Conseil Scientifique IN2P3 2020

Advanced Virgo+ and the road towards Einstein Telescope

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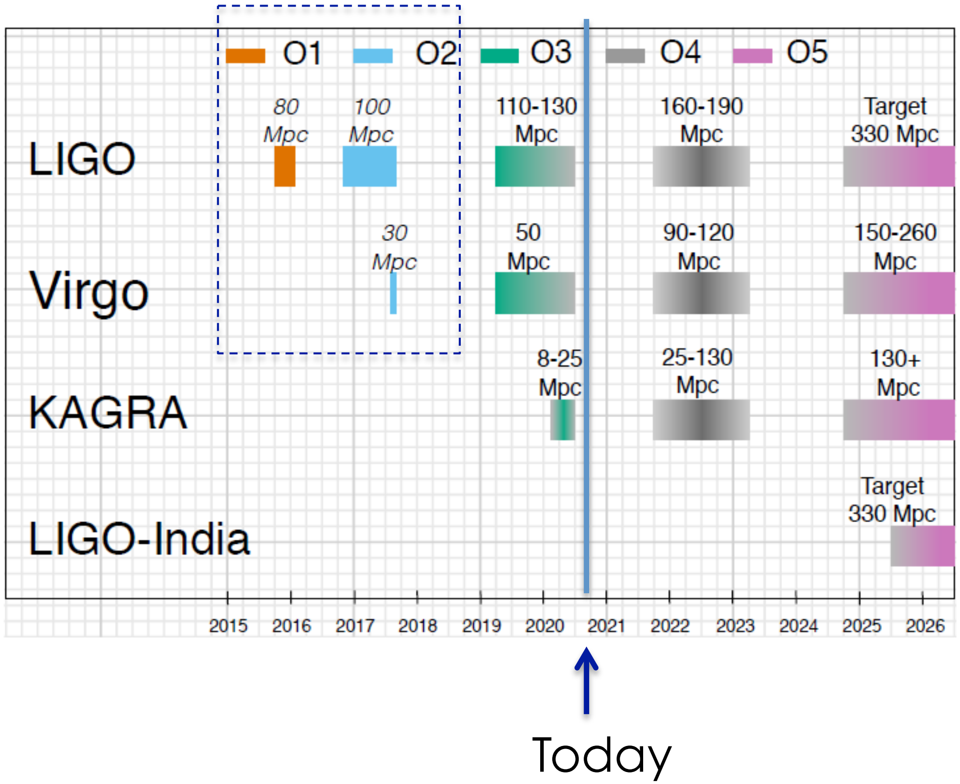
On behalf of the IN2P3 Virgo groups

(APC, IJCLab, IPHC, IP2I/LMA, LAPP)

2015-2017: O1 and O2 data takings



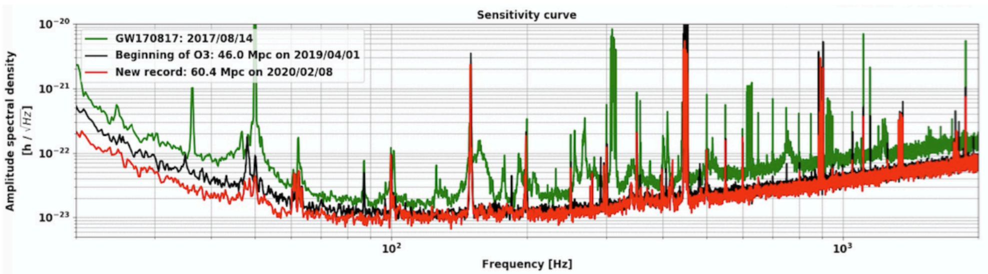
- “Advanced Virgo” and “Advanced LIGO” instruments
- O1: September 2015 to January 2016. 2 LIGO detectors only
- O2: November 2016 to August 2017. Virgo starting from August 2017
- 11 events (10 BBH and 1 BNS)
- GWTC-1 first catalog of GW transient sources (2019)

Abbott (B.P.) et al., *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. (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. X 9, 031040 (2019)

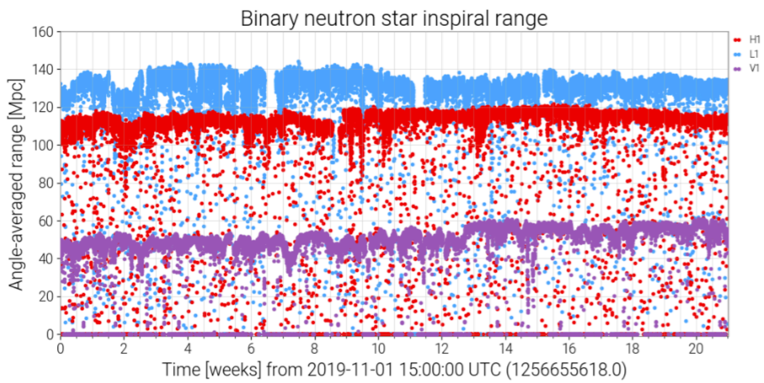
O3 data taking

- April 2019→March 2020 (1 month before for the COVID-19)
- BNS best range from 25 Mpc (O2) to 50-60 Mpc (end of O3)
    - Monolithic suspensions, squeezing, laser power increase, technical noises reduction
    - Further improvements during O3 (commissioning break in October 2019)

Virgo h_equivalent linear spectral density



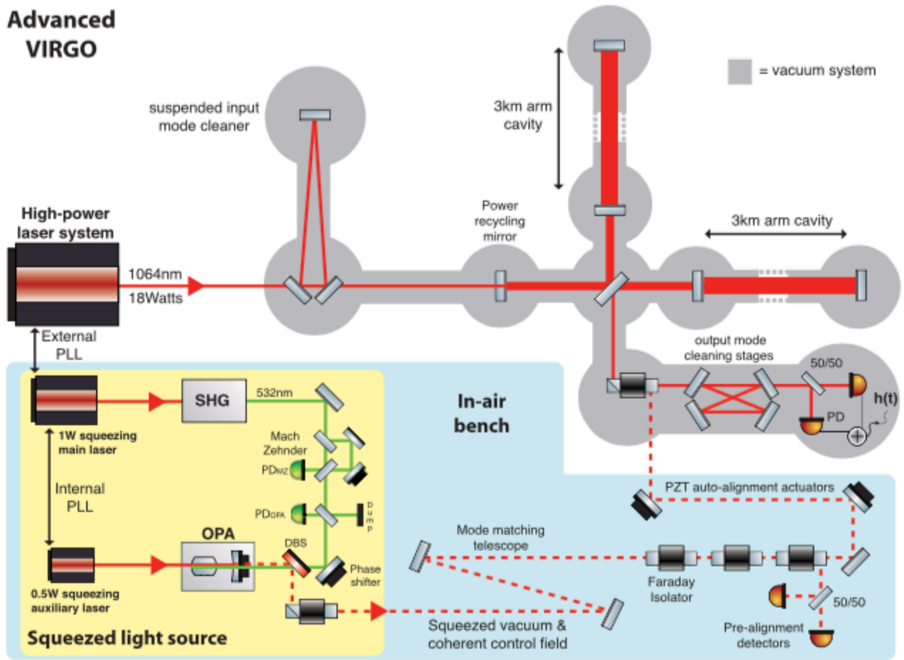
Virgo and LIGO BNS ranges during O3

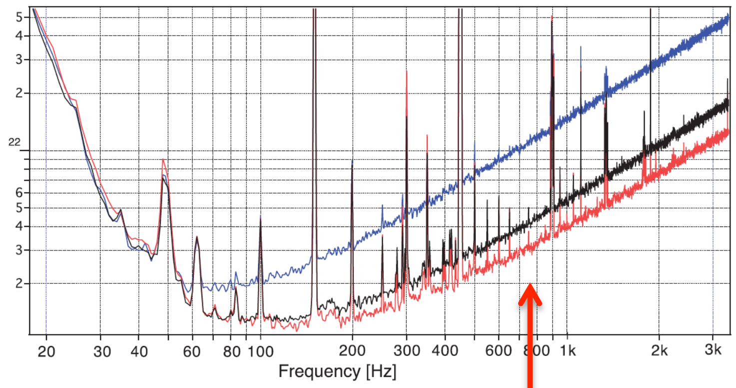


L1: 120-140 Mpc
H1: 110-120 Mpc

Virgo: 50 to 60 Mpc

Squeezed light injection during O3



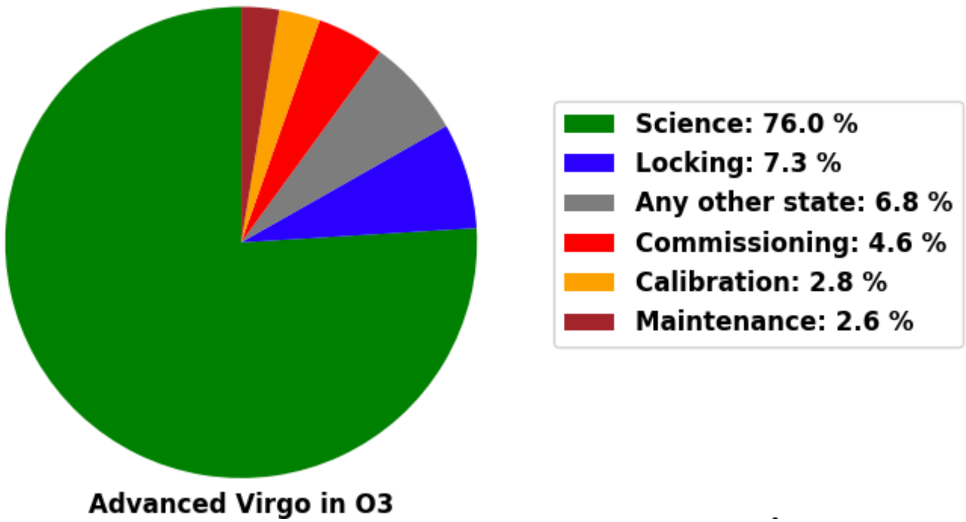


Squeezed vacuum injected

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)

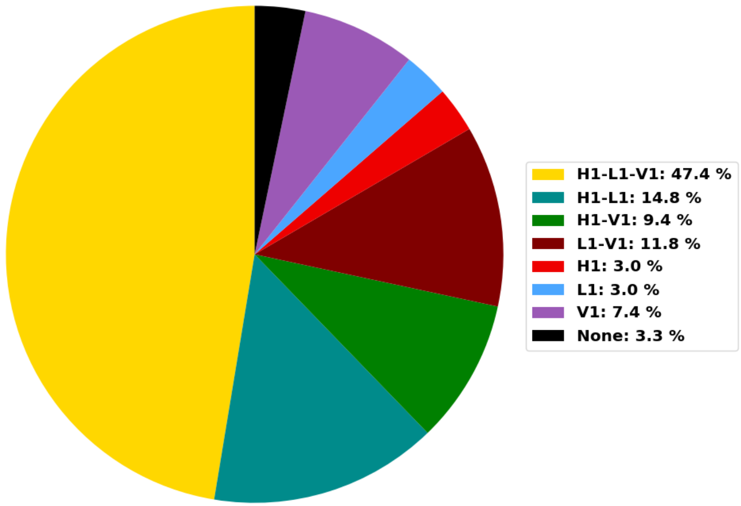
Duty cycle

Virgo



Virgo: 76 % in science mode

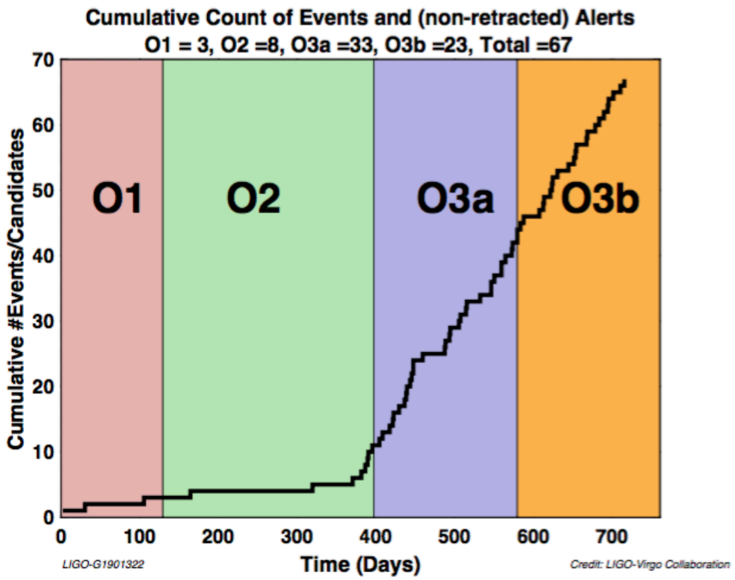
2 LIGO + Virgo network



47% 3 detectors

83% at least 2 detectors

O3 scientific results in short



- 56 candidates identified (~ 1/6 days)
- Public alerts

- 4 new « exceptional » astrophysical systems
- More distant sources (z=0.49 → 0.82)
- New tests of general relativity

- GWTC-2 (second catalog) O3a after tomorrow

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

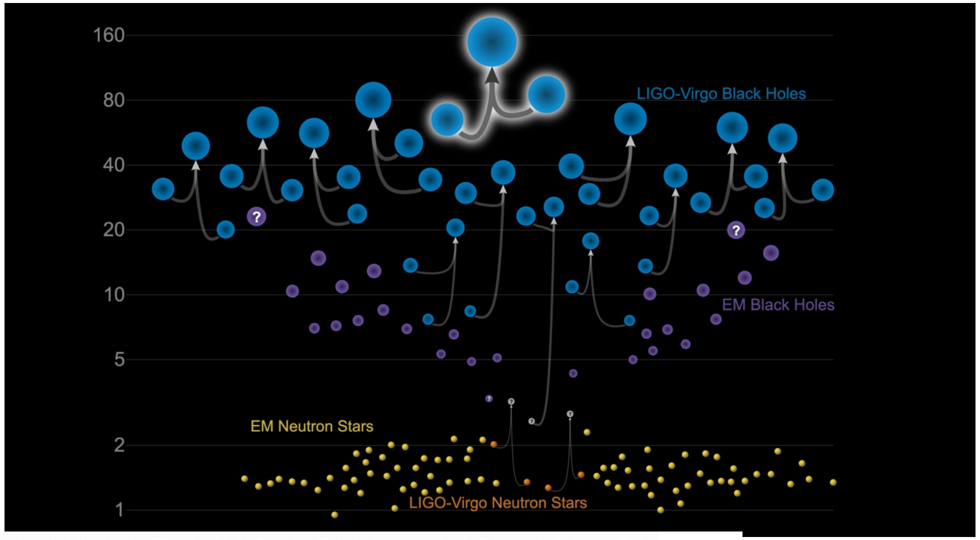
- GW190412, a BBH merger, with component masses ~ 8M⊙ and ~ 3M⊙
    - Mass asymmetry → observable GW beyond the leading quadrupolar order

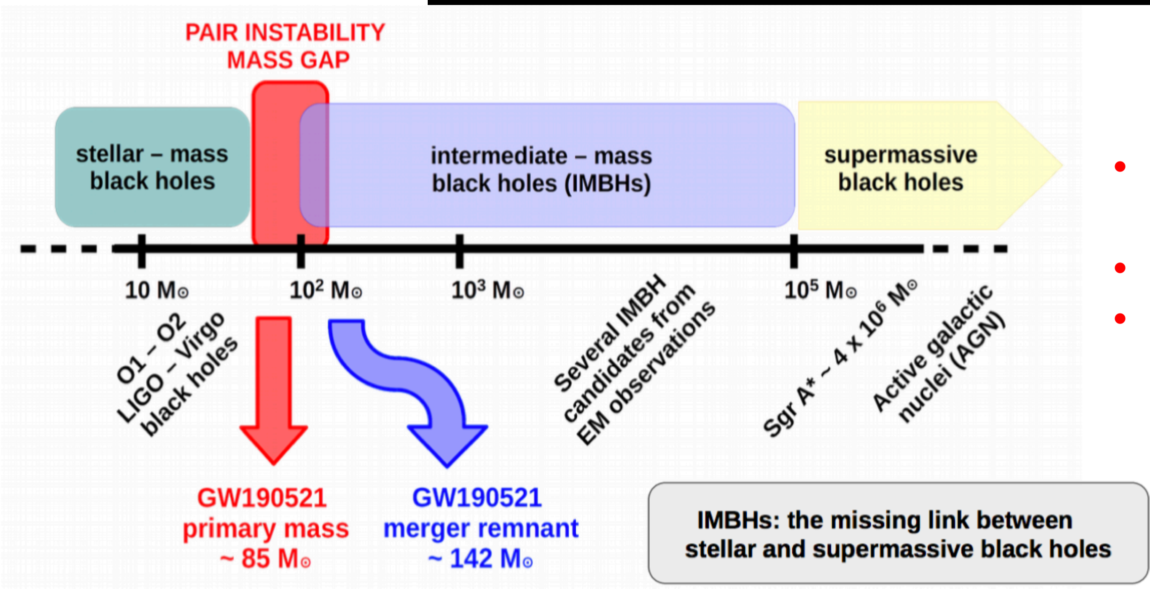
- GW190814, a compact object merger, with component masses ~ 23M⊙ (BH) and ~ 3M⊙
    - ~ 3M⊙ object: the lightest BH or the heaviest NS ever observed ?

- GW190425, a BNS merger, with a total mass of ~ 3.4M⊙
    - Total mass significantly larger than any of the other known BNS system

- GW190521, a BBH merger with component masses ~ 66M⊙ and ~ 85M⊙. The final BH is 142 M⊙

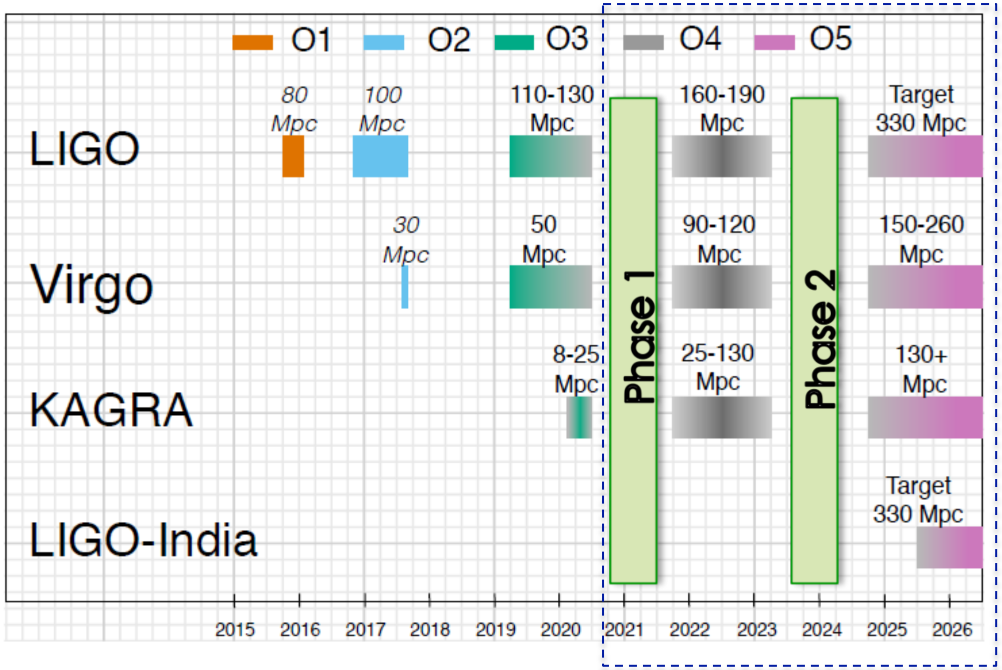
GW190521: the first intermediate-mass BH observed by LIGO and Virgo





- 85 M⊙ BH in the pair-instability mass gap
- final BH: intermediate mass BH
- Z=0.8, the most distant and massive system observed so far by LIGO-Virgo

Advanced Virgo+



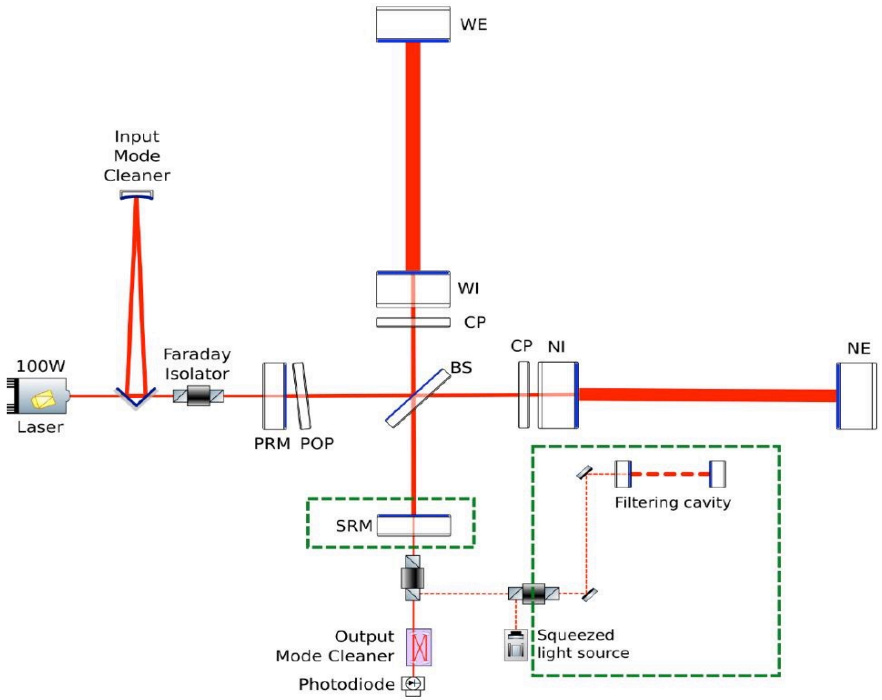
- Project proposed in 2017 by the Virgo Collaboration
- Goal: to increase the BNS range by a factor ~ 3-5 with respect to O3 (50→ 150-260 Mpc) ~ 1000 events / year during O5 (~ 4 events/day)
- phase 1 before O4 (2022)
- phase 2 before O5 (2025)
- 6.6 M€ + 13.8 M€

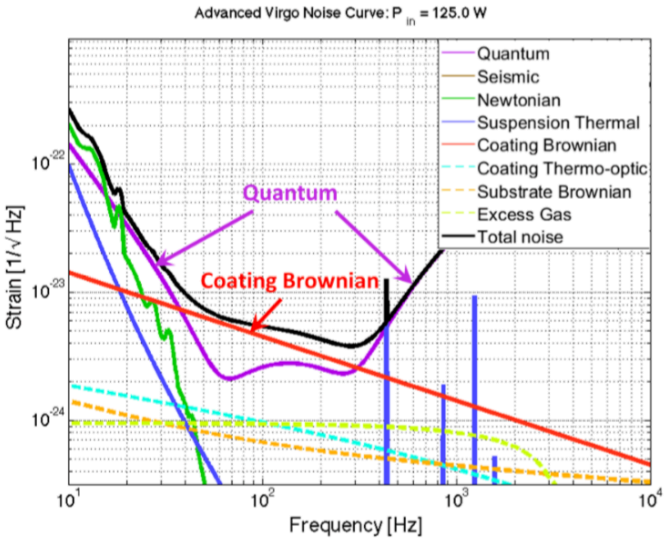
Advanced Virgo +: phase 1

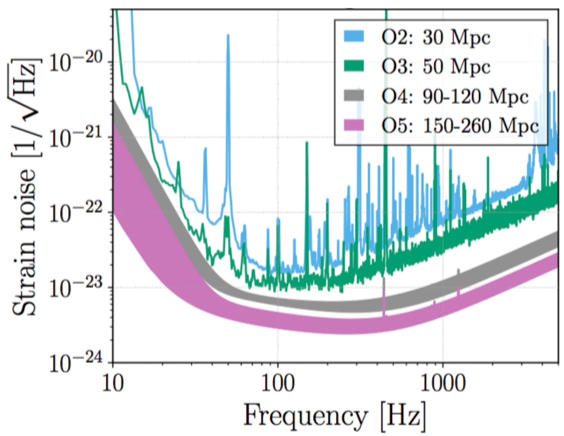
Quantum noise reduction

- Signal recycling
- Frequency dependent squeezing
- Laser power increase (26 W→40 W)

- Newtonian noise cancellation

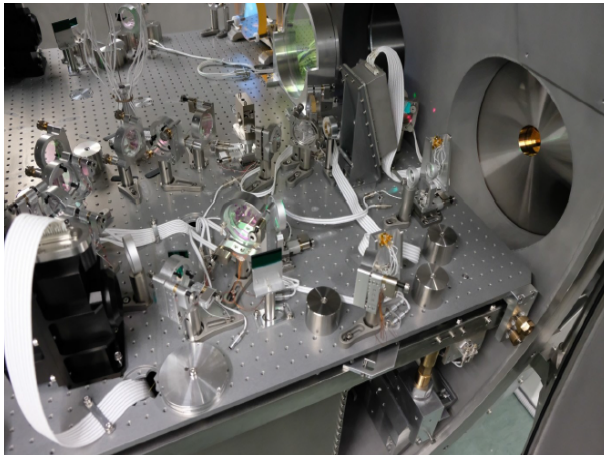


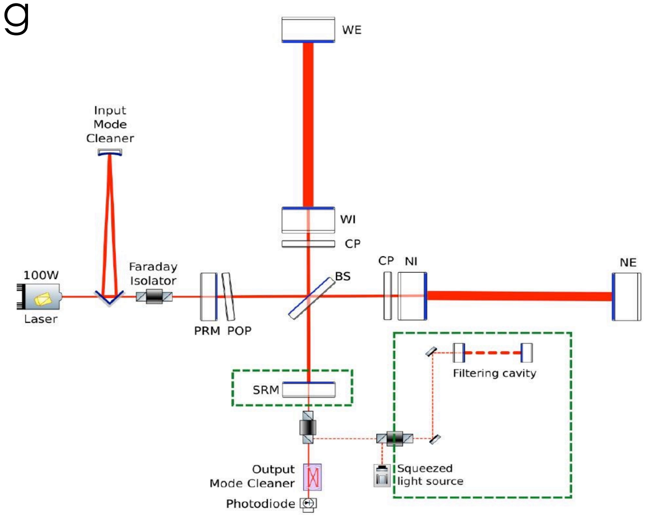




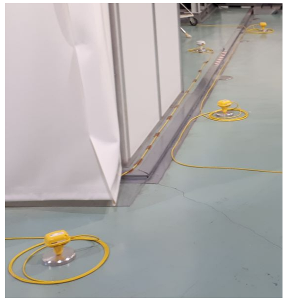
Construction/Integration highlights

Auxiliary green lasers for lock acquisition with signal recycling

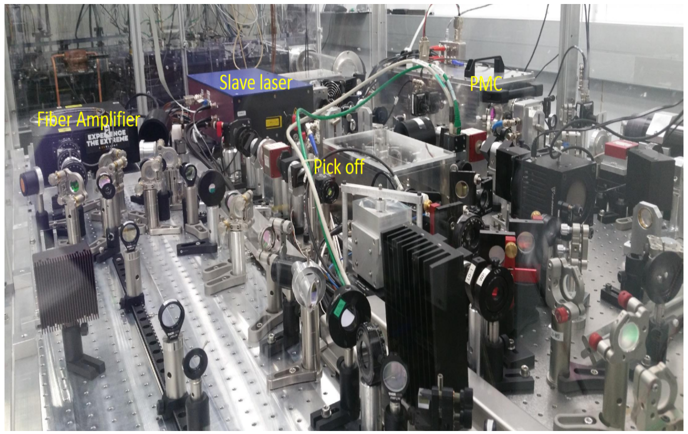




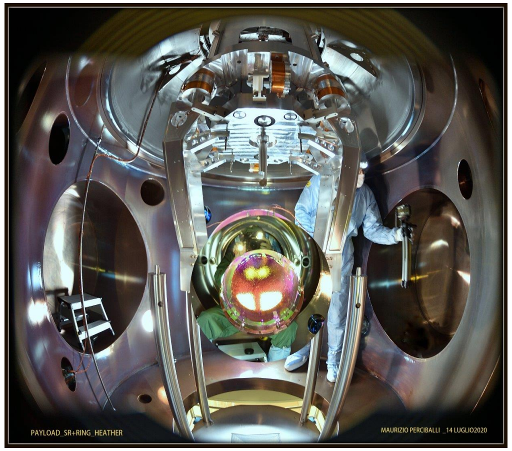
Seismometer for Newtonian noise substraction



Fiber laser, 125 W

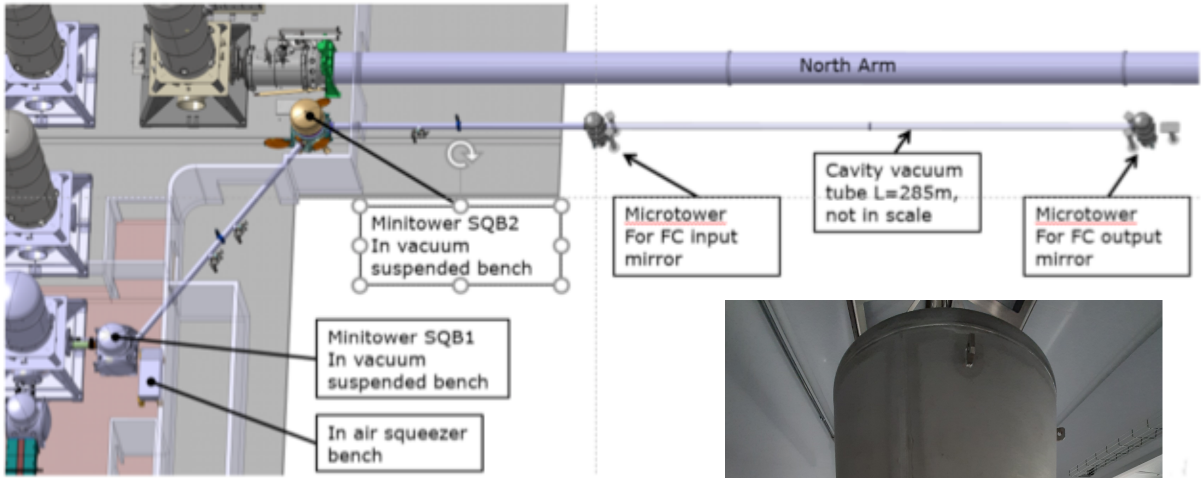


Recycling mirror with its suspension



Construction/Integration highlights - 2

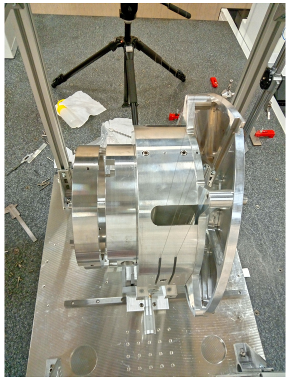
Filter cavity new infrastructure



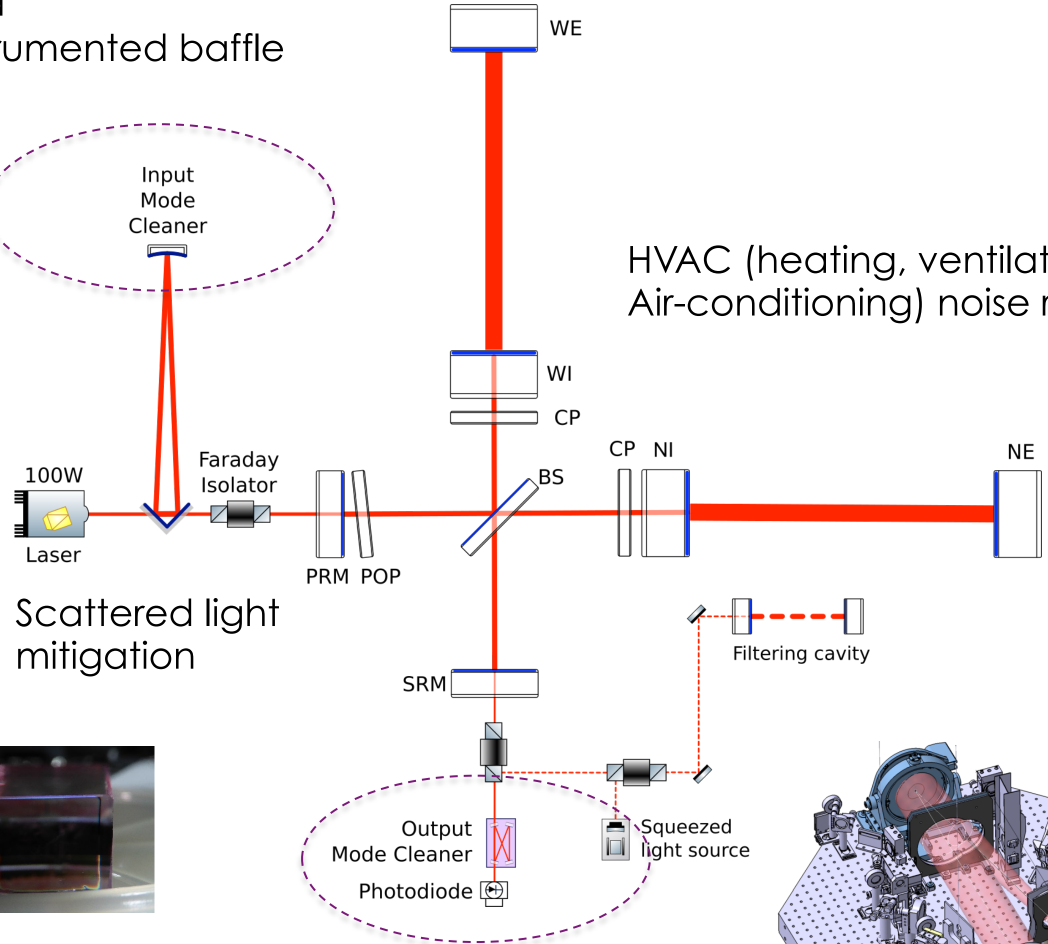
New suspensions

Filter cavity vacuum tube (300 m)

Phase 1: Other upgrades

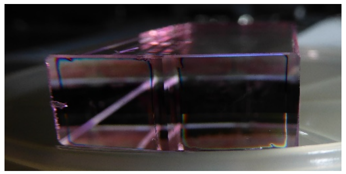


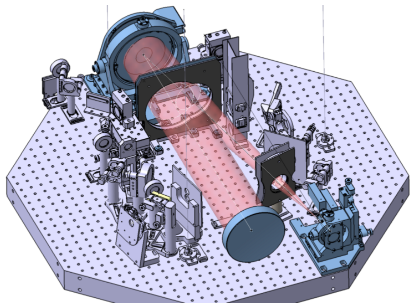
New input-mode cleaner payload
and
Instrumented baffle



HVAC (heating, ventilation and
Air-conditioning) noise reduction

Scattered light
mitigation



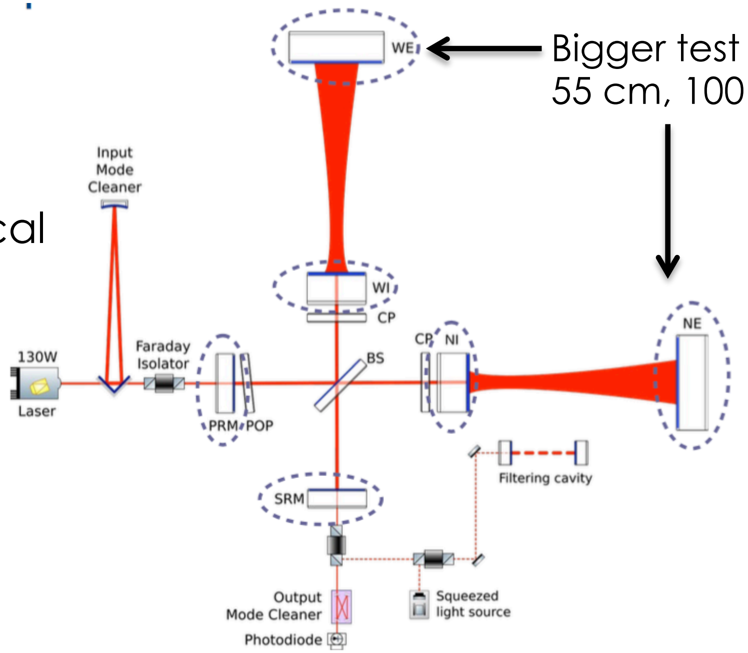


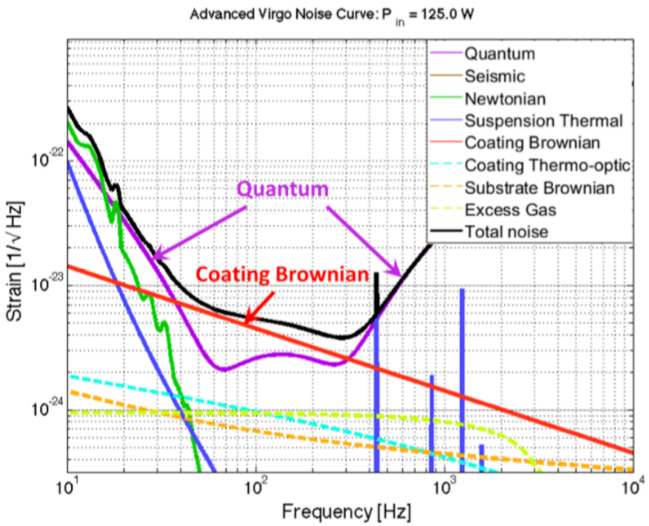
New output mode-cleaner
Scattered light mitigation
New photodiode electronics

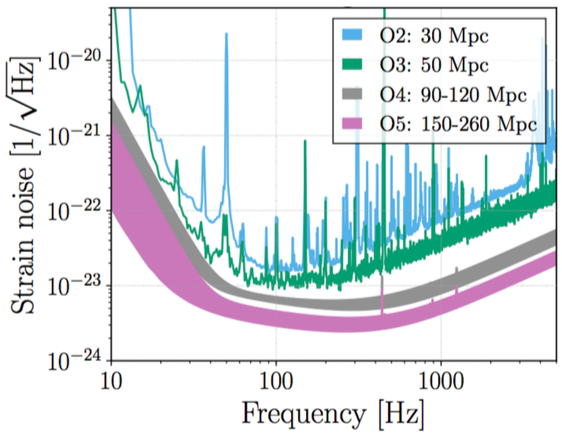
Advanced Virgo+: phase 2

- 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)

Bigger test masses: 55 cm, 100 kg







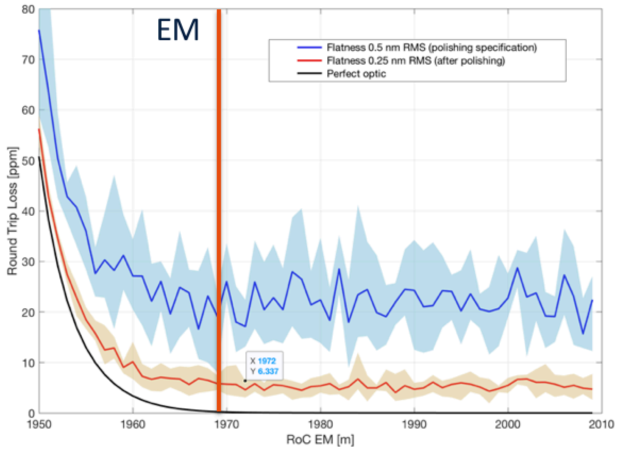
Phase 2: preparation

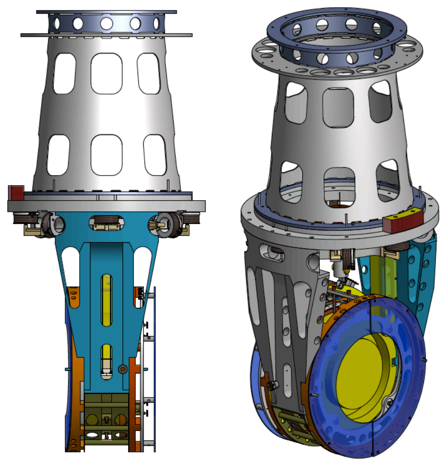
Main activities:

- Finalizing core optics design
- Design of large suspensions
- R&D on coatings

- New mirrors substrates to be ordered now (production, polishing, coating takes more than 2 years)

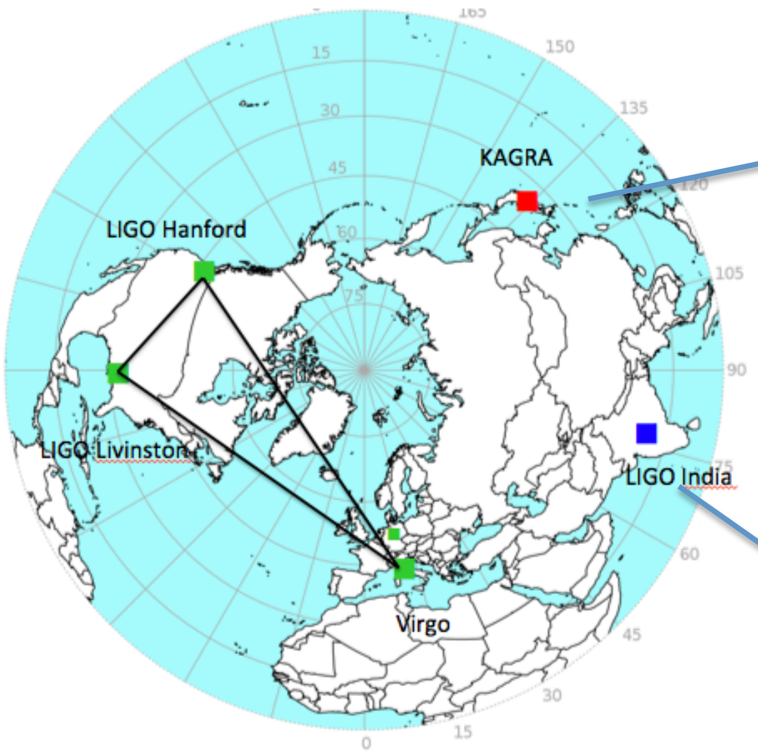
Arm-cavity losses vs radius of curvature end test masses





Design of the end test mass Suspension

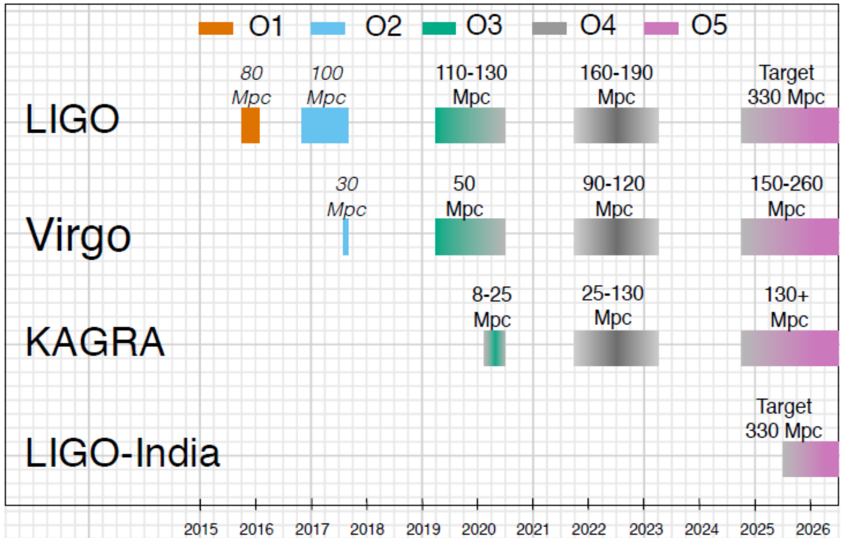
The GW detector network in the next years



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

Virgo after 2027 ?



- Einstein Telescope data not before ~ 2036
- No clear plans yet after O5
- Discussions started
- A cryogenic detector (Voyager) under study in US

Possibilities:

- Other data takings? O6,O7, O8?
- Further improvement of the sensitivity?
- Role of R&D crucial
    - See documents at the journées de prospective IN2P3
    - R&D Virgo France meeting in December
- Testing technologies for Einstein Telescope?

Virgo at IN2P3

- Virgo Collaboration: 13 countries, ~ 600 members, ~ 400 authors of the publications
- EGO consortium: mainly funded by France (TGIR) and Italy

- IN2P3 groups: APC (Paris), IJCLab (Orsay), IPHC (Strasbourg), IP2I/LMA (Lyon), LAPP (Annecy)
  - 98 persons (66 authors of the plublications), 63 FTE
  - Discussions on-going with other laboratories and IN2P3 researchers to contribute to Virgo

- Other groups in France: Artemis (Nice), LKB (Paris), g-MAG/ILM (Lyon)
  - 39 persons, 23.4 FTE

IN2P3 groups: (some of the) activities and responsibilities

Physics searches/Data-analysis

- search of GW by compact objects, stochastic background, tests of general relativity, cosmology using gravitational-waves, multi-messenger astrophysics

- co-chairs of the bursts and stochastic searches
- chair of the Virgo detection characterization group

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

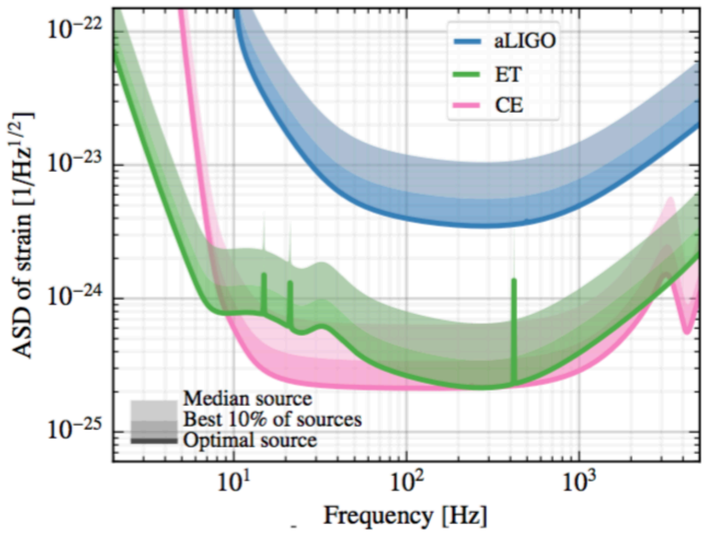
- Advanced Virgo+ project leader
- head of the "interferometer" system
- sub-system managers of: "detection", "data-acquisition", "auxiliary lasers", "squeezing injection", "mirrors" and "calibration" ("Laser" in Artemis)

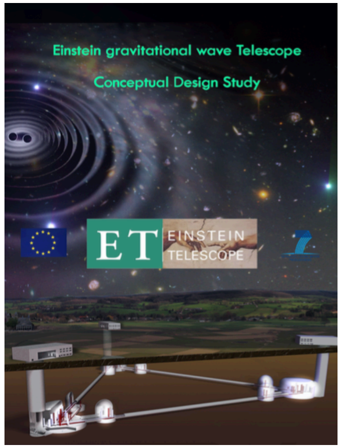
Einstein Telescope (ET), in short

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

- Conceptual design report in 2011

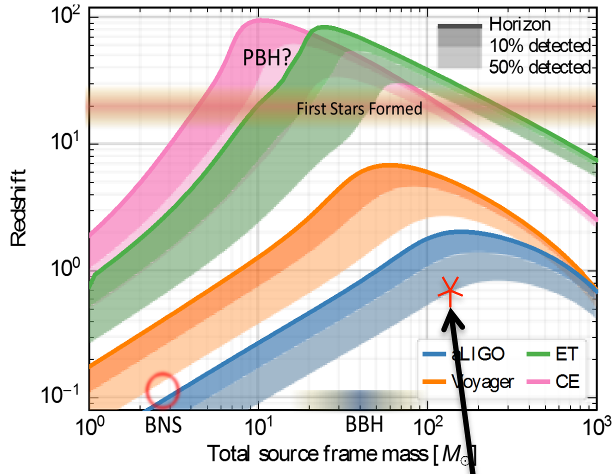
- Similar project in US: Cosmic Explorer (CE)



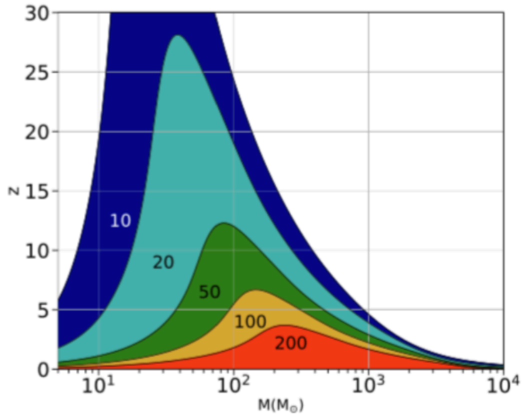


ET science

- Black-holes formation/ population studies
- Fundamental physics / nature of gravitation
- Cosmology / nature of dark energy
- Nuclear physics / ultra-dense matter
- Physics of Supernovae
- Multimessenger astrophysics
- Complementarity and synergies with LISA



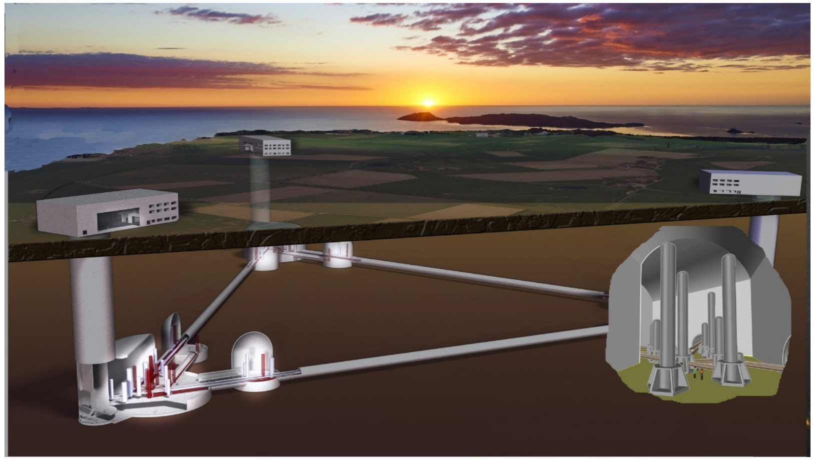
GW190521
z = 0.8, M=150

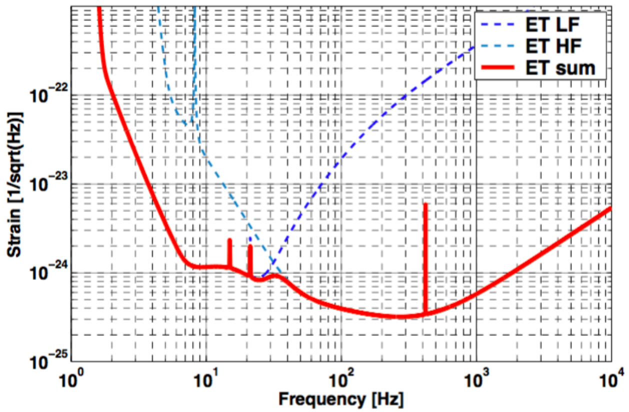


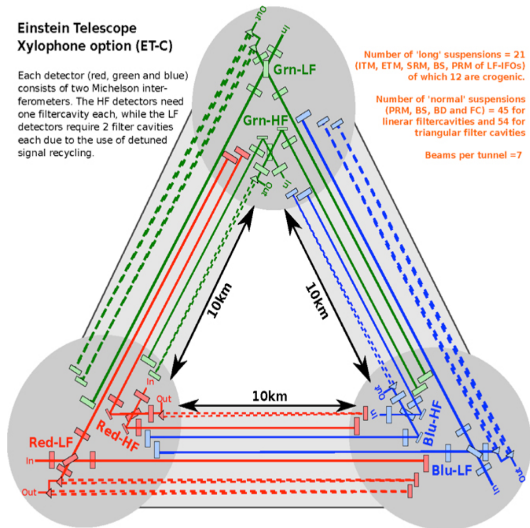
https://arxiv.org/pdf/1912.02622
ET science case

ET design features

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



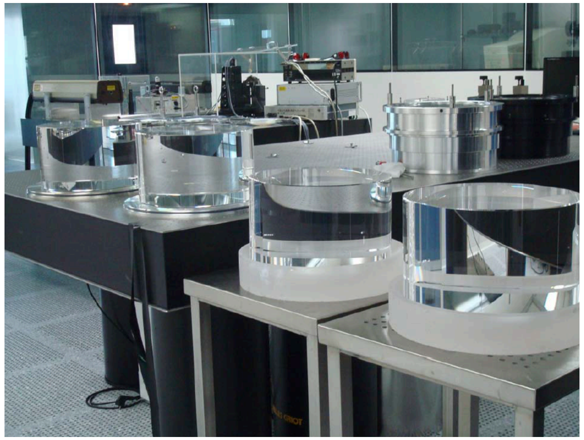




http://www.et-gw.eu/

The ET technologies and challenges

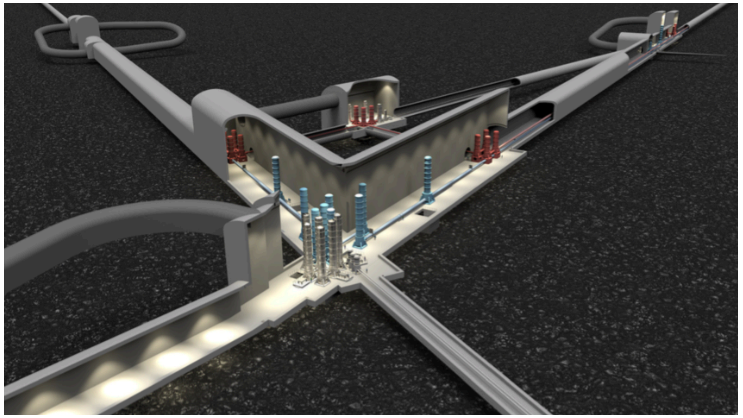
- Extrapolation of current or planned technologies for Virgo and LIGO
  - Squeezing (non classical states of light)
  - High-power lasers
  - Large mirrors
  - New mirror's coatings
  - Thermal compensation techniques
  - Seismic suspension systems



- Technologies not tested in Virgo and LIGO
  - Cryogenics (also in KAGRA)
  - New cryogenic materials
  - New laser wavelengths

- R&D program needed

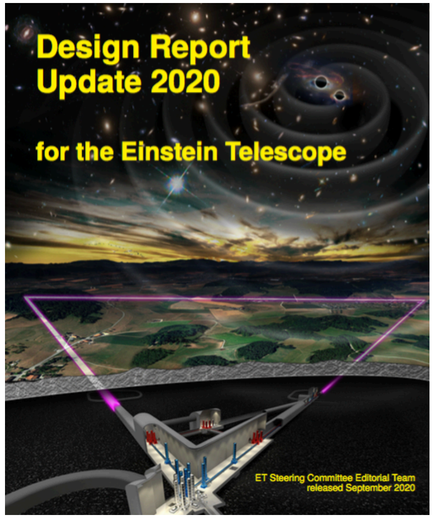
- Challenges in building a complex underground facilities



Possible planning

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

Design report update 2020

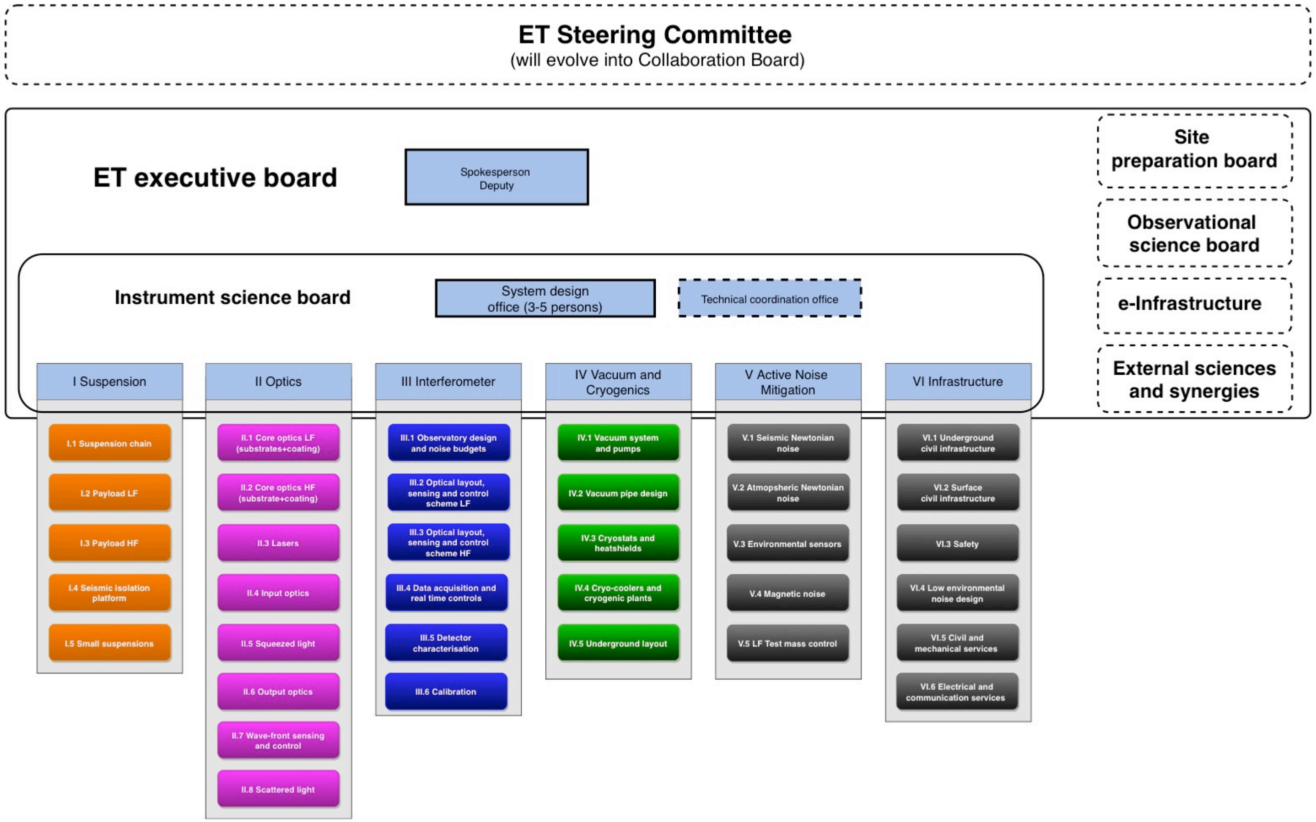


- 2021 Formalisation of the ET collaboration
- 2023 Technical design report
- 2024 Selection of the hosting site
- 2026 Full technical design report
- 2027 Beginning of the excavation works
- 2032 Start of installations
- 2036 Data taking

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

SOS Enattos mine Sardaigne (Italie)

Einstein Telescope: collaboration under construction



- 3 members in France in the ET steering committee (2 IN2P3)
- Instrumental Science Board: 2 IN2P3 members division co-chair of the ISB
- INP23 members are proposed for WP leading roles
- Other commitees (Observational science board, site preparation,...) not yet formed
- Discussions with other groups in France
- ET-France meeting - January 2021

Summary

- A successful O3 data taking
  - x2 sensitivity with respect to O2
  - 75% duty cycle
  - 56 candidates
  - public alerts
  - 4 exceptional events already published
  - catalog GWTC-2 will be published Thursday 29th (O3a) +3 accompanying papers
  - Analysis on-going

- Advanced Virgo+ is in progress
  - phase 1 under integration. Commissioning in 2021
  - phase 2 in preparation (need to order mirror's substrates to be online with LIGO)
  - O4 first semester 2022 (delays COVID-19 possible); O5 in 2025

- Filling the gap between O5 and ET: discussions just started

- Einstein Telescope is taking off
  - great scientific potential, data ~ 2036, complementarity with LISA
  - ESFRI submitted, collaboration organization on-going
  - effort to structure the community in France, fundamental role of Virgo groups