BHETSA Status
Novel prototype filter for the ET Superattenuator

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

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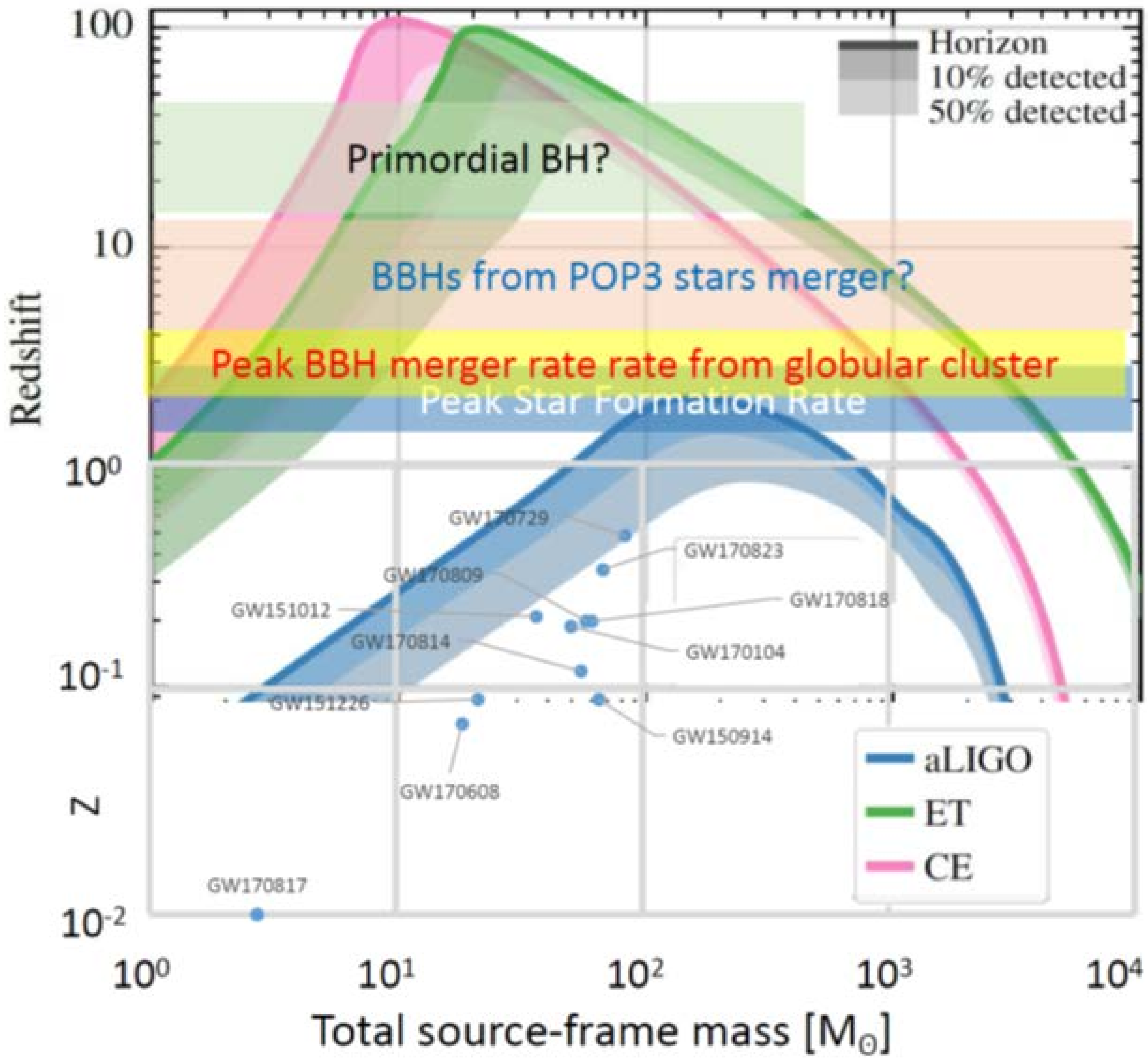
Low frequency motivation

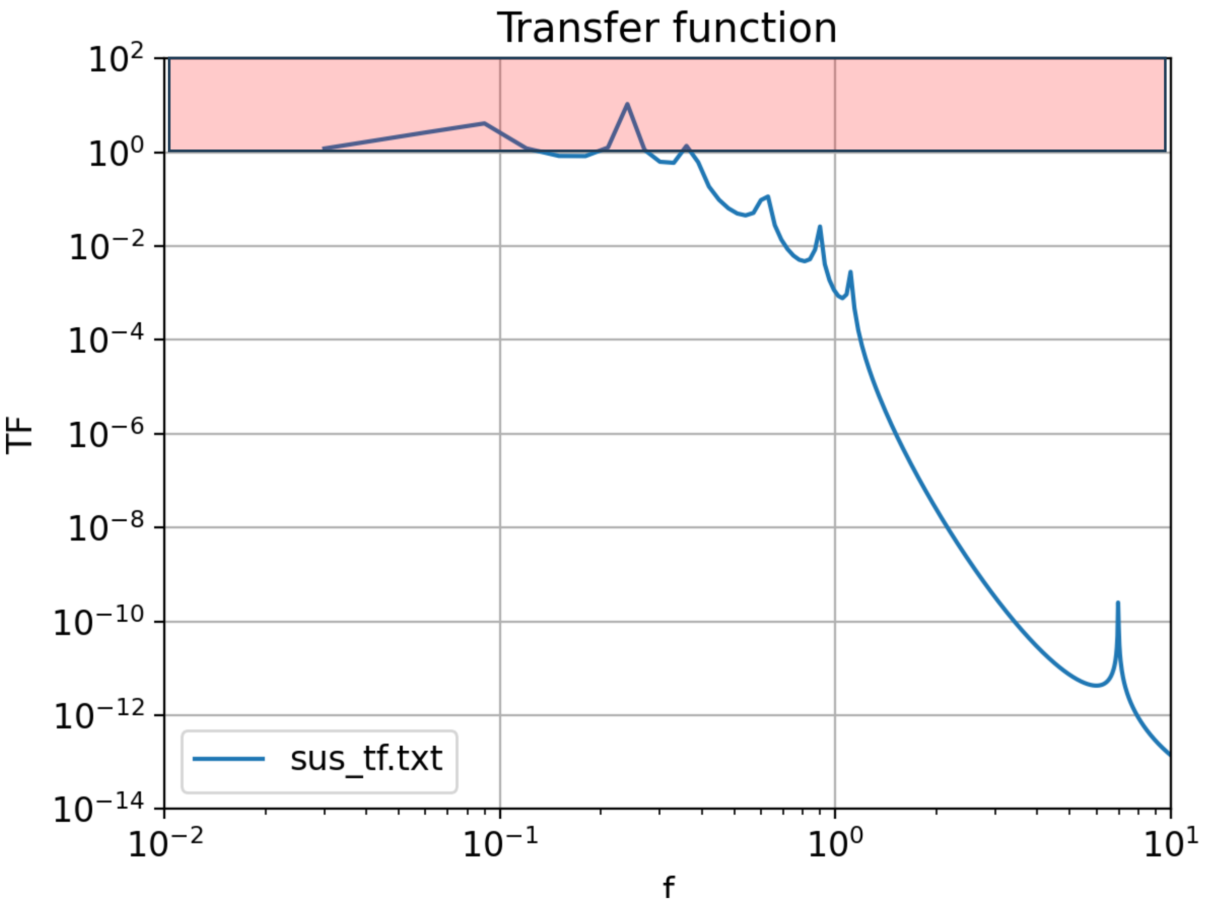
Sensitivity to low frequency:

- Higher system total mass
- Higher signal red shift, earlier in Universe history
- Earlier presence of signal in the detection band, earlier warning



Seismic attenuation in Virgo

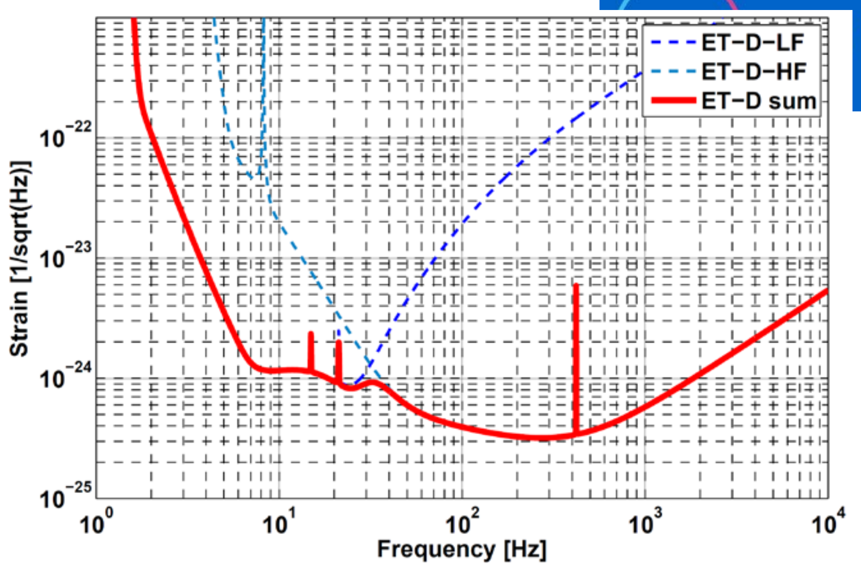
- **Ground motion 10^{-7} m $Hz^{-1/2}$ at 1 Hz vs 10^{-18} m $Hz^{-1/2}$ at 10 Hz**
- **Test mass asks for a very loose link**
  - Low pass filter with a steep frequency cut below the detection band
  - Cascade of harmonic oscillators (Second Order Sections)
  - Loose springs and high masses
- **Dissipation 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



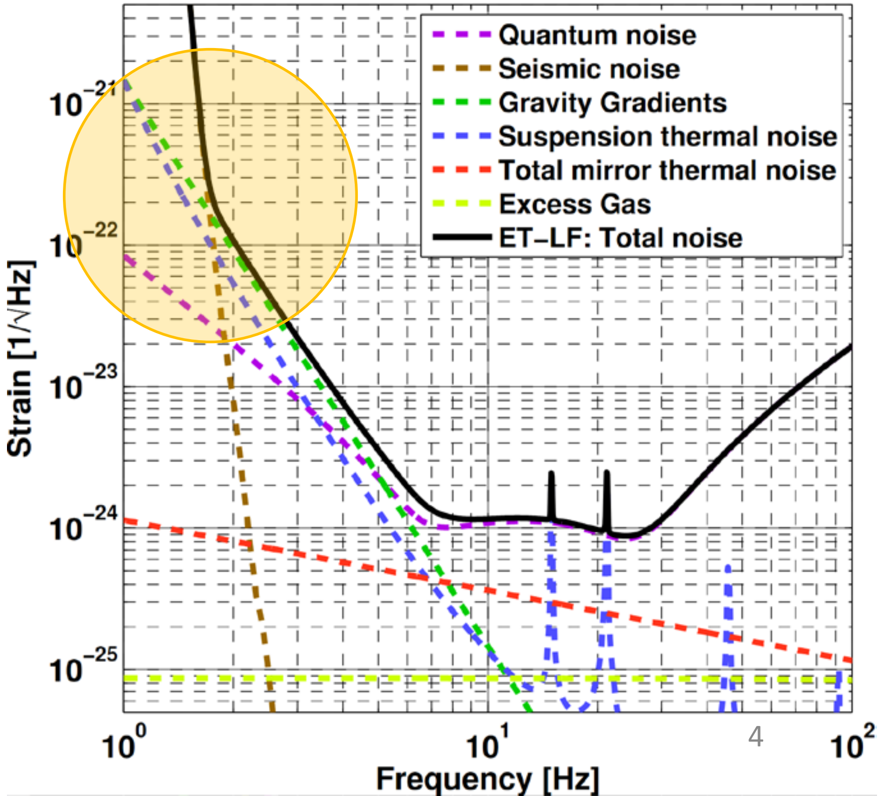
Design curve based on 17 m tall suspensions

Reduction to less than 10 m:

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

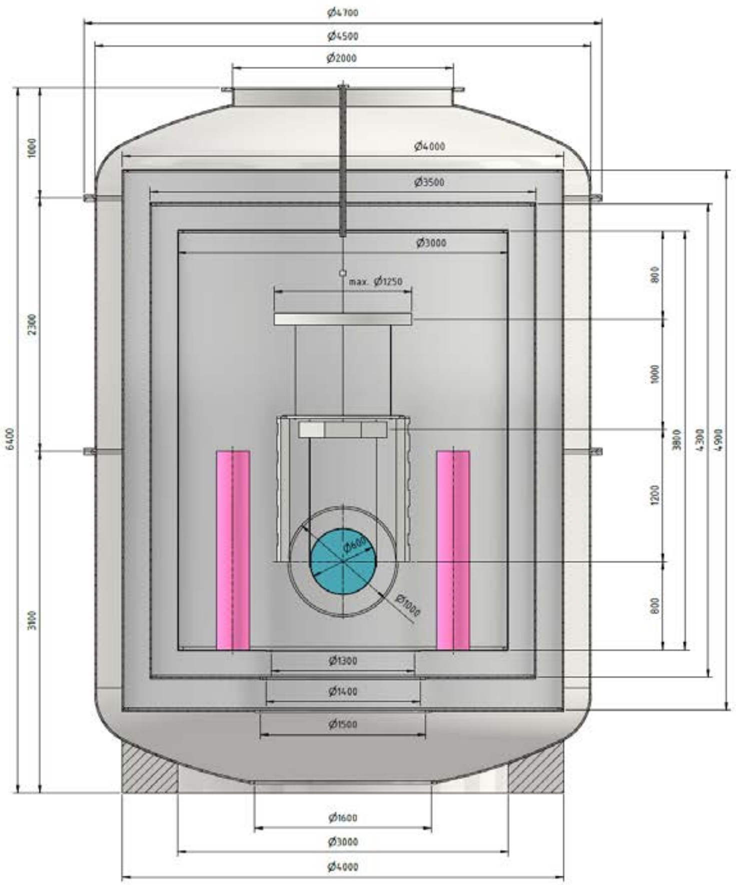
Newtonian noise crossing:

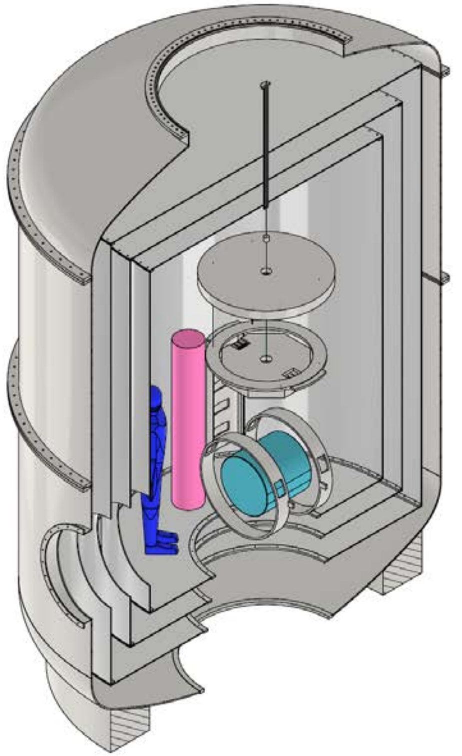
$2\ 10^{-22}\ Hz^{-1/2}$ at 1.8 Hz (AdV: 3.2 Hz)



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**



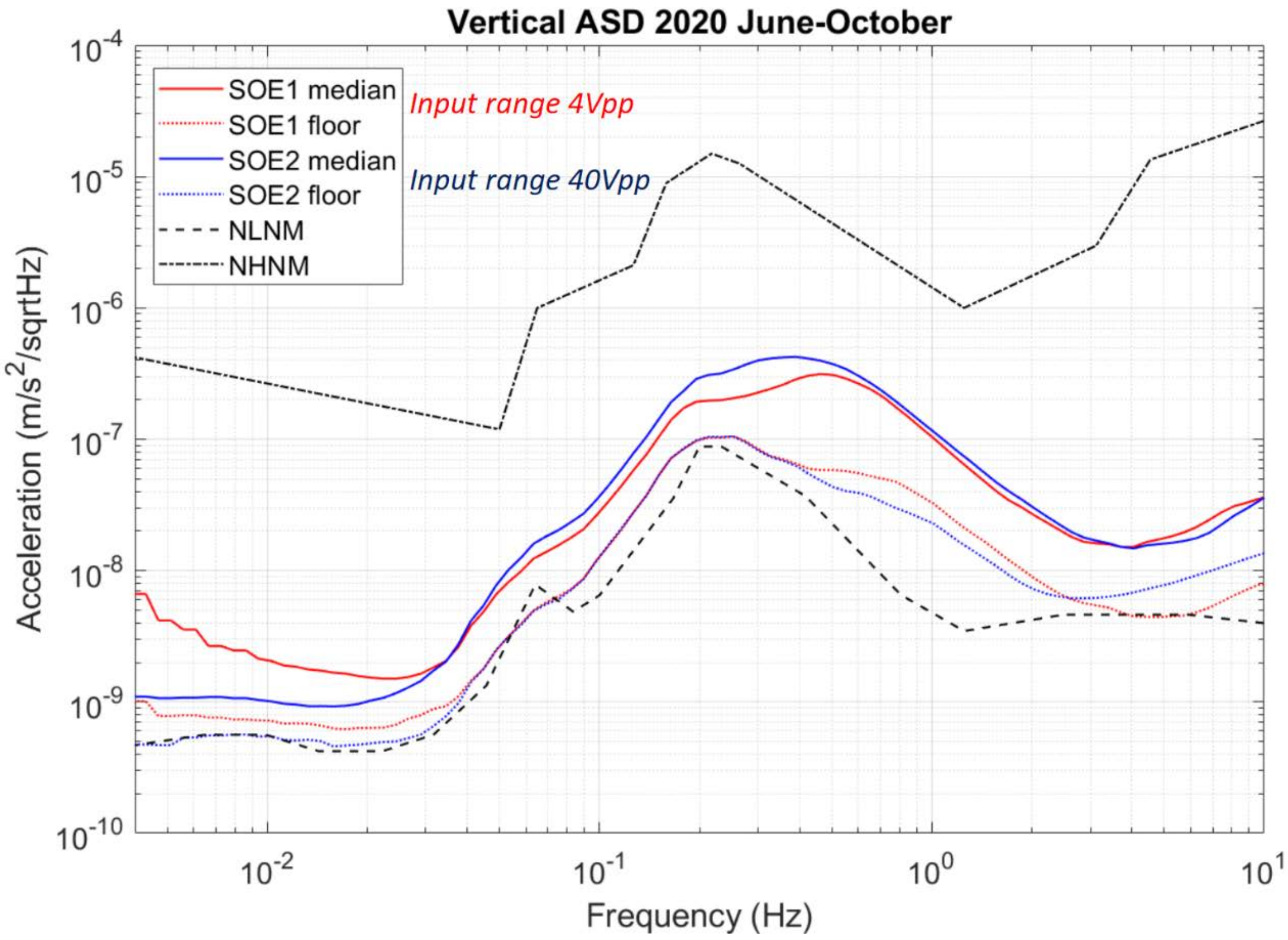


ET Seismic levels

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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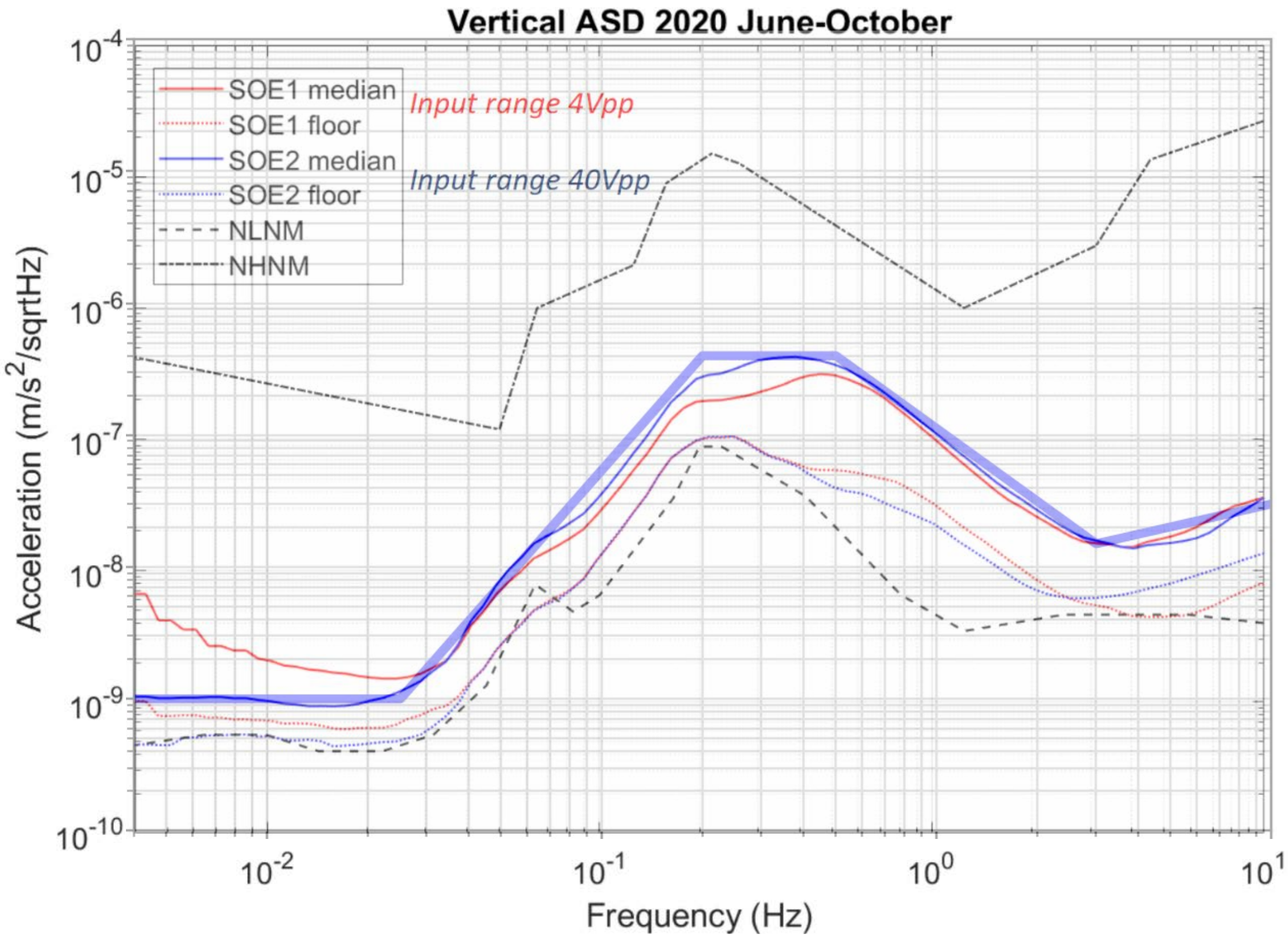
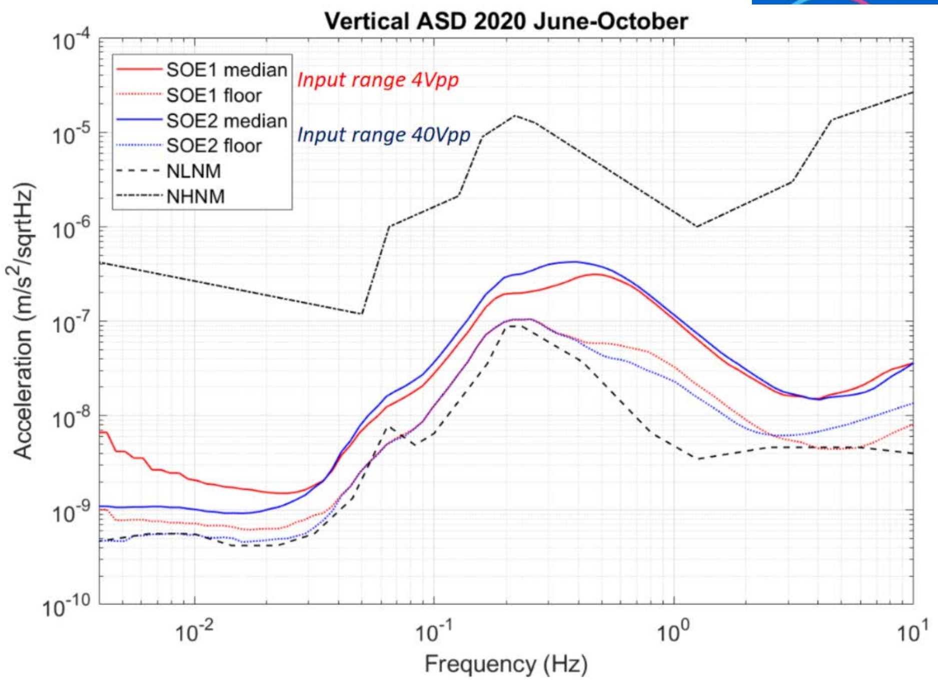


Seismic landscape



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
ET: 10^{-18} m $Hz^{-1/2}$ at 2 Hz

With factor 10 safety factor

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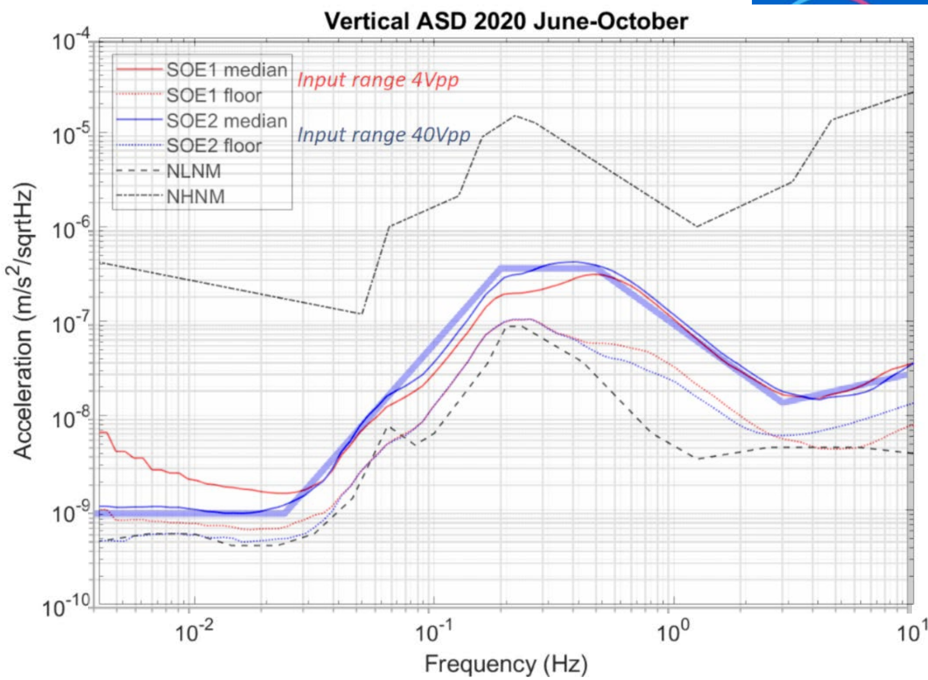
Seismic landscape



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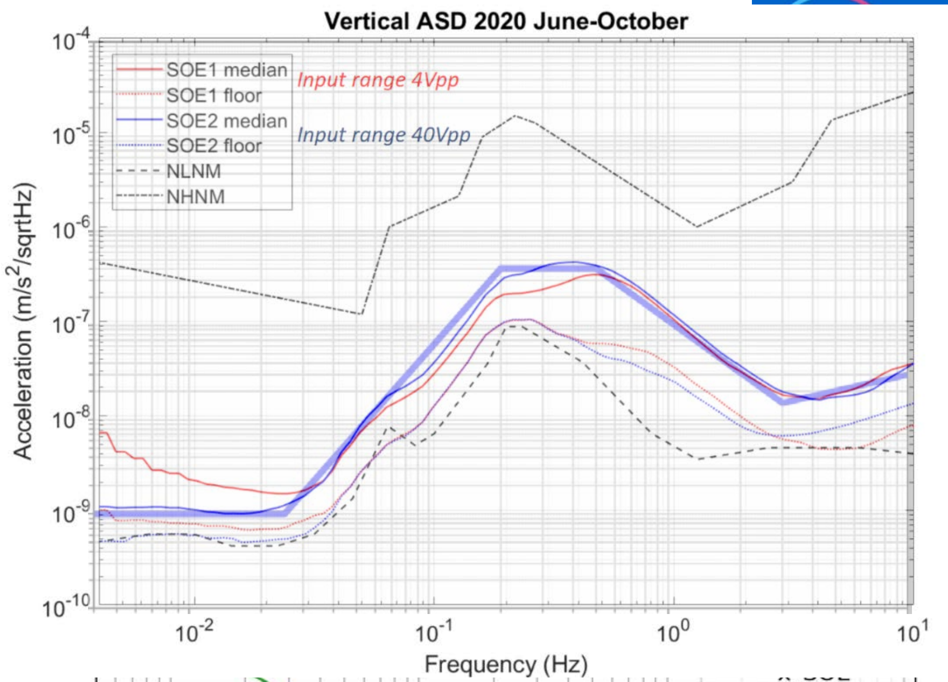

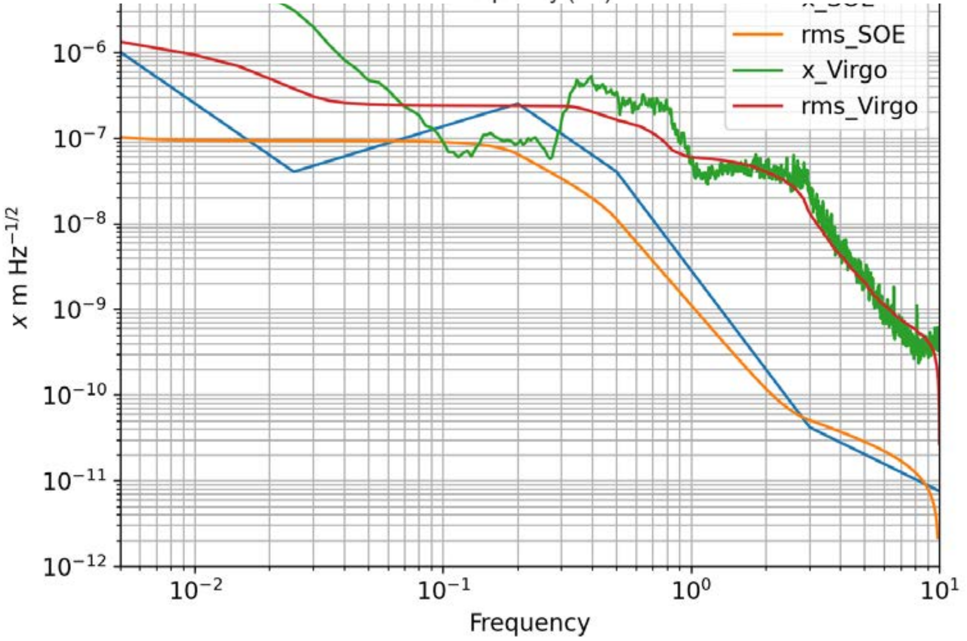

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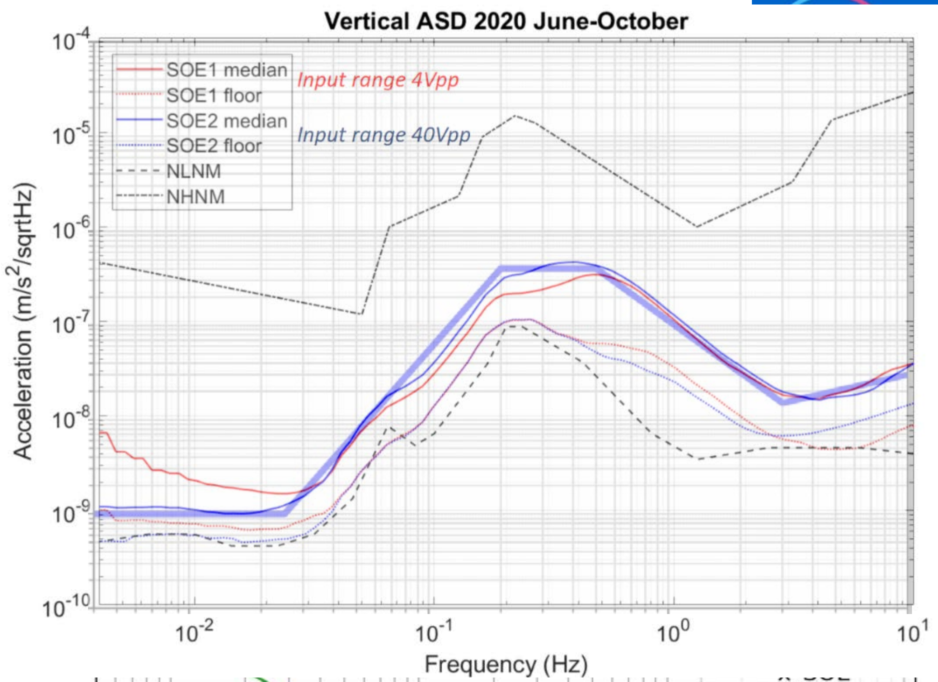

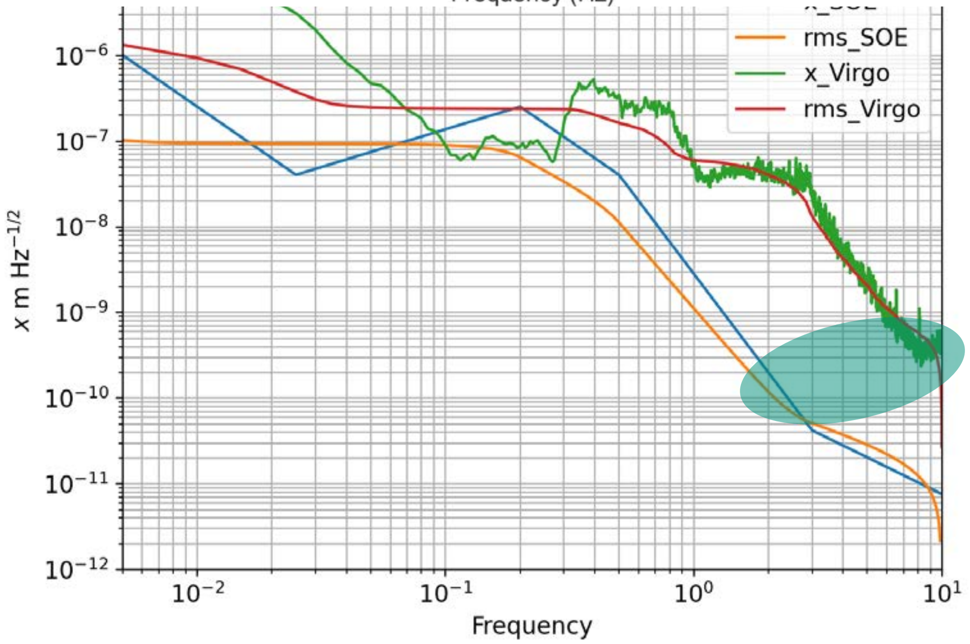

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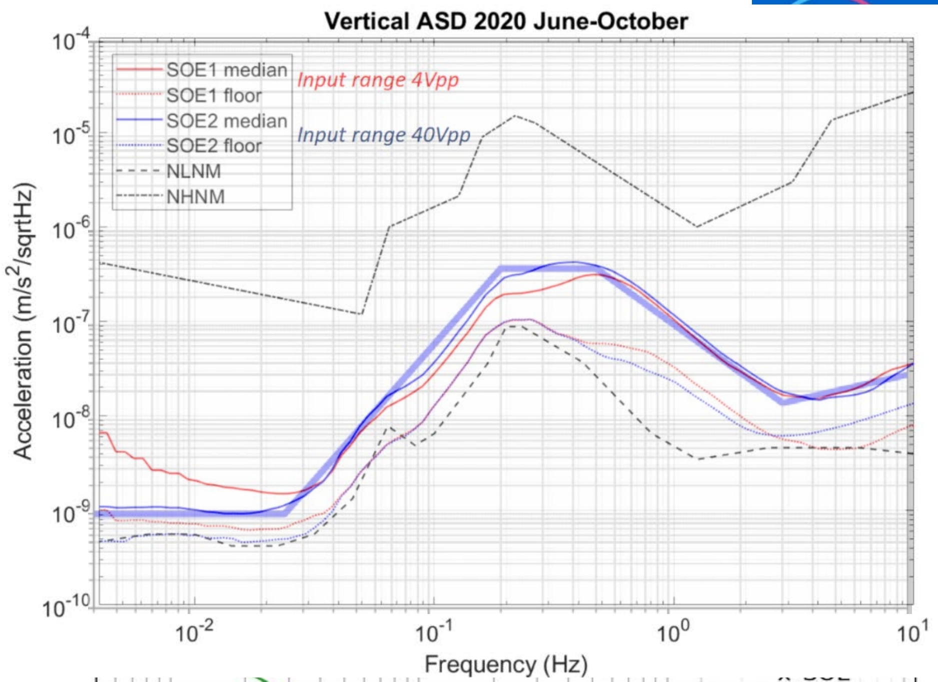

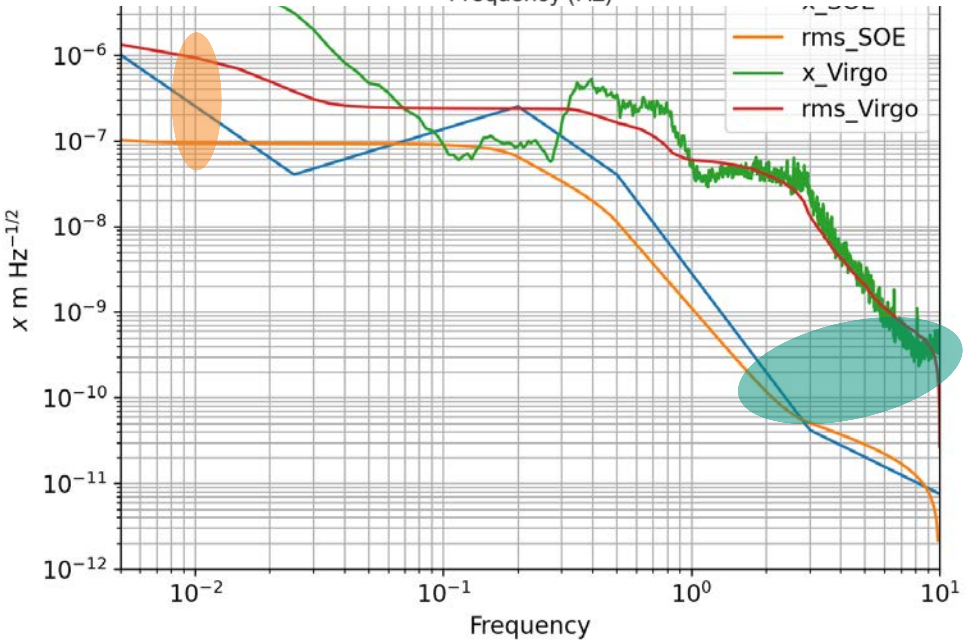

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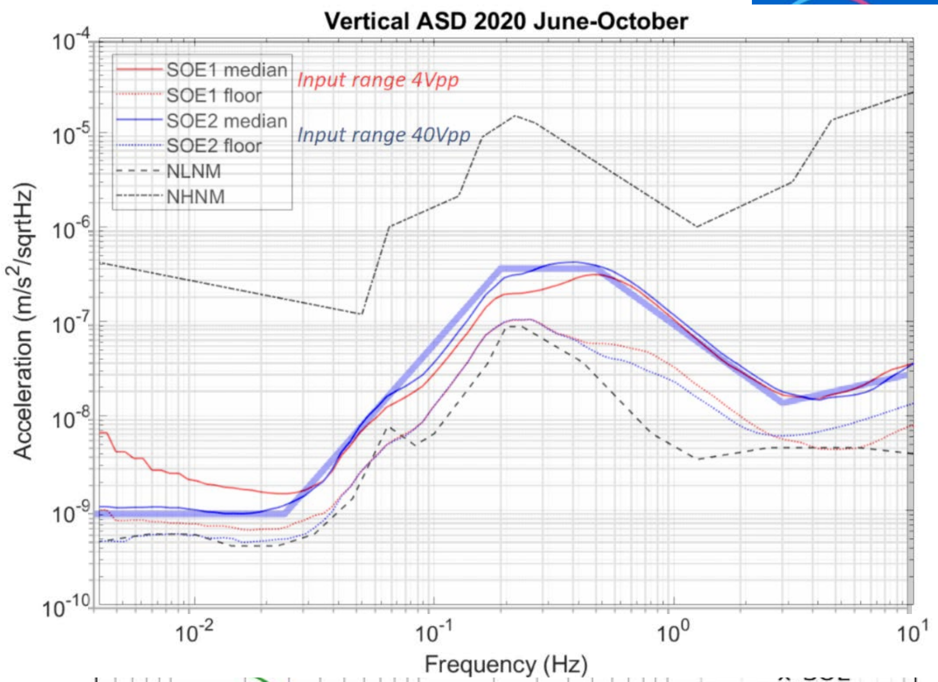
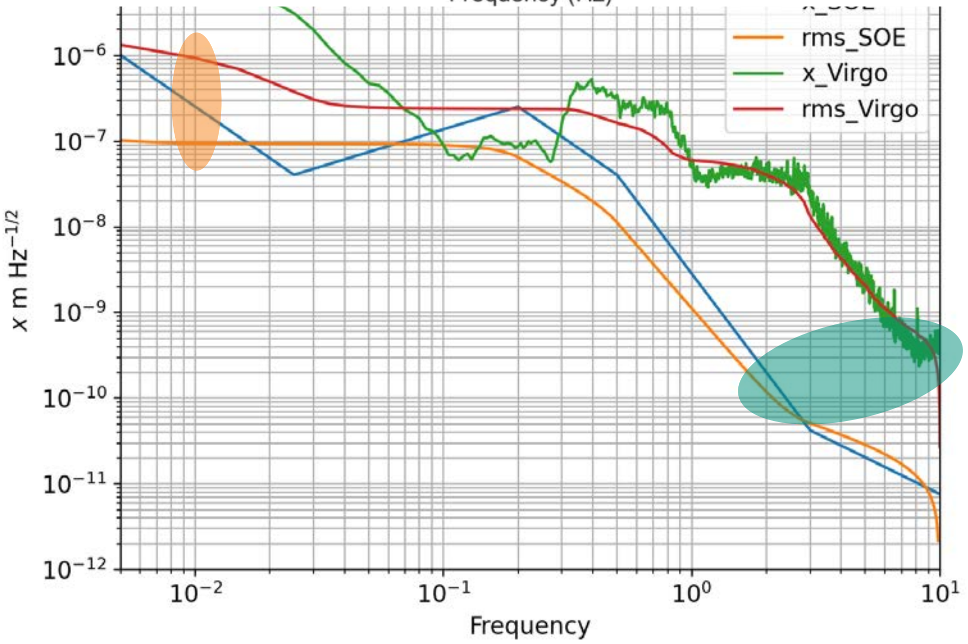




Attenuation required

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

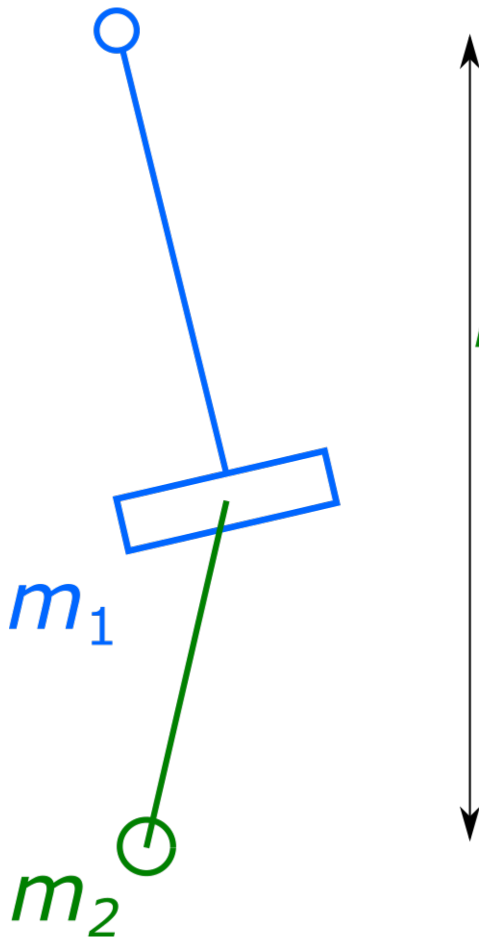
Remaining attenuation required

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

The Superattenuator

Cascade of pendulums

Using inertia and gravity



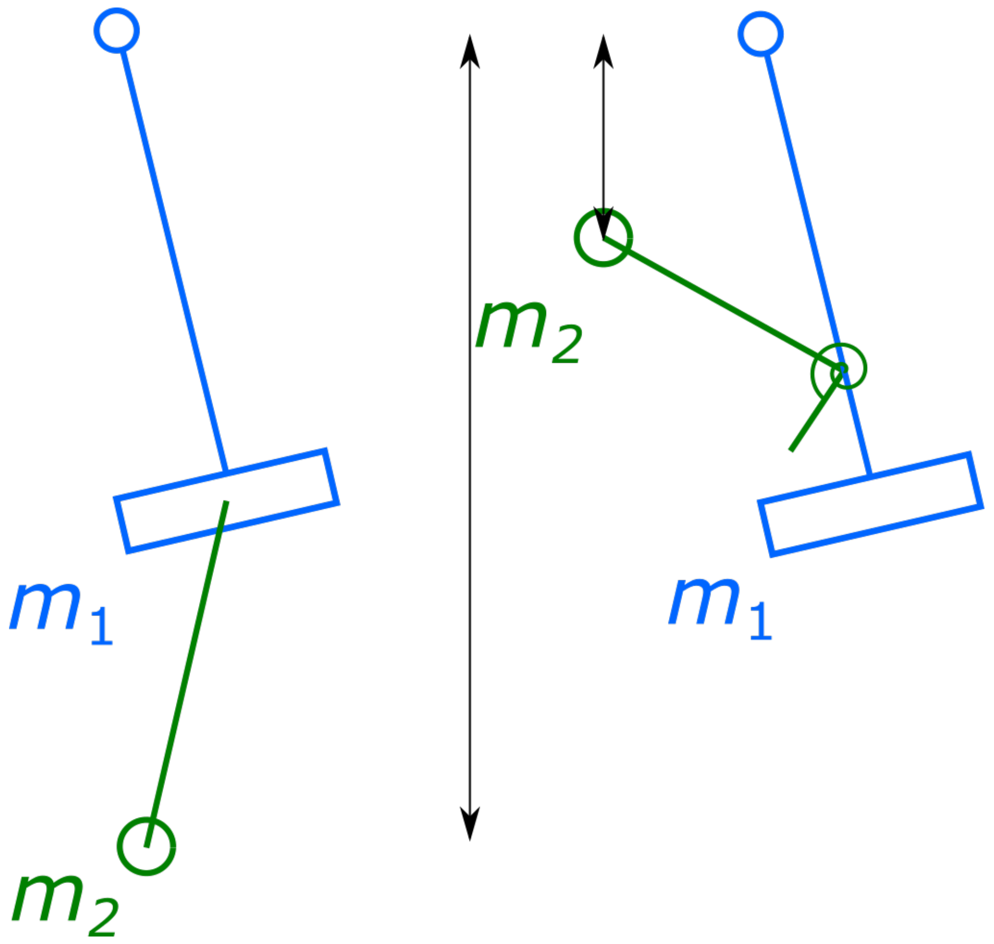
The Superattenuator

Cascade of pendulums

Using inertia and gravity

To using inertia, springs and gravity

Shortening the path to the test mass

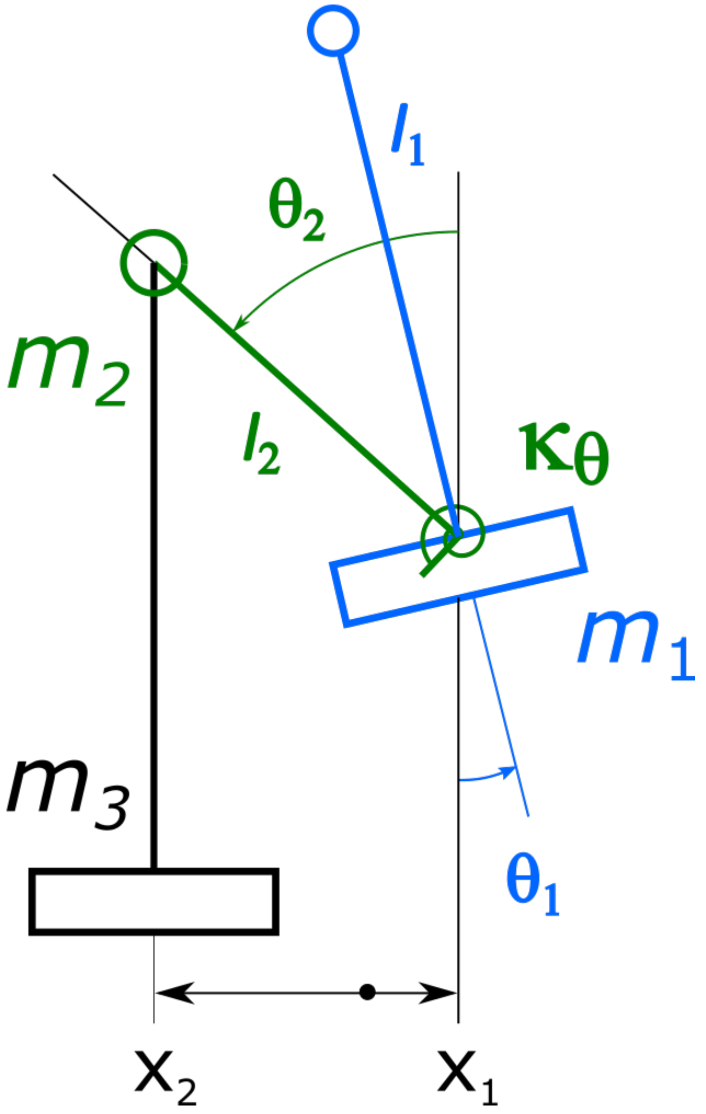


Pendulum – Inverted pendulum

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

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

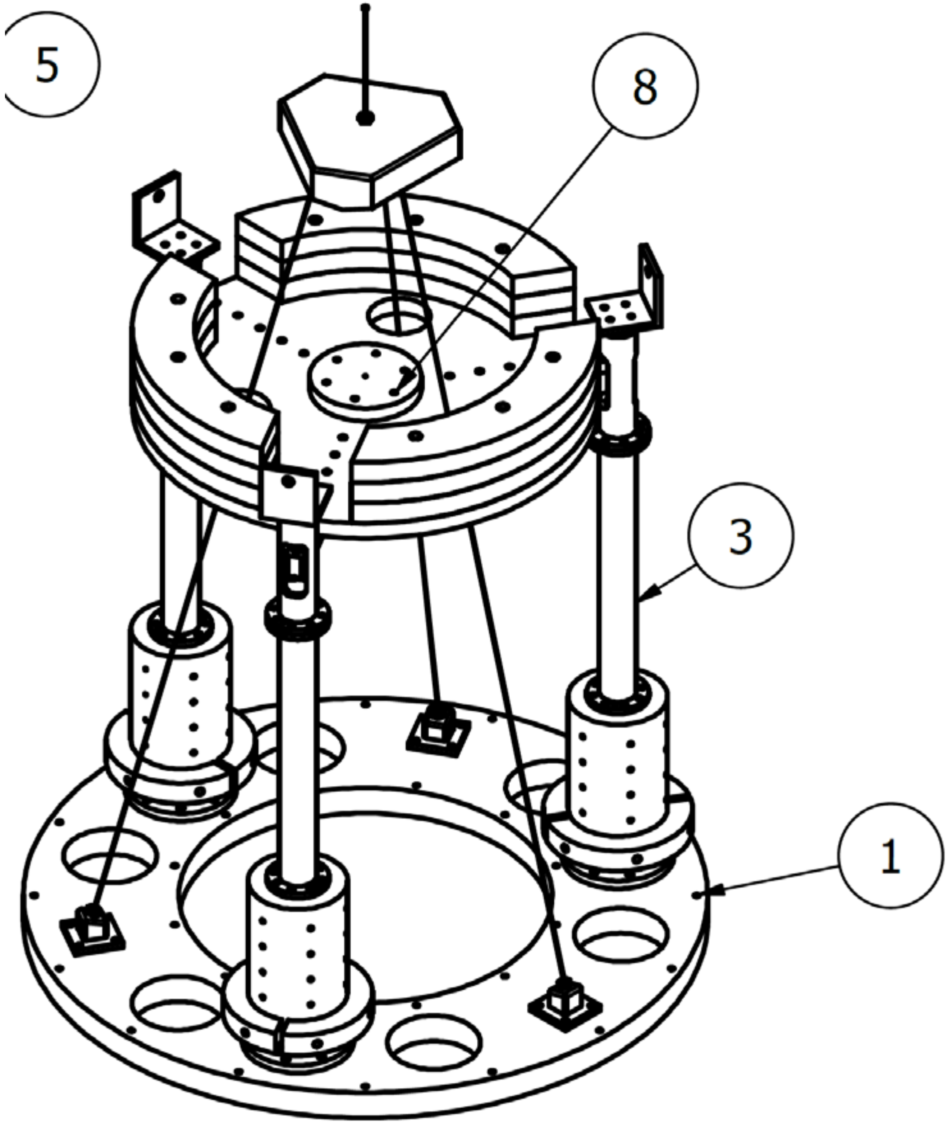
Horizontal attenuation of a single PIP
No damping

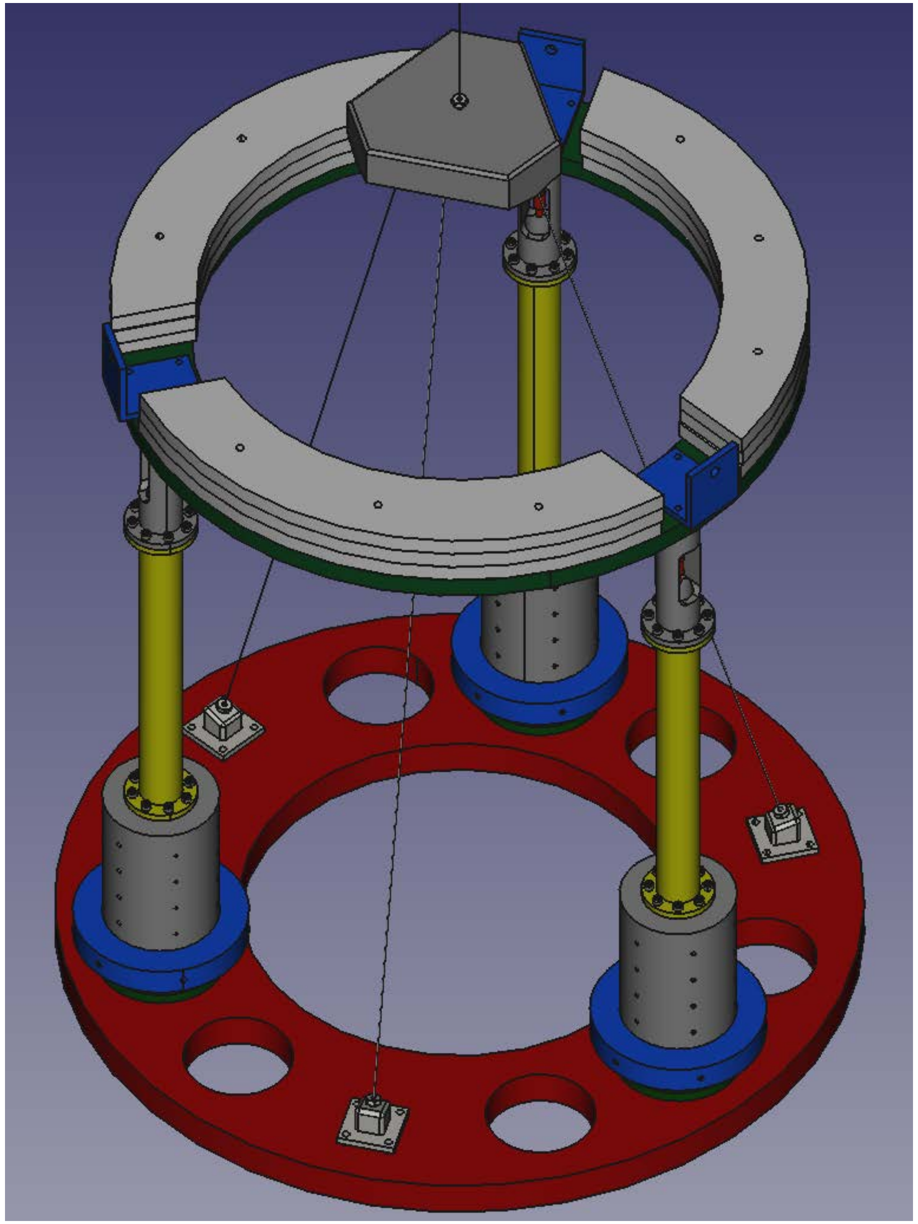
For f_0 = 0.75 Hz
A_2 : attenuation at 2 Hz — $2.7\ 10^{-2}$

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

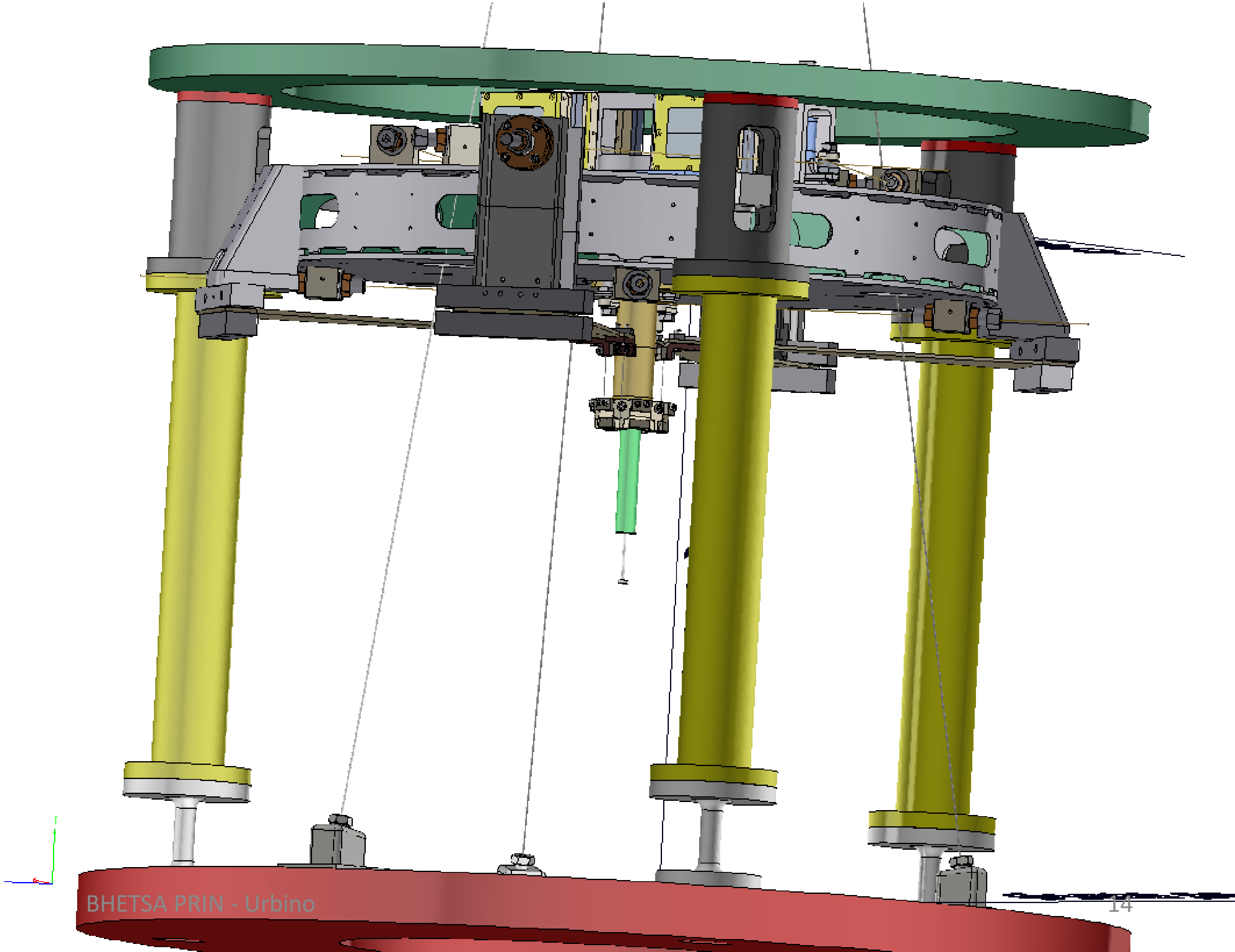




Use a standard F7 filter frame

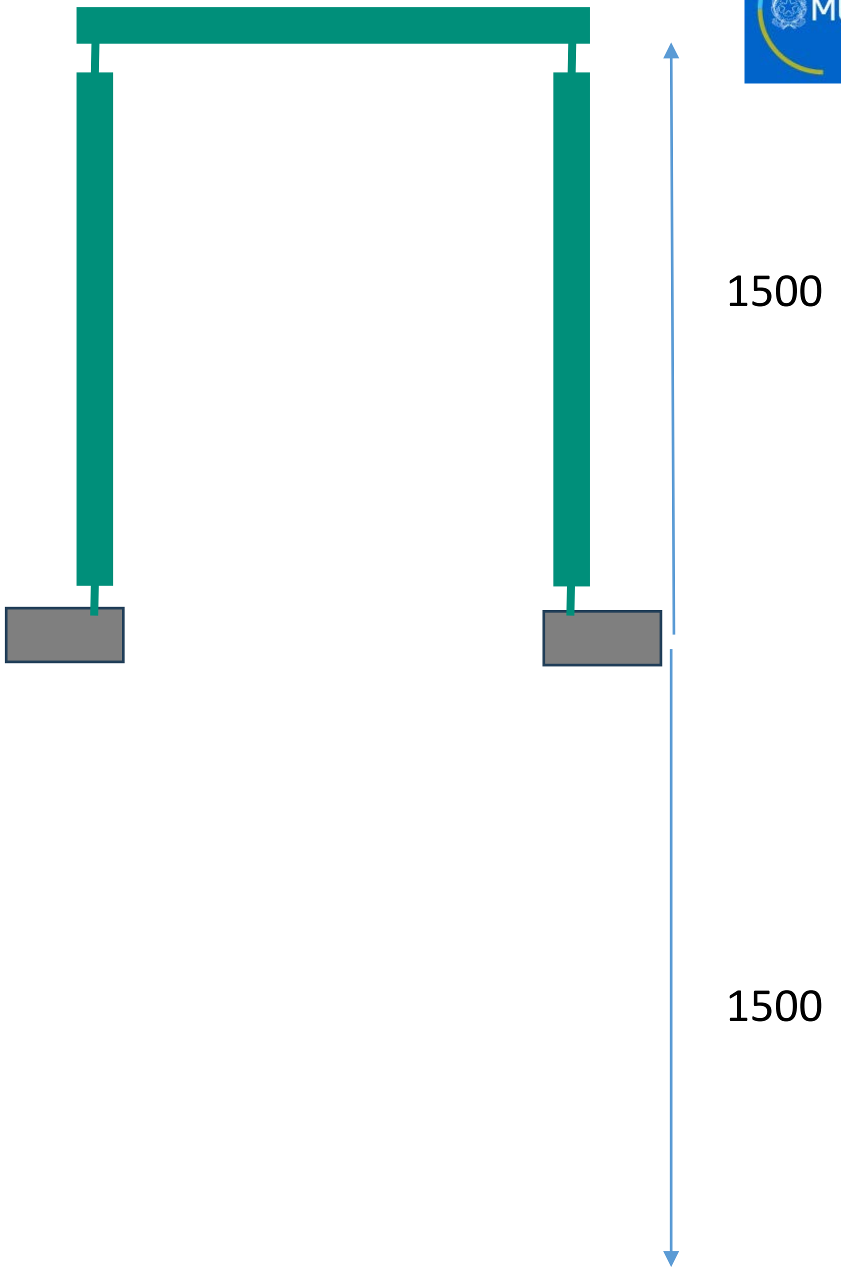
Standard filter addition for vertical attenuation

- 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



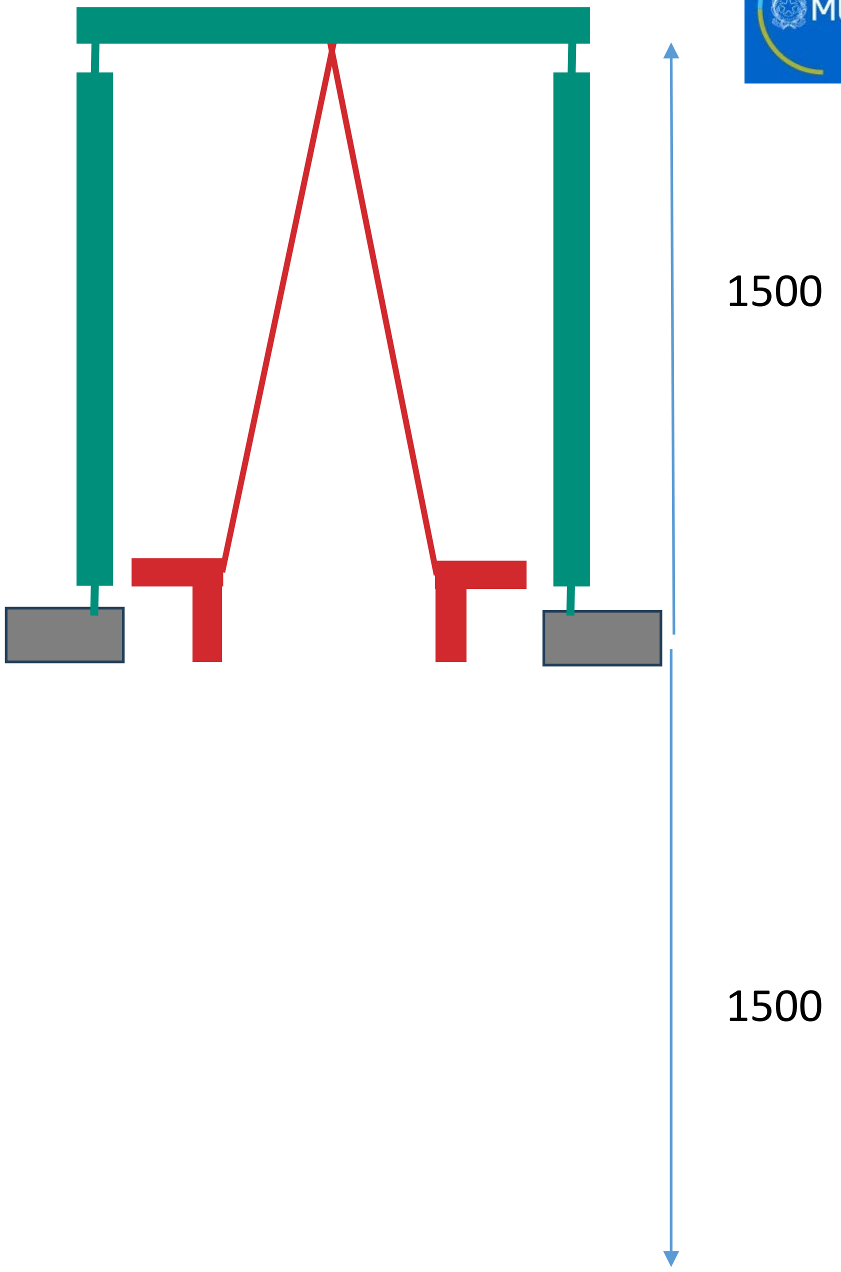
Additional considerations

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



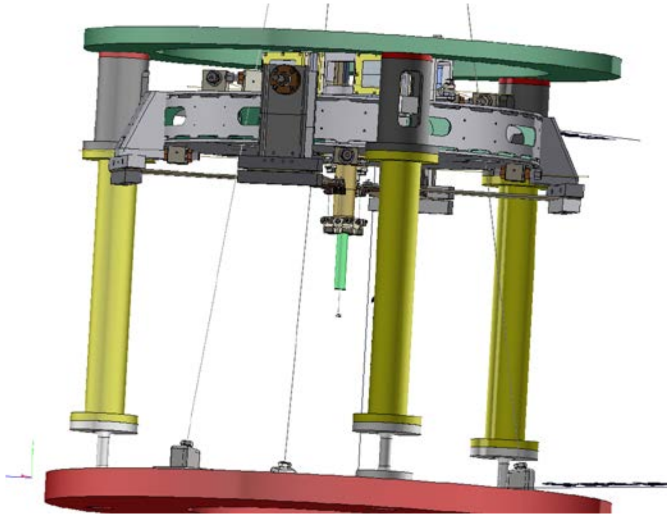
Additional considerations

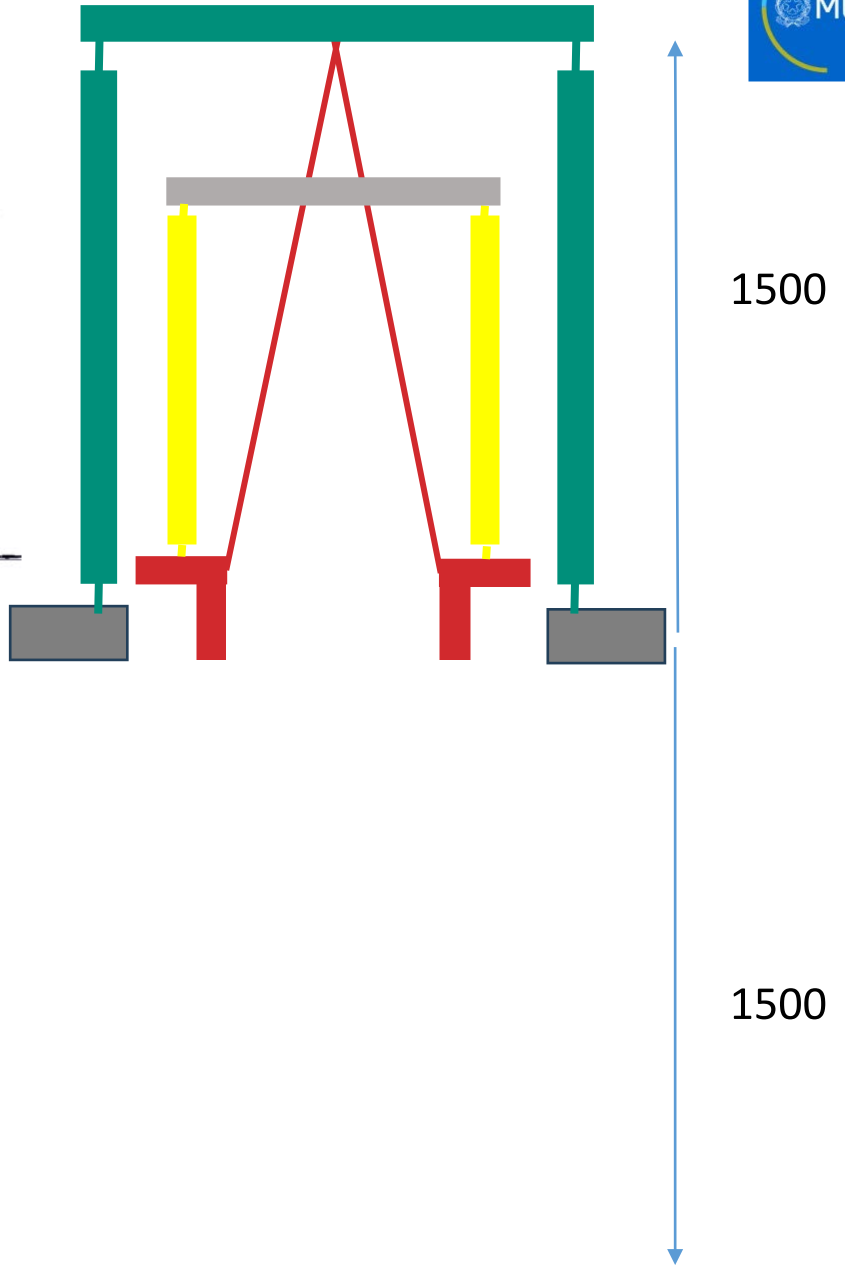
- **The high part of a suspension chain can be built**
  - Starting from an IP
  - Hanging a pendulum



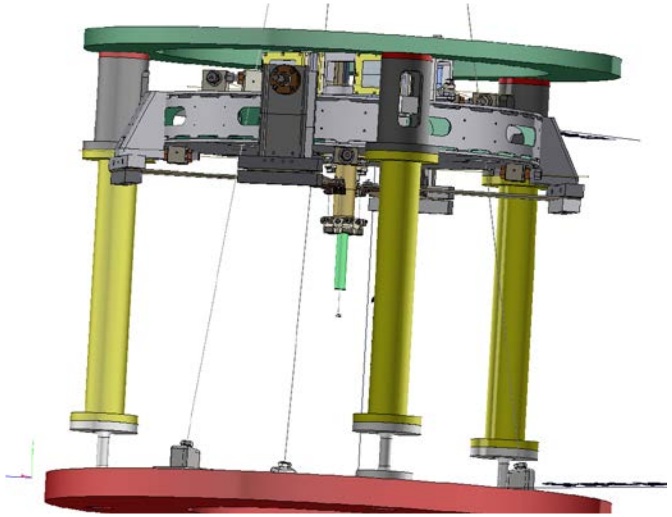
Additional considerations

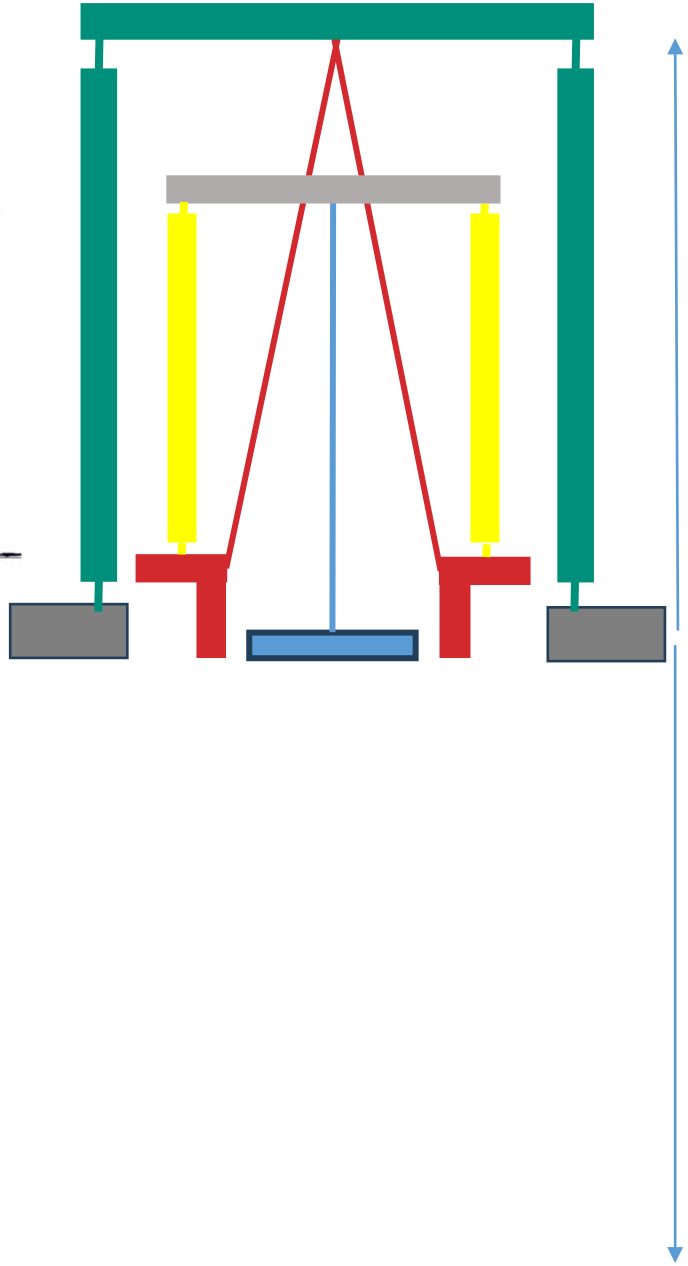
- **The high part of a suspension chain can be built**
  - Starting from an IP
  - Hanging a pendulum
  - Adding an Inverted Pendulum (-> PIP)





- **The high part of a suspension chain can be built**
  - Starting from an IP
  - Hanging a pendulum
  - Adding an Inverted Pendulum (-> PIP)
  - Suspend a vertical isolation filter





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- **The high part of a suspension chain can be built**
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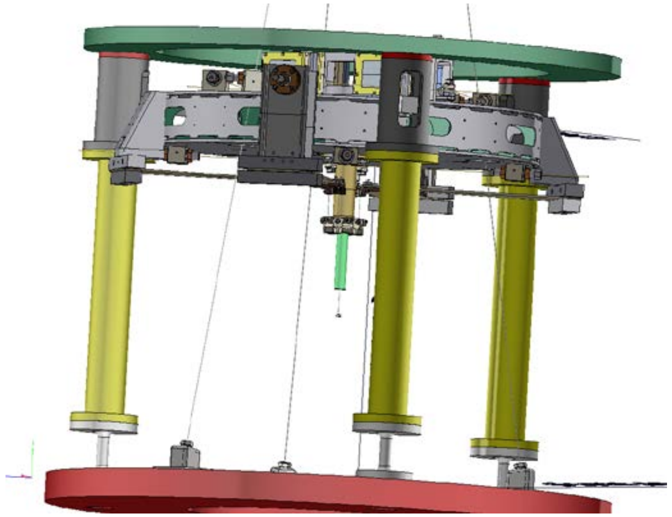
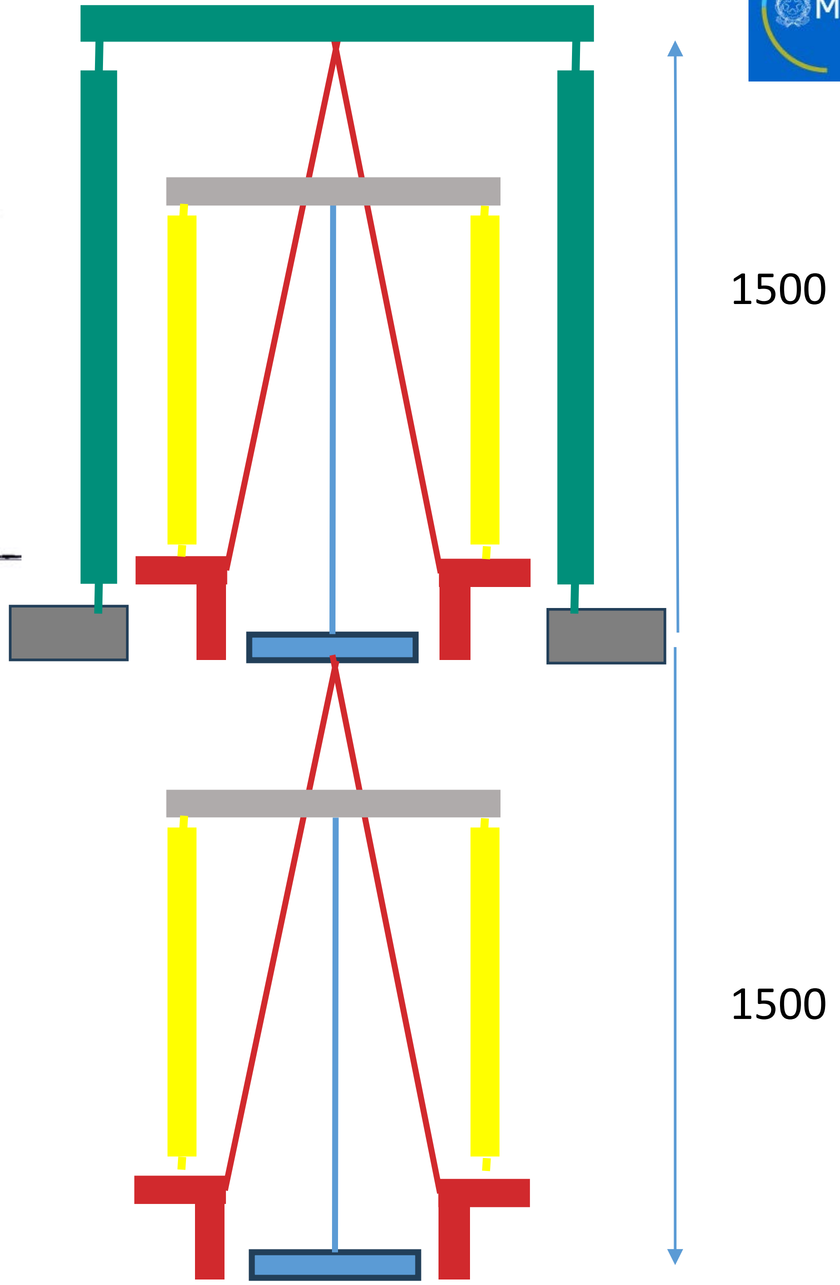
  - Suspend a vertical isolation filter
  - That suspends another PIP





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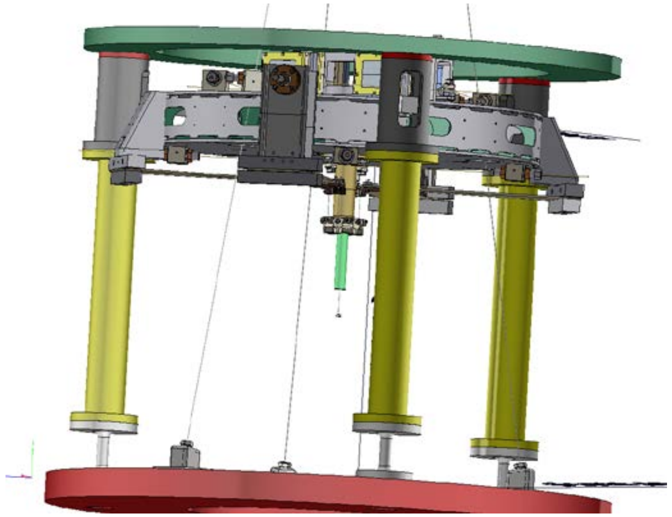
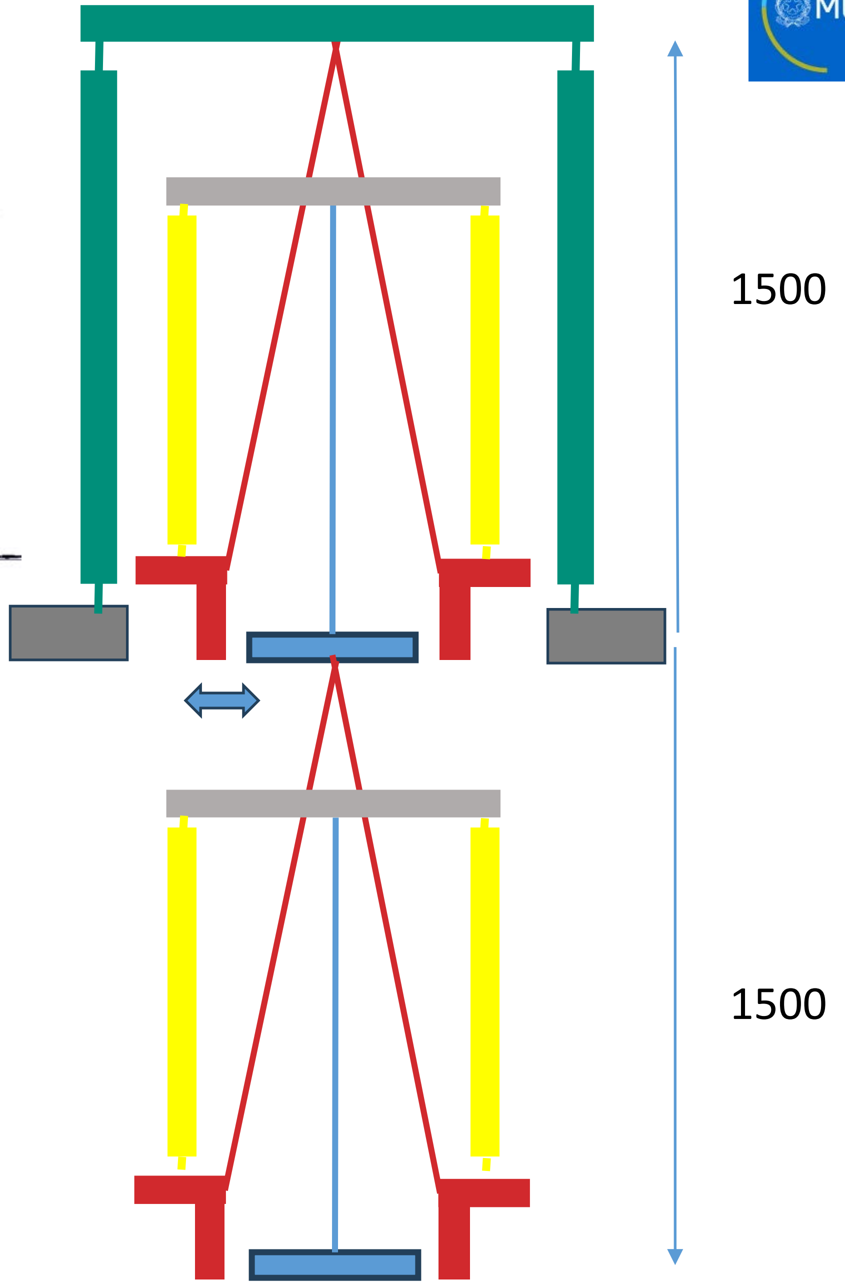
  - Hanging a pendulum
  - Adding an Inverted Pendulum (-> PIP)
  - Suspend a vertical isolation filter
  - That suspends another PIP
  - Possibility to apply inter-filter feedback

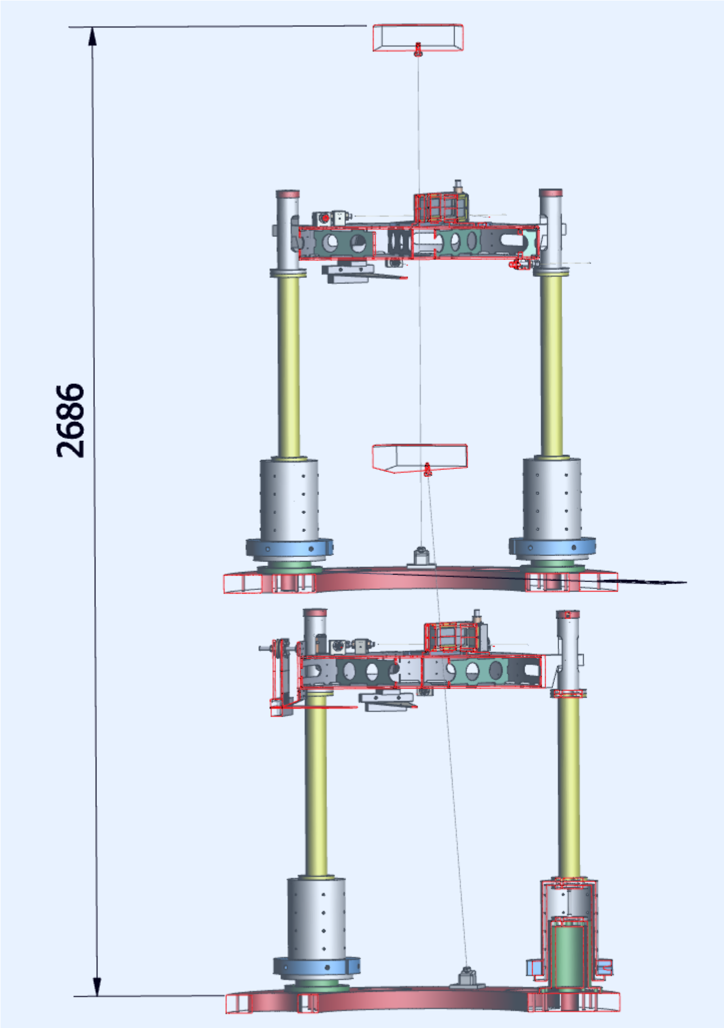


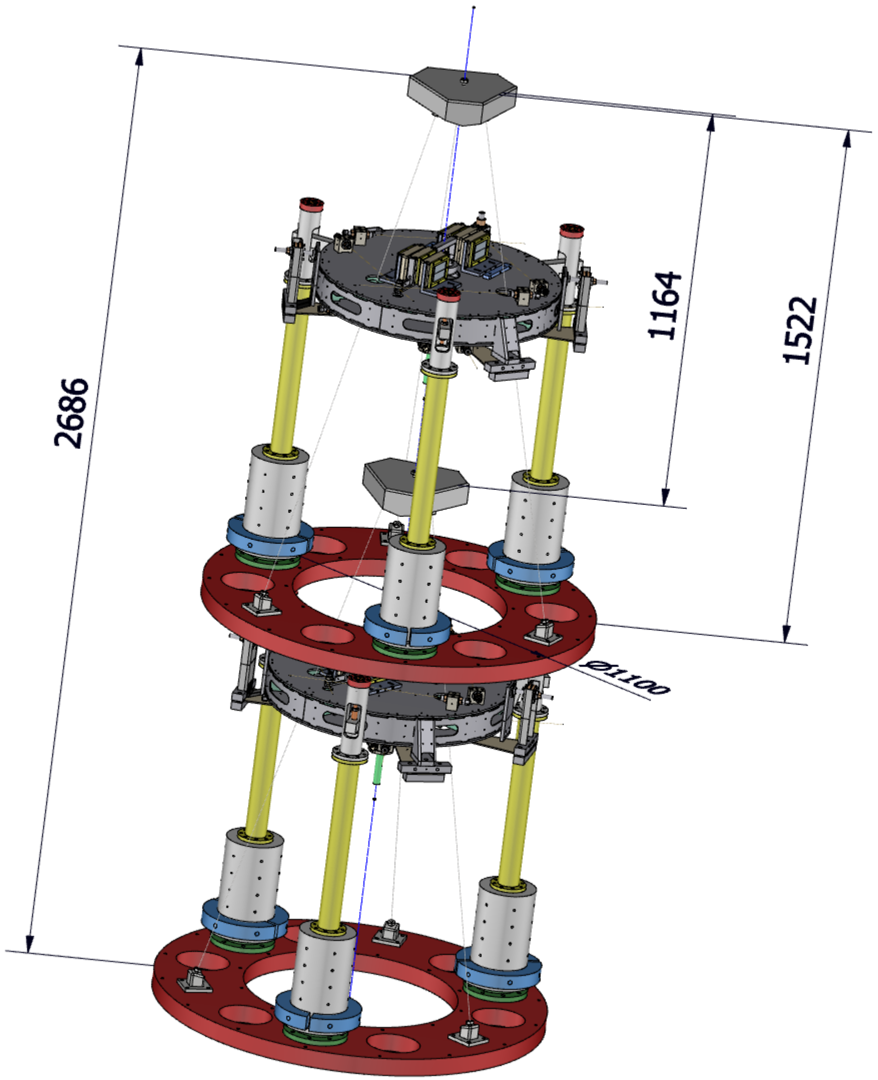


e-PIP

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 (see Lorenzo, Sara and Matteo’s talks)

WP2 Simulations are in progress (see Max, Matteo’s talks)

Modifications on Filter 7 (Andrea Basti)

Laboratory equipment and software support (see Lorenzo and Michele’s talk)

BHETSA program

WP3 Sensors and actuators

- Tiltmeter progress (Annalisa's talk)
- Develop new accelerometer with better position sensing
- Explore optical readout
- Explore microTCA electronics (Valerio's talk)

WP4 Control and ML (see Gaia and Maria's talks)

WP5 SarGrav (Davide, Domenico)

WP6 Outreach (Davide, Domenico)