Theory Meeting experiment: Particle Astrophysics and Cosmology 2020

STATUS OF THE ADVANCED VIRGO GRAVITATIONAL-WAVE DETECTOR

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On behalf of the Virgo Collaboration

Université de Paris

16th Rencontres du Vietnam
ICISE, Quy Nhon

OUTLINE

- **Introduction**

I. Technical overview of Advanced Virgo

a) Seismic noise

b) Thermal noise

c) Quantum noise

II. Plan for Advanced Virgo+

a) Phase I: hitting the thermal noise

b) Phase II: pushing the thermal wall

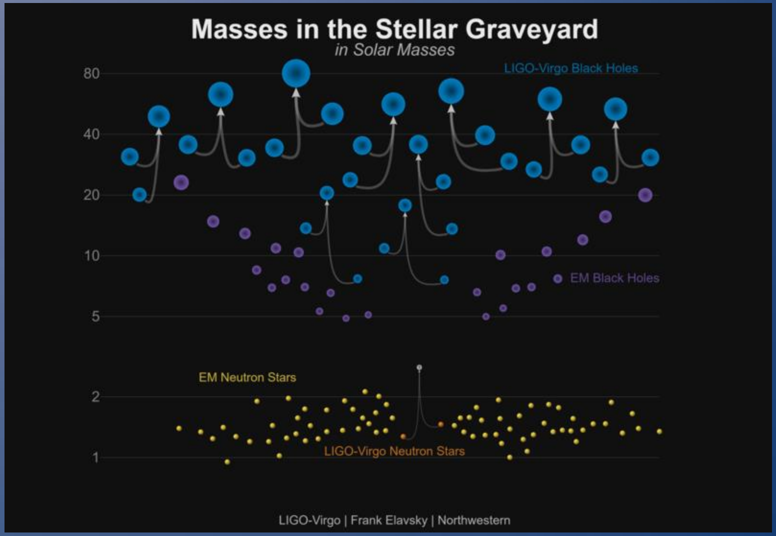
THE DAWN OF A NEW ERA

September, 14th 2015 : the beginning of gravitational-waves (GWs) astronomy

- **<u>Known sources:</u> "GWTC-1 : A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs." arxiv.1811.12907**

- **First and second science run : GW from 10 binary black holes merger and 1 binary neutron stars merger.**

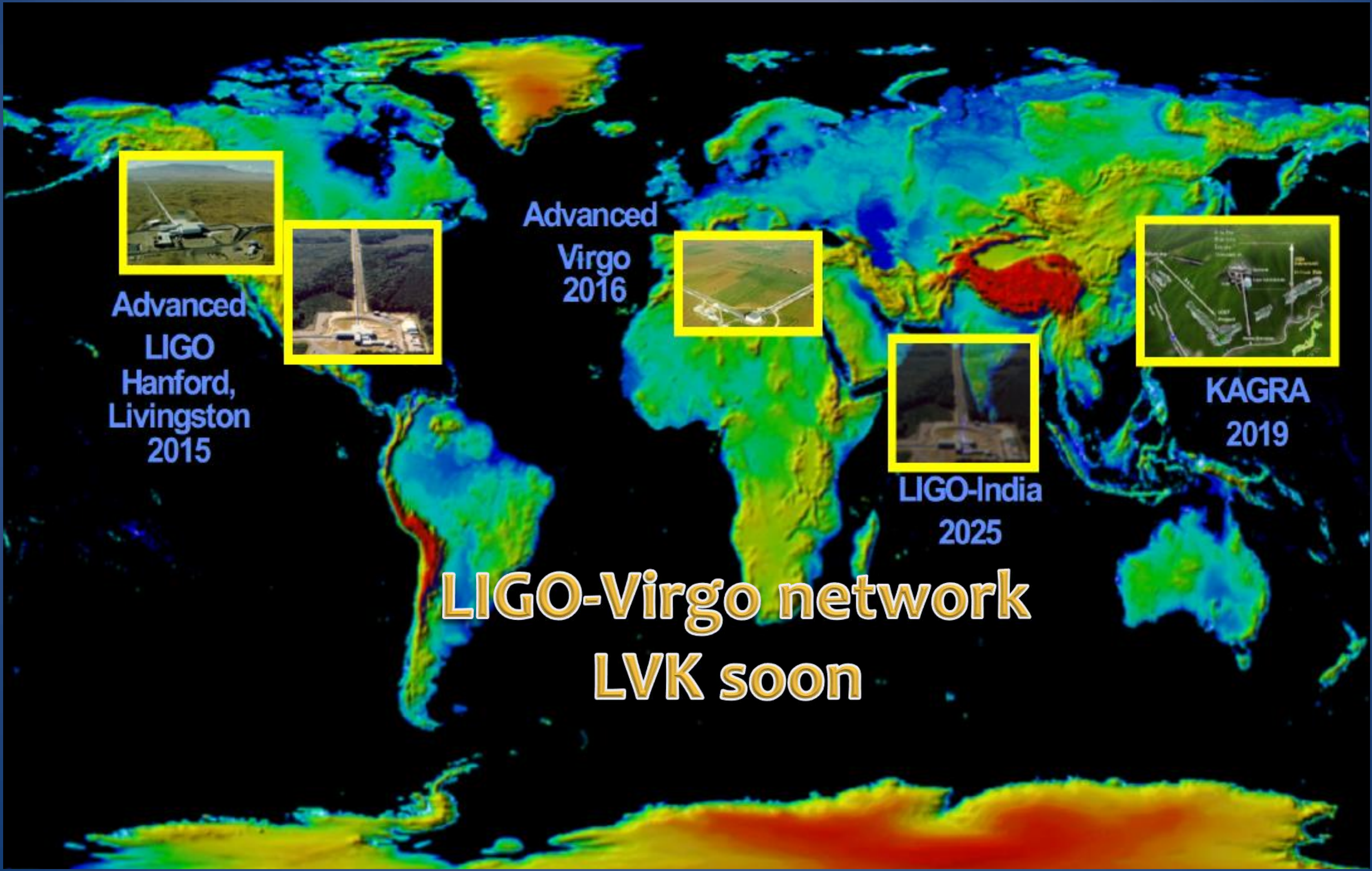
- **Ongoing science run n°3: "O3"**



<u>GWs of 10 BBH and 1 BNS observed (O1 and O2)</u>

See Pia Astone's talk on Monday

GW WORLDWIDE DETECTORS NETWORK



Virgo Collaboration

Virgo is a European collaboration with 502 members, 352 authors, and 98 institutes

Advanced Virgo (AdV) and AdV+: upgrades of the Virgo interferometric detector

Participation by scientists from France, Italy, Belgium, The Netherlands, Poland, Hungary, Spain, Germany

- Institutes in Virgo Steering Committee
  - APC Paris
  - ARTEMIS Nice
  - IFAE Barcelona
  - ILM and Navier
  - INFN Firenze-Urbino
  - INFN Genova
  - INFN Napoli
  - INFN Perugia
  - INFN Pisa
  - INFN Roma Sapienza
  - INFN Roma Tor Vergata
  - INFN Trento-Padova
  - IPHC Strassbourg
  - LAL Orsay ESPCI Paris
  - LAPP Annecy
  - LKB Paris
  - LMA Lyon
  - Maastricht University
  - Nikhef Amsterdam
  - POLGRAW(Poland)
  - University Nijmegen
  - RMKI Budapest
  - UCLouvain, Uliege, UAntwerp
  - Univ. of Barcelona
  - University of Sannio
  - Univ. of Valencia
  - University of Jena

New members since last STAC

In their first year: UMaastricht, IPHC (Benoit M)

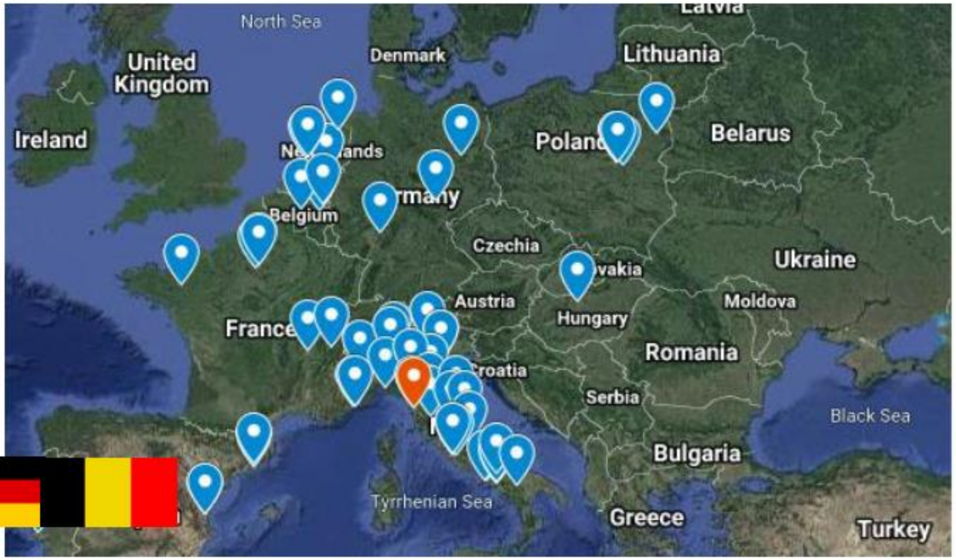
Fully approved: UBarcelona, UCLouvain/ULiege

Through existing groups: UAntwerp via UCL/UL and INFN-Torino through Jena-Prometeo

This week

Request for membership: GSSI, UUtrecht

Year-1 evaluation: IFAE



Jo van den Brand, Status of Virgo, VIR-1119A-19,

I. Technical review of Advanced Virgo

Seismic noise | Thermal noise | Shot noise

OPTICAL DESIGN

I. Technical review of Advanced Virgo

Seismic noise | Thermal noise | Shot noise

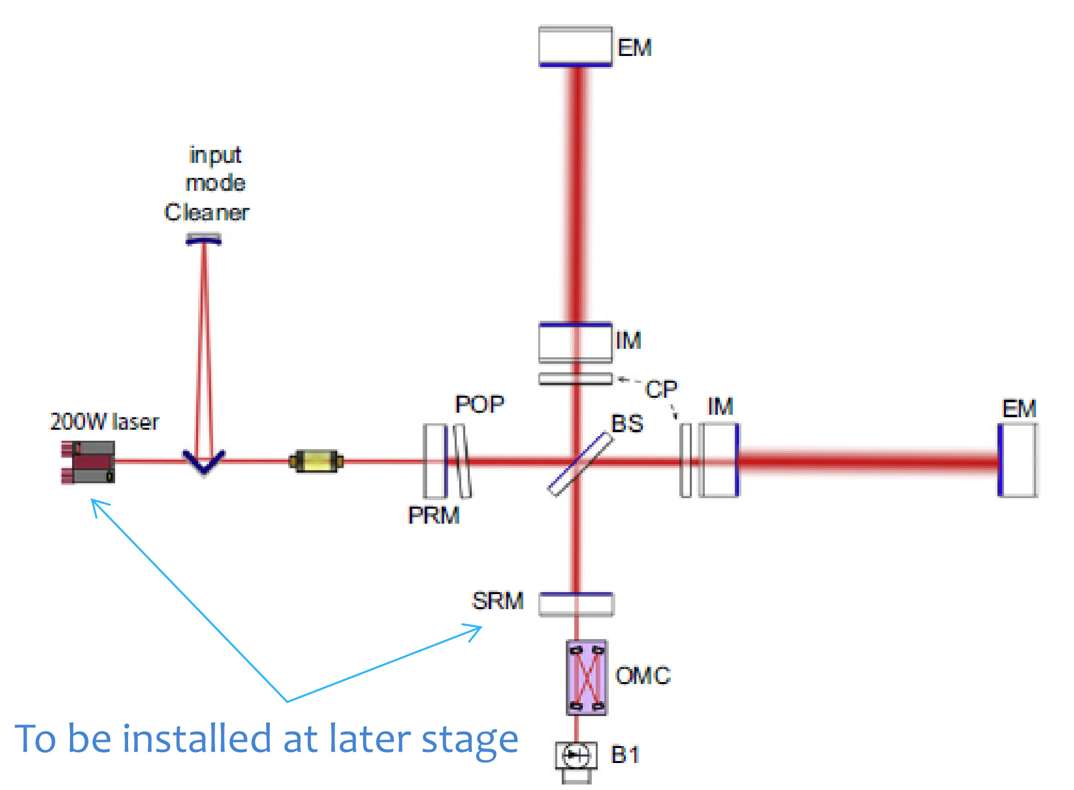
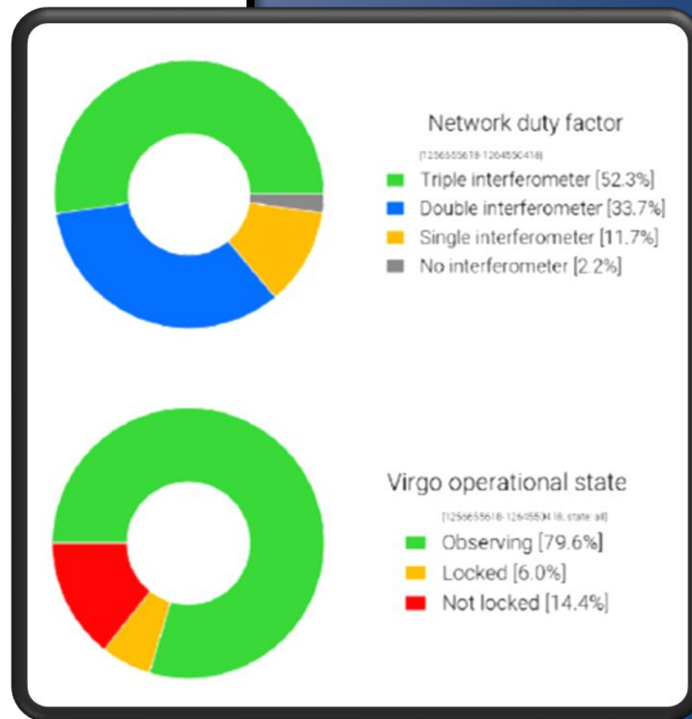


Figure 3. Simplified optical layout of the AdV ITF. Each 3 km long arm cavity is formed by an IM and an EM. The recycling cavities at the center of the ITF are 12 meters long and are formed by the PRM, the SRM and the two IM.

Duty cycle for O3a about >76%

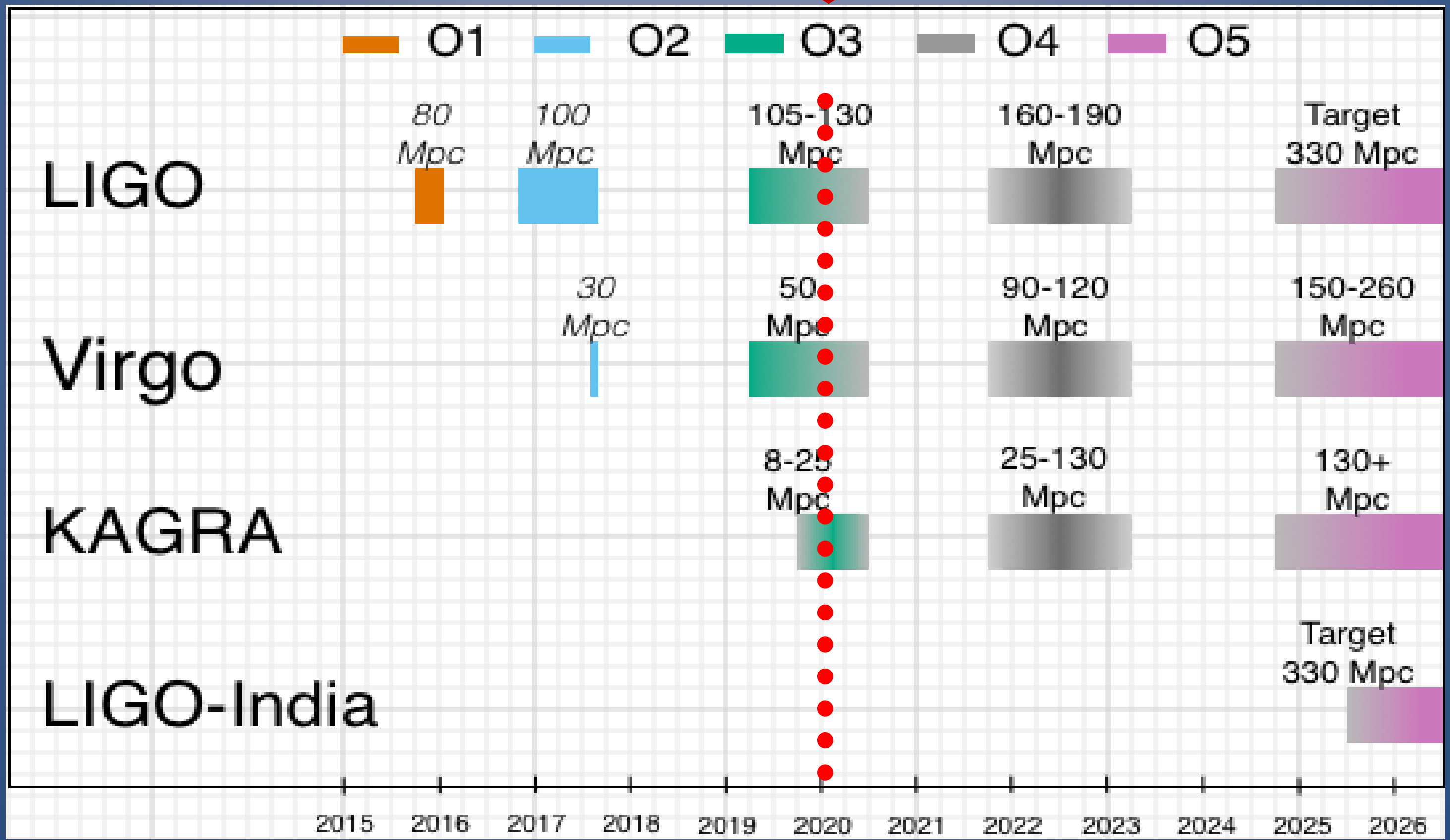


VIR-0006-20

OBSERVING SCENARIOS AND SENSITIVITY

I. Technical review of Advanced Virgo

Seismic noise | Thermal noise | Shot noise



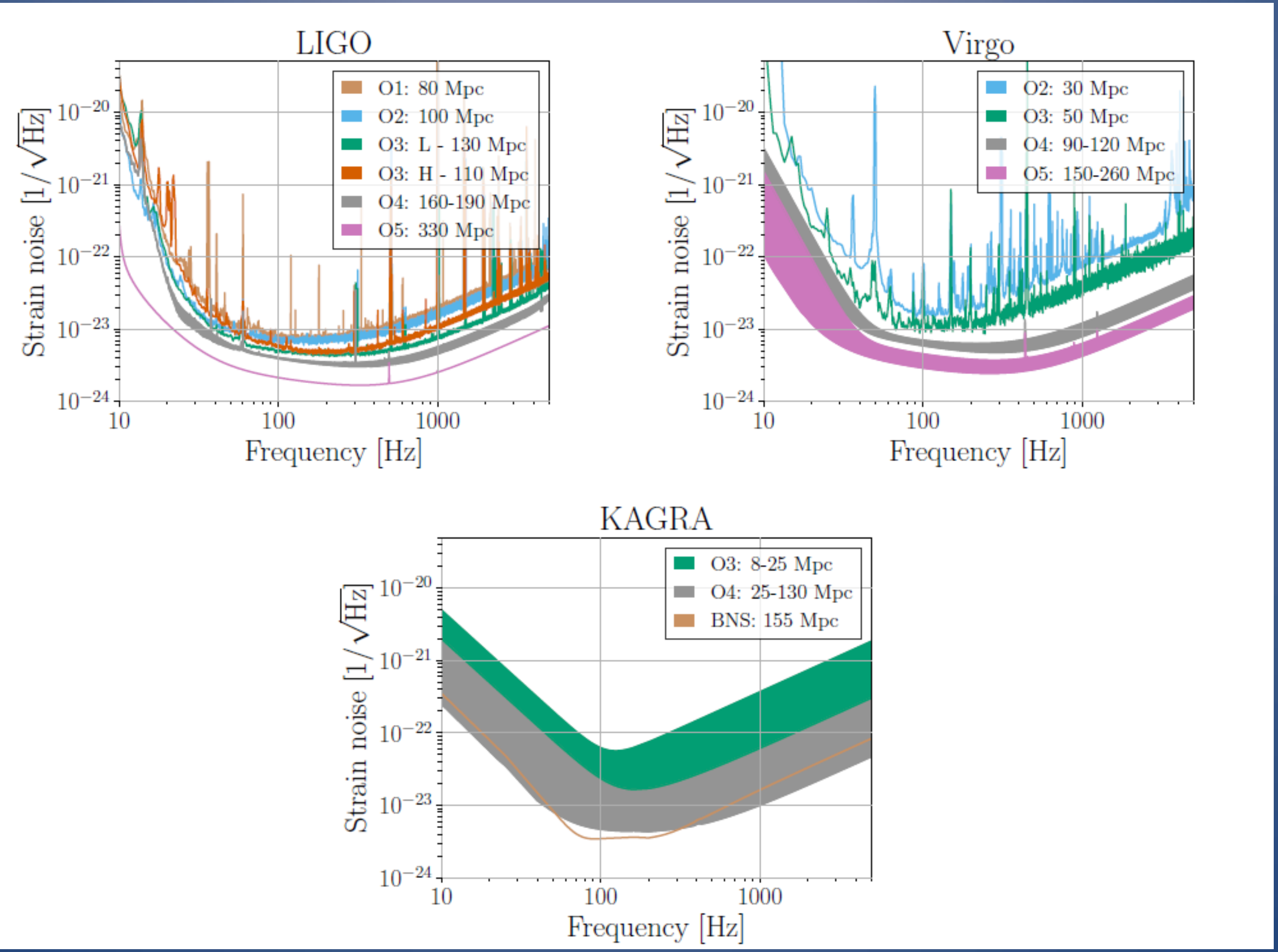
BNS range : Standard figure of merit for the sensitivity of the interferometer

Volume- and orientation– averaged distance at which a compact binary coalescence consisting of two 1.4 $M_{\odot}$ neutron stars gives a matched filter SNR of 8 in a single detector

SENSITIVITY IMPROVEMENT

I. Technical review of Advanced Virgo

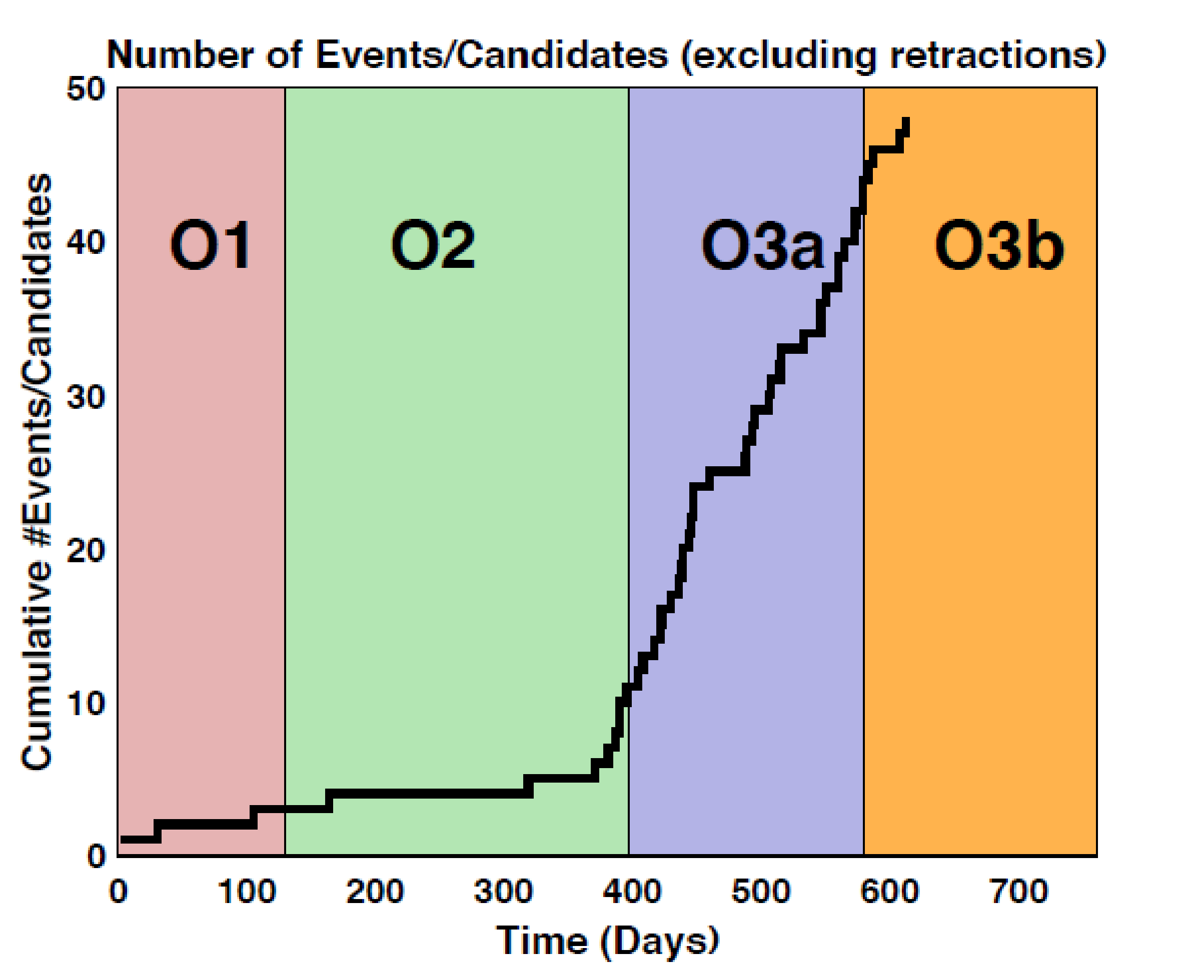
Seismic noise | Thermal noise | Shot noise



AS A RESULT …

I. Technical review of Advanced Virgo

Seismic noise | Thermal noise | Shot noise



Comissionning Report, 07/11/2019, M. Tacca

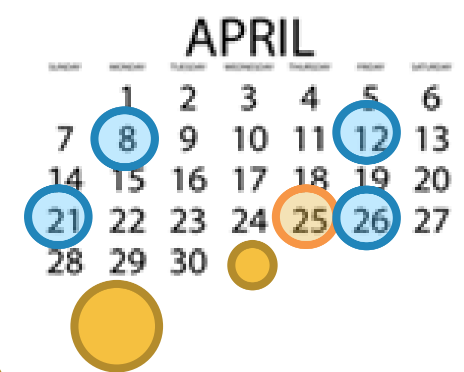
MANY CANDIDATES !

- O3 starts on April, 1st
- Public alerts
- Roughly 1 alert/week

Already 43 public alerts (up to 07/01/2020): more than O1 and O2 combined !

O3 FIRST ANNOUNCEMENT

- O3 starts on April, 1st
- Public alerts
- Roughly 1 alert/week

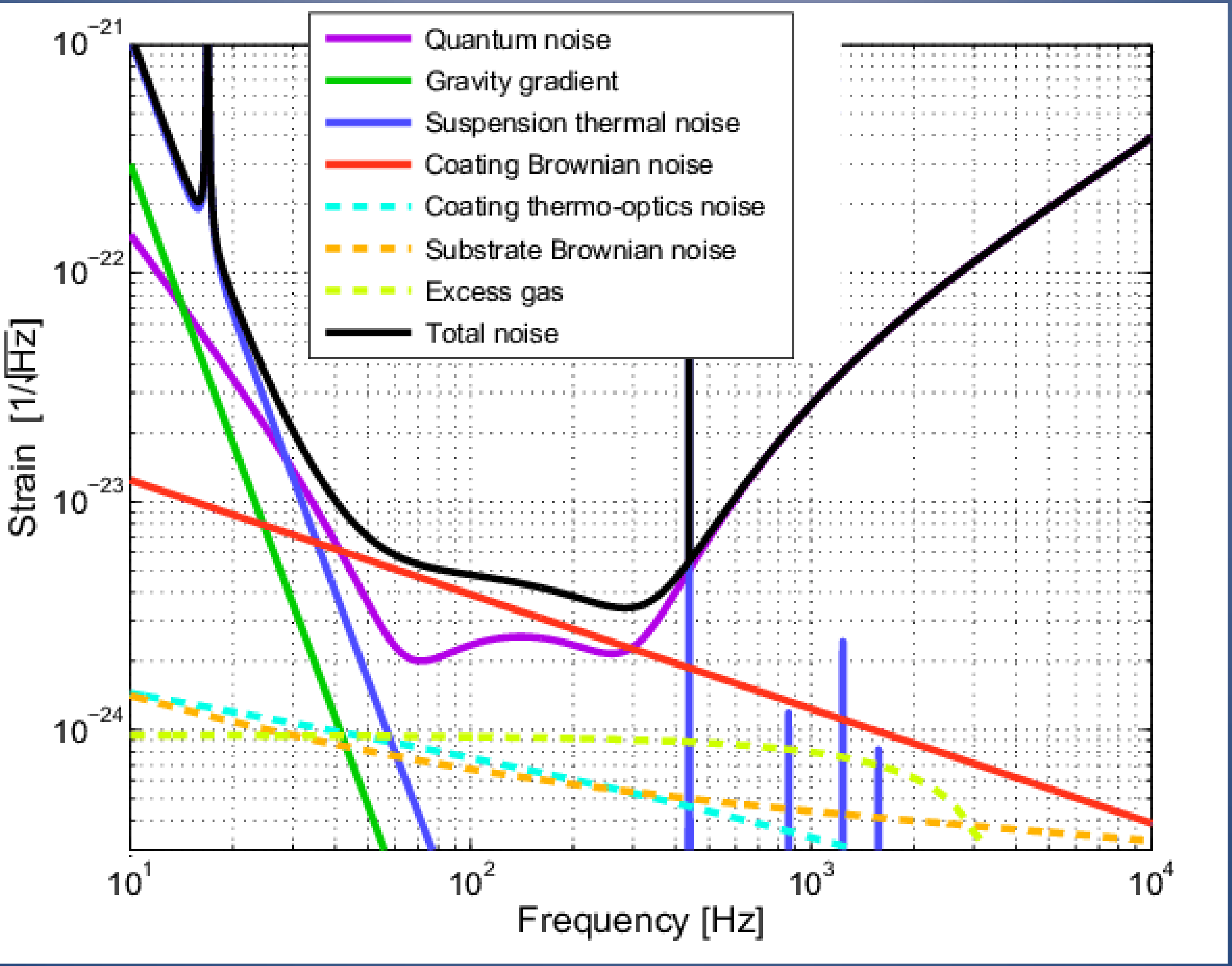


First O3 announcement of detection GW190425
AAS 235th meeting press conference
https://aas.org/press/AAS-press-conference-webcasts

HOW DID WE IMPROVE THE SENSITIVITY ?

I. Technical review of Advanced Virgo

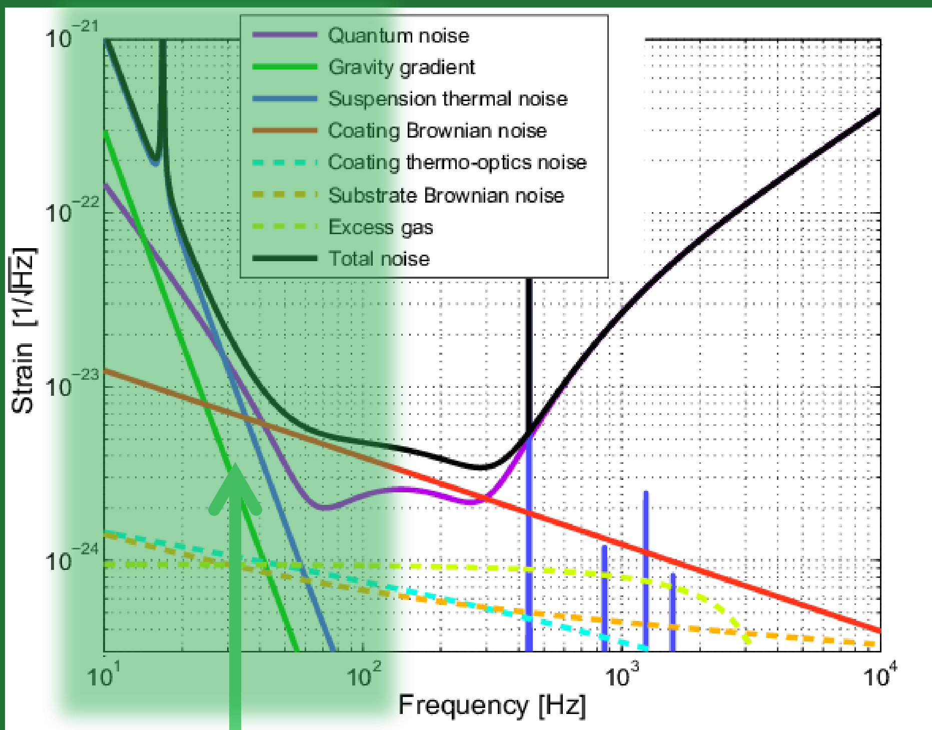
Seismic noise | Thermal noise | Shot noise



VIR-0128A-12

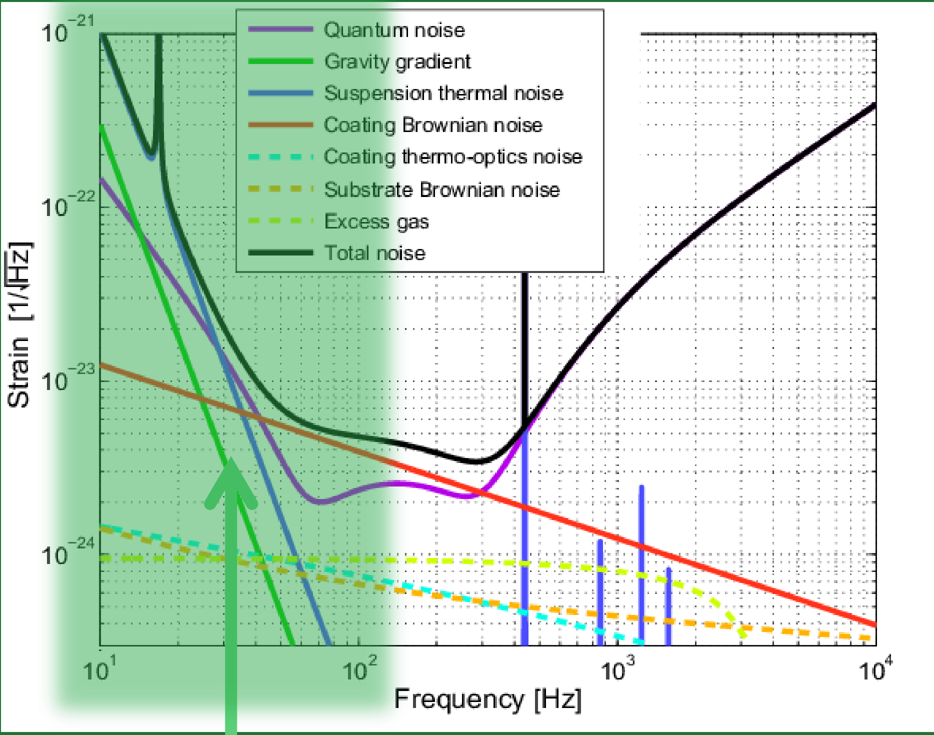
LOW-FREQUENCY NOISES

I. Technical review of Advanced Virgo | Seismic noise | Thermal noise | Shot noise



At low frequency: newtonian noise, residual technical noises, suspension thermal noise, seismic noise

SEISMIC NOISE



At low frequency: newtonian noise, residual technical noises, suspension thermal noise, seismic noise

Class. Quantum Grav. 32 (2015) 024001

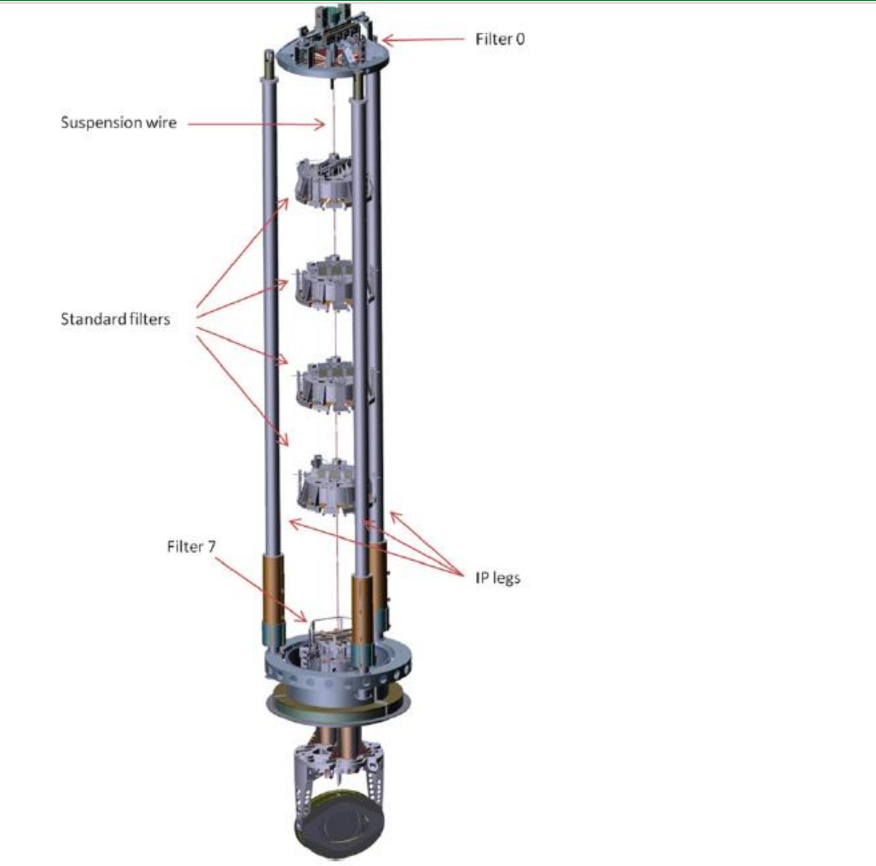
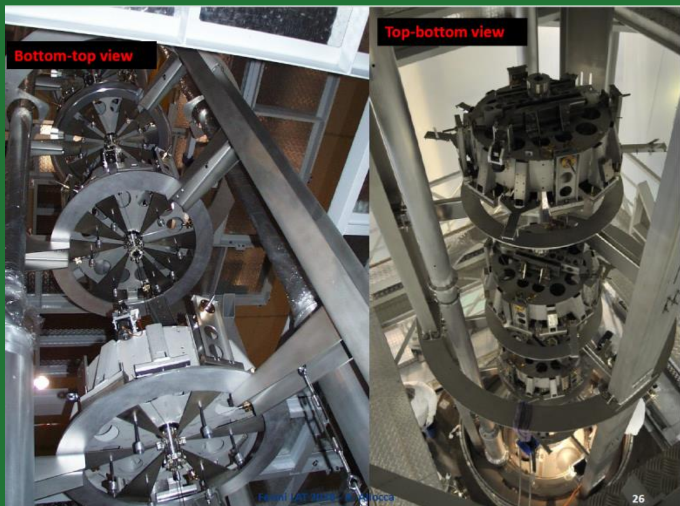


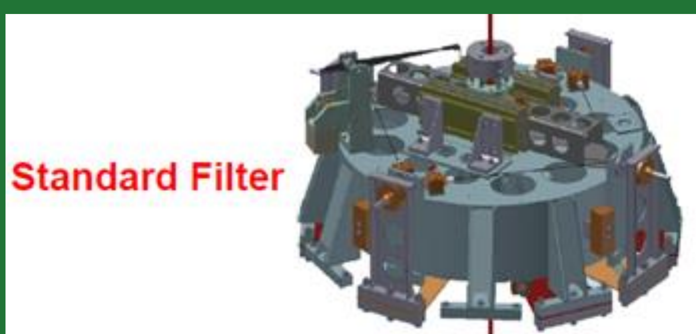
Figure 13. The AdV SA. We can distinguish, from top to bottom, the three legs of the IP, Filter 0, the top ring, the passive filters 1 to 4, and the mirror suspension. This last stage, composed of the steering filter, the marionette and the actuation cage, is dedicated to the control of the mirror position for frequencies $f > 10$ mHz.

SUPERATTENUATOR



- **Seismic isolation**

  - Reduces mirrors seismic vibrations by a factor 10^{11} @ 10 Hz



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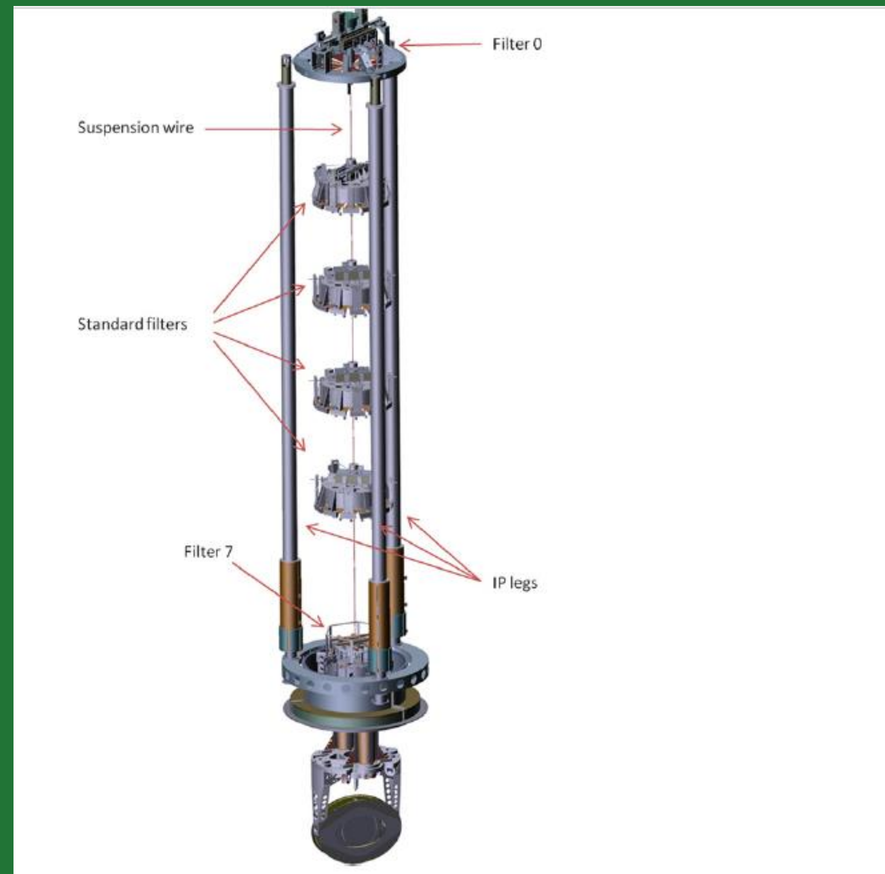
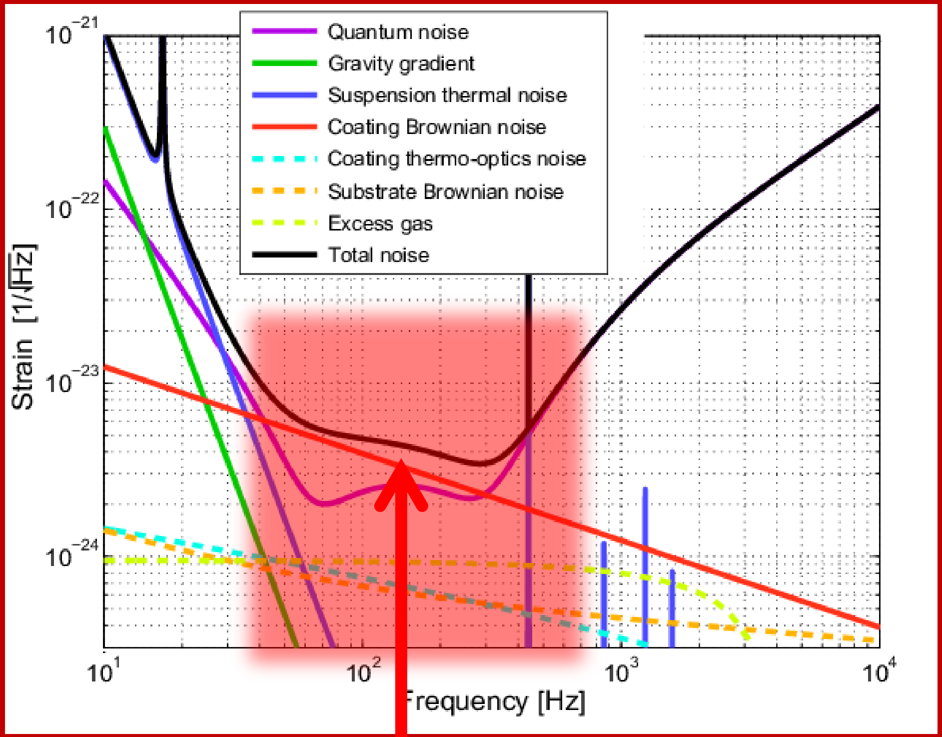


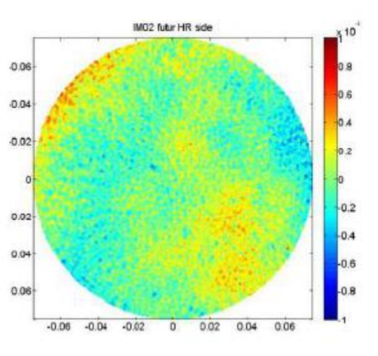
Figure 13. The AdV SA. We can distinguish, from top to bottom, the three legs of the IP, Filter 0, the top ring, the passive filters 1 to 4, and the mirror suspension. This last stage, composed of the steering filter, the marionette and the actuation cage, is dedicated to the control of the mirror position for frequencies $f > 10$ mHz.

MID-FREQUENCY NOISE

I. Technical review of Advanced Virgo | Seismic noise | **Thermal noise** | Shot noise

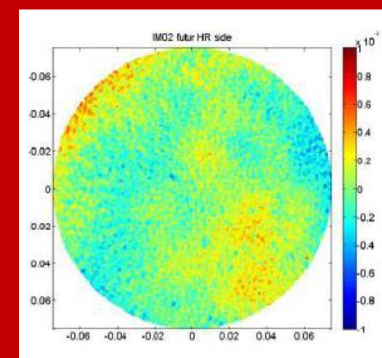


At mid frequency: thermal noise



THERMAL NOISE

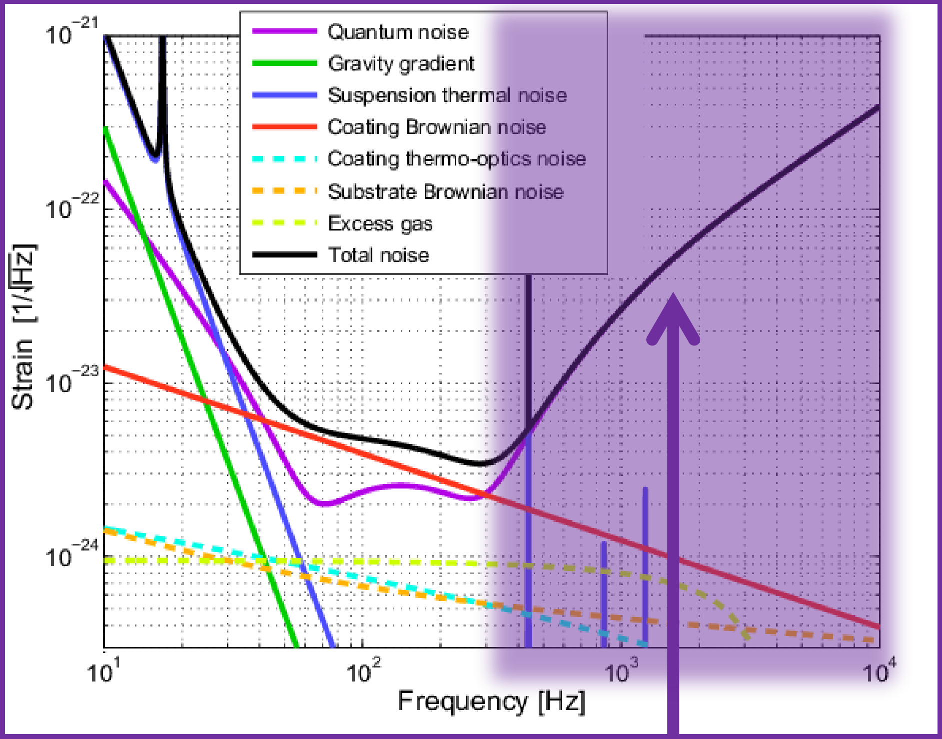
- **Increase beam size @ input test masses (2.5 x larger)**
- **Improved coatings for lower losses**



- **SiO2 monolithic suspensions**

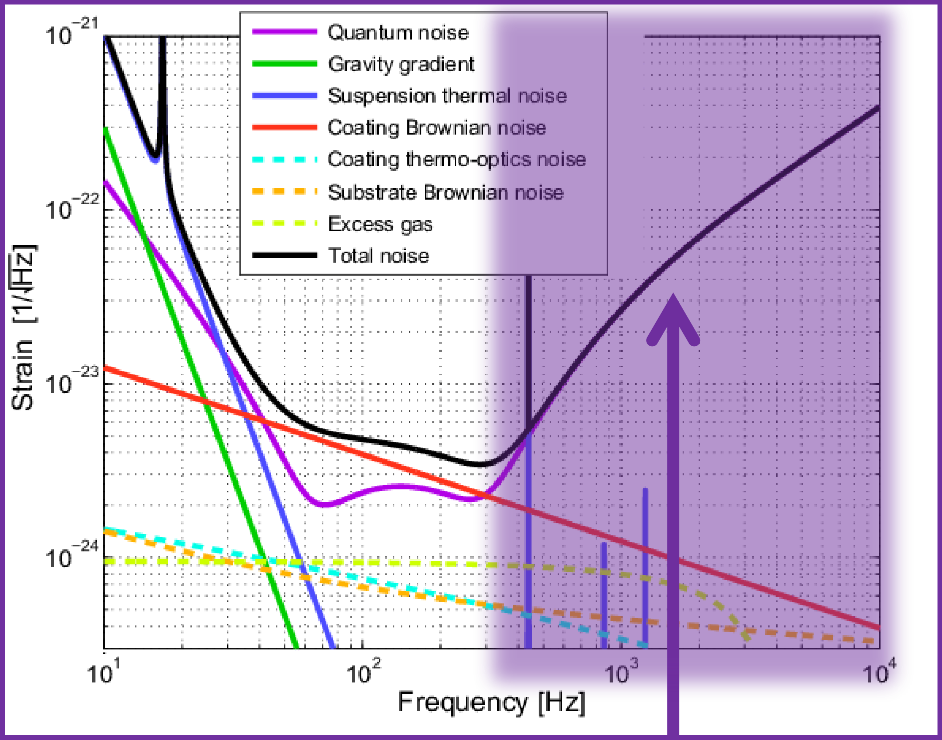
400 µm-diameter SiO2 fibers to suspend 42-kg mirrors to reduce the effect of the radiation pressure

HIGH-FRENQUENCY NOISE



At high frequency: shot noise (quantum noise)

SHOT NOISE



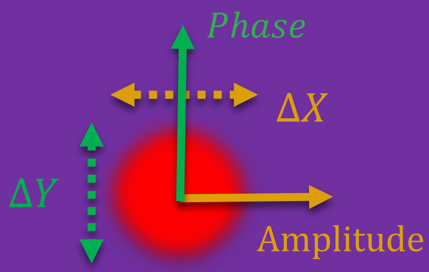
- input power increase to 18W

Reduction of shot noise/SN (high frequency component of quantum noise because SN is proportionnal to $1/\sqrt{P_{in}}$

At high frequency: shot noise (quantum noise)

SHOT NOISE

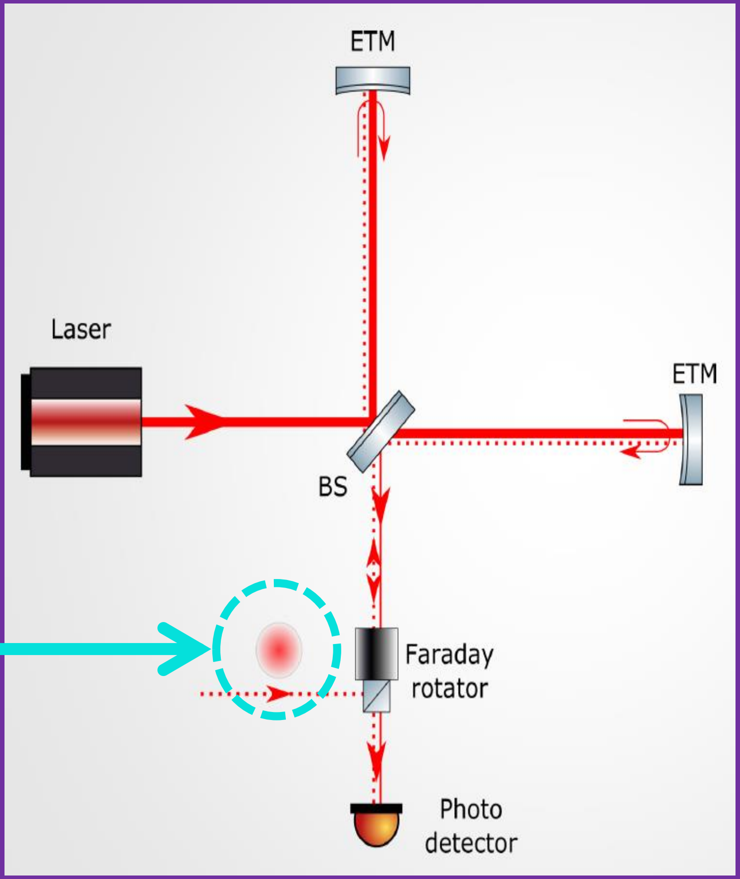
➢ **Frequency-independent squeezing : injection of phase-squeezed vacuum**



Quantum fluctuations in quadrature space

$$(\Delta X)^2(\Delta Y)^2 \geq \frac{1}{16}$$

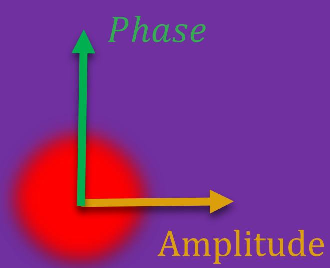
Heisenberg uncertainty principle: a multiplicative limit!

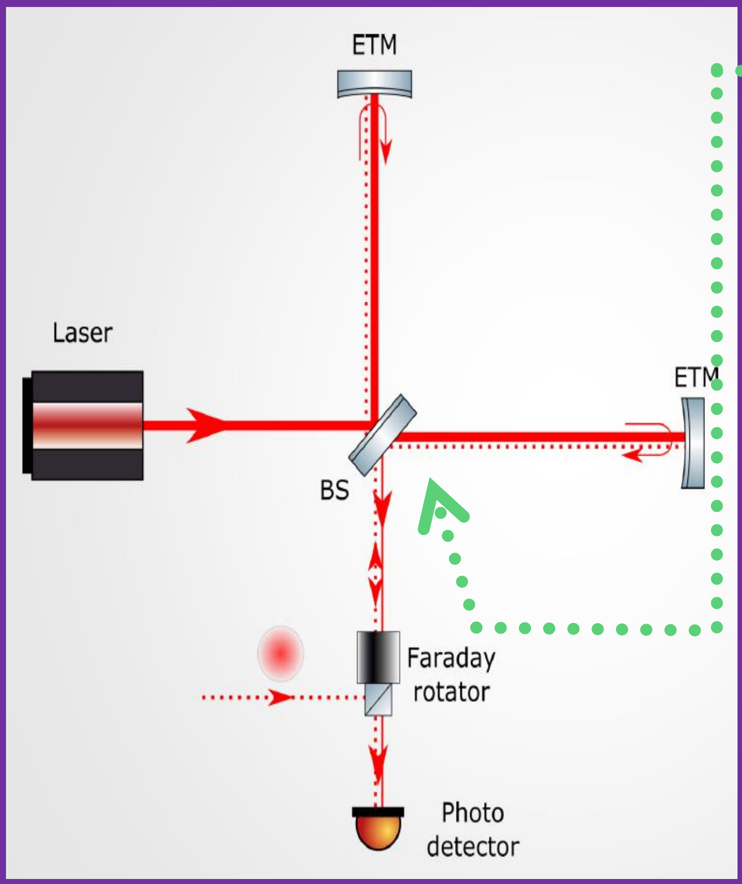


Credit : Jan Gniesmer & Min Jet Yap

FREQUENCY-INDEPENDENT SQUEEZING

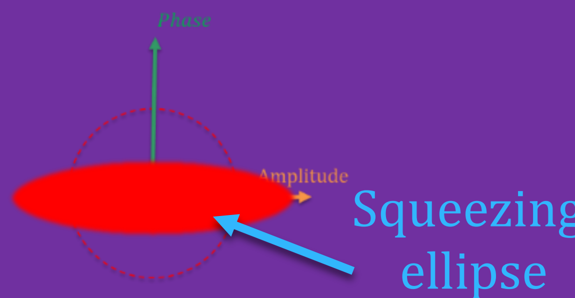
➢ **Frequency-independent squeezing : injection of phase-squeezed vacuum**





Credit : Jan Gniesmer & Min Jet Yap

Quantum noise is due to vacuum fluctuations entering the dark port (unused port) of the interferometer.



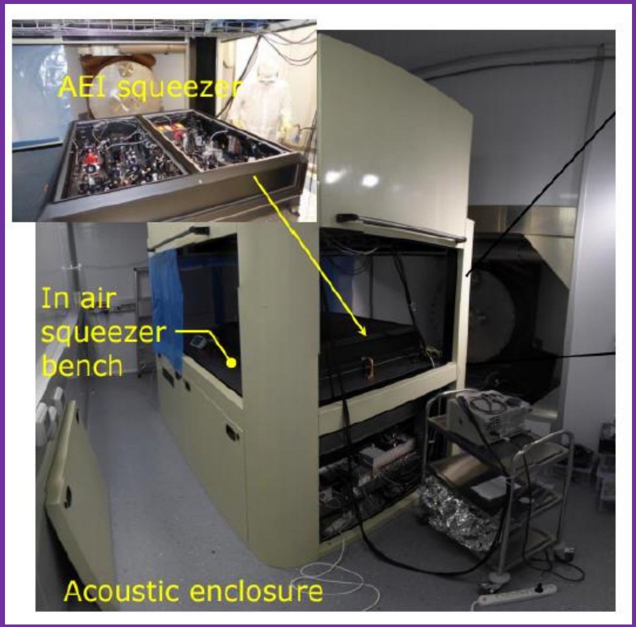
Squeezing was a solution proposed by Caves [Phys. Rev. D, 1981]

SHOT NOISE

➢ Frequency-independent squeezing : injection of phase-squeezed vacuum

The AEI squeezer can provide up to 14 dB of squeezing

Squeezing enables to improve the sensitivity from 52 Mpc to 55 Mpc !



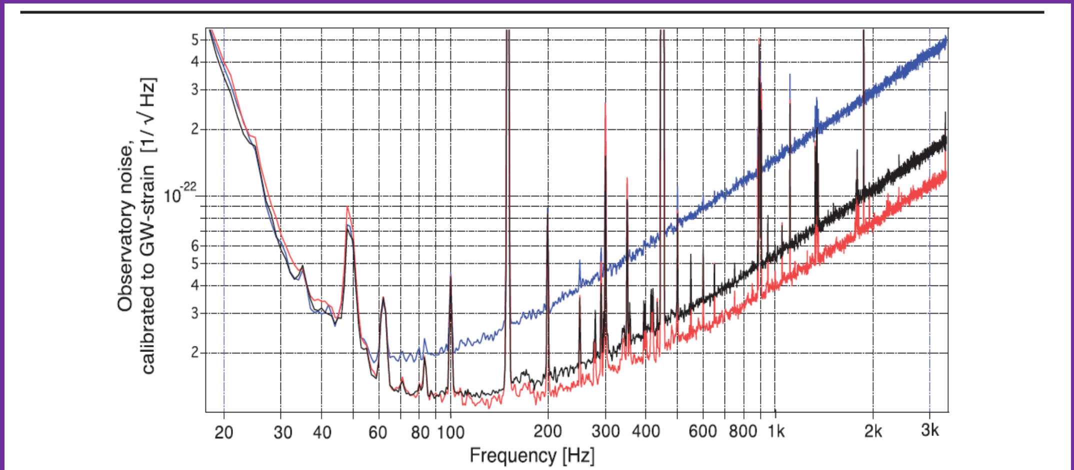


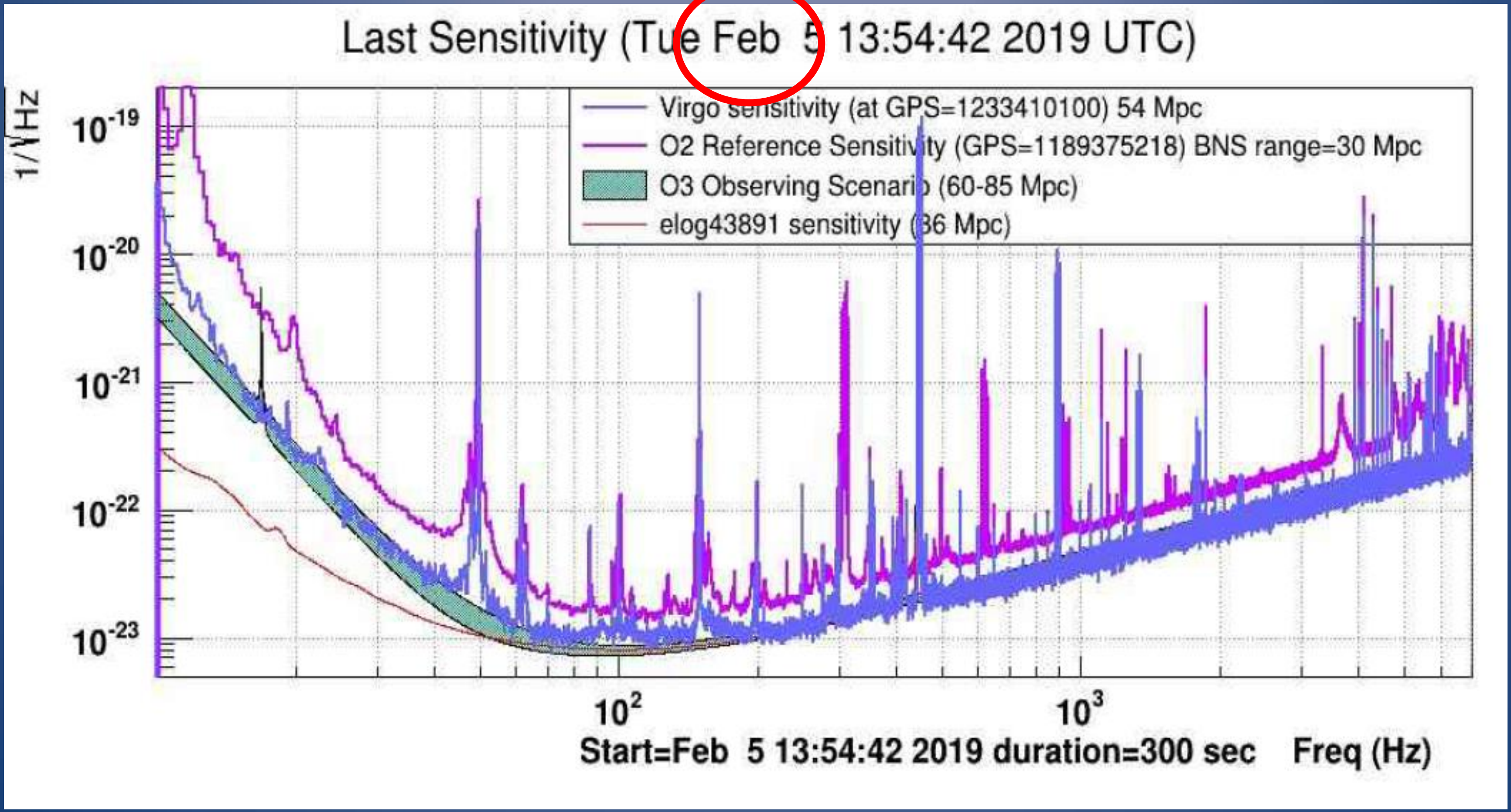
FIG. 2. Measured spectral strain sensitivity of the Advanced Virgo detector in different conditions of squeezed light injection. The black trace corresponds to the reference sensitivity in the absence of squeezed light. The measured sensitivity with squeezing or antisqueezing are shown as the red and blue traces, respectively. Our analysis yields a detected squeezing level of 3.2 ± 0.1 dB with the corresponding antisqueezing of 8.5 ± 0.1 dB, normalized to the reference at 2.8 kHz. For this set of measurements, the injected squeezing level was about 10 dB.

Physical Review Letters 123, 231108 (2019)

COMPARAISON WITH O2 SENSITIVITY

I. Technical review of Advanced Virgo

Seismic noise | Thermal noise | Shot noise



II. Plan for Advanced Virgo+

Phase I | Phase II

ADVANCED VIRGO+ ANTICIPATED SENSITIVITY

II. Plan for Advanced Virgo+

Phase I | Phase II

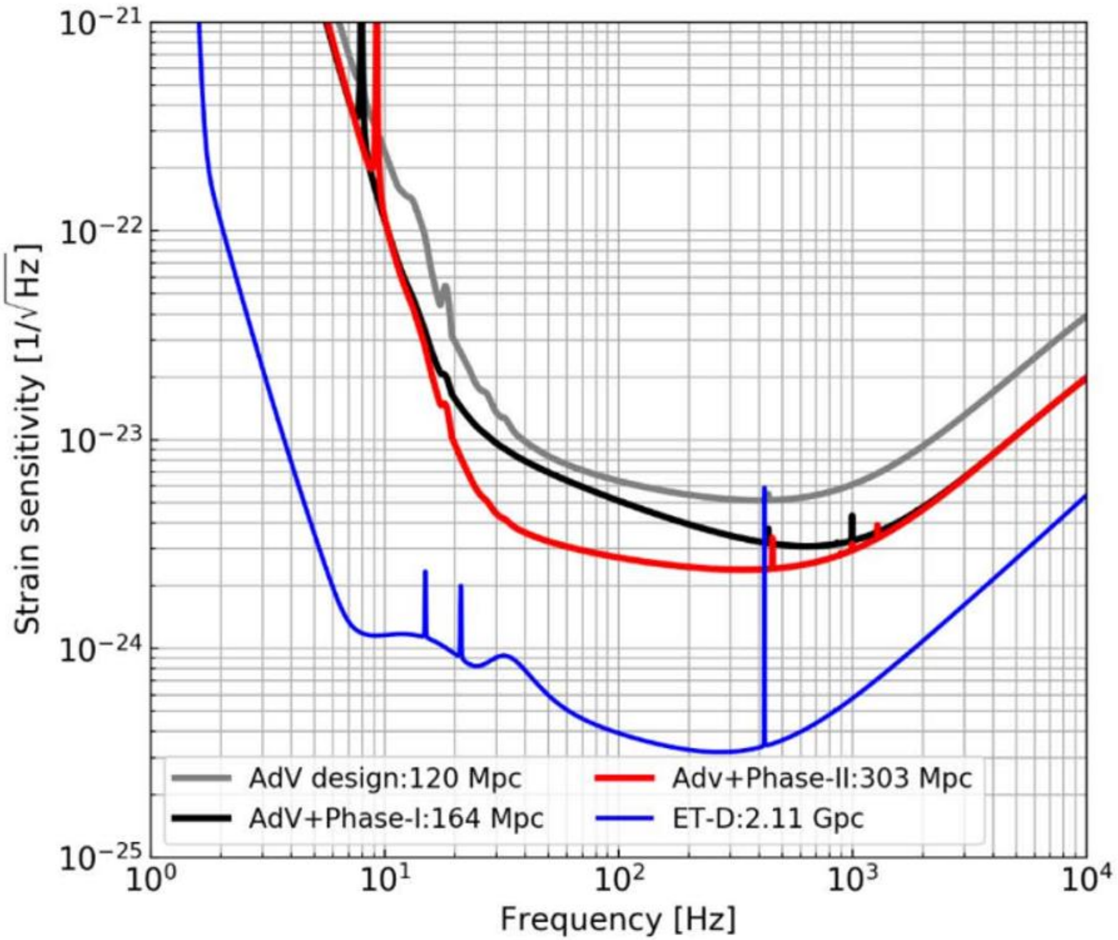
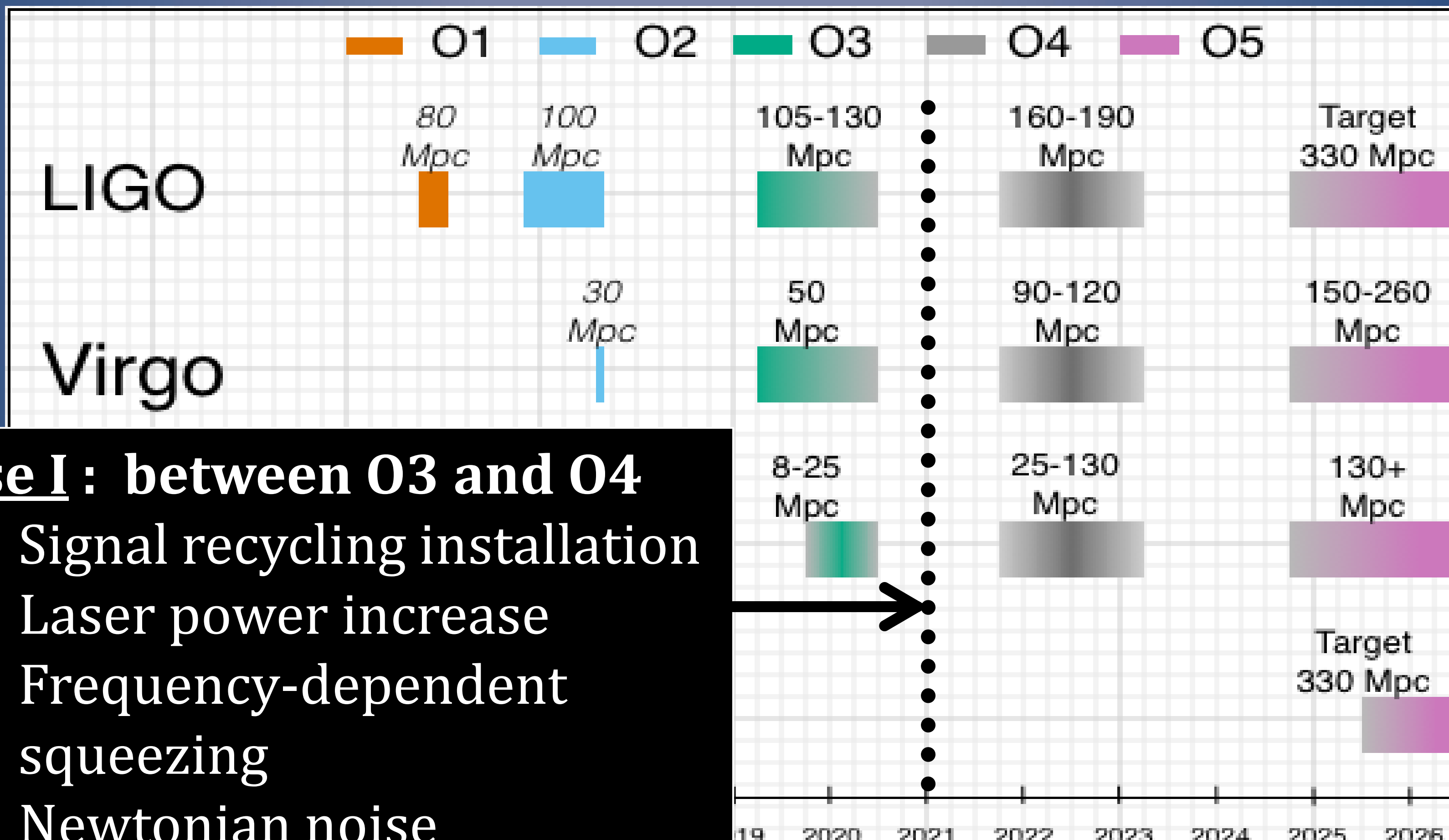


Figure 3.1: *Expected evolution of the Virgo sensitivity, and BNS range, after the completion of the two proposed upgrade phases. The design sensitivities of AdV and Einstein Telescope are also shown for reference.*

PHASE I: SIGNAL RECYCLING AND LASER POWER

II. Plan for Advanced Virgo+ | **Phase I** | Phase II

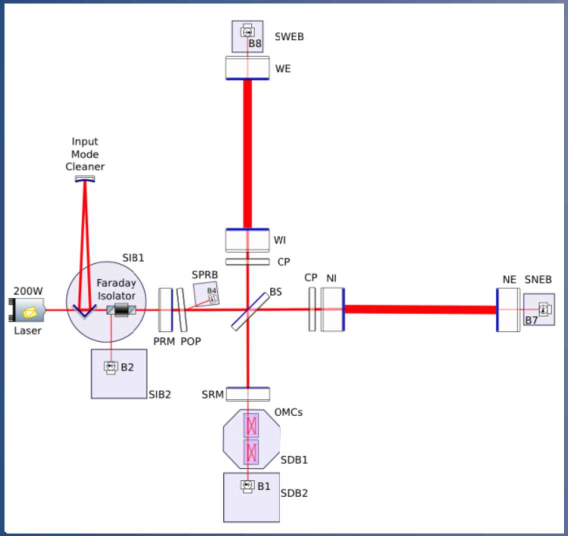


<u>Phase I</u> : between O3 and O4

- Signal recycling installation
- Laser power increase
- Frequency-dependent squeezing
- Newtonian noise cancellation

PHASE I: SIGNAL RECYCLING AND LASER POWER

II. Plan for Advanced Virgo+ | Phase I | Phase II



- **Signal recycling**
  - **Recycling payload already installed**
    - Output telescope lens
    - Lens replacement with mirror
    - Mirror coating
  - **Ring heater around Signal-Recycling Mirror**
    - Mirror radius of curvature correction
  - **Signal recycling control**
    - A long process with auxiliary lasers to lock the long cavities then lock of full signal recycled interferometer

- **Higher laser power:**
  - increase of 40W to 50W

The present laser can do the job but decision has been made to install a new fiber laser in parallel with the present one.

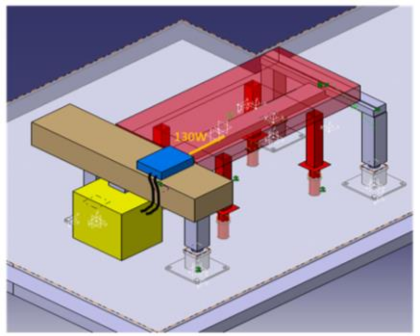


Figure 11 : implementation of the fiber amplifier

PHASE I: FREQUENCY-DEPENDENT SQUEEZING

II. Plan for Advanced Virgo+ | Phase I | Phase II

- **A broadband reduction of quantum noise is needed**

Advanced Virgo Plus Design Report (VIR-0596A-19)

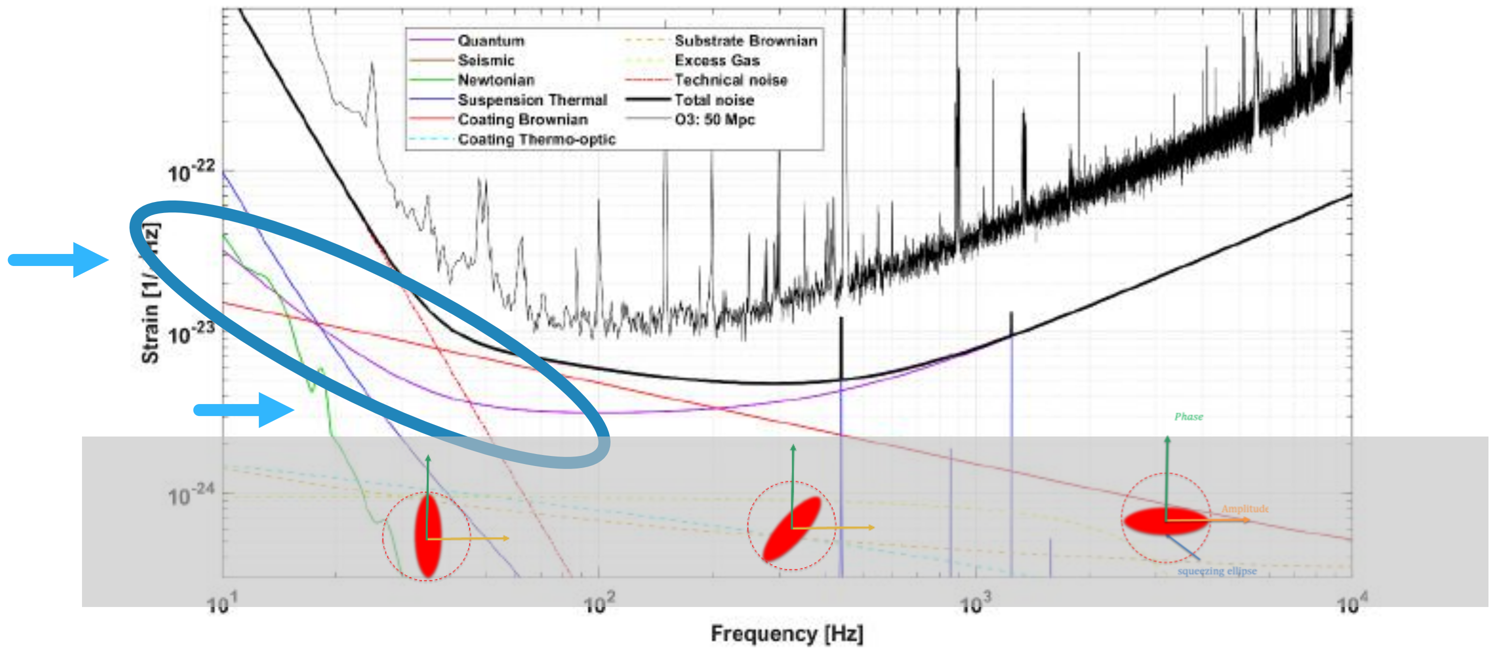


Figure 2. Anticipated best sensitivity of AdV+ during Phase I. For comparison the sensitivity at the beginning of O3 is shown.

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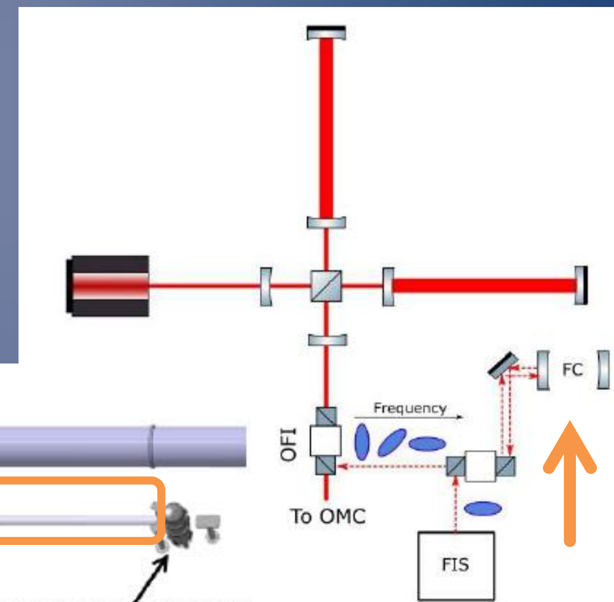
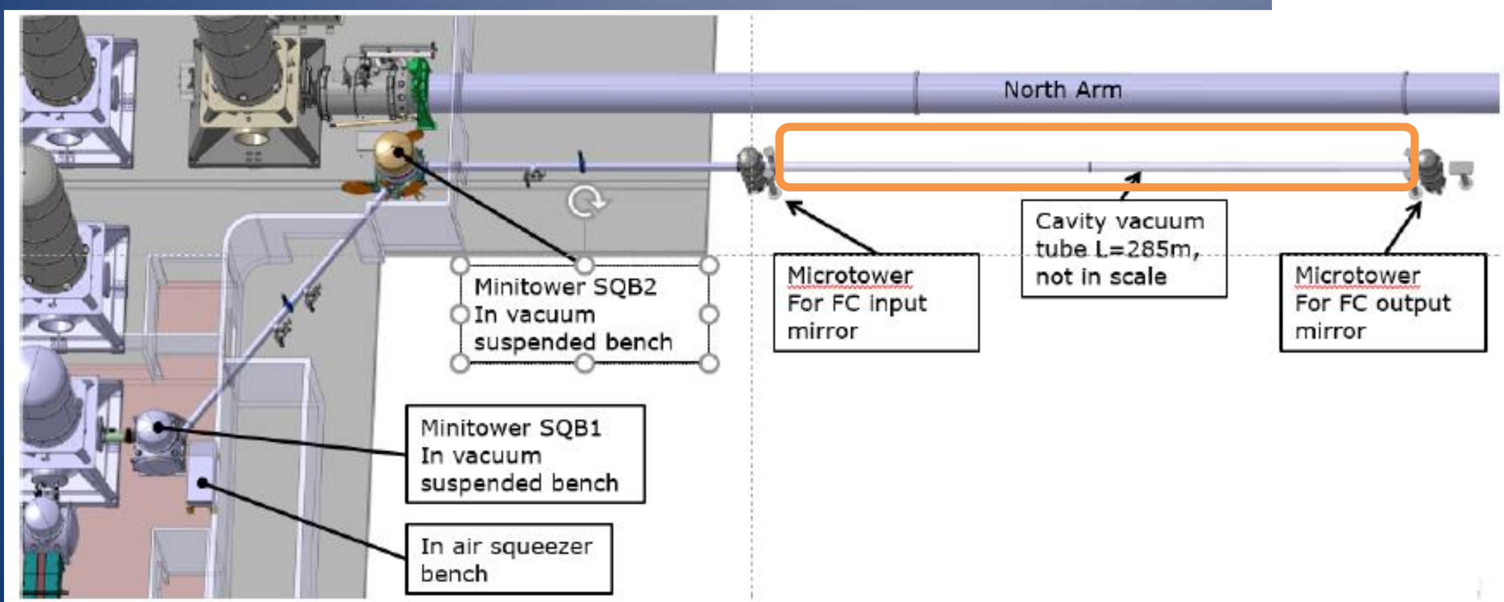
PHASE I: FREQUENCY-DEPENDENT SQUEEZING

II. Plan for Advanced Virgo+ | **Phase I** | Phase II

... by using a filter cavity L = 285m.



[Advanced Virgo Plus Design Report (VIR-0596A-19)]



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PHASE I: FREQUENCY-DEPENDENT SQUEEZING

II. Plan for Advanced Virgo+ | Phase I | Phase II

Preliminary design of the control system is completed

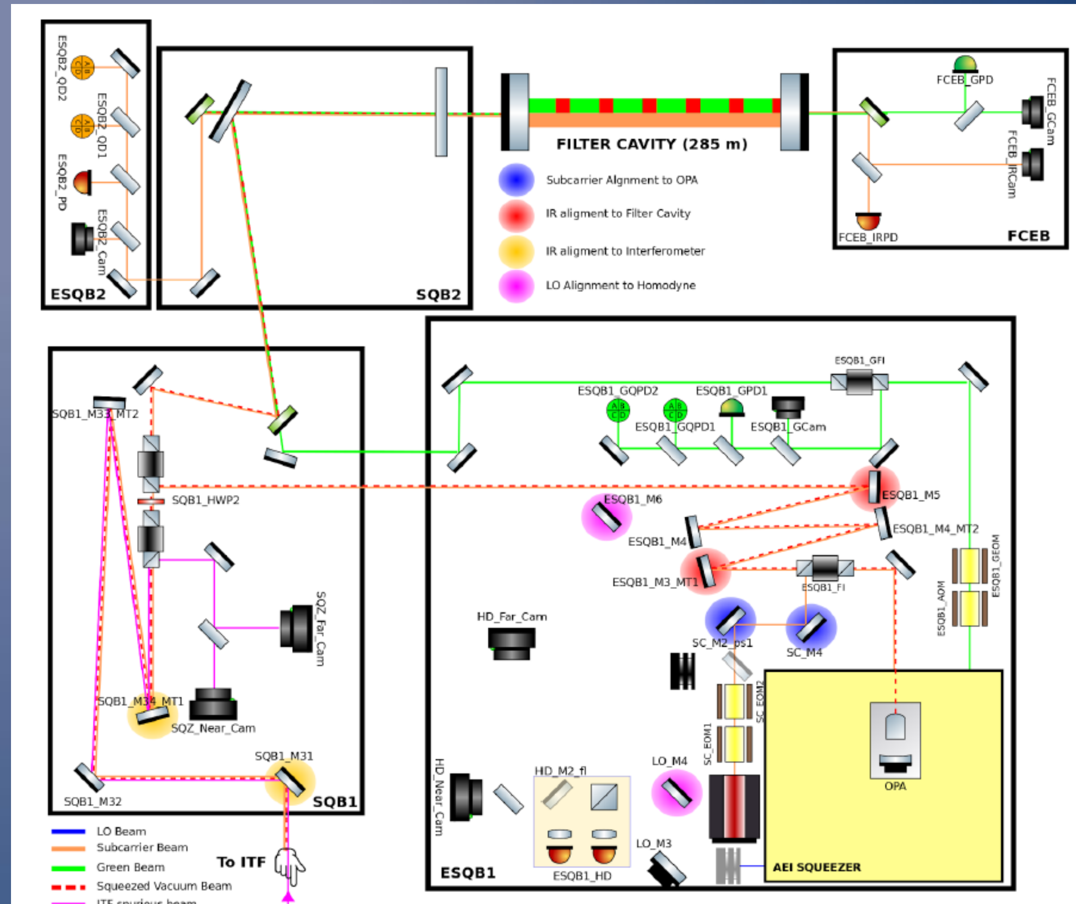


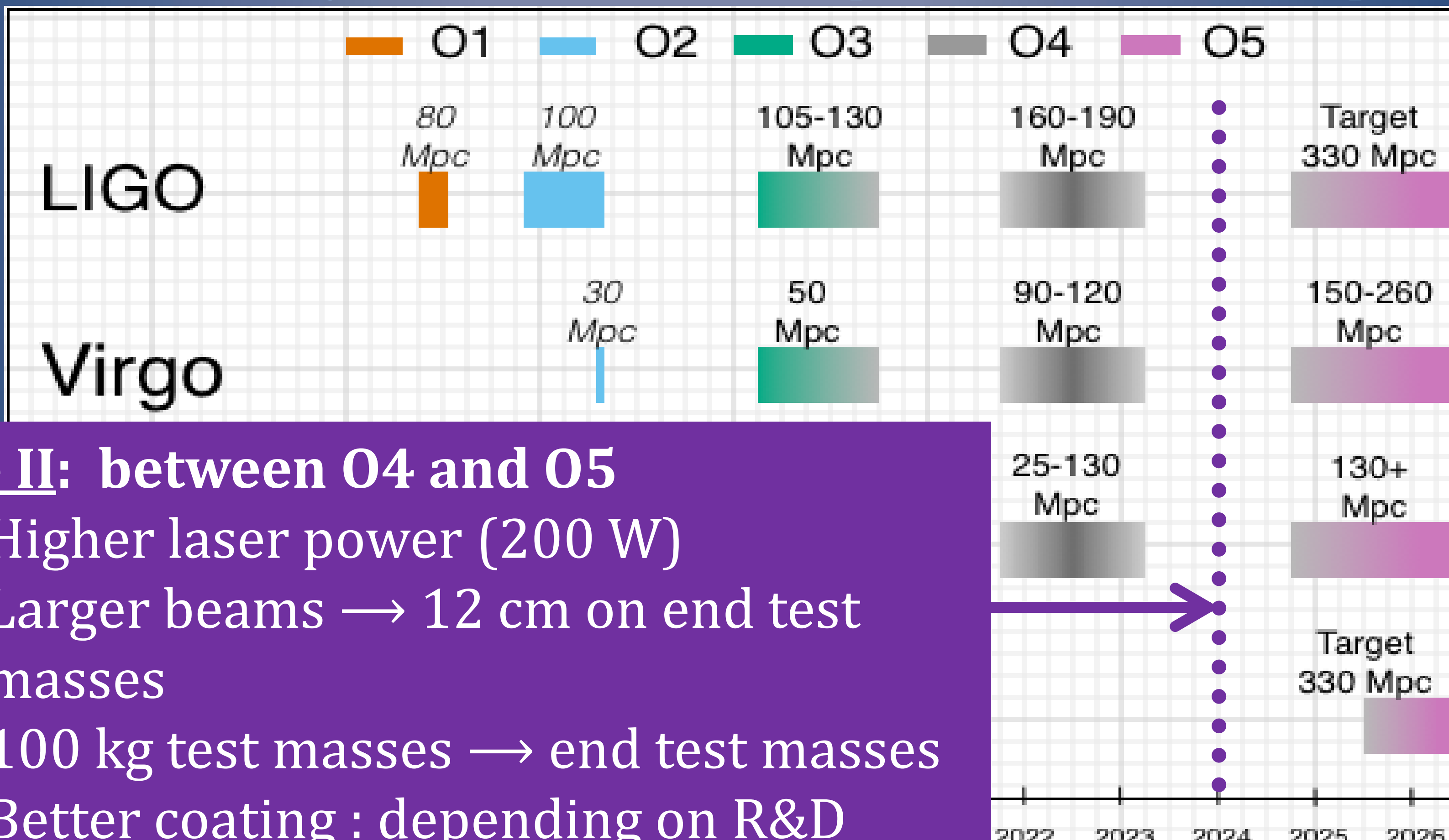
Figure 18: Simplified scheme of the optical system, showing sensors and actuators for the global control system.

[Advanced Virgo Plus Design Report (VIR-0596A-19)]

MIRROR TECHNOLOGY, PAYLOADS AND COATINGS

II. Plan for Advanced Virgo+ | Phase I | **Phase II**

Goal: sensitivity increase from ~100 Mpc to more than 200 Mpc



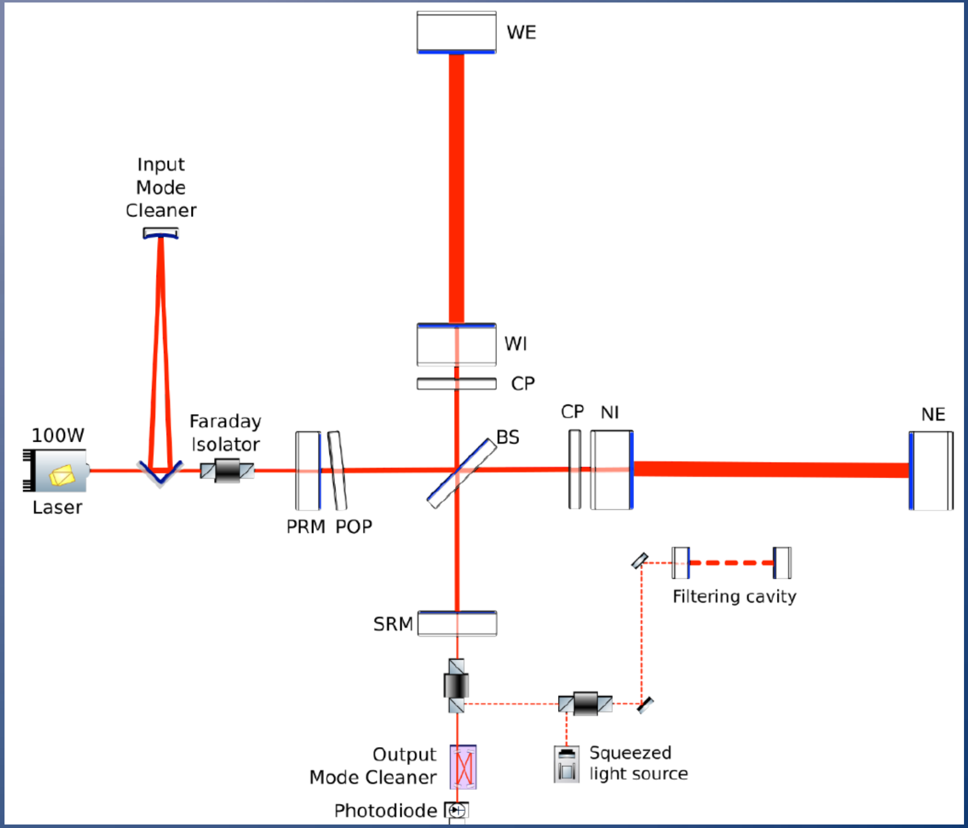
Phase II: between O4 and O5

- Higher laser power (200 W)
- Larger beams ⟶ 12 cm on end test masses
- 100 kg test masses ⟶ end test masses
- Better coating : depending on R&D results at the end of Phase I

LARGER BEAMS, LARGER MIRRORS

II. Plan for Advanced Virgo+ | Phase I | Phase II

- Increase beam size on end mirrors up to a radius of 10 cm



- Increase mirror diameter to 55 cm (currently 35 cm)
  - Mass: 100 kg

MIRROR TECHNOLOGY

II. Plan for Advanced Virgo+ | Phase I | Phase II

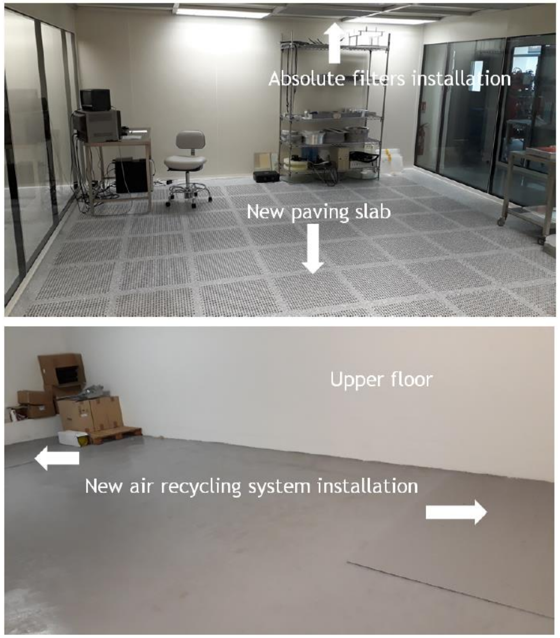


Figure 2: LMA ISO3 clean room area that will be modified. *top* : area where the new profilometer will be installed. *bottom* : on the upper floor, location of the future clean air station

- **Expand Laboratoire des Matériaux Avancés/ LMA (Lyon) capabilities**
  - Infrastructure and equipment upgrade to coat and characterize large mirrors (55 cm diameter): clean room extension, development of new handling tools, of the new profilometer, cleaning machine modification,...

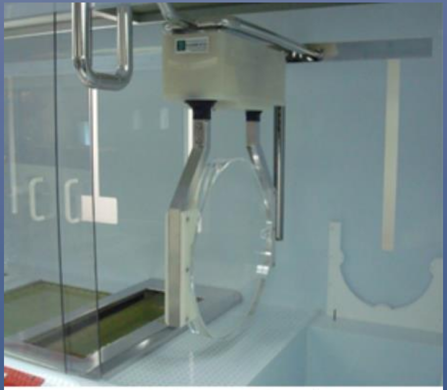


Figure 5: Cleaning Machine robot

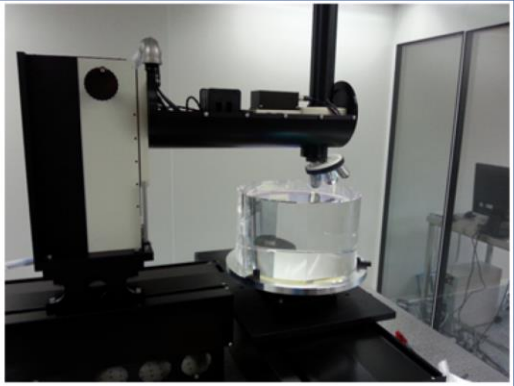


Figure 1: Present MICROMAP profilometer

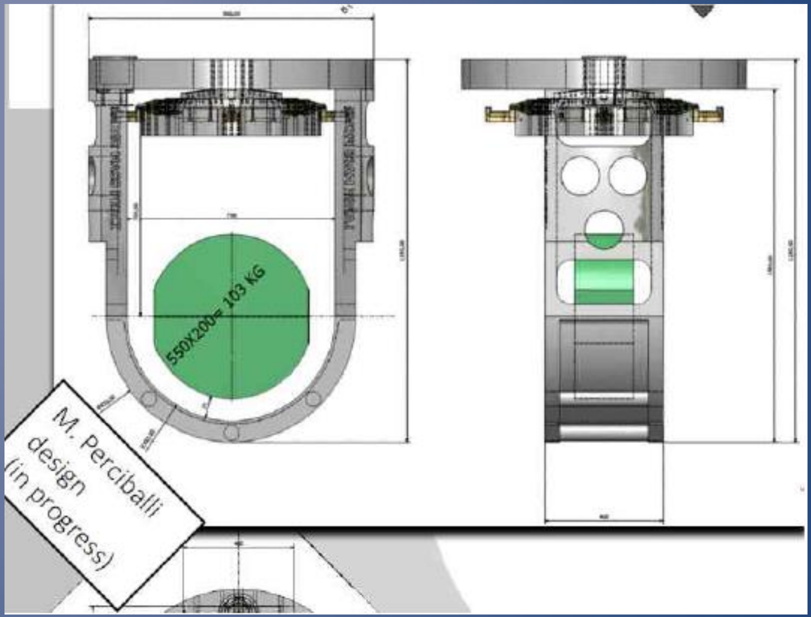
- **Coating R&D**

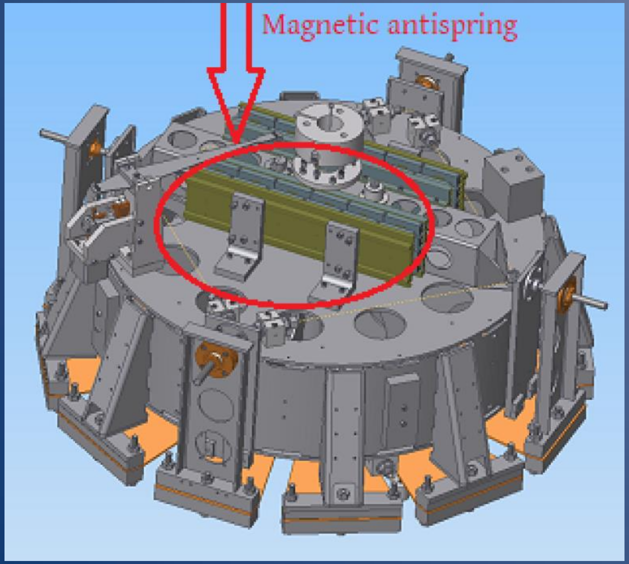
The goal is to reduce coating losses by 3 thanks to the collaboration of many laboratories

PAYLOADS

II. Plan for Advanced Virgo+ | Phase I | Phase II

➢ **Larger payload**
- Superattenuator load capability to be increased
- Handling tool for larger mirror (+60% in diameter)





➢ **Superattenuator**
- Upgrade seismic filter to cope with larger payload weight: magnetic anti-spring development,...

CONCLUSION

- Advanced Virgo contributed to O2 LIGO-Virgo data taking
  - First triple detection on August, 14th,2017
  - First BNS detection (GW170817) on August, 17th, 2017

- Increase of sensitivity of a factor ~2 between O2 and O3

- First public announcement of the first GW detection during O3, GW190425, from the coalescence of two neutron stars, at the 235th AAS meeting, on Monday.

- Current BNS range ~50 Mpc

- Advanced Virgo+ plans is divided in two phases :
  - phase 1 (mainly quantum noise reduction)
  - phase 2 (mainly thermal noise reduction)

THANK YOU FOR YOUR ATTENTION !

ANY QUESTIONS ?