Université Paris Cité

VIRGO

APC

Gravitational-wave astronomy with ground-based interferometric detectors: from birth to the future

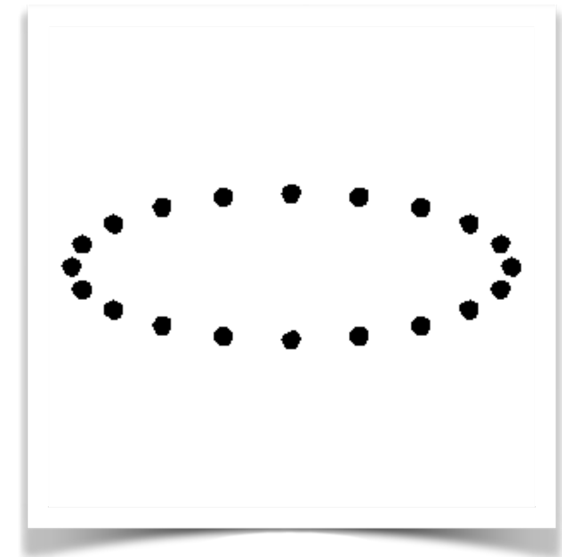
Eleonora Capocasa

LPNHE seminar

13 May 2024

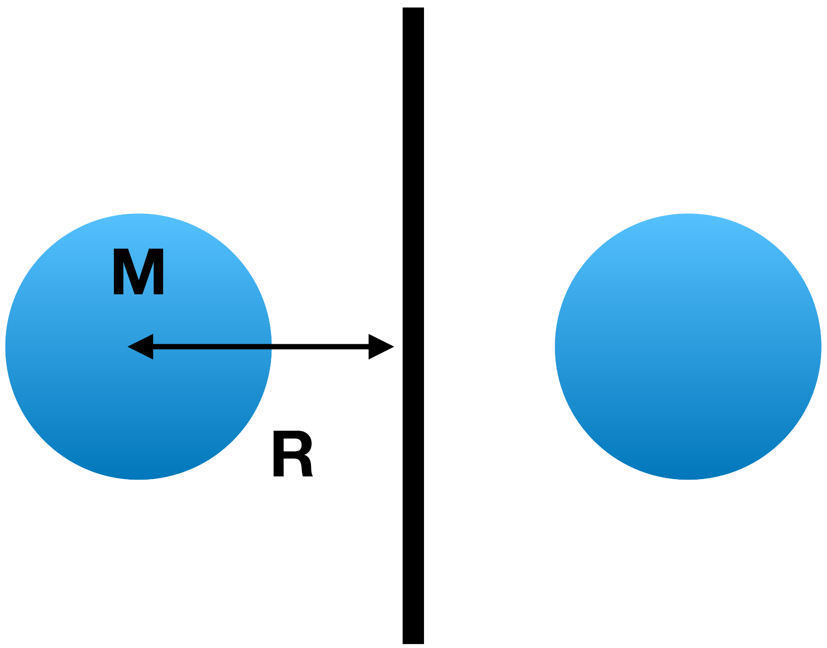
Gravitational waves

- Propagating ripple in the curvature of the space time
- They are produced by the variation of the quadrupole moment of a mass distribution
- They have transverse polarisation
- Compact objects are those who generate the strongest GW



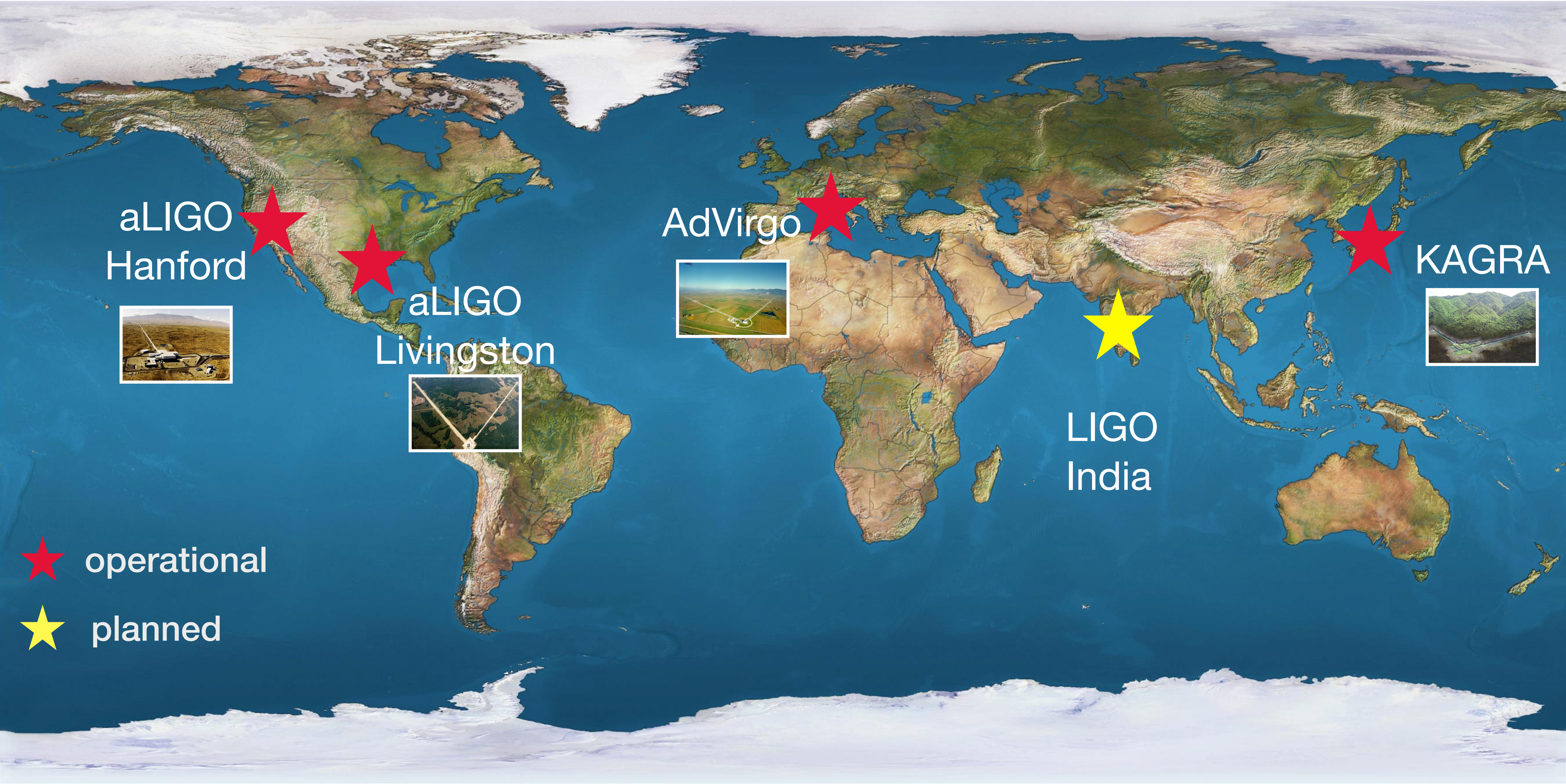
$10M_{\odot}$ Binary Black Hole System

$$h = \frac{8GMR^2\omega_{orb}^2}{rc^4} \simeq 10^{-21}$$

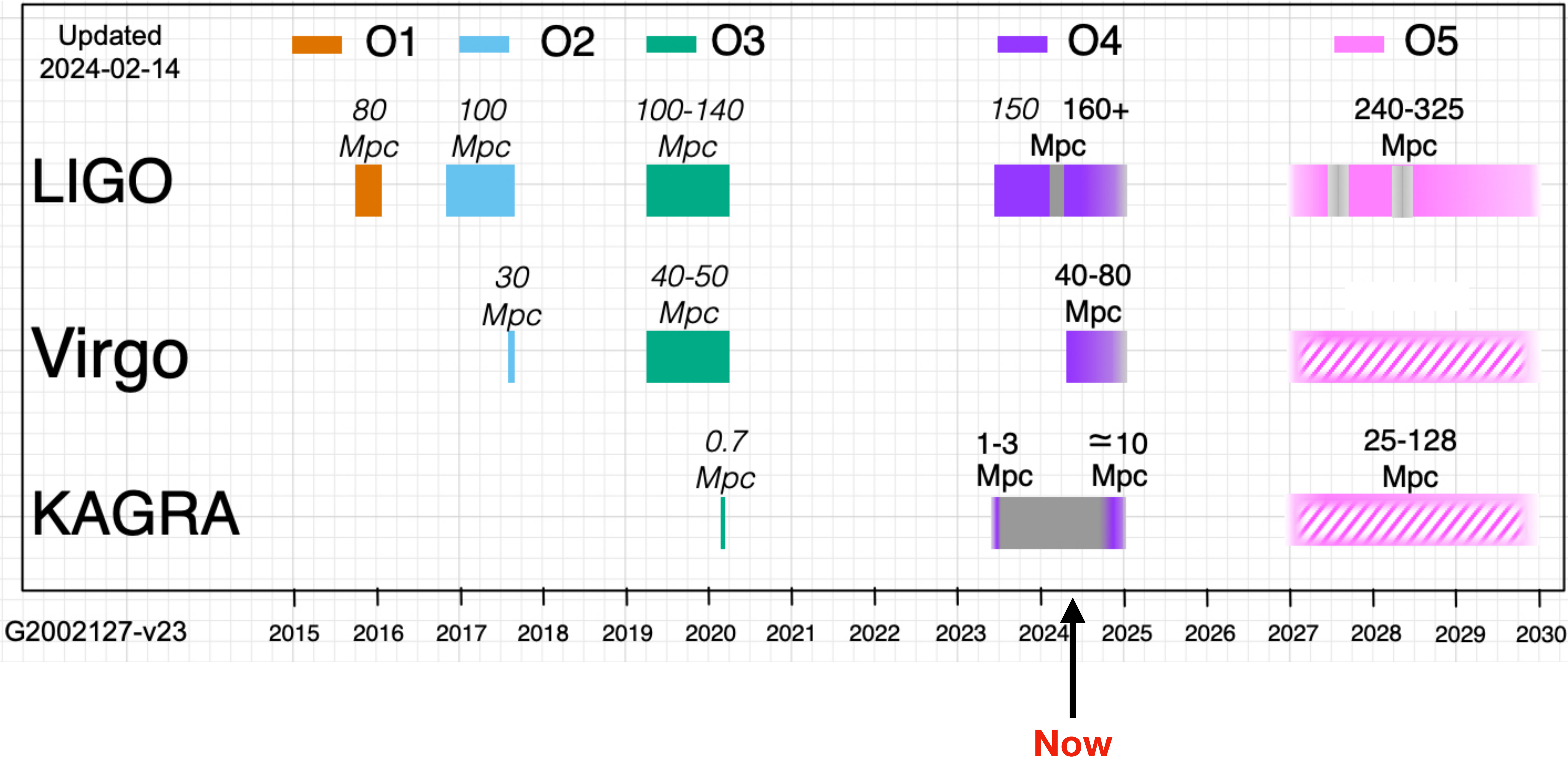


h is a strain: ΔL/L

Second generation GW detector network



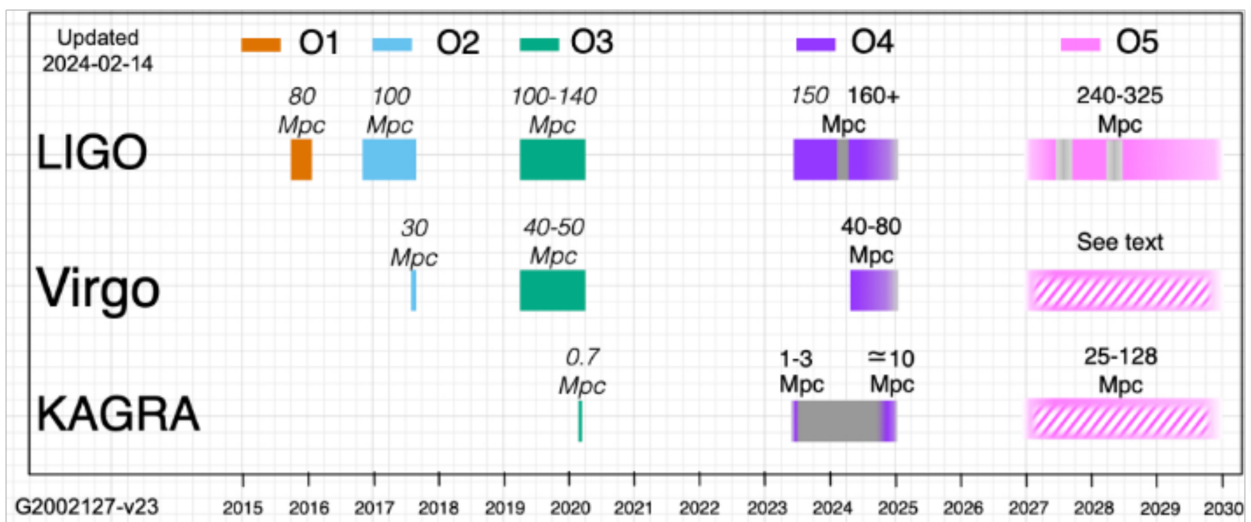
Network observing plan



* From O3 real-time alerts are sent to astronomers in order to search for counterparts gracedb.ligo.org

Network observing plan

Current infrastructures



First detection

90 sources

~180 sources

LIGO upgrade A#

Virgo nEXT

KAGRA upgrade

2030's

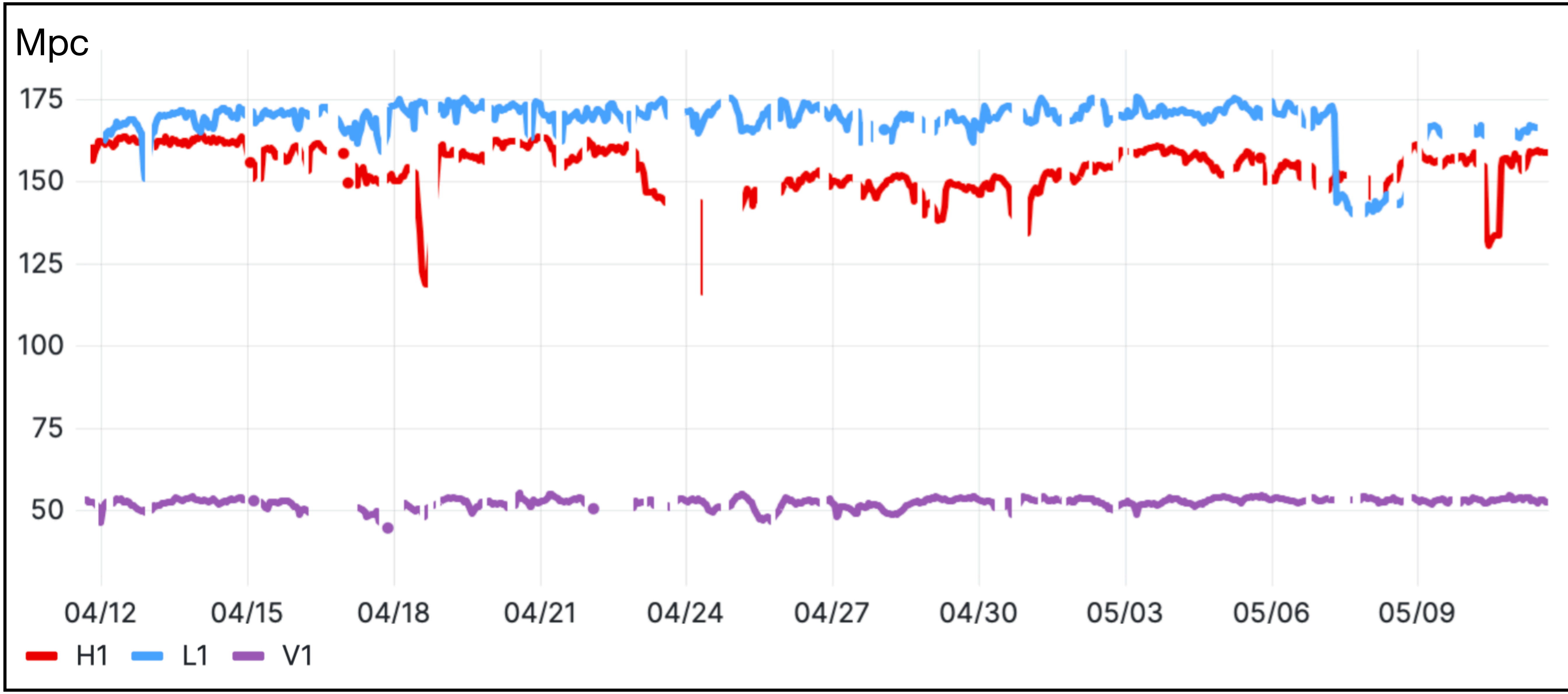
New infrastructures

Cosmic Explorer

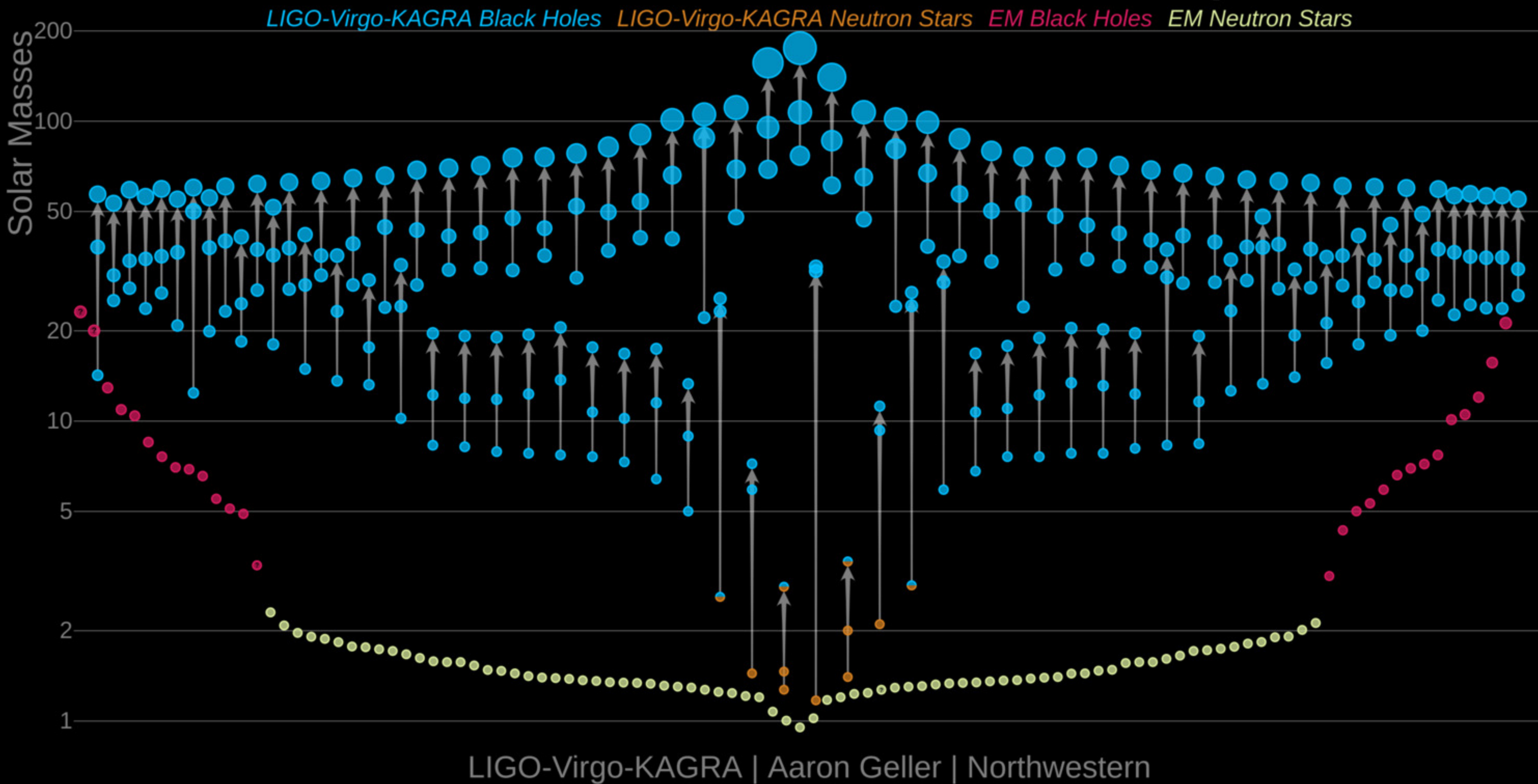
Einstein Telescope

Flight before end of 2030' decade

Network sensitivity in the last month

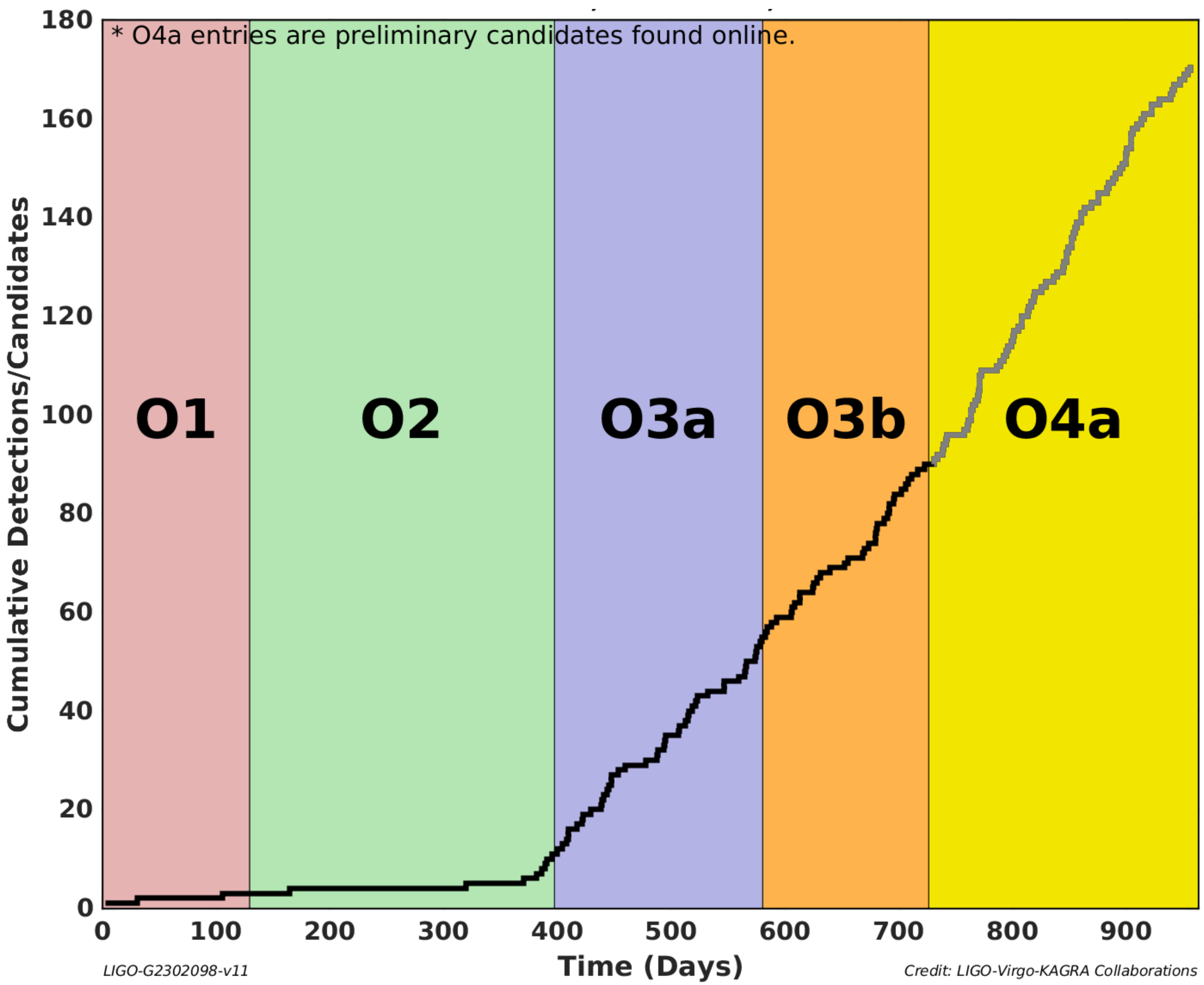


Masses in the Stellar Graveyard



- **Updated to O3**
- **about 90 more candidate event during O4 up to know**

Observations summary



O1-O2 (2015 - 2017)

- 11 detections (10 BBH, 1 BNS)
- GWTC-1 first catalog of GW transient sources (2019)

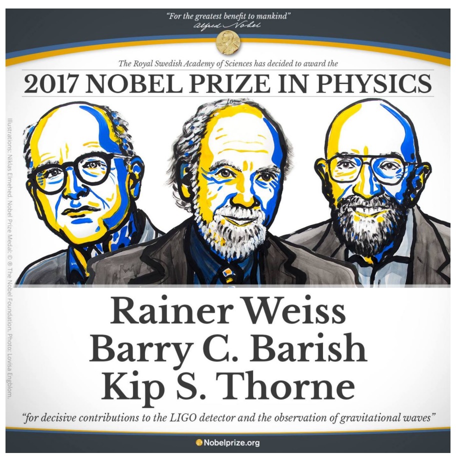
O3a - O3b (2019-2020)

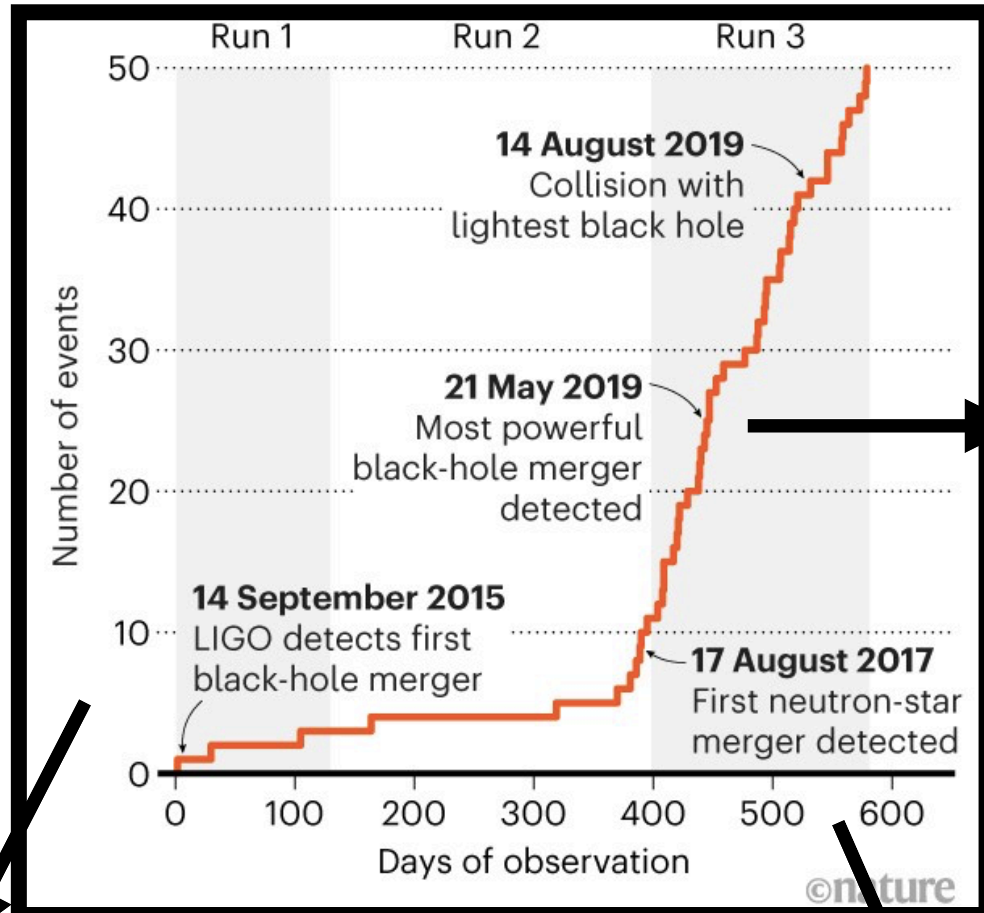
- 79 detections
- GWTC-2 (2020)
- GWTC-3 (2021)

O4a -O4b (2023-2025)

- 92 GW candidates so far

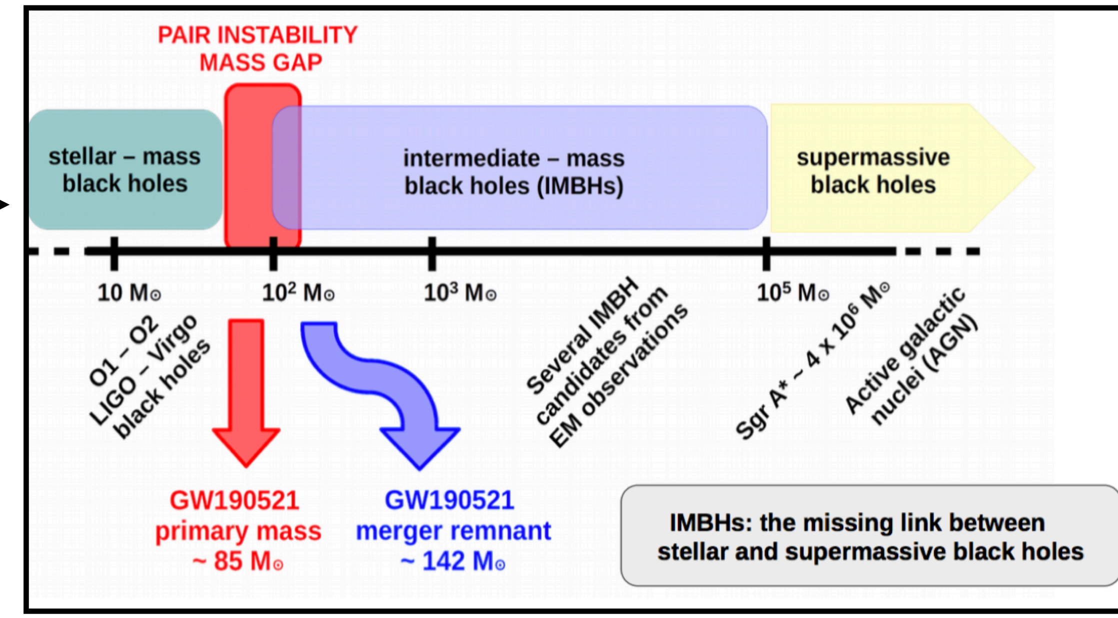
Few remarkable detections in O3



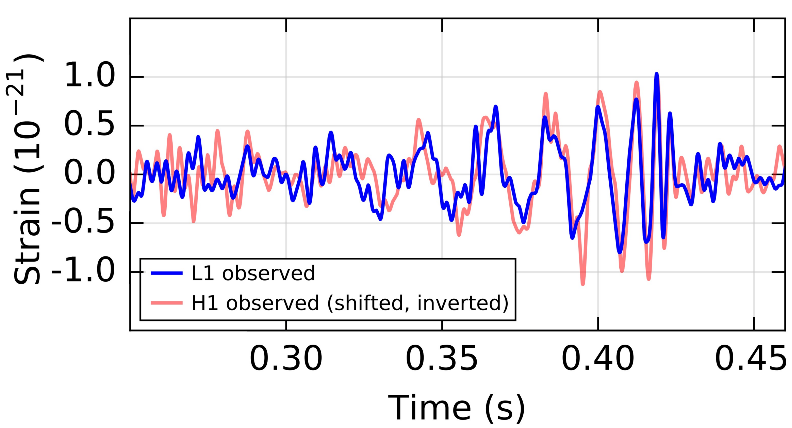


GW210519

First intermediate mass BH observed

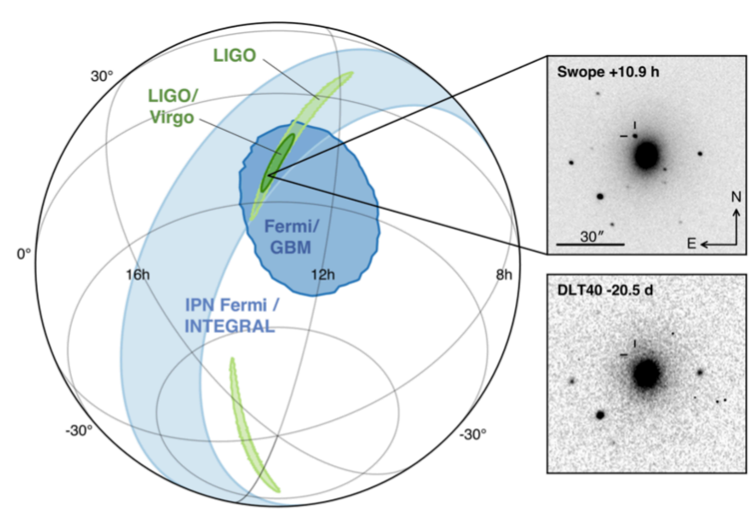


GW150914



GW170817

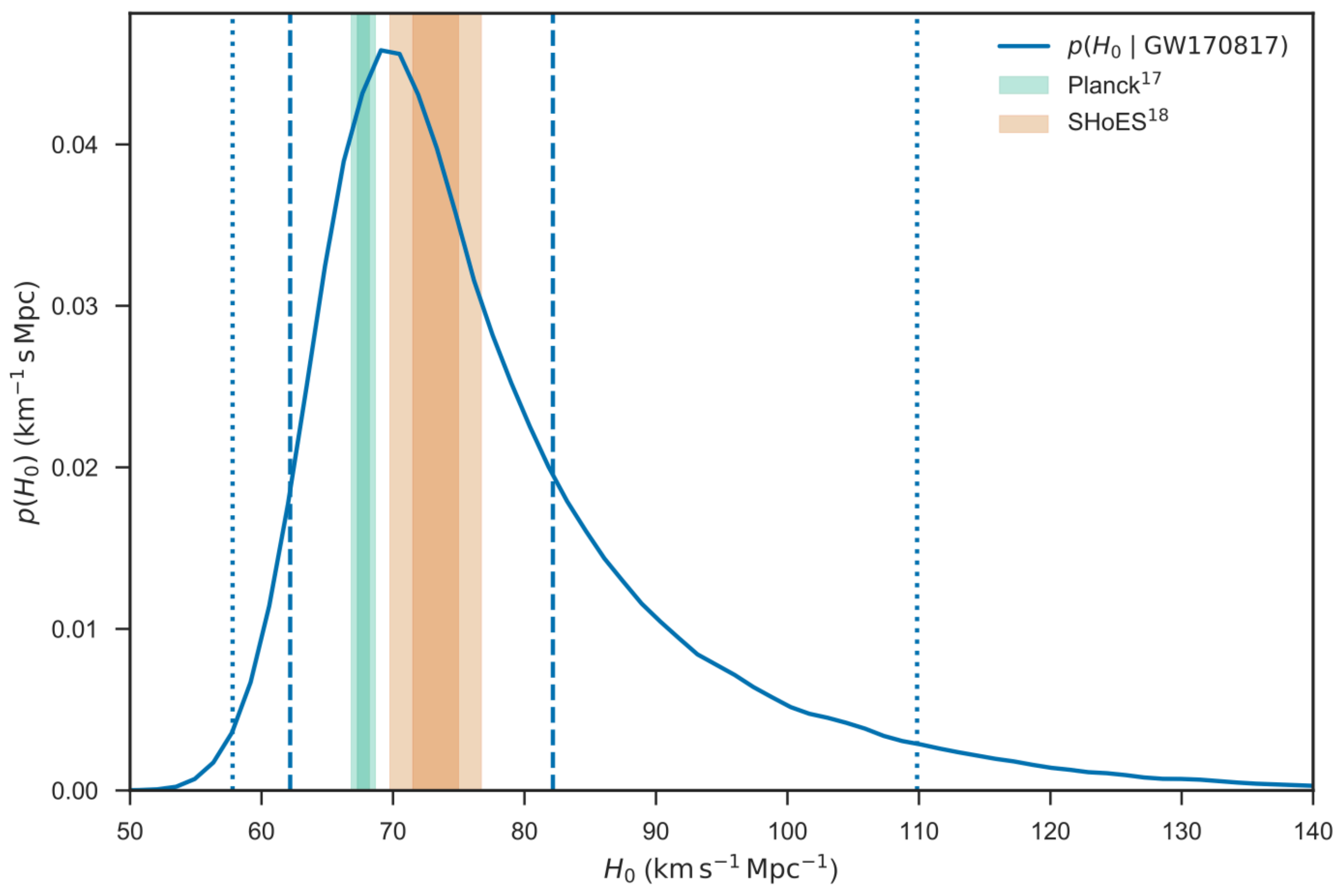
Multimessenger observation



A selection of scientific results from GW observations

- **Fundamental physics**
  - All tests of GR in the strong field regime passed
  - A range of constraints on alternative theories of gravitation

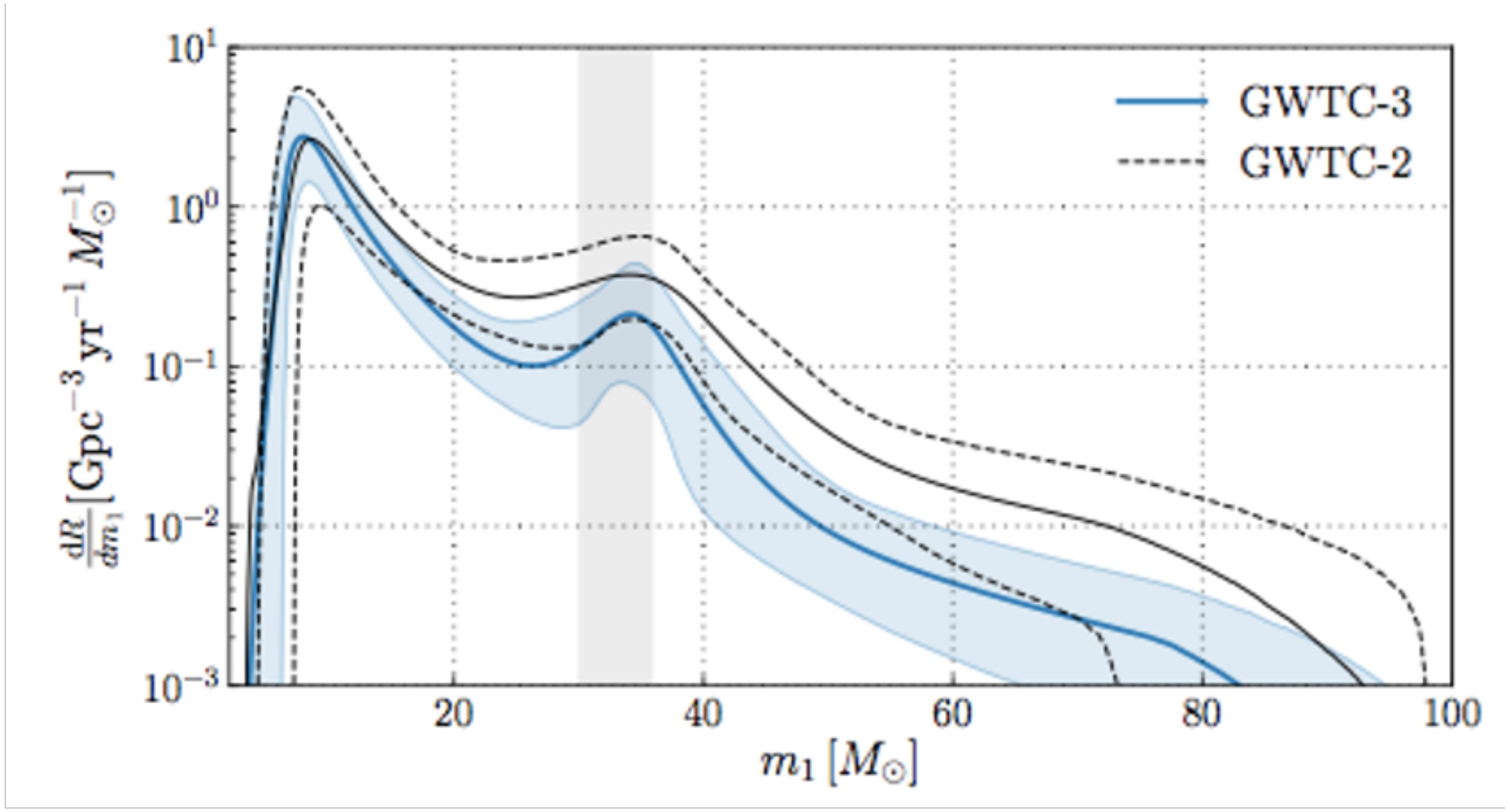
- **Cosmology**
  - Independent measurement of the Hubble constant



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

A selection of scientific results from GW observations

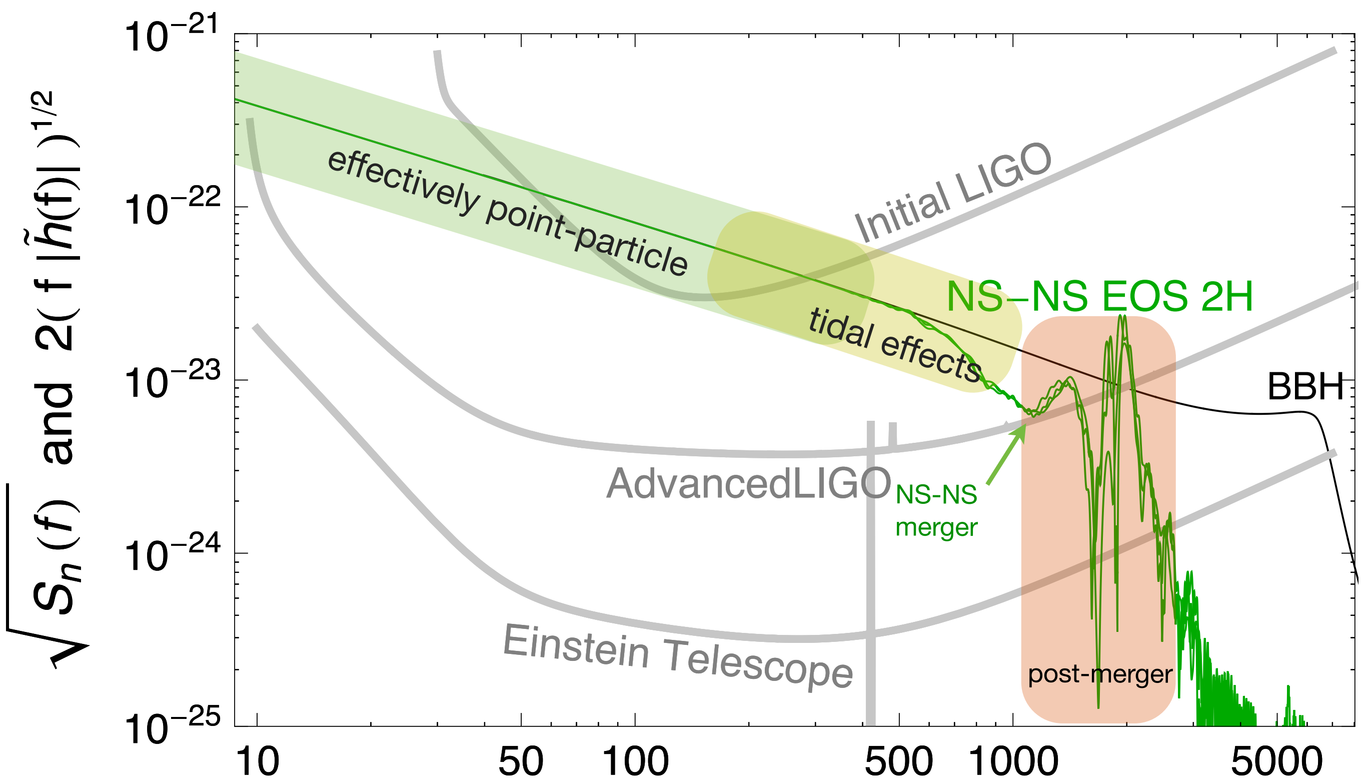
- **Astrophysics**
  - Properties of compact star binaries: mass and spin distribution, rate and populations
  - First observation of an intermediate mass black hole
  - Association of short gamma-ray bursts with binary neutron star merger



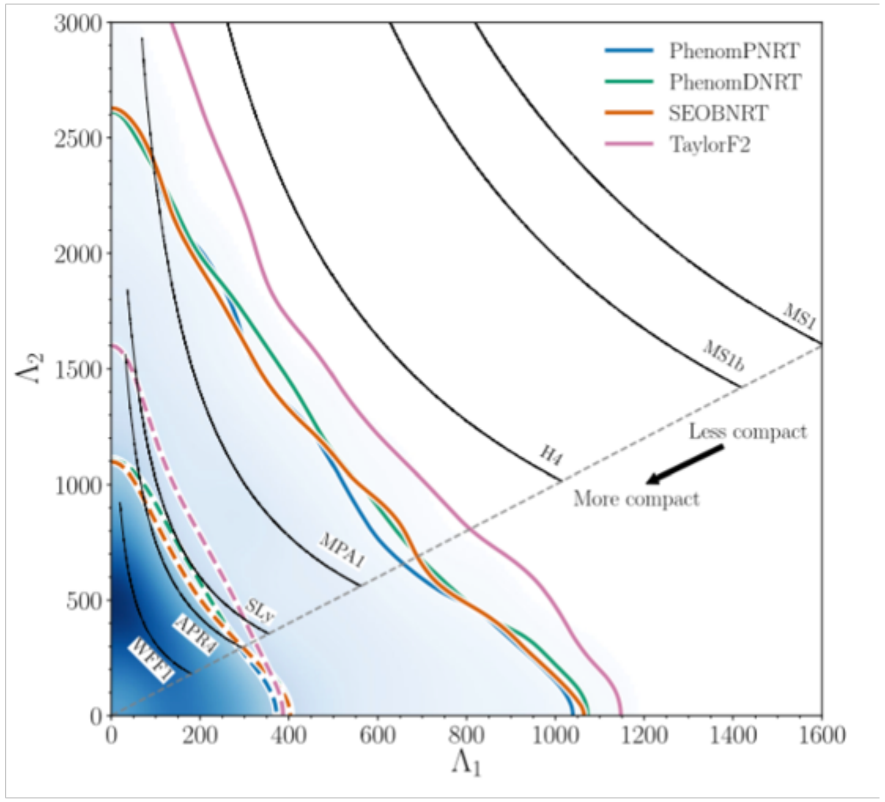
The population of merging compact binaries inferred using gravitational waves through GWTC-3, LIGO/Virgo/KAGRA Collaborations, arXiv:2111.03634

A selection of scientific results from GW observations

- **Nuclear and dense matter physics**
  - Indication on the origin of the heavy elements
  - Constraints on the equation of state of neutron stars

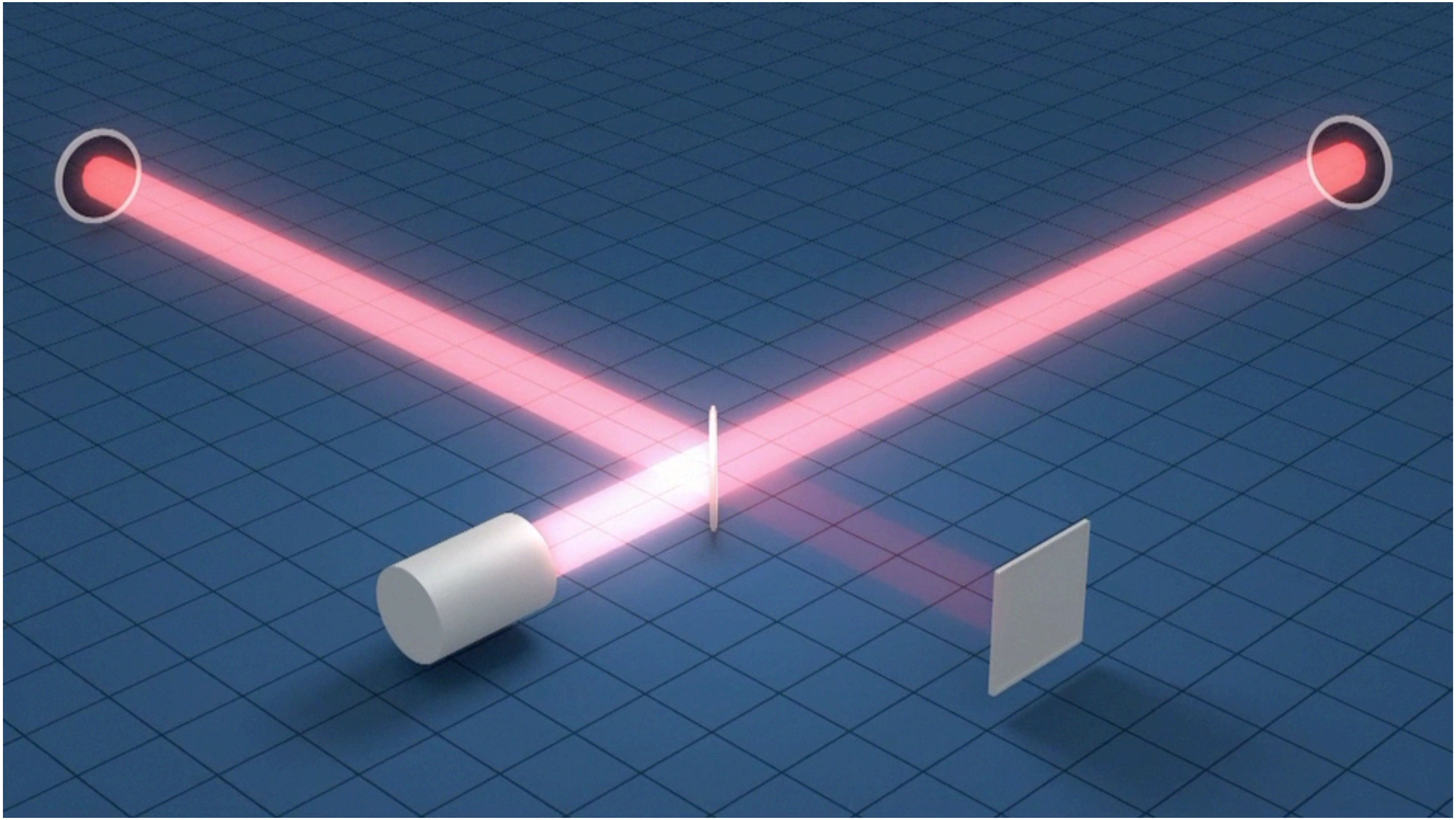


credit:J.Read



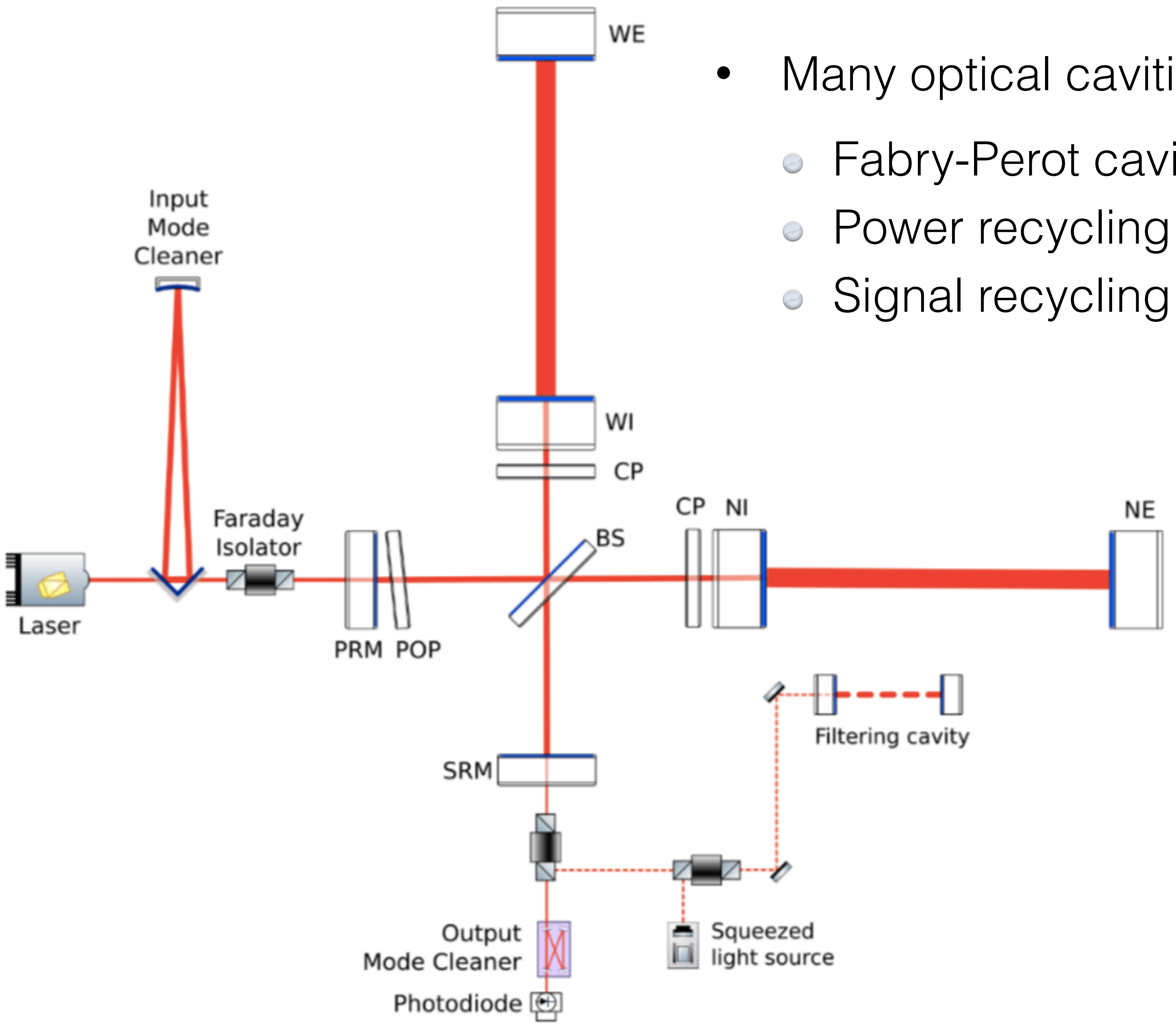
Measurements of Neutron Star Radii and Equation of State, Phys. Rev. Lett. 121, 161101 (2018)

Detection principle: Michelson interferometers



Link to the video: https://www.ligo.caltech.edu/video/ligo20160211v6

Modified Michelson interferometers



- Many optical cavities to improve the performances
  - Fabry-Perot cavities in the arms
  - Power recycling
  - Signal recycling

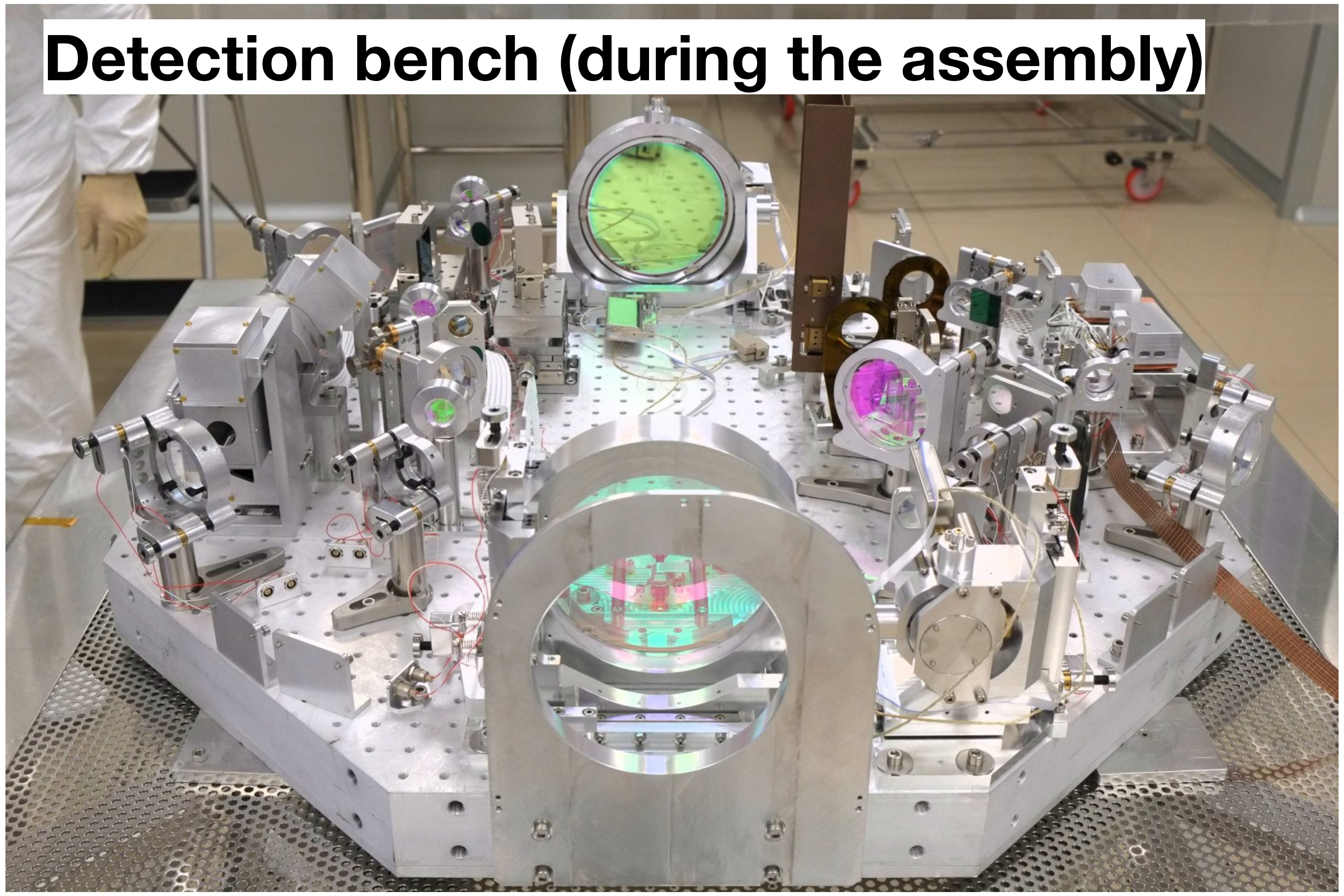
- .. and also
  - input mode cleaner
  - output mode cleaner
  - squeezing filter cavity

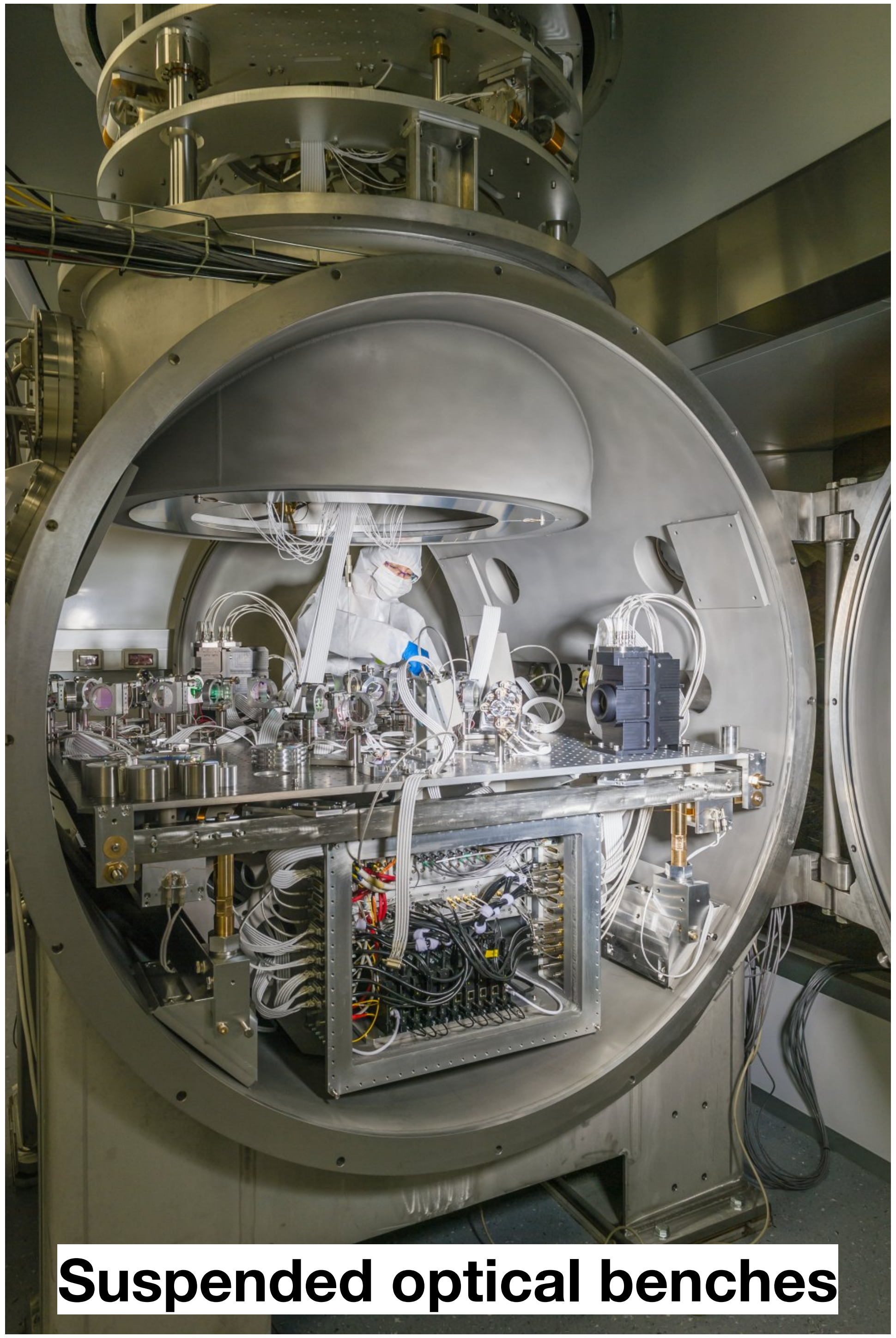
AdVirgo optical scheme

The vacuum system

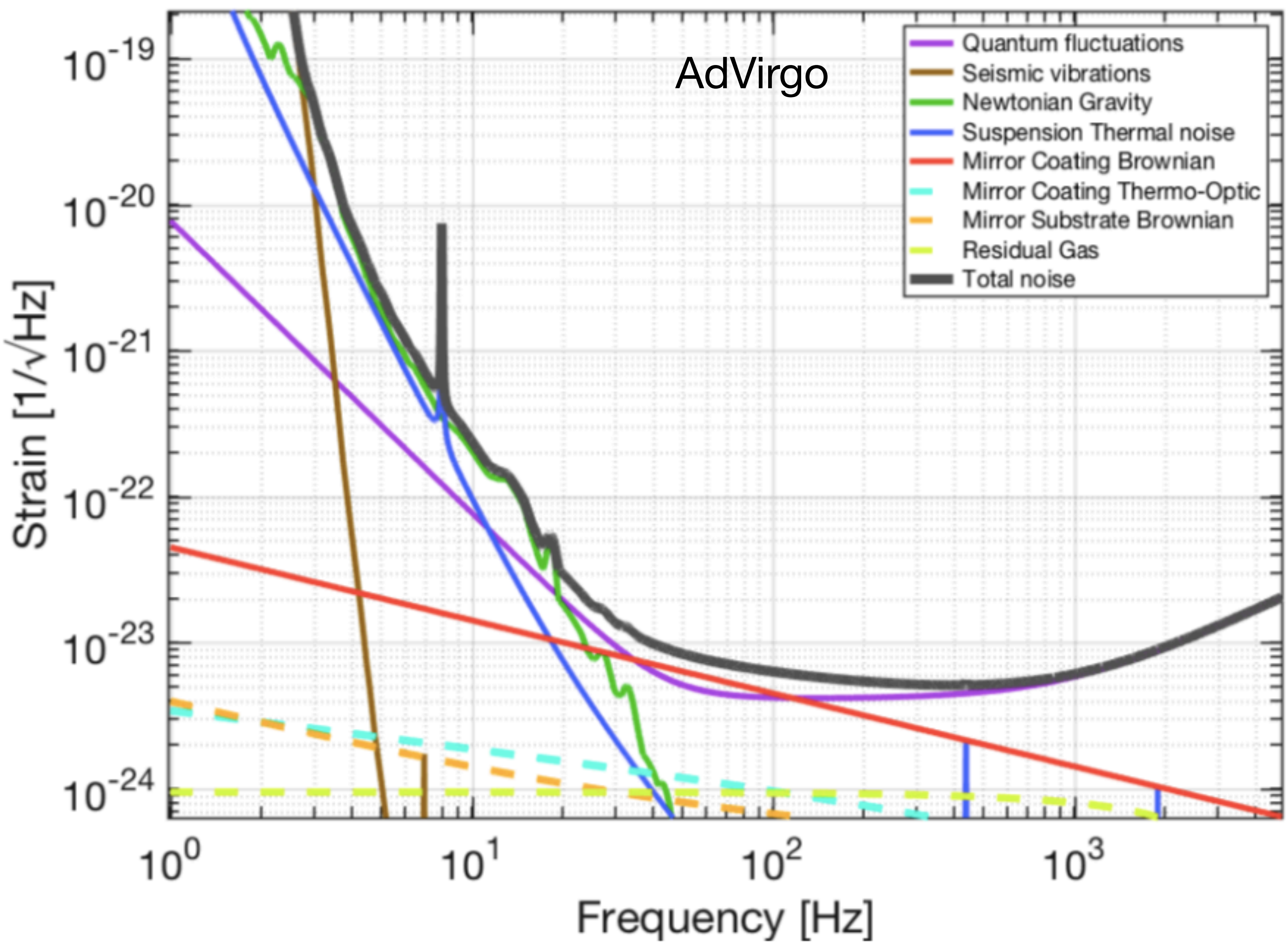
- Virgo is the largest ultra-high vacuum installation in Europe, with a total volume of 6.800 m^3
- In the two 3 km arms (1.2 m in diameter) the residual pressure is about 10^{-9} mbar


High power laser Nd-Yag 1064 nm


Detection bench (during the assembly)

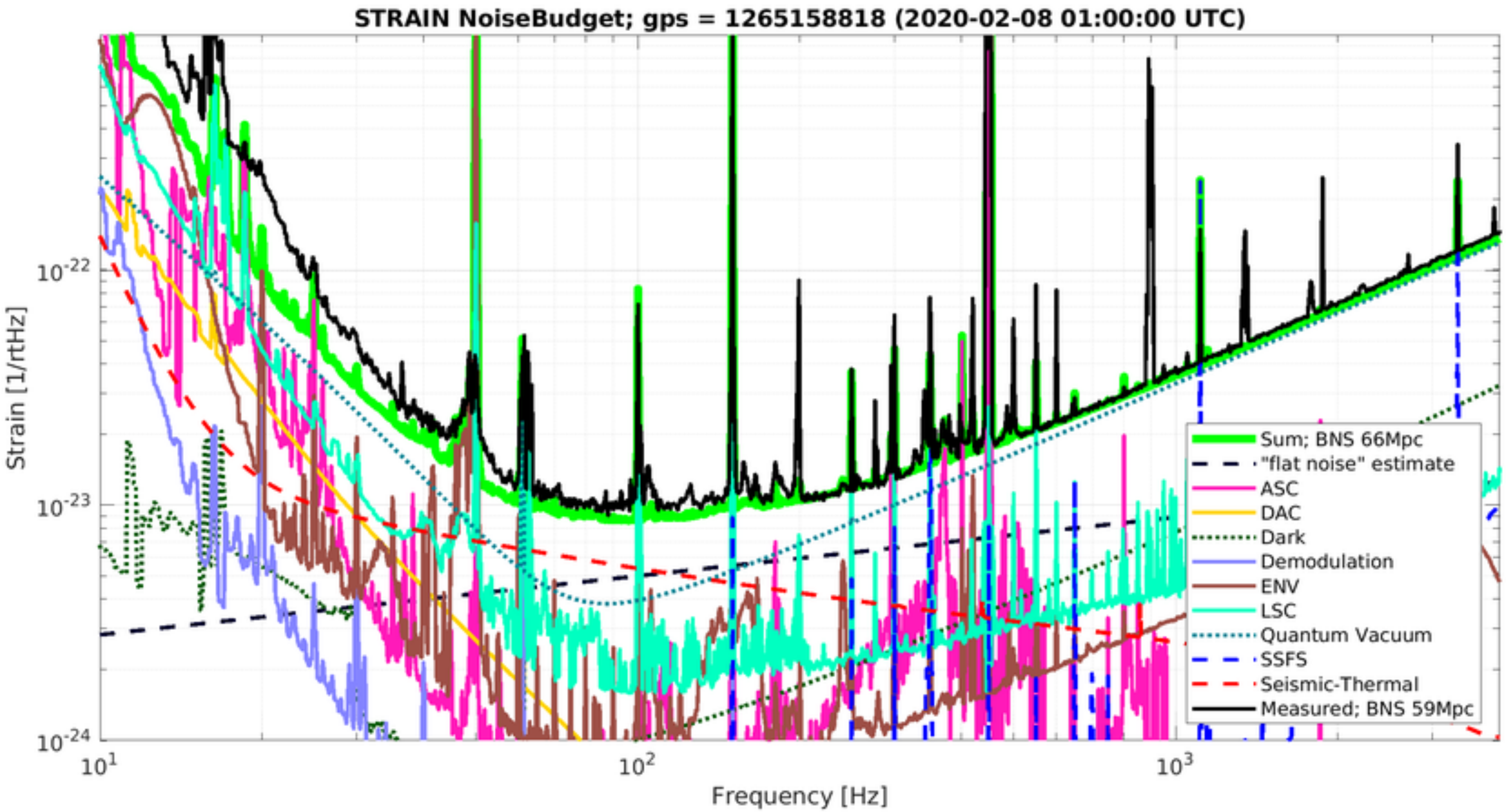

Suspended optical benches

GW detector noise budget



- Only fundamental noises considered here

The real sensitivity

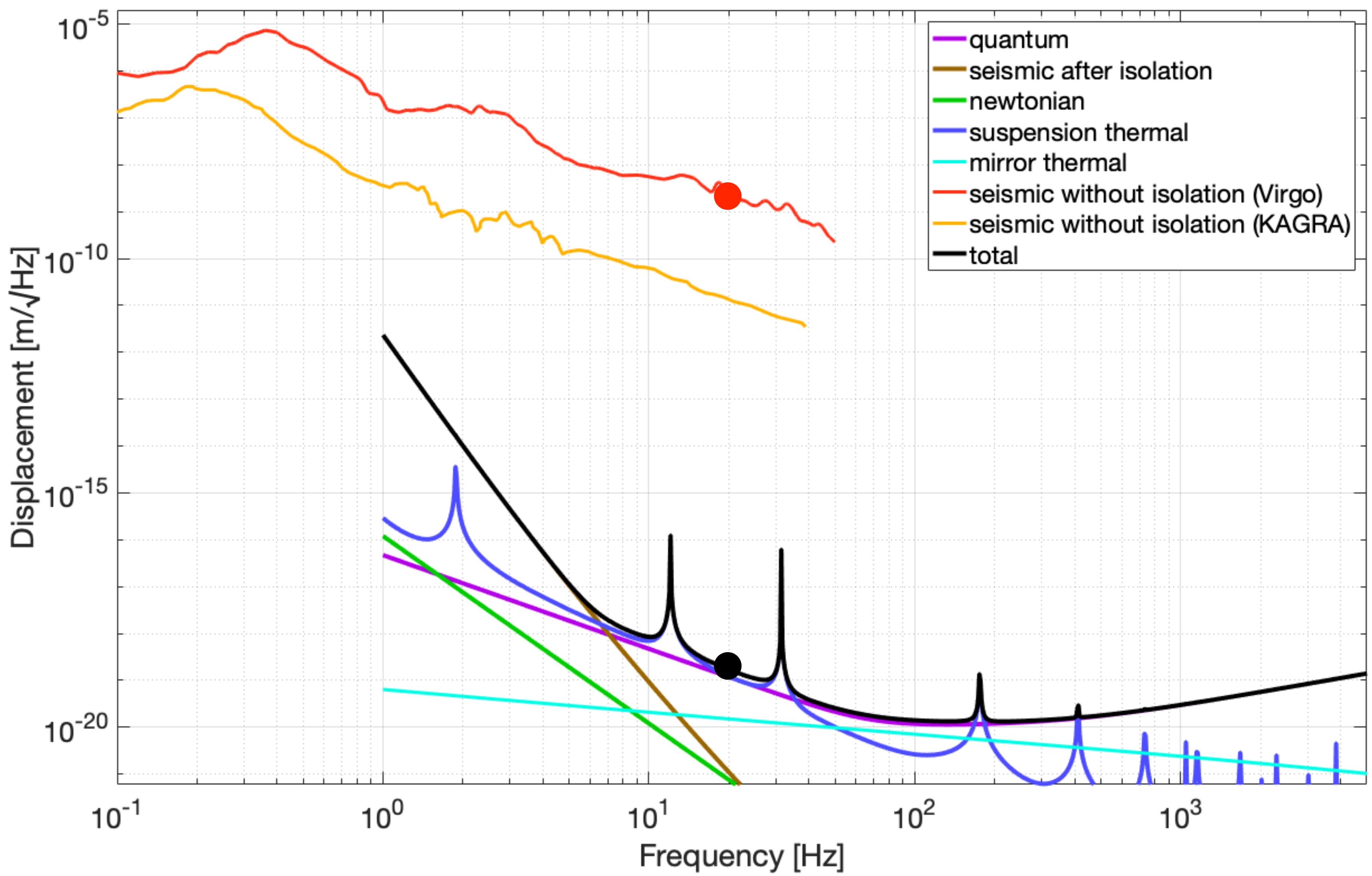


Seismic noise isolation requirement

- Seismic motion at ~20 Hz: ~ 10^{-9} m/√Hz
- Required mirror motion at ~20 Hz: ~ 10^{-19} m/√Hz

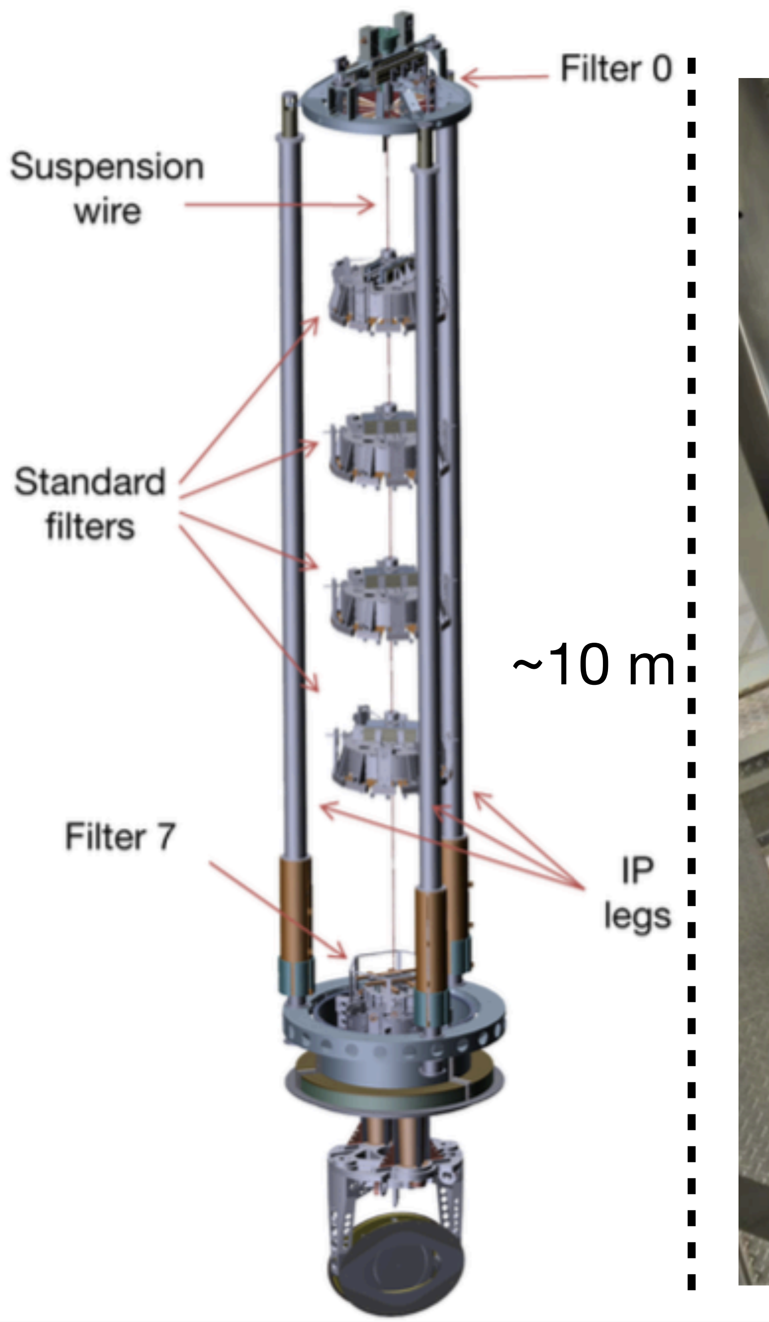
↓

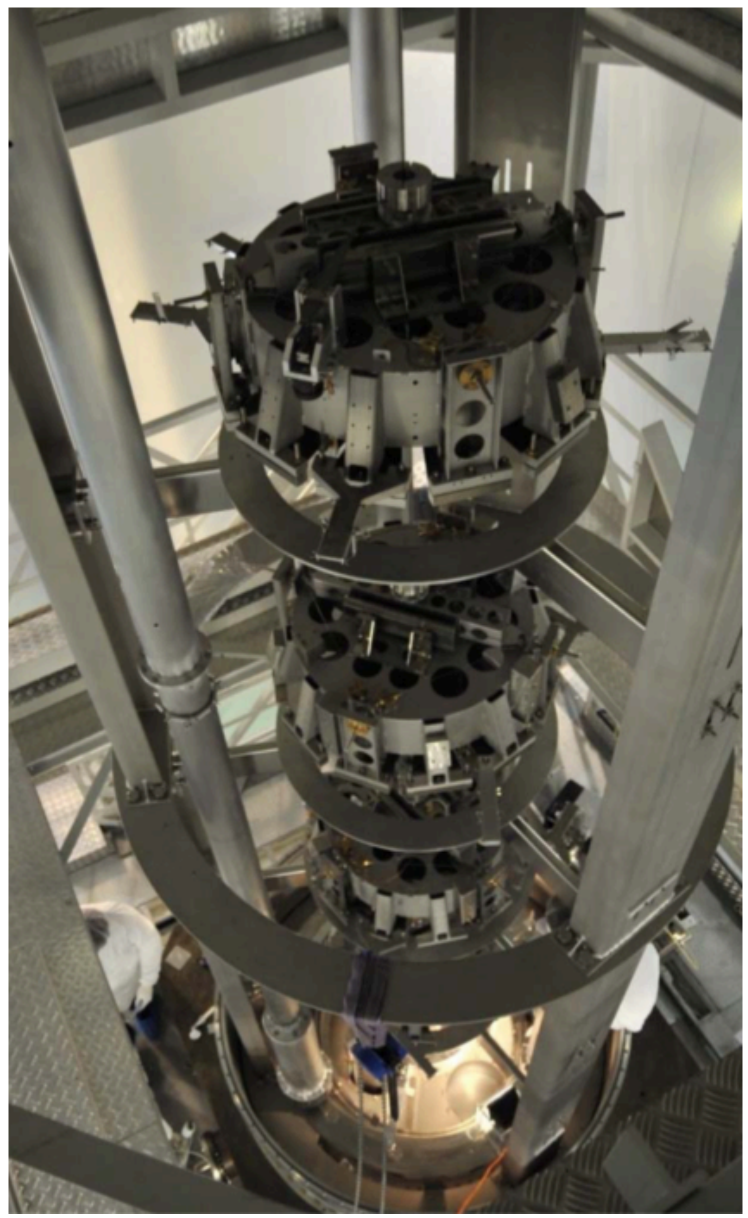
A high performance vibration isolation system is required (at least 10 order of magnitudes)

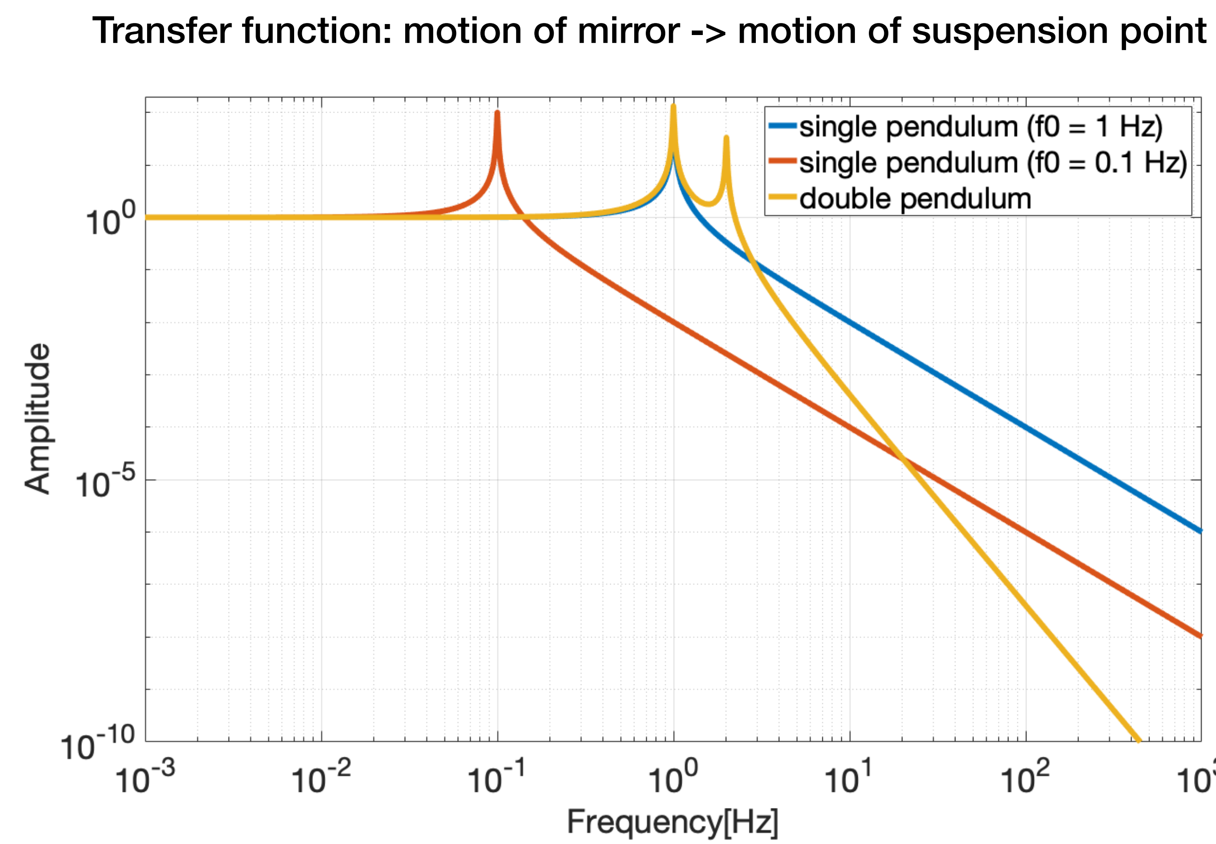


How to isolate mirrors from ground vibrations?

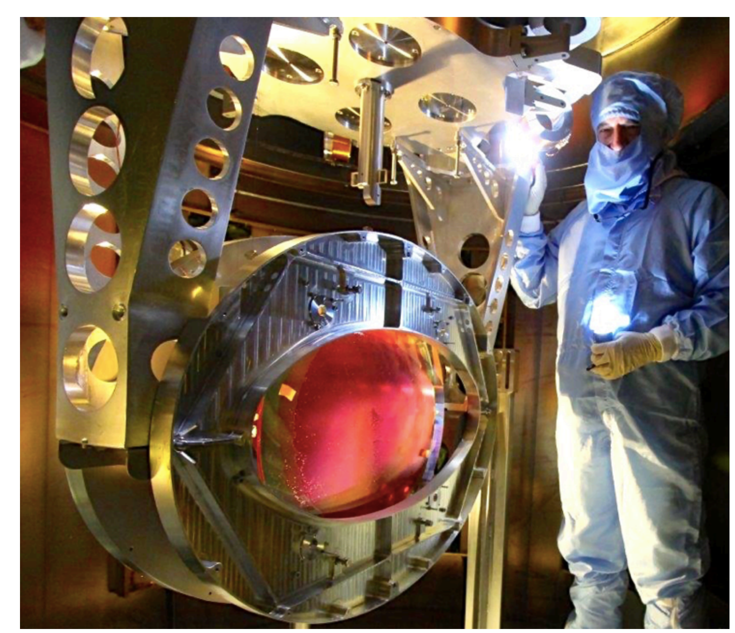
- System based on a chain of pendulums to isolate the test mass from the vibration of their suspension point





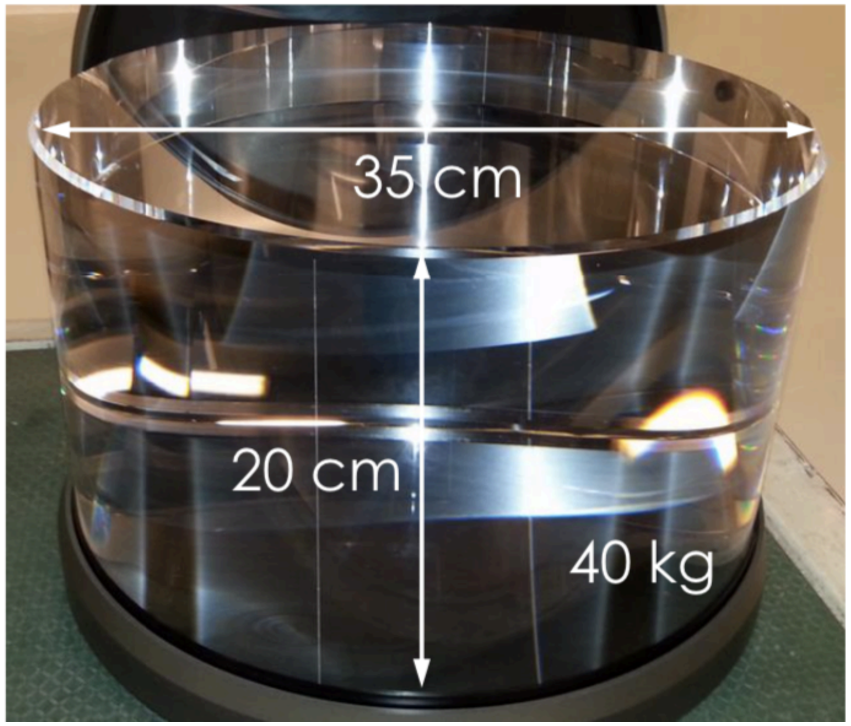


AdVirgo

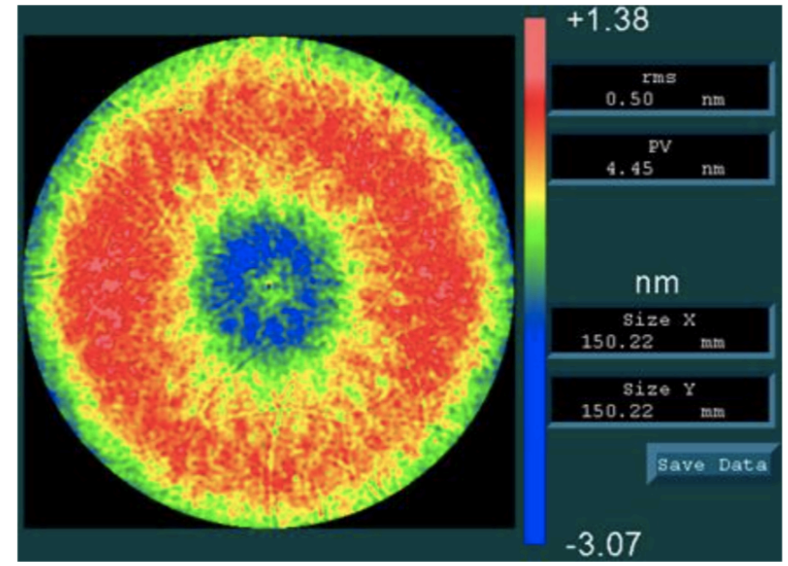


Mirrors

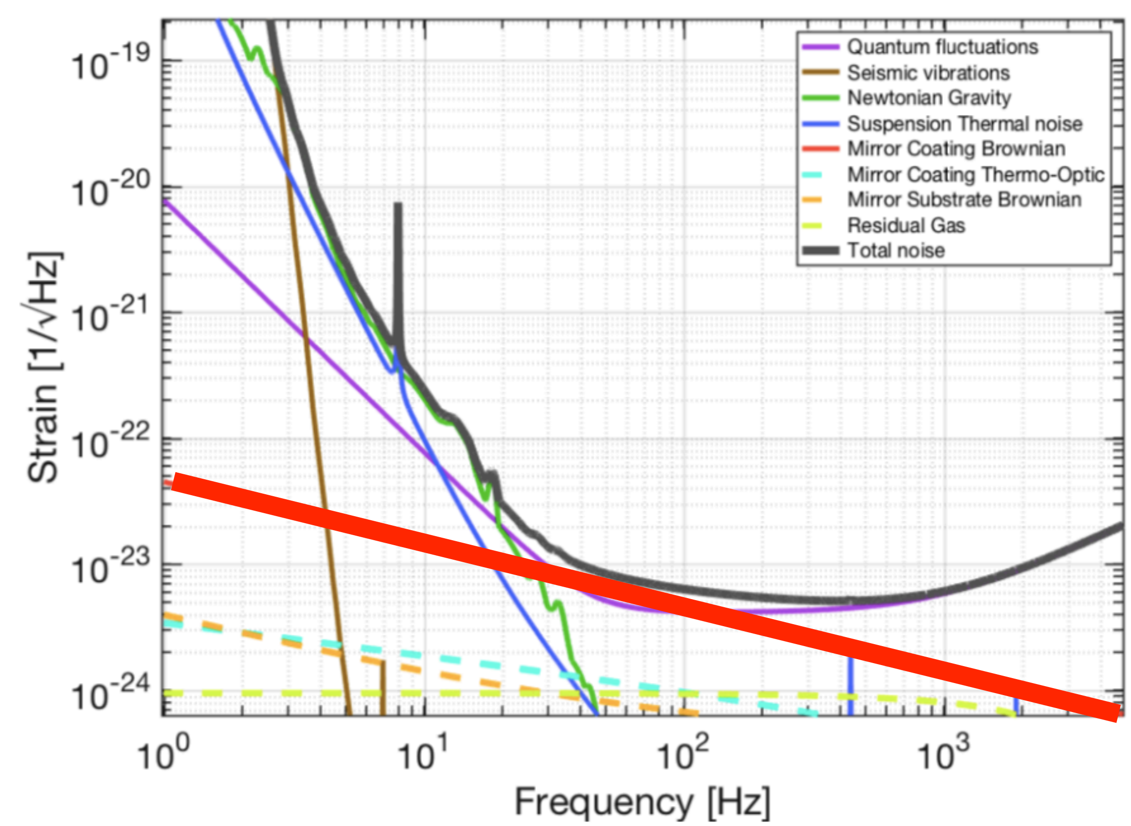
- Substrates: ultra-pure fused silica



- Extremely small roughness (<0.5 nm rms)



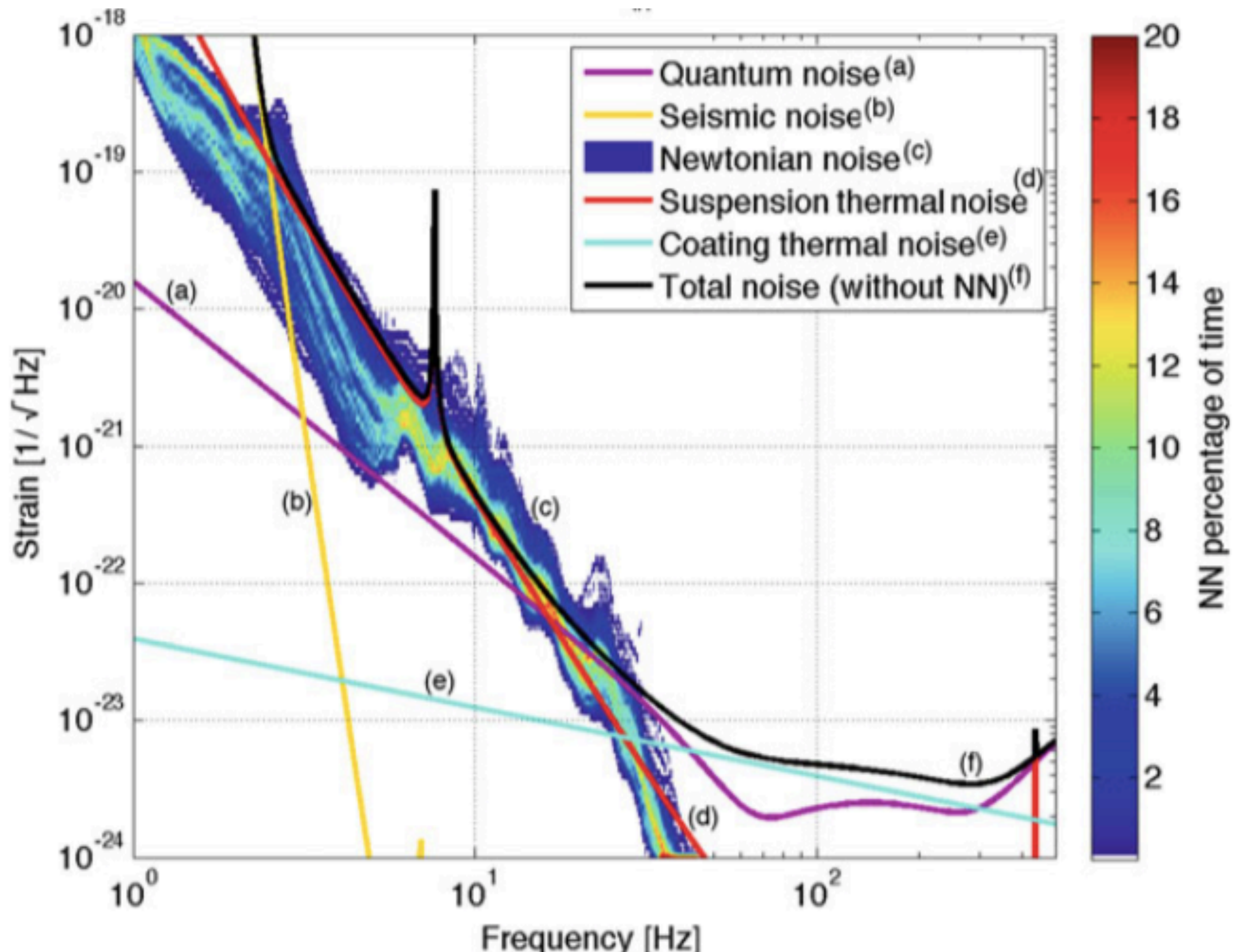
- Coatings
  - Multilayers of titania-doped tantala/silica
  - Main responsible for mirror thermal noise
  - Long term effort to find more performant materials



Newtonian noise

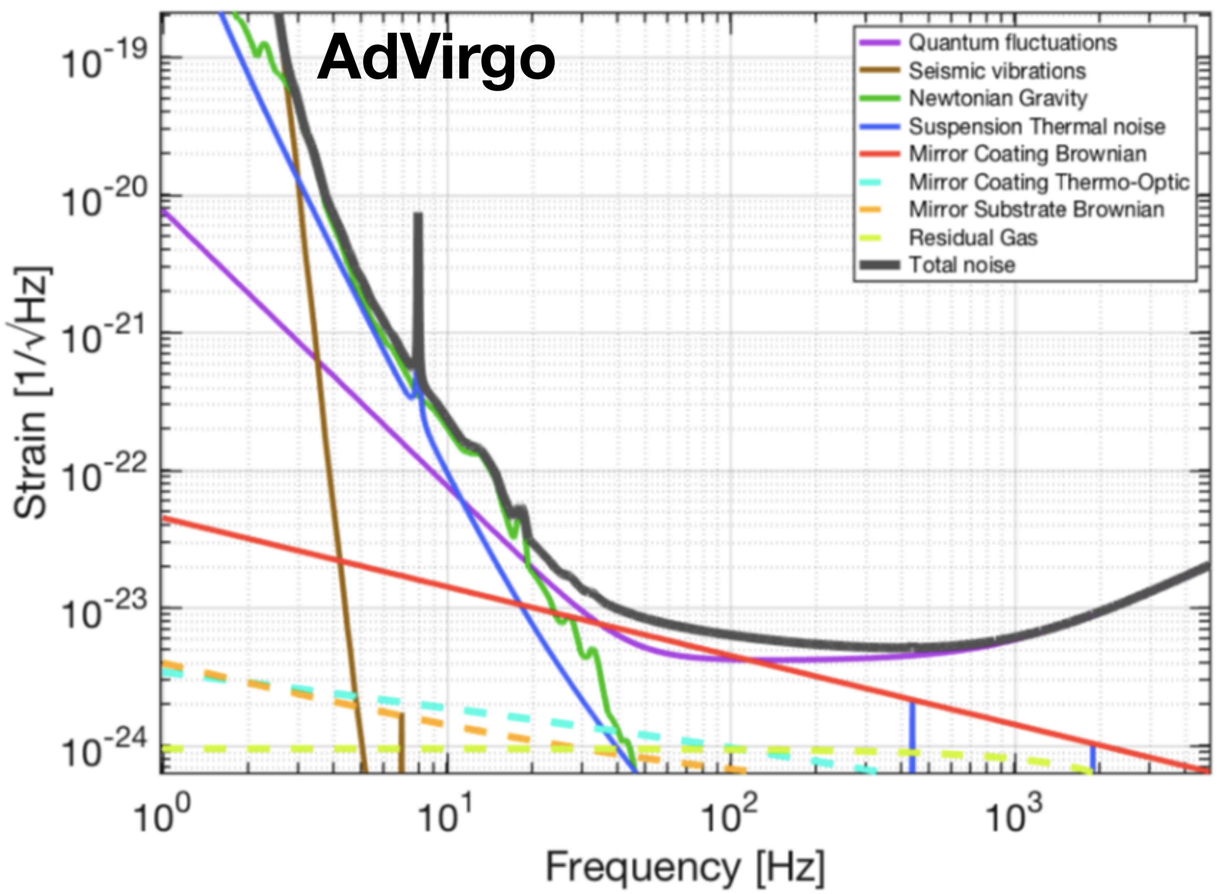
Due to fluctuations of the terrestrial gravity field

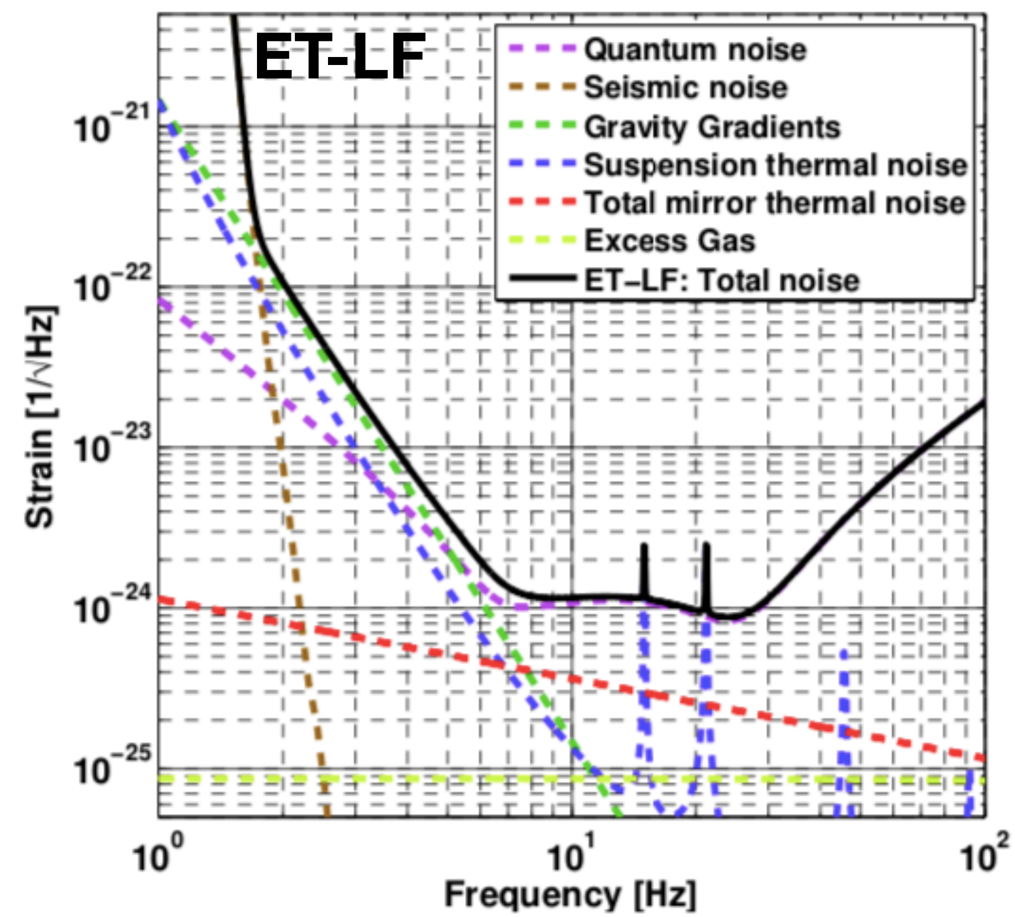
- Mainly produced by density perturbation in the ground (due to seismic waves) or in the atmosphere
- It couples directly to the mirrors, bypassing any isolation system
- It is expected to limit low frequency sensitivity
- Cancellation techniques recently implemented



Quantum noise

- Main limiting noise of current and future GW detectors

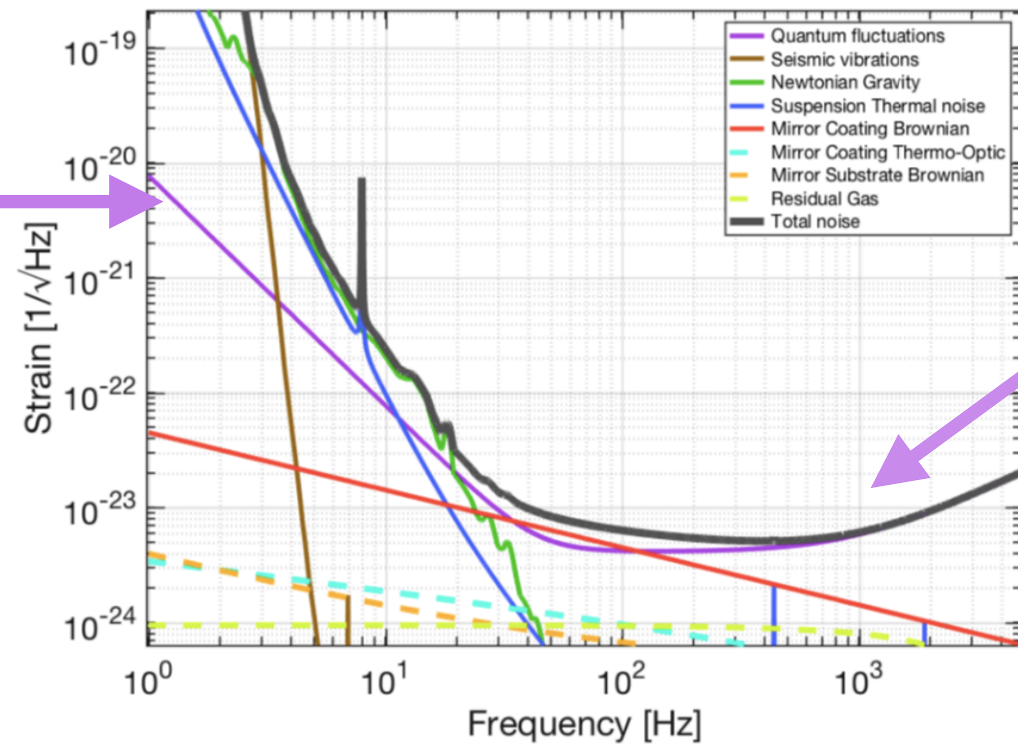




- Intrinsic limitation of the interferometric measurements

Quantum noise: a semiclassical picture

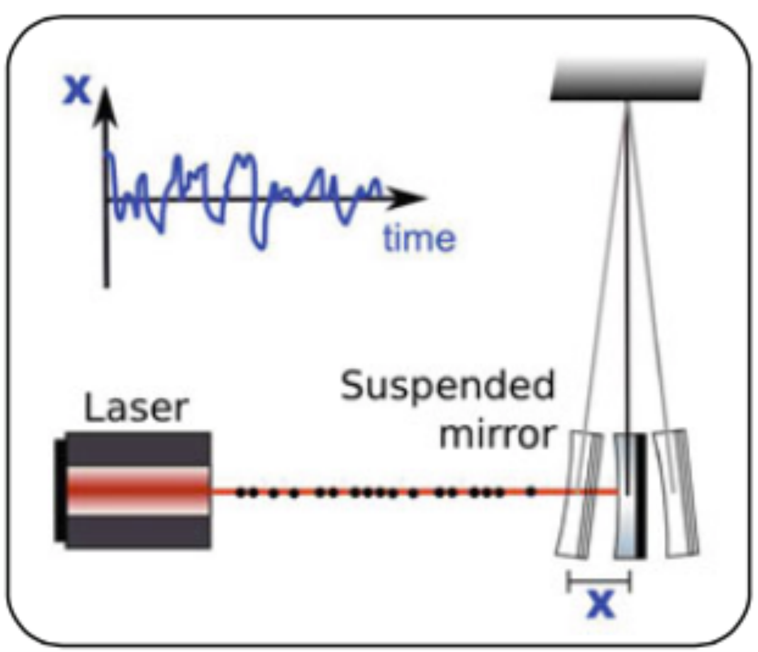
Radiation pressure noise

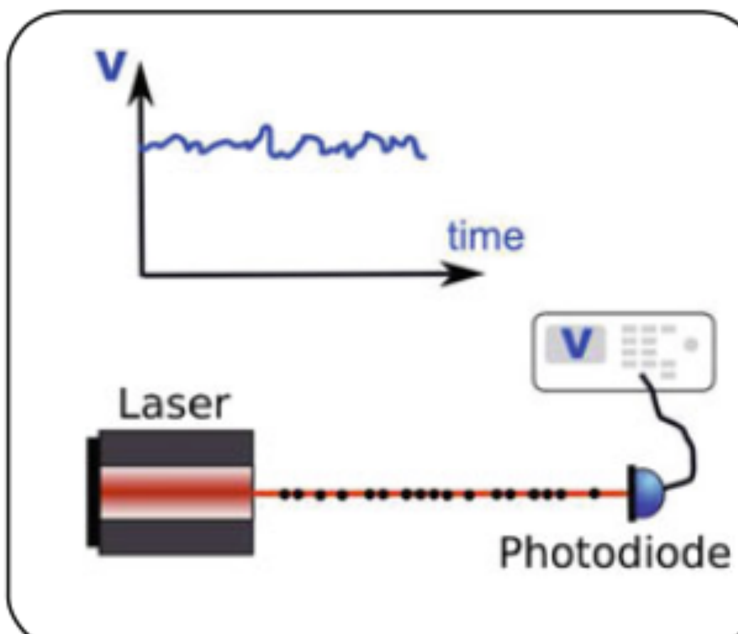


Shot noise

$$h_{\rm rp}(f) = \frac{1}{mf^2L}\sqrt{\frac{\hbar P}{2\pi^3 c\lambda}}$$

$$h_{\rm sn}(f) = \frac{1}{L}\sqrt{\frac{\hbar c\lambda}{2\pi P}}$$



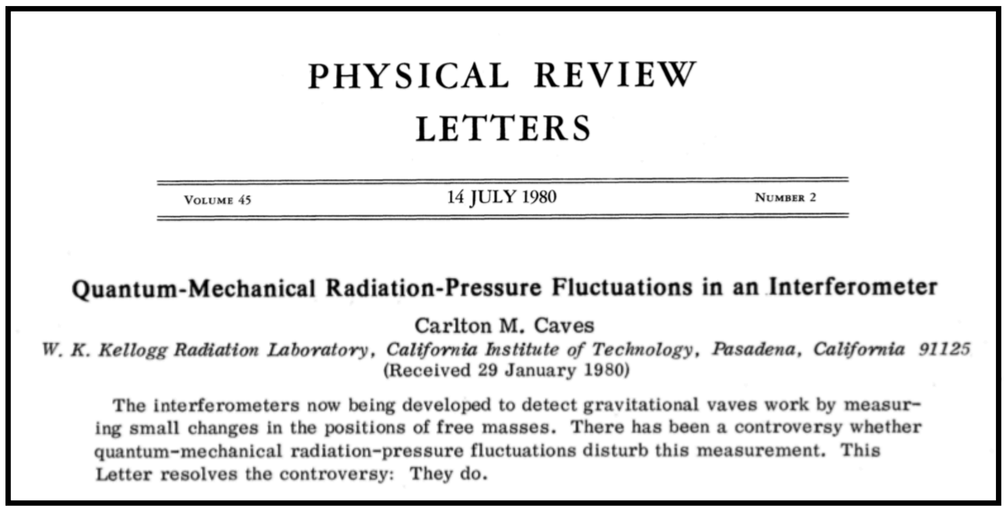


- Fluctuation in the momentum transferred to the mirror

- Poissonian statistics on the photon arrival time

Quantum noise origin

- In the '80 Caves proposes a fully quantum explanation of quantum noise in interferometers



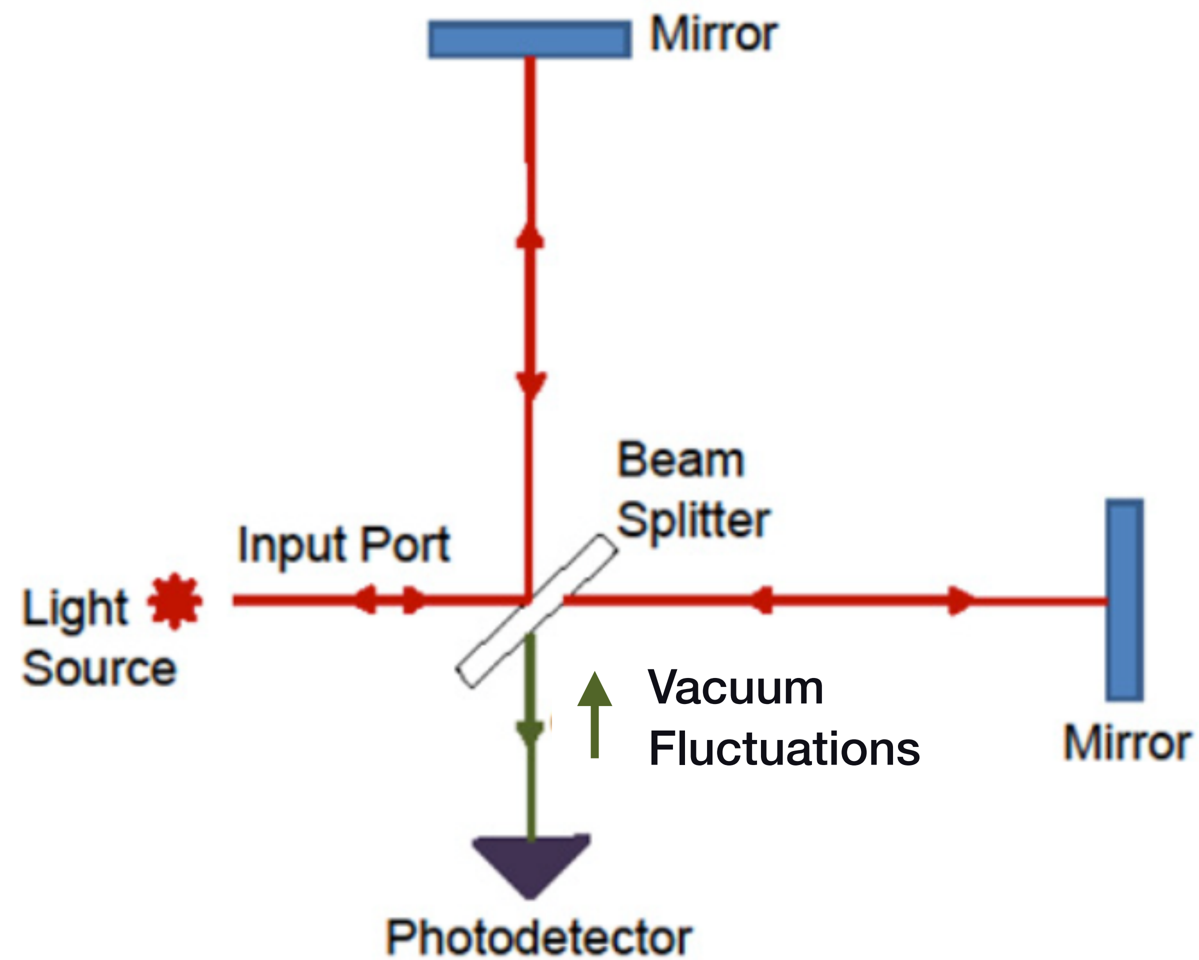
PHYSICAL REVIEW LETTERS

VOLUME 45 | 14 JULY 1980 | NUMBER 2

Quantum-Mechanical Radiation-Pressure Fluctuations in an Interferometer

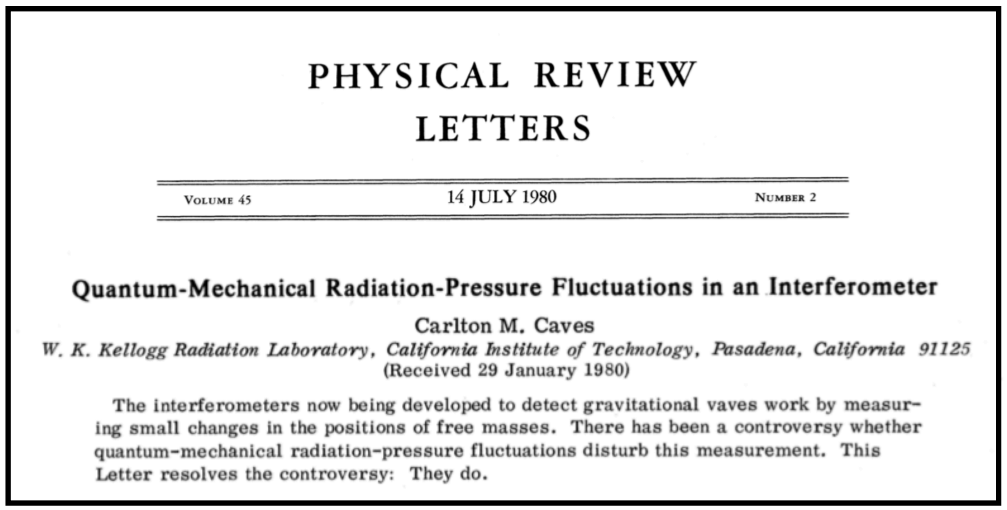
Carlton M. Caves
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125
(Received 29 January 1980)

The interferometers now being developed to detect gravitational vaves work by measuring small changes in the positions of free masses. There has been a controversy whether quantum-mechanical radiation-pressure fluctuations disturb this measurement. This Letter resolves the controversy: They do.



Quantum noise origin

- In the '80 Caves proposes a fully quantum explanation of quantum noise in interferometers



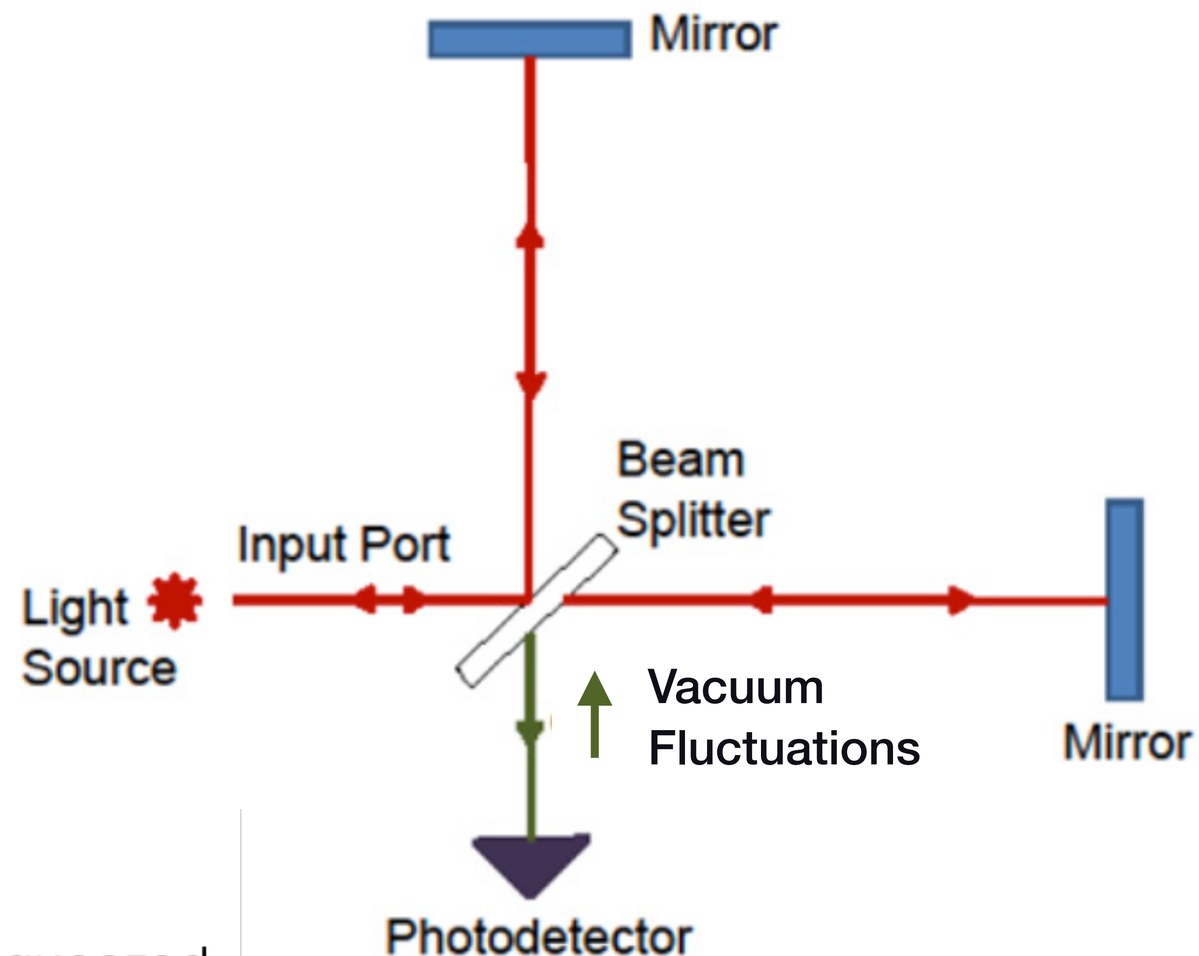
PHYSICAL REVIEW LETTERS

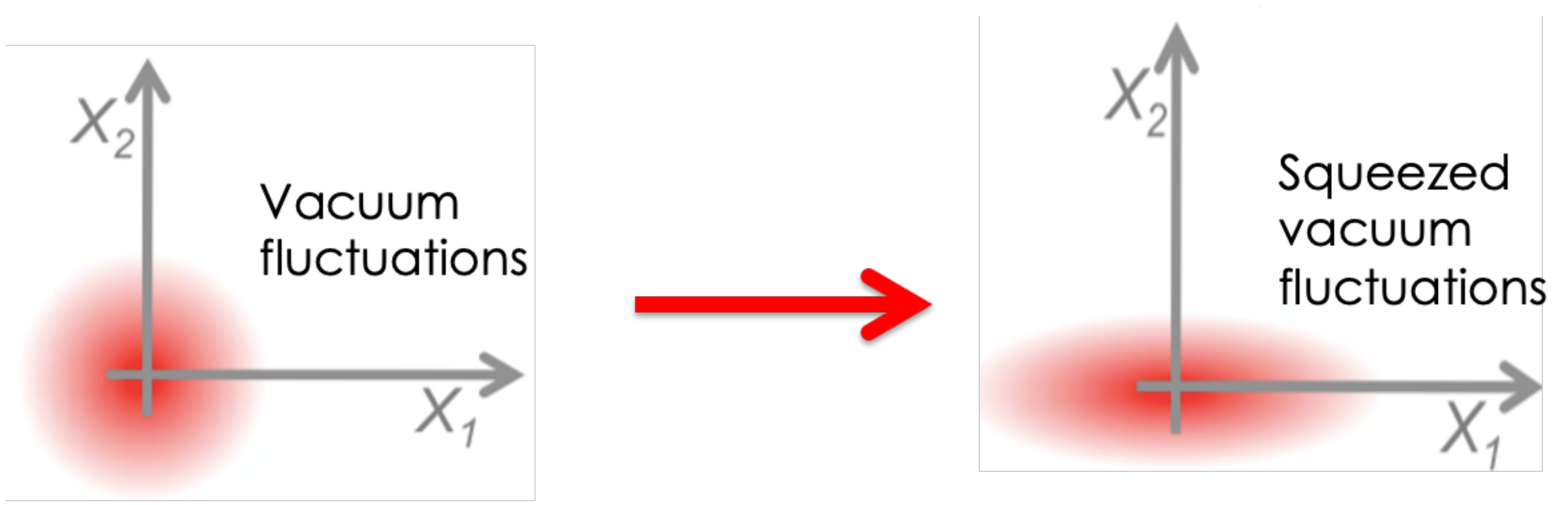
VOLUME 45 | 14 JULY 1980 | NUMBER 2

Quantum-Mechanical Radiation-Pressure Fluctuations in an Interferometer

Carlton M. Caves
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125
(Received 29 January 1980)

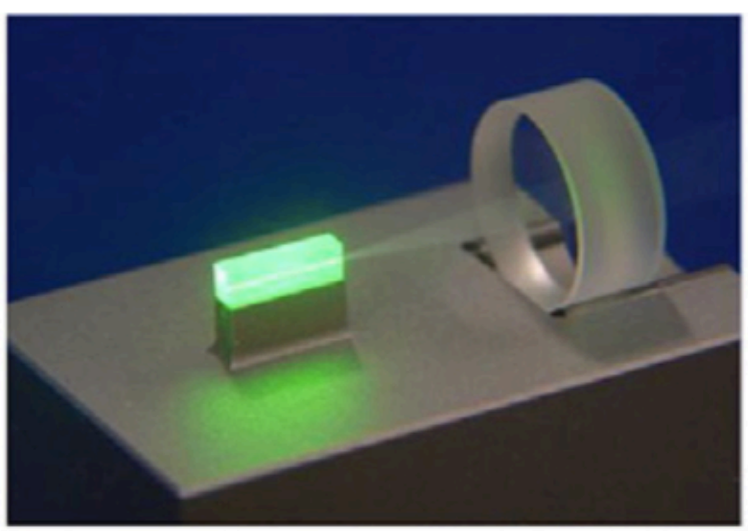
The interferometers now being developed to detect gravitational vaves work by measuring small changes in the positions of free masses. There has been a controversy whether quantum-mechanical radiation-pressure fluctuations disturb this measurement. This Letter resolves the controversy: They do.

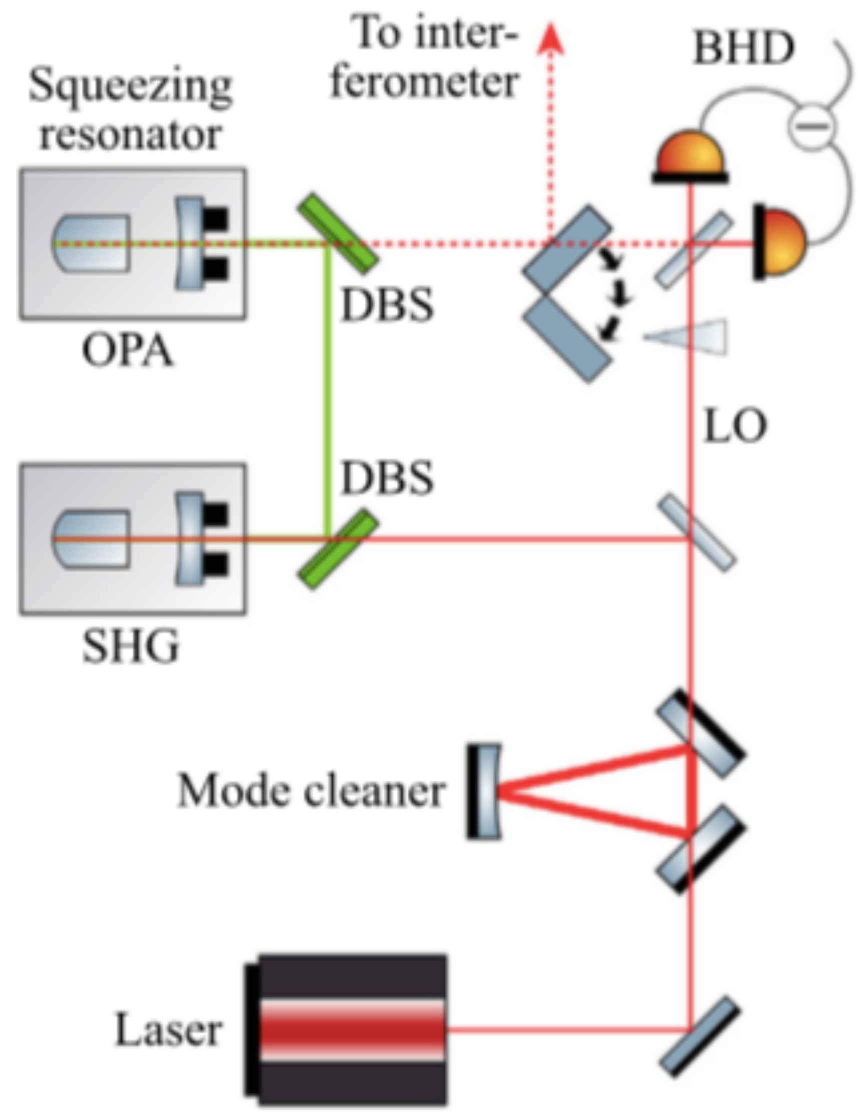




How to generate a squeezed state: non linear interaction

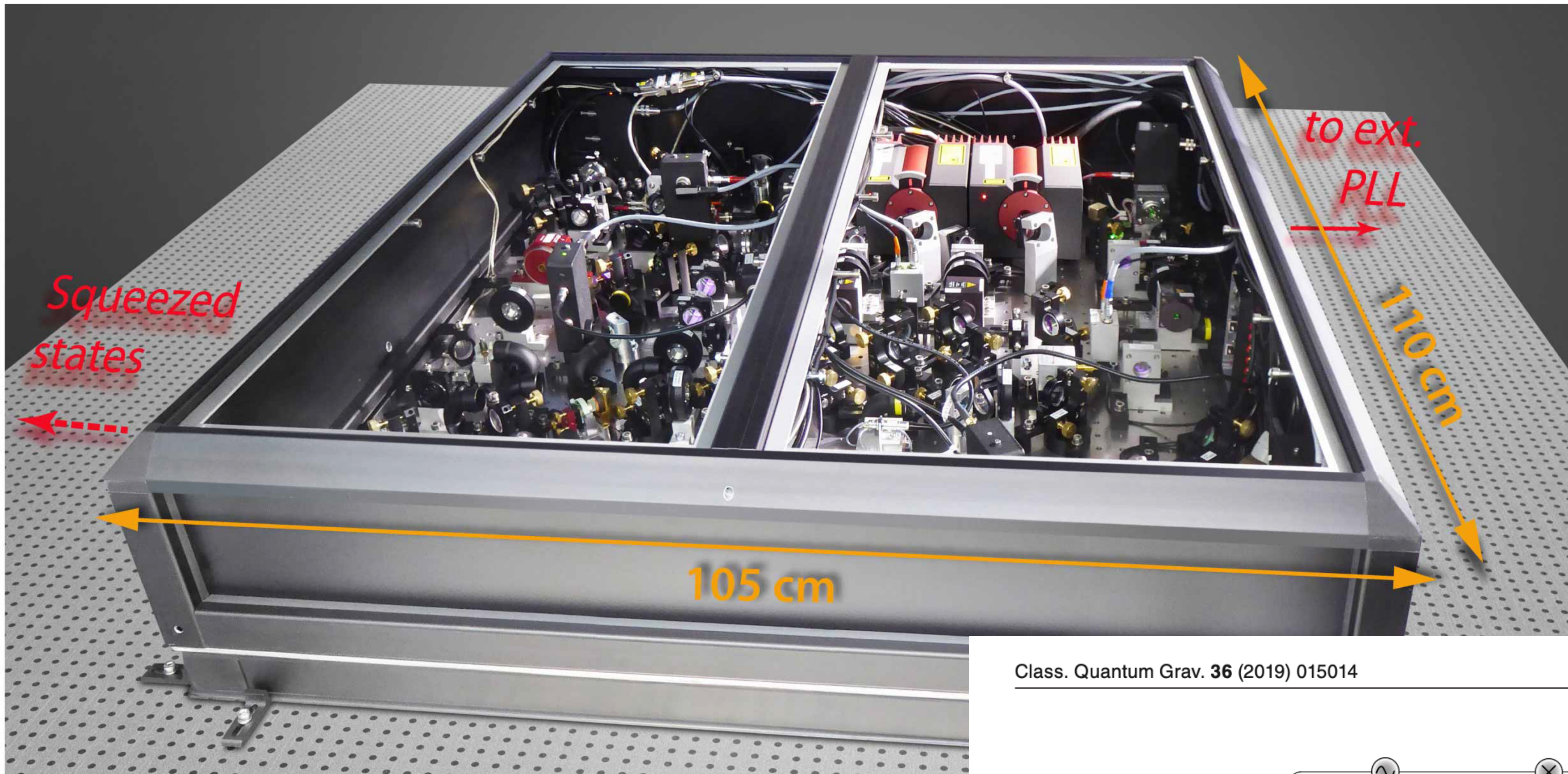
- Squeezing is produced inducing correlation between quantum fluctuations
- The most effective way to generate correlation is a optical parametric oscillator (OPO)
- OPO uses non linear crystal to create correlation between quadratures

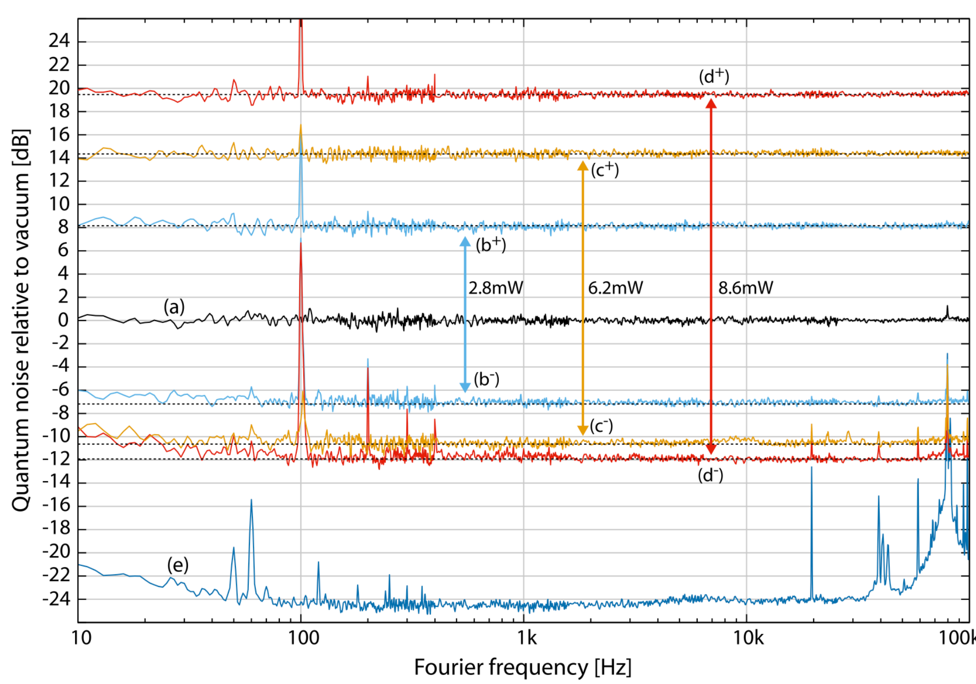




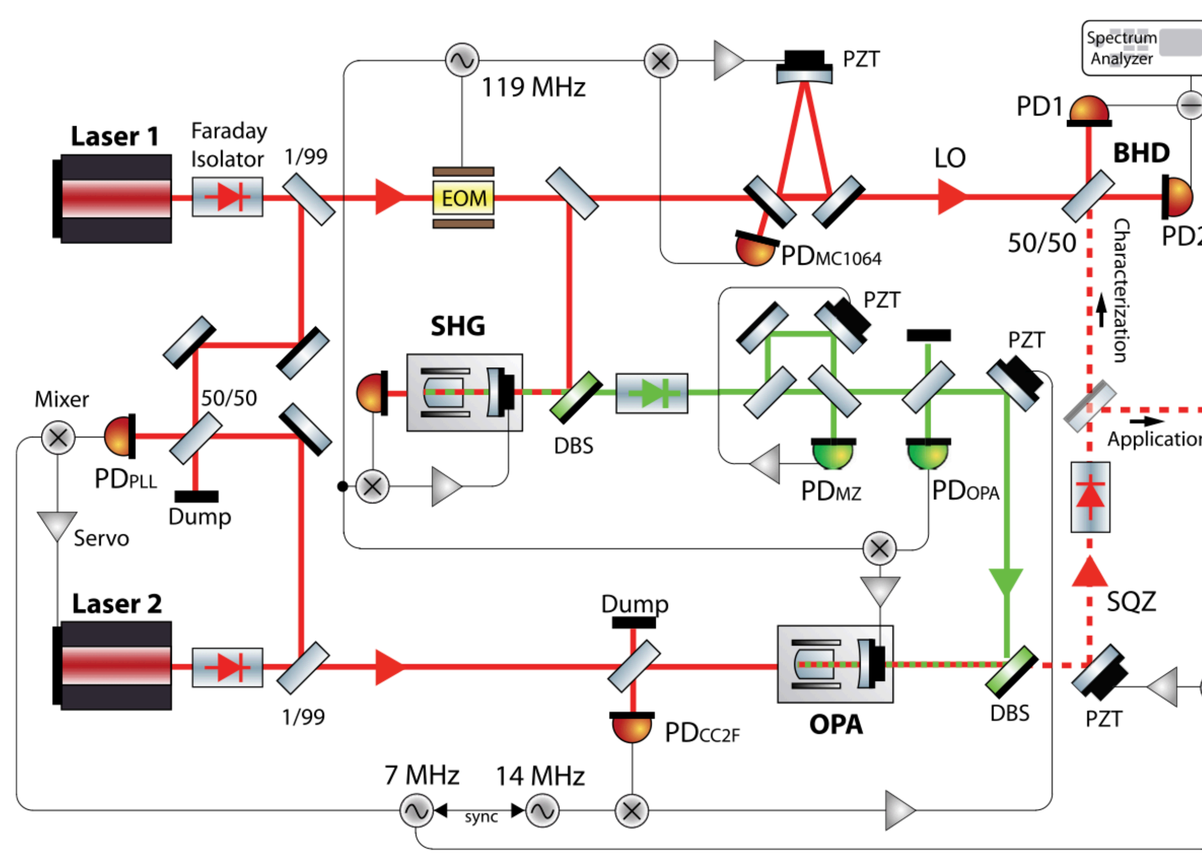
R. Schnabel- Physics Reports 684 (2017) 1–51

Vacuum squeezed source

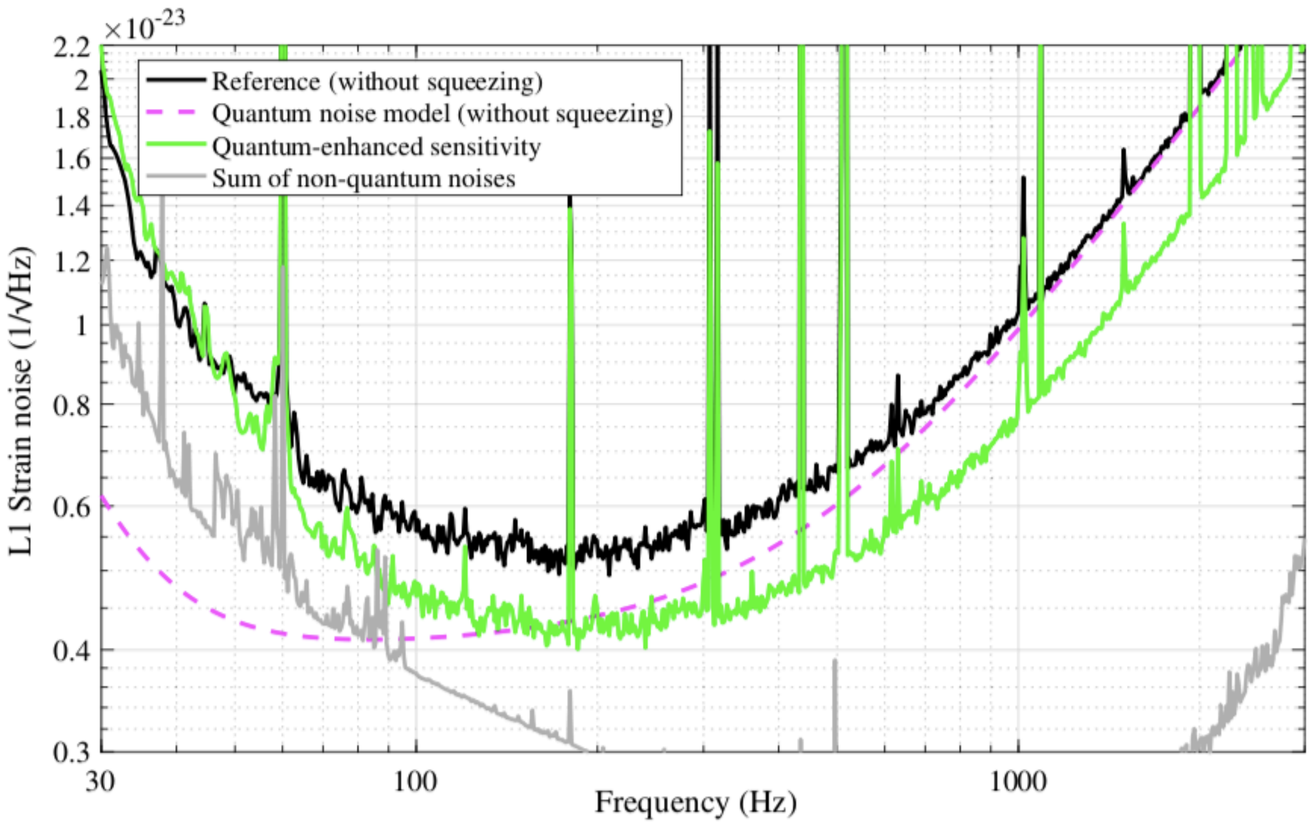




Class. Quantum Grav. **36** (2019) 015014 M Mehmet and H Vahlbruch



Application to 2G detectors: results

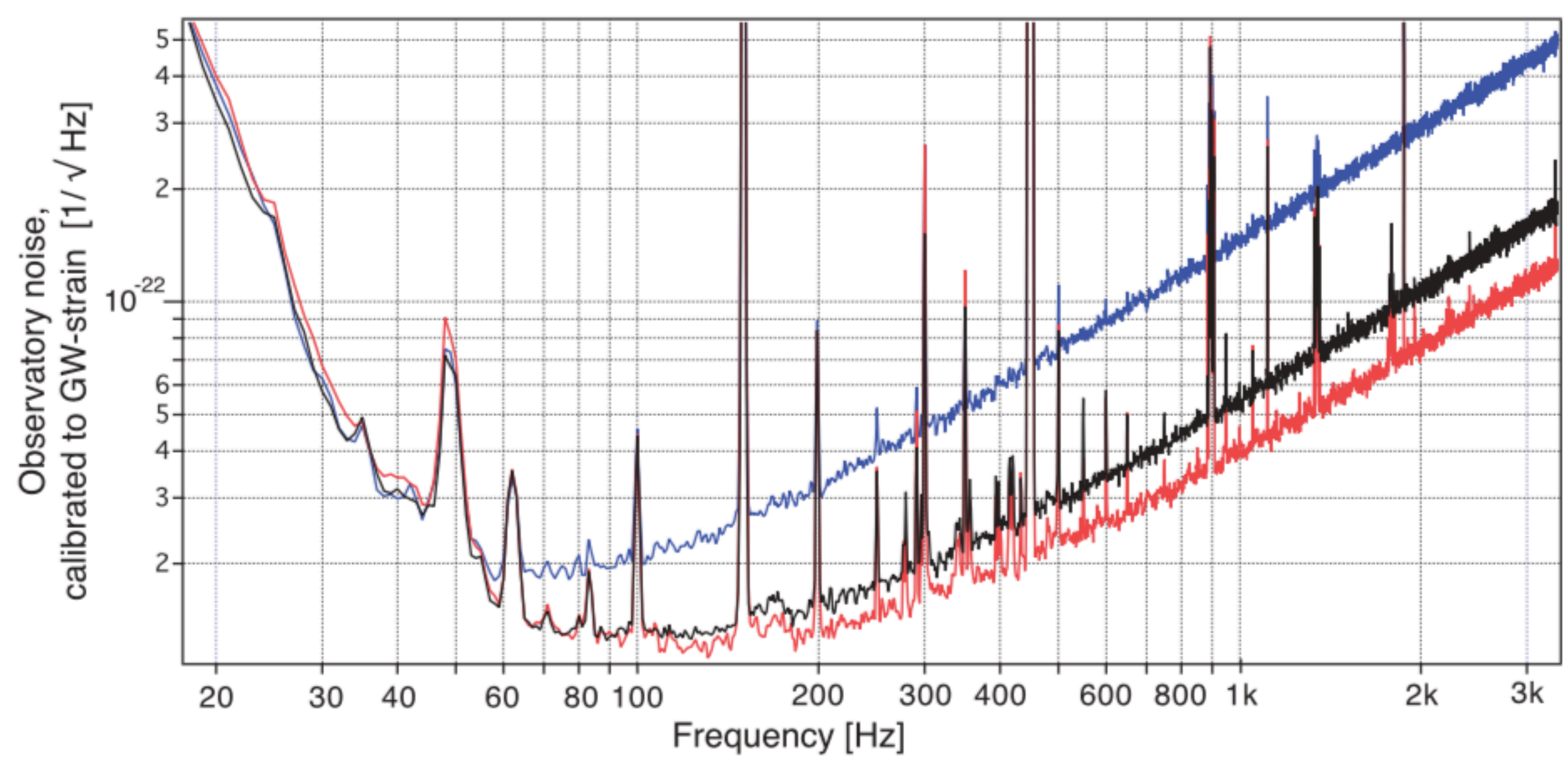


Advanced LIGO

- Best measured ~3 dB
- BNS Range improvement: 14%
- Detection rate improvement: 50%

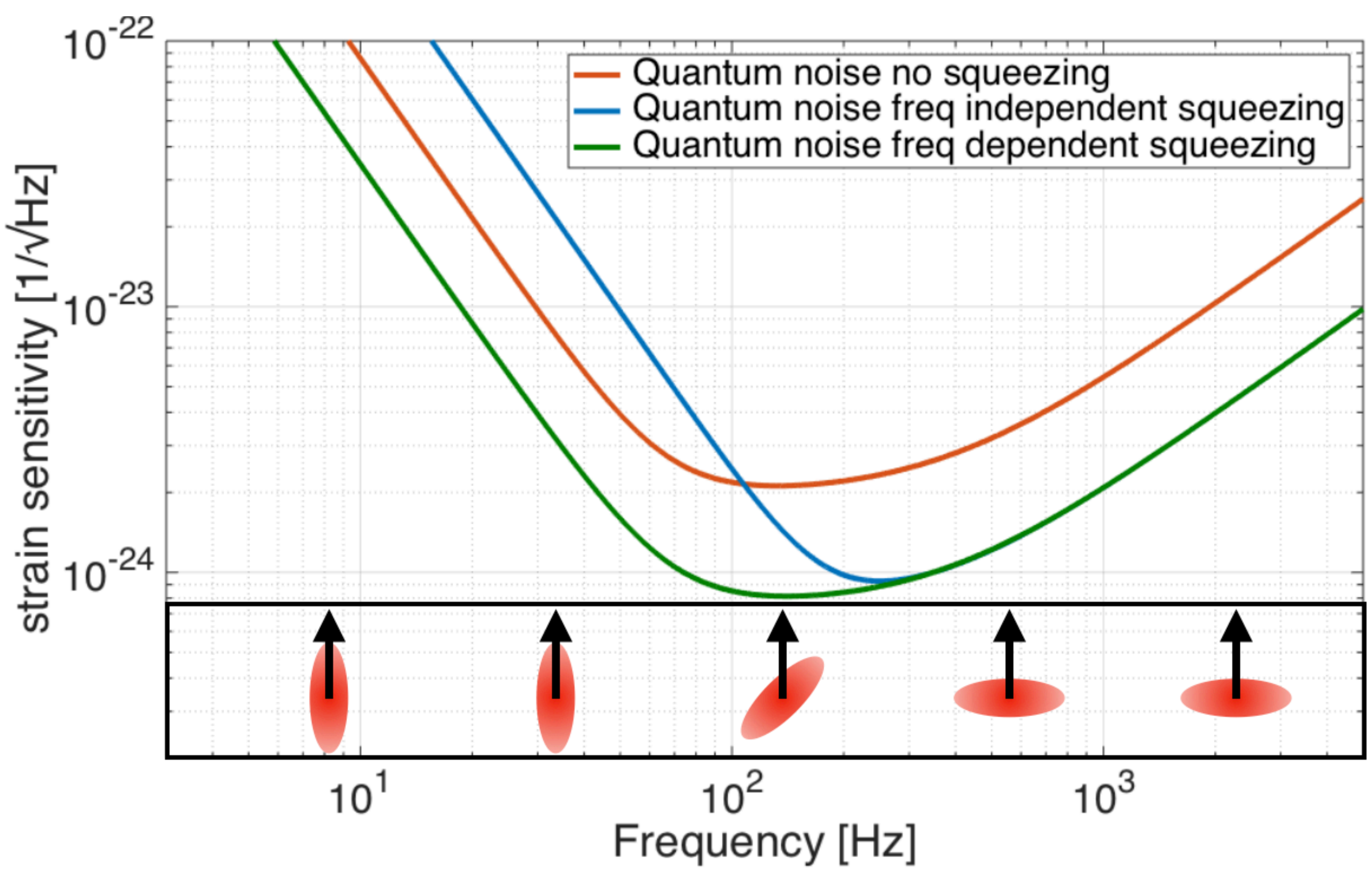
Advanced Virgo

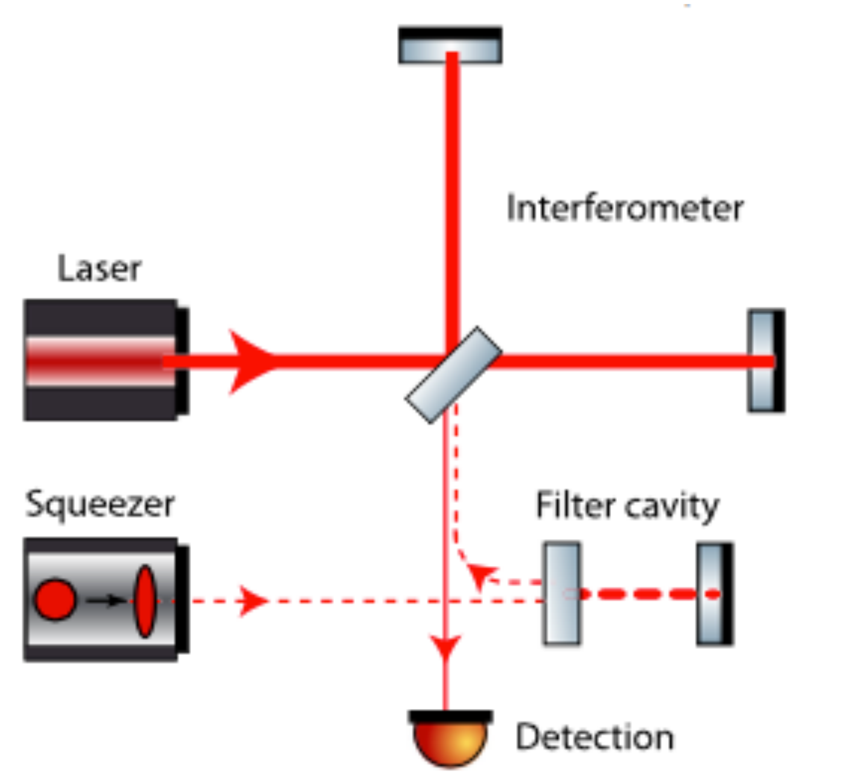
- Best measured ~3dB
- BNS Range improvement: 5%-8%
- Detection rate improvement: 16-26%



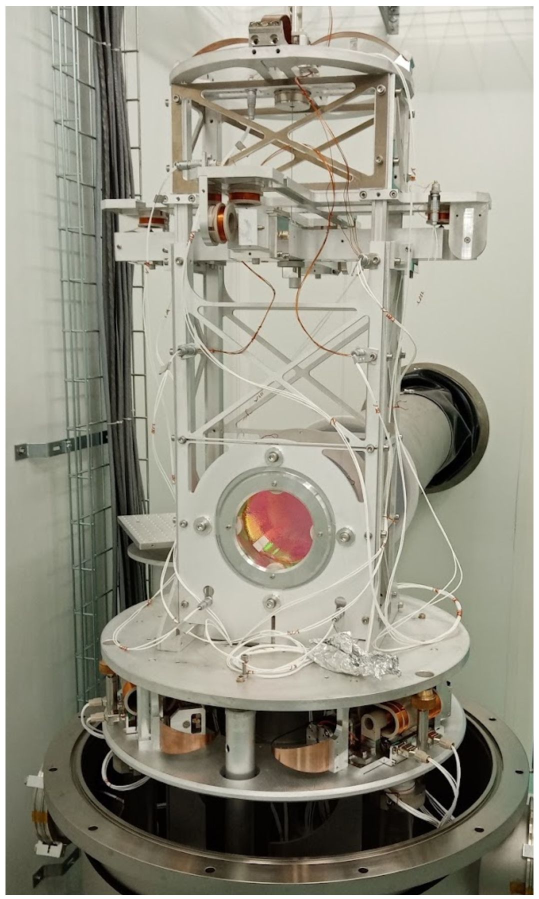
Broadband quantum noise reduction

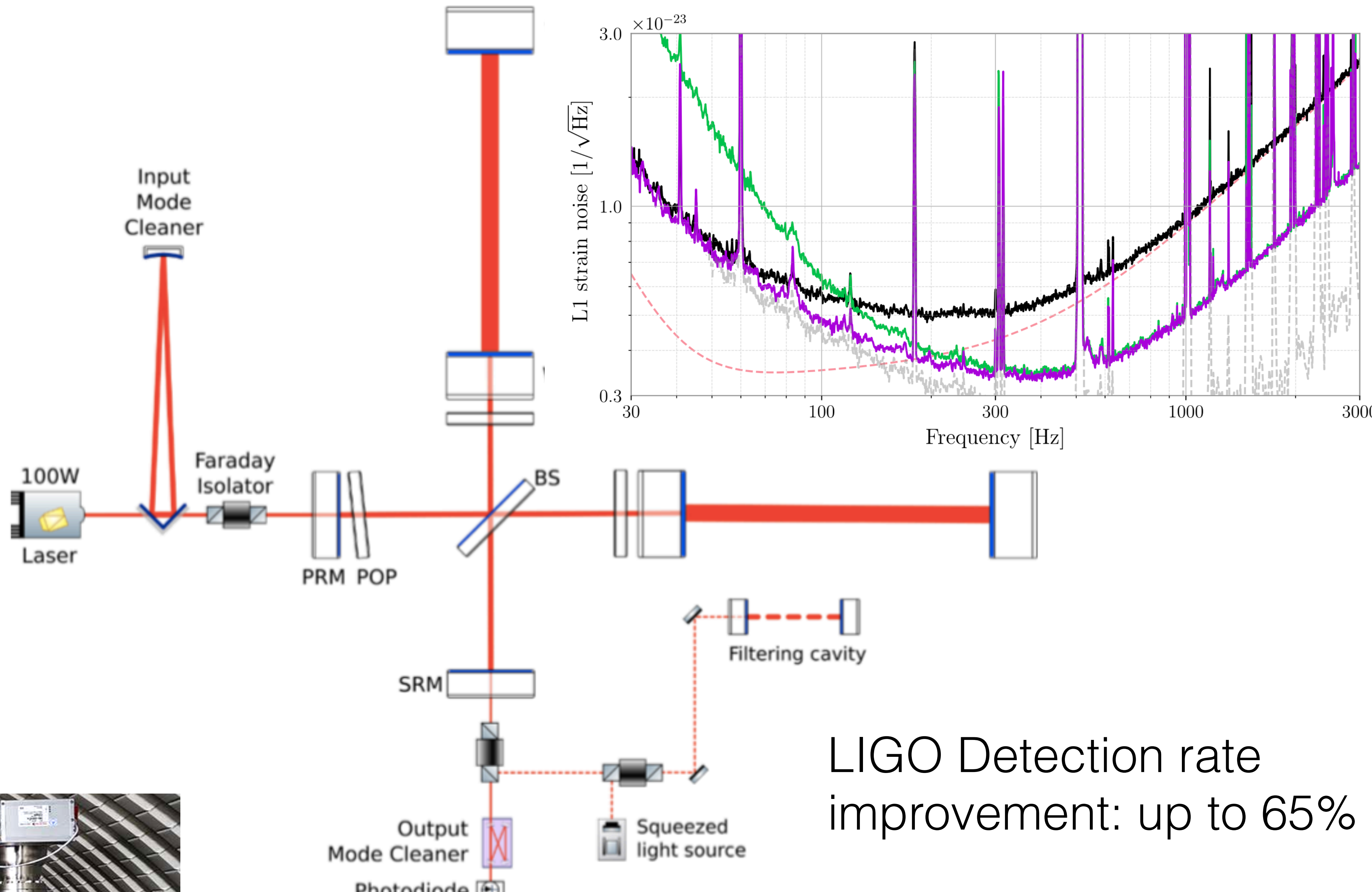
- Squeezing ellipse undergoes a rotation inside the interferometer
- Squeezing angle should change with the frequency for optimal noise reduction
- This can be realised reflecting the squeezing by a detuned Fabry-Perot cavity





Frequency dependent squeezing implemented for O4 in Virgo (and LIGO)





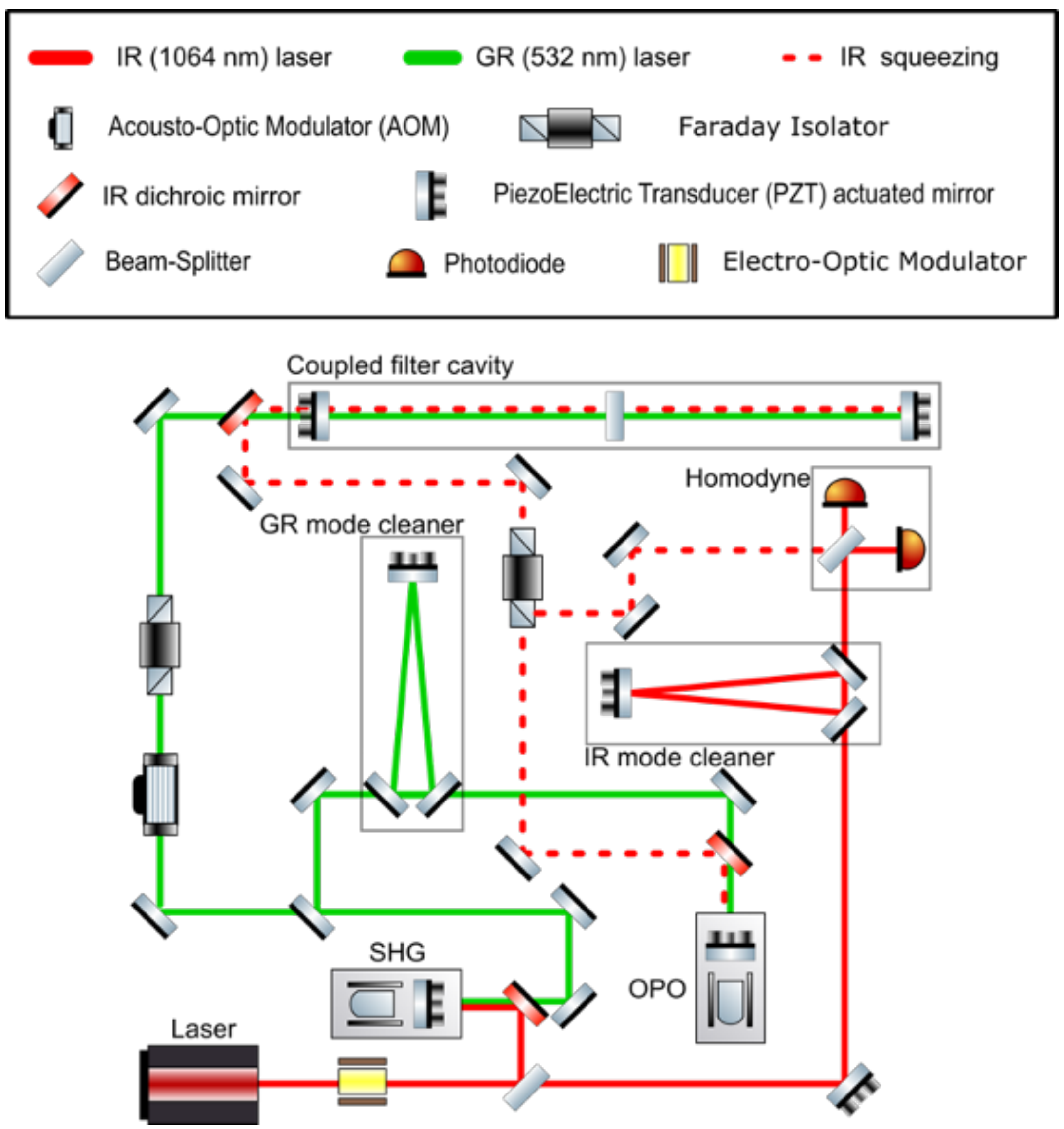
LIGO Detection rate improvement: up to 65%

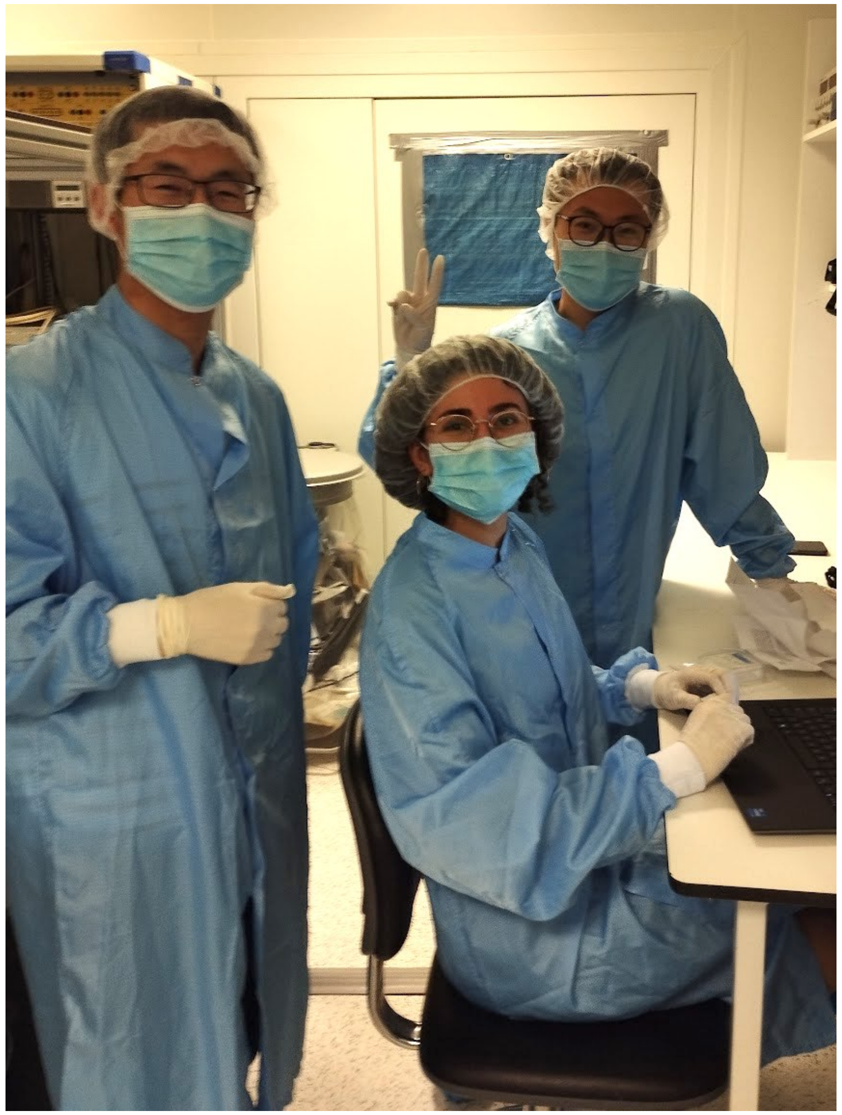
"Broadband Quantum Enhancement of the LIGO Detectors with Frequency-Dependent Squeezing" Phys. Rev. X 13, 041021 (2023)

"Frequency-Dependent Squeezed Vacuum Source for the Advanced Virgo Gravitational-Wave Detector." Phys. Rev. Lett. 131, 041403 – Published 25 July 2023

Quantum FRESCO project at APC: adapt squeezing technique to next generation detectors

- Squeezing rotation will be more complicated for next generation (detuned) detectors
- Table-top demonstration of a non-trivial rotation of a squeezing ellipse.

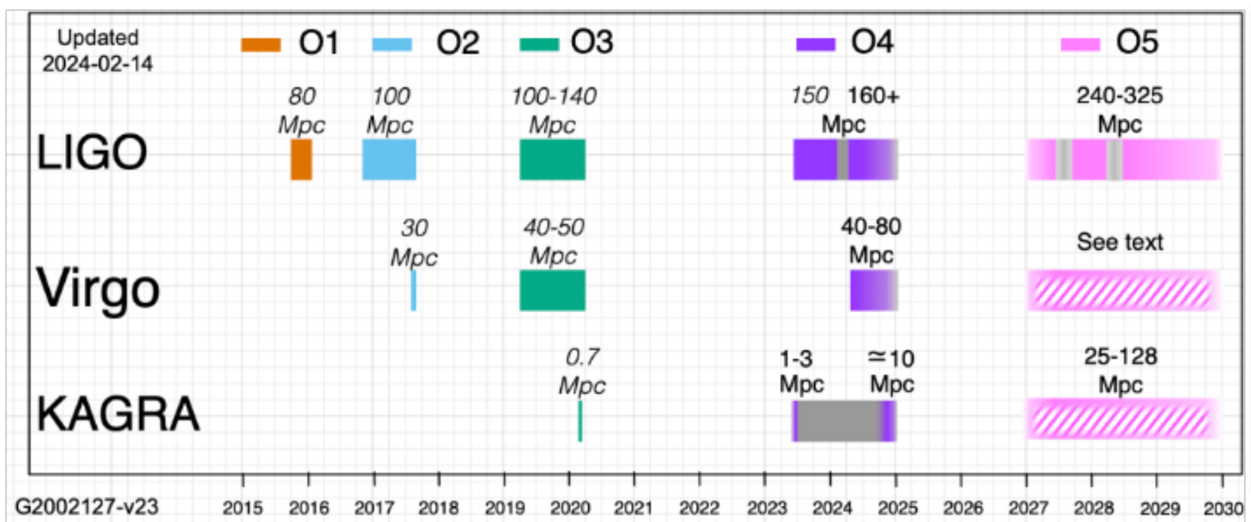




Network observing plan

Current infrastructures

New infrastructures



LIGO upgrade A#

Virgo nEXT

KAGRA upgrade

2030's

Cosmic Explorer

Einstein Telescope

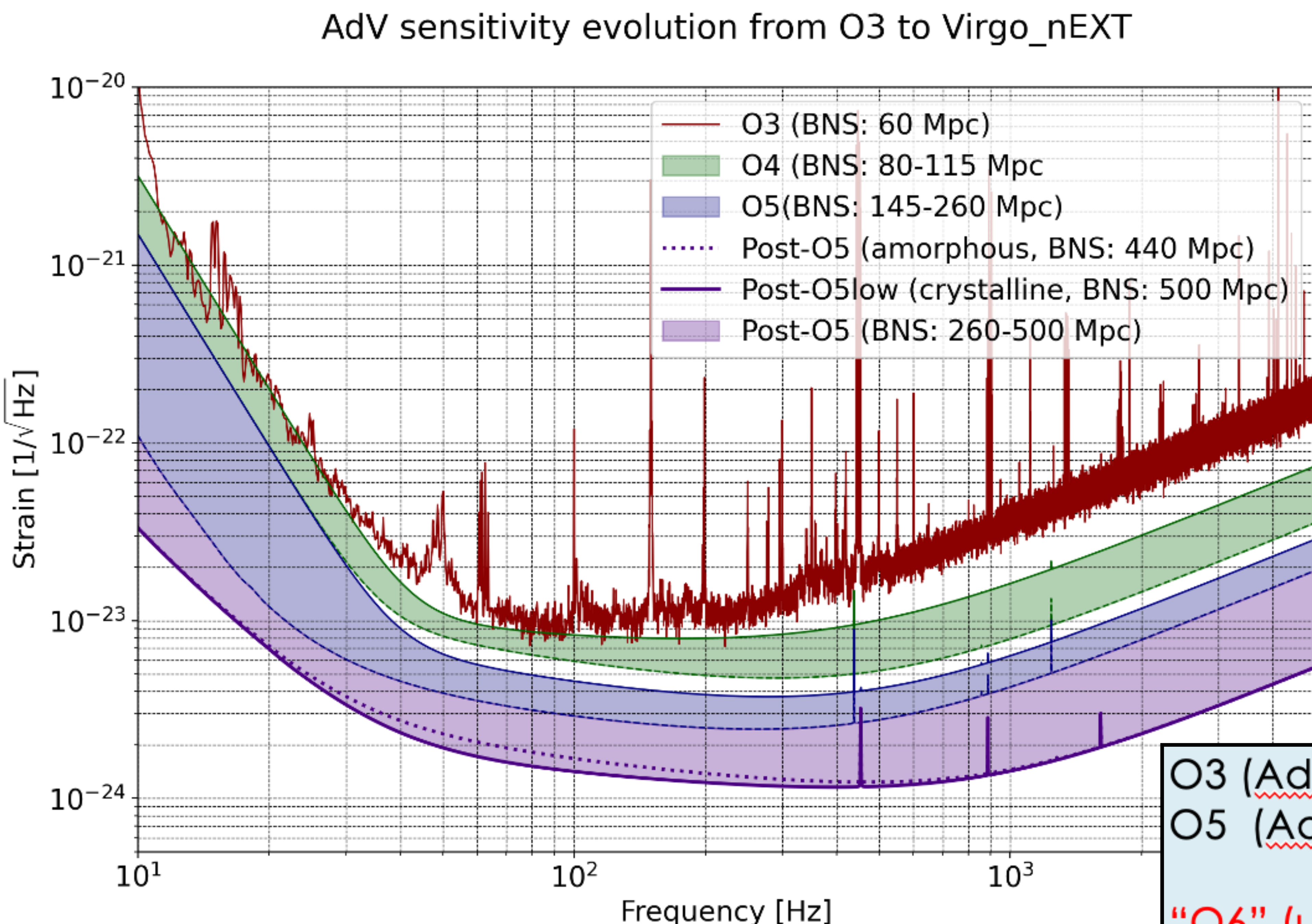
Flight before end of 2030' decade

First detection

90 sources

~180 sources

Expected sensitivity evolution



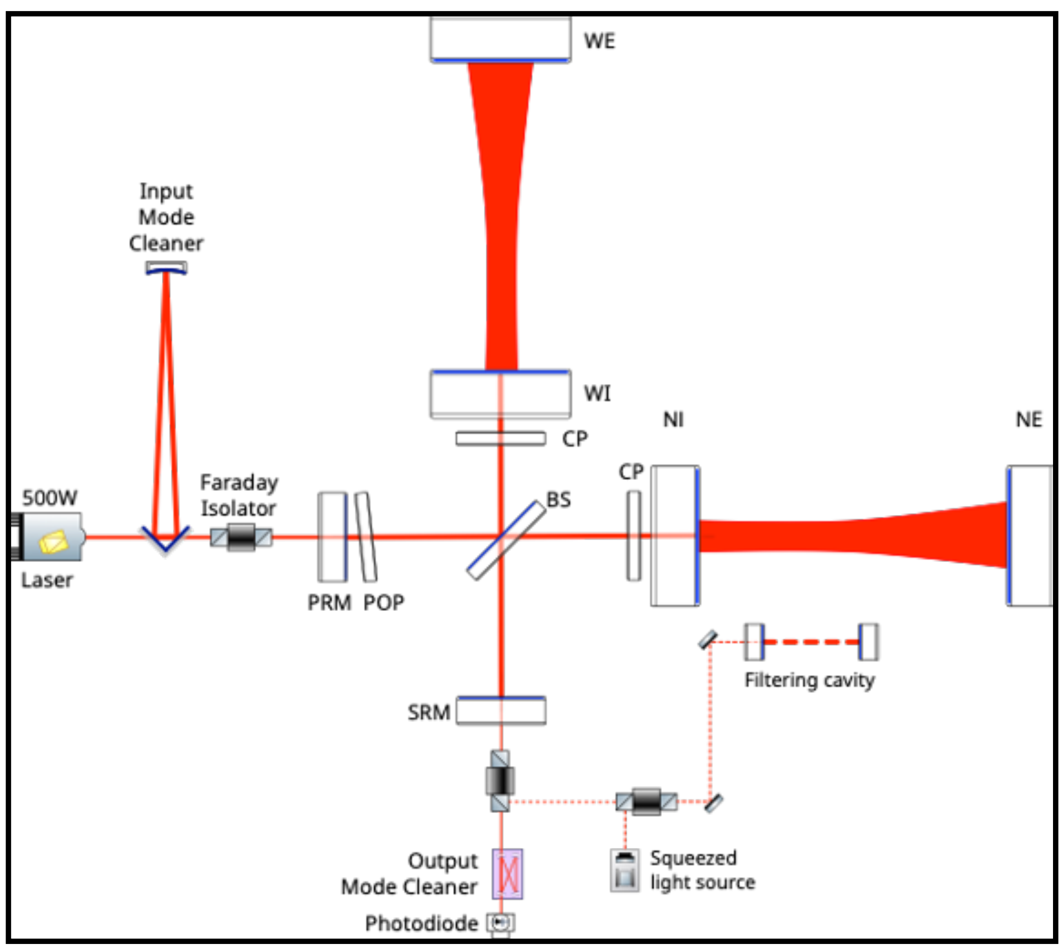
O3 (AdV) ~ O(10^2) BBH /year
O5 (AdV+) ~ O(10^3) BBH/year

"O6" (upgraded network)

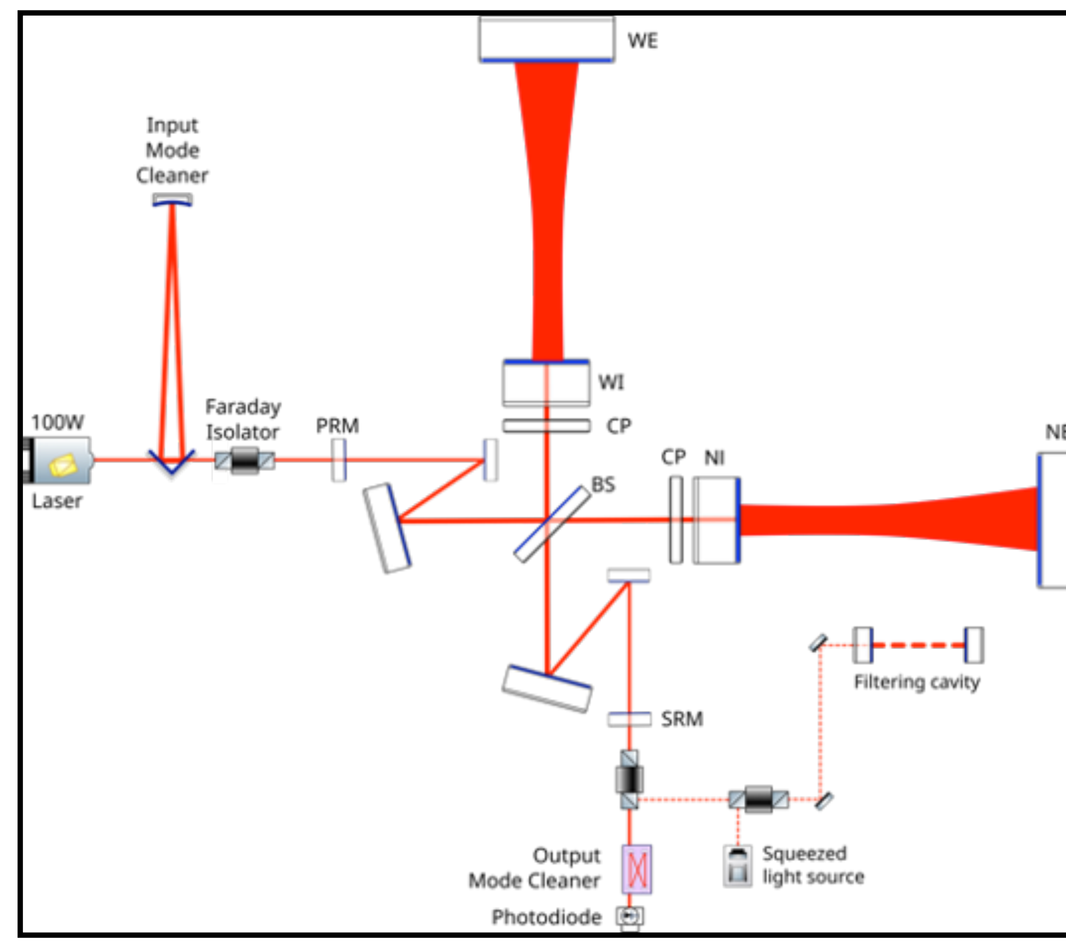
~ O(10^4) BBH/year
~ O(10^3) BNS /year

Detectors upgrades to reach sensitivity infrastructure limits

- Stable recycling cavities
- Power increase
- Better optics (coatings)
- More squeezing (reduction of optical losses)
- Larger test masses and beams



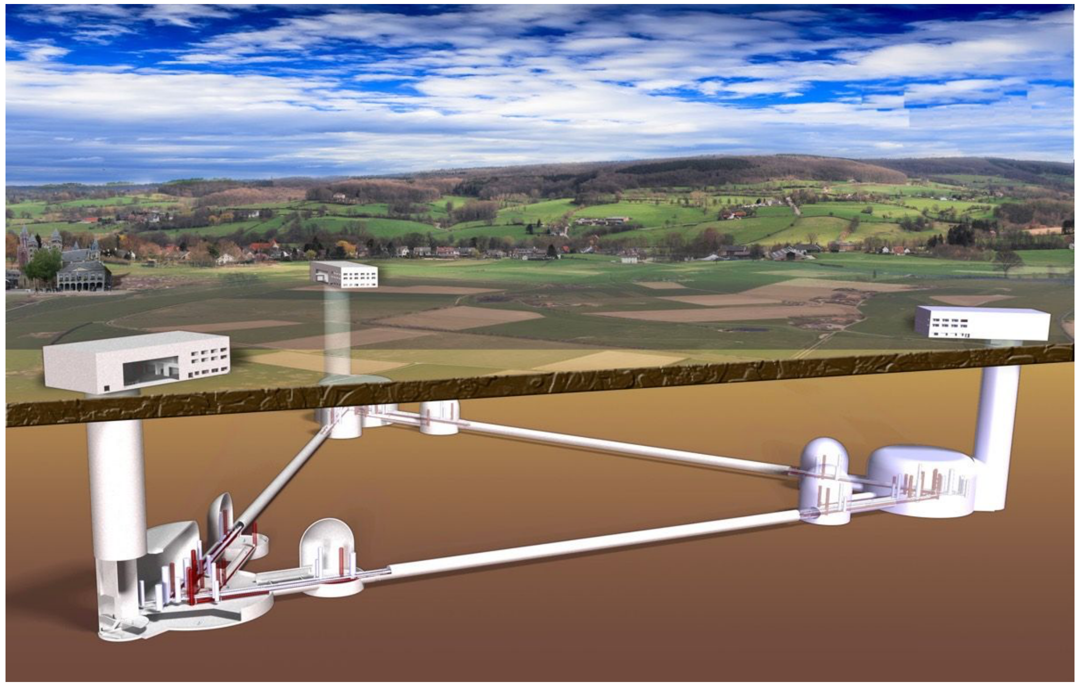
Marginally stable recycling cavities (now)



Stable recycling cavities

3G detectors : Einstein Telescope and Cosmic Explorer

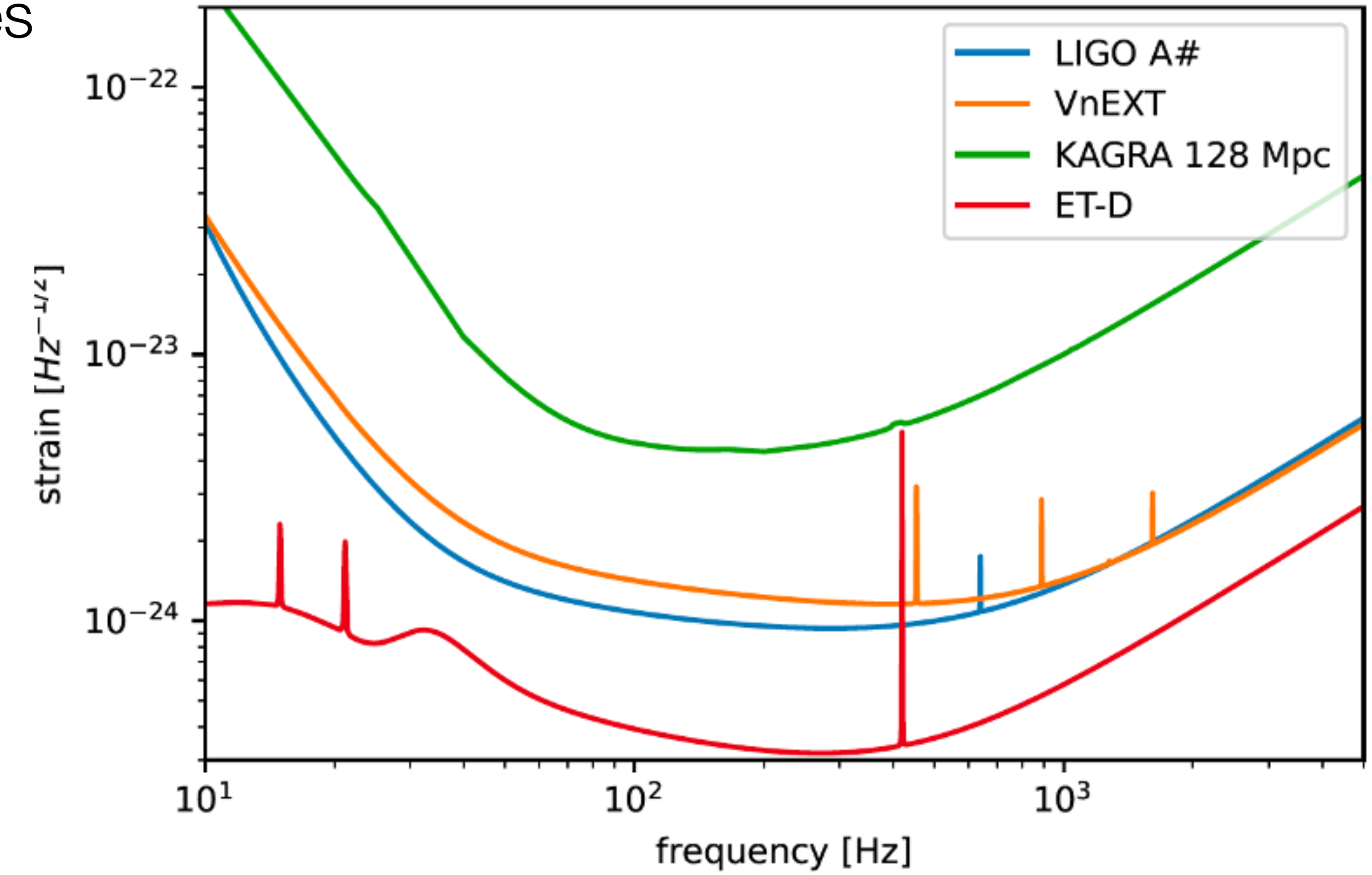
- Goal: 10-fold improvement in sensitivity compared to current detectors
- **ET**:10 km, underground, cryogenic
- **CE**: same configuration as LIGO but 10 times longer.



- First light expected before end of 2030' decades

Science case for future GW astronomy

- Improve precision of Hubble constant measurement
- Black-hole distributions / population sciences
- Multimessanger astronomy
- Nuclear physics – Equation of state
- Astrophysical stochastic background
- Ringdown - nature of black-holes
- Further test of general relativity
- Supernovae
- Dark matter (GW lensing, primordial black holes)



Summary

- Gravitational wave astronomy, born in 2015, provided already many scientific results ranging from general relativity to astrophysics and cosmology
- Virgo-LIGO-KAGRA network performing now the 4th observation run (O4)
- Over 100 GW signals detected from compact object binary merging (Black holes, Neutron stars)
- Still a lot of science to be done:
  - Upgrade of current detectors in the same infrastructure
  - Next-generation detectors with 10 times improved sensitivity in new infrastructure