



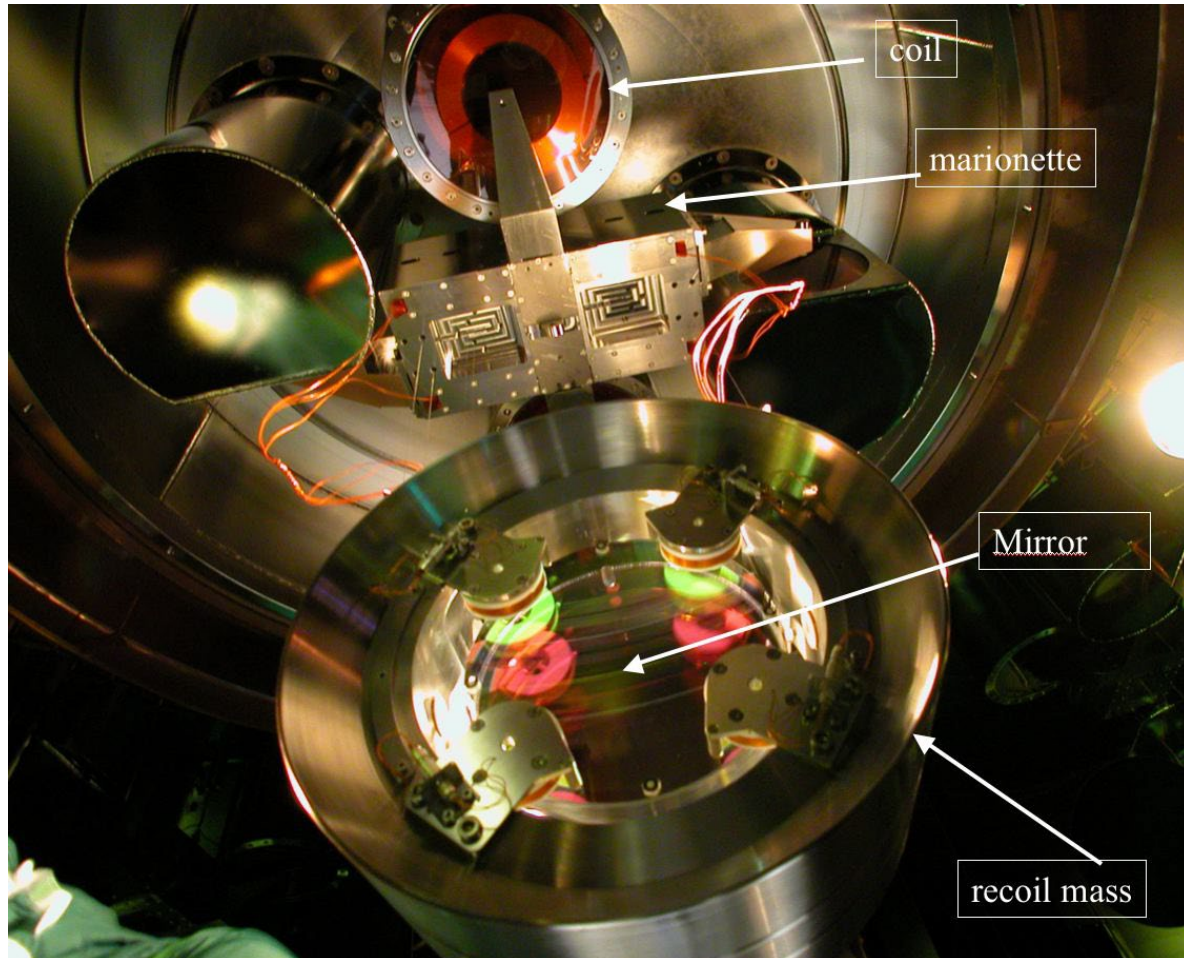
FEA models for the ET Payload: status and preliminary results

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GWADW



The mirror Last Stage Suspension

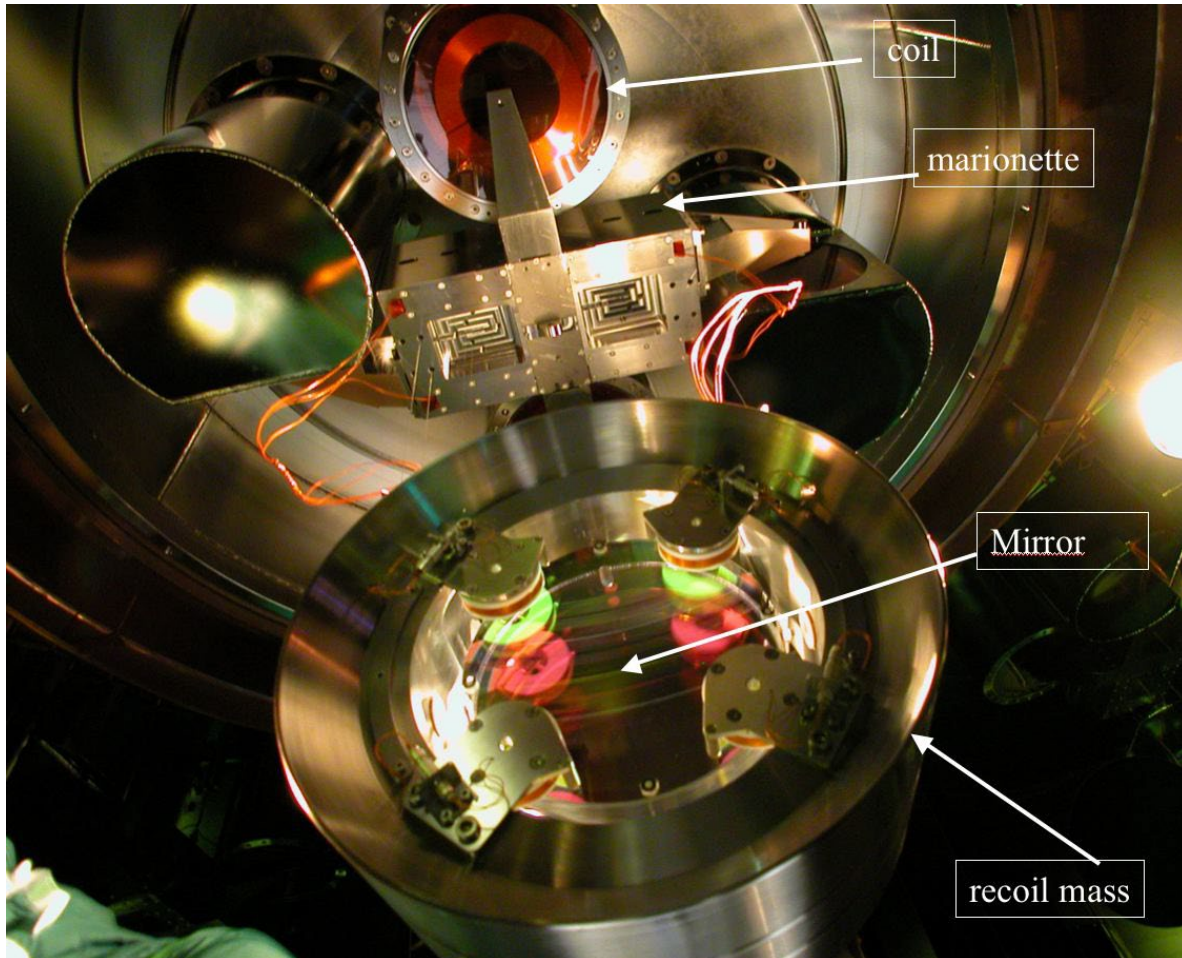
The role of the Last Stage Suspension is to compensate the residual seismic noise and to steer the optical components maintaining the relative position of the interferometer mirrors.

Components:

Marionette: Mirror control with actuators (coil-magnets, electrostatic) between the upper suspension stage and marionette;

Reaction Mass (RM): Mirror steering with (coil-magnets, electrostatic) actuator between RM and mirror; Mirror protection; **in AdV replaced with the cage**

Mirror: monolithic suspension.



Requirements:

Materials

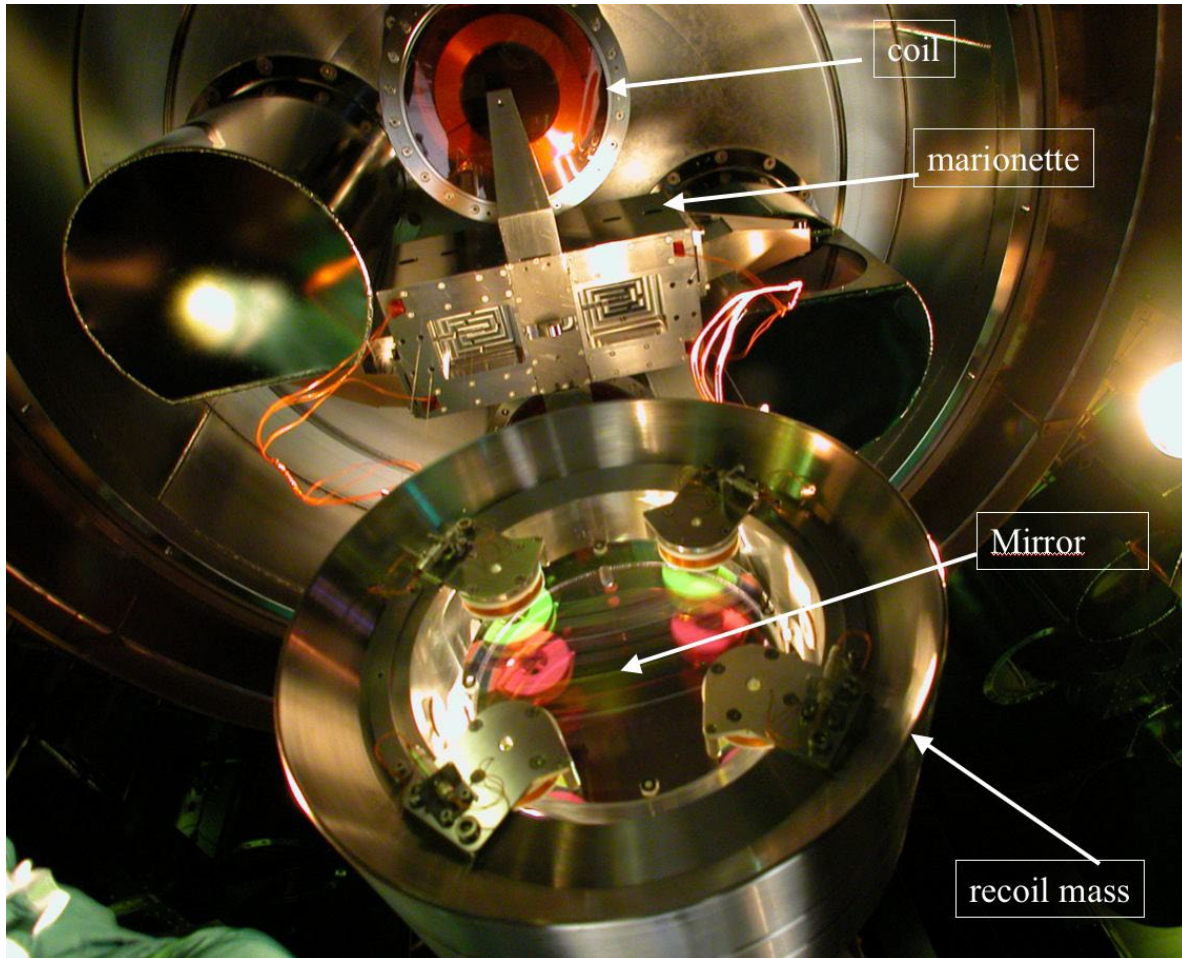
- UHV compatible;
- Amagnetic;
- No electrostatic charges;
- Internal Frequencies above the antenna bandwidth;
- Low frequencies of the system below control bandwidth;

Compatibility with SuperAttenuator and lower part of the tower:

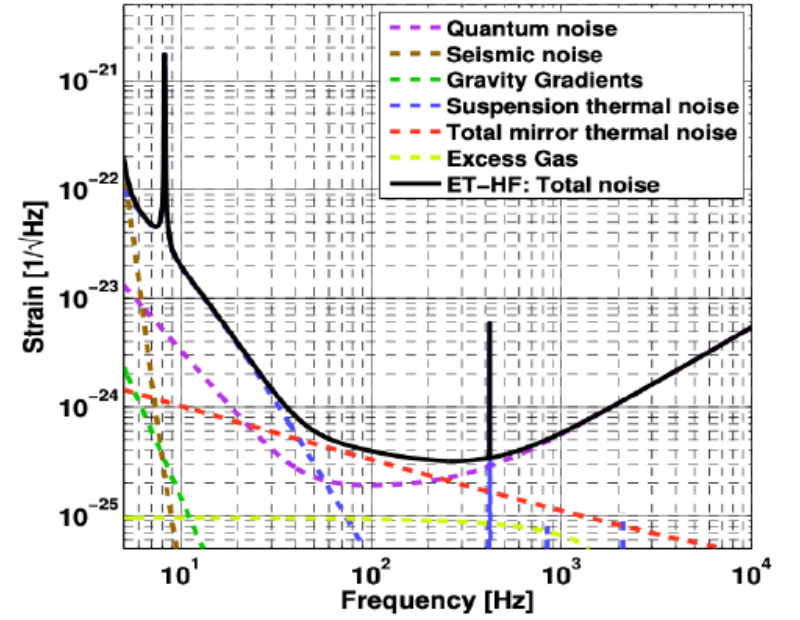
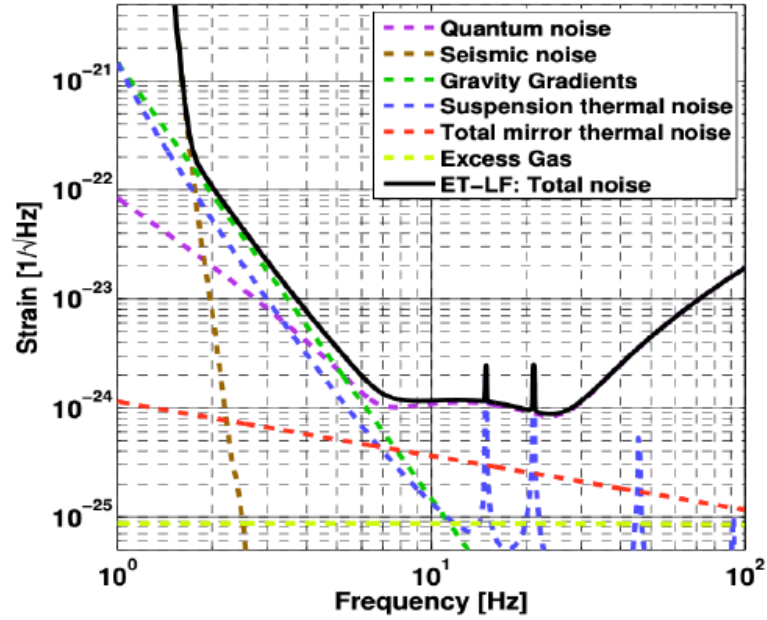
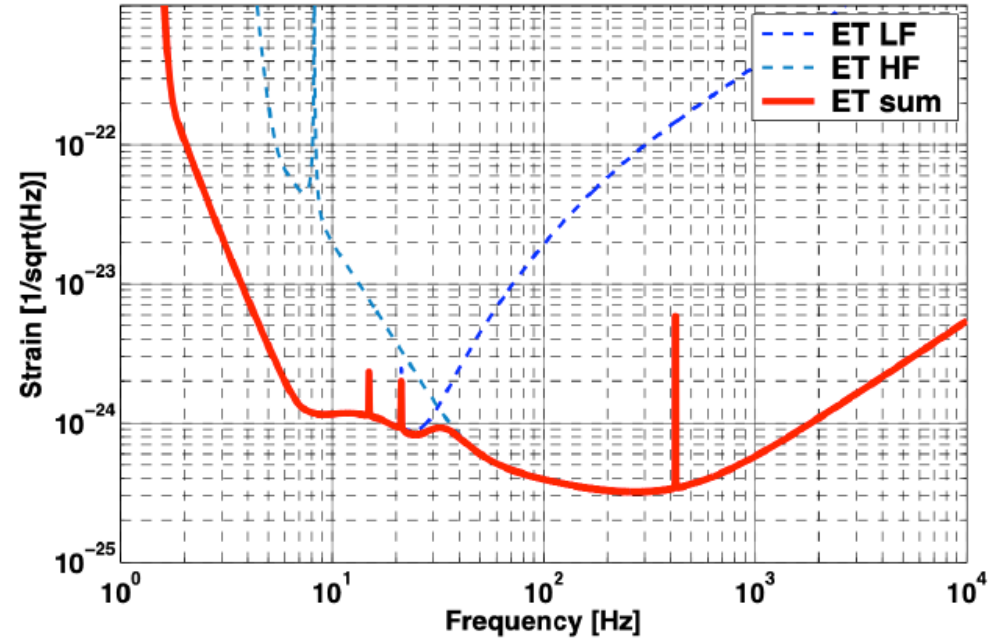
- Weights
- Shape

Cryogenics

Suspension Thermal Noise

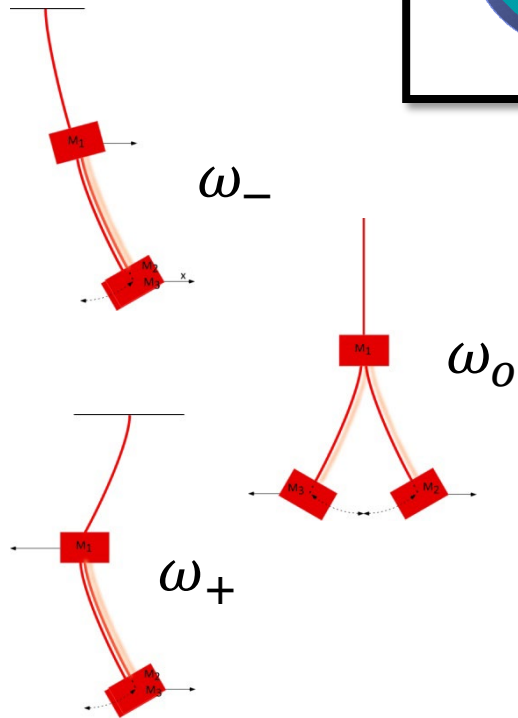
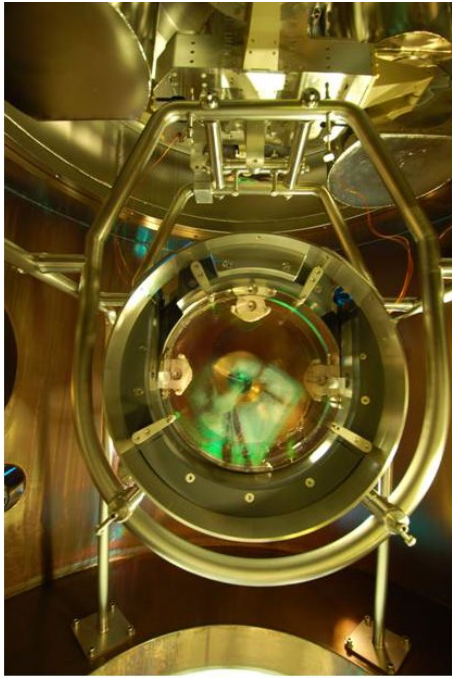
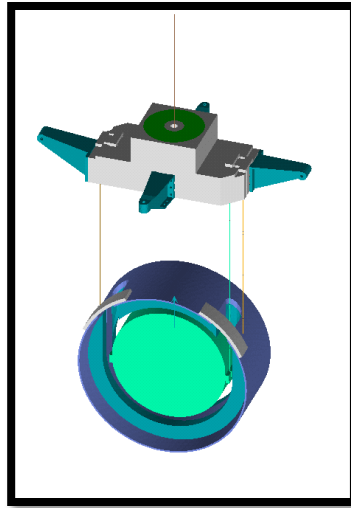


ET sensitivity
xylophone configuration

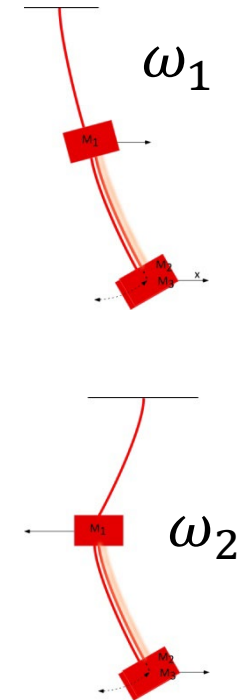
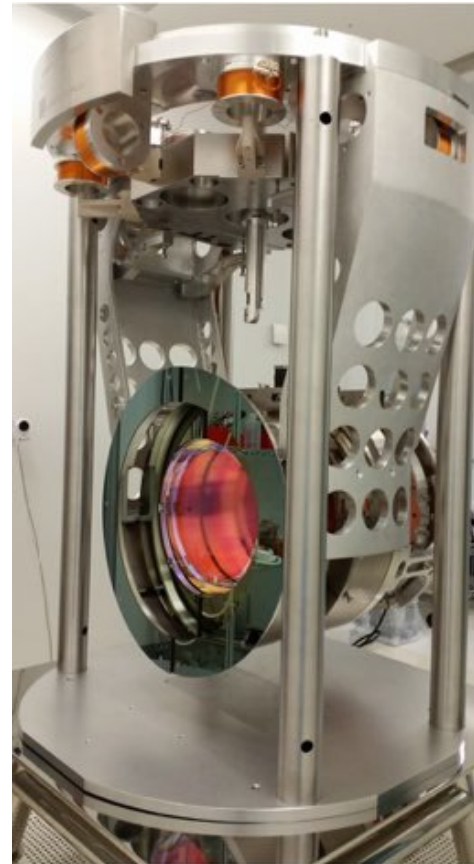
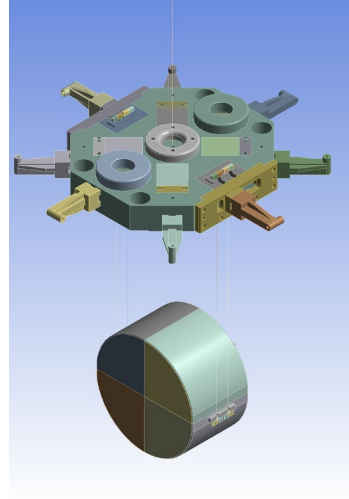


Thermal noise computation: payload analytical models

Virgo/Kagra Payload
Triple mode system

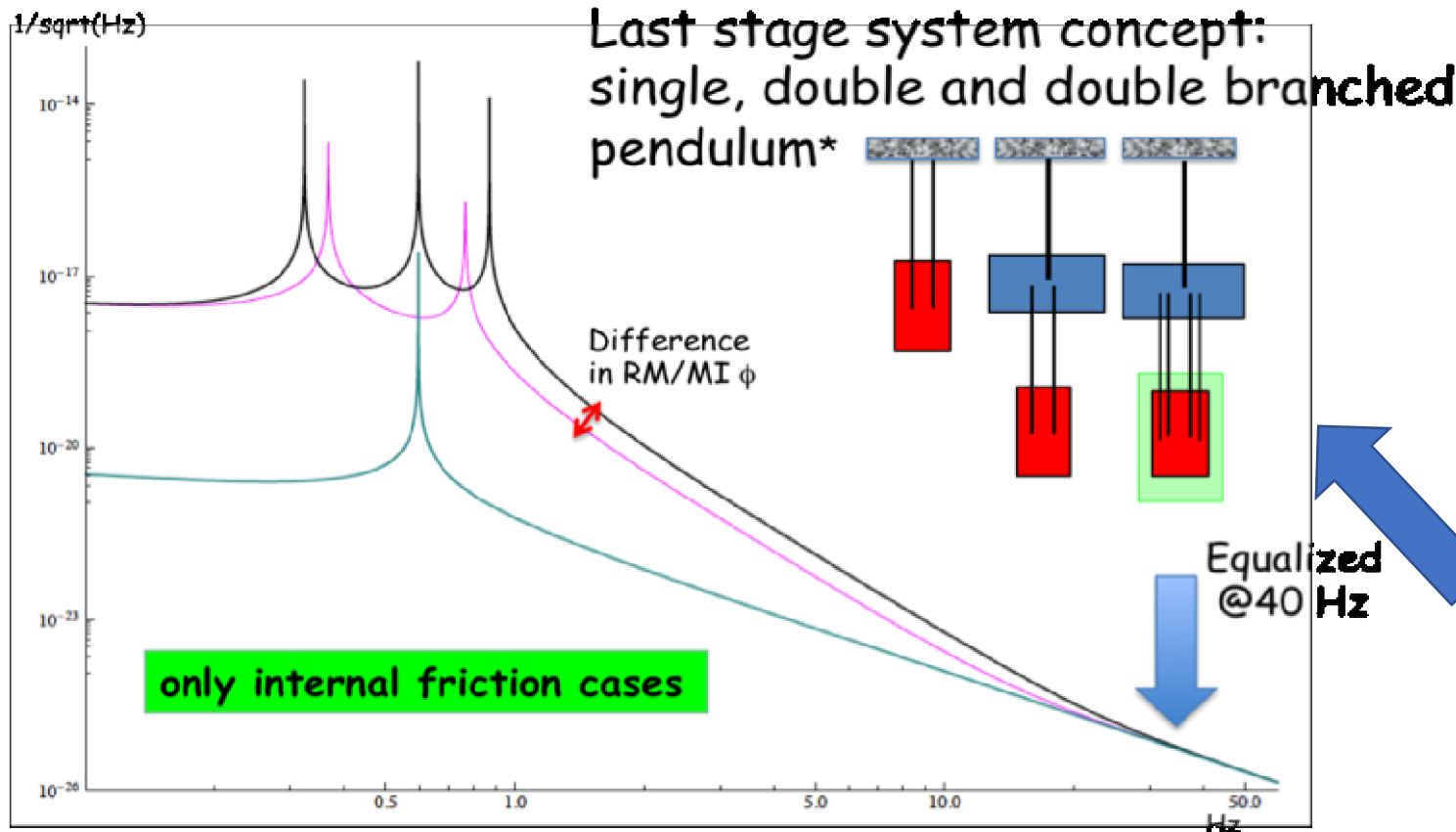


AdV Payload
Double mode system



Standard path for payload design 3:

From the Payload Scheme, we build a Dynamical Model with masses, momenta of inertia and control strategy (including locking of the ITF), to perform preliminary checks:



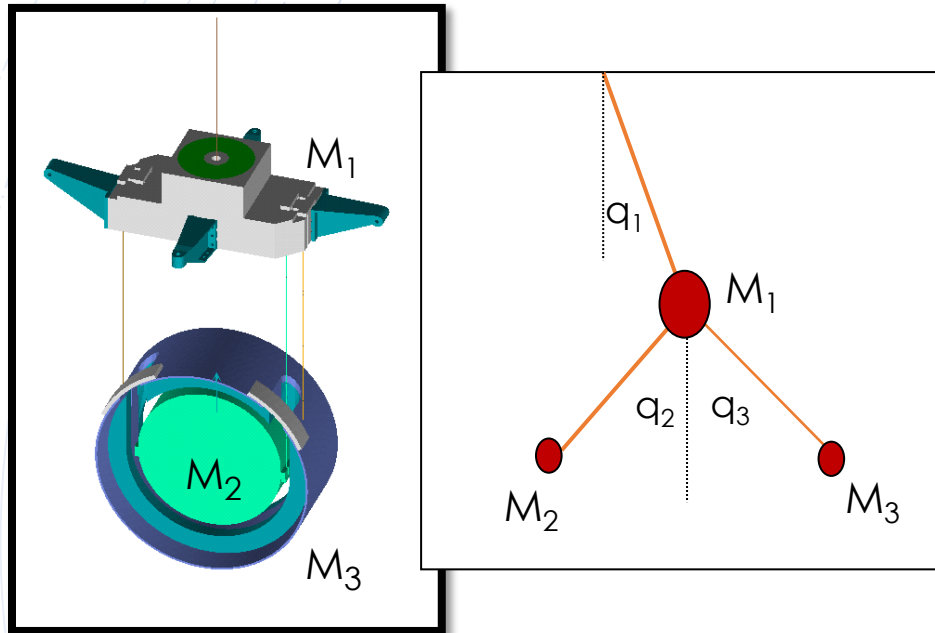
Thermal Noise check: Pendulum modes of the payload must not spoil sensitivity

Check for AdV scheme (2008)

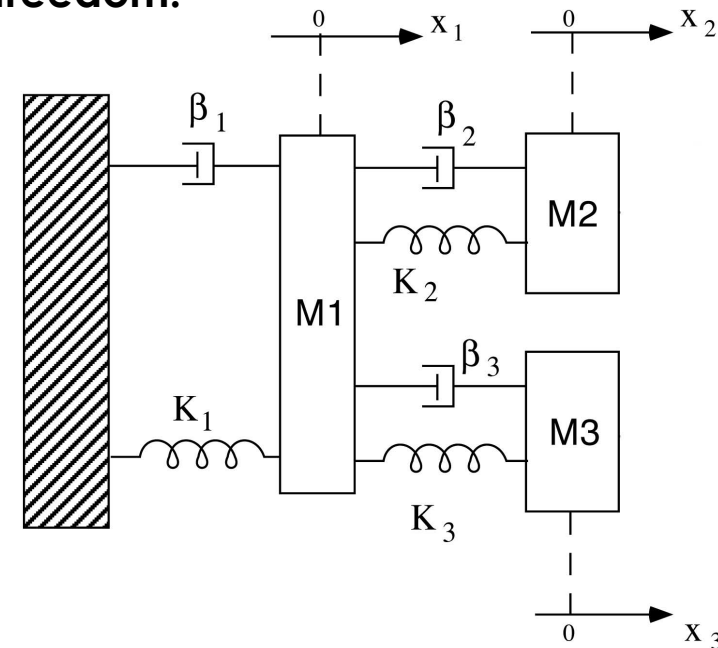
*reasonable values are assigned to describe double and simple pendulum parameters assumed here.

The mirror last stage suspension as a branched system

A Virgo-like last stage suspension is a cascade of three pendula. To the first pendulum (the marionette) the mirror and the recoil mass are hung as branches.



Equivalent to a branched combination of three harmonic oscillators [*], [**]. This is true for horizontal and vertical degrees of freedom.



M_1 marionette
 M_2 mirror
 M_3 recoil mass

[*] Bernardini A., Majorana E., Puppo P., Rapagnani P., Ricci F., Testi G. "Suspension last stages for the mirrors of the Virgo interferometric gravitational wave antenna." *Rev. Sci. Instr.* 70, no. 8 (1999): 3463.

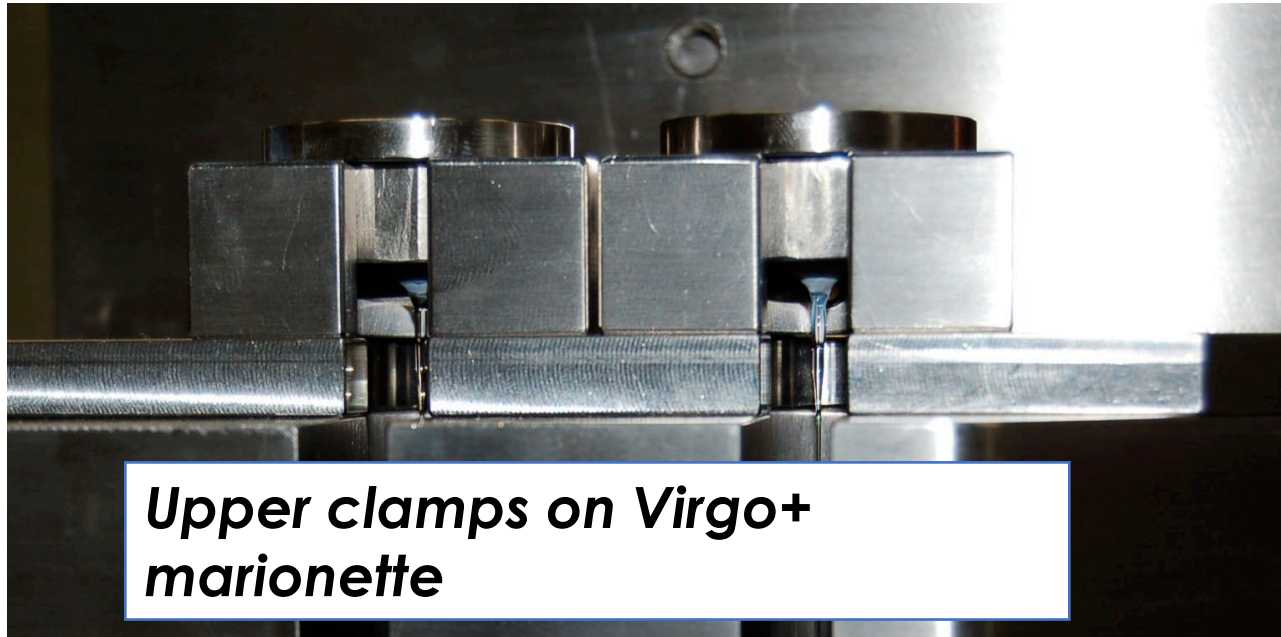
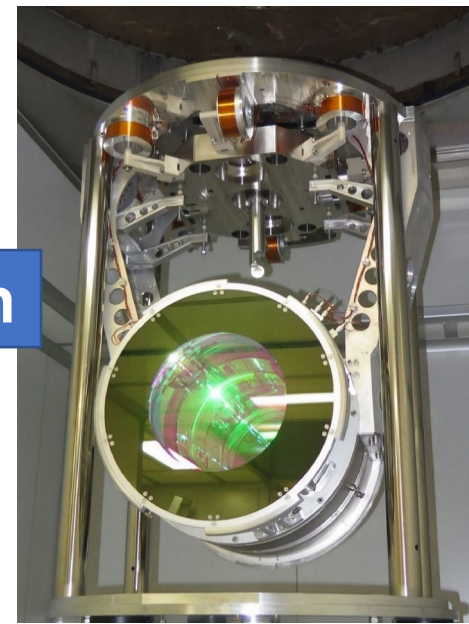
[**] The Twelfth Marcel Grossmann Meeting, pp. 1732-1734 (2012) A thermal noise model for a branched system of mechanical harmonic oscillators: some issues for the test masses suspensions, P. Puppo https://doi.org/10.1142/9789814374552_0311

INTERFACES must be included in the computation
this is not possible with analytical models

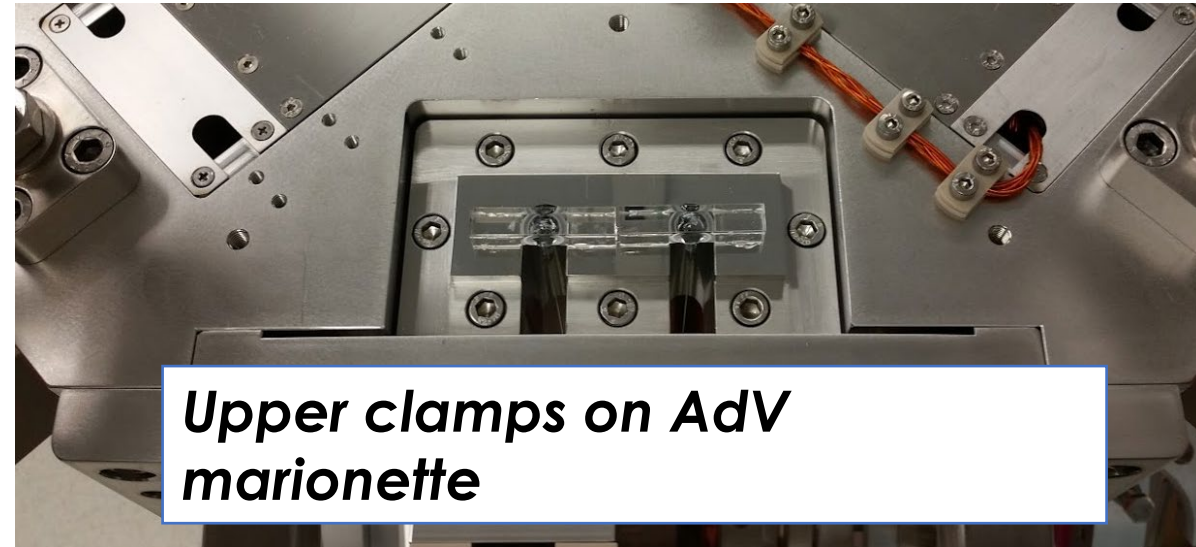


Ears and anchors in Virgo+/Adv

Monolithic suspension



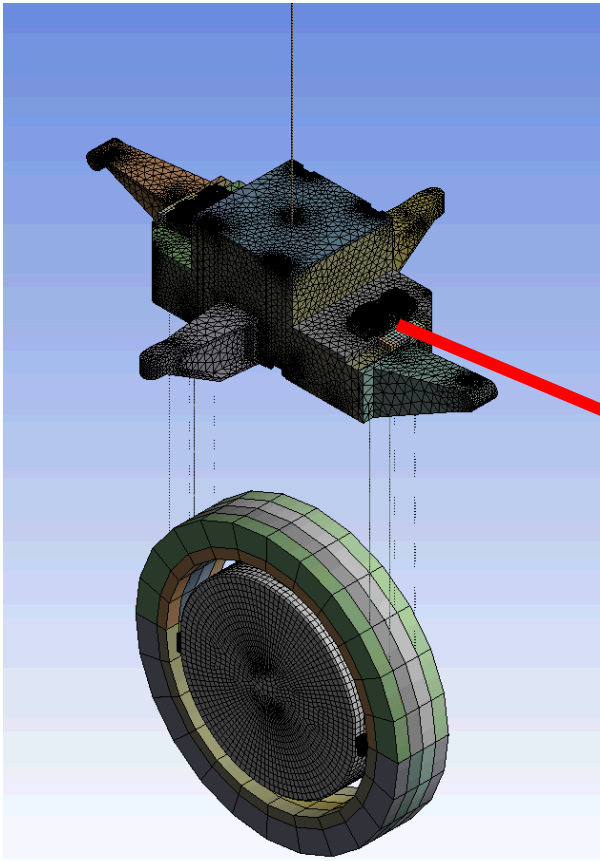
Upper clamps on Virgo+ marionette



Upper clamps on Adv marionette

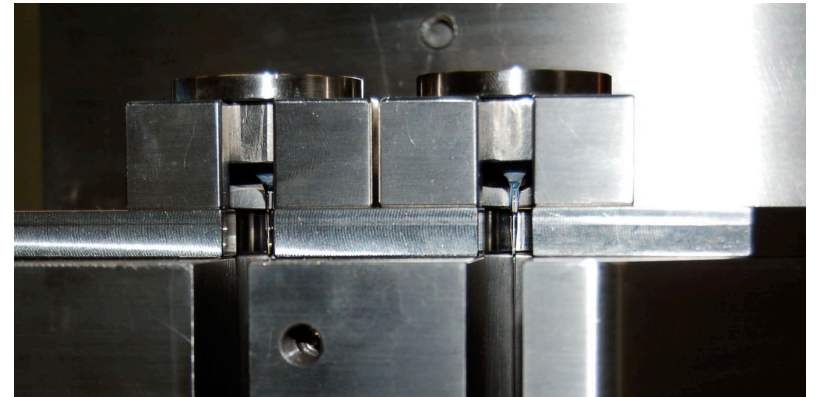
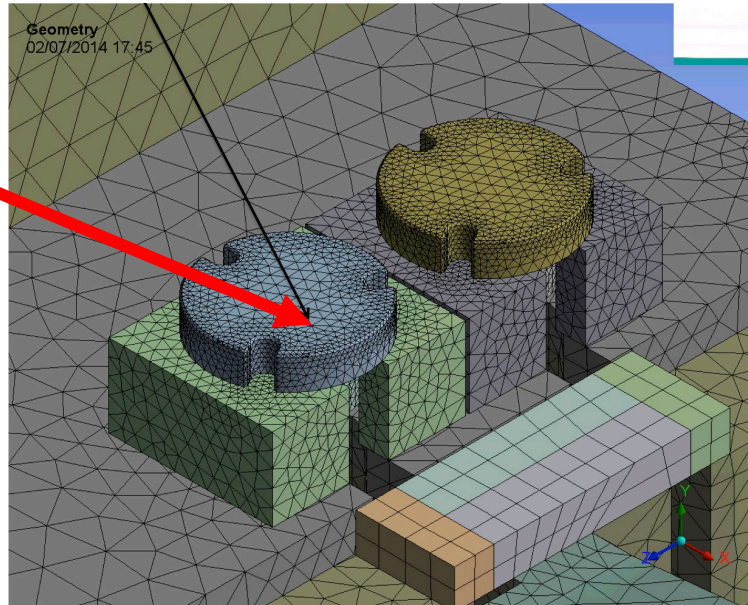
FEA Models

- FEA model of the mirrors payload using ANSYS;
 - elastic properties, losses
 - real shape of the payload system
 - Interfaces included
- Calculation of the expected modal frequencies and quality factors;
- Calculation of thermal noise using the Levin method;
- Calculation of temperature distribution with a thermal load

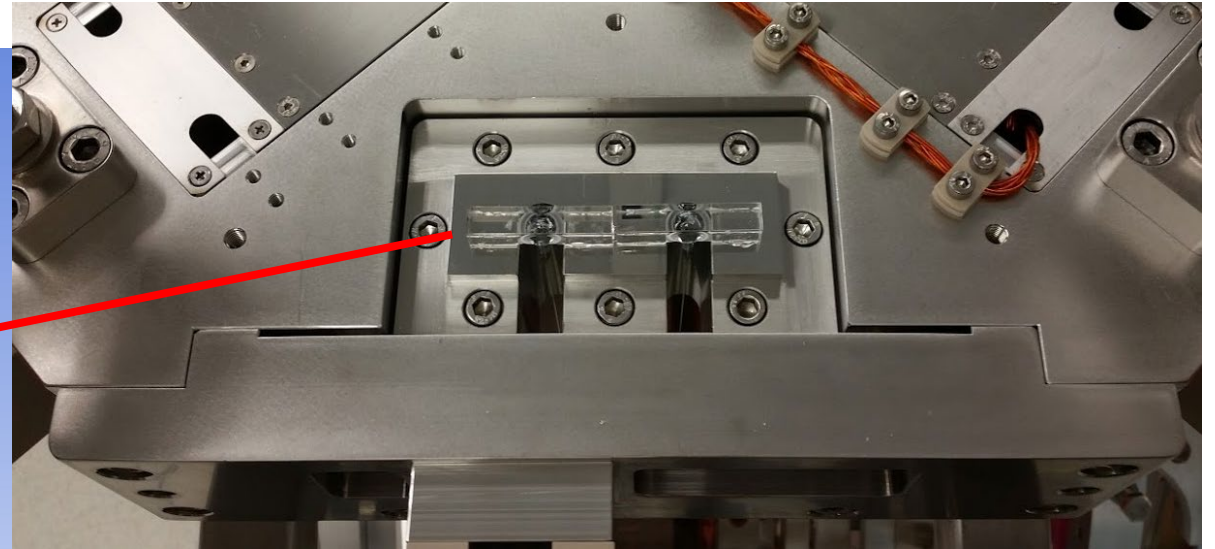
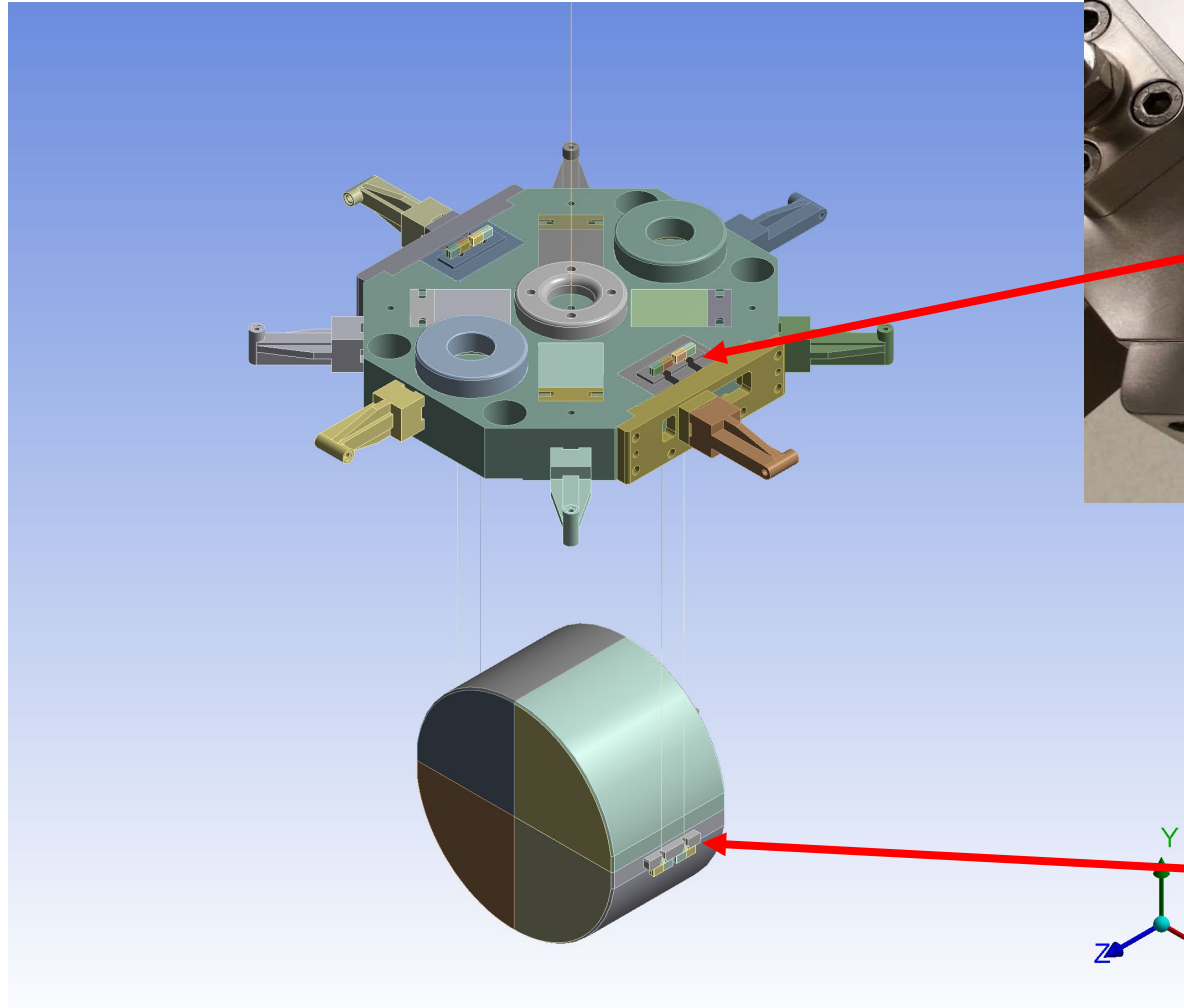


Virgo+ Mirror suspension
Test Mass=21 kg

upper boxes on Virgo+ marionette

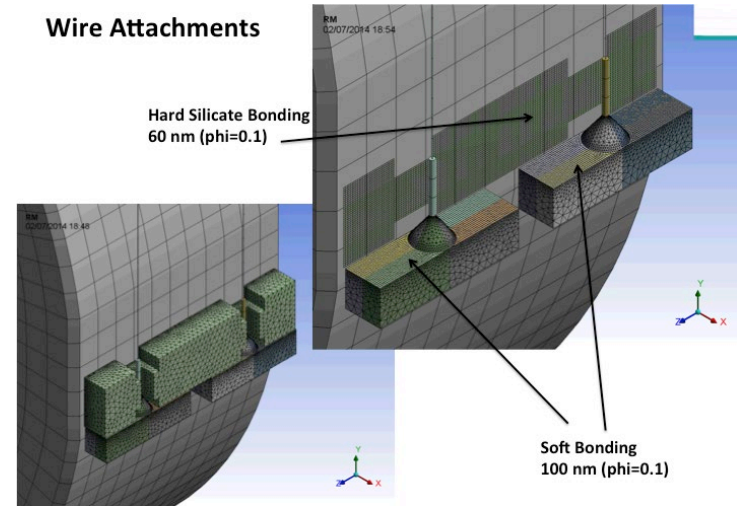


Interfaces



AdV Mirror suspension (Test Mass=42 kg)

Wire Attachments



Silicate Bonding Layers

Thickness=60 nm

Young Modulus=7.9 GPa

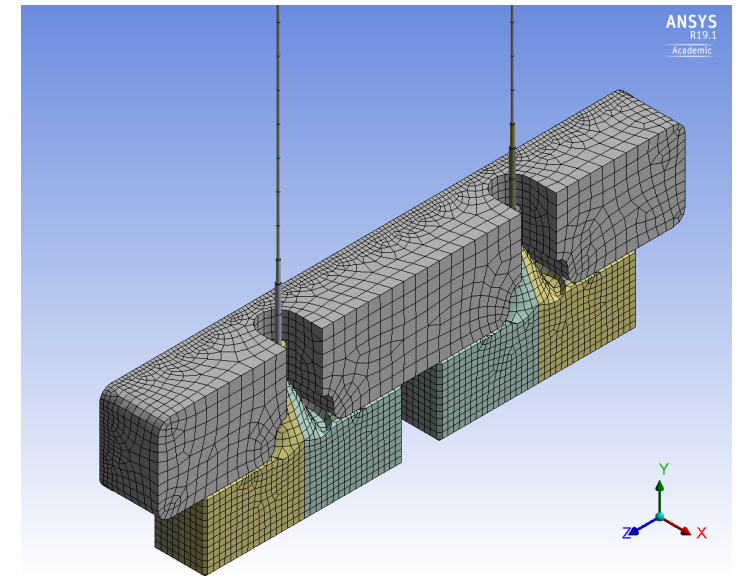
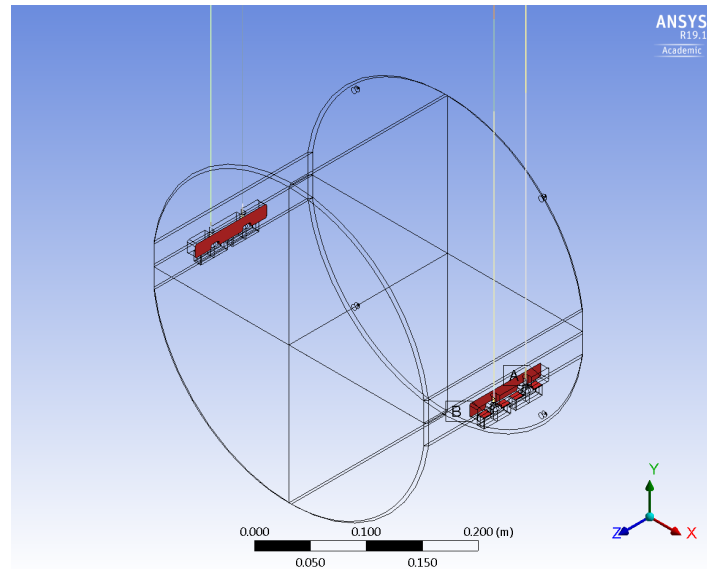
poisson ratio=0.17

density=2201 kg/m³

nominal loss angle 0.1

at low temperature better

tensile strength ≤ 20 MPa



We focus on the LF interferometer (a sapphire suspension)

- diam: 450 mm
- thickness: 220 mm
- M=140kg (sapphire)
- waist: 9cm
- Wire length: 0.8 m
- Wire diameter: 2.2mm
- Wire material sapphire
- substrate: 10ppm/cm
- coating (1-2ppm)
- $P_{arm}=18$ kW
- $F=880$
- $R_c=21.6$
- $PRC=18kW/(2F/\pi)=32$ W (Power in recycling cavity)
- $P_{sub}=28$ mW
- $P_{coat}=18mW$ (2ppm)
- $P_{tot} = 46mW$ (to be added radiation from the screens and safety factor)

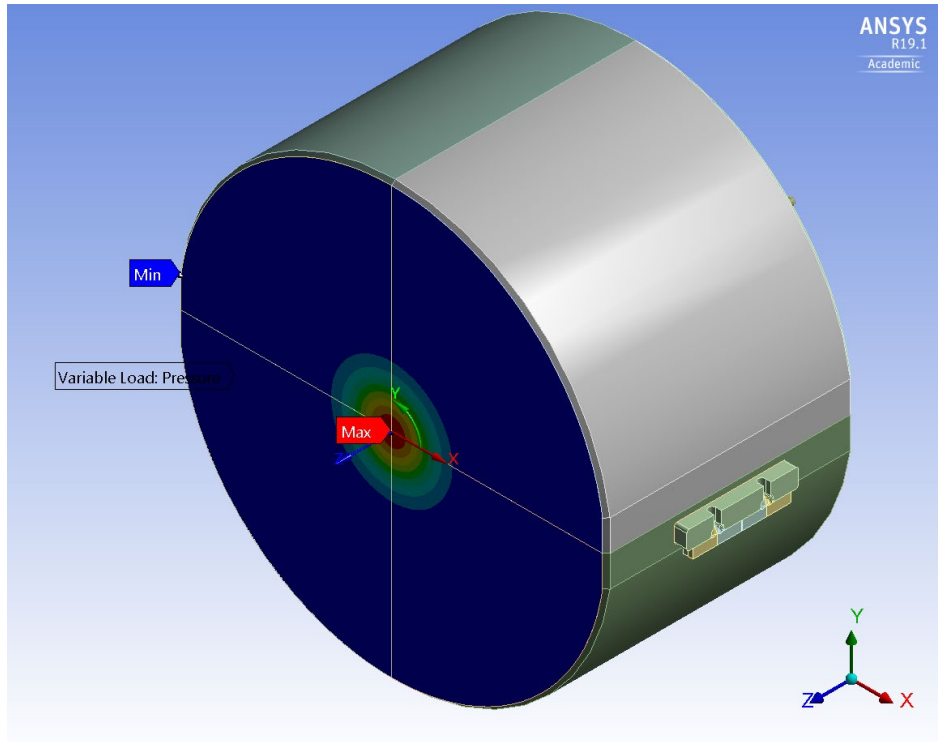
The wires stress is : 90MPa
Lower than the breaking strength
of about 200MPa (very variable),
but we must be careful

Same for the HCB attachment area

Suspension Thermal (Levin Formula)

$$S_X^{FEM}(\omega) = \frac{4 k_b T}{\omega F_o^2} 2 \left(\phi_{wires} E_{wires}(\omega) + \phi_{layers} E_{layers}(\omega) + \phi_{Mario} E_{Mario}(\omega) + \phi_{silica} E_{silica}(\omega) + \phi_{Mario} E_{Mario}(\omega) \dots \right)$$

parts parts Cable Cable



Strain energies $E_i(\omega)$ from the FEM applying a unitary gaussian force on the suspended mirror face.

Internal dissipation mechanisms

$$\varphi_s(\omega) = \varphi_{the}(\omega) + \varphi_{str} + \varphi_e$$

$\varphi_{th}(\omega)$ **Thermoelastic dissipations** (negligible below 40K)

φ_{str} **Structural dissipations**

φ_e **Superficial dissipations**

Dealing with temperature gradients

- Modal approach:

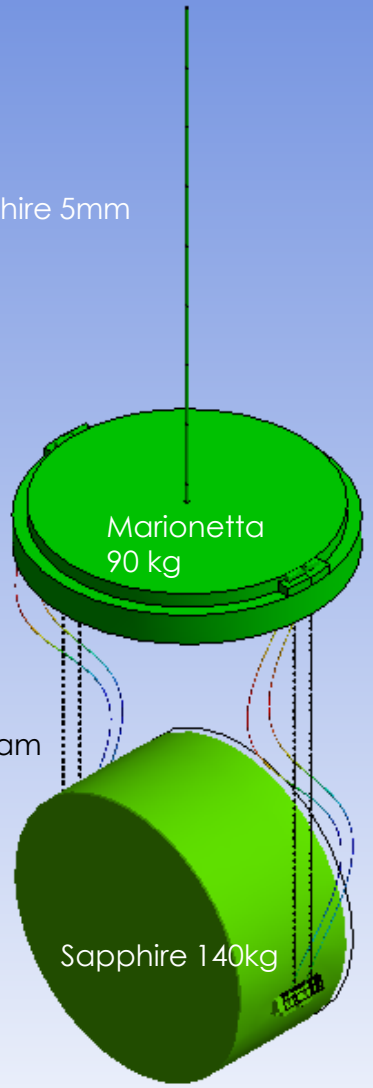
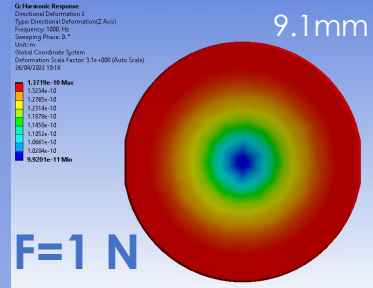
- **For branched:** The Twelfth Marcel Grossmann Meeting, pp. 1732-1734 (2012) A thermal noise model for a branched system of mechanical harmonic oscillators: some issues for the test masses suspensions, P. Puppo https://doi.org/10.1142/9789814374552_0311
- **For double pendulum:** Mechanical thermal noise in coupled oscillators, Y. Ogawa, E. Majorana, *Physics Letters A*, Volume 233, Issue 3, 25 August 1997, Pages 162-168, [https://doi.org/10.1016/S0375-9601\(97\)00458-1](https://doi.org/10.1016/S0375-9601(97)00458-1)

- FDT with different temperature input noises

- Direct approach for the fluctuation-dissipation theorem under nonequilibrium steady-state conditions, Kentaro Komori, Yutaro Enomoto, Hiroki Takeda, Yuta Michimura, Kentaro Somiya, Masaki Ando, and Stefan W. Ballmer, *Phys. Rev. D* **97**, 102001 – Published 3 May 2018

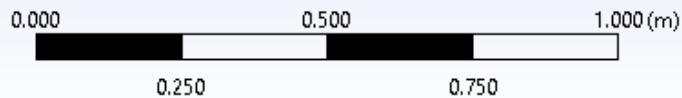
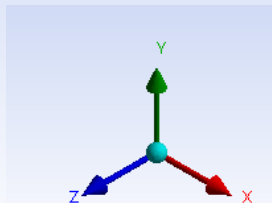
- Levin method with different temperatures with FEM

Sapphire 5mm



Sapphire 2.2mm diam

Sapphire 140kg



Suspension Thermal with FEM

- $S_{Bulks}^{FEM}(\omega) = \frac{4 k_b T}{\omega F_0^2} 2 \sum_i \phi_i E_i T_i$ (T_{mario} T_{mirror} )

- $S_{Wires}^{FEM}(\omega) = \frac{4 k_b T}{\omega F_0^2} 2 \sum_i \phi(T_i, y_i) E_i(y_i) T_i$

$$\phi(T_i, y_i) = \phi_{thermo}(T_i, y_i) + \phi_{material} + \phi_{extra}$$

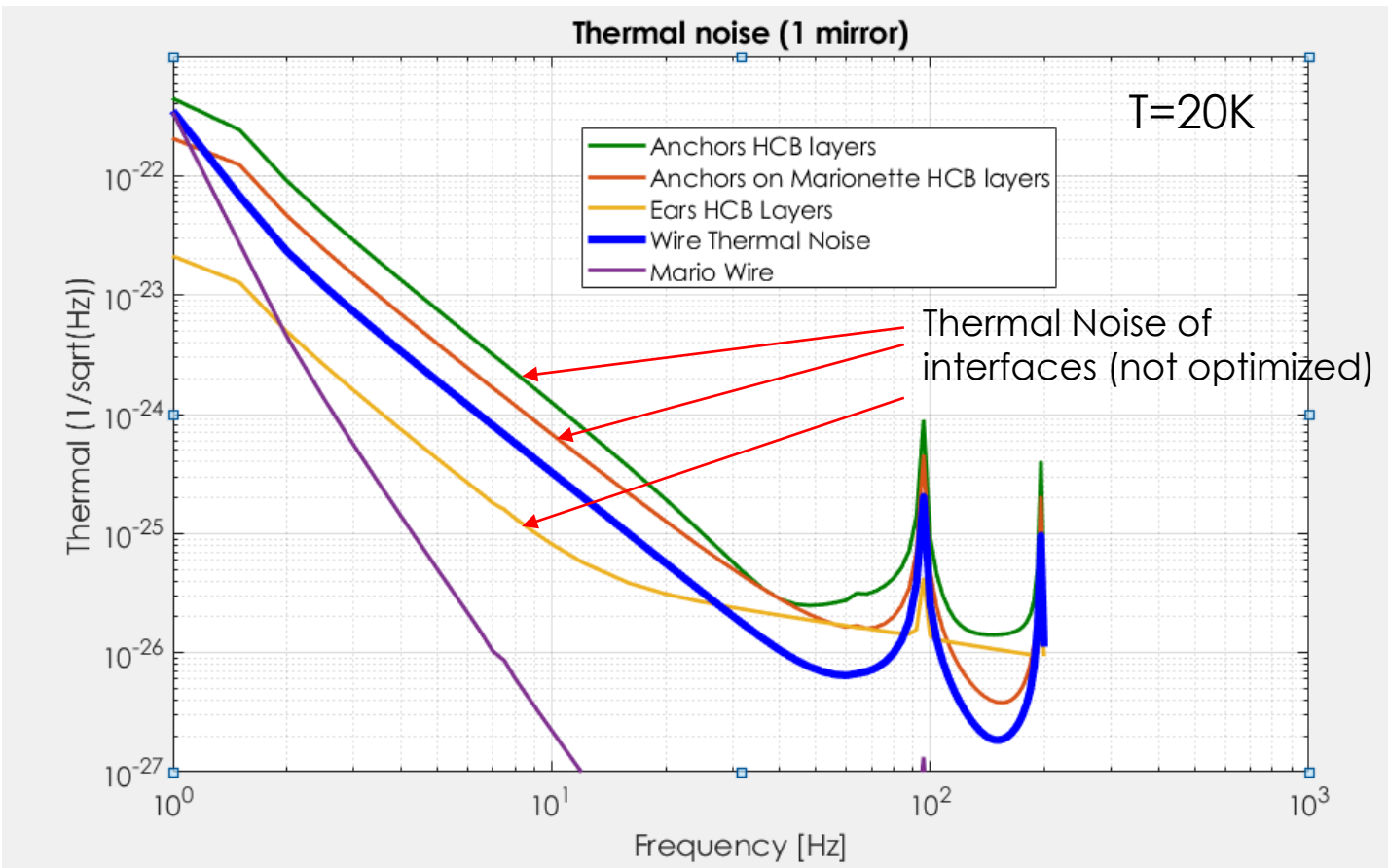
$E_i(y_i)$ from Mechanical
 $T_i(y_i)$ from Thermal Steady

Work in progress

Suspension Thermal (Uniform T)

$$S_X^{FEM}(\omega) = \frac{4 k_b T}{\omega F_o^2} 2 \left(\phi_{wires} E_{wires}(\omega) + \phi_{layers} E_{layers}(\omega) + \phi_{Mario} E_{Mario}(\omega) + \phi_{silica} E_{silica}(\omega) + \phi_{Mario} E_{Mario}(\omega) \dots \right)$$

parts
parts
Cable
Cable



Example of pendulum thermal for large masses in ET.

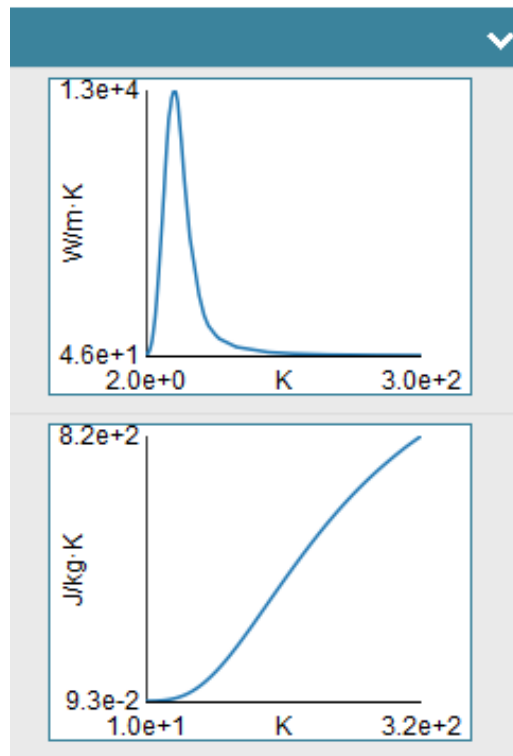
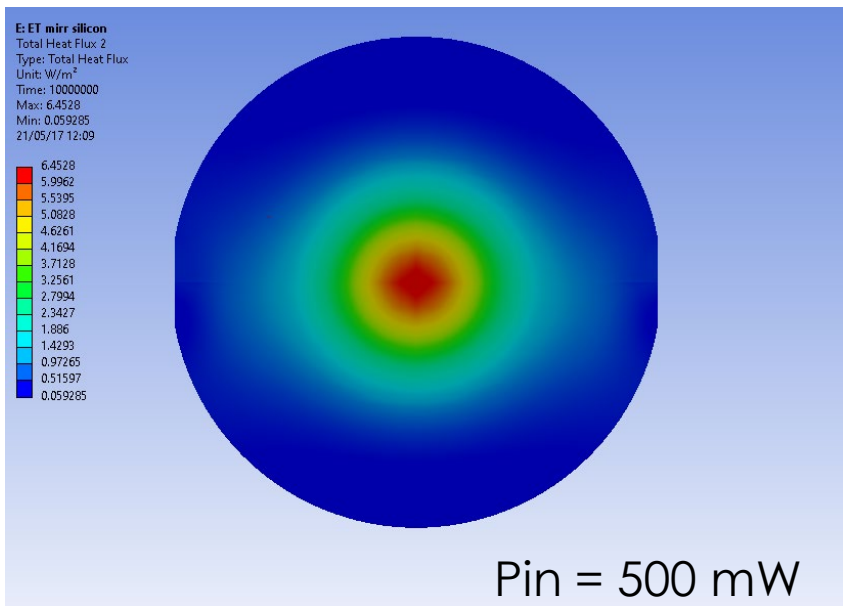
The interface has the effect of increasing the pendulum thermal noise level (red curve) so that the intersection with the CTN shifts up at frequencies higher than 10Hz. This is an unwanted result, because it spoils the sensitivity below 10 Hz.

Interfaces can matter also for thermal behavior introducing thermal resistances.

Sapphire Test Mass: 140 kg
 Sapphire wires: 2.2 mm diam
 Length: 0.8 m + 2* bending point (73 mm)

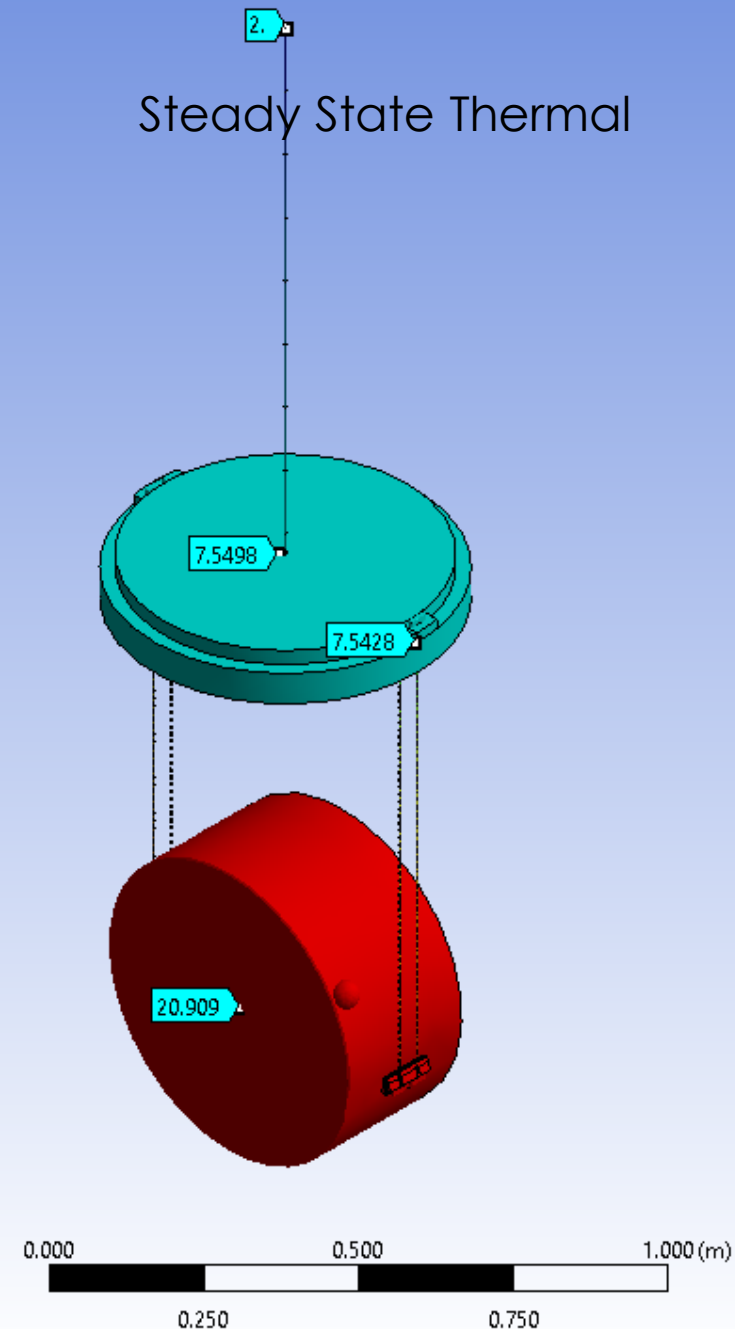
Marionette Wire: Sapphire
 Diam 5.0 mm

Upper point: 8 K



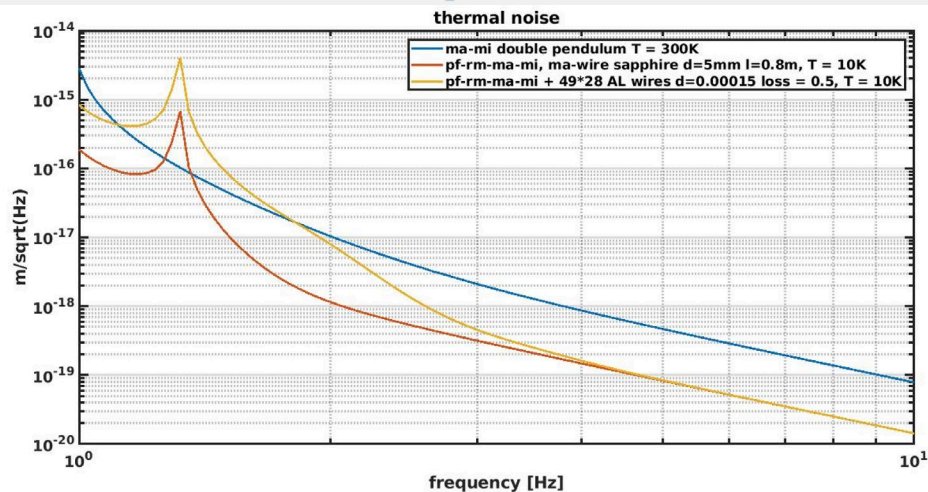
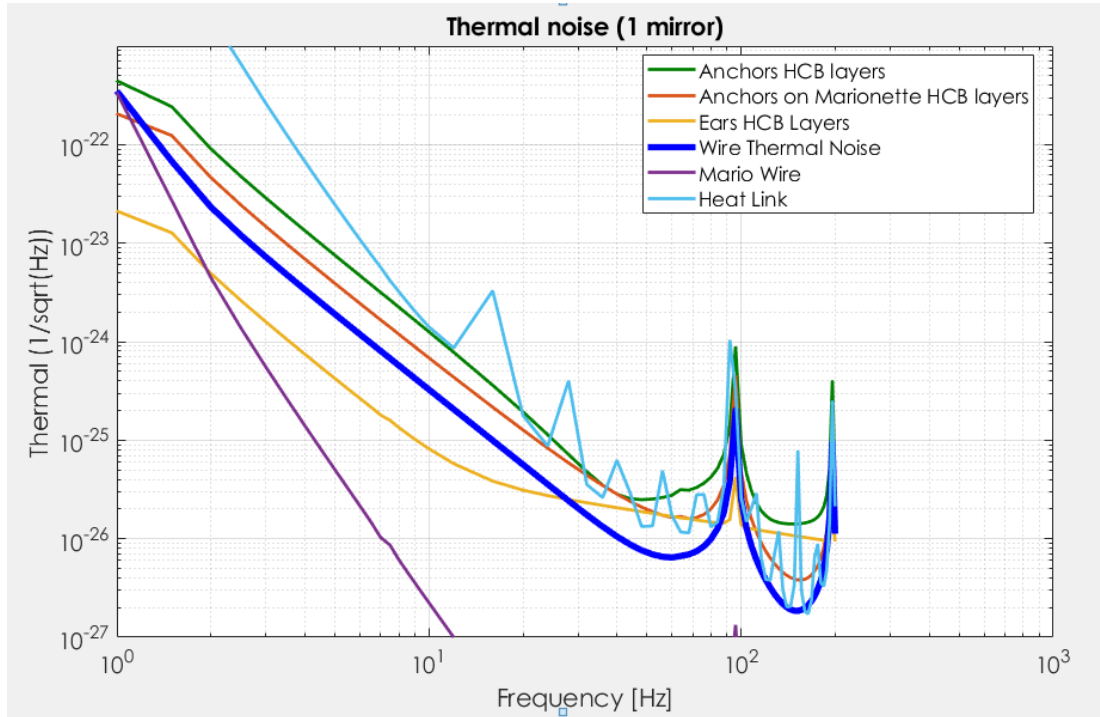
Sapphire Thermal conductivity from:
 T. Shishido, "A study of the sapphire suspension fiber for cryogenic gravitationalwave detector KAGRA", Master Thesis, The Graduate University for Advanced Studies (2019)

Steady State Thermal

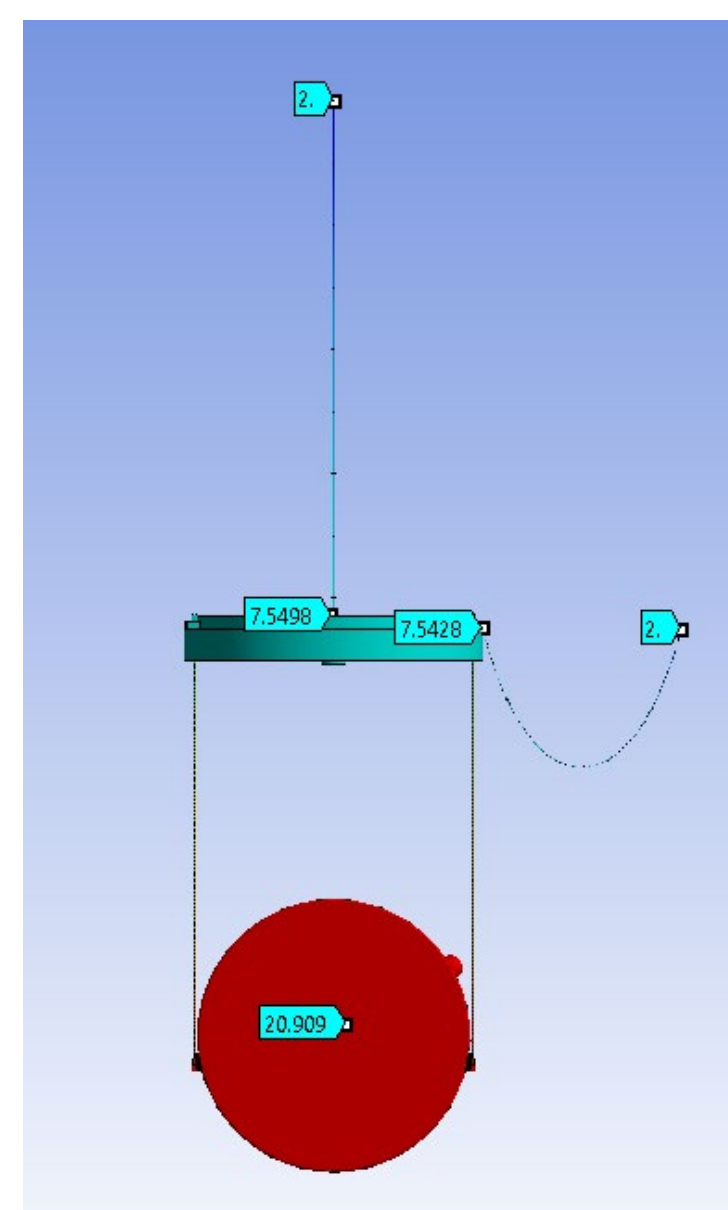


With heat links (a bad case)

Pure Aluminum Heat Link (loss angle: 0.5)



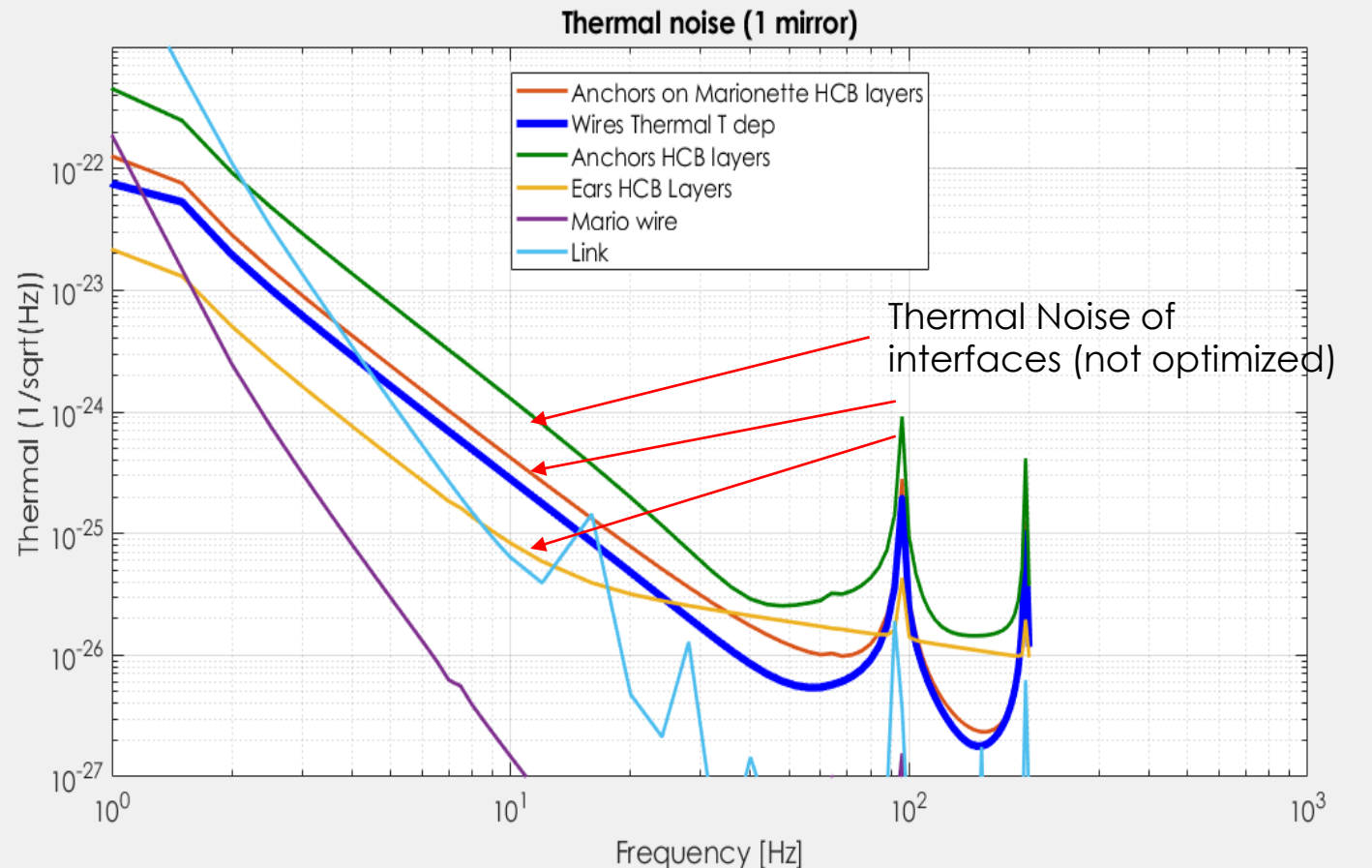
- The Heat Links cannot directly be attached to the marionette, they introduce vibrations and also increase the STN



- In agreement with the analitical study of the heat link effect based on the Saulson paper by P. Ruggi.

Suspension Thermal (Not Uniform T)

$$S_X^{FEM}(\omega) = \frac{4 k_b}{\omega F_o^2} 2 \left(T(y) \phi_{wires} E_{wires}(\omega, y) + T_{layers} \phi_{layers} E_{layers}(\omega) + T_{Mario} \phi_{Mario} E_{Mario}(\omega) + T_{Mir} \phi_{Mir} E_{Mir}(\omega) + \dots \right)$$



Example of pendulum thermal for large masses in ET.

The TN of the interface on the marionette is reduced.

The link effect is reduced

The interface (anchors and ears are the bottleneck of the STN, the optimization is important)

STN @ 10 Hz: (without interfaces)
 3.26 e-25 1/sqrt(Hz) with T=20K
 2.8 e-25 1/sqrt(Hz) with T distribution

Goal: $\leq 1.5e-25$ 1/sqrt(Hz)

Conclusions

- The FEM model is used both for temperature distribution and mechanical behavior.
- It is used to calculate the STN in a steady state with different temperatures.
- Marionette suspension losses are negligible;
- Interfaces effect on TN must be always checked and optimized during the design of the payload
- Heat link effect checked with FEM
- Temperature gradients matter in the computation of the thermal noise with the FEM and it is useful for understanding the role of the interfaces;
- The FE model can be implemented adding the radiative effects for a more accurate evaluation of the temperatures and consequently the STN
- Silicon suspension is going to be studied

Seed modelling for a “good payload”: alternative hypothesis

- ✓ An alternative design was considered (very preliminary) RM cage suspended to Room T filter (outside the cryostat)
- ✓ Lower seismic reinjection (without adding aux attenuators)
- ✓ No need of developing cryogenic vertical antispring filter
- ✓ Separation motor/active alignment control
- Relies on the feasibility of using 3 conductive crystal wires separated by 2 cm side triangle
- More careful design of the cage (mass and volume)
- Four feedthroughs RoomT/Cryostat
- A bit more complicated installation procedure (but similar to AdV)

Interfaces effect on TN must be always checked and optimized during the design of the payload

