The payloads for the Test Masses of the ET-LF interferometers

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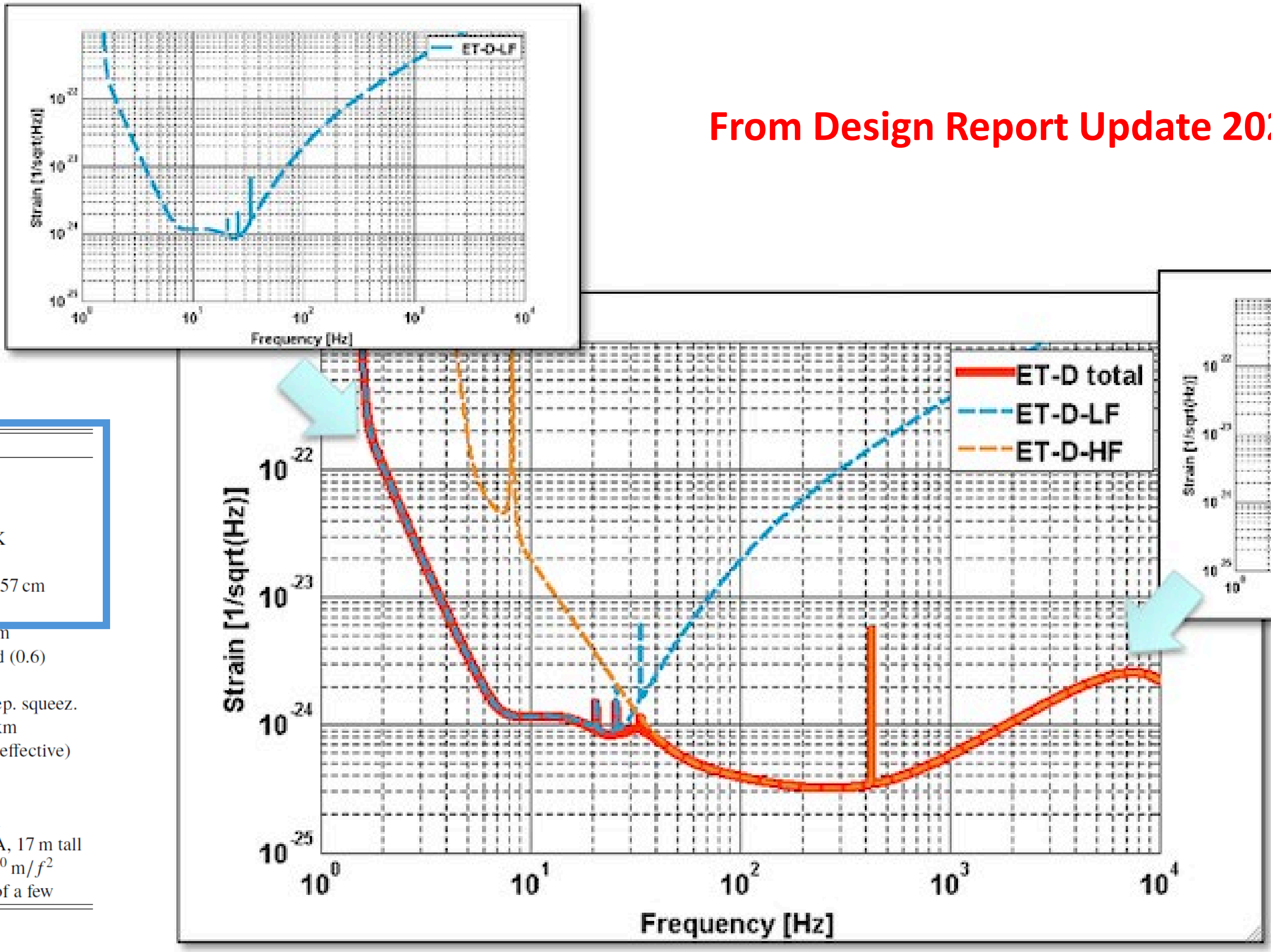
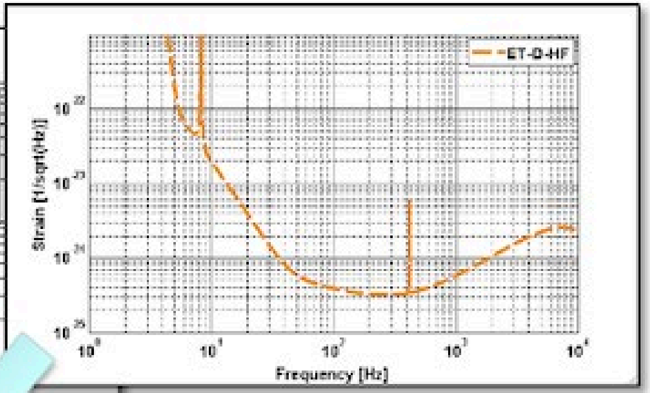
ET-LF Workshop TM Tower Integration
Isola d'Elba September 29-31 2025

Einstein Telescope is a hybrid detector composed of LF + HF interferometers

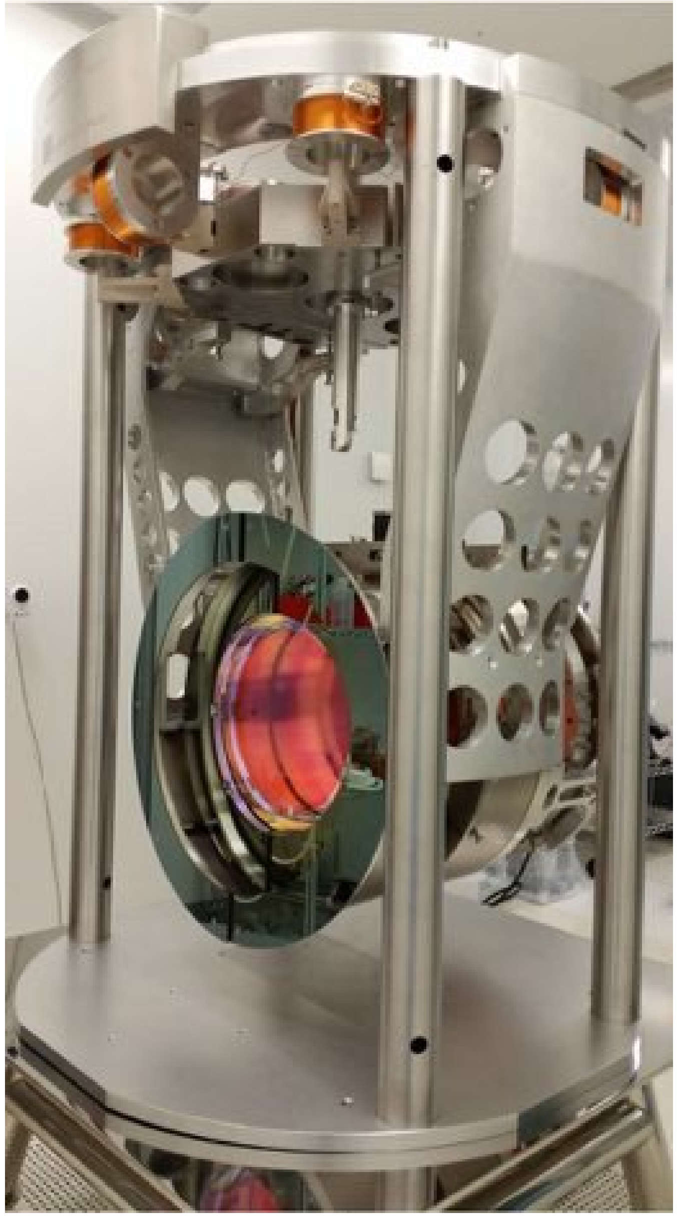
From Design Report Update 2020: ET-0007B-20





Parameter	ET-LF
Arm length	10 km
Input power (after IMC)	3 W
Arm power	18 kW
Temperature	10-20 K
Mirror material	silicon
Mirror diameter / thickness	45 cm/ 57 cm
Mirror masses	211 kg
Laser wavelength	1550 nm
SR-phase (rad)	detuned (0.6)
SR transmittance	20 %
Quantum noise suppression	freq. dep. squeez.
Filter cavities	2×1.0 km
Squeezing level	10 dB (effective)
Beam shape	TEM_{00}
Beam radius	9 cm
Scatter loss per surface	37 ppm
Seismic isolation	mod SA, 17 m tall
Seismic (for $f > 1$ Hz)	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$
Gravity gradient subtraction	factor of a few

Parameter	ET-HF
Arm length	10 km
Input power (after IMC)	500 W
Arm power	3 MW
Temperature	290 K
Mirror material	fused silica
Mirror diameter / thickness	62 cm / 30 cm
Mirror masses	200 kg
Laser wavelength	1064 nm
SR-phase (rad)	tuned (0.0)
SR transmittance	10 %
Quantum noise suppression	freq. dep. squeez.
Filter cavities	1×300 m
Squeezing level	10 dB (effective)
Beam shape	TEM_{00}
Beam radius	12.0 cm
Scatter loss per surface	37 ppm
Seismic isolation	SA, 8 m tall
Seismic (for $f > 1$ Hz)	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$
Gravity gradient subtraction	none



The Last Stage Suspension

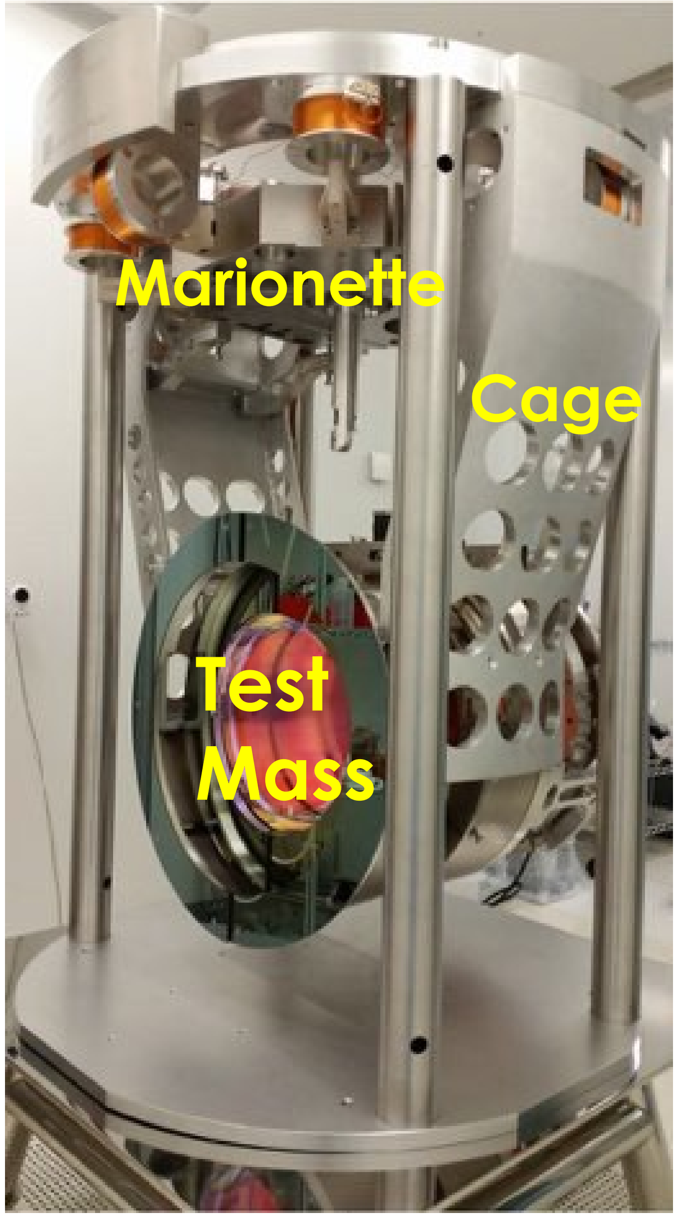
The **role** of the Last Stage Suspension is

- to compensate the residual seismic noise

- to steer the optical components maintaining the relative position of the interferometer mirrors.

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.

Attached to the Last Filter of the upper suspension



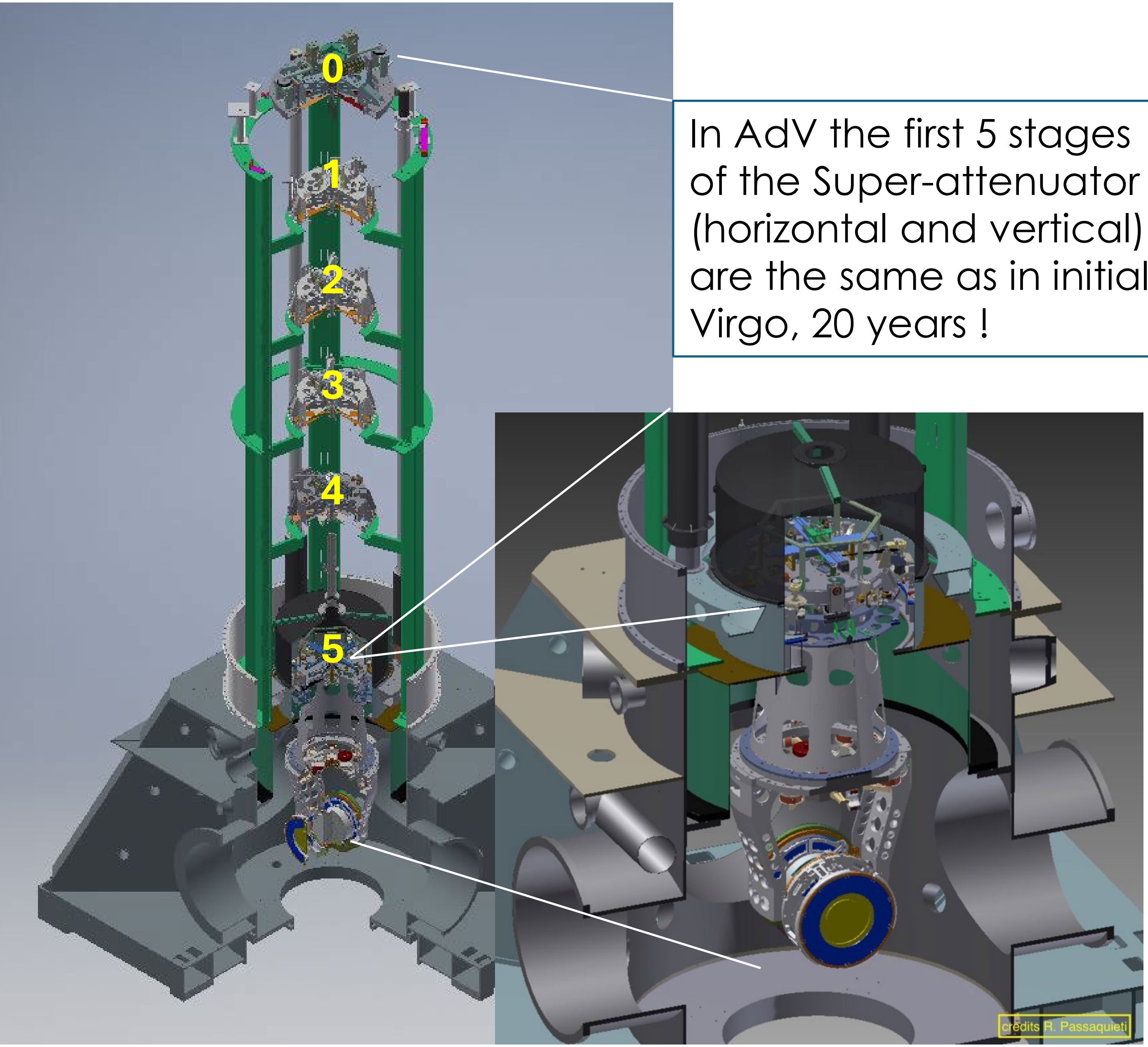
Marionette: Mirror control with actuators (coil-magnets, electrostatic)
between the upper suspension stage and marionette

Cage (or Reaction Mass):

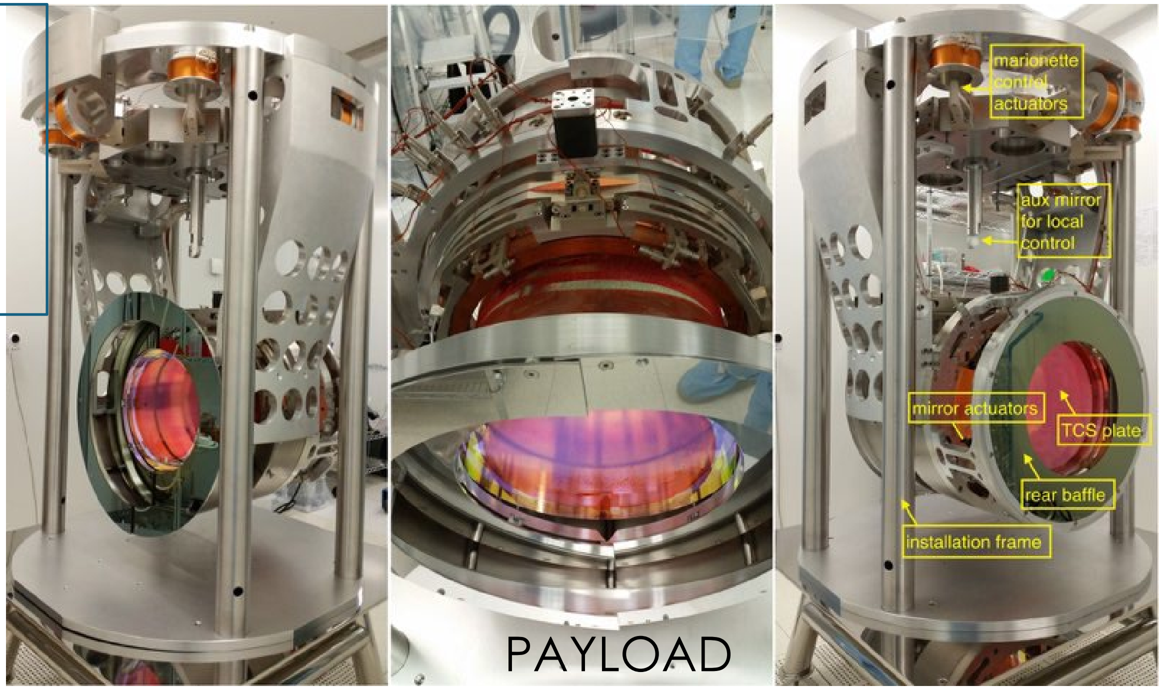
- Test mass and marionette steering with coil-magnets, electrostatic actuation;
- Support for baffle, instrumentation
- Test mass protection

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.

Test mass suspensions and seismic isolator in AdVirgo: overall system

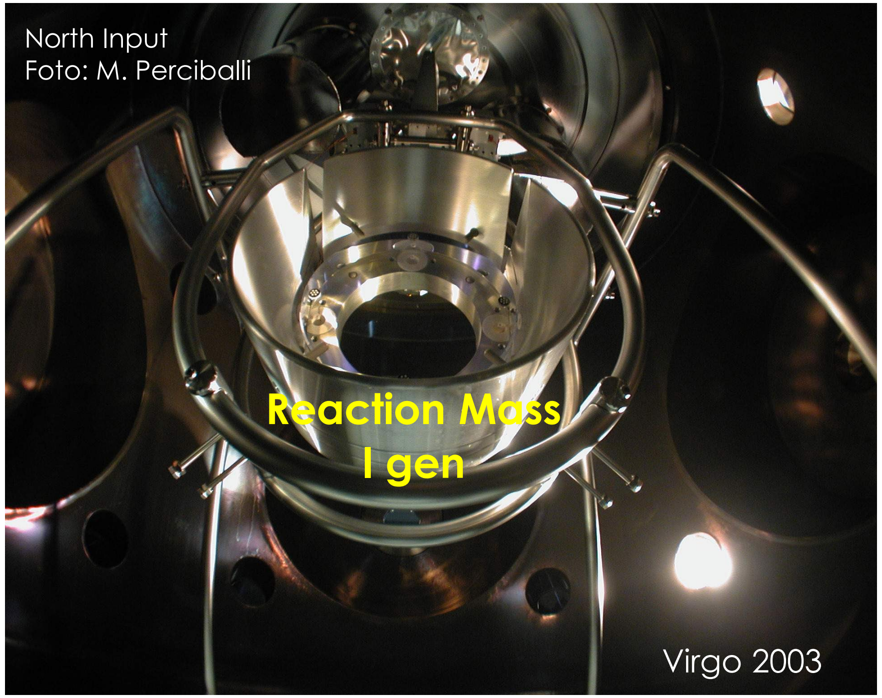


In AdV the first 5 stages of the Super-attenuator (horizontal and vertical) are the same as in initial Virgo, 20 years !



The last filter of the Super-attenuator, prolonged downwards, is in the same vacuum environment of the payload and surrounds it: the "actuation cage".

Payload evolution in time
Virgo (2003) → AdV (2017)



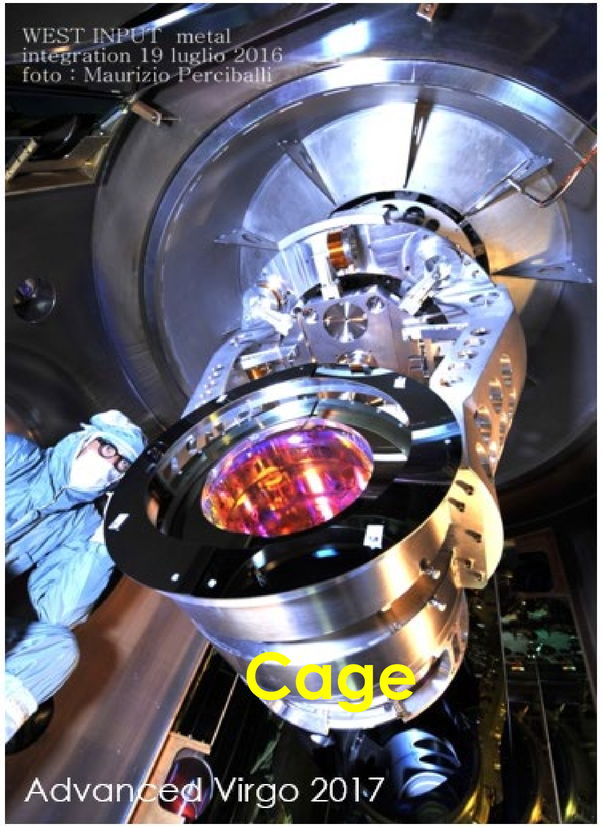
Masses

20 kg

350 mm diameter – 100 thick

Steel Suspension

with reaction mass



Masses

40 kg mass

350mm diameter – 200 mm thick

Monolithic suspension

with cage

Masses

20 kg

350 mm diameter – 100 thick

Monolithic Suspension

with reaction mass - new

Position Control of test mass

Scheme Last filter + Payload : Virgo → AdV

Virgo

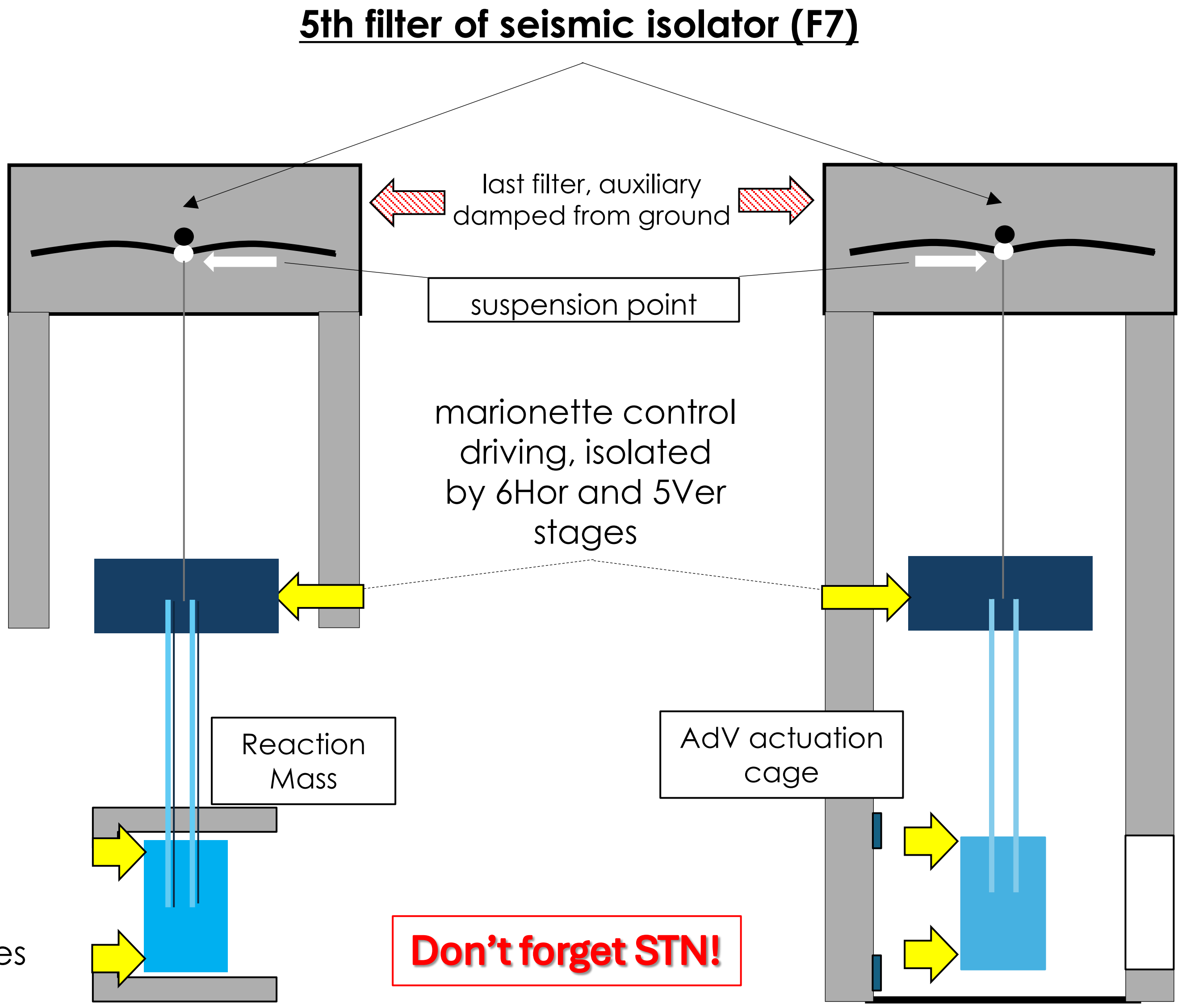
Two Reaction Bodies:

- Physical pendulum for the marionette (F7+Coil Legs)
- Pendulum for the mirror (Reaction Mass)

Notice:

- Locking using just actuation on mirror, simple
- hierarchical control (noise minimization) more complex

The TM suspension is a Branched triple pendulum



mirror control driving, isolated by 8Hor and 6Ver stages

AdVirgo

One Reaction Body

- Physical pendulum (cage) for the simple double pendulum

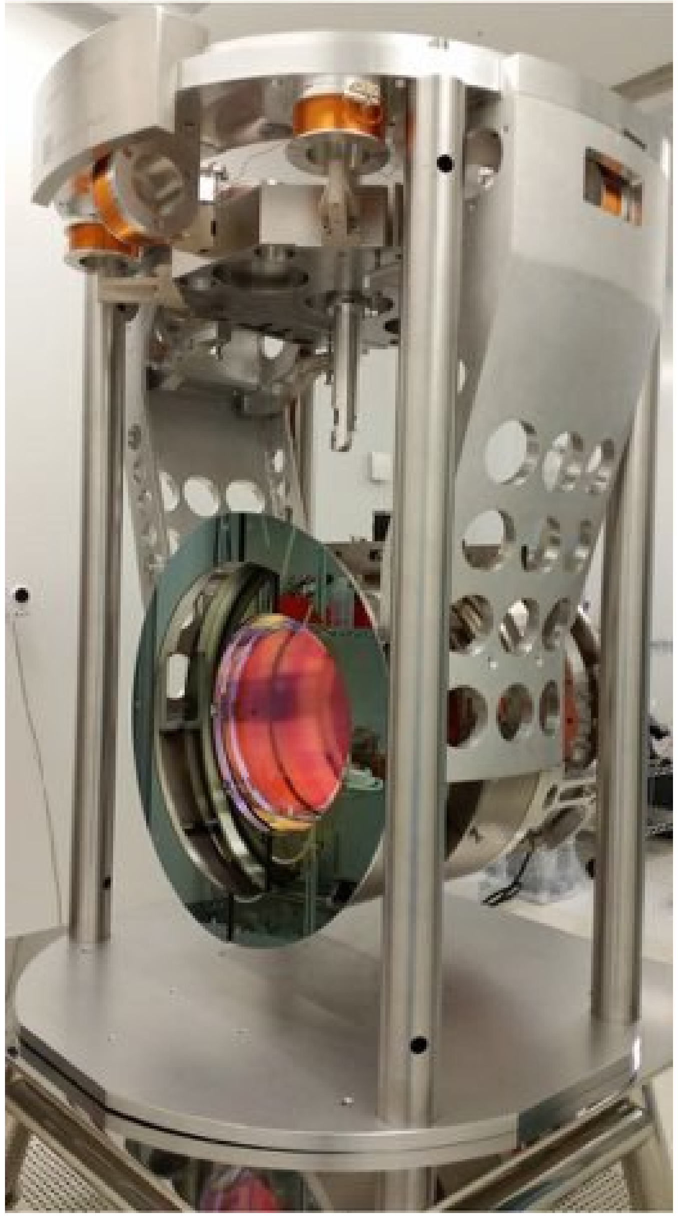
Notice:

Locking simple,

- hierarchical control easy

The TM suspension is Double pendulum

mirror control driving, isolated by 6Hor and 5Ver stages



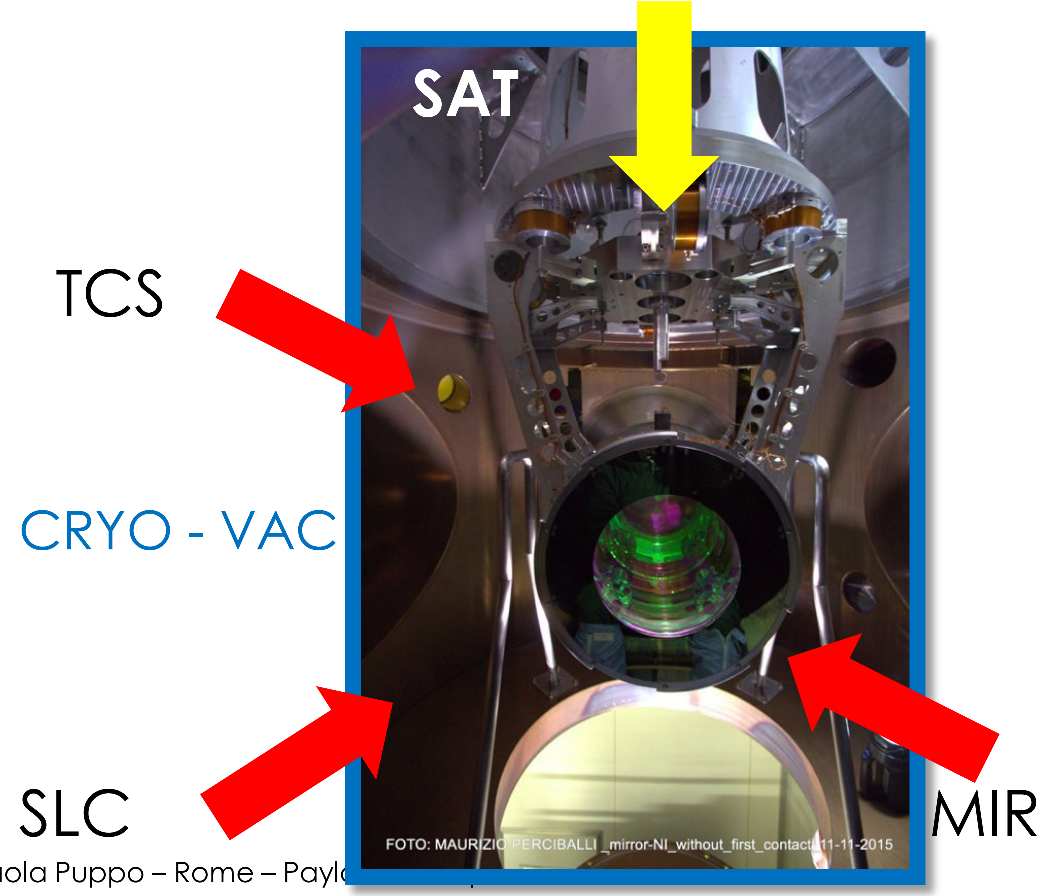
Requirements for the ET Payload

Payloads

- provide the last stage test-mass **suspension controllability** and accomplish with the **mechanical Thermal Noise** requirements;

- is a **composite SubSystem**, strongly interfaced with other SS, in some cases hosting parts of them

- For ET-LF: provide an efficient **heat extraction** from the test-mass to the cryogenic sink (cooling system);



Requirements

- Thermal noise limit
- Materials with low losses and good thermal properties
- Frequencies outside control band and sensitivity band

LF and HF

- Design compliant with the :
  - TM weight
  - Thermal Compensation System TCS (only for HF)
  - Baffles (SLC)

LF Cold

- Heat links connection (low vibrations)
- Thermal Properties, heat inputs, compliance with low cooling time
- Cryostat environment: assembly issues

Important Parameters for the suspension of the test masses

The bending point

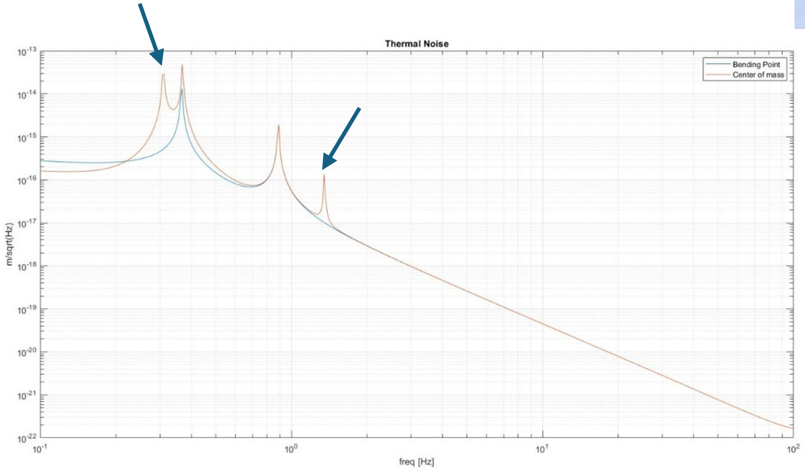
$$\lambda = \sqrt{\frac{Y\,I}{Tens}}$$

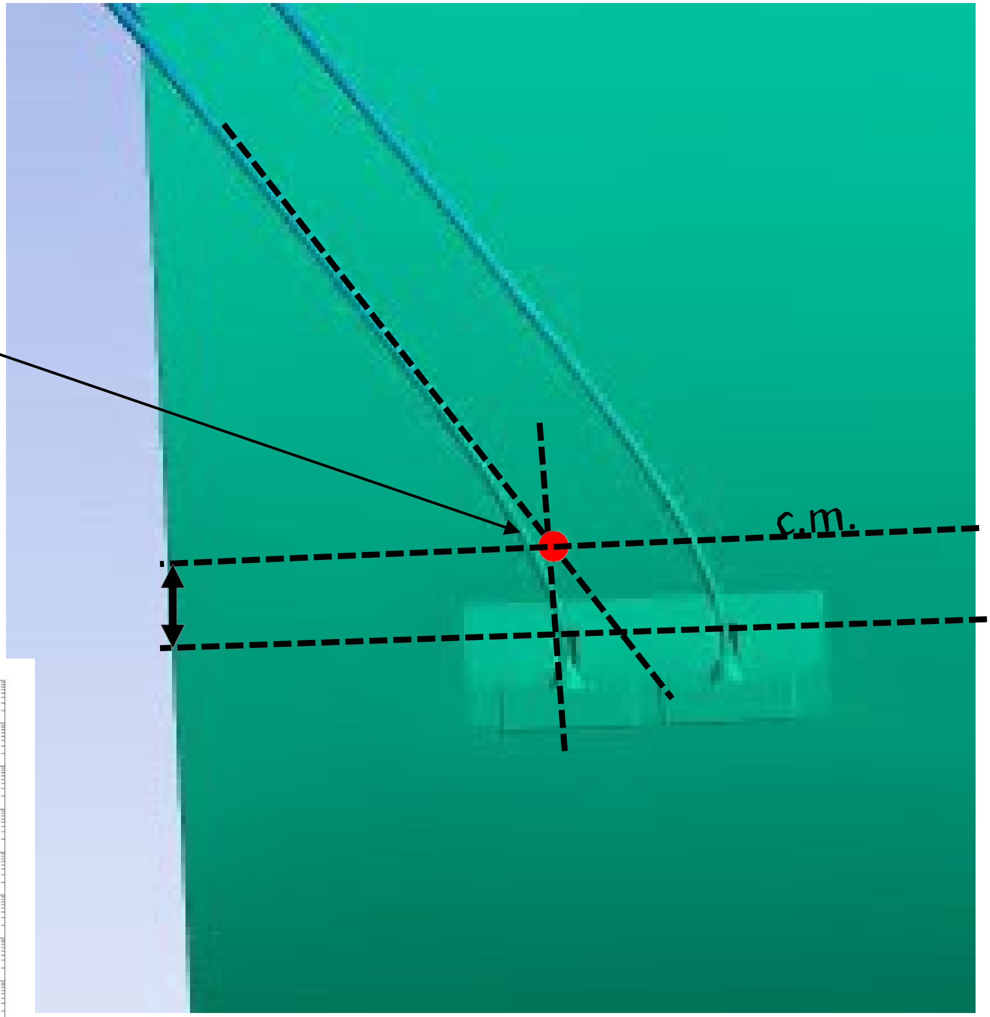
E: Young Modulus
I: Section moment of inertia Tens:
wire tension

The bending point must lay on the center of mass of the suspended body → wire length

$L=L_{cm}+2\,\lambda$ for mirrors

Extra peeks due to the wrong susp point → mixed dofs





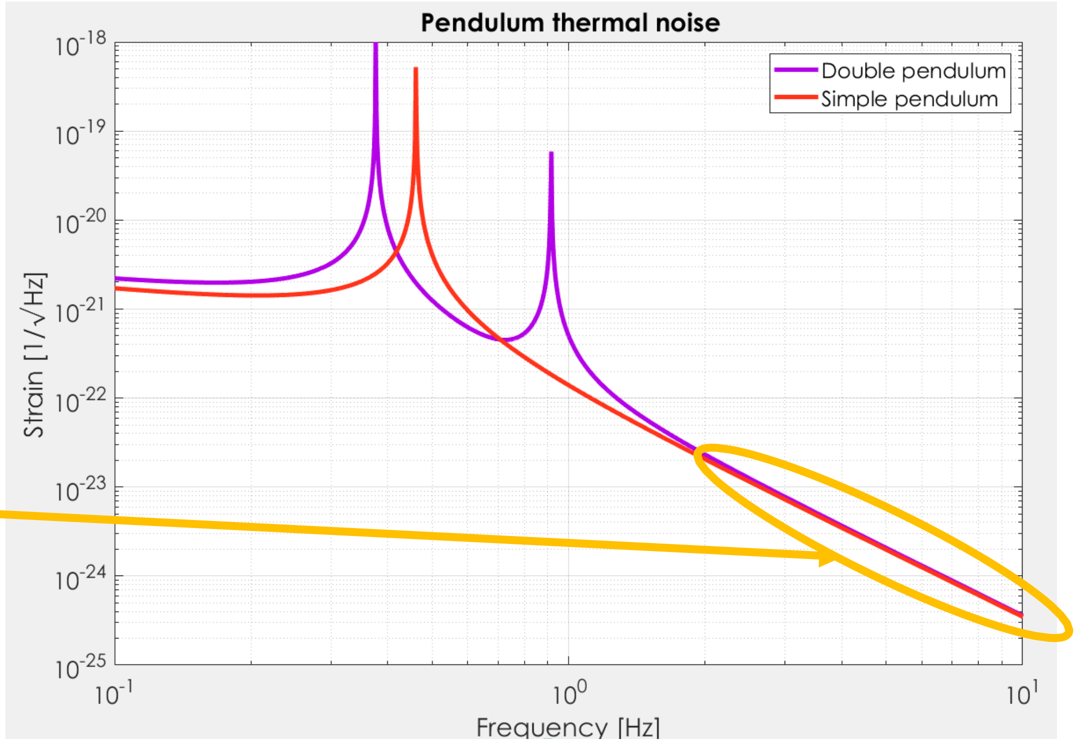
The dilution factor

$$D = \frac{L_w}{2\lambda}$$

E: Young Modulus
I: Section moment of inertia
L_w: wire length

$$X^2_{STN}(\omega) = \frac{4\, k_b T\, \omega_p^2}{M\, \omega^5} \frac{\phi_w}{D}$$

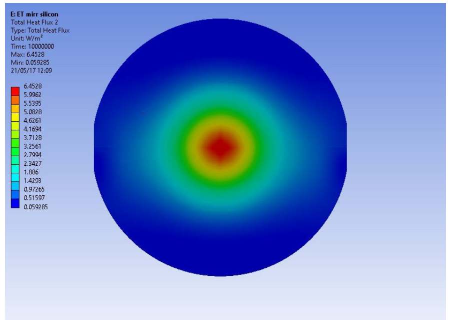
for $\omega \gg \omega_p$



Larger dilution implies a lower level of noise

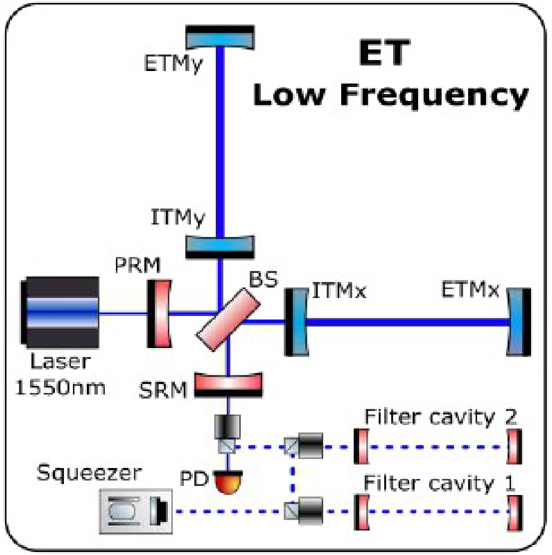
Heat extraction

Mirror mass 220 kg
Beam size 9cm
P in the arms 18 kW
Finesse 880
Recycling factor 21.6



P_{RC}=18kW/(2F/pi)=32 W (Power in recycling cavity)

	Sapphire Mirror	Silicon Mirror
Thickness (cm)	35 (diam 450mm)	36 (diam 550mm)
Substrate (ppm/cm)	50	10
Coating (ppm)	1	1
Pcoat (mW)	18	18
Psubstrate (mW)	112	12
Ptot (on ITMs)	**130**	**30**
Ptot (on ETMs)	**18**	**18**



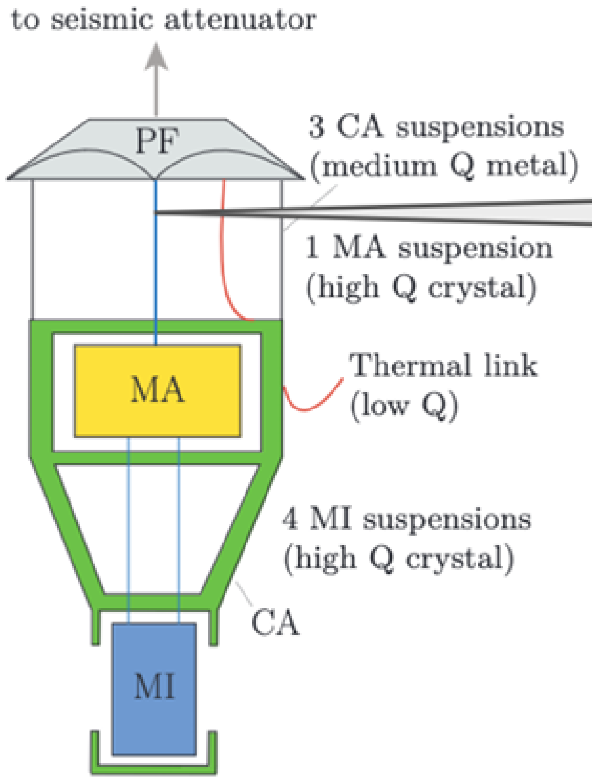
A conservative heat value of 500 mW is used for the payload design (see M. Ricci presentation).

These aspects have a strong impact on the choice of the cryostat dimensions)

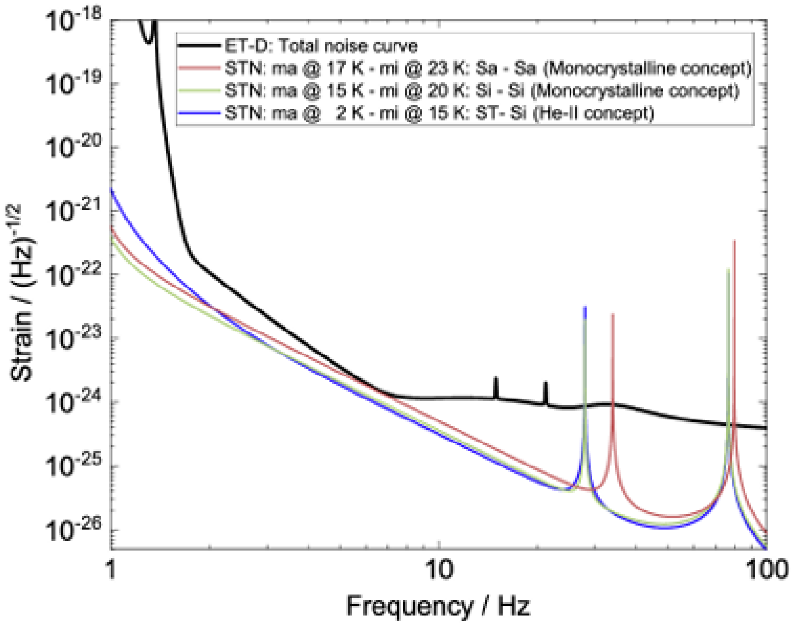
Close integration between suspension and cryogenics necessary

ET-LF payload cooling solutions

The robust solution ➔ R&D in Roma Sapienza...



Monocrystalline
MA suspension
(silicon or sapphire)

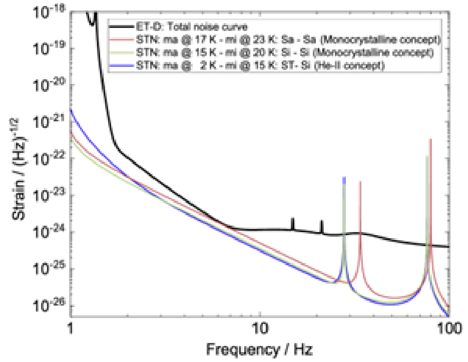


	Silicon	**Sapphire**
Mirror and Marionette Mass (kg)	200	220
Mirror thickness(mm)	360 (diam 550mm)	350 (diam 450 mm)
Mirror wire • **diameter (mm)** • **length (m)**	 3.0 1.2	 2.3 1.2
Marionetta wire • **diameter (mm)** • **length (m)**	 8.4 1.0	 6.4 1.0
Losses	10^{-9}	$5.6\ 10^{-9}$
Temperature (K)	20	20
Wire Tension (Mpa)	77	130
Breaking Strength (Mpa)	200	400

Paper: X. Koroveshi et al., PHYSICAL REVIEW D 108, 123009 (2023)

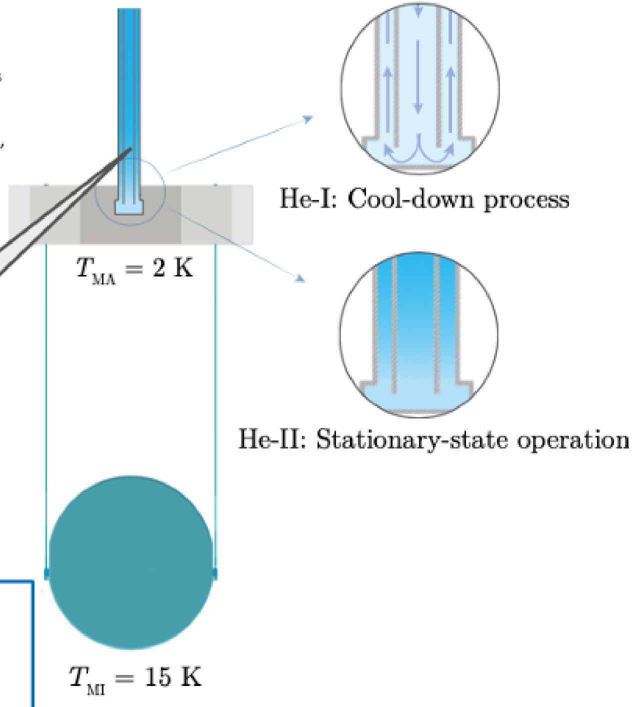
ET-LF payload cooling solutions

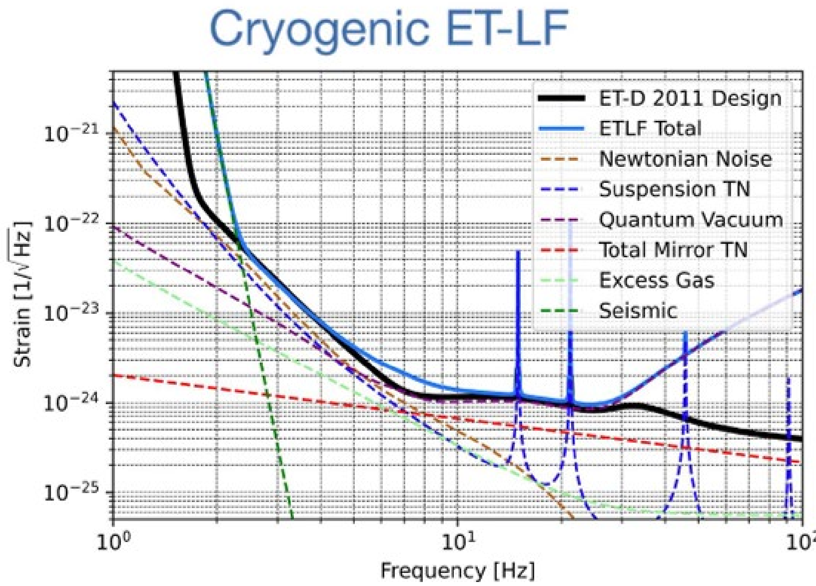
Quantum fluid payload ➔ R&D at Karlsruhe Inst. Tech. - KIT

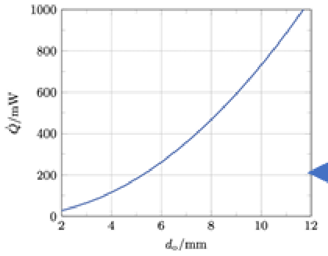


- L. Landau, Theory of the superfluidity of helium II, Phys. Rev. 60, 356 (1941).
- S. W. Van Sciver, Helium Cryogenics, 2nd ed., International Cryogenics Monograph Series (Springer, New York, NY, 2012)
- P. Puppo and F. Ricci, Cryogenics and Einstein telescope, Gen. Relativ. Gravit. 43, 657 (2011)
- X. Koroveshi et al. Physical Review D 108.123009

He-II filled MA suspension tube (titanium)







Cooling capacity of the He-II suspension as function of the outer tube diameter.

X. Koroveshi, S. Grohmann, P. Rapagnani, and V. Mangano, Experimental plans to validate the He-II based payload cooling concept, ECLOUD and GWDVac'22 Workshops, Portoferraio, Italy (2022), 10.5445/IR/1000153742/v2.

Paper: X. Koroveshi et al., PHYSICAL REVIEW D 108, 123009 (2023)

Design of the payload (recursive)

Mechanical design

- Materials → Mechanical, thermal properties, losses
- Breaking strength
- Interfaces → HCB, couplings
- Shapes of wires (diameter, length)
- Frequencies:
  - Must be outside sensitivity bandwidth
  - Must be compliant with control requirements
- Seismic attenuator interface

Thermal design (for Cryo-Pay)

Cooling efficiency, cryostat design, Heat to be extracted

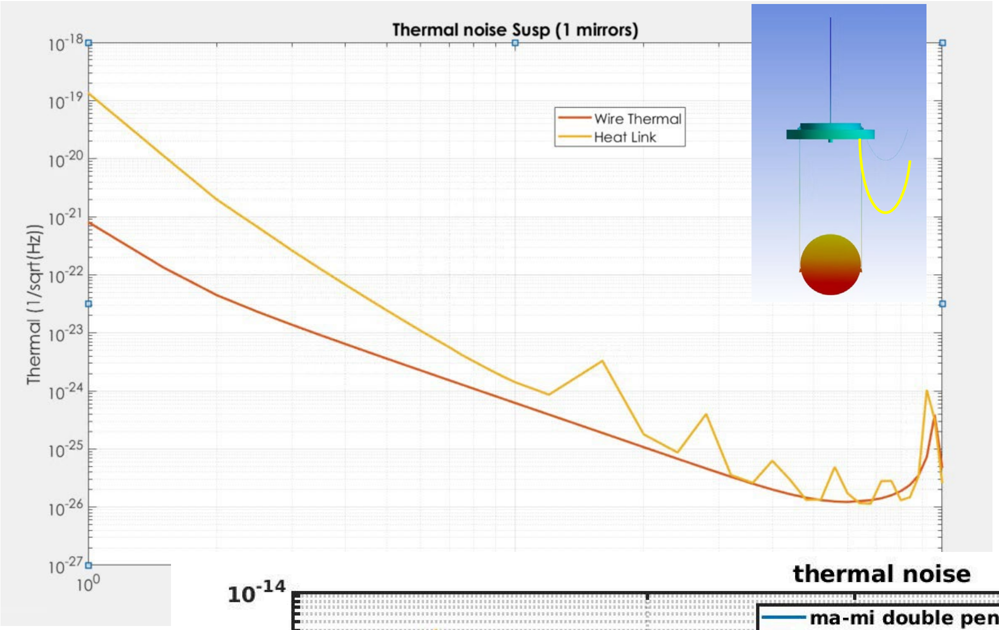
- Heat extraction
  - No noise injection from links
  - Thermal resistance of the interfaces as low as possible

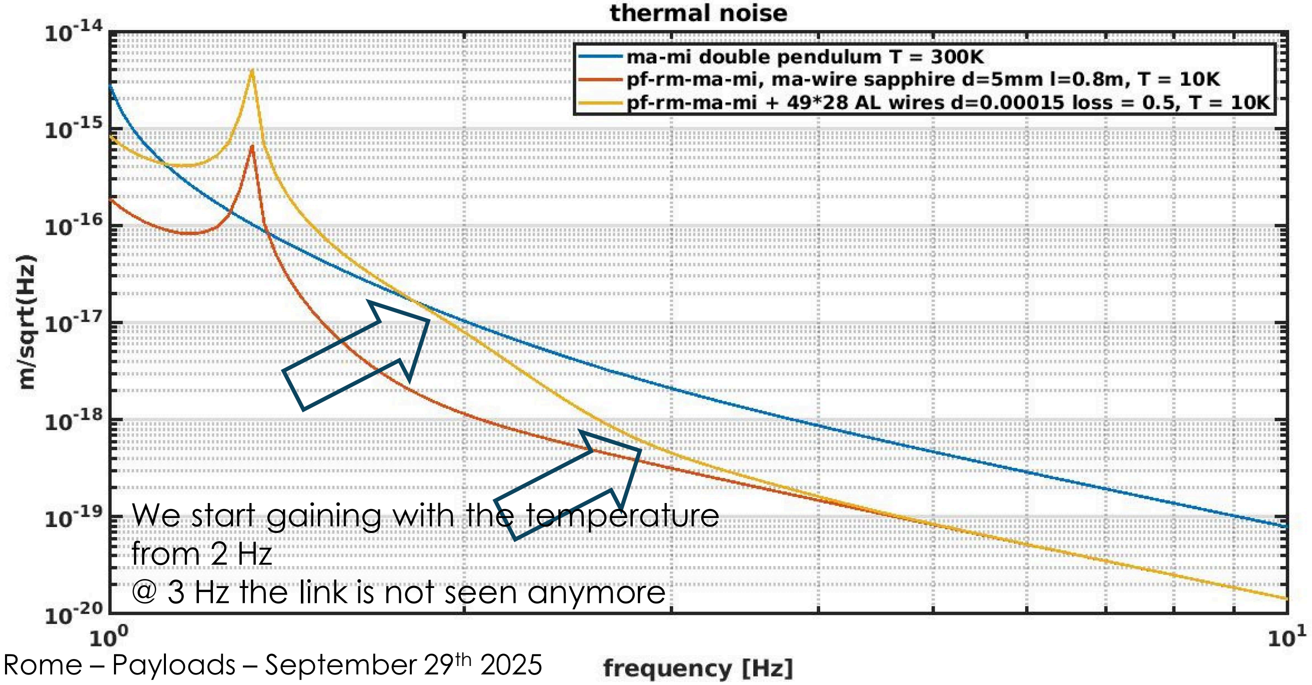
Suspension Thermal noise → Sensitivity

Noise limit : $3\ 10^{-20}$ m/sqrt(Hz), $5\ 10^{-21}$ m/sqrt(Hz) @ 10 Hz

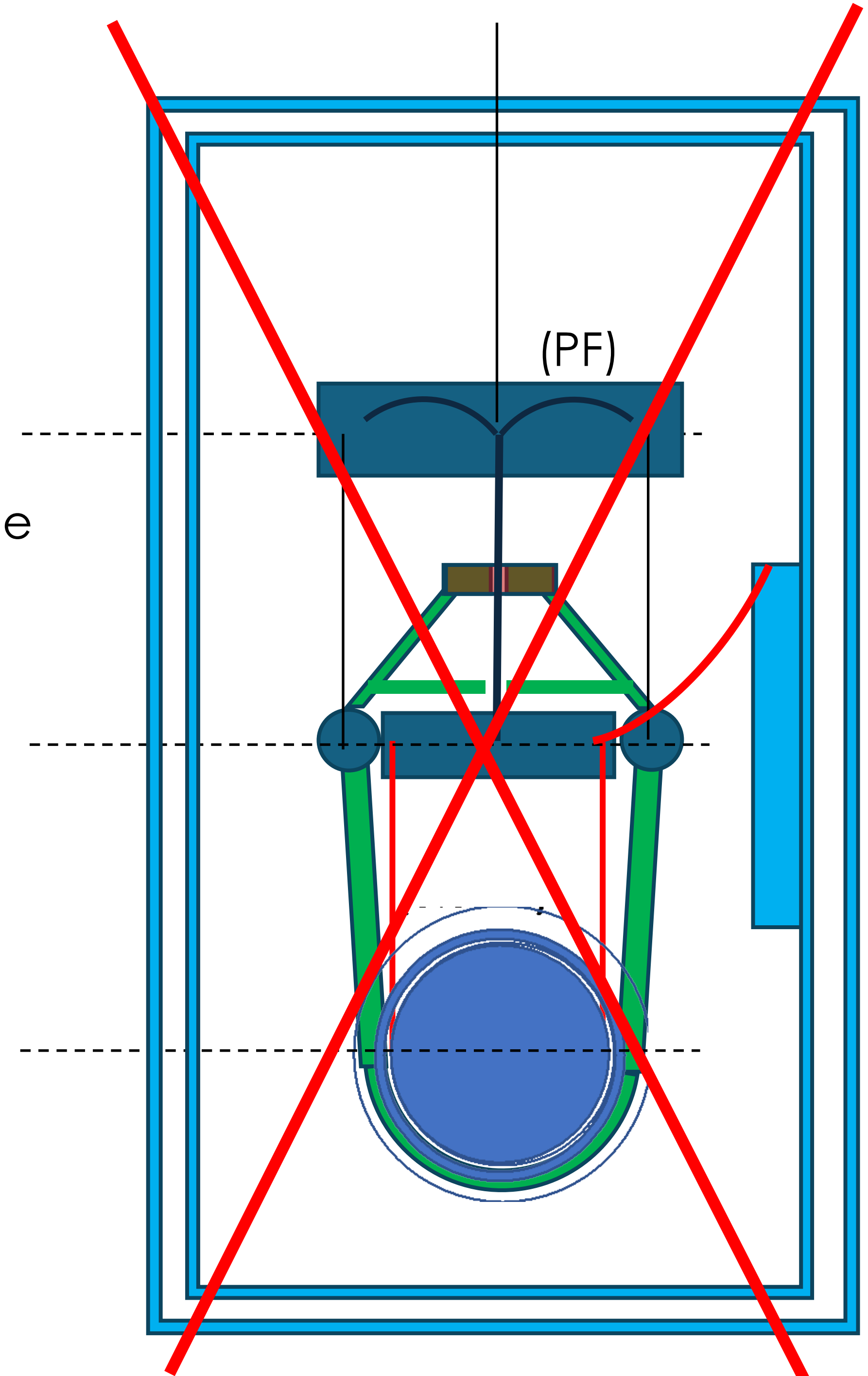
Issue on heat links (see also M. Ricci presentation)

Pure Aluminum Heat Link (loss angle: 0.5)





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



The vertical noise issue

$$STN_{total} = \delta TN_{hor} + g^2_{coupling}\,\delta TN_{VER}$$

pendulum

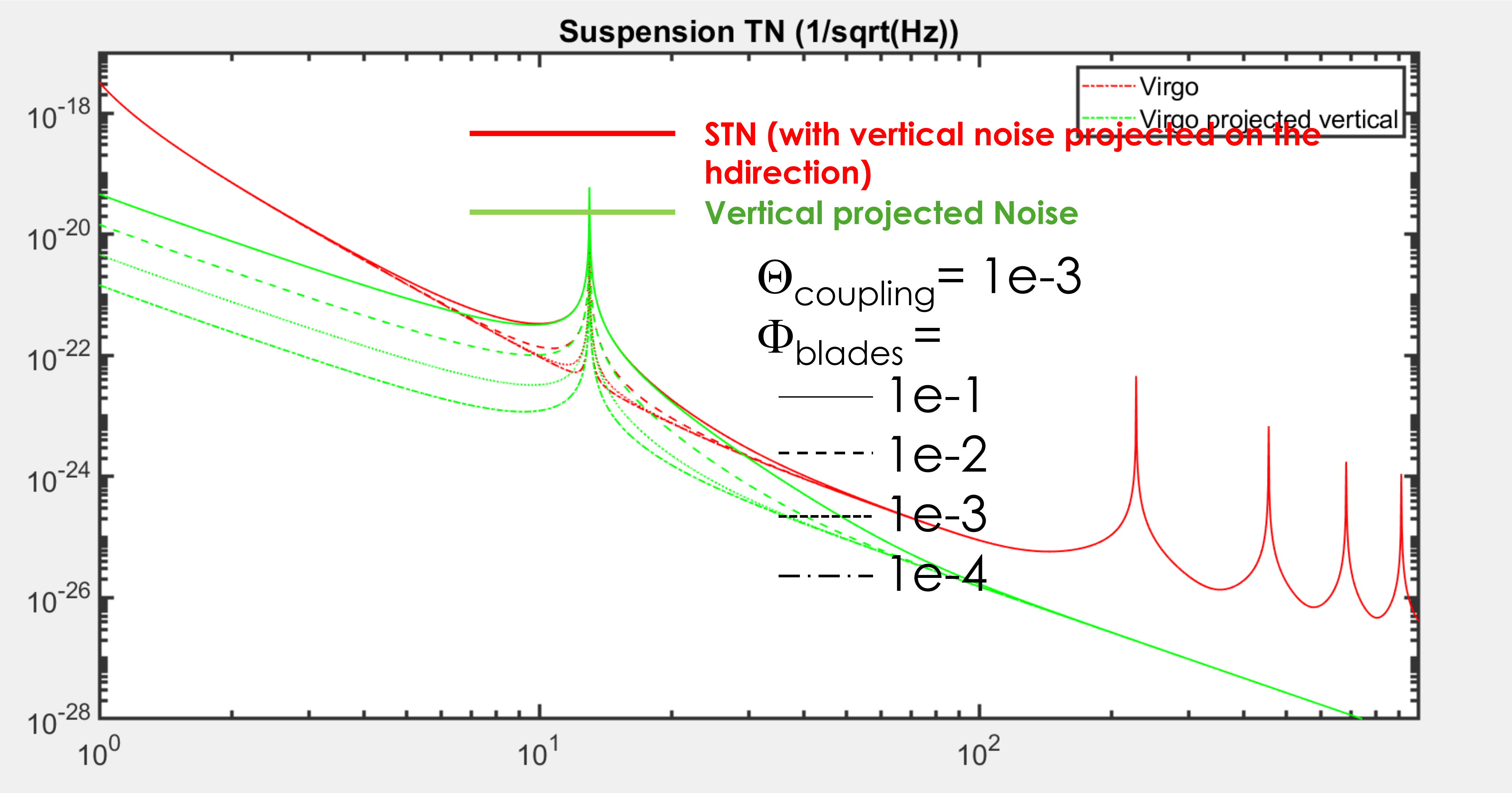
$$\mathrm{STN}_{\mathrm{hor}}(\omega) = \frac{4k_bT}{m\quad\omega}\cdot\frac{\omega_p^2\Phi_p(\omega)}{\left((\omega_p^2-\omega^2)^2+\left(\omega_p^2\Phi_p(\omega)\right)^2\right)}$$

$$\mathrm{STN}_{\mathrm{ver}}(\omega) = \frac{4k_bT}{m\quad\omega}\cdot\frac{\omega_{ver}^2\Phi(\omega)}{\left((\omega_{ver}^2-\omega^2)^2+\left(\omega_{ver}^2\Phi(\omega)\right)^2\right)}$$

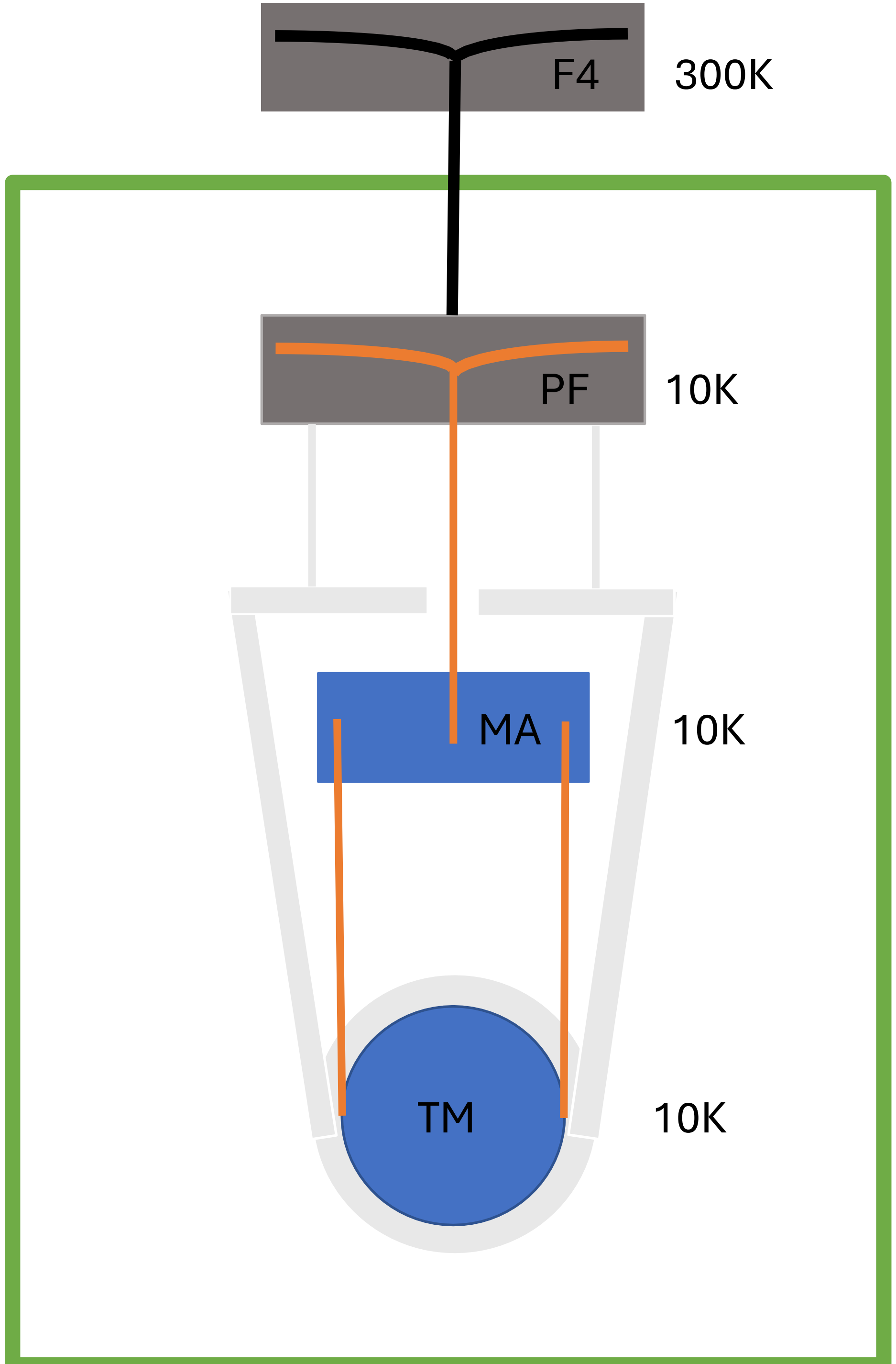
The loss angle of the pendulum is the loss angle of the wire material diluted by the presence of gravity.

<u>**The loss angle in the vertical is not diluted**</u>

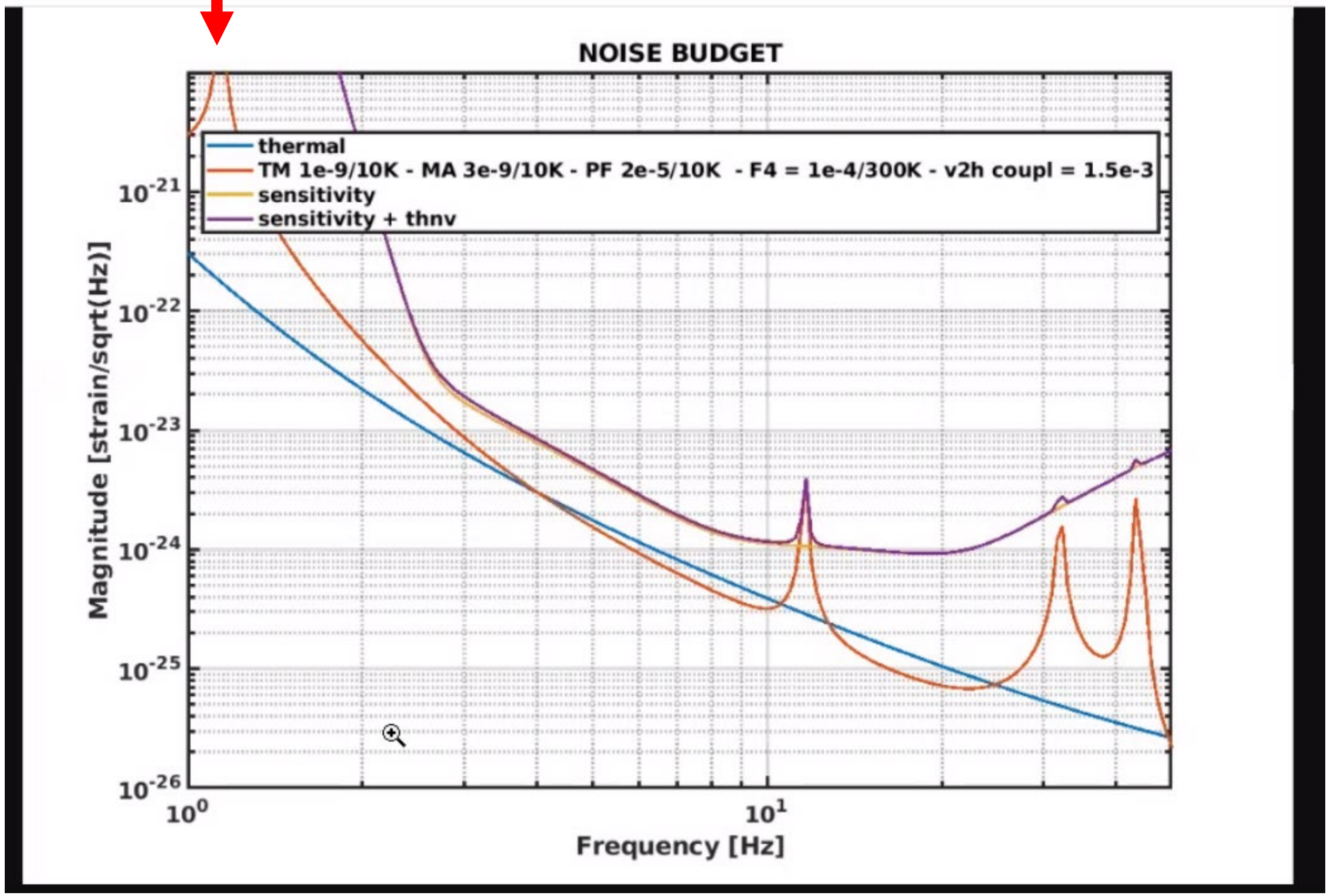
Virgo STN



Suspension TN (1/sqrt(Hz))
Virgo
Virgo projected vertical
STN (with vertical noise projected on the hdirection)
Vertical projected Noise
$\Theta_{coupling}$ = 1e-3
Φ_{blades} =
1e-1
1e-2
1e-3
1e-4
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^{-26}
10^{-28}
10^{0}
10^{1}
10^{2}



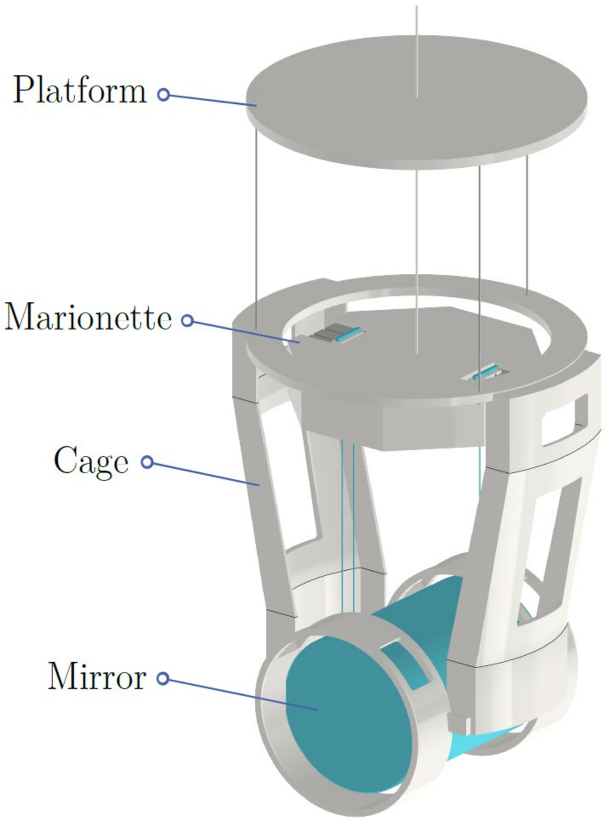
PF nuBlade ~ 1 Hz phi=2e-5



Paolo Ruggi computation of VTN (orange) with Octopus

Cooling and LF Payload parameters

- **Heat path** the <u>cage – platform – test mass</u>
- **Heat link** attenuated



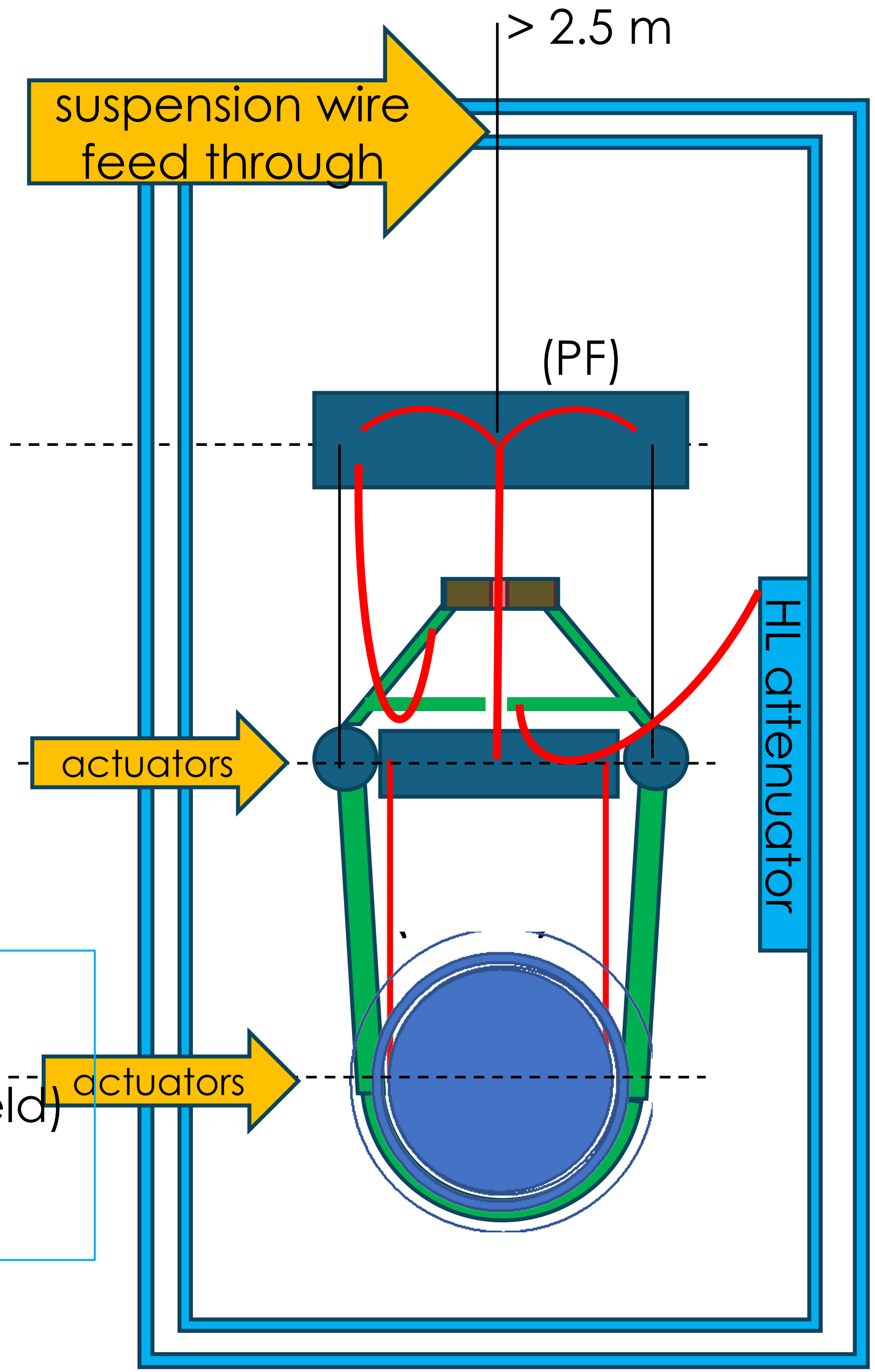
- Mirror Mass = **M**
- Cage(RM) = **M**

COM (center of mass) on PF COM

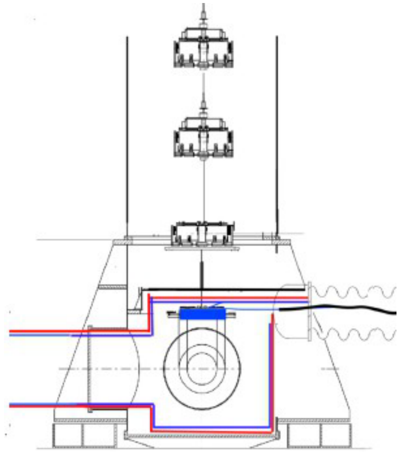
- Marionette =**M**
- PF Mass = **M+M/2**
- **Large mirrors (max diam 600mm)**
- Interval in the PBS is 140-220 kg
- On F7 = **M = 0.7-0.9 Tons**
- **Lmir (0.7-2)m**
- **Lmario (0.7-2)m**
- **LPF>2.5m**

Dimensions of the cryostat
Max diam = 3 m
Max Heigth = 3.8 m (innermost Cryo Shield)

Preferred the insertion from bottom side



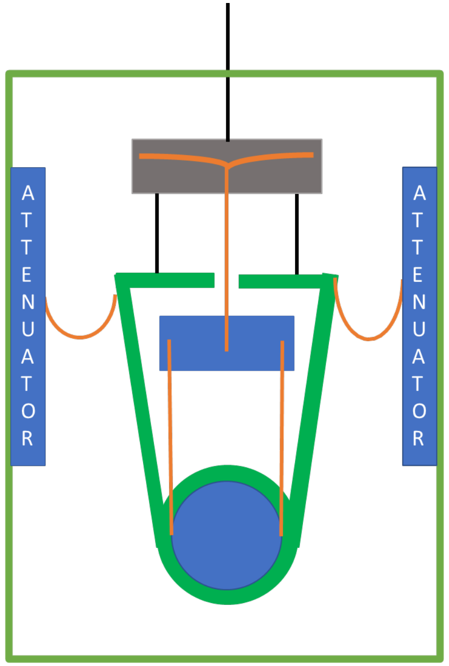
Cold Payload (ET-LF) Activities & Projects



ETIC ARC Cryo and **LoVeC-ET** projects at **Rome University**

- *Payload prototype. Virgo-like. Material sapphire*
- *Cryostat prototype*

*Project at **KIT** for a superfluid helium suspension cable.*



Glasgow: *cryo payload* on small scale, Ligo-like, silicon mirror suspended with sapphire wires, welding possible. Large scale with PT cooling is foreseen in future for test.

Nikhef: ET-Pathfinder

Other studies: Payload with compressed flexures (De Salvo),..

People involved in the Virgo-like payload:

- **Rome:** A. Cruciani, E. Majorana, V. Mangano, L. Naticchioni, S. Pirro, P. Puppo, P. Rapagnani, F. Ricci, M. Ricci, E. Tofani Eng: E. Benedetti, F. Hoang, M. Orsini, D. Pasciuto.
- **EGO**: P.Ruggi
- **KIT (***Karlsruhe Institute of Technology): S. Grohmann*
- **KAGRA collaborators**

Some comments on the overall mass (and TM)

- **Maximum allowed weight change for the Seismic Suspension:** 0.7 – 0.8 Tons (adjustment tollerance on payload - ballast);
- 10 kg per stage adjustment (on SA) without changing the blades;

- **The weight on payload** can be adjusted on ballast on payload;

- The value of TM is taken that as a starting point, as some sub-systems are ready for that.

- **Heat load must be considered** (300 mW on mirror and the rest on the payload (overall 500 mW))

- Heat load due to electrical cabling (considered in recent modelling at KIT) and viewports (in KAGRA the radiation through the viewports has negligible impact)

- TM mass impacts on QN → sensitivity range

Comments and Outlook

- Different concepts for monolithic solutions employing silicon or sapphire are in the panorama for ET-LF;

- Different cooling technologies

(CryoFluids, Pulse Tubes Rome, Quantum Fluid cooling KIT)

- Heat links issues

- Vertical noise issues → study on low loss blades are important

- From M. Pinto talk. Pitch frequency important for angular control and noise→ increase dZ (distance between wires)…depends also on mirror material, birefringence…

See the next talks for the mechanical and thermal studies of the Virgo-like cryo-payload (M. Ricci and E. Benedetti)