Advanced Virgo suspensions control

Lucia Trozzo

OUTLINE

- Advanced Virgo

- **Seismic noise and mechanical attenuators of the seismic vibrations: The Superattenuator.**

➢ Suspension control
  ➢ Blending technique
    - Above 100 mHz
    - Below 100 mHz
    - GIPC Control

➢ Suspension control Noise

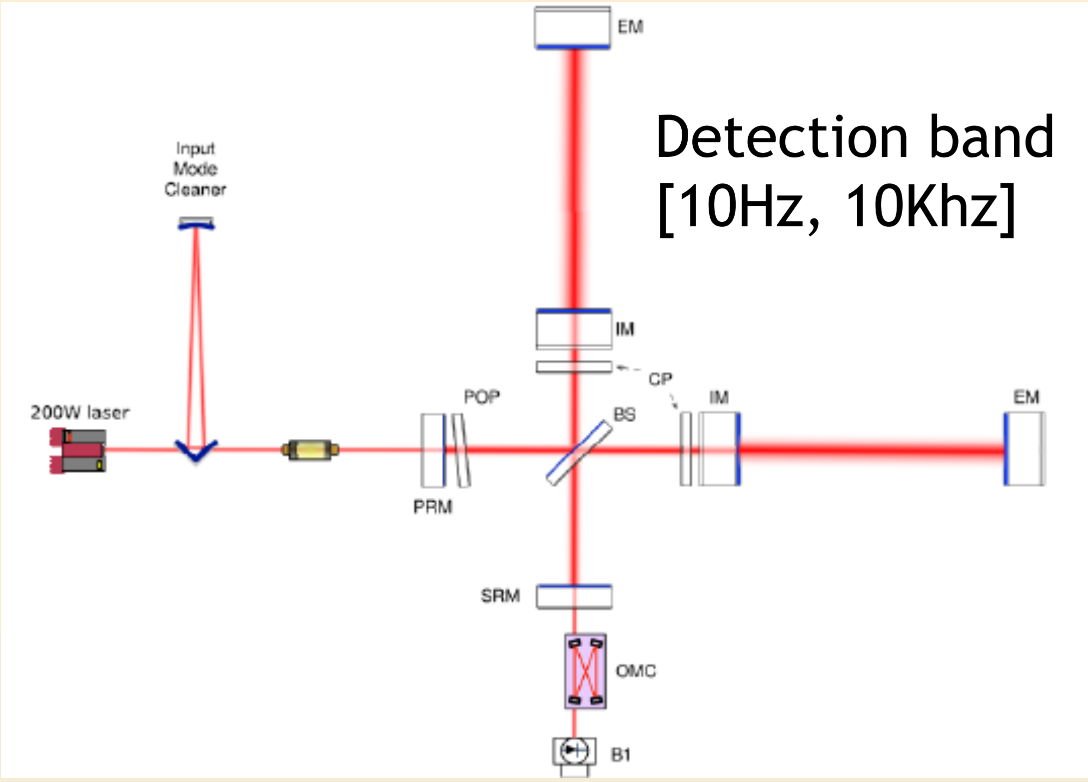
Virgo detector

- **Virgo is a ground based GWs detector located in Cascina (Pisa, Tuscany, Italy)**
- **The infrastructure is hosted in the European Gravitational Observatory (EGO)**

Virgo is designed and built by a collaboration between the French Centre National de la Recherché Scientifique (CNR) and the Italian Istituto Nazionale di Fisica Nucleare (INFN).

The EGO-Virgo is an international collaboration of scientist from France, Italy, Netherlands, Poland, Hungary and Spain.

Advanced Virgo

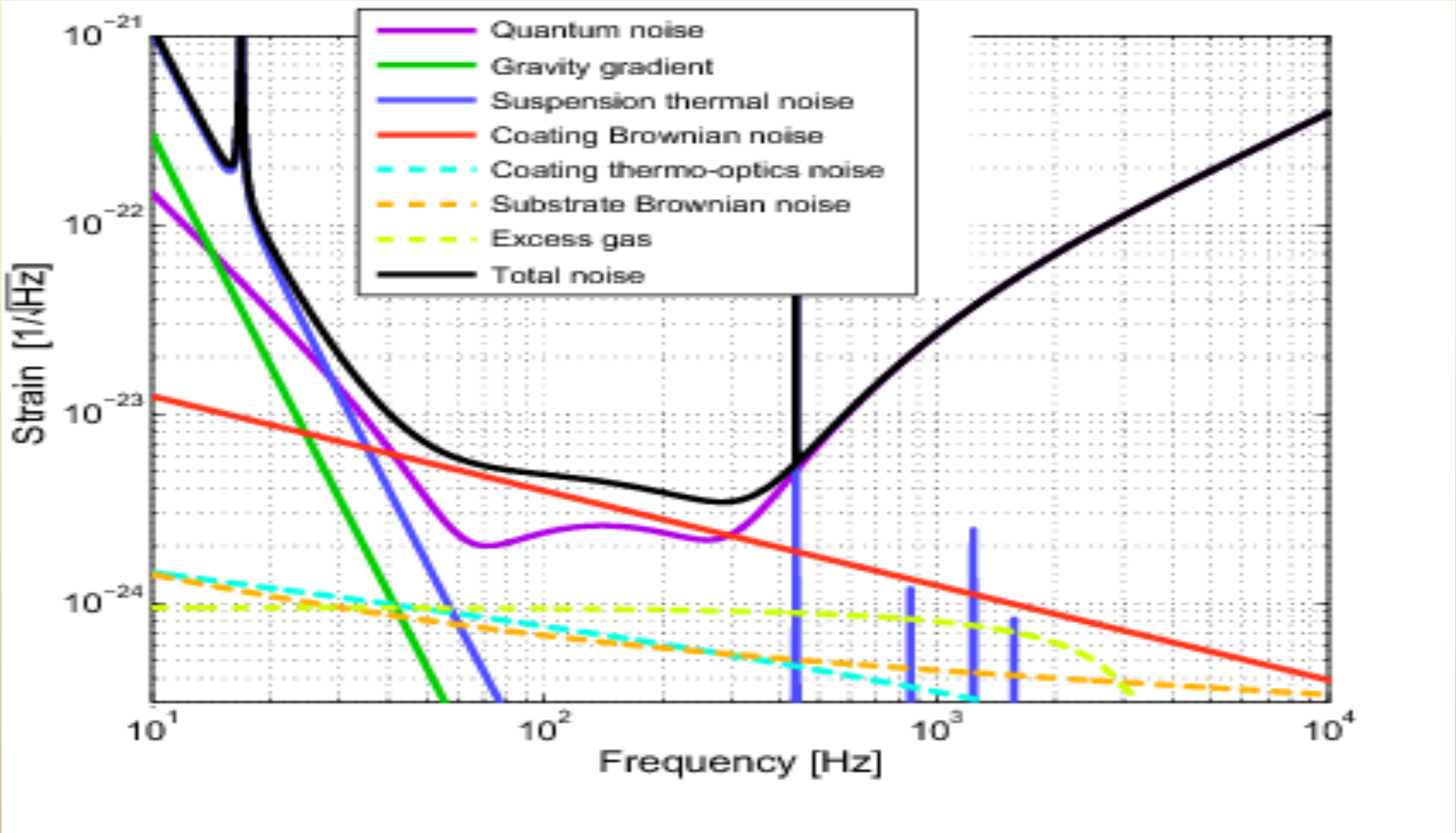


Detection band
[10Hz, 10Khz]

- Michelson ITF + 3 km long FP cavities
- Detection band [10 Hz, 10 kHz]

This makes possible to observe a signal coming from a typical binary system (NS-NS *of 1.4* $M_\odot$) **up to 150 Mpc with respect to the 15 Mpc of Virgo**

Design strain sensitivity curve



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  ➢Suspension control

    ➢Blending technique

      •Above 100 mHz

      •Below 100 mHz

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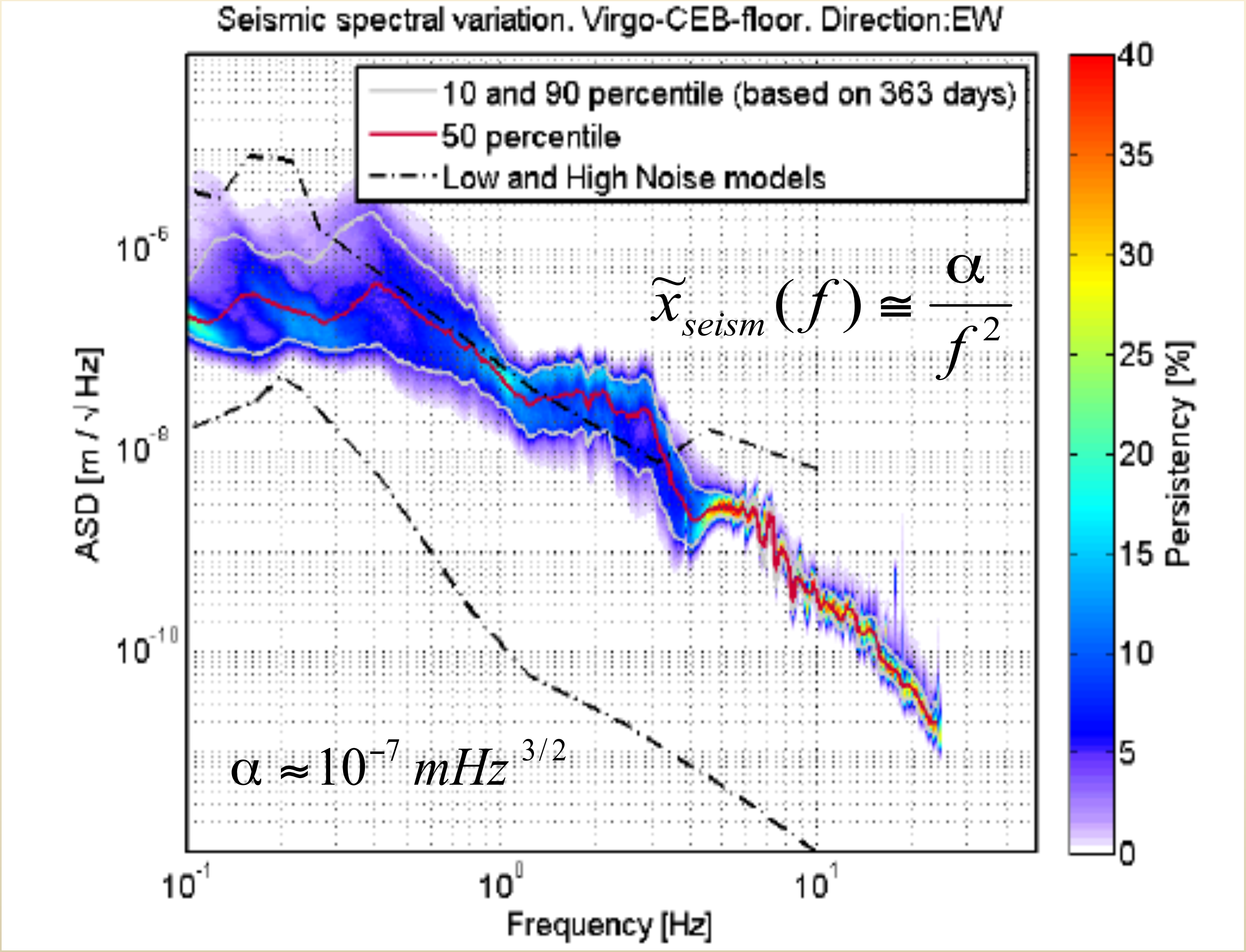
    ➢Suspension control Noise

Seismic noise

VIRGO interferometer has been designed to detect GW starting from 10 Hz

➢Seismic noise: is the dominant noise at low frequencies

Typical amplitude spectral density



In the detection band (f> 10 Hz) the seismic noise reaches the values:

$$\tilde{x}_{seism} \approx 10^{-9}\ m/Hz^{1/2} \quad f \approx 10 Hz$$

To detect the little displacement due to a GW we need a residual motion at 10 Hz of

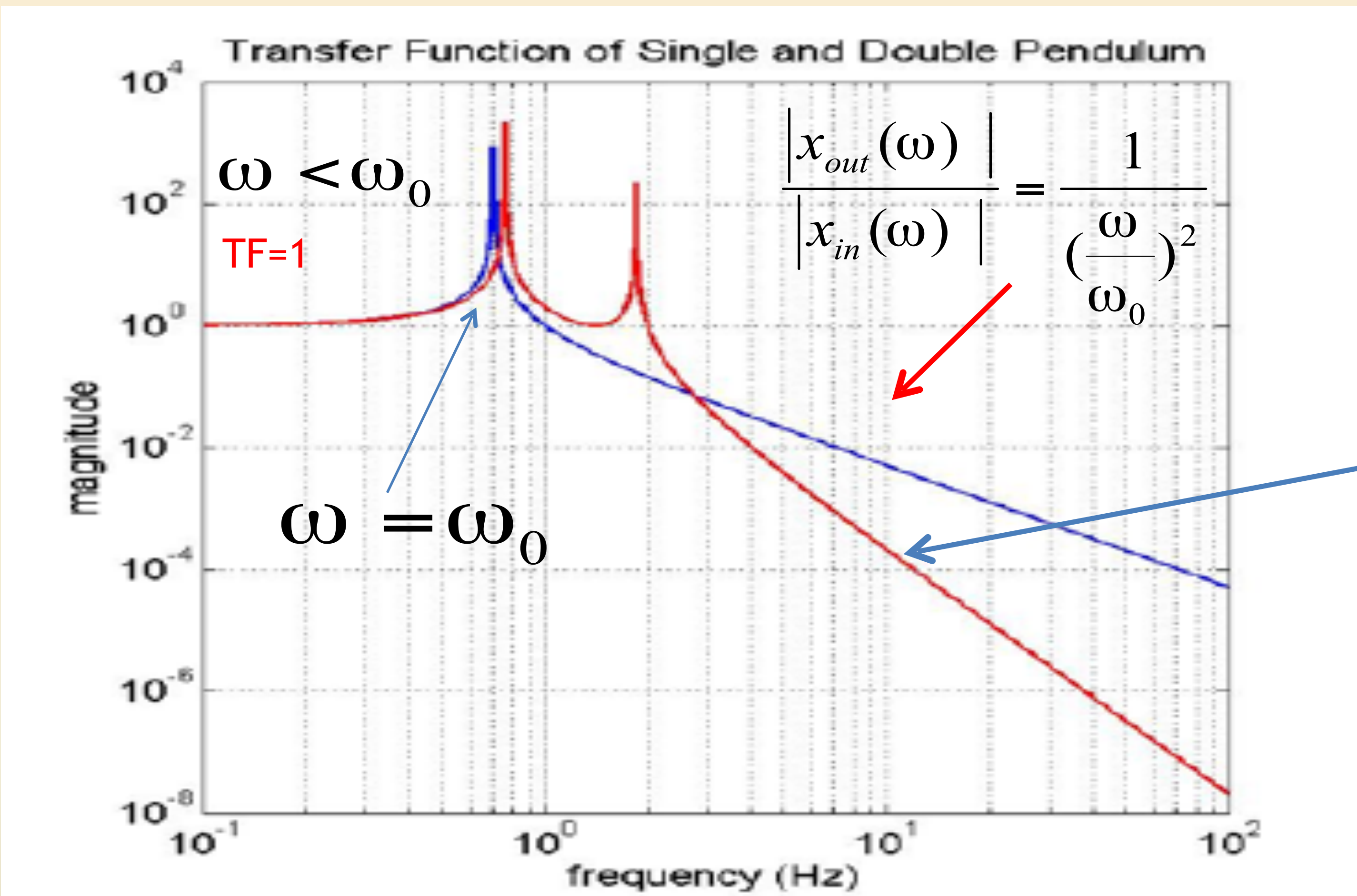
$$\tilde{x} \approx 10^{-18}\ m/Hz^{1/2}$$

a seismic isolation with an attenuation factor~ 10 order of magnitude is needed!!!

Mechanical attenuators of the seismic vibrations

A good approximation of the free falling mass is represented by the simple pendulum

$$\frac{|x_{out}(\omega)|}{|x_{in}(\omega)|} = \frac{1}{1-(\frac{\omega}{\omega_0})^2}$$



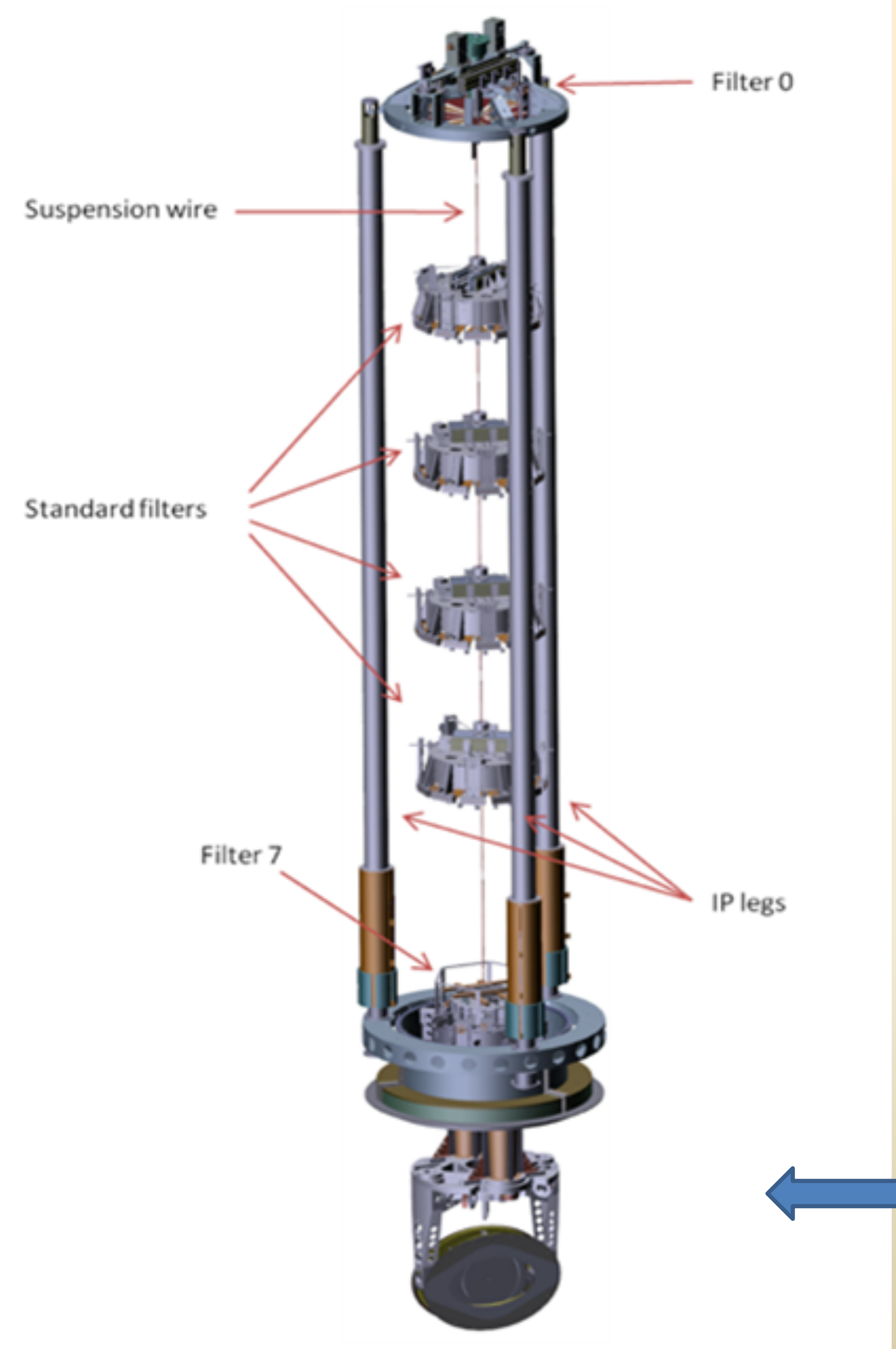
Having 2 cascaded harmonic oscillators we obtain

$$\frac{|x_{out}(\omega)|}{|x_{in}(\omega)|} = \frac{A}{(\omega)^4} \qquad A = \omega_1^2 \cdot \omega_2^2$$

Solution adopted in VIRGO is based on the idea to cascade a certain number of harmonic oscillators of length ~1 m to obtain a sophisticated mechanical structure:

The SUPERATTENUATOR

The Superattenuator



The suspension system is developed by INFN:

- **Superattenuator: INFN Pisa**
- **Payload: INFN Roma1**

VIRGO uses this system for all optics and benches excepted for auxiliary benches

√Pre-isolation stage:
the Inverted Pendulum (IP-3 legs structure) +mechanical filter (called Filter 0-F0)

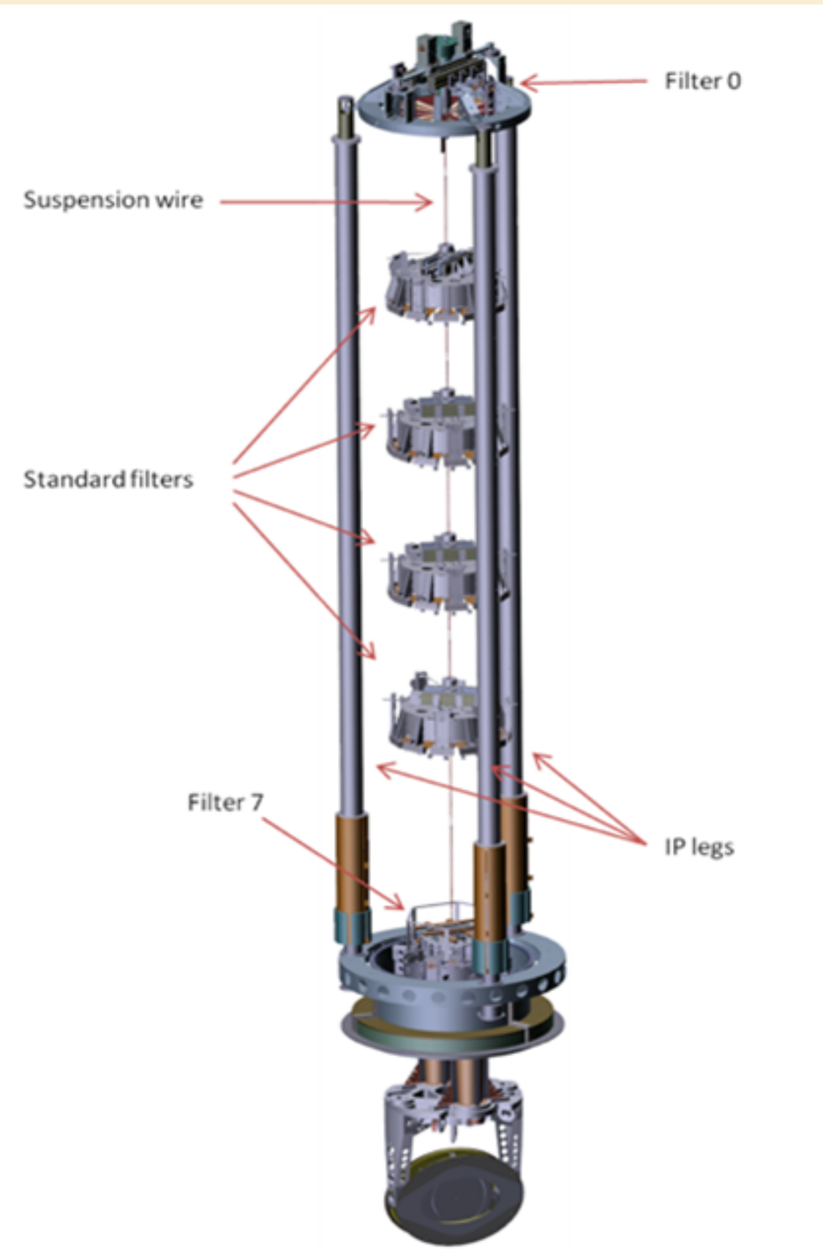
√The passive multi-stage pendulum chain: five mechanical filters F1, F2, F3,F4 and F7 (Steering Filter).

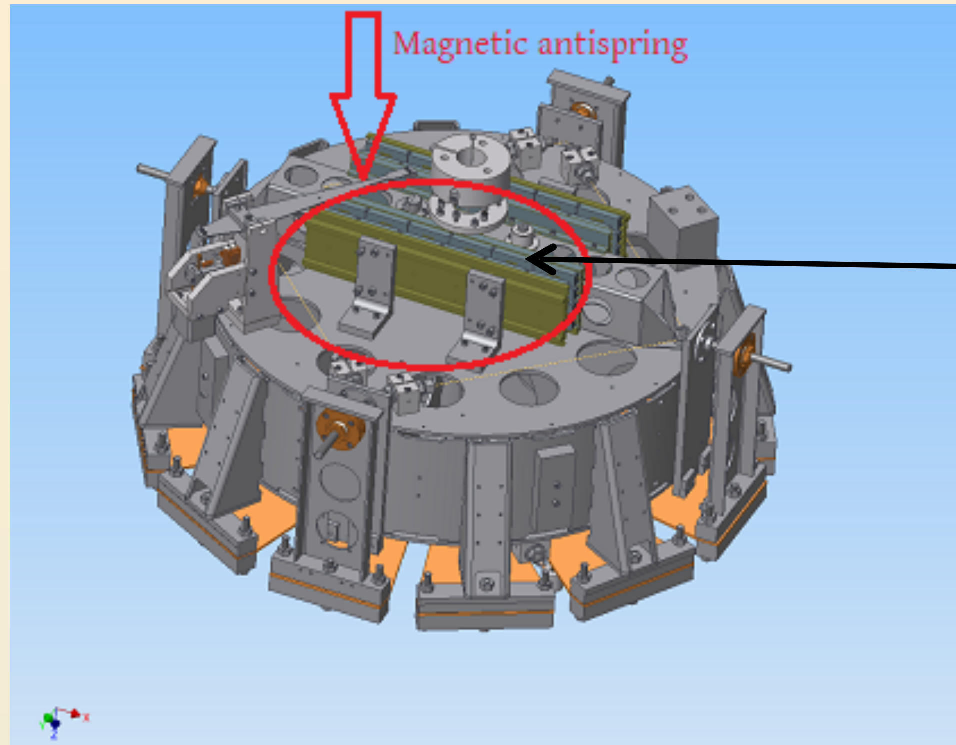
√Last stage or payload: the marionette and the mirror.

The normal modes of the pendulum mechanical structure are confined below 2 Hz

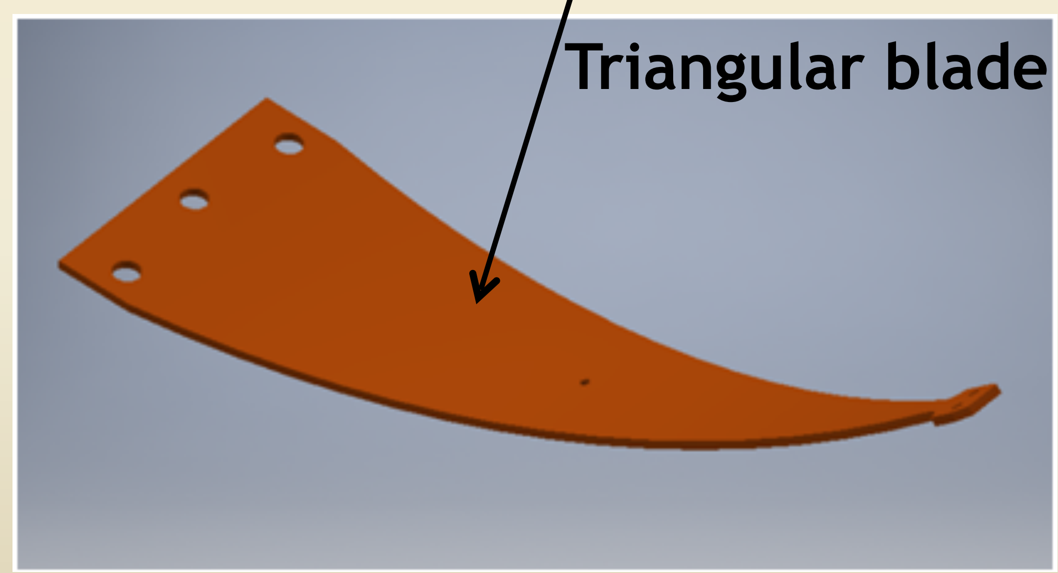
Mechanical attenuators of the seismic vibrations

The system provides a good seismic isolation in horizontal direction (IP) as well as the vertical one.





➢**Standard filter:**
- set of magnetic anti-sprigs
- elastic elements of triangular shape



The vertical normal modes of the mechanical filter are below 0. 4 Hz

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➢Suspension control
  ➢Blending technique
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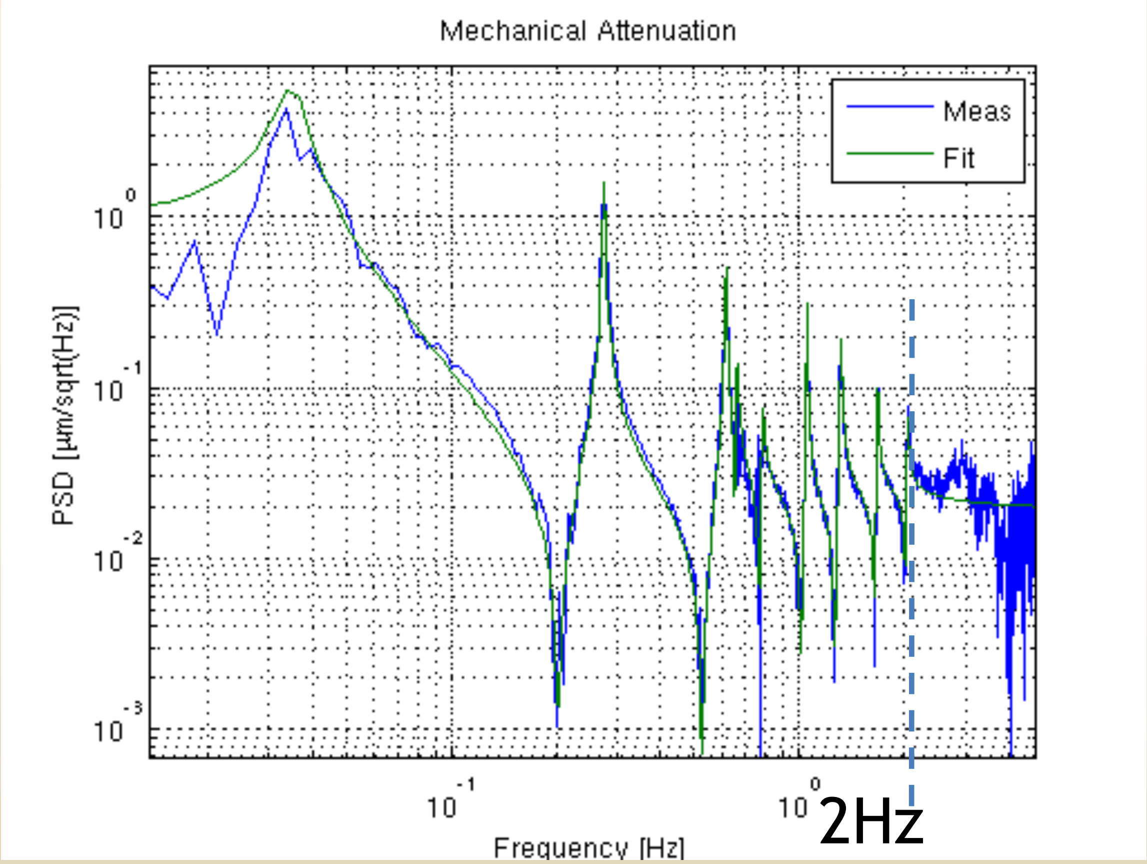
    •Below 100 mHz
    •GIPC Control

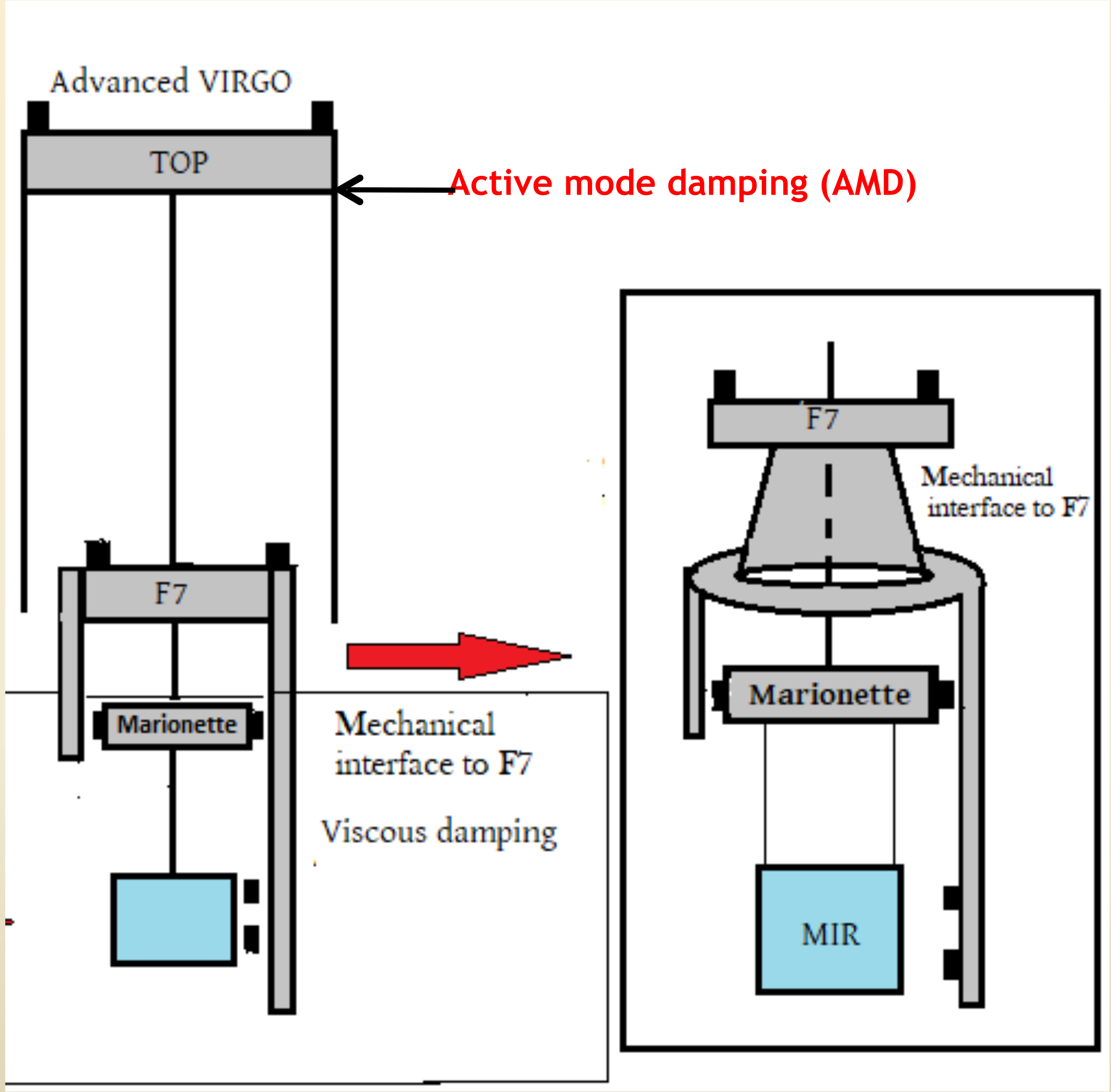
➢Suspension control Noise

Suspension control: *Introduction (I)*

By using sensors and actuators a hierarchical feedback control system has been implemented in four different points: on top of the suspension, on the Filter7, Marionette stage and on the Mirror. The goal of the feedback action is to reduce the swinging of the free falling masses.

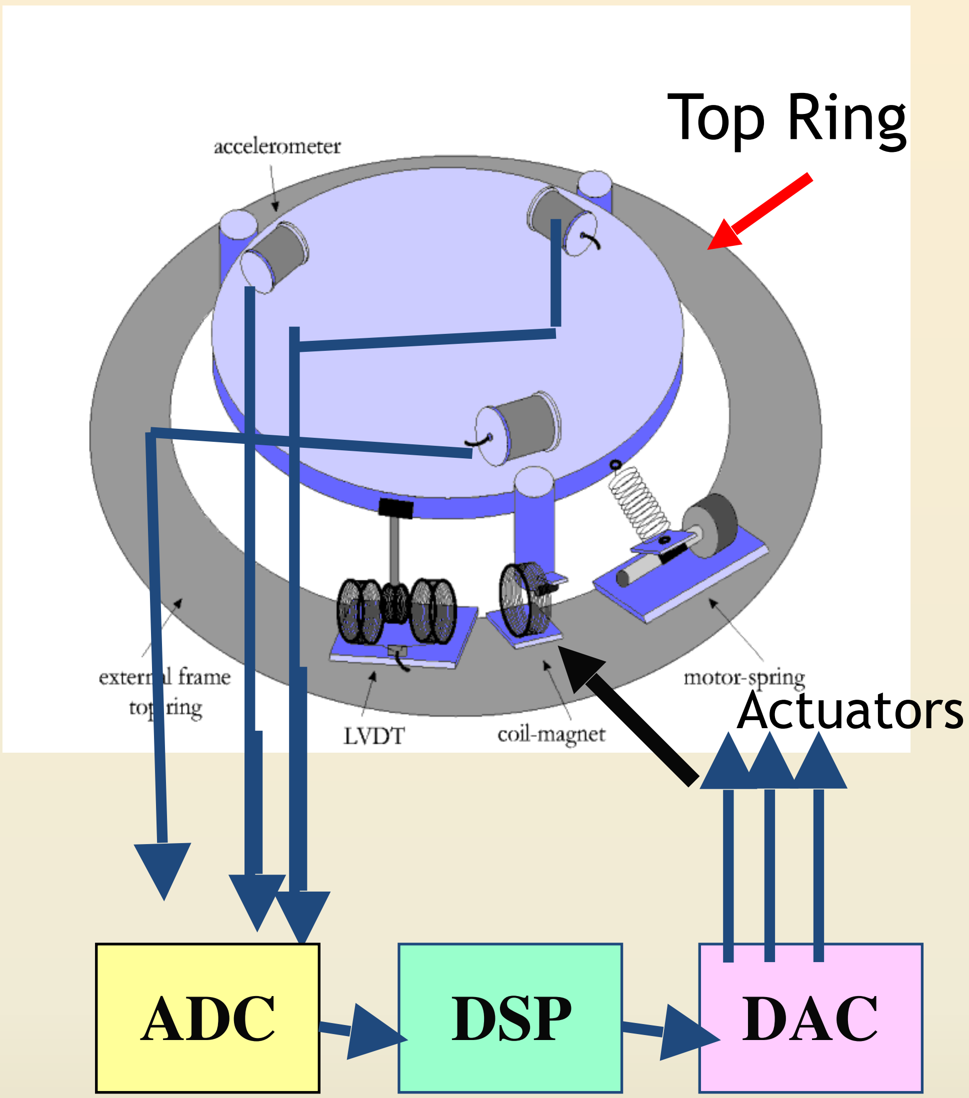
- **18 position sensors (LVDT)**
- **5 inertial sensors (ACC under digital control)**
- **23 magnetic actuators (coils)**





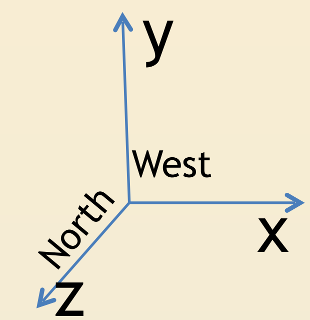
Suspension control: *IP control*

On the Superattenuator (SA) top ring a set of sensors and actuators are installed for feedback control purpose.



At this level is implemented an Active Mode Damping (AMD) of the SA resonance modes for seismic noise reduction.

➢ **To implement the AMD control we diagonalize sensors** **in Virgo reference frame**



For the horizontal translation we have (where $i = z, x;\ j = x, z;$ **):**

LVDT: $$\hat{s}_{iL}(\omega) = \hat{s}_i(\omega) - \hat{s}_{iLs}(\omega) + \hat{n}_{iLe}(\omega)$$

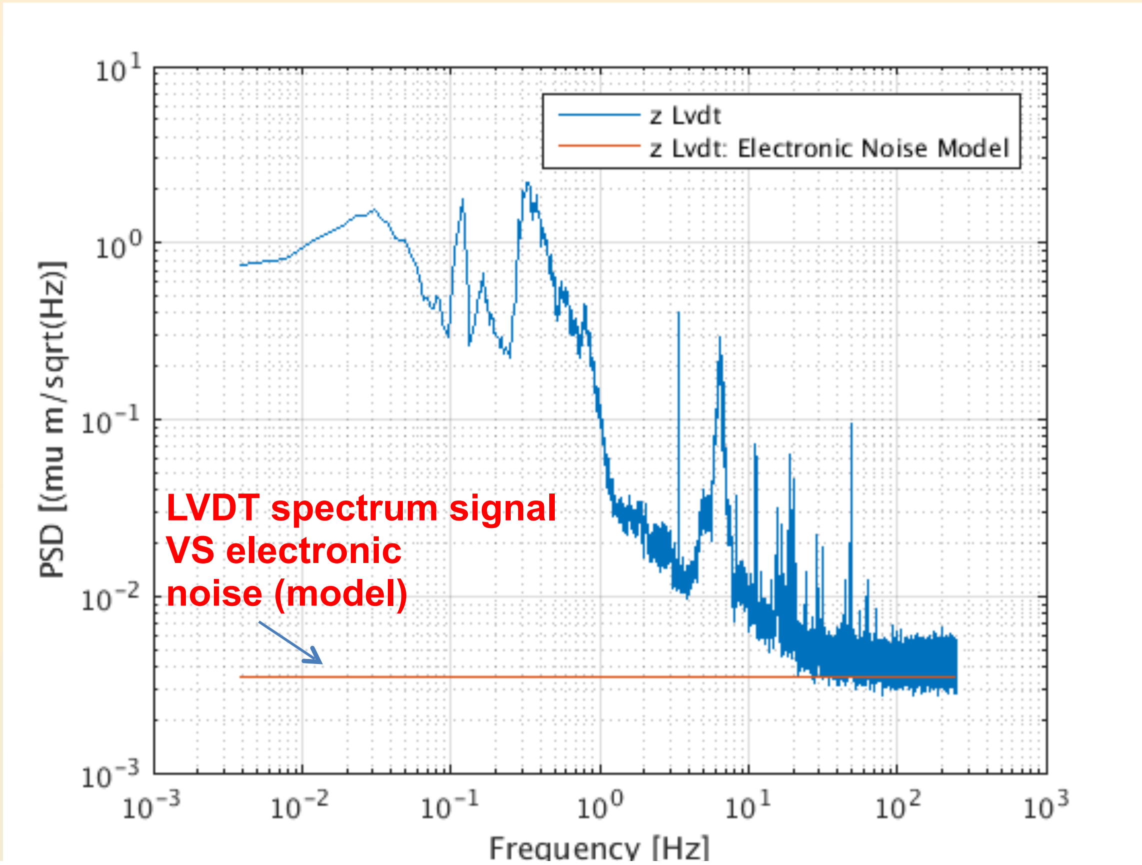
$\hat{s}_{iLs}(\omega)$ **is the seismic contribution** $\hat{n}_{iLe}(\omega)$ **is the electronic noise contribution**

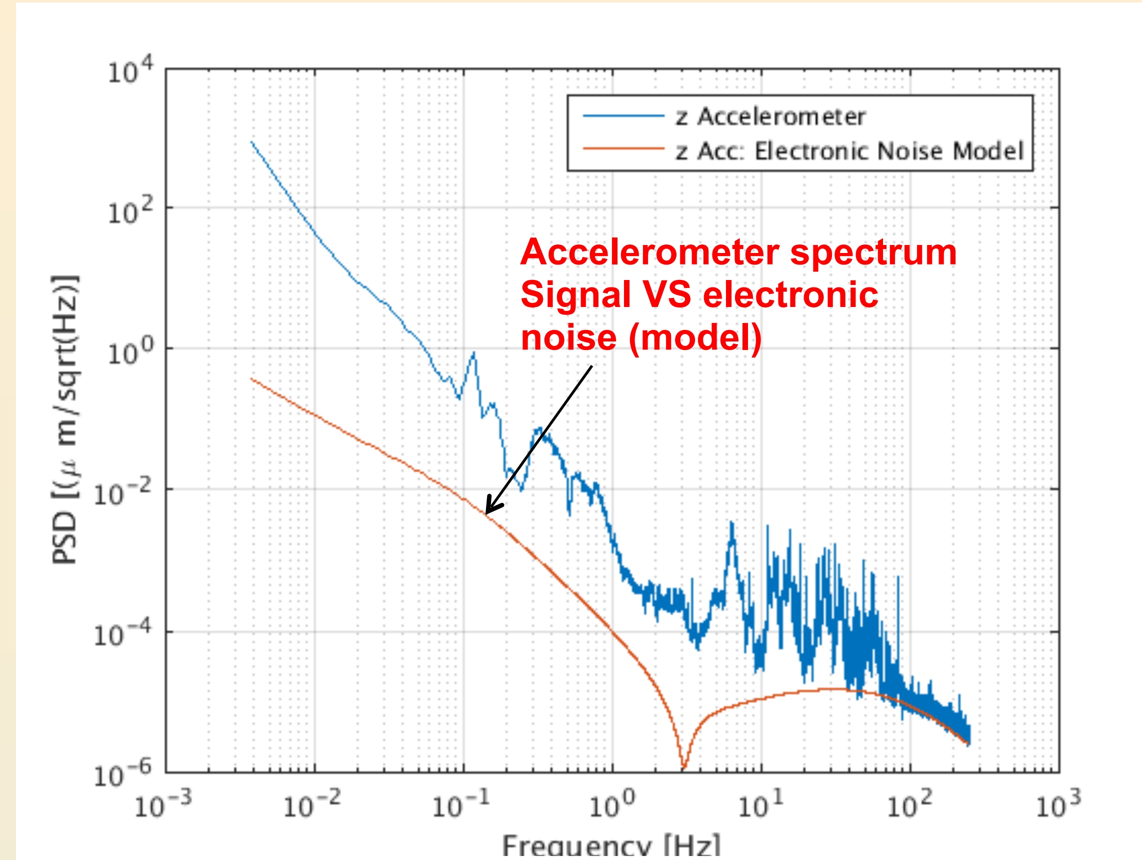
ACC: $$\hat{a}_{iA}(\omega) = \hat{a}_i(\omega) - g \cdot \hat{\theta}_j(\omega) + \hat{n}_{iAe}(\omega)$$

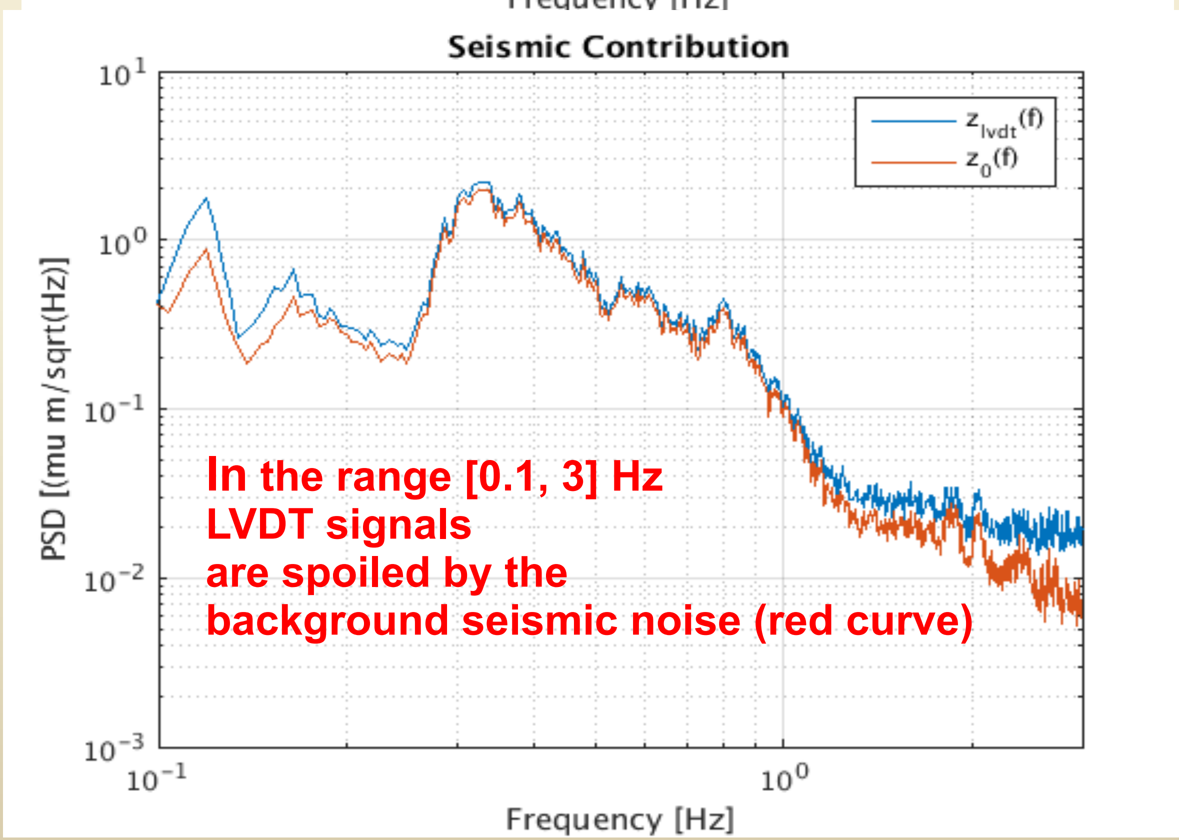
$\hat{n}_{iAe}(\omega)$ **is the electronic noise contribution** $g \cdot \hat{\theta}_j(\omega)$ **is the background tilt contribution**

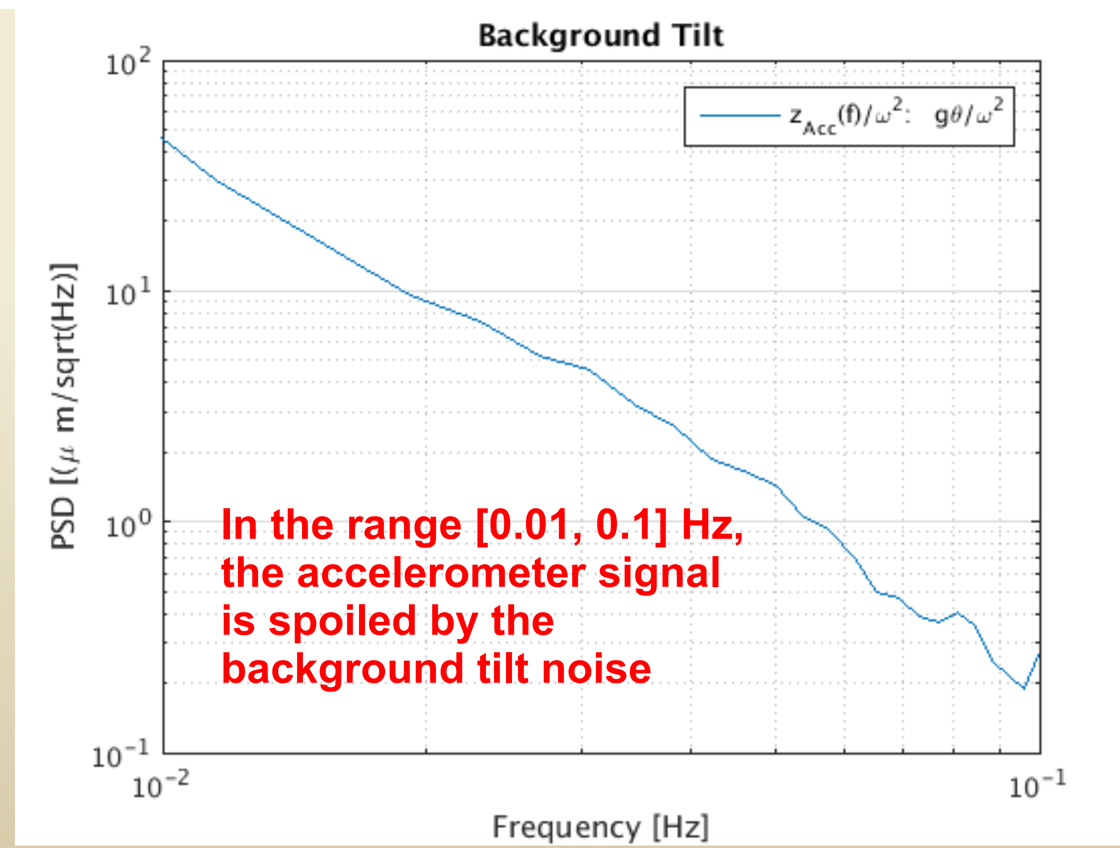
Active Mode Damping: *noise of sensors*

Let's consider the virtual sensors along z axis



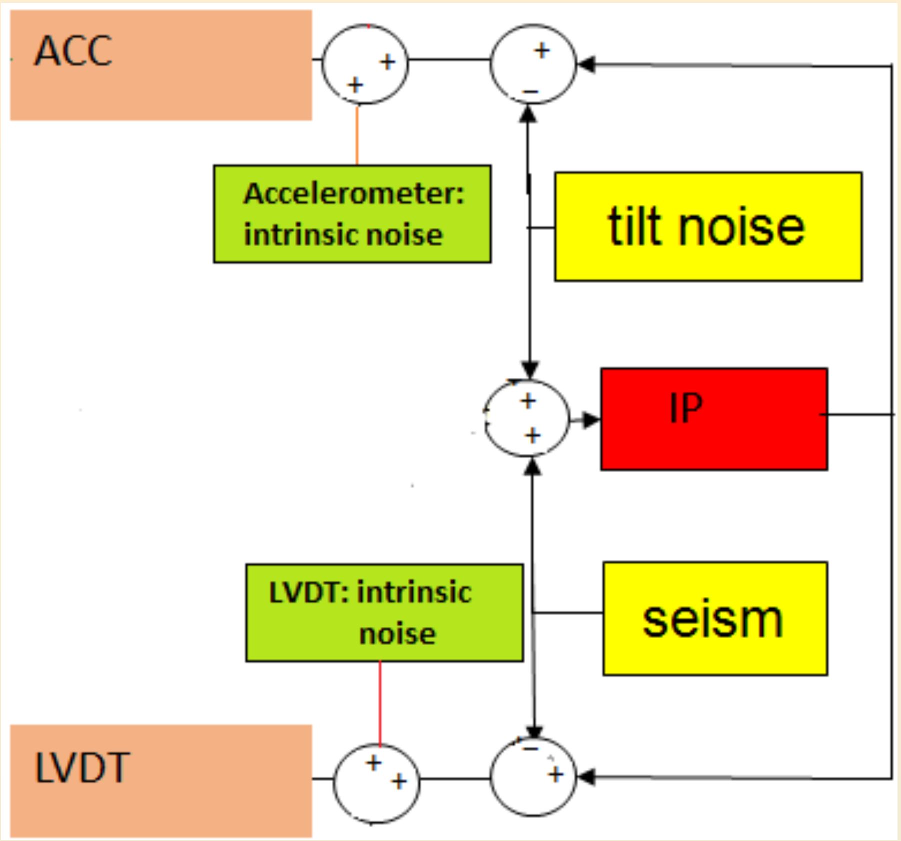


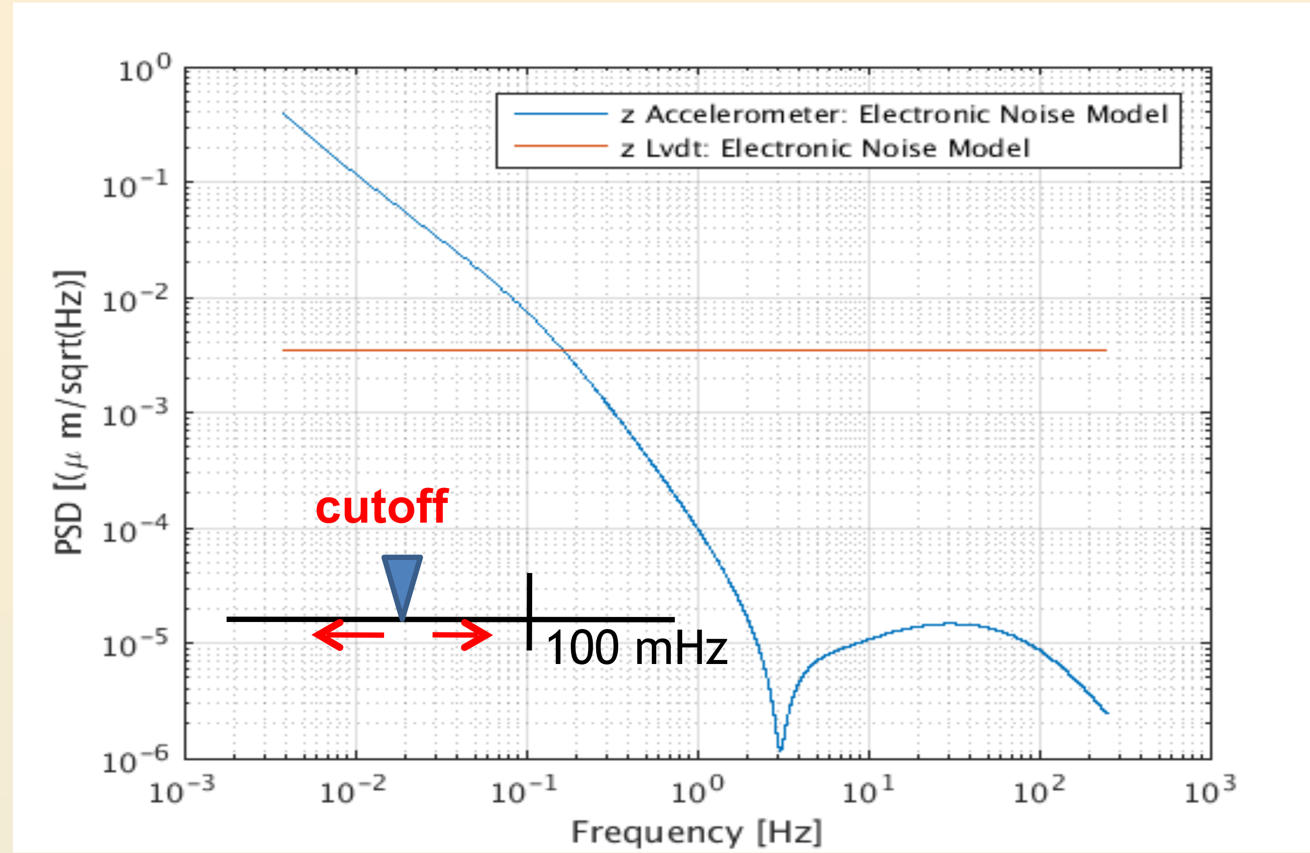




Active Mode Damping: *the Blended Virtual Sensor (BVS)*

To take the better part of both signals in Virgo a *blended virtual sensing signals*, Is obtained through neutral prefiltering.





At low frequencies we are limited by accelerometer electronic noise

From few hundred mHz we are limited by LVDT electronic noise

High Pass filter (HP)

$$\hat{HP}(\omega) + \hat{LP}(\omega) = 1$$

Low Pass filter (LP)

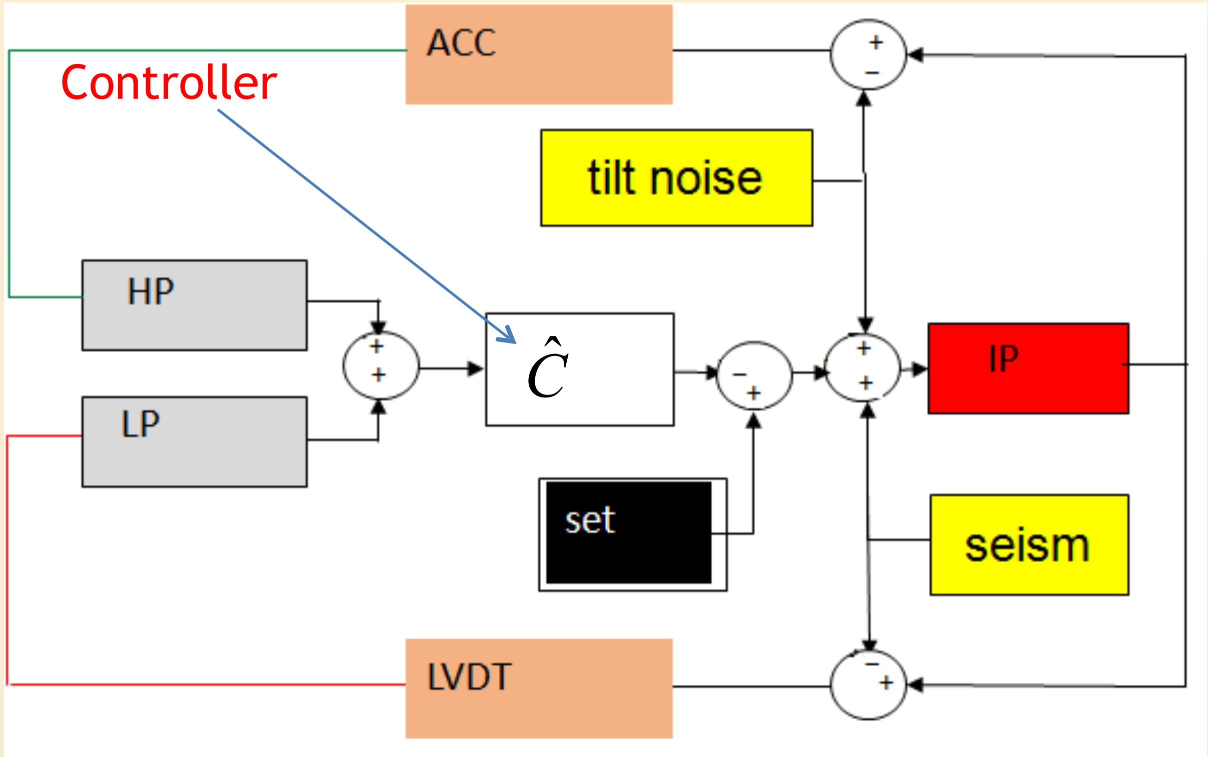
√LP filter must be shaped taking into account the background disturbance

√For LP filter typical cutoff is below 100 mHZ

For z d.o.f the BVS signal is :

$$\hat{S}_{zv}(\omega) = \hat{LP}(\omega)\cdot\hat{s}_{zL}(\omega) - \omega^{-2}\cdot\hat{HP}(\omega)\cdot\hat{a}_{zA}(\omega)$$

Inertial Damping: *block diagram*

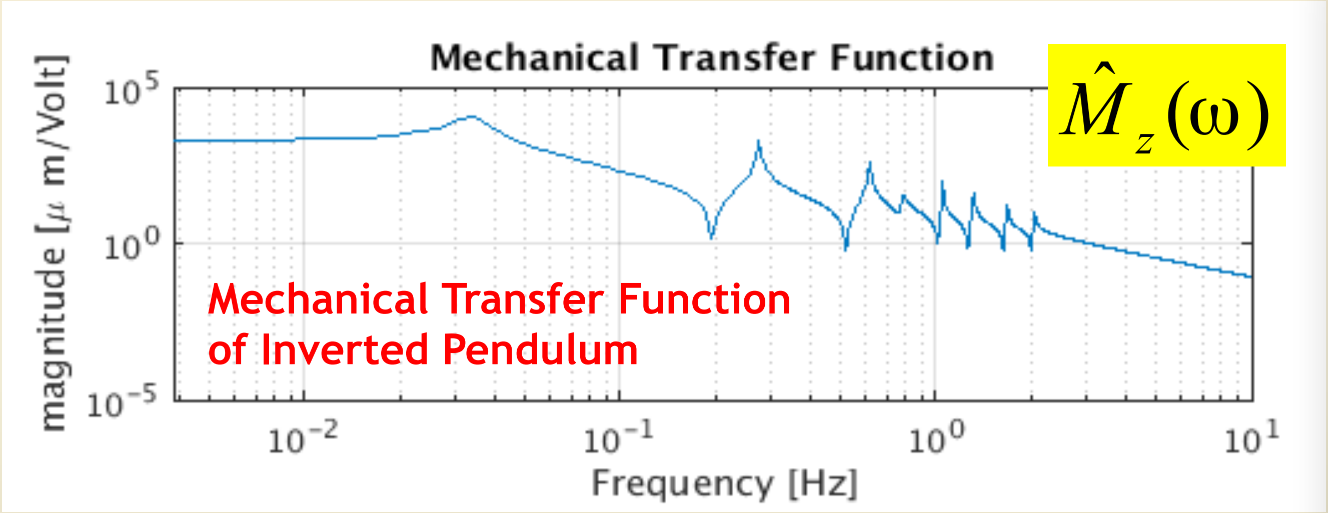


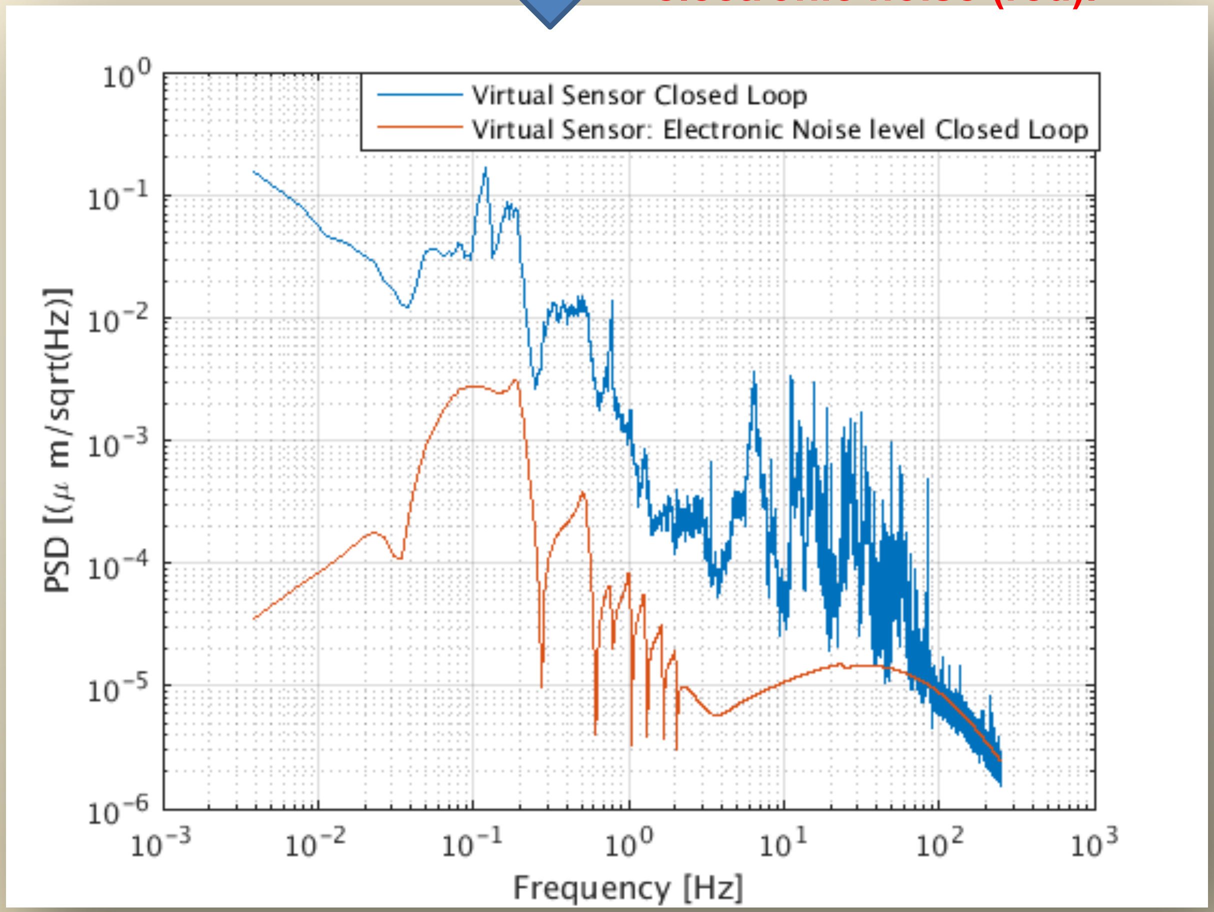
Block Diagram of Active mode Damping control used in Virgo

The closed loop signal along the i-th d.o.f is

$$\hat{S}^{CL}_{iv}(\omega) = \frac{\hat{S}_{iv}(\omega)}{1 - \hat{M}(\omega)\cdot\hat{C}(\omega)}$$

Virtual sensor closed loop, compared with its electronic noise (red).





In ideal condition, this spectrum should reach the electronic noise level

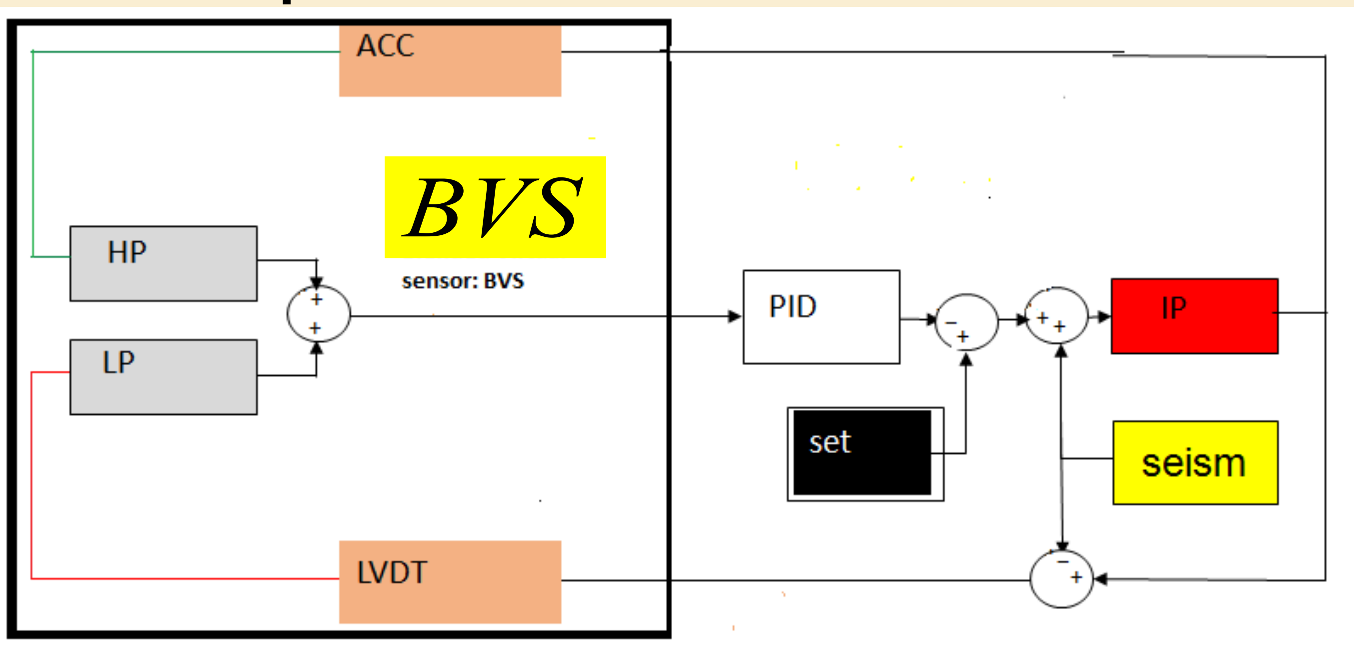
We have an excess of seismic noise in the region [0.1, 1]Hz!!!

L.Trozzo

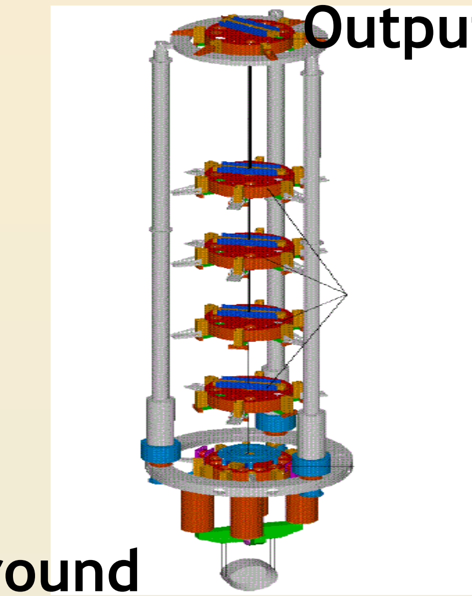
Blending technique: above 100 mHz

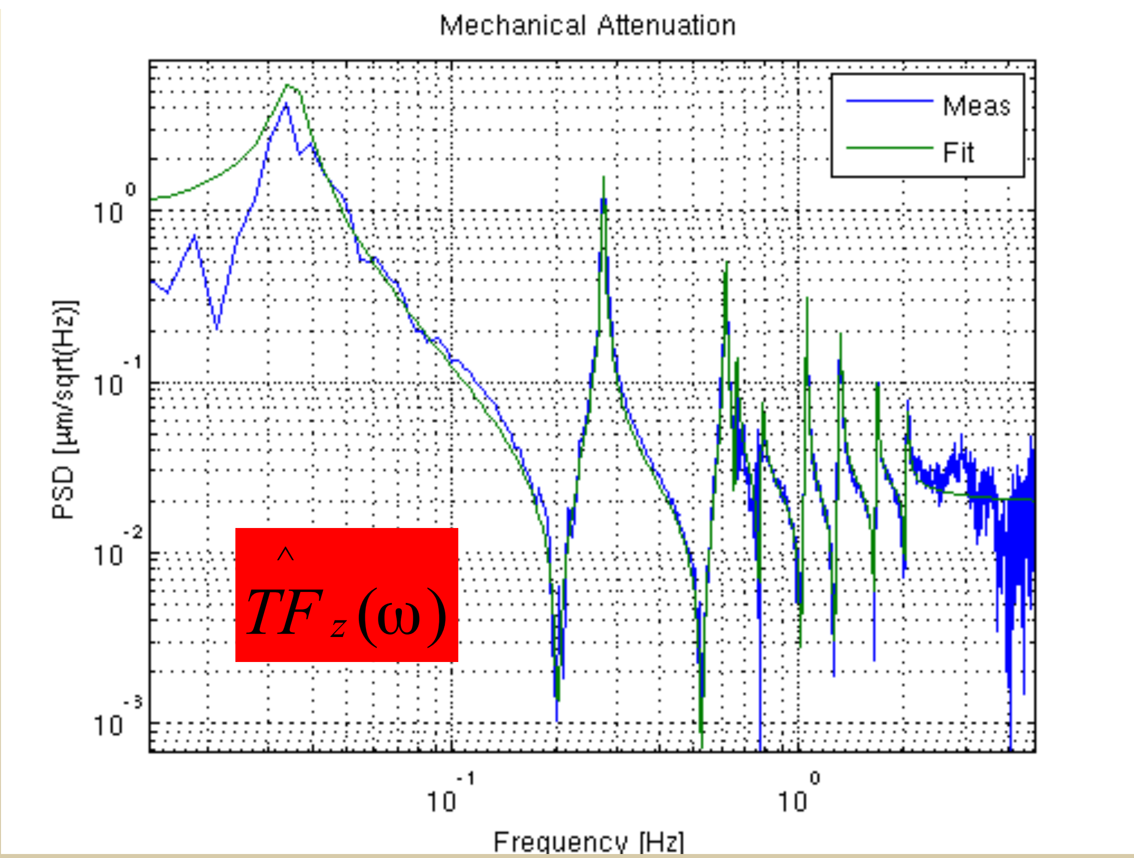
Above 100 mHz the main source of noise contaminating the BVS sensor, is the seismic noise: [0.100÷3]Hz.

To shape the LP filter and to tune the blending frequency we need to know the effective closed loop transfer function:



$$\hat{TF}^{CL}_{eff}(\omega) \approx \hat{TF}^{CL}_{mecc}(\omega) + \hat{TF}^{CL}_{sens}(\omega)$$





- Mechanical Contribution

$$\hat{A}(\omega) = \frac{\hat{TF}_z(\omega)}{1 - \hat{M}_z(\omega)\cdot\hat{C}_z(\omega)}$$

- Sensing contribution

$$\hat{B}(\omega) = -\frac{\hat{LP}(\omega)\cdot\hat{M}_z(\omega)\cdot\hat{C}_z(\omega)}{1 - \hat{M}_z(\omega)\cdot\hat{C}_z(\omega)}$$

$$\hat{s}^{CL}_{z_{TOP}}(\omega) \approx [\hat{A}(\omega) + \hat{B}(\omega)]\cdot\hat{s}_{zLs}(\omega)$$

Blending technique: above 100 mHz

✓**Mechanical contribution (A) composed by**
- The mechanical TF
- The corrector filter
- The mechanical attenuation

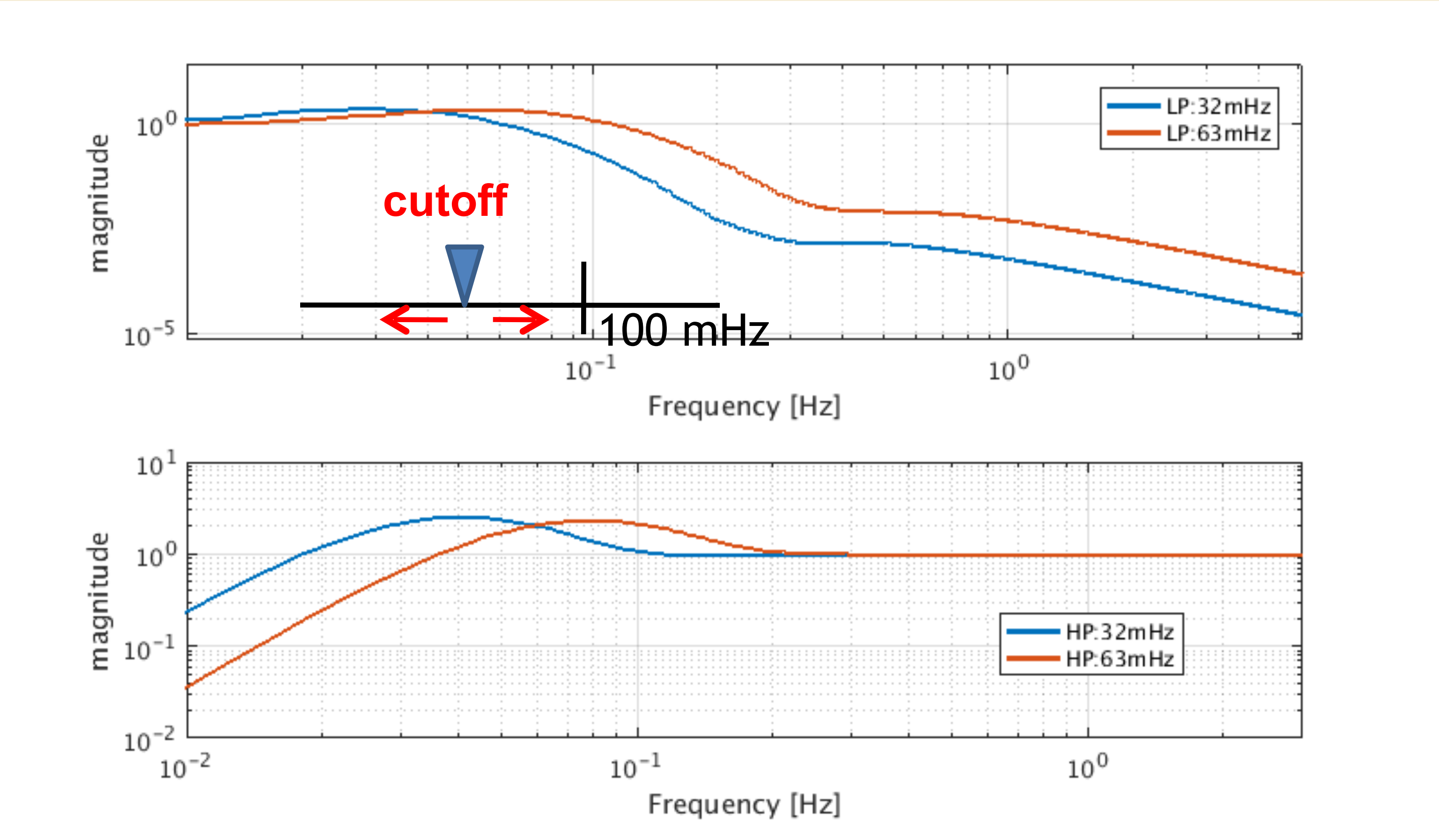
✓**Sensing contribution (B) composed by**
- The mechanical TF
- The corrector filter
- Low Pass pre-filtering

➢ **A and B are two available handles to optimize the blending strategy**

1) design preliminary corrector and a simple blending

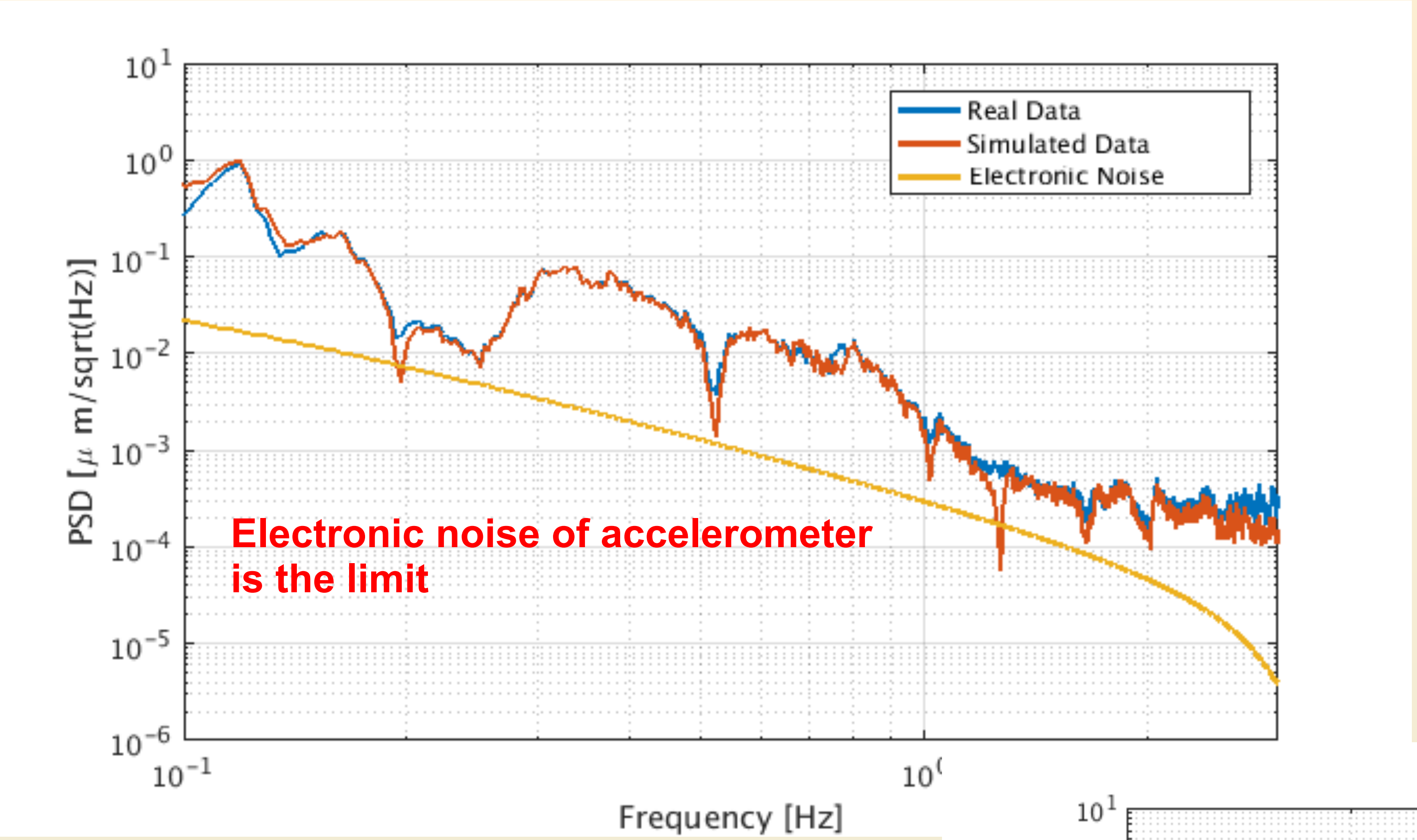
2) Measure $\hat{TF}_z(\omega)$

- **Work on** $\hat{C}_z(\omega)$
- **Work on** $\hat{LP}(\omega)$



Blending technique: above 100 mHz

➢ **STEP 1 Real Data Simulation**



➢ **STEP 2 low pass tuning**

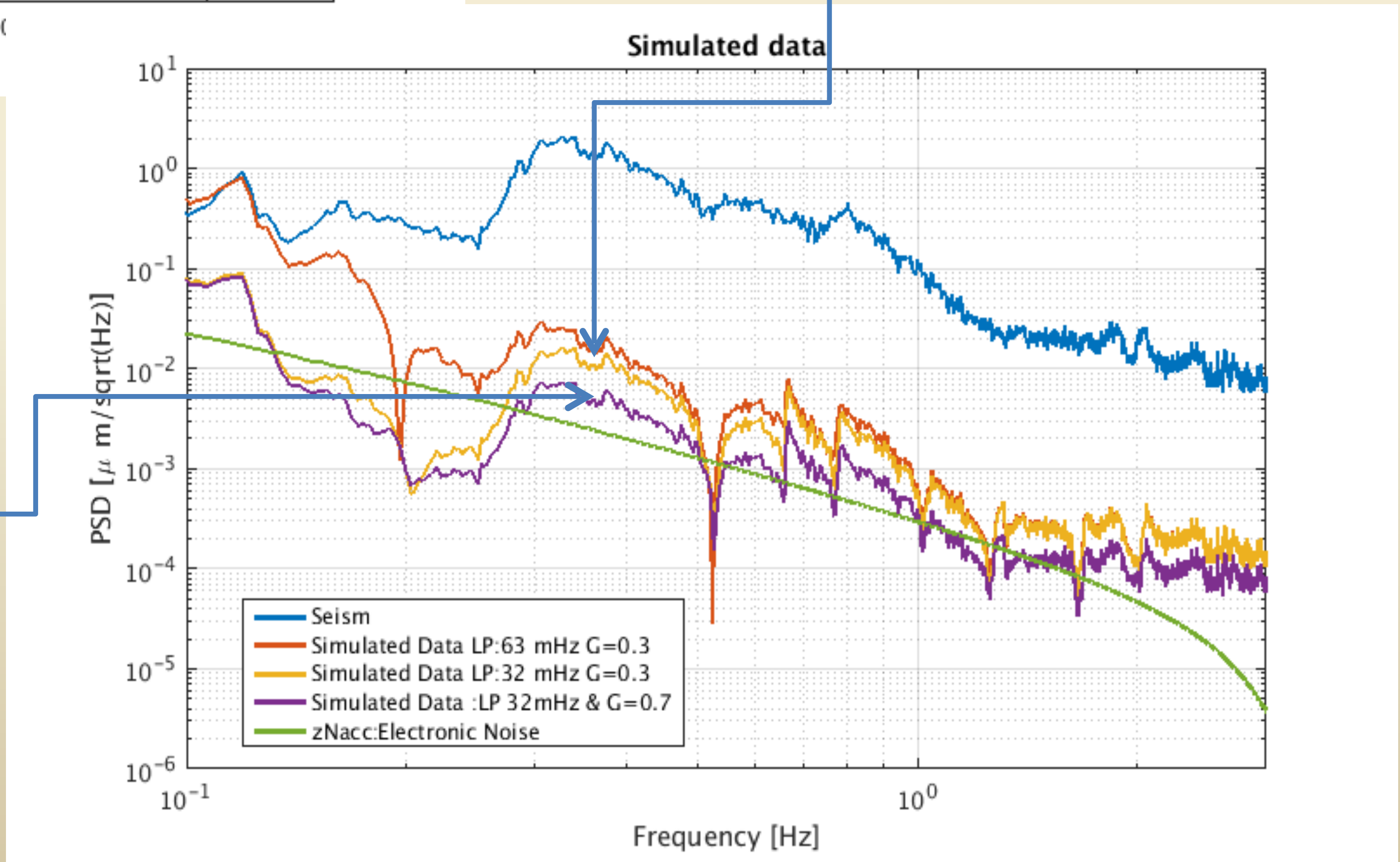
Tune LP (shape, blending frequency, etc.)

to change $\hat{B}(\omega)$

➢ **STEP 3 corrector filter tuning**

Tune $\hat{C}(\omega)$

to change $\hat{A}(\omega)$

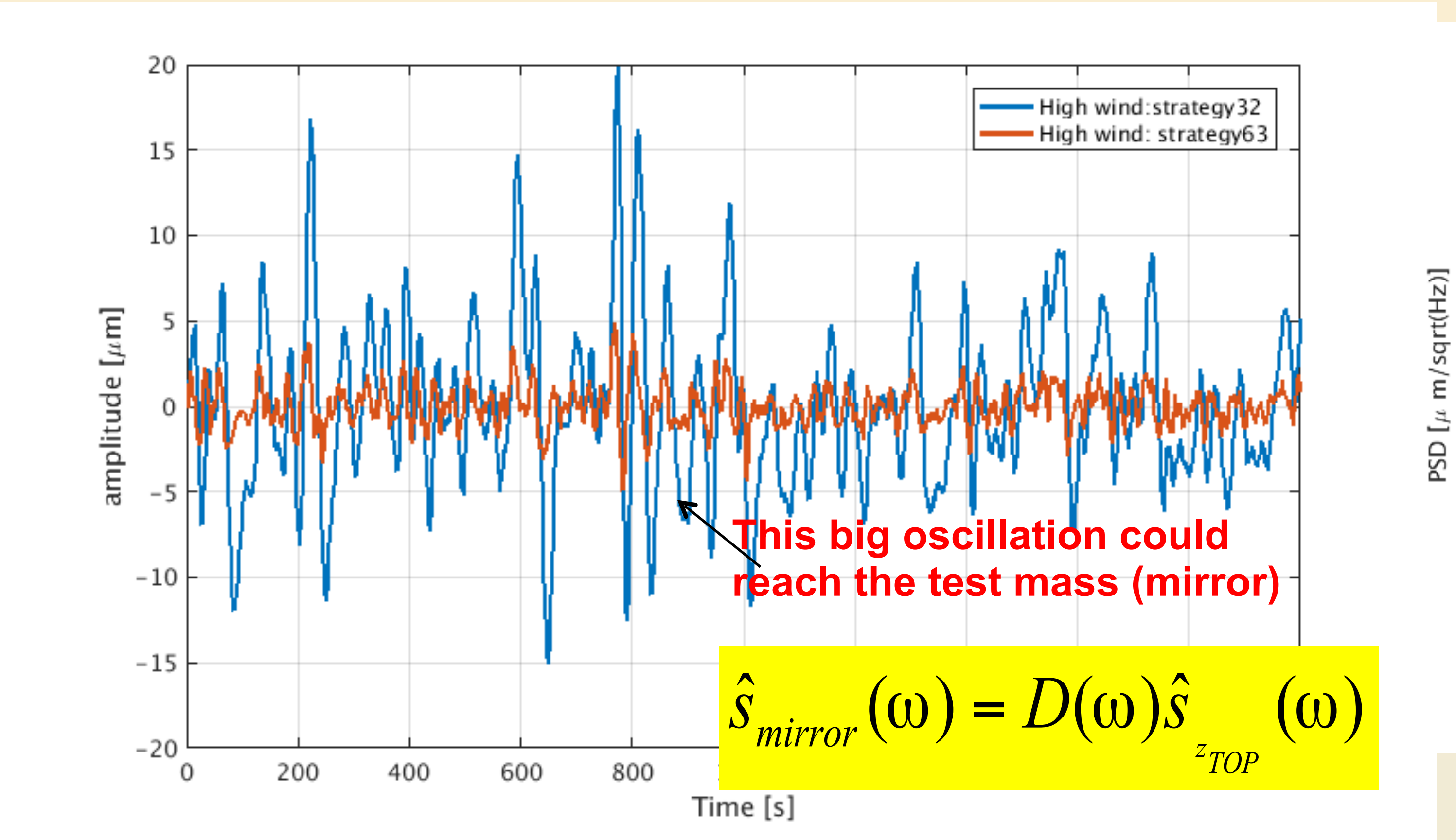


Blending technique: below 100 mHz

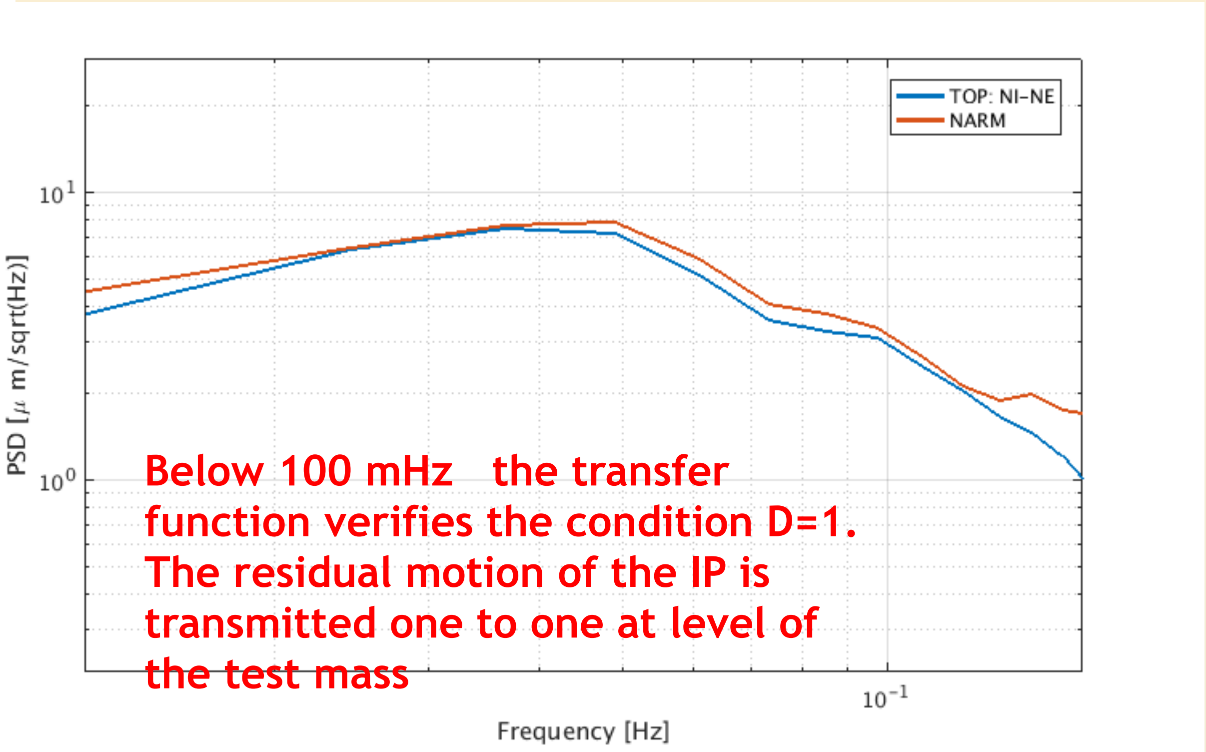
Below 100 mHz the noise of the accelerometer is dominant.

It is possible to quantify the re-injected accelerometer noise by defining the ratio of the HP filters:

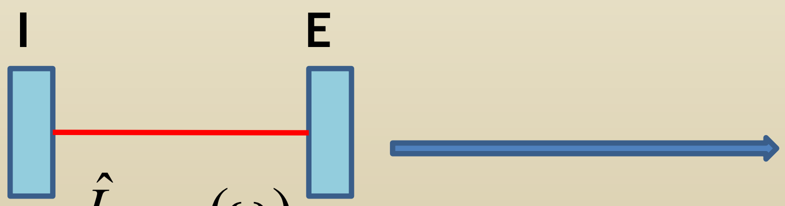
$$r(\omega) = \frac{\hat{HP}'(\omega)}{\hat{HP}(\omega)} \Rightarrow \hat{s}'_{z_{TOP}}(\omega) = r(\omega)\hat{s}_{z_{TOP}}(\omega)$$



$$\hat{s}_{mirror}(\omega) = D(\omega)\hat{s}_{z_{TOP}}(\omega)$$



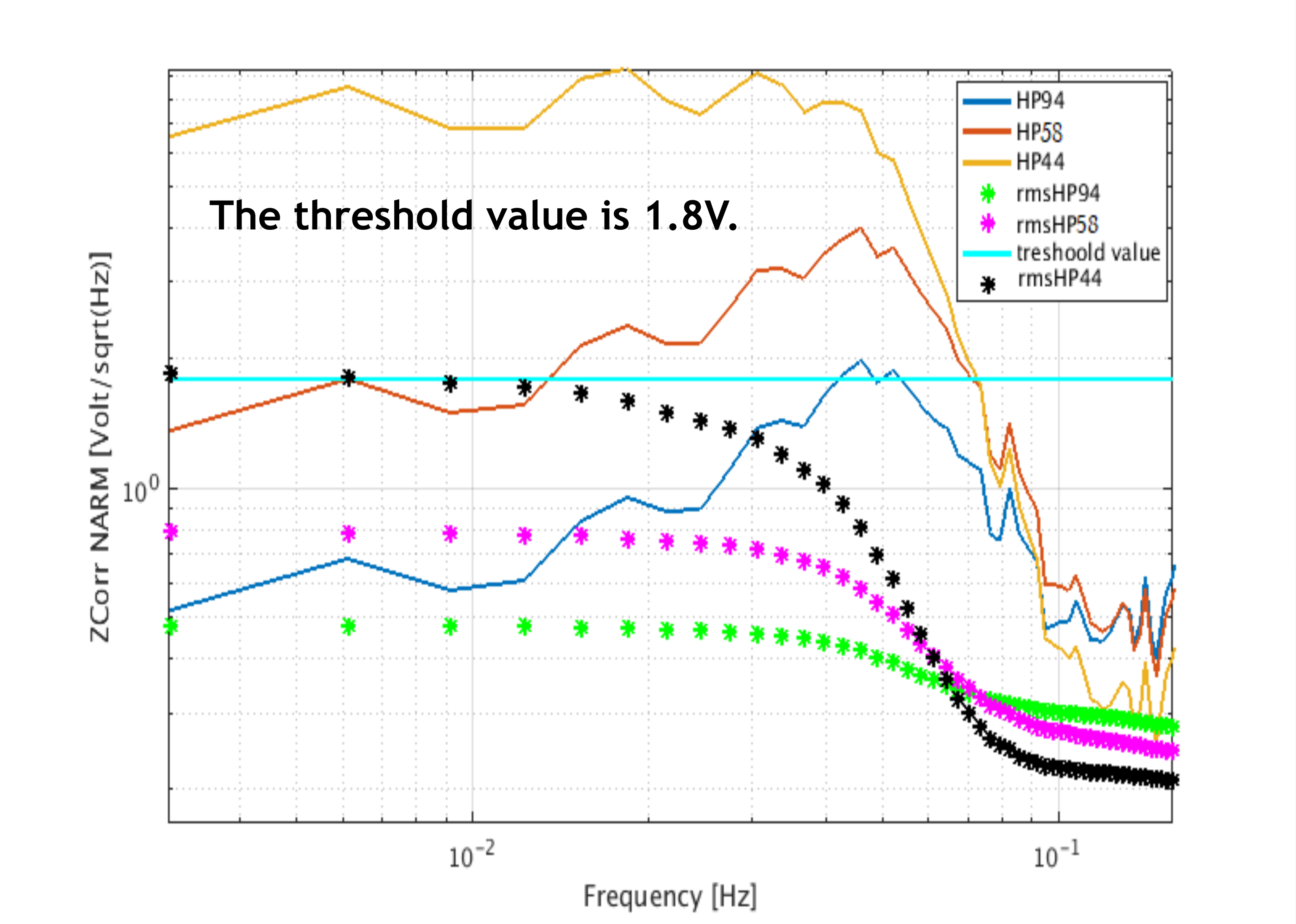
It is possible to study the impact of several strategies on the mirror motion and on the **locking correction signal** by using r(ω):



$$\hat{L}_{cavity}(\omega)$$

$$\hat{L}_{cavity} = c \cdot \hat{S}_{z_{Lock}} = \sqrt{(\hat{s}^{I}_{z_{TOP}})^2 + (\hat{s}^{E}_{z_{TOP}})^2}$$

Blending technique: below 100 mHz



We applied r on the locking correction signal to see which blending strategy makes it saturated.

The locking correction increases when moving the blending frequency from 94 mHz to 44 mHz. The rms of signal computed by applying the blending strategy with blending frequency at 44mHz (black star), in the range 10÷30mHz, is very close to the threshold value.

<u>The chosen compromise for the scientific run O2 was the strategy63 because it stays below the threshold value in a large part of the environmental conditions.</u>

Global Inverted Pendulum Control: GIPC

The tuning of the blending frequeny is a "compromise", to minimize at the same time the re-injection of seismic noise above 100 mHz and the disturbances due to the use of inertial sensors below 100 mHz.

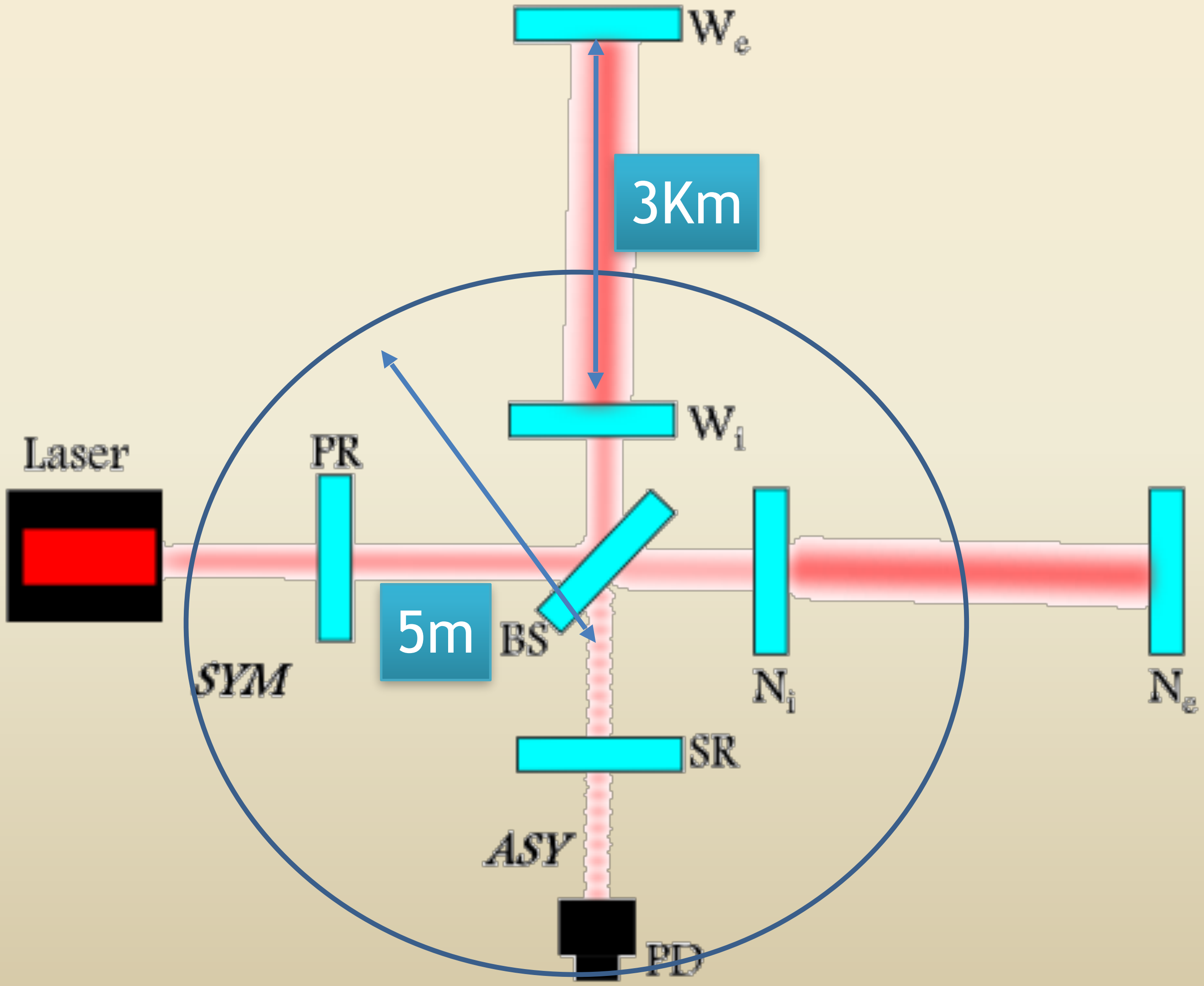
To apply a blending strategy with very low blending frequency we move to a different control scheme: Global Inverted Pendulum Control (GIPC).

Base changing: the translational coordinates of the different IP are mixed in order to build two common coordinates (one for X and one of Z), and many differential coordinates

the diagonalized LVDT sensors see, along the i−th direction, coherent seismic contributions.

Central area:

Not in scale!



GIPC Control

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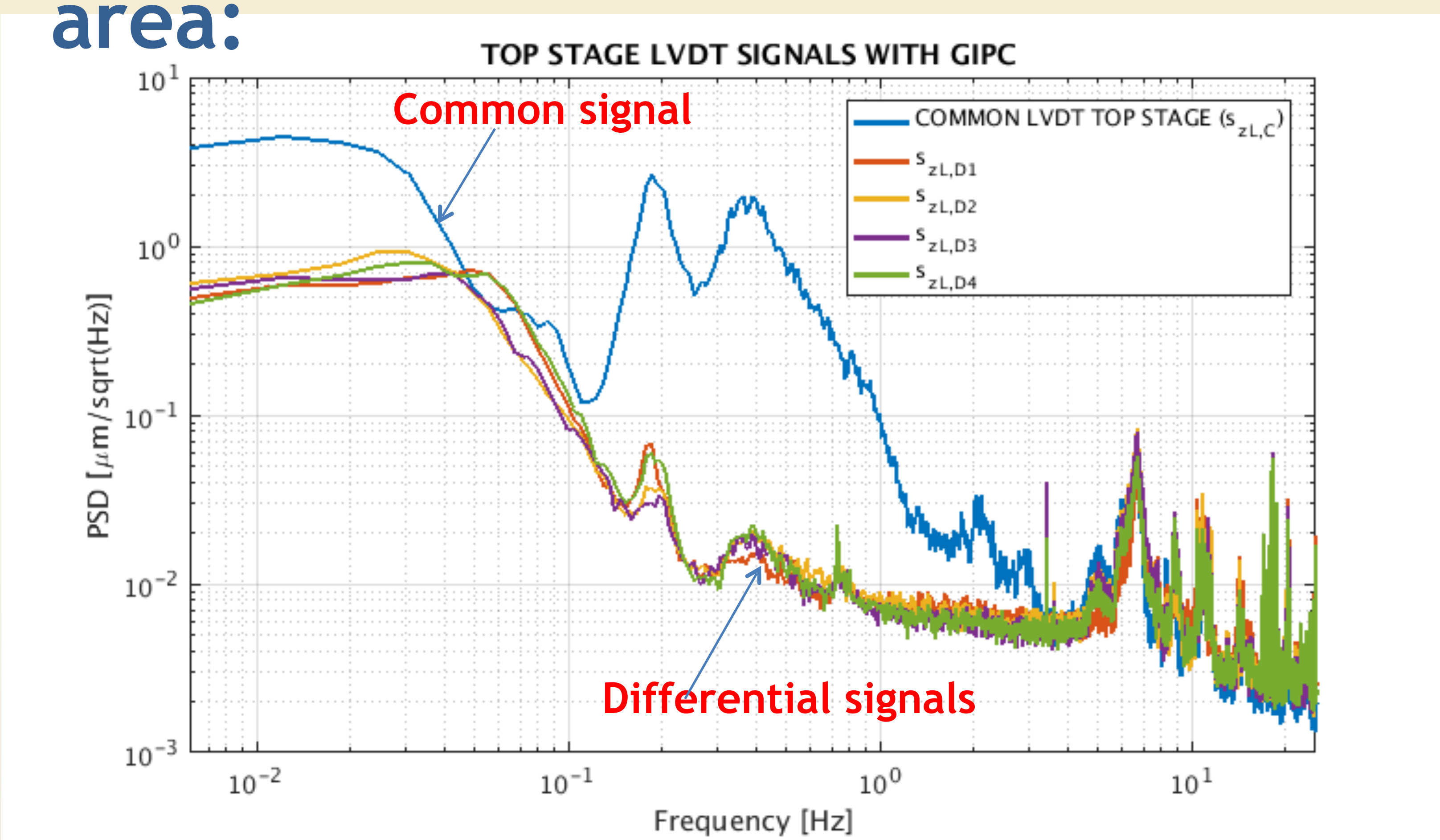
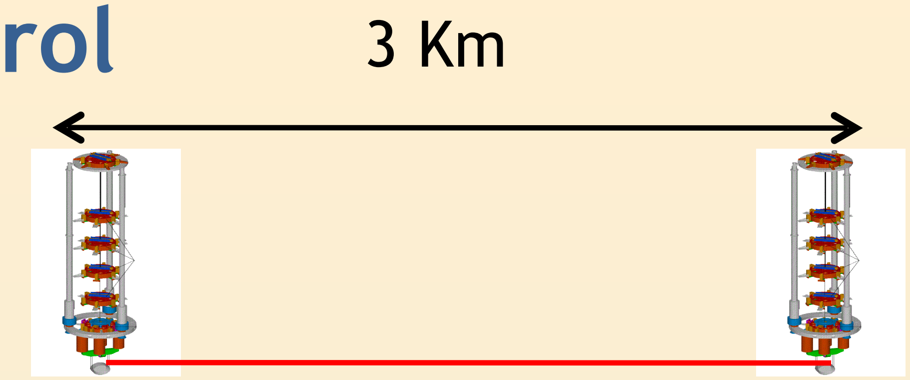


To clean the common signal from the seismic component we can use a blending strategy at 32mHz (without spoiling the locking signal of the interferometer).

We can apply a strategy at 63mHz on the differential signals because these not introduce seismic contribution

GIPC Control

For the cavity the situation is different: we have two IPs located at 3 Km from the central area

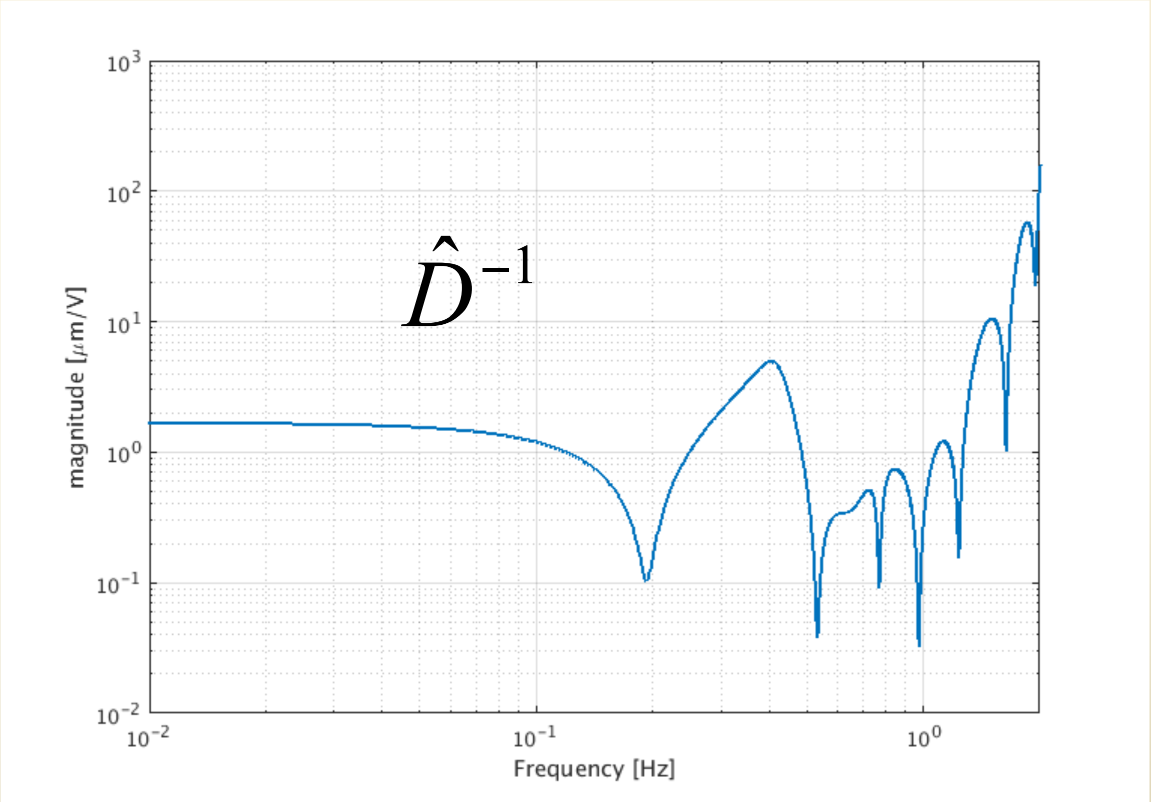


The seismic contributions contaminating the LVDT of End and Input suspensions are uncorrelated and, consequently, the recombination adopted for the central area is not effective.

We need an additional differential signal equivalent to the LVDT:

The signal monitoring the elongation of the cavity ΔL

From the top to the bottom there are 8 stages of attenuation
To correctly implement the GIPC control the signal must be treated in order to become equivalent to the LVDT



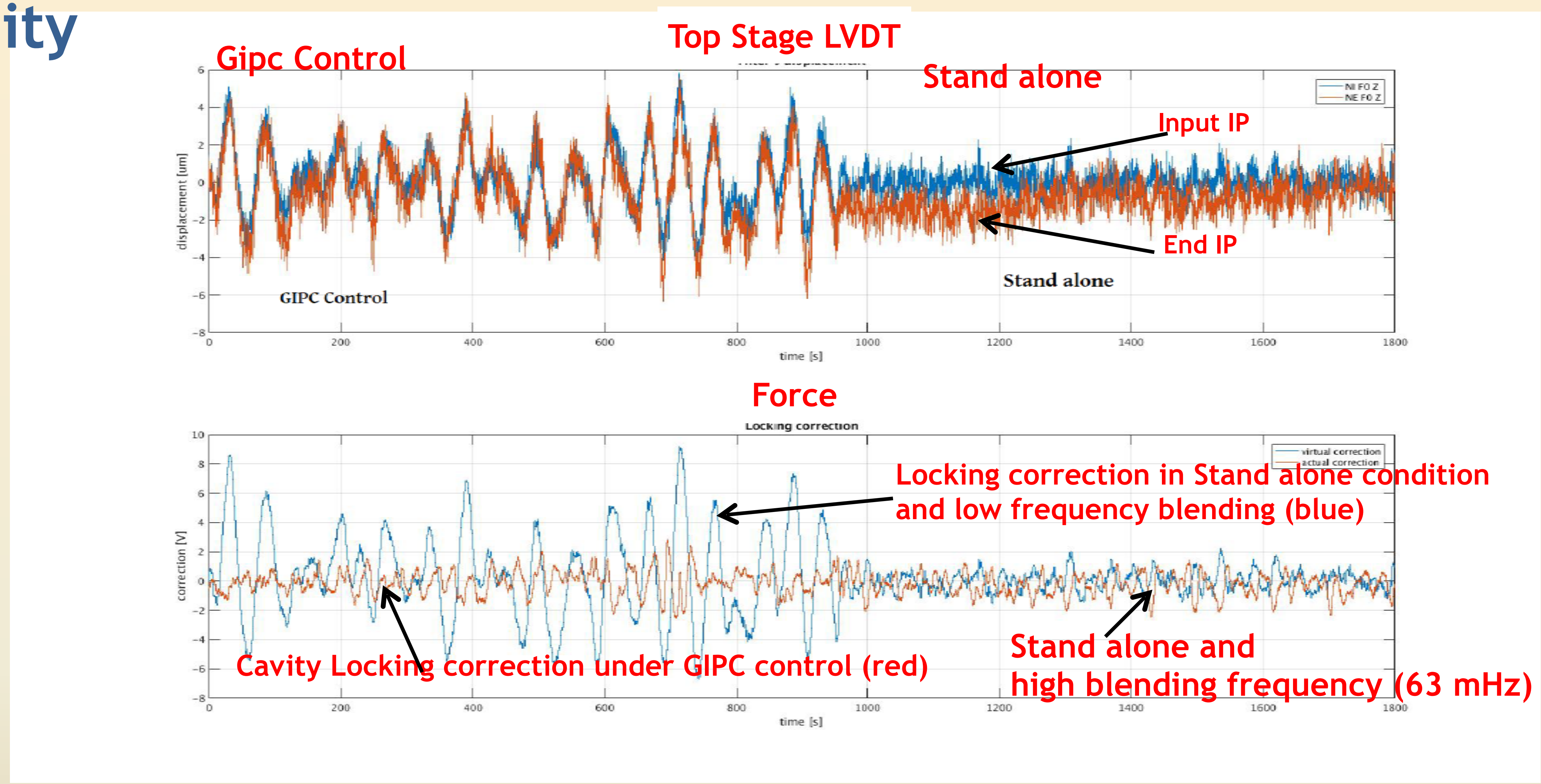
$$L_{vdt}^{end} \approx \hat{D}^{-1} \cdot \Delta L$$

D is the transfer function between top stage (input) to mirror (output)

GIPC Control

On the cavity

Blending technique (very low blending frequency)



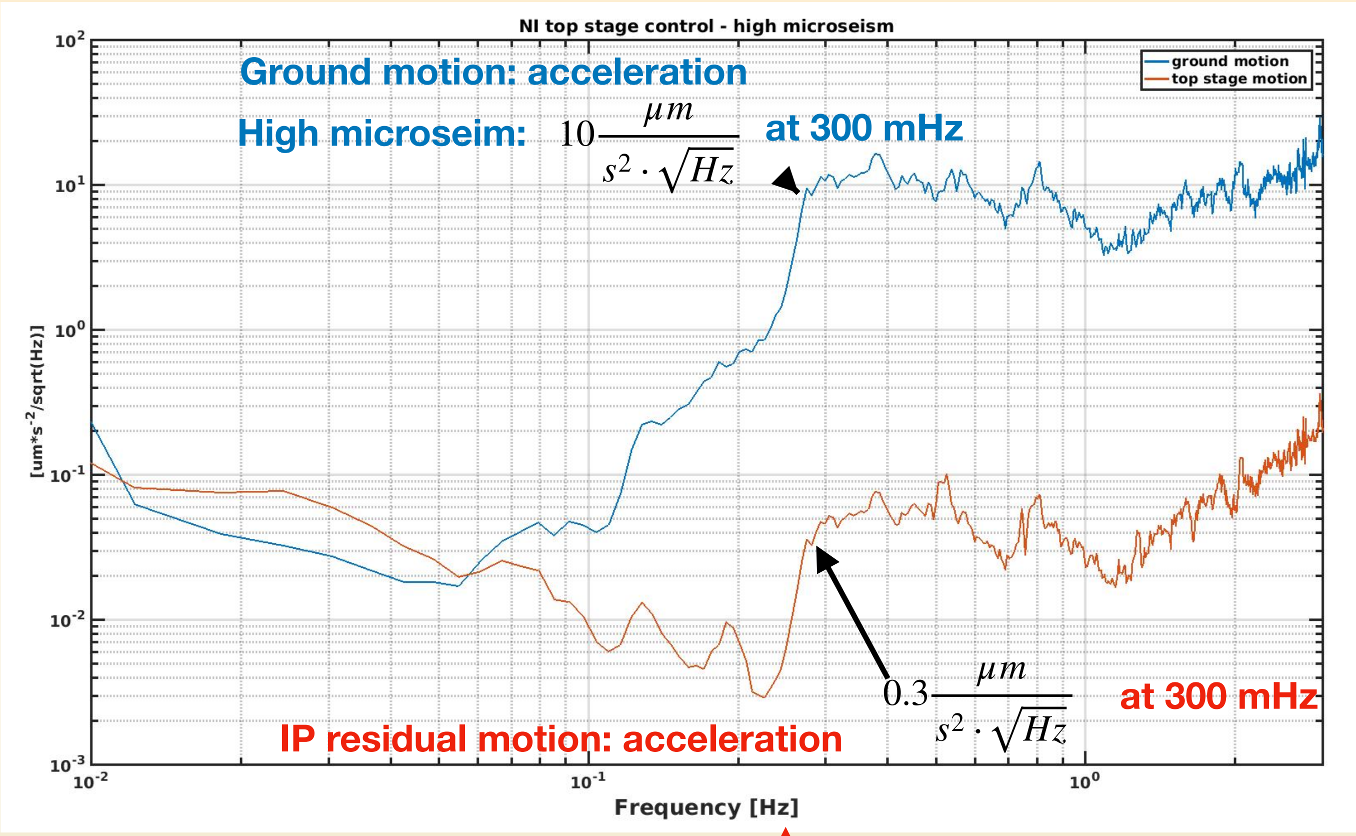
✓The length of the cavity remains unchanged and the locking correction is reduced

✓Since the End IP is controlled with the differential GIPC signals, it sees and consequently follows the motion of Input IP

VIRGO Suspensions: IP residual motion

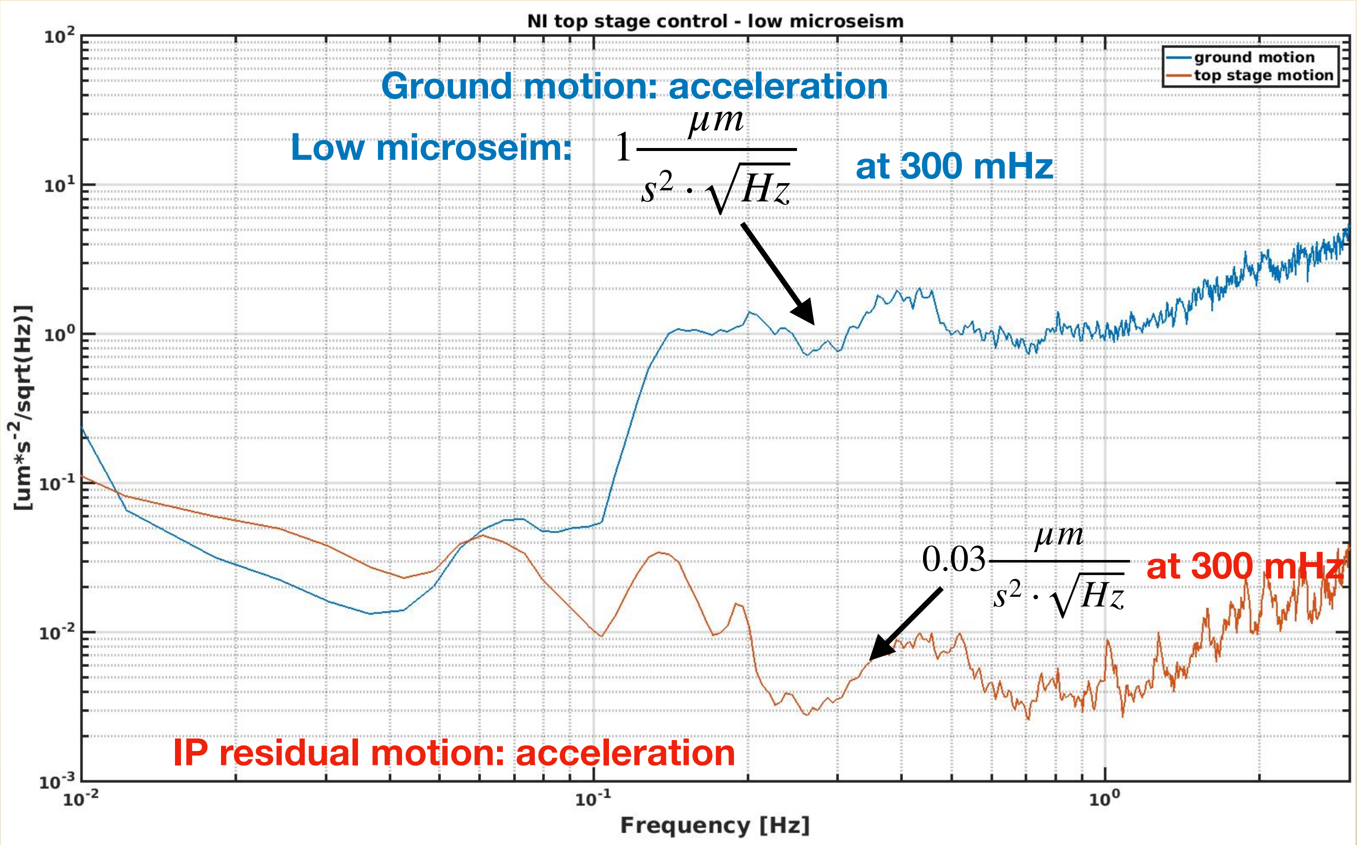
When the IFO is locked these loops are engaged

- ✦ IPs are under GIPC control (X,Z)
- ✦ Marionette: Pitch and Yaw under automatic alignment (global control)



High microseism

Here we show the IP residual motion in two different environmental conditions



Low microseism

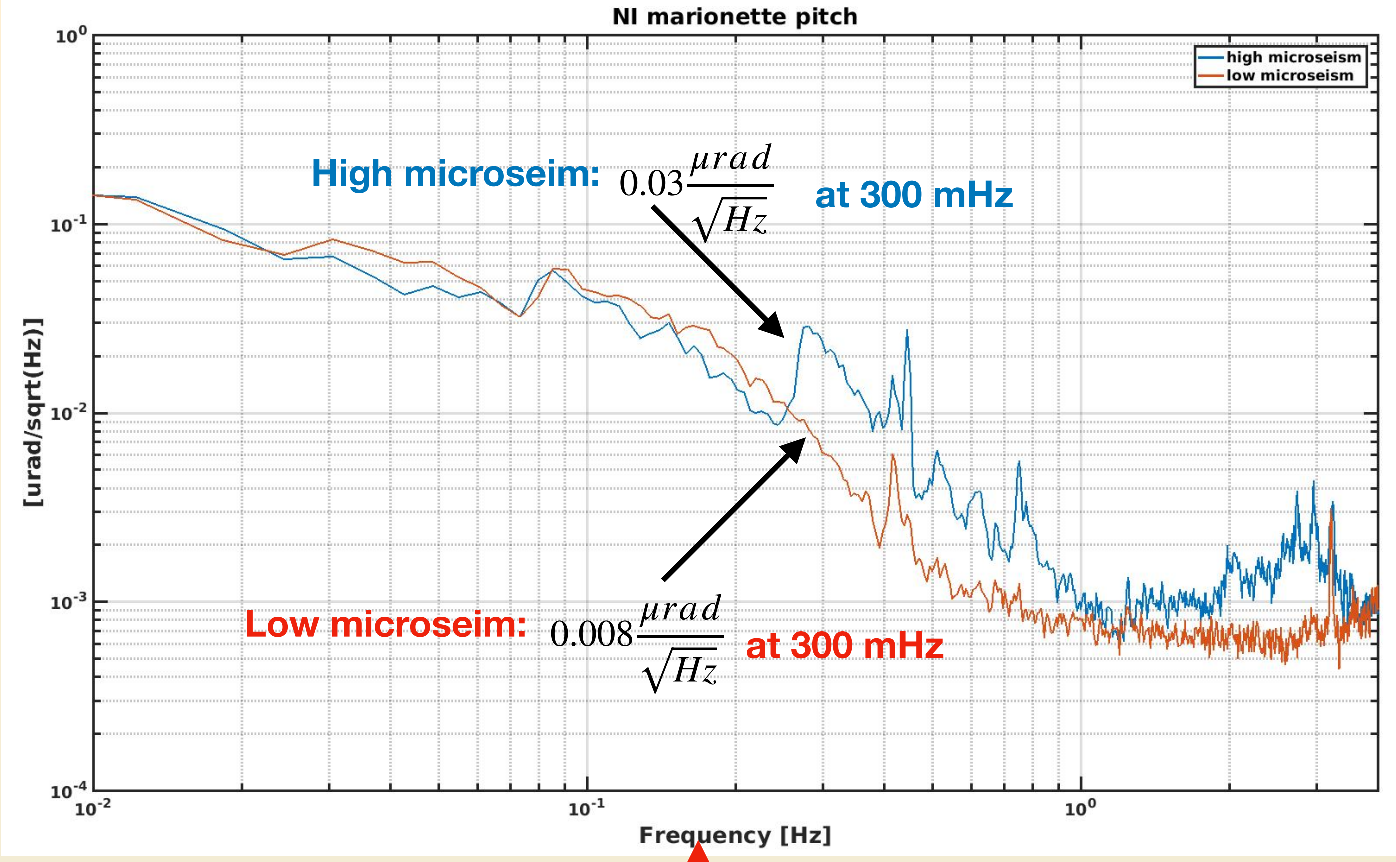
Plots by Paolo Ruggi (EGO-Virgo collaboration)

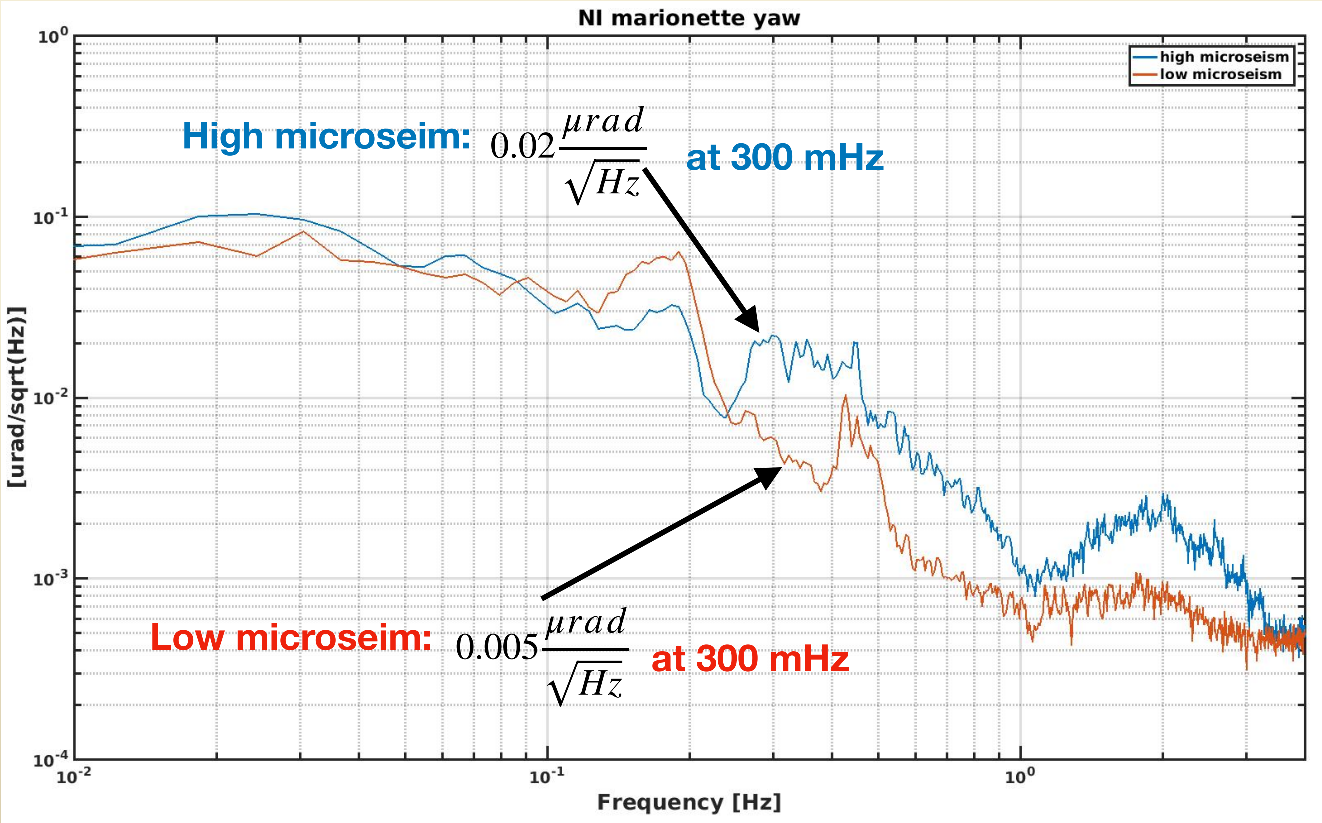
VIRGO Suspensions: residual angular motion

When the IFO is locked these loops are engaged

✦IPs are under GIPC control (X,Z)

✦Marionette: Pitch and Yaw under automatic alignment (global control)





Pitch

Here we show the marionette angular residual motion for Pitch and Yaw in two different environmental conditions:

Yaw

High microseism

Low microseism

Plots by Paolo Ruggi (EGO-Virgo collaboration)

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    •Below 100 mHz

    •GIPC Control

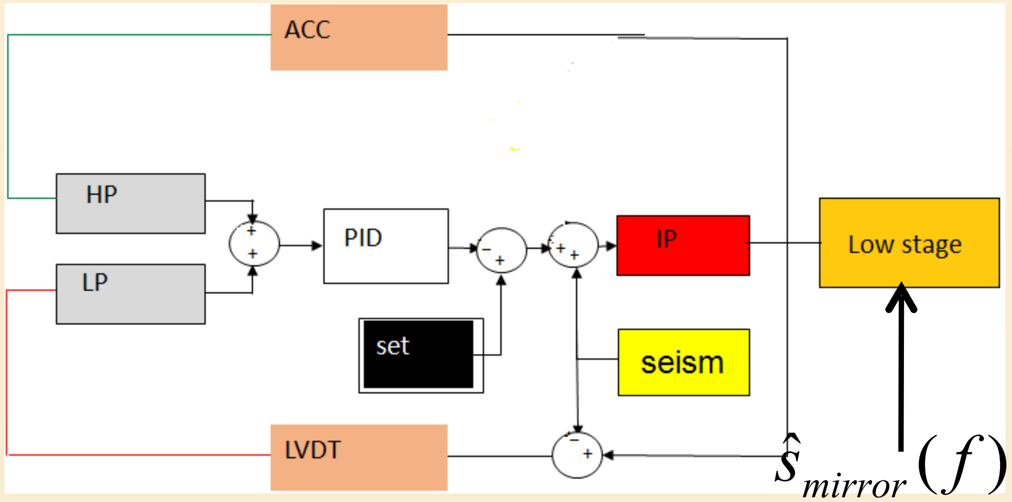
  ➢Suspension control Noise

VIRGO sensitivity: low frequency

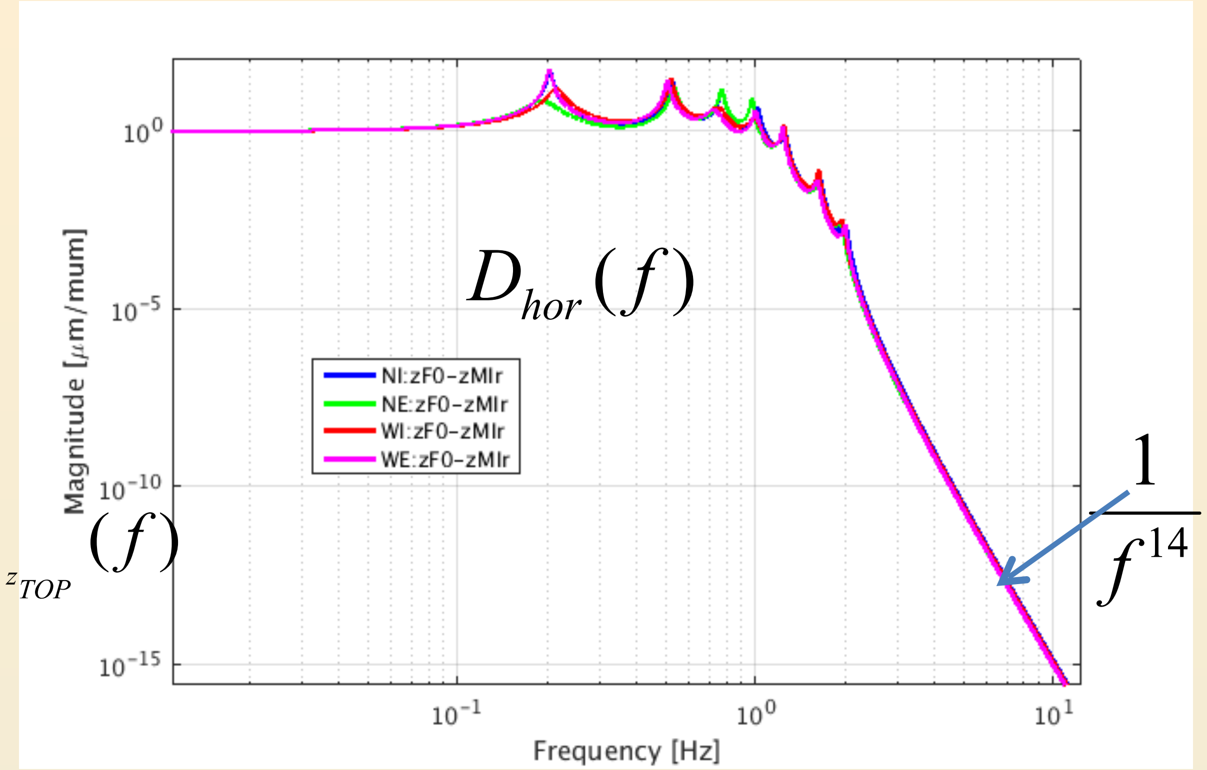
Below 10 Hz the Virgo sensitivity is limited by mechanical noise:

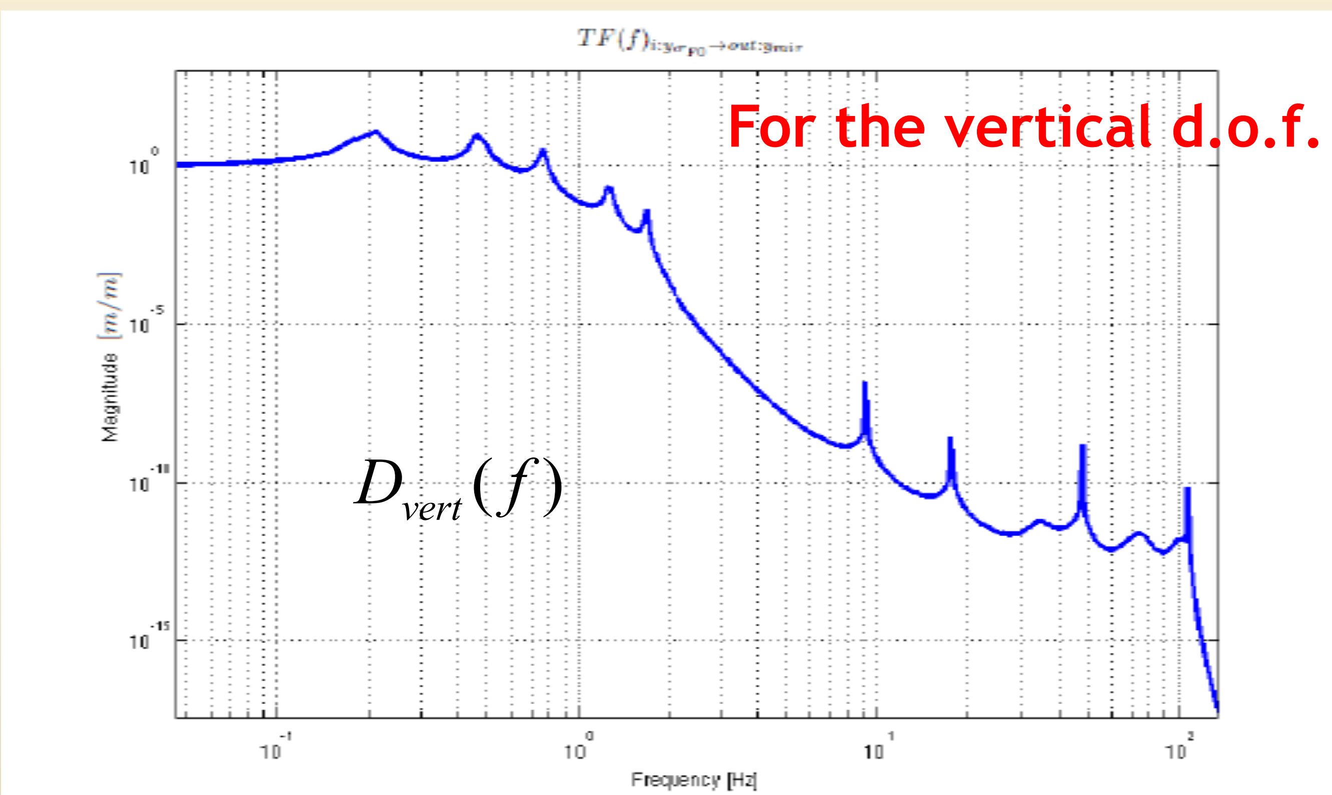
- ➢ Horizontal seismic noise where the mechanical attenuation is low f<2 Hz
- ➢ Vertical seismic noise transmitted to the horizontal direction due to the incliniation of the test mass
- ➢ Angular control noise f<10 Hz
- ➢ Other possible control or actuation noise

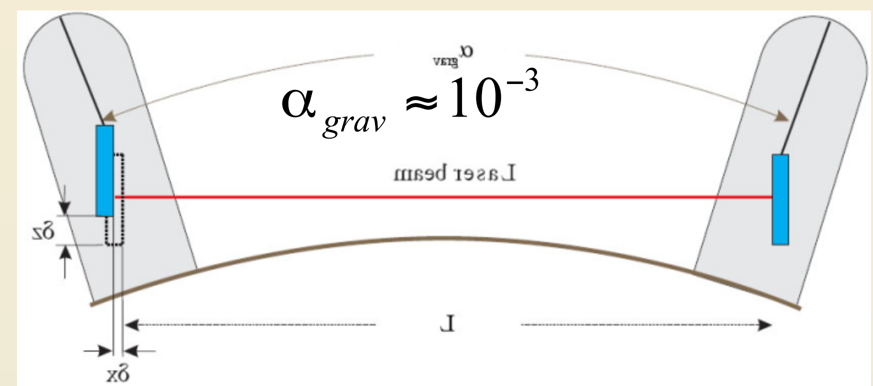
VIRGO low frequency sensitivity



$$\hat{s}_{mirror}(f) = D_{hor}(f)\hat{s}_{z_{TOP}}(f)$$





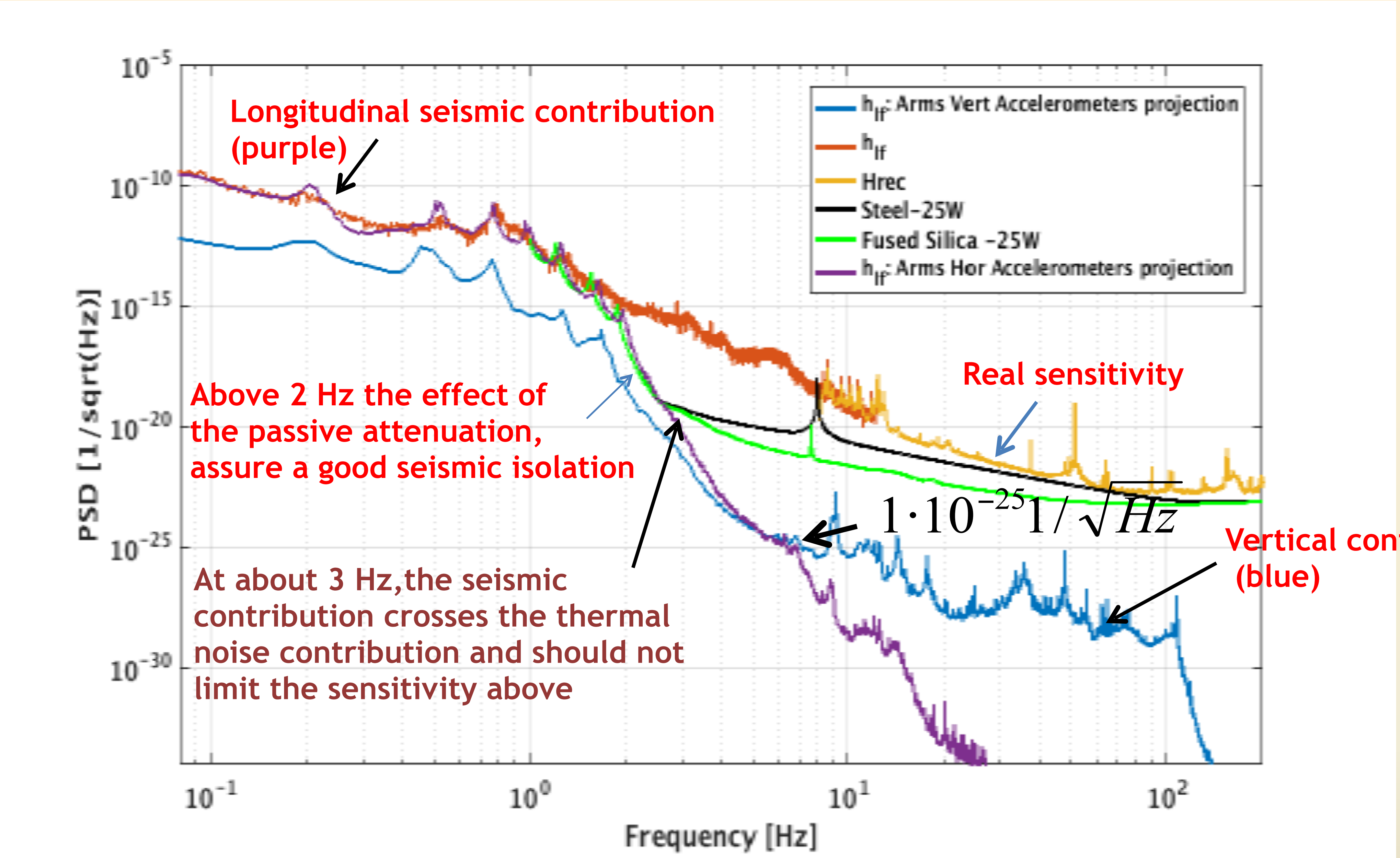


The coupling effect between the horizontal and vertical directions due to the Earth curvature on distance like 3 Km is not negligible

$$\hat{s}_{mirror}(f) = \alpha_{grav} \cdot D_{vert}(f)\hat{s}_{y_{TOP}}(f)$$

By combining the signals of the suspensions of the FP cavities we can compute the low-frequency strain sensitivity

Low frequency sensitivity at the time of GW170814



✓In the region [0.1, 0.8] Hz the rms of the test mass speed (v), in low seismic noise conditions reaches the value v < 10−7 m/s

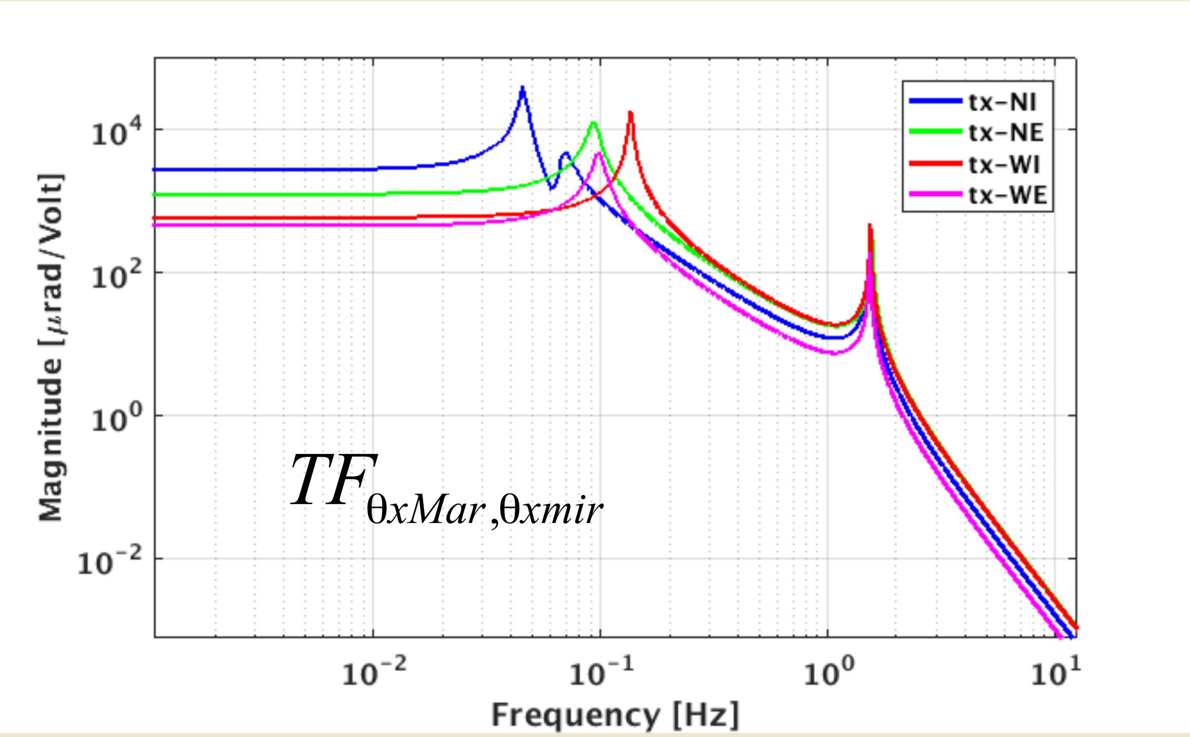
✓In high seismic noise conditions, is still low enough to acquire the lock (v < 5×10−7 m/s)

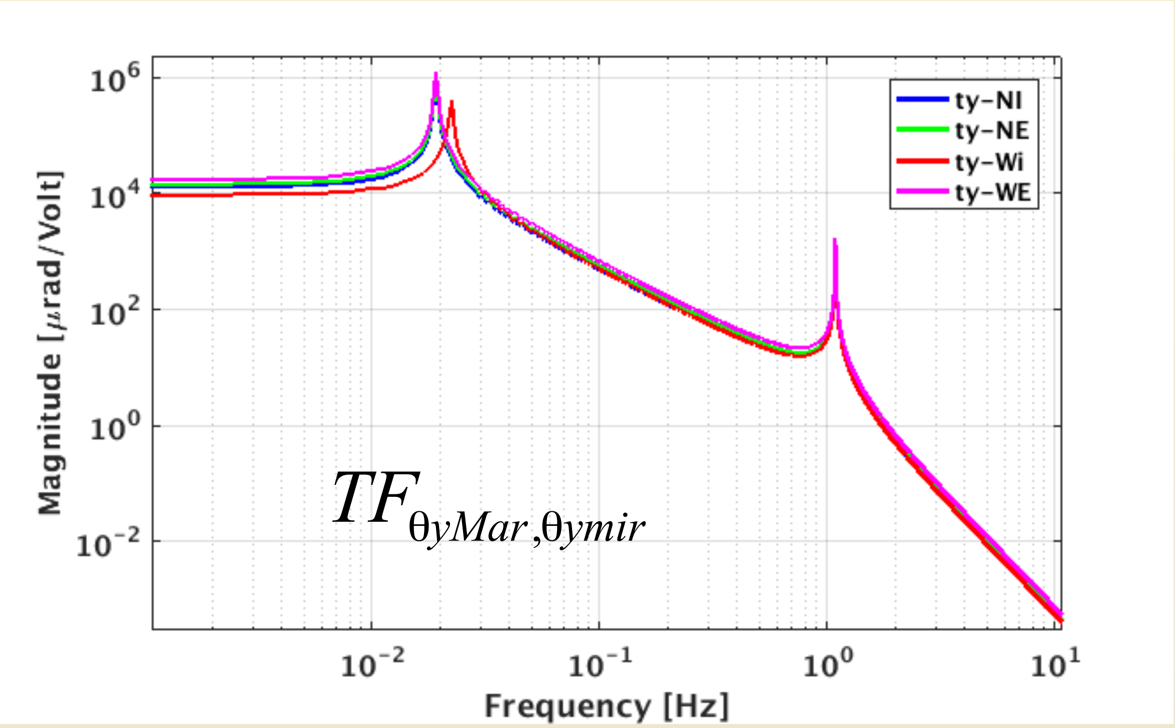
Angular control Noise

Above 2 Hz, the feedback force sent through the coils on the marionette can re-inject angular control noise

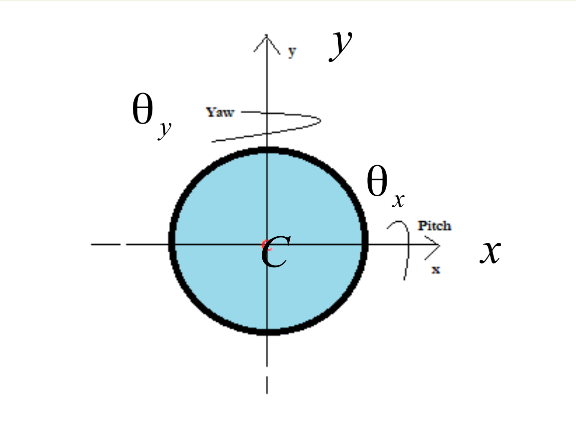
The residual motion of the mirror in Pitch and Yaw is

$$\hat{s}_{\theta_i mir}(f) = c_{\theta_i} TF_{\theta_i Mar,\theta_i mir} \hat{S}_{\theta i,Mar_{Corr}}$$

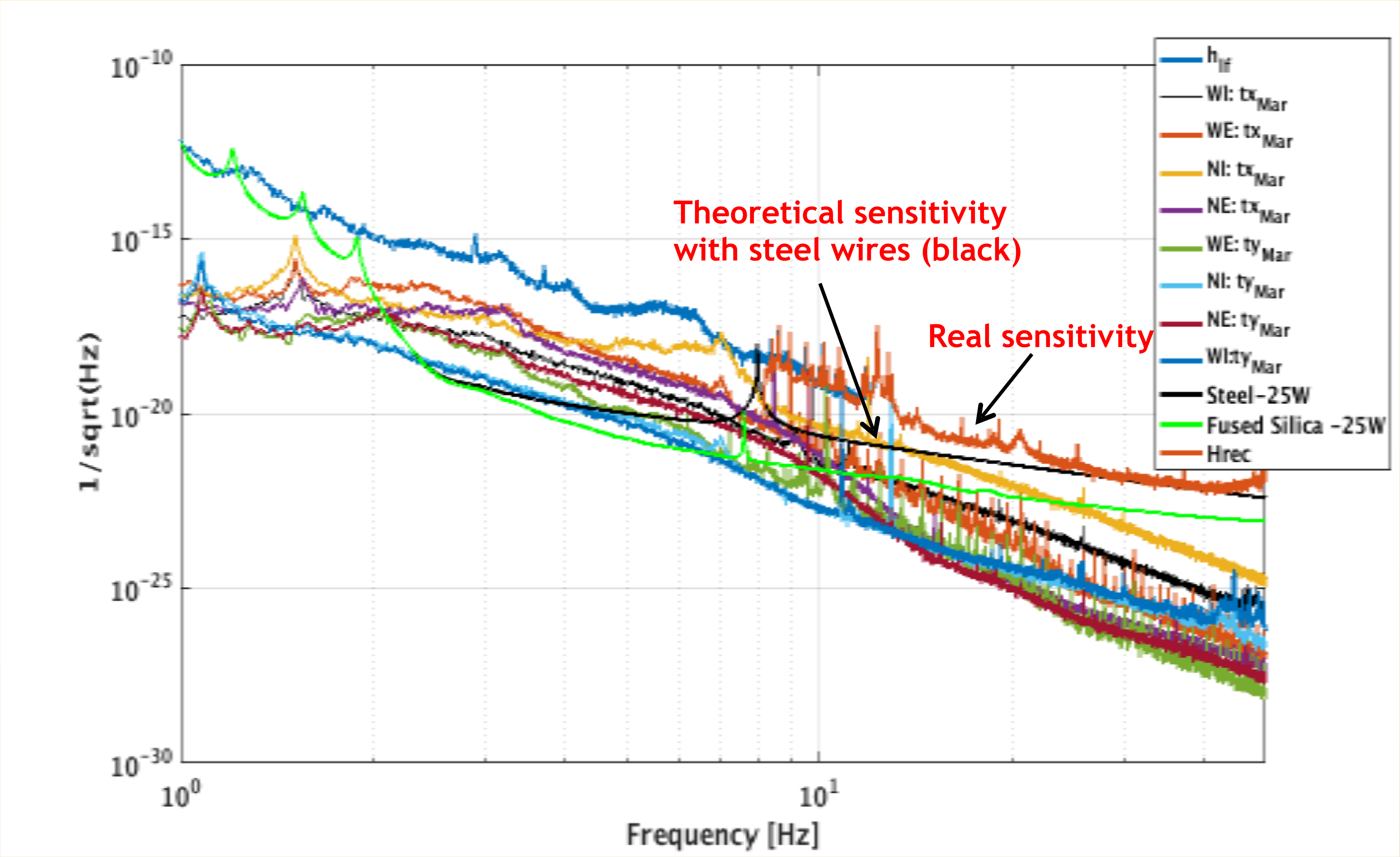




c_{θ_i} **is the parameter that quantifies the decentring of the beam with respect to the center of the mirror (C).**



Angular control noise budget at time of GW170814



Estimated $c_{\theta_i} \approx 50\mu m$

	c_{θ_i} Pitch (m)		c_{θ_i} Yaw (m)
NI	0.7×10^{-4}		0.8×10^{-5}
NE	0.3×10^{-4}		0.4×10^{-5}
WI	0.1×10^{-4}		0.7×10^{-5}
WE	0.2×10^{-4}		0.4×10^{-5}

Thanks for your attention!!!!