Istituto Nazionale di Fisica Nucleare
Sezione di PISA

Seismic noise filtering: the Advanced VIRGO Superattenuator

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APPEC Technology Forum 2018

Veldhoven (The Netherlands) - November 12, 2018

Gravitational Waves

- **Gravitational Waves (GW) detection** represents the most important achievement in scientific research of the last years (**GW170814** & **GW170817**): this has been possible thanks to the technological progress available in many fields and implemented into interferometric detectors developed to observe a so weak signal;
- The aim of modern detectors (2nd generation ground based interferometric detectors ITF – Advanced VIRGO, aLIGO, KAGRA) is the direct observation of GW together with the possibility to localize their source in the sky (detectors Network);
- According to the **Einstein's** theory (General Relativity), **GW** are perturbations of the "space-time" metric traveling in the Universe at the speed of light due to the acceleration of large masses.

Filtering Seismic Noise

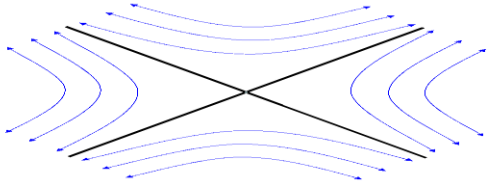
- Gravitational Waves (GW) detection with ground based interferometers depends on the capability to include into the experimental apparatus free falling masses, **the test masses**, well isolated from different noise sources the influence of which has great relevance on the detector sensitivity all over the detection bandwidth;
- **Seismic noise** gives the most important contribution in the low frequency range where GW emitted by Black Holes, Pulsars and Coalescing Binaries are expected:

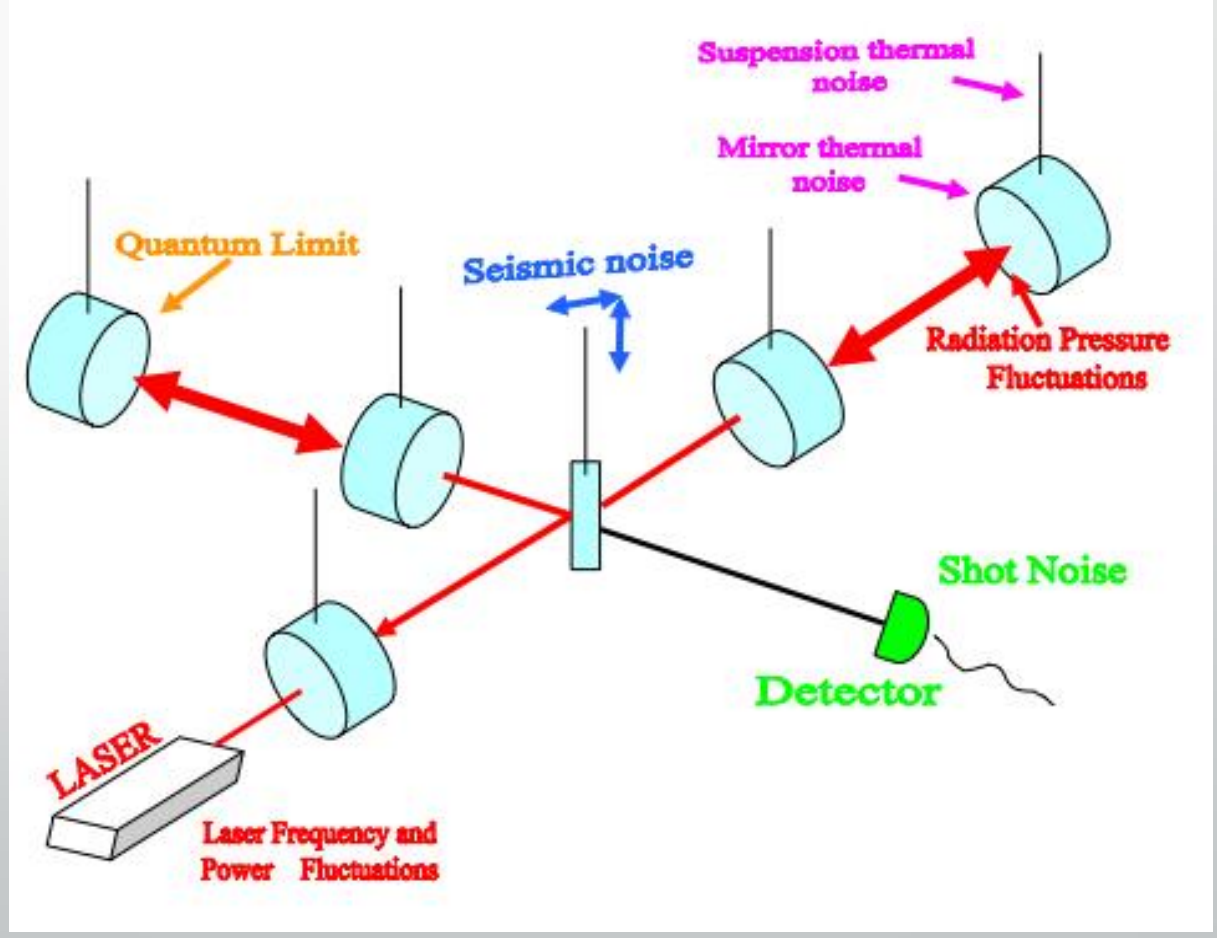
  - **VIRGO** and **AdV** have been equipped with a mirror suspension system conceived to reduce seismic noise transmission at the optical level extending the detection band below 100 Hz.

The broad band GW Interferometers

- The detector is sensitive to **h** the Gravitational Wave strain amplitude (a GW impinging on the plane of a suspended interferometer **stretches** one arm **compressing** the other one alternatively);
- The detector sensitivity is expressed in terms of the amplitude spectral density of the detector noise referred to its input

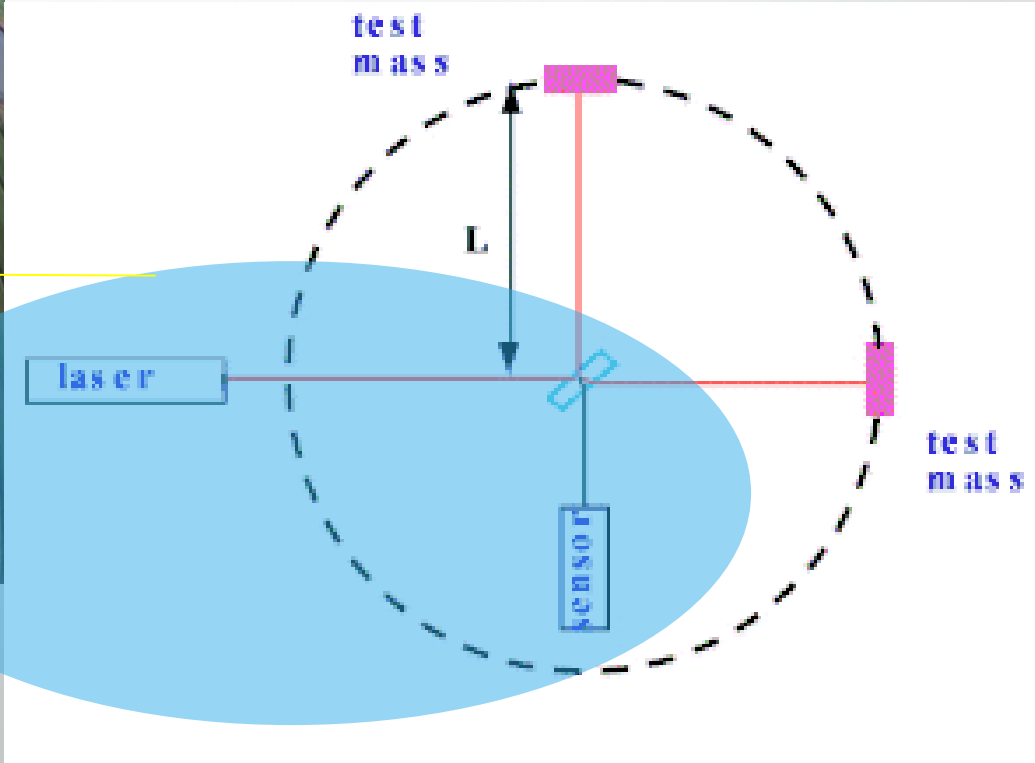
  H(f) $[(Hz)^{-1/2}]$





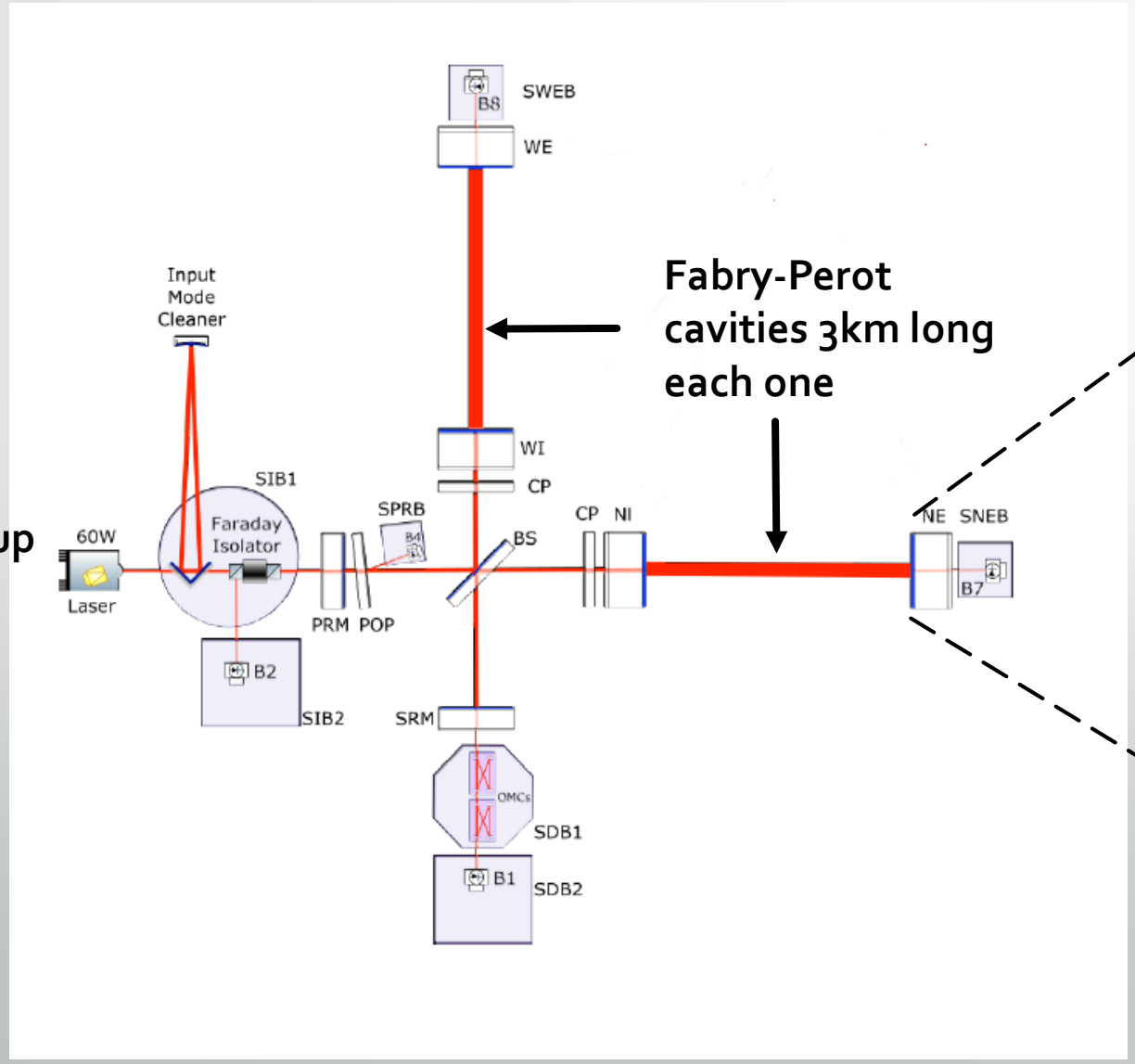
The Advanced VIRGO ITF @ EGO Site

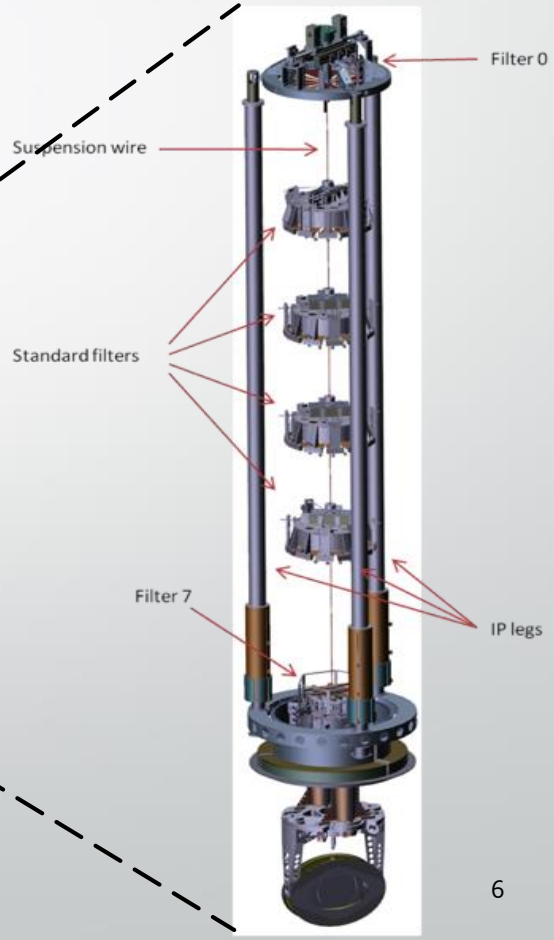
GW impinging on a suspended ITF



The Advanced VIRGO optical layout

High power laser source (up to 125 W with λ= 1064 nm)





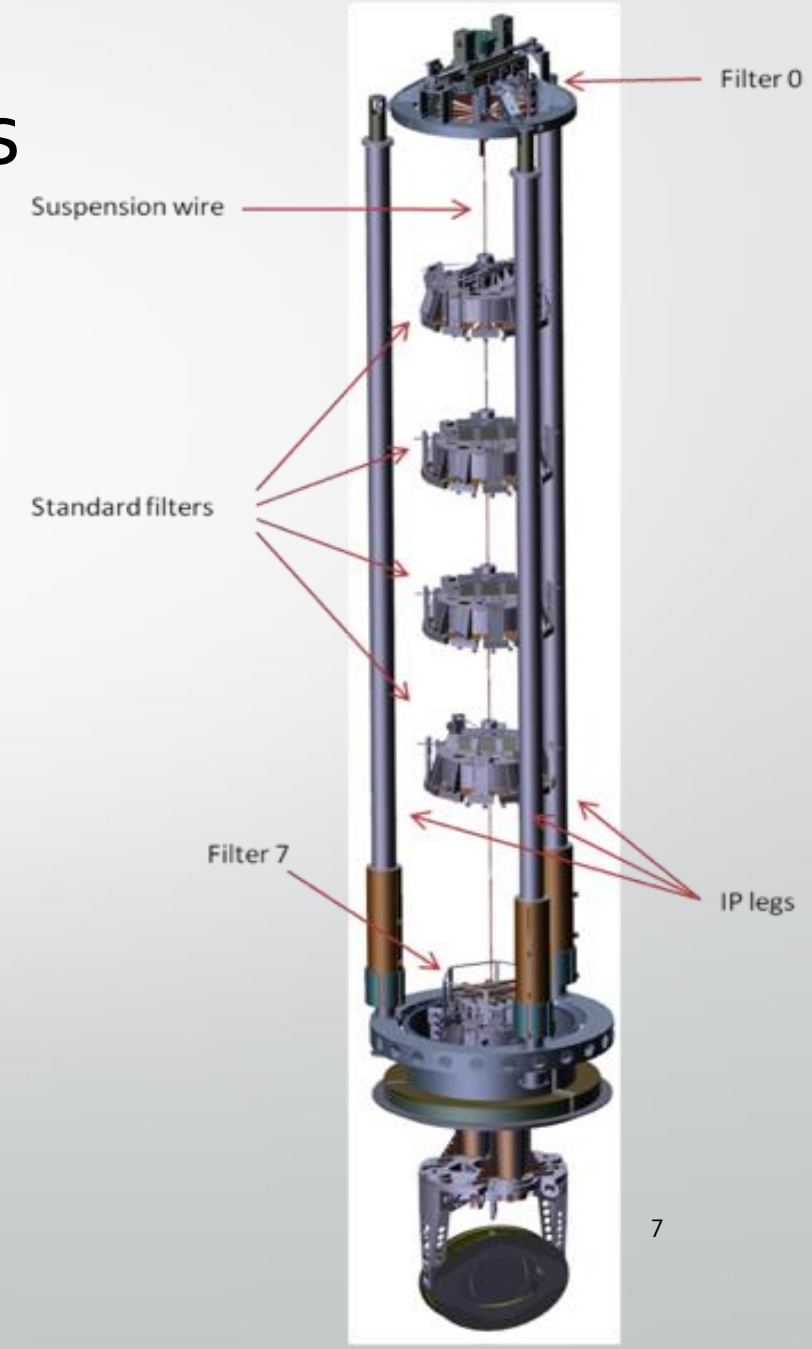
Mirror Suspensions

- The The **Super-Attenuator** (**SA**) is the mechanical system adopted to isolate the optical components from seismic noise and local disturbances. It is based on the working principle of a **multistage pendulum** and consists of:

  - a three legs Inverted Pendulum (IP)

  - 6 or 3 mechanical Seismic Filters (SF) with magnetic anti-spring (MAS)

  - a Monolithic Payload or Last Stage (LS)



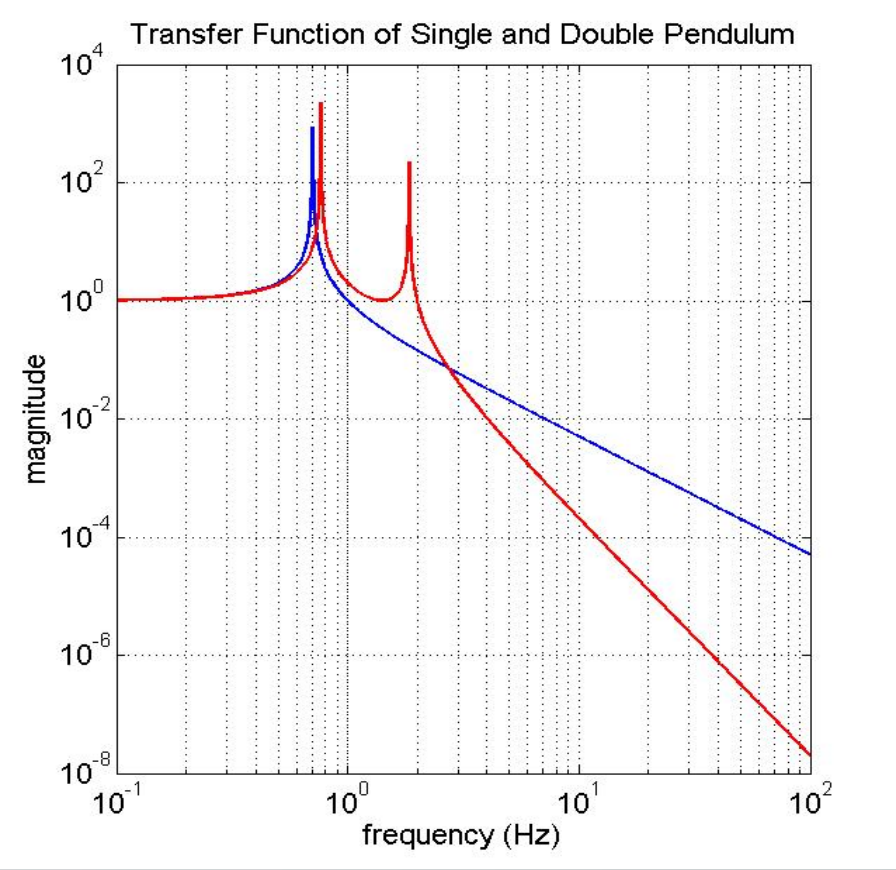
Multistage Pendulum

- Seismic noise limits the sensitivity of ground based detectors at low frequencies – **"seismic wall"**;
- Typical seismic noise at EGO/VIRGO site @ 10 Hz is ~ few x $10^{-10}\ m/\sqrt{Hz}$

  - many orders of magnitude above target noise level
- Solution: isolation system with a **multistage pendulum**;

$$TF \equiv \left|\frac{\tilde{x}_{out}}{\tilde{x}_{in}}\right| = \frac{1}{\omega^{2n}} \prod_{i=1}^{n} \omega_i^2$$

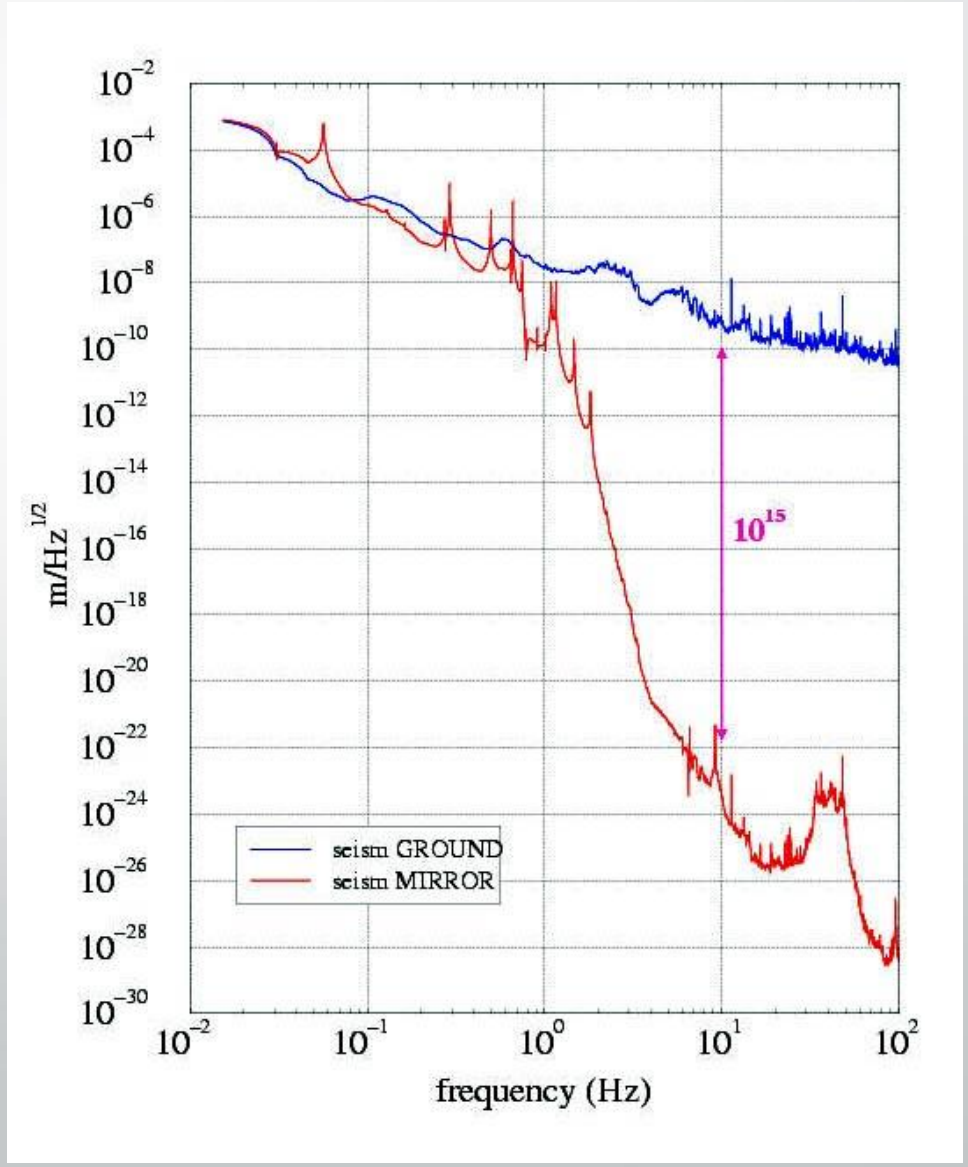
- Isolation required in vertical direction as well as horizontal due to cross-coupling (**triangular cantilever blades**).



Advantages of a **double** over **single** pendulum, same overall length

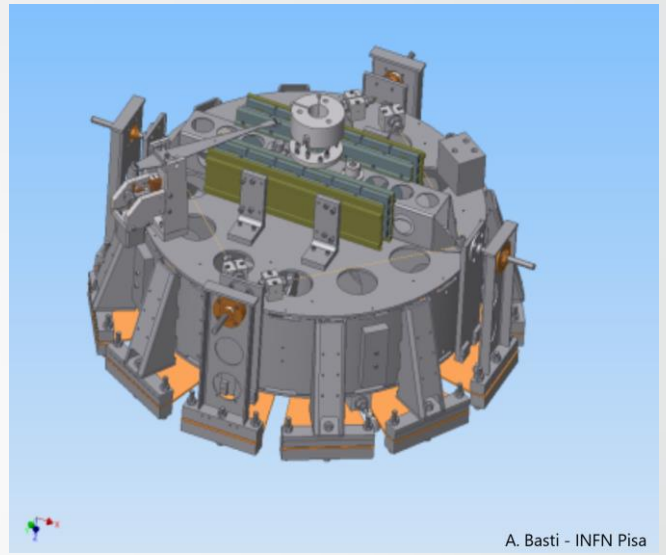
Main features of SA

- Two types of **SA**:
  - 3 Short Chains (4.5 m high) for **Benches**
  - 7 Long Chains (9.5 m high) for **Mirrors**
- **Hybrid** system:
  - **active** control below 3 Hz
  - **passive** attenuation starting from 3 Hz;
- Measured attenuation upper limit ("stage by stage" method): 10^{15} at 10 Hz (**detection band extended in the low frequency region**)

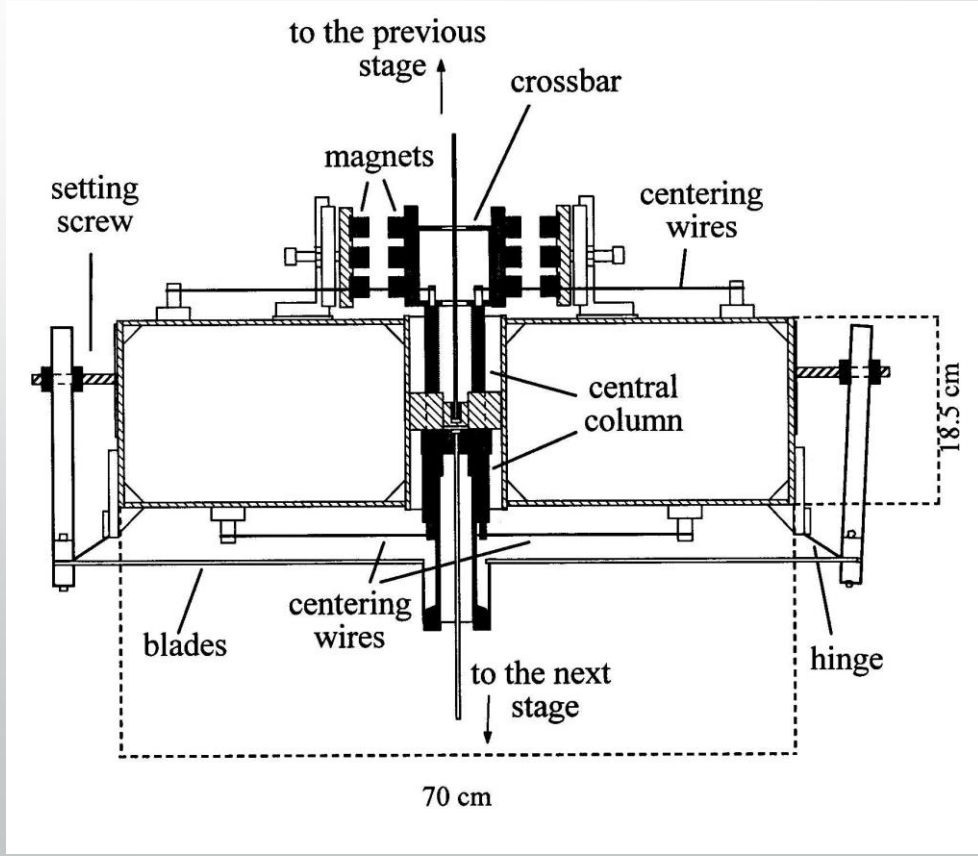


[see: G. Ballardin et al., Rev. Sci. Instrum., vol. 72, n. 9, Sep. 2001]

Mechanical Filters

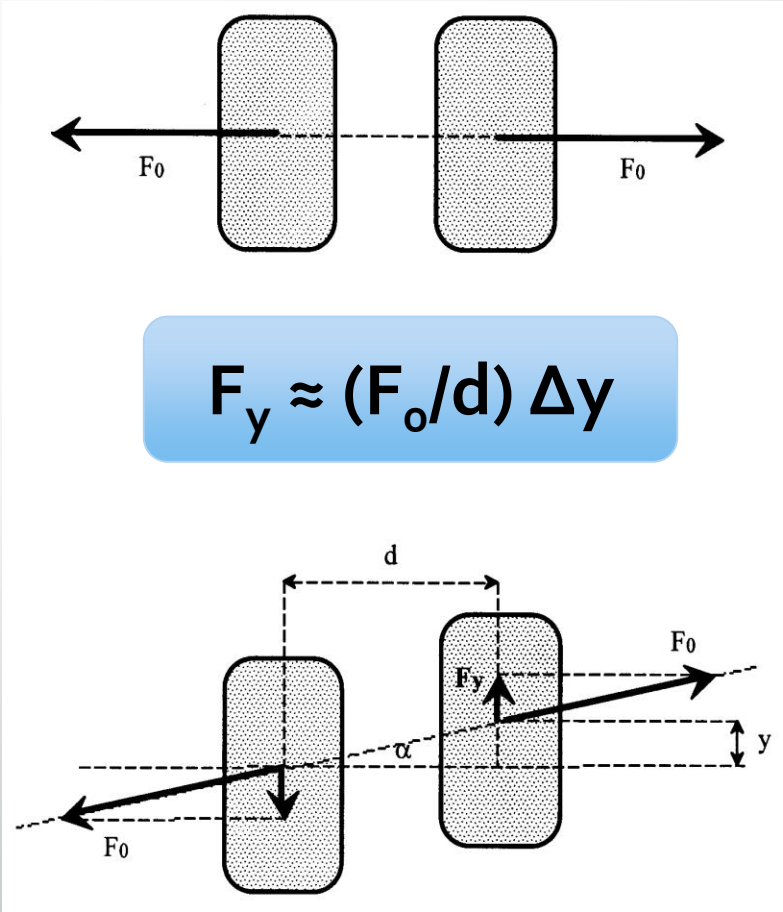


- A Seismic Filter (SF) is a drum shaped mechanical structure designed to reduce the vibrations transmission in all d. o. f.;
- The SF of the AdV Super-Attenuators are equipped with a set of triangular cantilever **blades** and **magnetic anti-springs** (acting as a **vertical harmonic oscillator**).



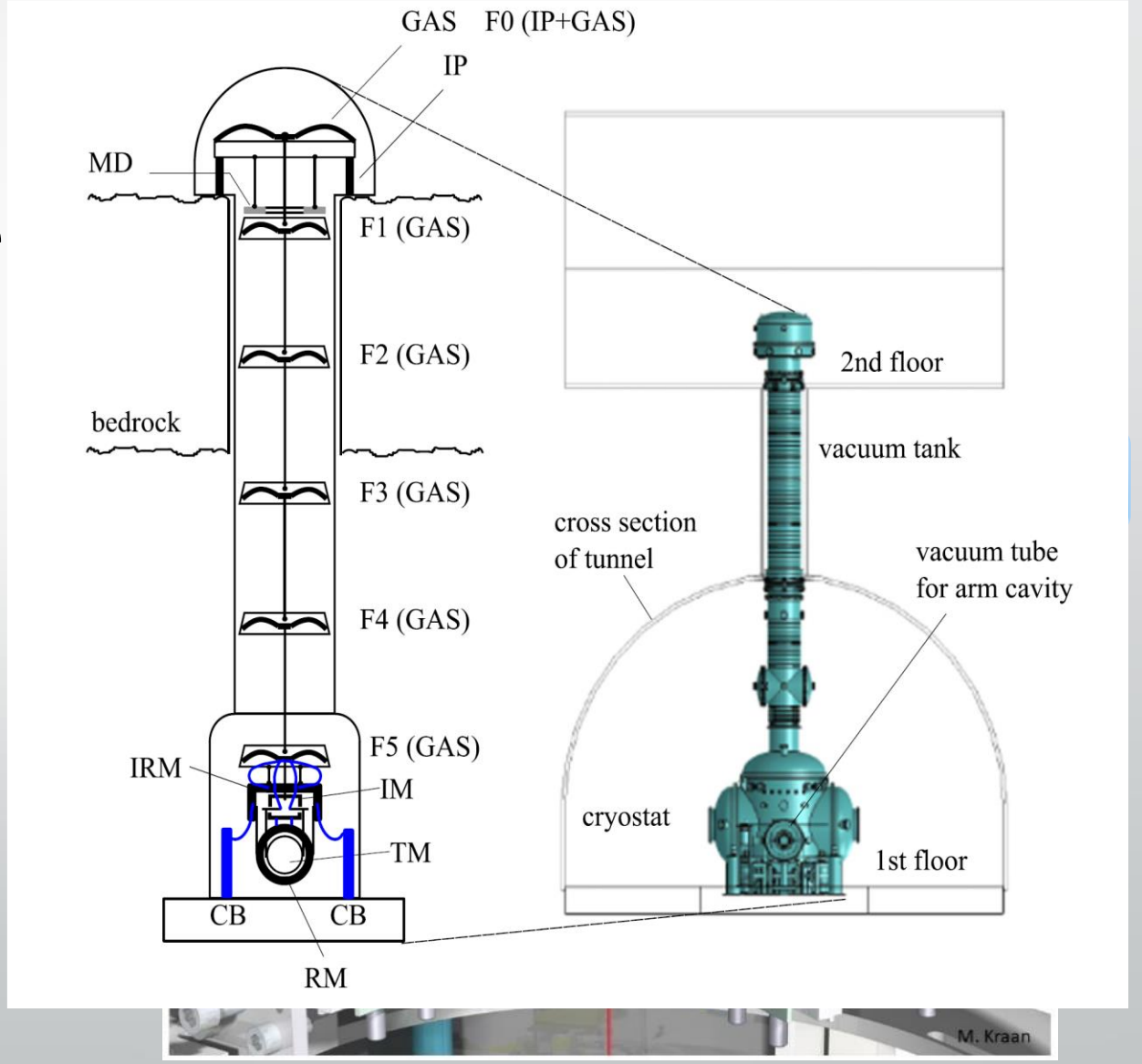
Magnetic Anti-Spring (MAS)

- Each mechanical filter is equipped with a **MAS** system consisting of **two permanent magnets matrices** mounted in repulsive configuration;
- The **MAS** acts on the crossbar, the moving part of the filter connected to the next stage, in parallel with the blade springs;
- In this way all the frequencies of the chain vertical modes are confined below the highest frequency of the horizontal one.



Geometric Anti-Spring effect

- Geometric Anti-Spring (**GAS**) effect is obtained applying a pushing force on the base of the triangular cantilever blade (not bent) installed into the mechanical structure of a filter;
- Solution adopted in the Seismic Attenuation System (**SAS**) of the **KAGRA** underground interferometer: thanks to the NIKHEF Group.



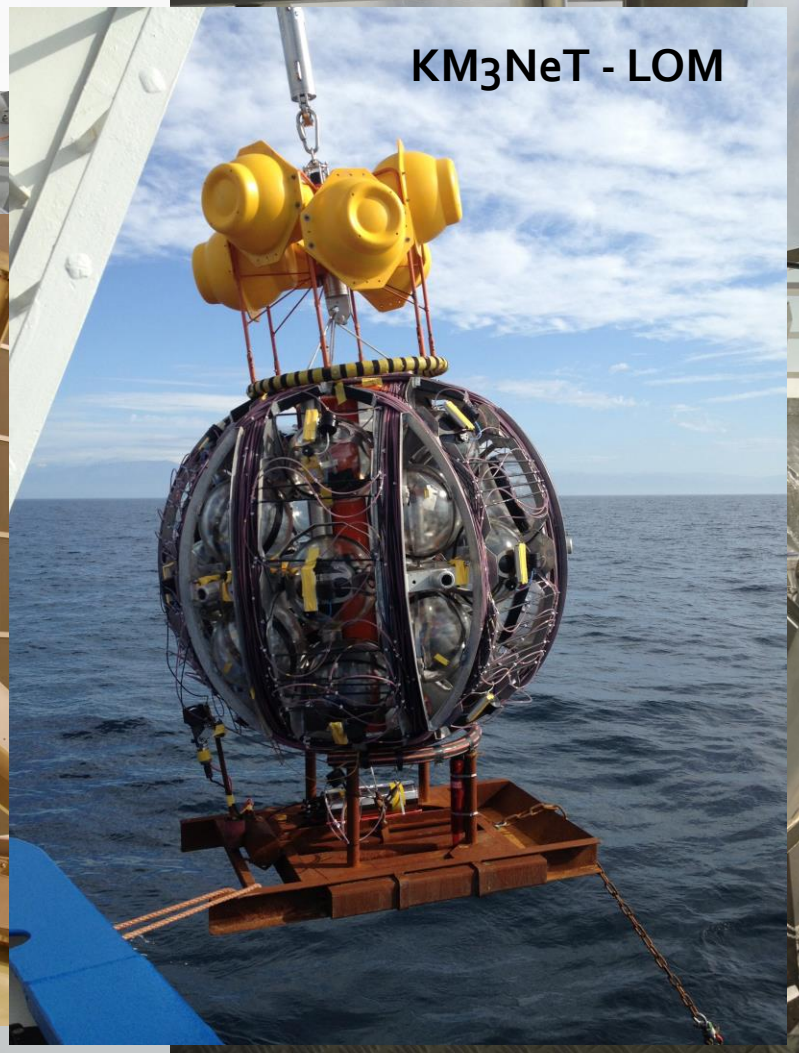
Technological Transfer

- **Galli e Morelli (Lucca – Italy)** as technological partner in the final construction of Super-Attenuator systems for VIRGO and Advanced VIRGO interferometers;
- Precision mechanical workshop, with fundamental expertize in machining and assembling of complex structures to be operated in high vacuum environment;
- Consolidated collaboration with Research Institutes, Universities and Centers of Excellence.

GALLI E MORELLI
OFFICINA MECCANICA DI PRECISIONE

Technological Transfer /2

- **Involvement in many scientific experiments:**



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Why do we need active controls ?

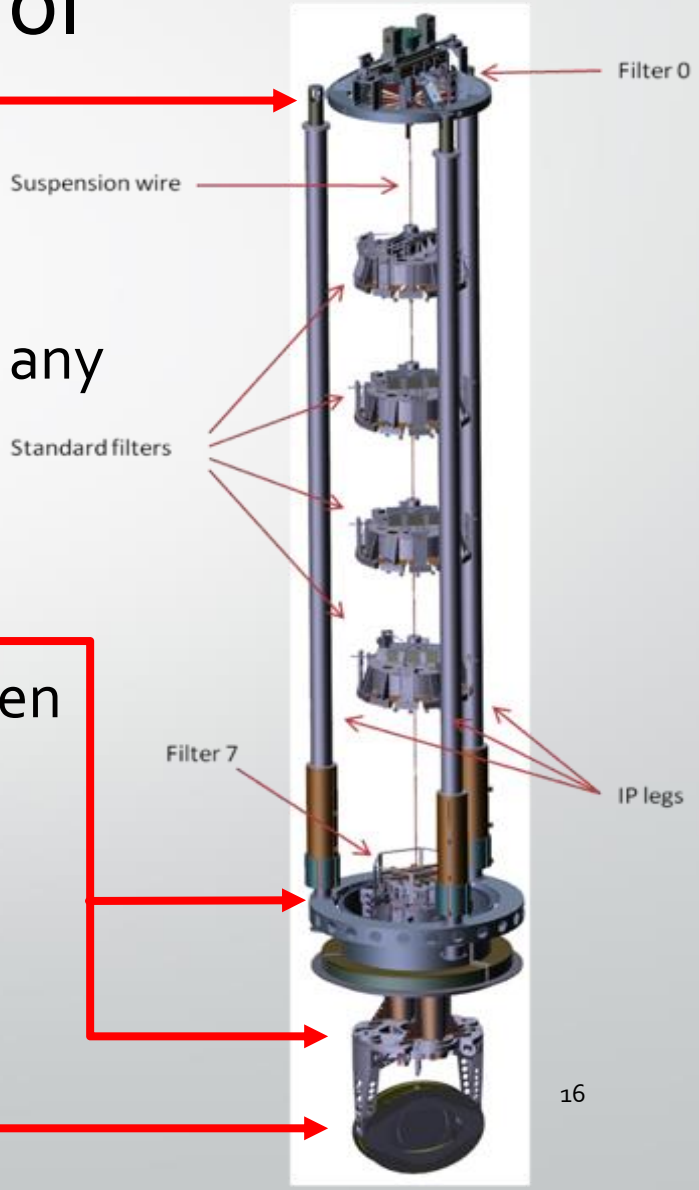
- The **Super-Attenuator** has been conceived confining all the resonance modes in a low frequency region (below 3 Hz);
- Passive attenuation is enough but in the frequency range 0.04 Hz< f < 2 Hz the chain resonance modes induces tens of micron mirror swings

Active **M**ode **D**amping (AMD) & Hierarchical Controls

Mirror Suspension Control

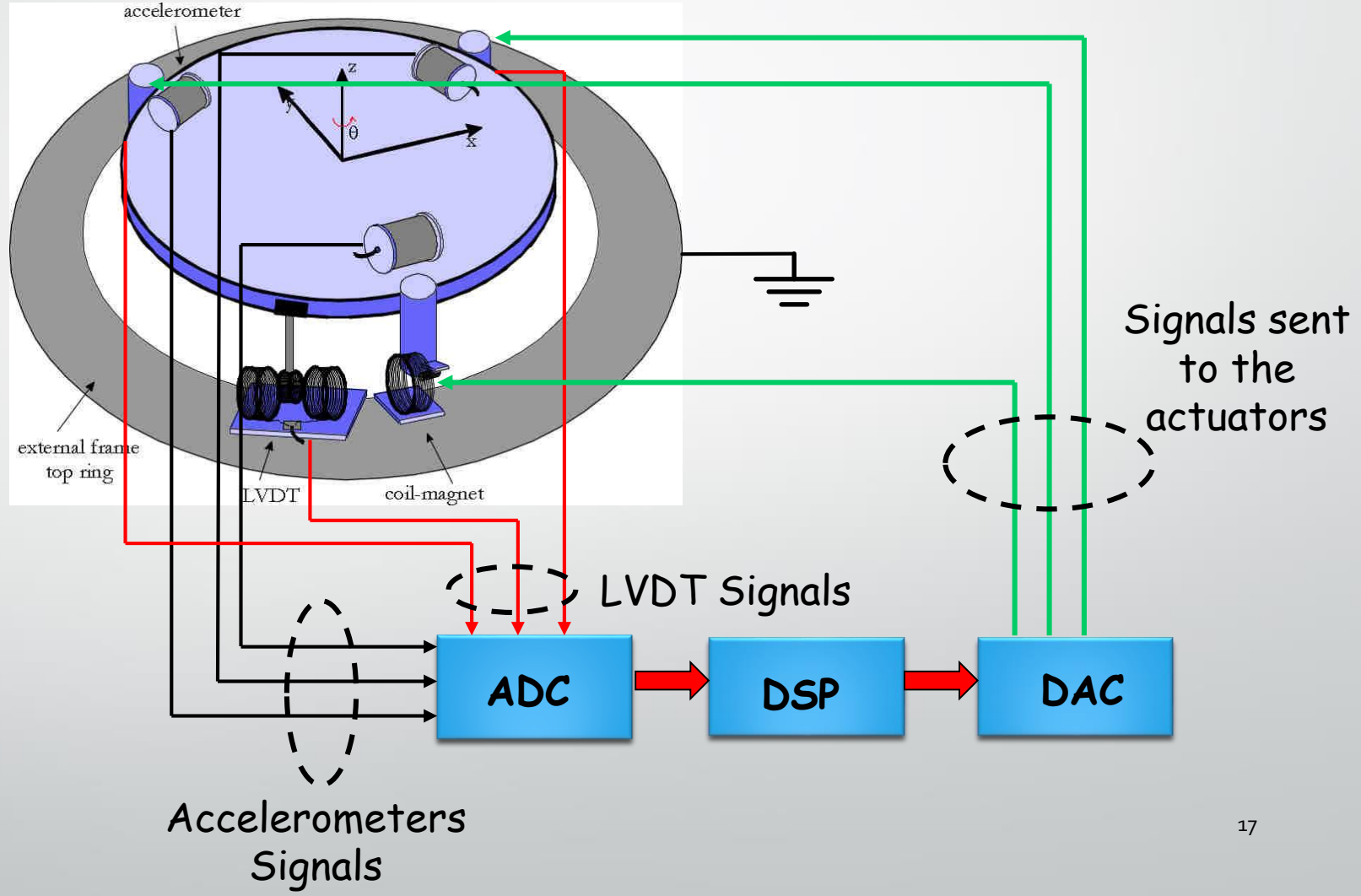
A **hierarchical feedback control** is implemented in 3 different points along the chain;

1. **Inertial Damping** on IP:
   - tidal control of the suspension point and its drift of any origin
   - AMD of the SA normal mode for seismic noise depression
2. **Local Control** on F7-Marionette:
   - Active Pre-Damping on F7 as back-action effect when feedback control engaged on Payload
   - z displacement and angular displacements reduced down to fraction of μrad;
3. **Local Damping** on Mirror (MIR):
   - viscous damping and locking acquisition



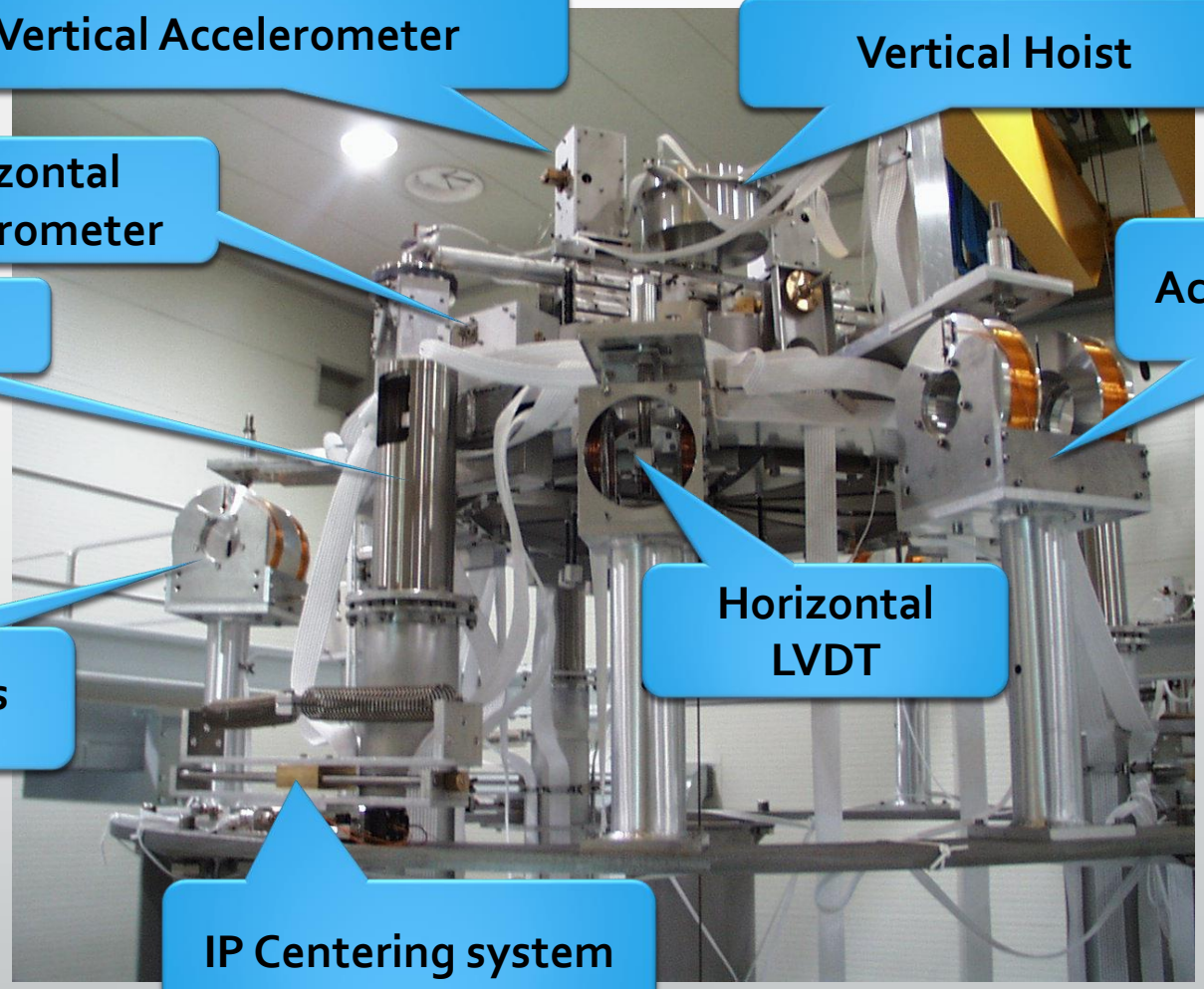
SA top stage: ID and Tidal Control

- New high performance feedback electronics for AdV based on DSP technology;
- Analog and digital part embedded in a single board developed by INFN VIRGO Pisa Group.



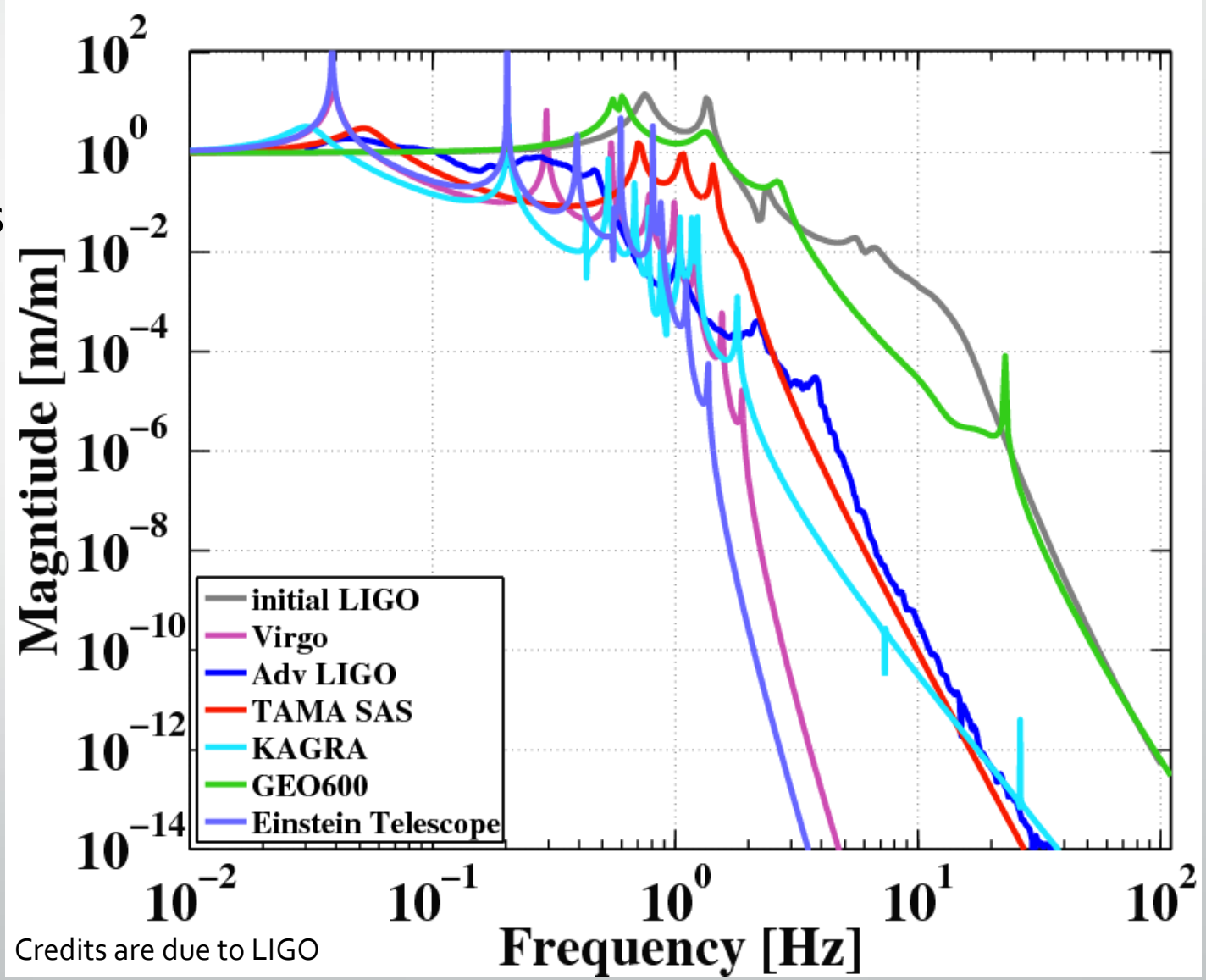
The Inverted Pendulum top stage

- **Sensors and Actuators**



Mechanical Transfer Functions

- The mechanical TF represents a figure of merit of any vibration isolation system



Credits are due to LIGO

Final Considerations

- Following the **VIRGO experience** (1st generation ITF) a big effort has been done implementing complex systems for seismic noise isolation (2nd generation detectors):
  - detector bandwidth extended in the low frequency region, below 100 Hz
  - improved sensitivity of a factor 10 with the possibility to observe a larger volume of the Universe
  - a Network of 2nd generation detectors played (and will play) a crucial role in the sky localization of GW sources: **multi-messenger astronomy just started**;
- R&D on new vibration isolation systems (**New SA**) - to be designed extending the detection bandwidth in the low frequency region – represents an hot spot also for the future ITFs (**Einstein Telescope** as 3rd generation underground detector for GW observation).

Thank you for your attention !!