Suspension noise modeling

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Outline of the topics in the document

- The last stage suspension of the ET interferometer;
- The model for the thermal noise;
- Parameters for the LSS in ET;
- Numerical evaluations and comparison with the ET goal curve.

WP2 Meeting - Glasgow - July 22nd, 2010

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 and roles:

- 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;
- Mirror: monolithic silicon suspension.

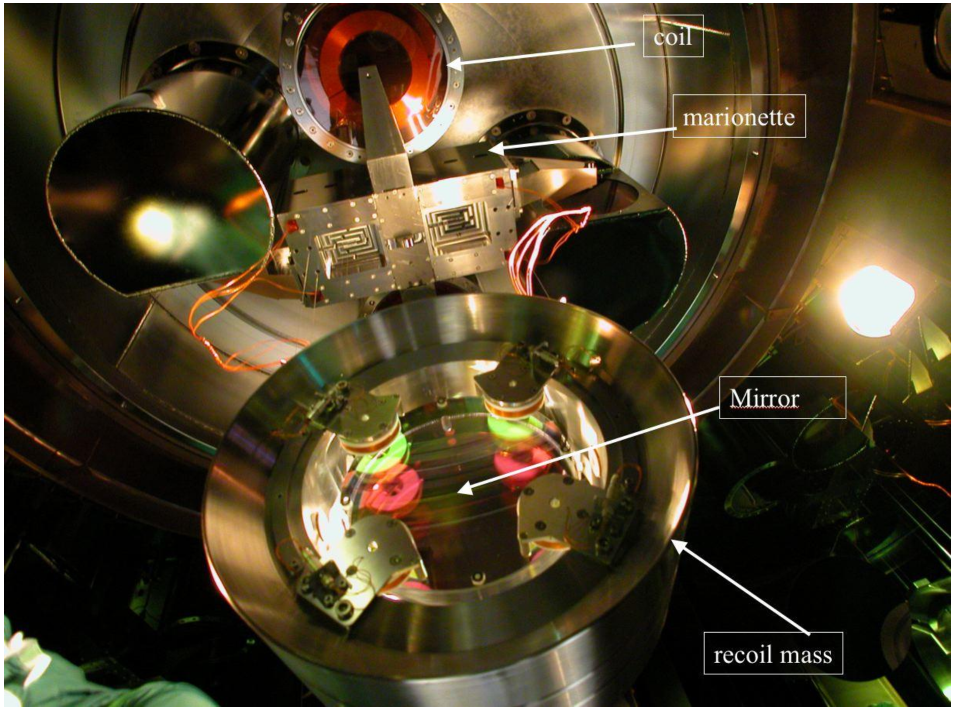
Requirements:

✧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



The ET mirror last stage suspension (Cryogenic)

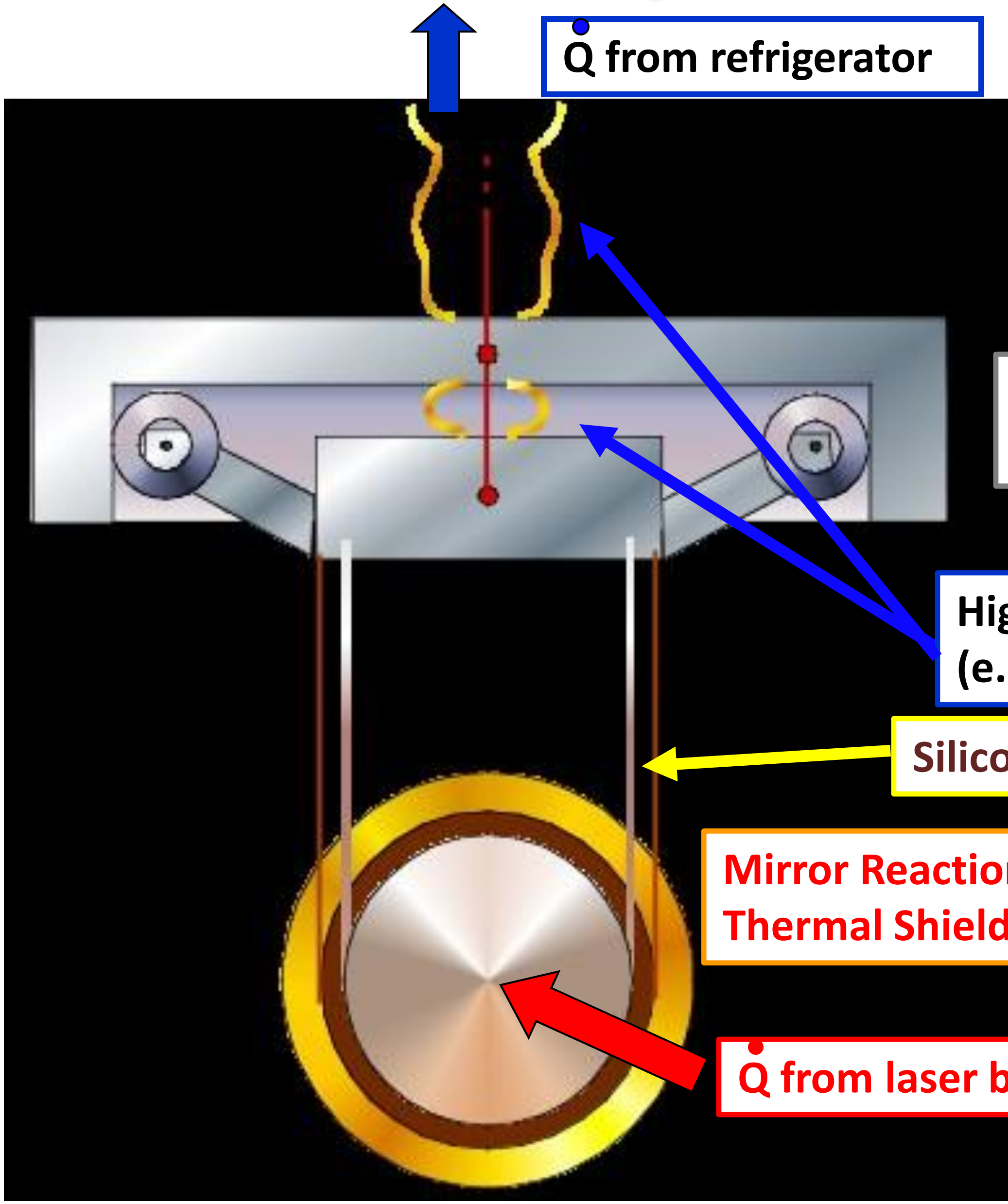
- Mirror and its suspension wires:
  - wires and mirror materials compatible with good mechanical and thermal properties;
    - High thermal conductivities materials;
    - Low mechanical and optical losses;

<u>a promising material both as mirror substrate and wire is silicon having</u>

•high thermal conductivity
•very low thermal expansion (zero below 17K)

Conceptual scheme

$\dot{Q}$ from refrigerator



Different stage temperatures at the steady state.

Marionetta Reaction Mass: Thermal Shield

High Efficiency Soft Thermal Links (e.g. pure Al, copper)

Silicon Monolithic Suspension

Mirror Reaction Mass: Thermal Shield

$\dot{Q}$ from laser beam

Mirror LS Suspension

Mechanical Issues

Big Masses:

☑ reduces the recoils (good for suspension thermal noise)
☑ increases the violin modes (good for control)
BUT
✘ reduces the vertical modes (not good for control)
✘look at the overall weight!!

Wires Length Increment

☑reduces the pendulum frequencies (good for suspension thermal noise)
BUT
✘ reduces the violin modes (not good for control)
✘ reduces the vertical modes (not good for control)

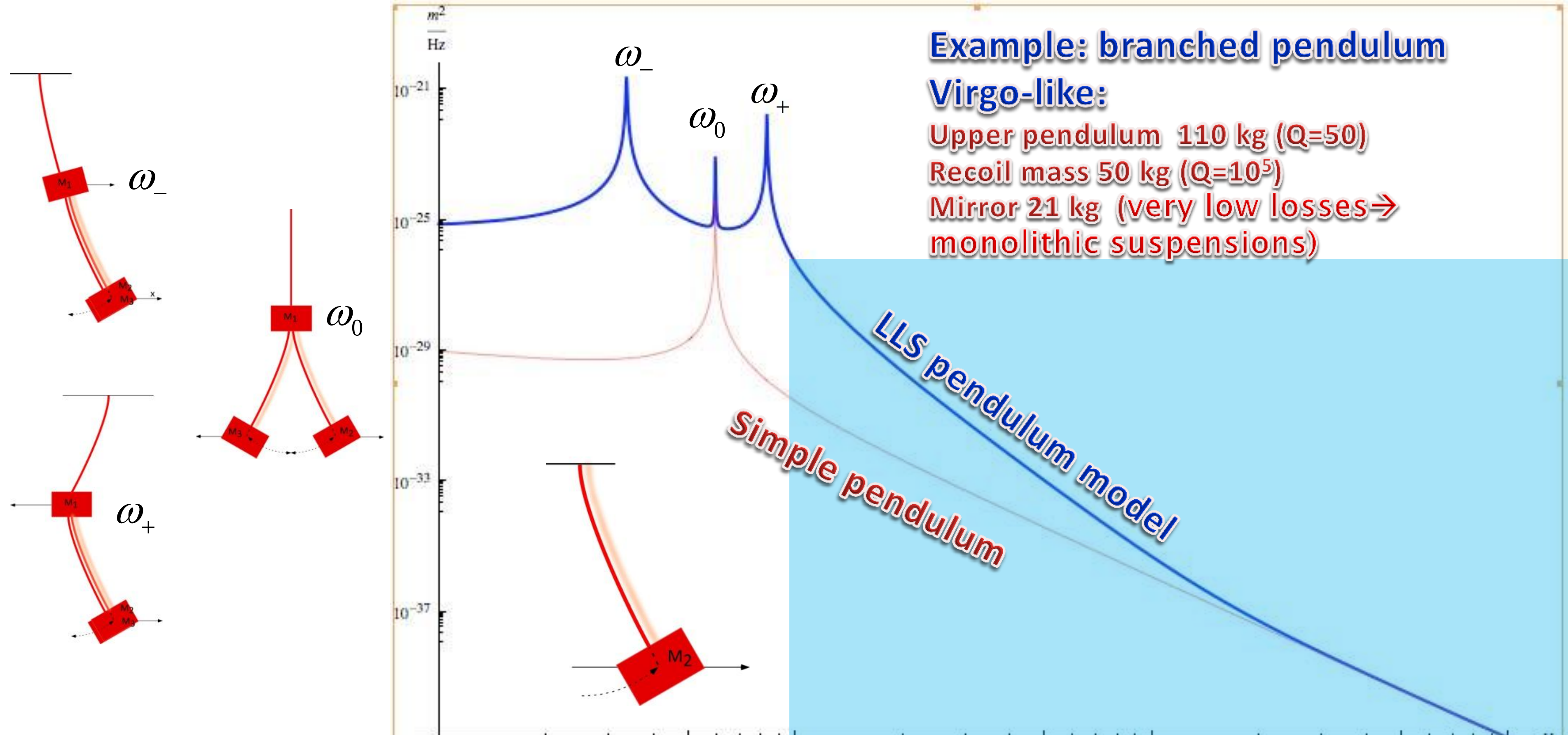
Wires Diameter Increment:

☑ increment of the wire sections (good for cooling)
BUT
✘ reduces the violin mode frequencies (not good for control)
✘reduces the dilution factor (not good for suspension thermal noise)

•The suspension thermal noise affects the sensitivity in the frequency range below 10 Hz;
• Importance of the different temperatures of the pendulum stages in the computation of the thermal noise
• The marionette stage thermal effect is very important
• The thermal noise of violin modes is negligible (but look at the frequencies)

THE SUSPENSION THERMAL NOISE

- In presence of low dissipative mirror suspensions, a new thermal noise estimation must be done by including the viscous and internal dissipations of the marionette and recoil mass pendulum.
- The marionetta's mechanical pendulum losses give a non negligible effect via its recoil, in the off-resonance high-freq. range [*].
- For cryogenic LSS the different temperatures of the pendulum stages is important in the computation of the thermal noise [**]

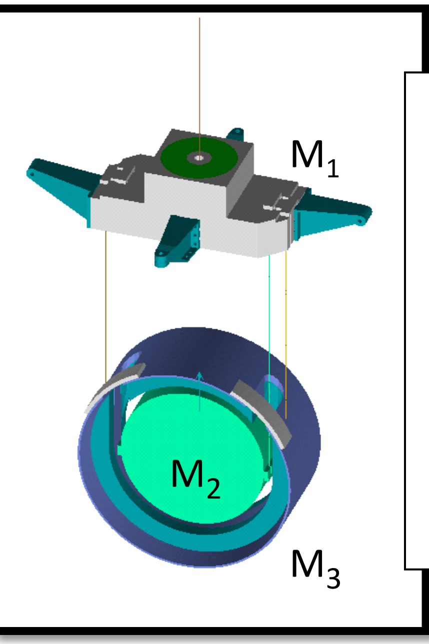


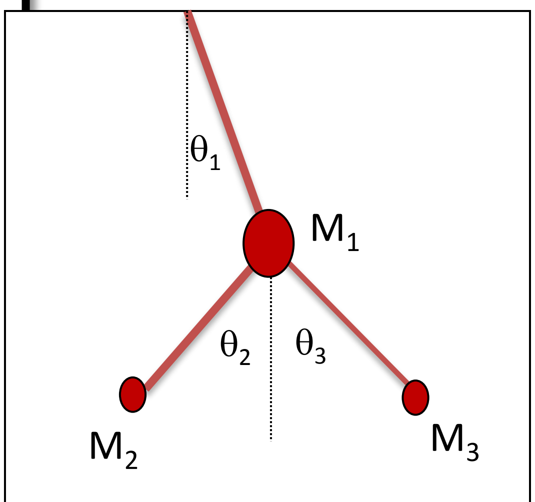
[*] VIR-015C-09, F. Piergiovanni, M. Punturo and P. Puppo, The thermal noise of the Virgo+ and Virgo Advanced Last Stage Suspension (The PPP effect).
[**] P. Puppo, Amaldi 8, New York, June 2009 and MG12, Paris , July 2009, proceedings

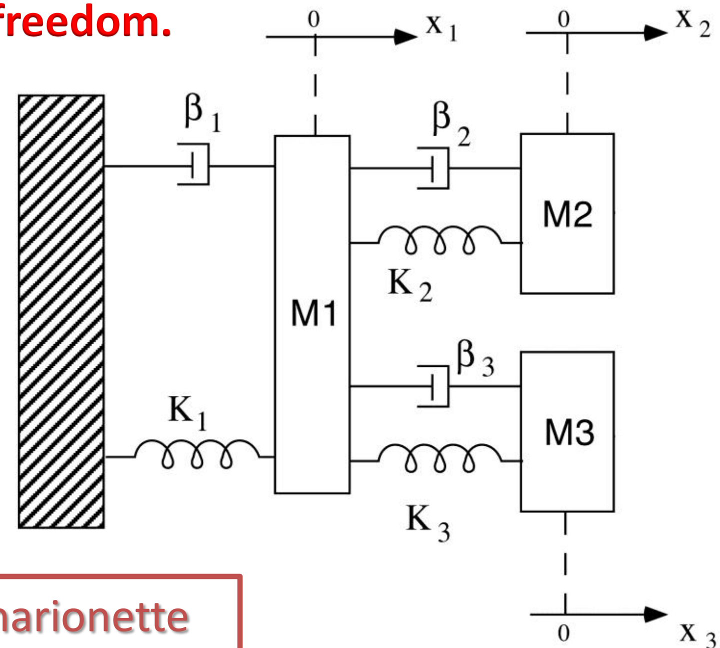
Suspension TN Modeling

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

modal expansion model for cryo LSS [**]

[*] 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.

[**] P. Puppo, Amaldi 8, New York, June 2009 and MG12, Paris , July 2009, proceedings

Parameters for the mirror

- Several different mechanisms contribute to the thermal noise of the mirror:
  - Brownian (BR)(substrate, coating) (T,ϕ)
  - Thermoelastic (TE) (substrate) (Thermal props)
  - Thermorefractive (TR) dn/dT (substrate)

  - Thermo-optic new correlated model (TR-TE) (coating)

- The coating brownian noise dominates over the other thermal sources

Issues *

Mirror Size:	**Thickness 30 cm, diam: 45 cm**
Beam Size:	**w=9.00 cm**
Substrate:	**Silicon ($Ø_s = 10^{-9}$, good temp. props)**
Mass:	**110 kg**
Coating:	**Ti:Ta2O5 / SiO2**
Working Temperature:	**T=10K (coating losses reduced)**

* see Erice's meeting talk of J. Franc and R. Nawrodt talk or ET-021-09.

Thermal Issues - (High power stored, curve B)

With liquid Helium

$$P_{HeII}(T_{mario}) = P_{abs} = 3\ W \Rightarrow T_{mario} = 2K$$

$$P_{abs} = 4\frac{\Sigma_w}{L} K_{mean}(T_{mario} - T_{mirror})$$

$$K_{mean} = \frac{1}{\Delta T}\int_{T_{mario}}^{T_{mirror}} K_{si}(T)\ dT \cong 938\ \frac{W}{m \cdot K}$$

$$\Rightarrow T_{mirror} = 10\ K$$

$$d_w = 8\ \ mm$$

With PT cooler

$$P_{cooler}(T_{mario}) = P_{abs} = 3\ W \Rightarrow T_{mario} = 5K$$

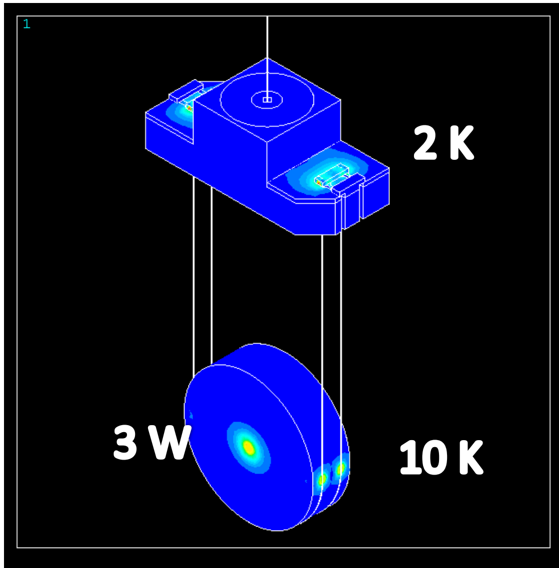
$$P_{abs} = 4\frac{\Sigma_w}{L} K_{mean}(T_{mario} - T_{mirror})$$

$$K_{mean} = \frac{1}{\Delta T}\int_{T_{mario}}^{T_{mirror}} K_{si}(T)\ dT \cong 1383\ \frac{W}{m \cdot K}$$

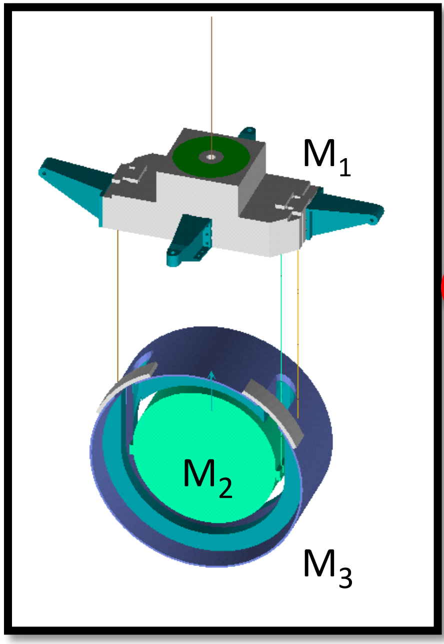
$$\Rightarrow T_{mirror} = 10\ K$$

$$d_w = 8.3\ \ mm$$

- To reach a temperature of 10K with a power of 3W on the mirror we need a silicon suspension wire with a diameter of 8 mm;
- The temperature of the marionette stage can be 5 K or 2K depending on which kind of refrigeration system is used



Parameters for the LSS – High Power Curve B



PAYLOAD

MARIONETTE: (TI6AL4V WIRE)

d = 3 mm, M_1: 400 kg, L=2 m T=2 K

MIRROR (SILICON WIRE)

dimensions: diam 45cm, thickness 30cm **(limit of present technology)**

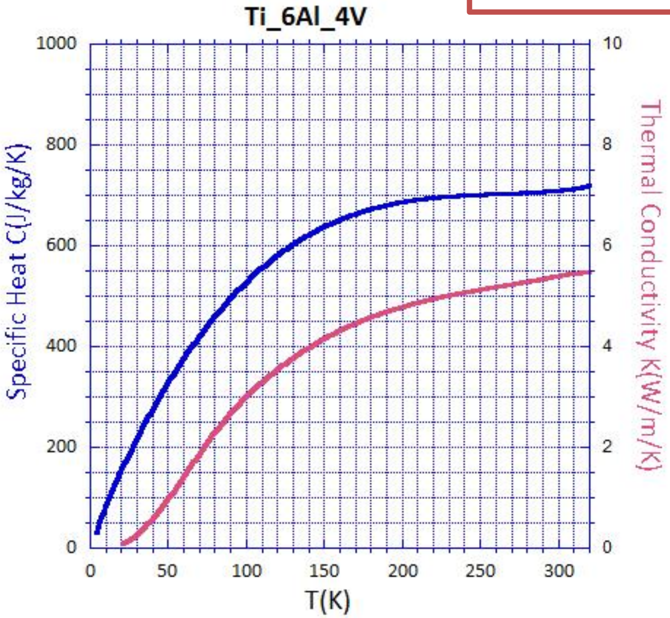
d = 8 mm, M_2: 110 kg, L=2 m T=10 K

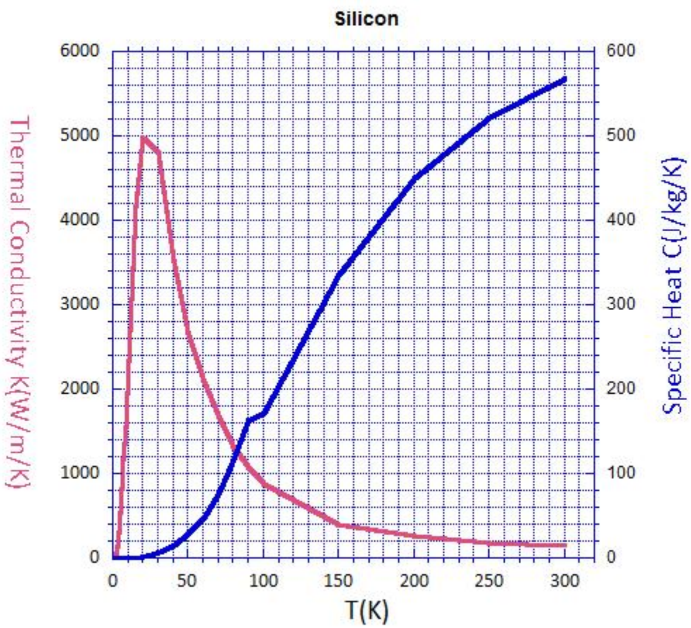
RECOIL MASS (SILICON WIRE)

d = 5 mm, M_3: 110 kg L=2 m T=10 K

Modes:	pendulum	0.28 Hz, 0.36 Hz, 0.50Hz
	vertical	0.4 Hz (blades), 23 Hz, 62 Hz
	violins	15.8 Hz, 31.6 Hz, 63.2 Hz, 126.4 Hz, …

Properties





Wires and substrate

Ti6Al4V

Mechanical @ 2 K

Density $\rho_{Ti6Al4V}$ $4.4532\ 10^{3}\ kg/m^{3}$

Young Modulus $Y_{Ti6Al4V} = 127\ GPa$

Poisson Ratio $\sigma_{Ti6Al4V} = 0.403$

Loss Angle $\Phi_{Ti6Al4V} = 10^{-4}$

Young Modulus gradient:

$$\beta_{Ti6Al4V} = (1/\ Y_{Ti6Al4V})(dY_{Ti6Al4V}/dT) = -4.6\ 10^{-3}\ (1/K)$$

Thermal @ 2 K

Specific Heat $C_{Ti6Al4V} = 0.07\ J/kg/K$

$$\left(C(T) = 8.8\times10^{-4} T^{3} \text{ up to 30K}\right)$$

Heat Conductivity $K_{Ti6Al4V} = 0.14\ W/m/K$

Thermal Expansion $\alpha_{Ti6Al4V} = -1.7\ 10^{-3}\ m/m/K$

Si

Mechanical @ 10 K

Density $\rho_{si} = 2.3315\ 10^{3}\ kg/m^{3}$

Young Modulus(100) $Y_{si} = 132\ GPa\ (100)$

$189\ GPa\ (111)$

Poisson Ratio $\sigma_{si} = 0.22$

Loss Angle $\Phi_{si} = 10^{-9}$

Young Modulus gradient (100):

$$\beta_{si} = (1/\ Y_{si})(dY_{si}/dT) = -7.7\ 10^{-5}\ (1/K)$$

Thermal @ 10 K

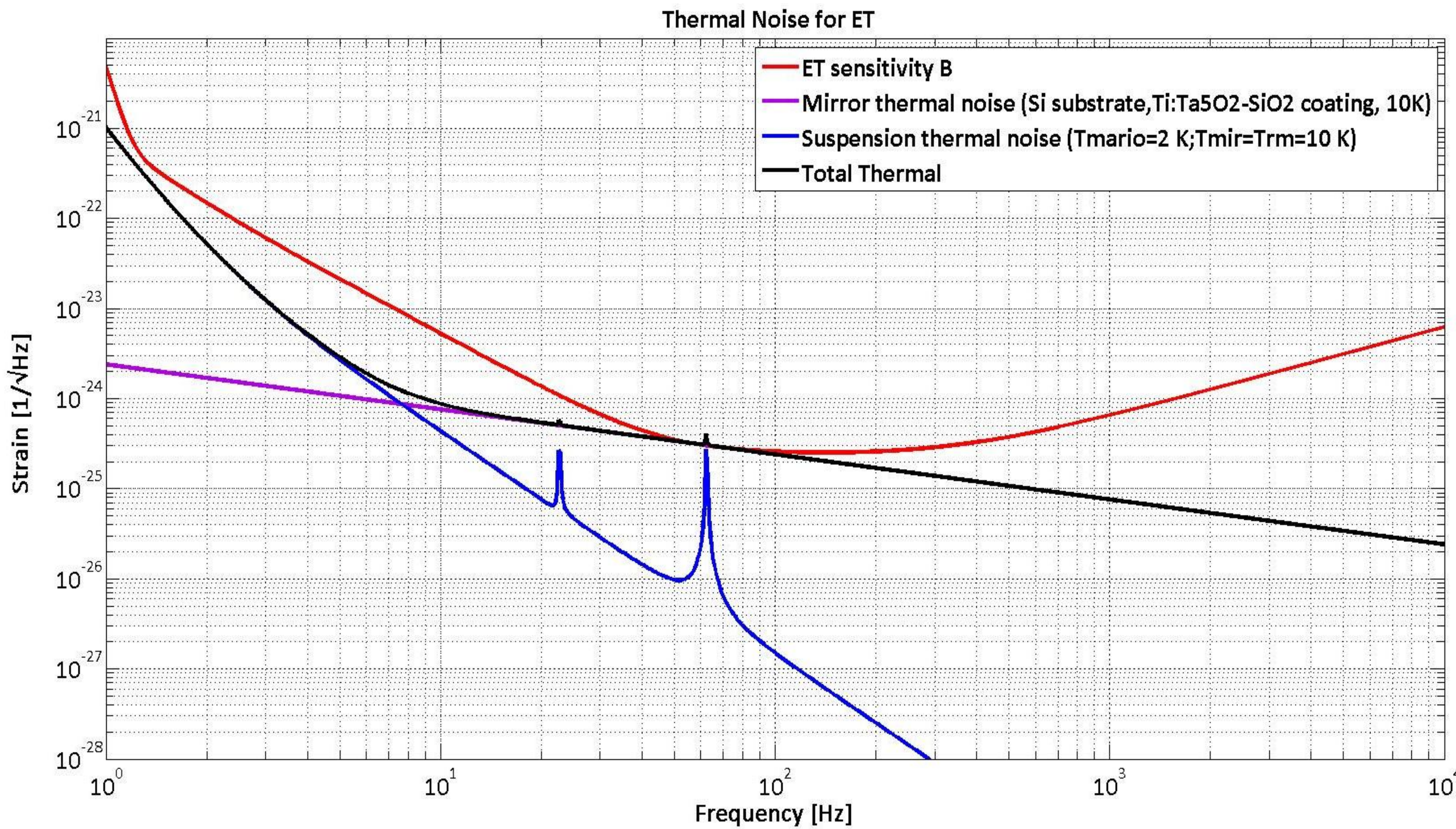
Specific Heat $C_{si} = 0.276\ J/kg/K$

Thermo-Optic coef dn/dT @ 30K: $5.8\ 10^{-6}\ K^{-1}$

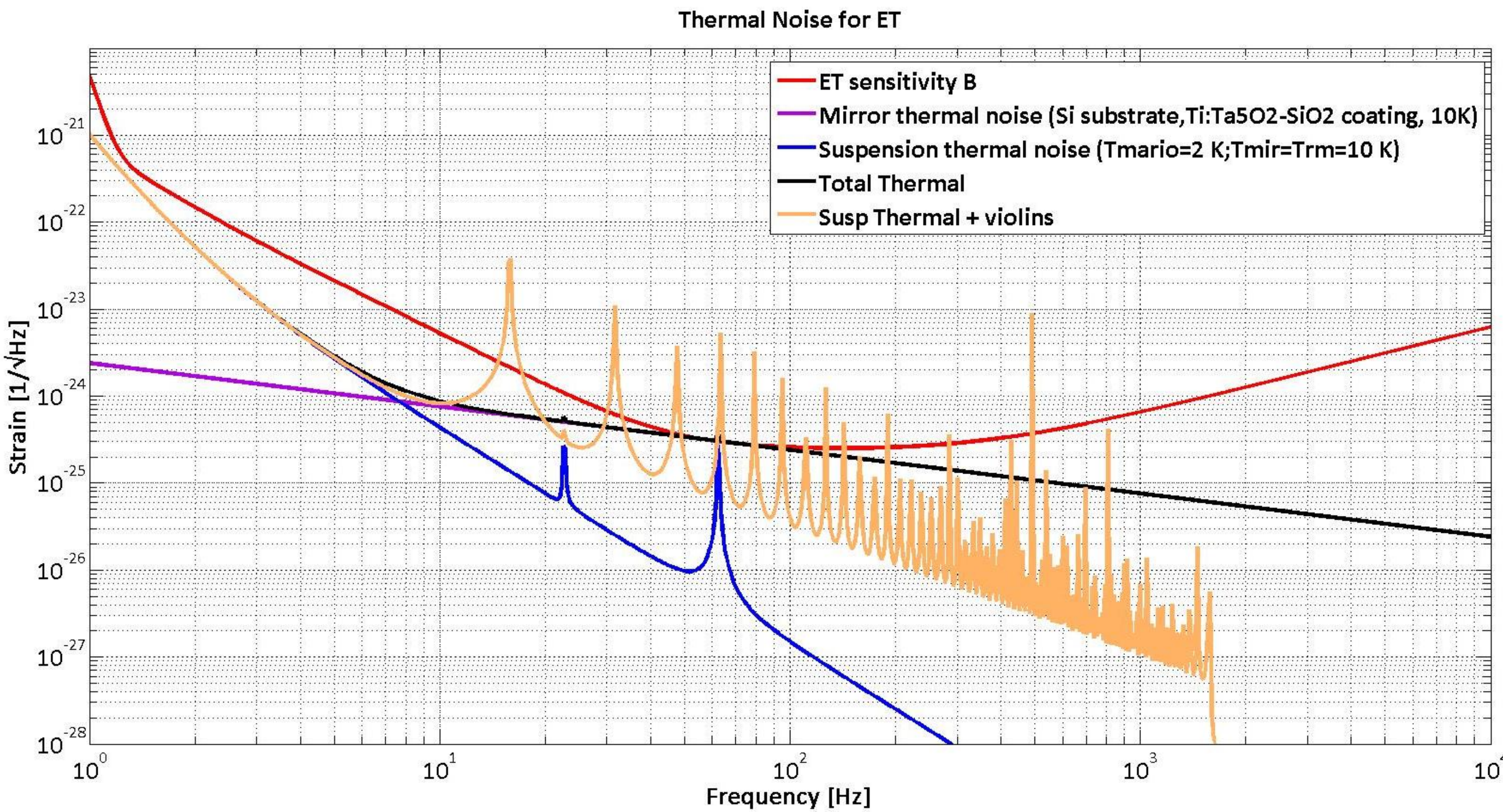
Heat Conductivity $K_{si} = 2330\ W/m/K$

Thermal Expansion $\alpha_{si} = 4.85\ 10^{-10}\ m/m/K$

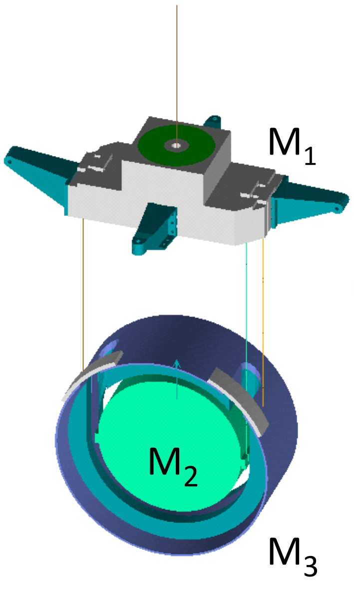
Thermal Noise Curve compared with the Sensitivity Curve B



Thermal Noise Curve with violins



Suspension thermal noise in the xylophone case (LF-Curve C).



PAYLOAD

MARIONETTE: (TI6AL4V WIRE)

d = 3 mm, M_1: 400 kg, L=2 m T=2 K

MIRROR (SILICON WIRE)

dimensions: diam 45cm, thickness 30cm **(limit of present technology)**

d = 3 mm, M_2: 110 kg, L=2 m T=10 K **(only 18kW in cavity, 600 μm enough for heat extraction)**

RECOIL MASS (SILICON WIRE)

d = 3 mm, M_3: 110 kg L=2 m T=10 K

Modes:	pendulum	0.28 Hz, 0.36 Hz, 0.50Hz
	vertical	0.4 Hz (blades), 20 Hz, 26 Hz
	violins	33 Hz, 67 Hz, 100 Hz, 200 Hz, …

Thermal Noise Curve compared with the Sensitivity Curve C