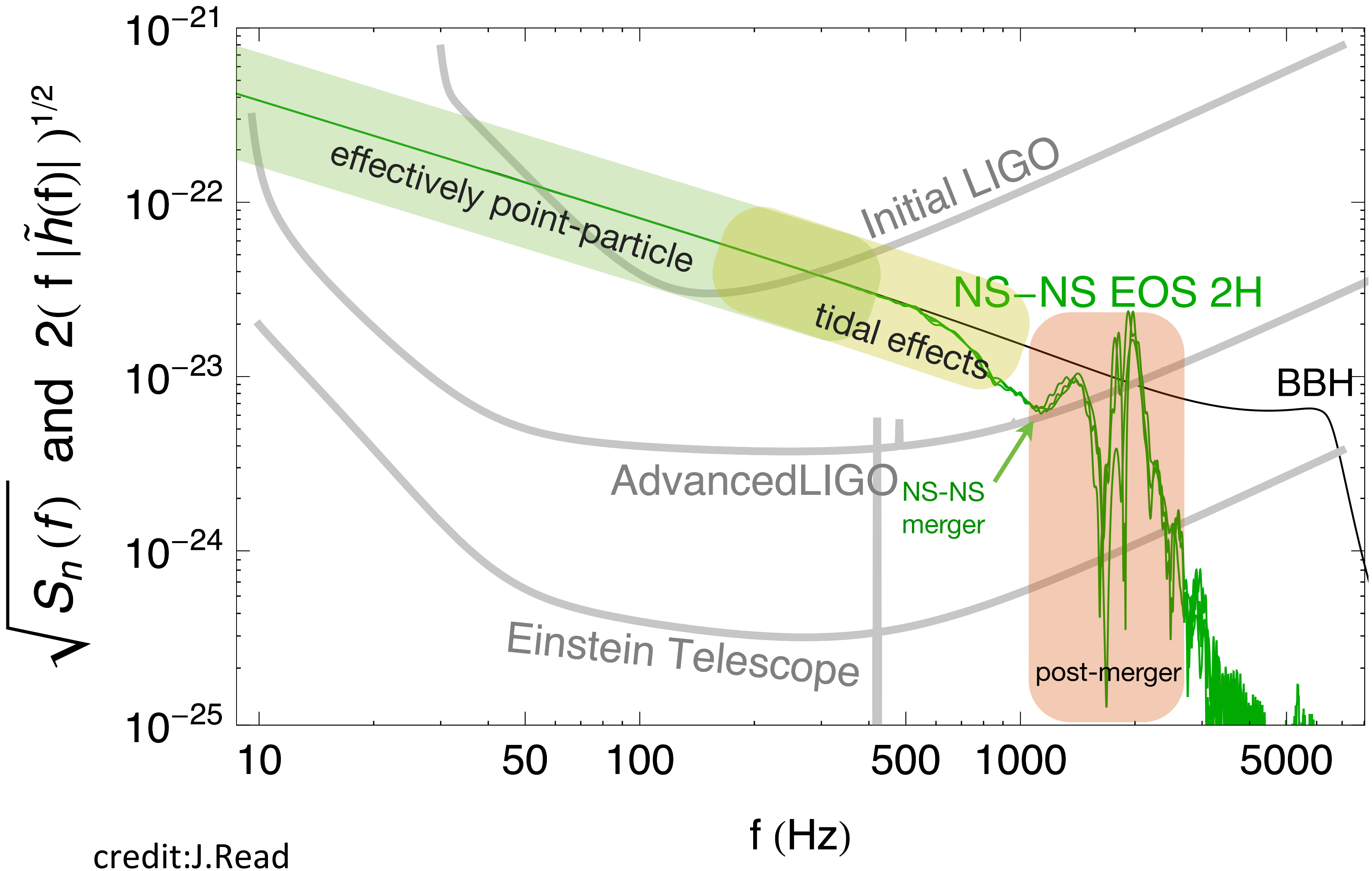
h ~ 10^{-21} for a realistic source at a realistic distance

Nuclear matter: GW for different equations of state



credit:J.Read

Nuclear matter: GW for different equations of state



credit:J.Read

Cosmology: « standard sirens »

Schutz, B. F. *Determining the Hubble constant from gravitational wave observations*. Nature 323, 310–311 (1986).

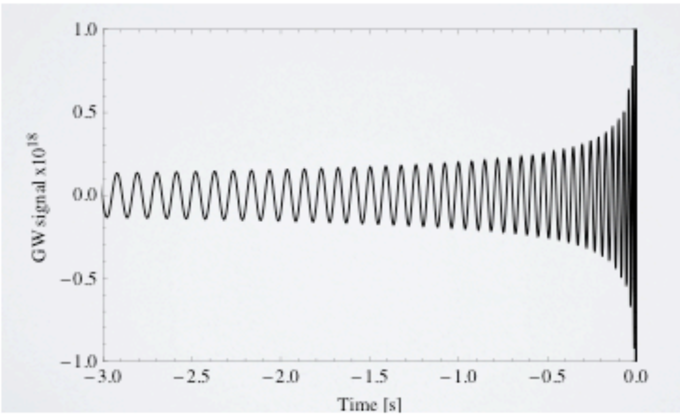
$$H_0 \times d = c\,z$$

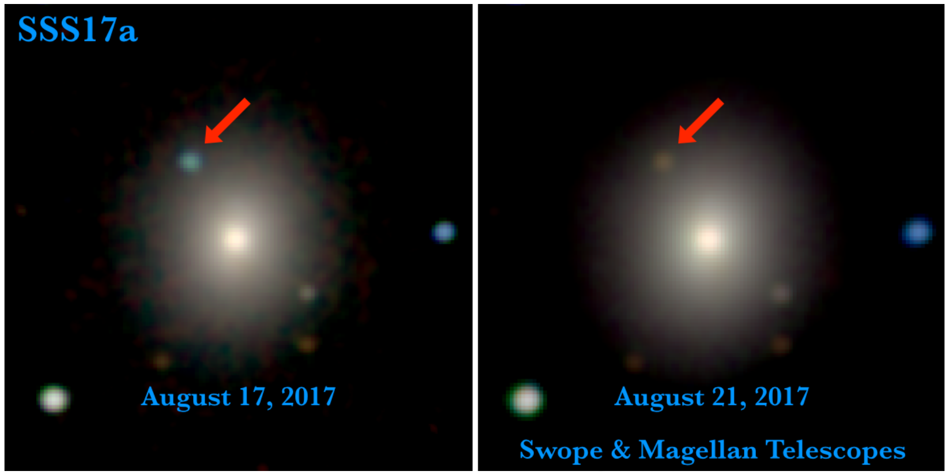
Method I "counterparts":

z from optical identification of the host galaxy (NGC4993)

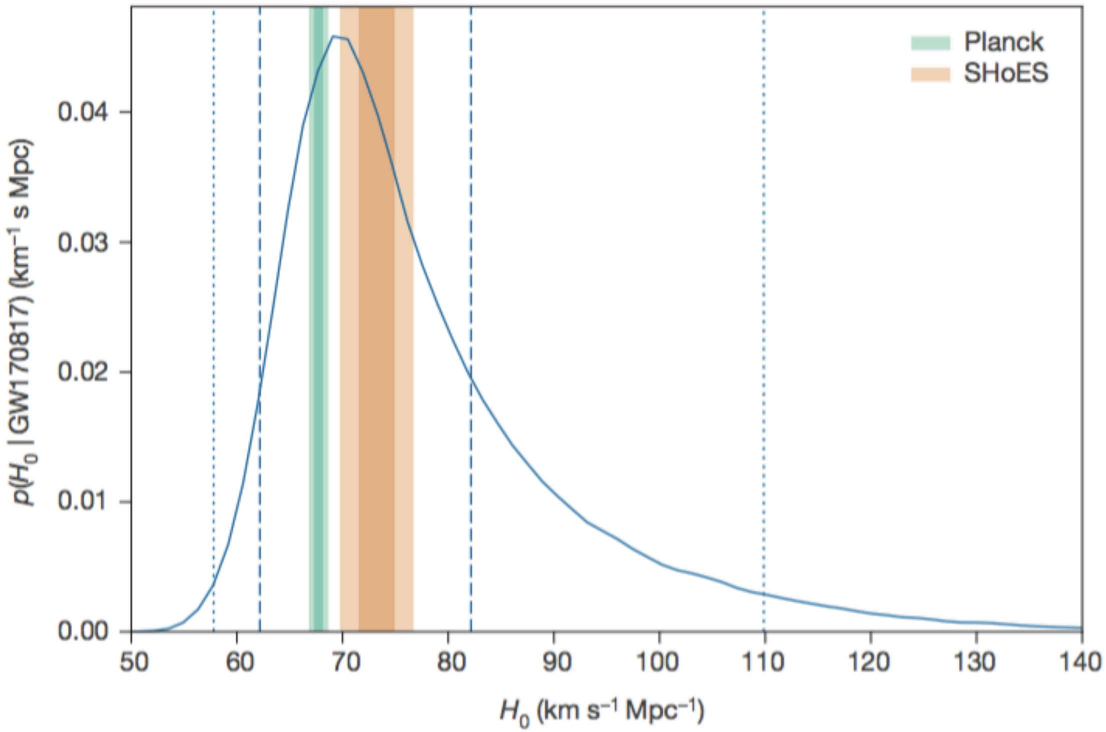
d from amplitude of signal in <u>gravitational waves</u> emitted by coalescing BBH or BNS (in case of GW170817).

No distance ladder. GWs don't give z.





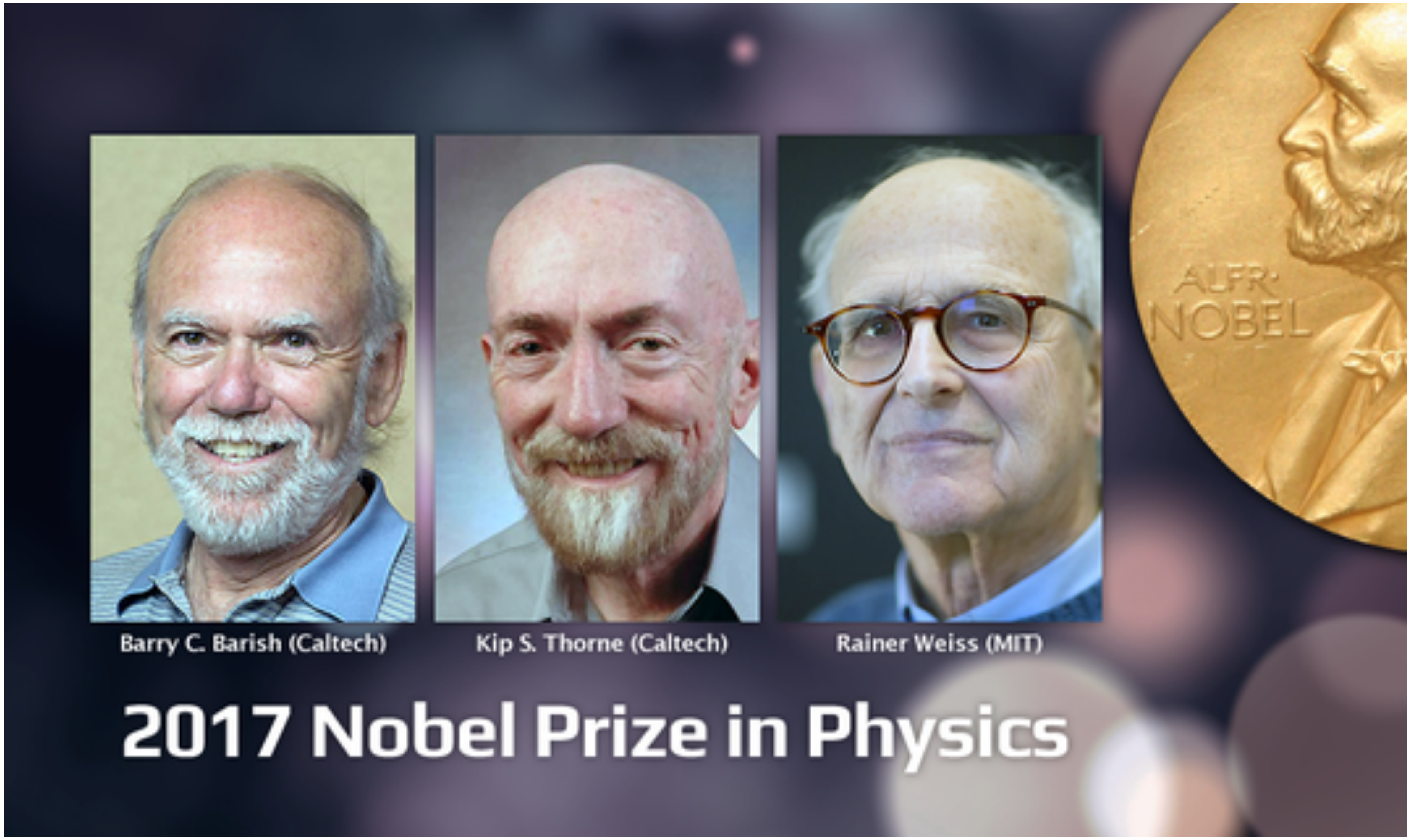
Cosmology: Measurement of Hubble constant using BBH and GW170817



A gravitational-wave measurement of the Hubble constant following the second observing run of Advanced LIGO and Virgo, B.P.Abbott et al

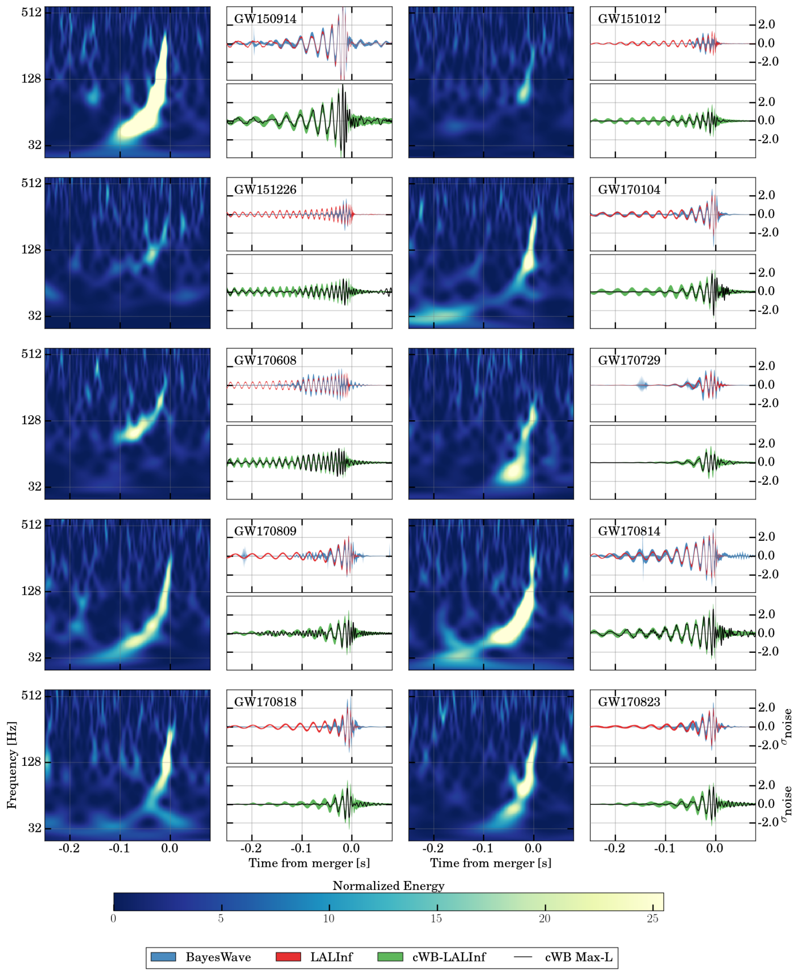
A gravitational-wave standard siren measurement of the Hubble constant , *Nature* **551**, 85–88 (2017)

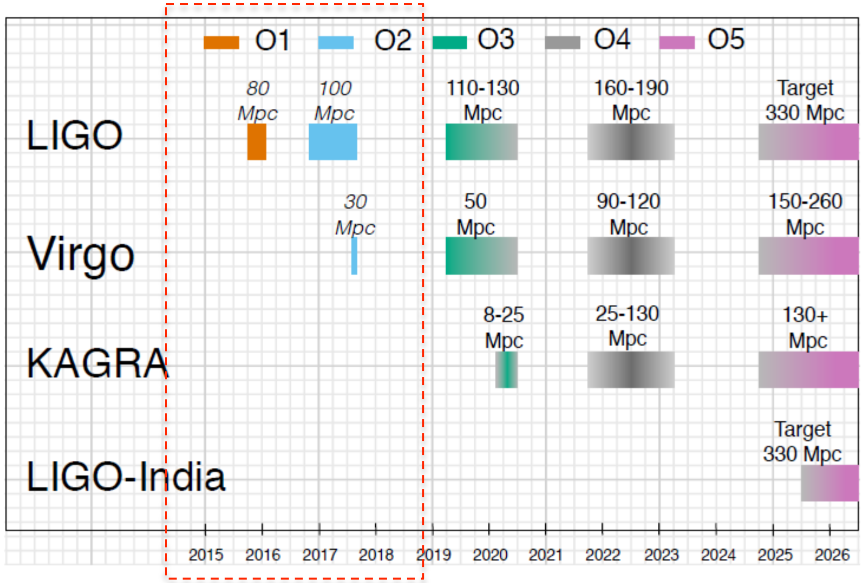
3 october 2017: Nobel prize in physics



www.nobelprize.org

First GW catalog: 11 detections during O1 and O2: Nov 2018





GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs, B.P. Abbott et al., Phys. Rev. X 9, 011001 (2019)

Public data - GWOSC

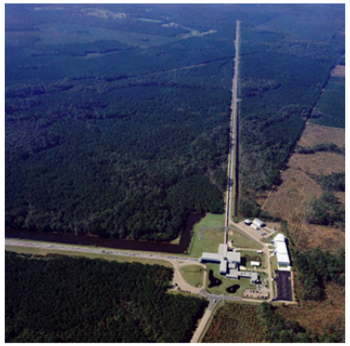
Gravitational Wave Open Science Center

line Tools▾ About GWOSC▾

The Gravitational Wave Open Science Center provides data from gravitational-wave observatories, along with access to tutorials and software tools.

LIGO Hanford Observatory, Washington

(Credits: C. Gray)



LIGO Livingston Observatory, Louisiana

(Credits: J. Giaime)

Virgo detector, Italy

(Credits: Virgo Collaboration)

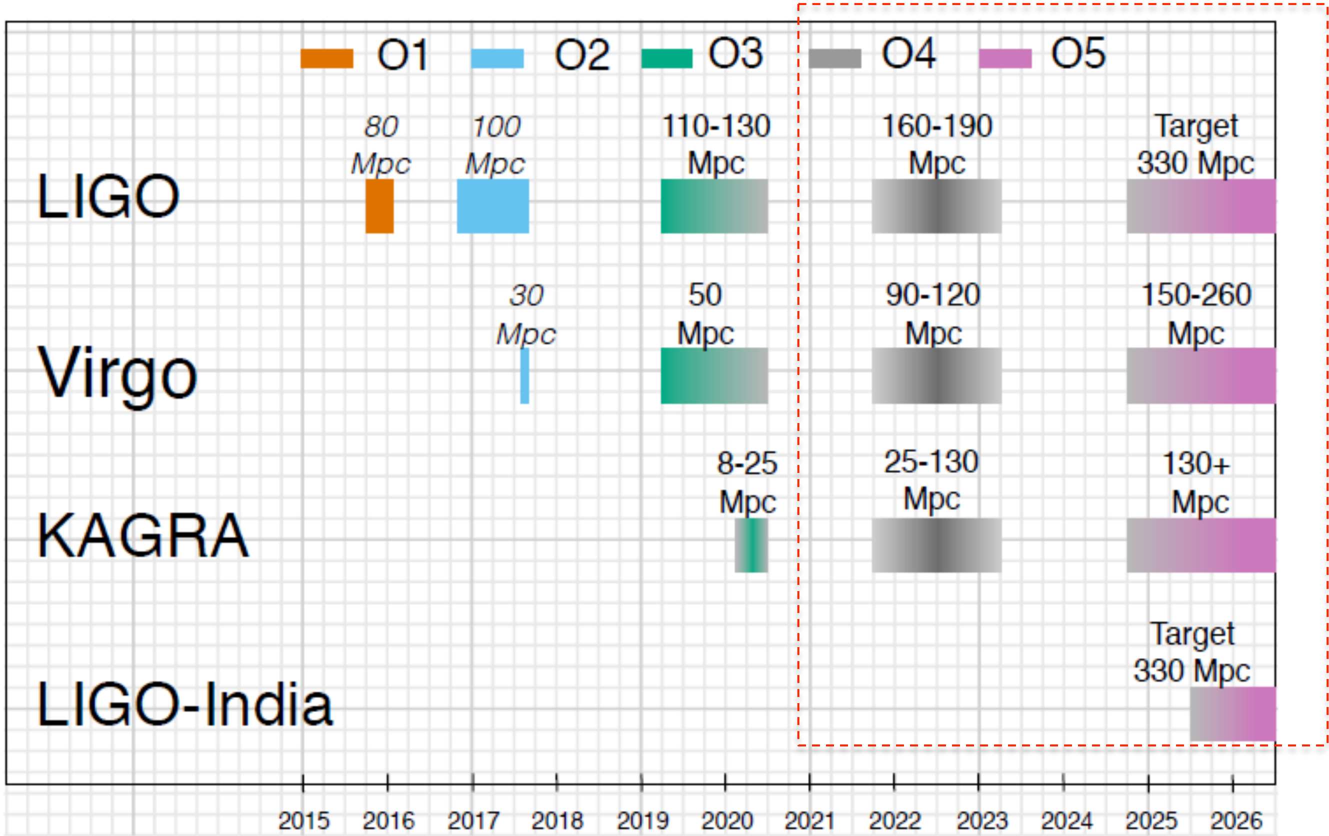
NEW **GWTC-2 data available!**

Get started

Download data

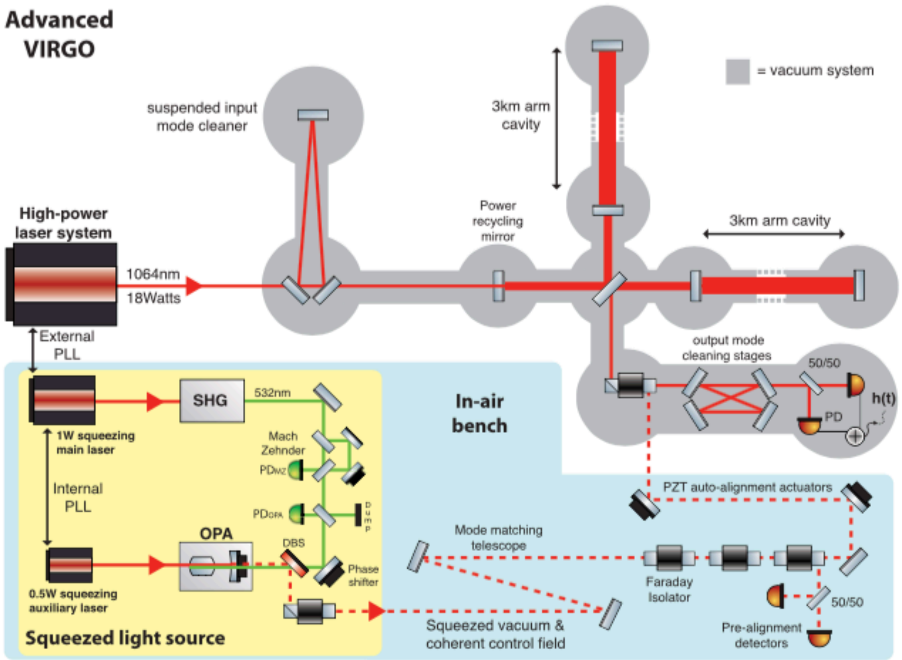
https://www.gw-openscience.org

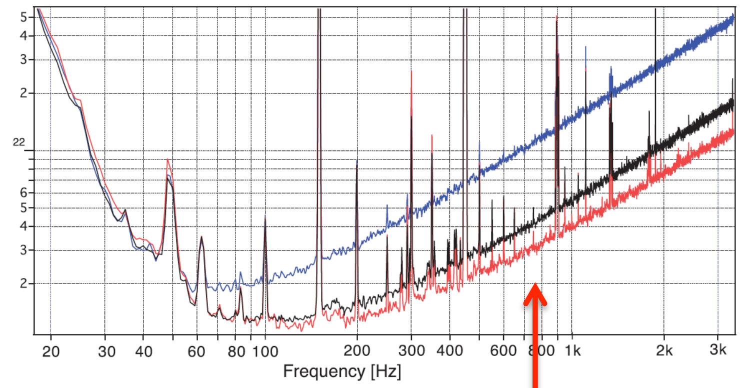
Next observing runs



Prospects for Observing and Localizing Gravitational-WaveTransients with Advanced LIGO, Advanced Virgo andKAGRA
Abbott, B. P. et al. (KAGRA Collaboration,LIGO Scientific Collaboration, and VirgoCollaboration), arXiv:1304.0670

Squeezed light injection during O3

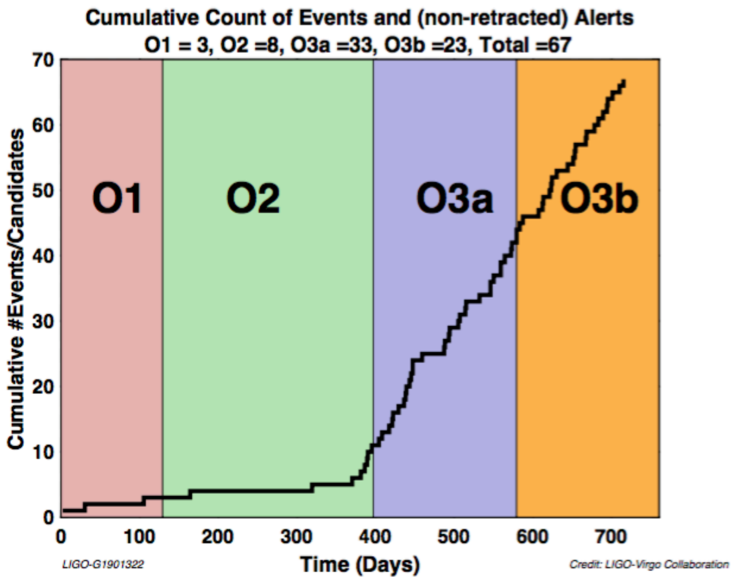




Squeezed vacuum injected

Increasing the Astrophysical Reach of the Advanced Virgo Detector via the Application of Squeezed Vacuum States of Light, F. Acernese et al. (Virgo Collaboration), Phys. Rev. Lett. 123, 231108 (2019)

O3 scientific results in short



- 56 alerts during O3(~ 1/6 days)
- Public alerts

- 4 new « exceptional » astrophysical systems
- More distant sources (z~ 0.5 → z~ 0.8)
- New tests of general relativity

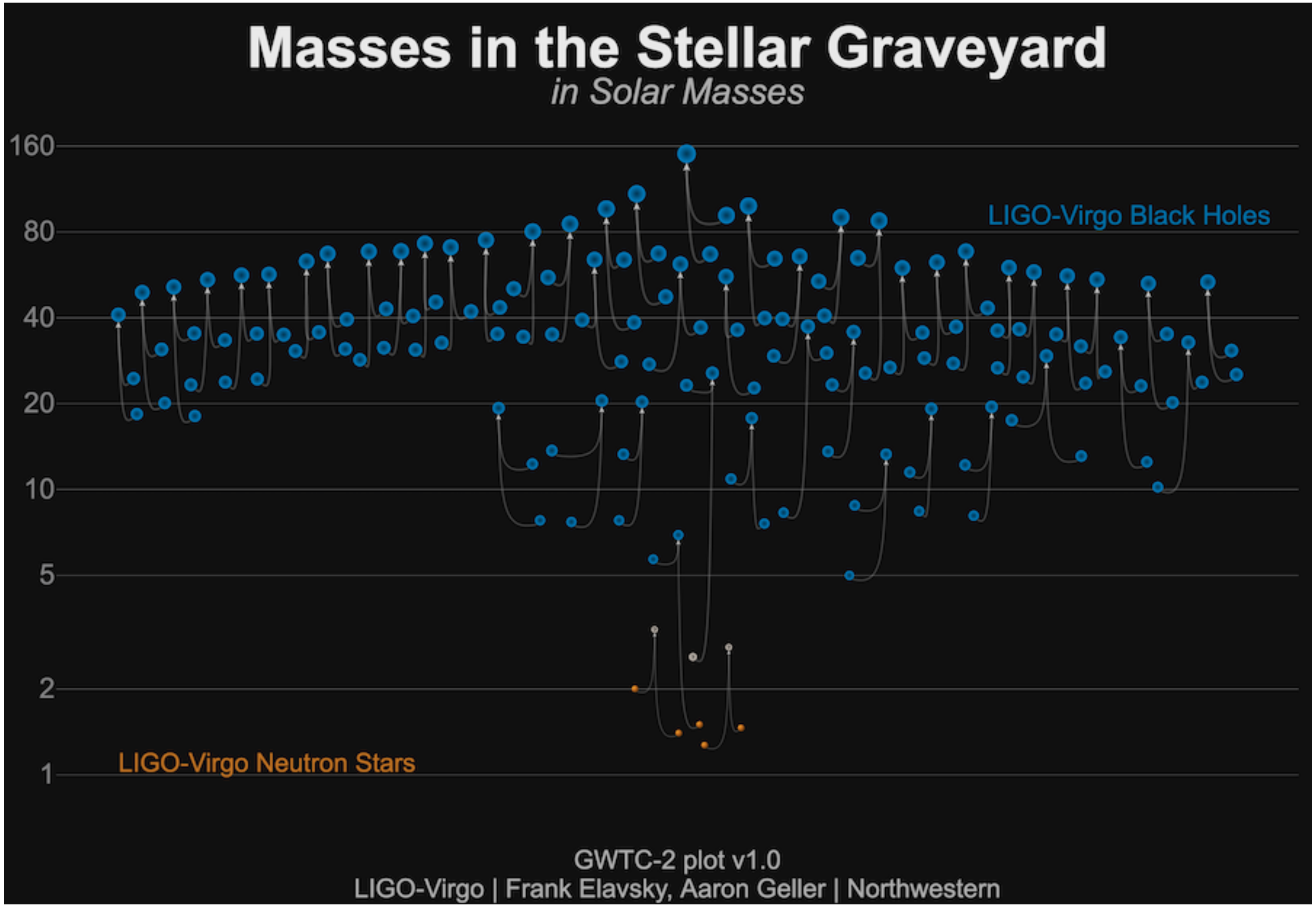
- GWTC-2 (second catalog) O3a
39 new sources

- Data analysis of O3b still on going

O3 scientific results: 4 new « exceptional » events already published

- GW190412, a BBH merger, with component masses ~ $8M_\odot$ and ~ $3M_\odot$
    - Mass asymmetry → observable GW beyond the leading quadrupolar order
- GW190814, a compact object merger, with component masses ~ $23M_\odot$ (BH) and ~ $3M_\odot$
    - ~ $3M_\odot$ object: the lightest BH or the heaviest NS ever observed ?
- GW190425, a BNS merger, with a total mass of ~ $3.4M_\odot$
    - Total mass significantly larger than any of the other known BNS system
- GW190521, a BBH merger with component masses ~ $66M_\odot$ and ~ $85M_\odot$. The final BH is 142 $M_\odot$

Second catalog: GWTC-2
39 new sources



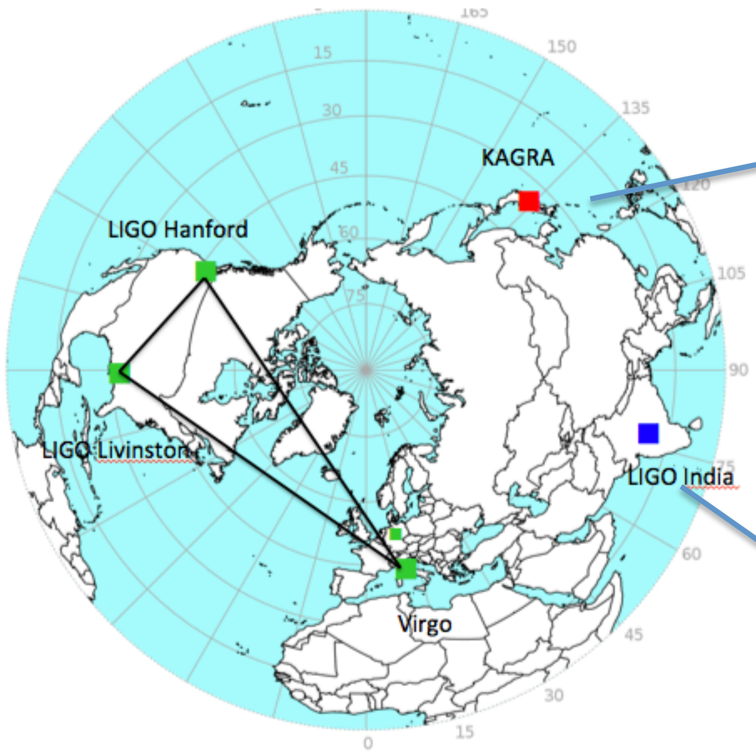
Summary of the results

- First detection of gravitational-waves
- First test of gravitational-wave polarisation
- Gravitational waves travel at the speed-of-light
- Tesf of the emission at higher harmonics of GW
- General test of GR in strong field regime
- Speed of gravity → consequences on gravity alternative theories

- First observations of a NS-NS merger
- First observations of BH-BH mergers
- A new population of BH with high masses
- First measurements on NS tidal deformability
- Link between GRB and neutron star mergers
- Kilonova powered by binary NS merger

- Alternative measurement of Hubble constant

The GW detector network in the next years



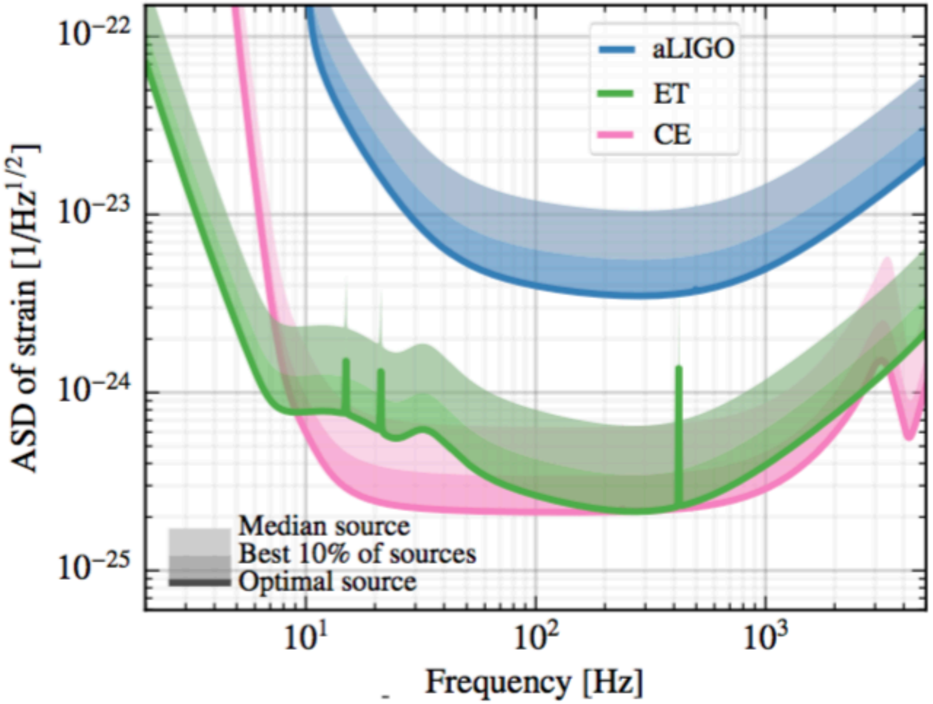
Advanced
Virgo+
and
Advanced
LIGO +

KAGRA

LIGO India

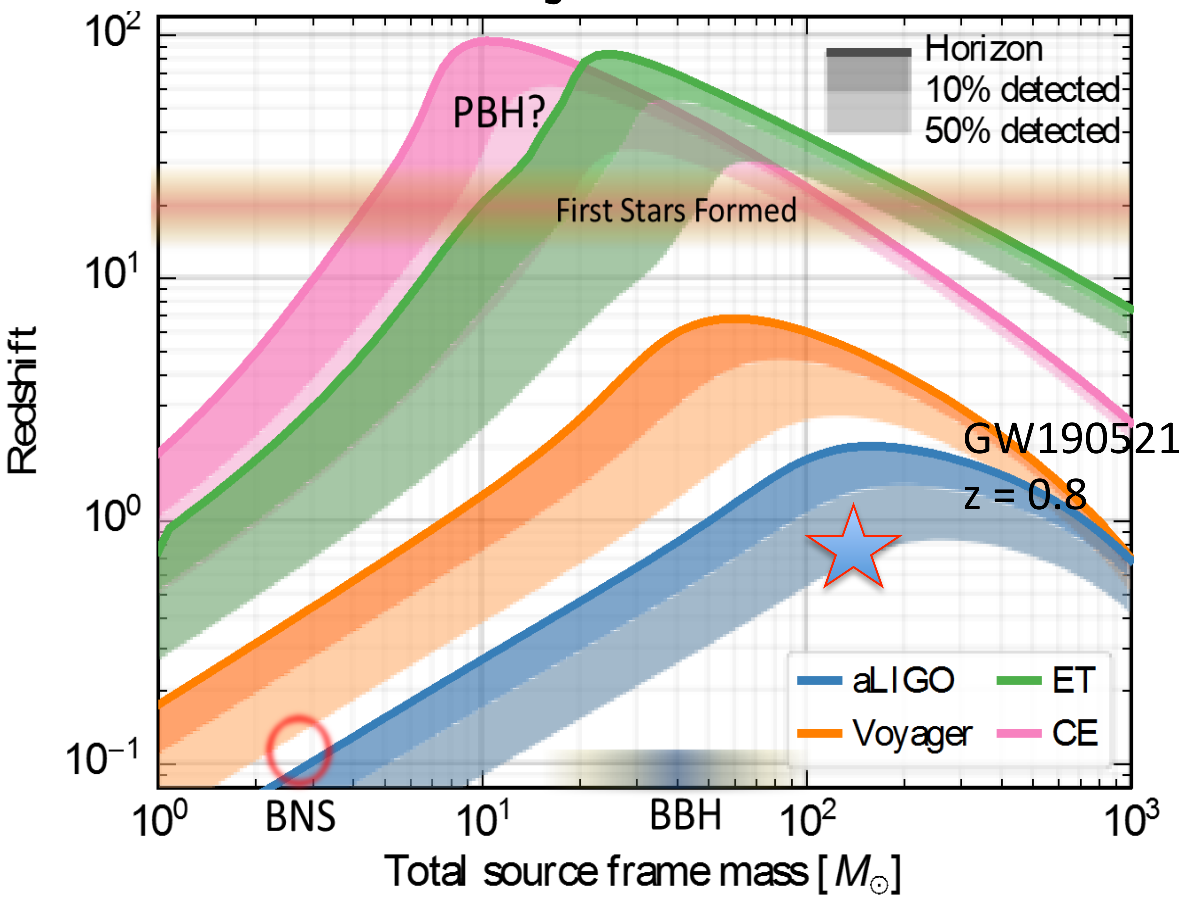
Einstein Telescope
a 3G detector

- An order of magnitude better than current detectors
- Pushing down to ~ 2 Hz the observational bandwdith (compared to ~ 10-20 Hz today



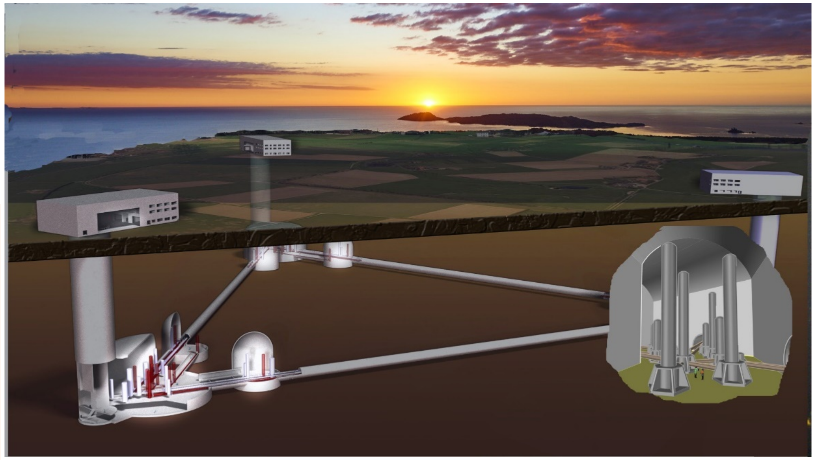
- In US: Cosmic Explorer

ET: Horizon for compact objects

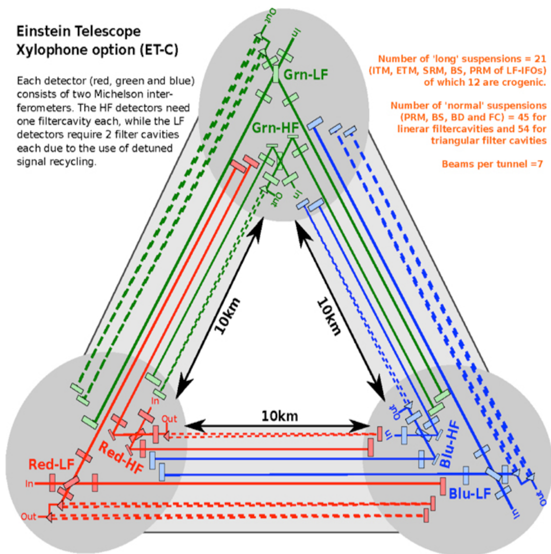


https://arxiv.org/pdf/1912.02622
ET science case

ET design



- Underground (seismic noise reduction)
- 10- km long arms (signal increase)
- Triangle configuration → polarisation
- « Xylophone » (two combined detectors)
- Cryogenics (20 K) (thermal noise reduction)



http://www.et-gw.eu/


barsu@apc.in2p3.fr