Virgo/LIGO upgrades. Plans & challenges

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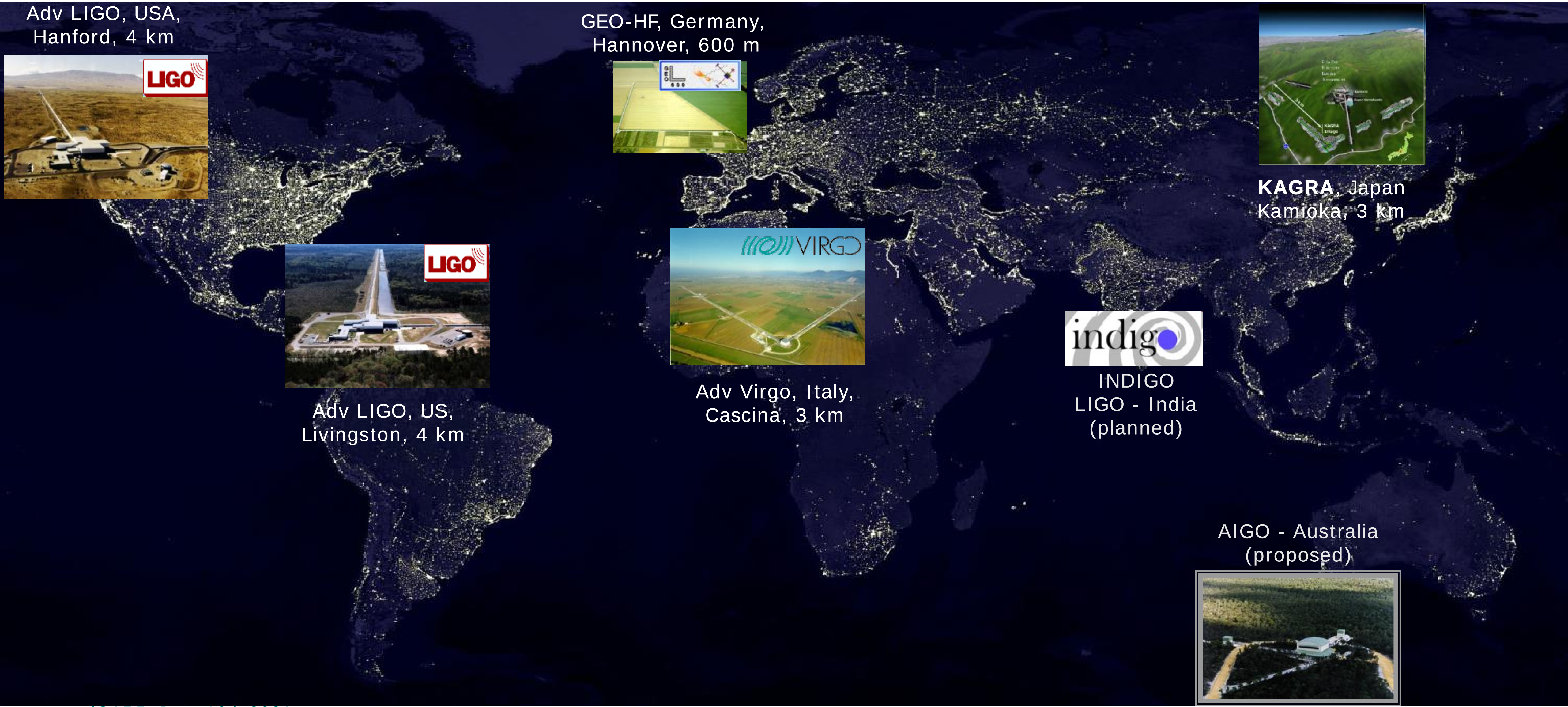
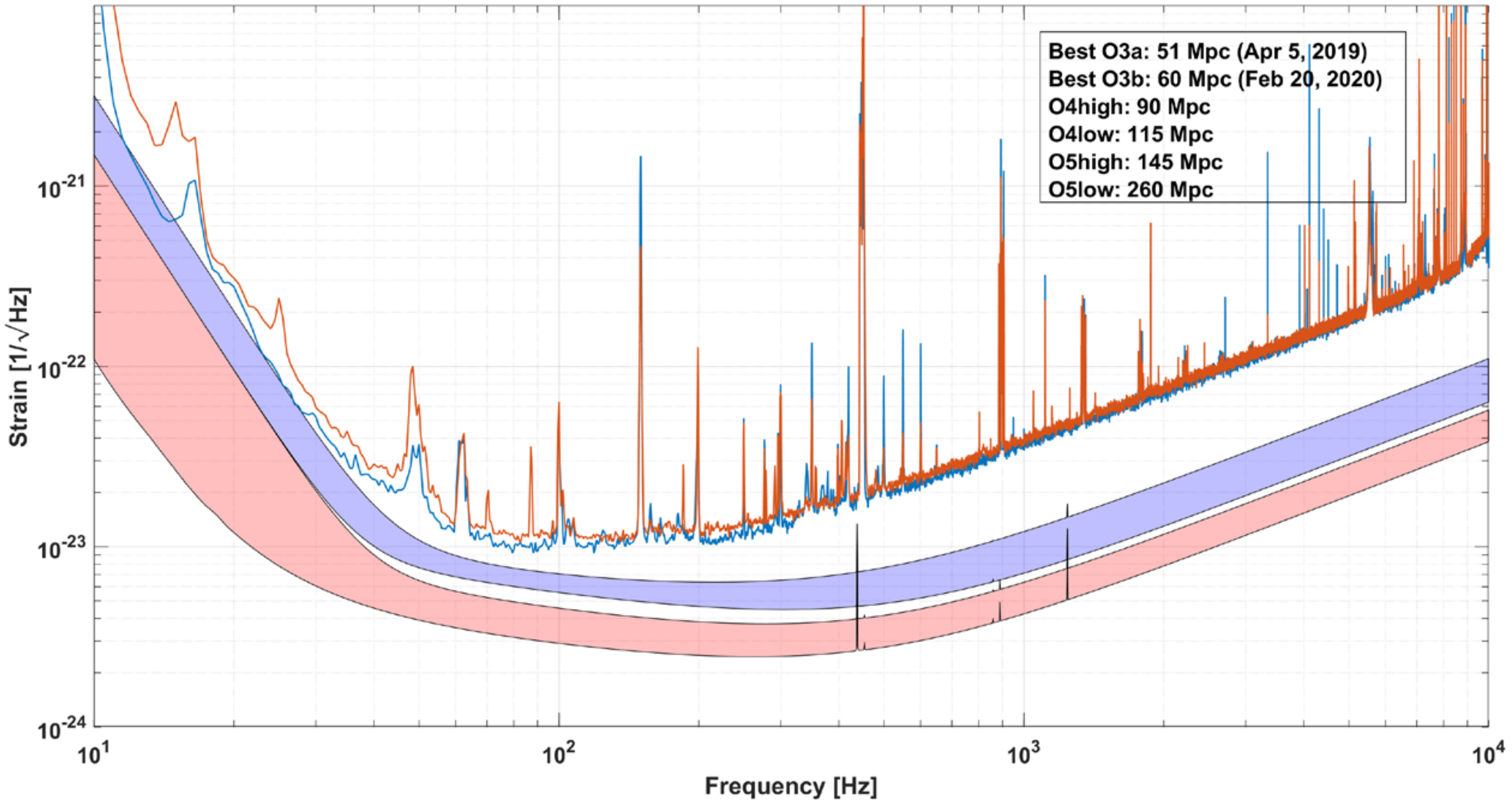
Worldwide GW network



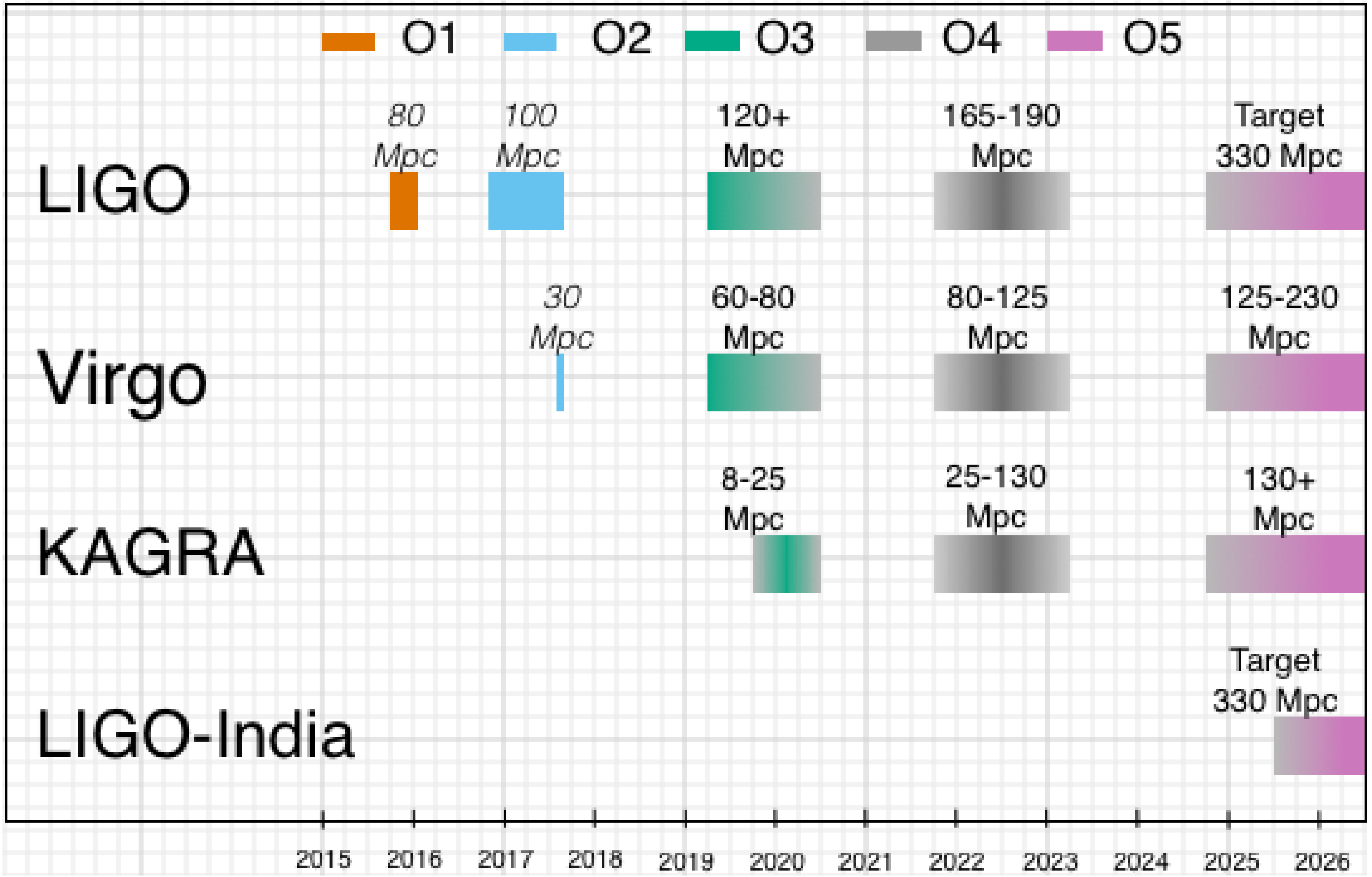
Perspectives (2020’s)

- Virgo and LIGO being upgraded (Advanced Virgo+ and A+)
- Goal: reach a BNS range of 200-300 Mpc in the mid-2020



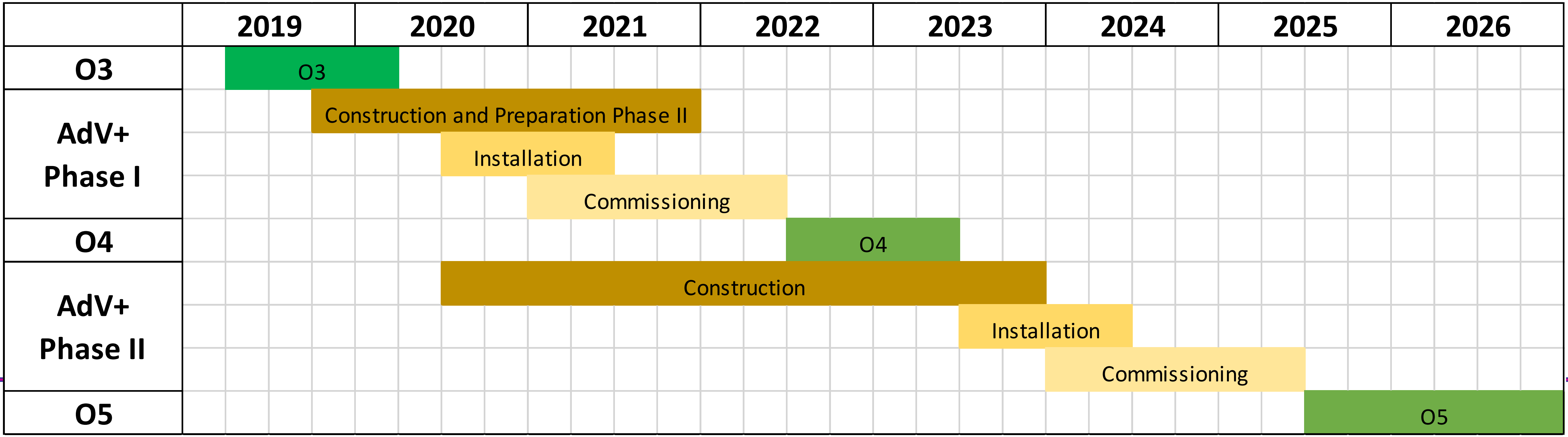
Perspectives (2020's)

- LIGO-Virgo-KAGRA (LVK) working in a network as a single detector



Advanced Virgo+: content & schedule

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



Detection principle

Gravitational wave

$\Downarrow$

Mirror displacement

$\Downarrow$

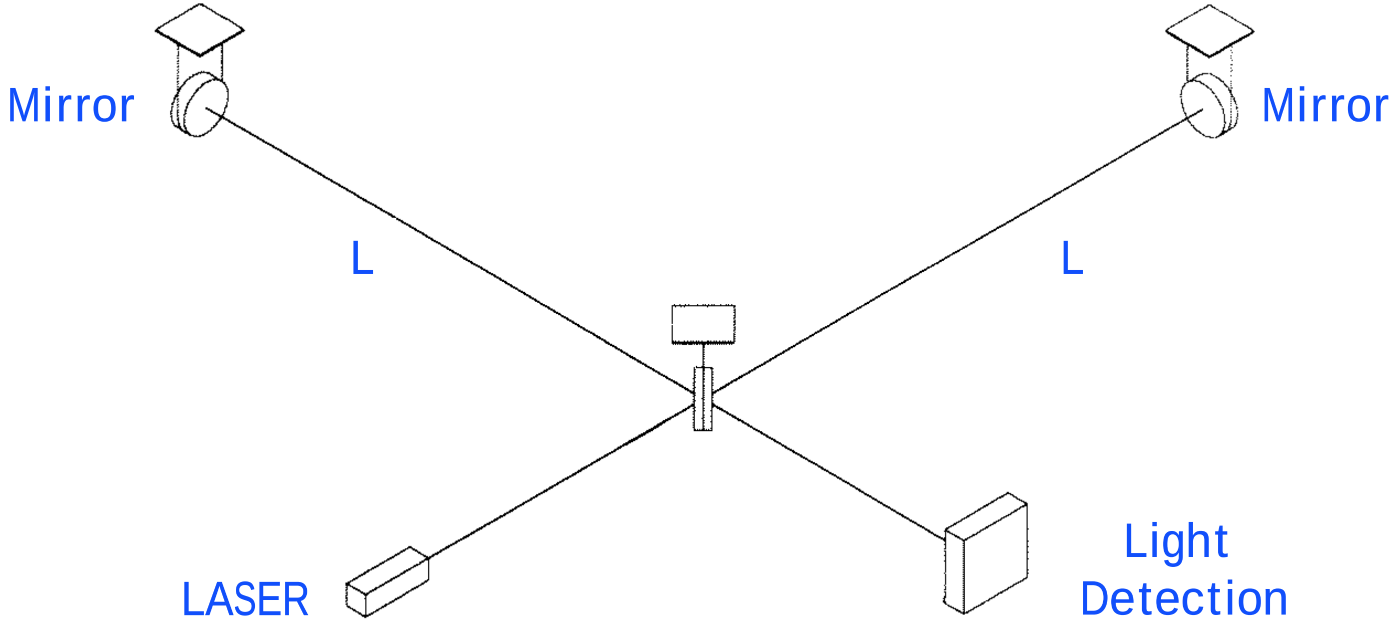
Light phase shift

$\Downarrow$

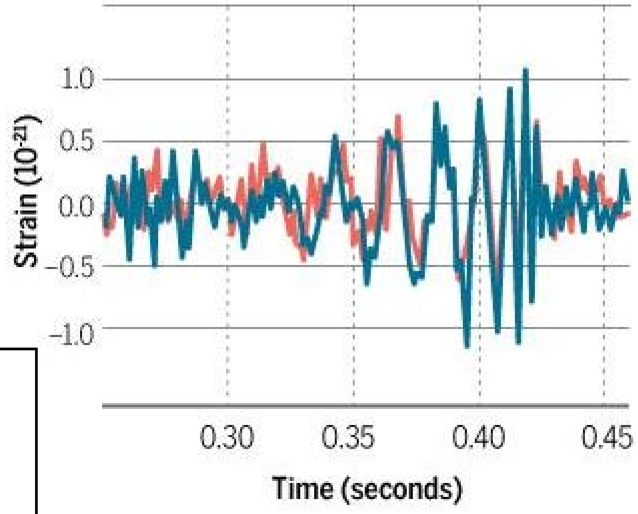
Light power variation

More details on detection principle

- "Free falling masses"
  - Mirrors suspended as pendulum



Orders of magnitude



- Gravitational wave amplitude
  - Ex. GW150914: $h \sim 10^{-21}$
- Mirror displacement: $3\ 10^{-18}$ m
  - Attometers!
- Light phase shift: 10^{-8} rad
- Power variation on photodetectors: $2\ 10^{-8}$ W

Competing noises

- Broadly speaking two categories
- Readout noises
  - Produce a variation in the power measured by the photo-detectors without a mirror displacement
- Displacement noises
  - Produce a real displacement of the mirrors

Shot noise

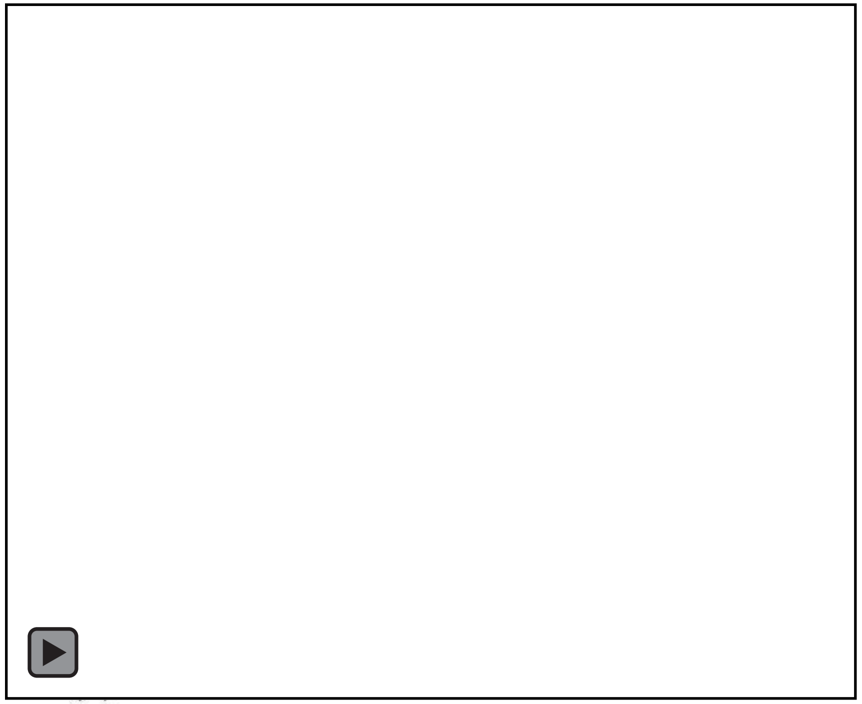
- Measurement of flux of photons reaching the photodetector
  - Shot noise

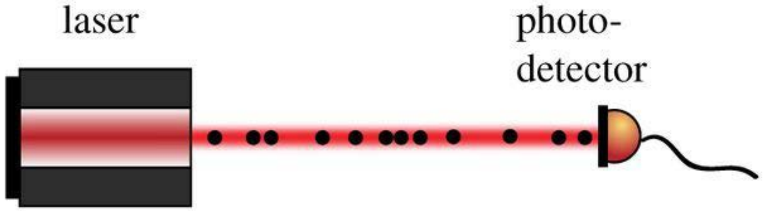
- Phase signal $\Delta\phi_s = \frac{4\pi}{\lambda} h\, L$ λ = laser wavelength

- Heisenberg principle $\Delta\phi_n > \frac{1}{\sqrt{N}}$ N = number of photons used

- Signal > Noise $h > \frac{1}{L} \frac{\lambda}{4\pi} \sqrt{\frac{2\hbar\omega}{P}}$ P = laser power

- Sensitivity improve when:
  - Arm length L ↑
  - Laser power P ↑

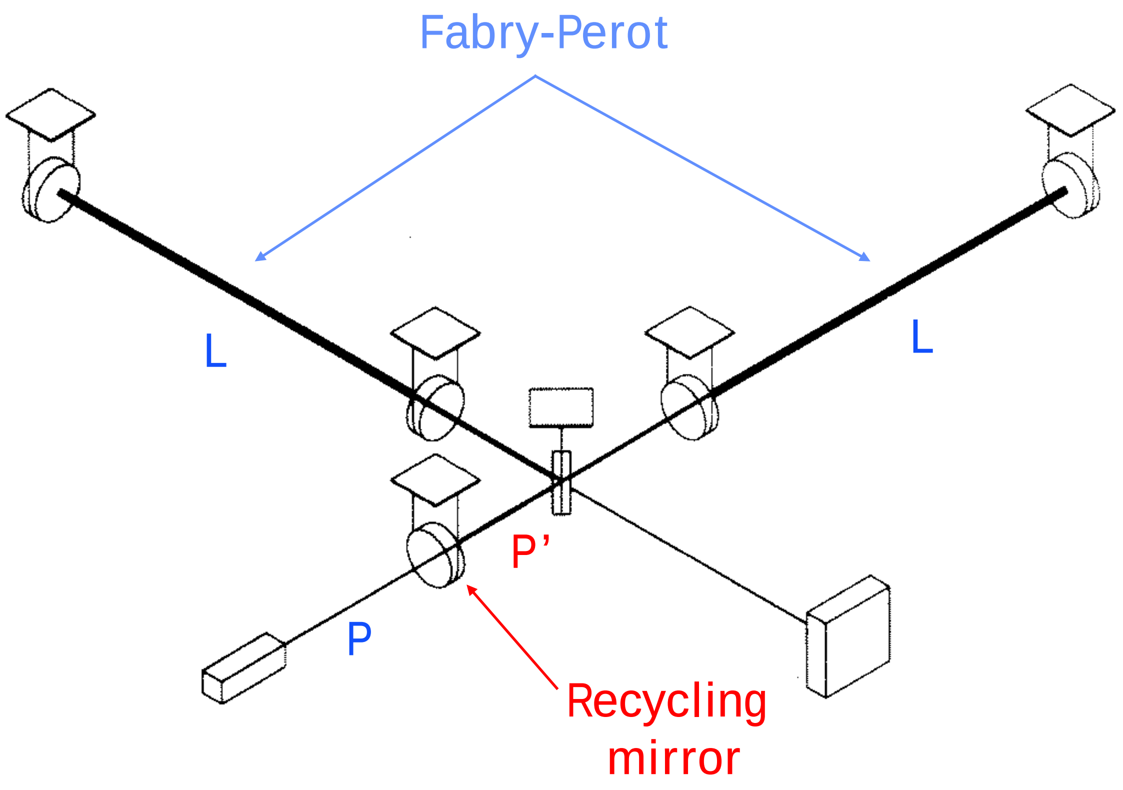




visualization of shot noise

Optical amplification

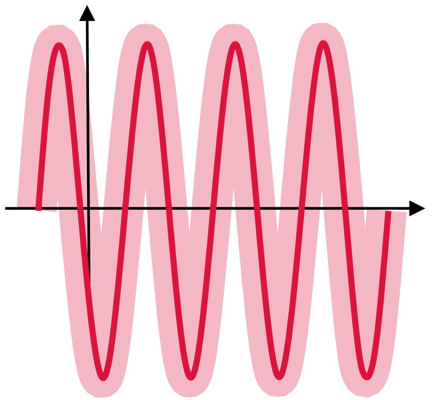
- Optical signal amplification
  - ◆ Fabry-Perot cavities in the arms
    - » Increase equivalent arm length
  - ◆ Power recycling
    - » Increase effective laser power
  - ◆ Signal recycling (not shown)
    - » Enlarge detector bandwidth

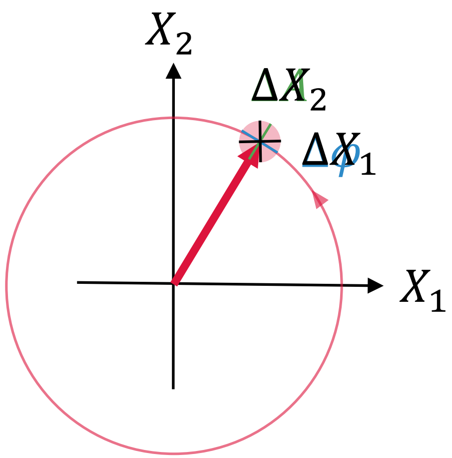


Quantum description of shot noise

- Laser field in quantum optics

Coherent state

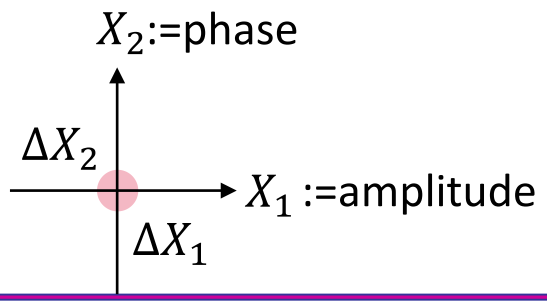




Heisenberg uncertainty principle

$$\Delta X_1 . \Delta X_2 \geq 1$$

Vacuum state



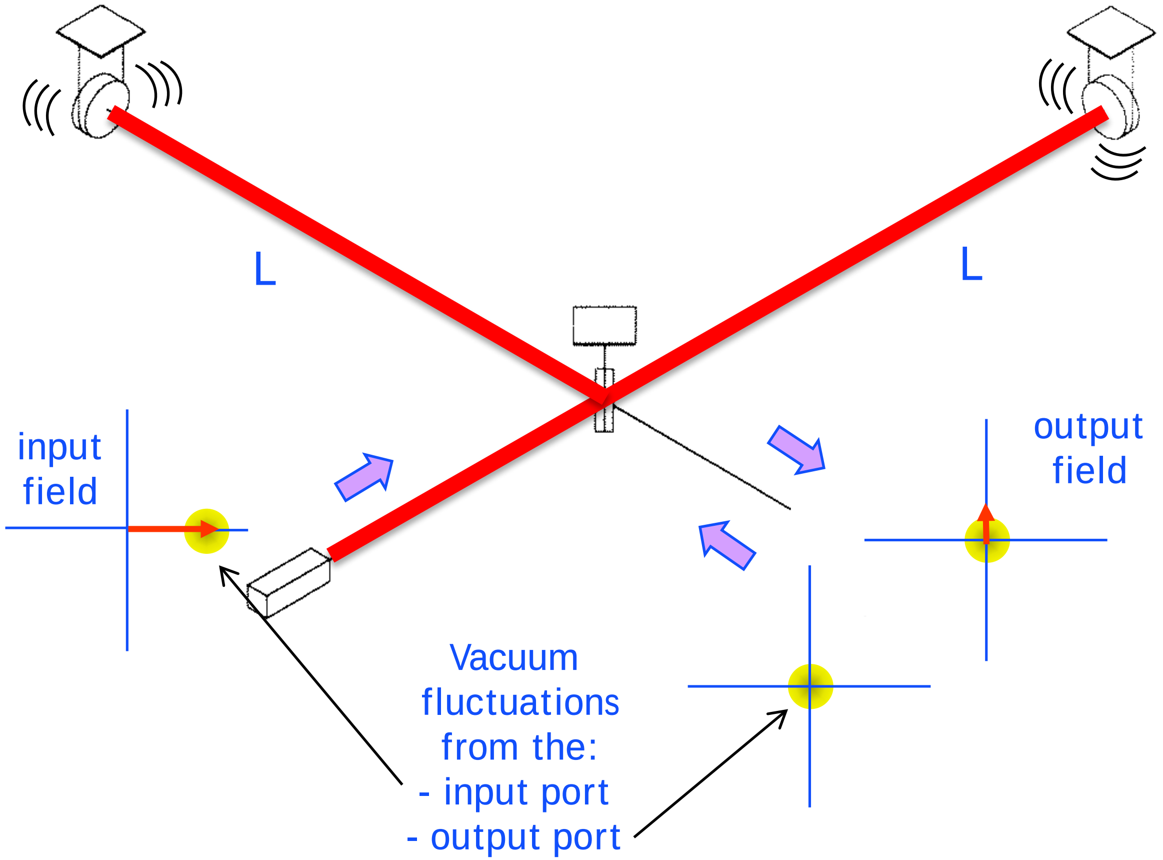
$$\Delta X_1 = \Delta X_2 = 1$$

Quantum description of shot noise

- Signal detection requires to measure electric field at the interferometer output

- Vacuum fluctuations enter from the input port
  - No effect since the ITF is on the dark fringe

- Vacuum fluctuations enter also from the output port !
  - Phase fluctuations limit the phase measurement
    - » Shot noise
    - » Smaller effect for larger laser power
  - Amplitude fluctuations create radiation pressure fluctuations on the mirrors
    - » Radiation pressure noise
    - » Larger effect for larger laser power



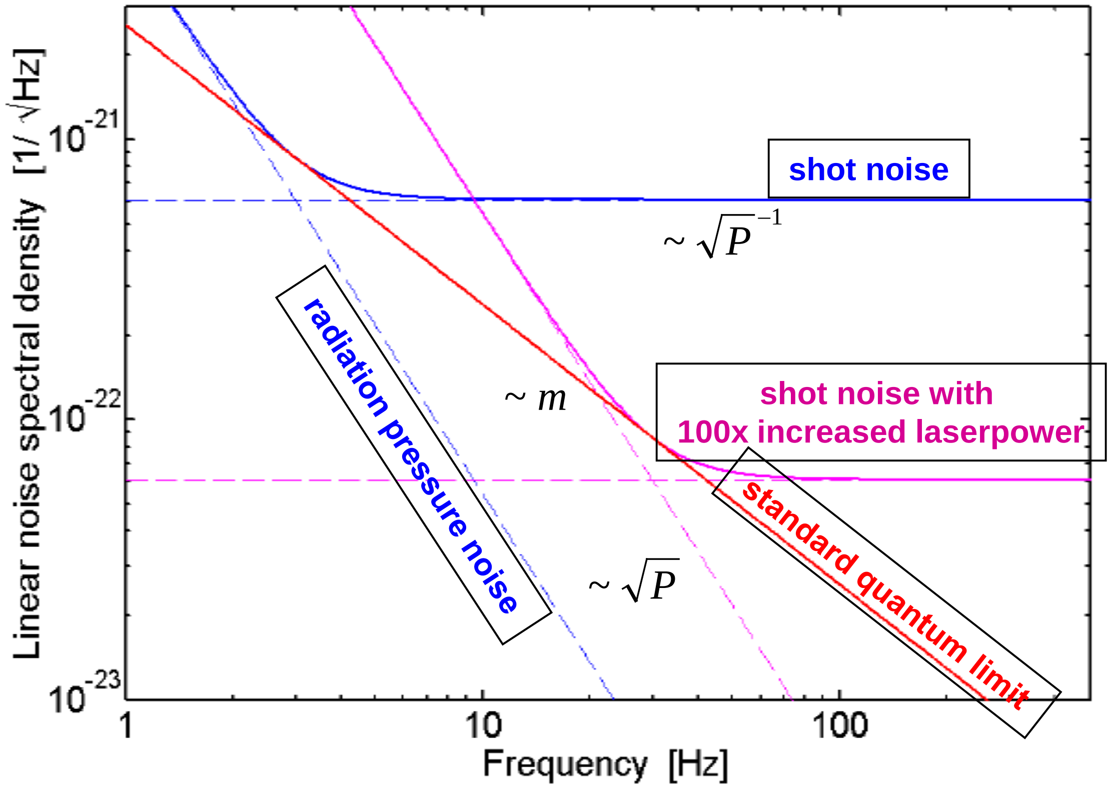
Quantum noise

- Quantum noise = Shot noise + Radiation pressure

- Heisenberg principle
  - If shot noise ⇓, then radiation pressure ⇑ (and viceversa)

- Standard quantum limit
  - Decreases as the mirror mass is increased

- Is it possible to circumvent the quantum limit?

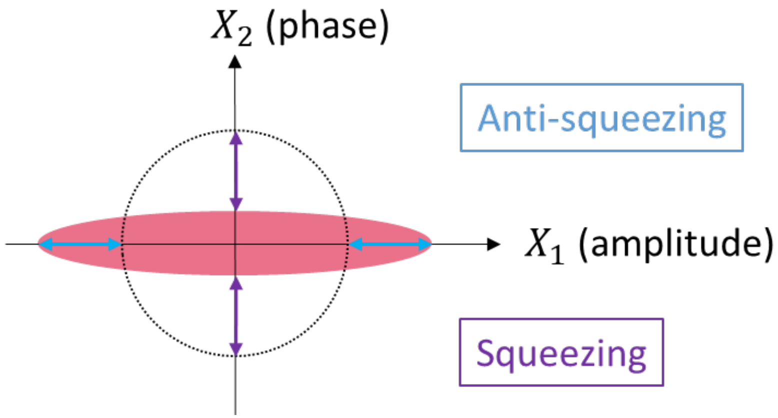


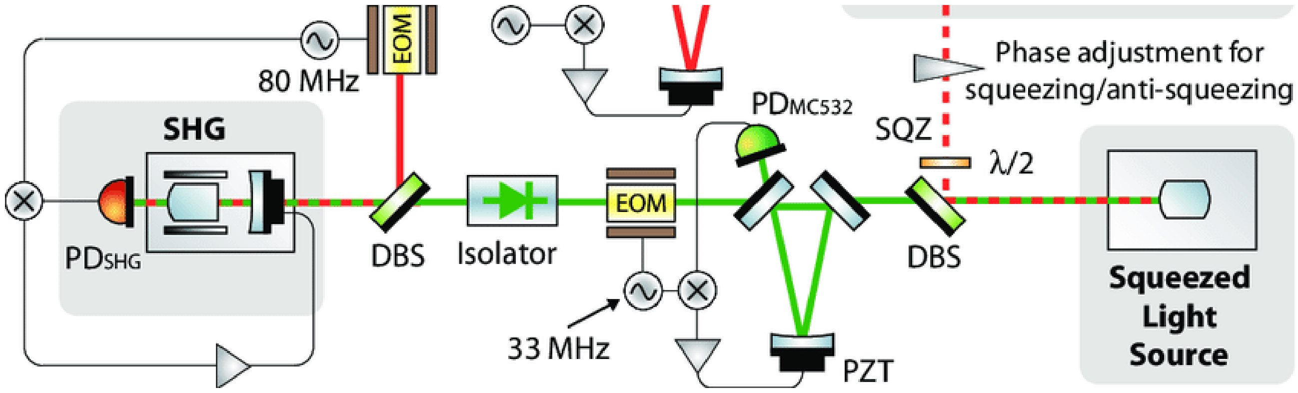
Squeezed vacuum state

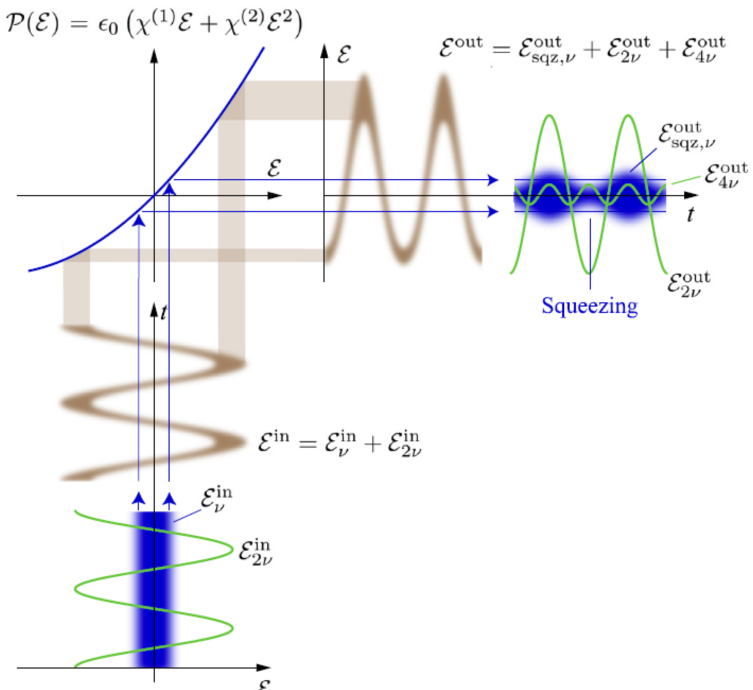
- Yes, with squeezed vacuum states
  - Can be produced using non-linear crystals

Squeezed vacuum state

$$\Delta X_2 \leq 1$$
$$\Delta X_1 \geq 1$$





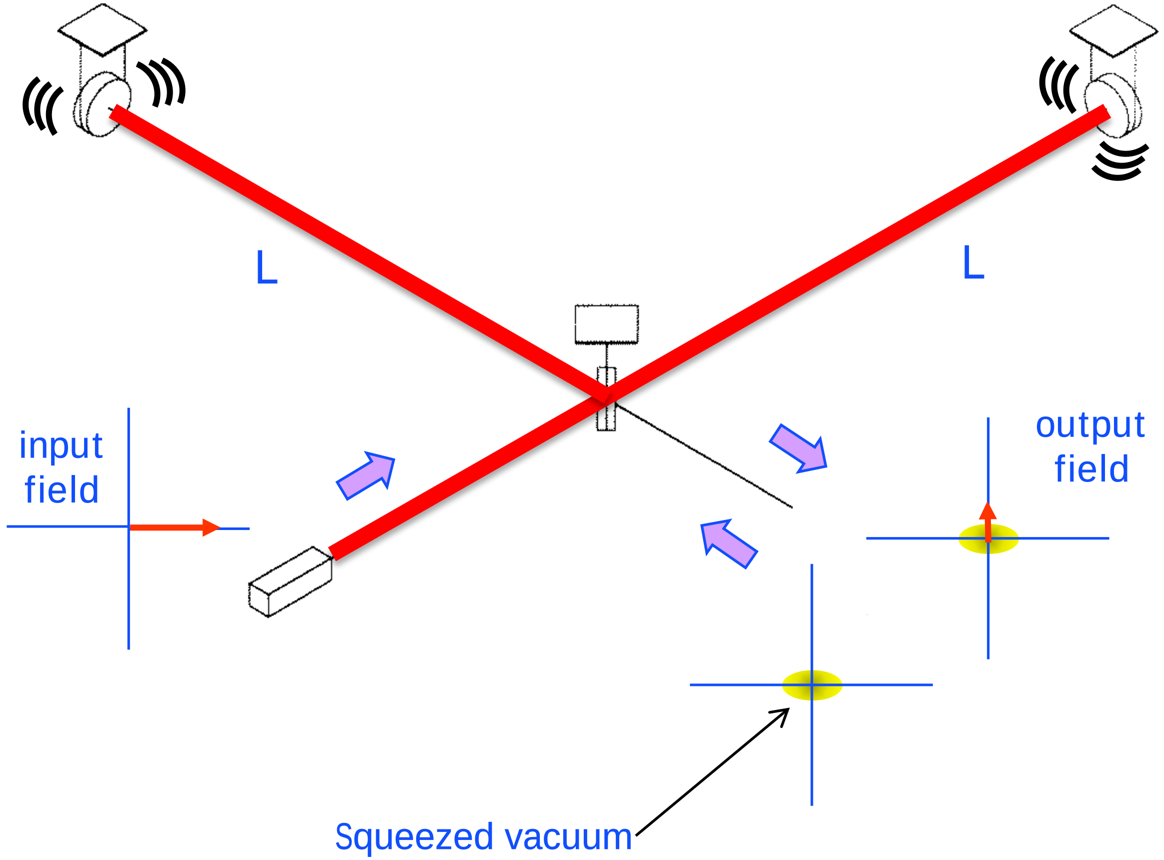


Use of squeezed vacuum state

- Inject phase squeezed vacuum from the output port

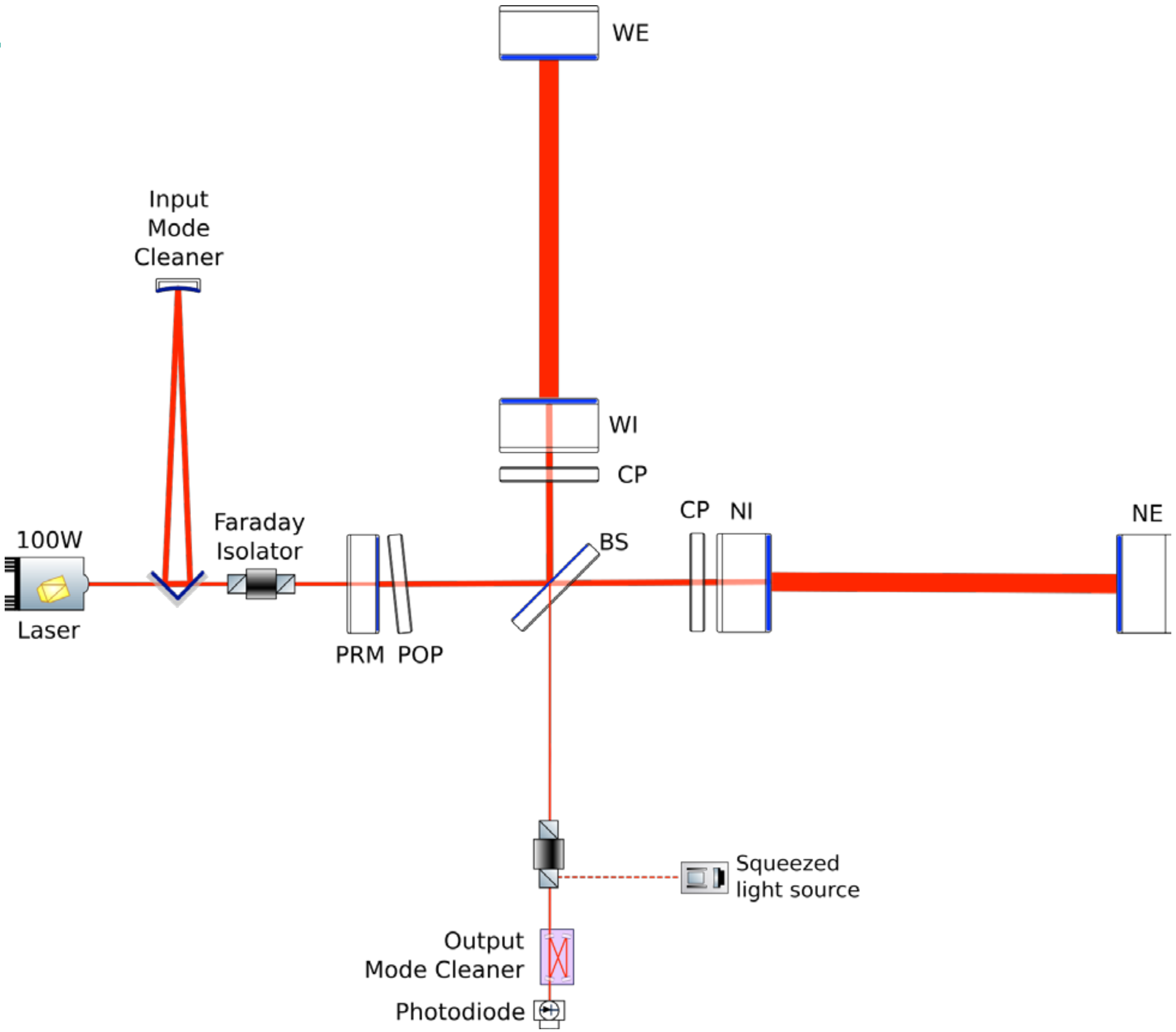
- Squeezed vacuum
  - Decrease shot noise
  - Increase radiation pressure noise
  - Equivalent to more power
    - Without the disadvantage of thermal deformation
  - Limit:
    - amount of feasible squeezing
    - optical losses

- Used both at LIGO and Virgo to reduce the shot noise



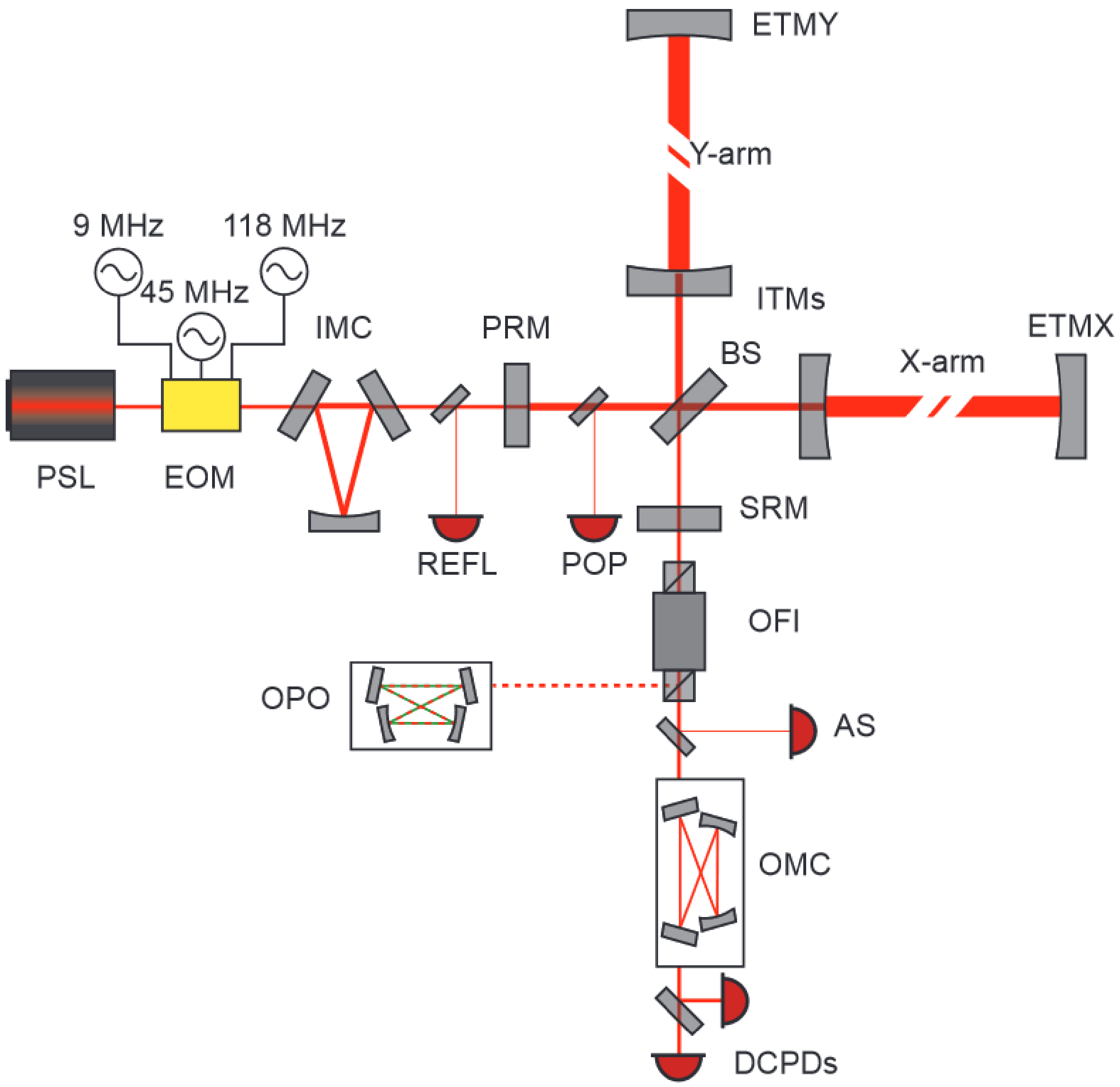
Virgo configuration during O3

- Power recycled Fabry-Perot interferometer
  - Marginally stable recycling cavity
- Laser solid state amplifier
  - Able to deliver 90 W
  - 25 W into the interferometer
- 150 m input mode-cleaner
- Monolithic glass output mode-cleaner
- In-air squeezed vacuum source



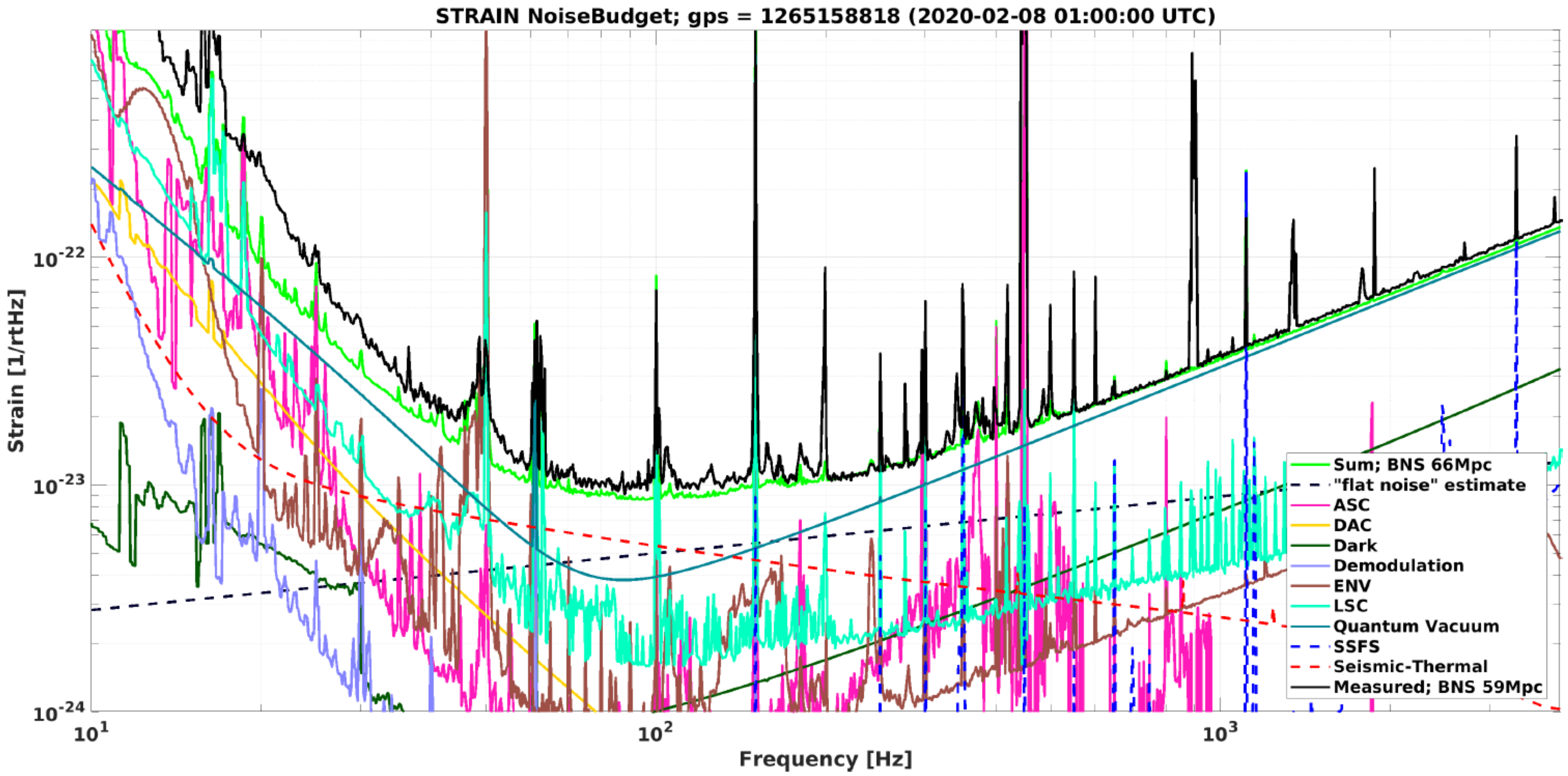
LIGO configuration during O3

- Dual recycled Fabry-Perot interferometer
  - Stable recycling cavities
- Laser solid state amplifier
  - Able to deliver 70 W
  - 40-50 W into the interferometer
- 33 m input mode-cleaner
- Composite output mode-cleaner
- In-vacuum squeezed vacuum source



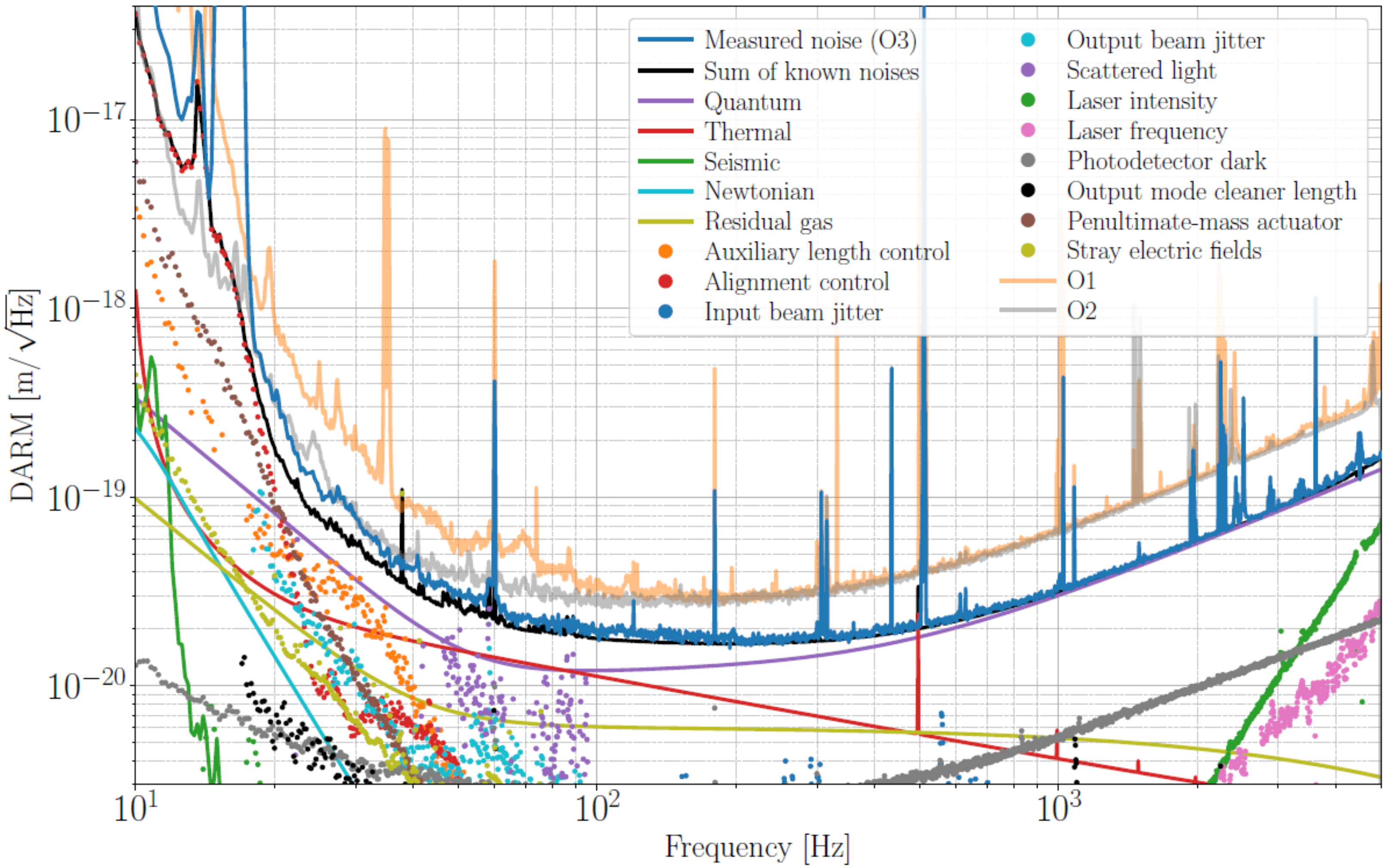
Virgo sensitivity during O3

- Noise budget (after subtraction)
- Main contributions
  - ◆ Quantum noise
  - ◆ Thermal noise
  - ◆ “Flat noise”’, not understood
  - ◆ Control noise
    - » Larger at lower frequencies
    - » Around 100 Hz mostly due to sidebands amplitude noise



LIGO sensitivity during O3

- Noise budget (LLO)
- Main contributions
  - Quantum noise
  - Mirror thermal noise
  - Control noise
    - Length control
    - Alignment control
  - Residual gas noise (at LLO)



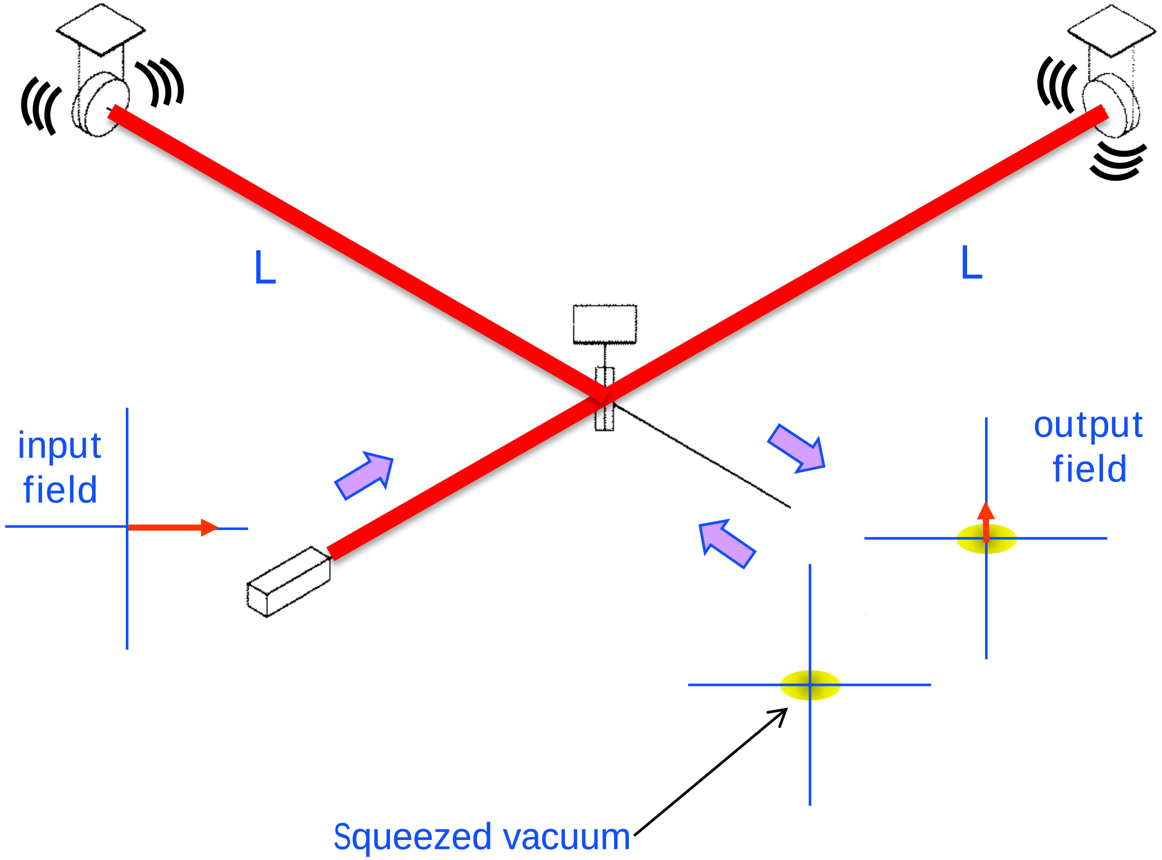
Use of squeezed vacuum state

- Inject phase squeezed vacuum from the output port

- Squeezed vacuum
  - Decrease shot noise
  - Increase radiation pressure noise
  - Equivalent to more power
  - Limit:
    - » amount of feasible squeezing
    - » optical losses

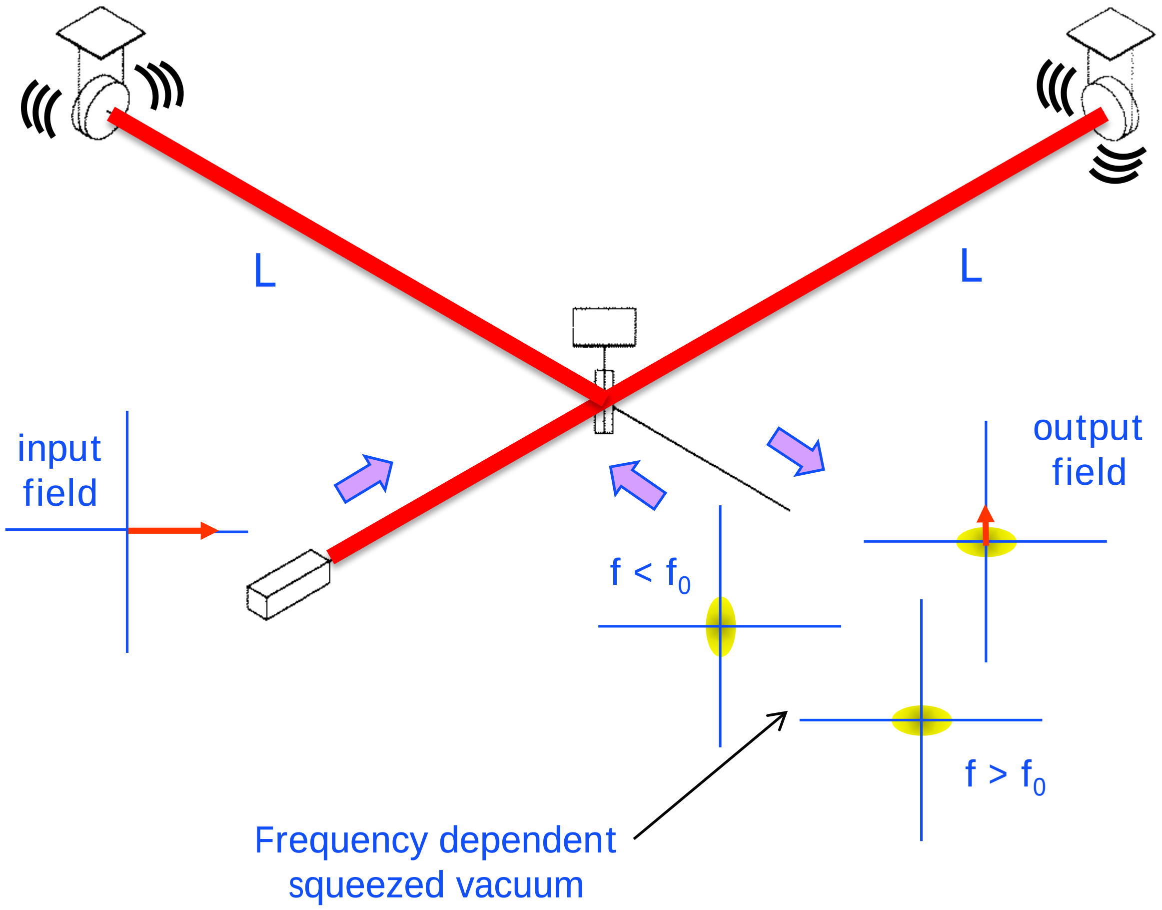
- Used both at LIGO and Virgo to reduce the shot noise

- Is it possible to reduce both shot noise and radiation pressure noise?



Use of squeezed vacuum state

- YES, inject frequency dependent squeezed vacuum from the output port
  - Phase squeezing at high frequency
  - Amplitude squeezing at low frequency
  - Decrease both shot noise and radiation pressure noise

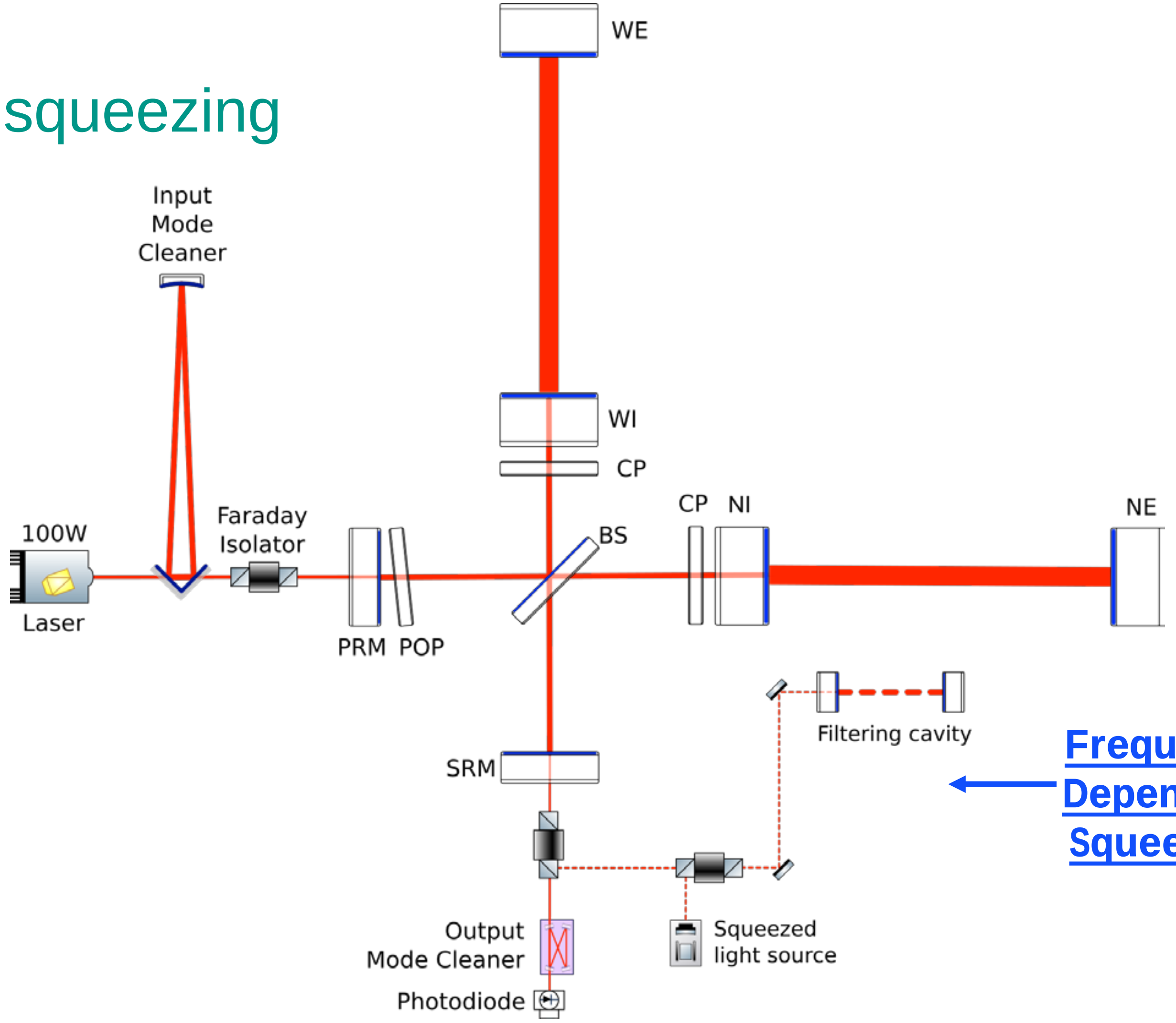


- How?
  - Generate squeezed vacuum state
  - Reflect on an high finesse optical cavity
  - Done!
  - Limitation: optical losses in the cavity

- Currently being built at Virgo and at LIGO

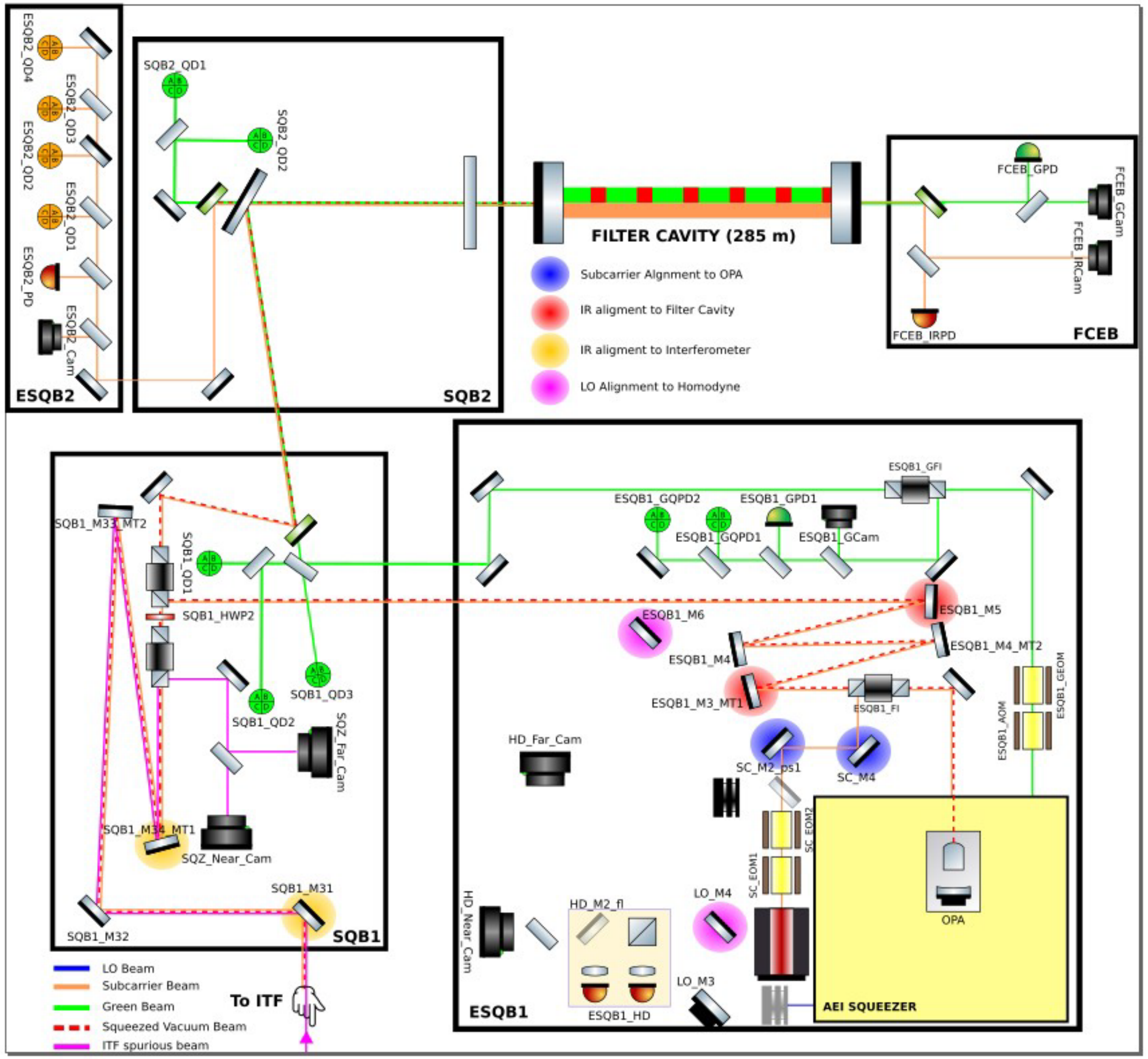
Frequency dependent squeezing

- AdV+ and A+ will use frequency dependent squeezing



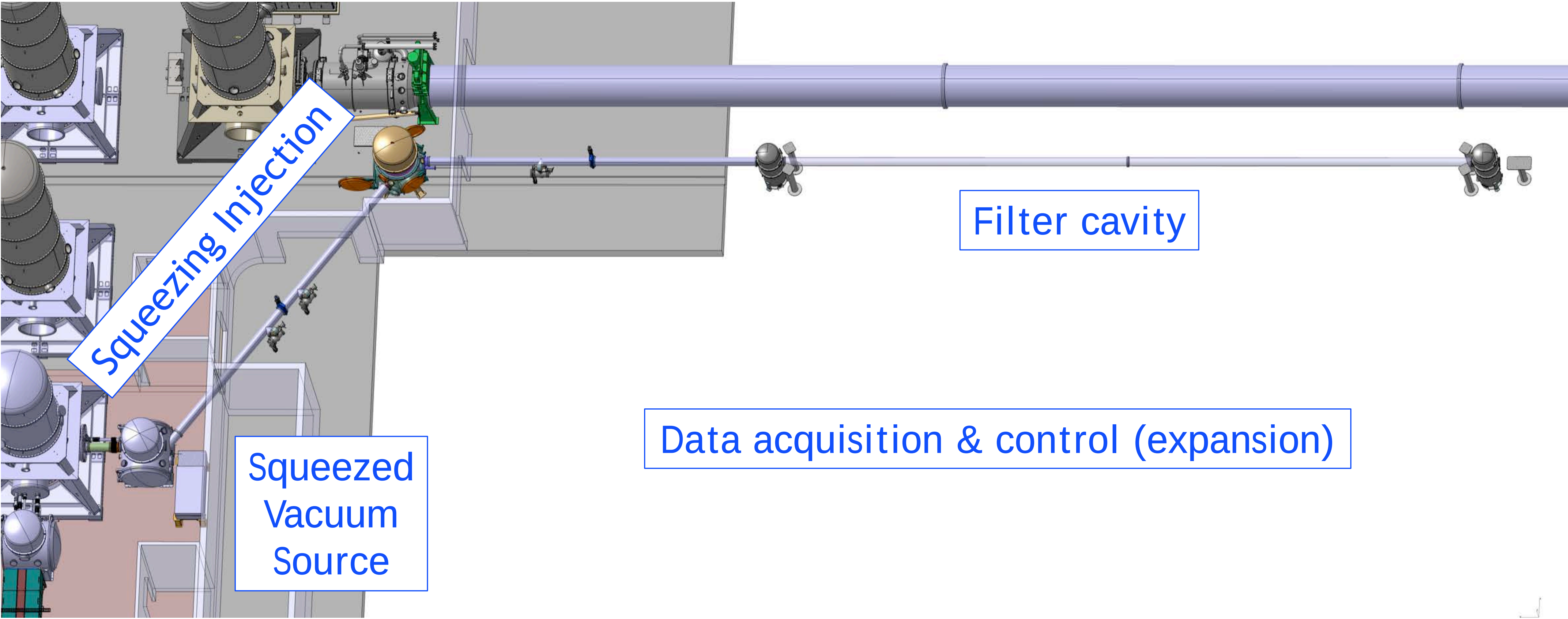
Frequency Dependent Squeezing ✓

Quantum noise reduction system



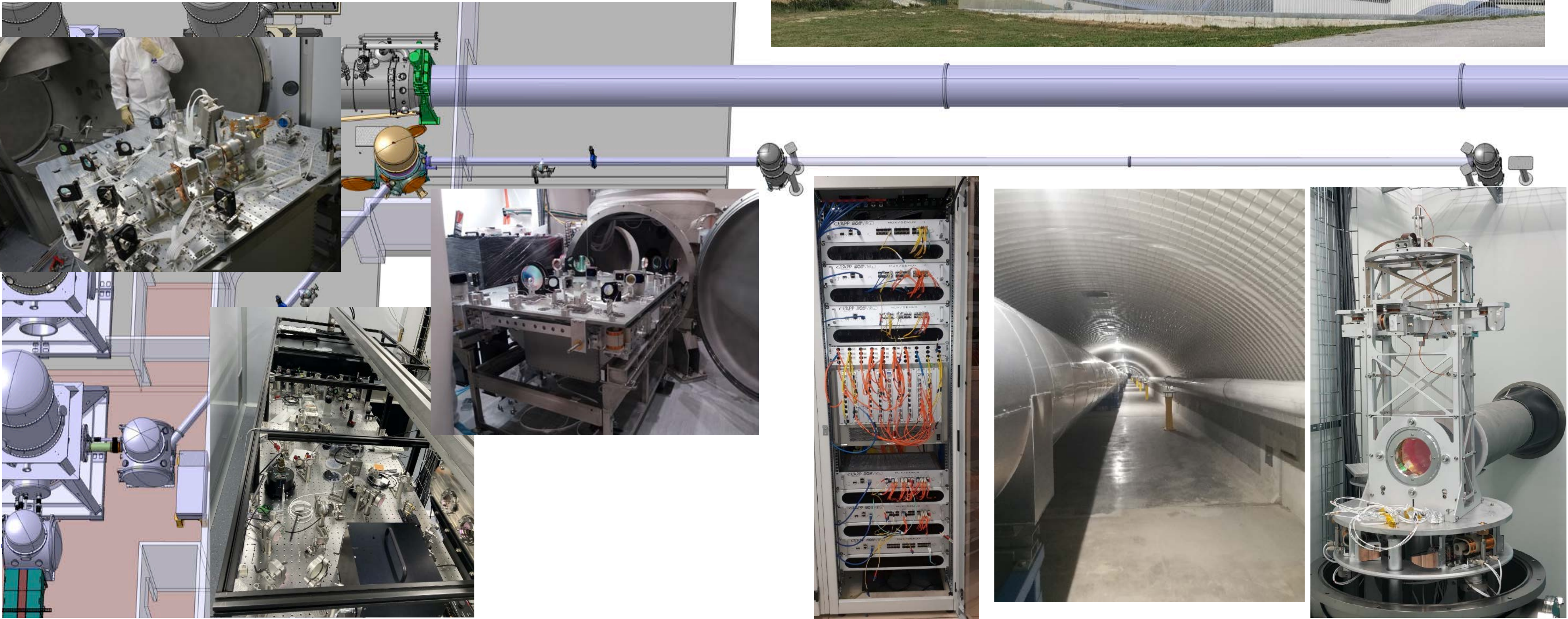
Quantum noise reduction system

- Goal: use frequency dependent squeezing in AdV+ Phase I



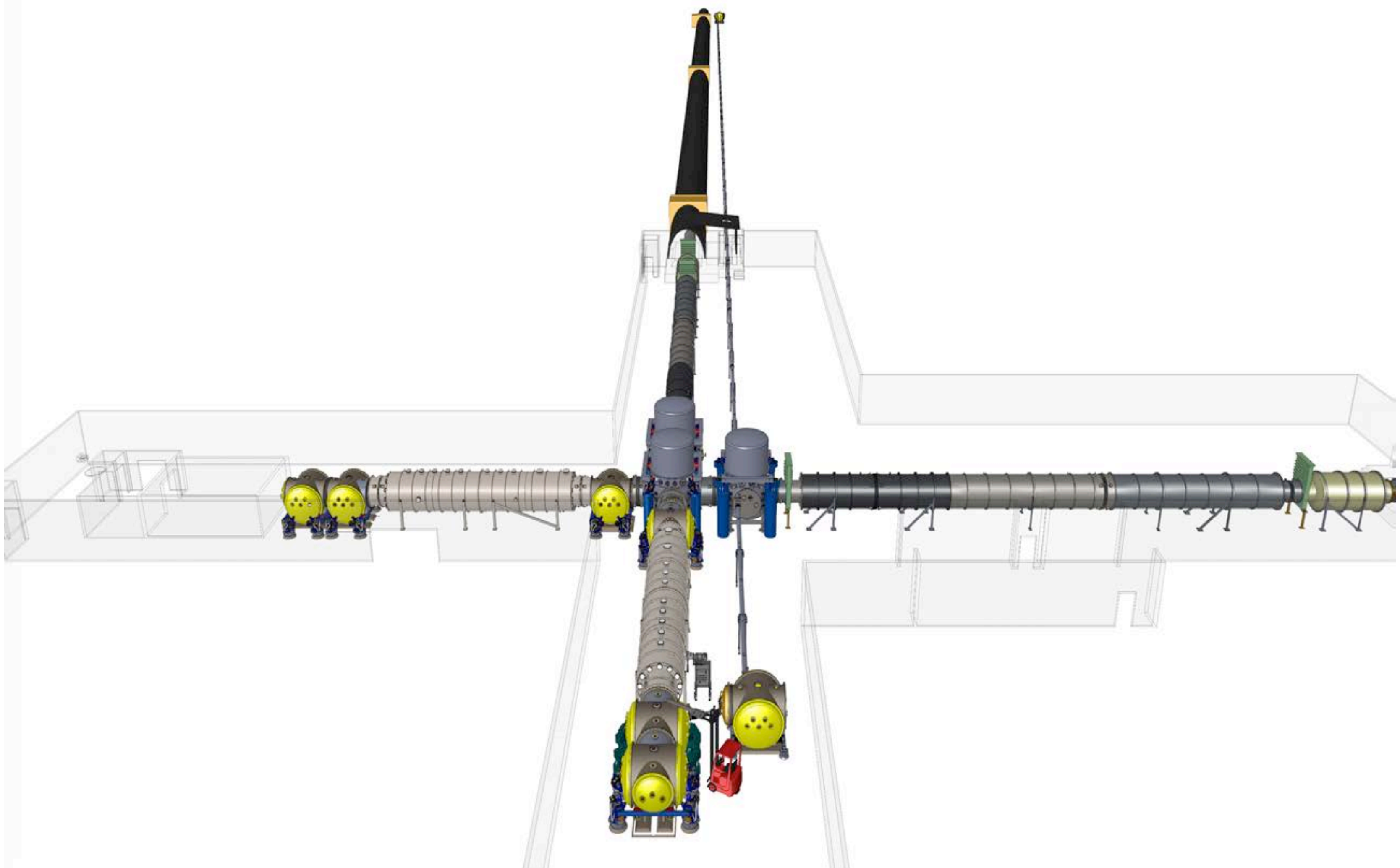
Quantum noise reduction system

Plan: operate frequency dependent squeezing by O4



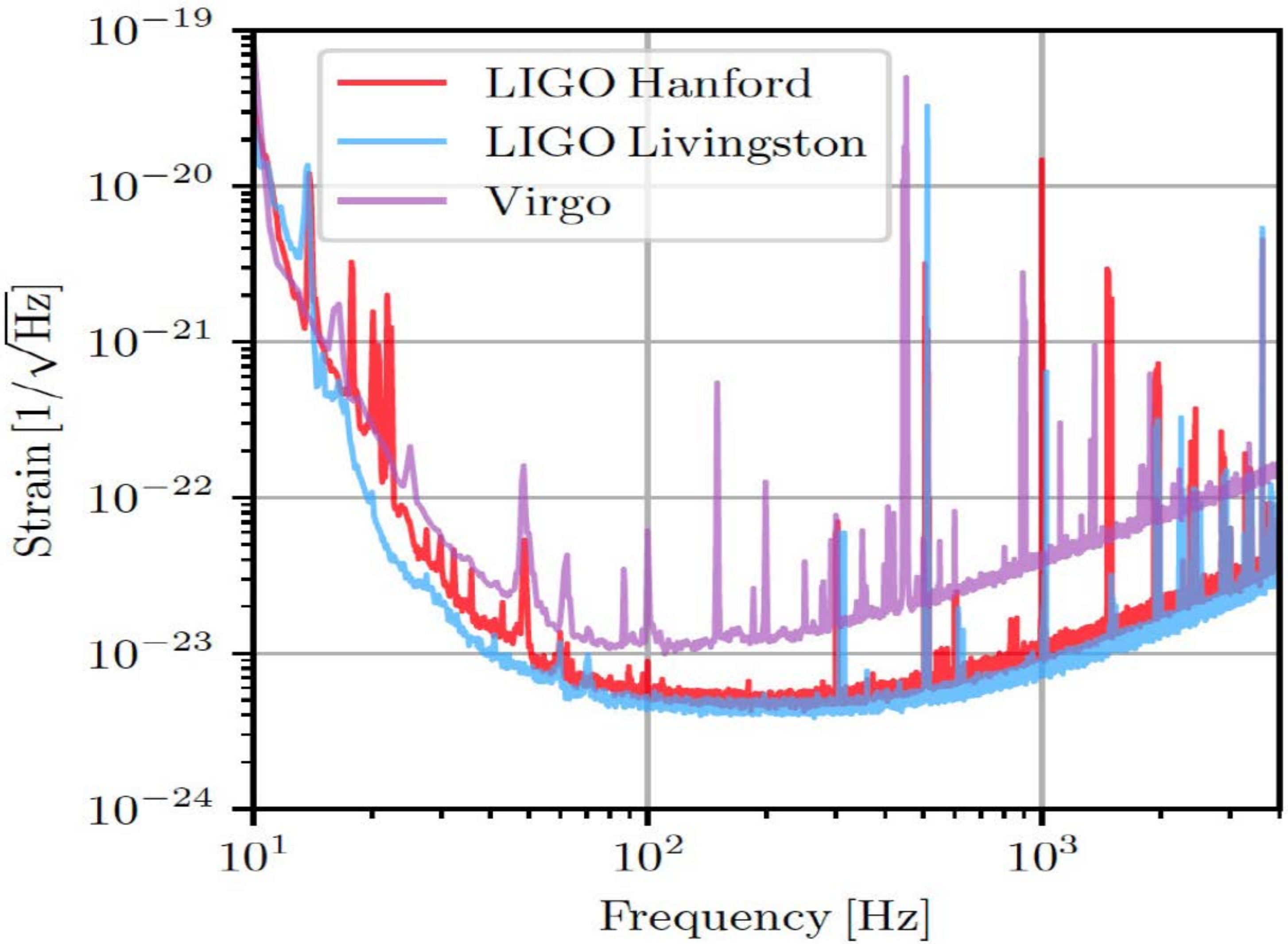
Quantum noise reduction system

- Similar plan at LIGO



Virgo-LIGO sensitivity during O3

- One remarkable difference
- Detector bandwidth
- Due to use of signal recycling in LIGO



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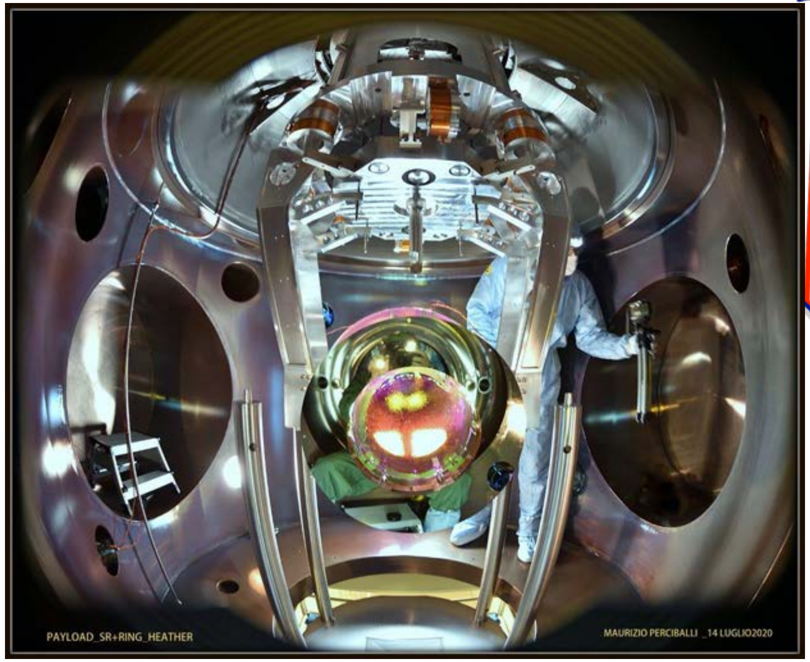
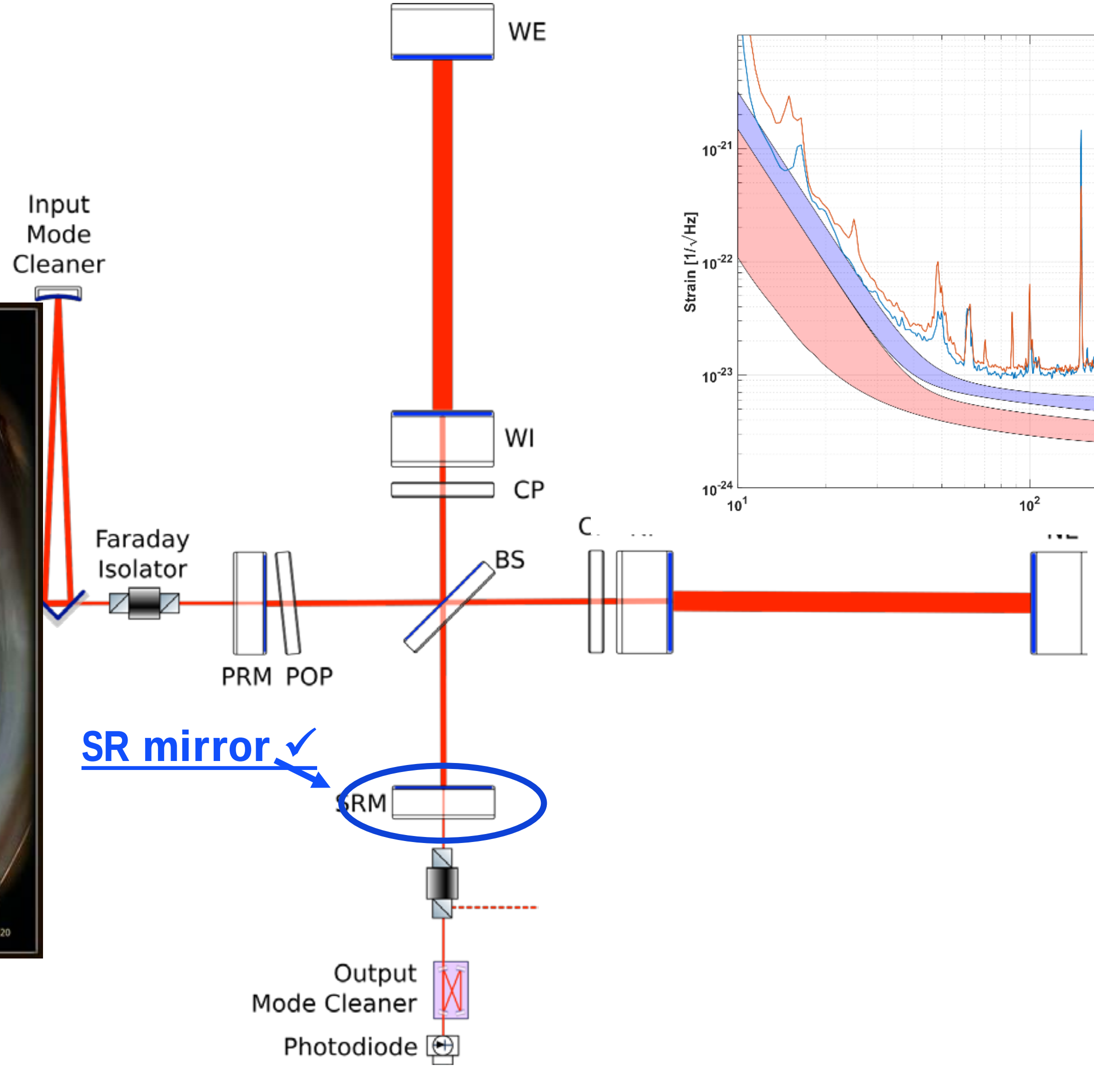
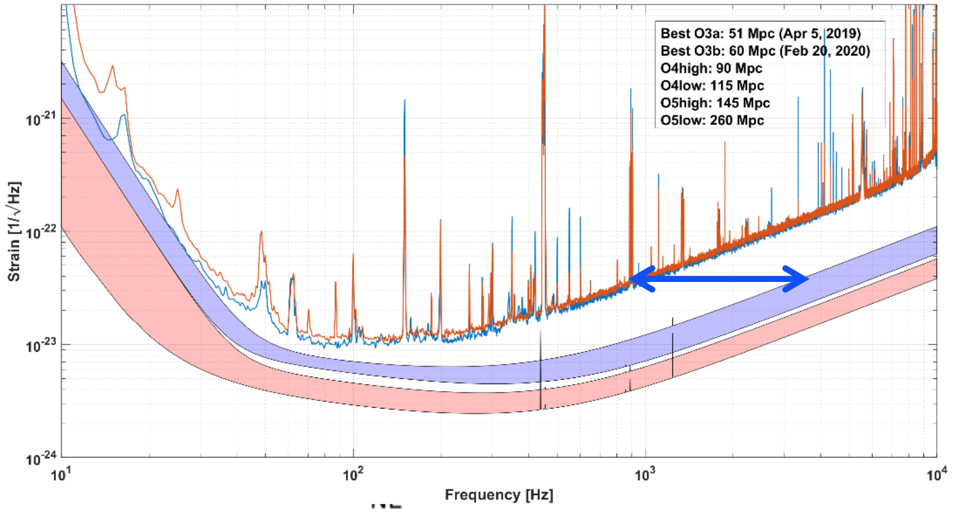
Signal recycling in AdV+

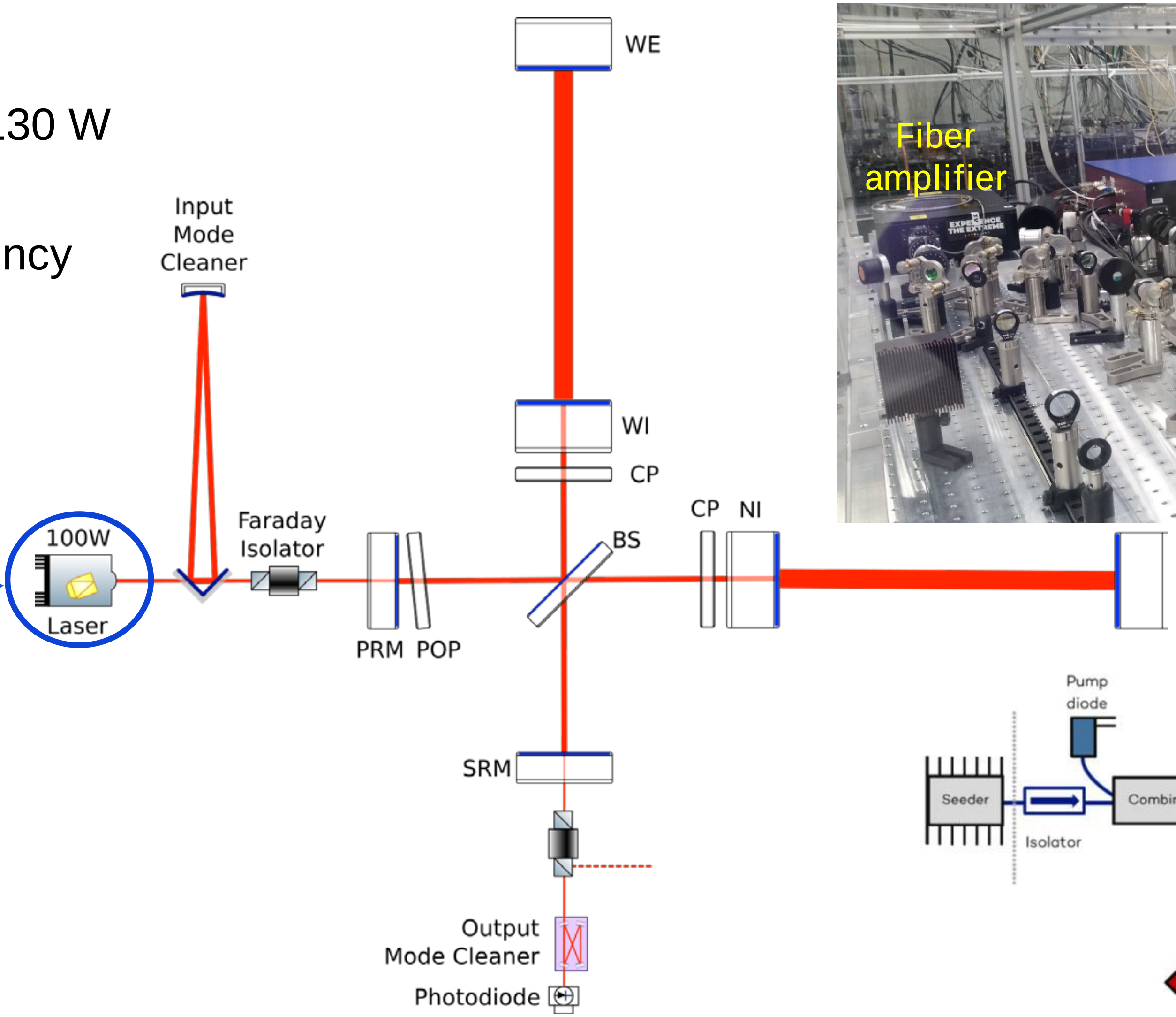




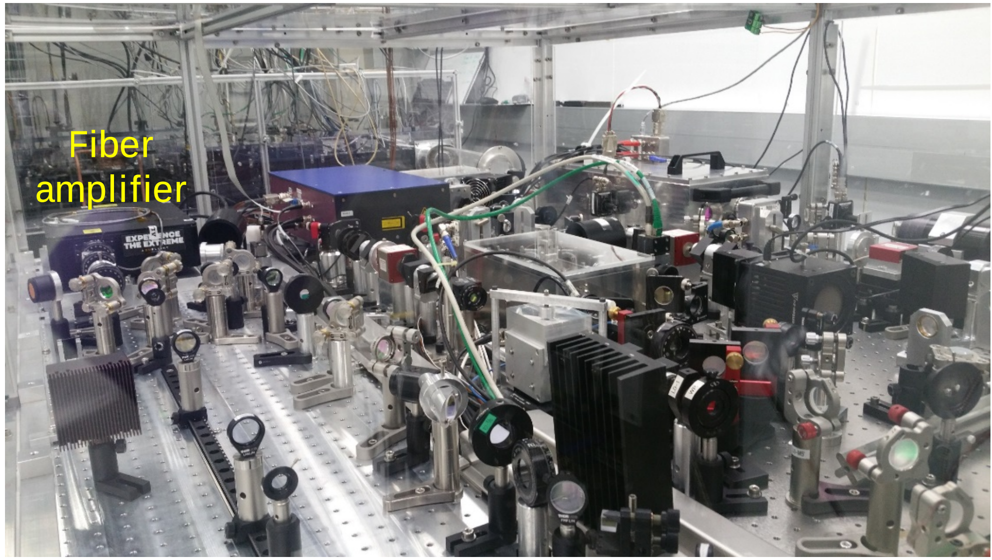


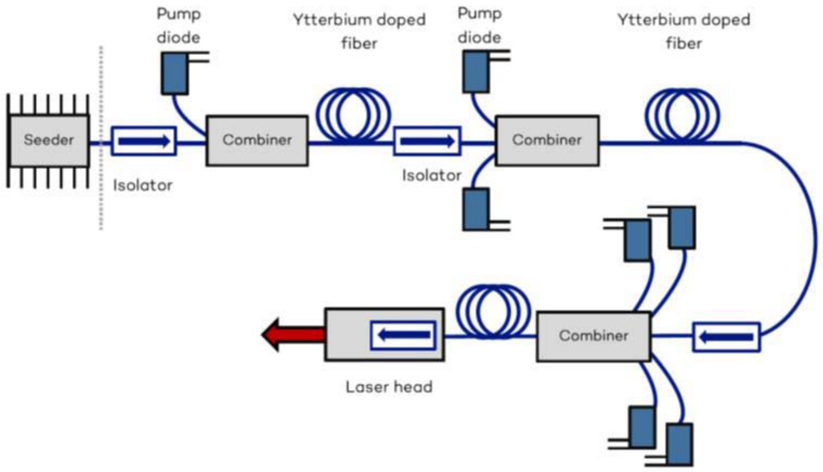
Laser power increase in AdV+

- Fiber amplifier
  - Can deliver more than 130 W
  - Excellent beam quality
  - Compliant power/frequency stability
- Goals
  - 40-50 W for O4
  - 60-80W for O5



Laser Upgrade ✓





Readout noises

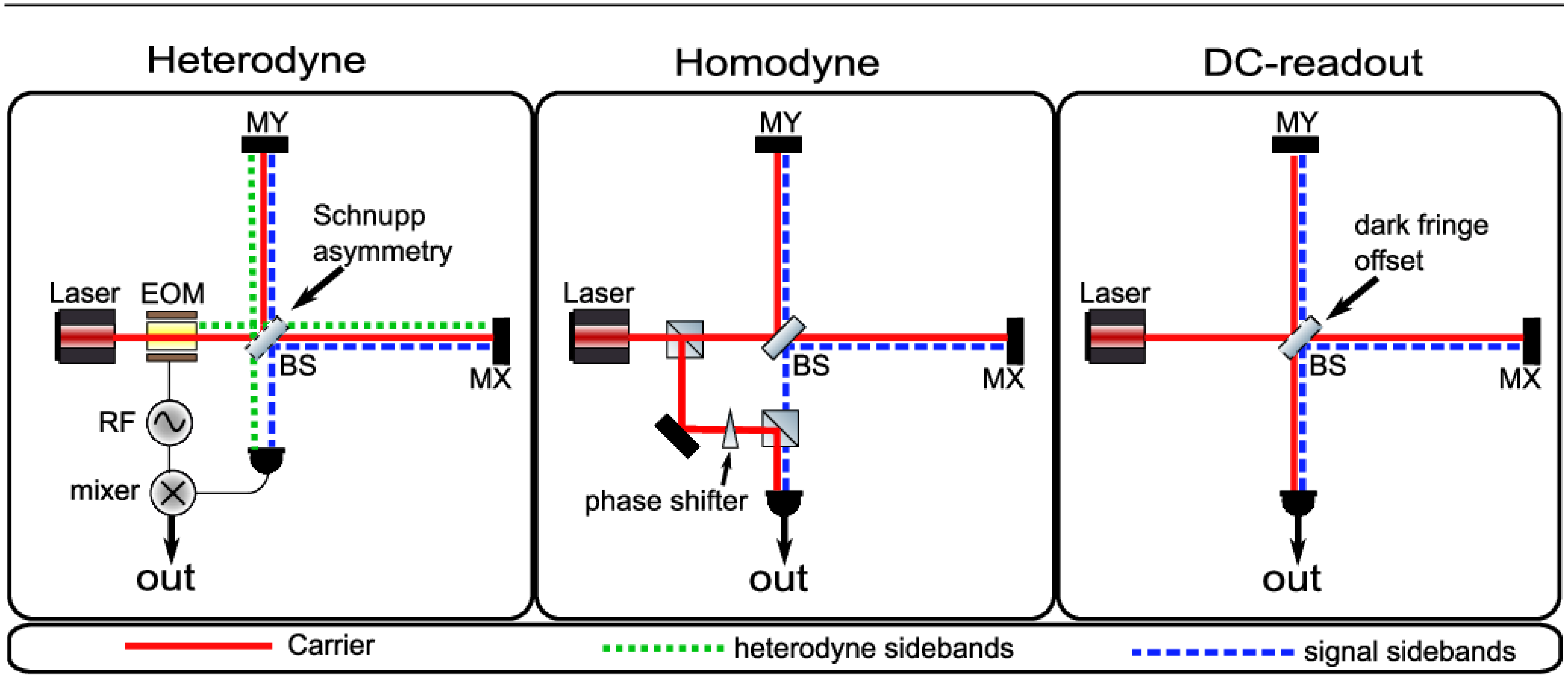
- Shot noise
  - Quantum fluctuations in the photon flux reaching the photodetectors
- Laser noise
  - Amplitude noise induces variations in the measured power on the photodetector
  - Frequency/phase noise induces a relative phase variation at the output port
  - Beam pointing noise induces a relative phase variation at the output port
  - Laser sidebands amplitude noise induces a variation in the measured power on the photodetector

Dealing with laser noises

- Interferometer common mode rejection factor
  - Mirror quality, output mode-cleaner, interferometer alignment, interferometer tuning with thermal compensation systems
- Laser intensity and frequency stabilization
  - Stabilization of the laser frequency using the interferometer cavity as frequency reference
    - Quietest reference on Earth
  - Stabilization of laser intensity using a low noise measurement of the power injected into the interferometer
  - Used both at LIGO and Virgo but always a potential offender
    - SNR of the laser intensity/frequency measurement can be critical
    - Need to reach shot noise
- Sidebands amplitude stabilization
  - Will be implemented in AdV+
- Adopt homodyne detection instead of DC detection
  - Will be implemented in A+

Dealing with laser noises

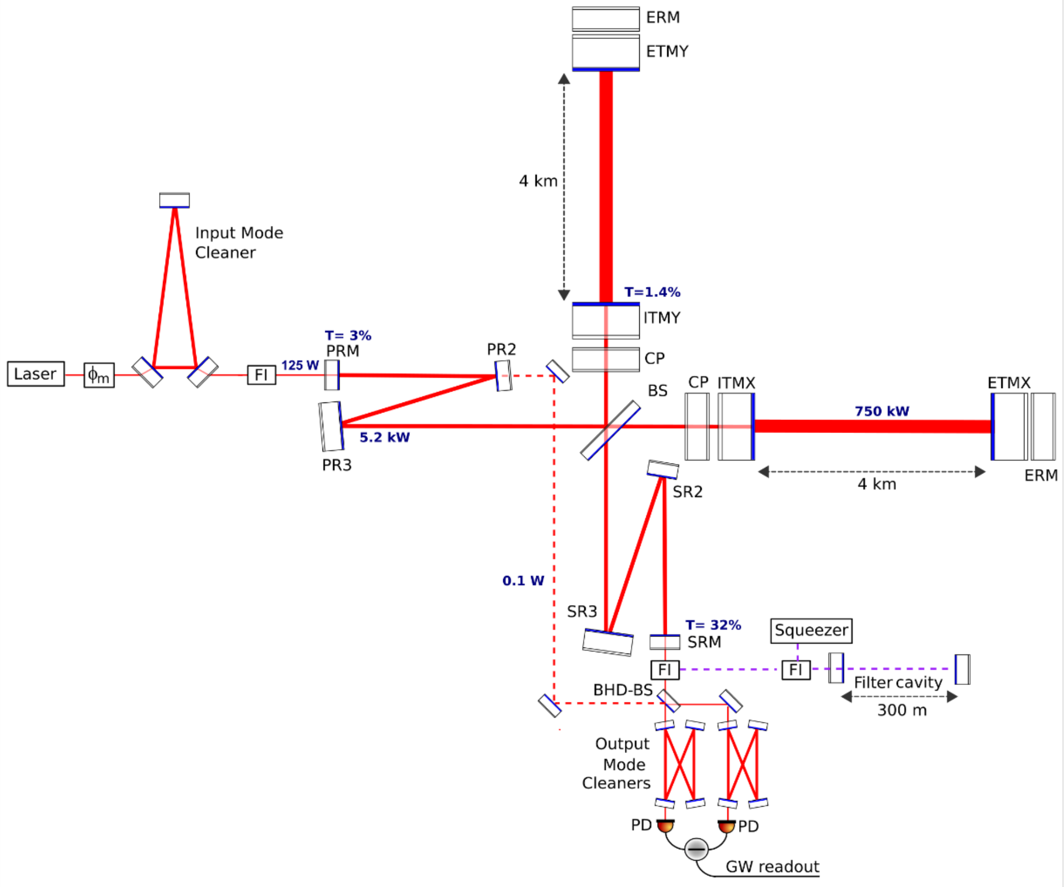
- Signal detection: DC-readout vs Homodyne



Dealing with laser/sensing noises

- Adopt homodyne detection instead of DC detection
  - Allow to lock interferometer exactly on the dark fringe

- Other motivations
  - Eliminate the coupling to SRC length noise that arises from the AS beam light power.
  - Reduce back-scatter in the AS port from the LO power.
  - Eliminate the RF offset in the AS port WFS.
  - Ability to tune the homodyne phase.
  - Ability to subtract the PD photocurrents directly to help with detector SNR.
  - Eliminate the off-resonant, radiation pressure coupling in the arm cavities.



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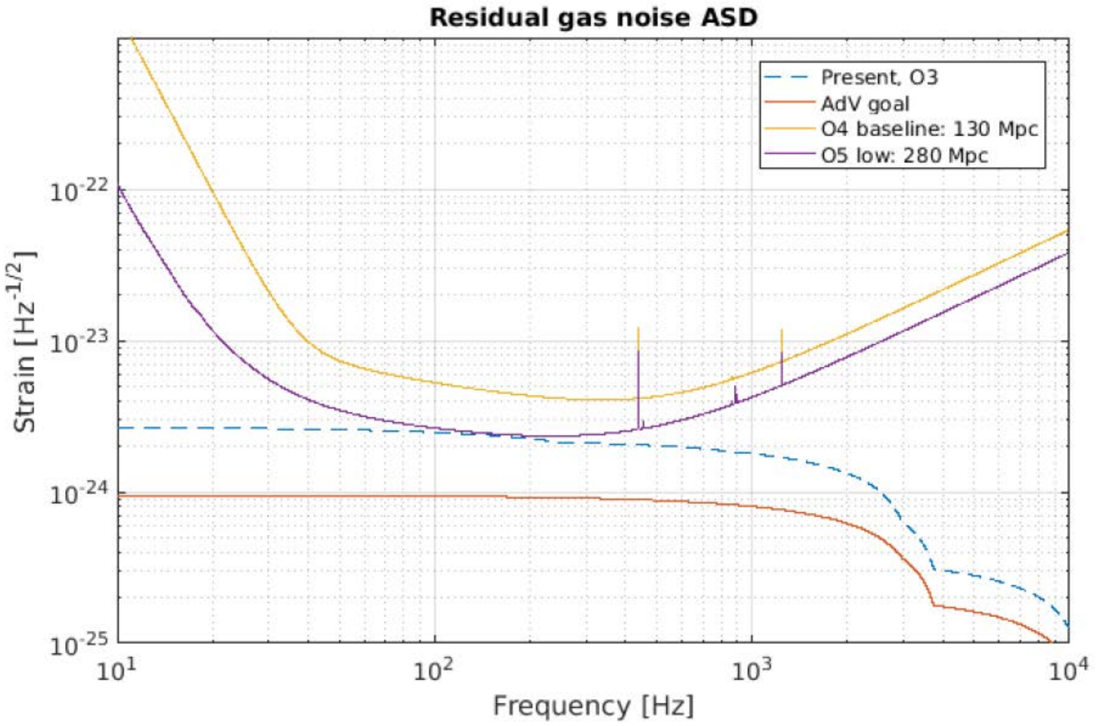
- Residual gas noise
  - Light phase noise due index of refraction fluctuations

Residual gas noise

- Vacuum needed to protect the interferometer from environmental noise
- Largest vacuum volume in the world
- Residual gas induced phase noise on the light
  - ◆ Very low pressure required (~10^{-9} mbar)

Residual gas noise

- Efforts ongoing at LIGO and Virgo to improve vacuum
  - Leak repairs
  - Better sealing
  - More pumps



Gas specie	Partial Pressure [mbar]	Noise [E-25 $Hz^{-0.5}$]
Total	**1E-8**	**26**
H_2	2E-9	3
H_2O	3E-9	11
$N_2 + O_2$ + others	5E-9	19
Hydrocarbon 100 uma	1E-12	3
Hydrocarbon 300 uma	1E-12	10
PFPE lubricant	1E-12	10

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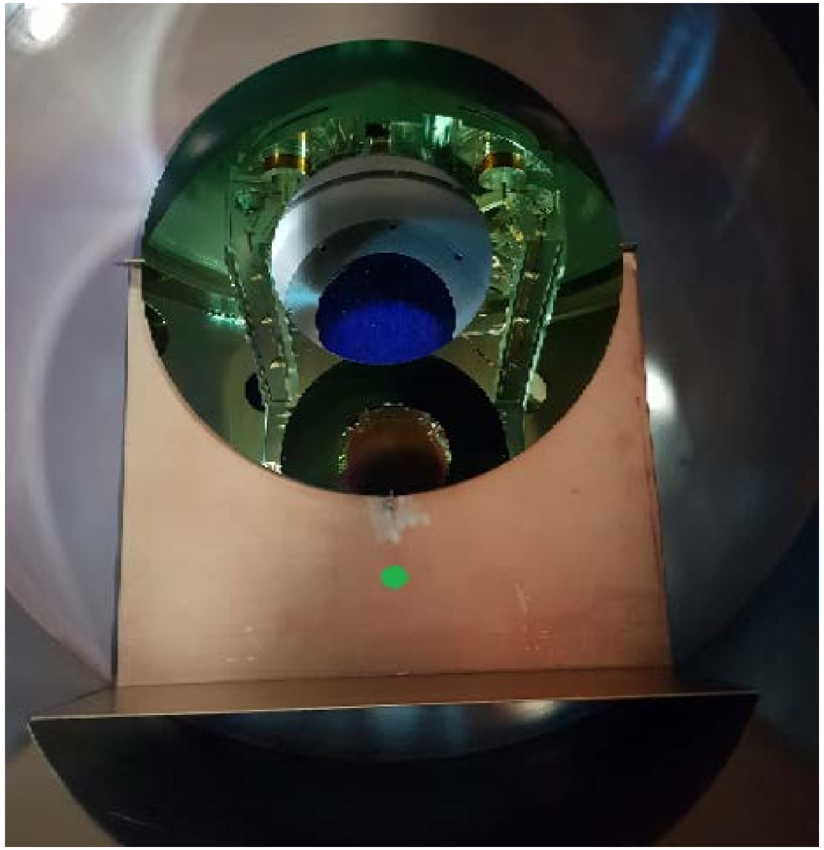
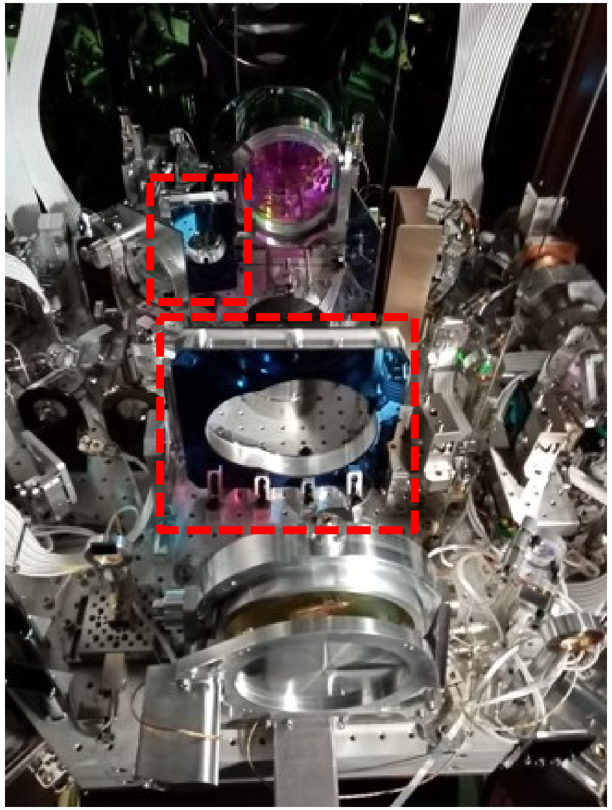
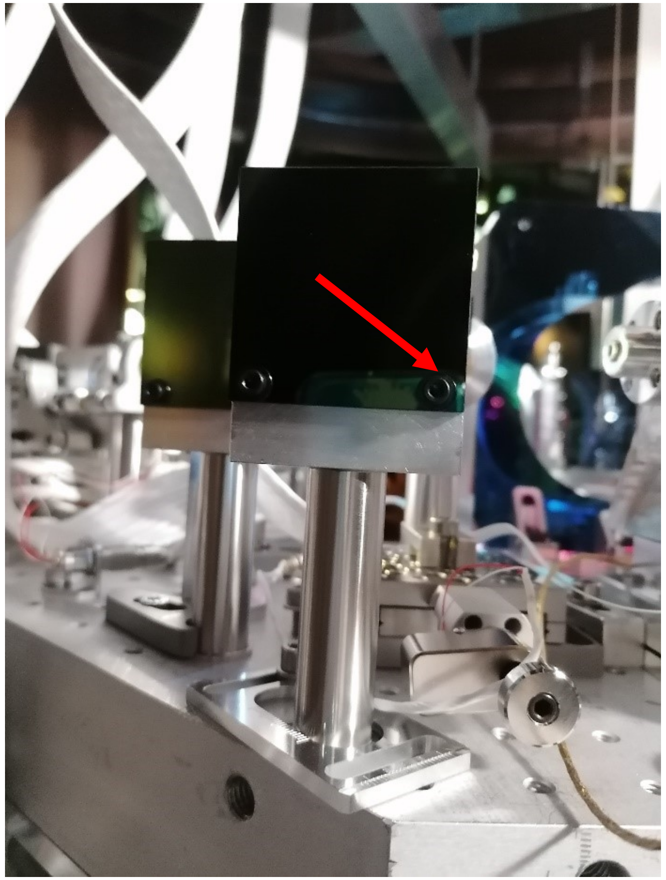
  - Laser sidebands amplitude noise induces a variation in the measured power on the photodetector
- Residual gas noise
  - Light phase noise due index of refraction fluctuations
- Environmental noise/Scattered light noise
  - Scattered light hits against a vibrating surface and recombines with the main beams at the output port

Reduction of scattered light

- Baffles to avoid that scattered light reach vibrating surfaces
- Identification and dump of spurious beams

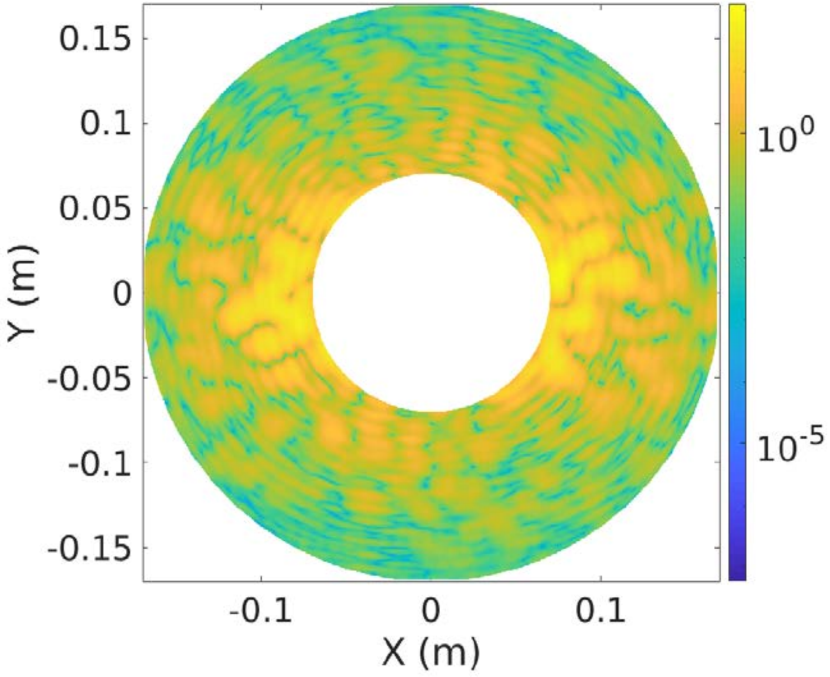


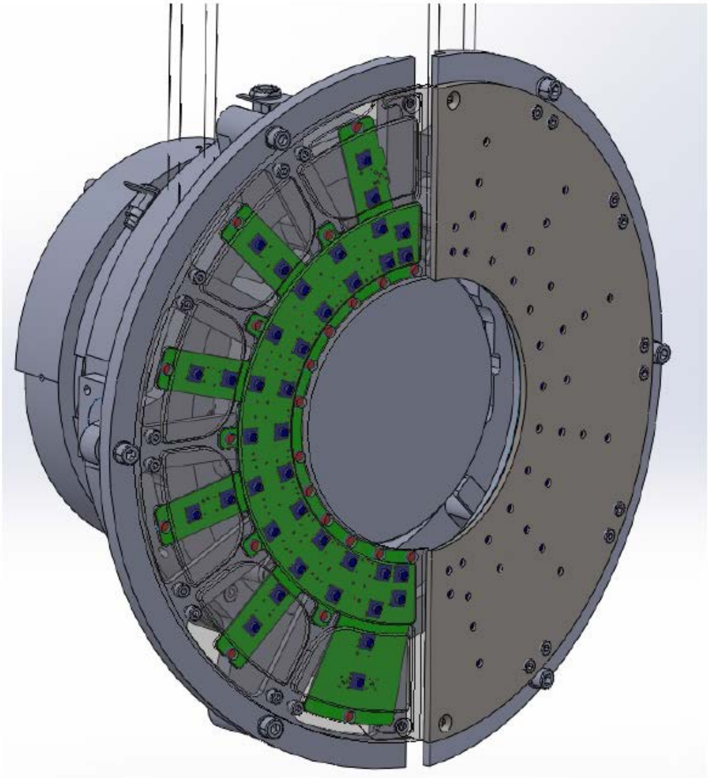


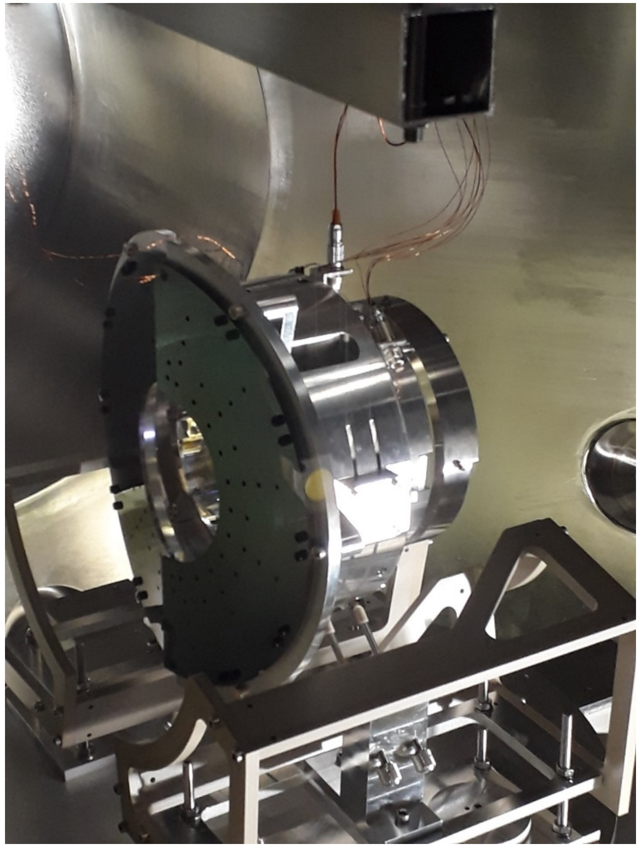


Monitoring of scattered light

- Baffles equipped with light sensors to measure scattered light around mirrors
  - First item installed in the Virgo input mode-cleaner this year
  - Future: installation around the mirrors in the arm cavities







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- Environmental noise/Scattered light noise
  - Scattered light hits against a vibrating surface and recombines with the main beams at the output port
- Electronic noise
  - Voltage/current noise in the photodetectors readout chain

Displacement noises

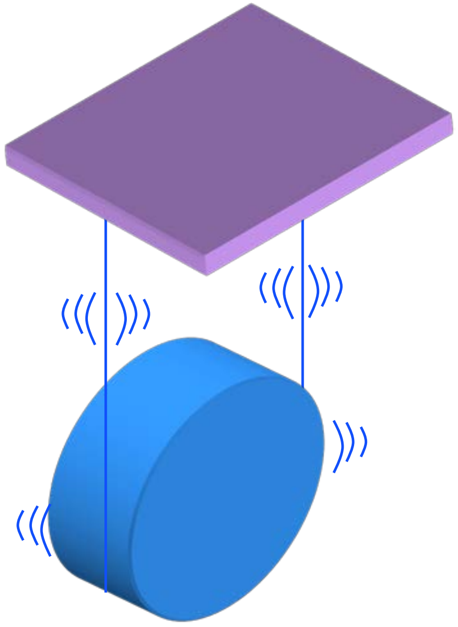
- Noises due to a real displacement of the mirrors

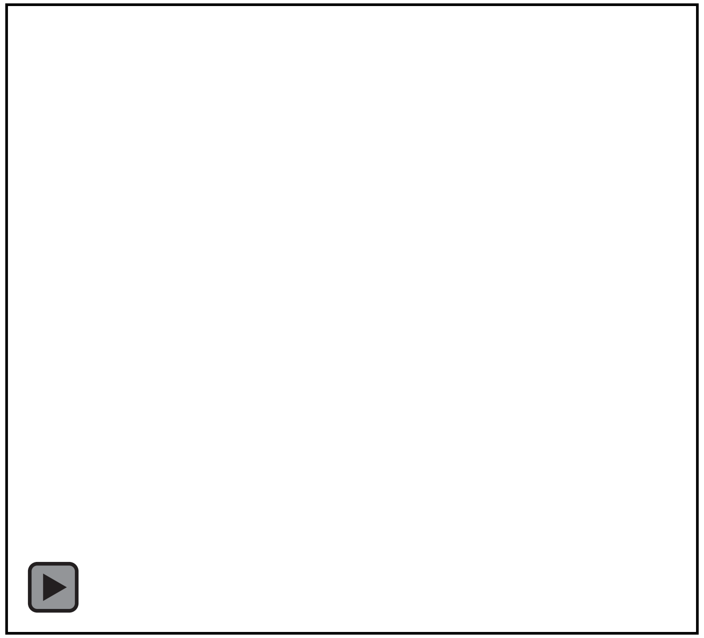
Displacement noises

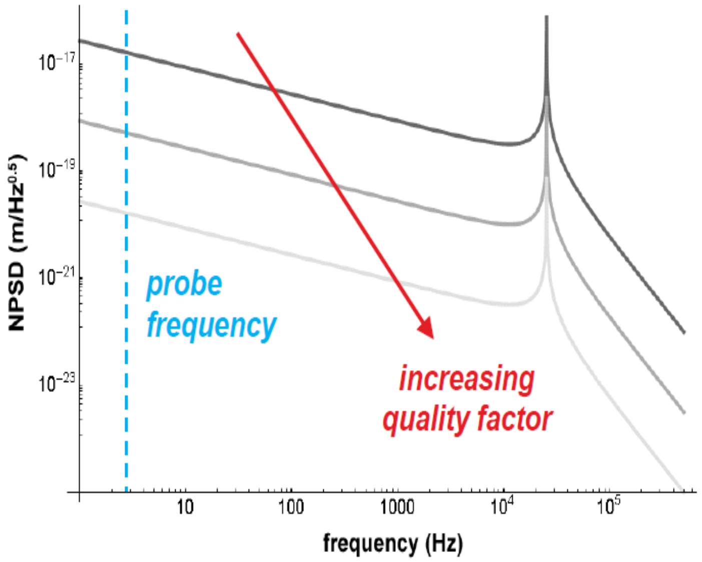
- Radiation pressure noise
  - Variation of the laser power impinging on the mirrors
- Thermal noise
  - Mirror surface motion due to mirror/suspension temperature

Thermal noise

- Thermal vibrations of the mirrors and of their suspensions
  - E =1/2 k T
  - But it is possible to concentrate thermal energy at the resonance
    - » Use systems with high mechanical quality factor

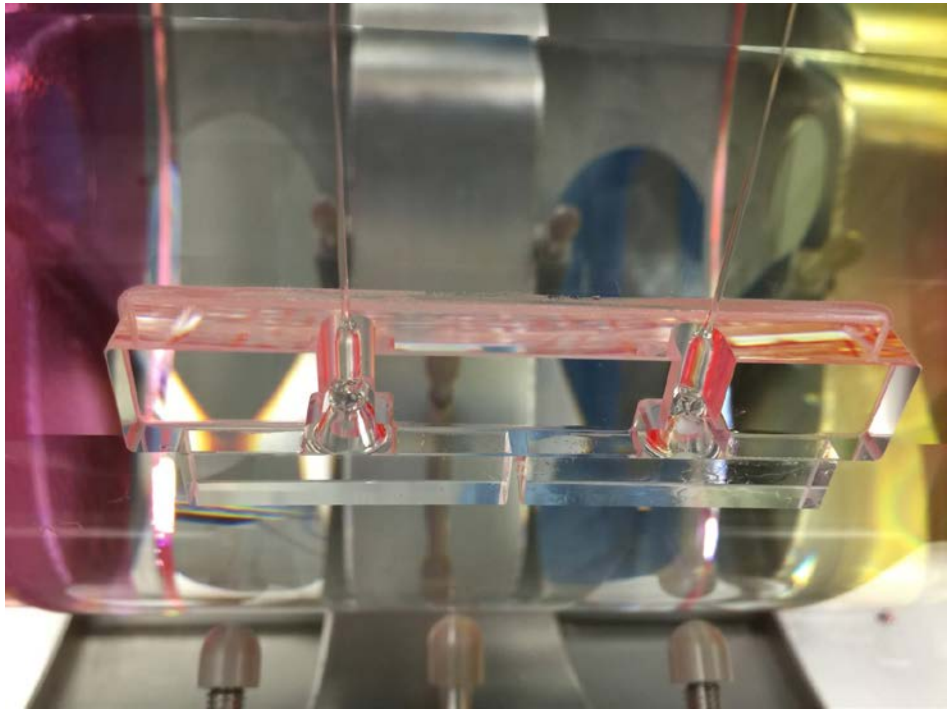






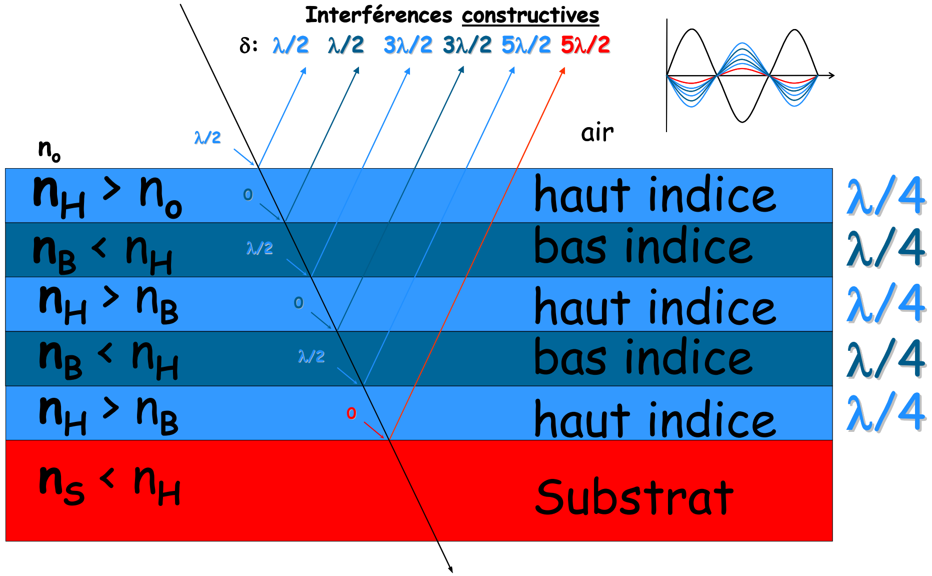
Monolithic suspensions

- Mirrors suspended with fused silica fibers
  - Fibers bonded to the mirror sides
  - Very high mechanical quality factors



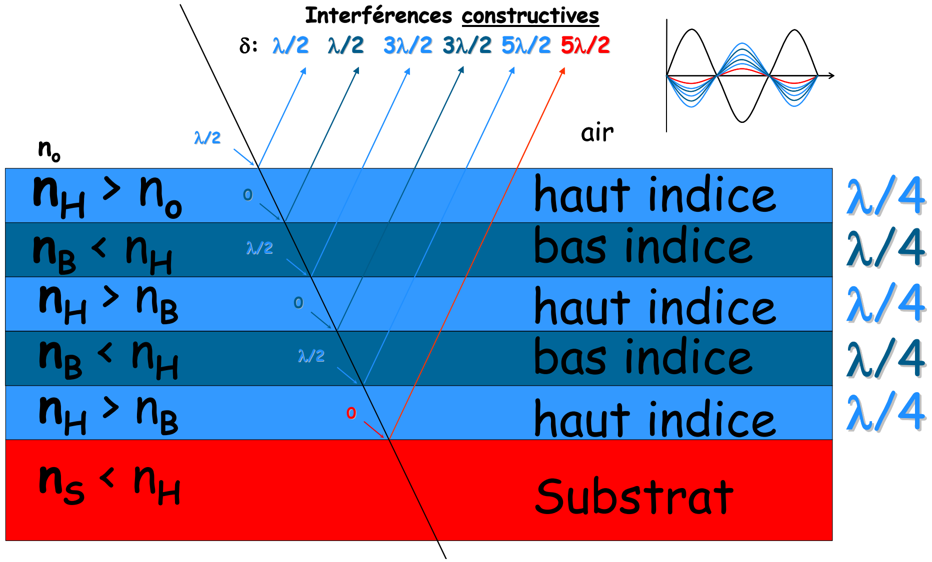
Mirror thermal noise

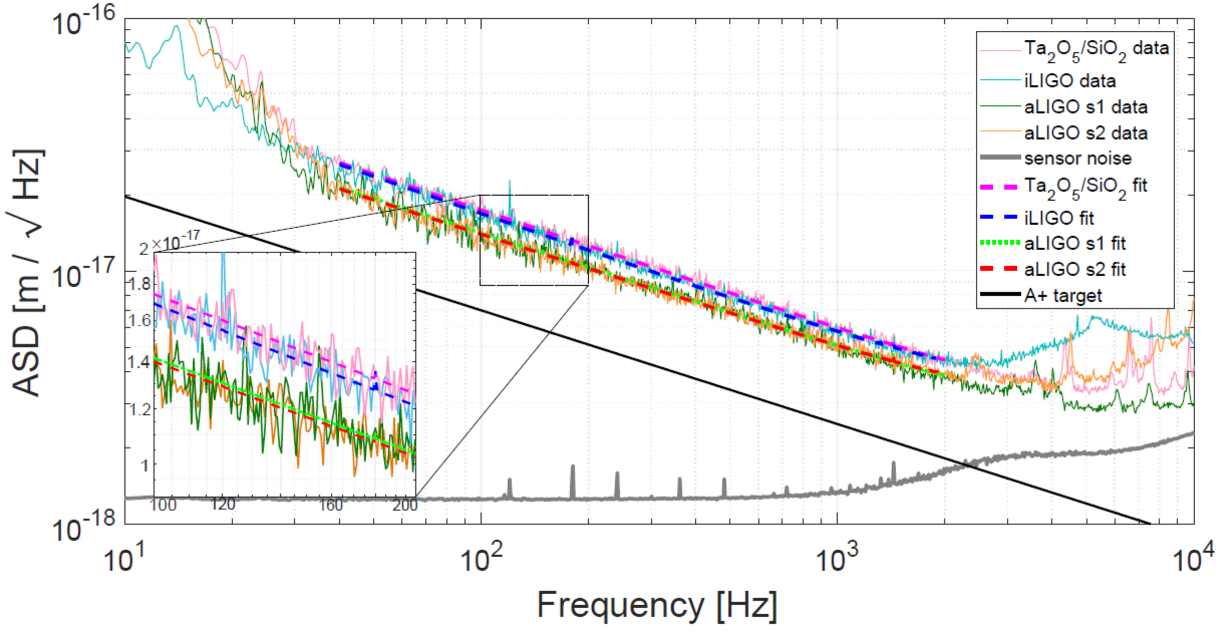
- LIGO/Virgo mirrors made of:
  - 40 kg fused silica cylinders
  - Multi layers coatings to provide high reflectivity at the laser wavelength
- Coatings are the main contributors to the mirror thermal noise



Coating thermal noise

- LIGO/Virgo coatings based on multilayer made of:
  - Ti:Ta2O5 for the high index material
  - SiO2 for the low index material
- Finding: mechanical losses dominated by Ti:Ta2O5
- R&D ongoing to find high index material with lower losses
- Several materials studied for AdV+ and A+
  - Best candidates
    - » Silicon Nitride
    - » Titania Germania mixture



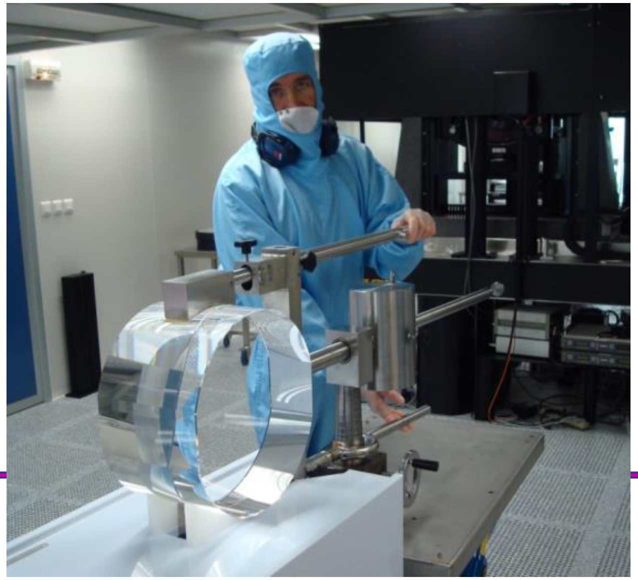


LMA: the Virgo facility for Mirrors

- The perfect coating
  - ◆ Low mechanical losses
  - ◆ Low scattering (< 10 ppm)
  - ◆ Low absorption (<1 ppm)
  - ◆ Small surface figure error (< 1 nm)

- Laboratoire des Materiaux Avancés, Lyon, France
  - ◆ Facility developed for the realization of the Virgo mirrors
    - » Coating machines based on Ion Beam Sputtering
    - » Mirror metrology equipment
    - » Large class 1 clean room

- Also used for LIGO and KAGRA



Coating thermal noise reduction

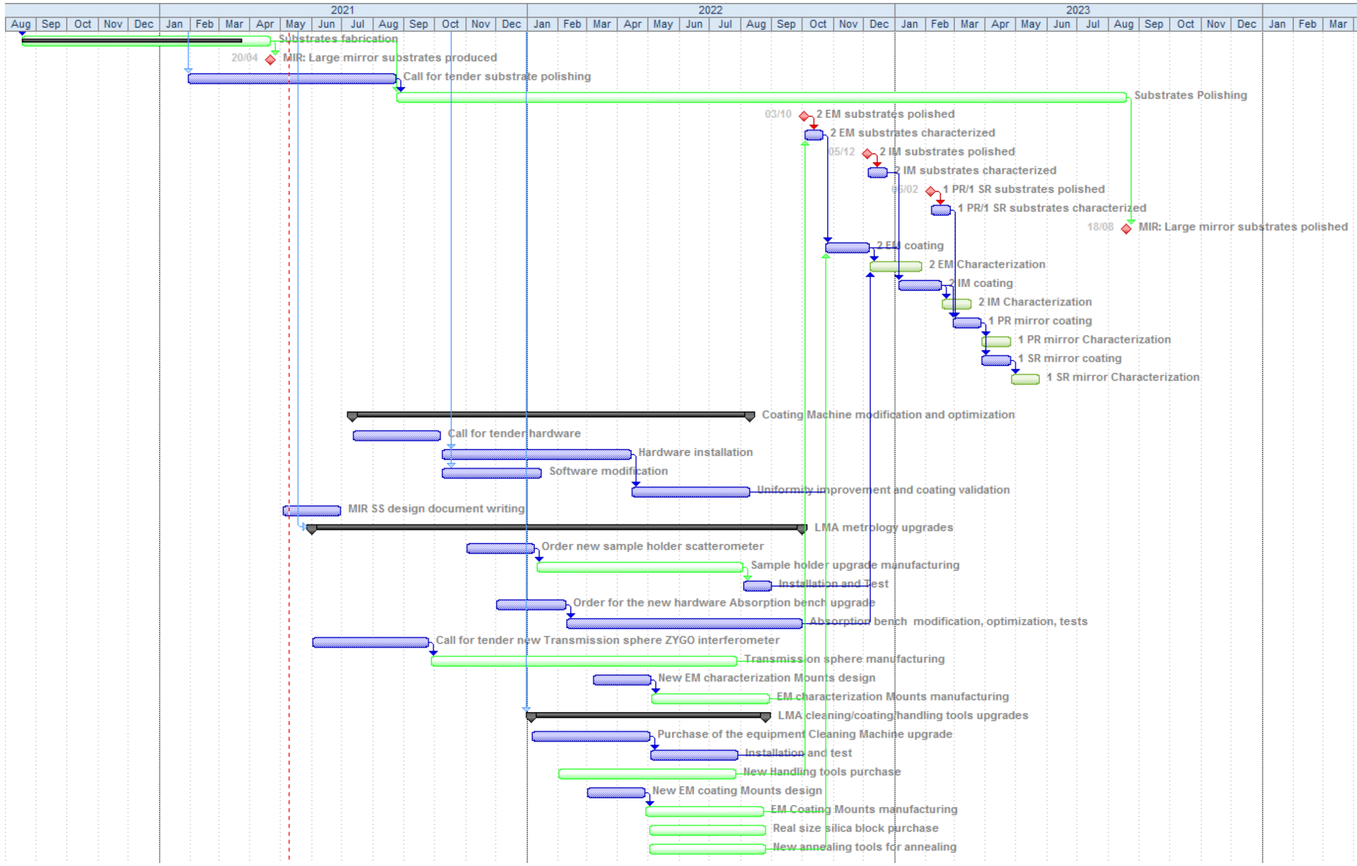
- Next steps

- Choose the most promising solution
  - TiO2:GeO2 / SiO2
  - SiN / SiO2

- Start its engineering at LMA

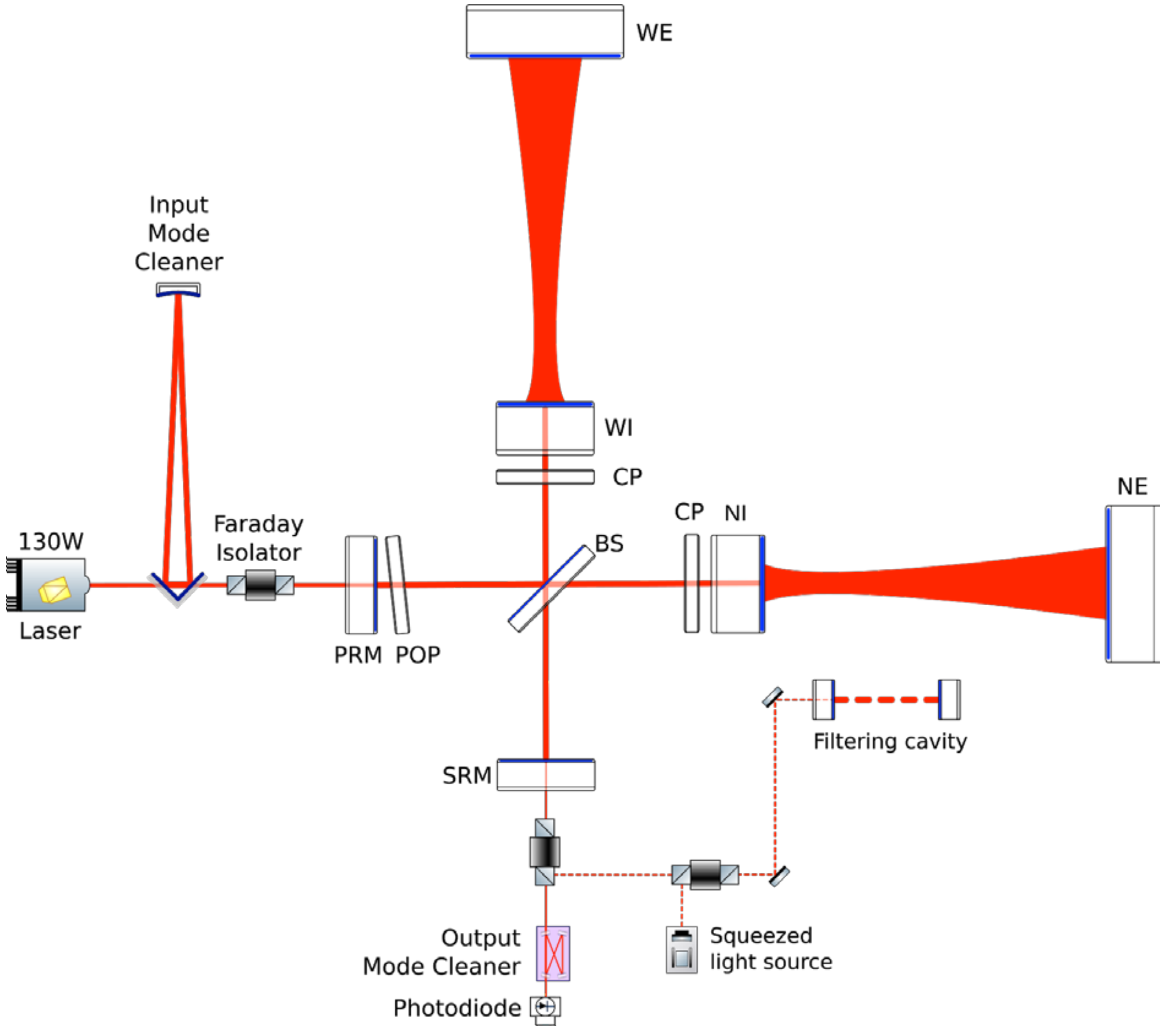
- Goal: have new coatings for the A+/AdV+ detectors to be used in O5

- NB. Mirrors production it’s a very long process
  - At least 3 years between glass production for the substrates and mirror installation



Thermal noise reduction in AdV+

- Not only coating losses reduction
- Increase beam size on end mirrors
  - From to 6 cm to 10 cm
- Why end mirrors?
  - End mirror have larger reflectivity
  - Thicker coatings
  - Larger coating thermal noise
- Challenge
  - Cavities has larger g-factor
  - Less stable
  - More difficult to keep aligned

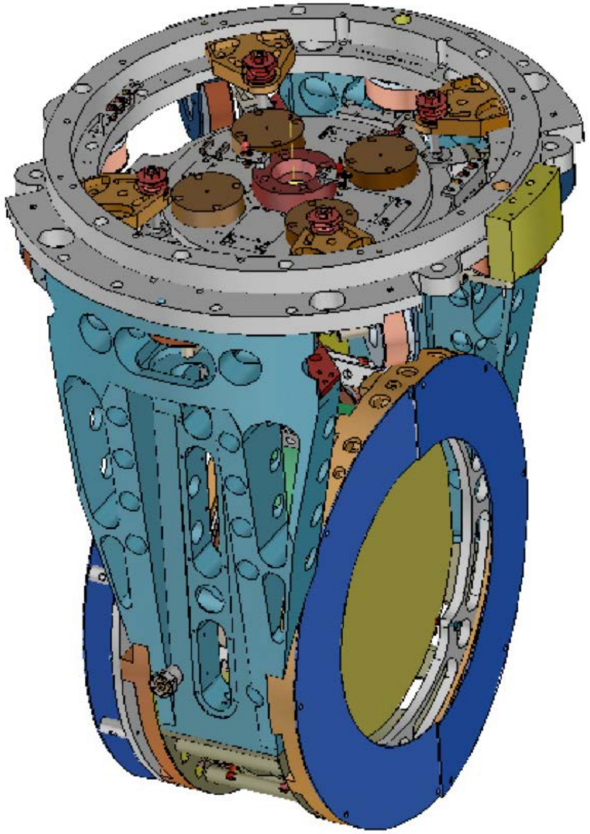


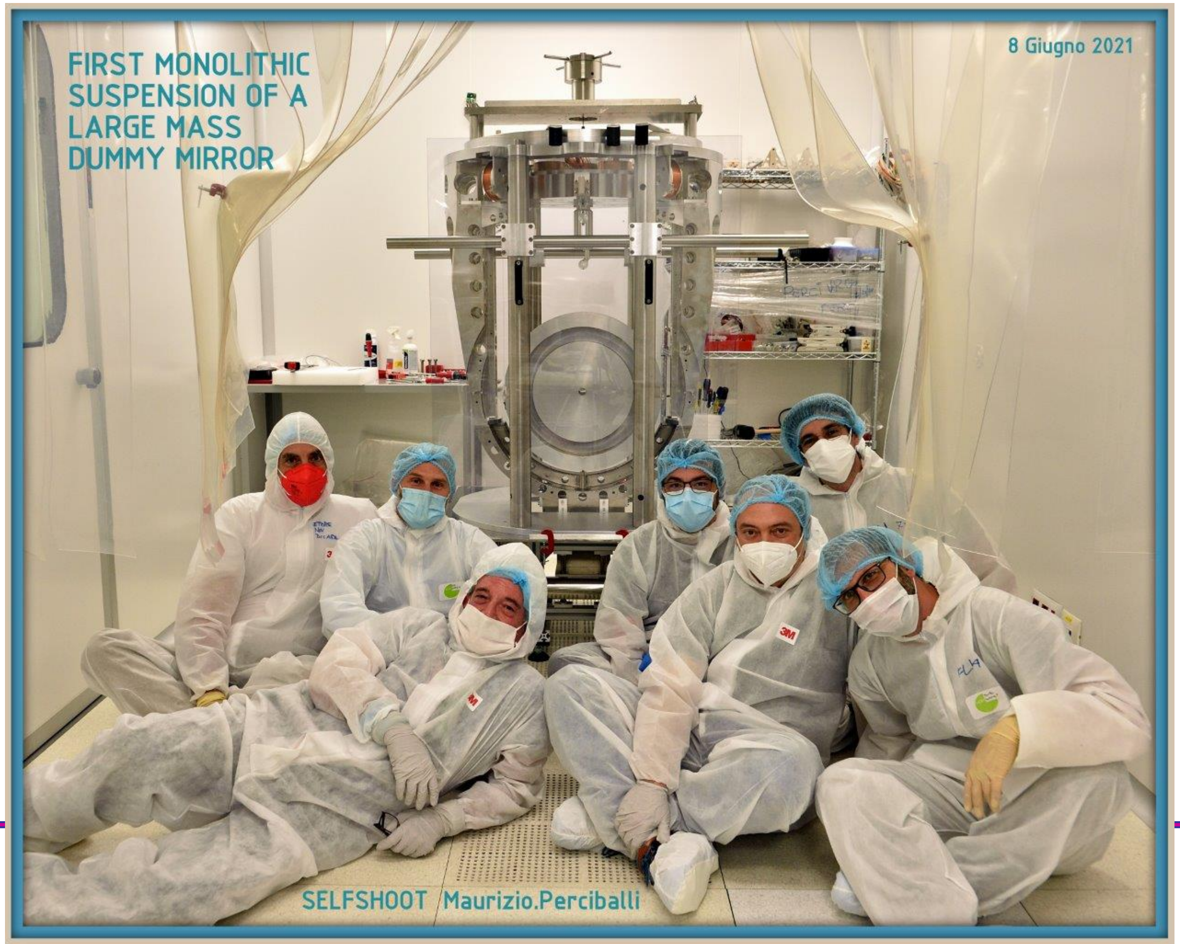
Thermal noise reduction in AdV+

- Need to realize larger mirrors
  - 55 cm diameter, 20 cm thickness
  - 100 kg in mass
- Polishing requirements as tight as those for AdV and AdL but on larger surfaces
  - 0.5 nm RMS on 30 cm diameter
  - Need to realize radius of curvature with <10 m precision (over ~1.5 km)

Thermal noise reduction in AdV+

- Need to suspend 100 kg mirror with fused silica fibers
- Need to control finely the mirror position once suspended
- New payload for 100 kg mirror being developed for AdV+



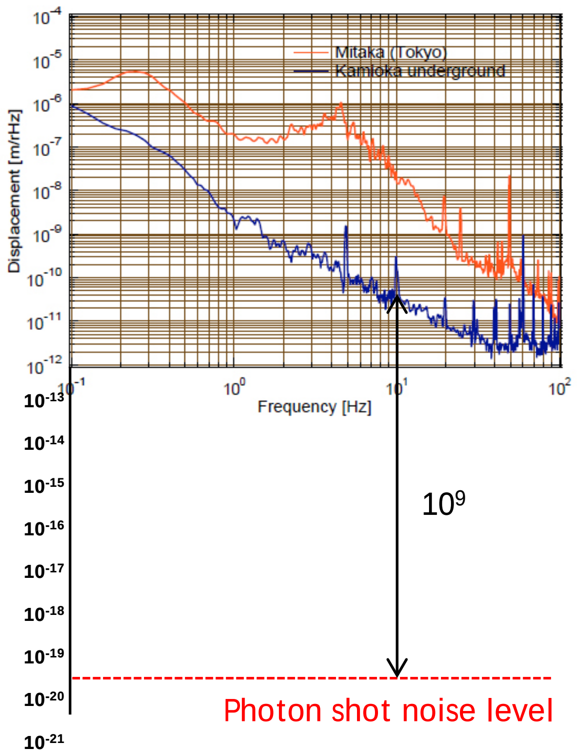


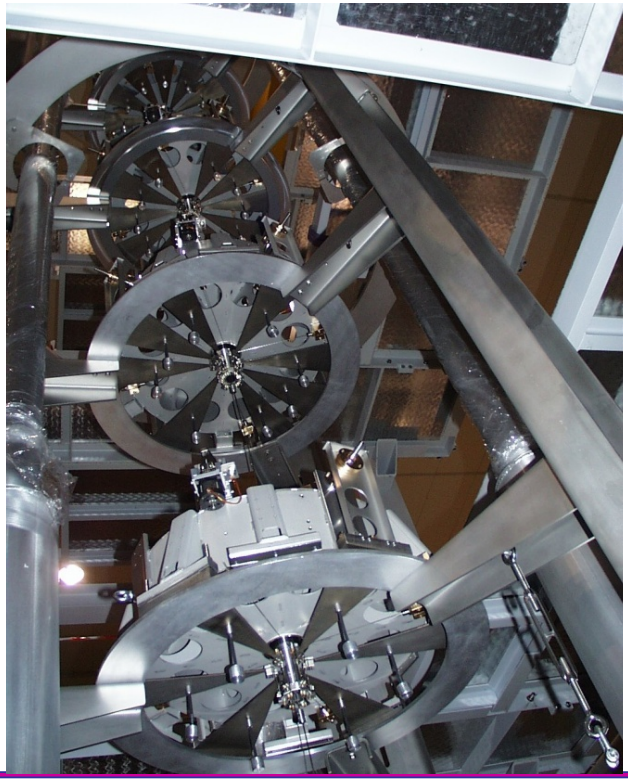
Displacement noises

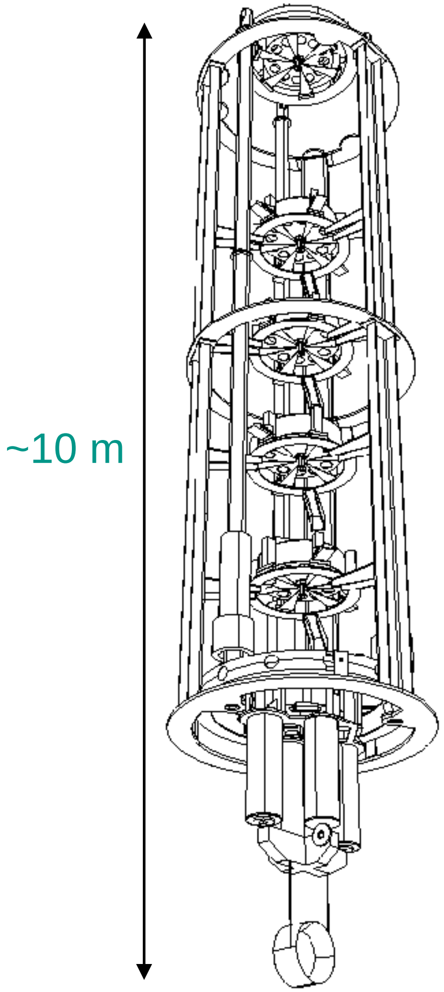
- Radiation pressure noise
  - Variation of the laser power impinging on the mirrors
- Thermal noise
  - Mirror surface motion due to mirror/suspension temperature
- Seismic noise
  - Seismic vibration propagating to the mirror

Seismic noise

- Natural ground vibrations much larger than GW signals
- Main solutions
  - Advanced seismic isolation systems (low frequency cut-off)
  - Multi-pendulum with vertical low frequency springs







Seismic noise

- Both LIGO and Virgo using a combination of active and passive seismic isolation
  - More passive isolation at Virgo
  - More active isolation at LIGO
- Both sufficient to reach the AdV+ and A+ seismic isolation requirements
  - Residual seismic noise smaller than Newtonian noise
  - No upgrades needed to reach sensitivity goals
- Upgrade of Virgo seismic isolation for end mirror required to suspend the heavier mirrors

Displacement noises

- Radiation pressure noise
  - Variation of the laser power impinging on the mirrors
- Thermal noise
  - Mirror surface motion due to mirror/suspension temperature
- Seismic noise
  - Seismic vibration propagating to the mirror
- Newtonian noise
  - Seismic vibration varying local gravity

Newtonian noise

- Local gravity variation due to masses motion around the mirror.
  - Originated from seismic noise (or air masses motion)
  - Main solutions:
    - » Go underground
      - – Less seismic noise
    - » Measure seismic noise precisely and subtract it from the ITF signal

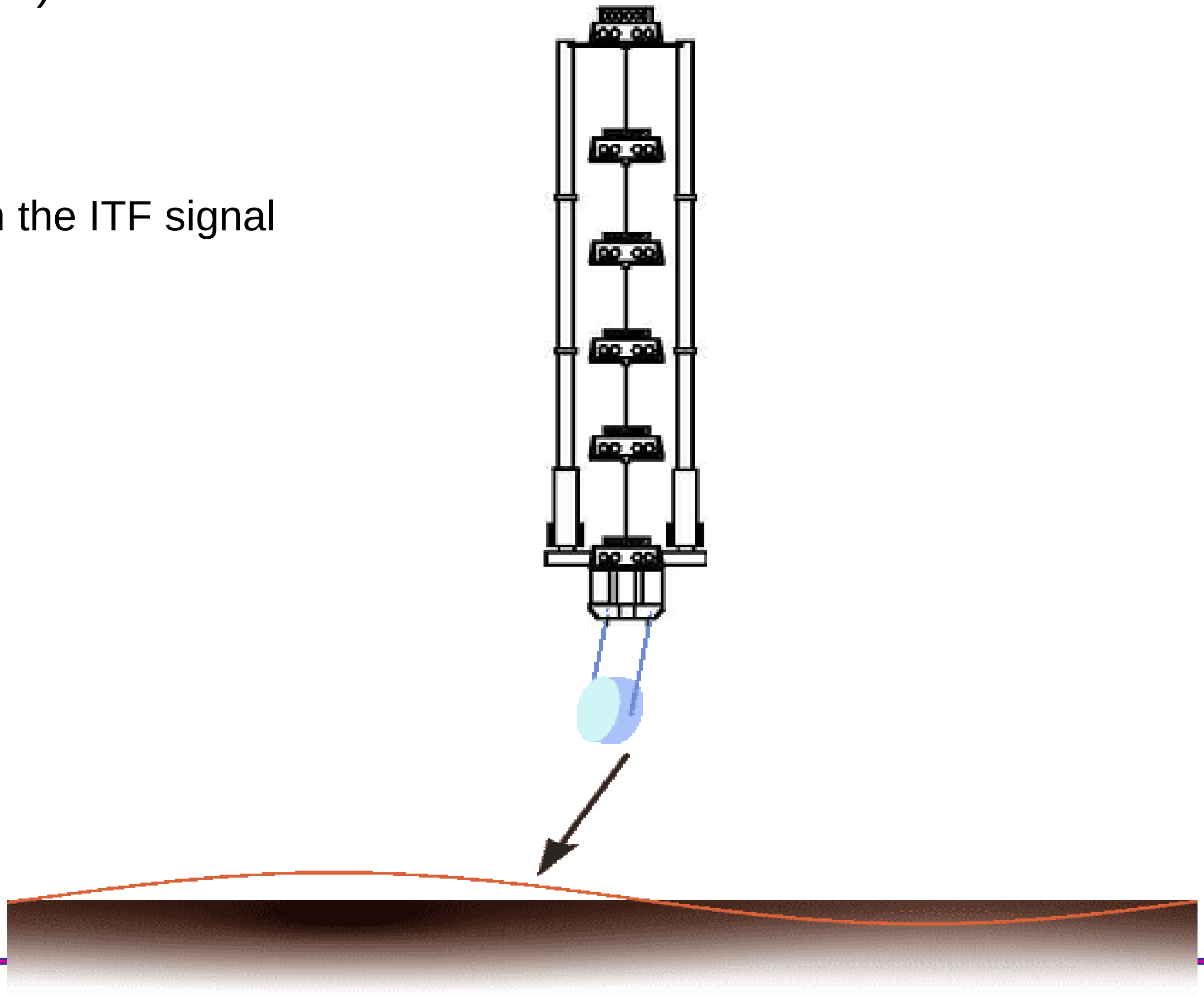
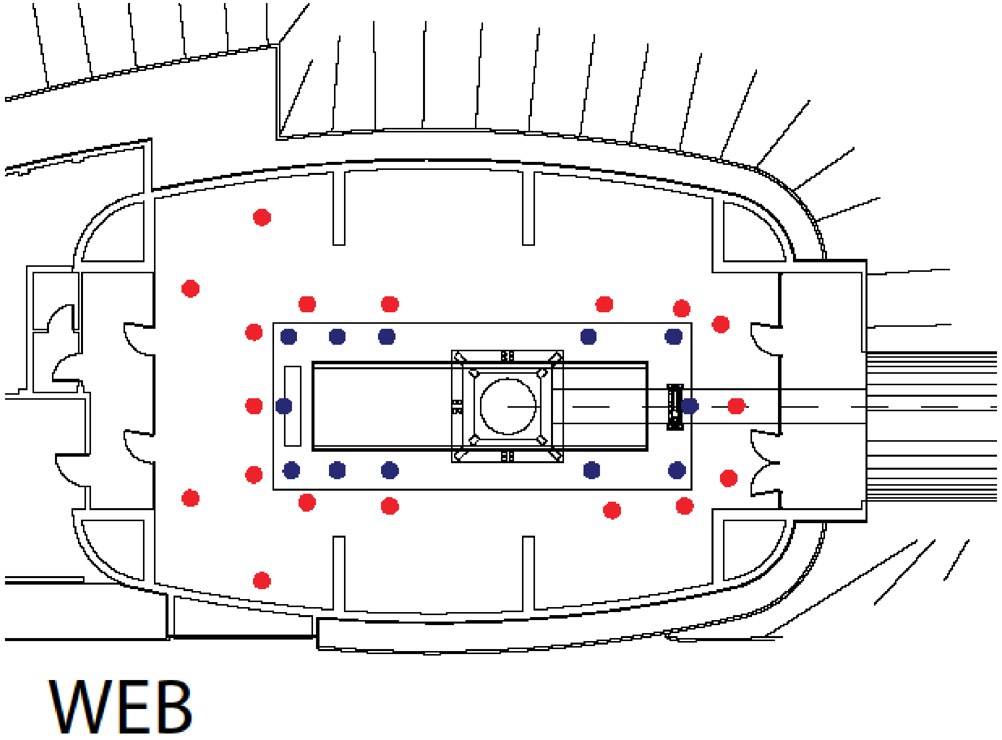


Figure: M.Lorenzini

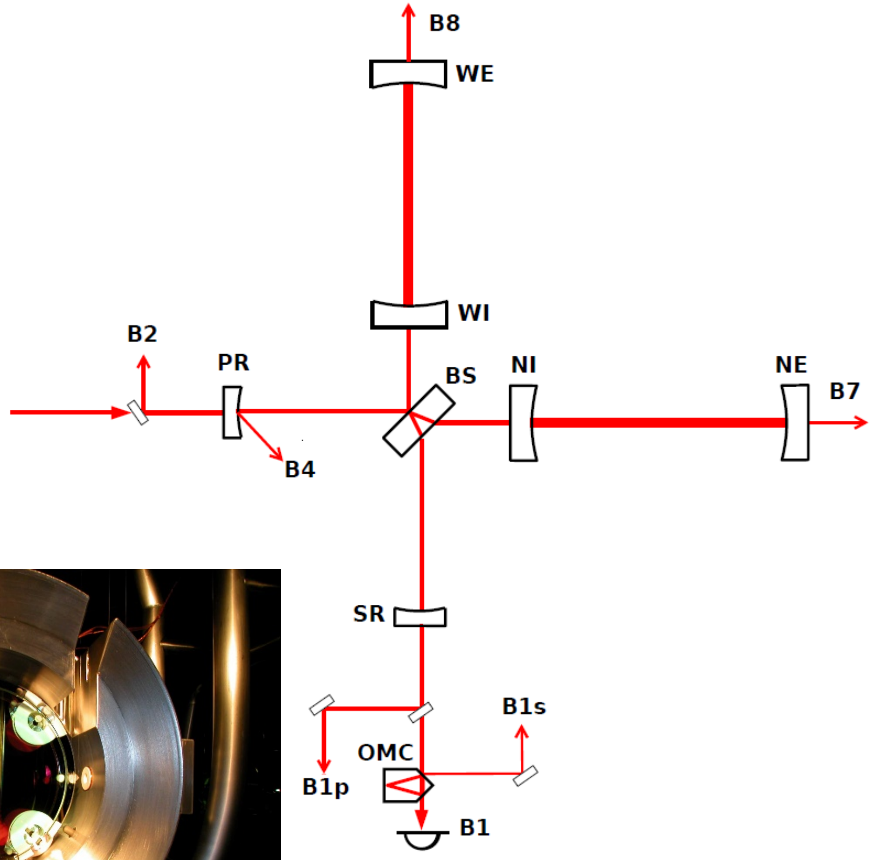
Newtonian noise cancellation

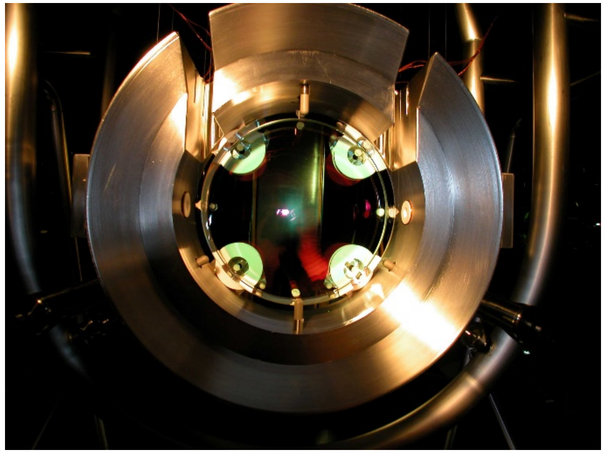
- AdV+ plan
- Deploy arrays of seismic sensors at each building
- Measure seismic waves and subtract Newtonian noise from the data



Interferometer control system

- Keep interferometer at the working point
  - Keep all mirrors aligned
  - Keep optical cavities at resonance
  - Keep interference locked to the “dark fringe”
- Control accuracy required
  - Less than nano-radiants
  - Less than pico-meters
- Control system architecture
  - Detectors to sense relevant optical lengths/alignments
  - Coil-magnets actuators to act on mirror positions
  - Digital control system to act in real time

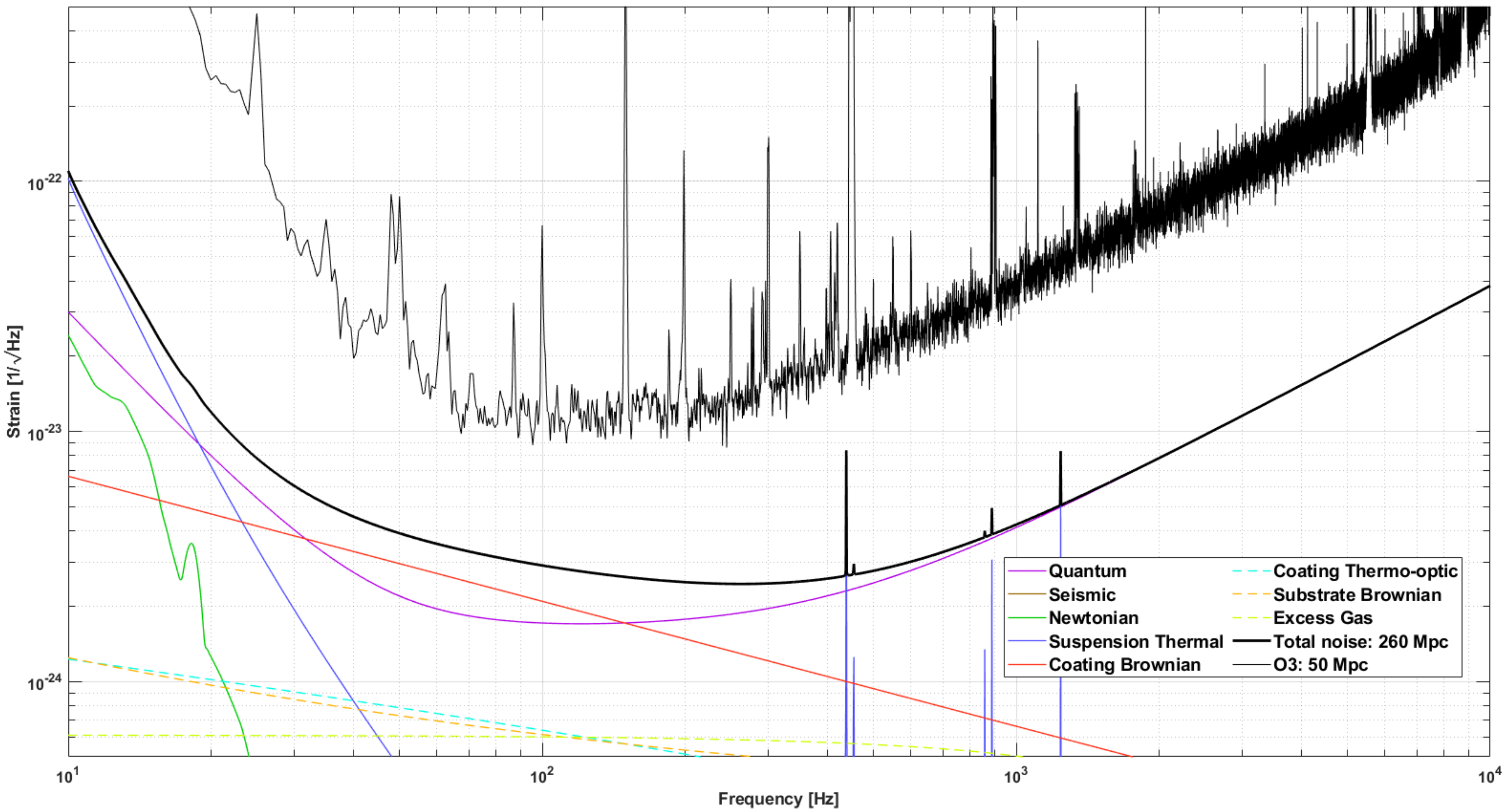




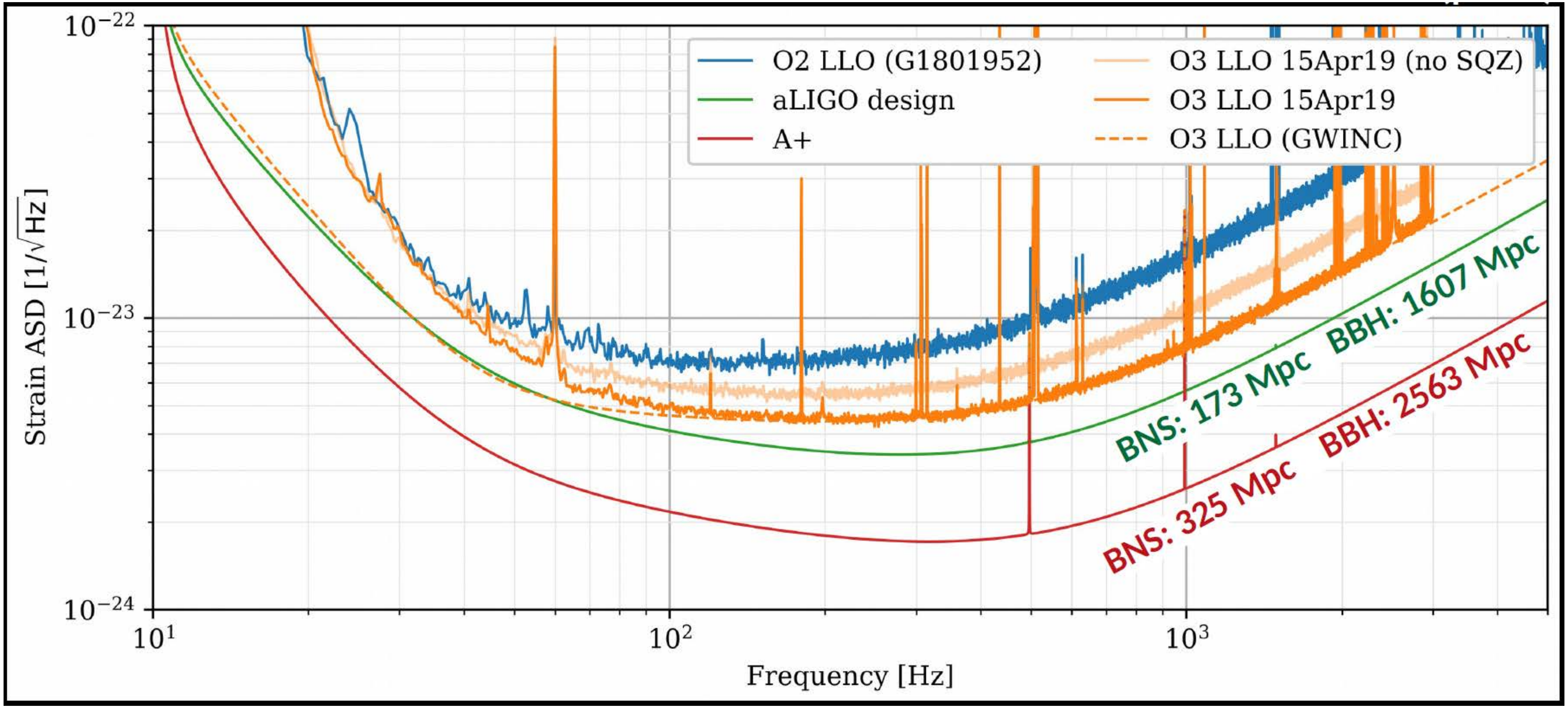
Displacement noises

- Radiation pressure noise
  - Variation of the laser power impinging on the mirrors
- Thermal noise
  - Mirror surface motion due to mirror/suspension temperature
- Seismic noise
  - Seismic vibration propagating to the mirror
- Newtonian noise
  - Seismic vibration varying local gravity
- Magnetic/Electric noise
  - Varying EM fields acting via mirror magnets or mirror residual charge
- Actuation noise
  - Voltage/Current noise in the coils-magnet actuators

AdV+ best sensitivity (O5)



A+ best sensitivity (O5)



After O5?

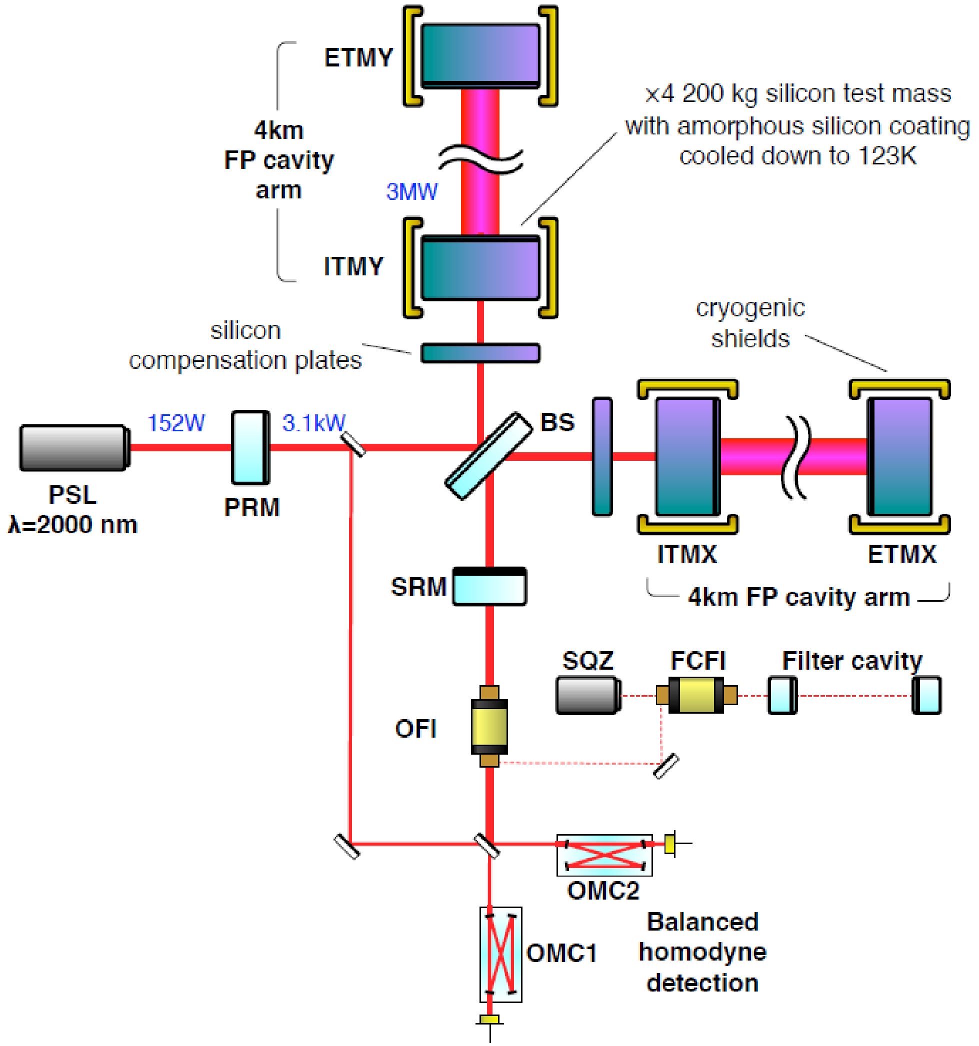
- No established plans yet

- Infrastructure limitations
  - Building size
  - Arm length
  - Vacuum system

- Path toward 3G?

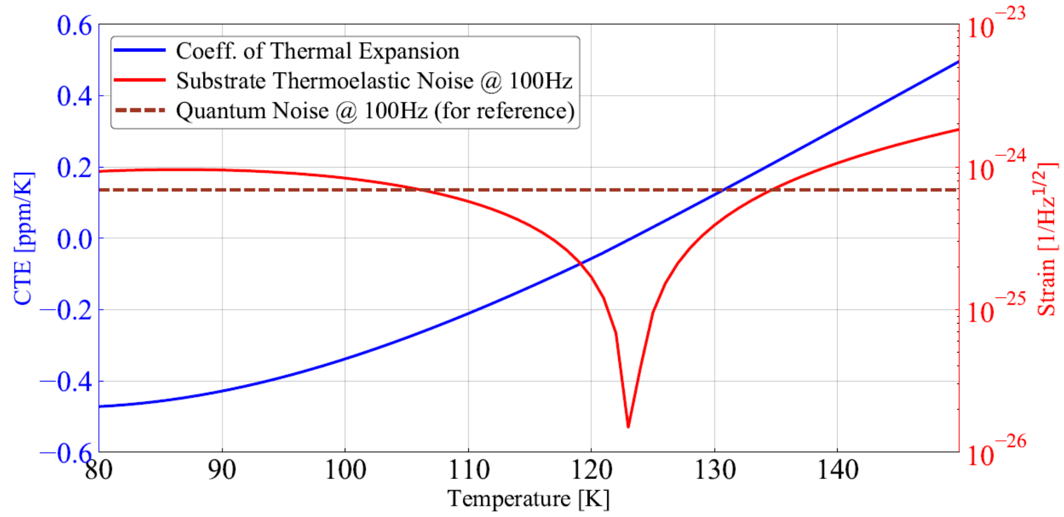
Voyager

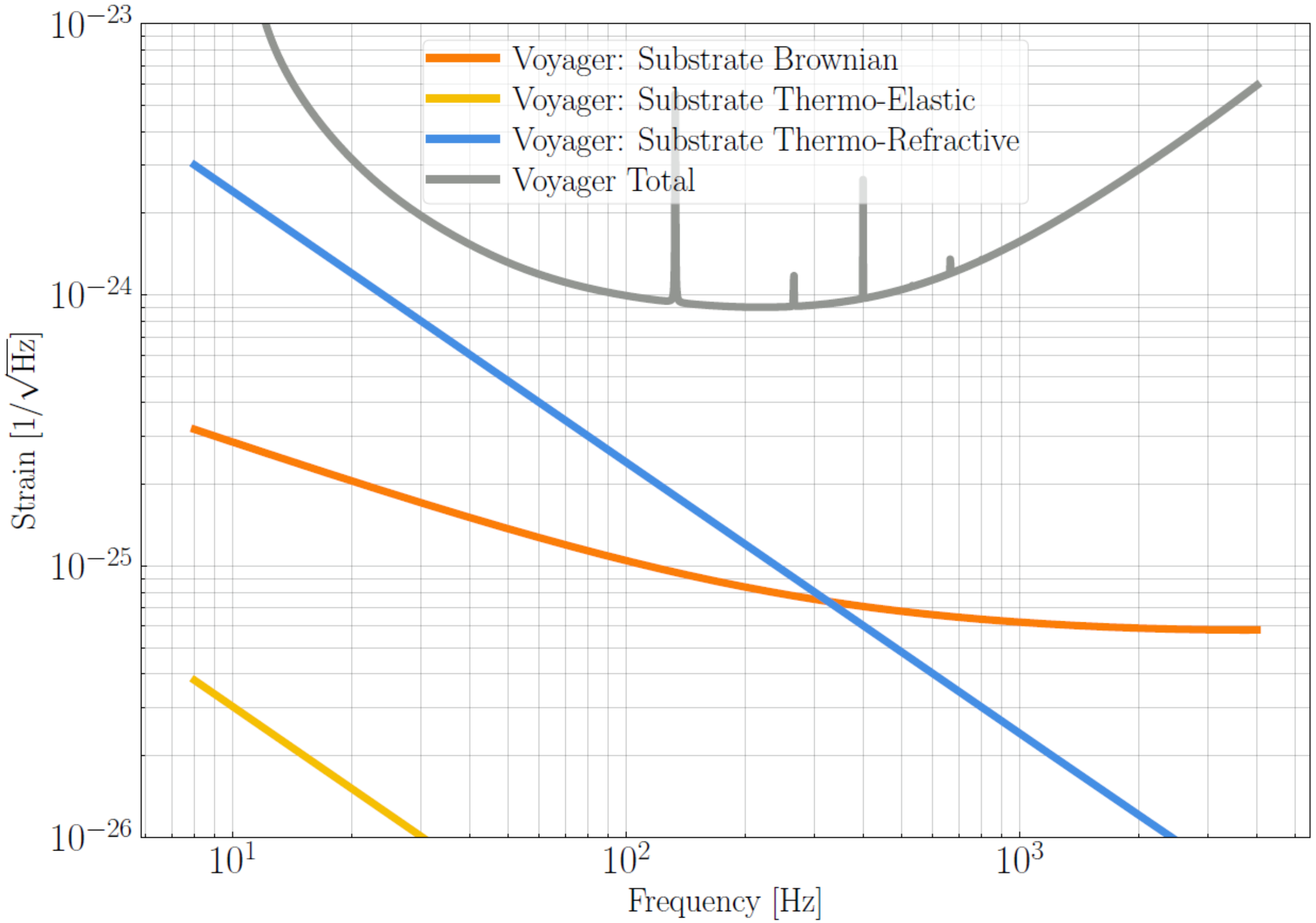
- LIGO/Virgo optical configuration
- Main keywords
  - ◆ Cryogenic (123 K)
  - ◆ Silicon test masses
  - ◆ laser wavelength 2 μm



Voyager

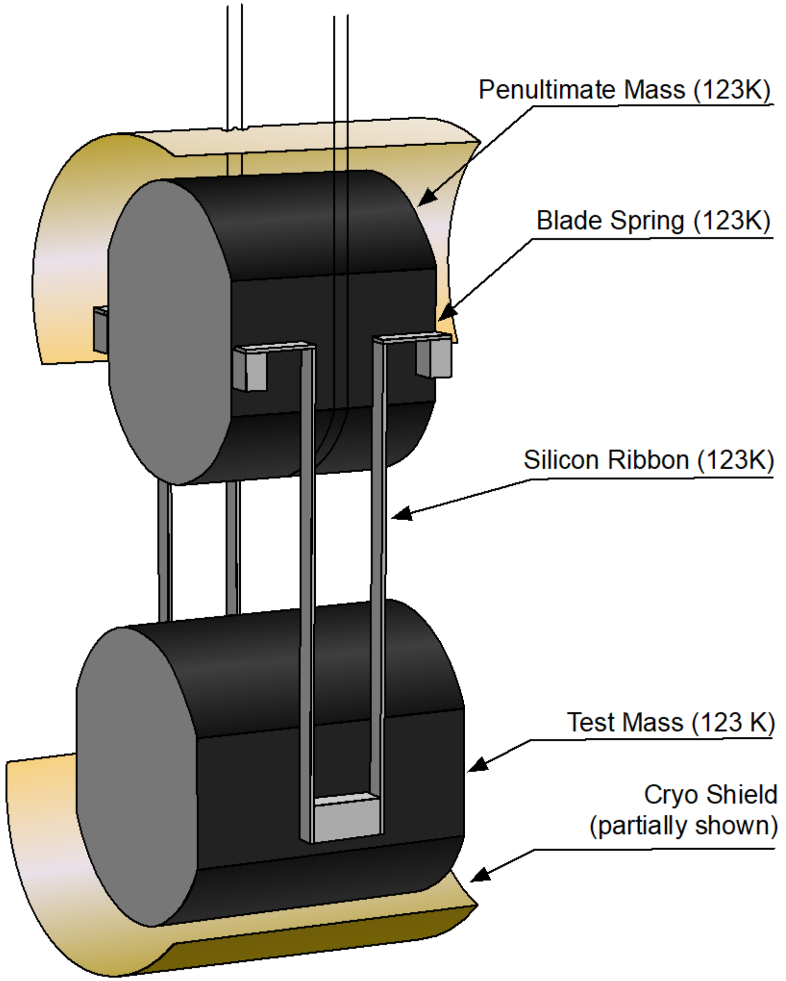
- Why 123 K?
- Substrate thermo-elastic noise





Voyager

- Suspension and cryogenic
  - ◆ Monolithic silicon suspension
  - ◆ Radiative cooling (efficient at 123 K)

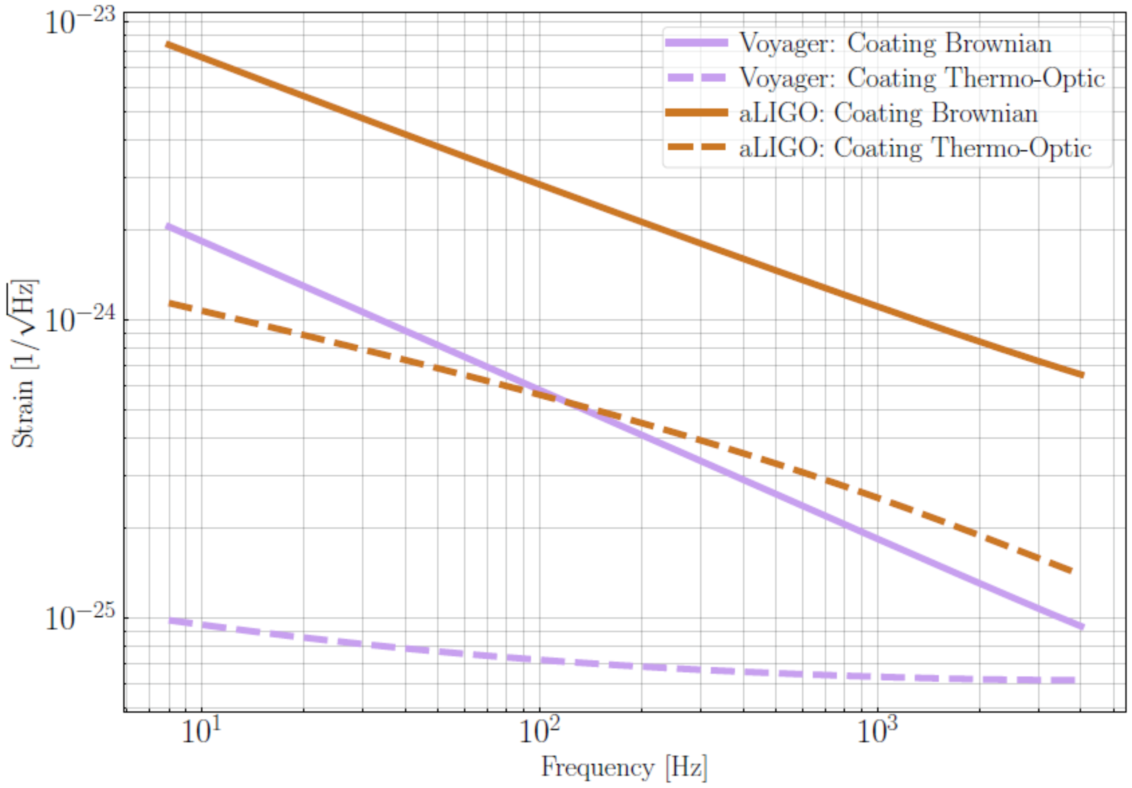


Voyager

- Mirror coating
  - Amorphous silicon as high index material
  - But low absorption not demonstrated yet

Parameter	Detector	Material	Loss-angle (ϕ)	Refractive Index n
Low index	aLIGO (300 K)	SiO_2	4.0×10^{-5}	1.45
High index	aLIGO (300 K)	Ta_2O_5	2.3×10^{-4}	2.07
Low index	Voyager (123 K)	SiO_2	1.0×10^{-4}	1.436
High index	Voyager (123 K)	α-Si	$\leq 1.0 \times 10^{-5}$[44]	3.5

TABLE 2: Summary of the coating material parameters. Note that, due to the peculiarities of glass, the loss-angle for the SiO_2 increases at cryogenic temperatures[45].



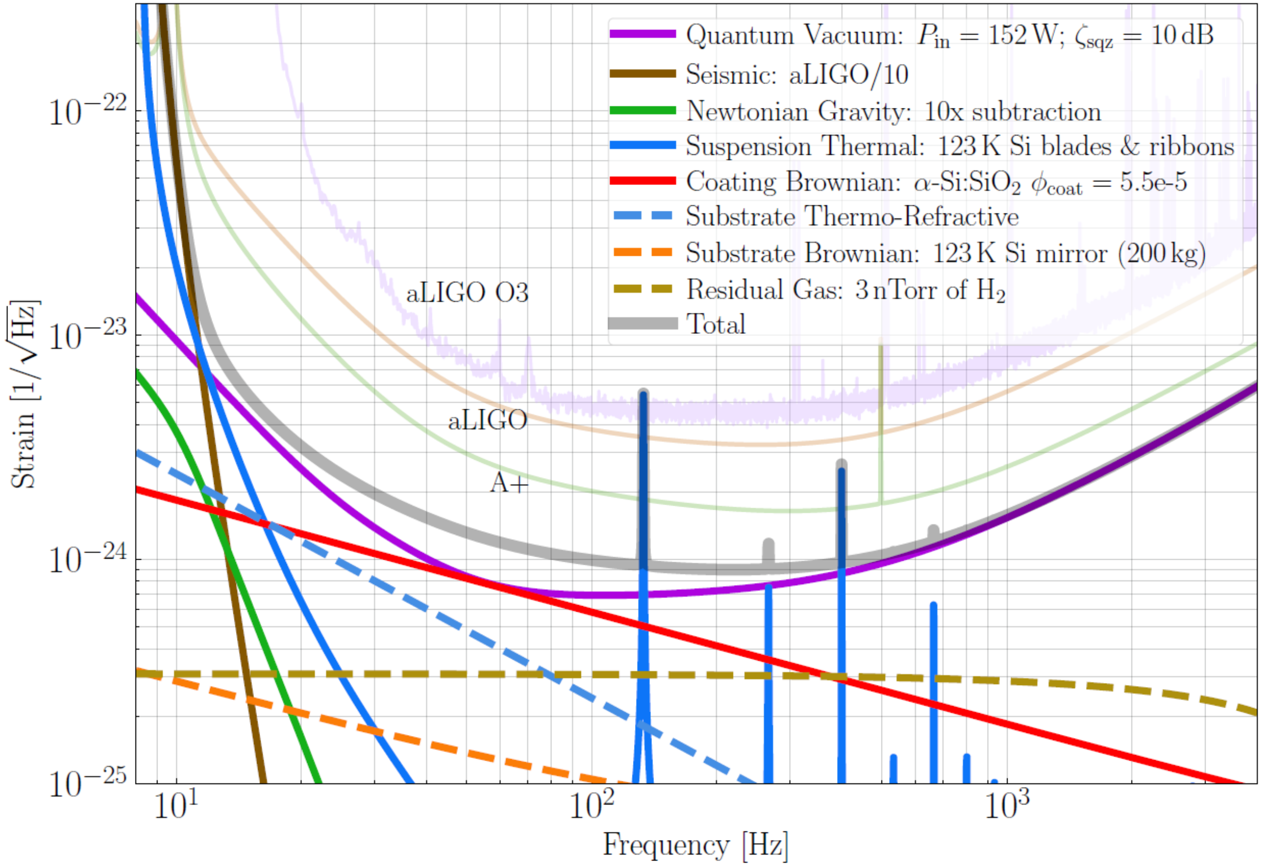
Voyager

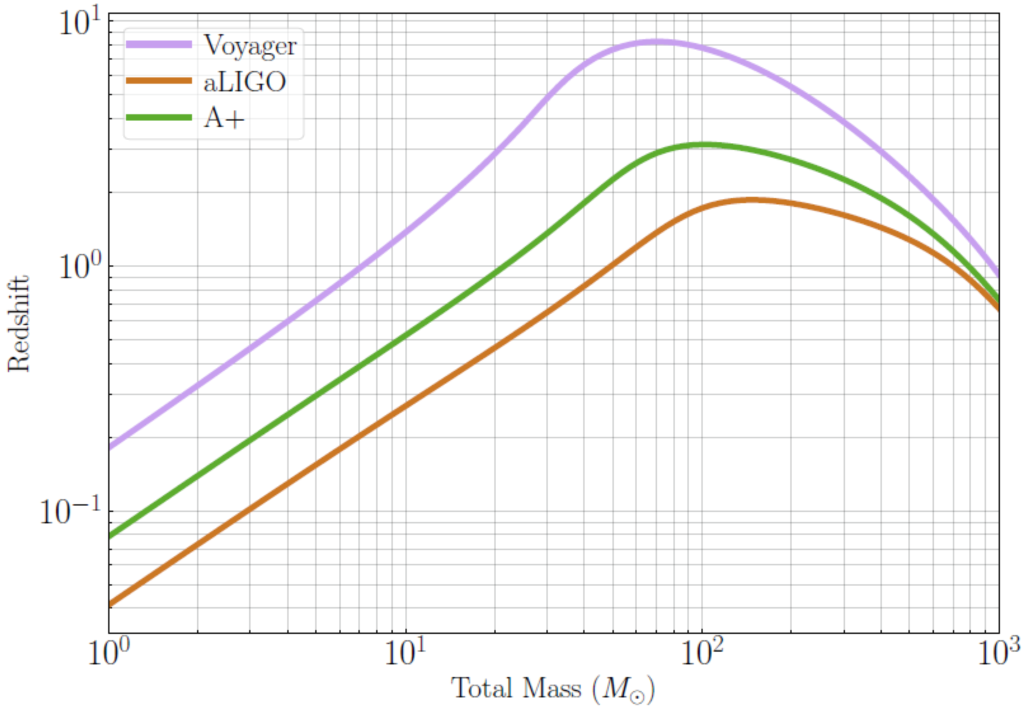
- Laser wavelength
  - Preferred is 2 μm
  - Main driver: optical absorption

Consideration	Wavelength			
	1550 nm	1900 nm	2000 nm	2128 nm
Photodiode Q.E.	$>99\%$	$\approx 87\%$. Promising trajectory (Section 5.4).		
Coating thermal noise	Low	$\approx 14\%$ larger		
Optical scatter loss	66% larger	Low		
Residual gas noise	low H_2O	some H_2O	low H_2O	
Coating absorption	High	Medium		
Si substrate absorption	Increases as λ^2 but not dominant effect			
SiO_2 substrate absorption	<1 ppm/cm	20 ppm/cm	40 ppm/cm	120 ppm/cm
Angular instability	Less stable	More stable arm cavity		
Parametric instability	Very little change with wavelength			

Voyager

- Potential sensitivity
  - Real improvement compared to room temperature detectors. Nice alternative path toward cryogenic detector
  - A lot of R&D to be done. Extended downtime probable.





Conclusions

- Still a lot to do with the LIGO/Virgo infrastructure
  - AdV+/A+
  - Post O5 plan to be established

- As 3G will approach they will progressively become nice places to test new solutions for 3G upgrades
  - As GEO was for AdL and AdV