Cryogenic session: GWADW 19

Glasgow update: Thermal conductivity measurements of silicon and HCB and other relevant properties.

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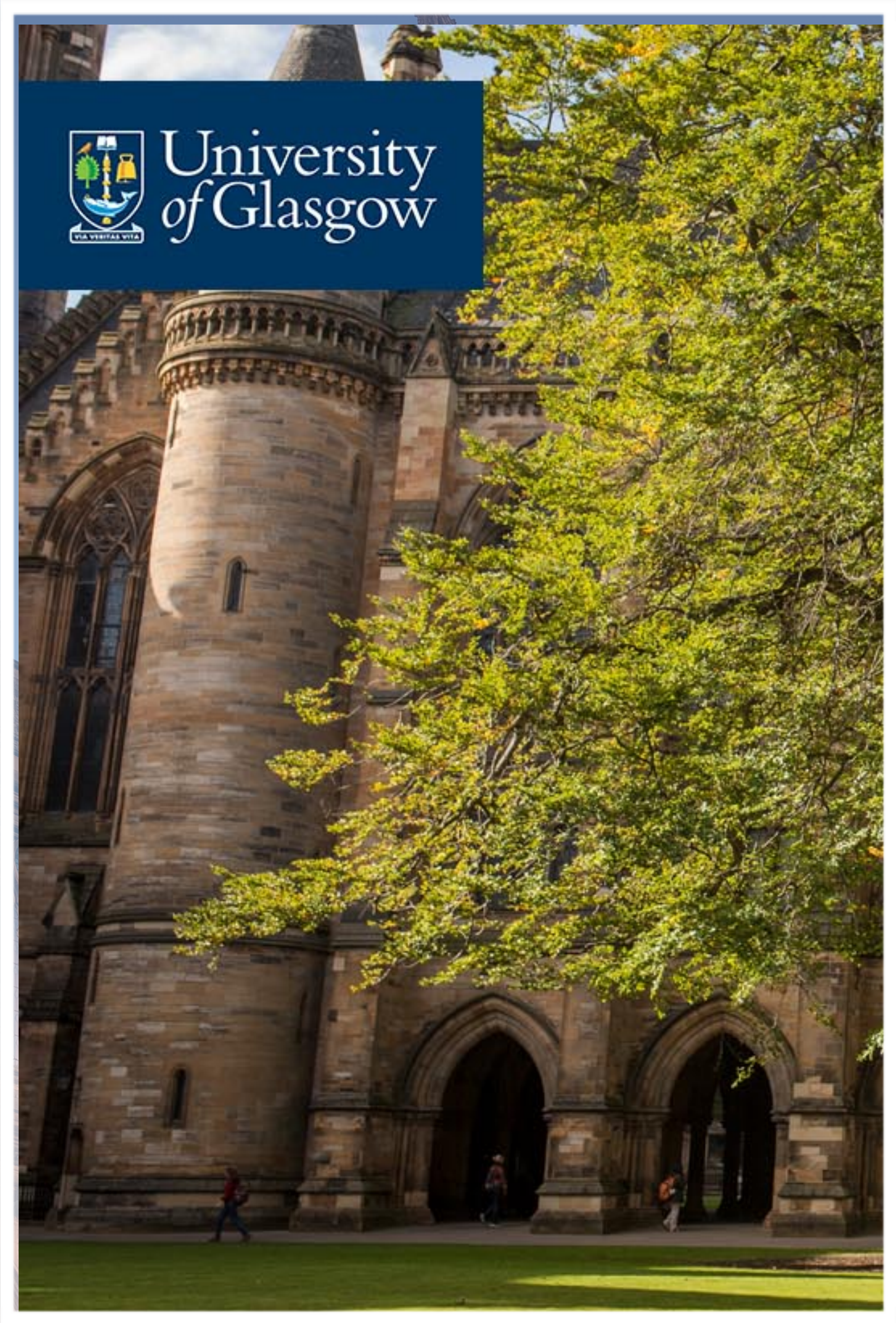

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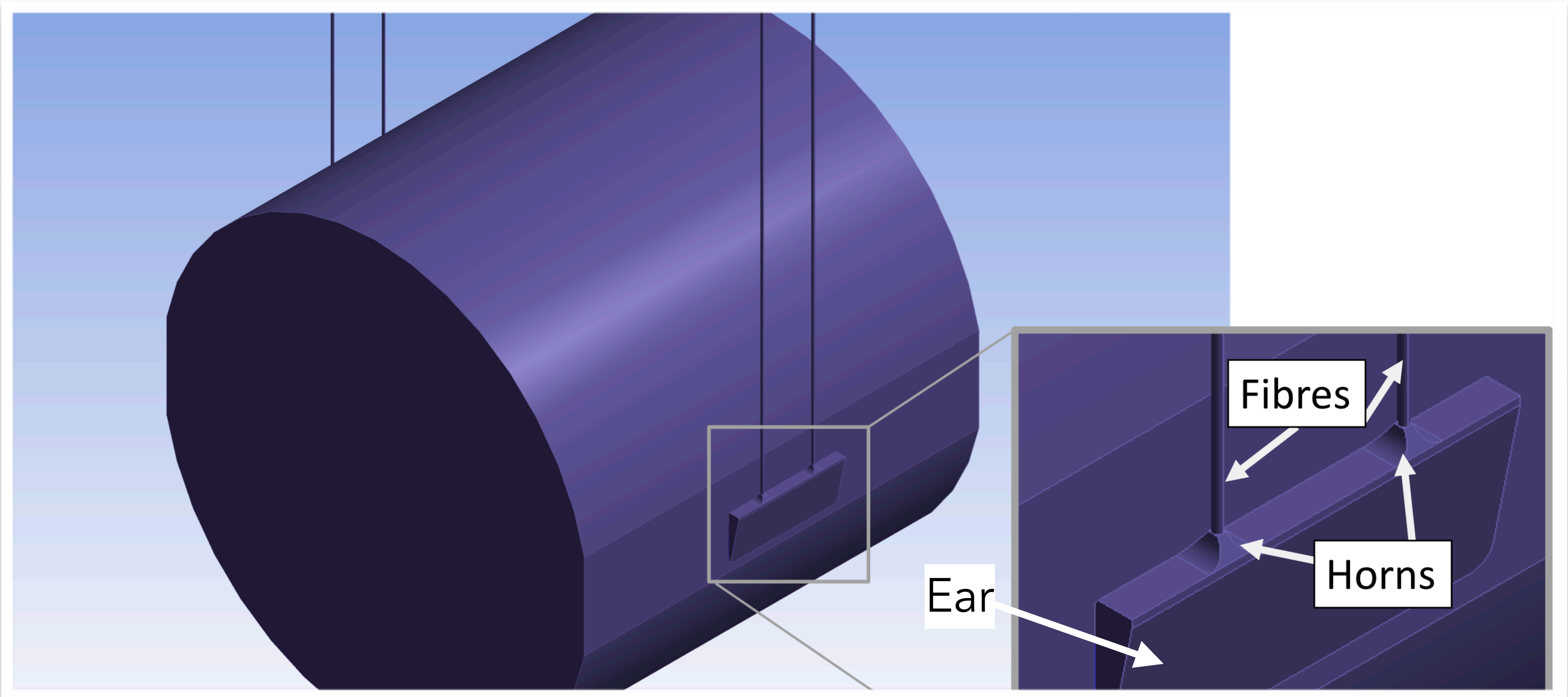


3G-like suspension

The ears (to provide welding horns) are hydroxide catalysis bonded to the sides of the silica masses.

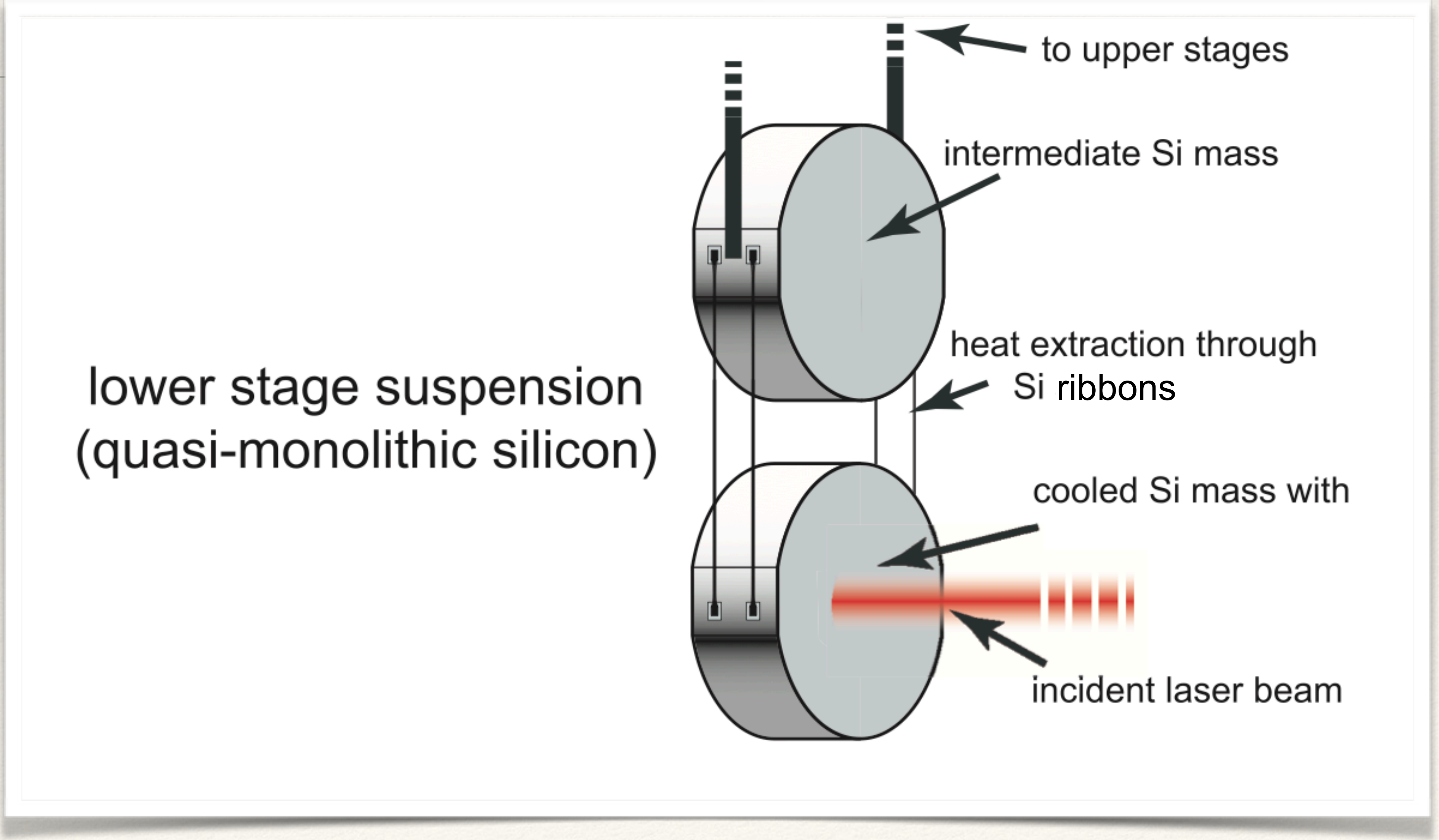
ET-LF
Silicon
20 K

Silicon: Mechanical dissipation decreases with temperature, and linear coefficient of expansion goes to zero (and thus the thermoelastic thermal noise also goes to zero [1]) at ~120K and ~20K

[1] Rowan et al, Test mass materials for a new generation of gravitational wave detectors.2003

Cryogenics

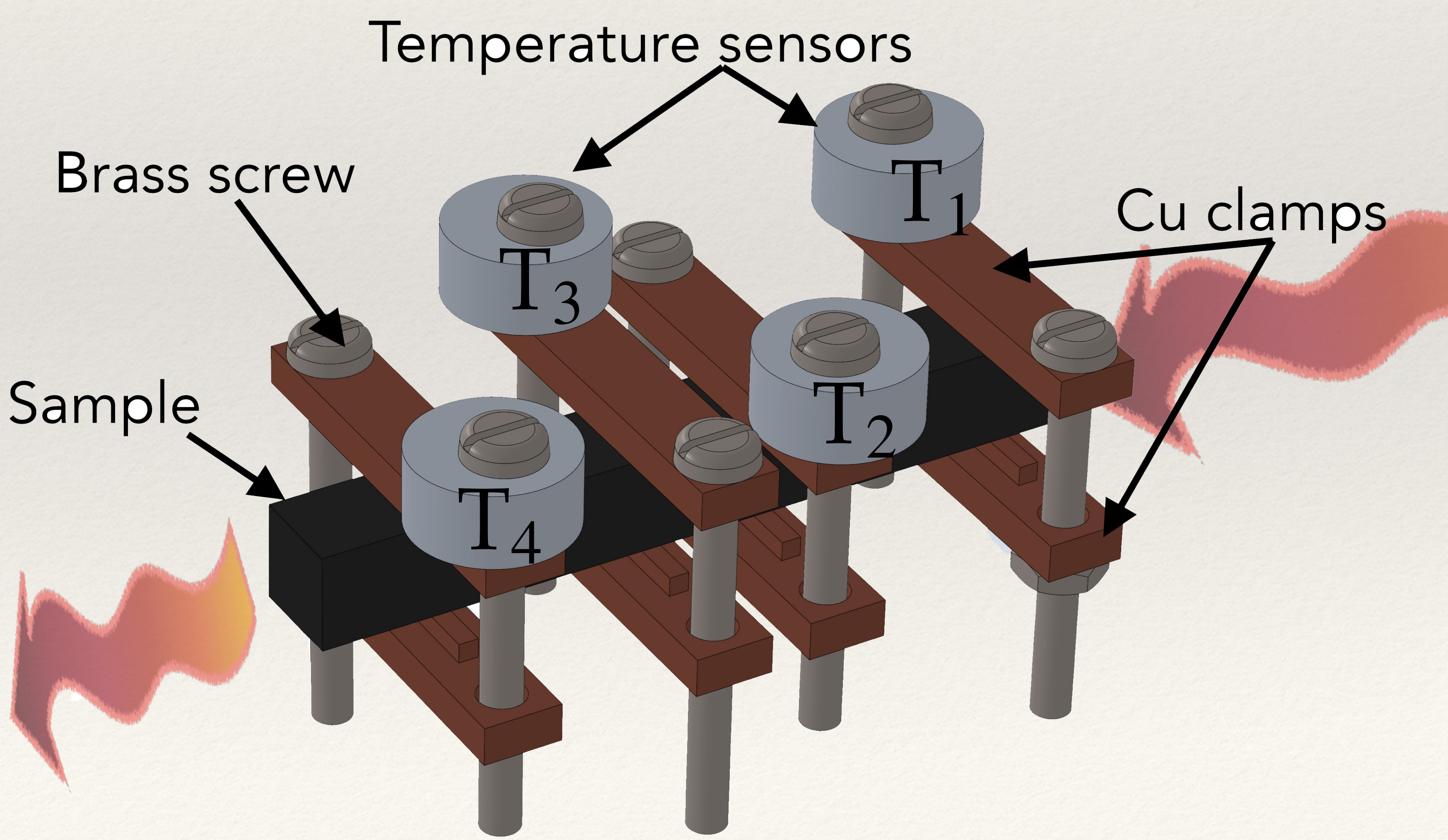
At cryogenic temperatures (below ~100K) the heat is extracted from the mirror and through the suspension fibres. This includes heat extracted through the connection points and therefore through the silicate bonds.



Thermal conductivity

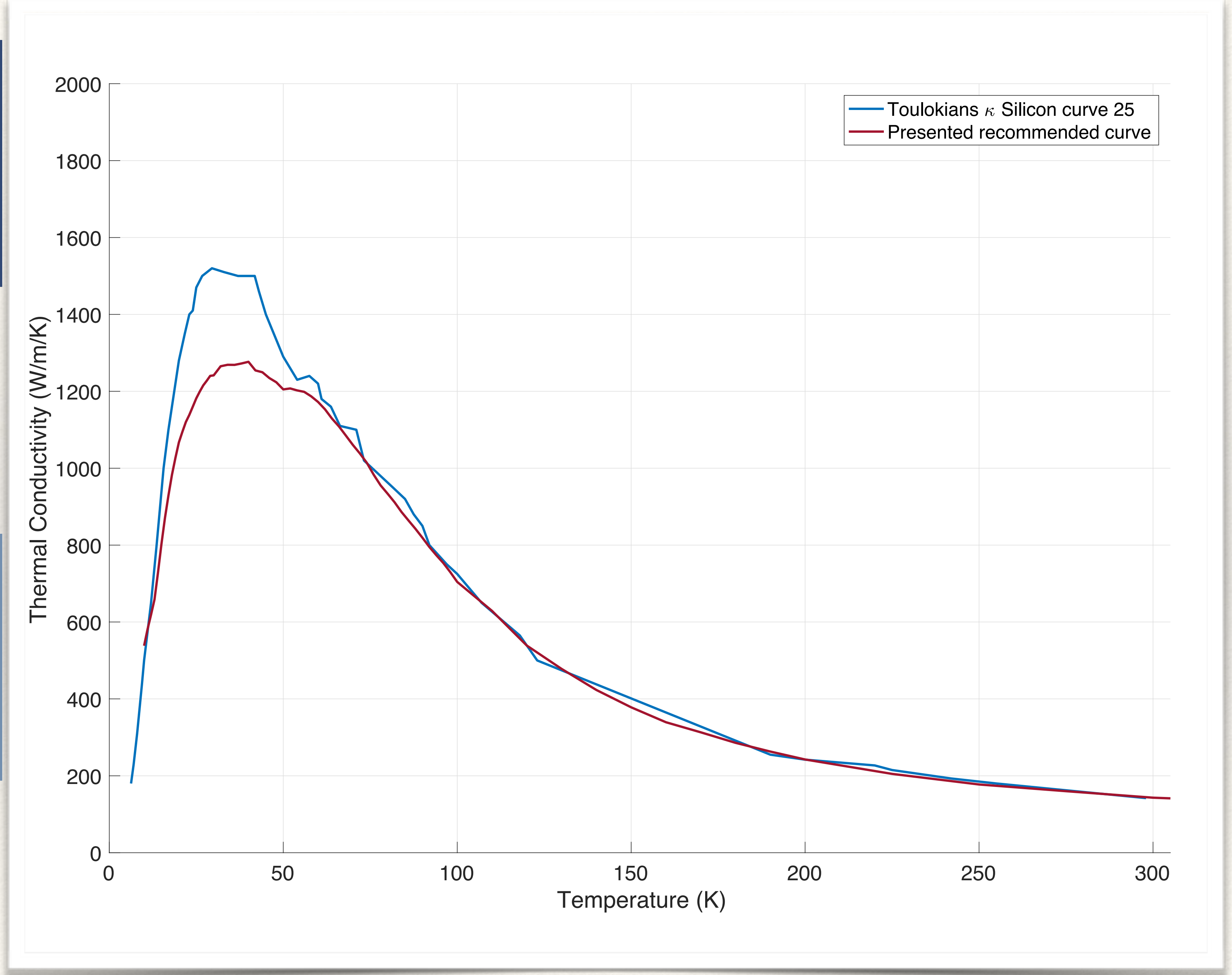
- P Power through the sample
- Δx Separation between sensors measuring the temperature
- A Cross sectional area of the sample
- ΔT Temperature difference between the sensors

$$\kappa = \frac{P \Delta x}{A \Delta T}$$



Thermal conductivity of silicon

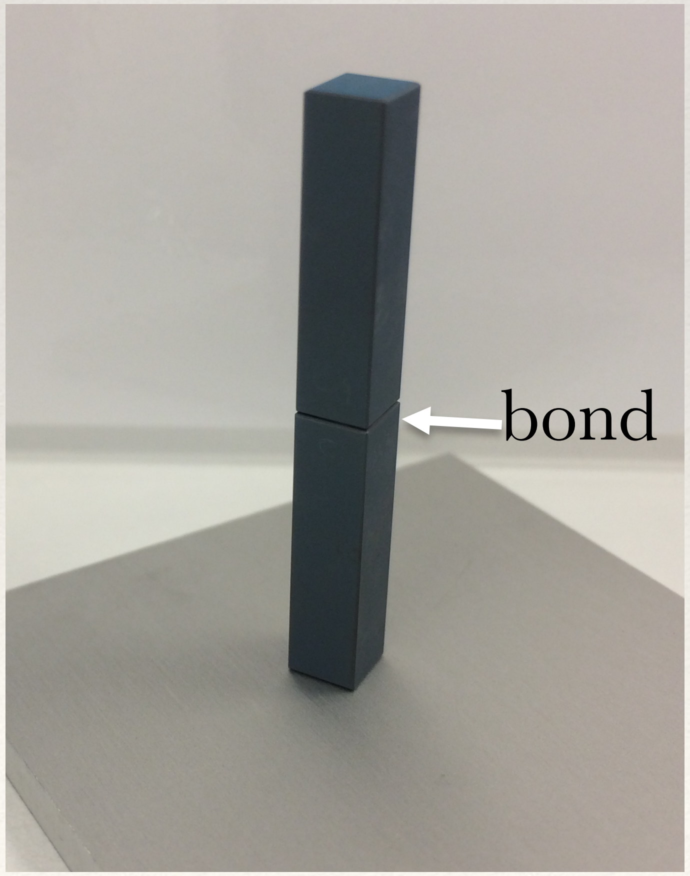
Sample specs	Measured curve	Curve 25 (Touloukian)
O_2 cm^3	5.15×10^{17}	7×10^{17}
Boron cm^3	6×10^{15} $< 0.01\%$	4.8×10^{15}
R	$2.32\ \Omega$ cm	$3\ \Omega$ cm

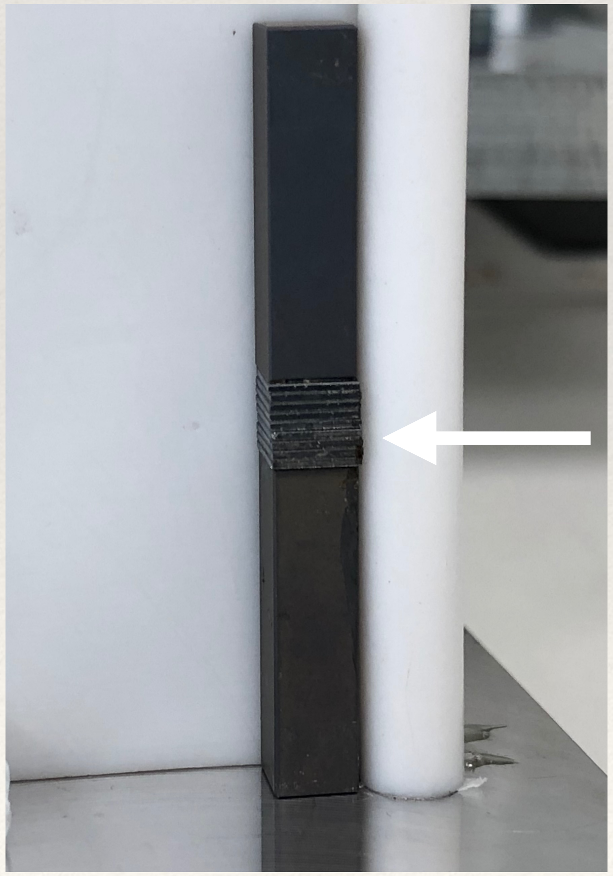


Silicon bonded samples

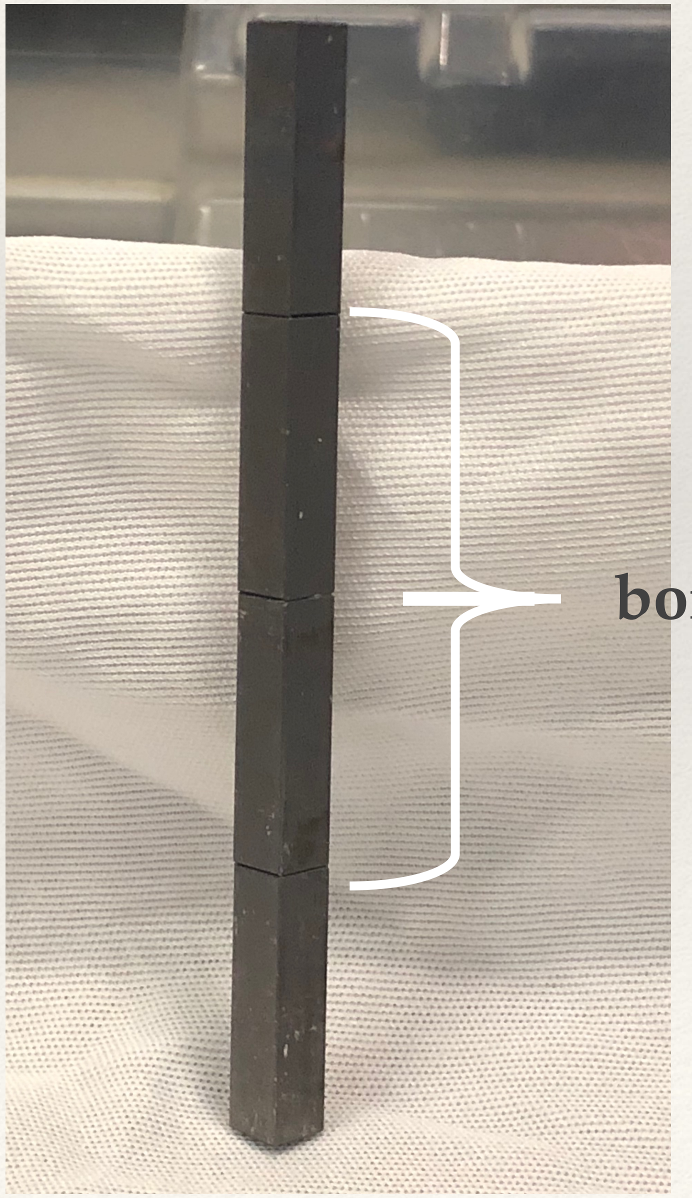
5 x 5 x 20 mm silicon (100) bonded samples

Single bond | *10 bonds* | *3 bonds*





bond



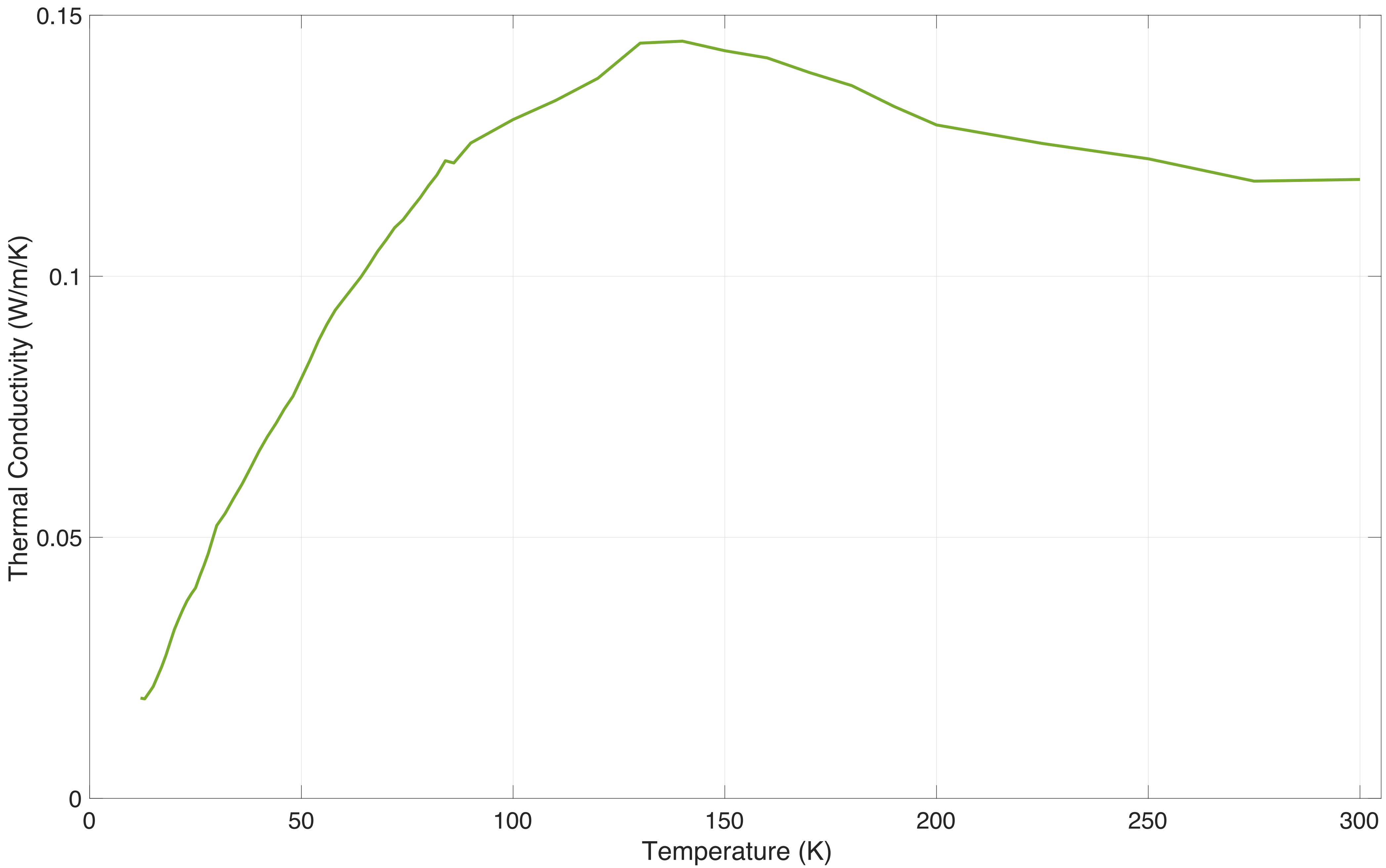
bonds

Extracting the thermal conductivity of the bond

$$\frac{L_{\text{total}}}{\kappa_{\text{total}} A_{\text{total}}} = \frac{L_{\text{bond}}}{\kappa_{\text{bond}} A_{\text{bond}}} + \frac{L_{\text{silicon}}}{\kappa_{\text{silicon}} A_{\text{silicon}}}$$

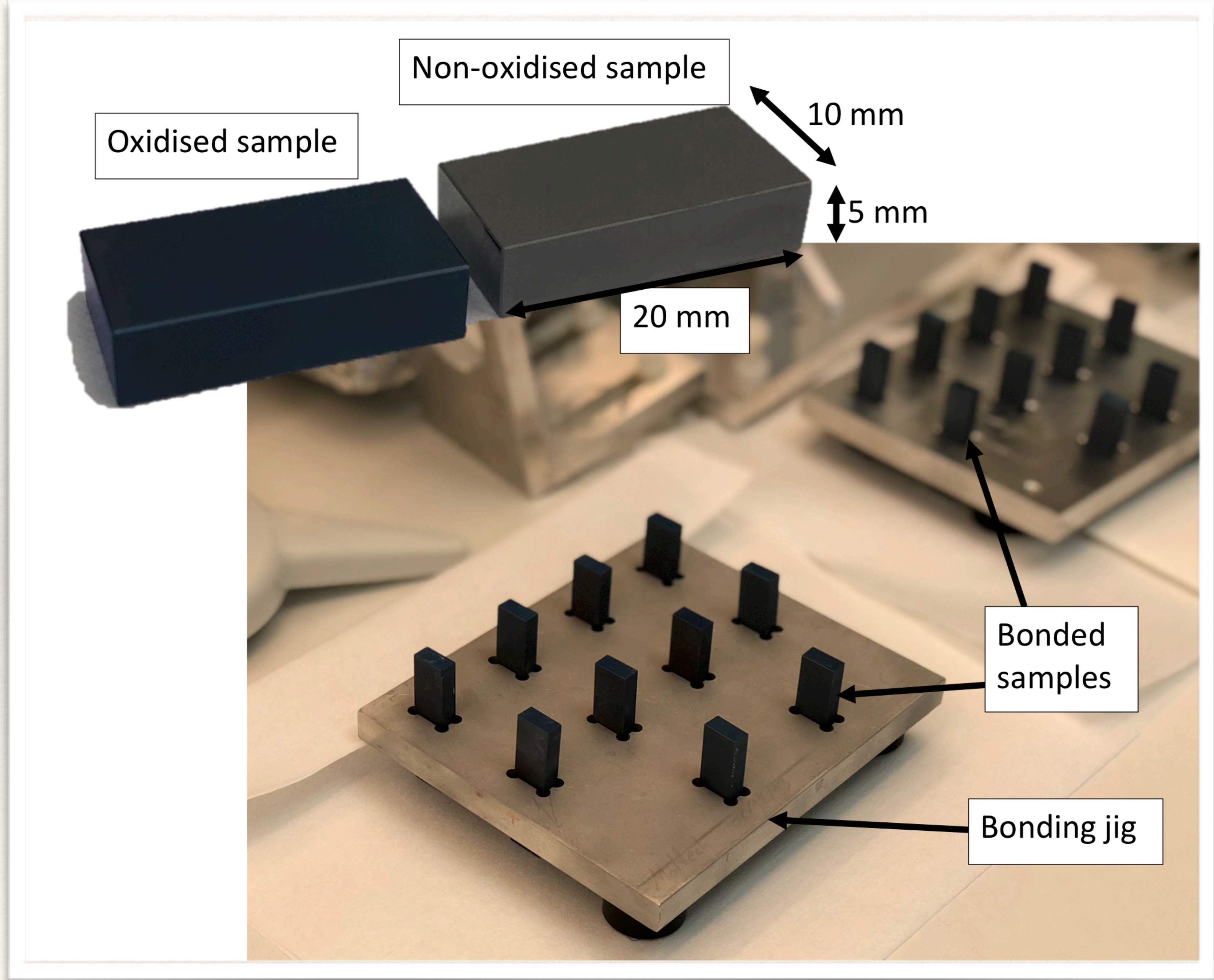
$$\kappa_{\text{bond}} = \frac{L_{\text{bond}}}{\frac{L_{\text{total}}}{\kappa_{\text{total}}} - \frac{L_{\text{silicon}}}{\kappa_{\text{silicon}}}}$$

Thermal conductivity of HCB



Strength testing

- 40 samples where strength tested using a 4 point bend tester. 10 sets of the samples were tested at various curing times: 1 week, 2 weeks, 4 weeks and 26 weeks.



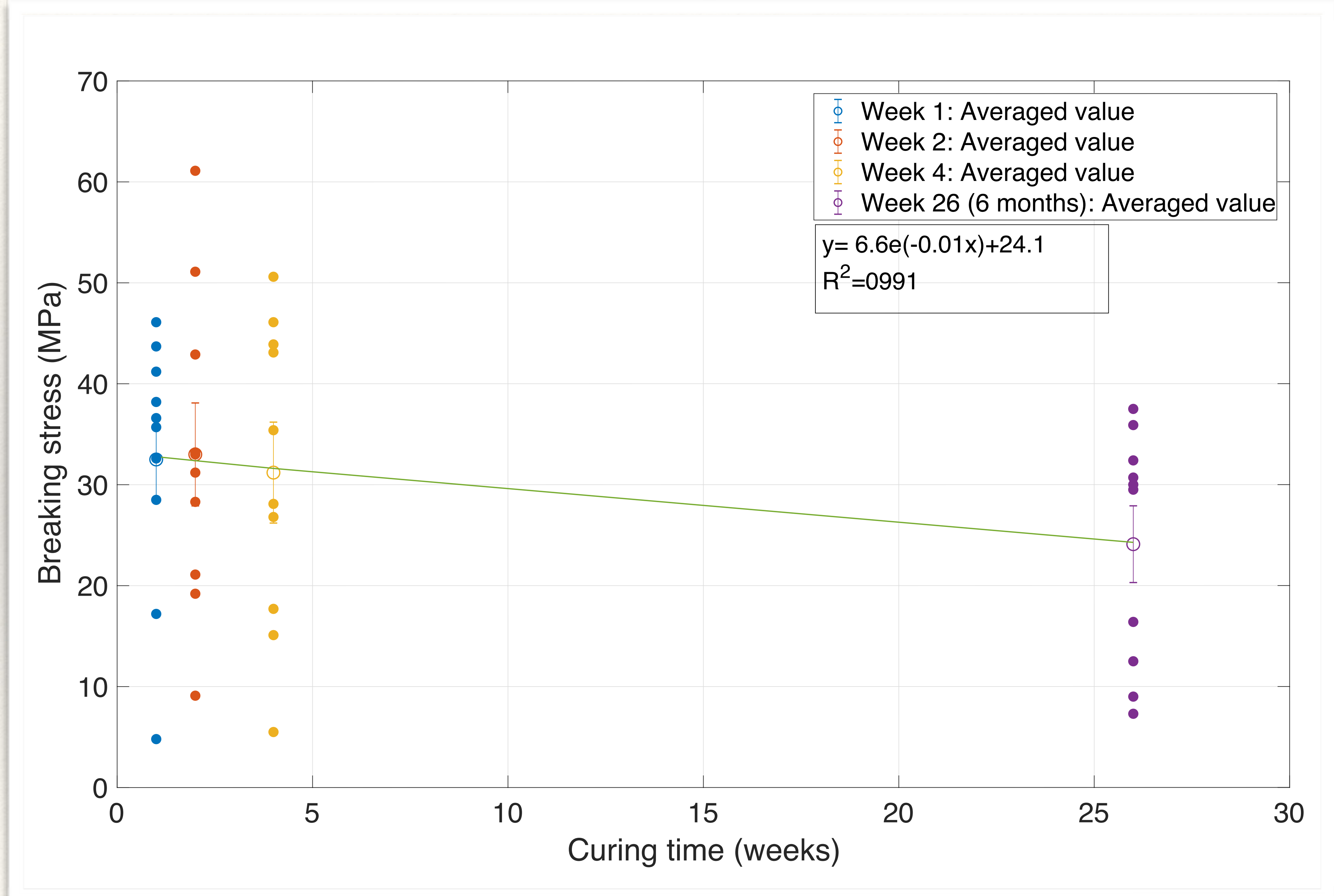
Strength testing over time

Breaking type

- Bond failure
- Bond break
- Diagonal break
- Oxide break

Weakest: 4.8 MPa.

Strongest: 61.1MPa.



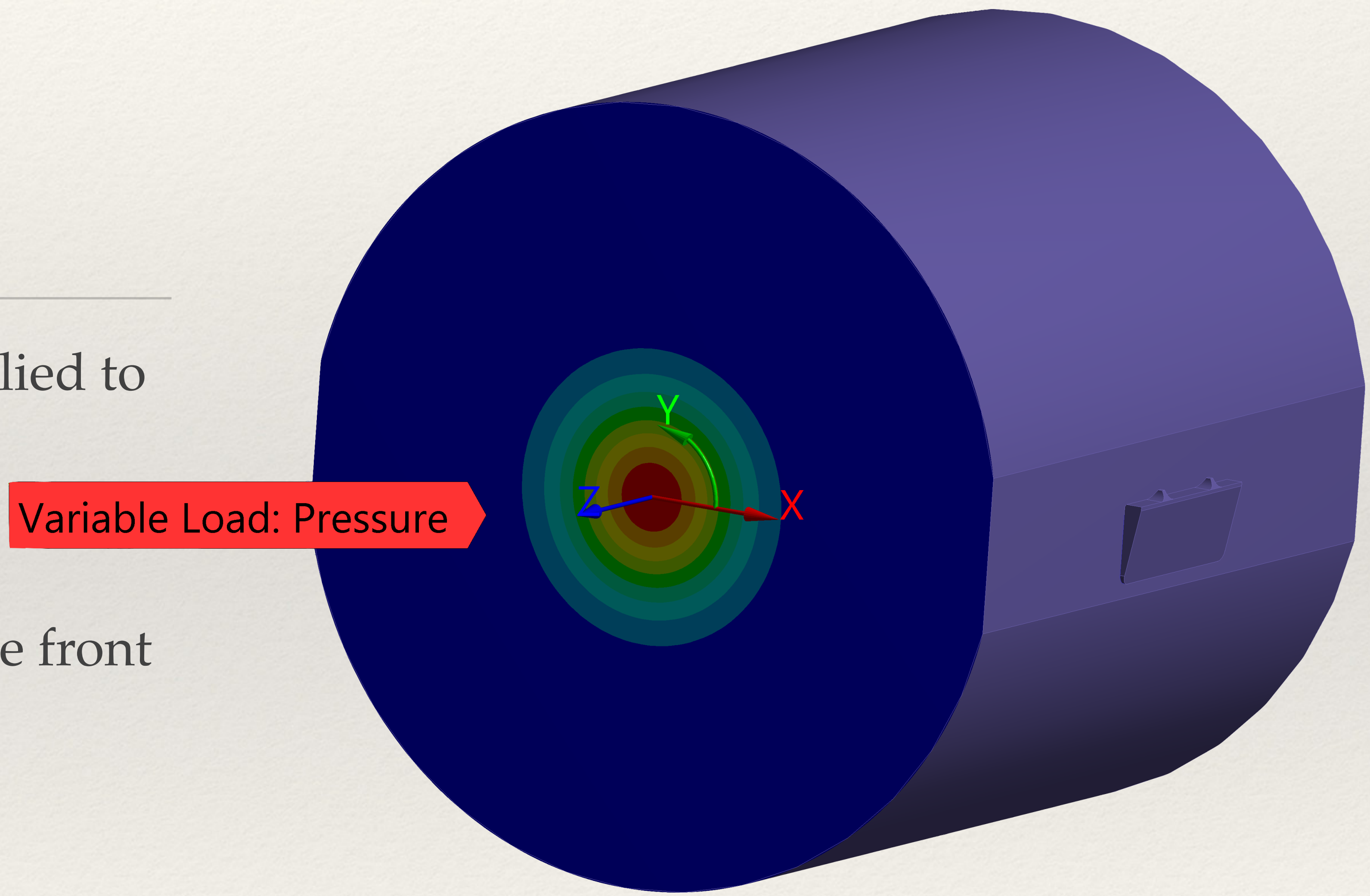
[2] M. Phelps, M. Masso Reid et al. *"Strength of hydroxide catalysis bonds between sapphire, silicon, and fused silica as a function of time"*, Phys. Rev. D 98 (2018), p. 122003.

FEA analysis

Pressure profile simulates the probing laser beam proposed for ET-LF[3]

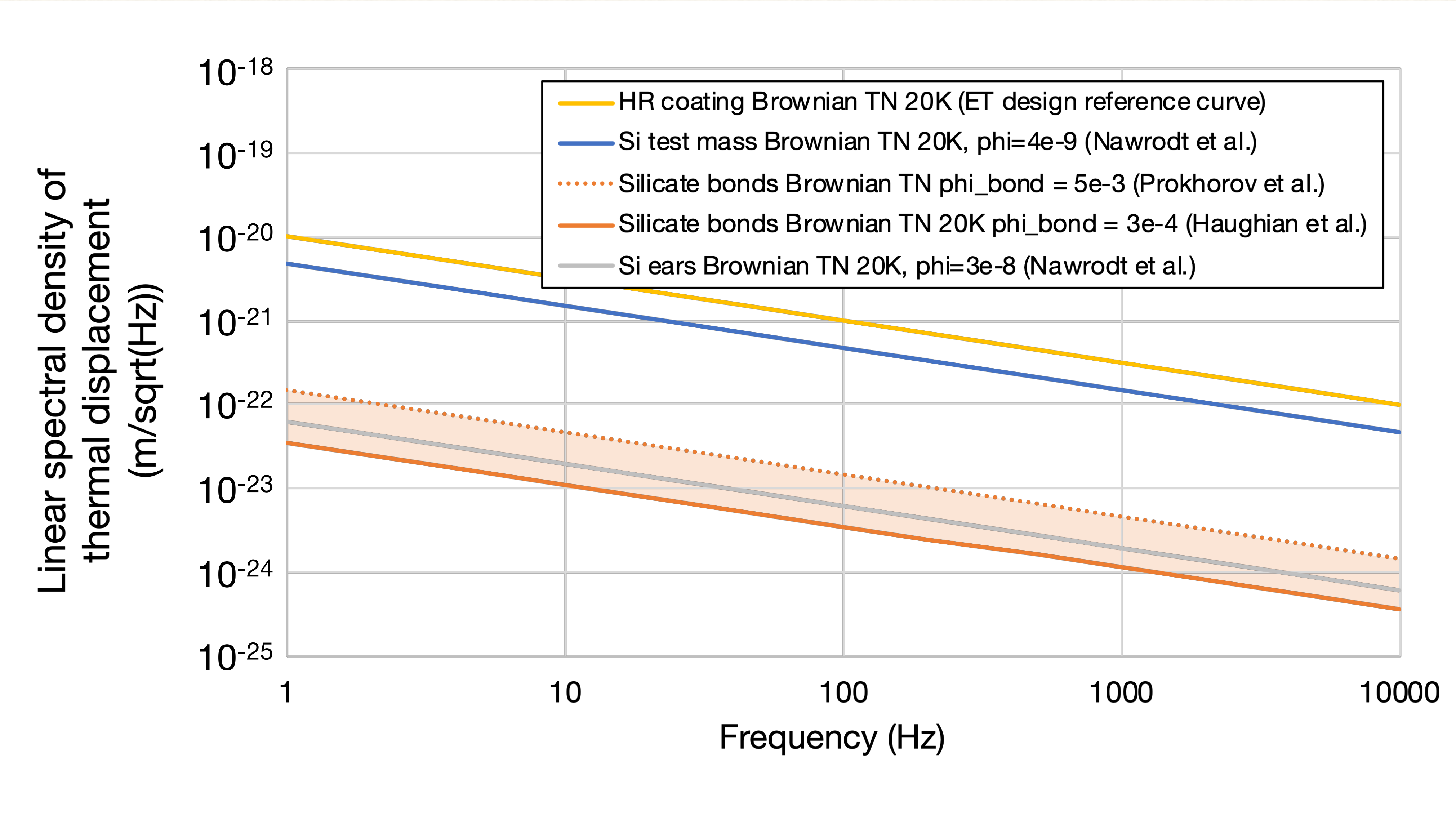
$$P = F_0 \frac{2}{\pi r^2} \exp\left(-2 \frac{x^2}{r^2} \right)$$

- P Gaussian pressure wave applied to the face of test mass.
- r Radius of beam (9 cm[3]).
- x Distance from optical axis (orthogonal and central to the front face of test mass).
- F_0 Constant force.



[3] Einstein gravitational wave telescope conceptual design study

Thermal noise for an 3G-like suspension



Prokhorov measured TN of bonds between silicon substrates at ~120 K.

Haughian measured TN of bonds between sapphire substrates at ~20 K

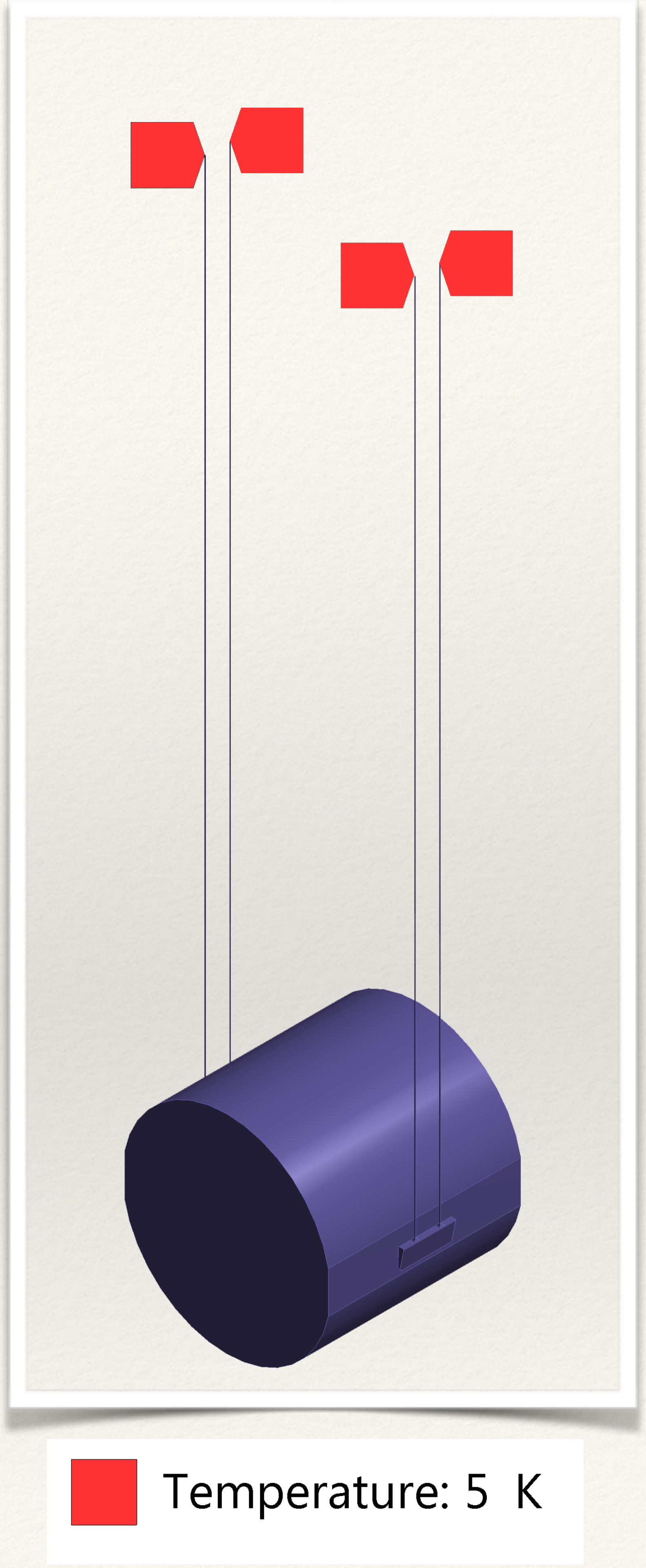
3G-like suspension at 20 K

FEA simulation for cool down of suspension

Taking the ET-LF concept design, the heatsink temperature will be at 5 K and an operating temperature of ~20 K. A fixed temperature of 5 K is applied at the top end of each fiber whilst the rest of the suspension is at 300 K.

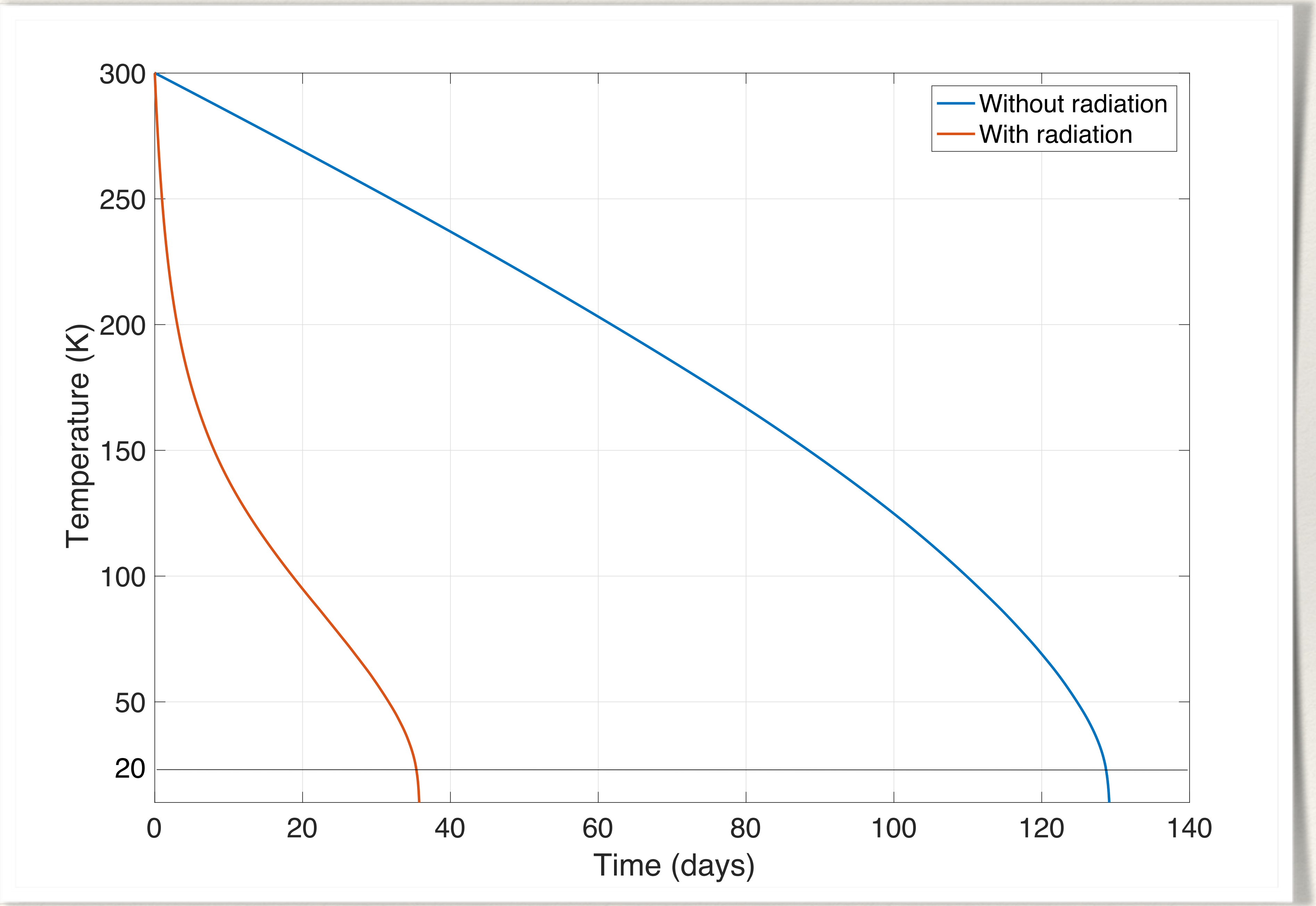
Two models were taken into account:

- Test mass cooled though conduction only (worst case scenario).
- Test mass cooled through conduction and radiation (surrounding at 5 K).



Cool-down rate for ET-LF silicon mirror suspension

- 3G-like final stage of suspension ~35.5 days to reach 20 K.



Conclusions

- Experimental measurements for the thermal conductivity of bonds between silicon substrates was conducted, showing a a thermal conductivity at 20 K of 0.05 W/m/K.
- For an 3G-like configuration with a 15 K temperature difference between the mirror (20 K) and marionette (5 K) [3], the additional temperature difference associated with the silicate bond is 14.5**μ**K (assuming 1ppm absorption) or 262.2**μ**K (assuming 20ppm absorption).
- Also for 120K test mass configuration, the thermal resistance of the bonds are negligible compare to that of the suspension elements (Voyager-like configuration gives ΔT of 0.5mK across bonds).
- Based on the strength measurements presented, for the weakest value obtained (4.8 MPa), this would leave a safety margin of a factor of ~ 5, further validating the use of hydroxide catalysis bonding for the construction of future, quasi-monolithic, silicon mirror suspensions.
- An FEA simulation of the cool-down rate of an ET-LF mirror using a combination of conduction and radiation was calculated. It was found that a total of 35.5 days are required to reach the desired temperature.
- All details of the experimental measurements and simulations are described in my PhD thesis[5] (available online).

[3] Einstein gravitational wave telescope conceptual design study

[4] Silicate Bonding Procedure (Hydroxide-Catalysis Bonding) LIGO-E050228-v4

[5] Masso Herrera, Mariela C. (2019) *Properties of bonded silicon for future generations of gravitational wave observatories.* PhD thesis, University of Glasgow.