R&D of new seismic filters
Black Holes for ET at Sos EnAttos
BHETSA

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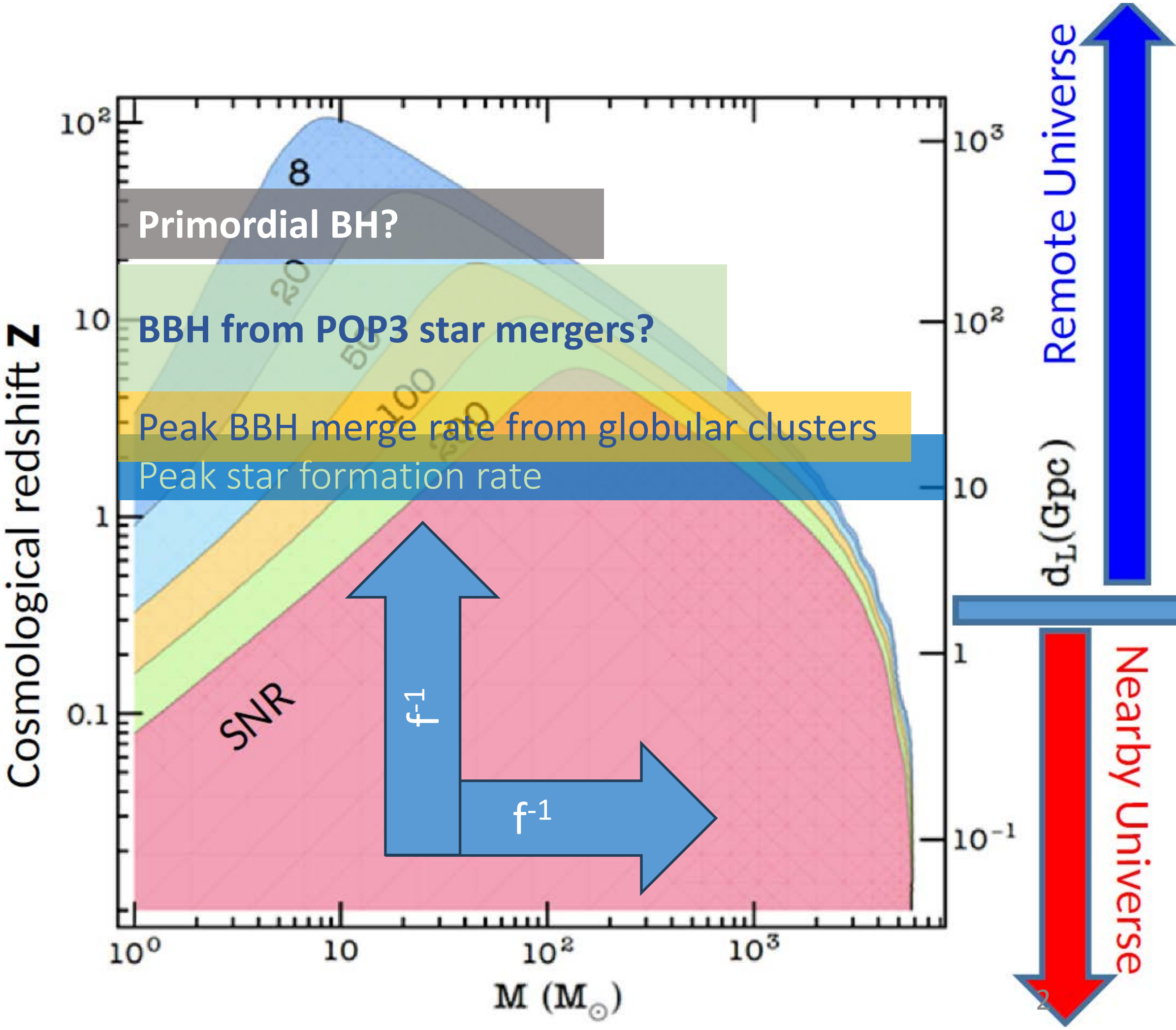
INFN – Na, INFN – Pi, Uni Napoli, Uni Pisa, Uni Sassari, Uni Urbino

Virgo Pisa workshop, May 22, 2024

LF Motivations

Low frequency sensitivity gives access to:

- Higher binary system mass $\propto f^{-1}$
- Higher generated amplitude, higher SNR
- Higher cosmological redshift
- Longer signal duration, early alert $\propto f^{-8/3}$
- Larger pulsar population
- Close encounters
- Higher stochastic background, if detectable



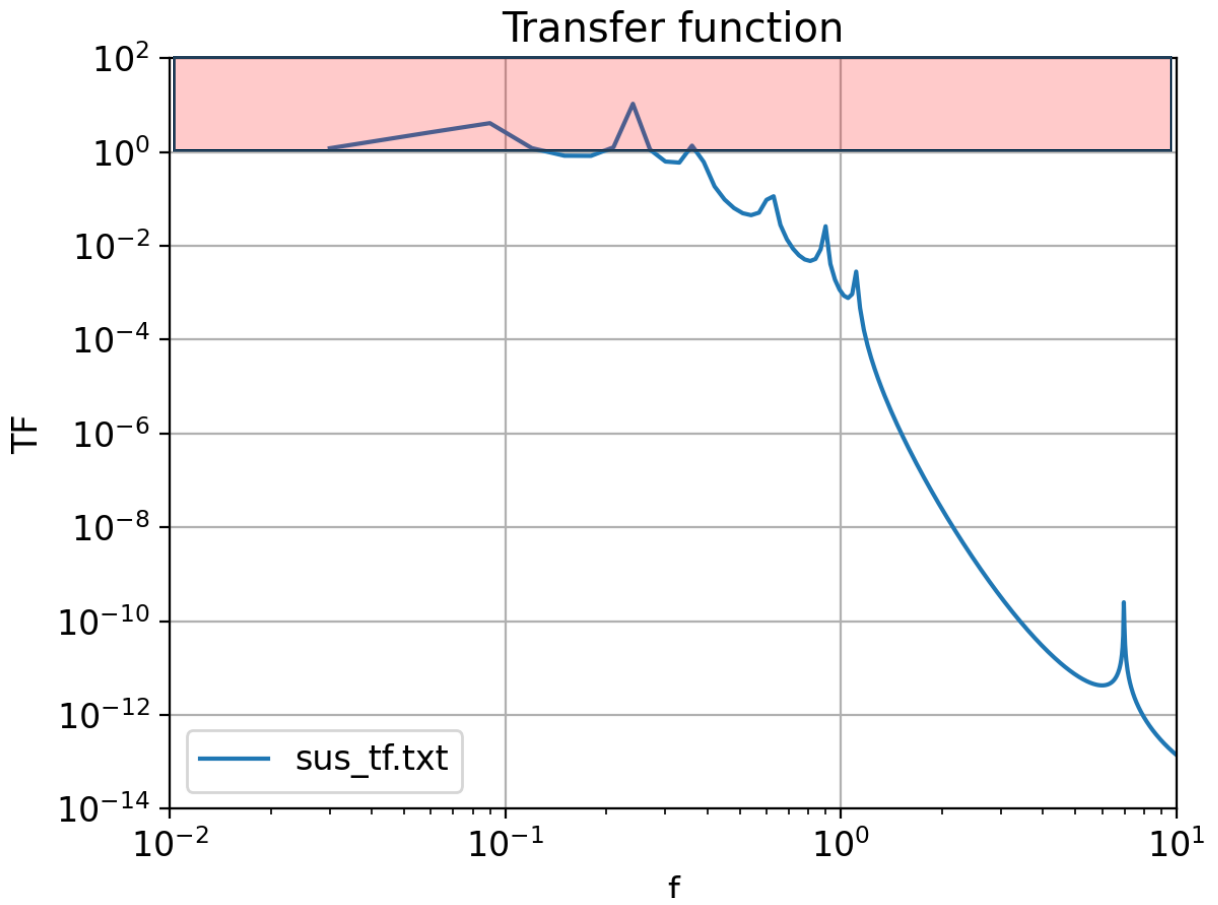
Low frequency noise

From the GW community: LF question requires to study

- **Size of the problem and origin of LF noise**
- **Reduce RMS motion**
- **Controls**
- **Diffuse light**

Seismic attenuation in Virgo

- **Ground motion 10^{-7} m $Hz^{-1/2}$ at 1 Hz vs 10^{-18} m $Hz^{-1/2}$ at 10 Hz**
- **Test mass asks for a very loose link**
  - Low pass filter with a steep frequency cut below the detection band
  - Cascade of harmonic oscillators (Second Order Sections)
  - Loose springs and high masses
- **Dissipation to be avoided, not compatible with loose link**
- **Loose link through local active control limited by sensor noise**
- **Passive isolation for a large fraction of the chain**
- **But amplification at normal modes**



ET-LF requirements

LF noise is given by

- Microseism motion
- Newtonian noise
- Upconversion of residual motion into the detection band
- Control noise

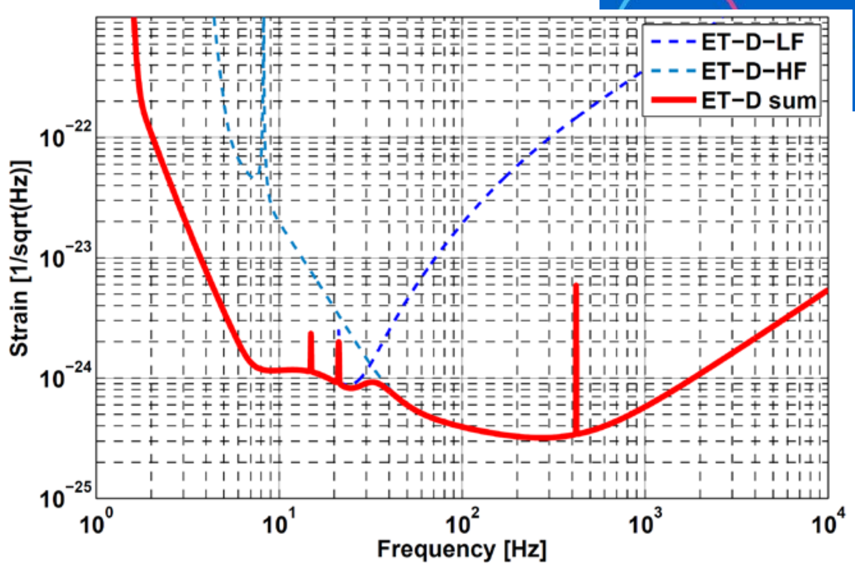
Design curve based on 17 m tall suspensions

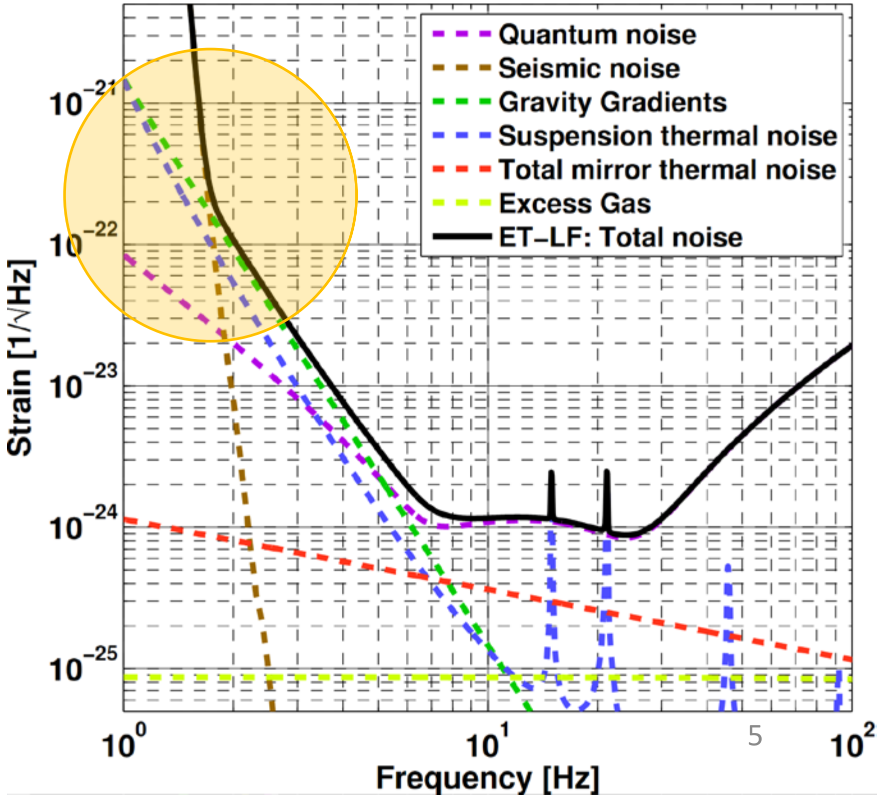
Reduction to less than 10 m:

- Significantly lower cavern excavation cost
- Suspension management similar to Virgo

Newtonian noise crossing:

2 10^{-22} $Hz^{-1/2}$ at 1.8 Hz (AdV: 3.2 Hz)





Additional requirements

- **RMS motion: precision of the working point settings $O(10^{-13})$ m**
- **Angular motion: not fully studied but 10^{-9} rad at 10 km gives a beam center displacement of 10^{-5} m or a cavity length variation of**

  $\delta L = 10^{-10} / 2 R_m$ ($R_m \sim 10^4$ m -> $\delta L = 5\ 10^{-15}$ m)

  which seems relevant even if averaged over the beam spot
- **Tides: full swing of spring tides: order of 300 μm**
- **Avoid reintroduction of noise by actuators (dynamic range)**
- **Controllability of the system**
- **Recovery from high excitation after feedback unlock, earthquakes**

General strategy

Seismic noise underground 200 times less than at Virgo

Position/acceleration sensors readout hits the noise floor of instrument

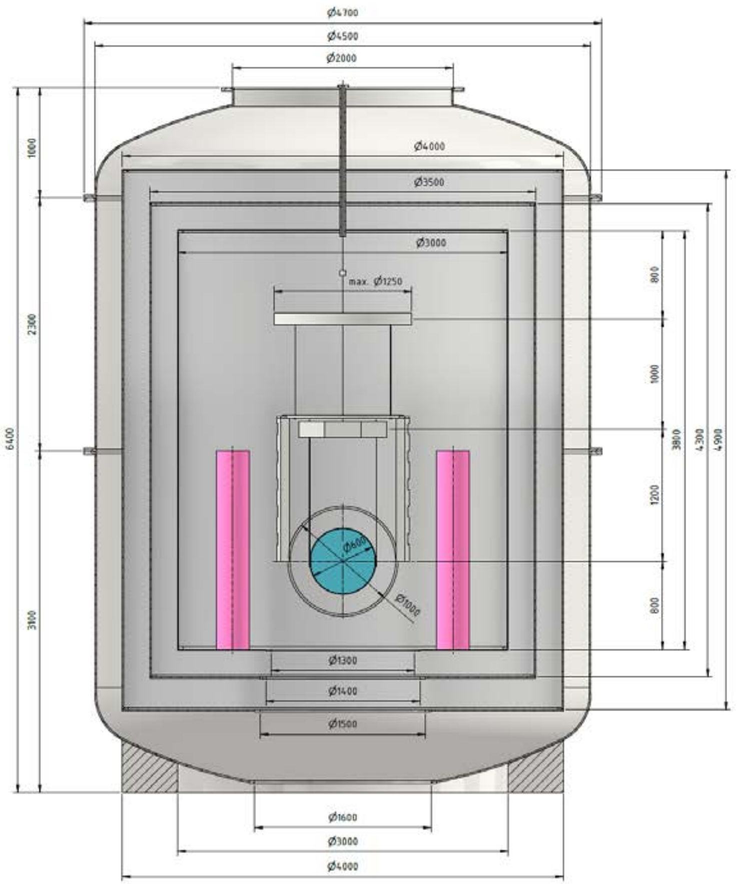
Local control is effective only upstream the attenuation chain

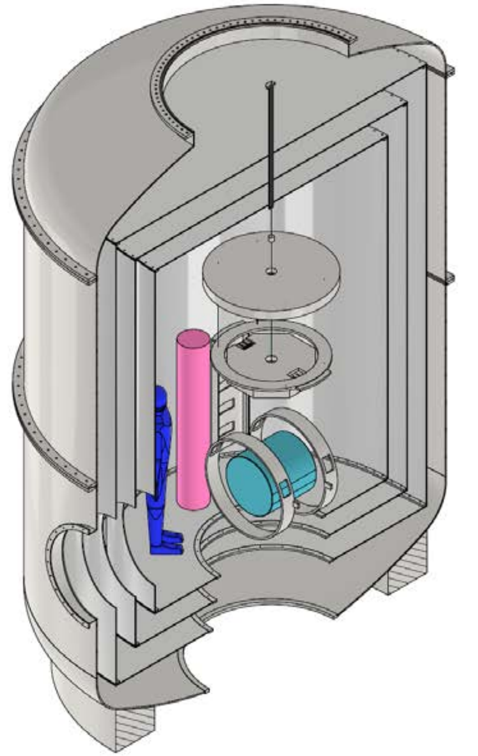
Otherwise one needs the full interferometer, which injects technical noise -> Active Noise Mitigation Division

- **Improve upstream isolation with better sensing and actuation**
- **Rely on passive attenuation**
- **Gain by reducing the normal mode frequencies**
- **2010 design: 17 m long suspensions to lower pendulum frequency, implications on civil engineering costs**
- **Vertical attenuation does not require additional height, but more stringent requirements (3 km to 10-15 km)**
- **Challenge: fit in 10 m**

Challenge: Fit suspension in 10 m

1. **Act on ground / suspension interface actively**
2. **Act on suspension point actively/passively**
3. **Superattenuator chain design**
4. **Payload design compatibility: large occupancy announced ϕ 4700 h 6400**



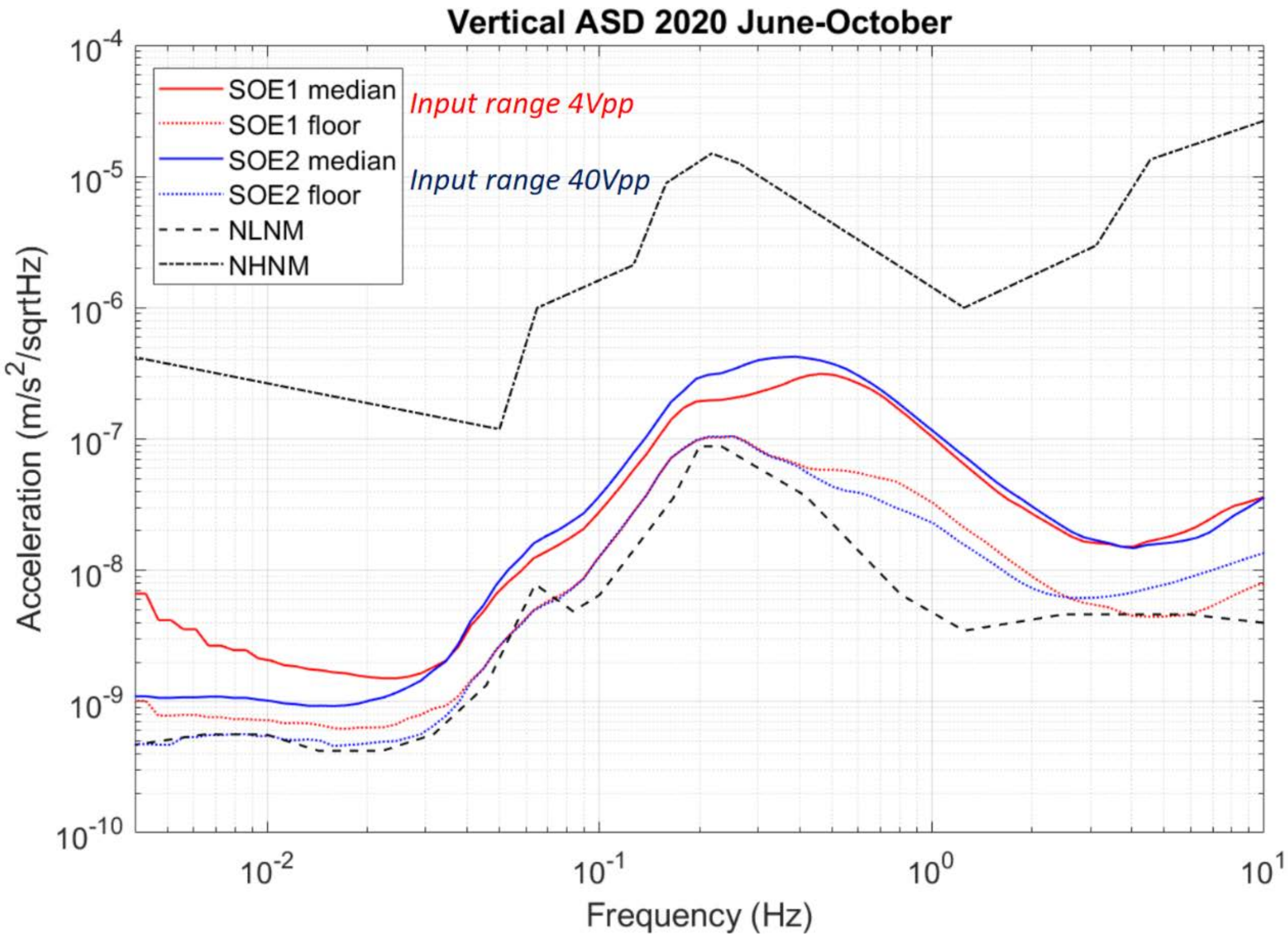


ET Seismic levels

Sardinia vertical

$3\ 10^{-8}\ ms^{-2}\ Hz^{-1/2}$ at 2 Hz

To be updated with borehole measurements at Sos Enattos (L. Naticchioni)



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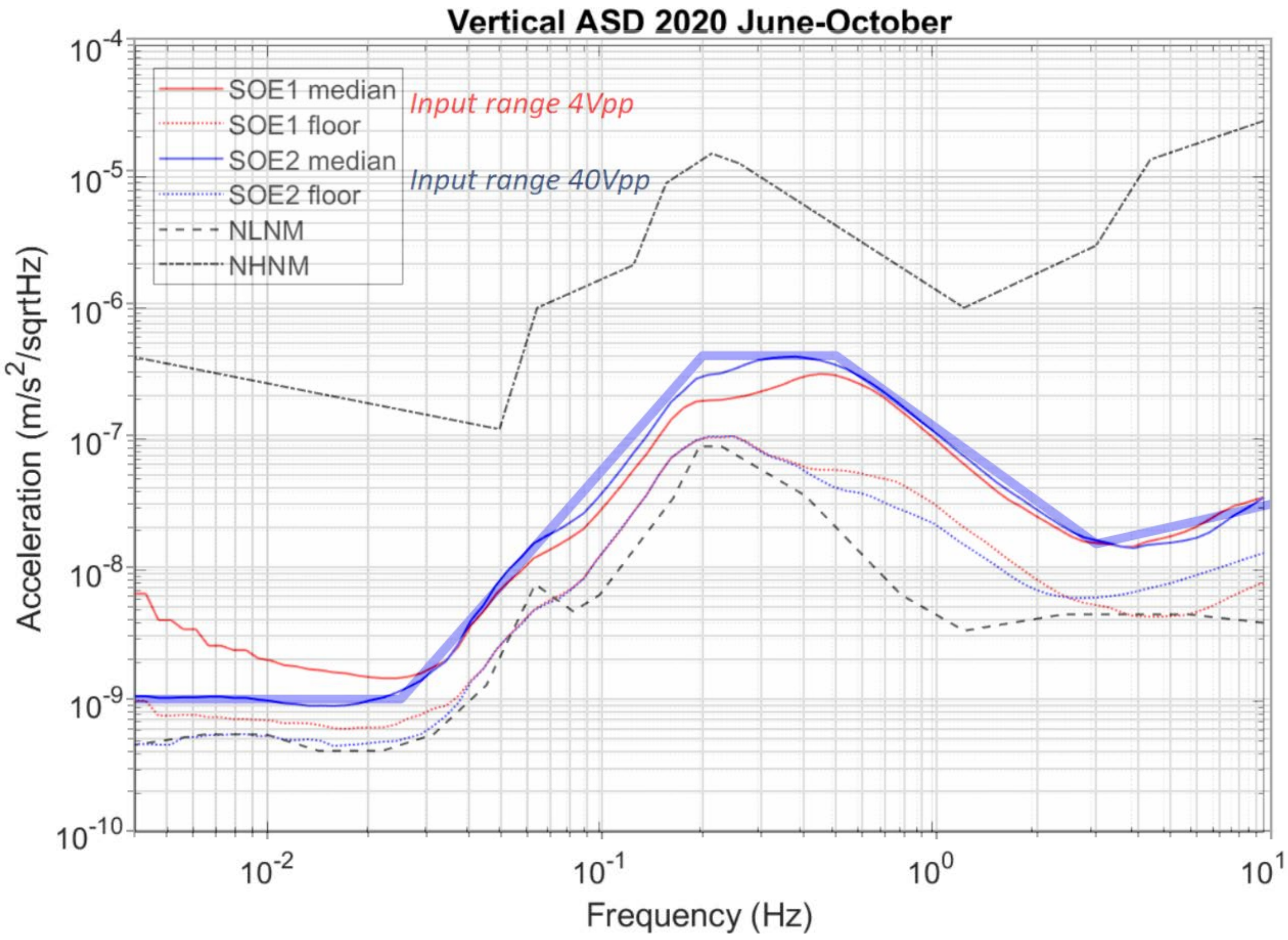
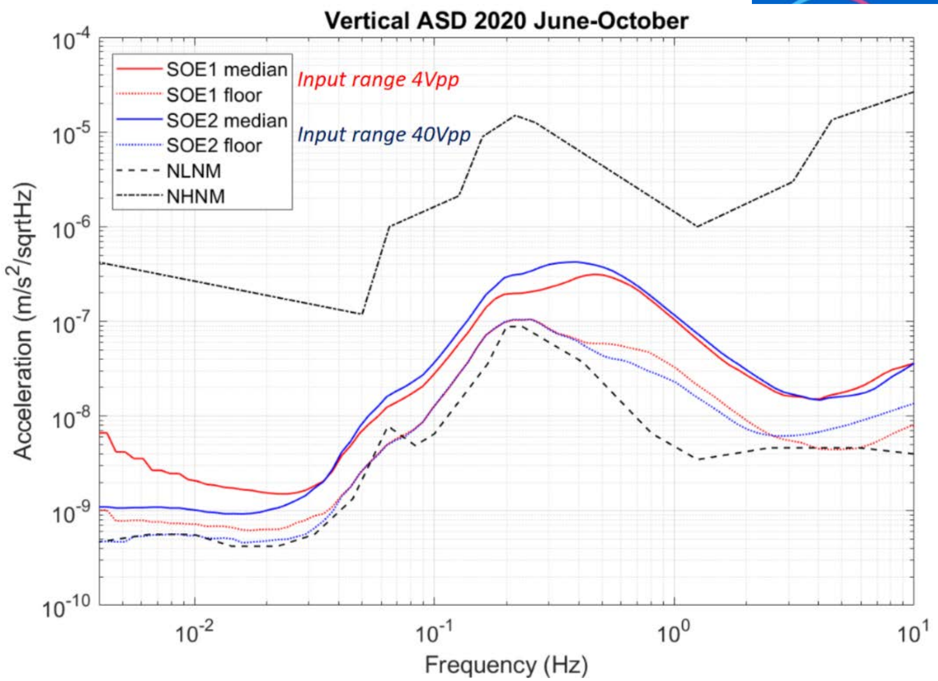


Seismic landscape



Vertical displacement spectrum

Virgo: 5 10^{-10} m $Hz^{-1/2}$ at 10 Hz
SOE: 3 10^{-10} m $Hz^{-1/2}$ at 2 Hz

RMS displacement over 100 s

Virgo: 10^{-6} m comparable to λ
SOE: 10^{-7} m well below λ

Strain

Virgo: 2 10^{-22} $Hz^{-1/2}$ at 10 Hz
ET: 2 10^{-22} $Hz^{-1/2}$ at 2 Hz

Four uncorrelated mirrors

Virgo: 1.5 10^{-18} m $Hz^{-1/2}$ at 10 Hz
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With factor 10 safety factor

Virgo: 1.5 10^{-19} m $Hz^{-1/2}$ at 10 Hz
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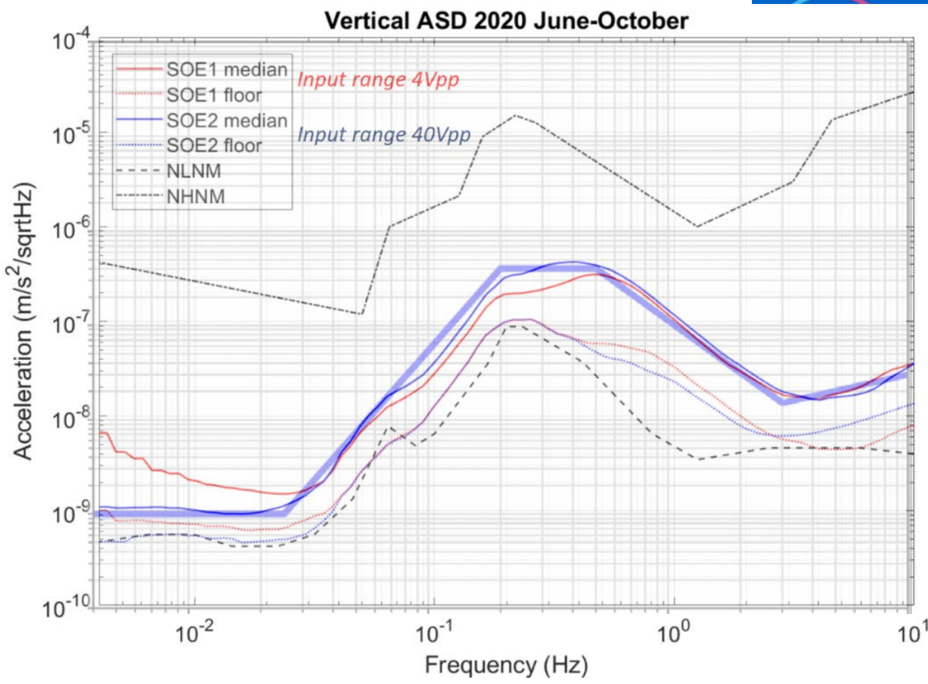
Seismic landscape



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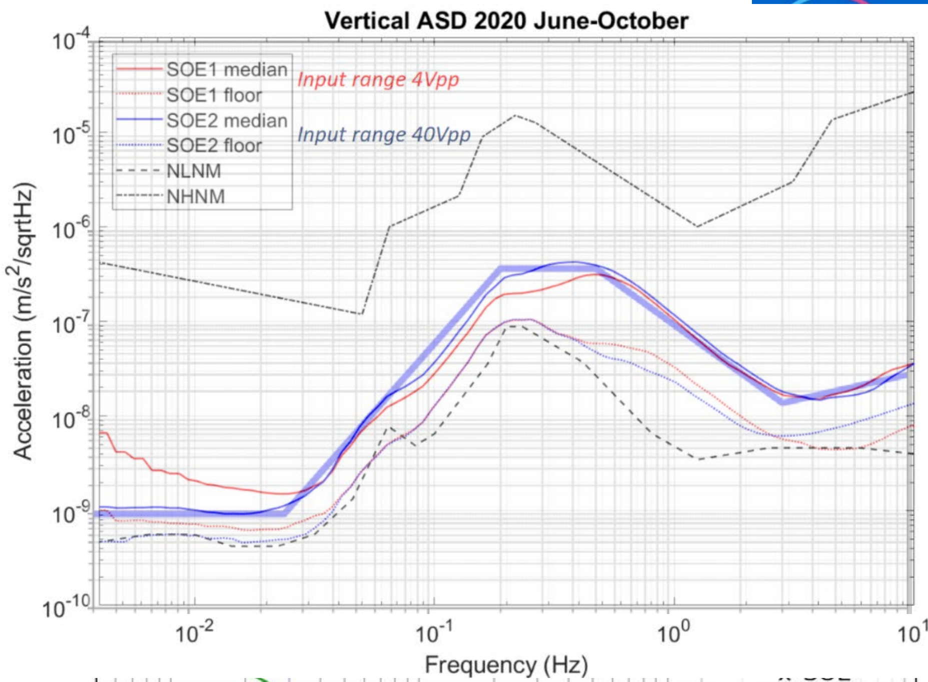

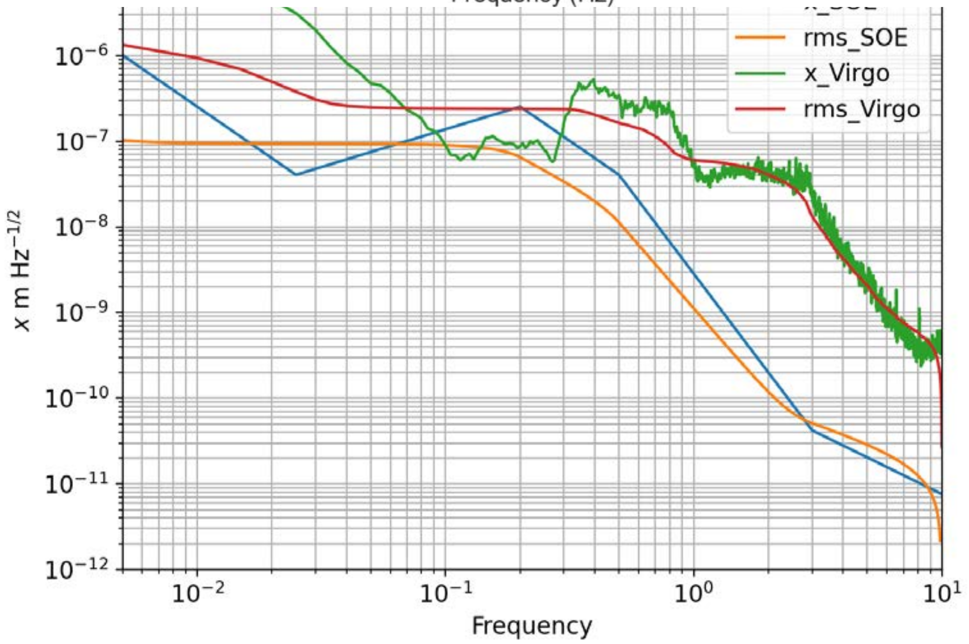

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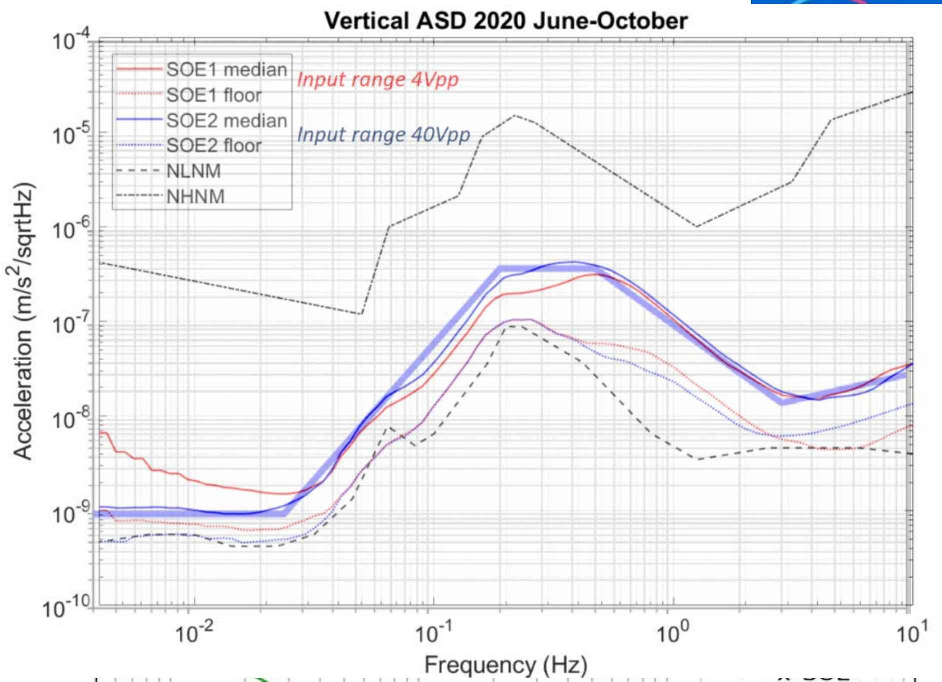

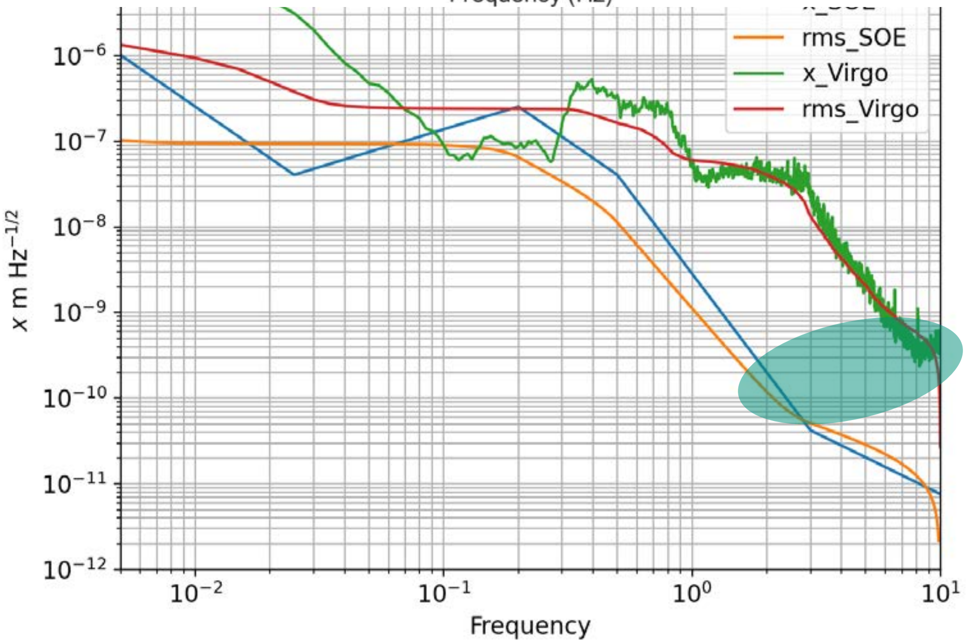

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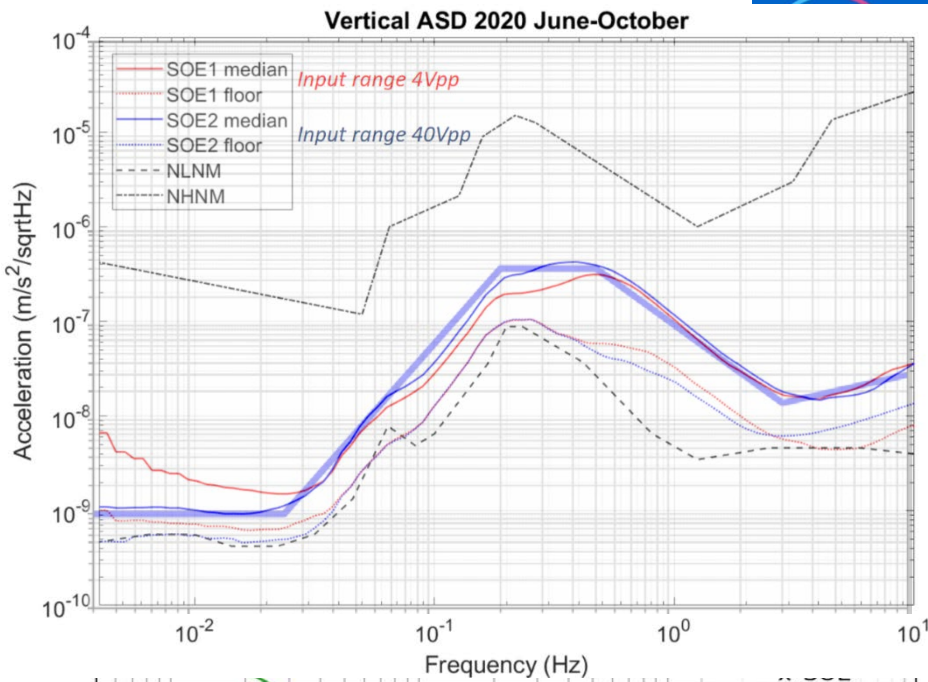

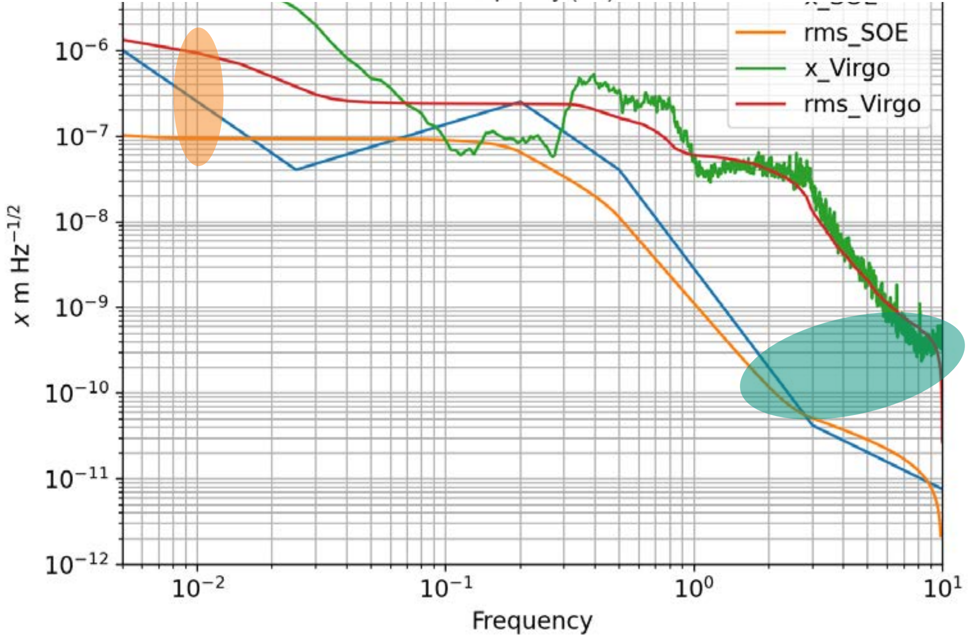

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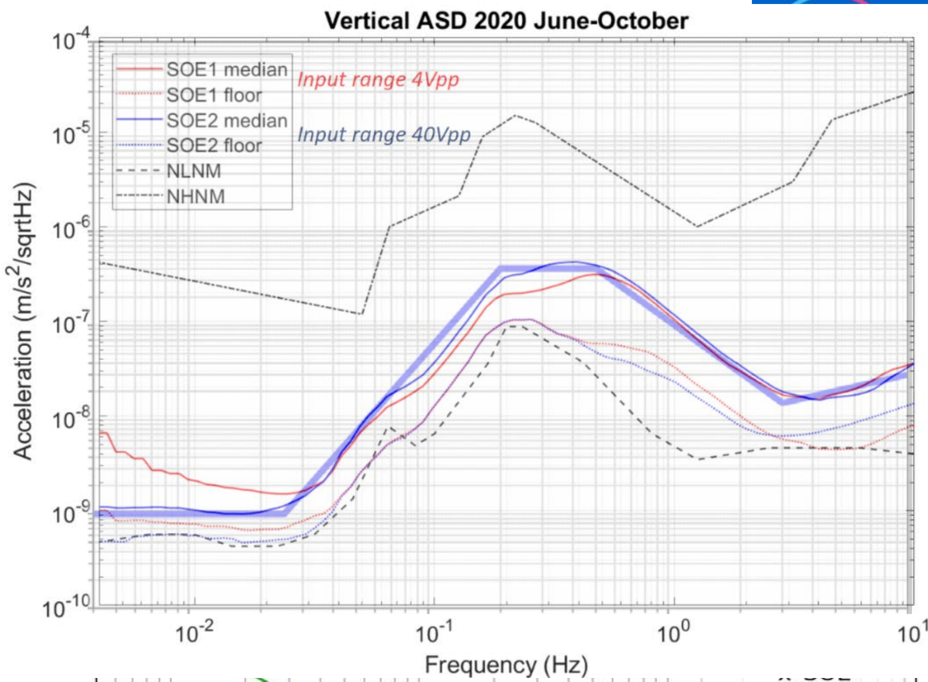
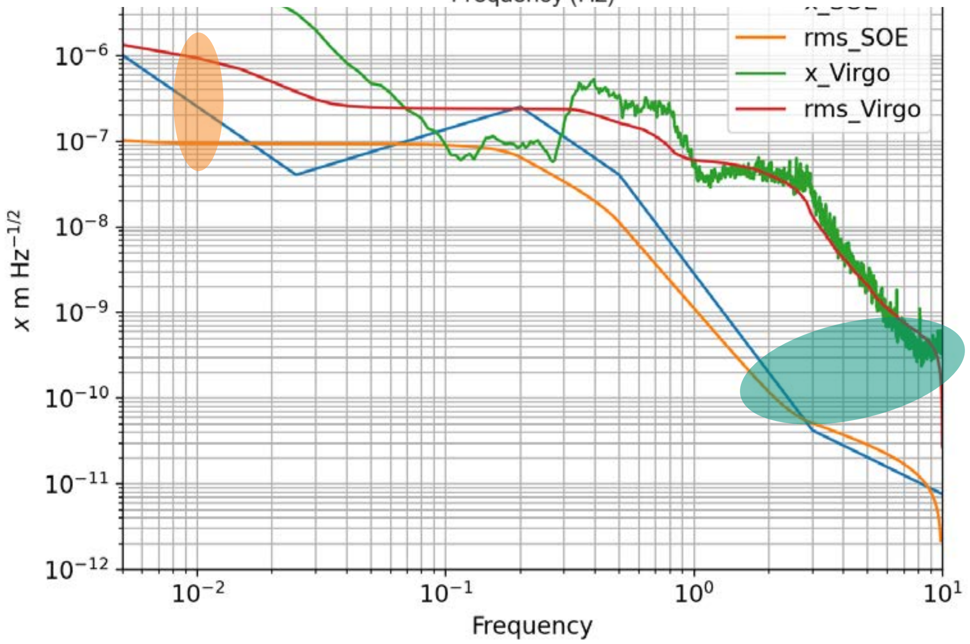




Attenuation required

Einstein Telescope

Vertical displacement spectrum

SOE: $3\ 10^{-10}$ m $Hz^{-1/2}$ at 2 Hz

30 mHz Inverted pendulum

Attenuation at 2 Hz: $2.3\ 10^{-4}$

Motion at 2 Hz: $7\ 10^{-14}$ m $Hz^{-1/2}$

Noise floor for local sensing

Virgo

Vertical displacement spectrum

Virgo: $5\ 10^{-10}$ m $Hz^{-1/2}$ at 10 Hz

30 mHz Inverted pendulum

Attenuation at 10 Hz: $9\ 10^{-6}$

Motion at 10 Hz: $5\ 10^{-15}$ m $Hz^{-1/2}$

Beyond noise floor for local sensing

Attenuation required

Einstein Telescope

Vertical displacement spectrum

SOE: $3\ 10^{-10}$ m $Hz^{-1/2}$ at 2 Hz

30 mHz Inverted pendulum

Attenuation at 2 Hz: $2.3\ 10^{-4}$

Motion at 2 Hz: $7\ 10^{-14}$ m $Hz^{-1/2}$

Noise floor for local sensing

With factor 10 safety factor

ET: 10^{-19} m $Hz^{-1/2}$ at 2 Hz

Full seismic attenuation required

ET: $1.5\ 10^{-6}$ at 2 Hz

Virgo

Vertical displacement spectrum

Virgo: $5\ 10^{-10}$ m $Hz^{-1/2}$ at 10 Hz

30 mHz Inverted pendulum

Attenuation at 10 Hz: $9\ 10^{-6}$

Motion at 10 Hz: $5\ 10^{-15}$ m $Hz^{-1/2}$

Beyond noise floor for local sensing

With factor 10 safety factor

Virgo: $1.5\ 10^{-19}$ m $Hz^{-1/2}$ at 10 Hz

Full seismic attenuation required

Virgo: $A = 3\ 10^{-5}$ at 10 Hz

Attenuation required

Einstein Telescope

Full seismic attenuation required

ET: $1.5\ 10^{-6}$ at 2 Hz

Mandatory filters

Mirror: pendulum at 0.46 Hz

Marionetta

Assume 2 filters mode at 0.75 Hz:

$A = 2.7\ 10^{-2}$ at 2 Hz

Remaining attenuation required

$A_{ch} = 5.6\ 10^{-5}$ at 2 Hz

Virgo

Full seismic attenuation required

Virgo: $A = 3\ 10^{-5}$ at 10 Hz

Mandatory filters

Mirror: pendulum at 0.6 Hz

Marionetta

Assume 2 filters mode at 0.75 Hz:

$A = 5.6\ 10^{-3}$ at 10 Hz

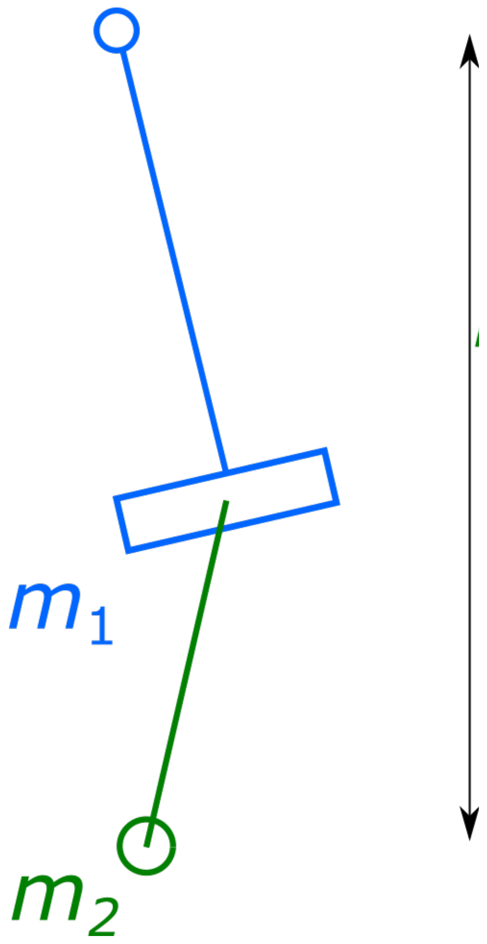
Remaining attenuation required

$A_{ch} = 5.4\ 10^{-3}$ at 10 Hz

The Superattenuator

Cascade of pendulums

Using inertia and gravity



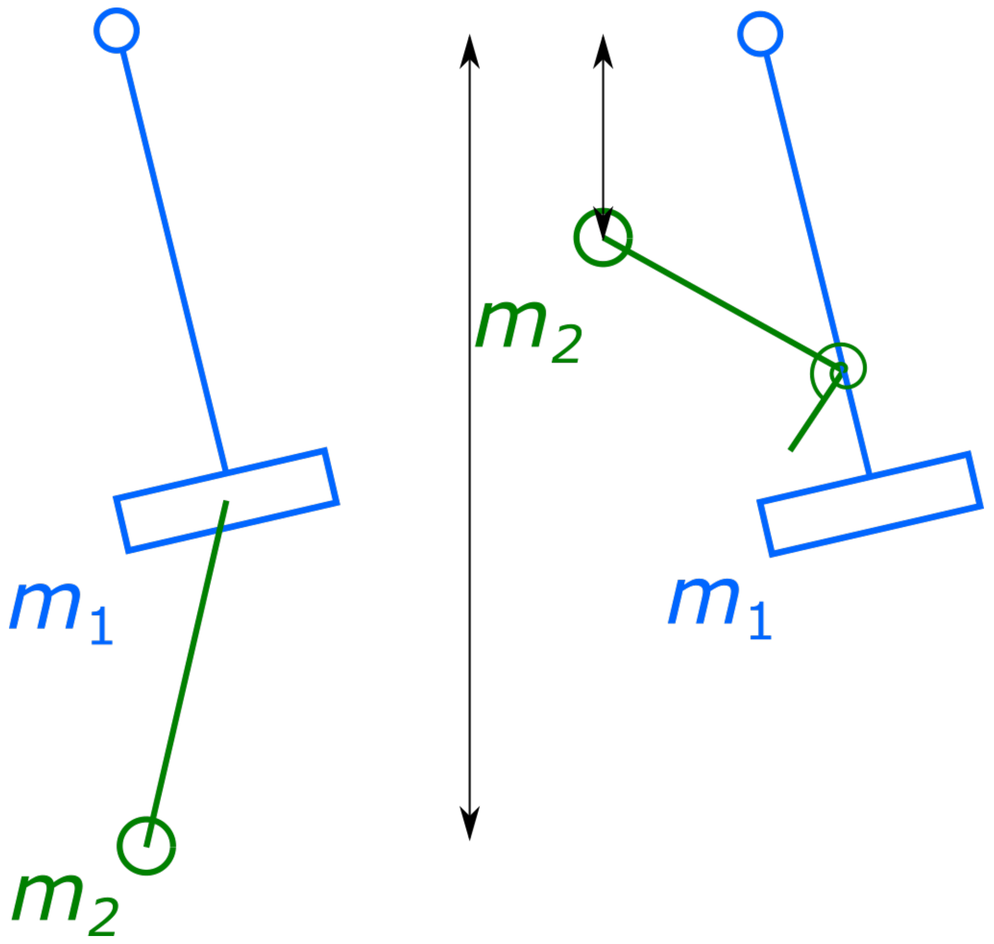
The Superattenuator

Cascade of pendulums

Using inertia and gravity

To using inertia, springs and gravity

Shortening the path to the test mass

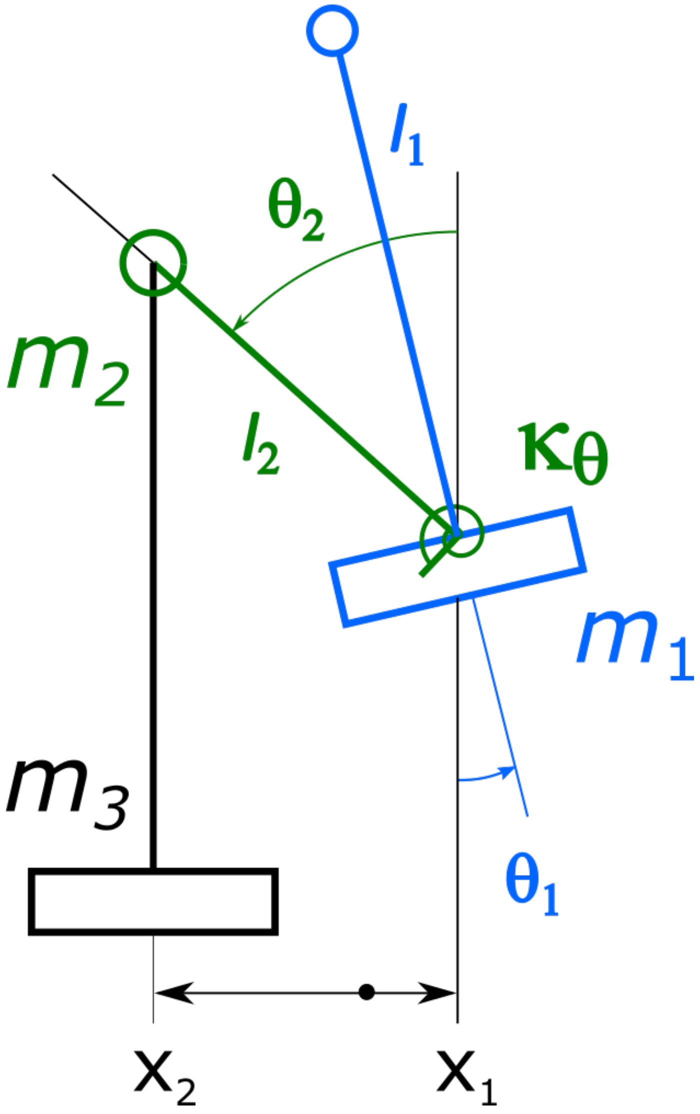


Pendulum – Inverted pendulum

How to soften a suspension stage

- Spare length
- For κ_θ sufficiently stiff, the system is stable

```
• l1:   1.544, # Pendulum length\
• l2:   0.520, # IP length\
• T1: 2551.0, # Pendulum tension\
• T2: 1766.0, # IP compression\
• m1:    80.0, # Pendulum mass\
• m2:    80.0, # Filter mass\
• m3:   100.0, # Load\
• I1s:   20.0, # Pendulum moment of inertia \
• I2s:    0.8, # IP moment of inertia\
• k:  1700.0, # flex joint elastic constant\
```



Normal mode frequencies

0.68 Hz 0.74 Hz

Attenuation of Pendulum-Inverted Pendulum

$$A = \left(\frac{f_0^2}{f^2 - f_0^2}\right)^2$$

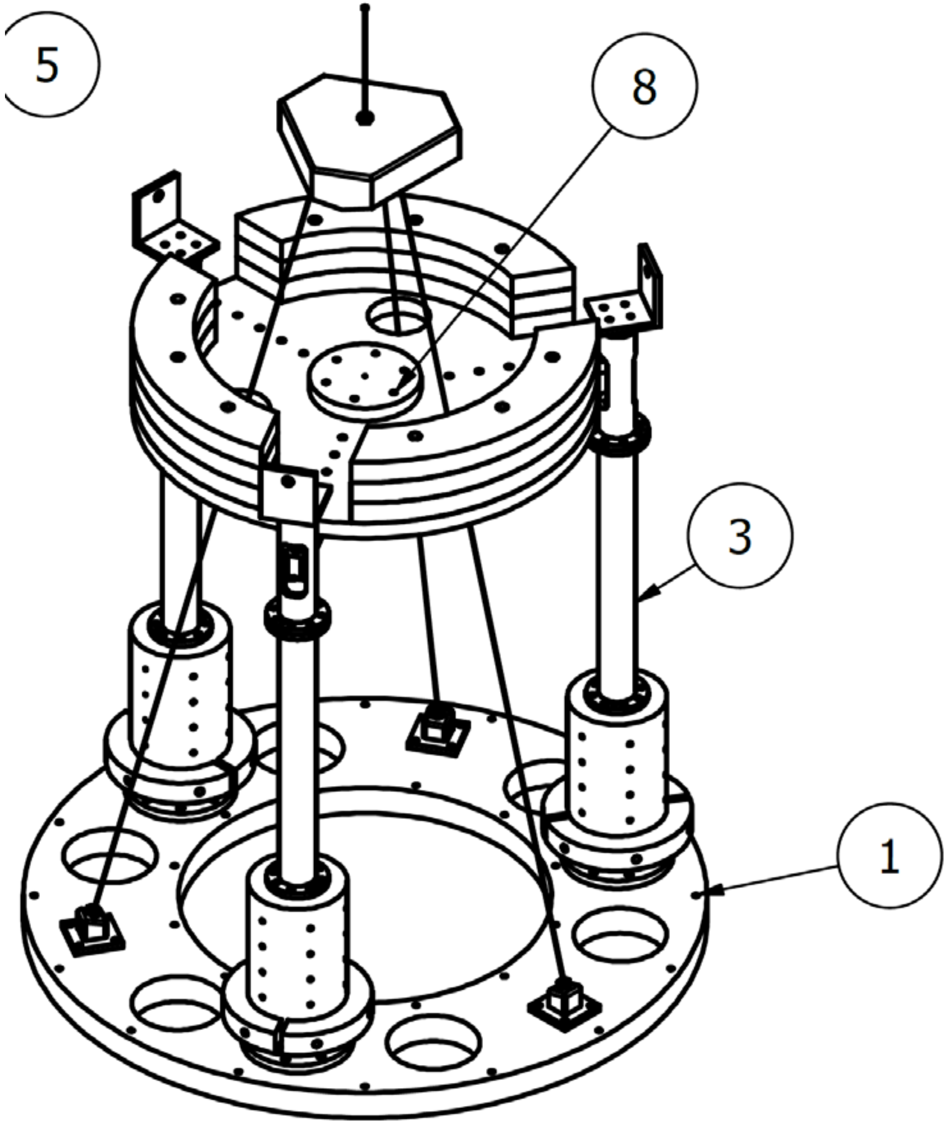
Horizontal attenuation of a single PIP
No damping

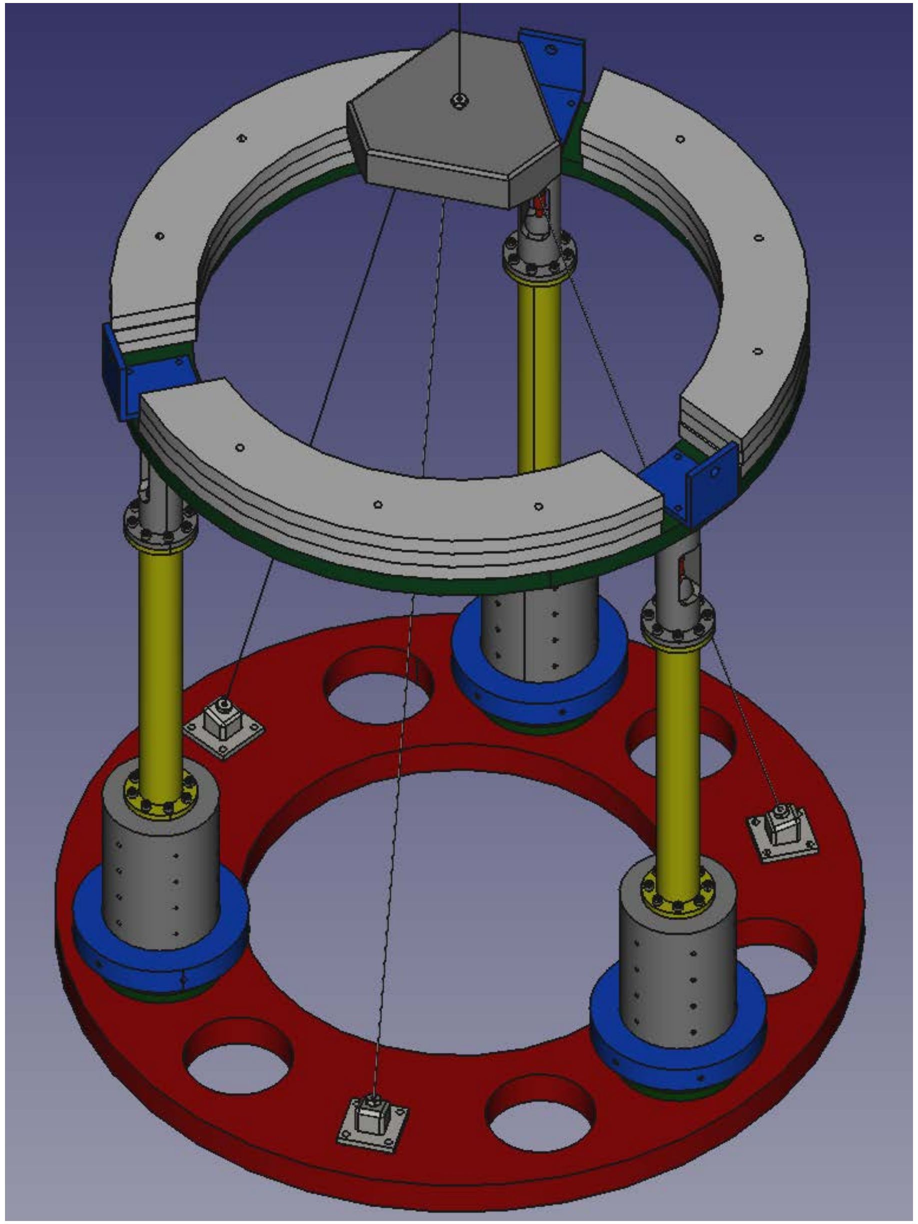
For f_0 = 0.75 Hz
A_2 : attenuation at 2 Hz — $2.7\ 10^{-2}$

Two PIP
A_2 : attenuation at 2 Hz — $7.2\ 10^{-4}$

Three PIP
A_2 : attenuation at 2 Hz — $1.9\ 10^{-5}$

Basic structure

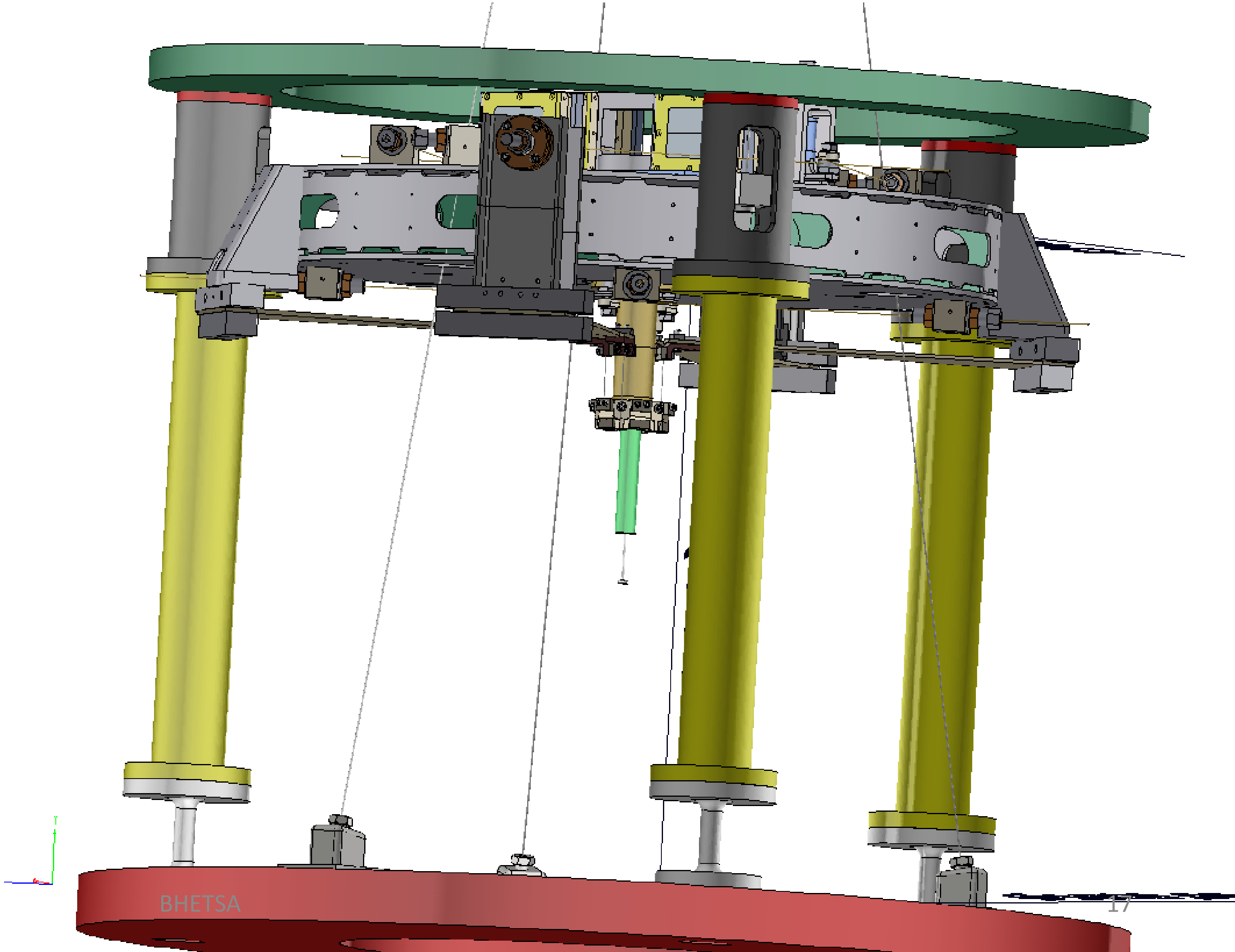




Use a standard F7 filter frame

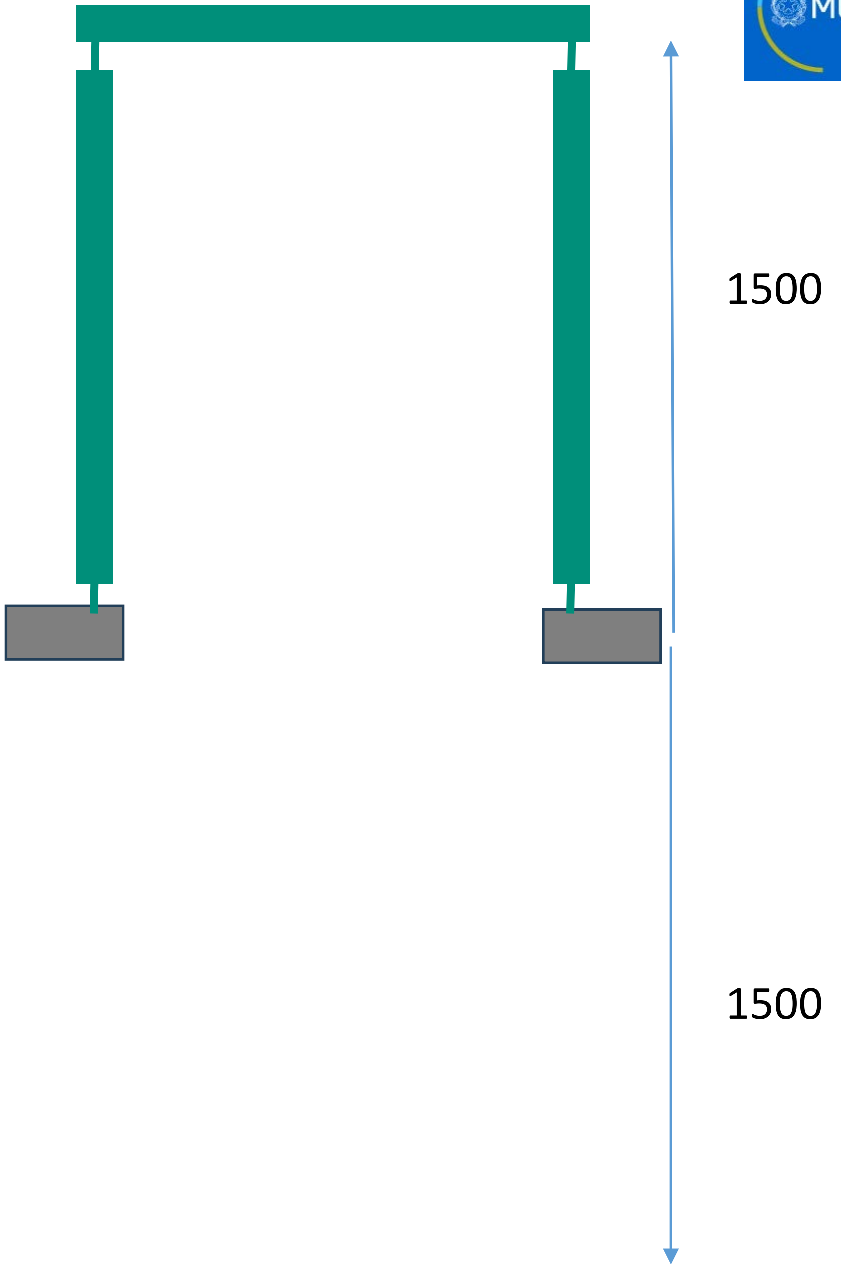
Standard filter addition for vertical attenuation

- Filter suspended to IP legs
- IP counterweights not represented
- Includes one stage of vertical attenuation
- Hook to next stage above first pendulum mass
- Additional vertical attenuation can be suspended below the filter



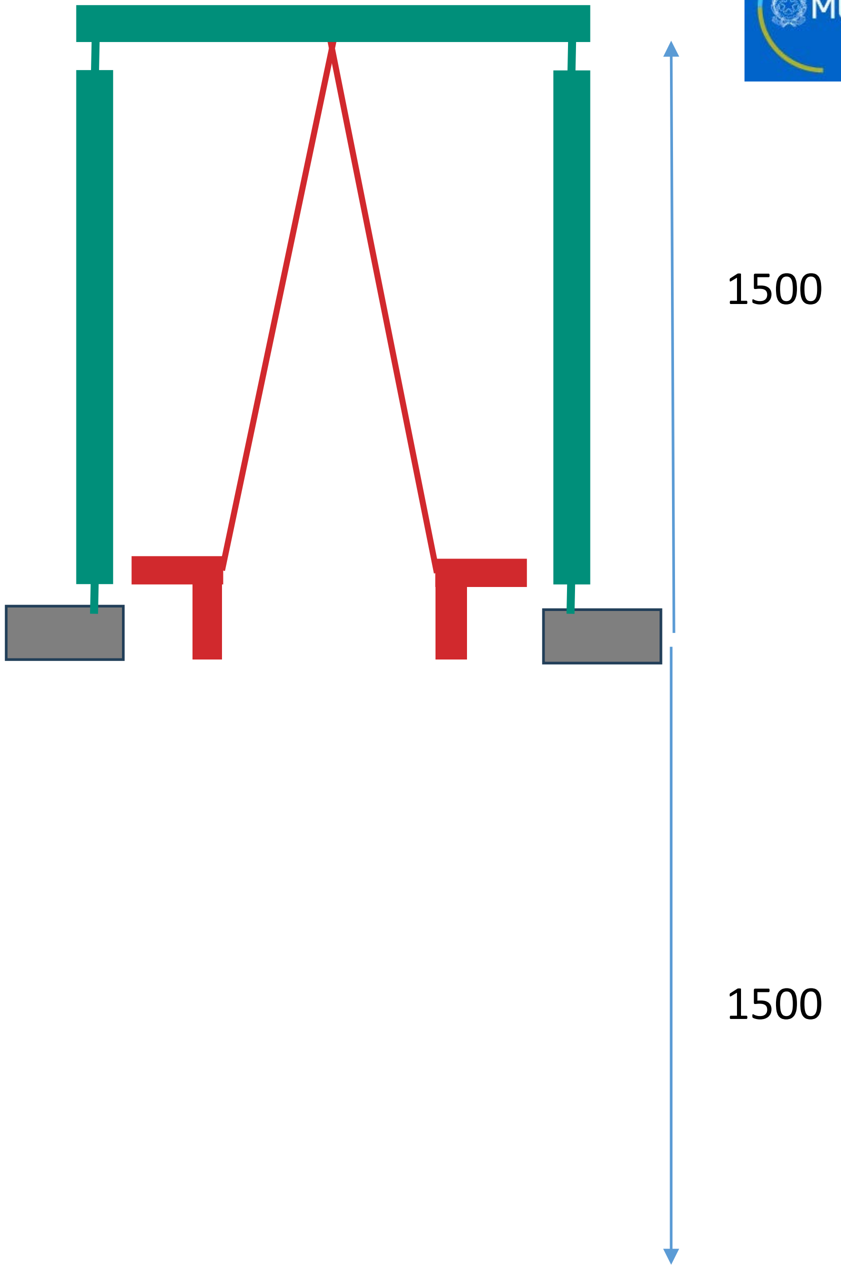
Additional considerations

- **The high part of a suspension chain can be built**
  - Starting from an IP



Additional considerations

- **The high part of a suspension chain can be built**
  - Starting from an IP
  - Hanging a pendulum



Additional considerations

- **The high part of a suspension chain can be built**
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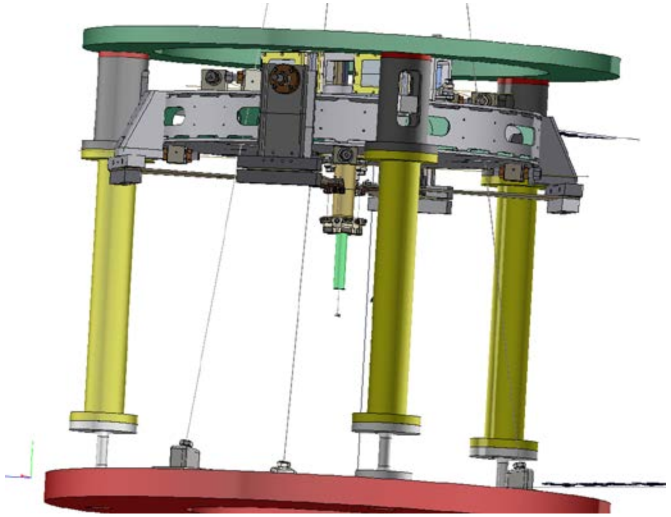
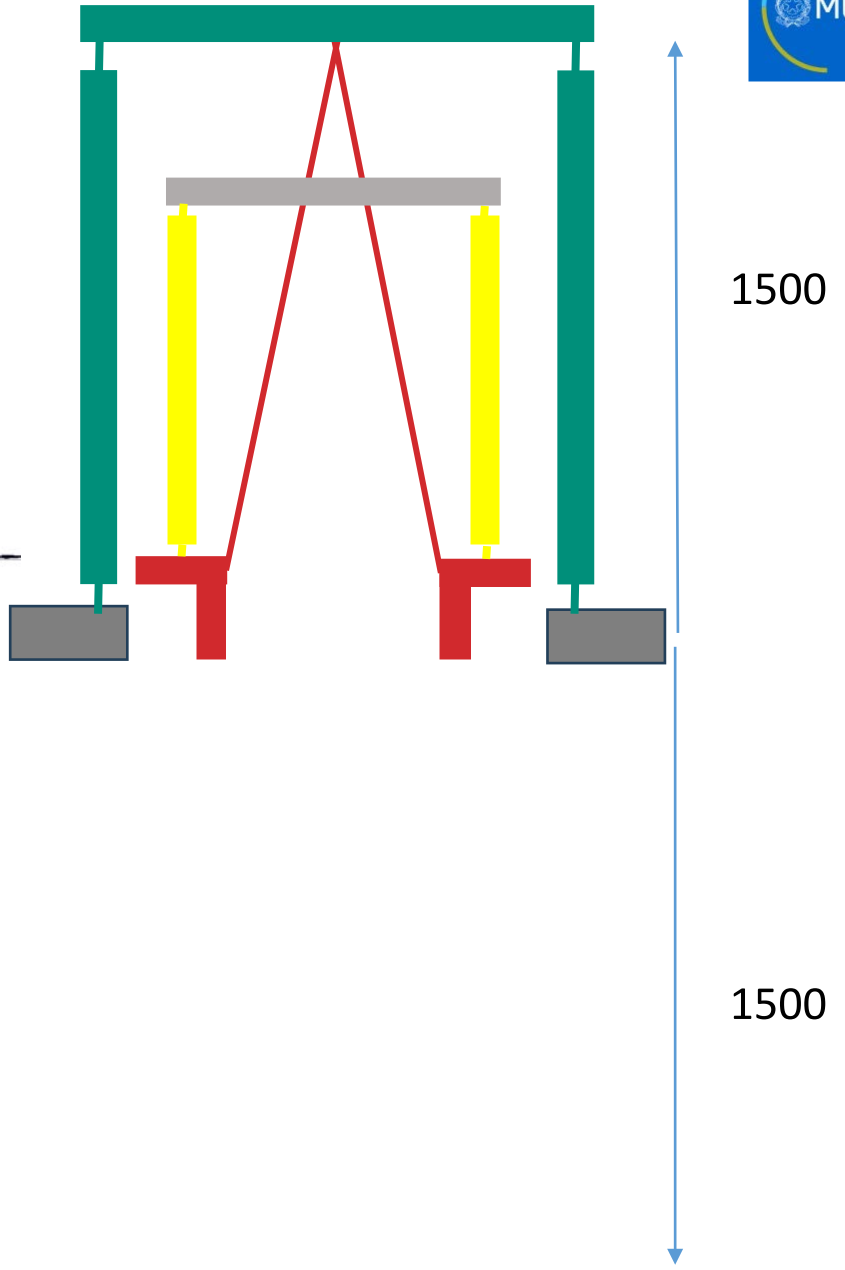
  - Hanging a pendulum
  - Adding an Inverted Pendulum (-> PIP)





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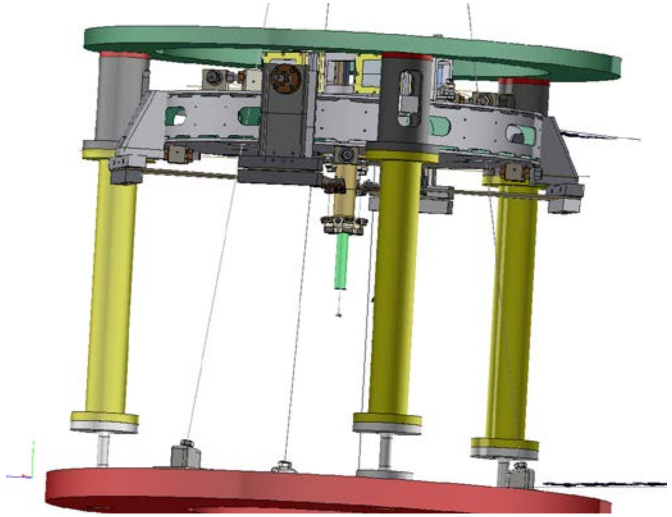
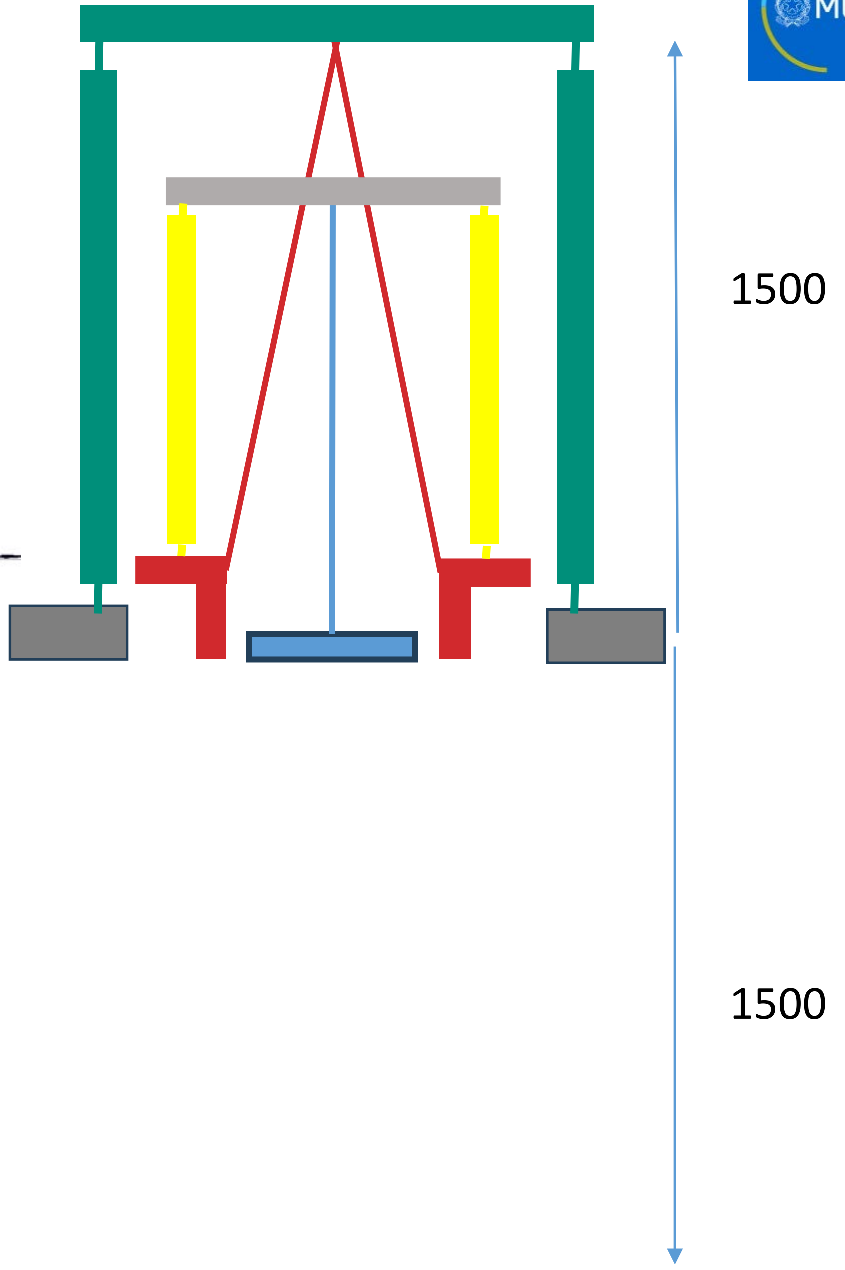
  - Starting from an IP
  - Hanging a pendulum
  - Adding an Inverted Pendulum (-> PIP)
  - Suspend a vertical isolation filter





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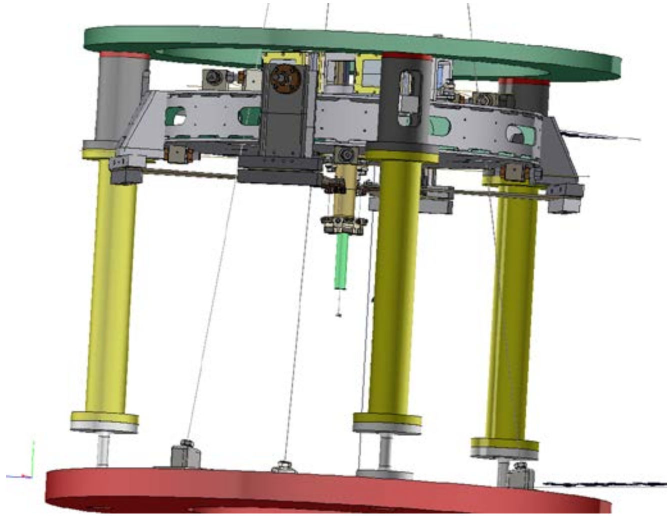
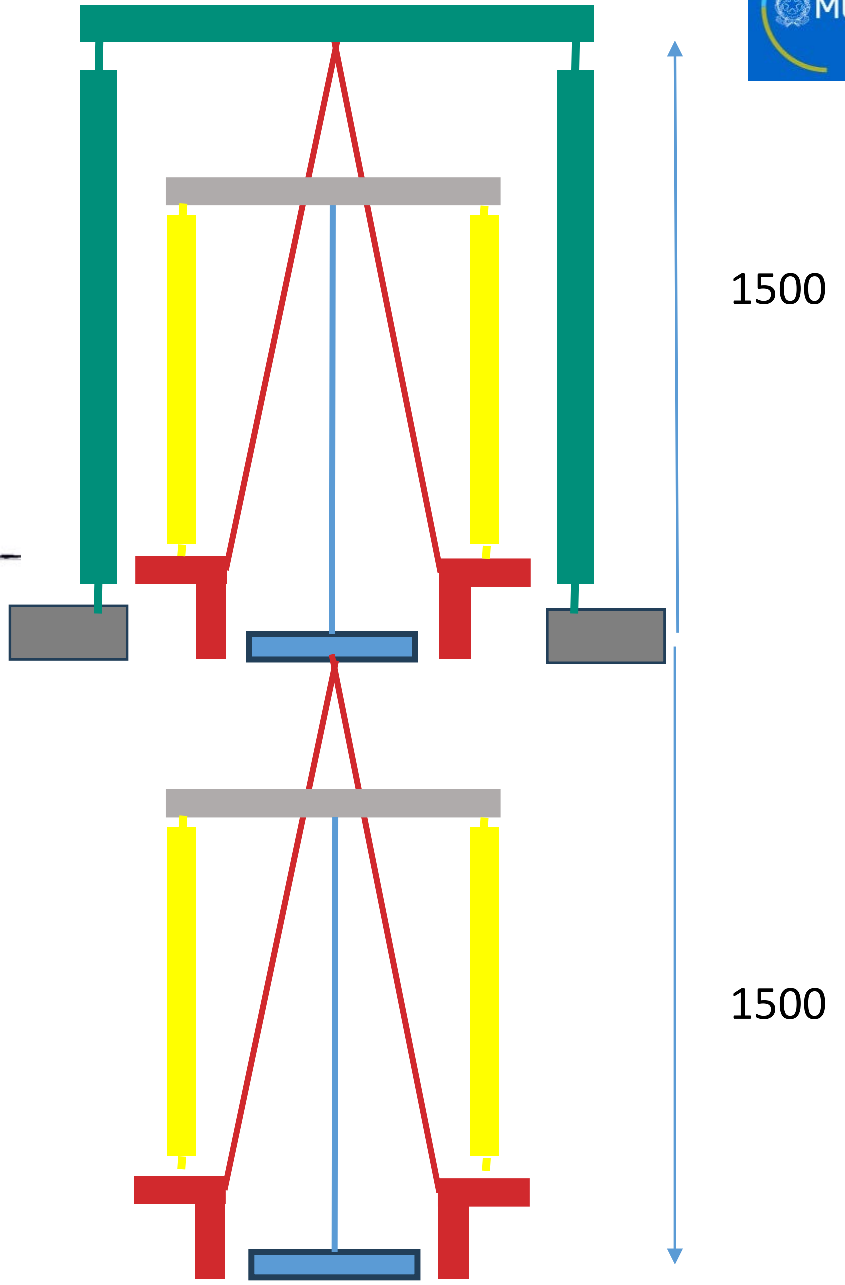
  - Suspend a vertical isolation filter
  - That suspends another PIP





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  - Hanging a pendulum
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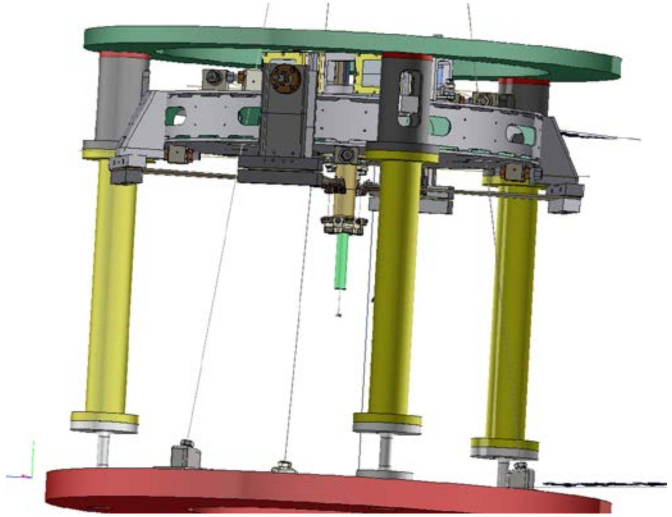
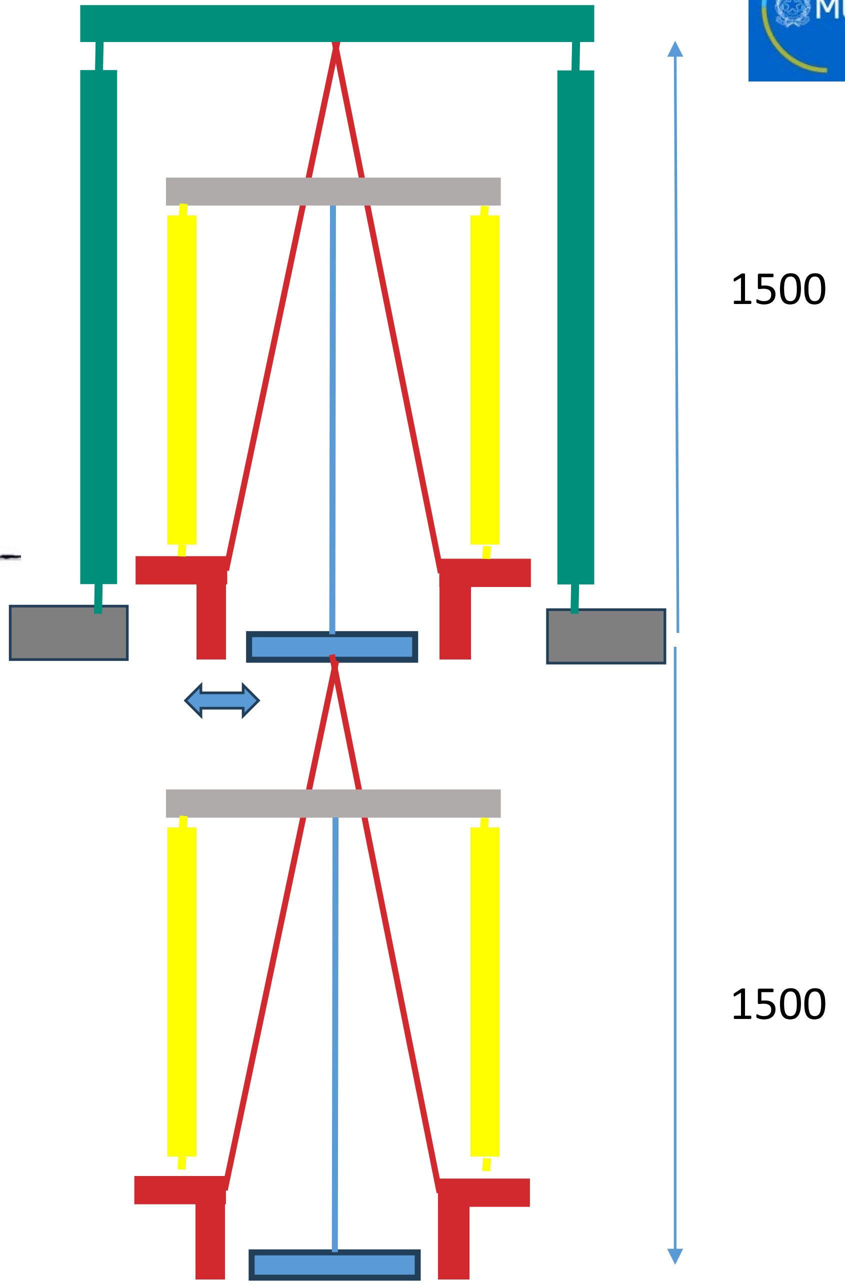
  - Suspend a vertical isolation filter
  - That suspends another PIP
  - Possibility to apply inter-filter feedback

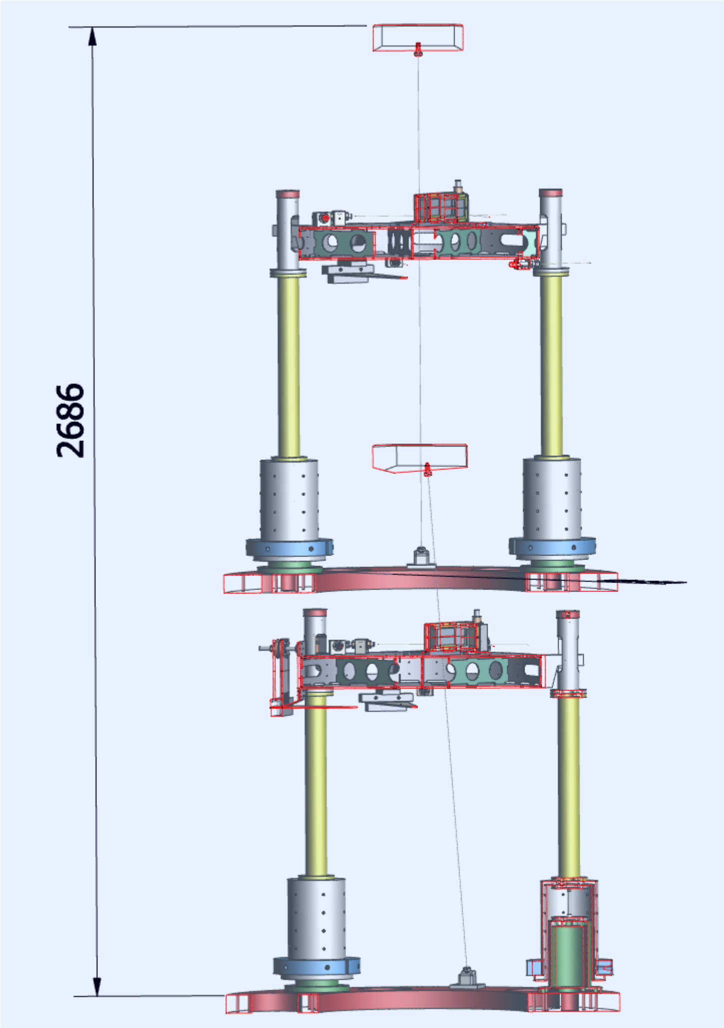


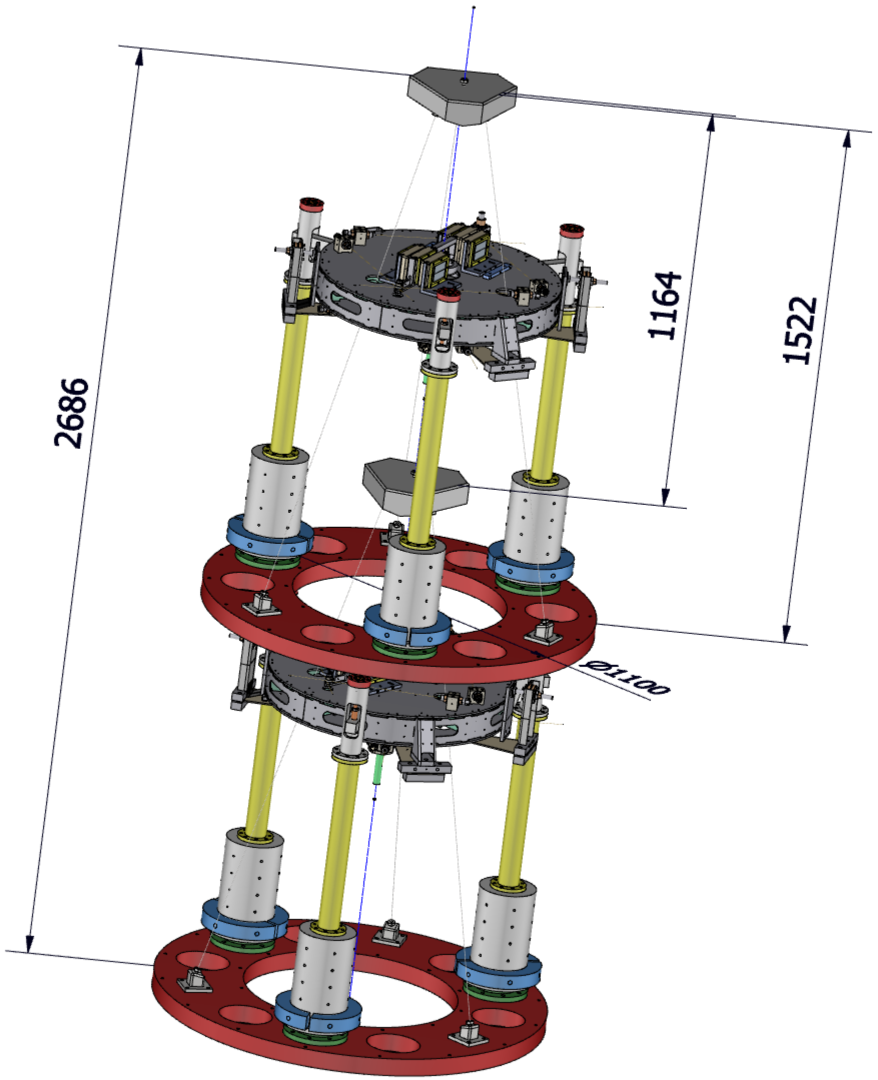


e-PIP

Work in progress on entangled PIP

Four filters in 2.70 m





Overall length

- **A PIP chain can be built**
  - Hook of the second PIP above the first filter
  - Current PIP length 1.55 m
  - Two PIP can live in 2.70 + 0.30 = 3.0 m accounting for a dedicated vertical attenuation stage
  - Three PIP can live in 4 m
- **The goal of a 10 m tall suspension seems in sight**

BHETSA program

WP1 A prototype PIP has been manufactured (SarGrav, G&M)

Goals

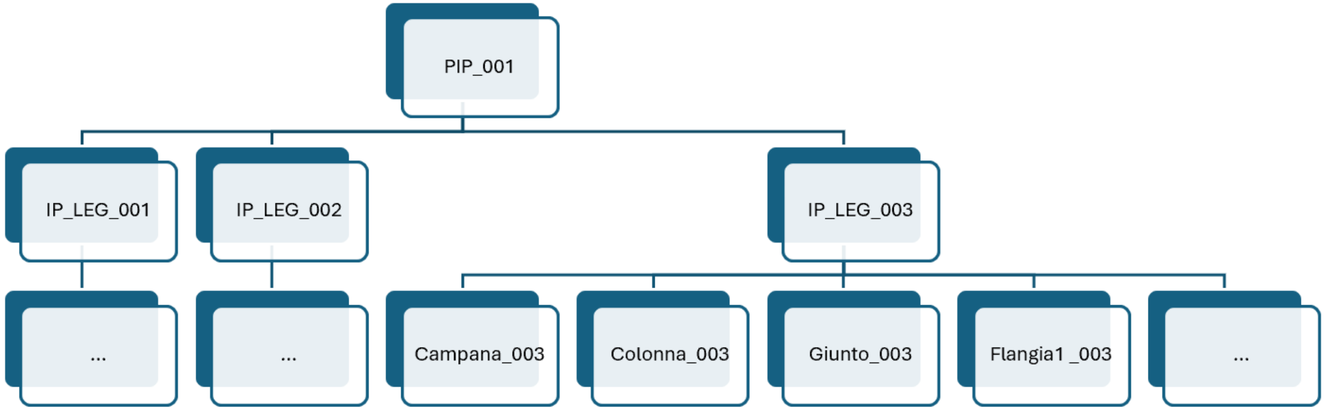
- Verify the dynamical behaviour: large roll-displacement coupling
- Expected resonances
- Cross coupling
- Vertical bouncing modes

Test of components (LVDT and force coils, Lorenzo, Matteo, Sara)

WP2 Simulations are in progress (Max, Matteo M, Lucia T)

Filter design (Andrea)

Laboratory equipment and software support: hardware database (Lorenzo, Michele)



BHETSA program

WP3 Sensors and actuators

- Tiltmeter progress (Annalisa Allocca, NA)
- Develop new accelerometer with better position sensing (Alberto)
- Explore optical readout (Alberto)
- Explore microTCA electronics (Valerio)

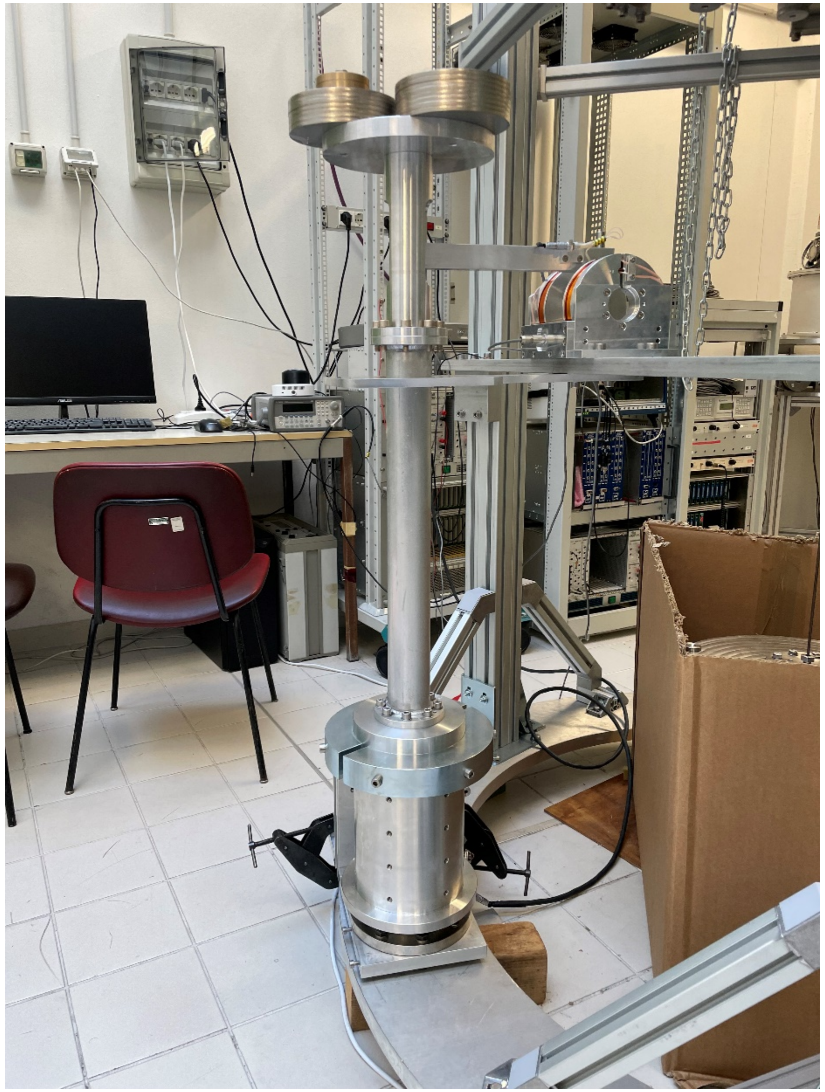
WP4 Control and ML (Gaia and Maria)

WP5 SarGrav (Davide, Domenico, Sassari)

WP6 Outreach (Davide, Domenico, Sassari)

Work on PIP

- **PIP being assembled in Virgo lab**



PIP simulation

GWLab@Pisa Logbook

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PIP (Mechanics) EDIT COMMENT

Lorenzo Bellizzi - 17:03 Tuesday 23 April 2024 (62)

New measurements on PIP Mounted

Yesterday I collected data using only the LVDT 1.

Currently the Pendulum Inverted Pendulum is mounted and it leans on three supported of wood on the floor. In this way the bottom ring is not freee. The top ring is leant on the three inverted pendulum.

I stressed the bottom ring with an hammer and I collected data with the Moku for one minute. The data are computed to obtain the power spectral density (PSD).

The plot "Difference hit point on PIP" shows three several measure. The line blue is the gorund noise where I take a minute of data without stressed the PIP. The orange and green lines are the PSD computed in hitting the PIP in two different point. How we expected the PSD is similar and the resonance peaks are the same frequencies due to the geometry of the PIP.

In the next step I mounted the first ring of Weight: in this way the mass on the top ring is increased of 50.4 Kg. In the picture "TF in function of weight" we can see the two previous lines (respectivaly blue and orange lines) while the green line is the PSD after to charged the weight on the top. The peak of resonance moved toward lower frequencies (1.2207 Hz)

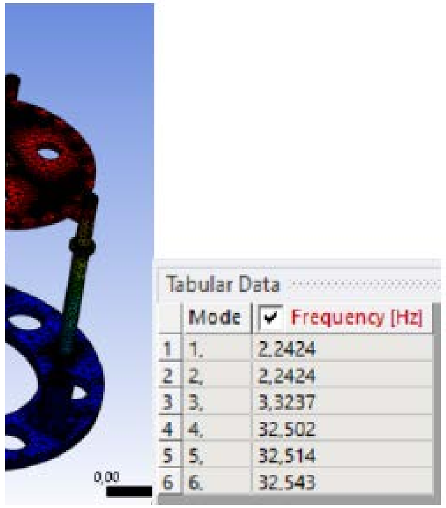
It is interesting the third peak, which is flashy in the orange line.In figure called "Third Peak" is possible to recognised this peak also on the blue and green line so suggesting possible that this is an effect of the ground noise and the improved masses is able to decrease this effect.

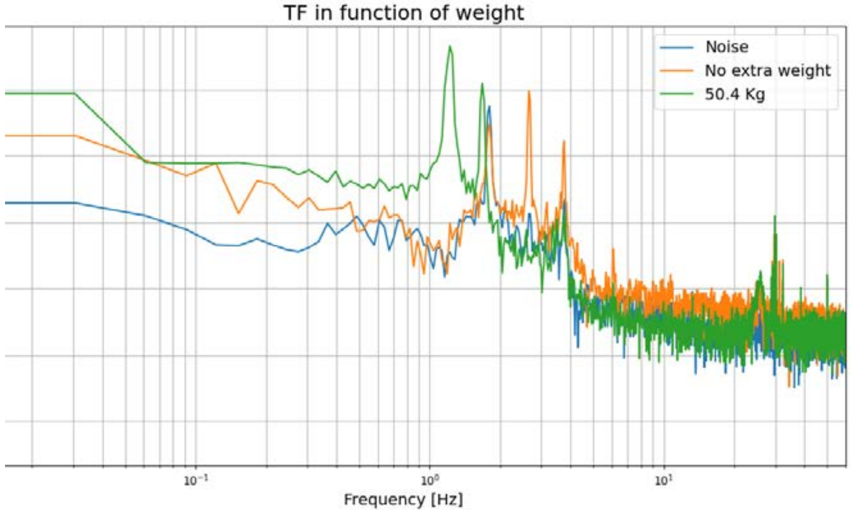
In the table I am comparing the frequencis measurements with the expected frequencies (from Basti's simulation):

frequencies simulated (mass)	frequencies measured (mass)
2.38 Hz (10 kg)	1.83 Hz (10.5 Kg)
2.24 (No masses added)	1.800 (No masses added)

In the first row the data are taken on a single inverted pendulum (Leg_1) when we put the little steel disk on the top. In the second row the data are taken with the configuration that I describe above.

on components



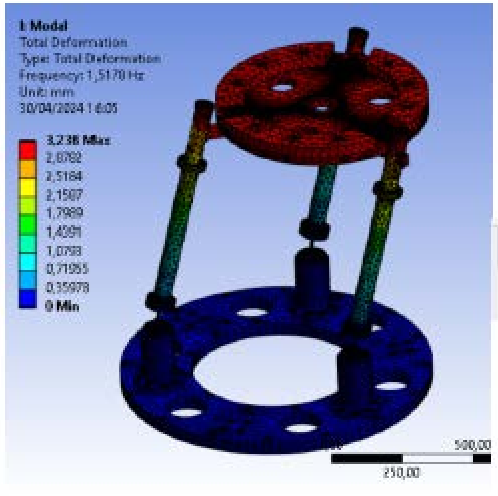


rt simulations, need more detailed

PIP simulation

- **Simulations by Andrea Basti**
- **PIP on ground waiting for suspension components**

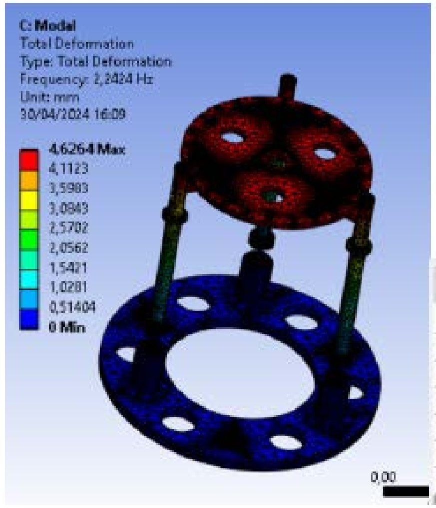
2) Carico - 50 Kg



Tabular Data

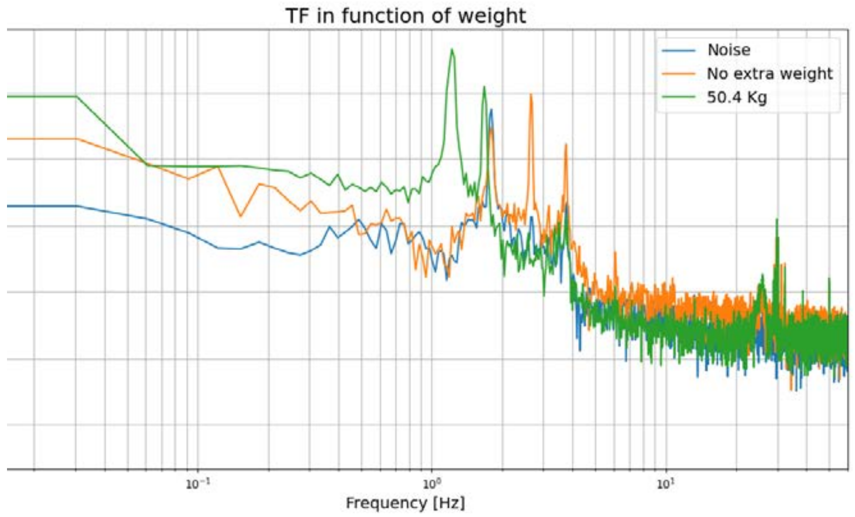
	Mode	Frequency [Hz]
1	1.	1,5178
2	2.	1,5178
3	3.	2,0931
4	4.	33,33
5	5.	33,341
6	6.	33,372

4) NO Carico



Tabular Data

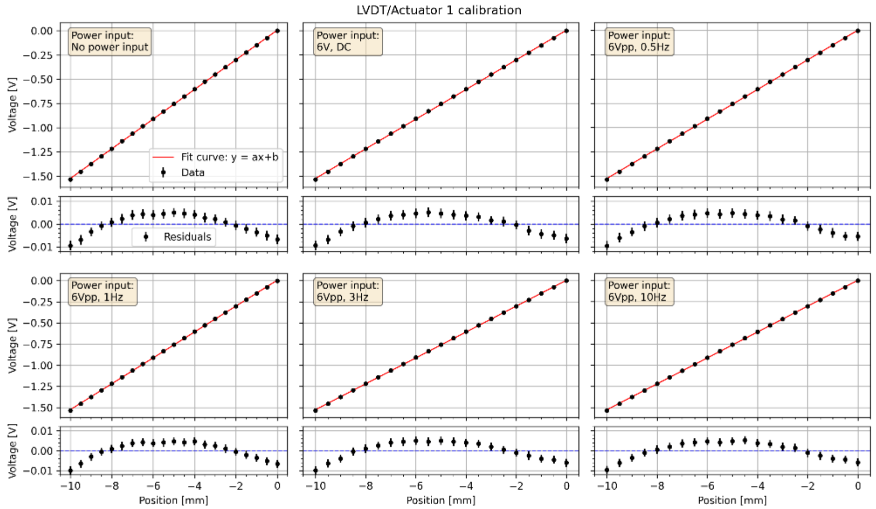
	Mode	Frequency [Hz]
1	1.	2,2424
2	2.	2,2424
3	3.	3,3237
4	4.	32,502
5	5.	32,514
6	6.	32,543

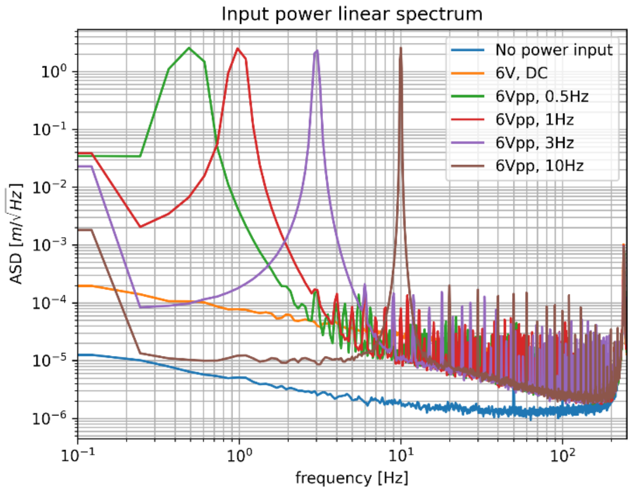


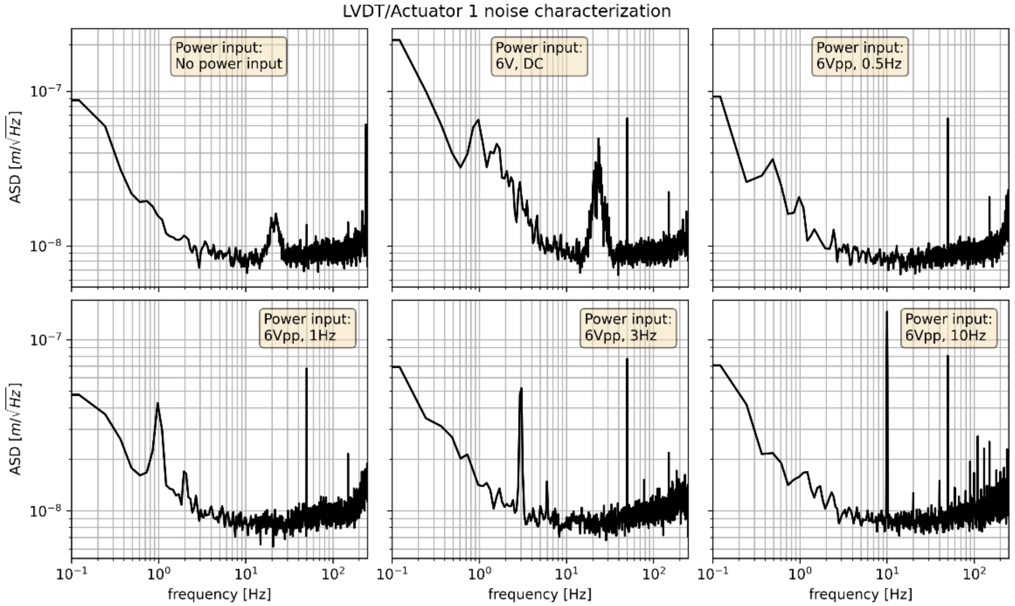
- **Resonance frequency seems low wrt simulations, need more detailed description of joint connection**

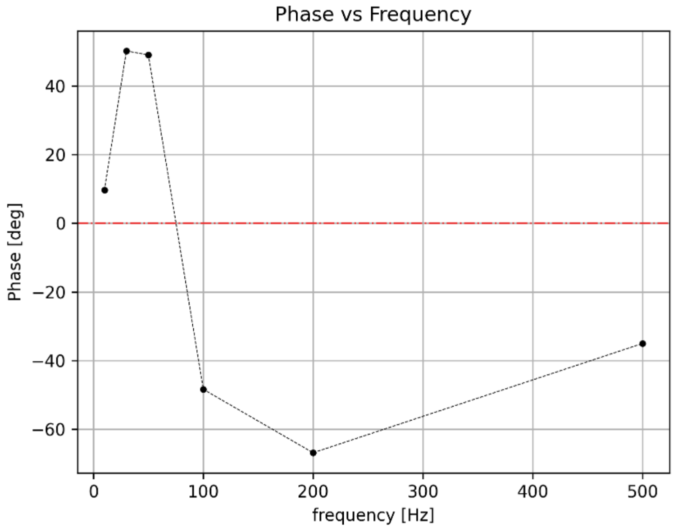
LVDT Characterization

- **Calibration of LVDT + actuator Matteo Baratti**
- **xtalk check when actuating**
- **Noise 10^{-8} m $Hz^{-1/2}$**
- **Mechanical xtalk: 80 Hz resonance**









Normal mode damping

- **Vertical normal mode damping Sara Ardito**
- **Simulation and control from the F0 crossbar: example**

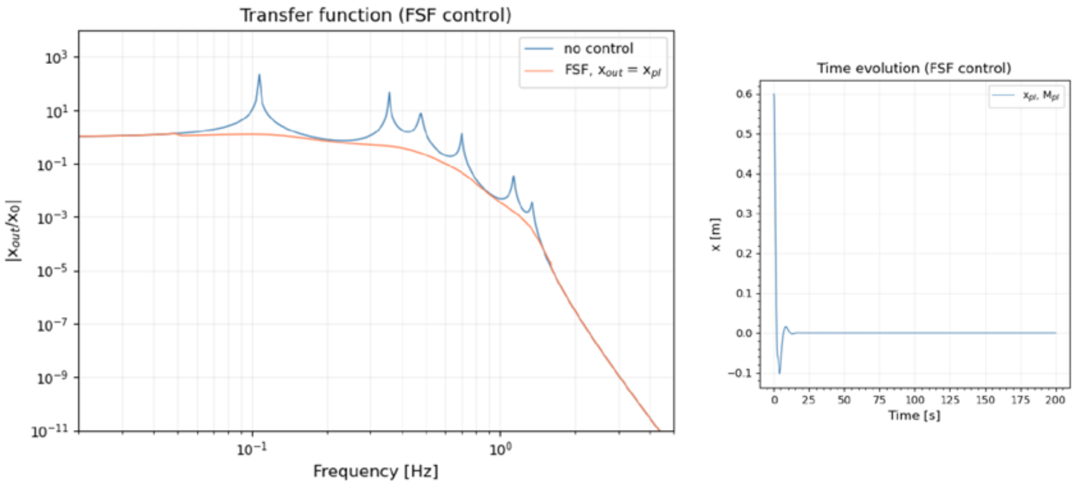
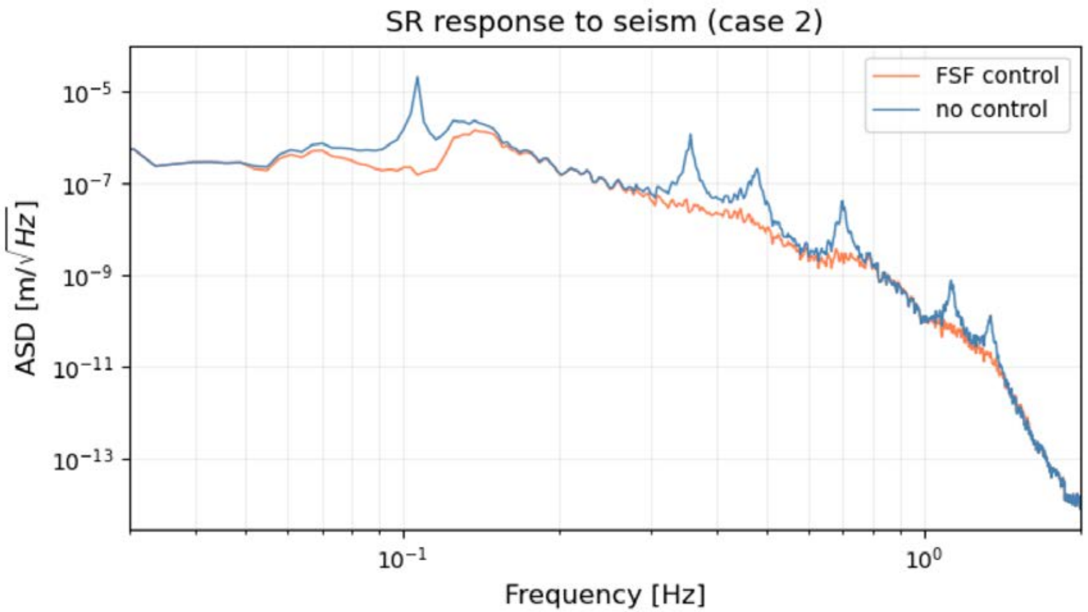


Figure 5.17: Case 3: (left) In blue the transfer function of the system not controlled, while in orange the transfer function of the system when FSF control is applied in the range f = [0.05, 1.6] Hz. (right) Temporal evolution of the controlled system.



- **Achieve RMS well below $\lambda/2$, gain of several expected**
- **Prototype project to achieve similar results in the horizontal DOF**

Conclusions

- **Revisiting seismic filters and related subjects in view of**
- **Einstein Telescope**
- **Virgo_Next**
- **Stable Recycling Cavities ?**

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