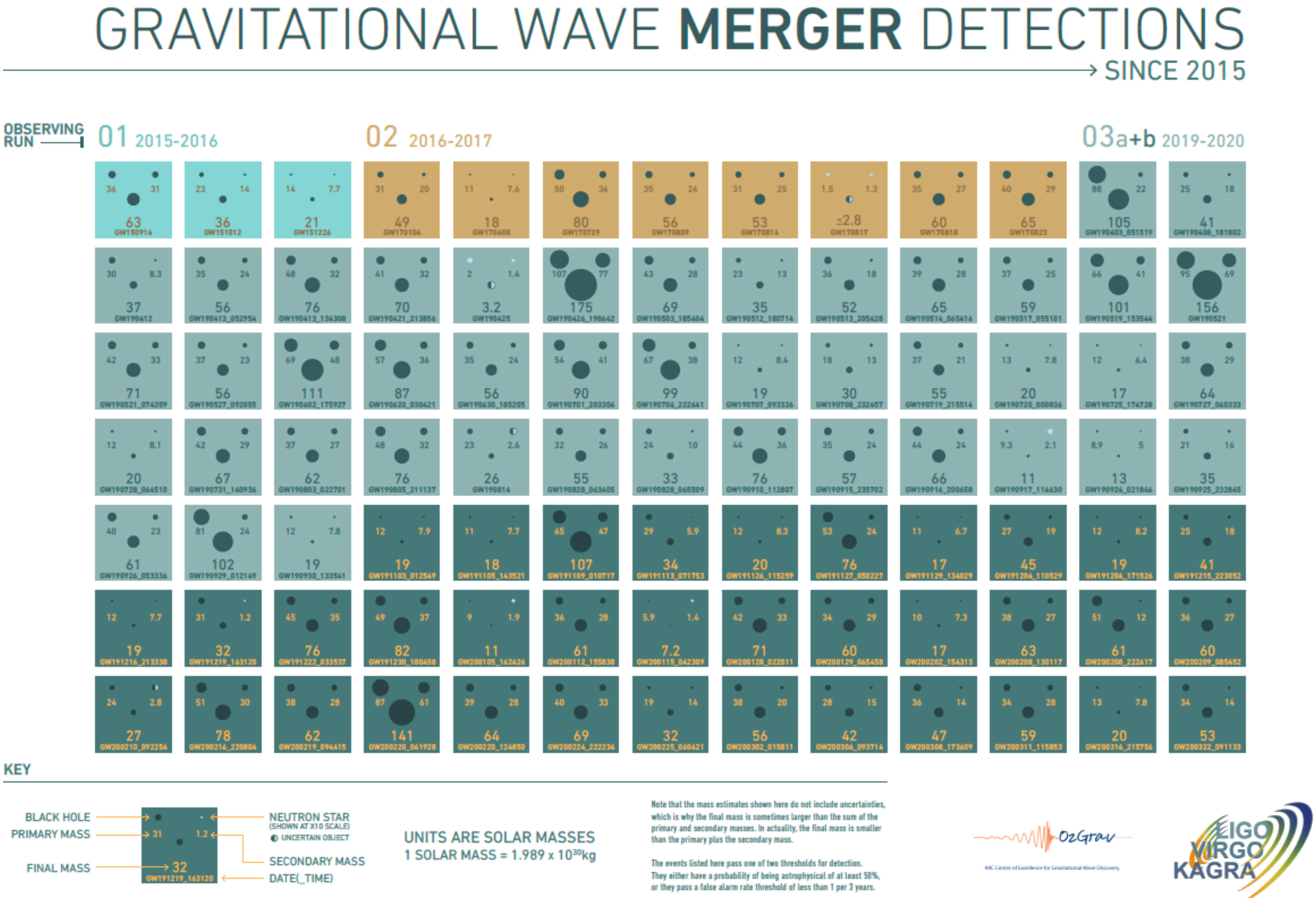
Status and Ongoing research at EGO

Fiodor Sorrentino – INFN Genova
On behalf of the Virgo collaboration

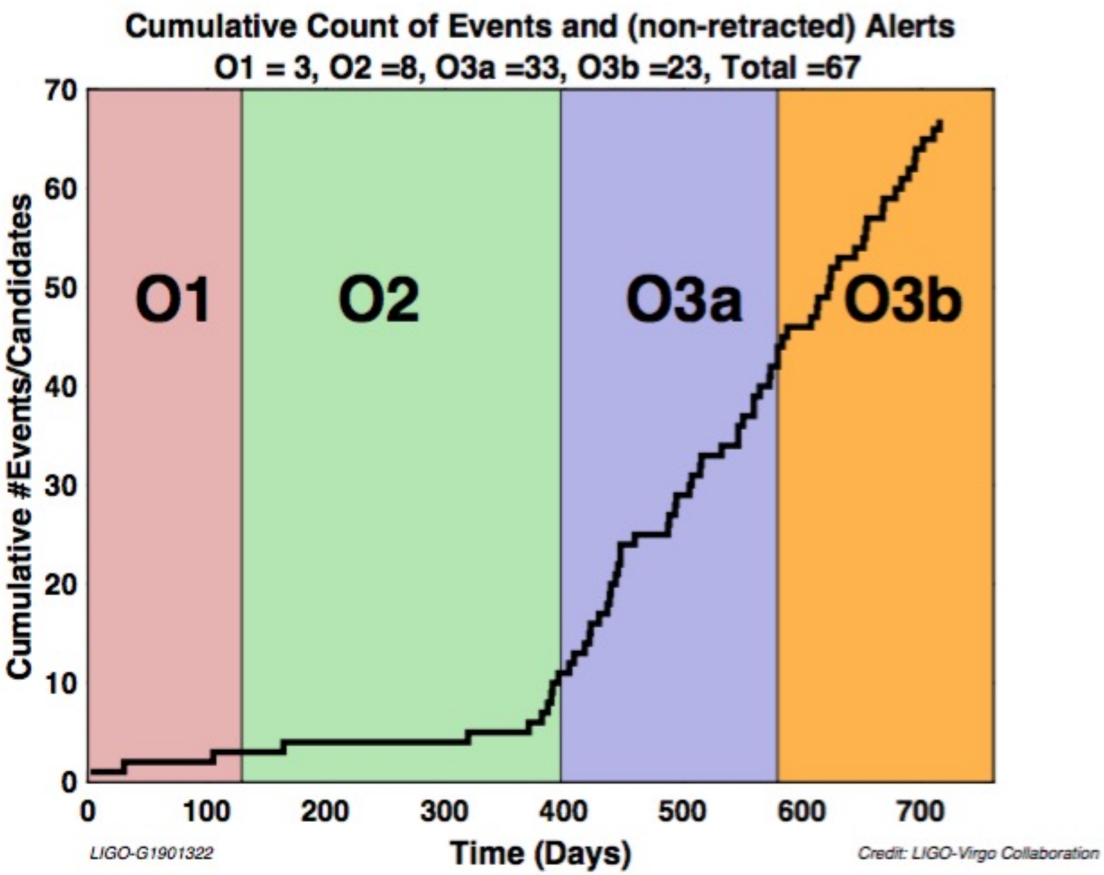
Highlights from O3 science run



Highlights from O3 science run

O3 ended on March 2020

- more than 1 GW event/week observed
- Mostly BH-BH coalescences
- Several exceptional events
  - **NS-BH coalescences**
  - **GW191219_163120** : extremely unequal mass components: 31 M⊙ + 1.2 M⊙, and the lightest NS ever observed
  - **GW200115_042309**: the brightest BH-NS coalescence detected up to now 6 M⊙ + 1.4 M⊙
  - **BH-BH coalescences with IMBH**
  - **GW190521_030229**: 85 M⊙ + 66 M⊙ -> 142 M⊙
  - **GW200220_061928**: 87 M⊙ + 61 M⊙ -> 148 M⊙
  - Coalescing BHs in the “pair instability mass gap” ~ 65 -- 120 M⊙



- GW191109_010717: 65 M⊙ + 47 M⊙ -> 107 M⊙
Negative effective spin of the binary system: spins of the two BHs opposite to the orbital angular momentum

The Virgo collaboration

2016: 19 European teams, 5 countries

EGO
(CNRS, INFN)

NIKHEF, Amsterdam
Radboud University , Nijmegen
The NETHERLANDS

ITALY:
INFN + Universities
Firenze-Urbino
Genova
Napoli
Perugia
Pisa
Padova
Roma La Sapienza
Roma Tor Vergata
Trento

HUNGARY
RMKI,
Academy of sciences
Budapest

POLAND
Institute of Mathematics
Polish Academy of Sciences
Varsaw

FRANCE :
Laboratoire de l'Accélérateur Linéaire (U. Paris-Sud+CNRS)
Laboratoire d'Annecy de Physique des Particules (CNRS)
Astroparticules et Cosmologie (U. Paris 7+CNRS)
Laboratoire des Matériaux Avancés (Lyon-CNRS)
Laboratoire Kastler-Brossel (ENS – U. Paris 6 - CNRS)
Observatoire de la Côte d'Azur (CNRS, Nice)

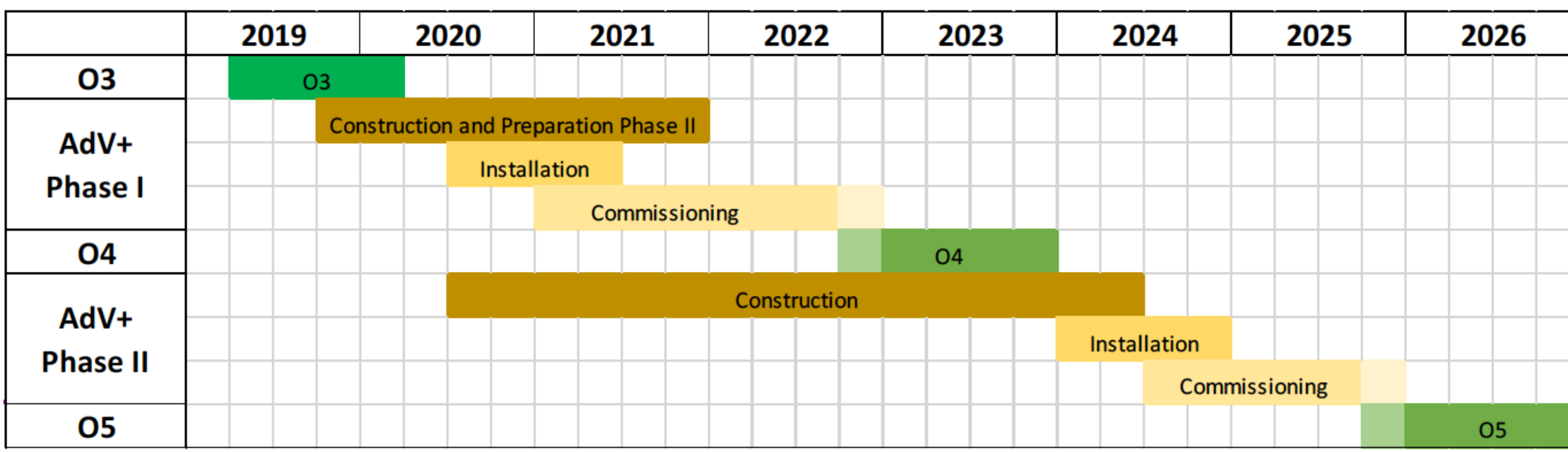
2022: more than 50 European teams from 9 countries

EGO
(CNRS, INFN, NIKHEF)

After O3: the AdV+ project

Two phases

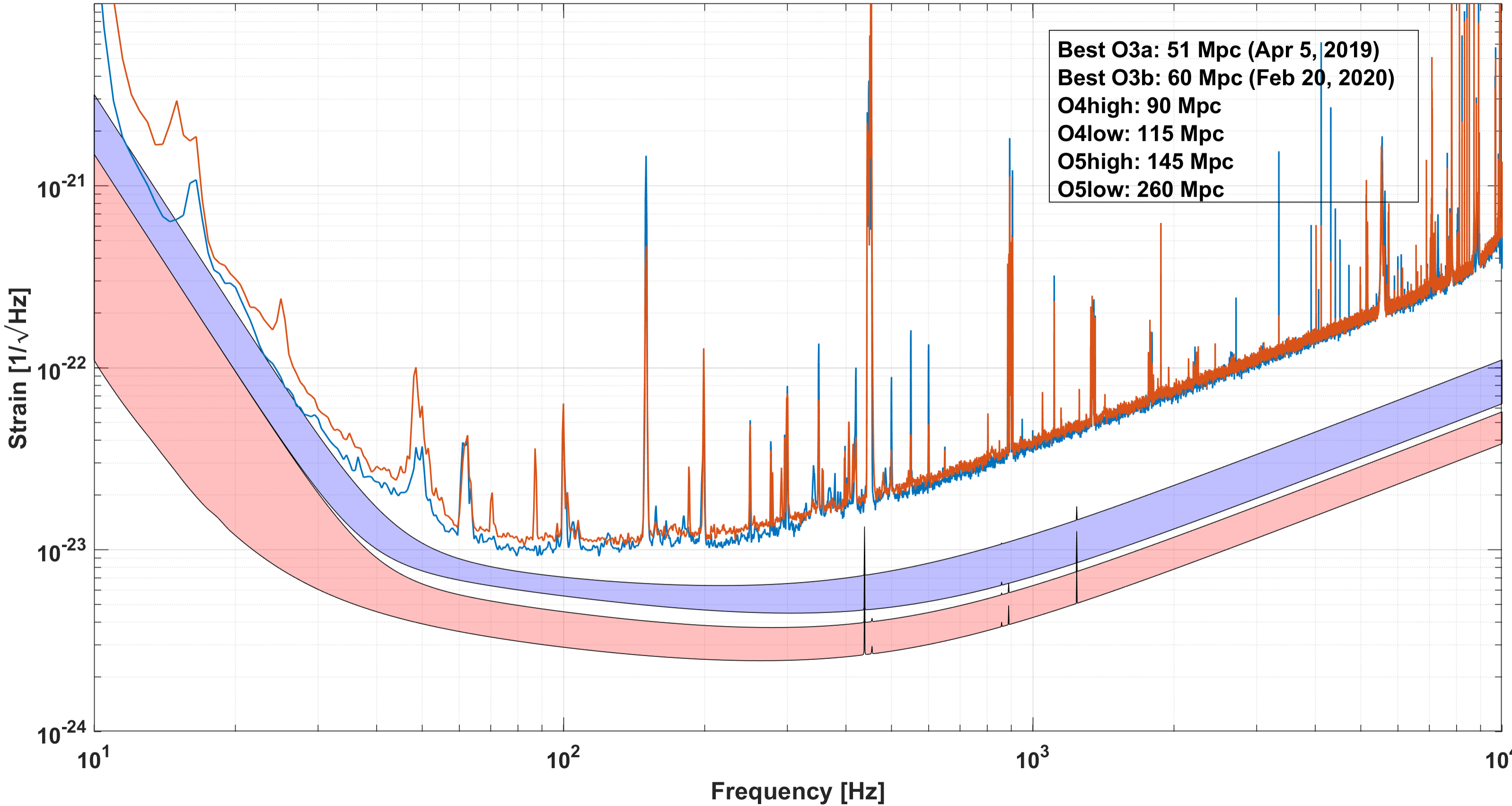
- Phase I (before O4 run/2022-23)
  - Mainly an upgrade to reduce quantum noise: no mirrors change
  - Reduction of technical noises
  - Preparation of Phase II
- Phase II (before O5 run/2025-26)
  - More invasive upgrade to reduce thermal noise: mirrors change



AdV+ sensitivity targets

Two phases

- Phase I
  - reduce quantum noise, reach thermal noise wall. **BNS range: ~100 Mpc**
- Phase II
  - lower the thermal noise wall. **BNS range: ~200 Mpc**

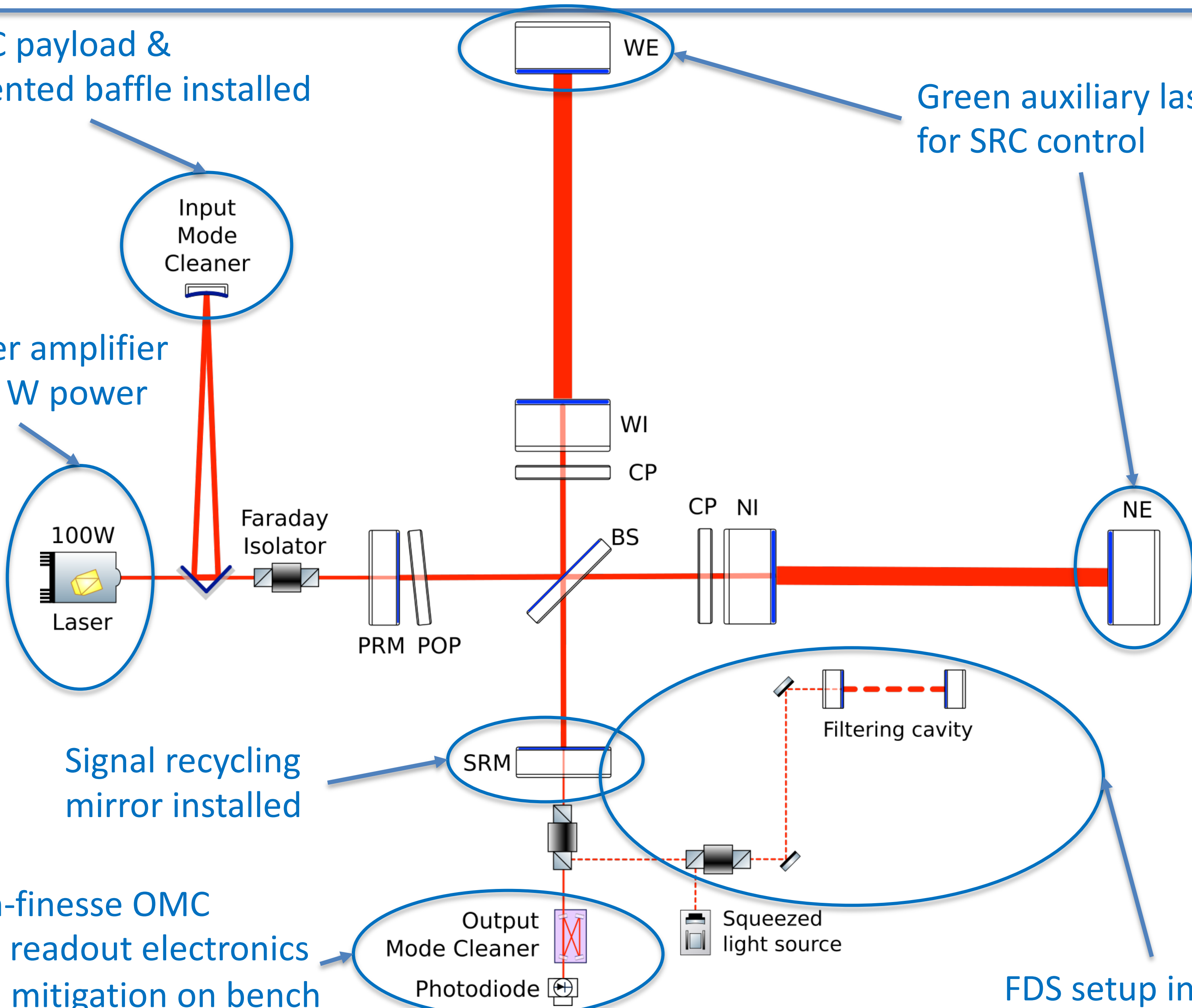


Status of AdV+ phase 1

New IMC payload &
Instrumented baffle installed

New laser amplifier
for >100 W power

Green auxiliary laser
for SRC control



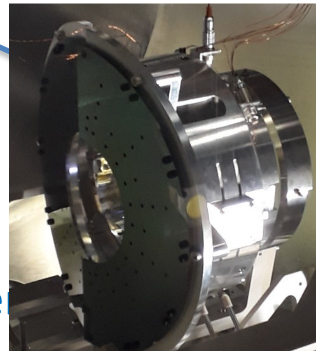
Signal recycling
mirror installed

New, high-finesse OMC
low-noise readout electronics
stray ligth mitigation on bench

FDS setup installed

Status of AdV+ phase 1

New IMC payload &
Instrumented baffle installed



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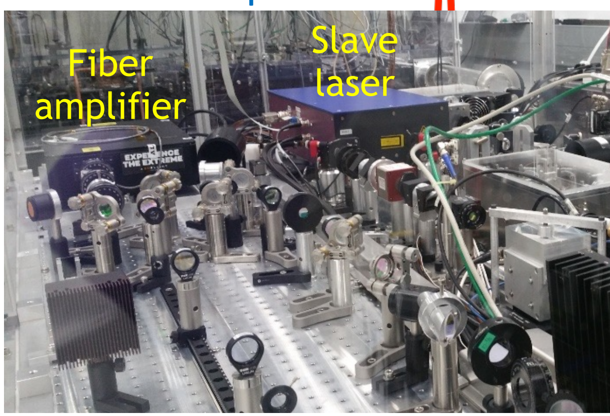
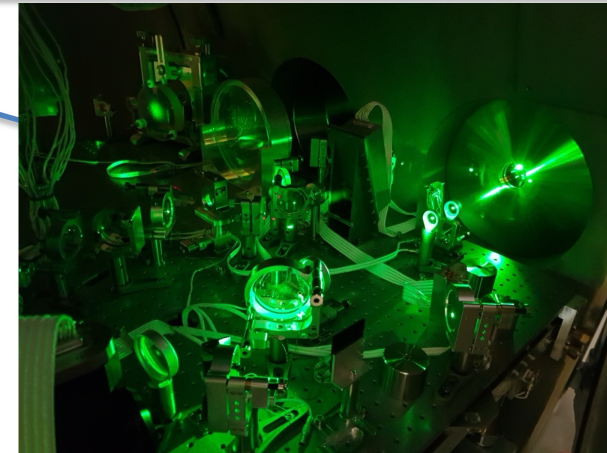
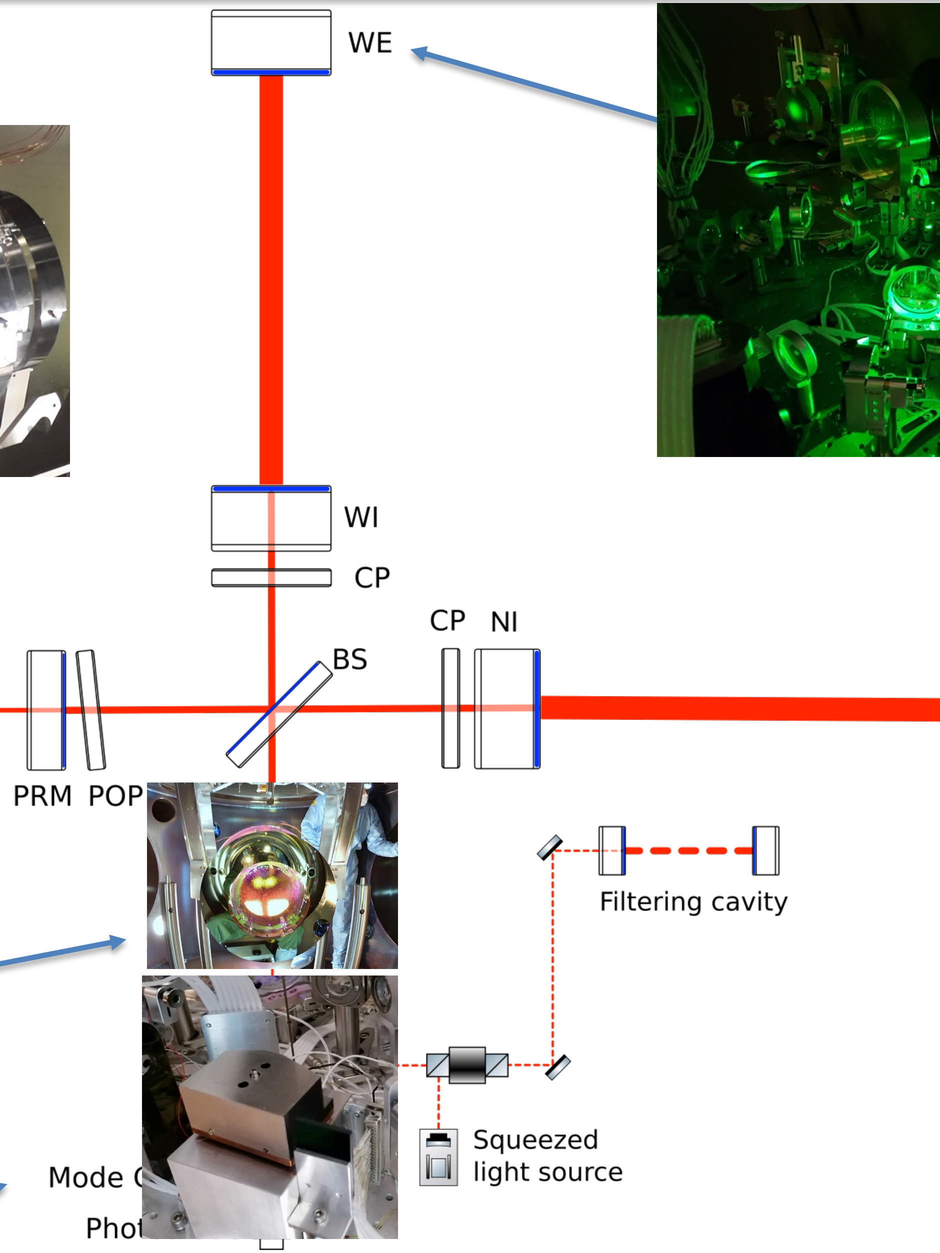




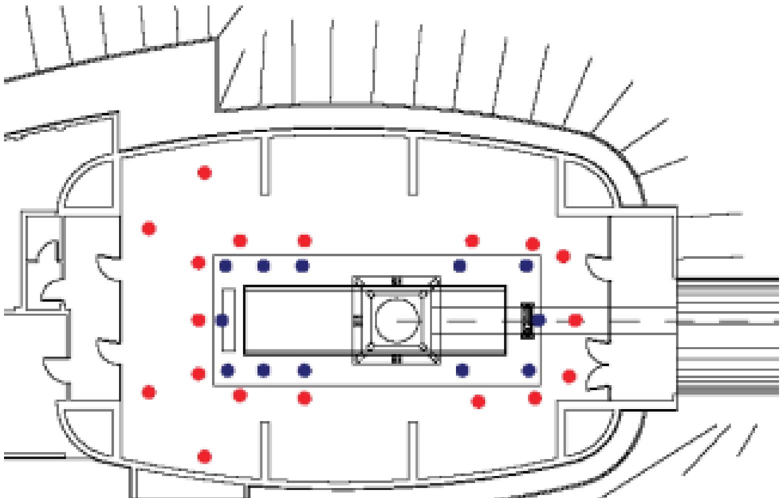


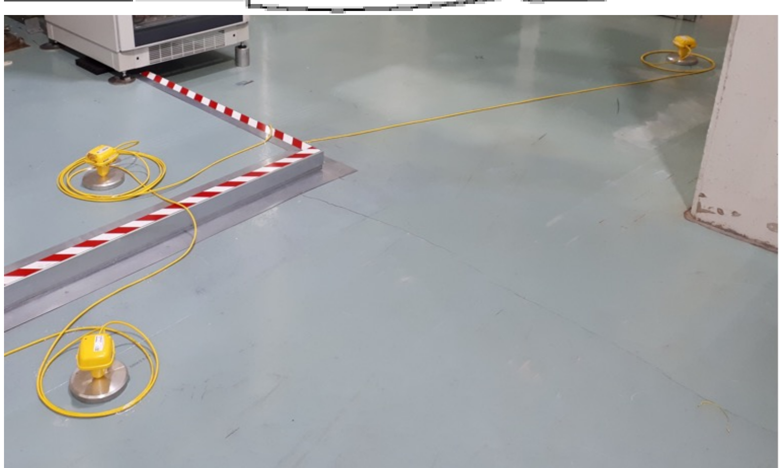
Signal recycling
mirror installed

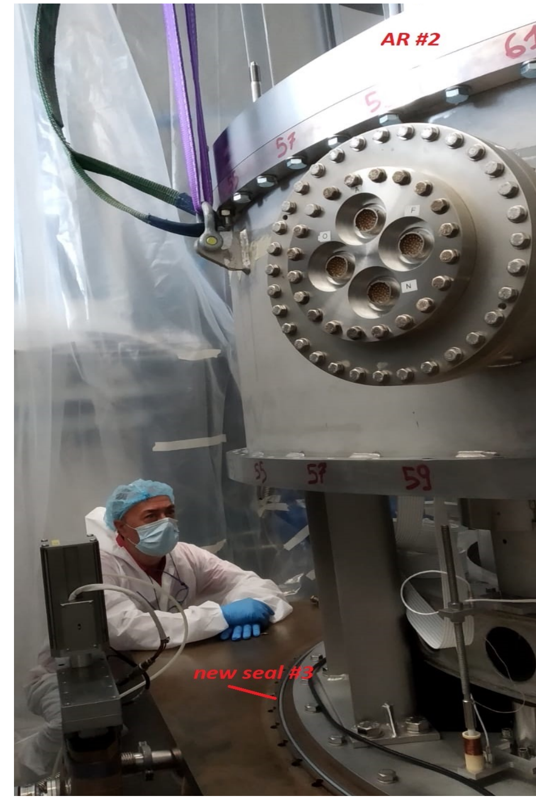
New, high-finesse OMC
low-noise readout electronics
stray ligth mitigation on bench

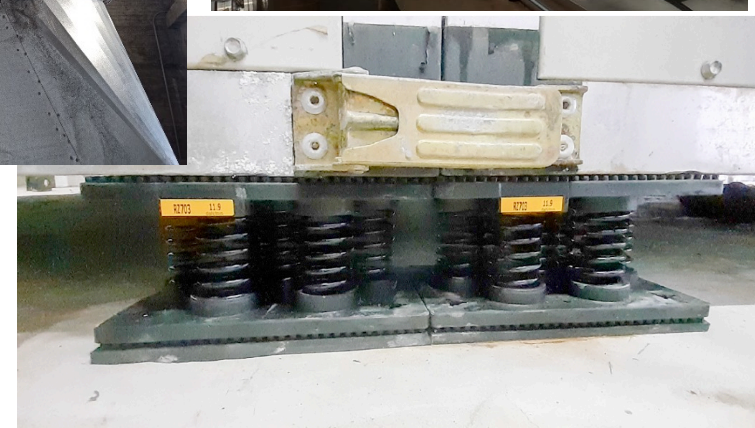
Other upgrades

- Improved vacuum level in central interferometer
- Seismometer array for Newtonian noise mitigation
- Reduction of vibration noise from vacuum system





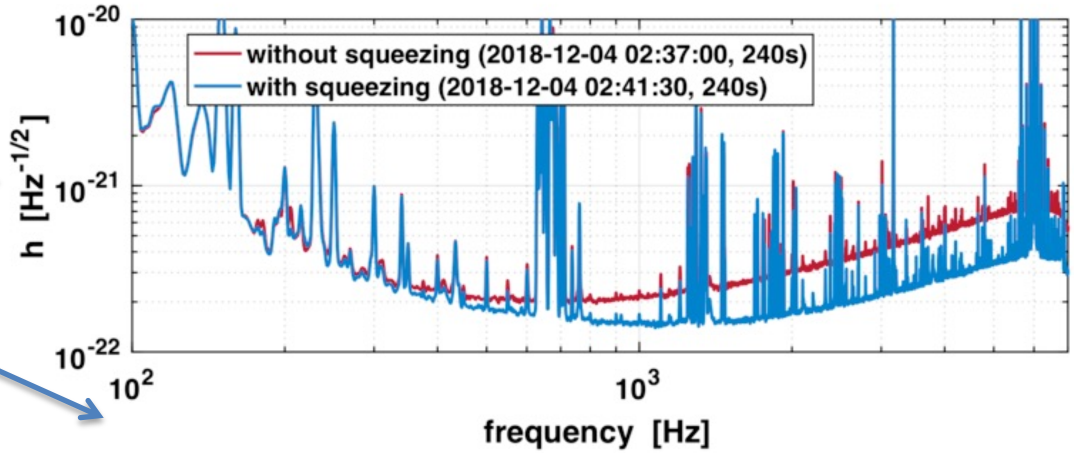


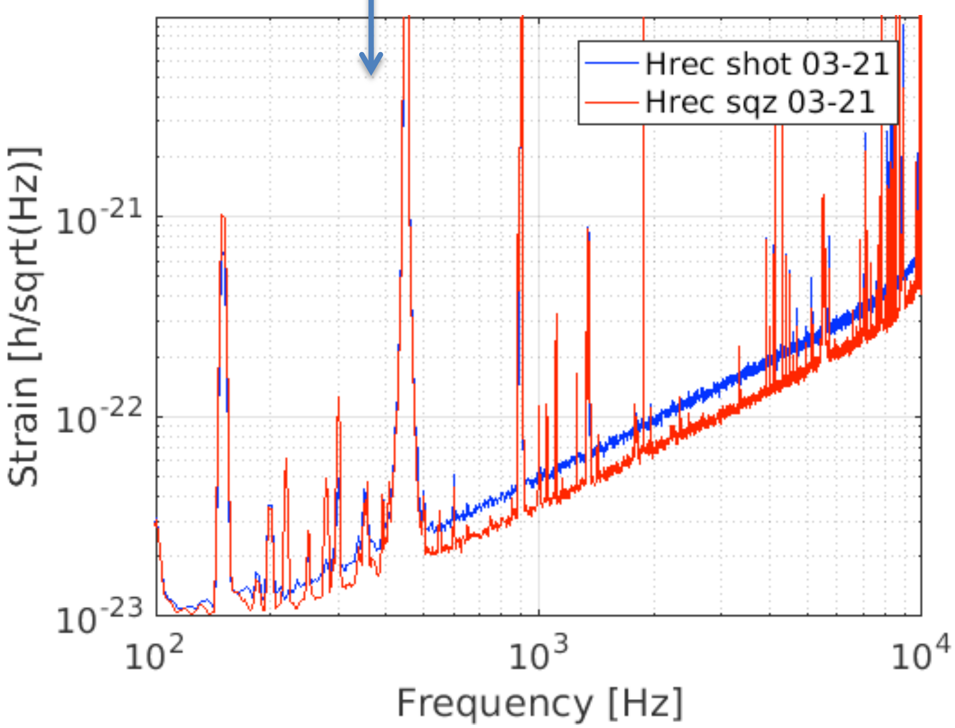


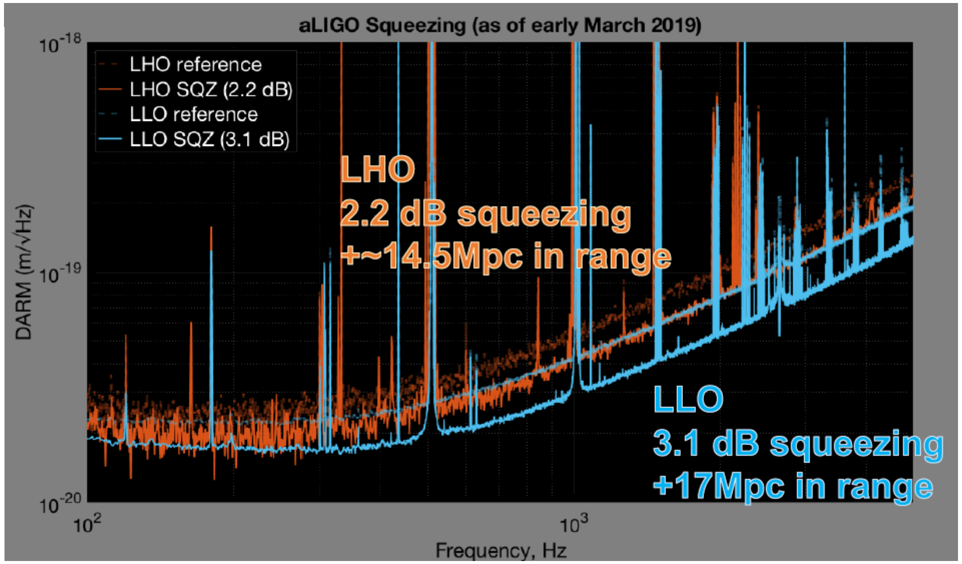
Squeezing in GW detectors

Performances during O3

- GEO600: 6 dB
- A-LIGO: 3.1 dB
- AdV: 3.2 dB

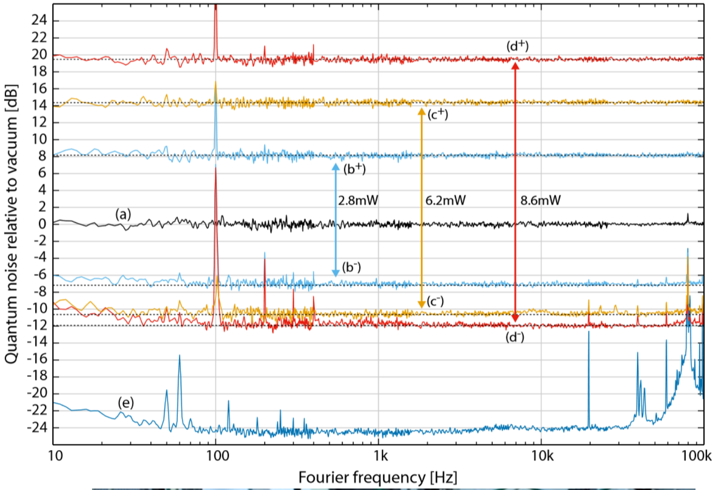


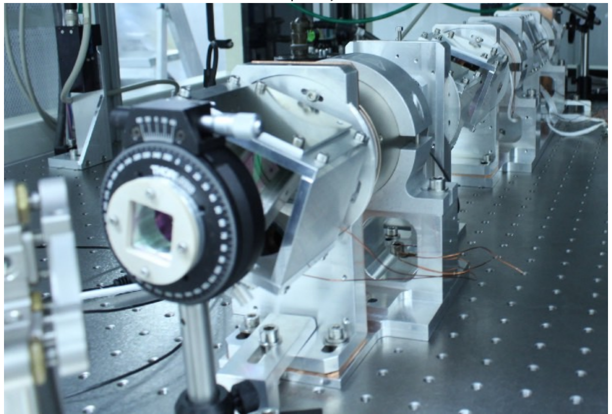




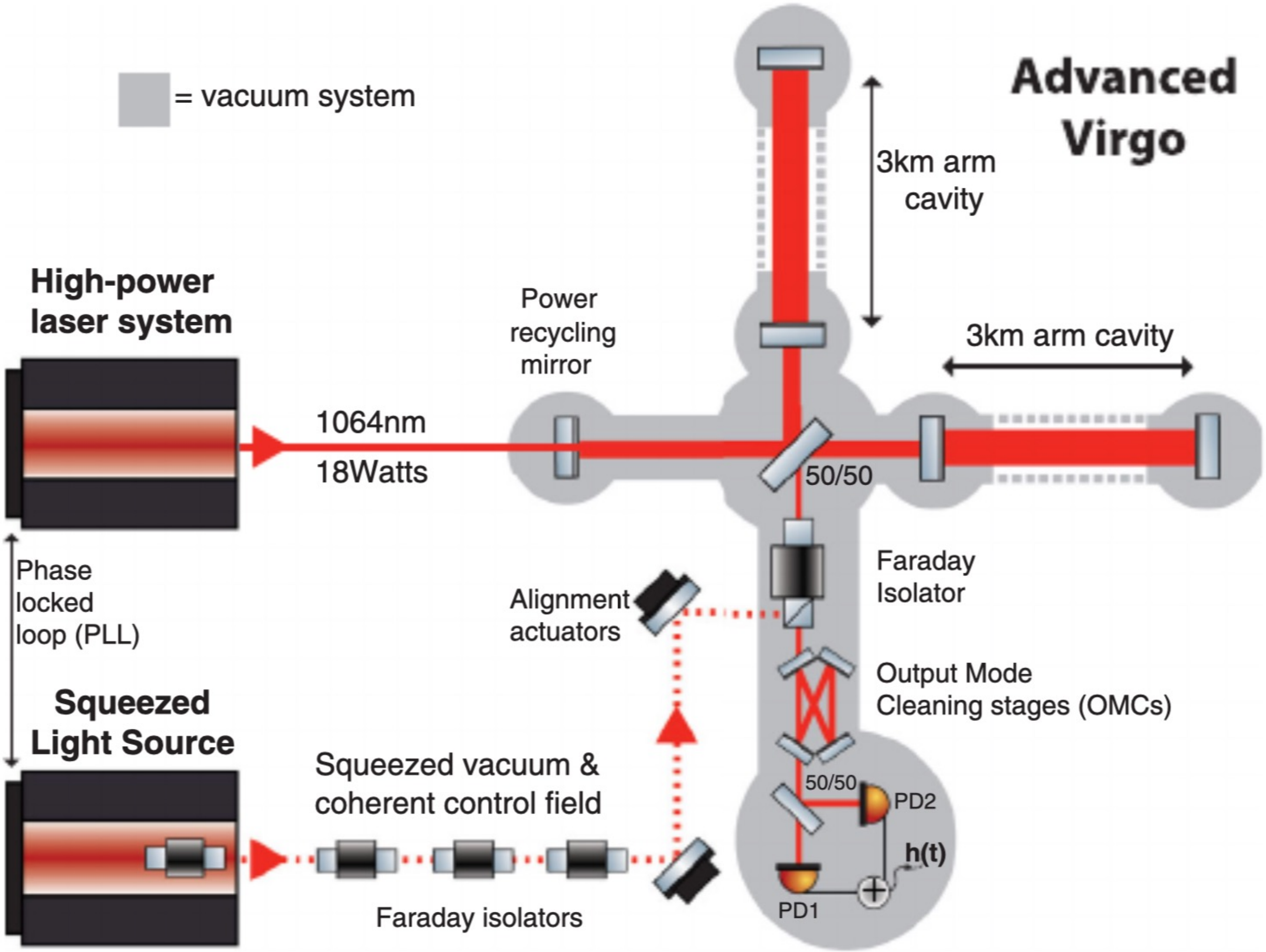
Squeezing injection in AdV

- Frequency-independent squeezed light source
  - From AEI
  - Up to 14 dB of squeezing
  - size $1m^2$, duty cycle around 100%
  - *M. Mehmet and H. Vahlbruch, CQG 36, 015014 (2019)*
  - installed at EGO in January 2018
- Mitigation of scattered light
  - Multiple stage Faraday isolator to decouple OPO from interferometer
  - Each stage: throughput >99%, isolation>40 dB
  - *E. Genin et al. Applied Optics 57, 9705 (2018)*
- Optical losses
  - Telescope for mode-matching to ITF
  - Minimal # of optical components
  - Lossless optical components (FI)
  - Accurate automatic alignment on ITF



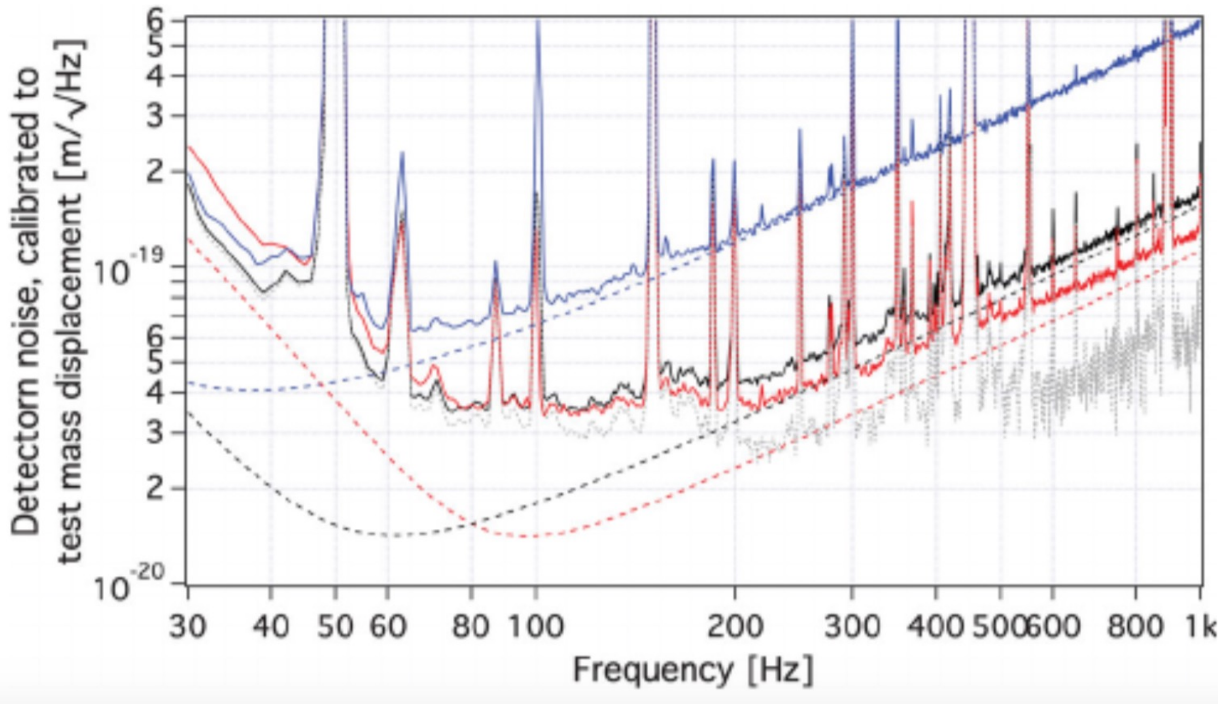


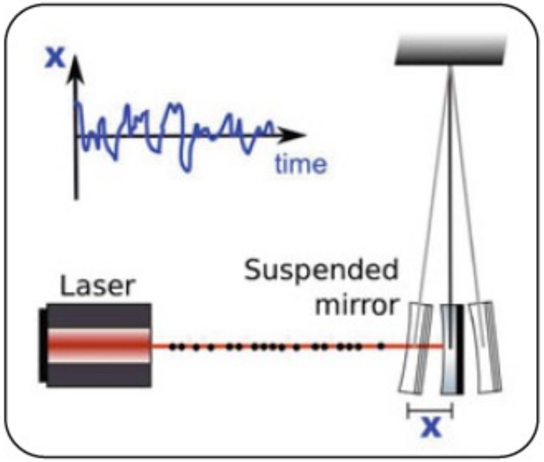
Squeezing in Virgo: O3

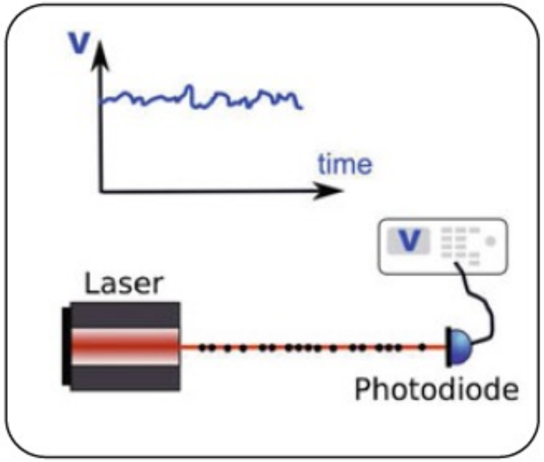


Squeezing in Virgo: O3

- Phase squeezing reduces shot noise, which dominates at high frequencies
- However the corresponding amplitude anti-squeezing (due to Heisenberg uncertainty) enhances radiation pressure noise, which shows up at low frequencies

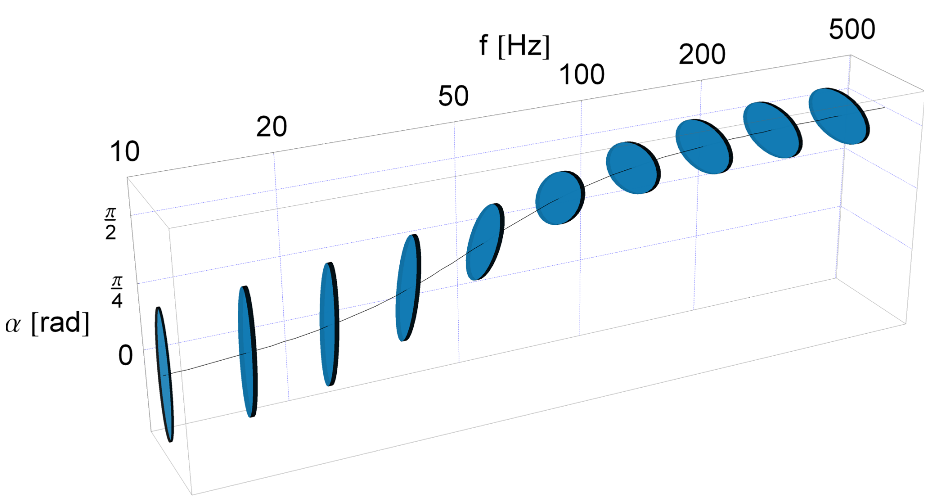


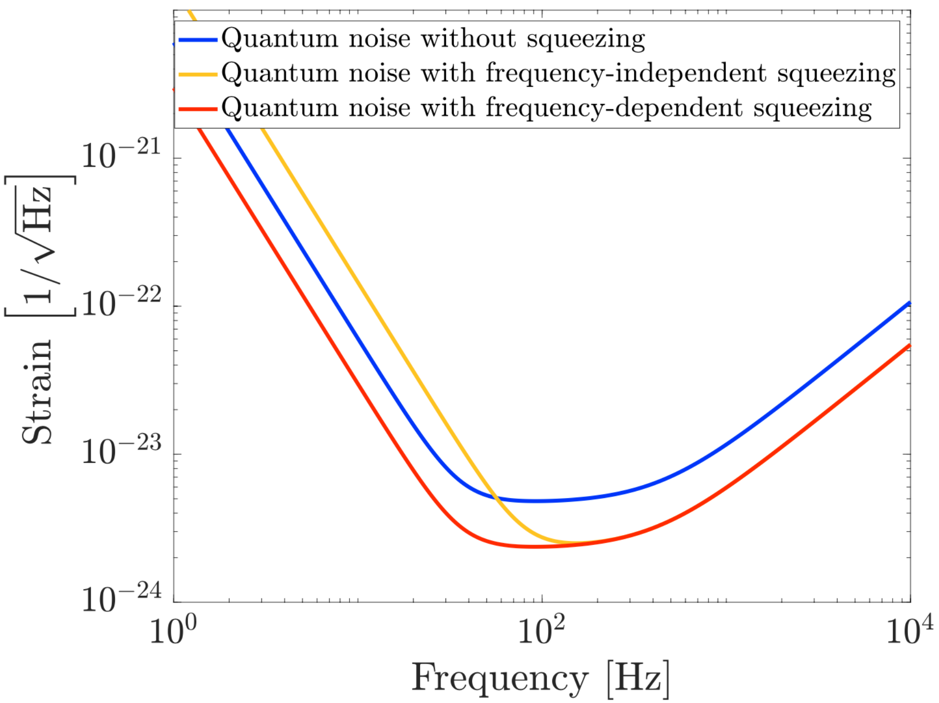




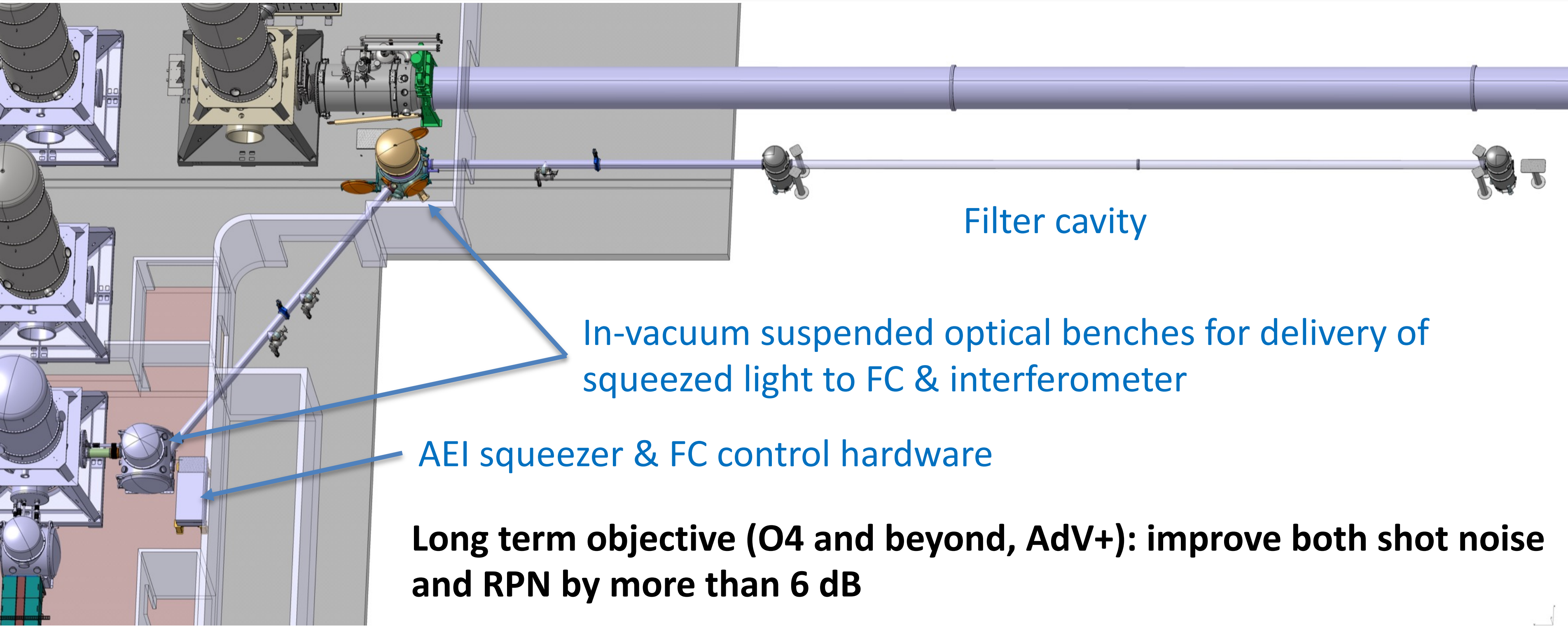
Frequency-dependent squeezing

- Frequency-dependent rotation of the squeezing ellipse to reduce
  - phase fluctuations (shot noise) at high frequency
  - amplitude fluctuations (radiation pressure noise) at low frequency
- Can be achieved by coupling the frequency-independend squeezed light to an optical resonator
  - squeezing ellipse rotation at QSN/QRPN crossover in Virgo requires an optical cavity pole ~50 Hz
    - either very high finesse (large optical losses) or very long optical cavity





AdV+: frequency-dependent squeezing

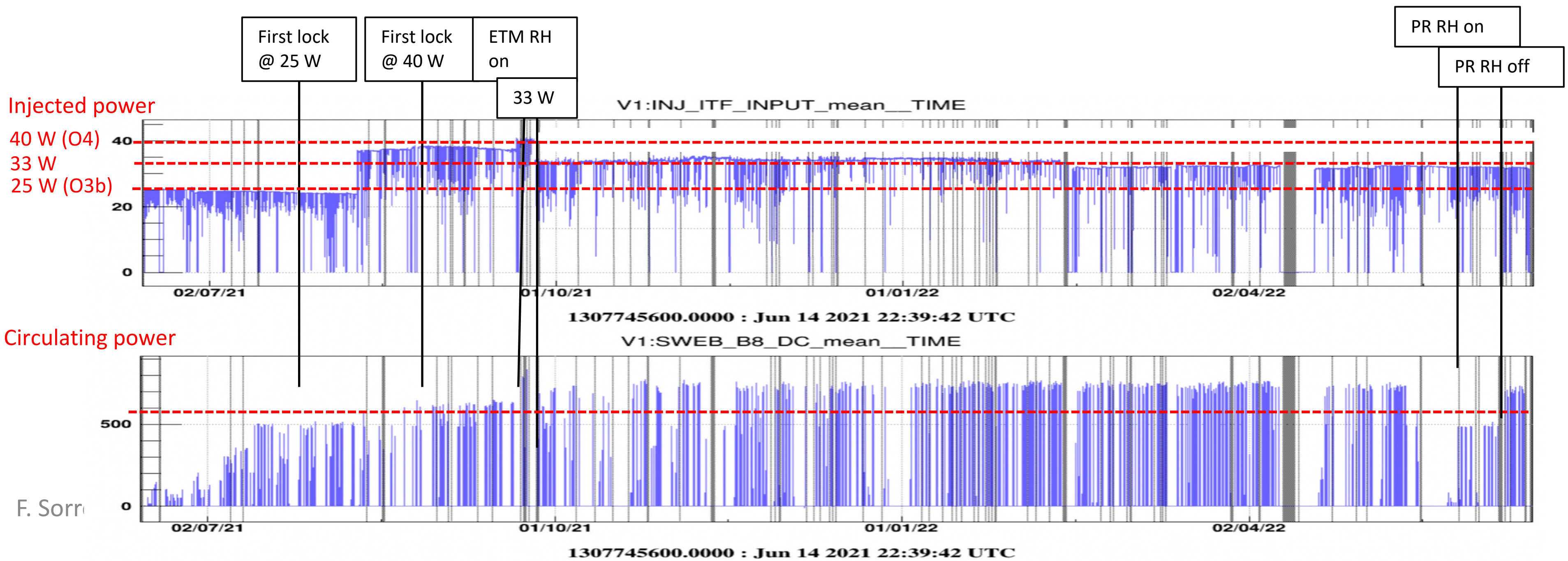


Long term objective (O4 and beyond, AdV+): improve both shot noise and RPN by more than 6 dB

- In-air squeezed-light source
  - From AEI, already employed for frequency-independent squeezing during O3
- High-throughput Faraday isolators and beam delivery optics suspended under vacuum for stray-light mitigation
- 300 m long linear cavity for squeezing ellipse rotation below 50 Hz
- Green and IR auxiliary beams for FC control

AdV+: status of commissioning

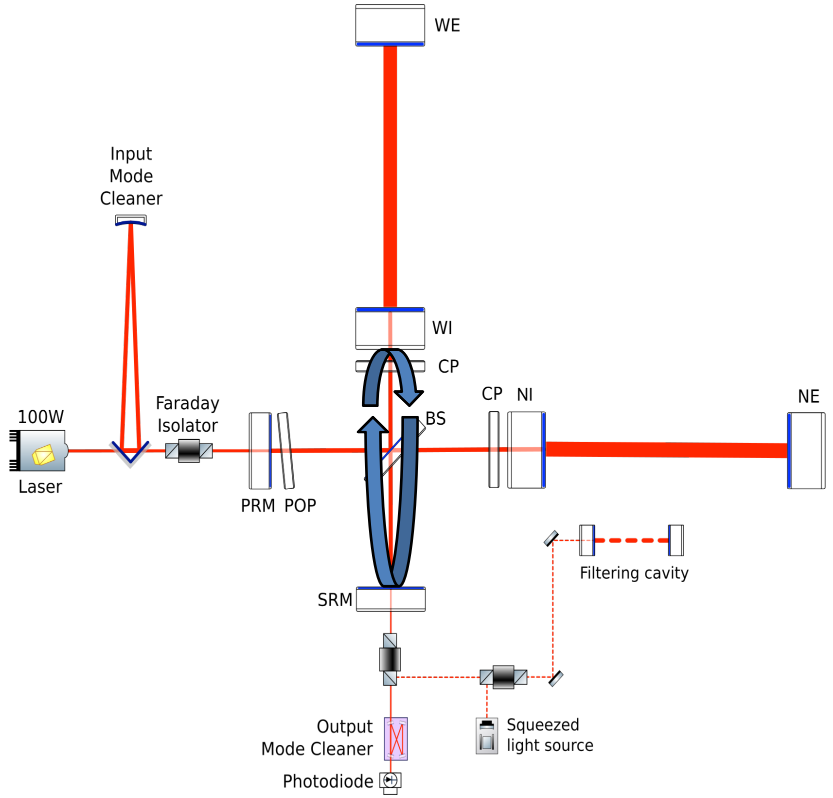
- The installation of the main interferometer was completed in December 2020
- The commissioning of the main interferometer started in January 2021
  - August 21: first lock of the interferometer with the O3 input power level (25W)
  - September 21: first lock with the O4 input power level (40 W)
  - October 21: decrease input power to 33 W due to locking instabilities
  - November 21 ÷ June 22: work on interferometer control & automation, issues on locking stability
  - July 22: installation of new actuator for RoC control of PR mirror (CHRoCC)
  - Current status: stable and reproducible lock achieved
  - Next steps: DC readout, noise hunting, SQZ injection



F. Sorr

Double recycling in Virgo

- In AdV design the PR and SR optical cavities are close to instability region
  - makes mode matching and alignment extremely critical
- PRM designed to reach proper RoC at full optical power
  - cold RoC error of -40 m
  - to be compensated with PRM RH in principle
  - however compensation limited to <10 m due to hardware issues
- Compensation of PR RoC was done until last July with TCS (CO_2 actuators on input CPs)
  - however SR cavity matching is affected too
  - optomechanical couplings (optical spring) depending on both PRM and SRM RoC
  - limited bandwidth of DARM transfer function, which determines ITF sensitivity



Resonant sideband extraction

$$\varphi_c^{00} + \varphi_{SRC} = (2n+1)\pi$$

HOM not resonant in FP

$$\varphi_c^{mn} \sim \varphi_c^{00} + \pi$$

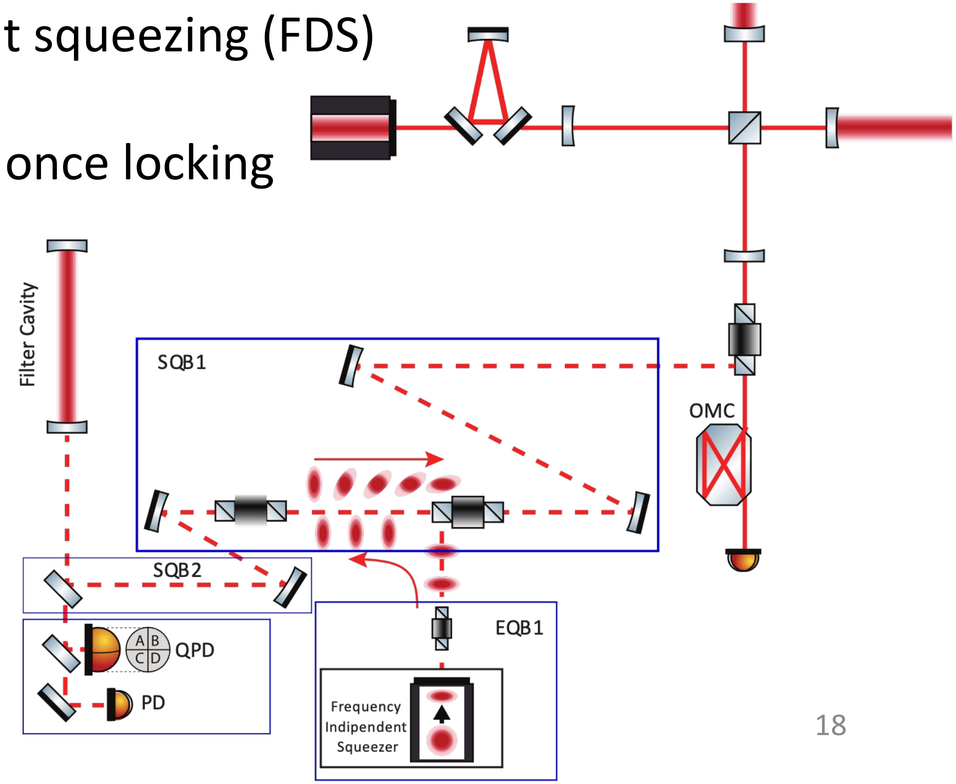
φ_{SRC} same for all modes (SRC cavity degeneracy)

$$\varphi_c^{mn} + \varphi_{SRC} \sim 2n\pi$$

HOM are close to resonance in SRC cavity

Commissioning of frequency-dependent squeezing

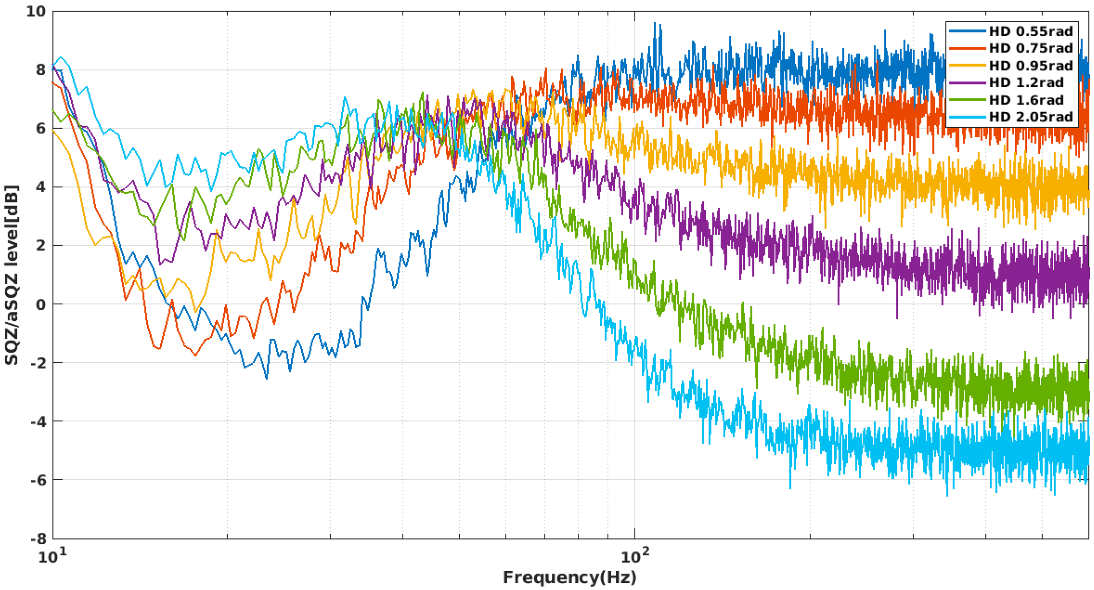
- Precommissioning of QNR subsystem completed
- In-air bench with SQZ source (AEI), sensors & actuators for filter cavity control
- Suspended benches for beam delivery to FC and to interferometer
- Filter cavity for squeezing ellipse rotation
- Commissioning of frequency-dependent squeezing (FDS) with external homodyne detector
- Final commissioning on interferometer once locking configuration is consolidated

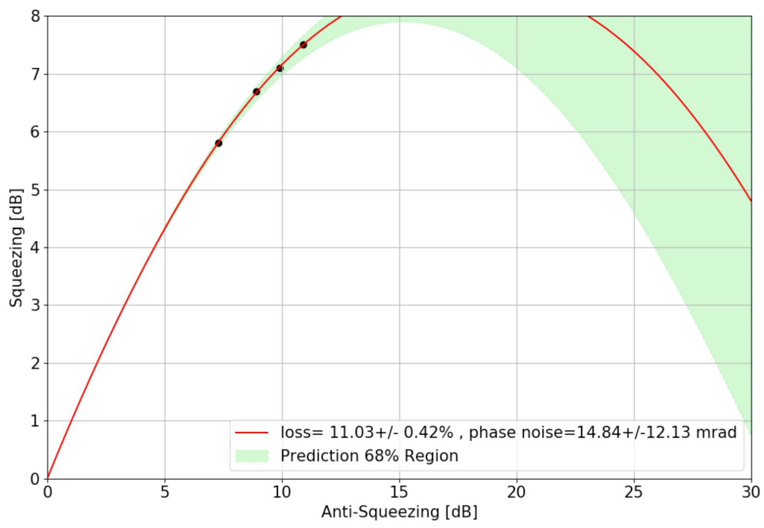


AdV+: status of FDS

Commissioning of frequency-dependent squeezing

- Double stage longitudinal and angular control of filter cavity with auxiliary beams
- 532 nm from SHG of main SQZ laser
- 1064 nm from subcarrier laser (FC) with 1.2 GHz detuning
- Commissioning of frequency-dependent squeezing (FDS)
- FSD measured down to 20 Hz FC detuning (better than target 40 Hz)
- Filter cavity control automated
- Ready to be injected on ITF

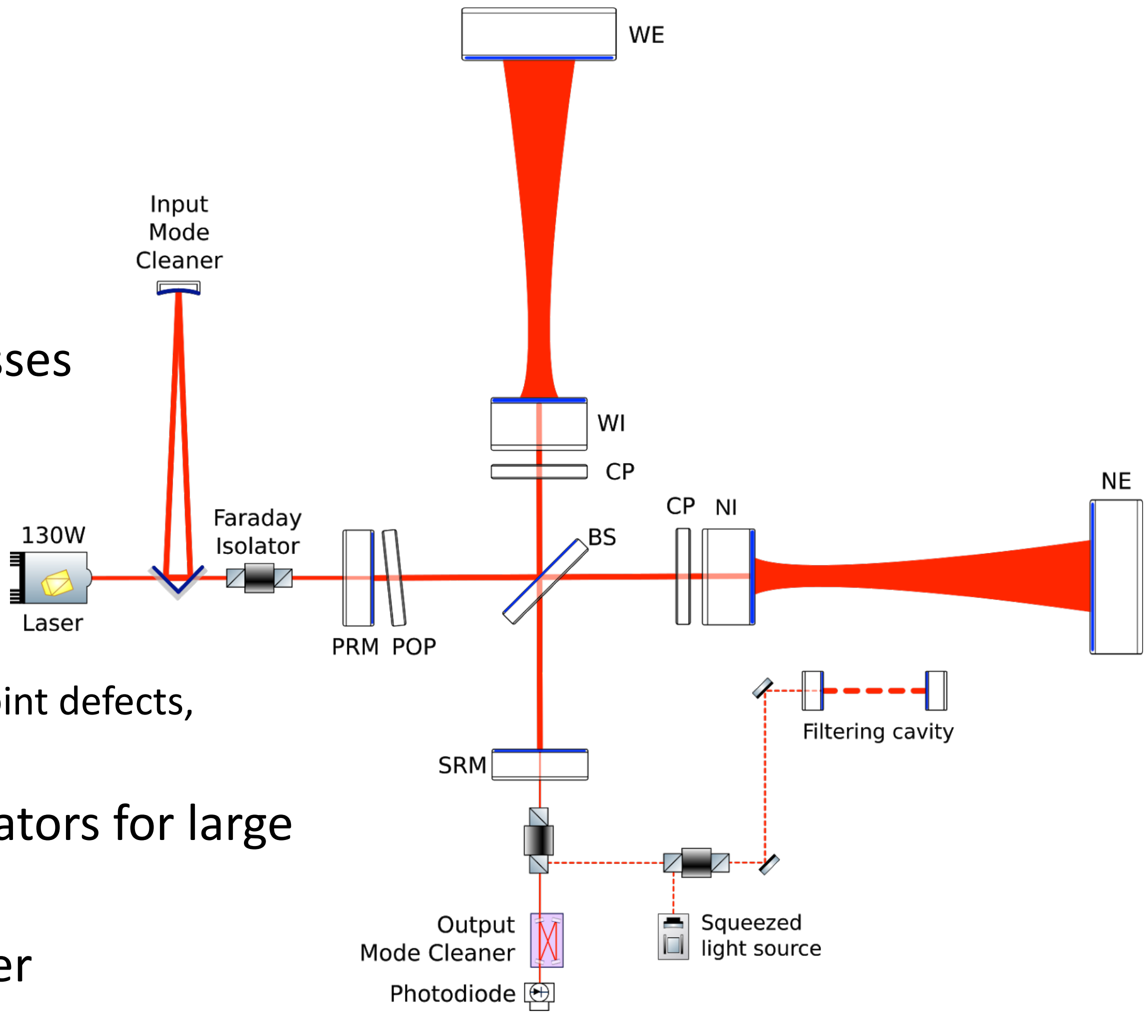




AdV+ phase 2

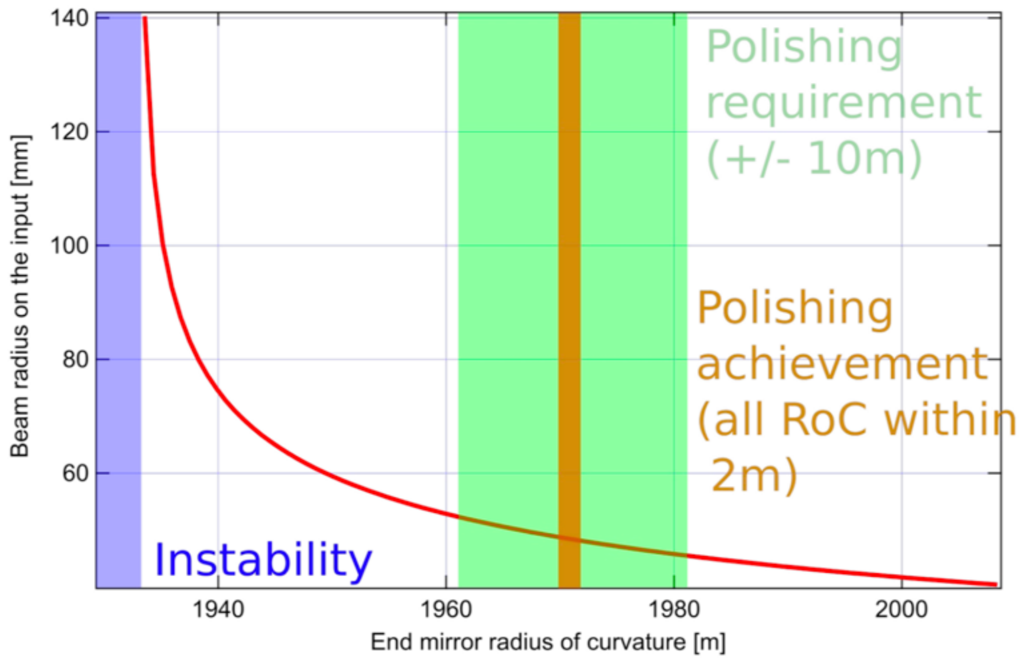
Main upgrades

- Larger beams on end test masses
  - 6 cm radius -> 10 cm radius
- Larger end mirrors
  - 40 kg -> 100 kg
- Better mirror coatings
  - Lower mechanical losses, less point defects, better uniformity
- New suspensions/seismic isolators for large mirrors
- Further increase of laser power
- 40W -> 60W -> 80 W



Geometry of arm cavities

- Larger optical g-factor
- Tighter angular control requirements during pre-alignment
  - 0.2 µrad
- Tight requirements RoC control
  - ΔRoC~0.3 m
- Increasing beam size on end mirrors makes arm cavities close to instability
  - makes controls more critical
  - makes polishing requirements thighter
  - increases sensitivity to aberrations



	Phase I	Phase II
EM diameter	350mm	550mm
beam radius @ EM	58mm	91mm
beam radius @ IM	49mm	

	Phase I	Phase II
EM RoC	1683m	1969m
IM RoC	1420m	1067m
g factor	0.87	0.95

AdV+ phase 2 – larger mirrors

- Project schedule driven by mirror production (high risk)
  - so far constrained by budget availability
  - budget for phase II now partly available @ EGO (5.4 M€ out of 13.9 M€)
  - substrates acquired and received at LaboratoireMateriauxAvancés (LMA), Lyon
  - call for tender for mirrors polishing issued
    - Polishing started on December 2021
  - several upgrades at LMA needed to prepare the realization of mirrors & coatings
  - coating
    - Large mirror mounts and handling tools
    - Upgrade of cleaning machine
    - Large silica crystallizers for annealing
    - Large coater upgrade
  - metrology
    - Upgrade of scattering bench
    - Upgrade of absorption bench
    - New reference sphere for flatness/RoC measure
    - Upgrade of profilometer(done during Phase I)
    - Clean room enlargement (done during Phase I)

AdV+ phase 2 – mirror coating

- Several coating formula studied in the R&D phase
- Outcome
  - LIGO and Virgo agreed to pursue together the development of TiO_2:GeO_2/SiO_2coatings at LMA
  - Joint LIGO-Virgo working group settled up
  - First monolayers and multilayers produced in the Grand Coater at LMA
  - Critical path for AdV+
- Final decision on the coating for O5 to be made in a few months

LMA LABORATOIRE MATÉRIAUX AVANCÉS — **Conclusion** — Advanced Virgo

- **Ti-GeO_2 working point founded and defined**
- **Samples for characterizations produced**
- **First characterization cycle in progress**
- **HR stacks produced**
  - **optical losses within specs for annealing at 500 °C**
  - **CTN measurements for annealing at 500°C in progress**
- **Problem of bubbles/blistering for long annealing at 500 °C or short annealing at 600°C**
  - **different solutions will be tested**
    - **silica stress optimization**
    - **deposition at higher temperature**
- **Possibility of inserting an PR coating in the schedule without impacting Ti-GeO_2 development plan**

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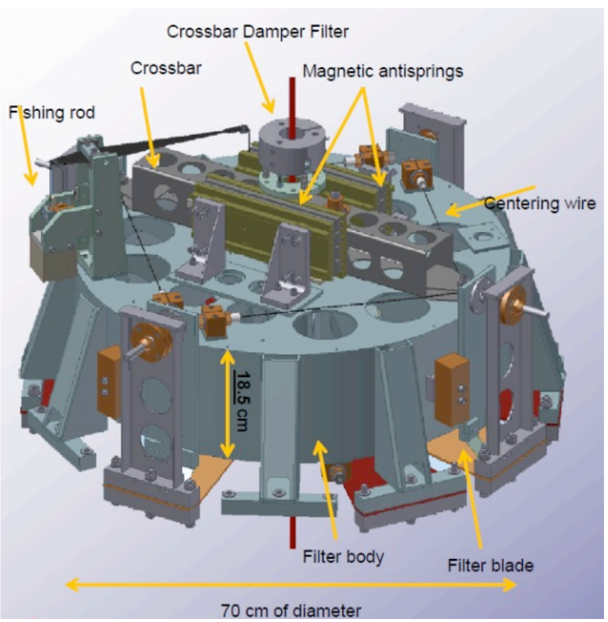
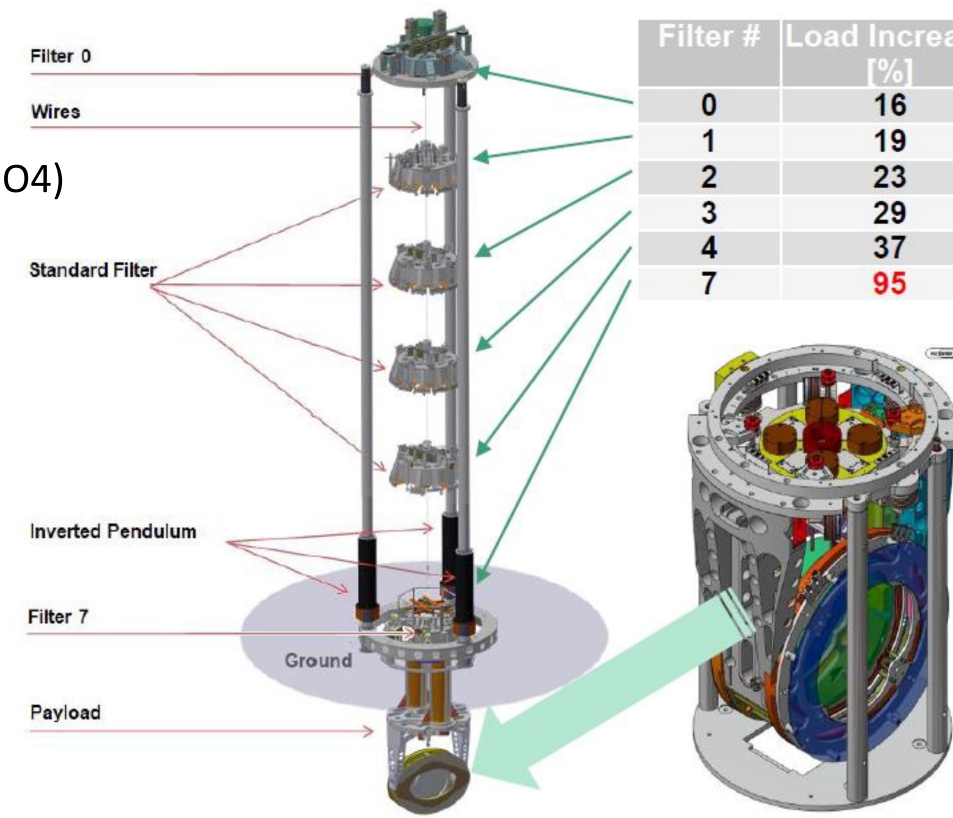
AdV+ phase 2 – test masses suspension

- Super Attenuators and Payloads for Large End Mirrors
  - Development of blades springs and anti-magnetic springs for super-attenuators started
  - Large payload prototype already set up
    - Including fused silica fibers Ø640 µm suspending 100 kg dummy mirror
- Goals:
  - Suspend 100 kg mirrors
  - Construction in 2022-2023
  - Installation from mid-2023 (at the end of O4)





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3	29
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7	95

See talk by F. Fidecaro

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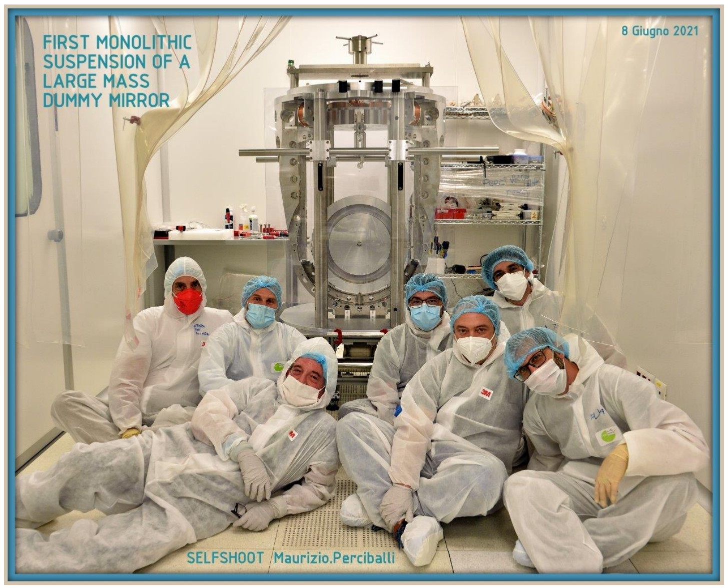

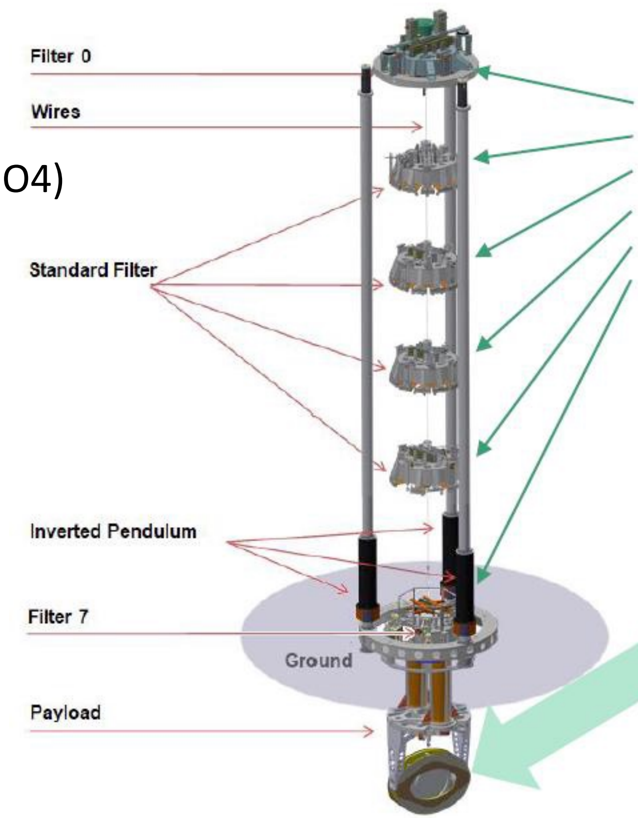

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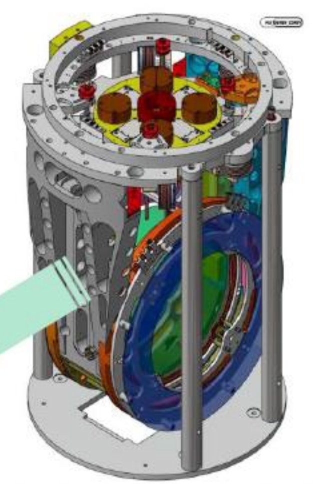
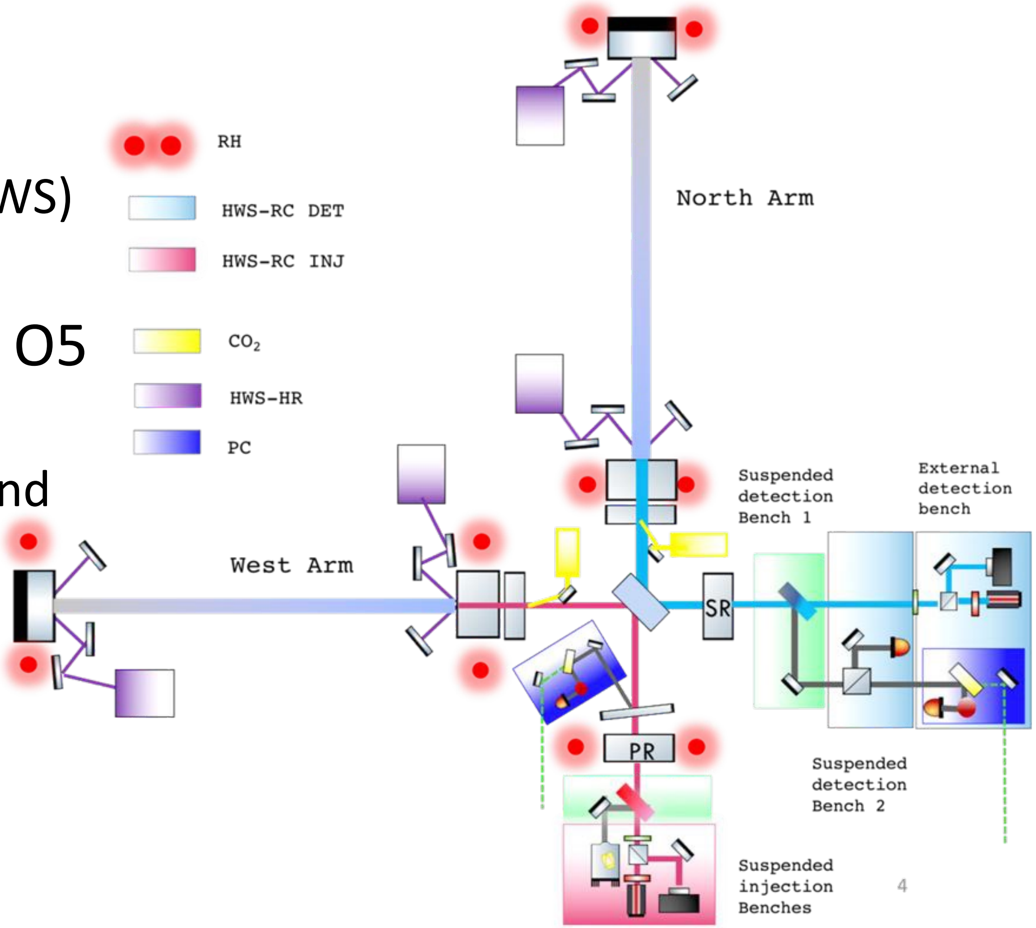


See talk by F. Fidecaro

Thermal compensation system

- Actuators:
  - Ring-heaters for fine tuning of RoCs
  - CO2 heaters
- Sensing
  - Hartman wave-front sensing (HWS)
  - Phase cameras
- Several upgrades foreseen for O5
  - New cameras for HWS
  - Upgraded HWS telescopes for end mirrors
  - Mode-cleaners for CO2 beams
  - DC CO2 laser beam shapers via deformable mirror
  - More remote controls
  - More phase cameras

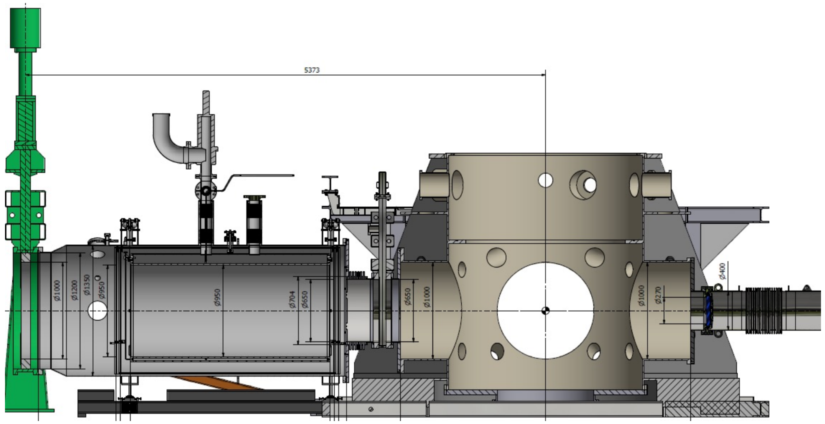


See talk by D. Lumaca

Vacuum & cryogenics in Virgo

- Chief requirement is to mitigate optical length noise from density fluctuations of background gas
  - UHV level requirement for AdV+ is <10^{-9} mbar over a ~7000 m^3 volume
- Several issues & challenges
  - Mitigate vibrations from pumping system
  - stray light from apertures/pipes
  - dust contamination
  - electrostatic charging

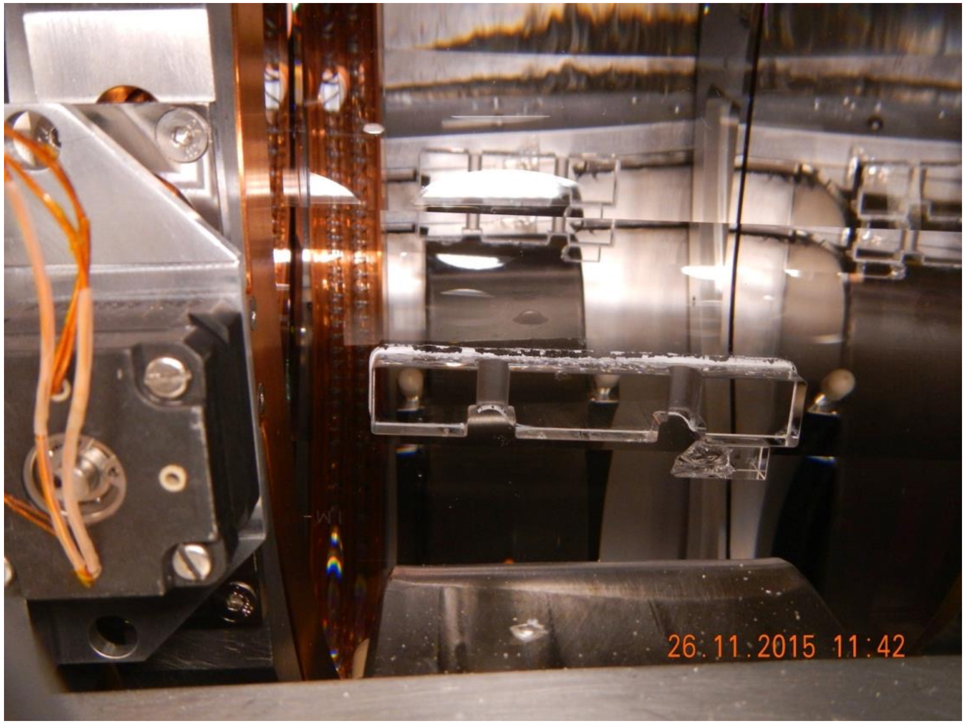
Gas species	Pressure (mbar)	Phase noise ($Hz^{-0.5}$)
H_2	10^{-9}	$2.1\,10^{-25}$
H_2O	10^{-9}	$7.0\,10^{-25}$
Air + others	$5\,10^{-10}$	$6.1\,10^{-25}$
Hydrocarbons(atomic mass units):		
100	10^{-14}	$9\,10^{-27}$
300		$3\,10^{-26}$
500		$6\,10^{-26}$
Total	$2.5\,10^{-9}$	$9.5\,10^{-25}$

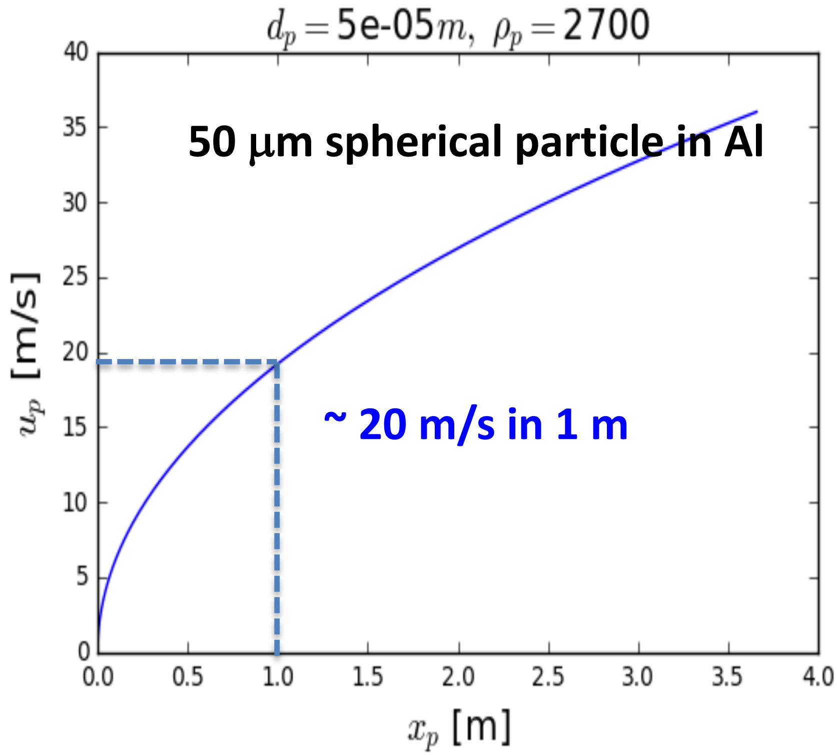


See talks by G. Gemme & A. Pasqualetti

Impact of dust contamination

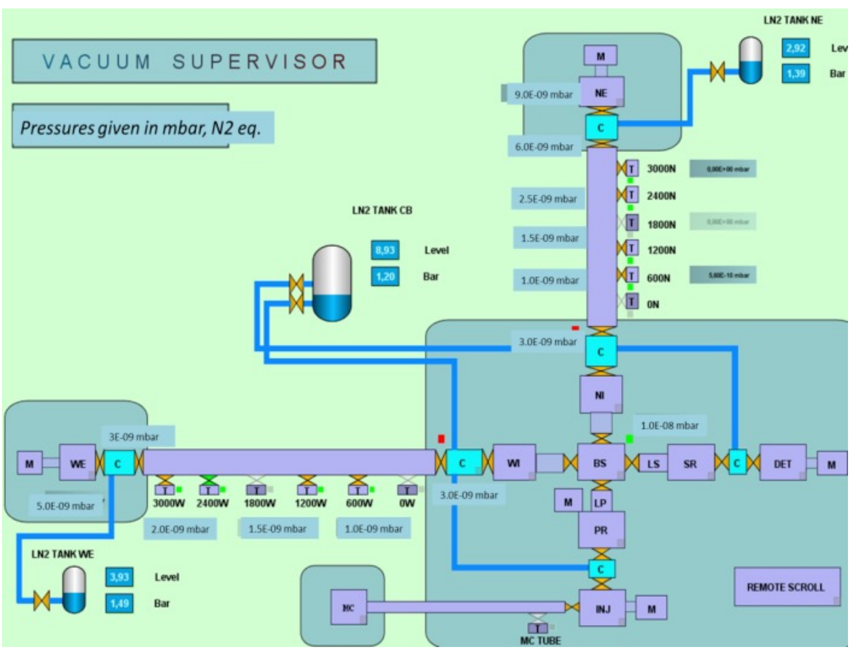
- Failure of monolithic suspensions in 2015÷2016
- Understood as caused by impact of dust particles under vacuum
- Solution
  - Venting circuit separation
  - replacement of scroll pumps

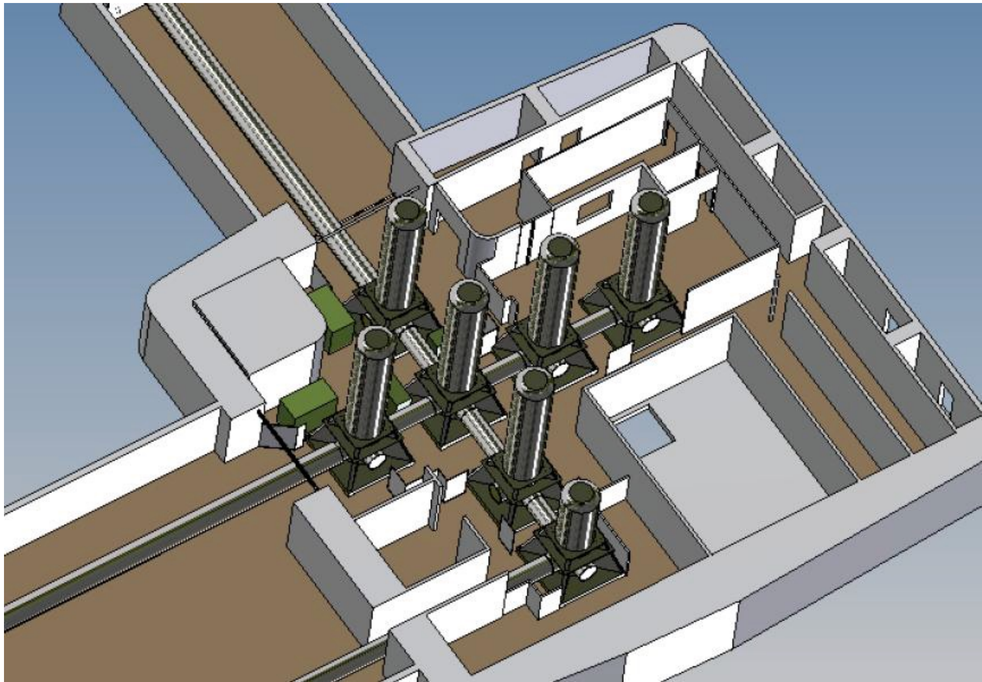




Vauum & cryogenics: phase 2

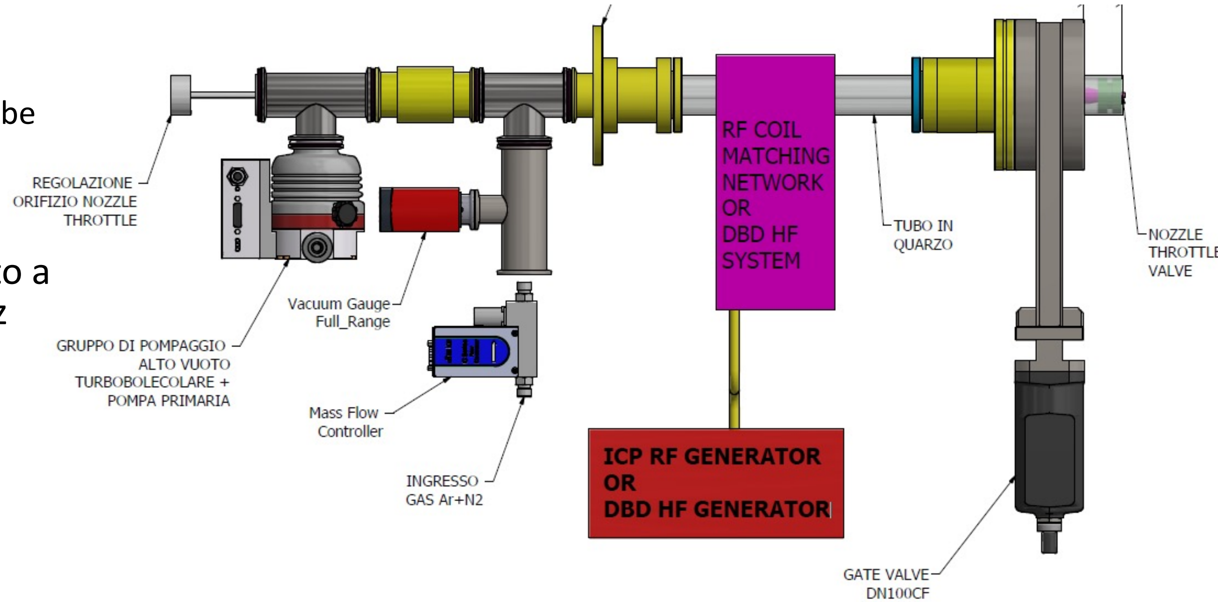
- Several upgrades foreseen for the vacuum system
  - Increase apertures (valves, bellow assemblies, etc)
  - Additional pumping stations along the tube
  - Low noise ion pumps for most critical vacuum chambers (TBC)
  - Cryogenic pump in the central area to reduce noise
  - Electrostatic mirror discharging device

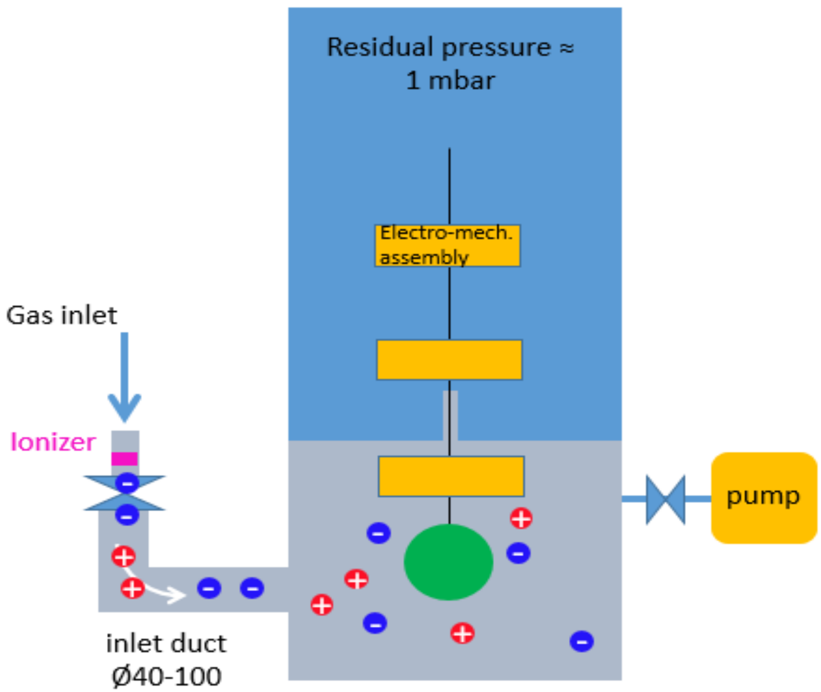


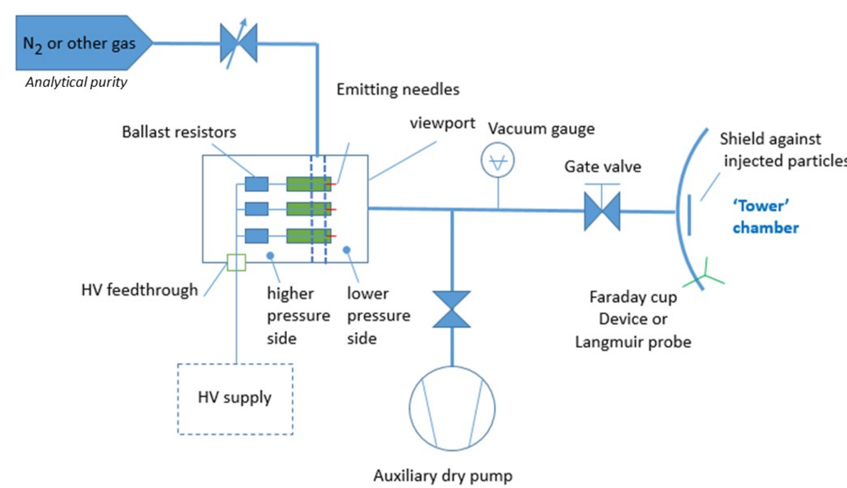


Test mass discharge system

- 1st method: ionization by 'corona' discharge with HV needles.
  - Risks due to electrodes erosion to be verified
  - HV supply to be extensively tested
- 2nd method: nization by alternating current at RF (13.56 MHz) applied to a coil externally mounted on a quartz tube containing N2 ;
  - No electrodes under vacuum
  - UV emissions to be checked





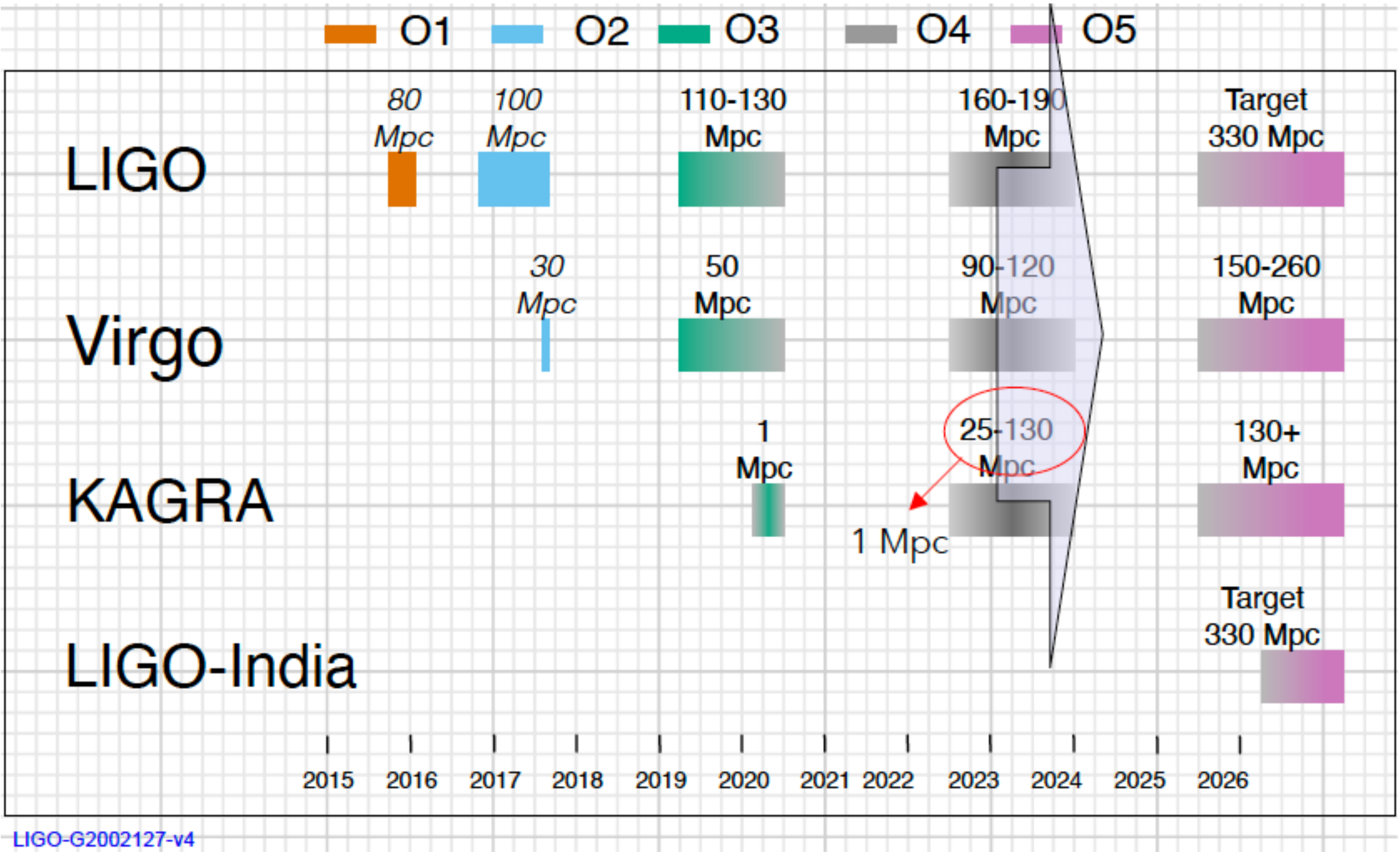


Towards next science runs

- LIGO, Virgo, and KAGRA are closely coordinating to start the O4 Observing run together.
- We plan to start the O4 Observing run in March 2023
  - LIGO projects a sensitivity goal of 160-190 Mpc for binary neutron stars.
  - Virgo projects a target sensitivity of 80-115 Mpc.
  - KAGRA should be running with greater than 1 Mpc sensitivity at the beginning of O4, but will work to improve the sensitivity toward the end of O4.

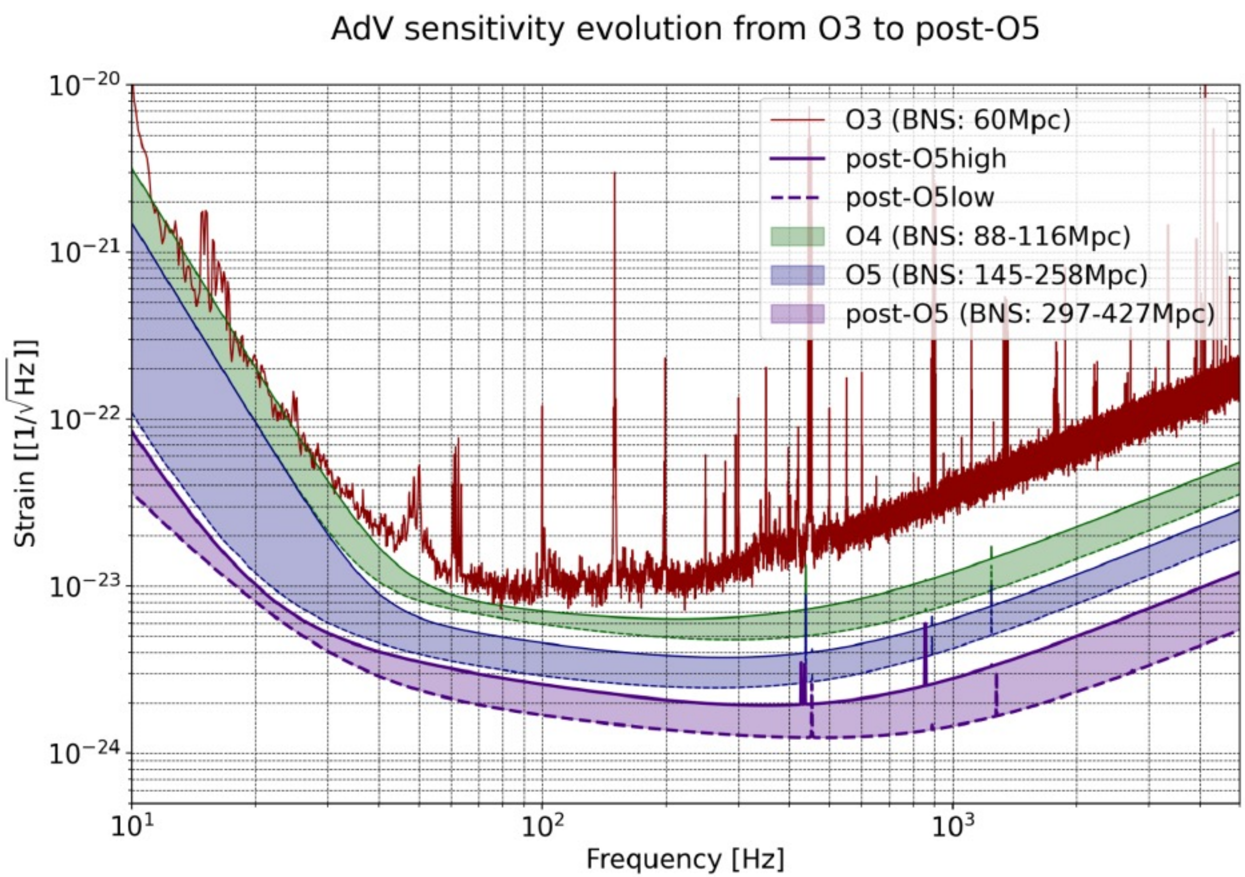
https://www.virgo-gw.eu/#news_***o4***_plans

Long term plan of GW network



Virgo beyond O5

- Explore ultimate limits of the Virgo infrastructure
  - Reduce suspension thermal noise using larger test masses with a monolithic intermediate mass (triple pendulum)
  - Improved models for subtraction of Newtonian noise
  - 10 dB frequency-dependent squeezing
  - lower coating thermal noise -> loss angle reduced by at least a factor of 3-4



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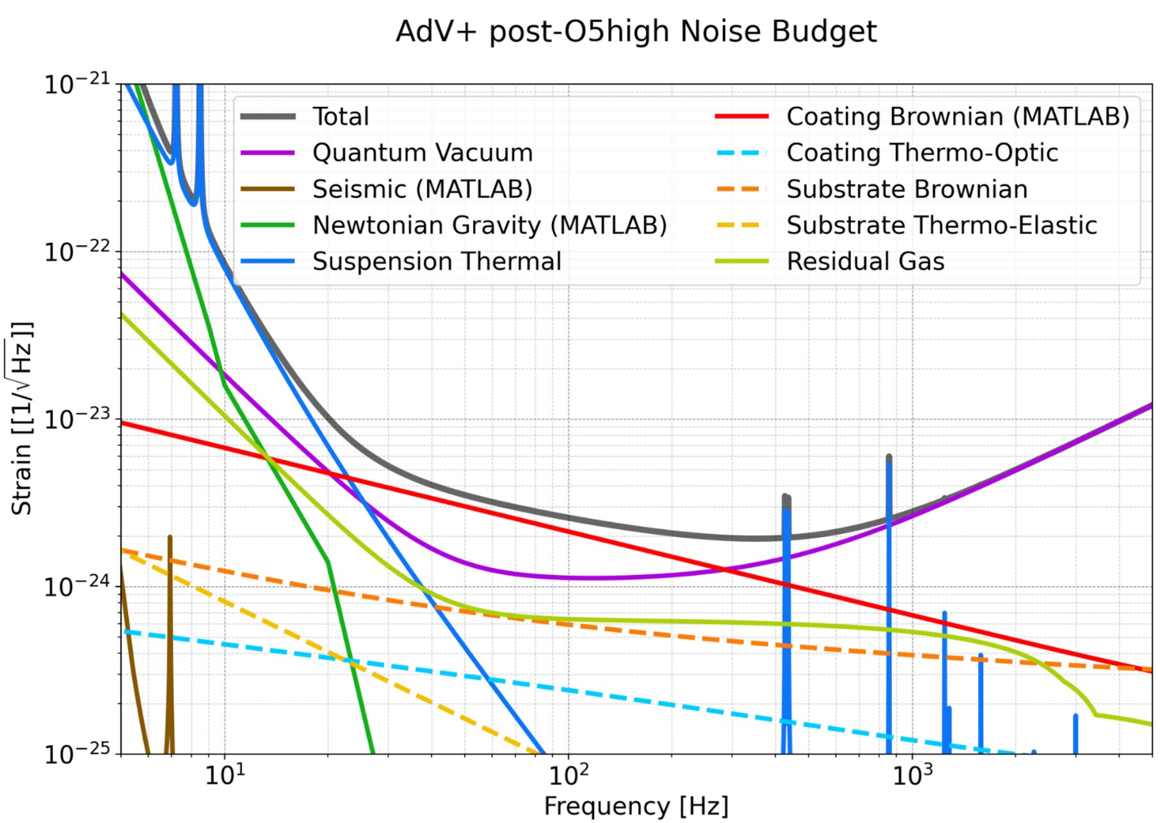

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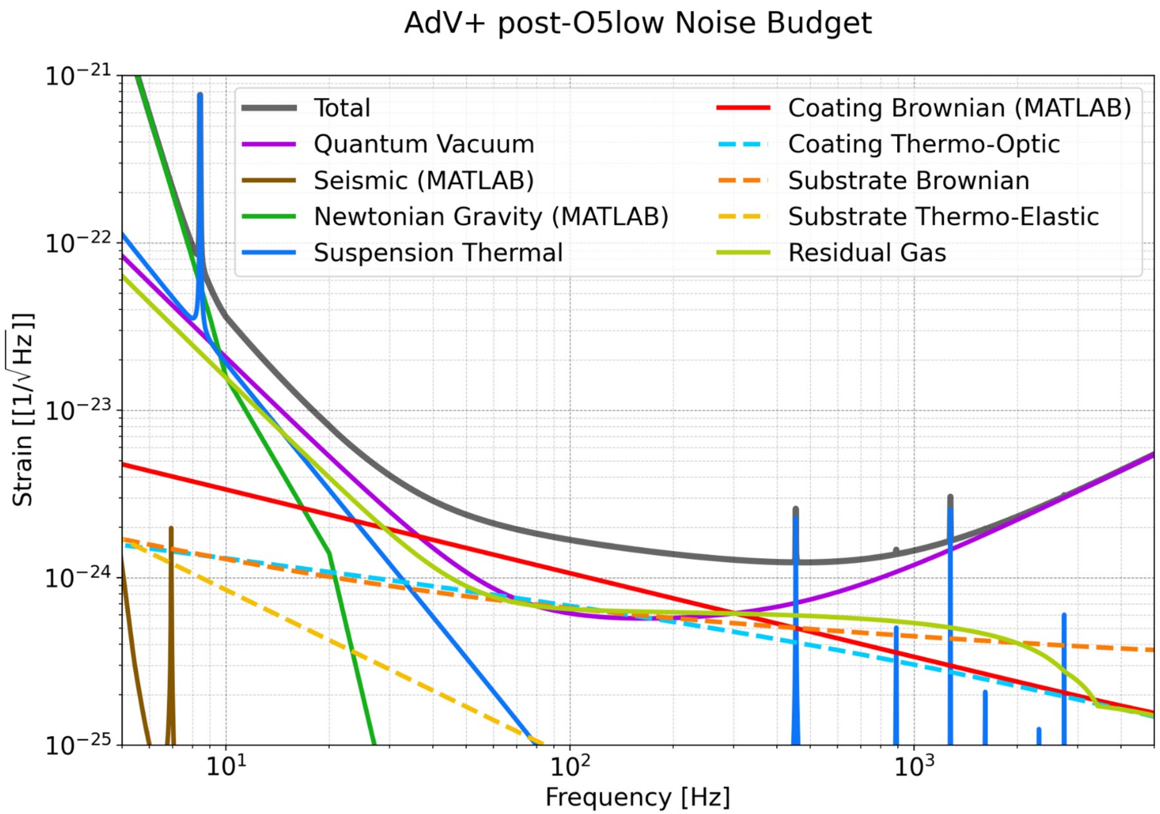

Conclusions

- Large science reach during the first 3 observing runs
- Currently upgrading advanced detectors to approach design sensitivity
- AdV+ Phase I (towards O4)
  - Installation of AdV+ Phase I completed
  - Commissioning of main interferometer & QNR system progressing
- AdV+ Phase II (towards O5)
  - Large part of design done and reviewed
  - Substrates received, call for tender for mirrors polishing done
  - Coating to be developed further chosen
- Post-O5 plan to reach ultimate limits of Virgo infrastructure