Development of silicon mirrors and coatings

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Overview

- Silicon optical absorption
- Silicon optical scattering
- Coating thermal noise at low temperature
- Amorphous silicon coatings
- Multi-material coating designs for optimising mechanical loss and absorption

Silicon substrates - absorption

- Silicon grown with Czochralski method has relatively high optical absorption due to impurities
- Fewer impurities and lower absorption from float zone technique, but not available for larger (~400mm) diameters
- Magnetically assisted Czochralski
  - Magnetic fields reduce convection currents in Si melt, reduced dissolved oxygen from interaction with crucible
  - 450mm diameter available

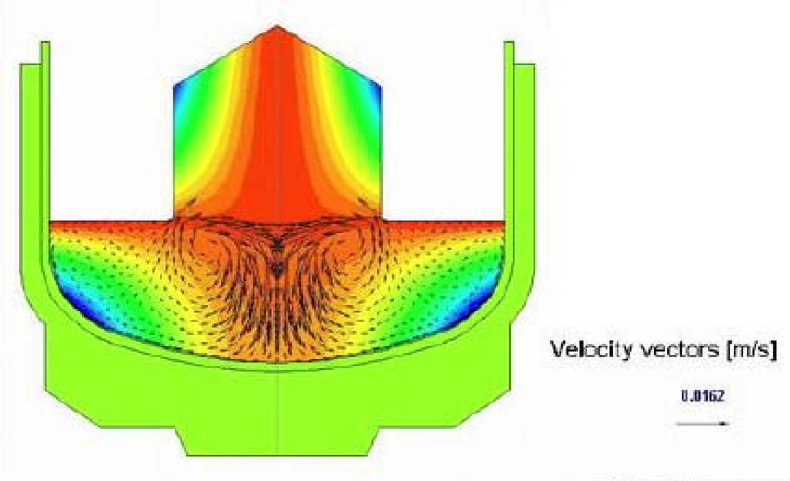
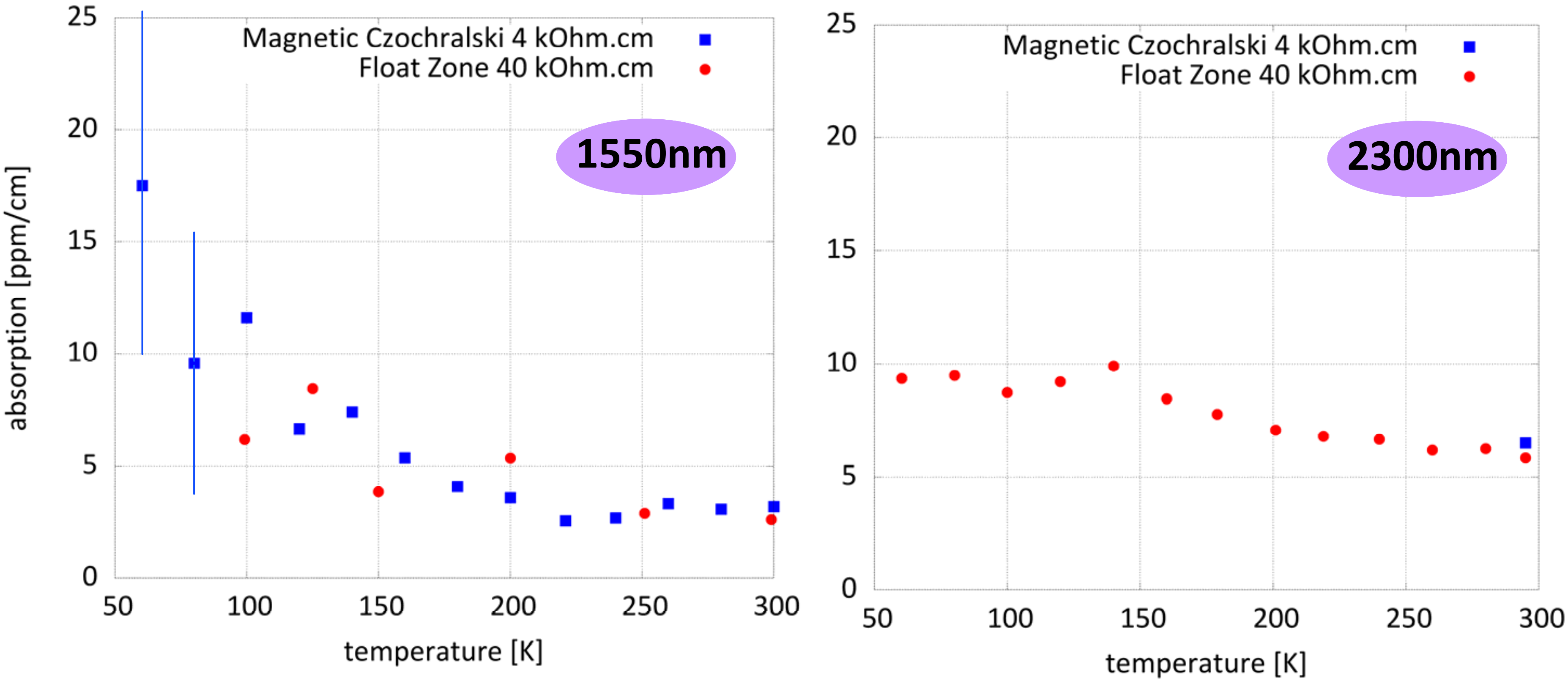


Image credit

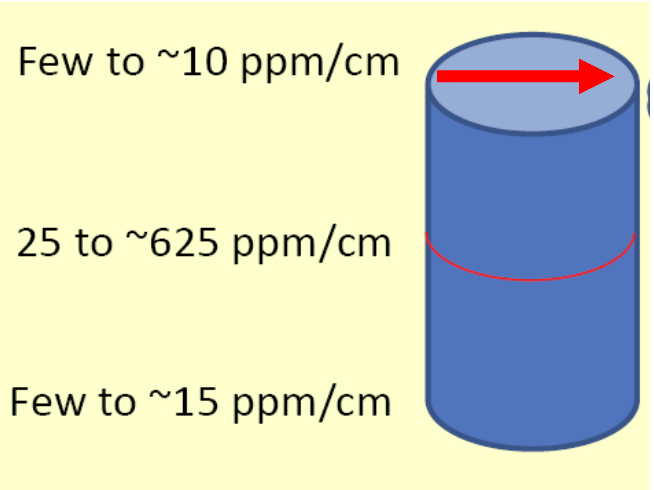
Silicon substrates – mCz absorption

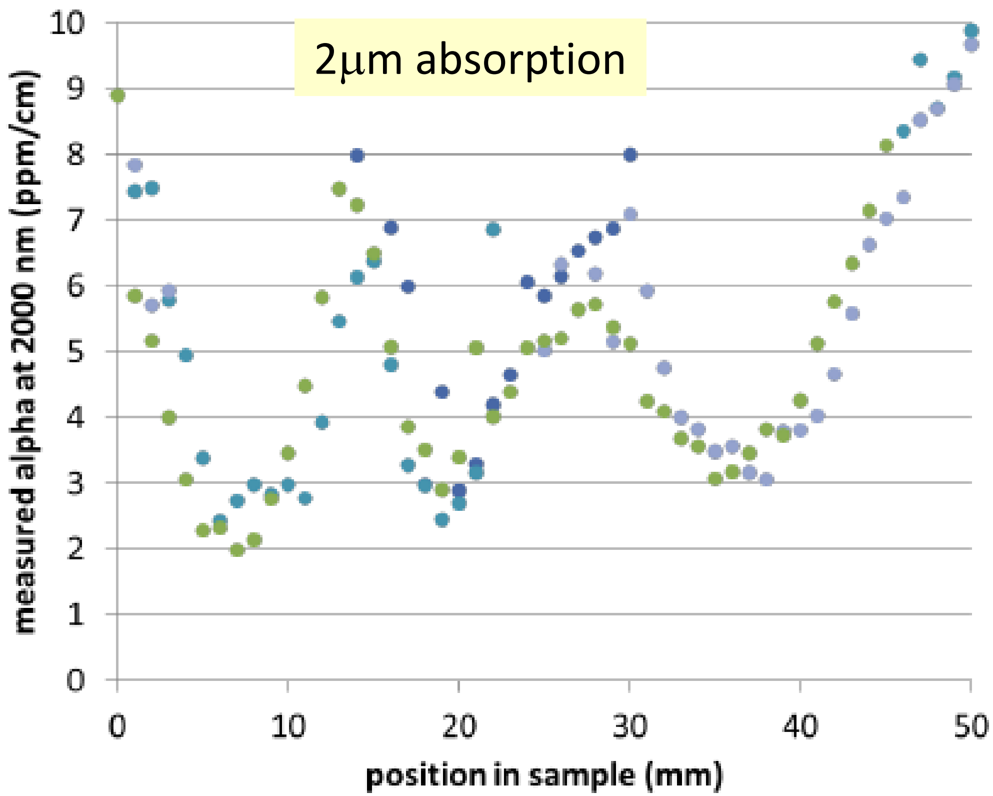


- mCz (~4kΩcm) can have similar absorption to float zone (40 kΩ/cm) – few ppm/cm at room temperature, increasing at low temperature
- Slightly higher absorption at 2um in both cases

A. Markosyan, A. Bell LIGO-G1700480

Silicon substrates – mCz absorption

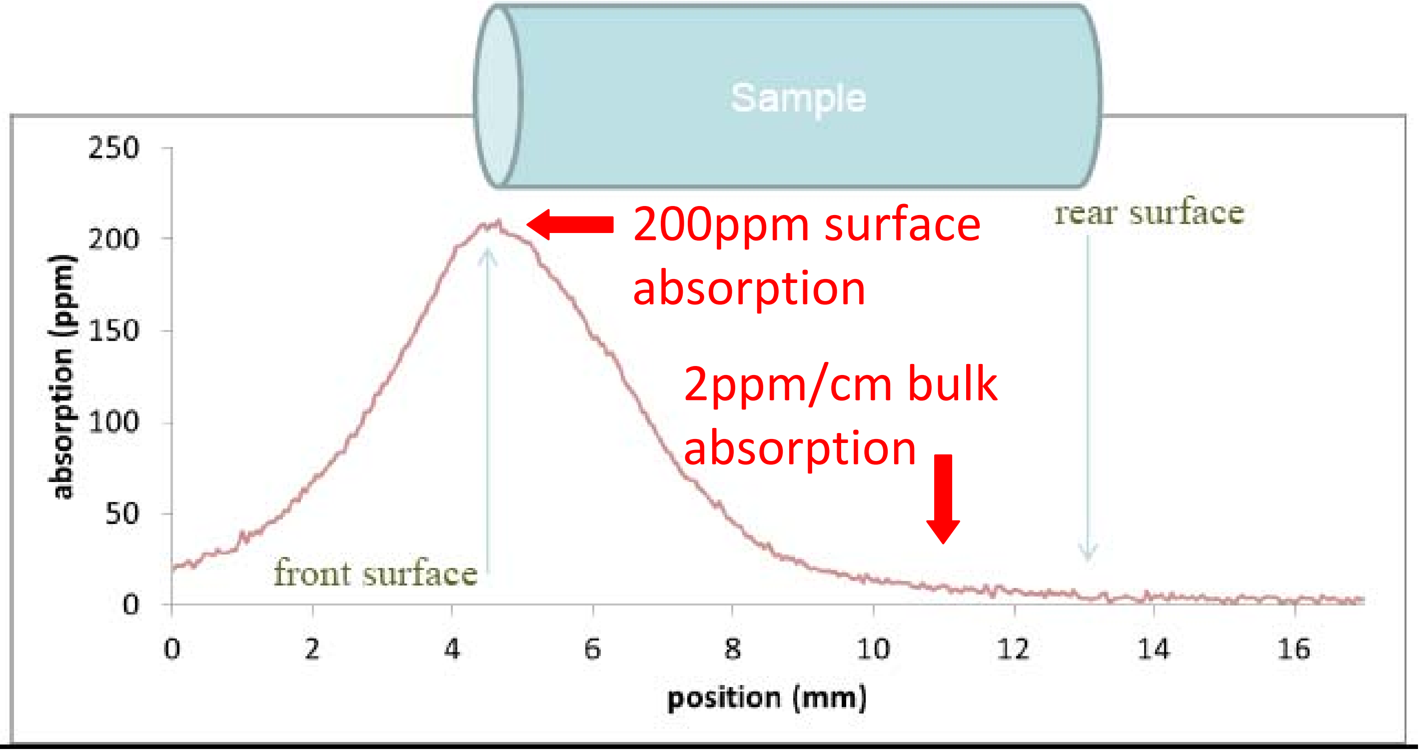




- absorption along ingot radius varies at different points in ingot
- some evidence of periodic variations in absorption
- further investigations needed, but material looks very promising

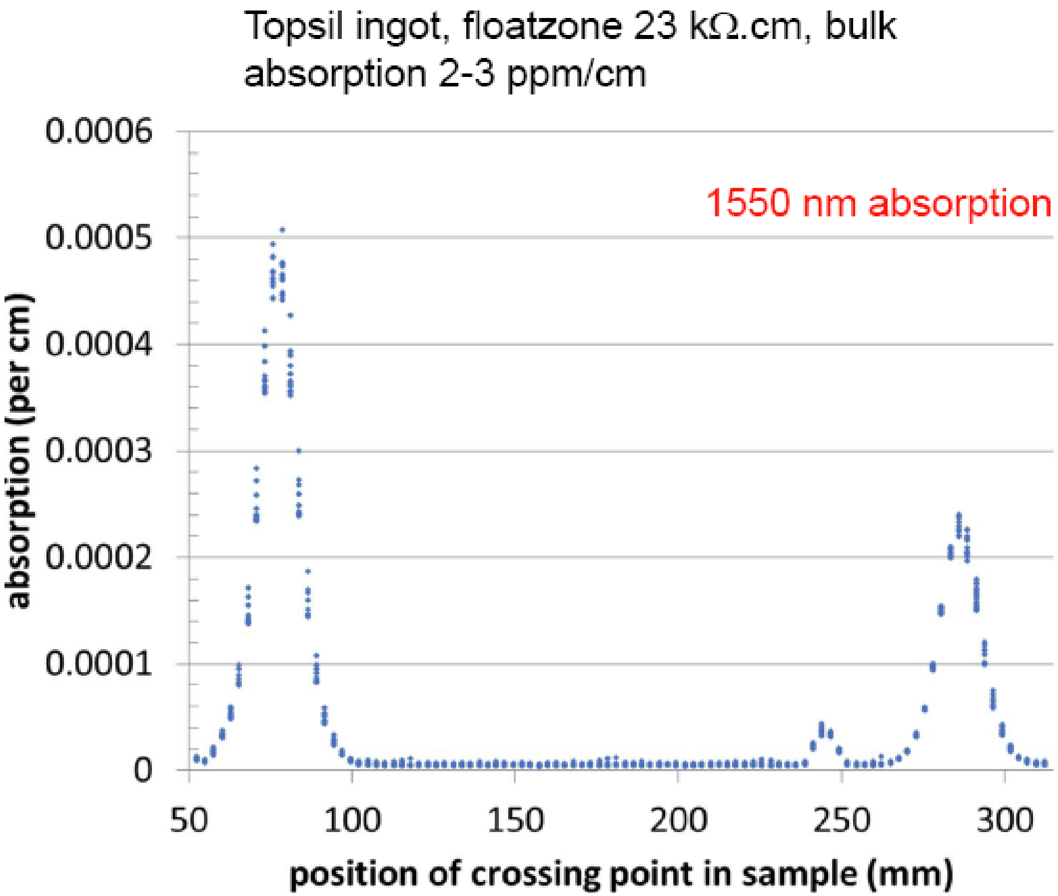
Silicon substrates – surface absorption

- Some Si surfaces with nominally identical treatments show large differences in absorption
- e.g. float zone sample:



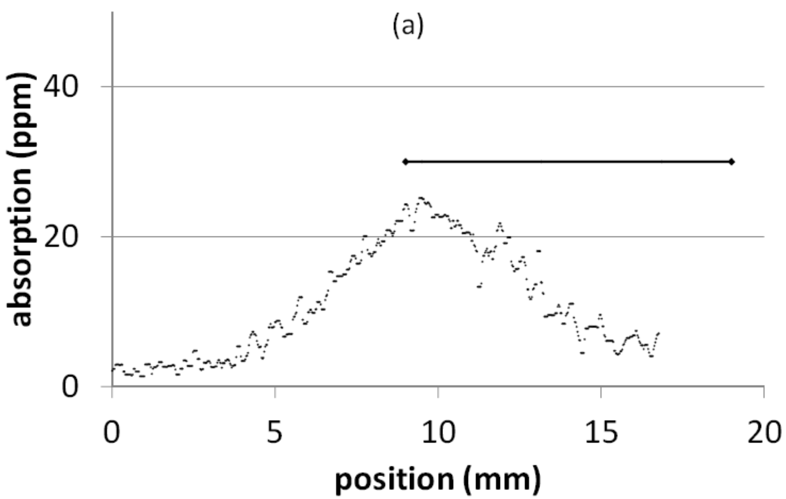
Silicon substrates – surface absorption

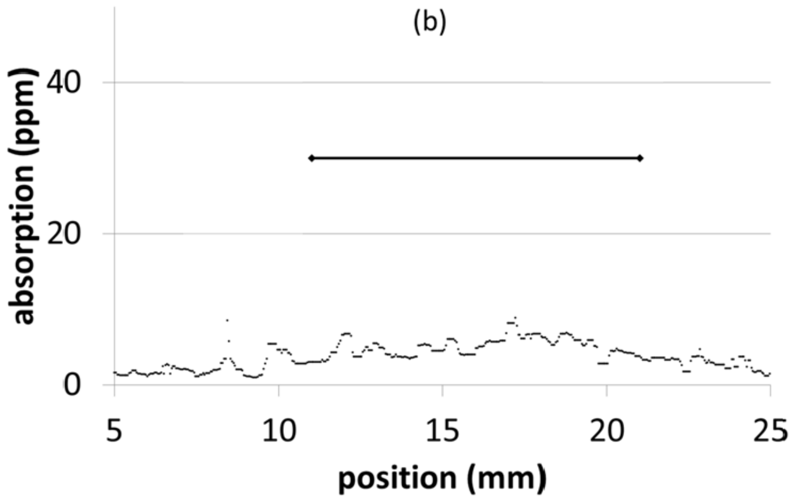
- Float zone ingot polished with diamond slurry and pitch lap
    - Consistently gives ~0.1% absorption at the surface
    - Results with colloidal silica slurry are better
- Etching tests: absorption not related to oxide layer (HF etch) removing 100nm of surface no effect (KOH etch)
- More systematic studies underway – effect of polishing slurry compound, pH, duration of polish….



Silicon substrates – surface absorption

Investigation of polishing compounds



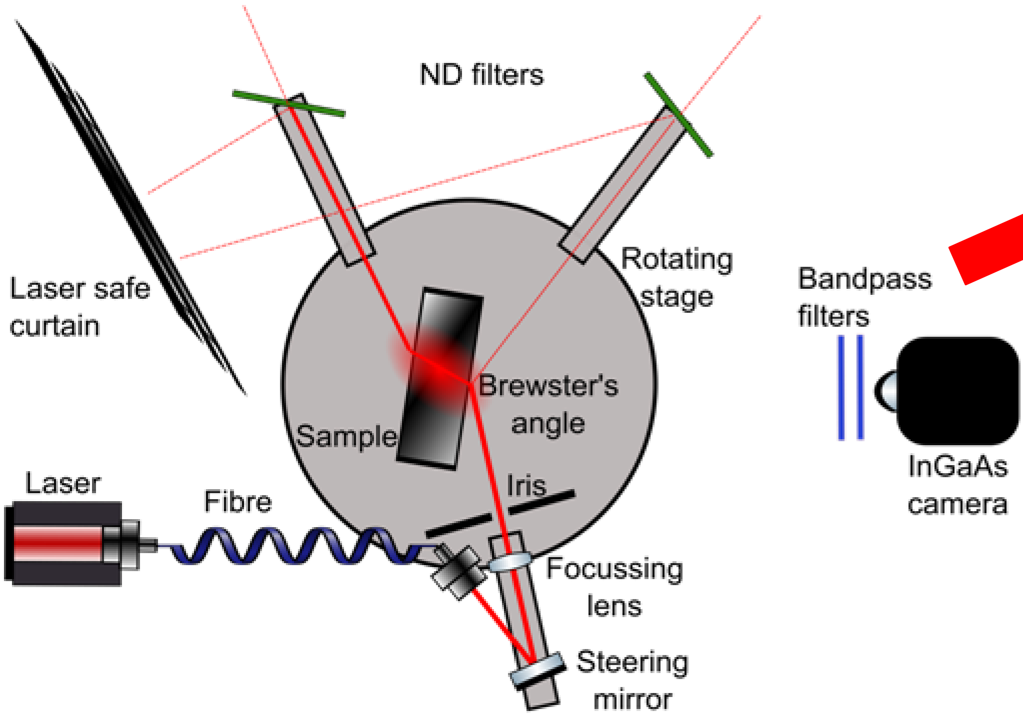


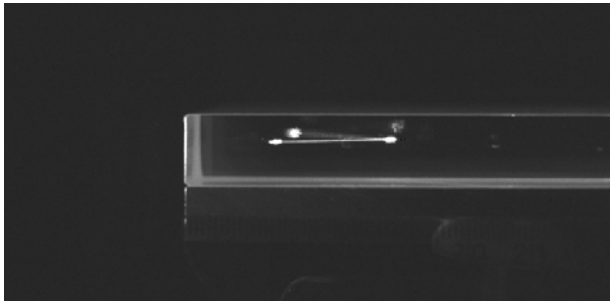
• Polish with Bindzil slurry: created consistent surface absorption on several samples, including previously 'clean' sample

• Grinding to remove 100 nm and polishing with Nalco slurry removed surface absorption

mCz silicon substrates – scatter

- High void density in mCz silicon – how does this affect scattering?
- Imaging scatterometer set up in Glasgow (Zeno Tornasi) at 1550 nm



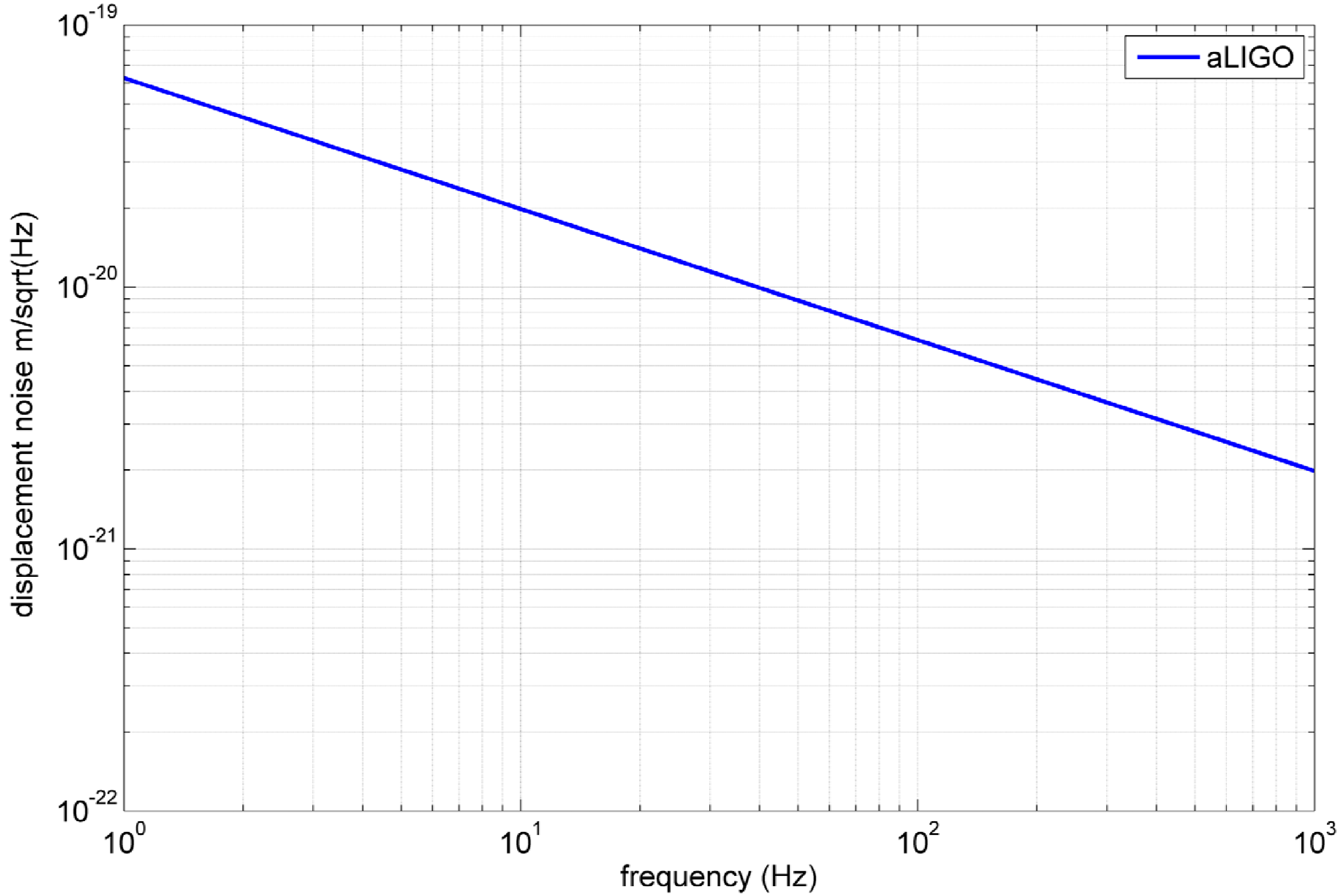


- Initial estimate ~1 ppm/cm scatter: appears higher than for float zone silicon
- Assumes Rayleigh scatter – angular / polarisation dependence needed for more accurate result – ongoing work

Coatings for cryogenic mirrors

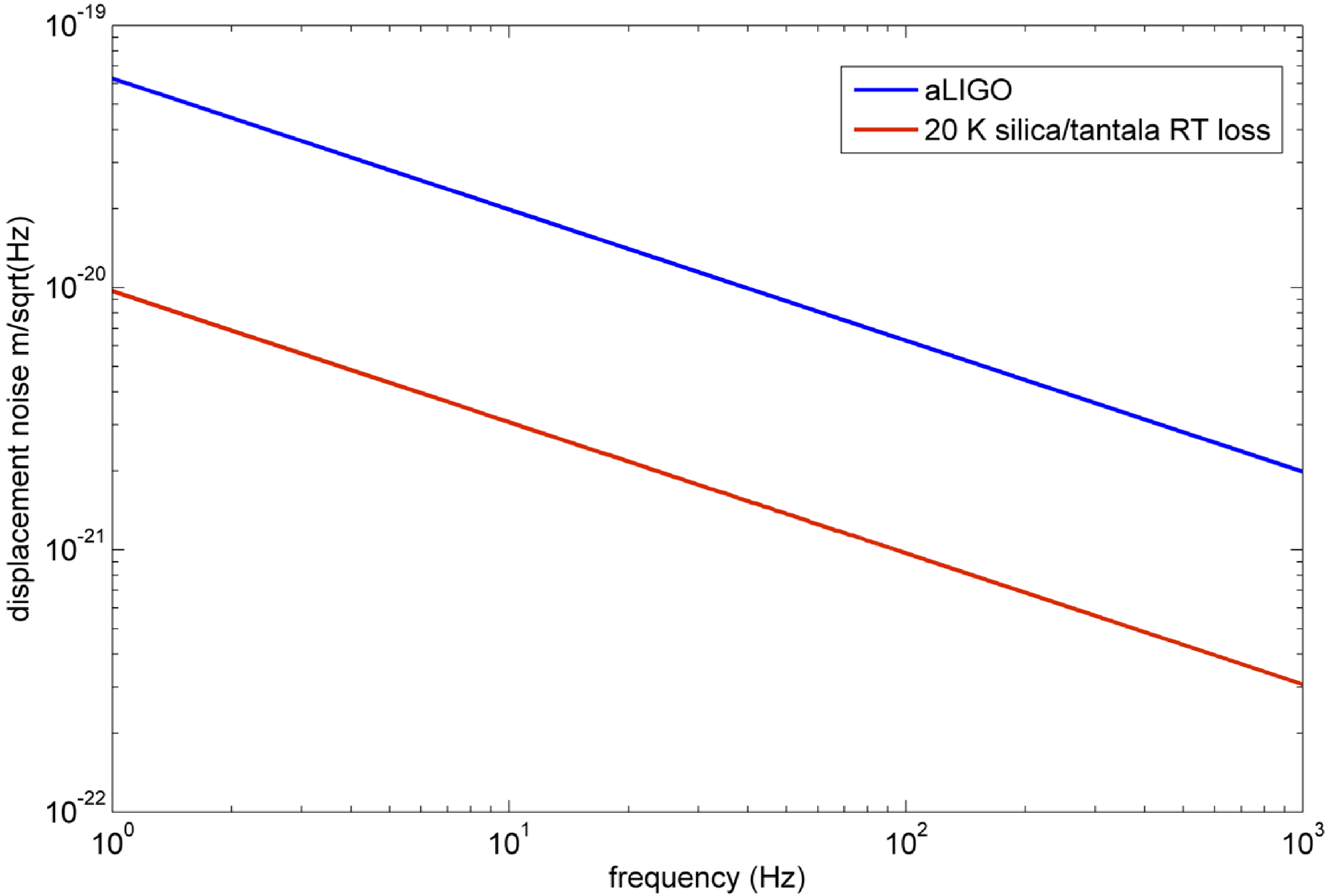
- Several options, here focus on amorphous coatings
- Requirements for ET-LF
  - Thermal noise: factor of 8.2 reduction in displacement noise
  - Optical absorption – exact requirements depend on detailed design and heat-extraction, but similar to current coatings ~1ppm, seems a reasonable target

Coating thermal noise



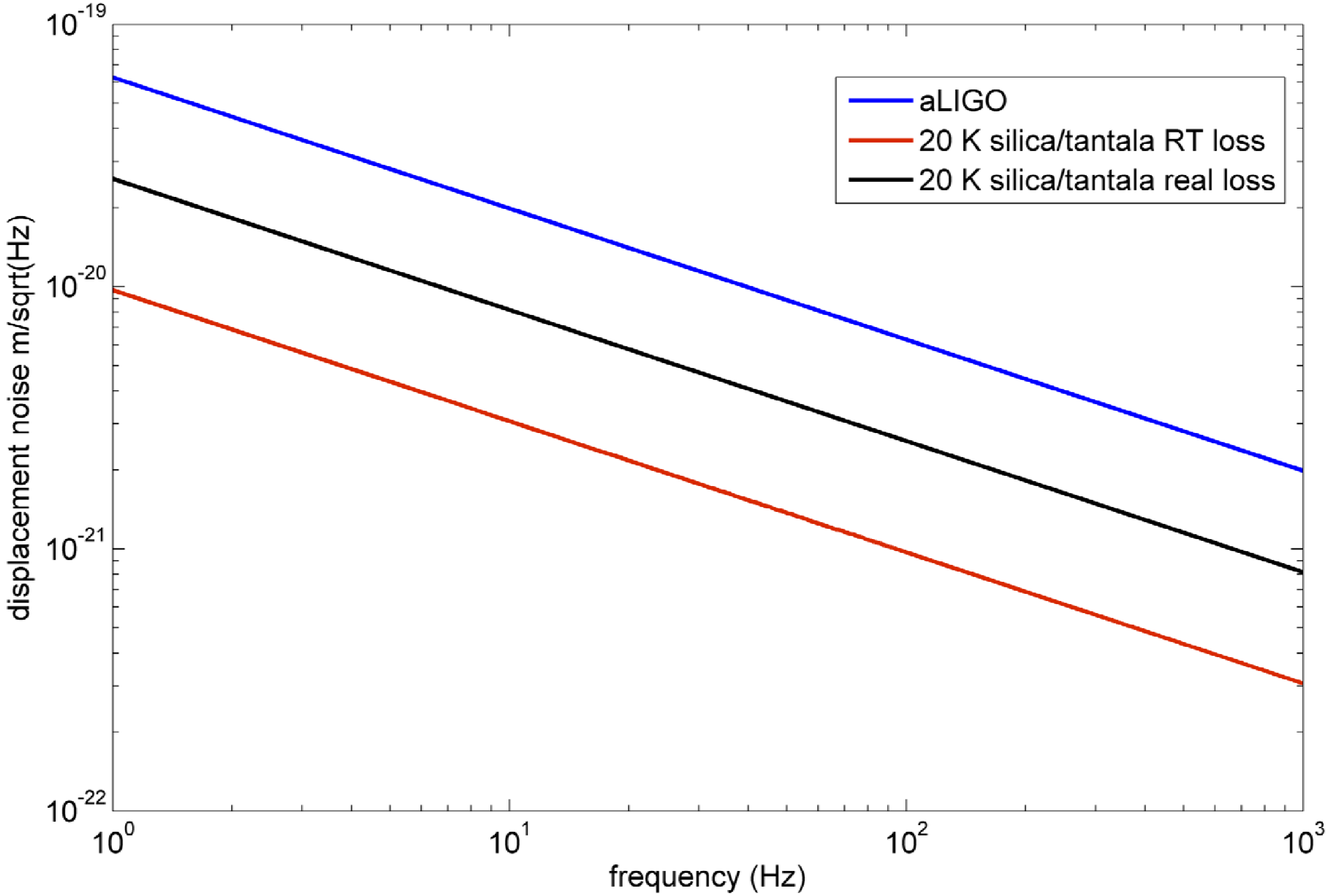
- Advanced LIGO ETM coating thermal noise
  - Silica substrate, 10640nm coating, 6.2cm beam radius

Coating thermal noise



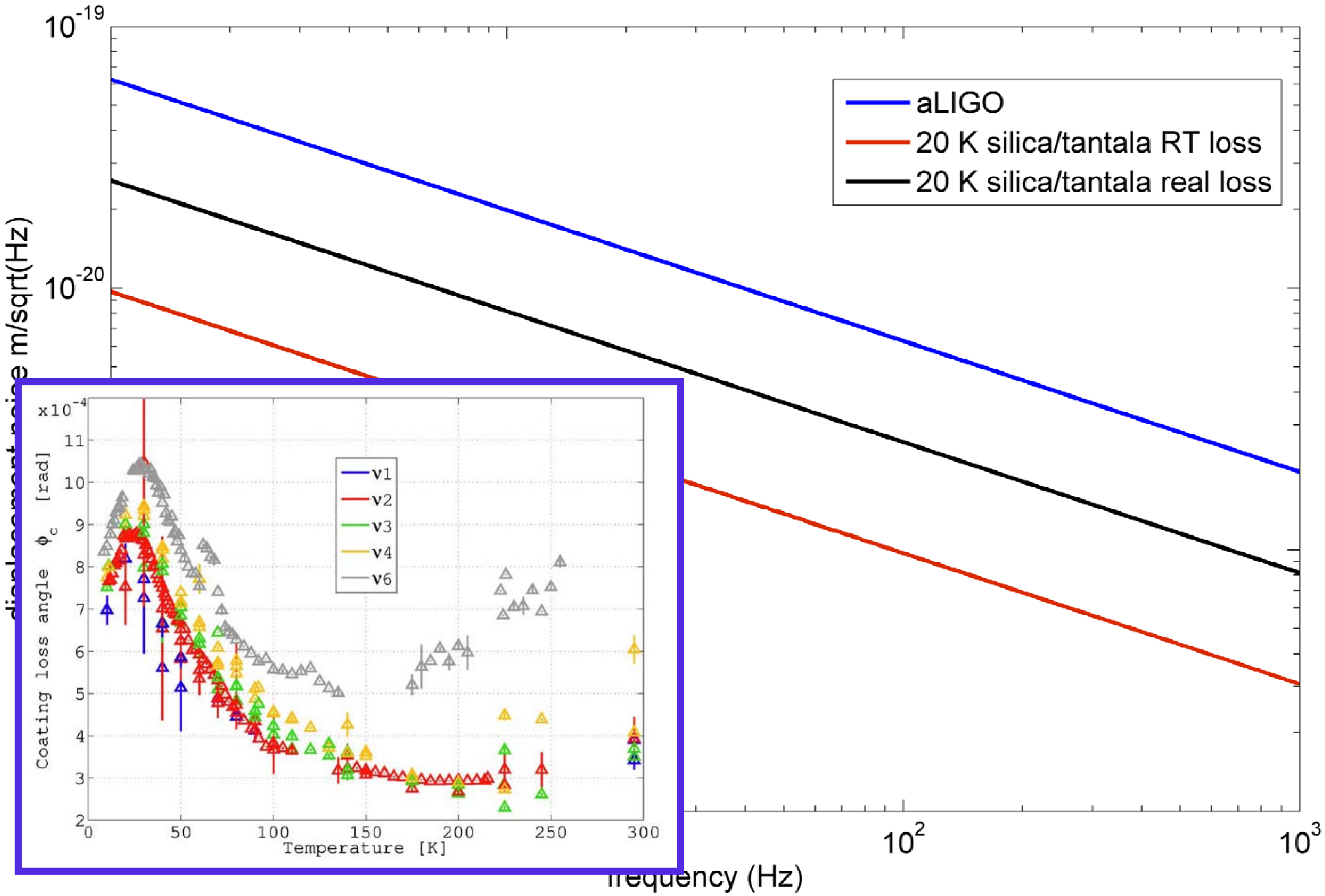
- 20 K coating thermal noise if lost constant with temperature
  - Silicon substrate, 1550nm coating, 9cm beam radius

Coating thermal noise



- 20 K coating thermal noise with measured coating loss
  - Silicon substrate, 1550nm coating, 9cm beam radius

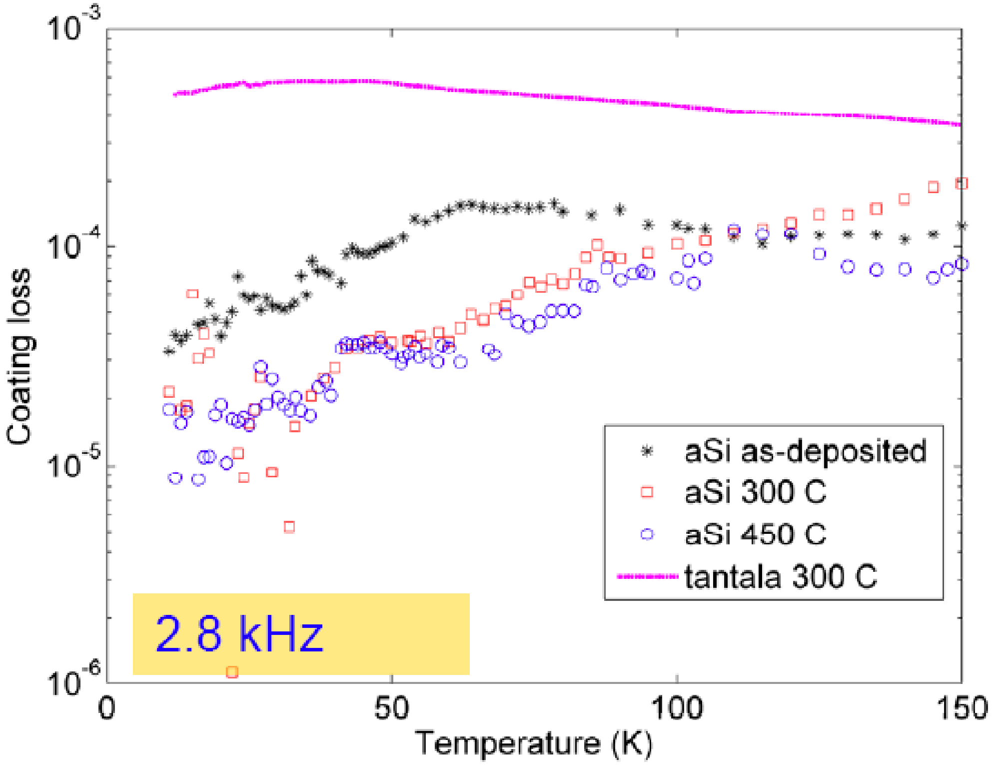
Coating thermal noise



- Less reduction than expected with cooling due to cryogenic coating loss peaks [Granta et al, Optics Letters 38 (2013)]

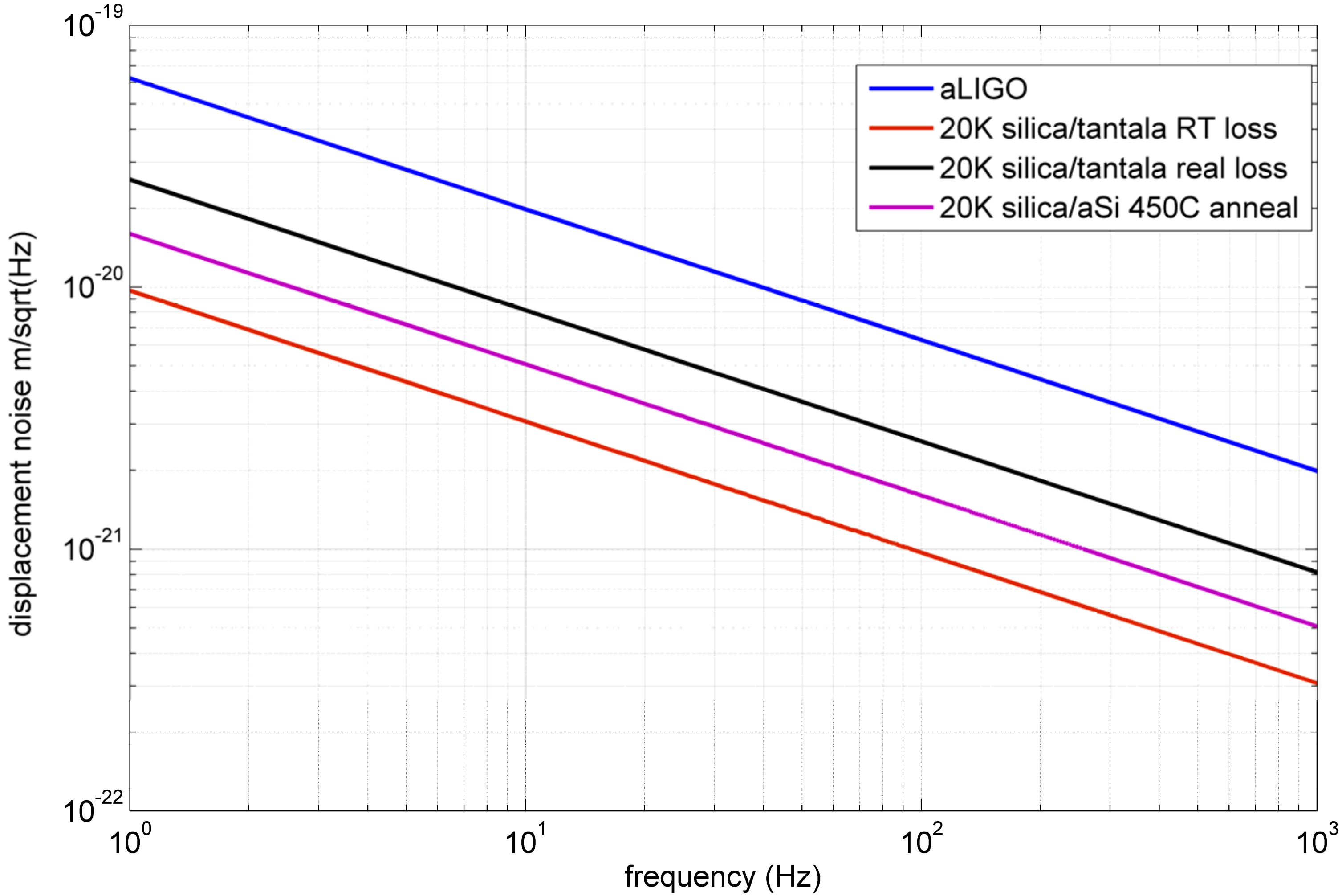
Coating thermal noise - aSi

- Amorphous silicon
  - Low mechanical loss, 2E-5 at 20 K (commercial IBS - ATF)
  - High index n=3.5: thinner coatings, less thermal noise
  - Can have high optical absorption, but work in progress (later, and David Vine's talk)



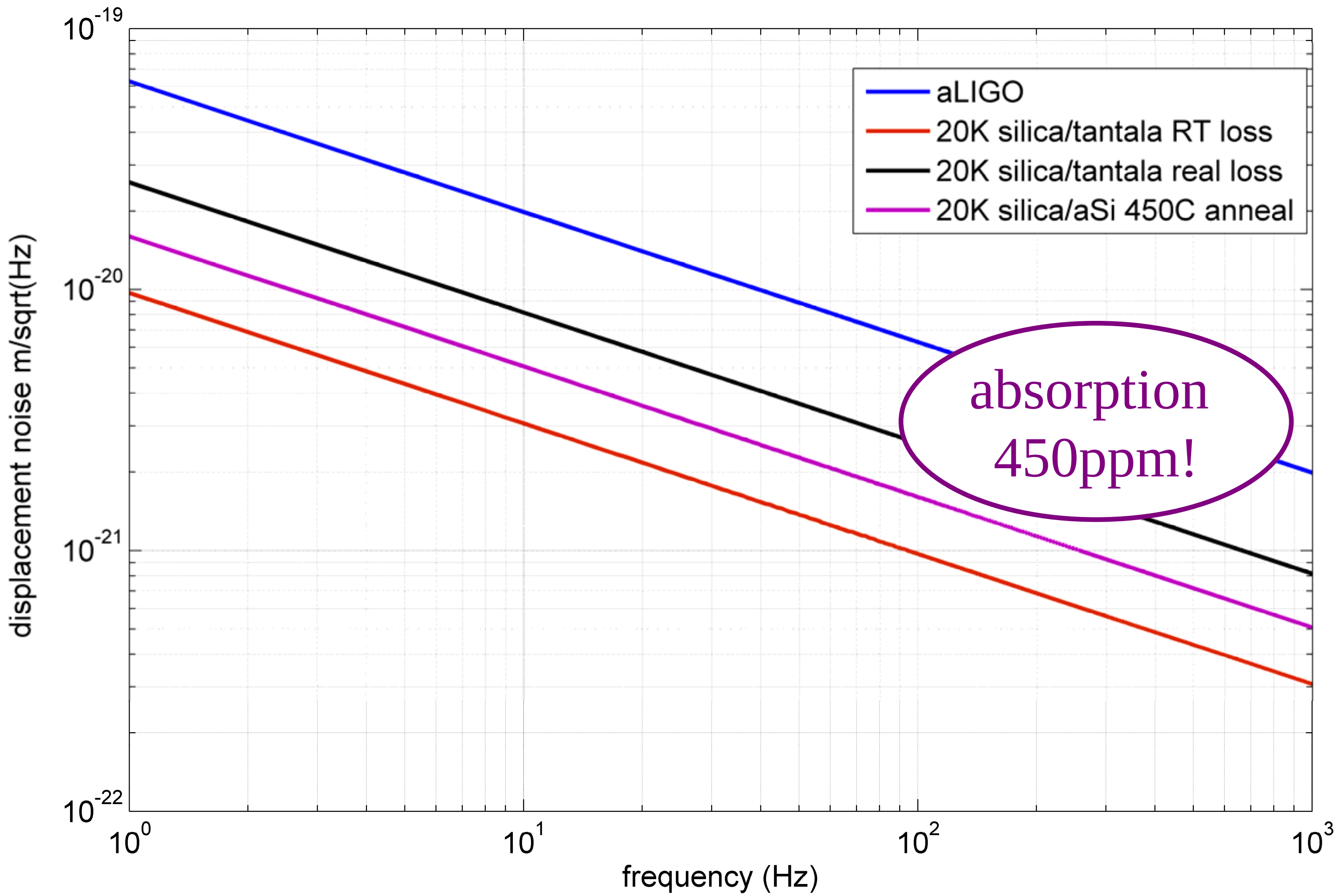
Murray et al., Phys. Rev. D. 92 (2015)

Coating thermal noise



- 20 K coating thermal noise for 7 bilayer IBS aSi/SiO2 coating
  - Silicon substrate, 1550nm coating, 9cm beam radius, annealed 450 C

Coating thermal noise



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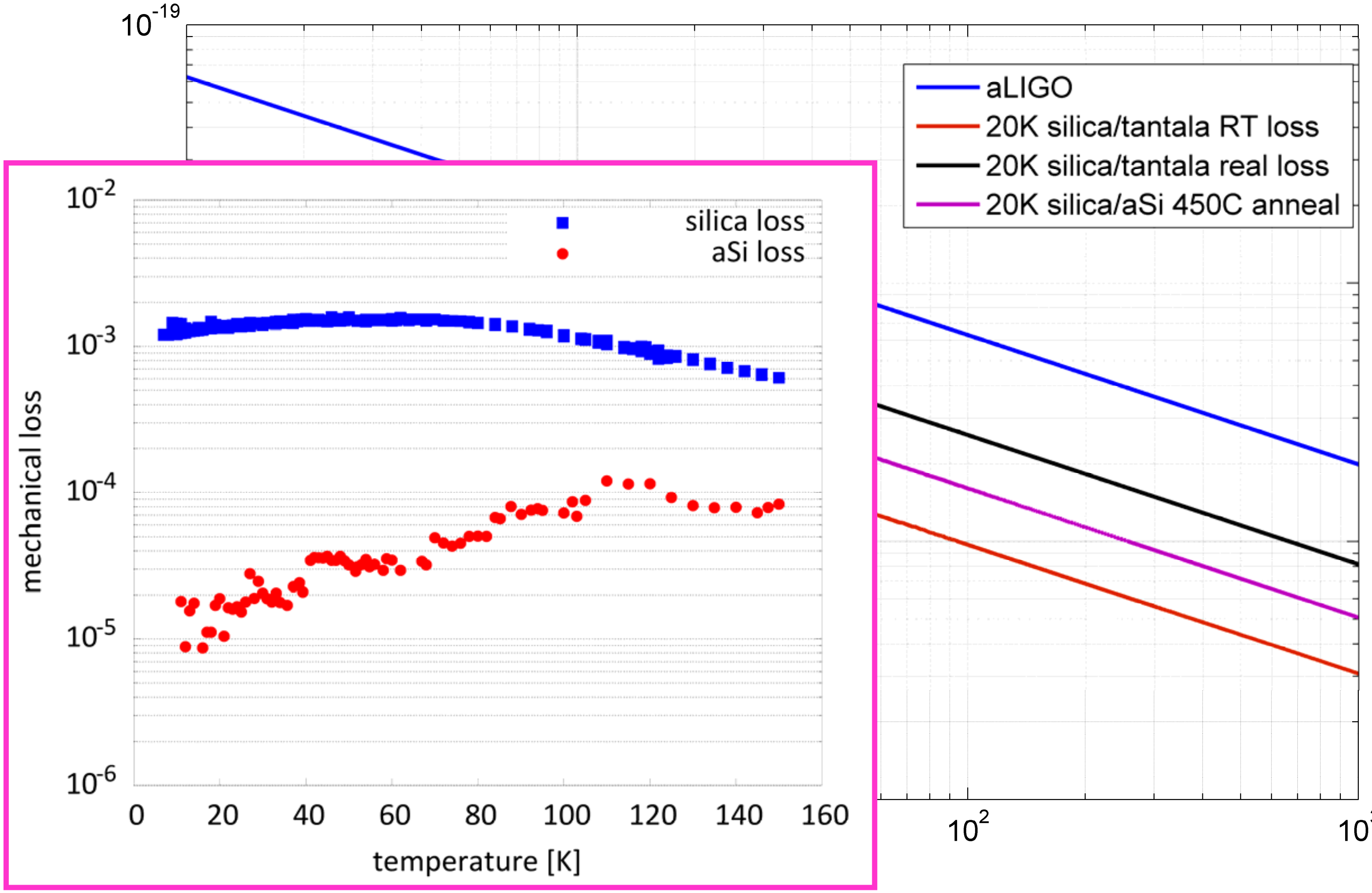
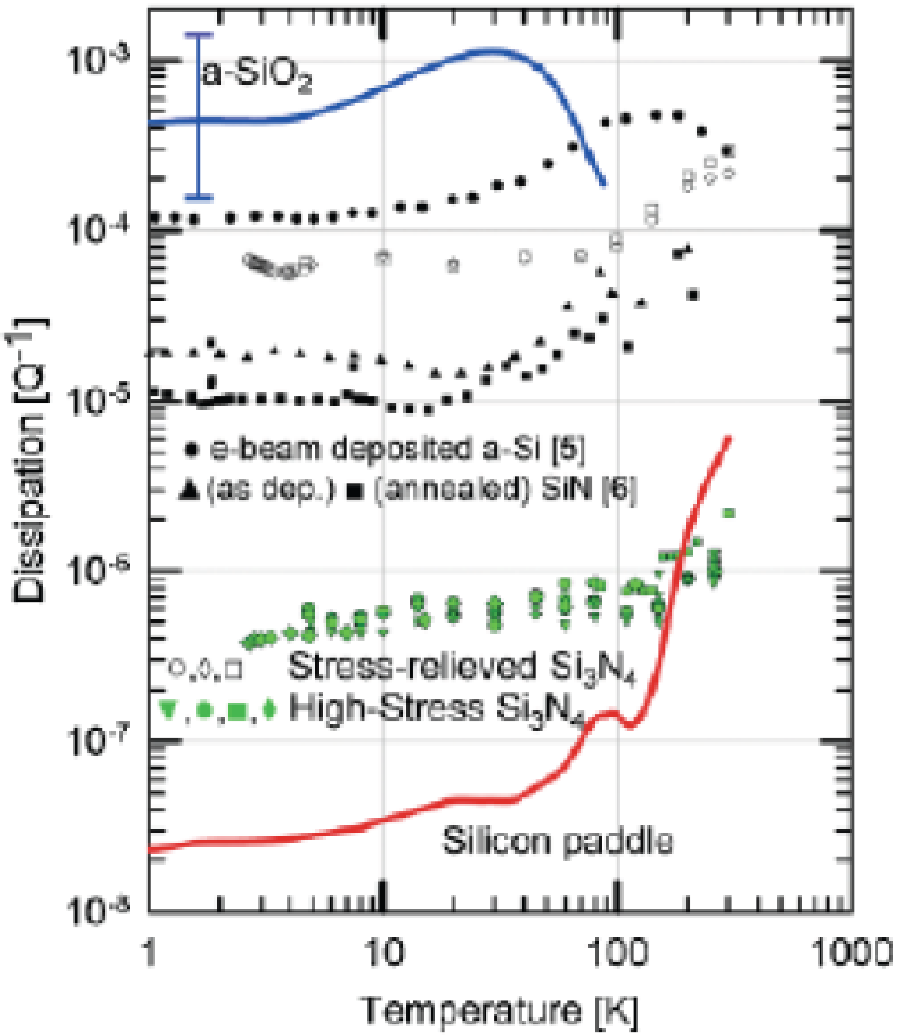
Coating thermal noise



- IBS aSi/SiO2 coating – thermal noise limited by high loss SiO2 layers – need alternative low index material

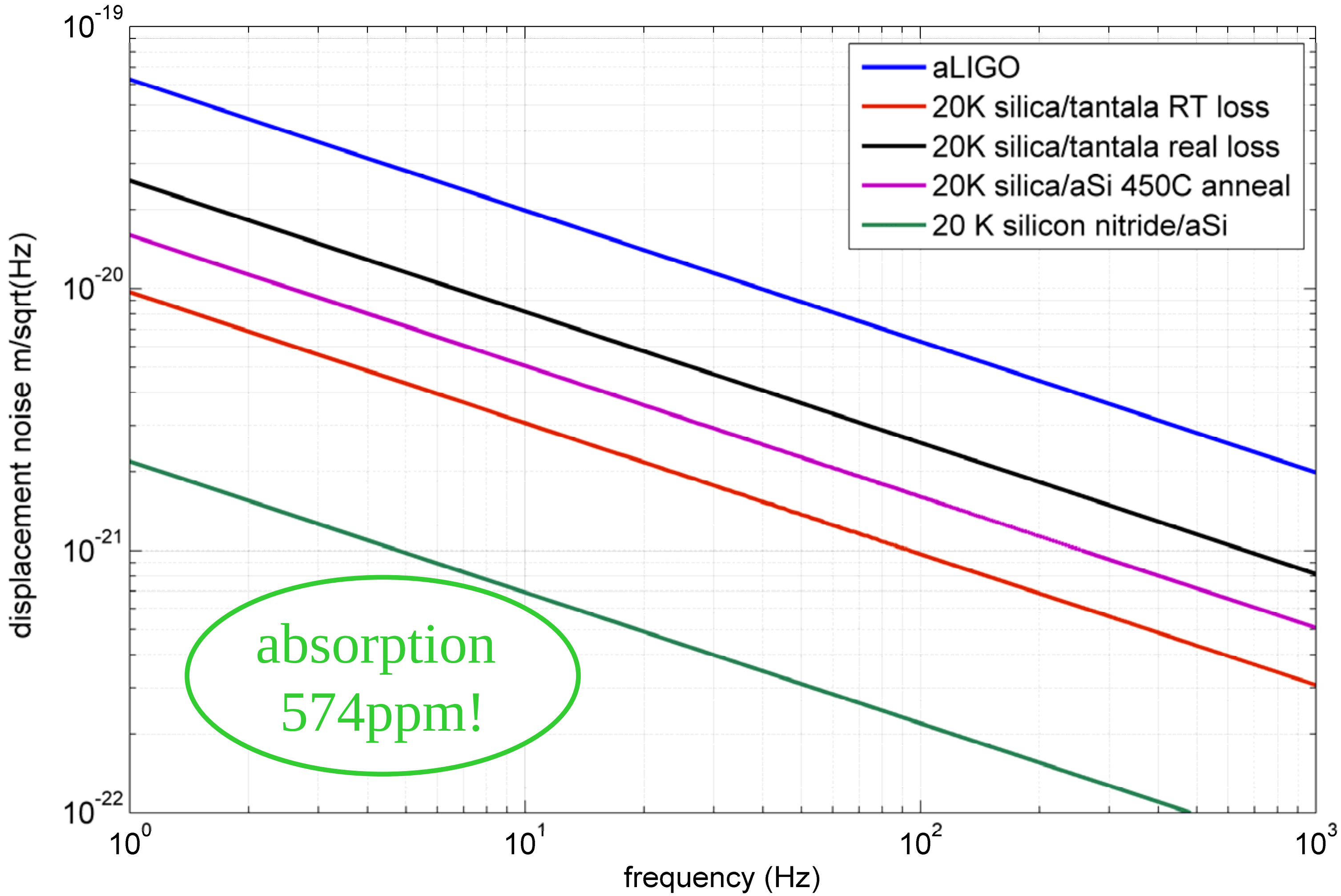
Silicon nitride as a low-index material

- Silicon nitride
  - Low cryogenic mechanical loss: 1E-5 to 1E-7 around 20K
  - Index n=2.05 – use as low index partner to aSi instead of SiO2?
  - Absorption ~20ppm for HR SiN/SiO2 coating
  - Work done by Shiuh Chao indicates reasonably low loss at room temperature also (e.g. LIGO G1600363-v2)



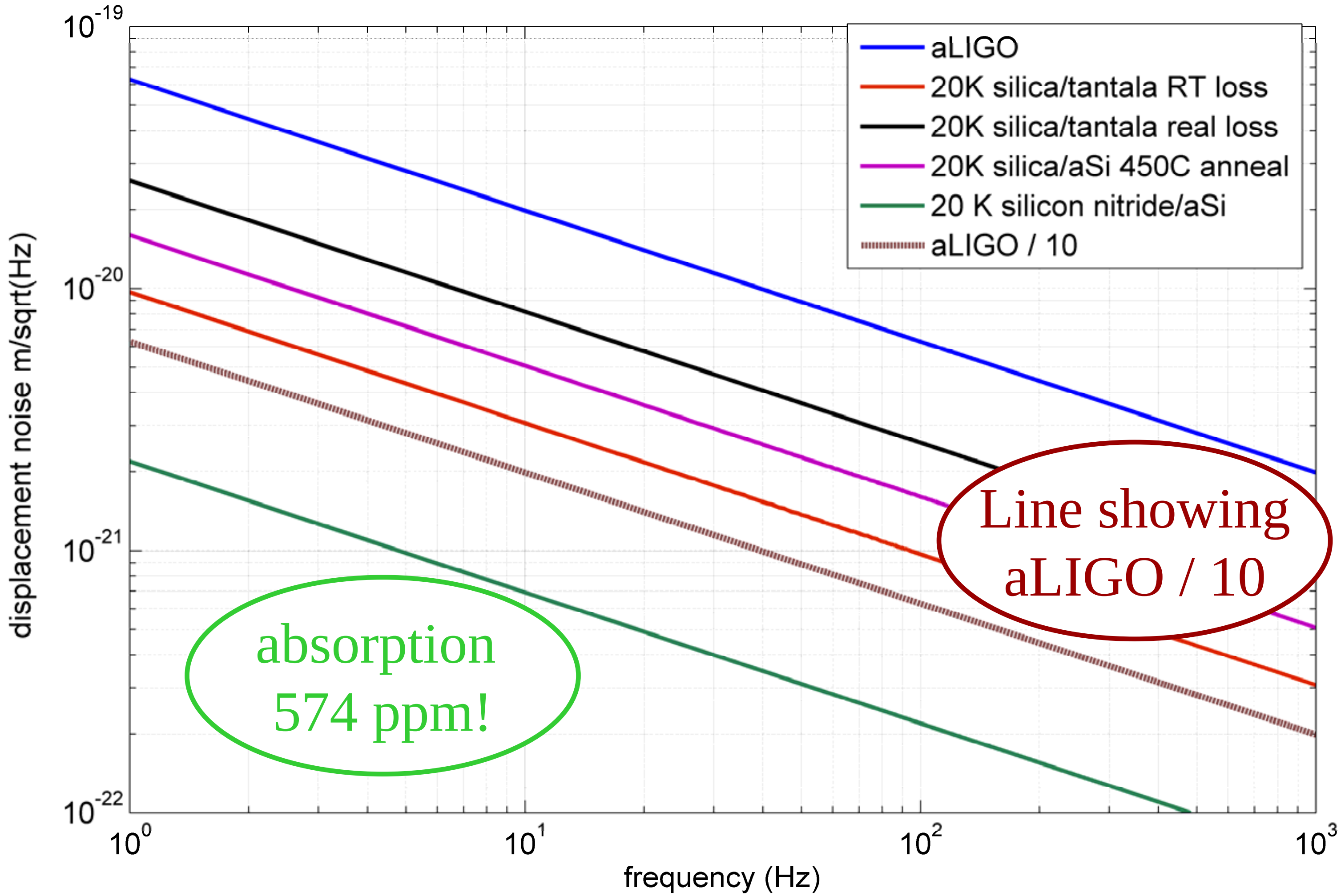
Ref. 1: D. R. Southworth , et al. PhysRevLett.102.225503(2009)

Coating thermal noise



- 20 K coating thermal noise for SiN/aSi coating
  - Silicon substrate, 1550nm coating, 9cm beam radius

Coating thermal noise



- 20 K coating thermal noise for SiN/aSi coating
  - Silicon substrate, 1550nm coating, 9cm beam radius

aSi coating absorption

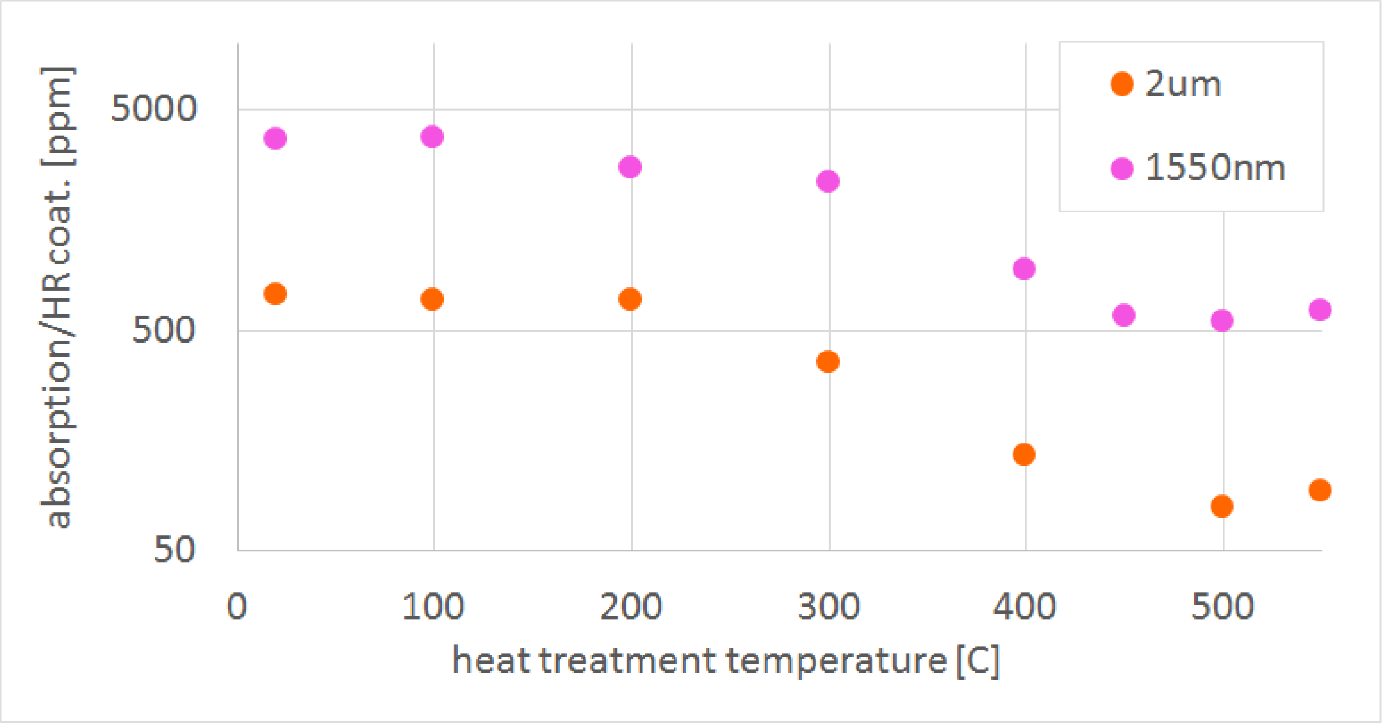
- aSi coatings show great potential for cryogenic thermal noise

- Absorption is too high and dominates the absorption of aSi/SiO2 and aSi/SiN coatings. Strong variation with deposition method:
  - Commercial IBS (ATF) 14 000 ppm / HR aSi/SiO2 stack (as-deposited)
  - Ion-plating (Tafelmaier) 3600 ppm / HR aSi/SiO2 stack (as-deposited)
  - IBS (UWS) lower – more details in David Vine's talk

- Efforts to study and reduce aSi absorption
  - Heat-treatment
  - Temperature
  - Wavelength

aSi coatings – reducing absorption

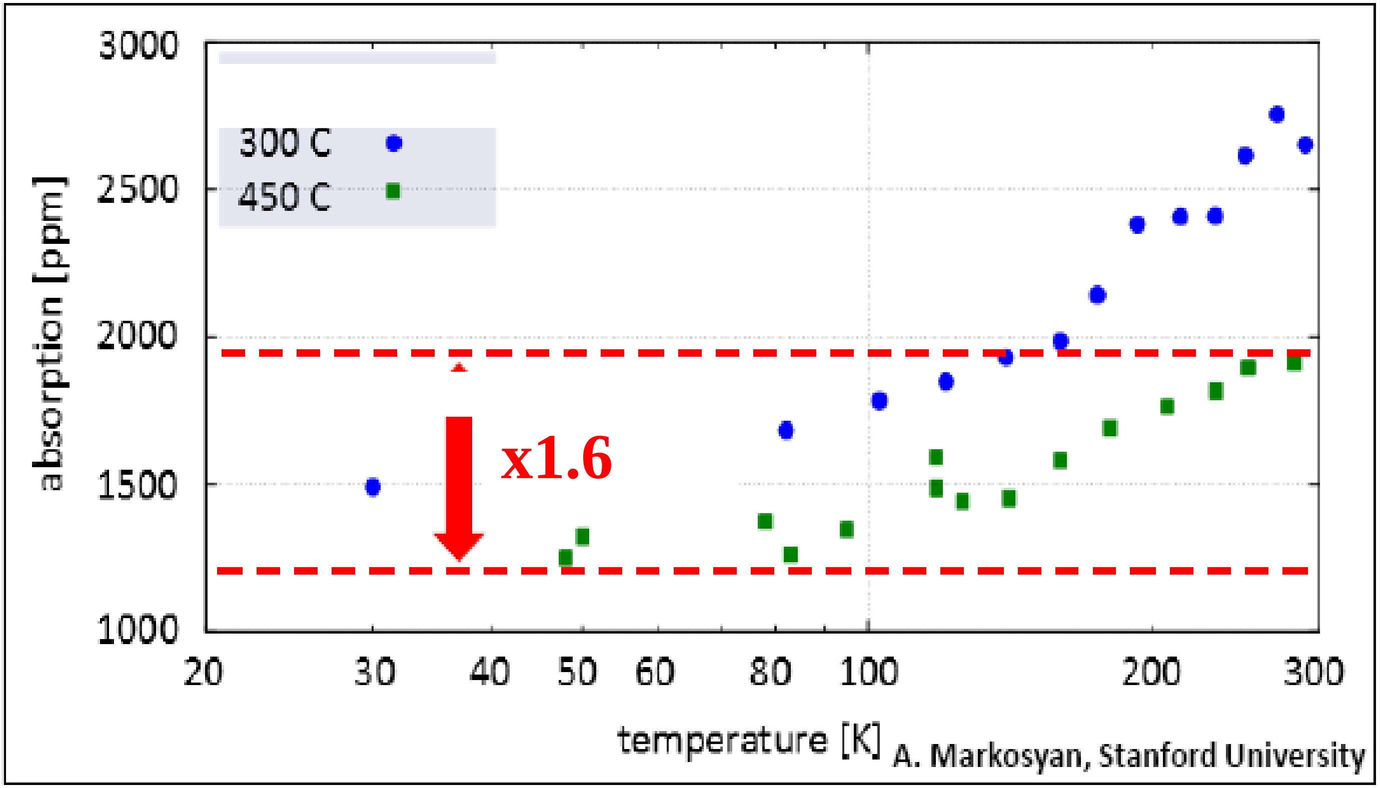
Ion-plating aSi coating



- Absorption minimum with heat-treatment at ~500°C
- x7 absorption decrease when moving from 1550nm to 2µm

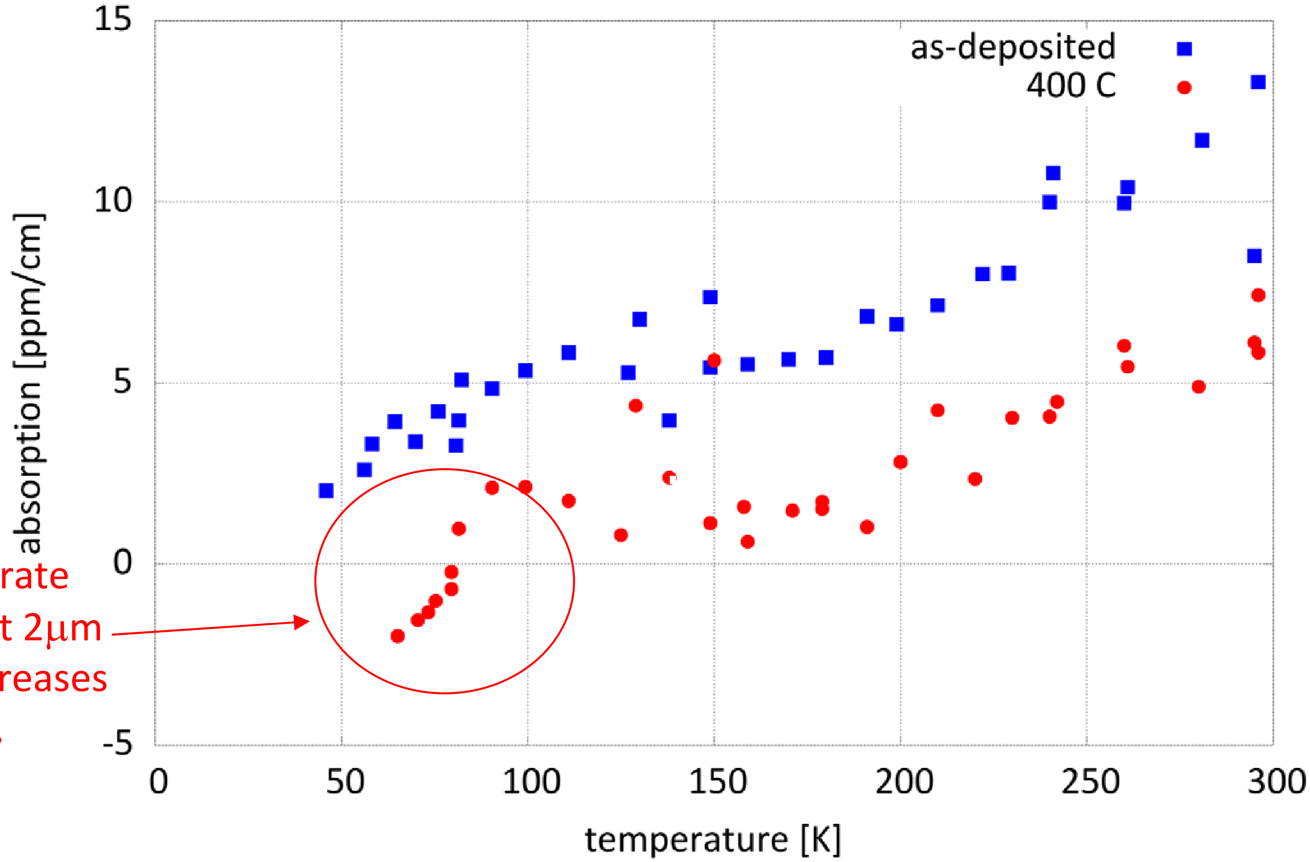
aSi coatings – reducing absorption

Ion-beam sputtered aSi coating (ATF)



- x 1.6 absorption reduction on cooling to 50 K

aSi coatings - cryogenic 2 μm absorption

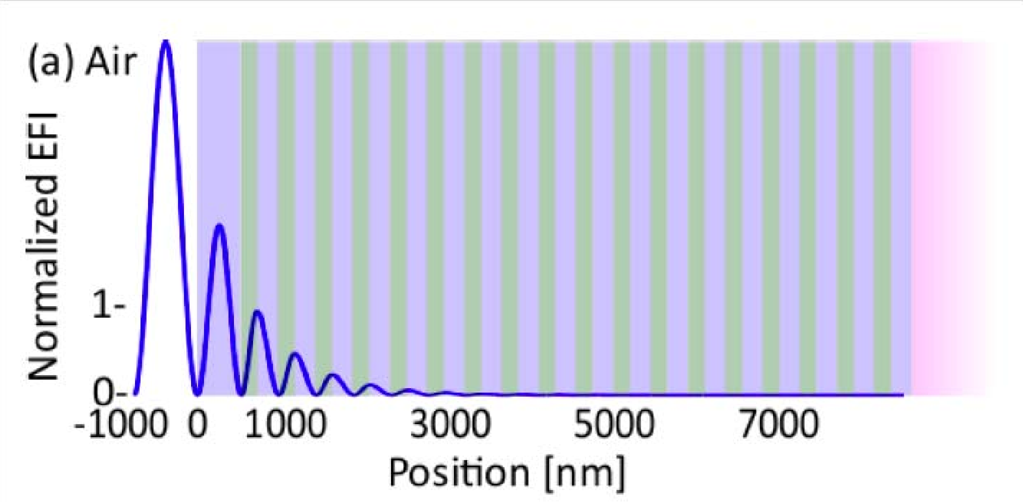


Due to substrate absorption at 2μm the error increases below 100 K, resulting in negative absorption values

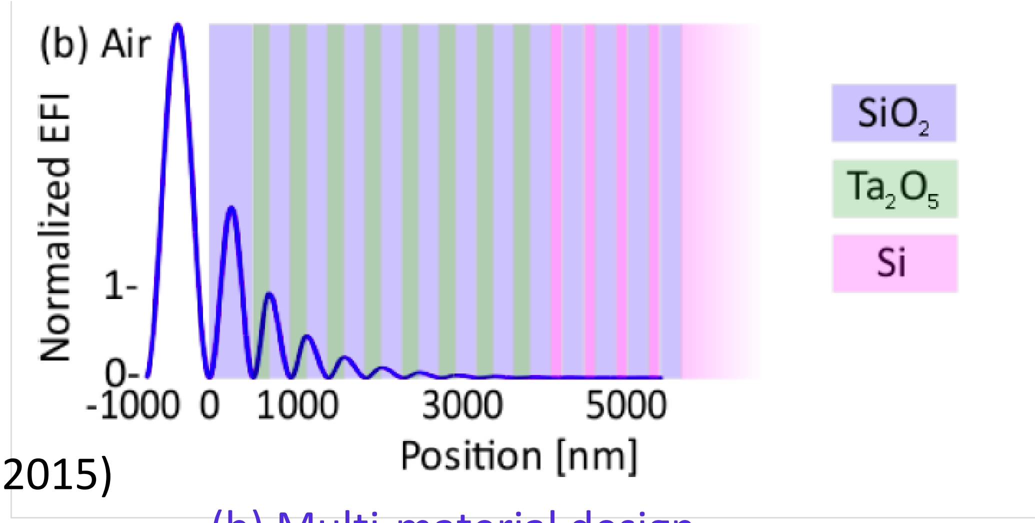
- Absorption reduction by factor of 2-3 on cooling to 100 K
- Strong case for 2 μm operation for low aSi absorption

aSi coatings – multimaterial designs

- Absorption of aSi still too high
- Multi-material design:
  - Replace 10 lower silica/tantala layers (where laser power is already low) with 4 layers of silica/aSi
  - Same reflectivity, lower mechanical loss, similar absorption
  - Number of layers of tantala replaced depends on absorption of aSi



(a) 18-layer silica/tantala coating



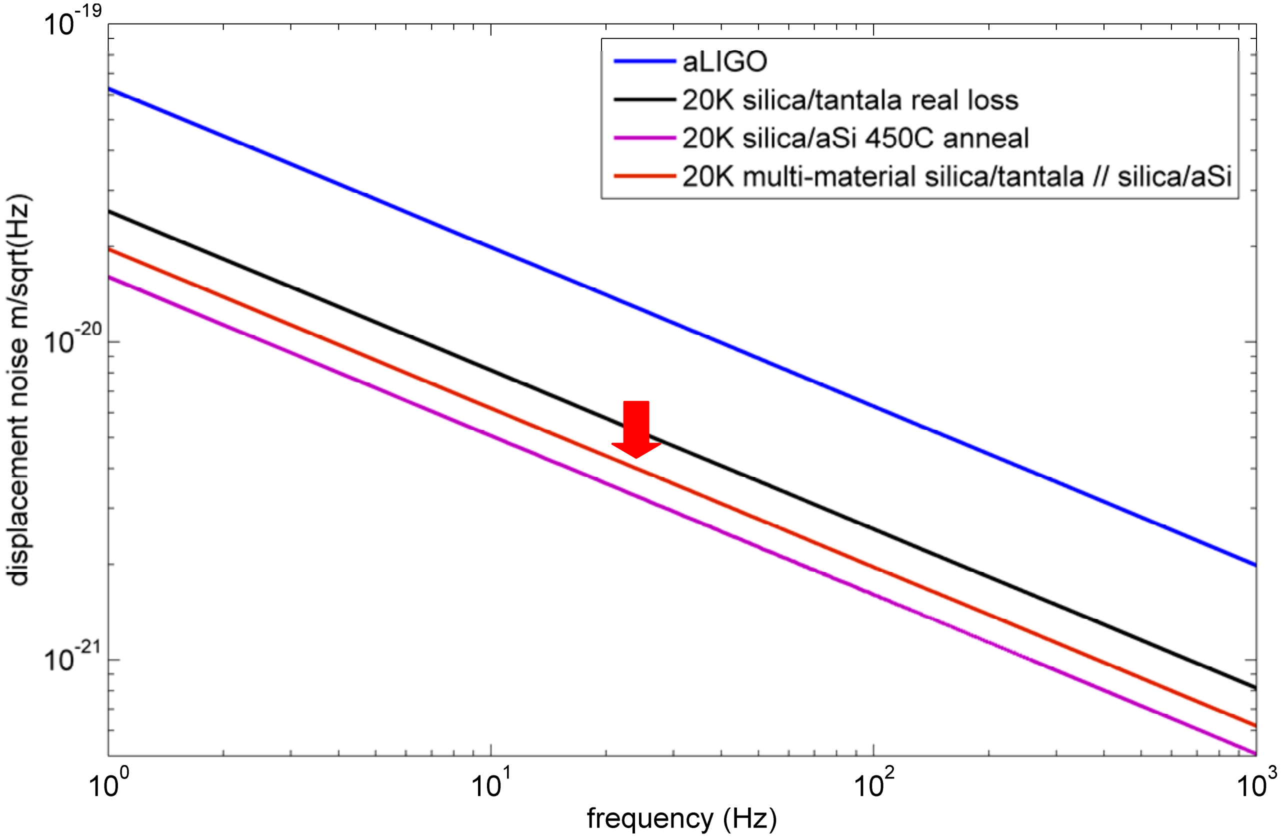
(b) Multi-material design

Steinlechner, Martin et al., Phys. Rev. D. 91 (2015)
Yam et al., Phys. Rev. D. 91 (2015)

aSi coatings – multi-material designs

- ETM multi-material: 8 bilayers silica/tantala and 4 bilayers of silica/aSi

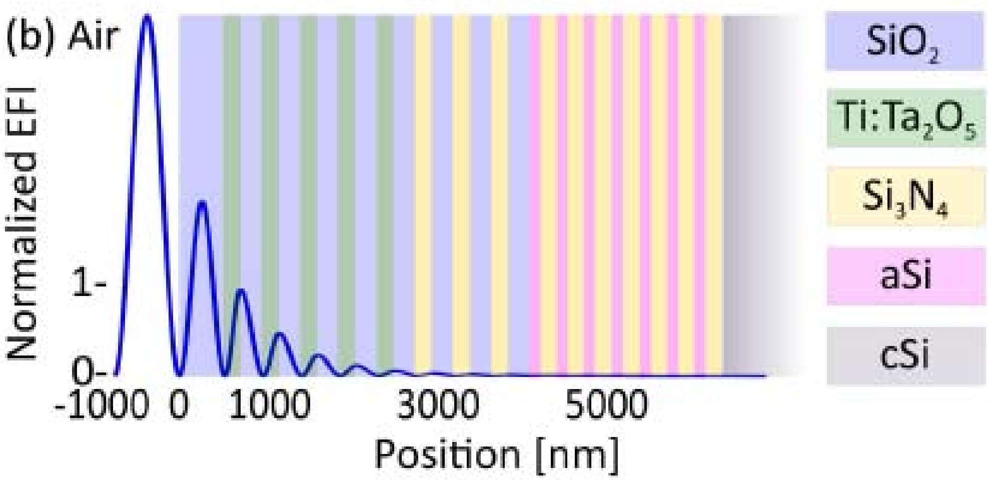
- R = 99.99995%
- Absorption: 5ppm (as-deposited ion plating aSi)
- 24% TN reduction at 20 K
- Modest but real improvement, pushing towards the best we could do with an aSi/silica coating



aSi coatings – multi-material designs

- Further improvements with multi-material designs
  - Each factor of 2 absorption reduction allows a lossy tantala layer to be replaced with aSi, further reducing coating loss and coating thickness
    - e.g. 2μm: aSi absorption in 7x lower, gives significant benefits

- Other materials/designs e.g. incorporation of silicon nitride, silica-doped hafnia as low-index partners to aSi



40% reduction in CTN over silica/tantala

Summary

- Absorption of mCz silicon appears similar to float zone, around a few ppm, slightly increasing at 2μm and at low temperatures
- Surface absorption is not intrinsic to silicon and can be prevented / removed by appropriate polishing techniques
- Initial scattering measurements of mCz Si underway
- Moving away from oxide coatings to aSi and/or silicon nitride is promising for reducing coating thermal noise
- Multi-material designs enable some thermal noise benefits from aSi without introducing excessive coating absorption
- aSi absorption is a driver towards 2μm to maximise thermal noise benefits of aSi