Coating Absorption and its implications on Suspension Thermal Noise

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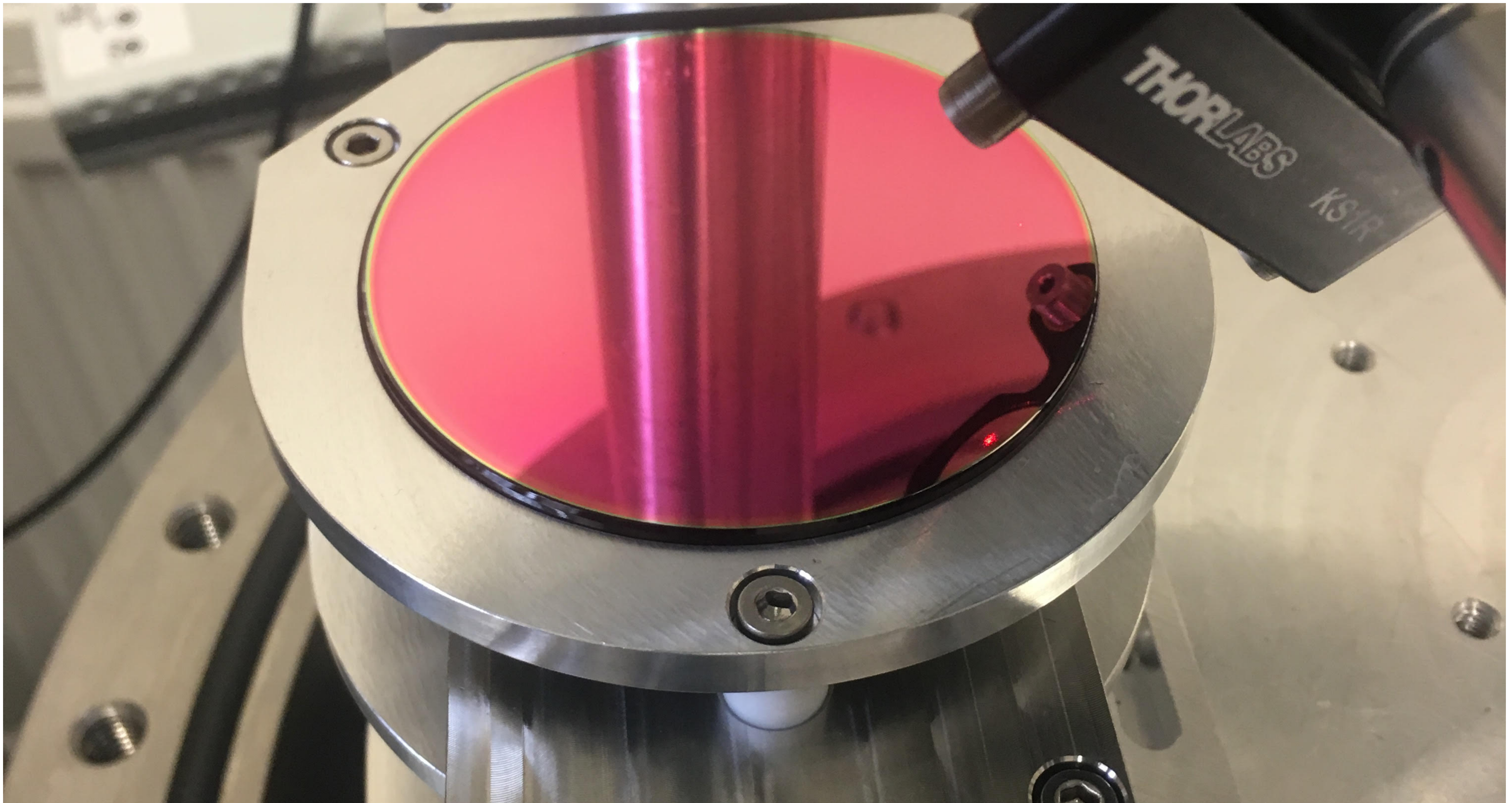

Overview

- Ongoing research in multi-material coating designs
  - Room temp mechanical Loss with heat treatment
  - 2um absorption with heat treatment

- Coating absorption and suspension thermal noise
  - Finite element modelling of End Test Mirrors
  - Implications of coating absorption on operation temperature
  - Coating absorptions effect of suspension thermal noise

estimated using losses previously measured for (different) IBS coatings

Thermal noise reduction with aSi-based coatings

	Loss $\phi \times 10^{-4}$					Brownian th. noise (100 Hz) $\times 10^{-21}$		
	SiO_2	aSi	Ta_2O_5	SiO_2/Ta_2O_5	Multimat.	SiO_2/Ta_2O_5	Multimat.	
290 K	0.4 [15]	4.0 [16]	2.3 [15]	1.26	1.62	4.9	4.3	**- 12%**
120 K	1.7 [6]	0.5 [16]	3.3 [17]	2.58	2.1	4.5	3.5	**- 22%**
20 K	7.8 [6]	0.4 [16]	8.6 [17]	8.24	6.98	3.4	2.6	**- 24%**
10 K	7 [6]	0.3 [16]	6 [17]	6.46	5.64	2.2	1.7	**- 23%**

- aSi has very low loss, but too high absorption
- despite progress in reducing aSi absorption still > ET design requirement
- multi-material design tries to exploit low loss while minimising impact on coating absorption

Recent Publications:

J Steinlechner et al, PRL 120 (2018) 263602.

R Birney et al, PRL 121 (2018) 191101

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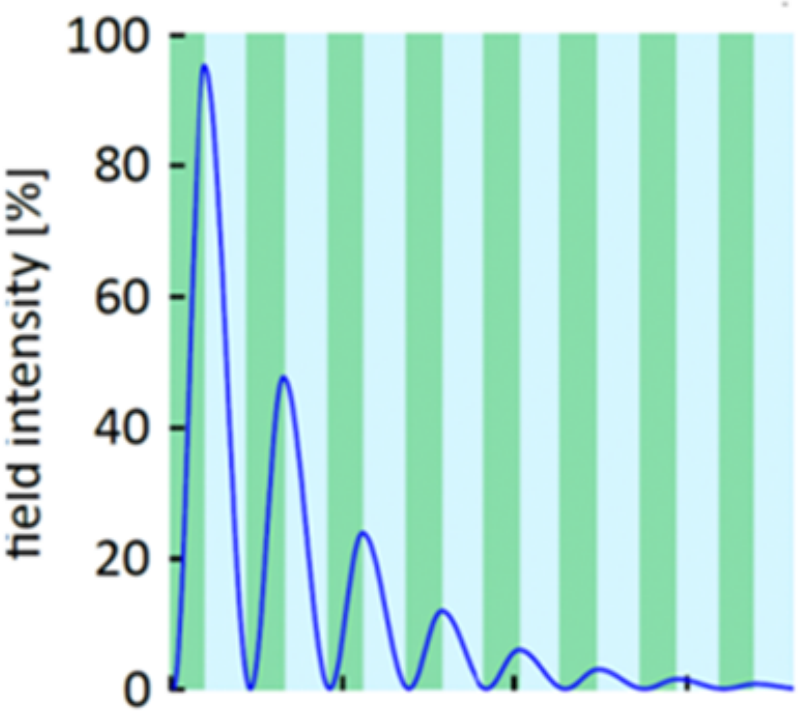
8 bilyers of SiO_2/Ta_2O_5

bilayers of aSi/SiO_2



+

→ R > 99.999 %
= 5.7ppm

R ≈ 99.6%
1.7ppm

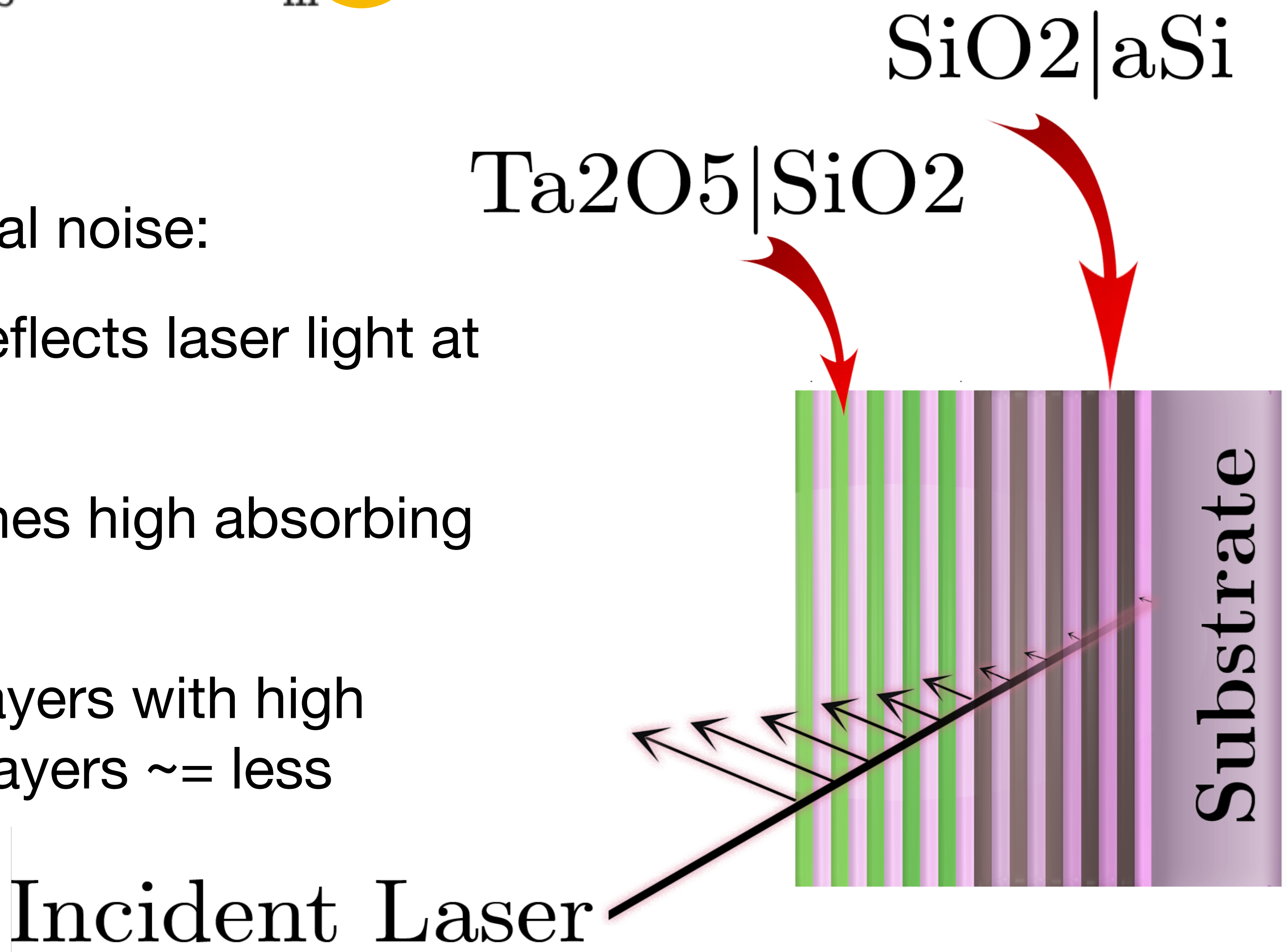
R ≈ 99.75
+ (1 – 0.996) x 1000ppm

Illustrative Case

Multimaterial Coating Design

$$s_x(f) = \frac{4k_B T}{\pi^2 f} \frac{(1+\sigma_S)(1-2\sigma_S)}{E_S} \frac{d}{w_m} \phi_C$$

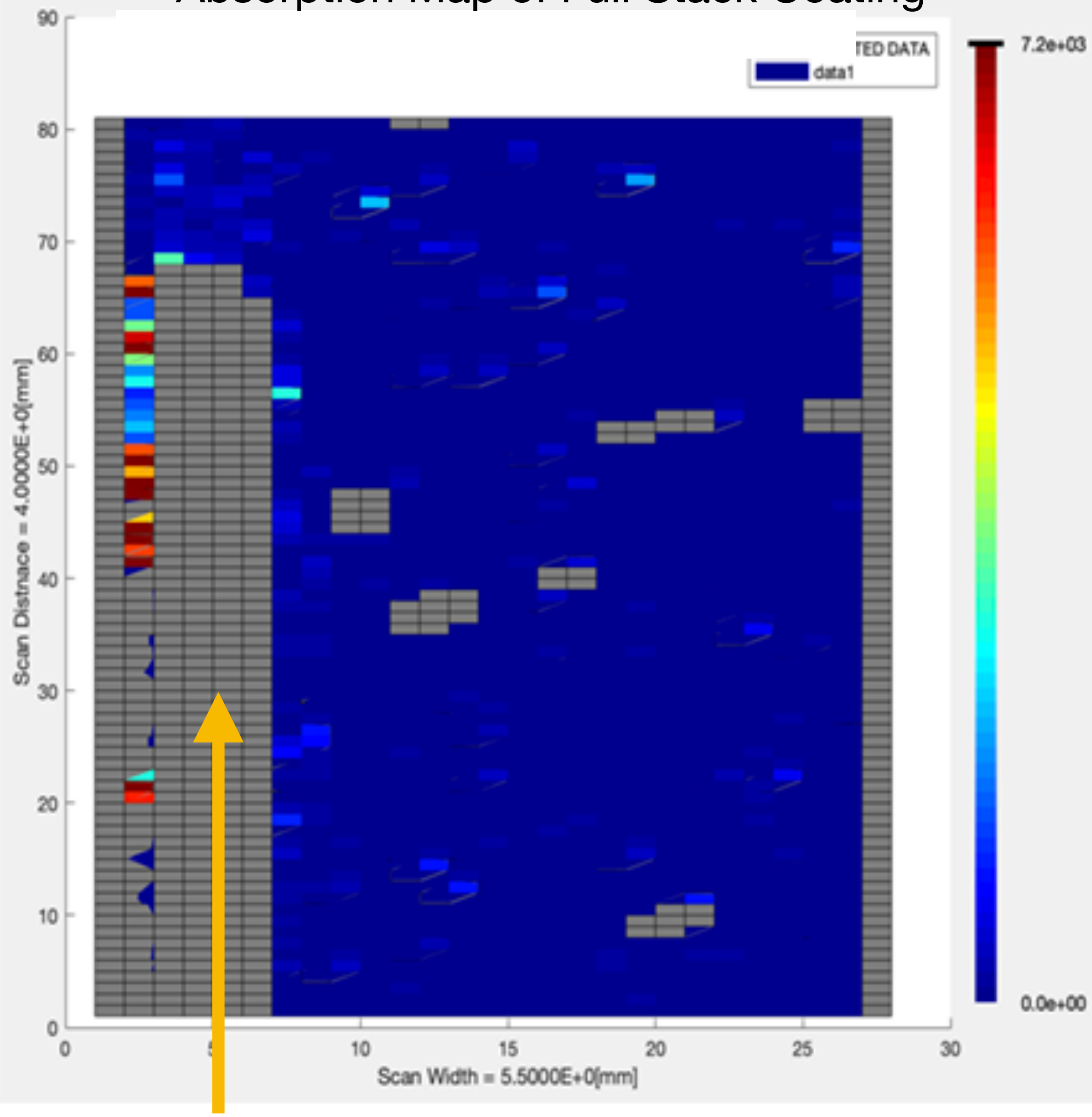
- To minimise coating thermal noise:
  - Alternating layer design reflects laser light at every boundary.
  - Highly reduced field reaches high absorbing aSi
  - Less number of coating layers with high refractive index contrast layers ~= less coating thermal noise

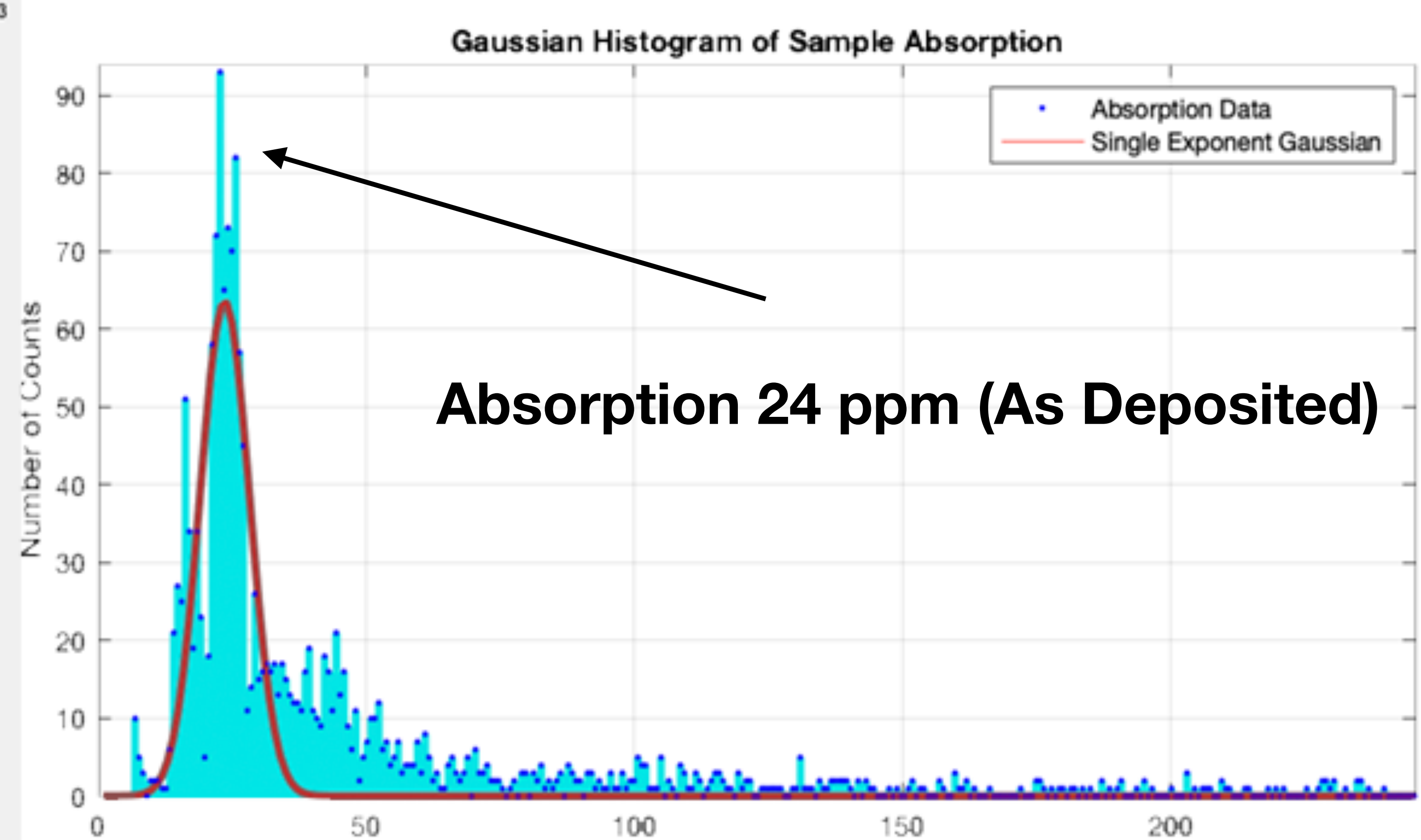


Absorption at 2um

Absorption Measured with Photo-thermal Common Path Interferometry (PCI)

Absorption Map of Full Stack Coating

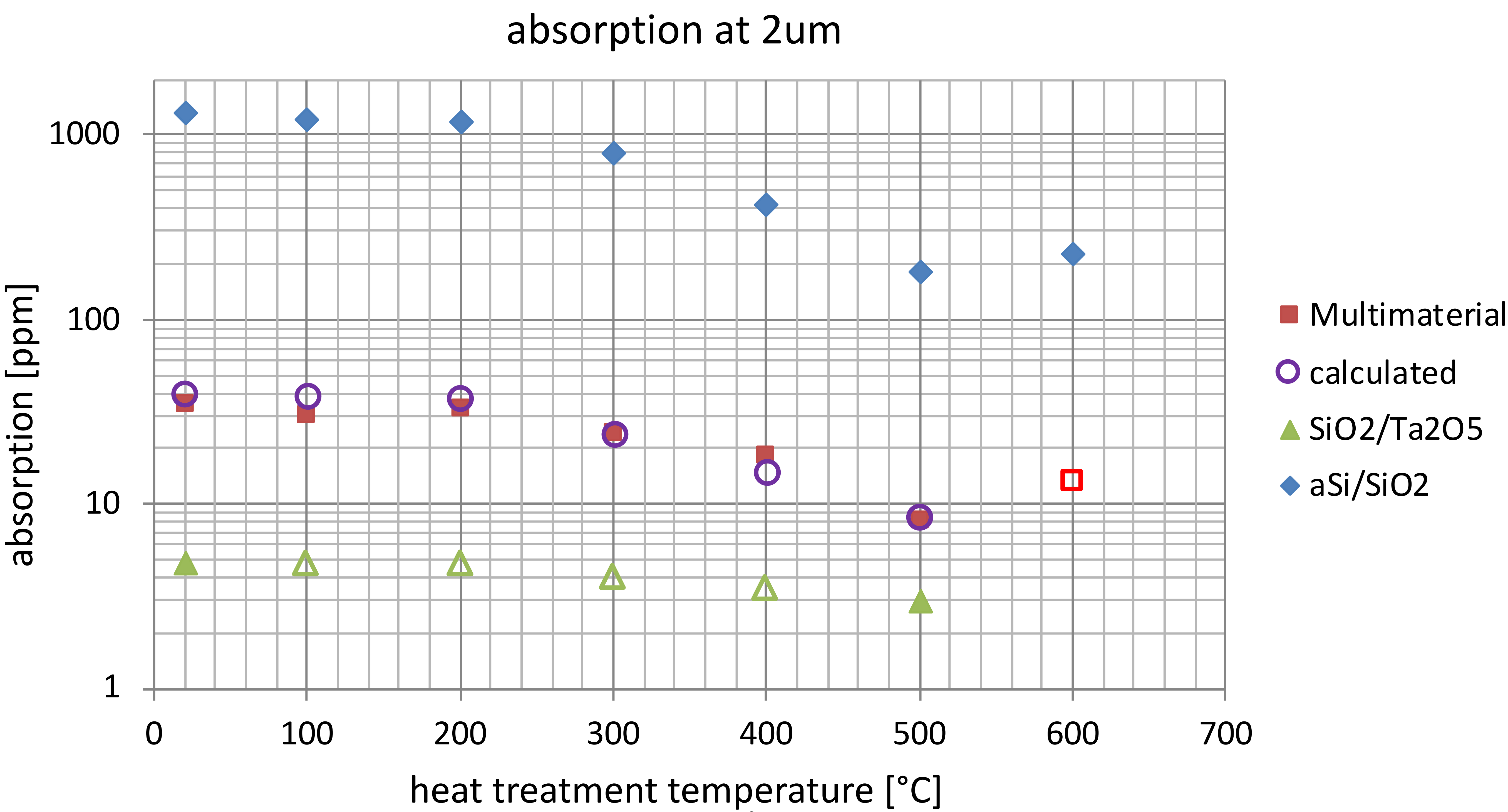




Histogram of Absorption

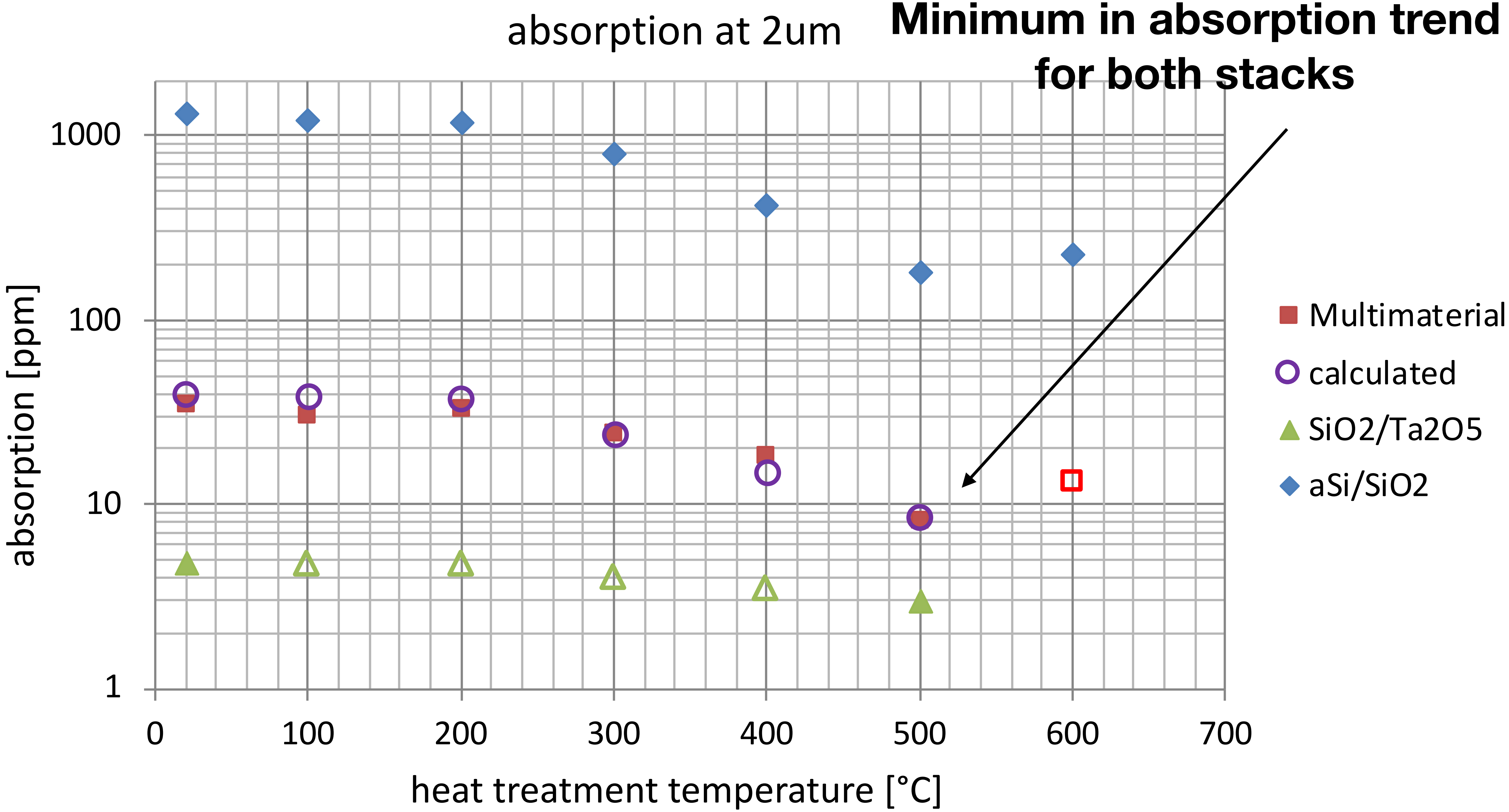
High absorption section exposed to too much laser power (damaged)

Absorption with Heat Treatment



Absorption with Heat Treatment

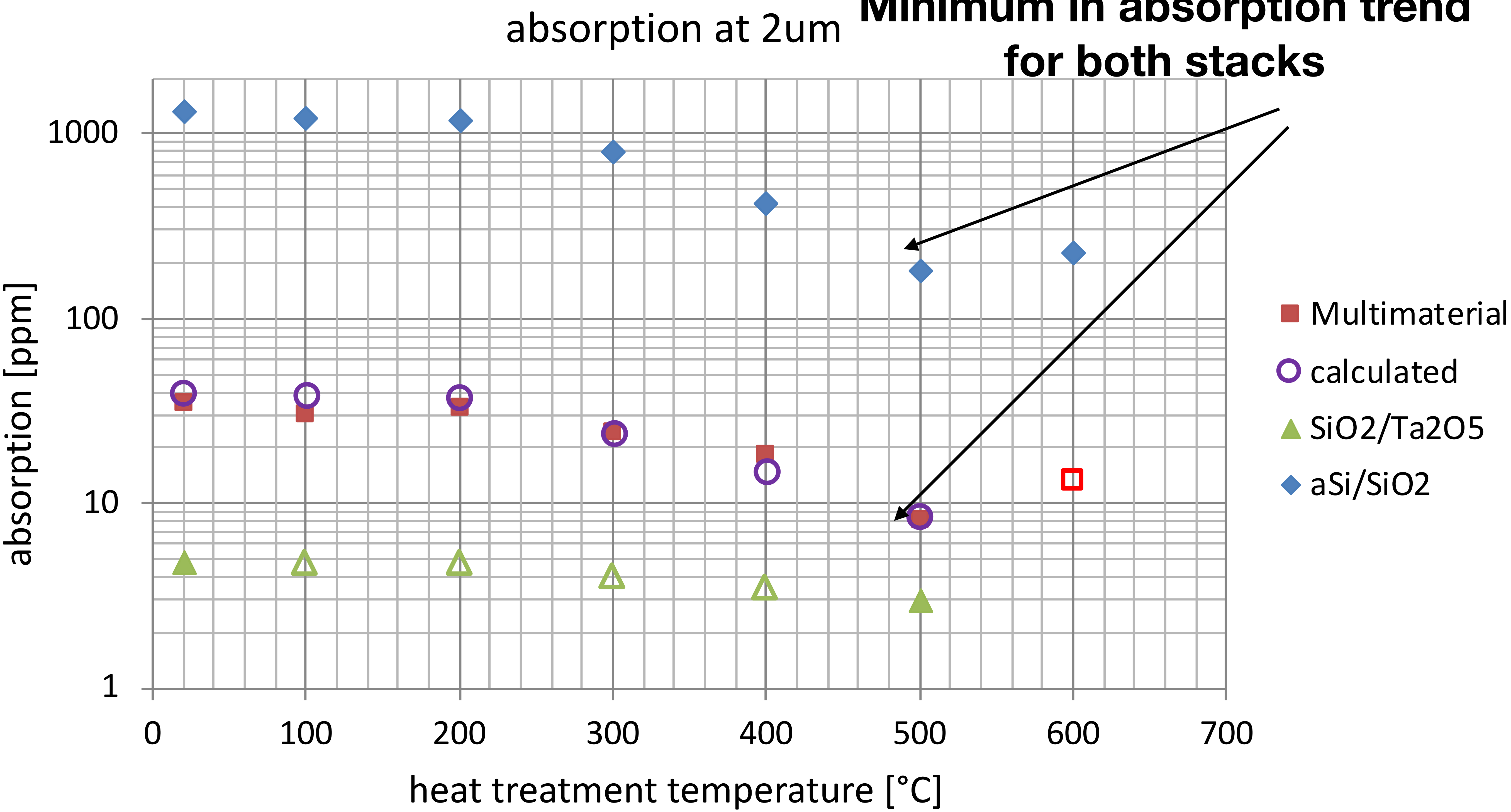
Minimum in absorption trend for both stacks



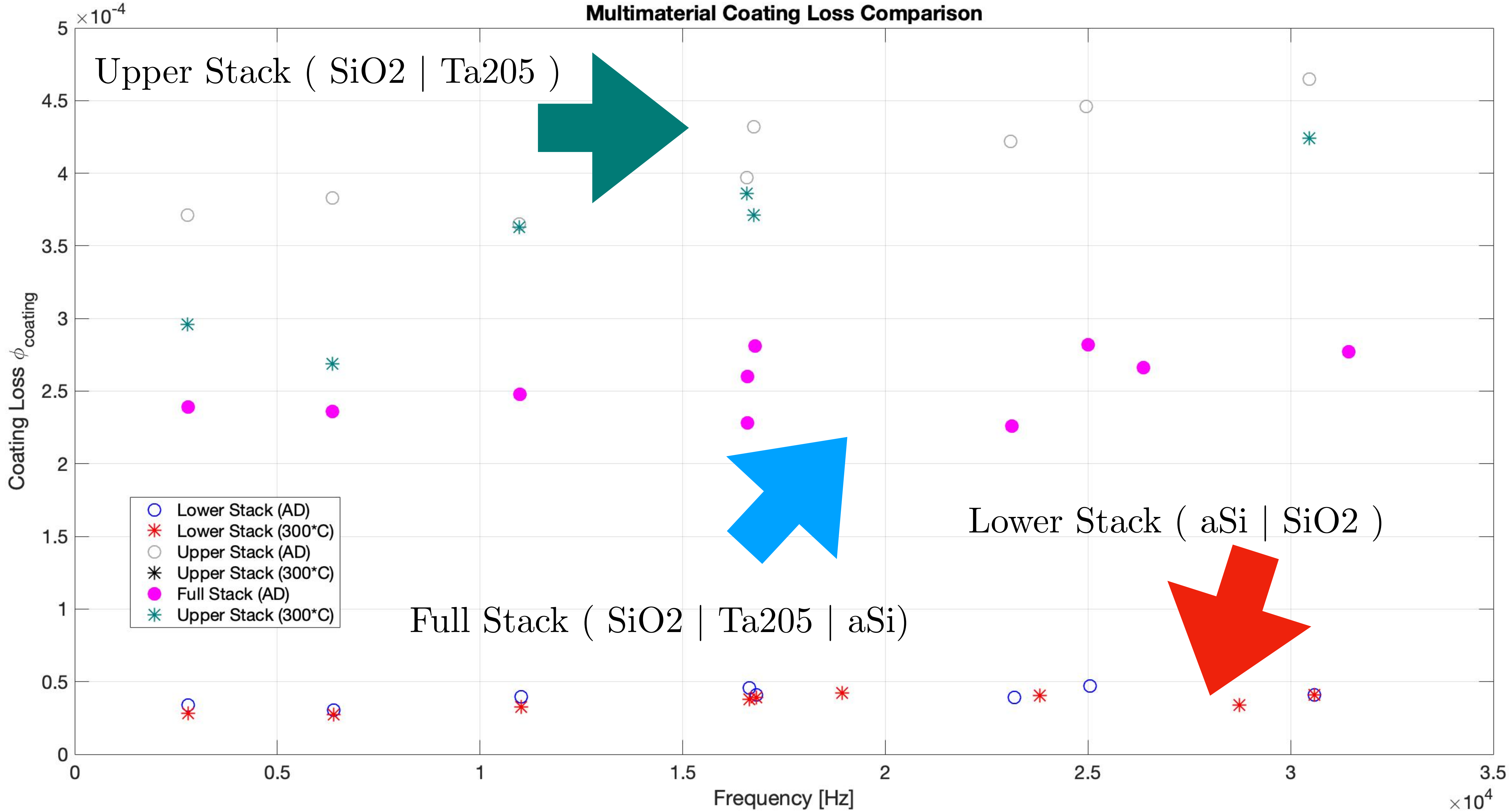
Absorption with Heat Treatment

University of Glasgow

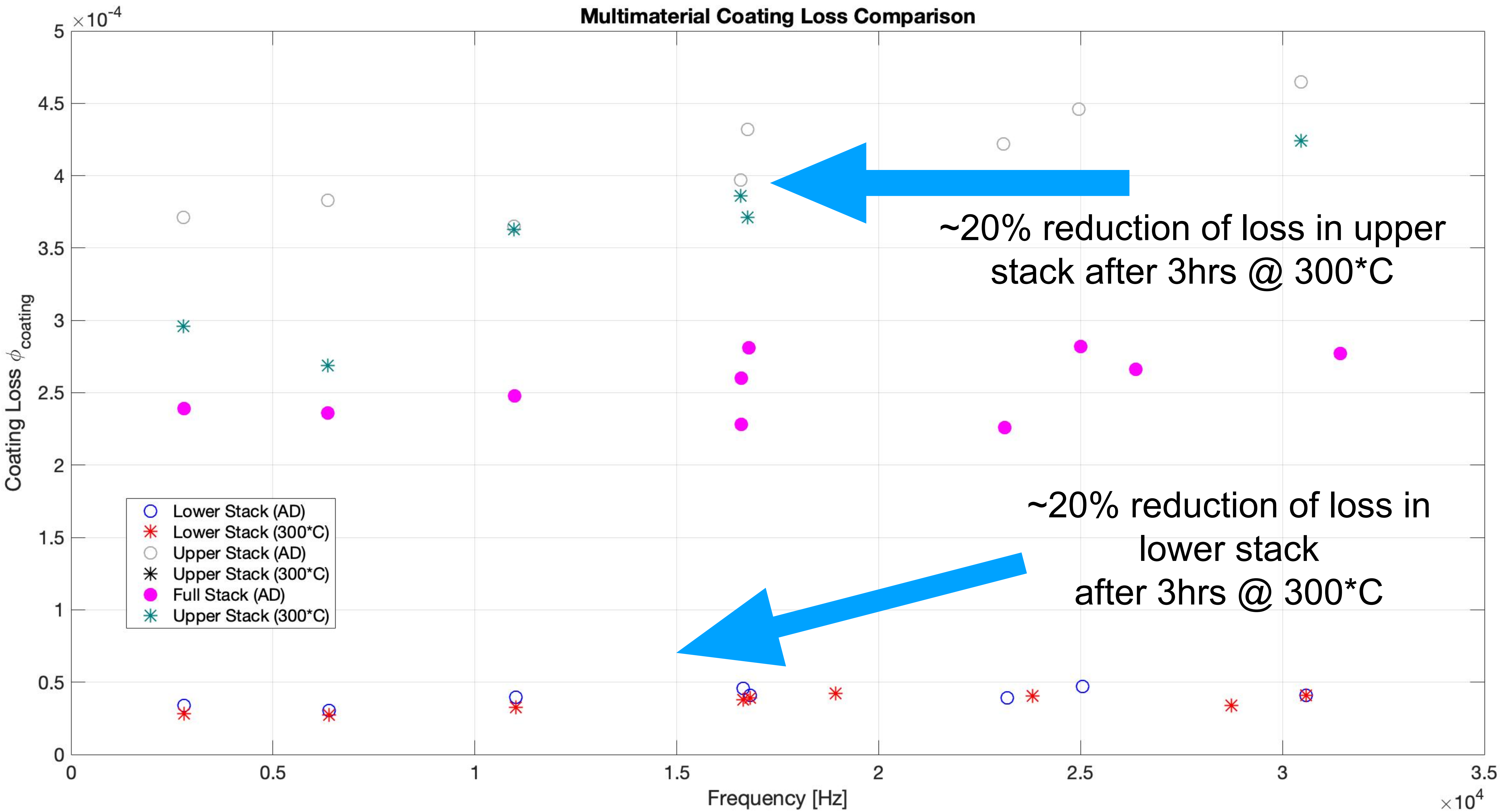
Minimum in absorption trend for both stacks



Room Temperature Coating Losses



Prototype multi material coating performs as expected
Mechanical loss measurements after progressive heat treatments underway

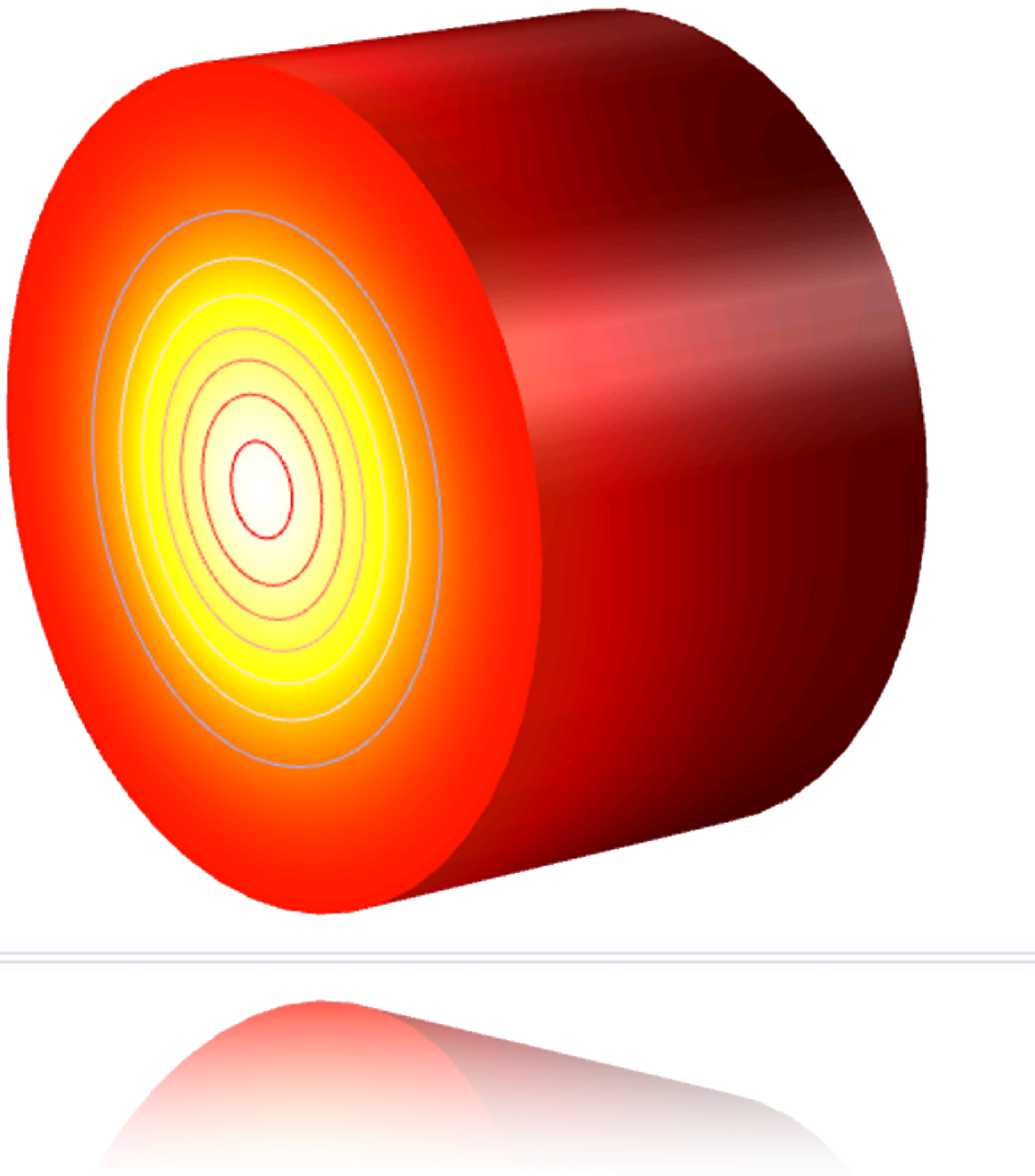


For more details on cryogenic coating loss on silicon substrates and predictions please see the poster by Peter Murray:

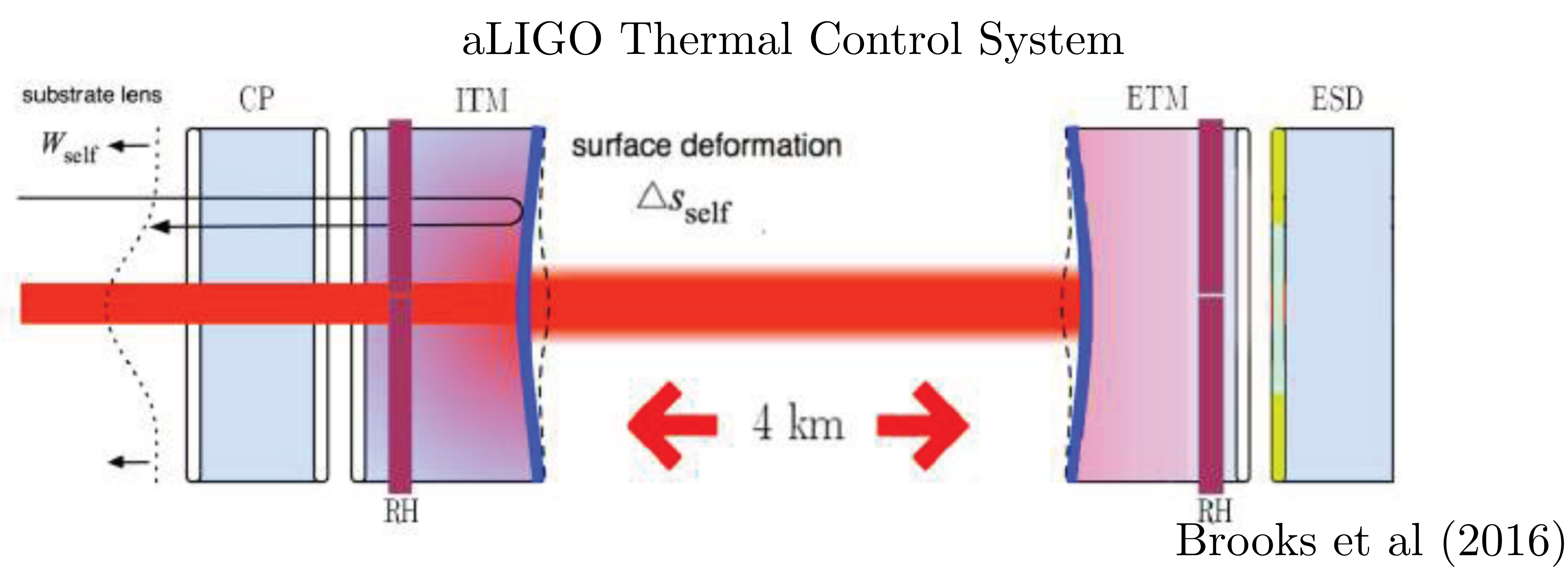
"Multimaterial Coatings for 3rd Generation Gravitational Wave Detectors"

Maximum Tolerable Absorption - a comparison

Comparison of current and cryogenic detector operation in relation to optical absorption.



Room Temperature Detectors



Silica Test Masses
Active thermal control using radiative heating

- **Interferometer Laser power passing through test masses causes temperature gradient (dn/dT dominated)**
- **Power buildup inside Fabery-Pèrot Cavity causes change in Test mass radius of curvature ΔS (coating absorption dominated)**

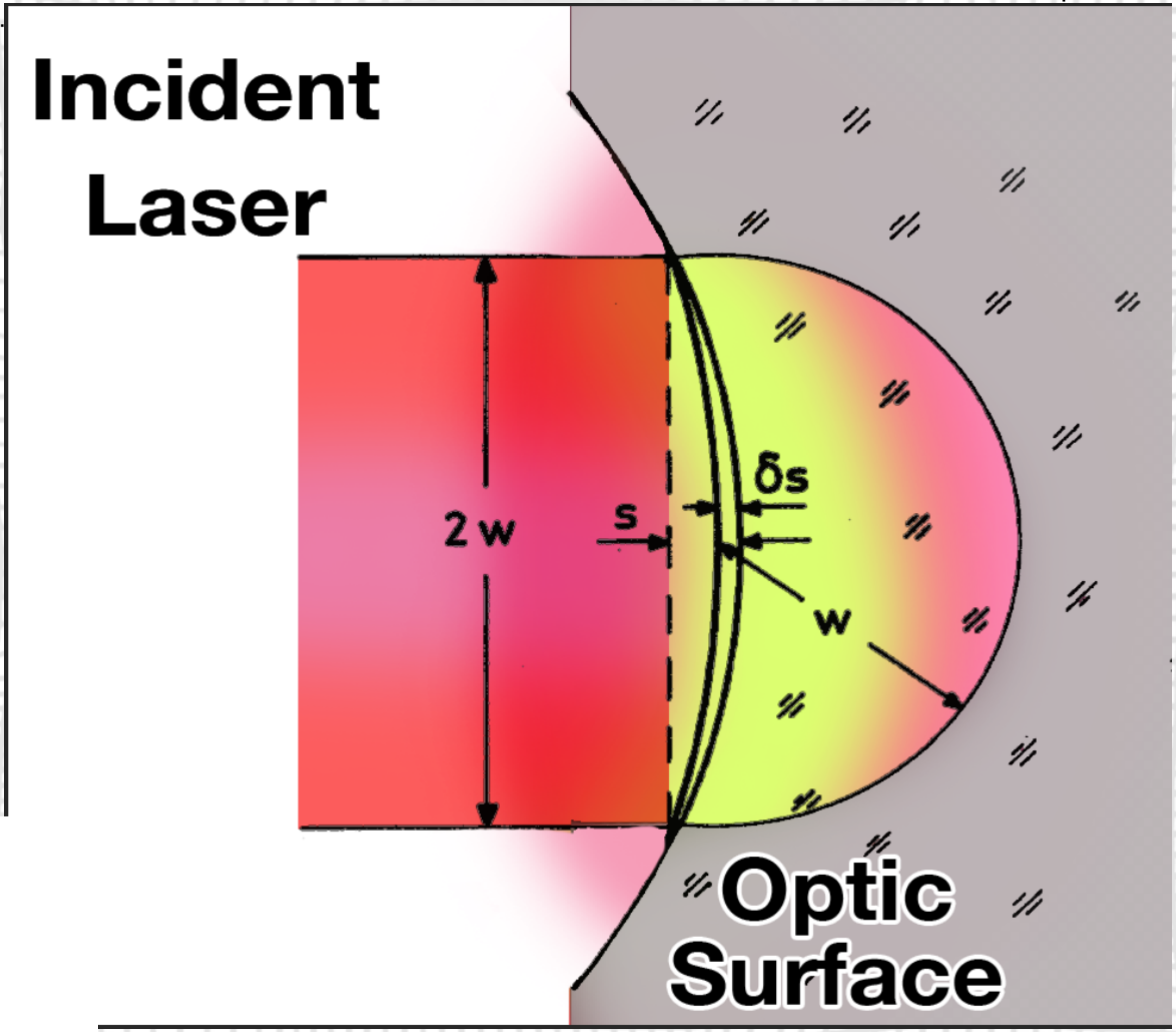
∂S - Change in Sigatta

If the incident gaussian laser beam is matched to the RoC of the mirror

the change in the heated area can be assumed as a hemispherical distortion on the mirrors surface.

The relative change in curvature can be simplistically calculated if the thermal expansion, absorbed power and wavelength are known using:

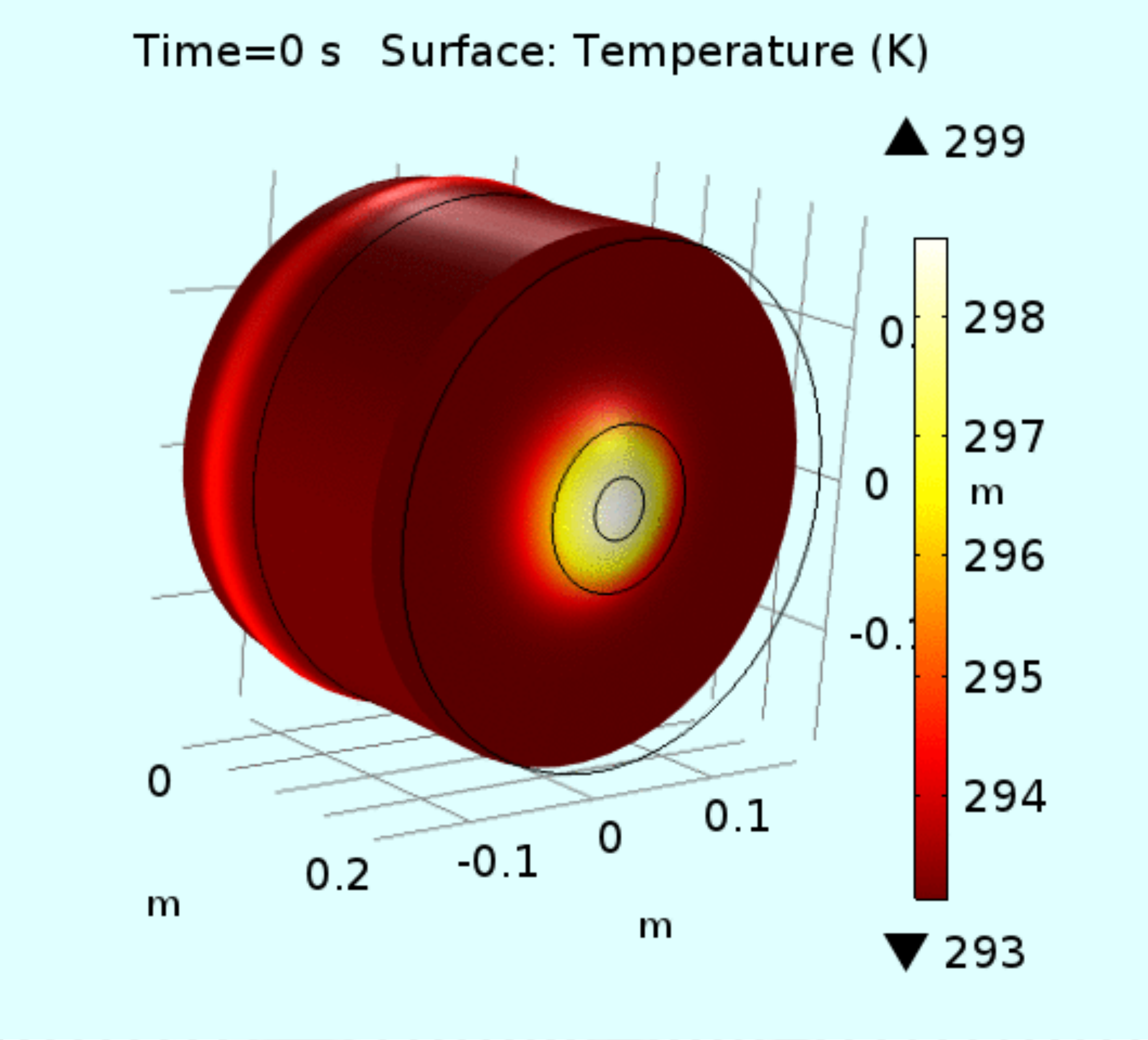
$$\frac{\delta s}{s} \approx \frac{\alpha}{2\kappa\lambda} P_a$$

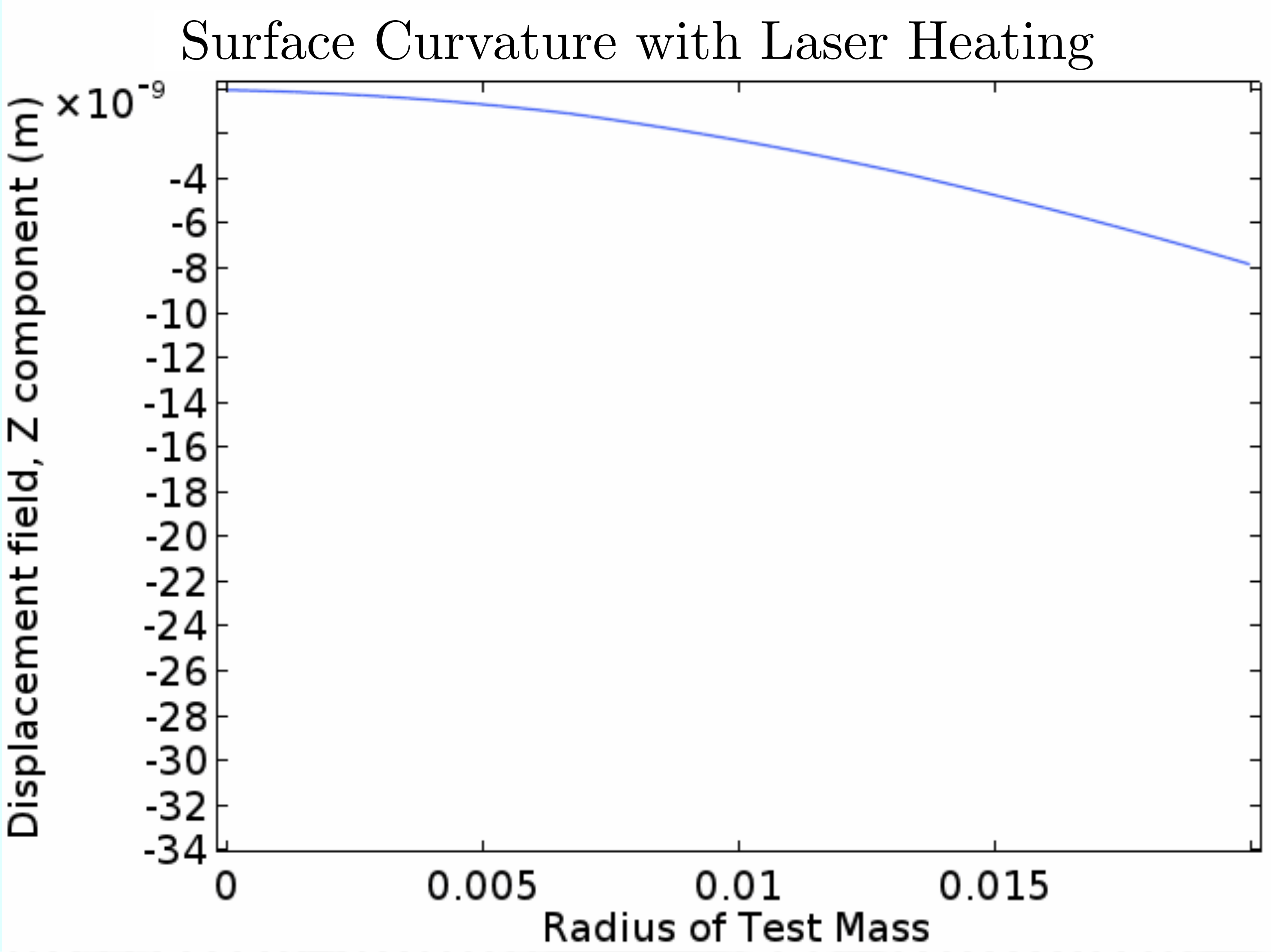


W. Winkler ,et al.(1991)

FEA Analysis

Room Temperature





Using methods described by R.C.Lawrence (1997) and building on the work of A. Brooks. the test mass is modelled as a 2D approximation of a cylindrical mass: vastly decreases computation time.

Tolerable Absorption

To zeroth order due the thermoelastic expansion of silicon under these conditions can be considered relatively small (~ 0.0001% for R=10 km) .

For ETMs - Heat absorption from incident laser becomes dominating

Assuming a thermally isolated test mass the thermal effects on a cryogenic optic can be modelled to predict heat distribution through test mass

How much conductive cooling can the suspension fibres provide ?

What effect does this have on suspension thermal noise?

Conductive Cooling

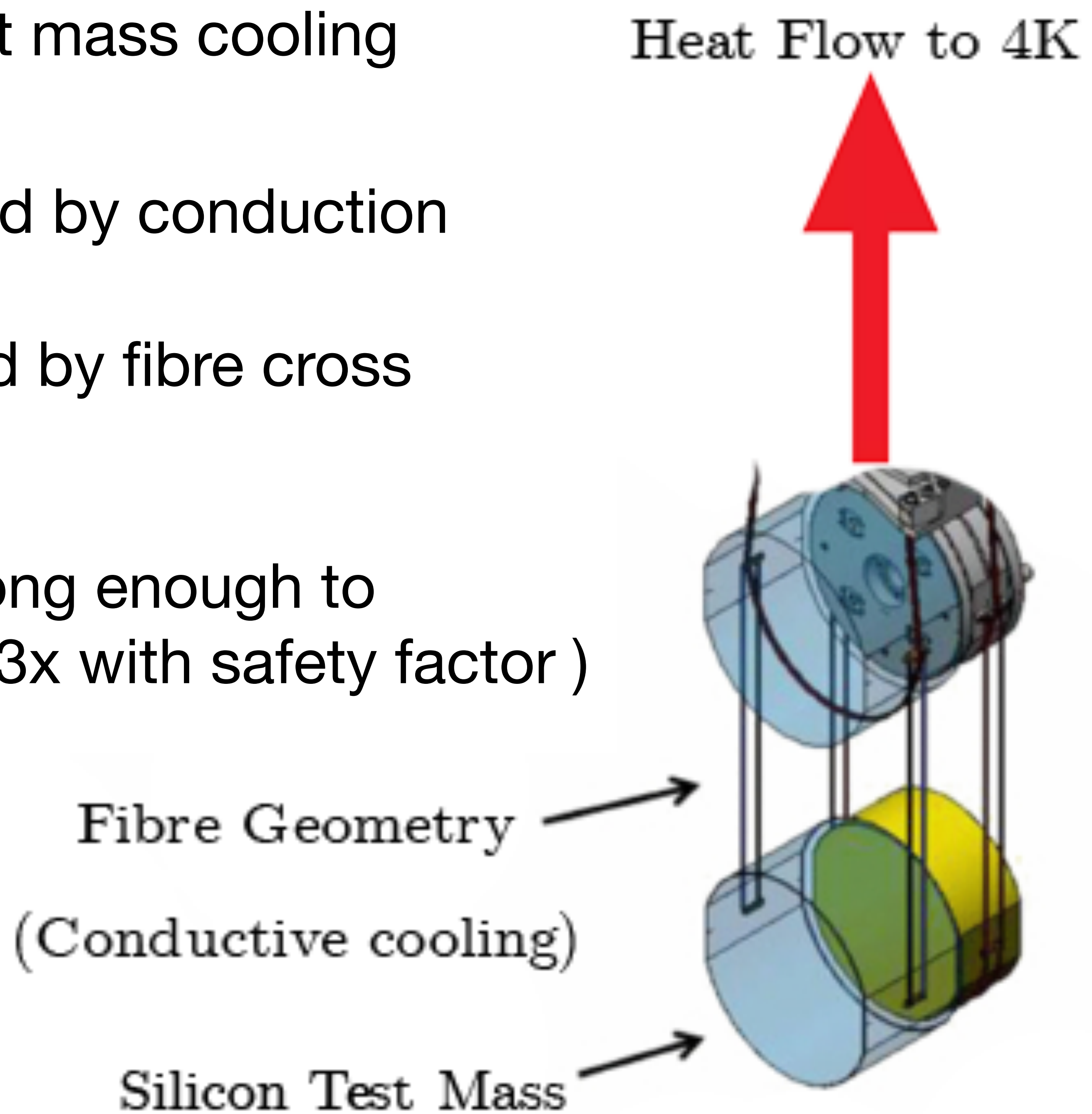
- Under cryogenic conditions test mass cooling becomes more difficult

- <120K cooling power dominated by conduction through suspension fibres
- <40K conductive cooling limited by fibre cross section (phonon scattering)

  - We need fibres which are strong enough to support the 200 kg masses (3x with safety factor)

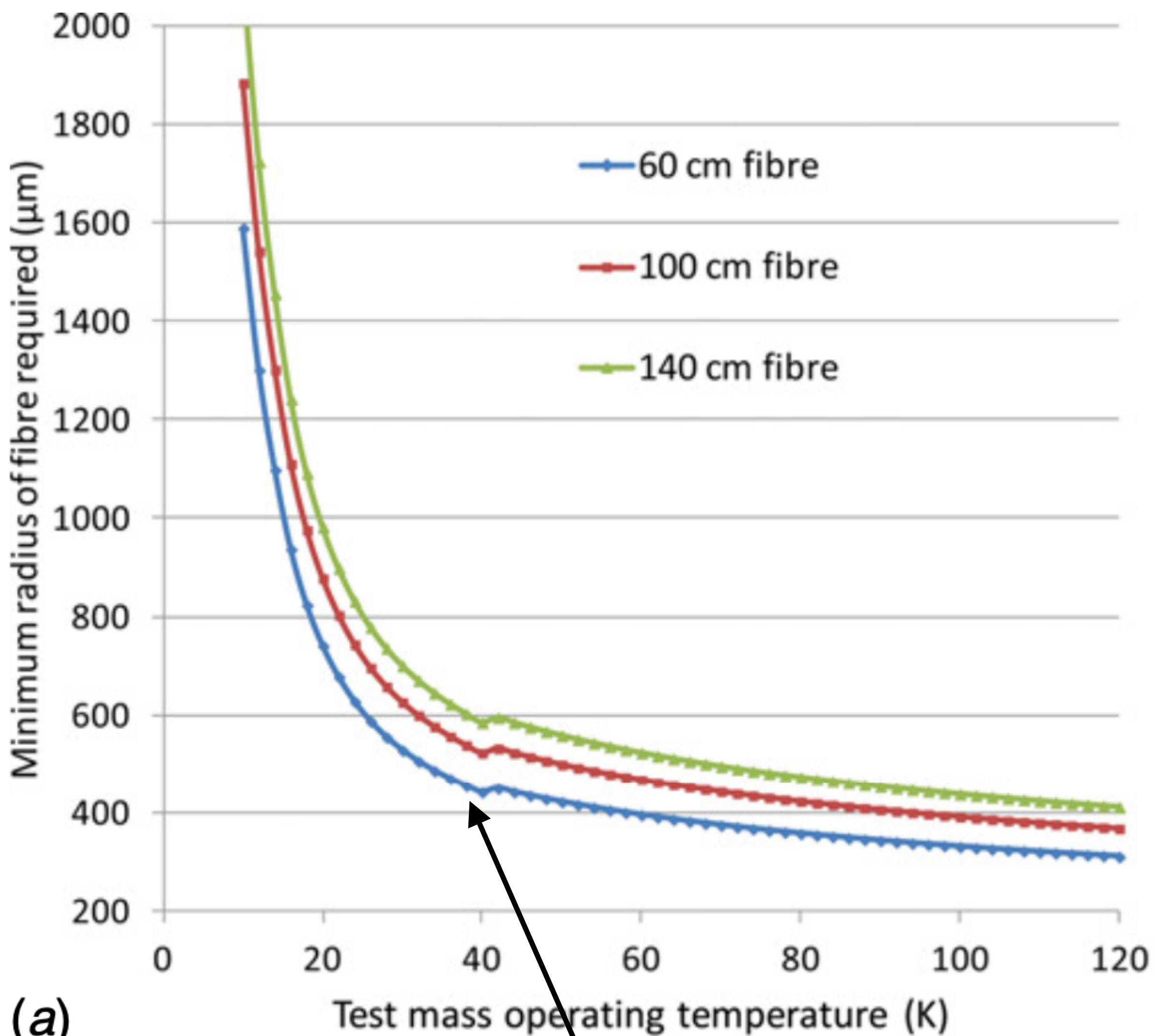
- **Requires thicker suspension fibres**

- **Increases suspension thermal noise**

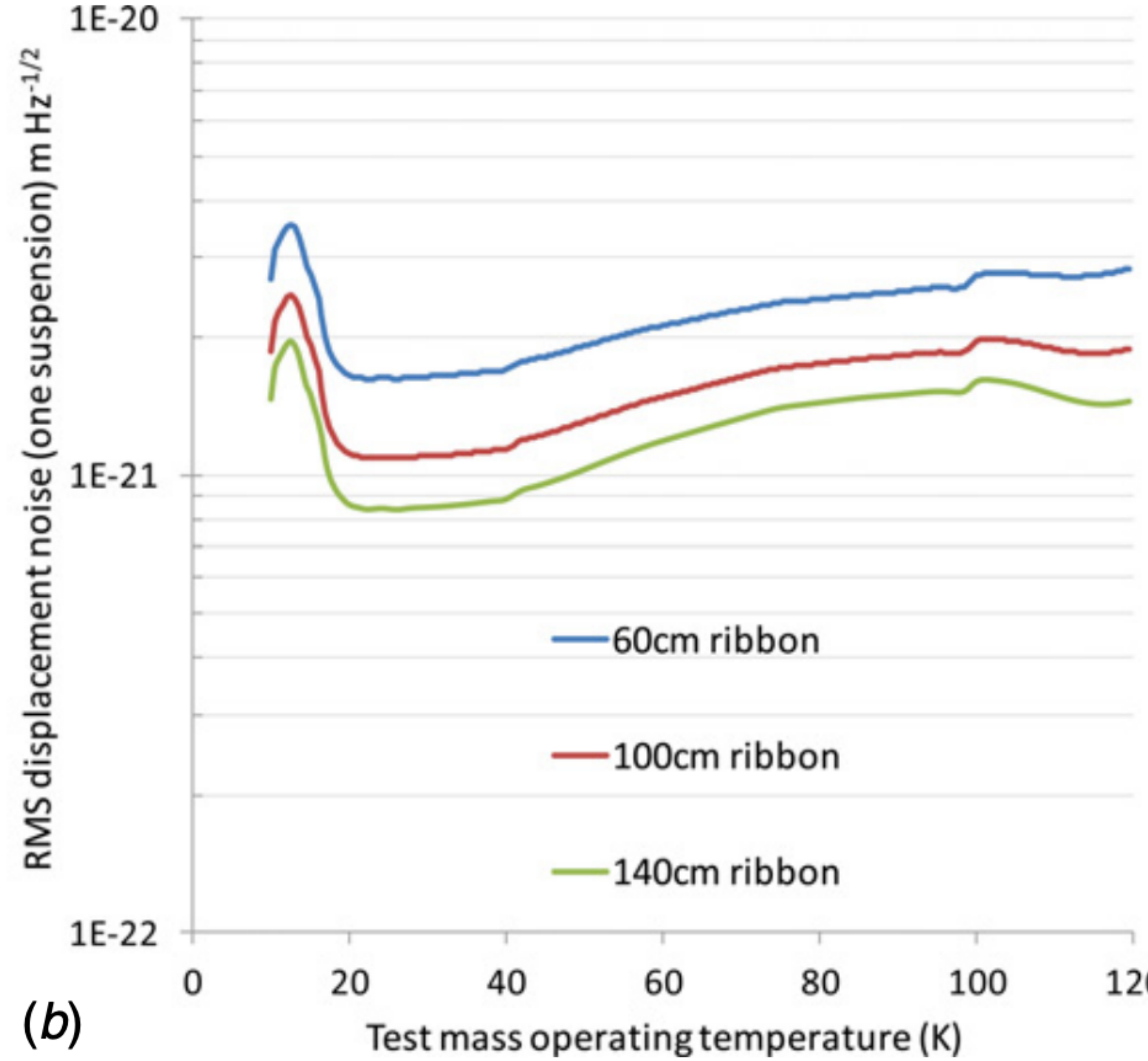


Suspension Fiber Requirements

Required $t_{suspension}$ ($T_{operation}$)



Suspension Thermal noise ($T_{operation}$)

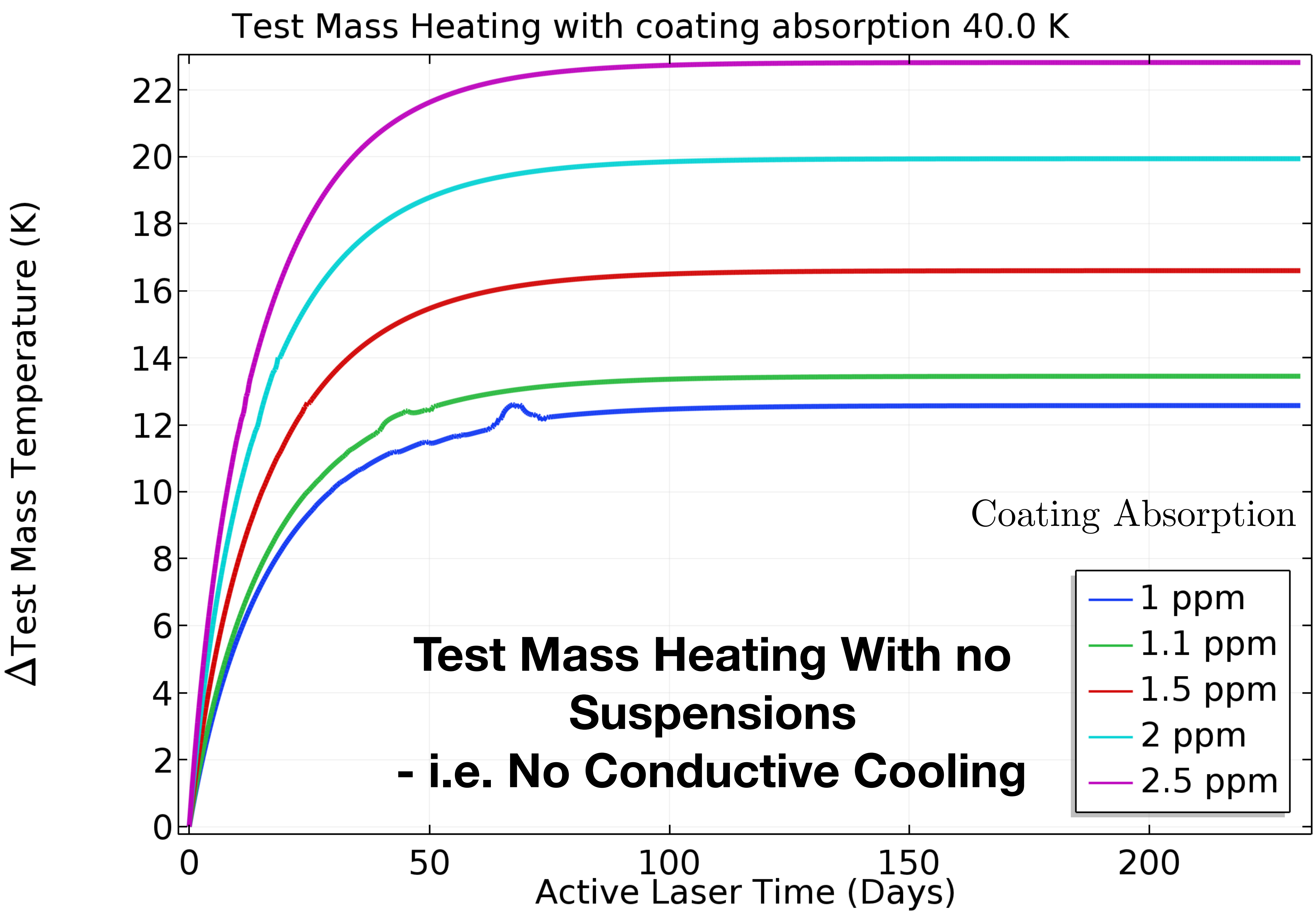


Operating at ~40K would require a minimum 500um thick fibre

How much heat extraction can this provide ?

A V Cumming et al 2014 Class. Quantum Grav. 31 025017

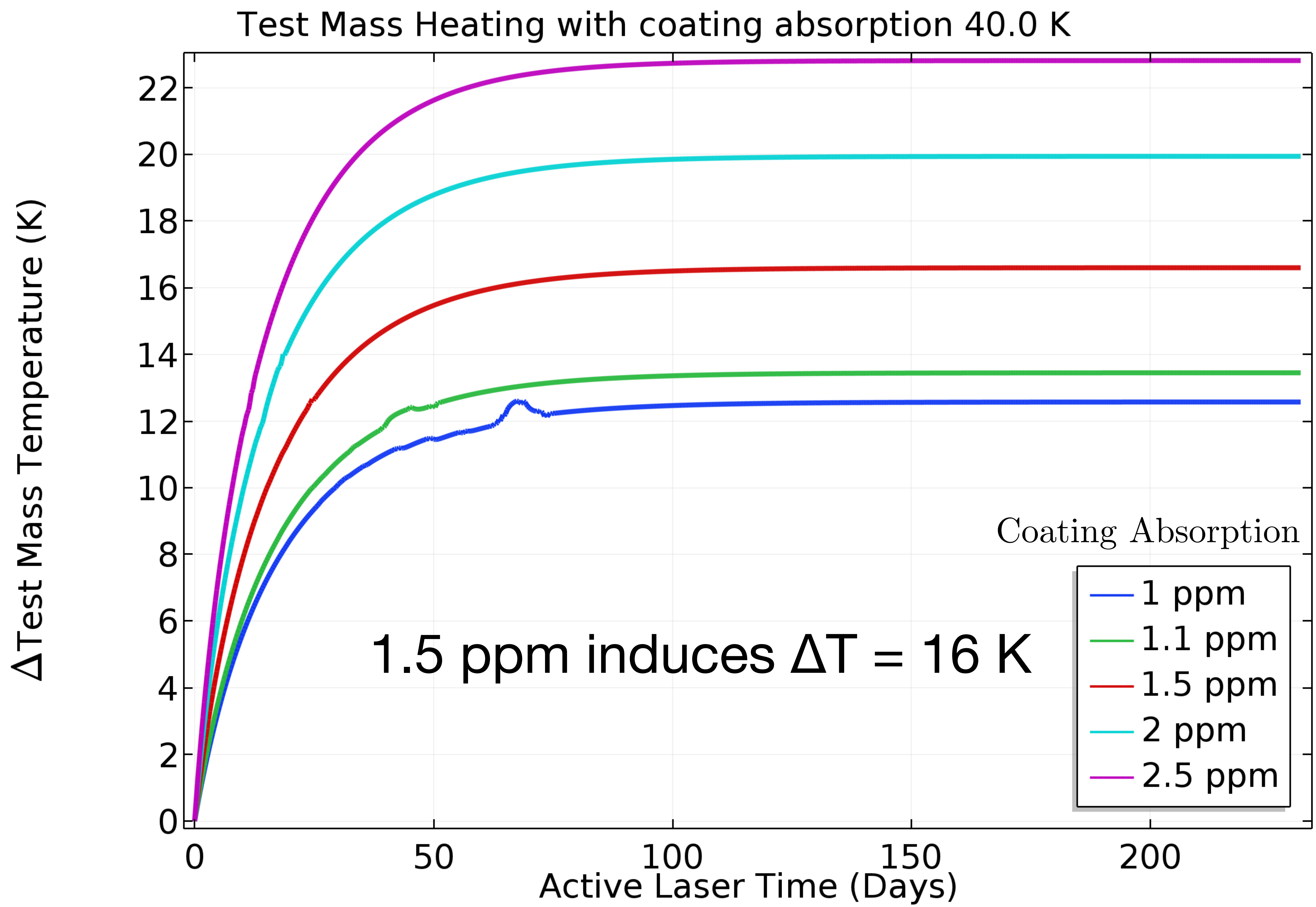
40 K Operation

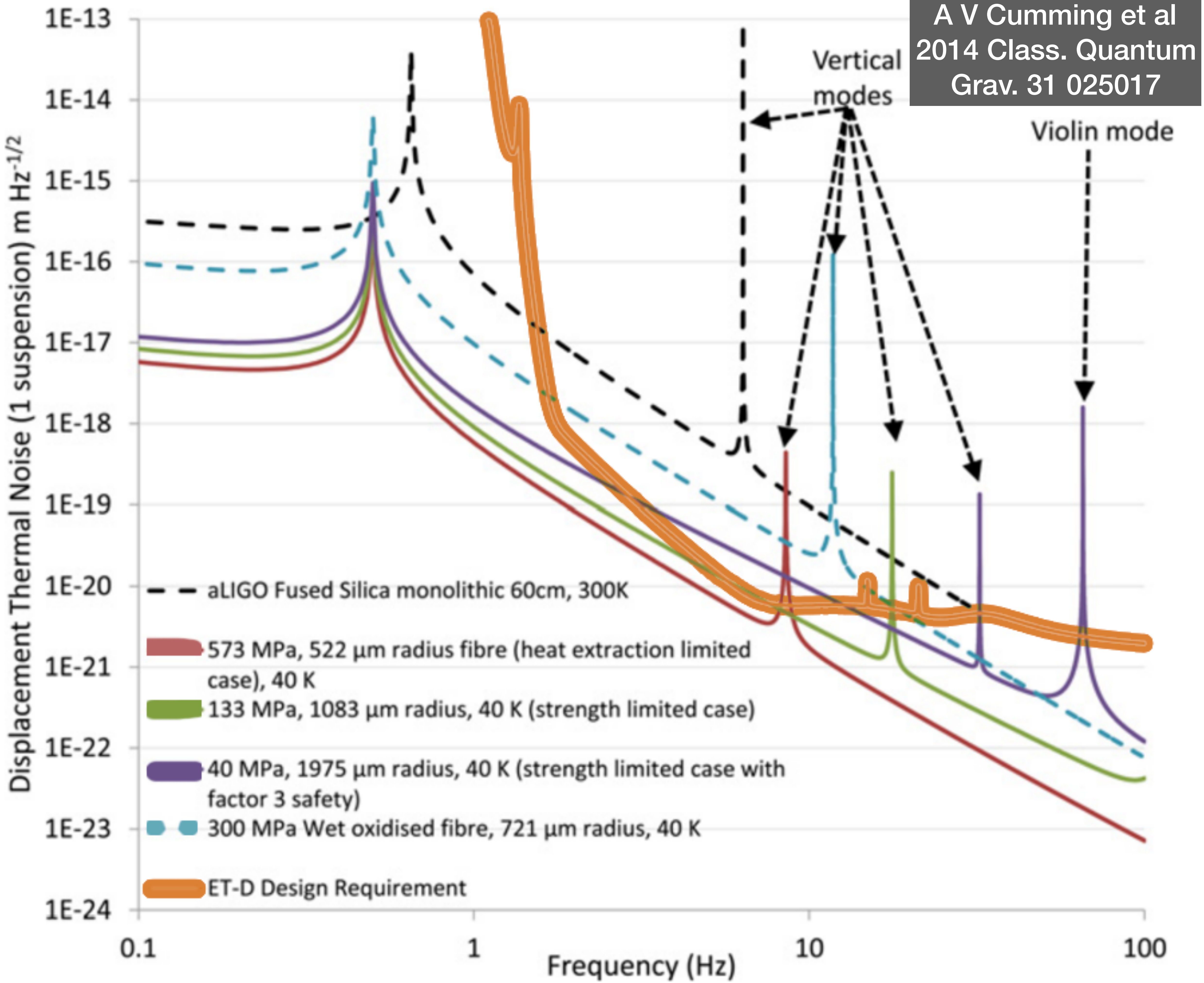


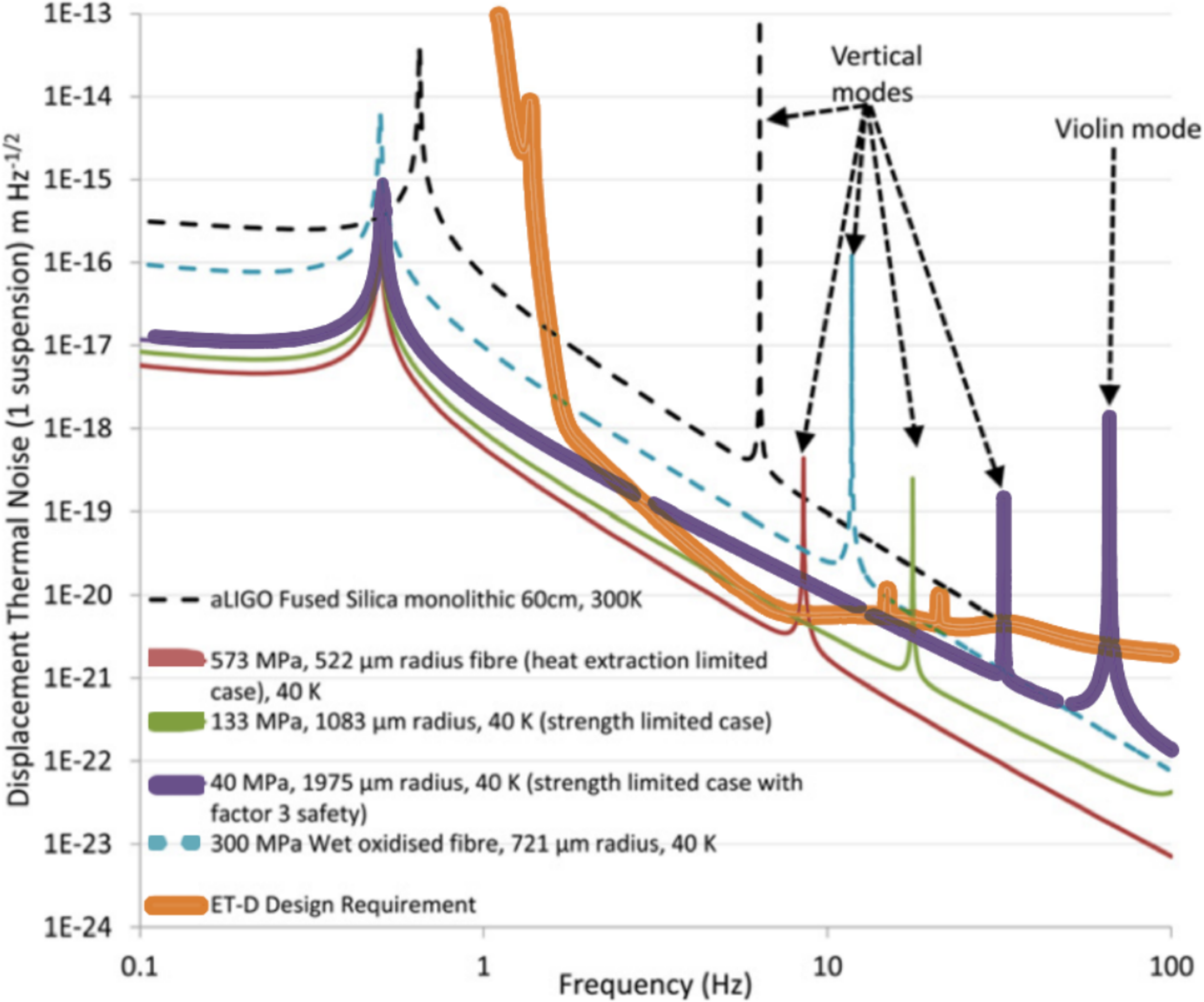
Test Mass Heating With no Suspensions

- i.e. No Conductive Cooling

ΔT with No Fibres




A V Cumming et al
2014 Class. Quantum
Grav. 31 025017
Vertical
modes
Violin mode
Displacement Thermal Noise (1 suspension) m Hz^-1/2
Frequency (Hz)
1E-13
1E-14
1E-15
1E-16
1E-17
1E-18
1E-19
1E-20
1E-21
1E-22
1E-23
1E-24
0.1
1
10
100
aLIGO Fused Silica monolithic 60cm, 300K
573 MPa, 522 µm radius fibre (heat extraction limited case), 40 K
133 MPa, 1083 µm radius, 40 K (strength limited case)
40 MPa, 1975 µm radius, 40 K (strength limited case with factor 3 safety)
300 MPa Wet oxidised fibre, 721 µm radius, 40 K
ET-D Design Requirement



Vertical modes
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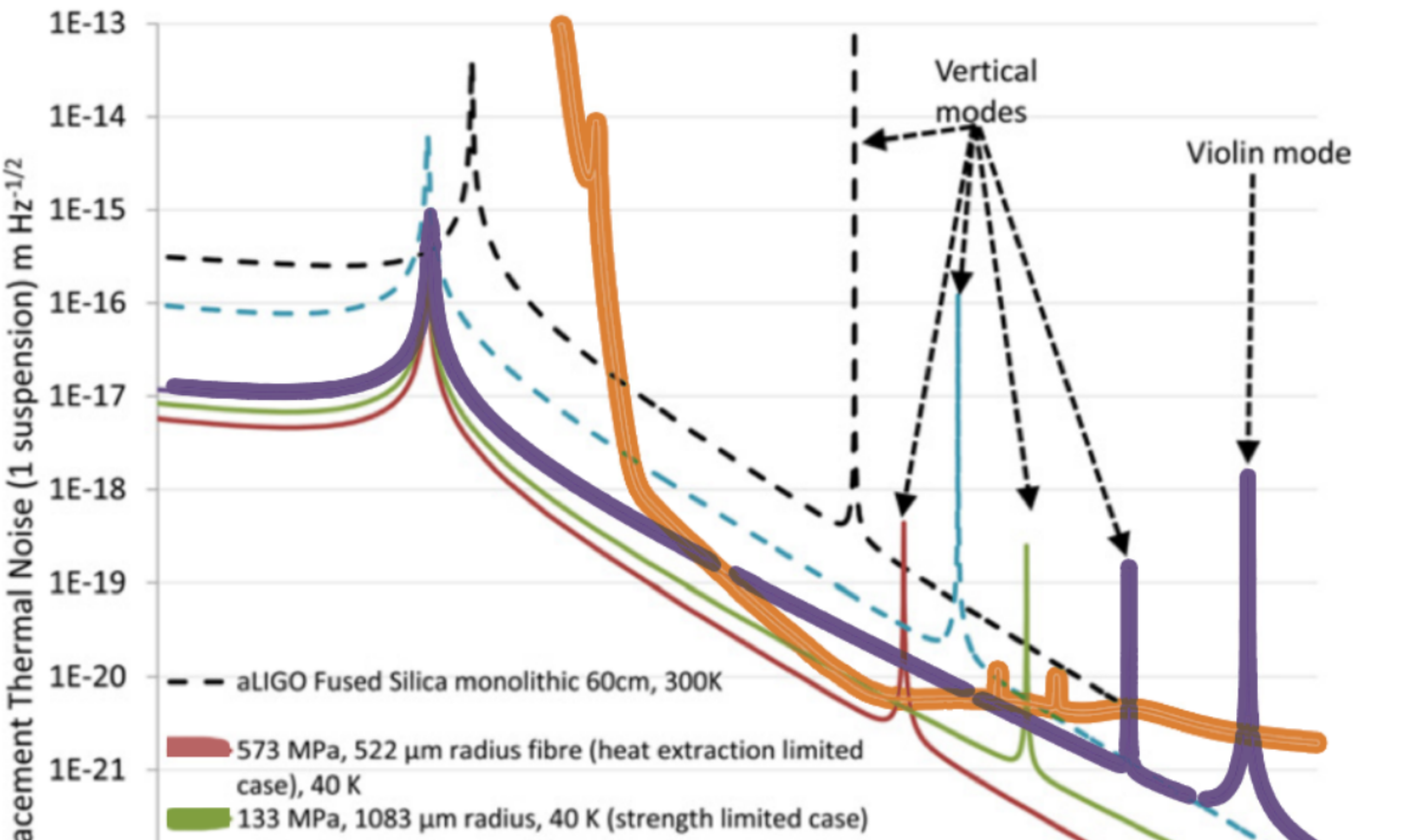
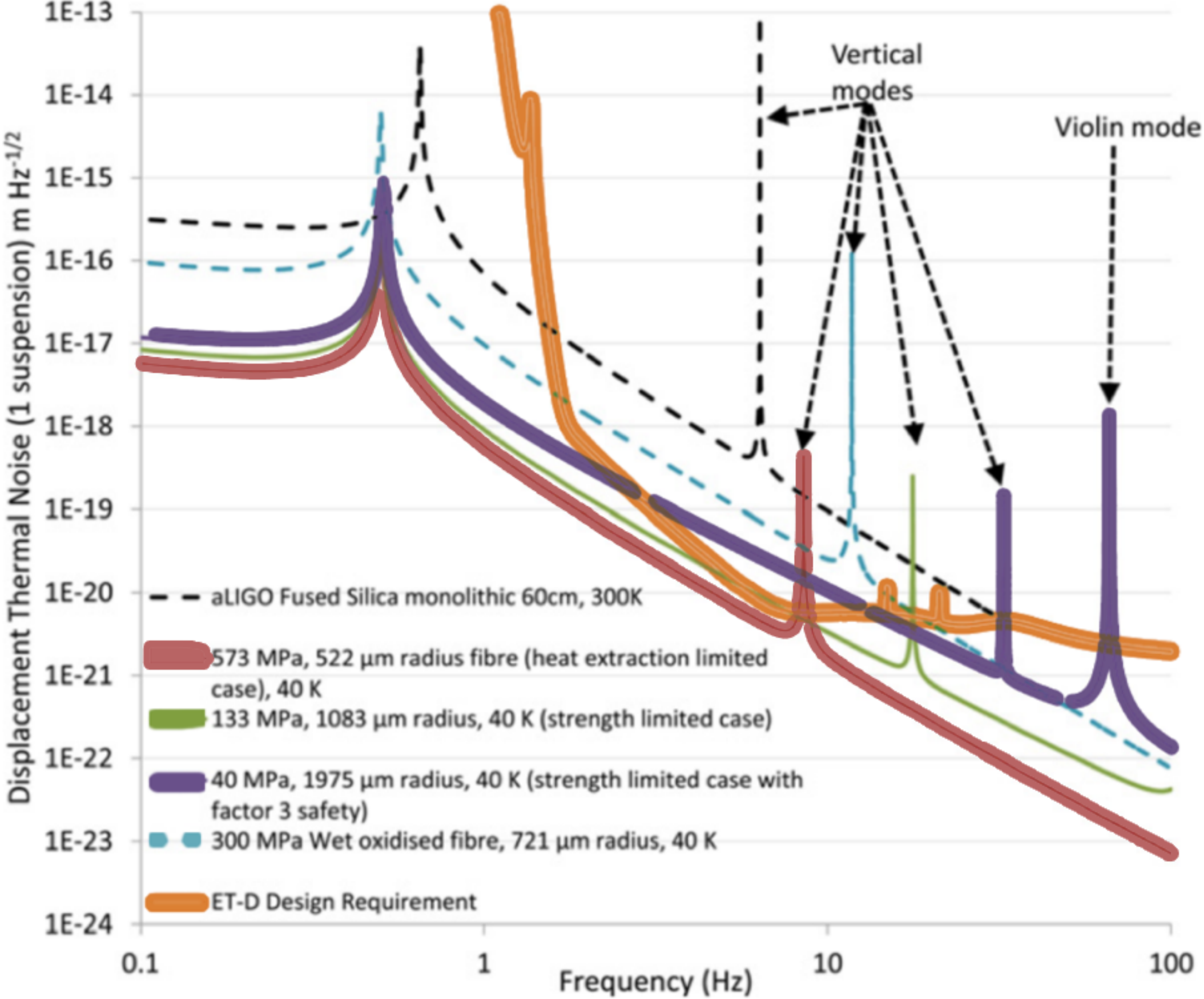


Thicker Fibre does not meet ET Thermal noise



1E-13
1E-14
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1E-24
Displacement Thermal Noise (1 suspension) m Hz-1/2
0.1
1
10
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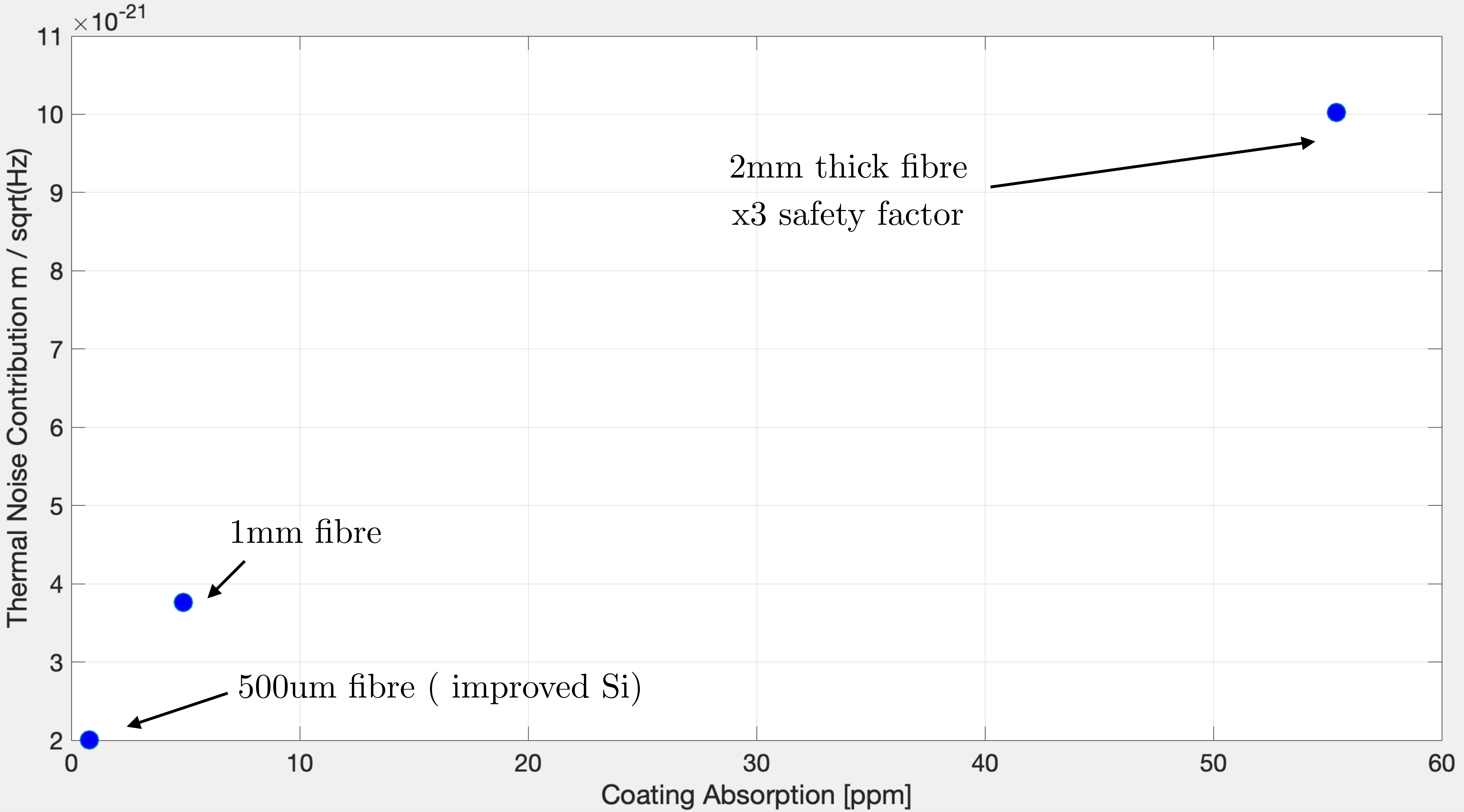
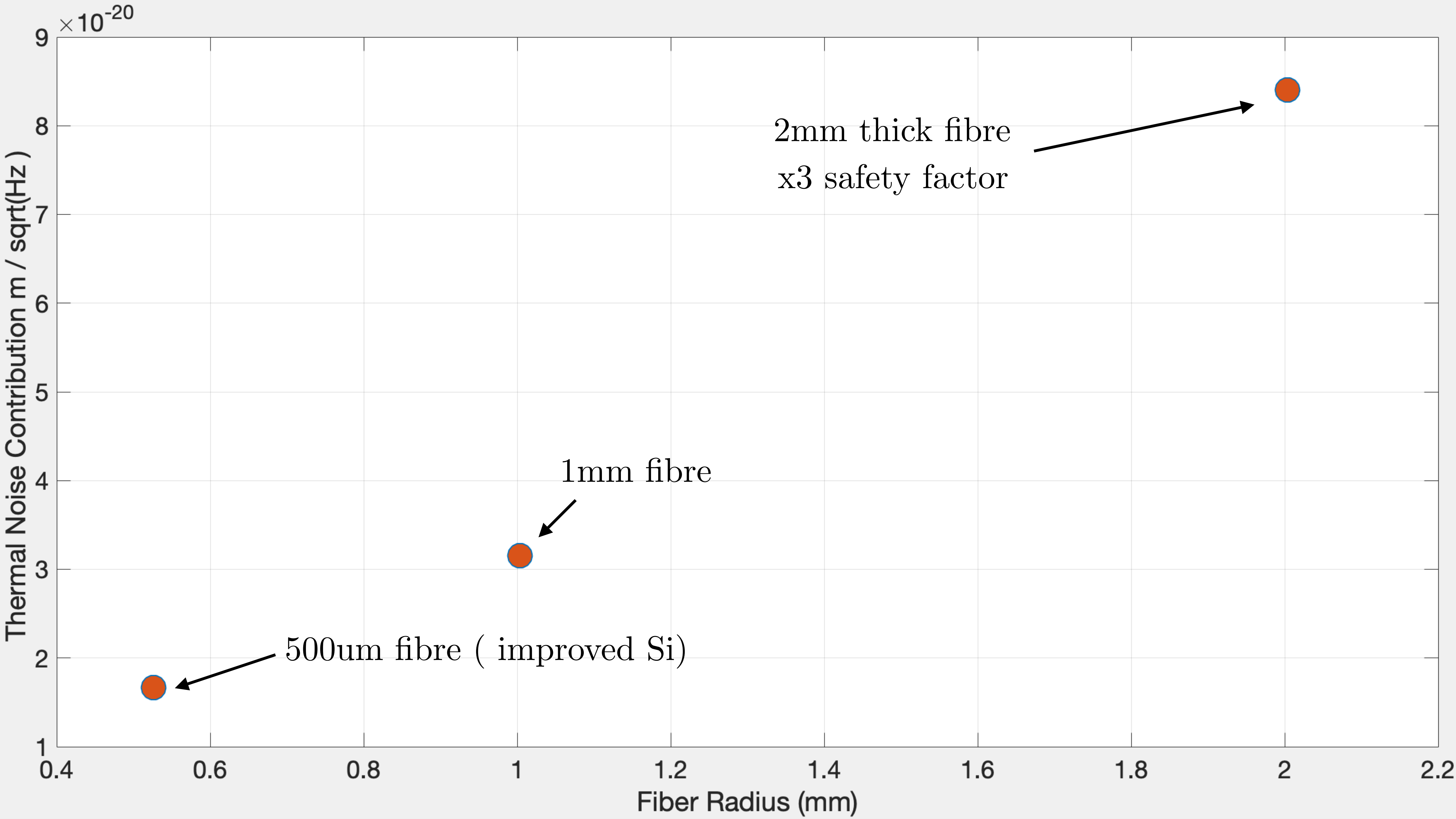
Thermal Noise with Coating Absorption



Thermal Noise with Fibre Radius



Interesting talking points

- The tolerable level of coating absorption is dominated by heat conduction through the fibres
- Based on initial strength studies we need thick (~2mm) fibres to support 200kg mass.
  - Does not meet ET requirements
  - Can extract 55ppm of absorbed laser power
  - Higher absorption allows for more layers of aSi inside a multilayer stack. - reducing overall coating loss
- 500um fibres would be below ET-LF total noise budget (@10 Hz)
  - Si fibre strength must be improved over initial measurements
  - Thinner fibre tightens requirements on tolerable absorption (1ppm)

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