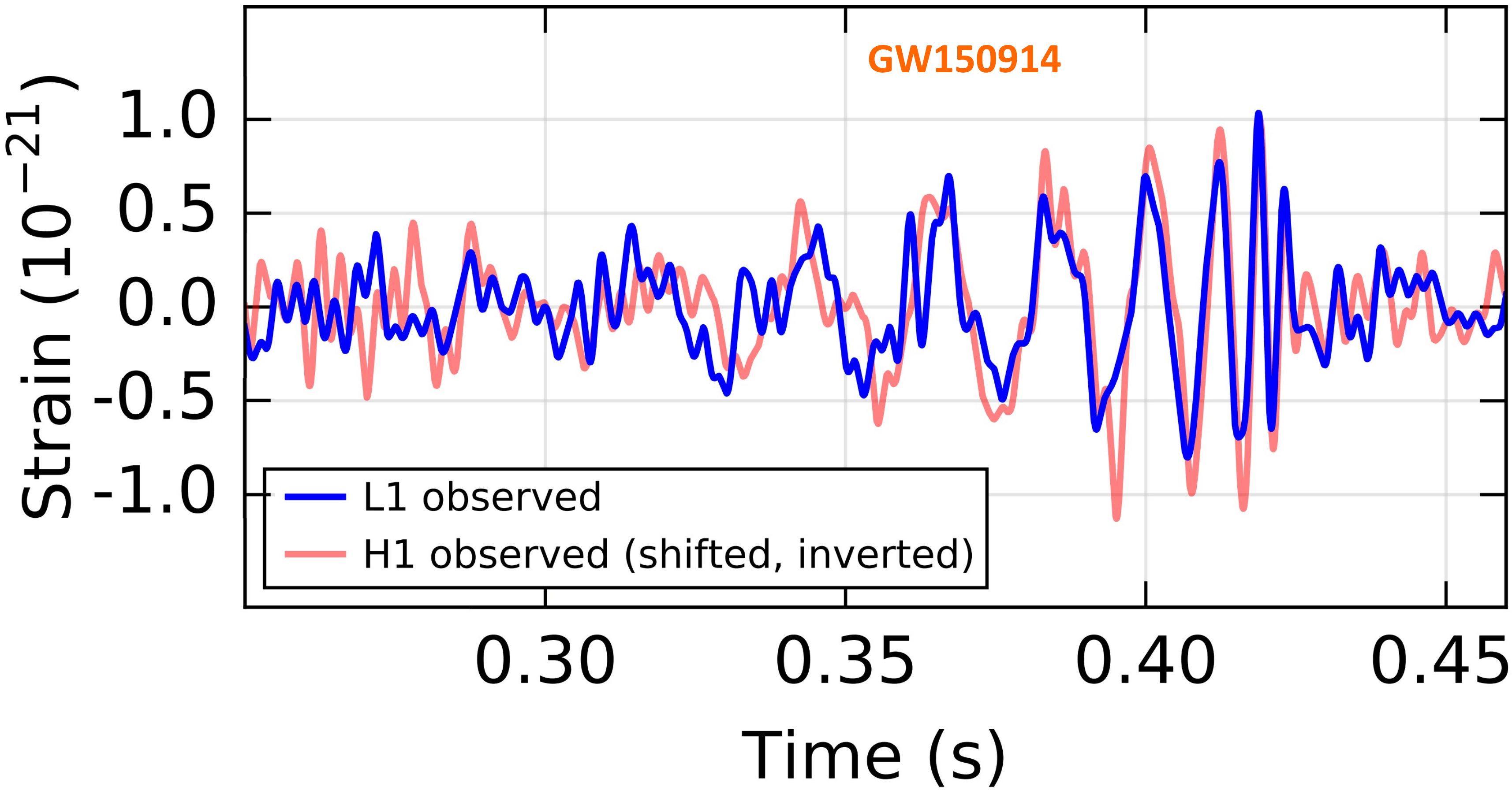
Workshop GdR détecteurs, 23 juin 2021

Gravitational waves

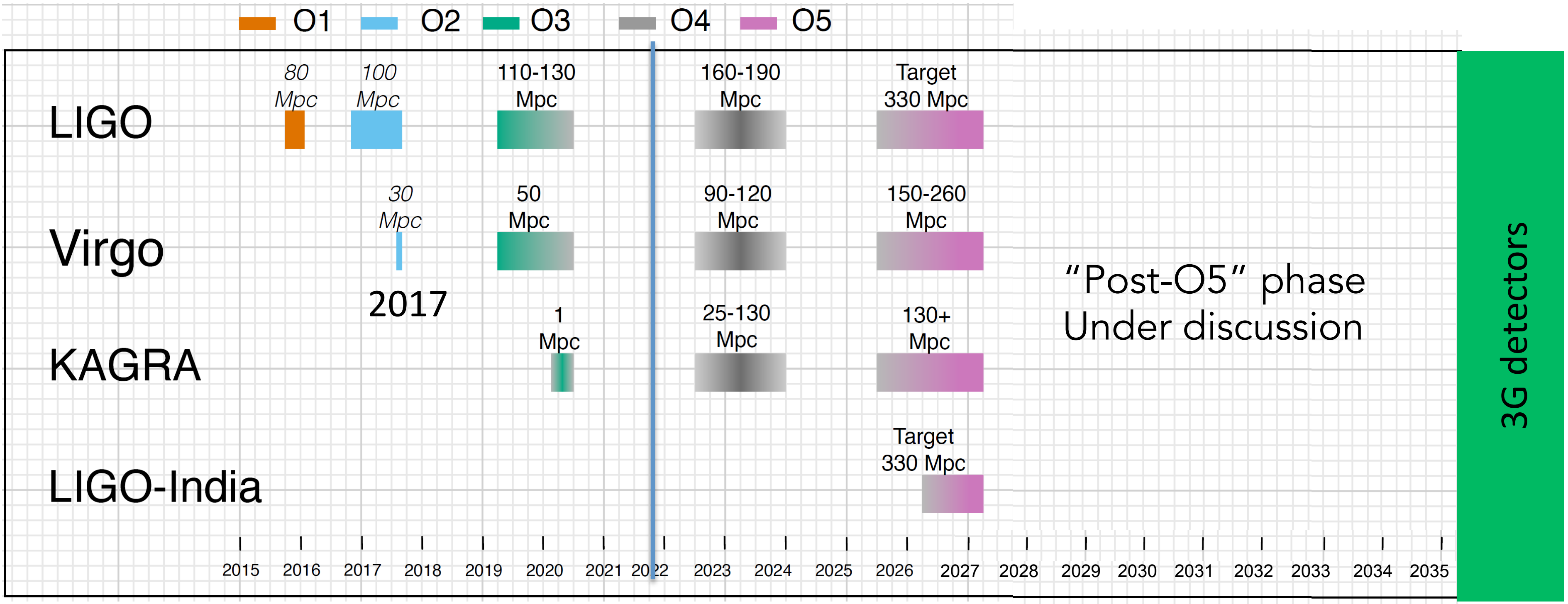
Matteo Barsuglia

(APC)

14 september 2015
(almost 6 years ago)



The observational runs

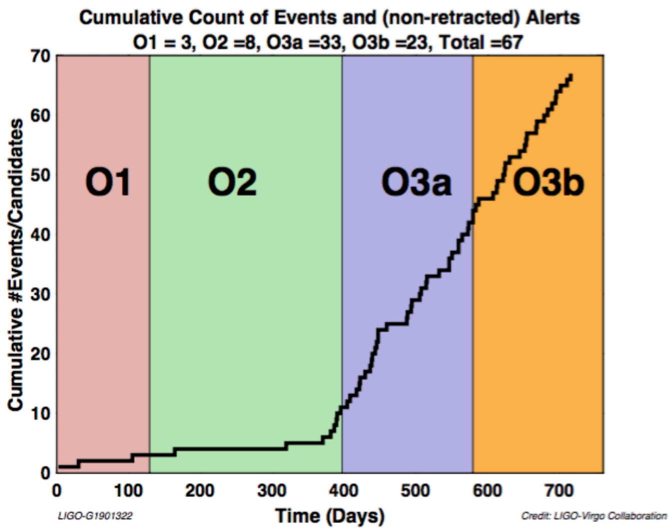


- Advanced Virgo
- Advanced LIGO

- Advanced Virgo+
- Advanced LIGO+

- Einstein Telescope
- Cosmic Explorer
- Nemo

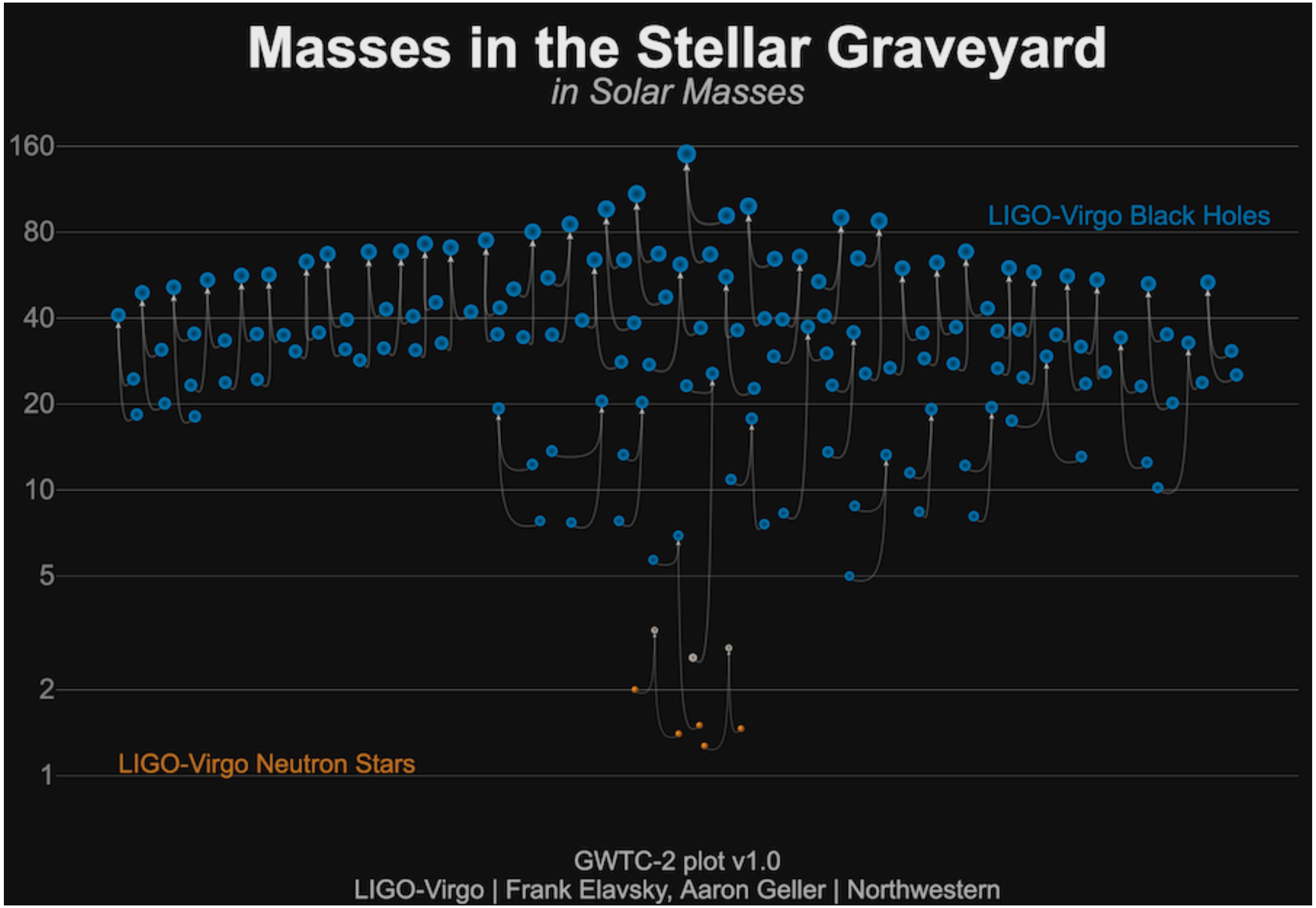
O3 results so far - **in short**



- 4 new *exceptional* astrophysical systems published
- More distant sources (z ~ 0.5 → 0.8)
- We started to make statistics on black-hole populations
- New tests of general relativity (i.e. harmonics of the GW signal)
- Upper limits on several sources and physical effects (i.e. GW background, lensing, dark matter)

- GWTC-2 (second catalog of GW sources) O3a (6 months)
- 39 gravitational-wave sources → 39+11 = 50
- Since April 2021 O3a data are public
    - Many other groups are analyzing Virgo-LIGO data

Second catalog: GWTC-2 (oct 2020)
39 new sources (total 50 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

- 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

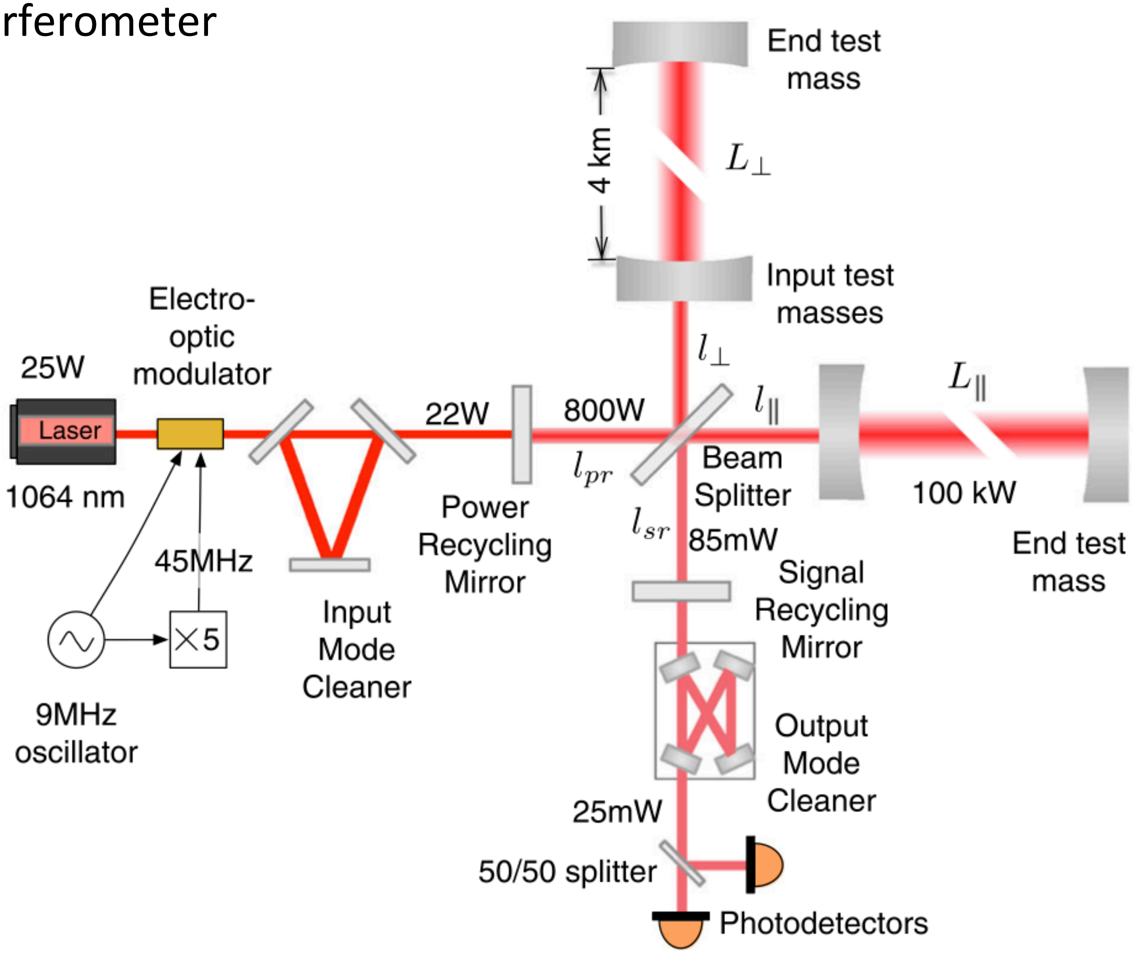
50 sources published

O3b analysis on going

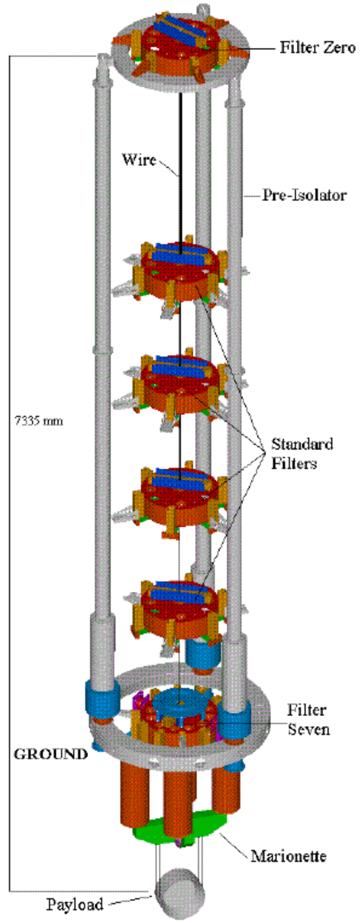
- Alternative measurement of Hubble constant
- Speed of gravity → consequences on gravity alternative theories

The GW detectors, in short

Modified Michelson interferometer



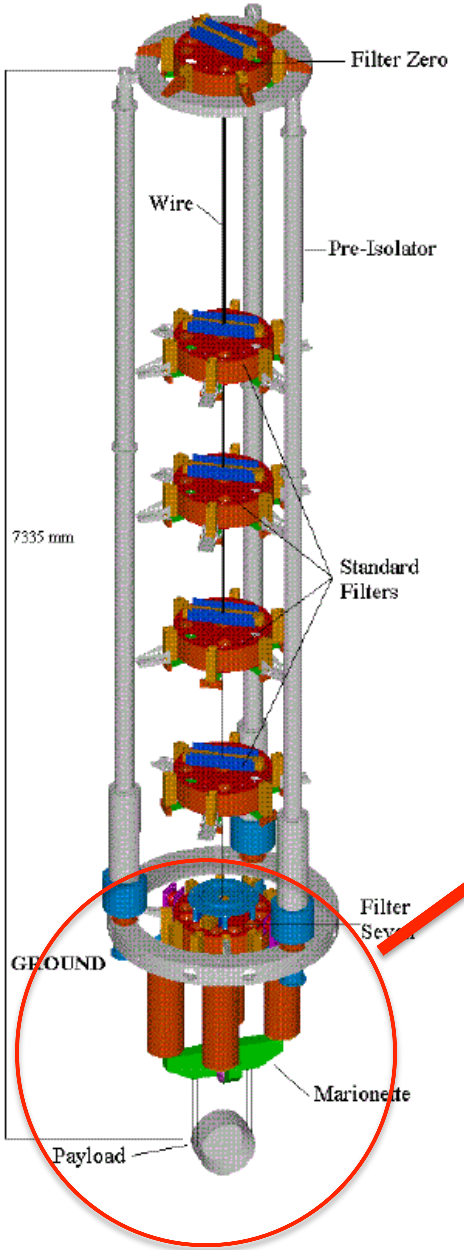
Suspended test masses

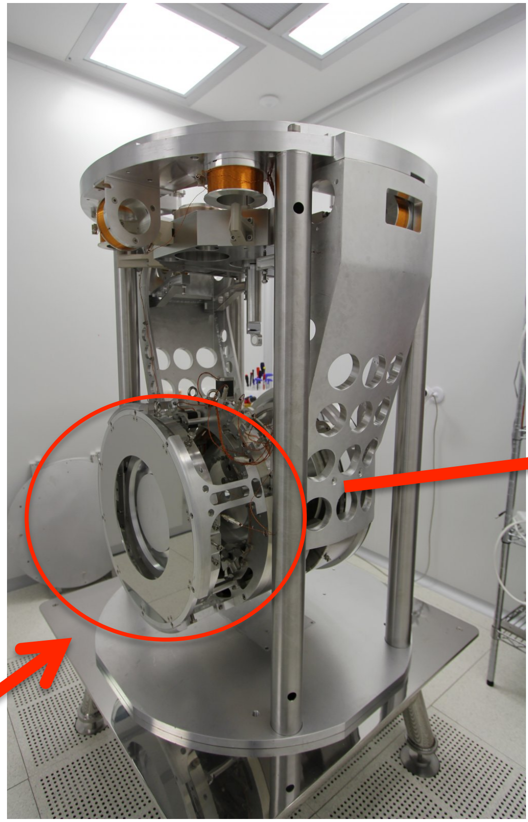


Technologies – a few keywords

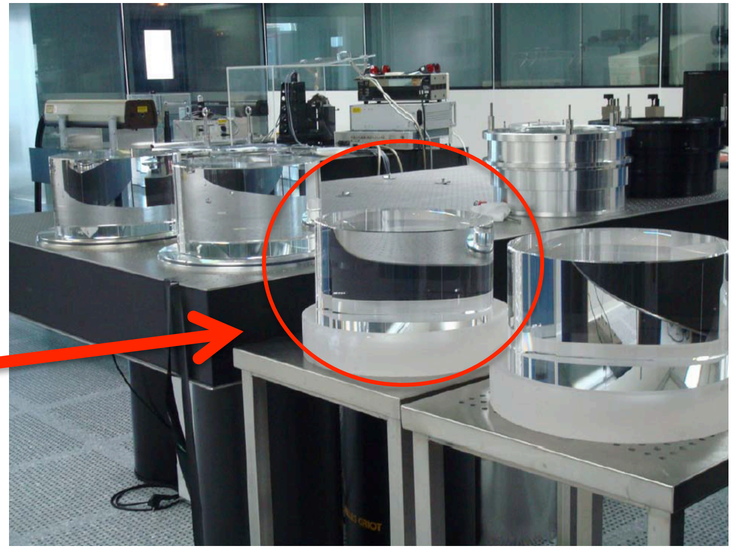
- Laser interferometry
- Quantum technologies
- Suspended optical benches
- High power stabilized lasers
- Coatings
- Surface metrology
- Material science
- Diffusion – stray light
- Vacuum technologies
- Suspension systems
- Digital control systems
- DAQ
- Radio-frequency electronics

Suspensions and mirrors





Credit Virgo



applied optics

Mirrors used in the LIGO interferometers for first detection of gravitational waves

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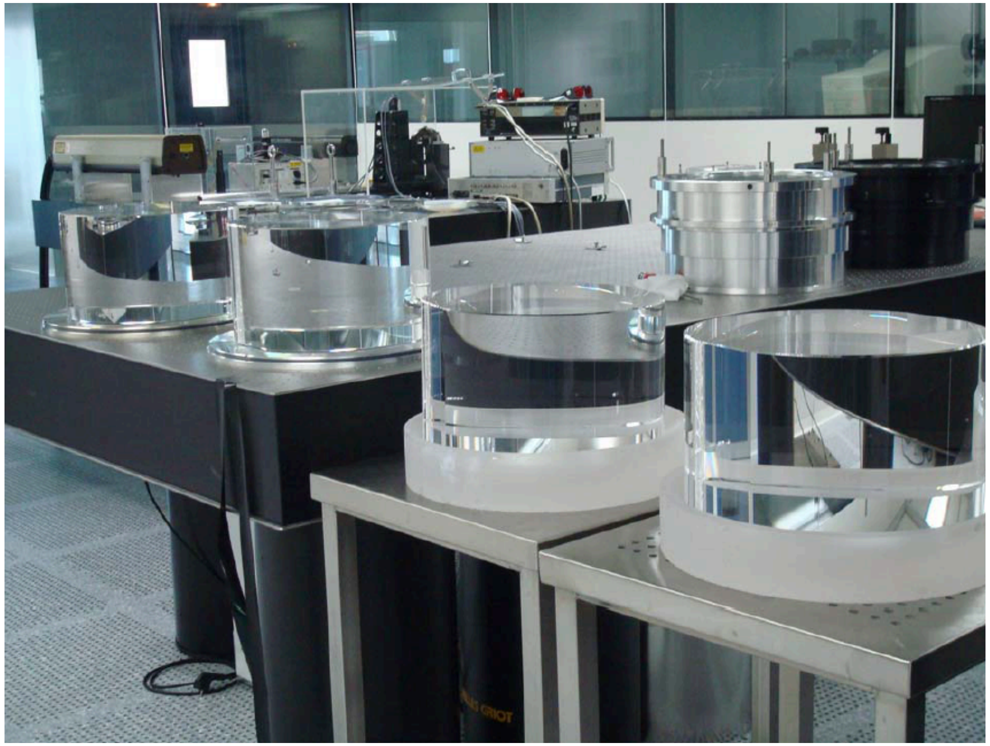
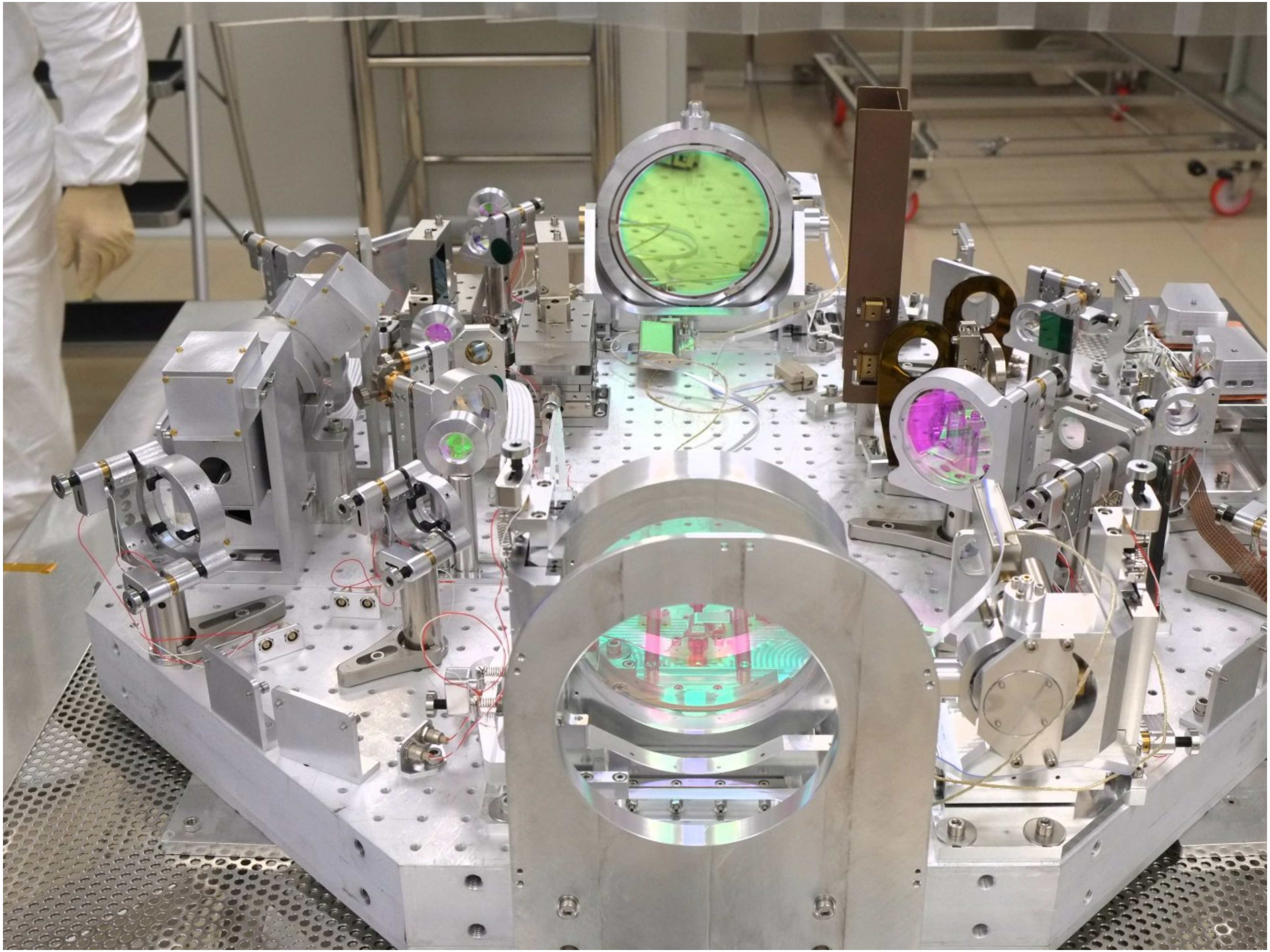
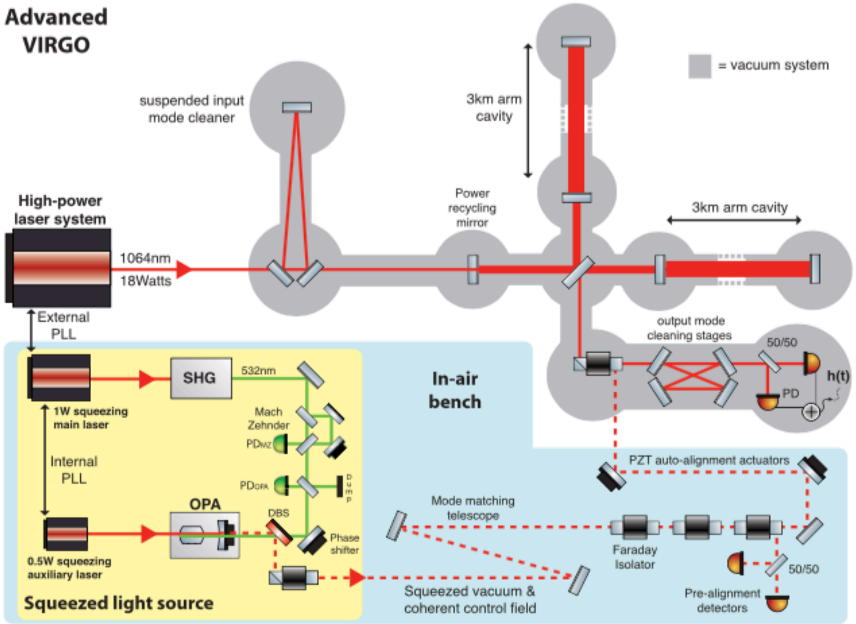
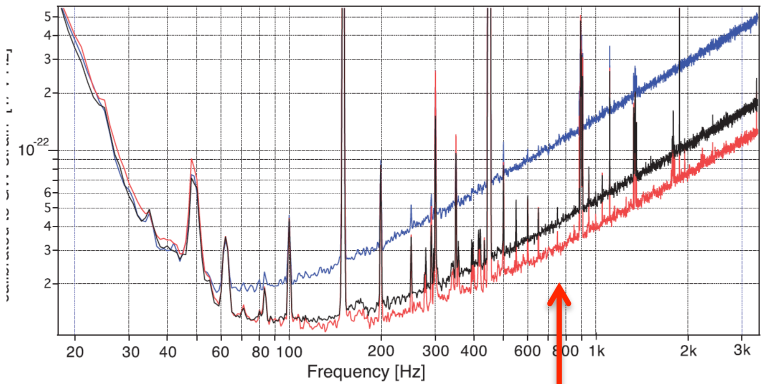




Squeezed light- quantum technologies





Squeezed vacuum injected

Quantum technologies and GW detectors

Appel à contributions pour l'exercice de prospective nationale "Technologies quantiques pour les deux infinis"

Quantum technologies and gravitational-wave detectors

Authors:

The Virgo groups of: APC, Artemis, IJCLab, IPHC, IP2I, LAPP, LKB, and the g-MAG Virgo group (ILM, INL,INSP, Navier)

Contact: Matteo Barsuglia (barsu@apc.in2p3.fr)

May 2021

Quantum technologies and gravitational-wave (GW) detectors have a long standing link: the need for gravitational-wave detectors to push more and more the limits of their performances was one of the drivers for the development of *squeezing* sources and *quantum non demolition* studies and techniques. After many years of R&D, GW detectors are today routinely using quantum technologies to improve their astrophysical reach.

1. Background

Quantum noise is one of the main limitations of current gravitational-wave detectors. It arises from vacuum fluctuations entering from the interferometer output "dark" port [1]. In Virgo and LIGO, squeezing techniques are used since the O3 data taking to reduce the shot noise (high-frequency component of the quantum noise), with a gain of ~ 3 dB [2,3] and a very good duty cycle, allowing an extension of the detection range up to ~ 25% for Virgo and ~ 50% for LIGO. This technique is referred to as *frequency independent squeezing*. The expected increase of the radiation pressure noise at low frequency, due to the use of this technique, is at present barely visible, because of the presence of other noise sources.

- Document for the working group "Technologies quantiques pour les deux infinis"

- Interest for GW detectors
- Experience of the CNRS groups
- Interest for fundamental physics (quantum mechanics on kg scale objects)
- Possible spin-off towards other communities

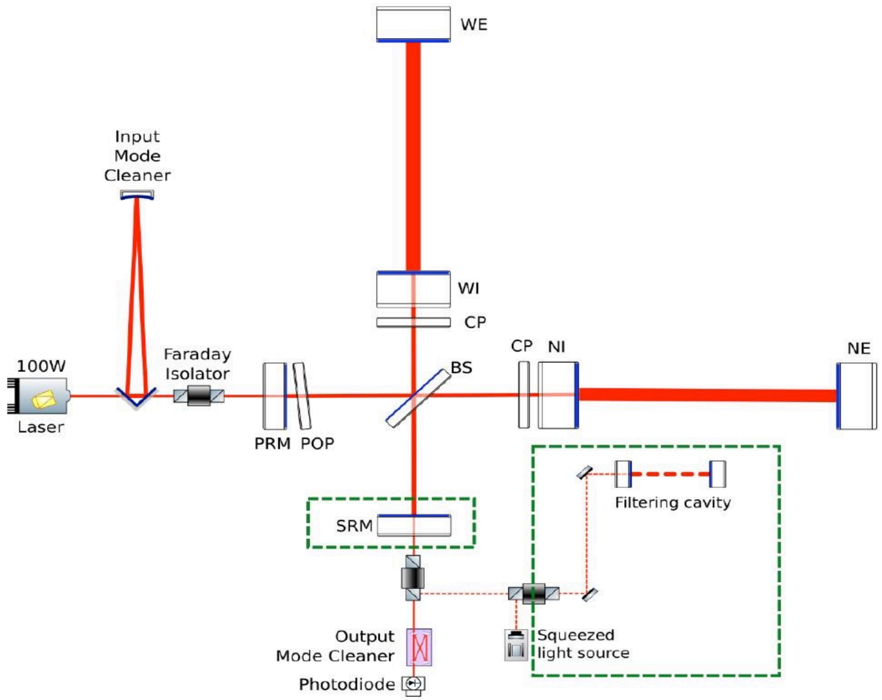
Advanced Virgo +: phase 1

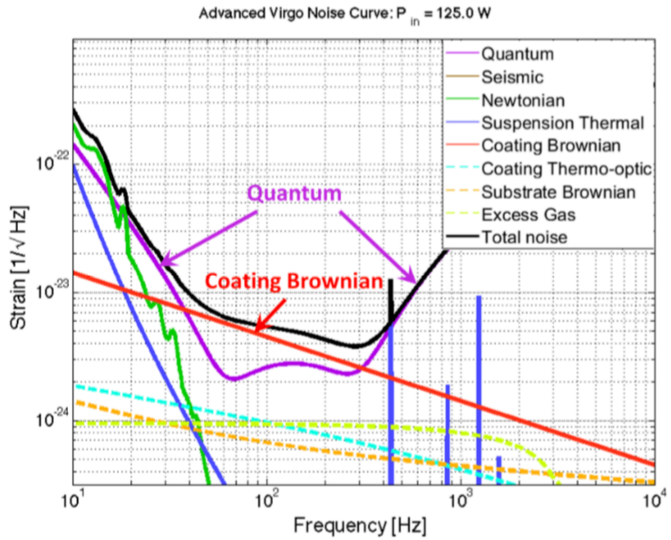
Quantum noise reduction

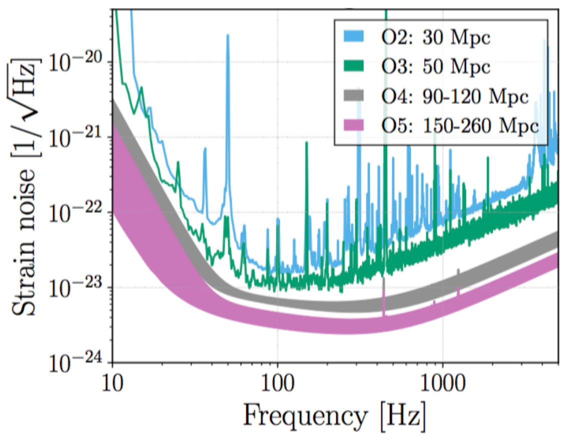
- Signal recycling
- Frequency dependent squeezing
- Laser power increase

(26 W→40 W)

- Newtonian noise cancellation

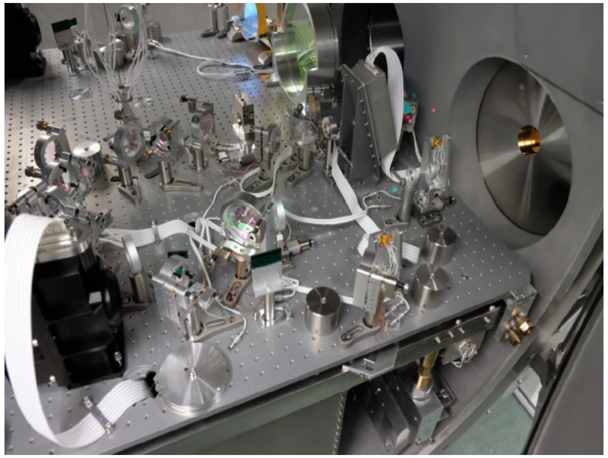


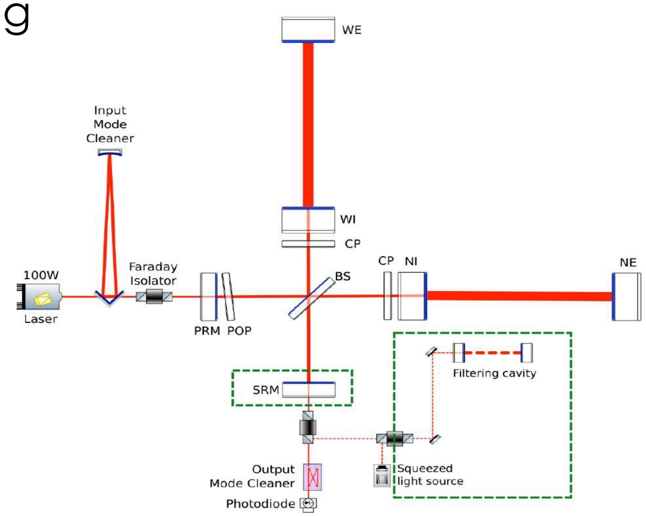




Construction/Integration highlights: main interferometer

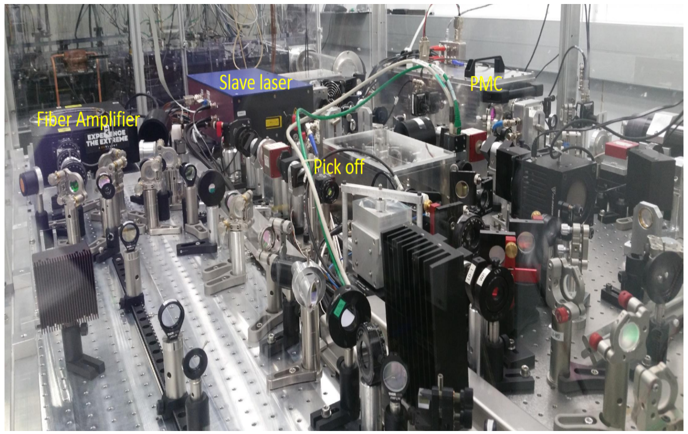
Auxiliary green lasers for lock acquisition with signal recycling



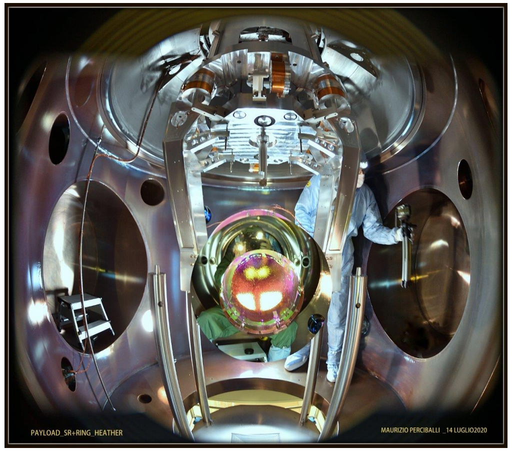


Seismometers for Newtonian noise substraction

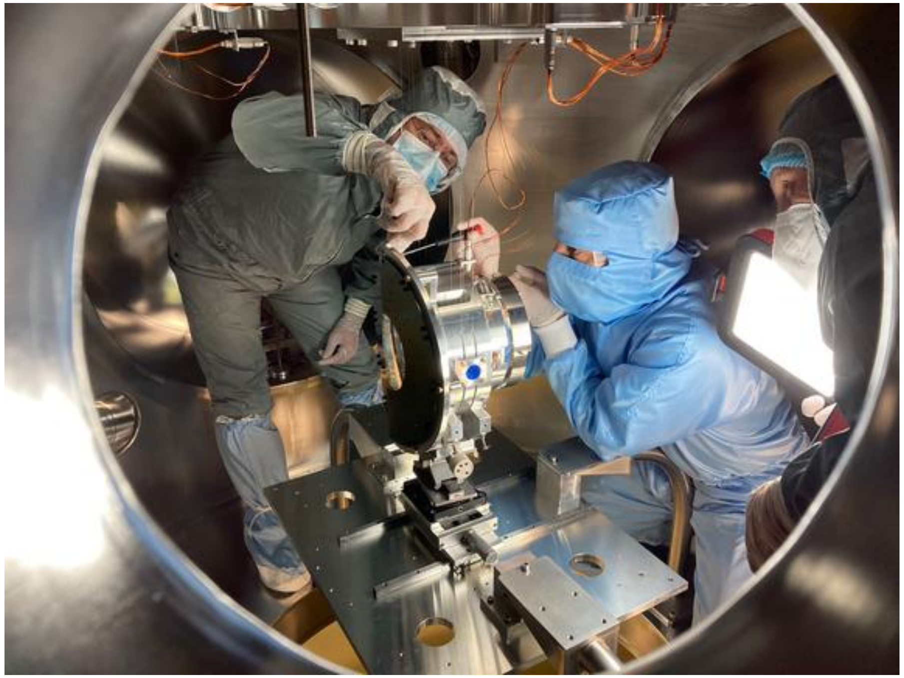
Fiber laser, 125 W

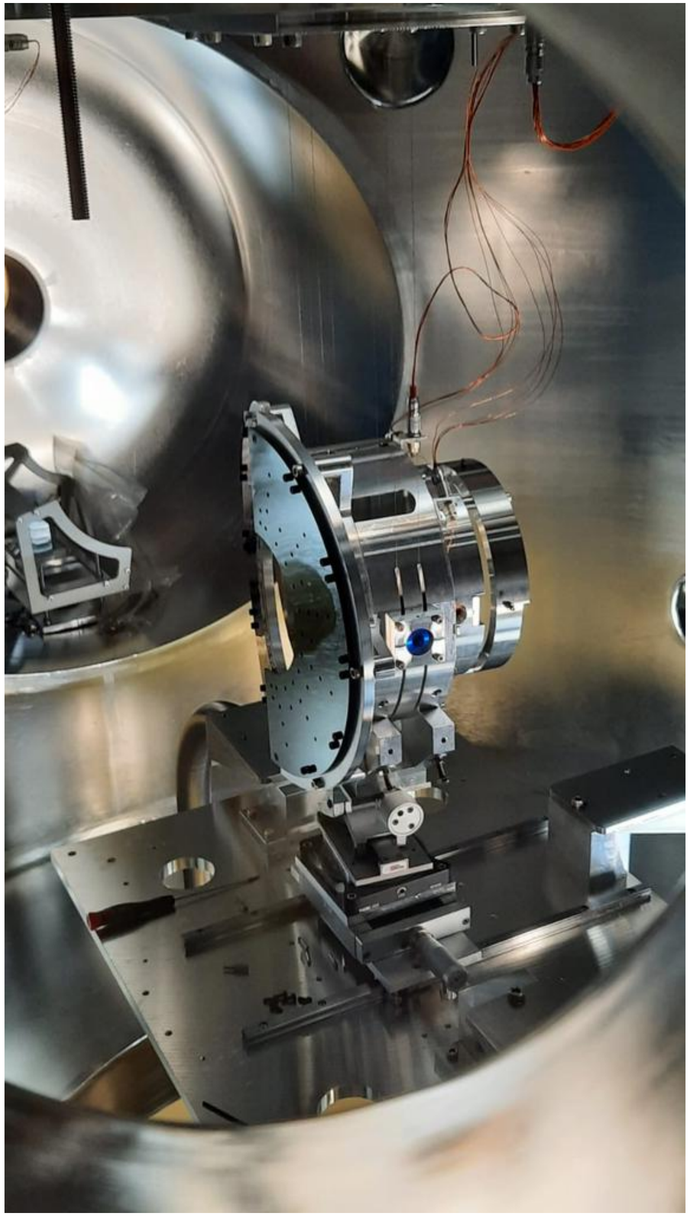


Recycling mirror with its suspension



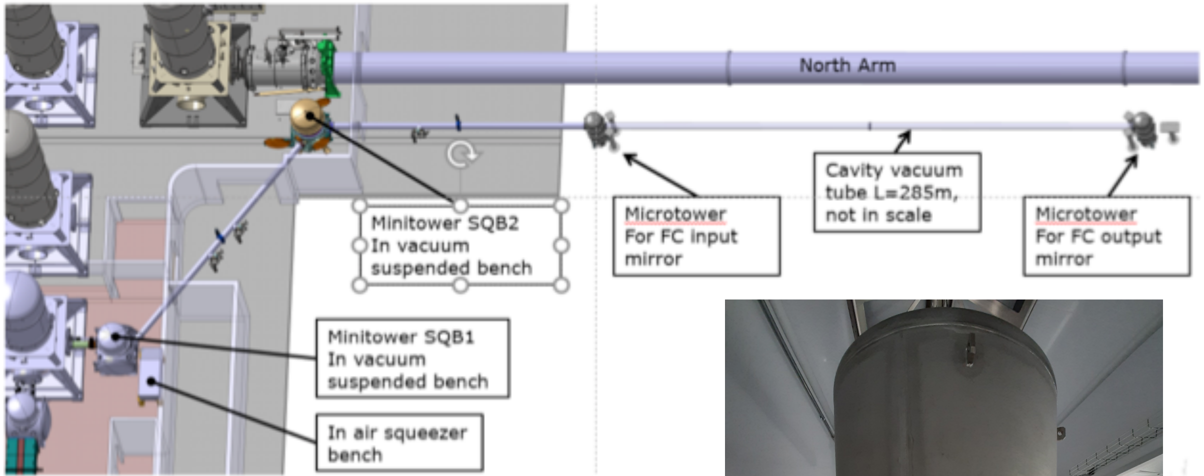
Construction/Integration highlights/2: main interferometer





Construction/Integration highlights: squeezing

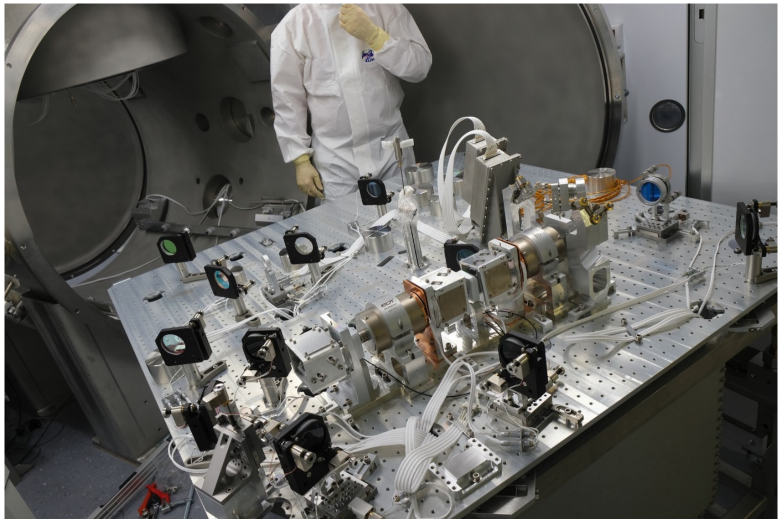
Filter cavity new infrastructure



New suspensions

Filter cavity vacuum tube (300 m)

Construction/Integration highlights/2: squeezing

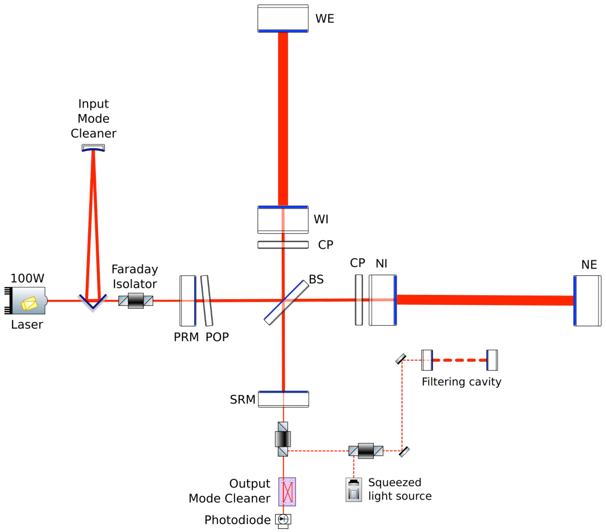


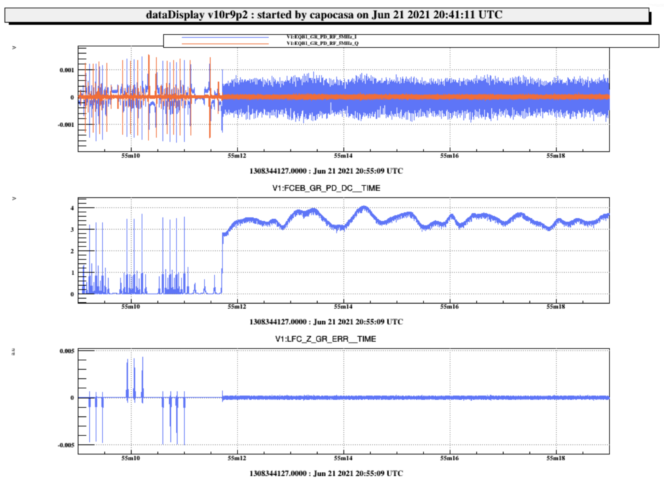
Commissioning

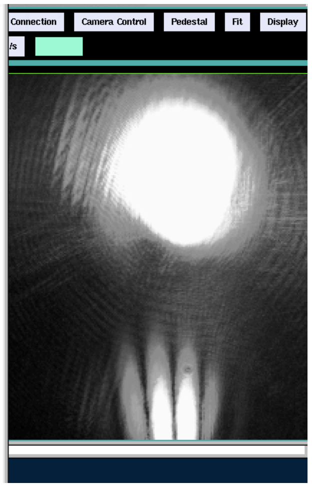
- **Installation concluded – commissioning on-goings**

- Full interferometer: control of 5 coupled degrees of freedom
  - Arms locked on green lasers on a detuned point
  - Central part locked on infrared laser
  - Going to the working point in an adiabatic way

- Filter cavity:
  - Filter cavity locked 2 days ago



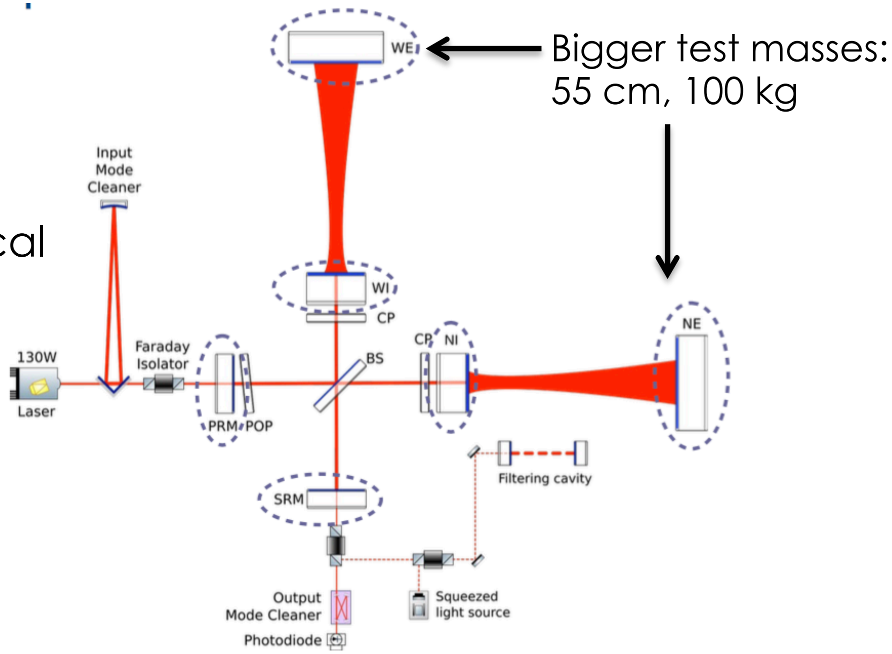


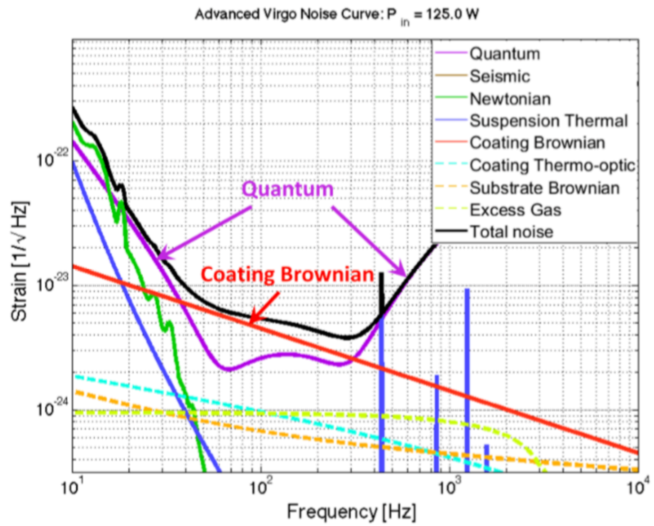


Advanced Virgo+: phase 2

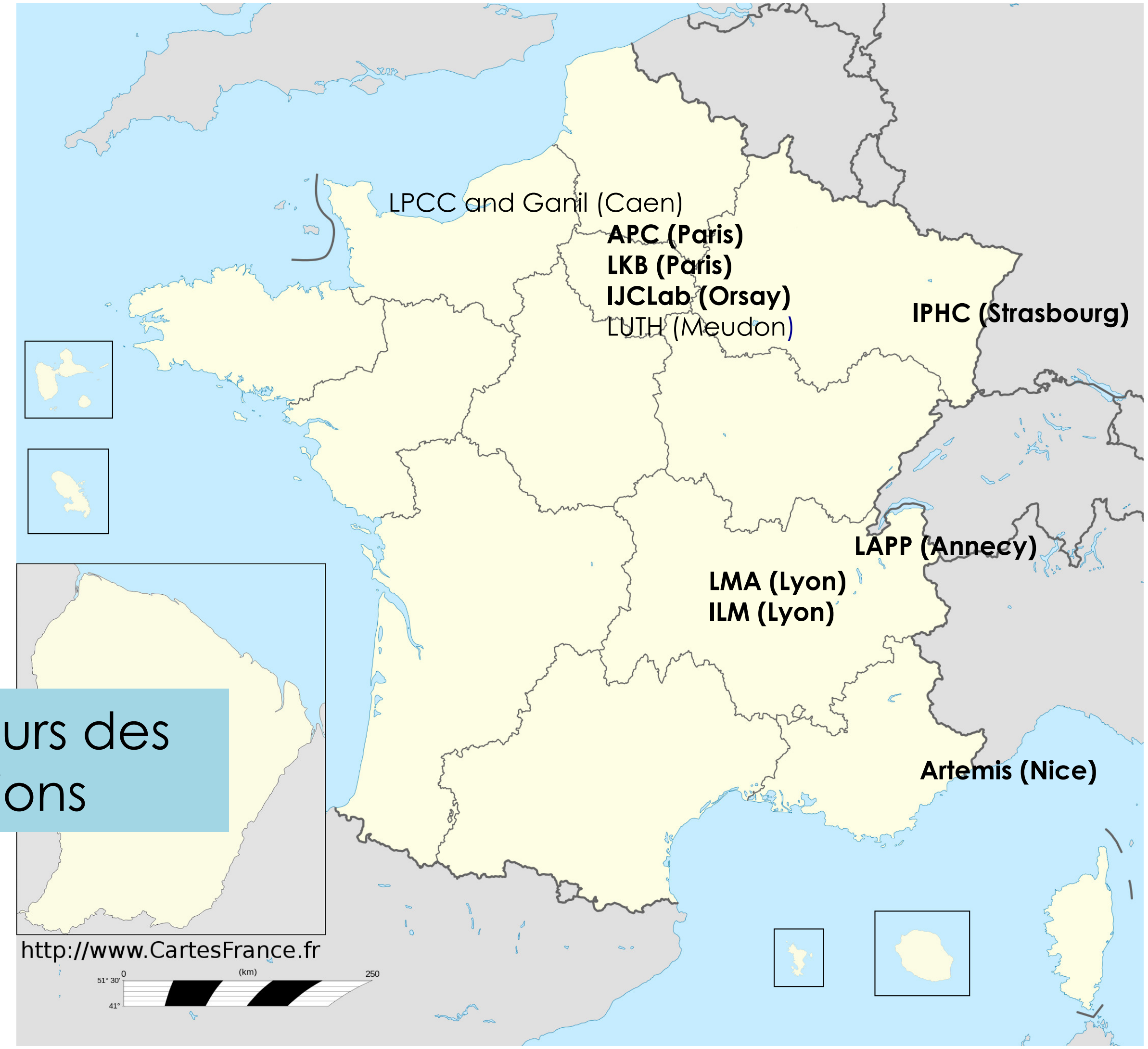
- **Thermal noise reduction :**
  - Beam size increase on end test masses
  - R&D on coating mechanical and optical properties

- Quantum noise reduction
  - Laser power increase (40 W → 80 W)





Virgo teams in France



102 auteurs des publications

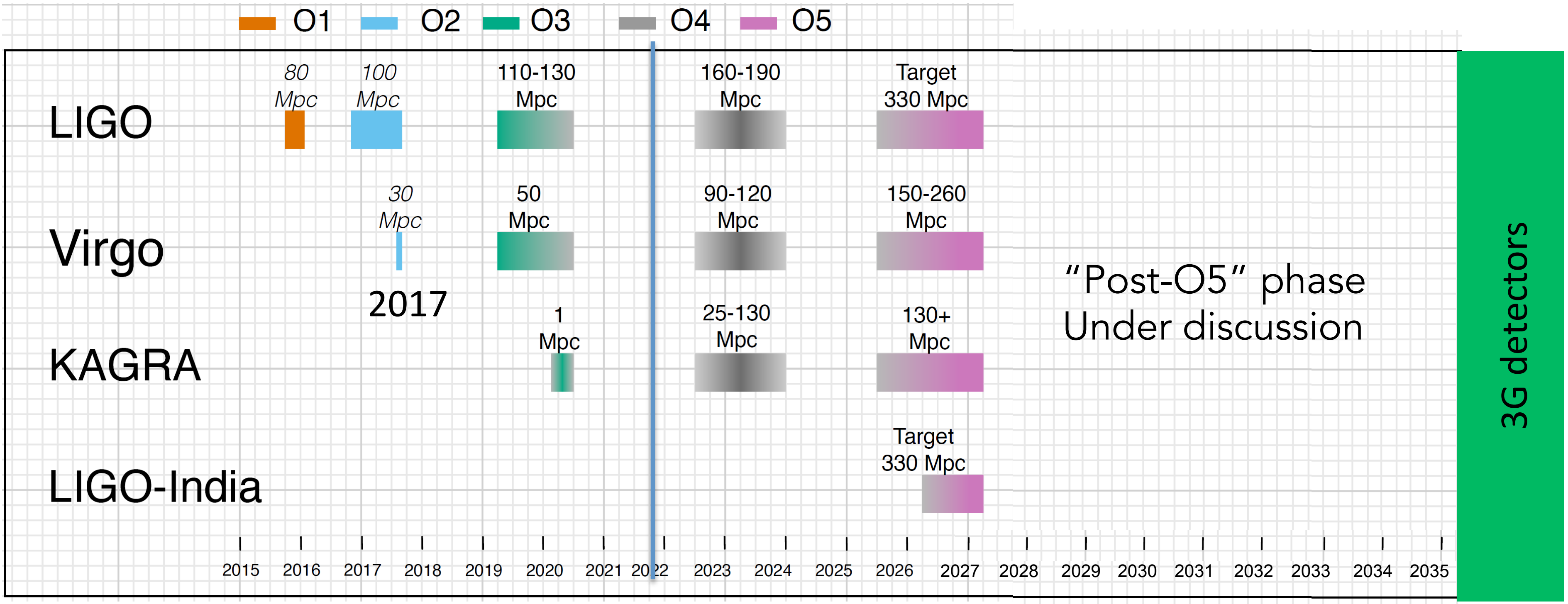
Some of the activities and responsibilities in France on Advanced Virgo+

Advanced Virgo+

- Development, construction and commissioning of the detector, in particular:
    - mirrors and coatings
    - detection system
    - squeezing
    - digital and analog electronics
    - new suspended bench under vacuum
    - laser

- Advanced Virgo+ project leader
- head of the "interferometer" system
- Sub-system managers of: "detection", "data-acquisition", "auxiliary lasers", "squeezing injection", "mirrors", "calibration", "Laser", "coatings"

The future



- Advanced Virgo
- Advanced LIGO

- Advanced Virgo+
- Advanced LIGO+

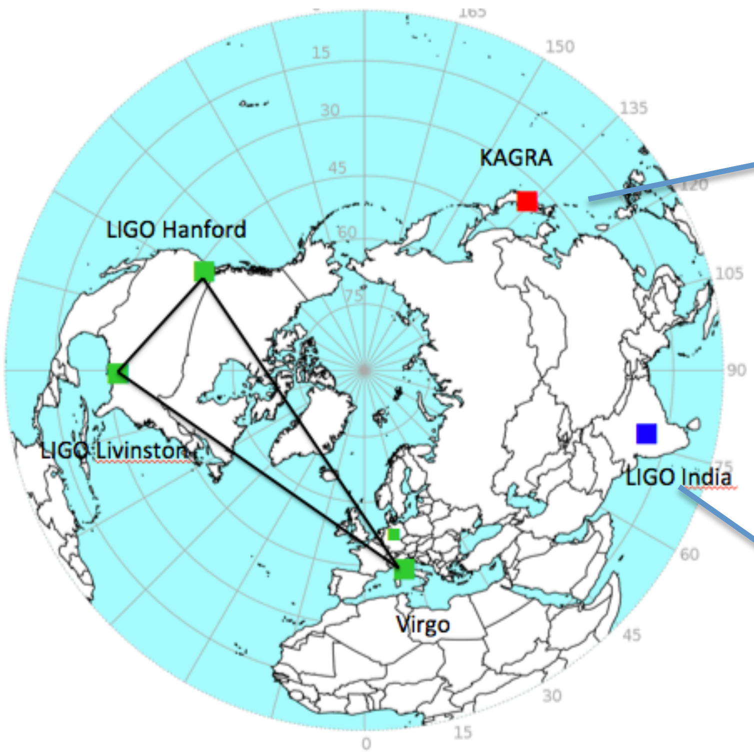
- Einstein Telescope
- Cosmic Explorer
- Nemo

Possible upgrades being evaluated for post-O5 phase

- New coatings
- Large mirrors/beams on all test masses
- New vacuum links in the central area
- Fully monolithic payloads
- Control noise improvements
- Enhanced Newtonian noise subtraction
- Superattenuator upgrade
- Scattered light additional mitigation
- Higher input power
- Stable recycling cavities

- Improved thermal compensation system
- Improved frequency dependent squeezing
- Change readout scheme
- DAQ/phase and demodulation noises
- Changes in the ITF mirror reflectivities
- Changes in the signal recycling (tuning, reflectivity)

The GW detector network in the next years



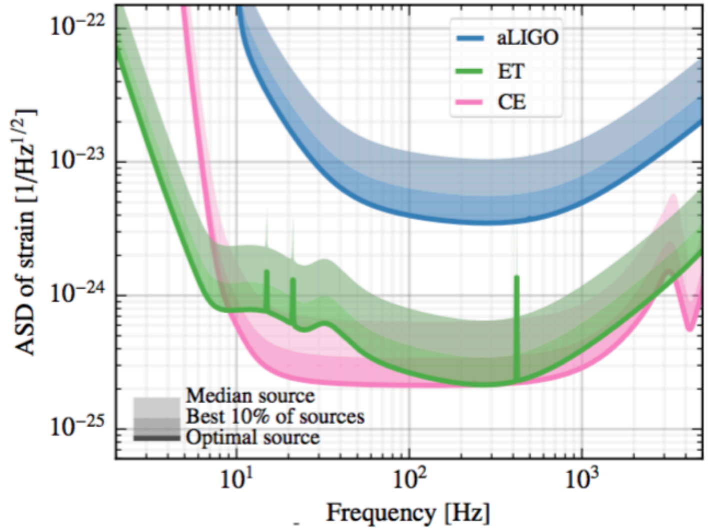
KAGRA
- cryogenic and underground
- Under commissioning
- Best sensitivity ~ 1 Mpc

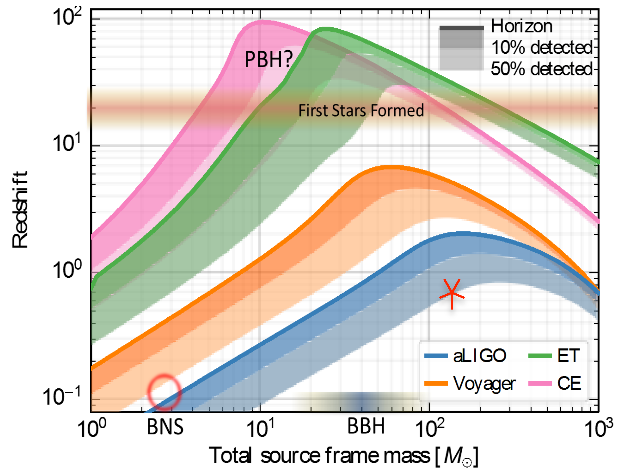
LIGO India
- Site in Maharashtra state
- Land acquisition completed
- Study of vacuum system
- Off-site building constructed

Einstein Telescope (ET), in short

- An order of magnitude better than current detectors
- Pushing down the observational bandwdith: 10-20 Hz → 2 Hz

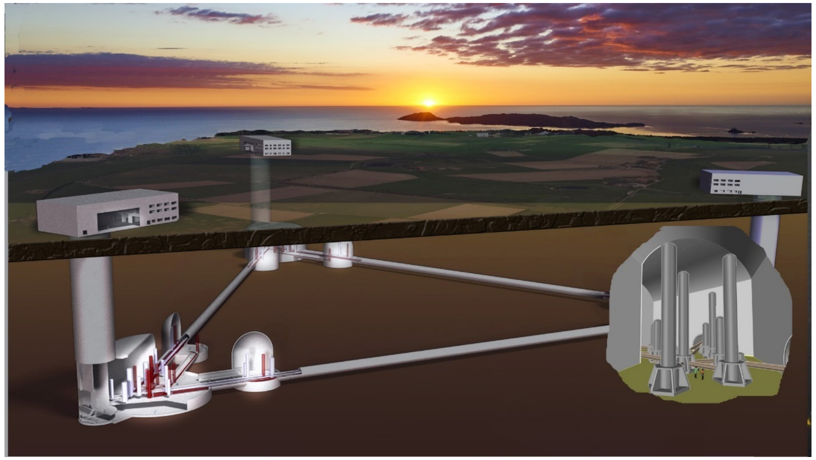
- Conceptual design report in 2011

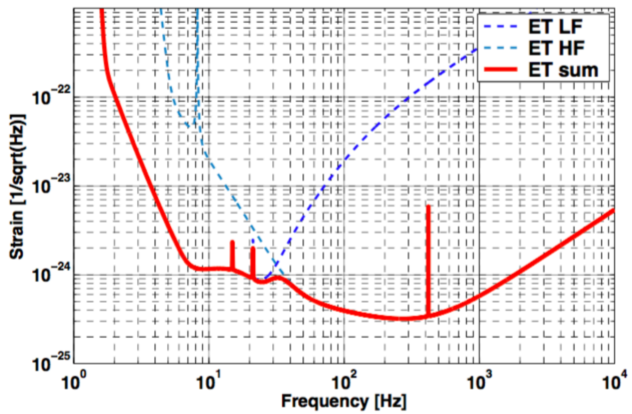


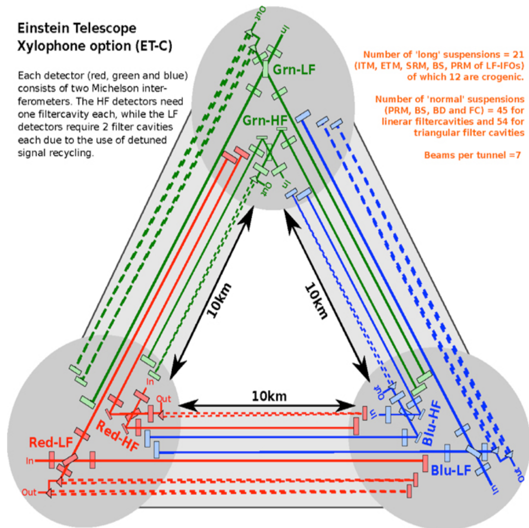


ET design features

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

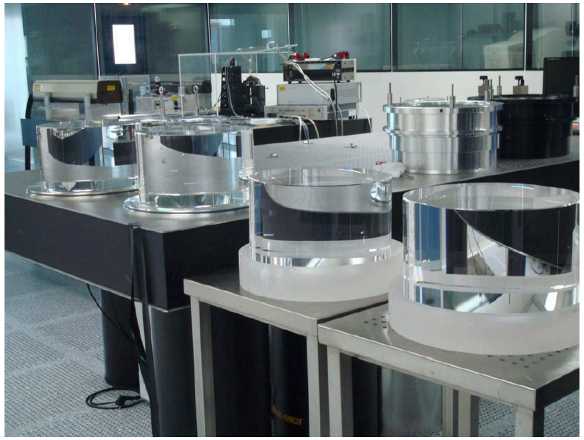




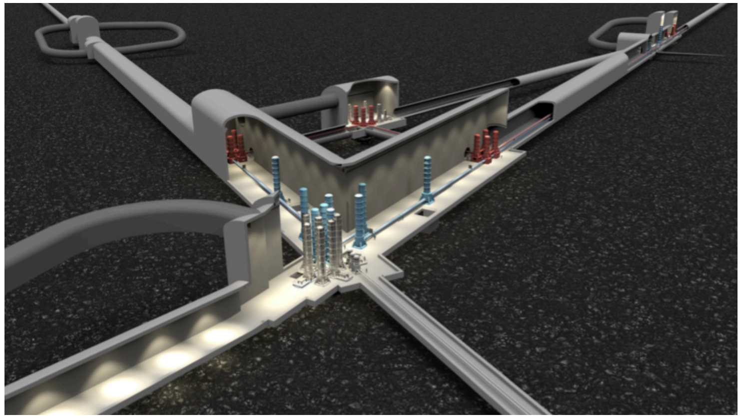


http://www.et-gw.eu/

The ET technologies and challenges



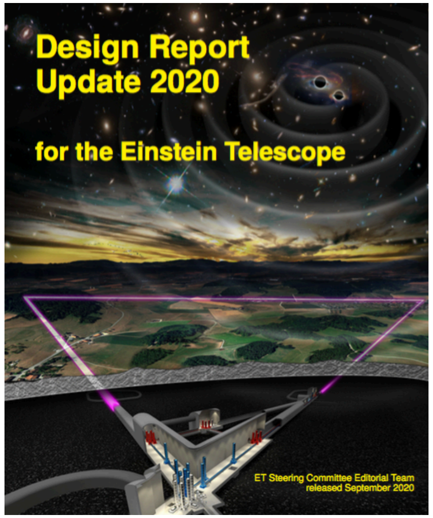
- Extrapolation of current or planned technologies for Virgo and LIGO
  - Squeezing (non classical states of light)
  - High-power lasers
  - Large mirrors
  - New mirror's coatings
  - Thermal compensation techniques
  - Seismic suspension systems
- Technologies not tested in Virgo and LIGO
  - Cryogenics (also in KAGRA)
  - New cryogenic materials
  - New laser wavelengths
- R&D program needed
- Challenges in building a complex underground facilities



Possible planning

September 2020 ET submitted at ESFRI (result in September 2021)

- 2021 Formalisation of the ET collaboration
- 2023 Technical design report
- 2024 Selection of the hosting site
- 2026 Full technical design report
- 2027 Beginning of the excavation works
- 2032 Start of installations
- 2036 Data taking



Euregio Meuse-Rhin (Pays-Bas, Allemagne, Belgique)

SOS Enattos mine Sardaigne (Italie)

Summary

- GW science
  - 4 exceptional events published in O3 (last one is the intermediate BH)
  - catalog GWTC-2: 39 new sources during O3a – Total = 50 sources
  - New analysis on going for O3 and O3a

- Detecor
  - A modified Michelson interferometer with suspended test masses
  - Keyworkds: Optics, vacuum, electronics, control, quantum technologies

- Advanced Virgo+ is in progress
  - Phase 1 installaton concluded
  - Commissioning (full interferometer and filter cavity) started and progressing well
  - Phase 2 in preparation
  - O4 as of today in June 2022, O5 in 2025

- Filling the gap between O5 and ET
  - work started
  - post-O5 committee document planned end 2021

- Einstein Telescope is taking off
  - Great scientific potential, possible starting date ~ 2036
  - ESFRI submitted - collaboration organization on-going
  - Work on technical design report started
  - Extrapolation of Virgo technologies and new technologies (i.e. cryogenics)