LIGO/Virgo physics and technology

Maddalena Mantovani

EGO - European Gravitational Observatory

ISAPP Summer School on Gravitational Waves 2021

Global network of GW detectors

Second generation detectors

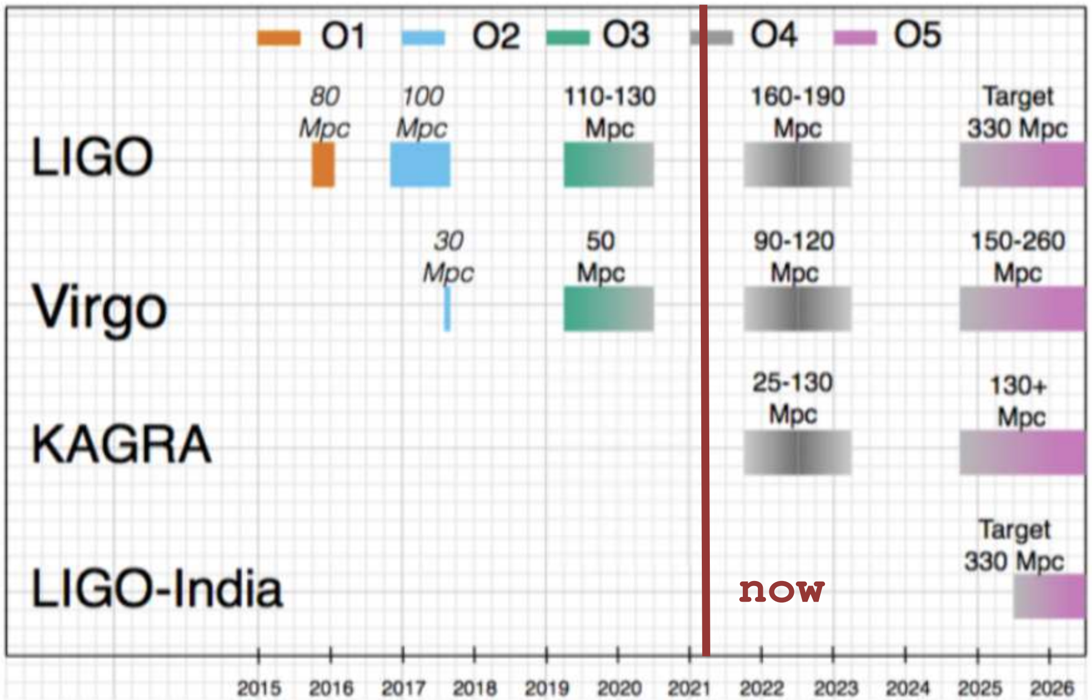
Global network of GW detectors

E.Capocasa's presentation

Second generation detectors

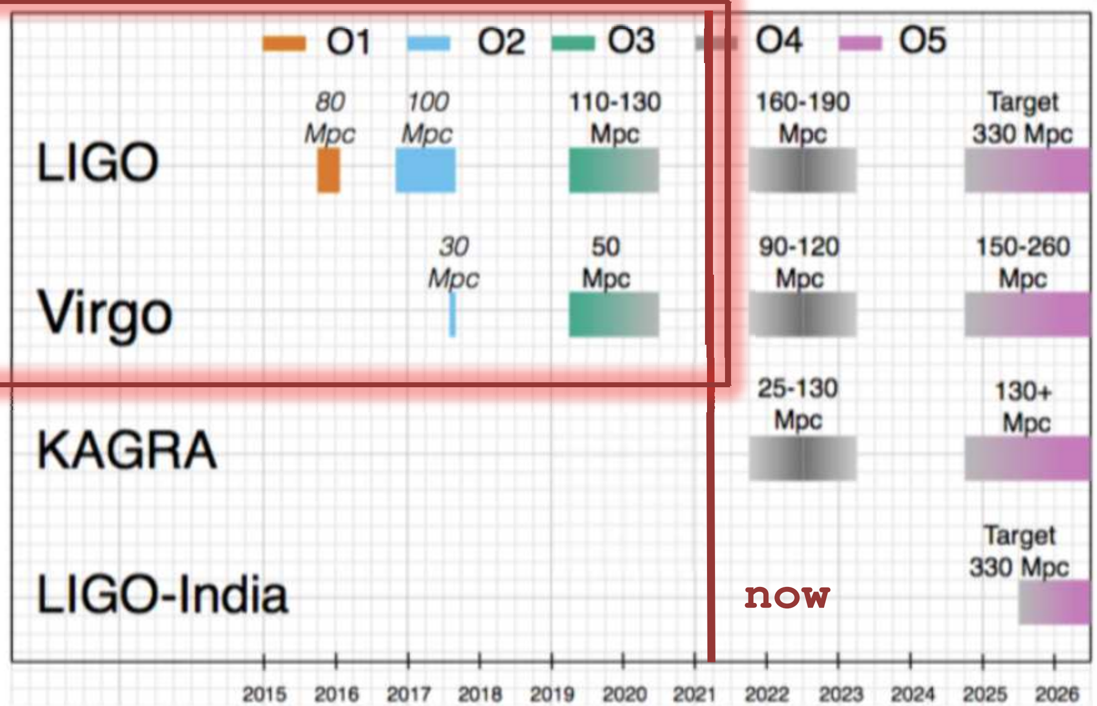
Third generation detectors: ET, Cosmic Explorer

Global network of GW detectors: joint observational runs



Abbott, B.P. et al. "Prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo and KAGRA". Living Rev Relativ 23, 3 (2020)

Global net-work of GW detectors: joint observational runs



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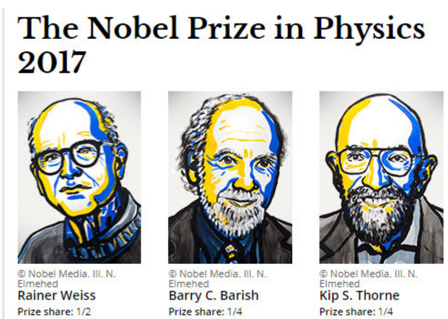
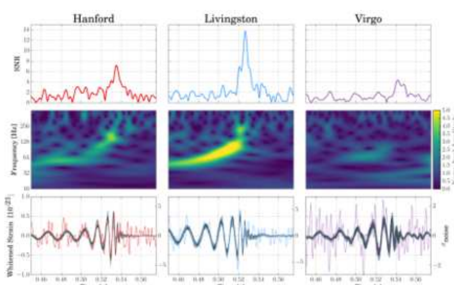
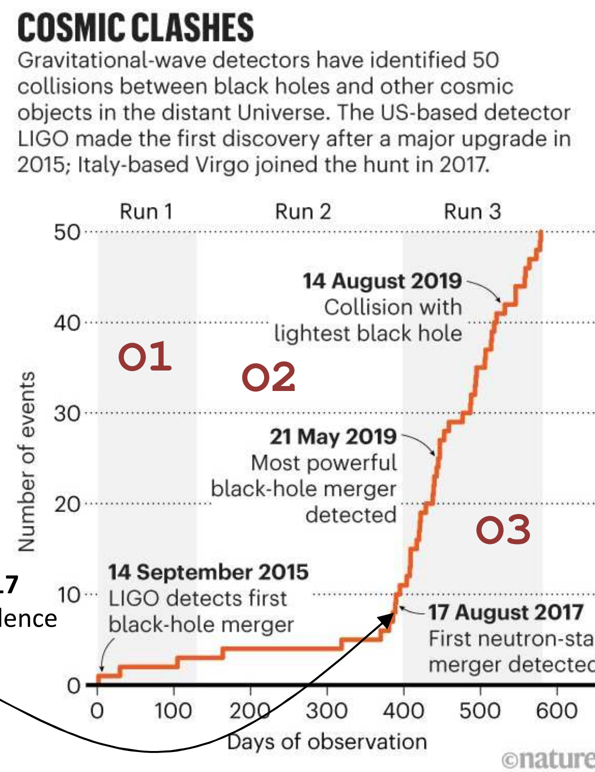
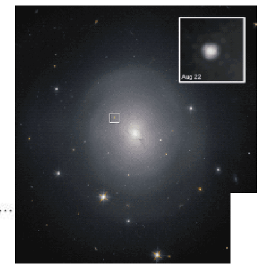
Global network of GW detectors: joint observational runs



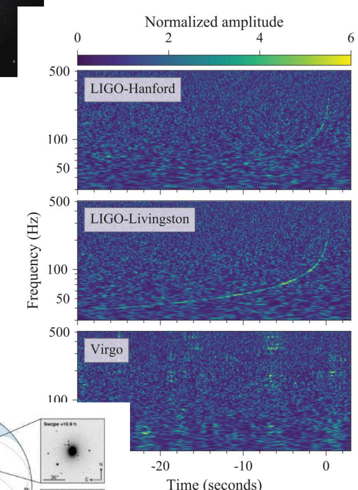


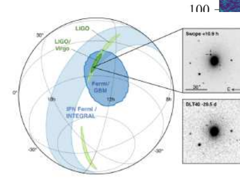
14 August 2017
First triple coincidence
LIGO/Virgo



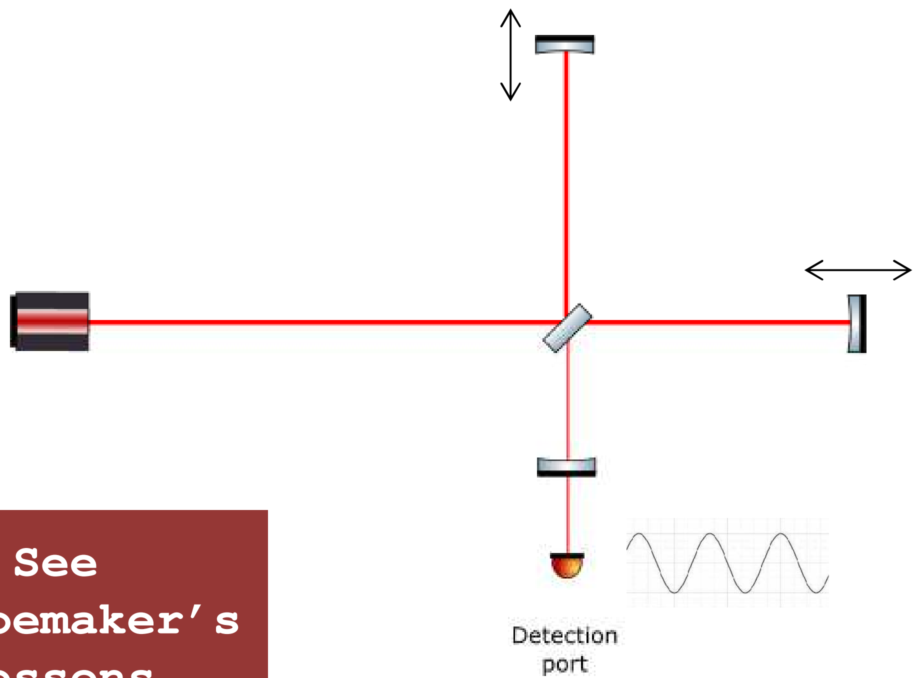


Electromagnetic followup





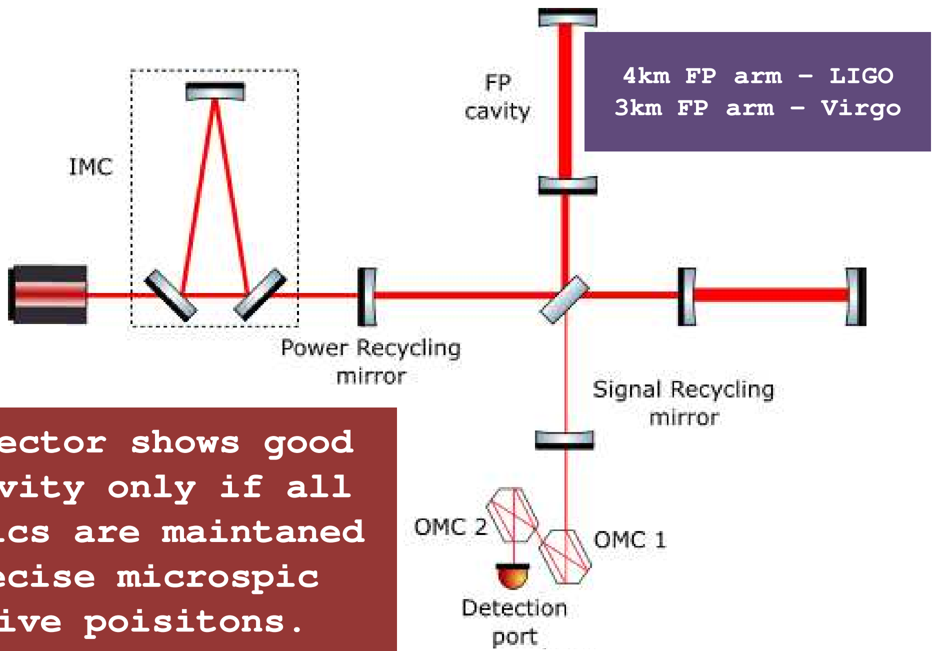
How these detectors work?



The detection principle is based on the Michelson working principle where the passage of a gravitational wave modify the interference condition at the detection port (dark fringe condition)

See D.Shoemaker's lessons

But, … it is more complex



The detector shows good sensitivity only if all the optics are maintaned at precise microspic relative poisitons. Called Working point – see later

Additional cavities are added to the detector in order to:

- Input Mode cleaner – to stabilize and clean the input laser beam
- Fabry-Perot cavities – to increase the optical path length
- PR cavity – to increase the circulating power
- SR cavity – to enanche the dark fringe signal
- OMCs to clean the output beam

Vacuum

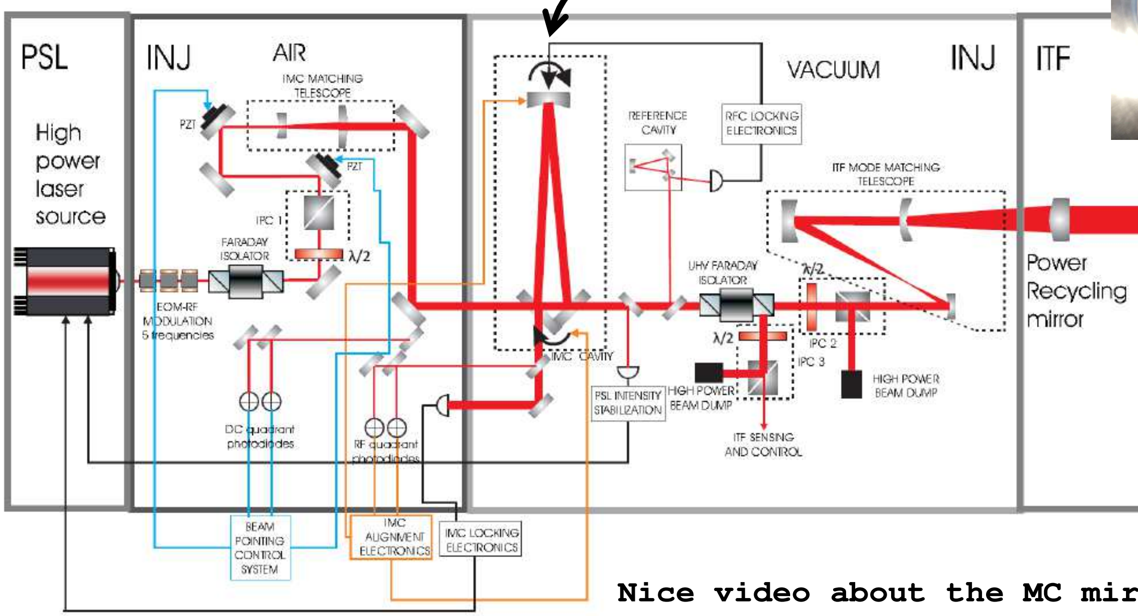
The residual gas noise is due to the interaction of the laser beam with the particles which creates fluctuation of the optical path length. To mitigate the residual gas noise the detector is maintaned in ultra-high vacuum (residual pressure 10^{-9} mbar).

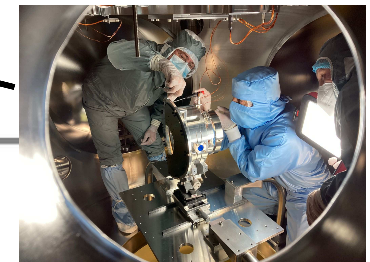
Virgo is the largest ultra-high vacuum in Europe, with a total volume of 6.800 m^3 .

LIGO is the largest worldwide ultra-high vacuum, with a total volume of 9000 m^3.

Injection: generation of laser beam to the interferometer

High power laser @1064nm P=125 W



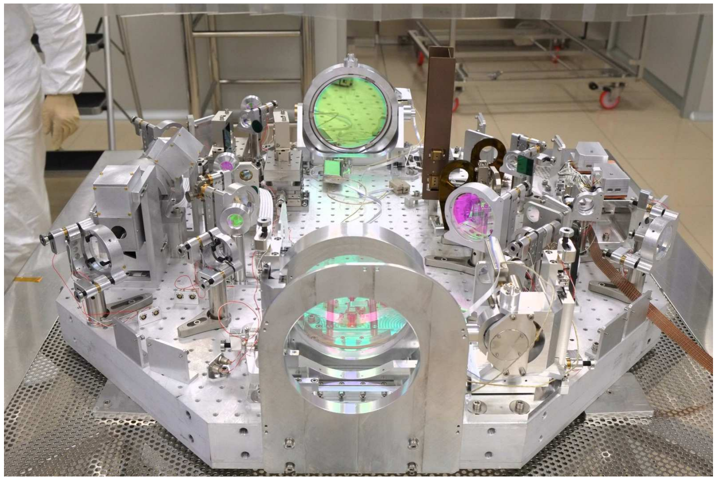


Installation of the Mode cleaner mirror

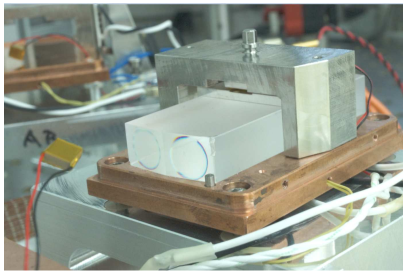
Nice video about the MC mirror installation

https://youtu.be/kYu1MCJHx-A

Detection



Detection bench



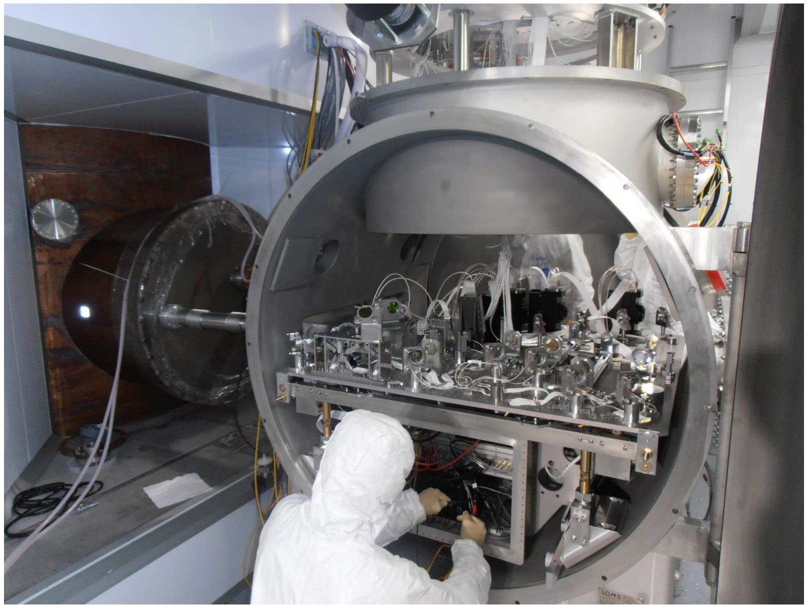
OMC

Mode Matching telescope: to re-size the beam coming from the Interferometer

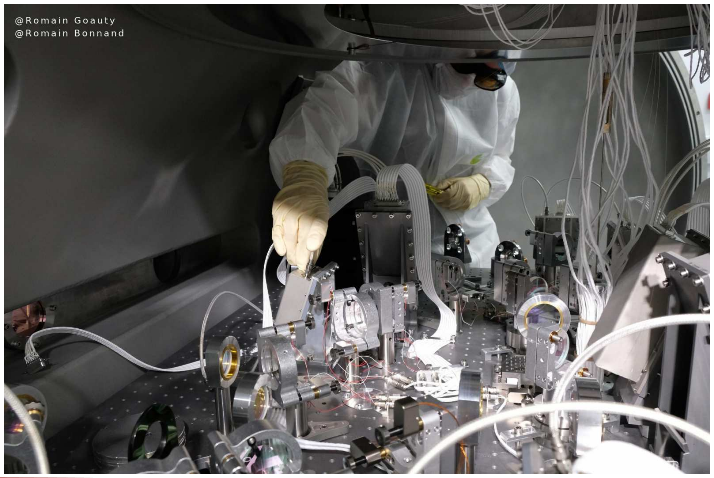
Output Mode cleaner: to clean the beam mode before detection

Dark fringe photo-detector: sensing detector for destuctrive interference fluctuation

Detection

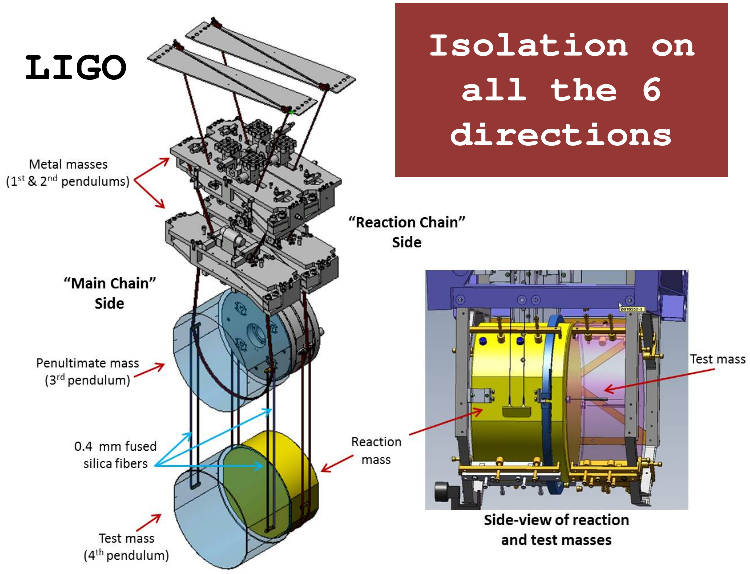


All the sensors, not only the main gravitational wave sensor, are kept suspended under vacuum to reduce the envinronmental noise that can spoil the signals

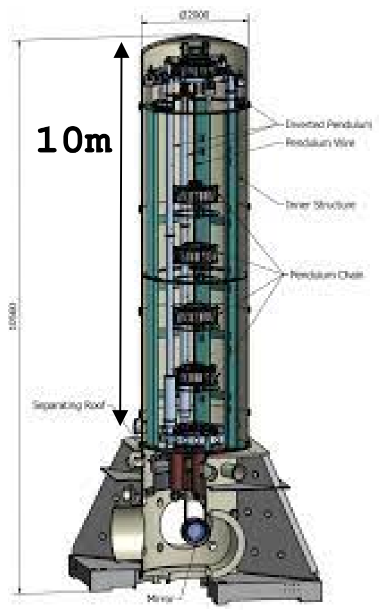


Suspensions

LIGO



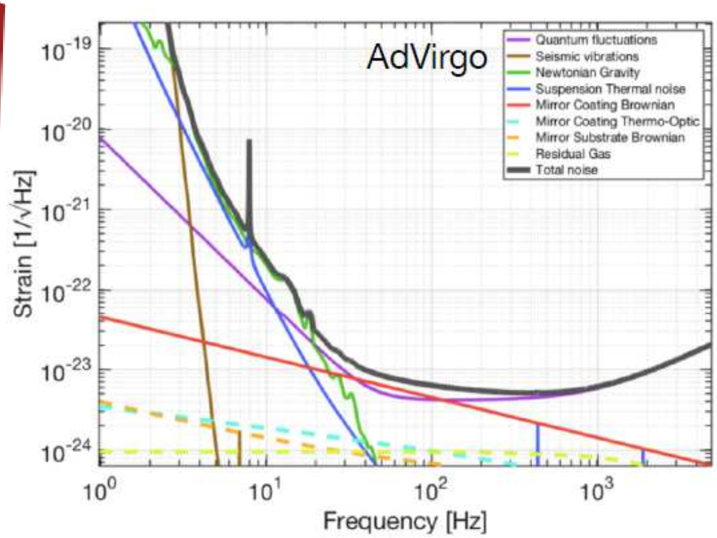
Isolation on all the 6 directions



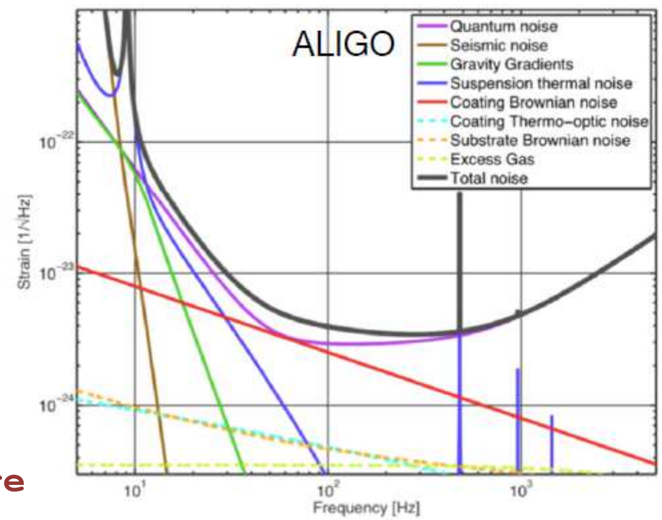
Virgo

You can see more in the EGO/Virgo virtual visit on Friday

Detectors sensitivity



Only fundamental noises are shown



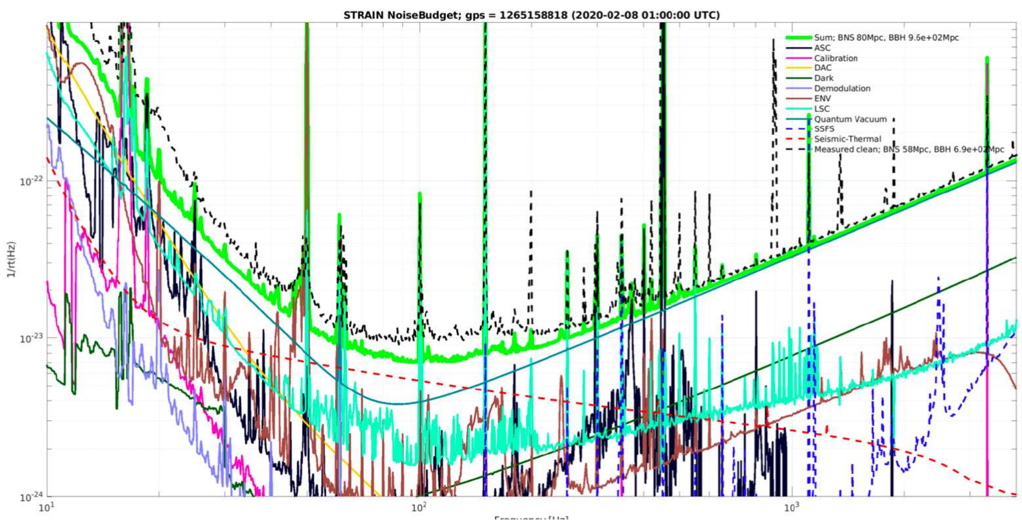
More in detail:

- Residual gas noise
- Seismic noise
- Newtonian noise
- Quantum noise
- Thermal noise

Technical noise sources

But not only the fundamental noises are important, the **Techincal noises** play an important role.

The techincal noises are mostly due to the fact that the position of the optics has to be actively controlled to keep the working point



Virgo online noise budget

Global working point

The detector provide good sensitivity only if all the main compontens are positioned in a very precise relative microscopic position. These relative positions are the so called longitudinal dofs

Operational conditions:
- Arm cavities on resonance
- Recycling cavities on resonance
- Michelson on destructive intereference

And
The mirrors aligned with respect to the beam (alignment working point)

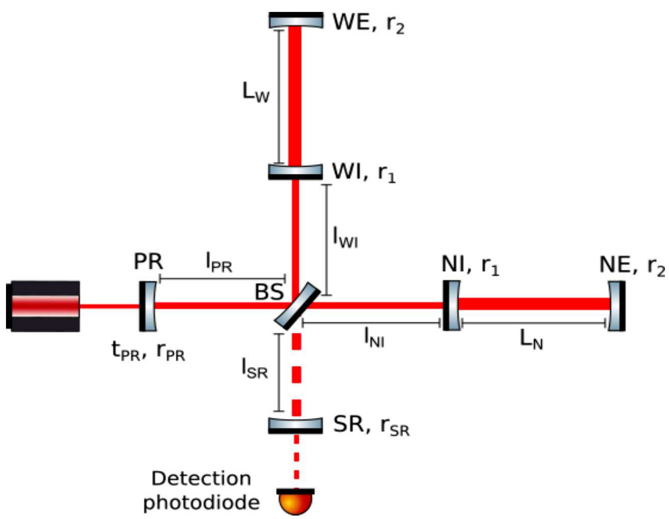
$$DARM = \frac{L_N - L_W}{2}$$

$$CARM = \frac{L_N + L_W}{2}$$

$$MICH = l_{NI} - l_{WI}$$

$$PRCL = l_{PR} + \frac{l_{NI} + l_{WI}}{2}$$

$$SRCL = l_{SR} + \frac{l_{NI} + l_{WI}}{2}$$



The working point has to be kept for long time to ensure high duty cycle for scientific data taking

What is a cavity and a cavity resonance?

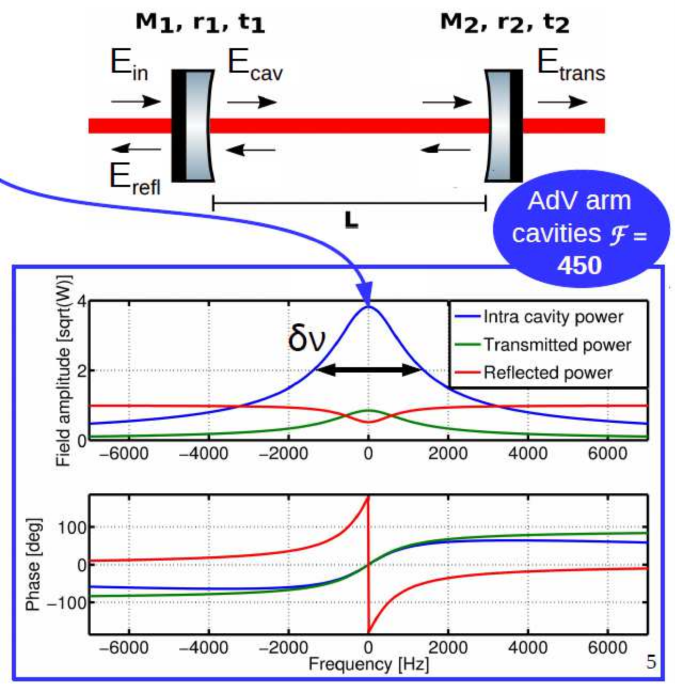
Optical resonator: allows light to circulate in a closed path.
When it is on resonance the optical path is a multiple of λ

Resonance: maximum power resonating inside the cavity

$$\delta\Phi \propto (\nu \cdot \delta L + L \cdot \delta\nu)$$

Finesse: it quantifies the quality factor of the cavity

$$P_{rec} / P_{in} \approx 2 \cdot F / \pi$$



J. Casanueva

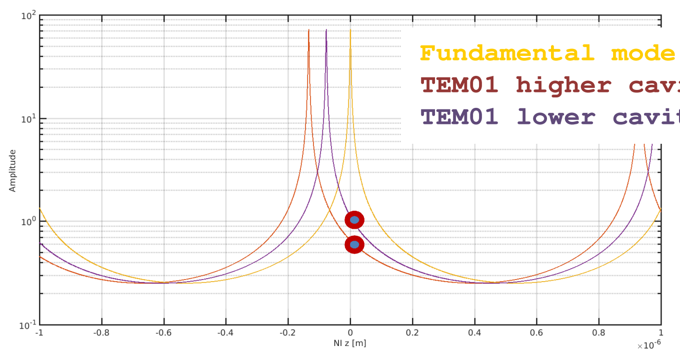
What is a stability of a cavity?

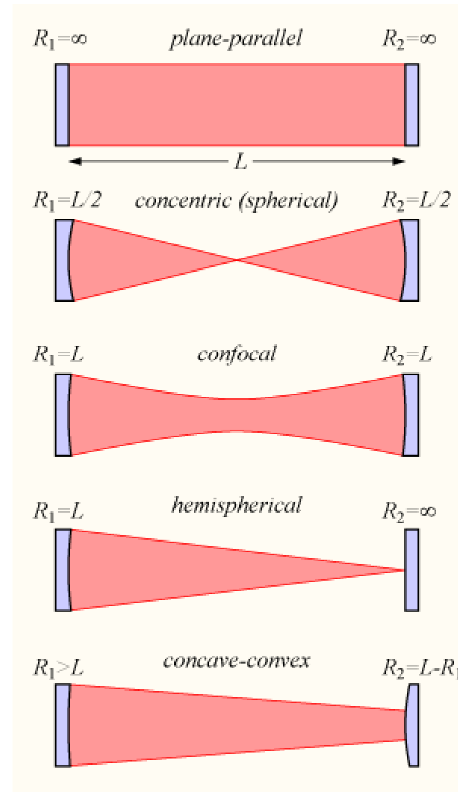
Only certain ranges of values for R_1, R_2, and L produce stable resonators in which periodic refocussing of the intracavity beam is produced(*) (STABLE CAVITY). If the cavity is unstable, the beam size will grow without limit, eventually growing larger than the size of the cavity mirrors and being lost.

$g_i = 1-L/R_i \quad 0<g_1g_2<1 \Rightarrow$ stable cavity

The stability of a cavity set also the capability of the cavity to “clean” the resonating beam from modes different from the fundamental mode.

The resonance position of the modes depends on the cavity parameters





(*) cit wikipedia

How to sense a cavity length deviation?

The beam is phase modulated creating *sidebands* around the carrier (ω_0) at $\pm$ the modulation frequency, Ω.

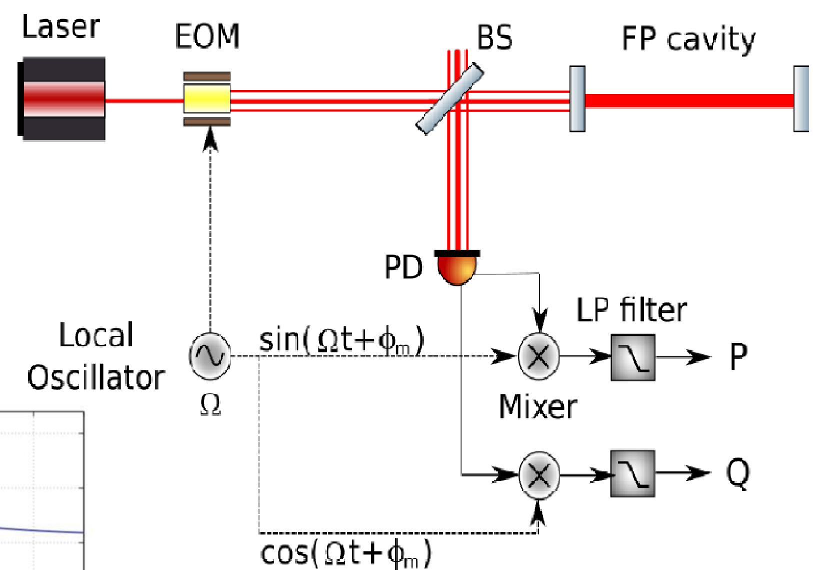
The Error signal (PDH) → *beat note between carrier and non-resonant sidebands*

The signal in reflected is demodulated to select the interesting term.

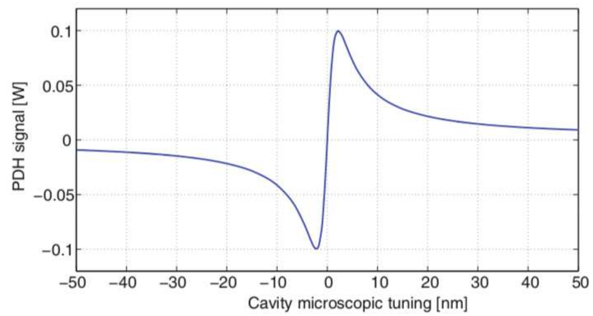
Two signals:

-in-phase (P)

-in-quadrature (Q)

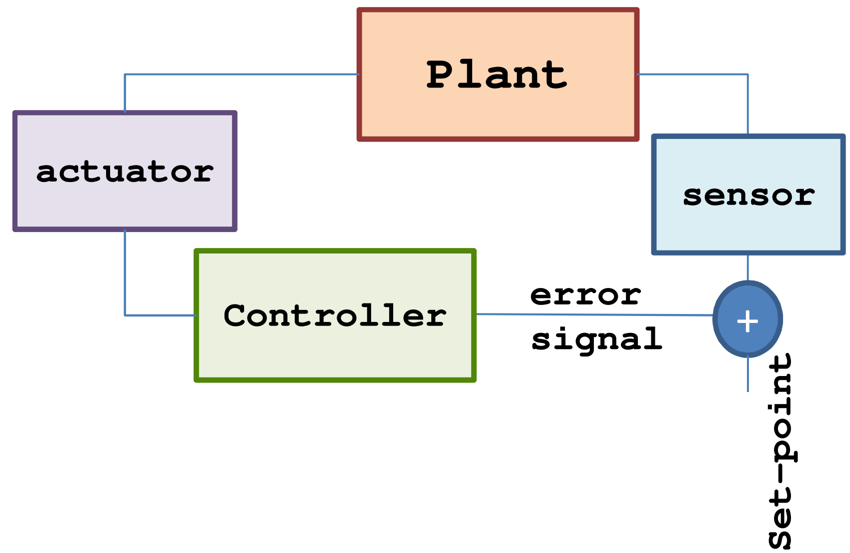


Example of Pound-Drever-Hall (PDH) signal



How to control a cavity length deviation?

The control is done implementing active feed-back which correct the length variation by acting on the mirror suspension.



Lock acquisition LIGO & Virgo

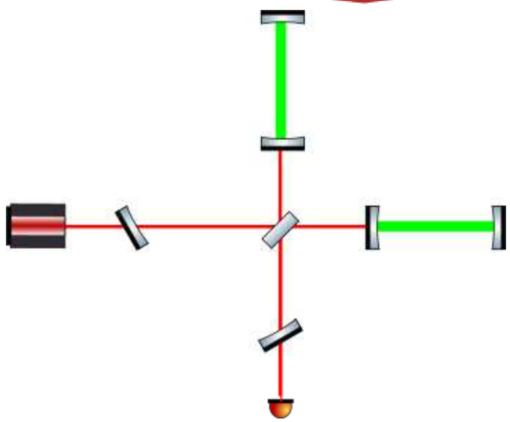
The lock of the whole system is not easy like the lock of a single cavity (more dofs to be taken into account and coupled cavities).
For this reason a procedure to bring the mirrors from un-controlled state to be controlled in the final working point has to be implemented. The so called lock acquisition.

Which is the trick?

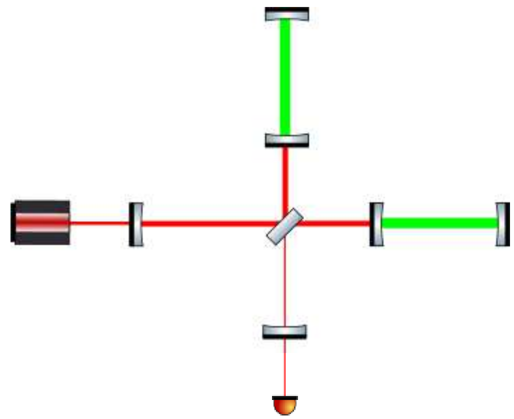
The trick is to start from a simple un-controlled configuration and then pass to more and more complex configurations (adding dofs to be controlled).

(*) D. Martynov, 'Lock Acquisition and Sensitivity Analysis of Advanced LIGO Interferometers', PhD, Cali-fornia Institute of Technology, Pasadena (2015)
(*) K. Izumi, S. Dwyer, L. Barsotti, 'Simulation Study for aLIGO Lock Acquisition', LIGO note, LIGO-T1400298-v1
(*) J. Casanueva, N. Leroy "Auxiliary Laser system: study of the lock acquisition strategy" Virgo note, https://tds.virgo-gw.eu/ql/?c=14154

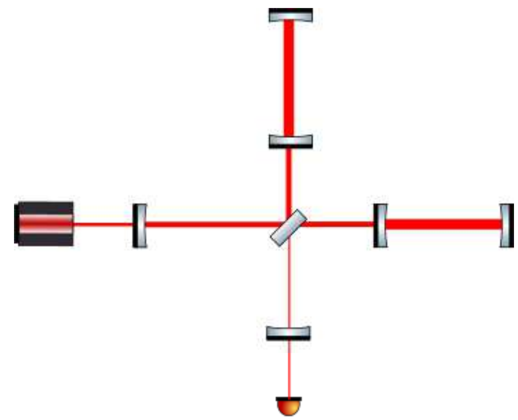
Lock acquisition LIGO & Virgo



Misalign the PR & SR mirror in order to have only the CARM and DARM dofs.
Lock DARM & CARM using an auxiliary laser (green beam).
2 dofs: DARM & CARM

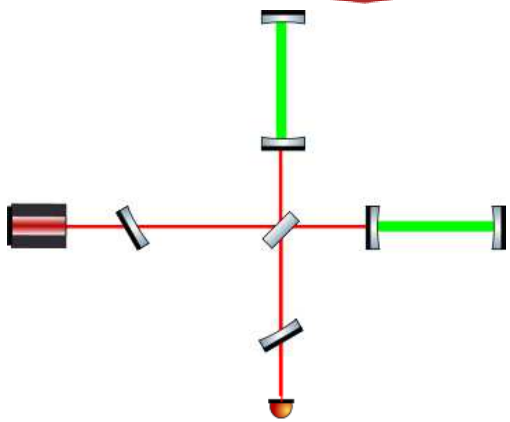


Move the resonance of the arms far from the IR resonance (Central ITF does not sees anymore the arm cavities). Realign the recycling mirrors and lock the central area dofs:
3 dofs: MICH, PRCL and SRCL



Bring back the resonance of the arms to the IR, having all the dofs controlled.
5 dofs: CARM, DARM, MICH, PRCL and SRCL

Lock acquisition LIGO & Virgo

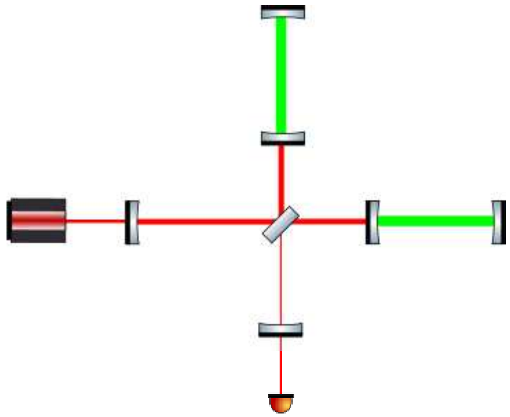


Misalign the PR & SR mirror in order to have only the CARM and DARM dofs.
Lock DARM & CARM using an auxiliary laser (green beam).
2 dofs: DARM & CARM

In this phase the opto-mechanical system is reduced to two single cavities.
The cavity is on resonance of a green laser (injected from the back side of the end mirrors).
The lenght of the cavity is controlled with the mirror actuators at low frequency to match the resonance of the green beam (below 10Hz) while at high frequency the frequency of the green laser is tuned to match the length of the cavity

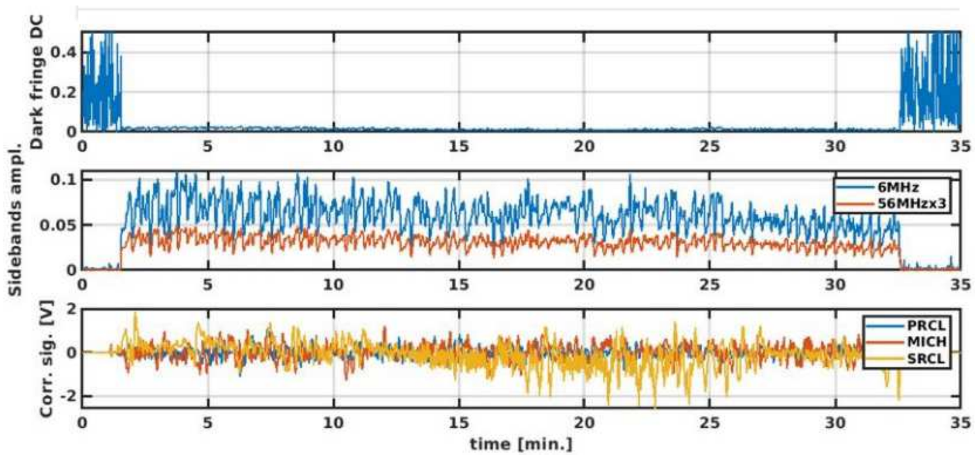
R. Bonnand

Lock acquisition LIGO & Virgo

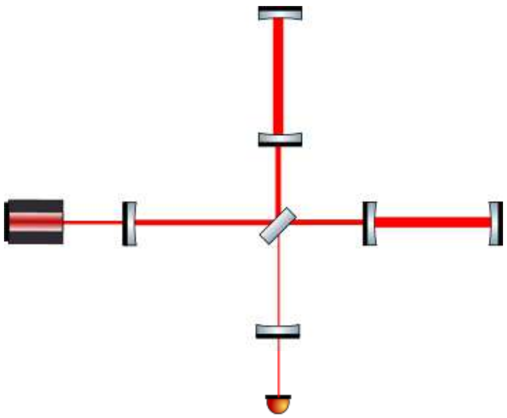


Move the resonance of the arms far from the IR resonance (Central ITF does not sees anymore the arm cavities). Realign the recycling mirrors and lock the central area dofs:
3 dofs: MICH, PRCL and SRCL

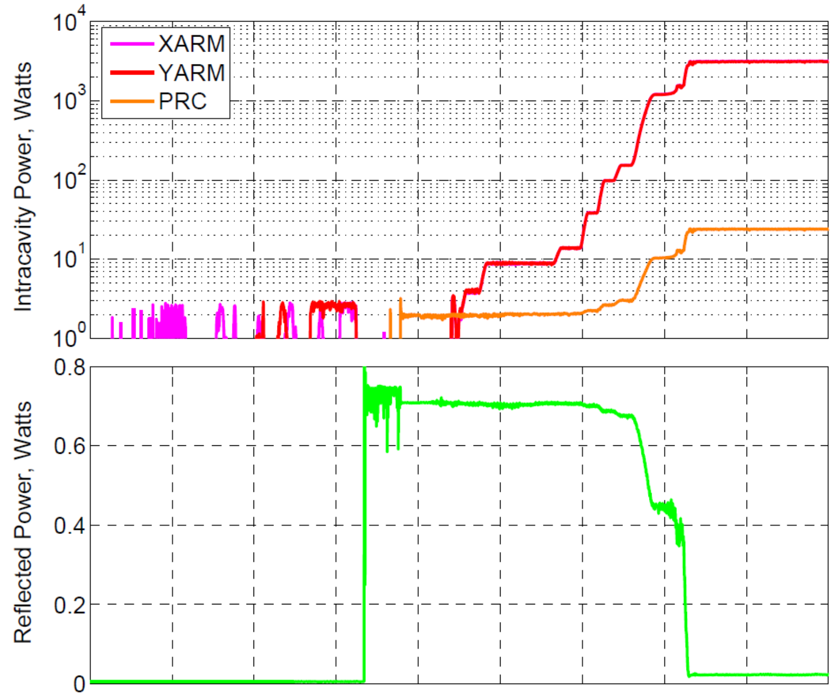
The arms, thanks to the green lock, are driven away from the resonance of the Infra-Red (the main laser). Then the opto-mechanical system is reduced only to the central area.
PRCL MICH and SRCL are locked simultaneusly.



Lock acquisition LIGO & Virgo



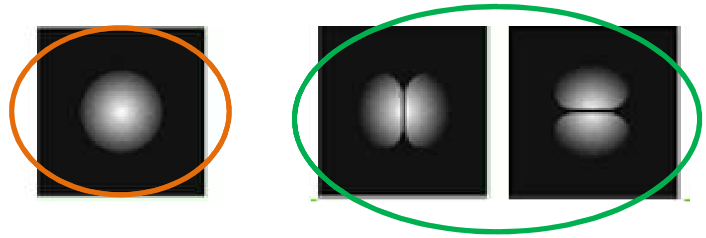
Bring back the resonance of the arms to the IR, having all the dofs controlled.
5 dofs: CARM, DARM, MICH, PRCL and SRCL

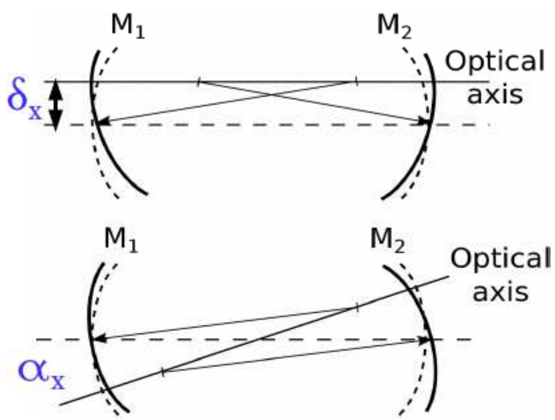


D. Martynov PhD thesis

Alignment in a cavity

When a misalignment in a cavity is present, the generation of Higher order modes (HOMs) occurs.





$$E(x+\delta_x) \approx A \cdot \left[H_0(x) + \frac{\delta_x}{w_0} \cdot H_1(x) \right]$$

$$E(x+\alpha_x) \approx A \cdot \left[H_0(x) + i \cdot \frac{\alpha_x}{\theta_d} \cdot H_1(x) \right]$$

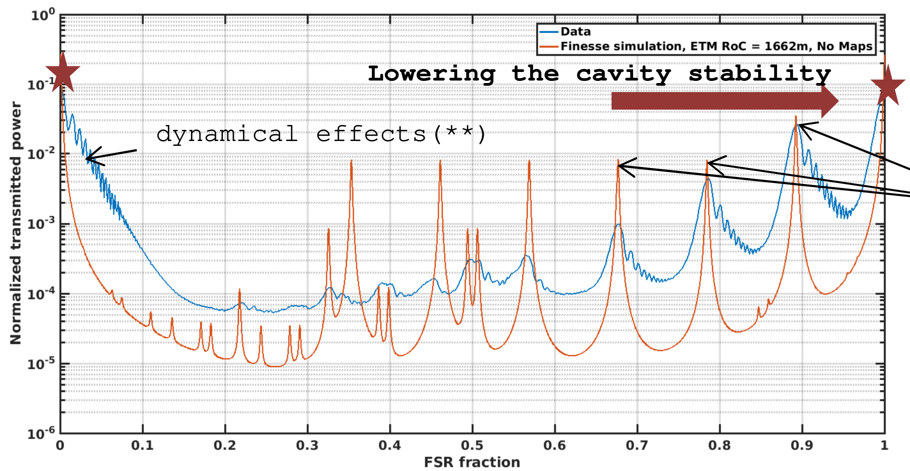
(*) D. Z. Anderson, "Alignment of resonant optical cavities", Appl. Opt. 23 (1984) 2944-2949.

What is the effect of a misalignment?

The main effect of a misalignment in a cavity(*) is:

- **Geometrical lenght variation** (the variation of cavity length due to the displacement of the cavity axis (easily recoverable with the longitudinal lock)
- **Power loss** due to the generation of HOMs (the cavity does not let circulate the HOMs, accordingly to finesse and cavity stability)
- strong modification of the longitudinal error signal (for low stability cavities)

A. Allocca Virgo logbook



★ Longitudinal working point

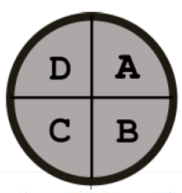
HOMs resonances, the frequency position depends on the cavity geometry. Lower is the stability closer their resonance will be with the TEM00 (fundamental mode)

(*) A.E. Siegman, "Lasers", University Science Books, Mill Valley, 1986.

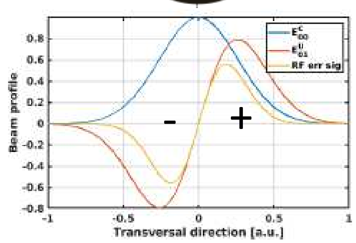
(**) D. Bersanetti, et.al. "New algorithm for the Guided Lock technique for a high-Finesse optical cavity". Astropart. Phys. 117, (2020)

How to sense misalignments?

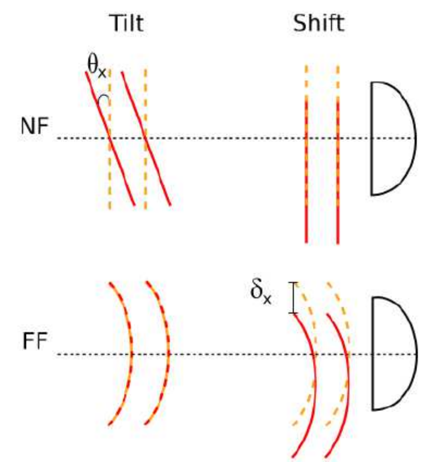
The sensing of a misalignment can be performed by taking advantage from the generation of the TEM 01/10 itself, by using a quadrant split photo-detector. Analogously to the longitudinal error signal, the alignment error signal comes from the beating of the 00 of the carrier and the 01 of the sidebands and viceversa(*)



$$S_{hor} = (A+B)-(D+C)$$
$$S_{ver} = (A+D)-(C+B)$$



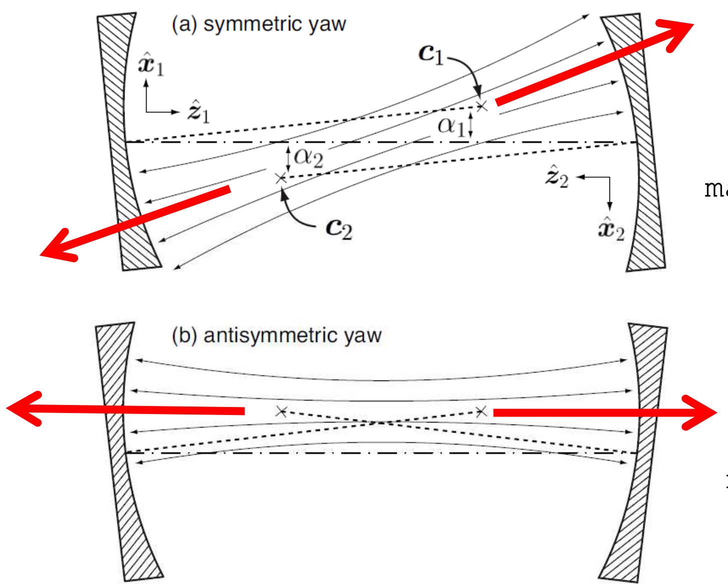
In order to disantangle the tilt and the shift of the cavity axis two QPDs will be used to image two different position of the cavity axis (Near field i.e. The waist positon, and the Far field)



(*) E.Morrison, B.J.Meers, D.I.Roberston, H.Ward "Automatic alignment of optical interferometers", Applied Optics Vol.33 No.22, 1994

Important effect for alignment: Sidle-Sigg radiation pressure effect

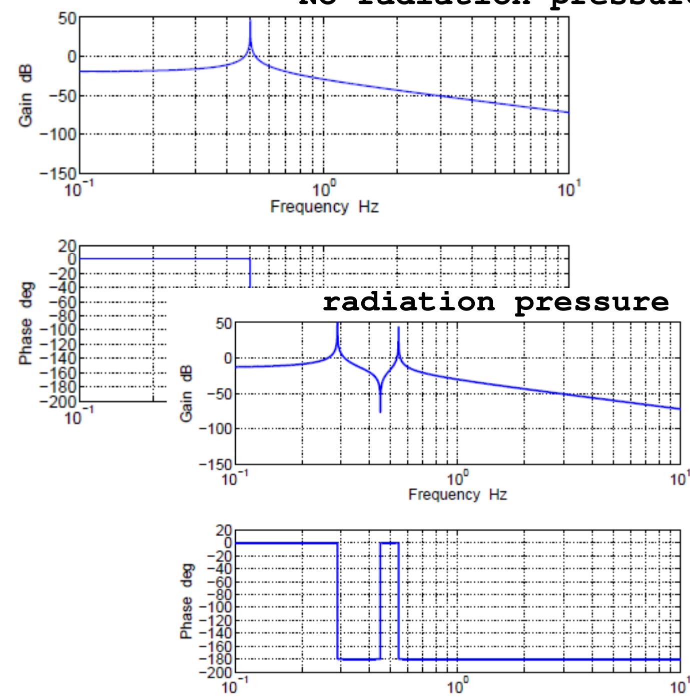
In a high power cavity the laser beam acts as a spring between the two mirrors (torsion pendula) modifying the overall opto-mechanical TF.



The laser beam apply a torque against the misalignment, making the system **harder** to be misaligned

The laser beam apply a torque towards the misalignment, making the system **softer** to be misaligned

No radiation pressure



(*) D. Sigg et al., Phys. Lett. A 354 3 (2006) 167-172.

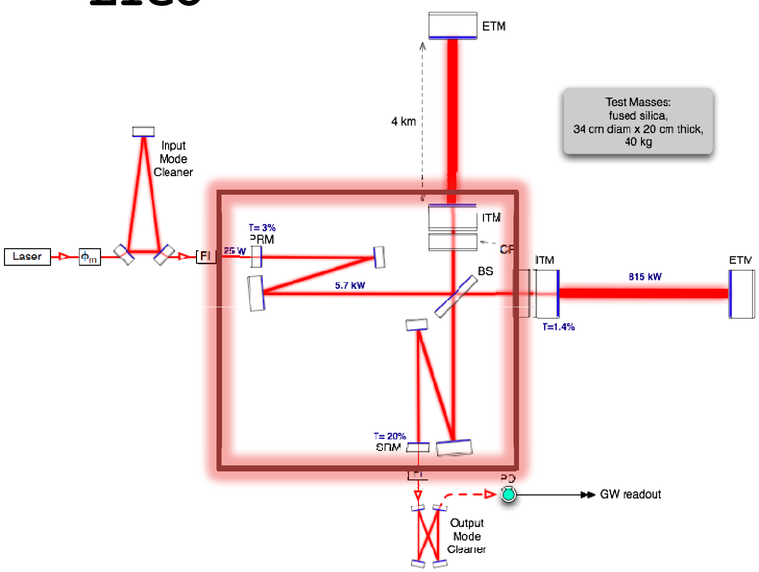
Other defects that can spoil the ITF performances

The alignment is not the only defect in the spoils the interferometer perfomances.

Cold defects: all the deviations from ideal optical configuration due to lack of accuracy in the manufacture (different radius of curvatures for mirrors, etc...)
Thermal effects: all the modifications to the optical configuration due to the heat produced by the high amount of circulating power.

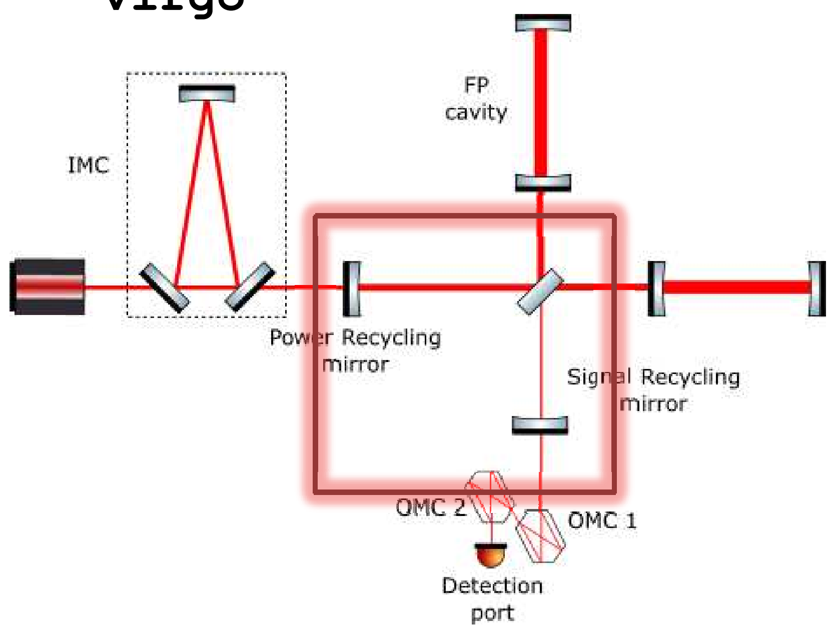
LIGO vs Virgo

LIGO



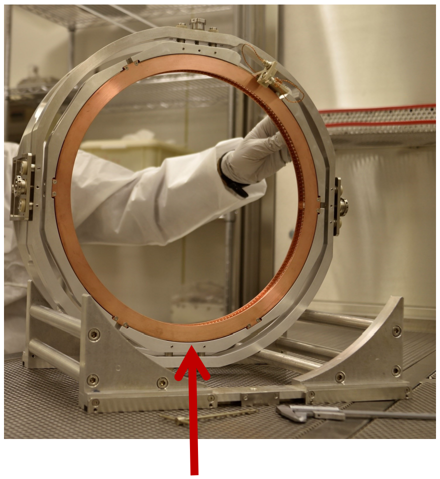
LIGO has much longer recycling cavities to have STABLE recycling cavities (which can filter out the HOMs generated by the defects).

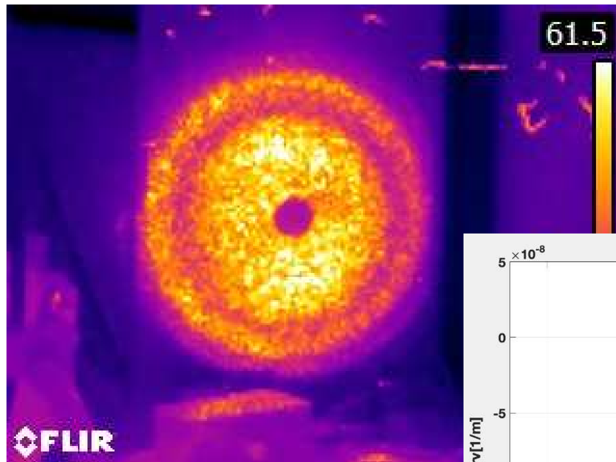
Virgo



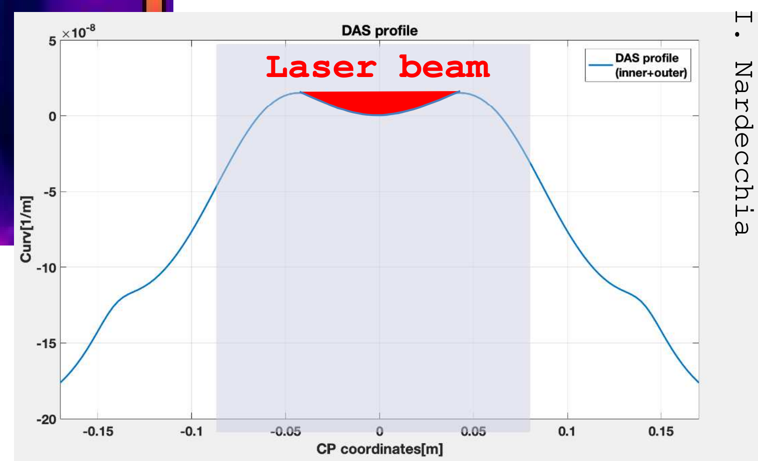
Virgo shorter recycling cavities, nearly unstable (called marginally stable cavities). The HOMs are circulating together with the fundamental mode. Defects have stronger impact

Cold/Hot defects compensation





The CO_2 laser heats the "mirror" where it is not heated by the laser beam



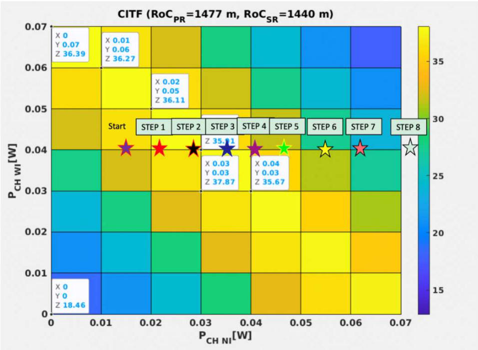
I. Nardecchia

The "Ring heater" is a copper ring that heat up the back face of the mirror to stretch it to change the RoC

A. Rocchi et al., "Thermal effects and their compensation in Advanced Virgo", Proceedings, 9th Edoardo Amaldi Conference on Gravitational Waves - Cardiff, United Kingdom, 2011,

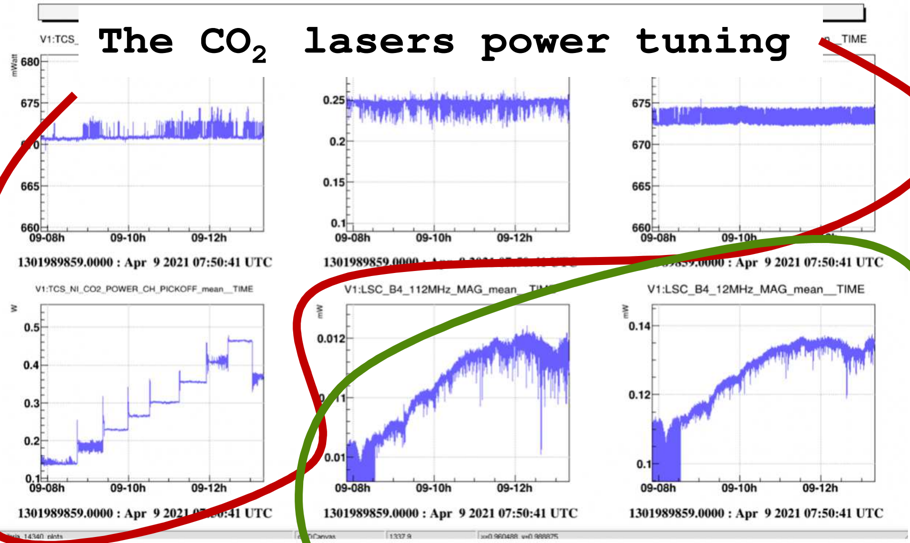
Tuning of the compensation system

Example of tuning of the thermal compensation system in Advanced Virgo+. As all for the "knobs" available to tune the interferometer parameters the initial tuning is done starting from simulation and the fine one is done directly on the machine



I. Nardecchia

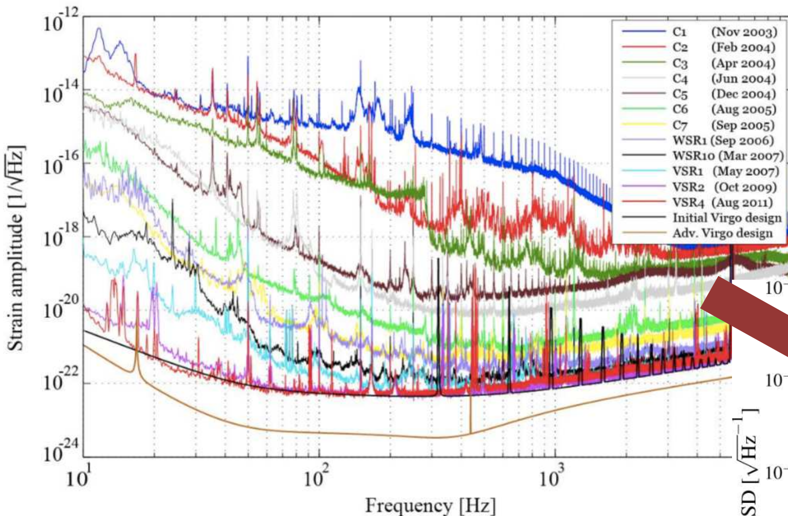
The CO_2 lasers power tuning



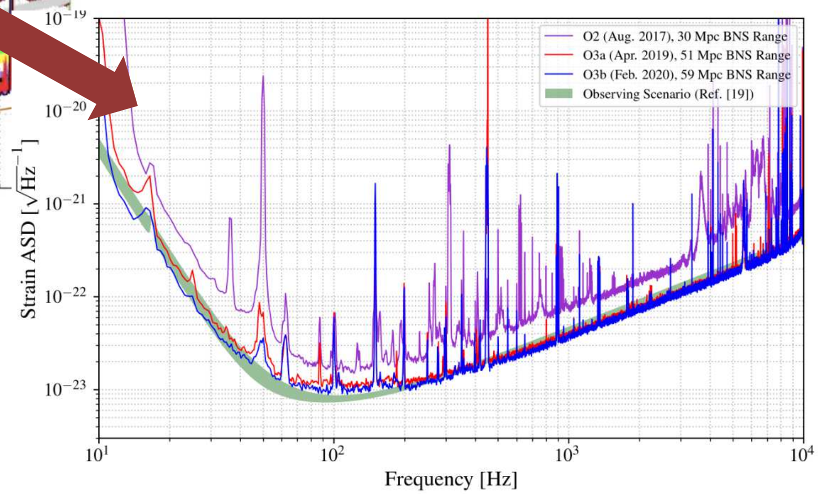
Sidebands power in the recycling cavities

https://logbook.virgo-gw.eu/virgo/?r=51373

Commissioning and sensitivity improvement



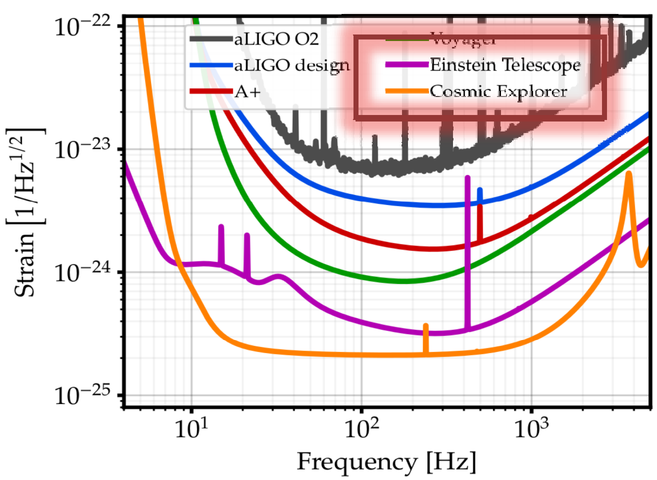
Commissioning is long... It took years to improve the sensitivity to be able to detect gravitational waves



What's next: 3g detectors

Improving the present 2g detectors: see R. Flaminio presentation

And then…



- **Einstein Telescope:** 10 km, xylophone configuration, cryogenic, underground.
- **Cosmic Explorer:** LIGO scaled to 40 km

See A. Freise presentation

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- D. Sigg et al., Phys. Lett. A 354 3 (2006) 167-172.


Questions?

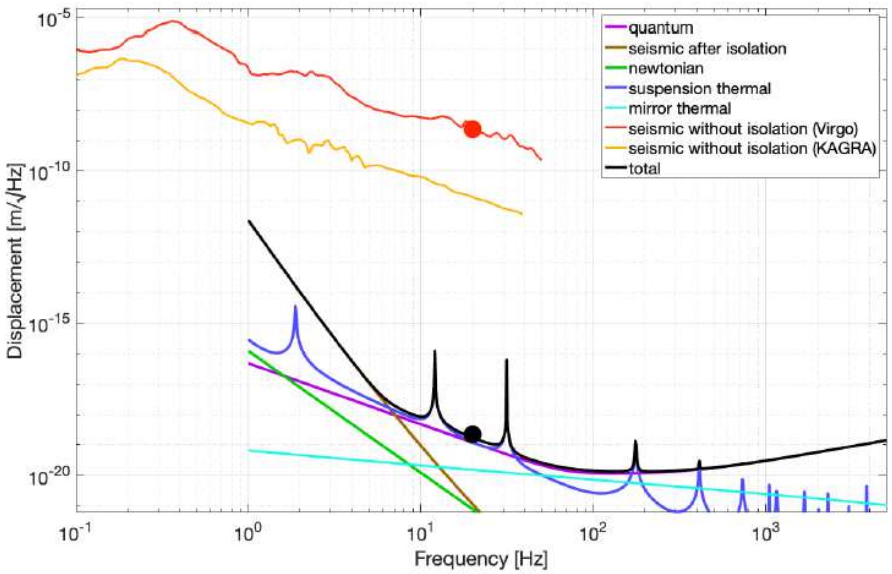
Residual gas noise: Vacuum

The residual gas noise is due to the interaction of the laser beam with the particles which creates fluctuation of the optical path length. To mitigate the residual gas noise the detector is maintaned in ultra-high vacuum (residual pressure 10^{-9} mbar).

Virgo is the largest ultra-high vacuum in Europe, with a total volume of 6.800 m^3 .

LIGO is the largest worldwide ultra-high vacuum, with a total volume of 9000 m^3.

Seismic noise



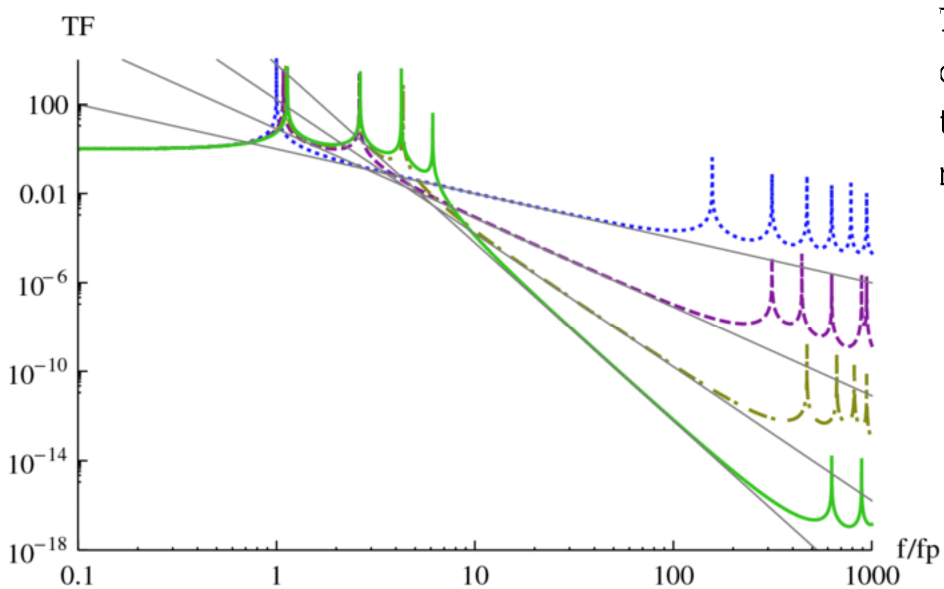
E. Capocasa "Introduction to LIGO/Virgo detectors (Open data workshop #4)"
https://tds.virgo-gw.eu/ql/?c=16743

The seismic natural motion of the optics (due to ground motion) would be at 10Hz ~ 10−9 m/√Hz.

In order to achieve the required sensitivity the seismic noise has to be suppressed more than 10 orders of magnitude.

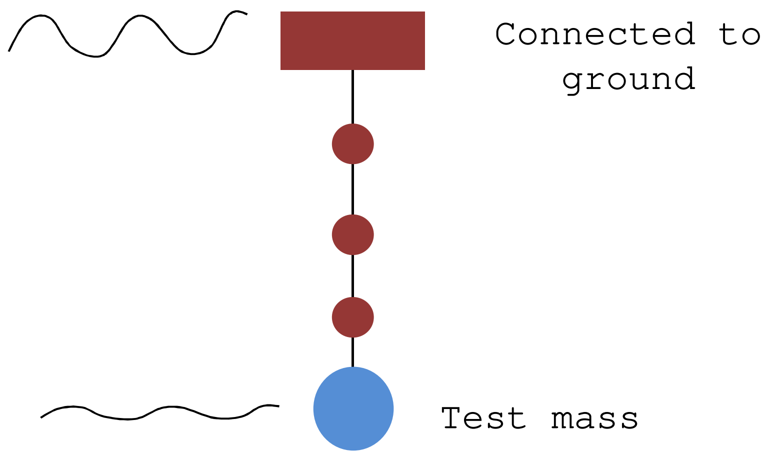
The mirrors have to be suspended

Seismic noise: suspensions



https://doi.org/10.1063/1.3652857

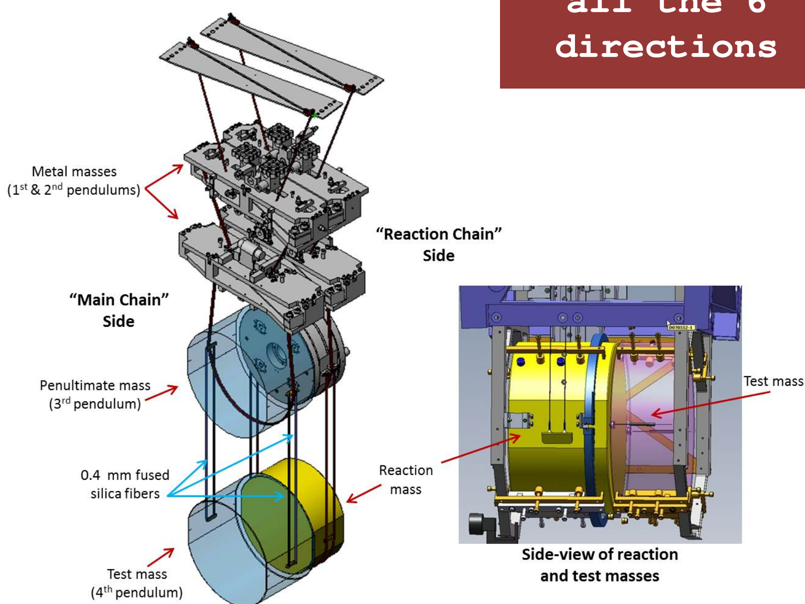
The mirrors are suspended by a chain of pendula to isolate the test mass from the seismic noise of their suspension point



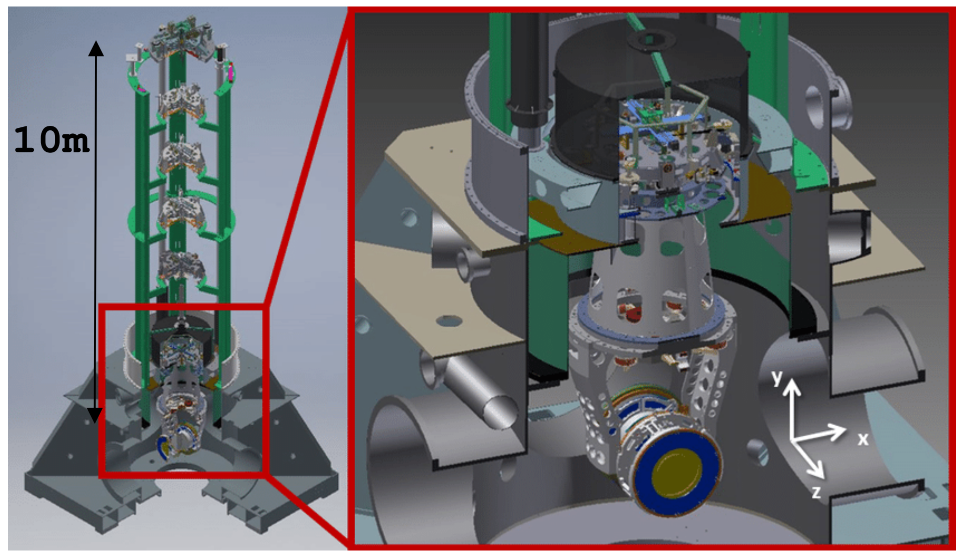
Suspensions in LIGO & Virgo

Isolation on all the 6 directions

LIGO



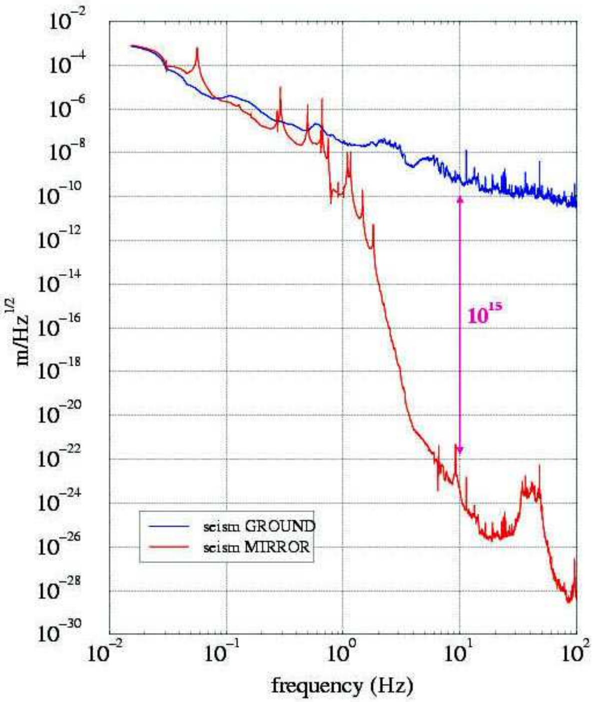
Side-view of reaction and test masses



Virgo

Silica fibers are used for the last stage suspension to reduce pendulum thermal noise

Seismic noise suppression Virgo



Newtoninan noise

The Newtonian noise can not be mitigated by the mirror suspensions since it couples directly to the mirrors.

It is mainly due to the density perturbation in the ground or in the atmosphere

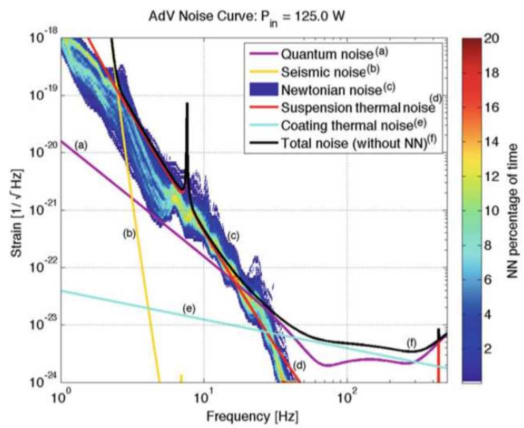
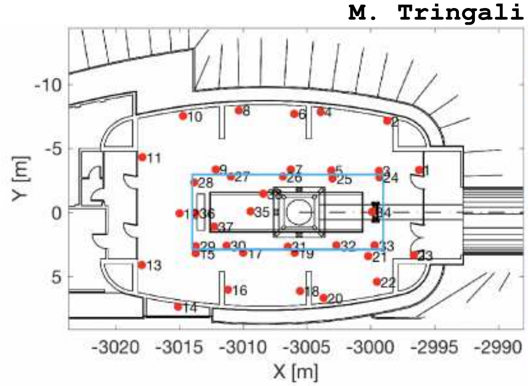


Fig. 13.6 Newtonian noise estimated in [38] for the Advanced Virgo detector. Estimation is based on formula 13.3 and on one week of seismic data taking; in the figure it is indicated the amount of time spent in each level of noise amplitude spectral density

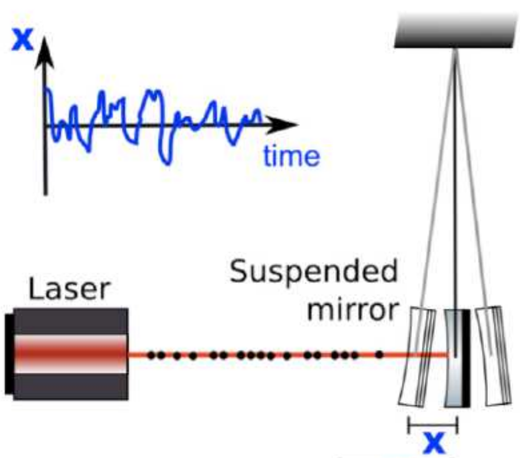
M. Tringali https://arxiv.org/abs/1912.08619



Subtraction of seismic signals from detector data by using an array of seismic sensors installed close to the test masses

Quantum vacuum noise

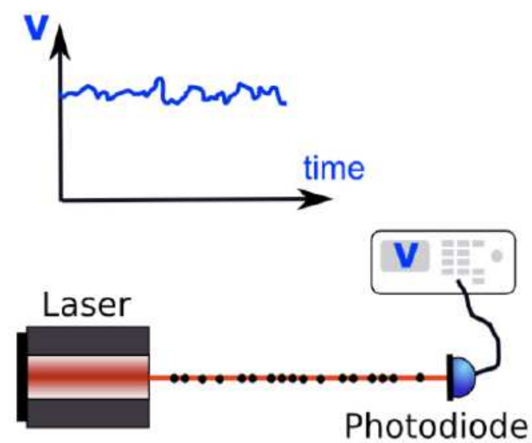
Radiation pressure noise



$$h_{rp}(f) = \frac{1}{mf^2L}\sqrt{\frac{\hbar P}{2\pi^3 c\lambda}}$$

P: laser power

Shot noise

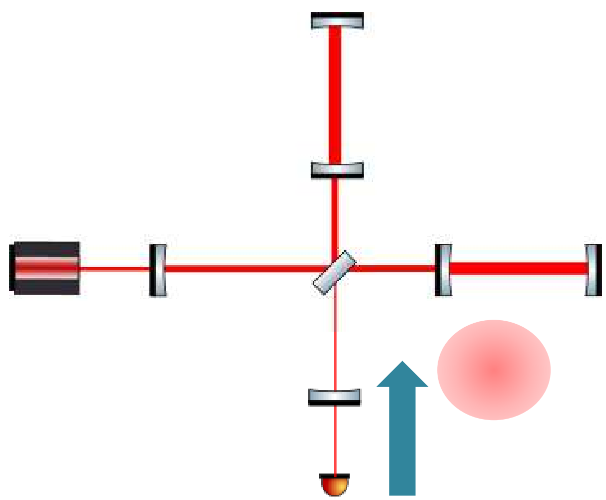


$$h_{sn}(f) = \frac{1}{L}\sqrt{\frac{\hbar c\lambda}{2\pi P}}$$

The photons in a laser beam are not uniformly distributed, but follow Poissonian statistics

M. Vardaro https://tds.virgo-gw.eu/ql/?c=14766

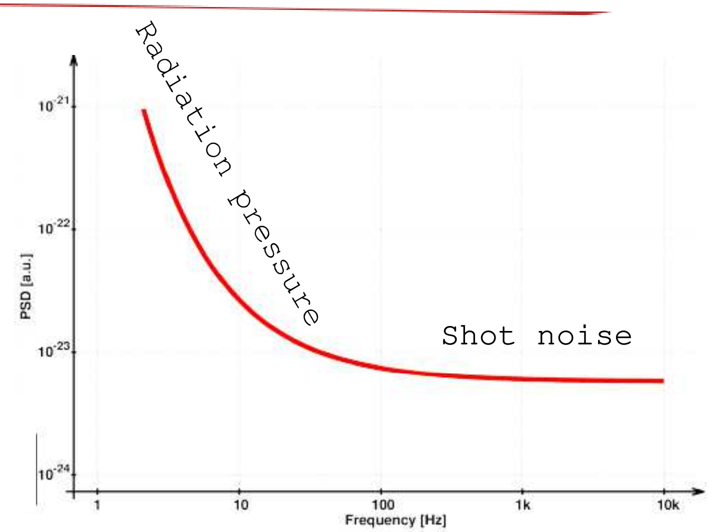
Quantum vacuum noise



Quantum vacuum noise enters trough the dark port.

Vacuum quantum noise is related to the zero-point fluctuations of the electric field in the vacuum state. Such fluctuations exist even though the vacuum state has a photon number of zero.

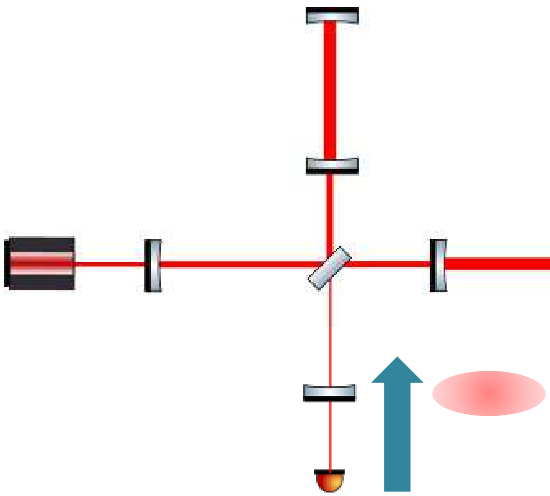
C.Caves "Quantum-mechanical noise in an interferometer" Phys. Rev. D 23 (1981)



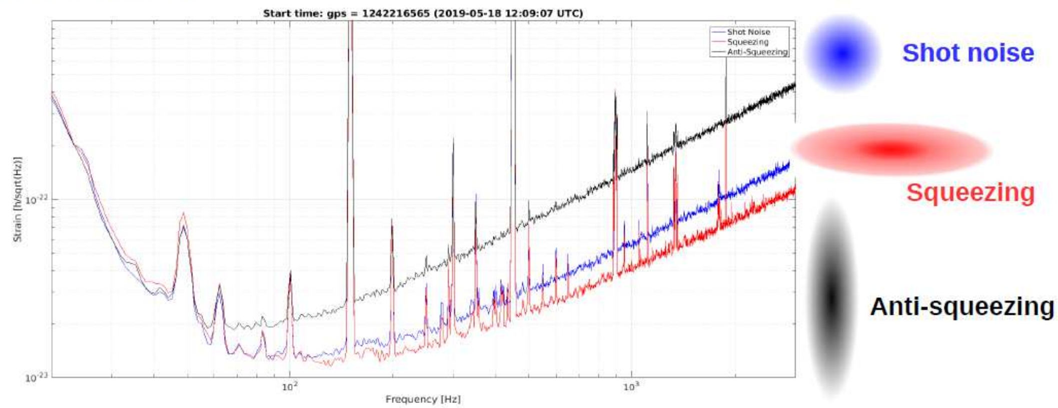
How to mitigate?

By injecting squeezed ligth

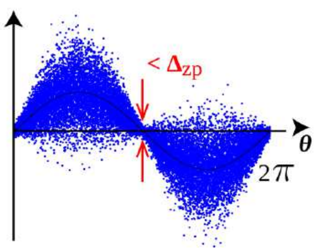
Quantum noise: squeezing



Virgo sensitivity



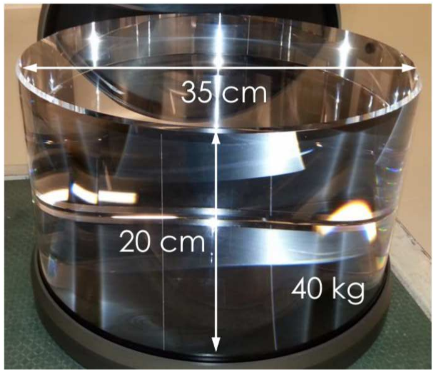
M. Vardaro



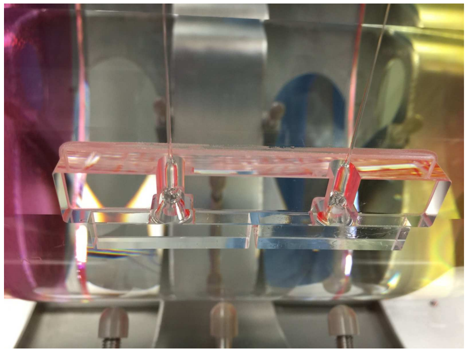
The uncertainty area is the same of coherent states but the noise in one quadrature is decreased whereas the one in the other is increased

Thermal noise

The **thermal noise** affecting gravitational wave interferometers has two different origins. The first one is due to dissipation in the wires used to suspend the test masses; this is the so called **suspension thermal noise.** The second one is due to dissipation processes inside the test masses themselves, the so-called **mirror thermal noise.**



Substrate: fused silica
Coatings: Multilayers of titania-doped tantala/silica (TiO_2-doped Ta_2O_5/SiO_2)
Ultralow absorption (<0.5 ppm)



Last stage of suspension made of silicon fibers