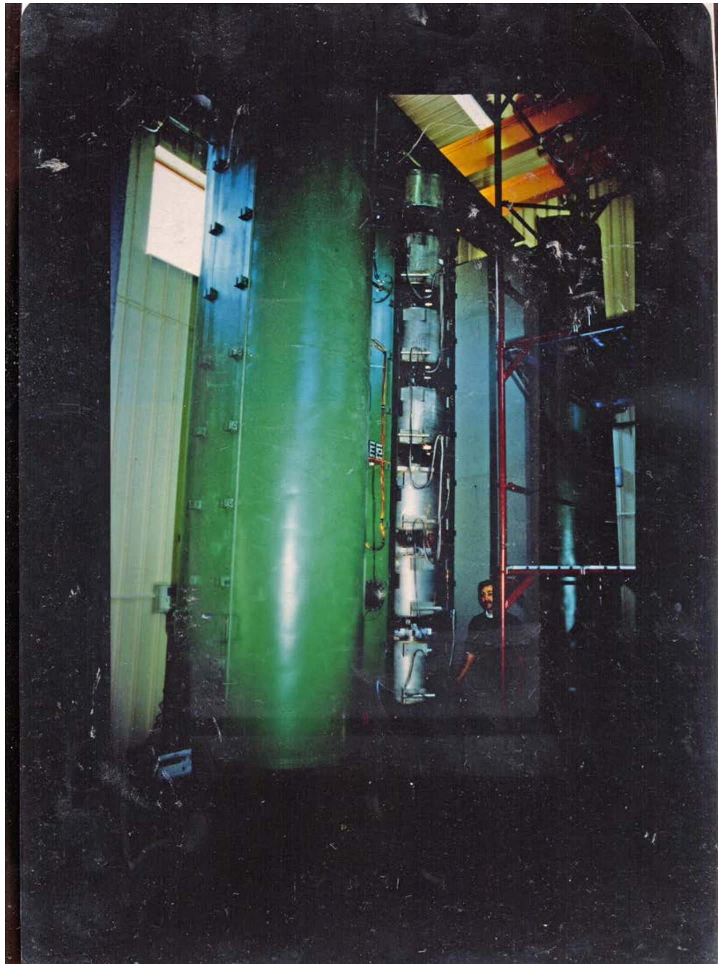
Suspensions and Seismic Isolation Systems

Francesco Fidecaro for NGSA and BHETSA

EGO - Cascina

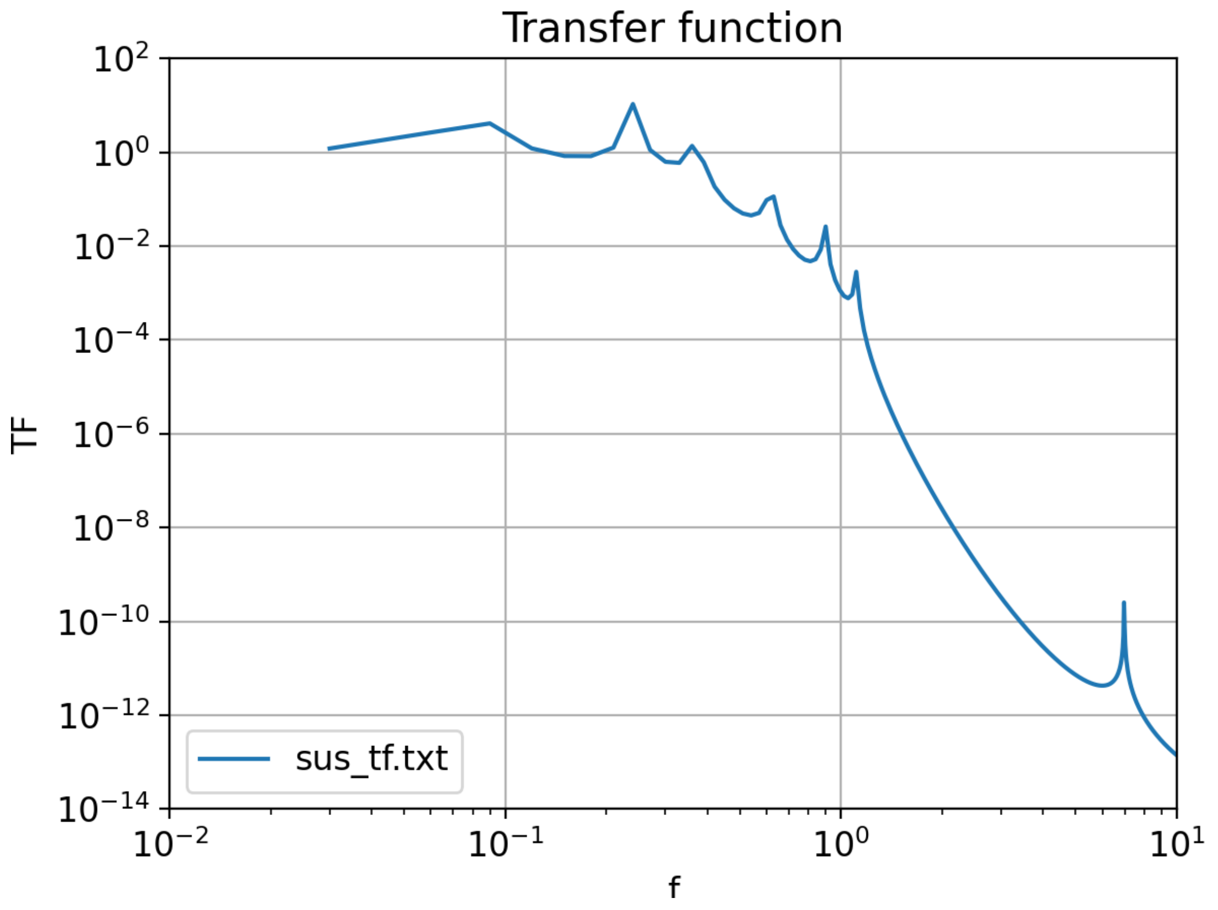
Seismic isolation work

- **Pioneering work in Pisa by Adalberto Giazotto and collaborators**
  - Started in 1985 with the «1 mile» pendulum
- **Demonstration of seismic attenuation at low frequency convinced INFN and CNRS that Virgo was worth the effort**
- **Virgo superattenuator**
  - Magnetic antisprings for vertical attenuation
  - Inverted pendulum for tide compensation
  - Superattenuator performance could be verified only with a fully performing Virgo in 2010: sensitivity and long locks needed
- **Seismic isolation is the same since 1998**
  - Pushing the terrestrial low frequency limit calls for a revision
- **R&D projects to reduce the ET Superattenuator height (17 m -> 12 m)**
  - NGSA: New Generation SuperAttenuator
  - ETIC: ET Infrastructure Consortium
  - BHETSA: Black Holes for ET in Sardinia



General principles

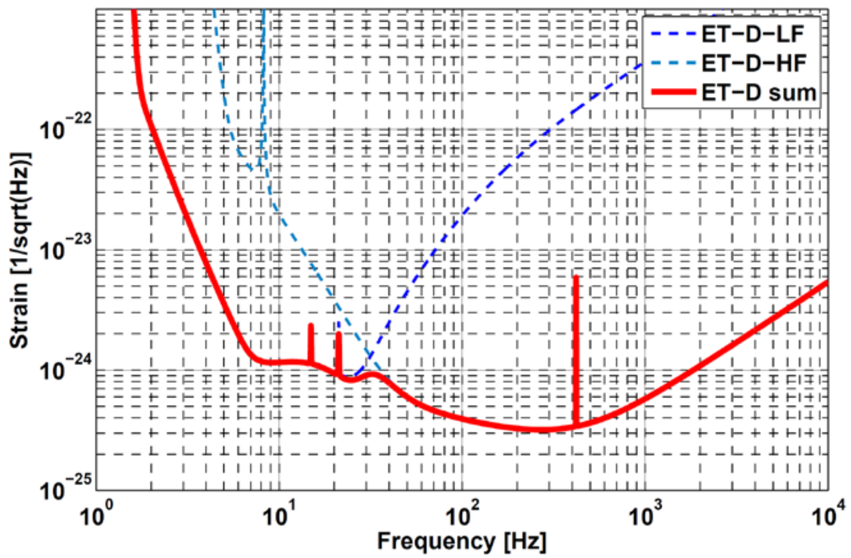
- **Ground motion 10^{-7} m $Hz^{-1/2}$ at 1 Hz vs 10^{-18} m $Hz^{-1/2}$ at 2 Hz**
- **Test mass asks for a very loose link**
  - Low pass filter with a steep frequency cut below the detection band
  - Cascade of harmonic oscillators (Second Order Sections)
  - Loose springs and high masses
- **Dissipation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



ET-LF requirements

LF noise is given by

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



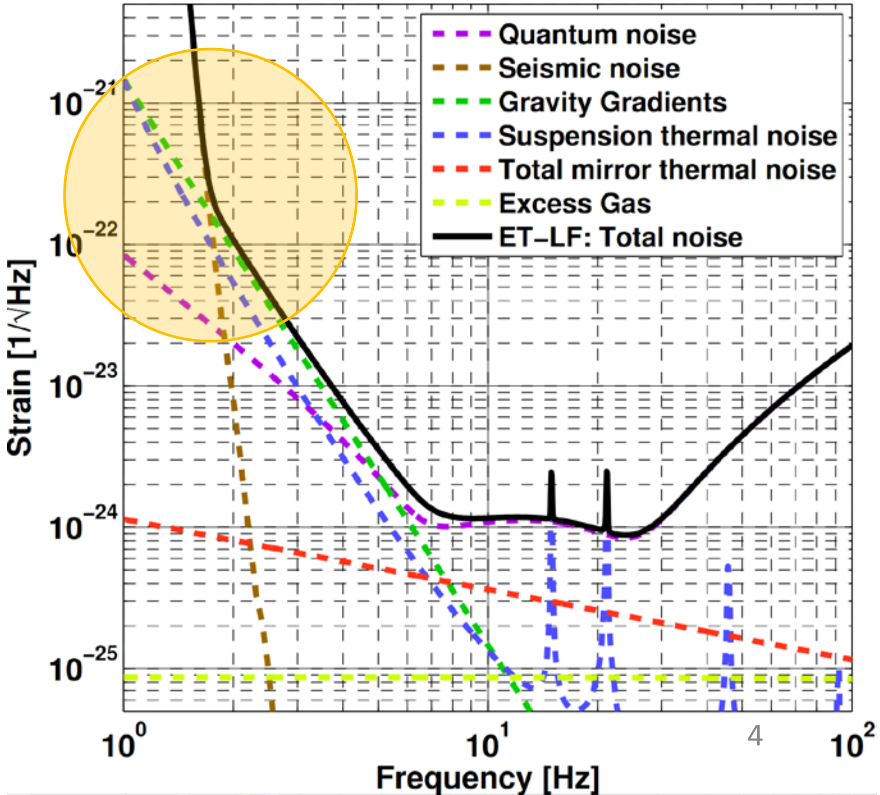
Design curve based on 17 m tall suspensions

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 vertical occupancy announced**

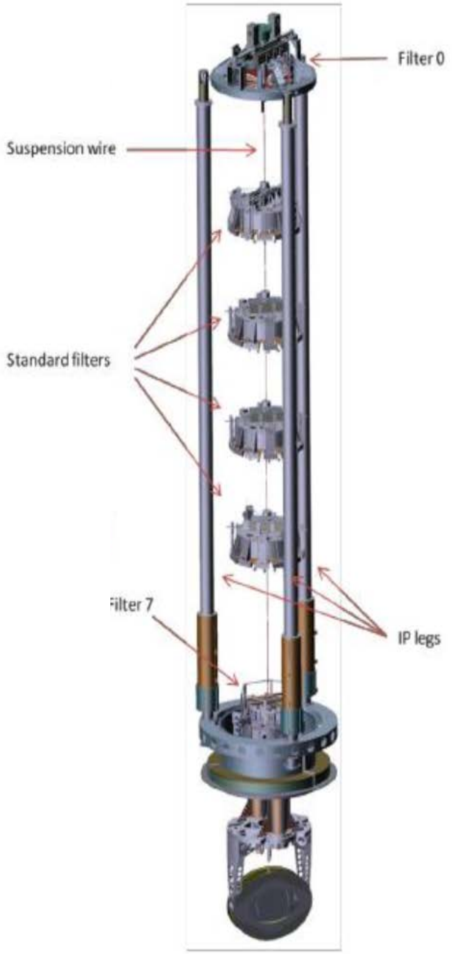
NGSA

New Generation Super-Attenuator

A. Bertocco, M. Bruno, R. De Rosa, **L. Di Fiore,** D. D'Urso,
F. Frasconi, A. Gennai, L. Lucchesi, F. Pilo, D. Rozza,
P. Ruggi, V. Sipala, I. Tosta e Melo, L. Trozzo

INFN-Pisa, INFN-Napoli, INFN-LNS/UniSS) and a participation by EGO

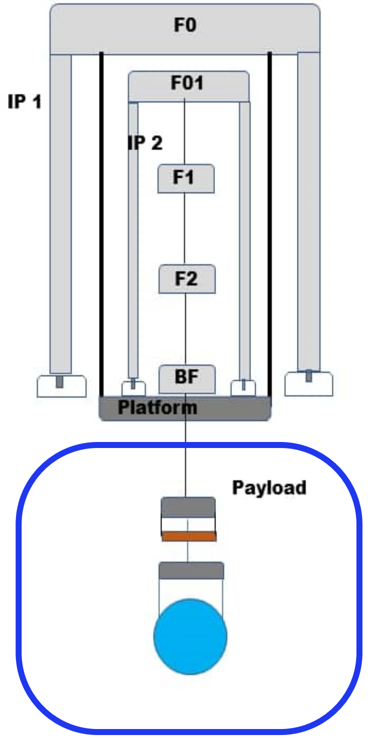
From AdV SA to ET-NIP SA



- Complex, heavy cryogenic payload (~ 600 kg) will be surrounded by a big cryostat
- The legs of the inverted pendulums must start above the cryostat

Shorter IPs legs (~ 4 m)

Larger SA total mass



Cryostat

Optimization of filter chain

The starting point is a quite old paper based on an analytical approach with a simplified model (point-like masses):

"Optimization of multipendular seismic suspensions for interferometric gravitational-wave detectors",
A. Bove, L. Di Fiore, E. Calloni and A. Grado, ***Europhys. Lett., 40*** *(6), pp. 601-606 (1997)*

K_i = stiffness between *i*-th and *(i-1)*-th stage For horizontal motion: $K_i = \frac{g}{l_i} M_i = \frac{g}{l_i}\left(\sum_{h=i}^{N} m_h\right)$
m_i = mass of *i*-th stage

A N stages system presents N resonance frequencies $\mathrm{TF}\,(\omega > \Omega_N) \cong \frac{\prod_{i=1}^{N} \Omega_i^2}{\omega^{2N}}$ It can be shown that: $\prod_{n=1}^{N} \Omega_n^2 = \prod_{i=1}^{N}\left(\frac{K_i}{m_i}\right)$

For horizontal motion: $\prod_{n=1}^{N} \Omega_n^2 = \left(\prod_{i=1}^{N} \frac{g}{l_i}\right)\left(\prod_{j=1}^{N} \frac{\sum_{h=j}^{N} m_h}{m_j}\right) = a(l_1 \ldots l_N) b(m_1 \ldots m_N)$

Optimizing the TF is equivalent to minimize the product of the resonant frequencies, whit some parameters fixed:

Pendulum total length $L = \sum_{i=1}^{N} l_i$, mirror mass $m_N = m$ and total mass $M = \sum_{i=1}^{N} m_i$

It can be shown that:

The minimum of *a(l_i)* is for: $l_i = \frac{L}{N}$ **➔ All the wires have the same length**

The minimum of *b(l_i)* is for: $\frac{M_i}{M_{i-1}} = \frac{M_{i+1}}{M_i} = q \qquad (i = 2, \ldots, N-1)$ **➔ The loads $M_i = \sum_{n=i}^{N} m_i$ are in a geometrical progression**

with $q = \left(\frac{M}{m}\right)^{\frac{1}{1-N}}$ ➔ $m_i = m\left(\frac{M}{m}\right)^{\frac{N-i}{N-1}}\left[1 - \left(\frac{M}{m}\right)^{\frac{1}{1-N}}\right] \qquad (i = 1, \ldots, N-1)$

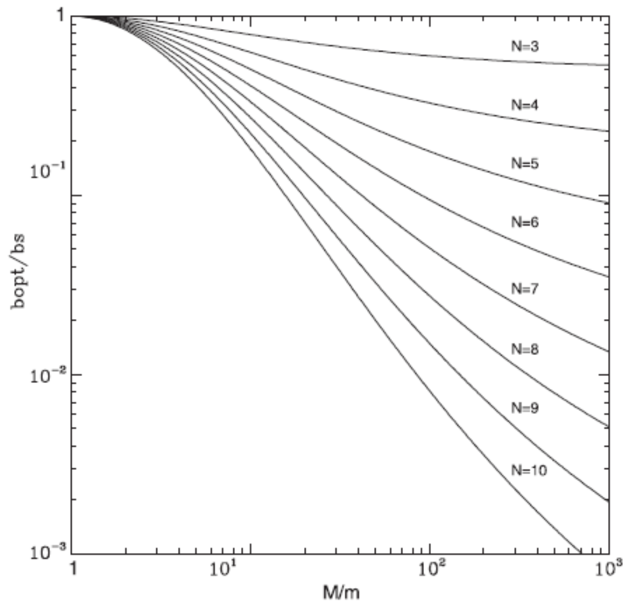


Fig. 1

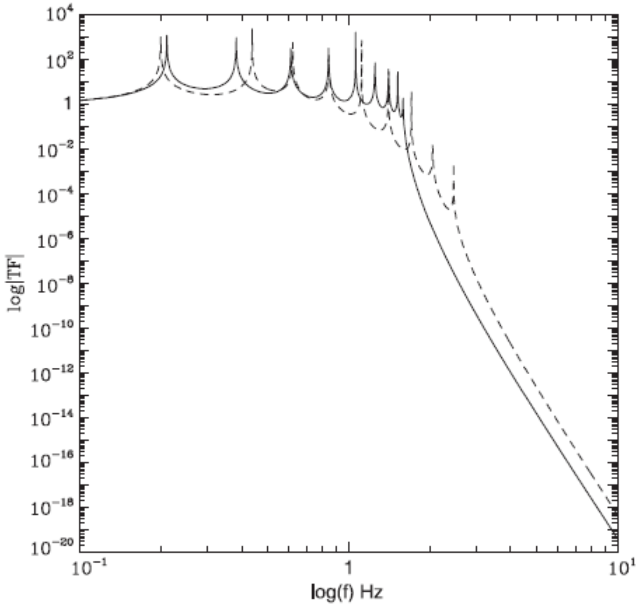


Fig. 2

Fig. 1. – Plot of $b_{\text{opt}}/b_{\text{S}}$, the ratio of the optimum b over the standard one, as a function of M/m, for a SA with a number of stages ranging from 3 to 10. This ratio gives directly the increase in attenuation obtained by using the optimized configuration.

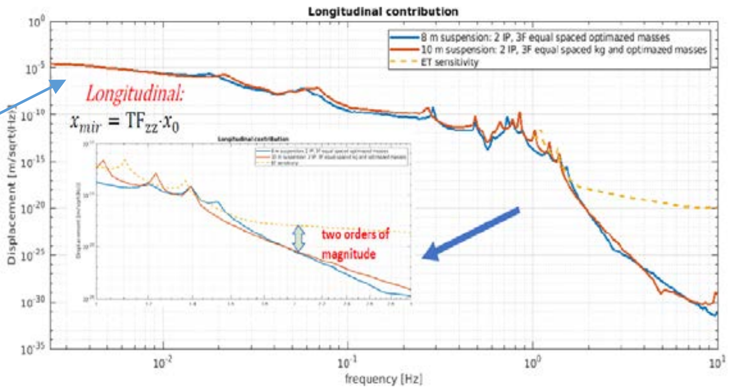
Fig. 2. – Comparison of the horizontal TF of a 9-fold SA similar to the one designed for the VIRGO antenna, computed for the optimized (solid line) and standard (dashed line) mass distribution.

- The analytic optimal mass distribution gives a starting point for the design
- A complete 6 DOF model (Octopus) is then used for a complete design considering solid bodies and cross-talks

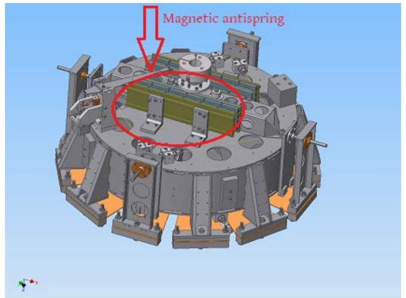
NGSA project Organizzation : WP

The project is organized in 4 WP:

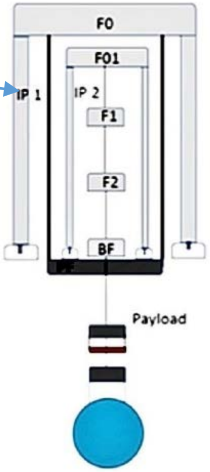
WP1 – Simulation and optimization of the Superattenuator
Coordinator: L. Trozzo (INFN-NA)



WP2 – Mechanical filter with improved Magnetic Anti-Spring (MAS)
Coordinator: F. Frasconi (INFN-PI)



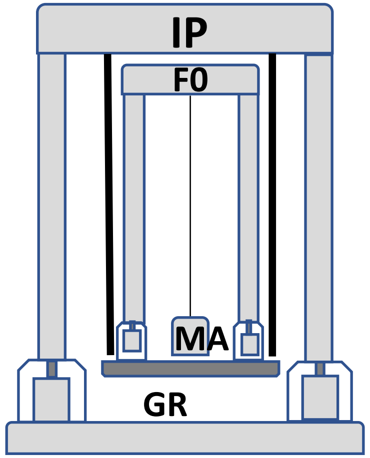
WP3 – Development and test of a Nested Inverted Pendulum (NIP)
Coordinator: R. De Rosa (INFN-NA)



WP4 – Sensing and Control (S&C)
Coordinator: A. Gennai (INFN PI)

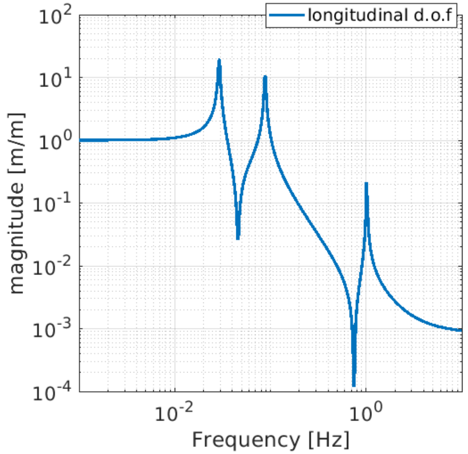
WP1 – Simulation and design of the NIP prototype

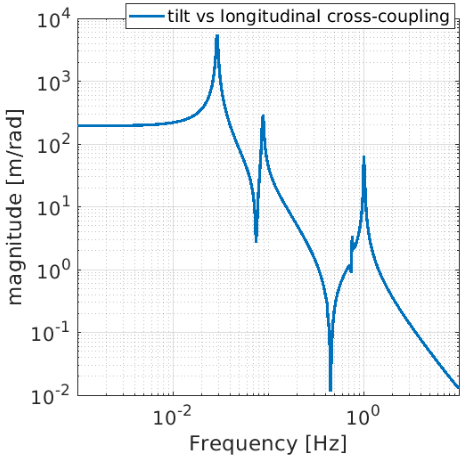
- Masses, flex-joints, legs, etc. have been defined
- Al the TFs have been computed with Octopus
- This was the starting point for the mechanical design of the prototype
- Simulation tools are crucial to evaluate the effect of mechanical design choices on system performance



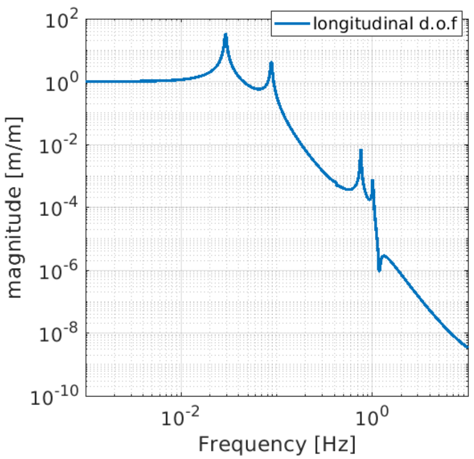
TF examples

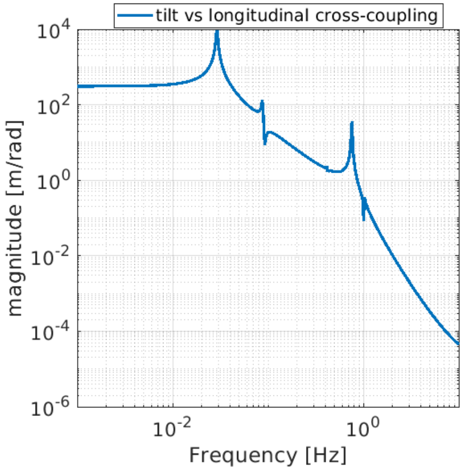
Ground to F0 TFs





Ground to Ma TF





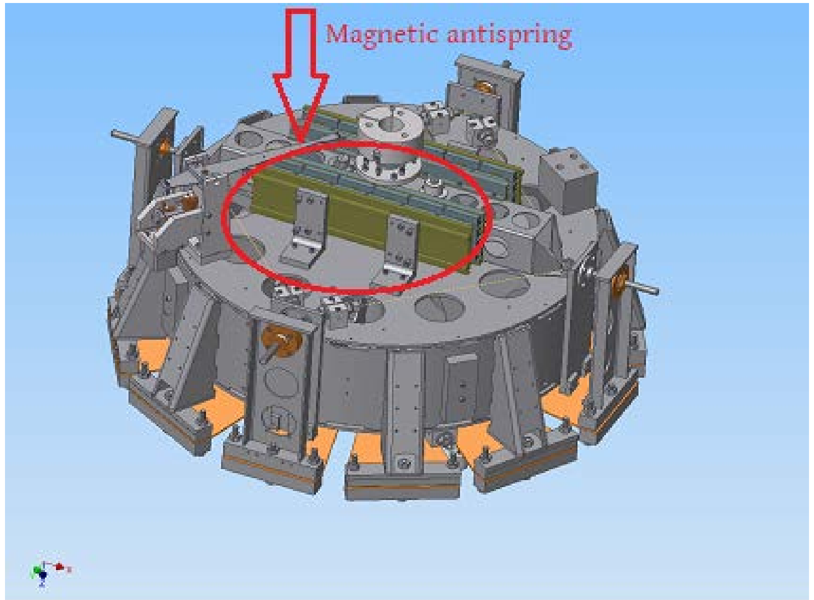
WP2 – Mechanical filter with improved Magnetic Anti-Spring (MAS)

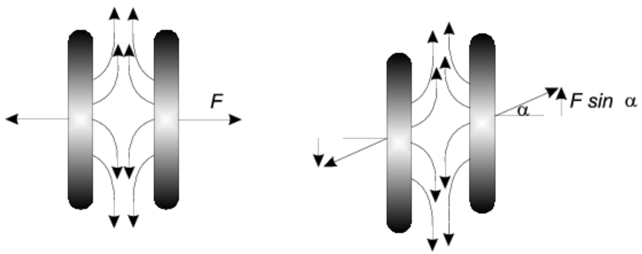
The goal is to improve the present MAS design

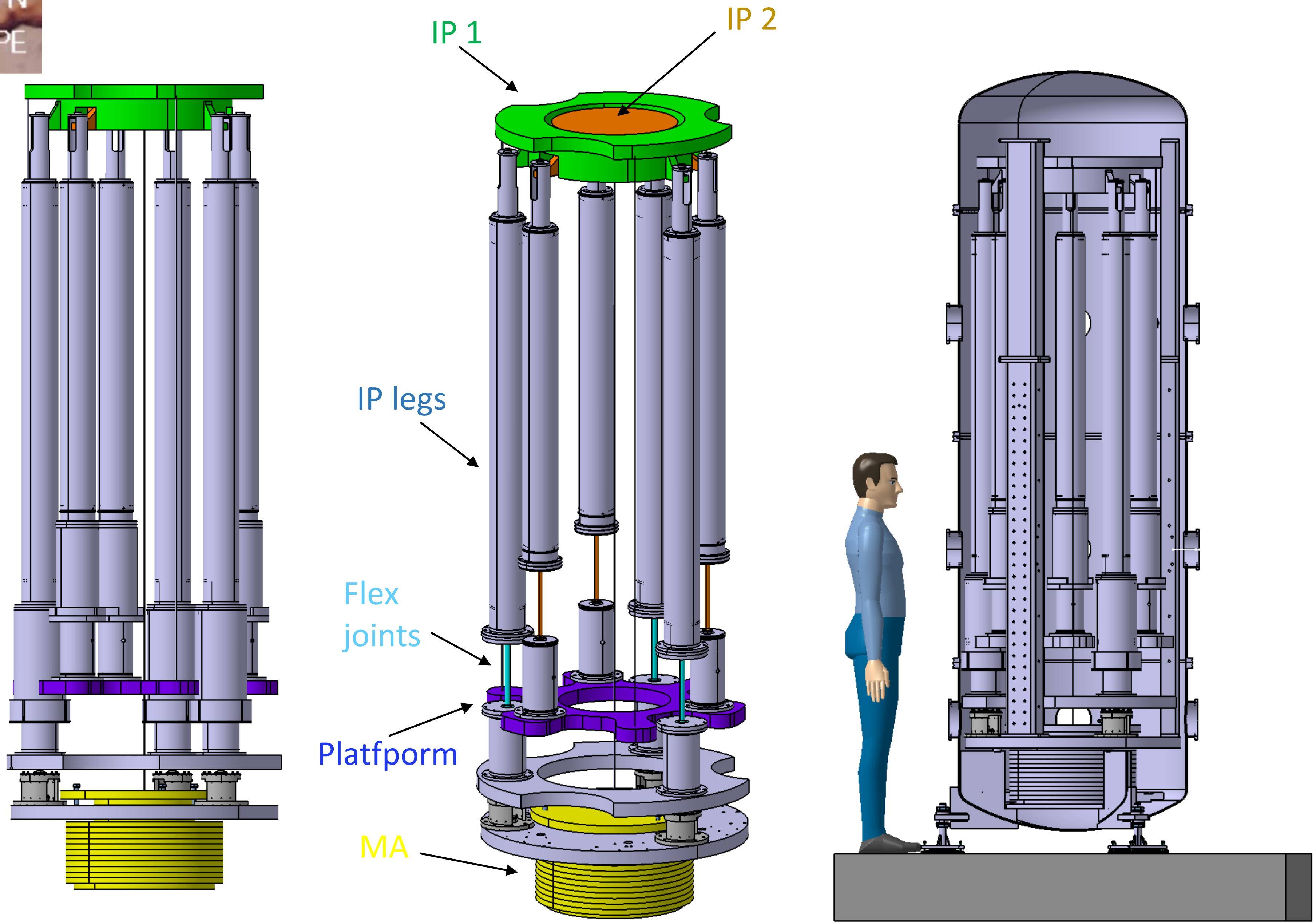
The ides is to replace ferrite magnets (0.35 T) with rare earth (SmCo or NeFeB) magnets (0.8 T)

The advantage is the larger Magnetic flux density providing:

- Large anti-stiffness with a reduced volume
- Lower filter resonance
- New cross-bar design to move its resonances at higher frequency







IP 1
IP 2
IP legs
Flex
joints
Platfporm
MA

WP4 – Sensing and Control (S&C)

	LVDT	Accel	ORO	ADC	DAC-A	DAC-B	Coil-Mag	Motors
IP	3	3 1-axis			3	3	3	3
BR			3	9-12	3 (6?)		3 (6?)	6 for ORO
F0			3	9-12	3 (6?)		3 (6?)	6 for ORO
TM		1 3-axial		3	3			

DAC_A 24 bit, 2 channels per card - DAC_B 16 bit, 6 channels per card

National instrument input/output hardware based on LabView software has been identified for the data acquisition and control and ordered:

- Crate, CPU and most relevant components/boards arrived @ INFN Pisa
- DAC board is still missing. Delivery announced for the end of June 2023
- Preliminary configuration and arrangement in progress
- Development and training of LabView in progress waiting for the DAC board
- Preparation of some “acceptance” tests for the HW configuration selected

ETIC – SAMANET
ETIC – CISUP@UNIPI

SAMANET

WP4 SAMANET

- **ET Superattenuator development in close collaboration with NGSA**
- **Design and test of critical electronic circuits involved in the control strategy**
- **Study of the electromagnetic noise sources associated to the experimental to define a mitigation strategy**
- **Study of the ultra-high-vacuum compatibility of all components (mechanics, electronics and optics)**
- **Thermal and surface treatments of special materials to be used in the realization of the Superattenuator**

WP7 CISUP@UNIPI

- **2 PhD fellowship on suspensions since March 1**

Shortening
the seismic attenuation chain
A compact mechanical filter

A. Allocca, L. Bellizzi, S. Bianchi, V. Boschi, E. Calloni, M. Carpinelli, P. Chessa , D. D'Urso, R. De Rosa, L. Di Fiore, F. Fabrizi, I. Ferrante, F. Fidecaro, A. Fiori, A. Gennai, A. Longo, L. Massaro, M. Montani, L. Papalini, M. Palaia, M. Razzano, D. Rozza, P. Ruggi, L. Trozzo, M. Vacatello, A. Viceré

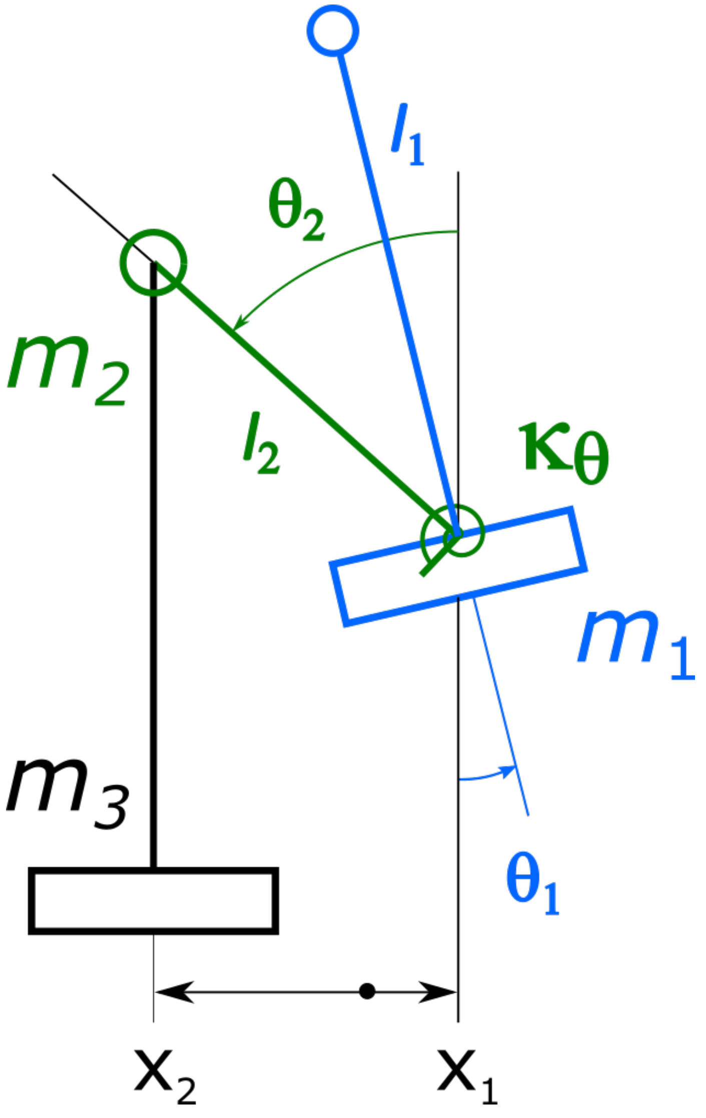
INFN – Na, INFN – Pi, Uni Napoli, Uni Pisa, Uni Sassari, Uni Urbino

Pendulum – Inverted pendulum

How to soften a suspension stage

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

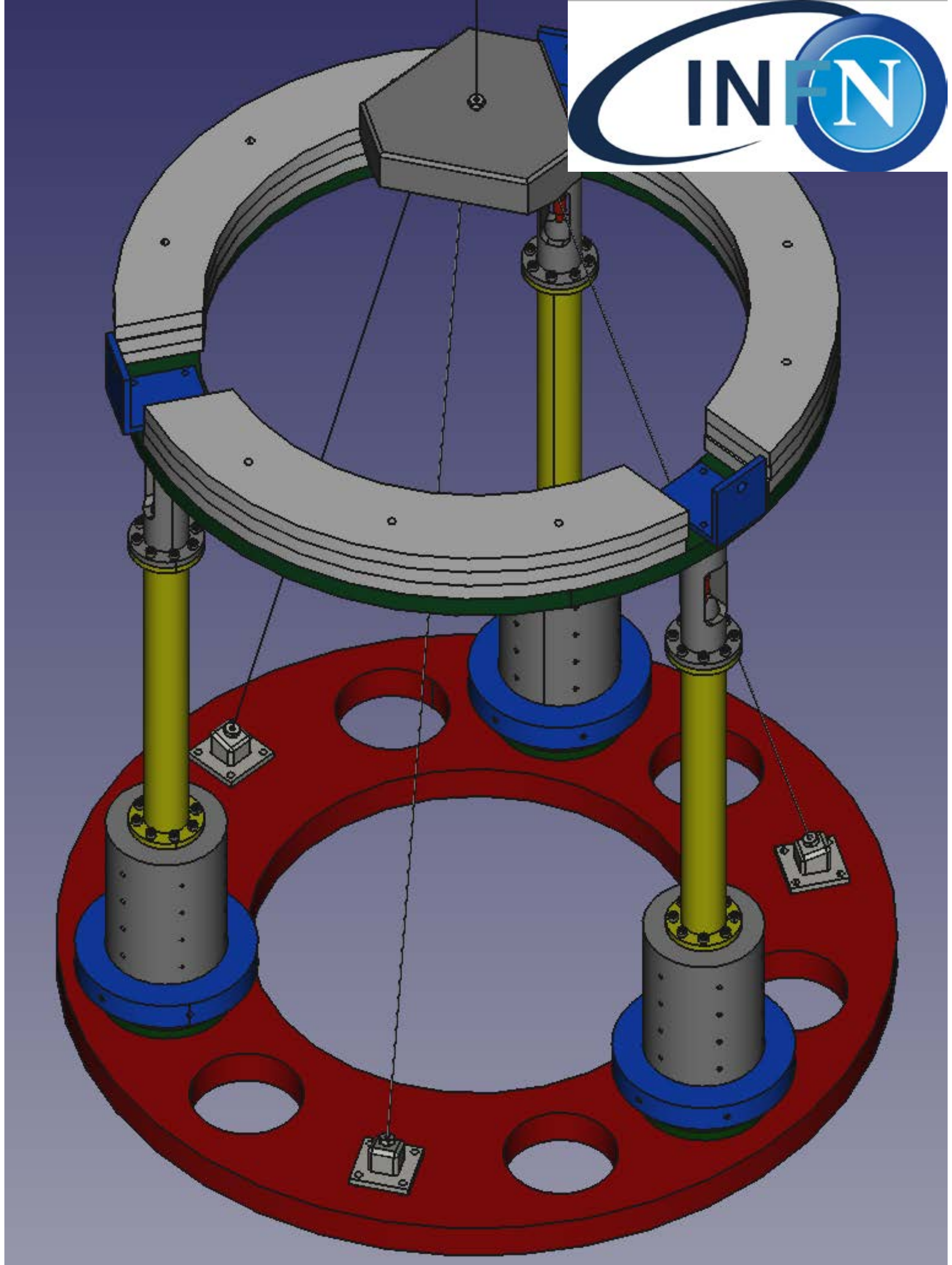
```
• l1:  1.544, # Pendulum length\
• l2:  0.520, # IP length\
• T1: 2551.0, # Pendulum tension\
• T2: 1766.0, # IP compression\
• m1:   80.0, # Pendulum mass\
• m2:   80.0, # Filter mass\
• m3:  100.0, # Load\
• I1s:  20.0, # Pendulum moment of inertia \
• I2s:   0.8, # IP moment of inertia\
• k: 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



Normal mode frequencies
0.68 Hz 0.74 Hz

Basic structure

Explicit coupling of pendulum and roll DOF



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 2.60 + 0.40 = 3.0 m accounting for a dedicated vertical attenuation stage
  - Three PIP can live in 4 m
  - Proximity of different stages allows feedback control of normal modes, at least where sensor noise is not dominant (em or optical sensors like HoQI)

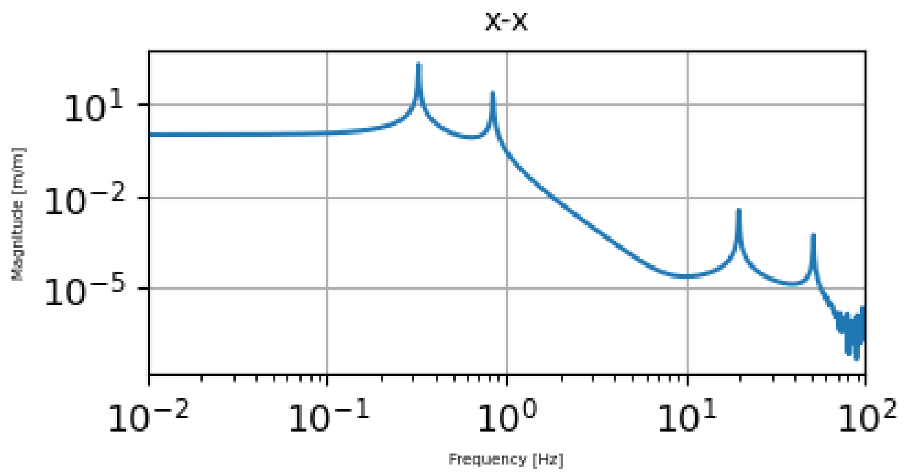
Simulation needs: OctoPYus package

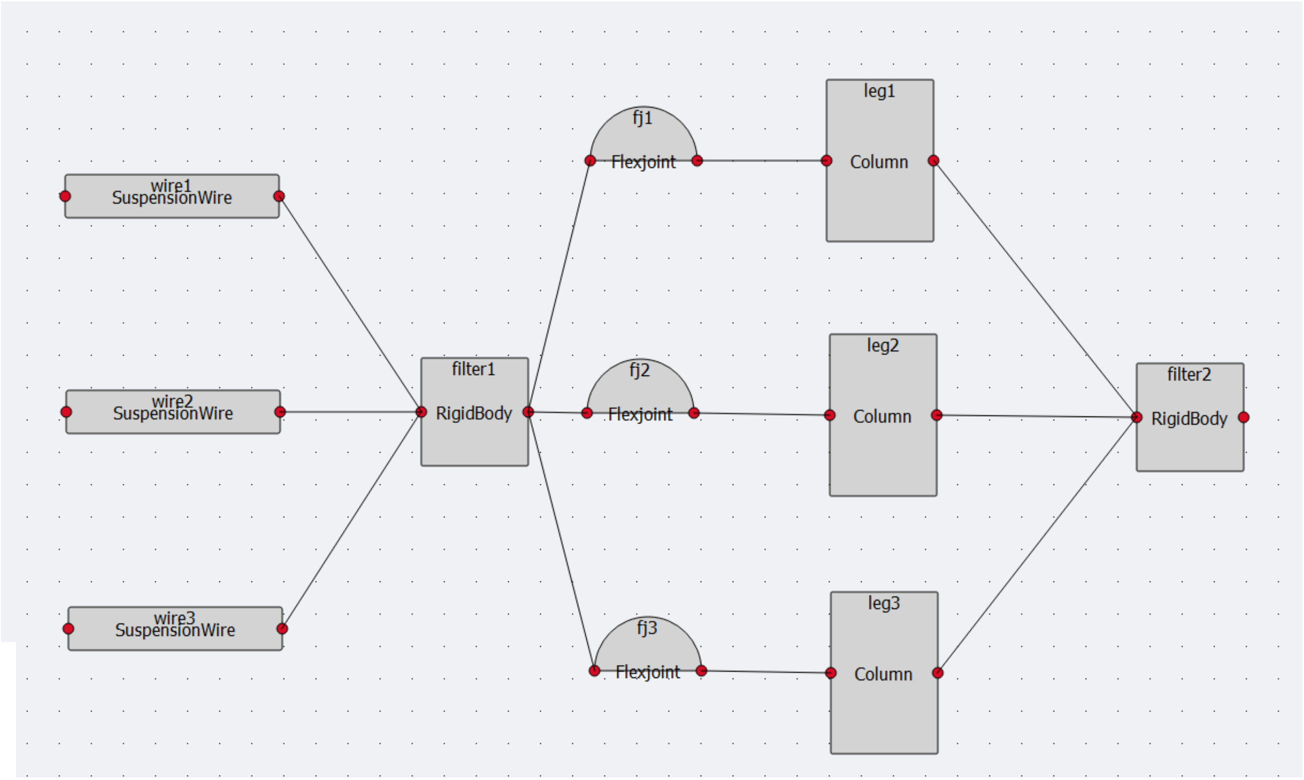
- **Package overview**
  - MATLAB version developed by Paolo Ruggi
  - To be hosted on Gitlab
  - Now private repo, at some point public
  - Available for developers (via git)
  - Available for end users (via PIP, only on gitlab Package Registry, then move to Python Package Index

- **Structure**
  - Creation of configuration via GUI
  - Configuration saved to JSON format
  - Network solving to include feedback loops
  - Calculation of transmission matrices
  - Calculation of Transfer Function

Test case: schematic PIP

- **PIP**
  - Resonances @0.2 Hz (pend) and 0.8 (IP)
  - attenuation $1/f^4$





L. Massaro Master thesis

Summary

- **Revision of an essential element of GW interferometers, present in several variants and high multiplicity**
- **Large experimental work needed to develop new ideas and validate them**
- **Spanning many fields of physics, engineering and information processing**
- **Already started due to the impact on the infrastructure**