Suspension design for ET
– thermal noise of cryogenic optics –

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GWADW09 Meeting, Fort Lauderdale/FL
10th - 15th May 2009

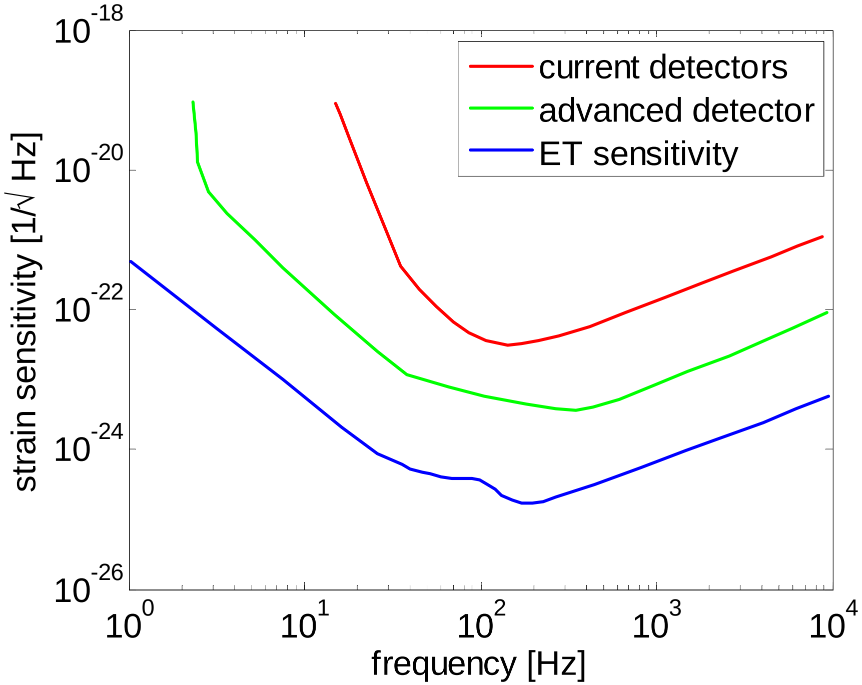
ET Design Study – contract # 211743

Overview

- introduction (ET, desired design sensitivity...)
- mirror thermal noise (initial guess of geometry)
- overview of possible coating techniques (dielectric, resonant waveguide, monolithic)
- open questions, tasks to be done

Introduction

- ET – Einstein Telescope
- 3rd generation detector
- sensitivity improvement by a factor of 10 in all frequency regions



- considered:
  - sophisticated suspension system (superattenuator)
  - arm length ~ 10 km, underground
  - squeezed light, non-Gaussian beams
  - cryogenics

Thermal noise calculation

- restrictions for this talk:
  - only end mirror considered
  - start with Advanced LIGO geometry (crosscheck possible)
- reasons:
  - transmissive components could be avoided (use of all-reflective components)
  - contribution of tantala layers can be reduced (e.g. thickness, novel concepts)
  - thus, further reduction of thermorefractive noise

Main thermal noise contribution

- Brownian thermal noise
  - bulk material
  - coating material

- thermoelastic noise
  - bulk material
  - coating material

- other contributions were lower for final mirror

- detailed calculation including temperature dependent values ↔ BENCH

Bulk Brownian Noise

infinite test mass: $$S_X^{ITM}(f,T) = \frac{2k_BT}{\pi^{3/2}\, f} \times \frac{1-\sigma^2}{w\,Y} \times \phi_{substrate}(f,T)$$

[Liu, Thorne 2000]

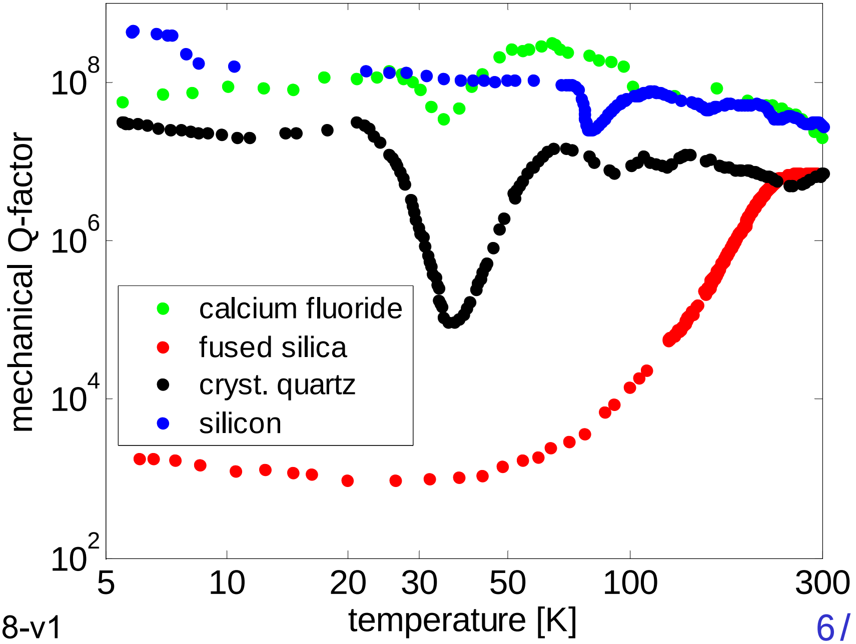
finite test mass: $$S_X^{FTM}(f,T) = C_{FTM}^2 \times S_X^{ITM}(f,T)$$

[Liu, Thorne 2000; Bondu, Hello, Vinet 1998]

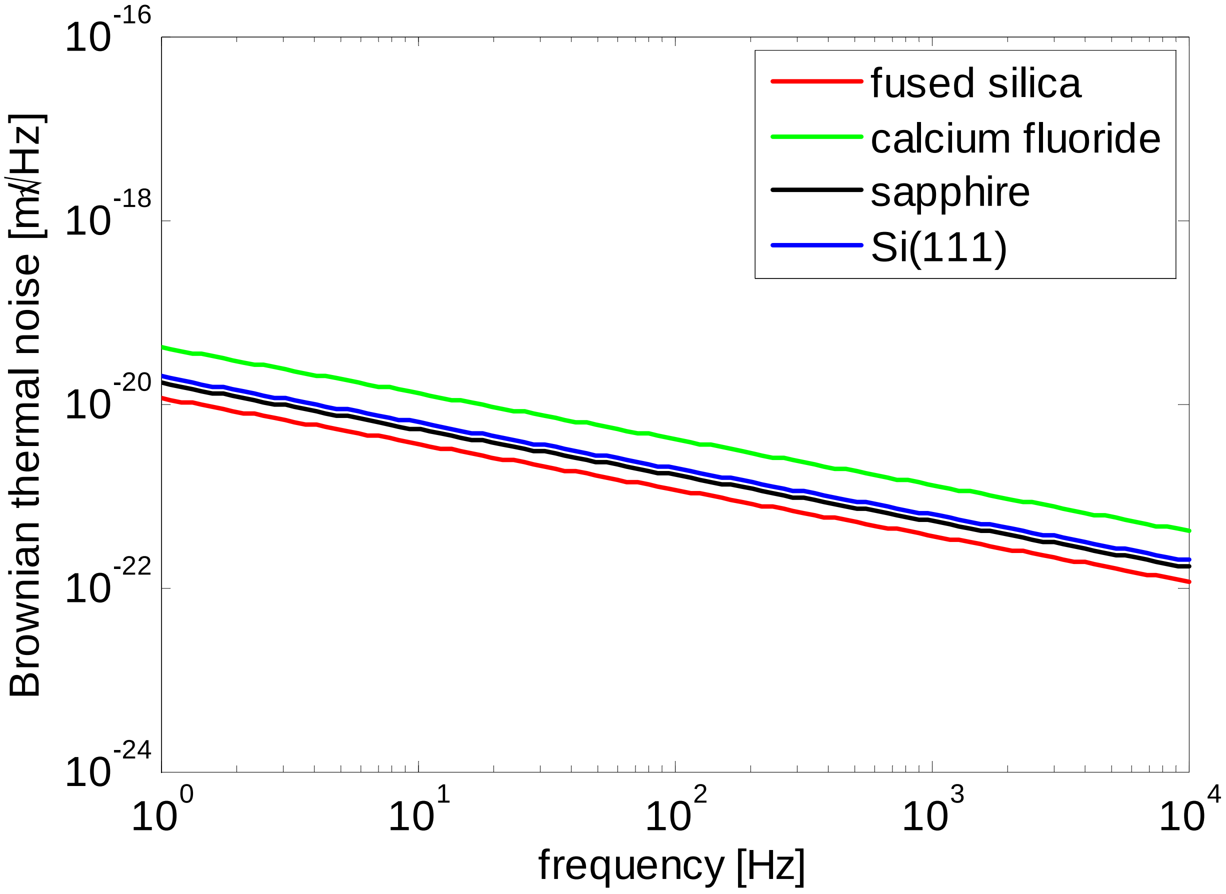
- material selection:
  - Young’s modulus Y
  - mechanical loss ϕ

mechanical Q-factor measurements

[see Chr. Schwarz’s talk]

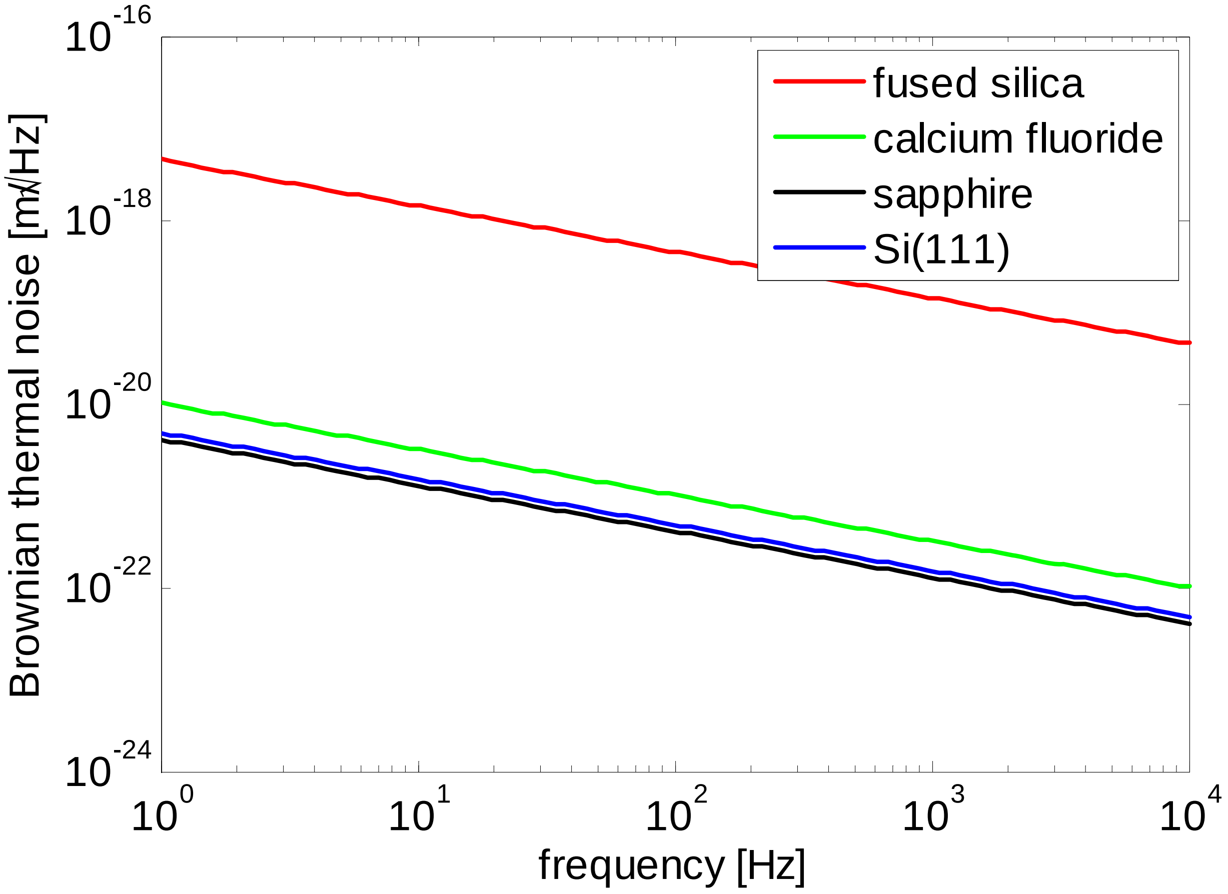


Bulk Brownian Noise



300 K

Bulk Brownian Noise



18 K

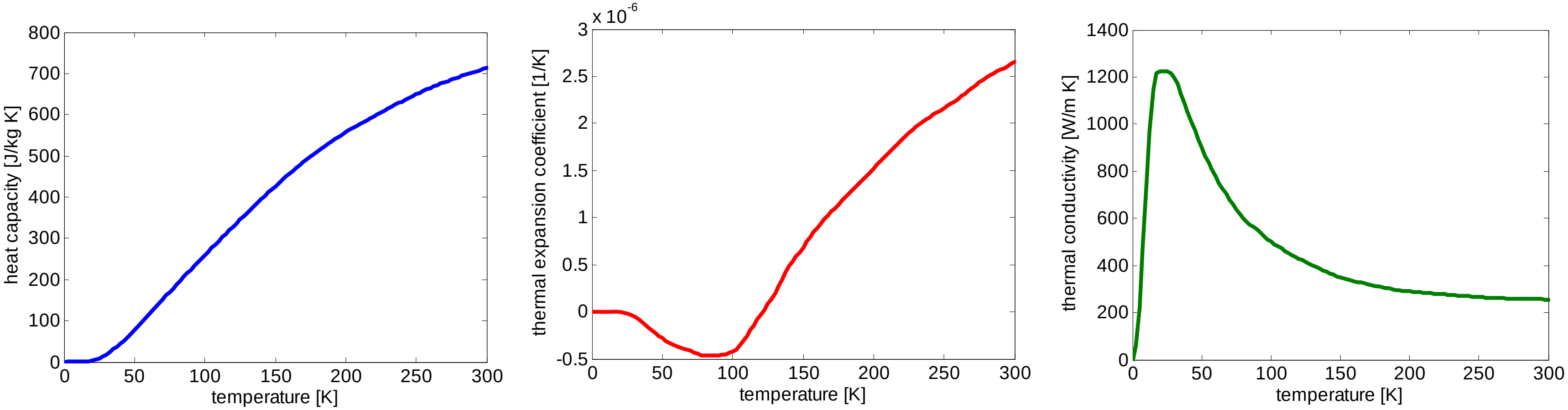
high mechanical loss of silica at 18 K ($\phi \sim 10^{-3}$)

Bulk thermoelastic noise

infinite test mass: $$S_{TE}^{ITM}(f,T) = \frac{4k_B T^2 \alpha^2 (1+\sigma)^2 \kappa}{\pi^{5/2} \rho^2 C^2 f^2 w^3}$$

finite test mass: $$S_{TE}^{FTM}(f,T) = C'^2_{FTM} \times S_{TE}^{ITM}(f,T)$$ [Liu, Thorne 2000]

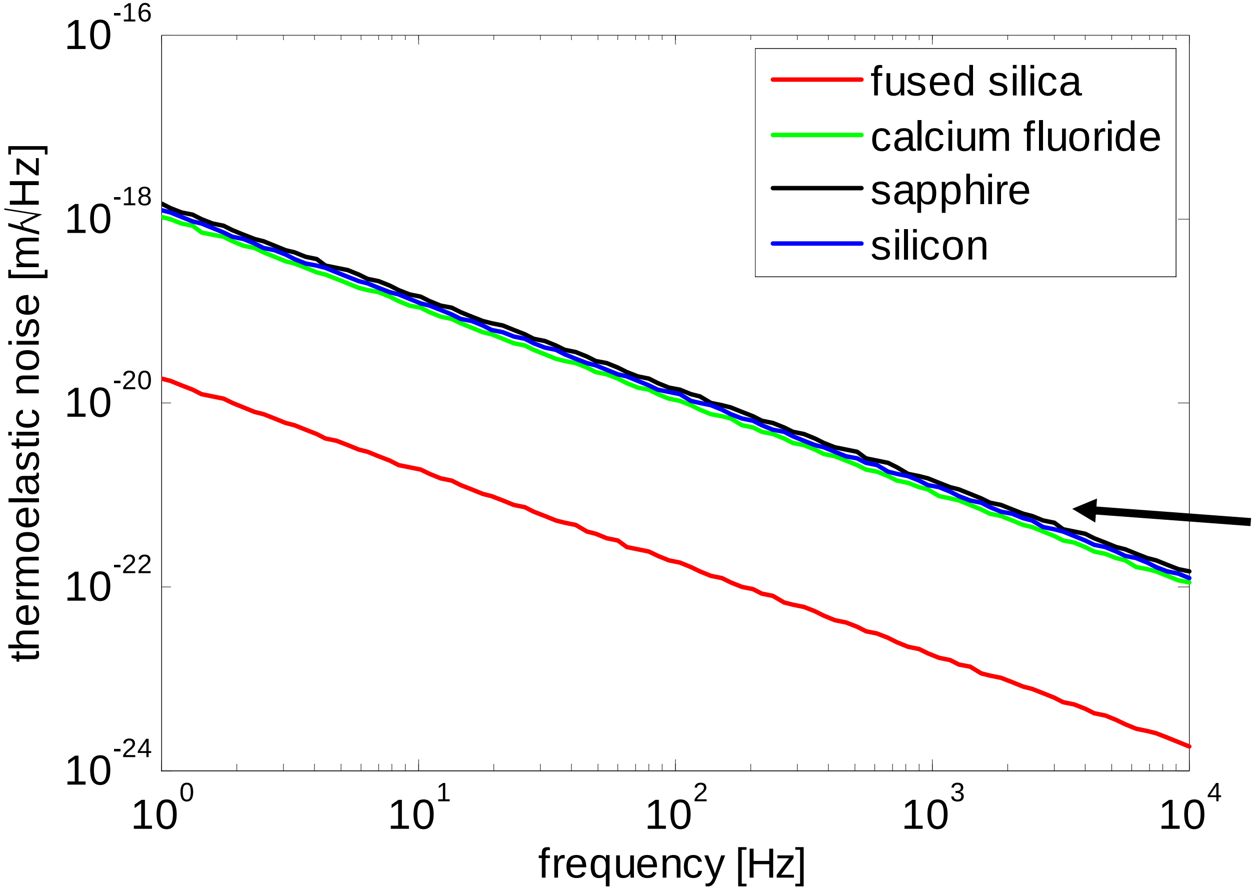
- thermal properties (thermal expansion, heat capacity and thermal conductivity) govern thermoelastic noise
- e.g. silicon:



[Hull 1999]

Bulk thermoelastic noise

- thermoelastic (room temperature)



crystalline materials (high CTE)

fused silica has a very low CTE

Bulk thermoelastic noise

- thermoelastic (low temperatures)
  - crystalline materials have higher thermal conductivity at low temperatures
  - reduced amount of fluctuating heat contributes to thermoelastic noise (“non-adiabatic” case)

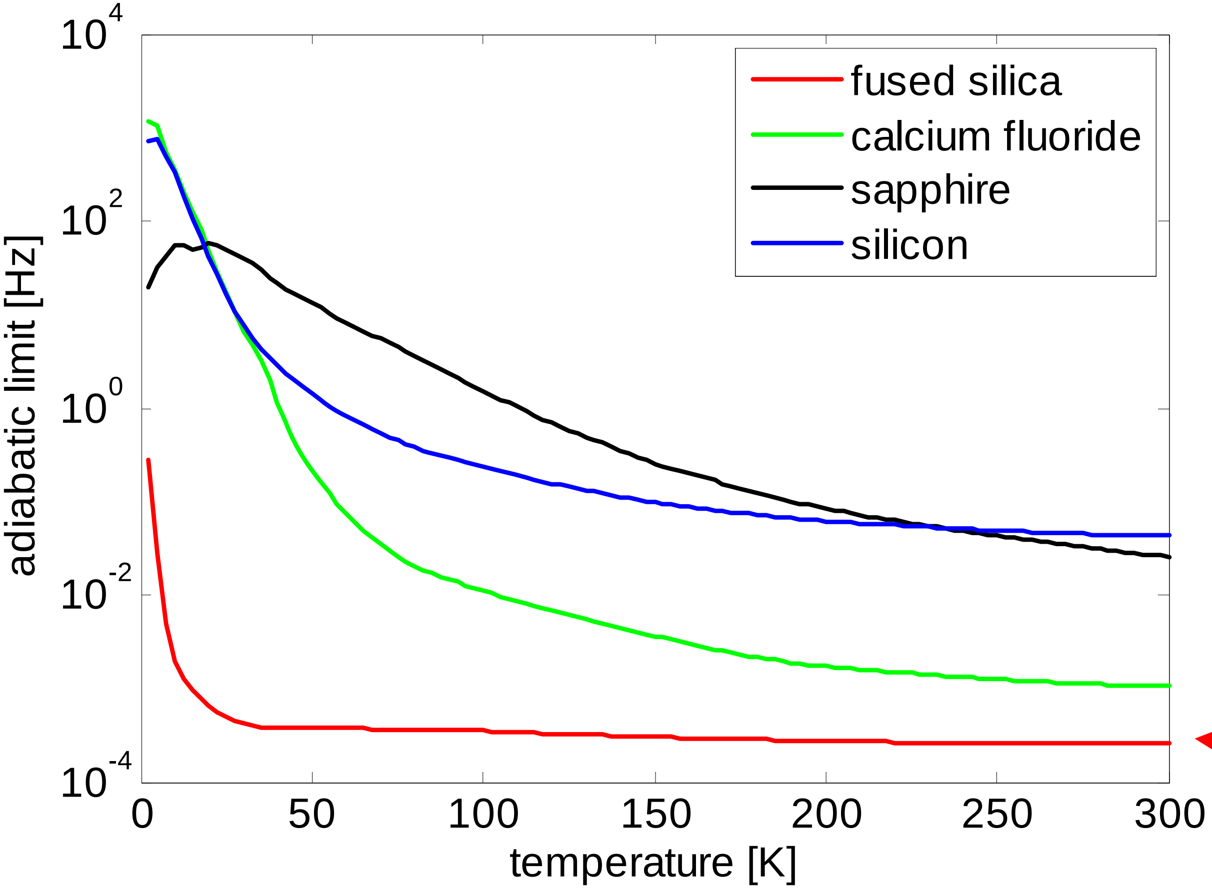
$$S_{TE}(f,T) = \frac{8}{\sqrt{2\pi}} \alpha^2 (1+\sigma)^2 \frac{k_B T^2 r_0}{\kappa} \times J(\Omega)$$

[Rowan et al. 2000, Aspen Meeting]
[Cerdonio 2001]

$$J(\Omega) = \sqrt{\frac{2}{\pi^3}} \int_0^{\infty} du \int_{-\infty}^{+\infty} dv \frac{u^3 e^{-u^2/2}}{(u^2+v^2)[(u^2+v^2)^2+\Omega^2]}$$

$\Omega = \frac{\omega}{\omega_C}$ with the adiabatic limit $\omega_C = \frac{\kappa}{\rho C r_0^2}$

Bulk thermal noise

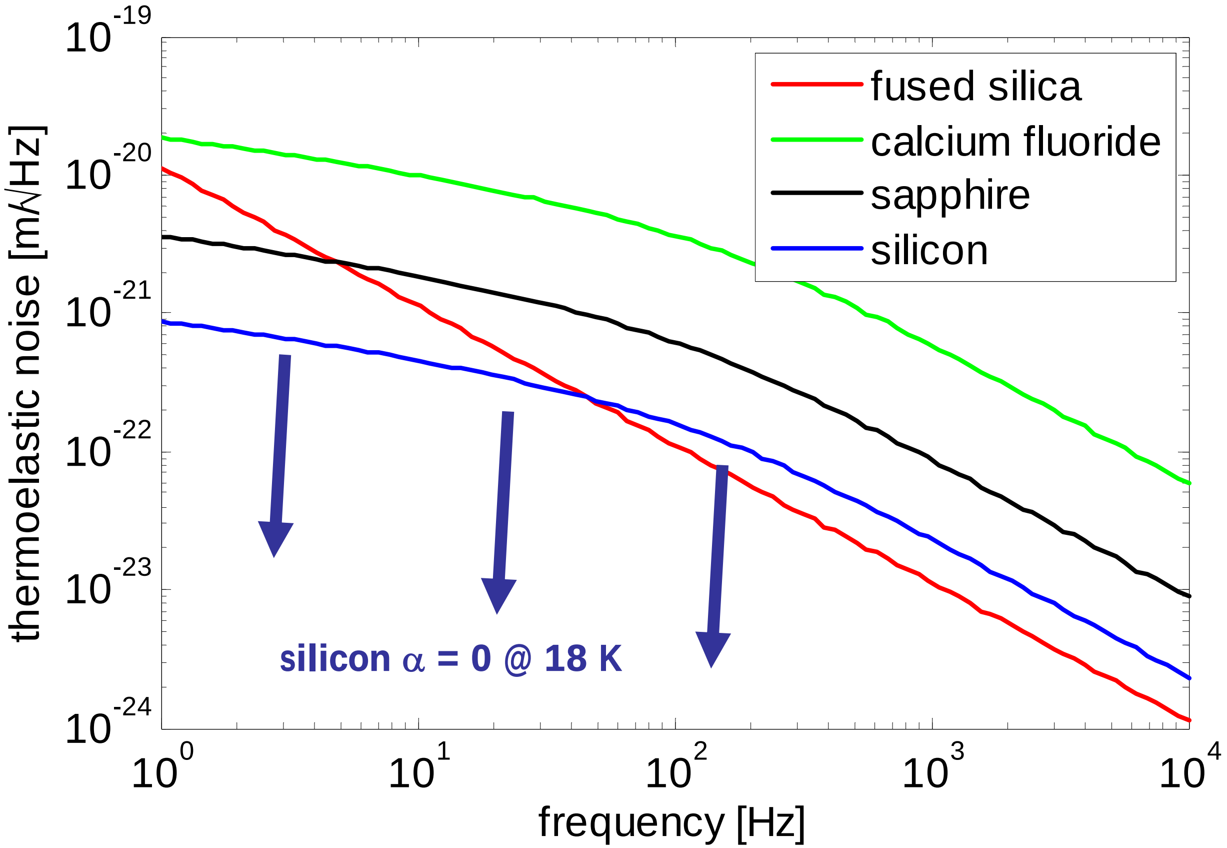


w = 60 mm

coatings stay adiabatic

Bulk thermal noise

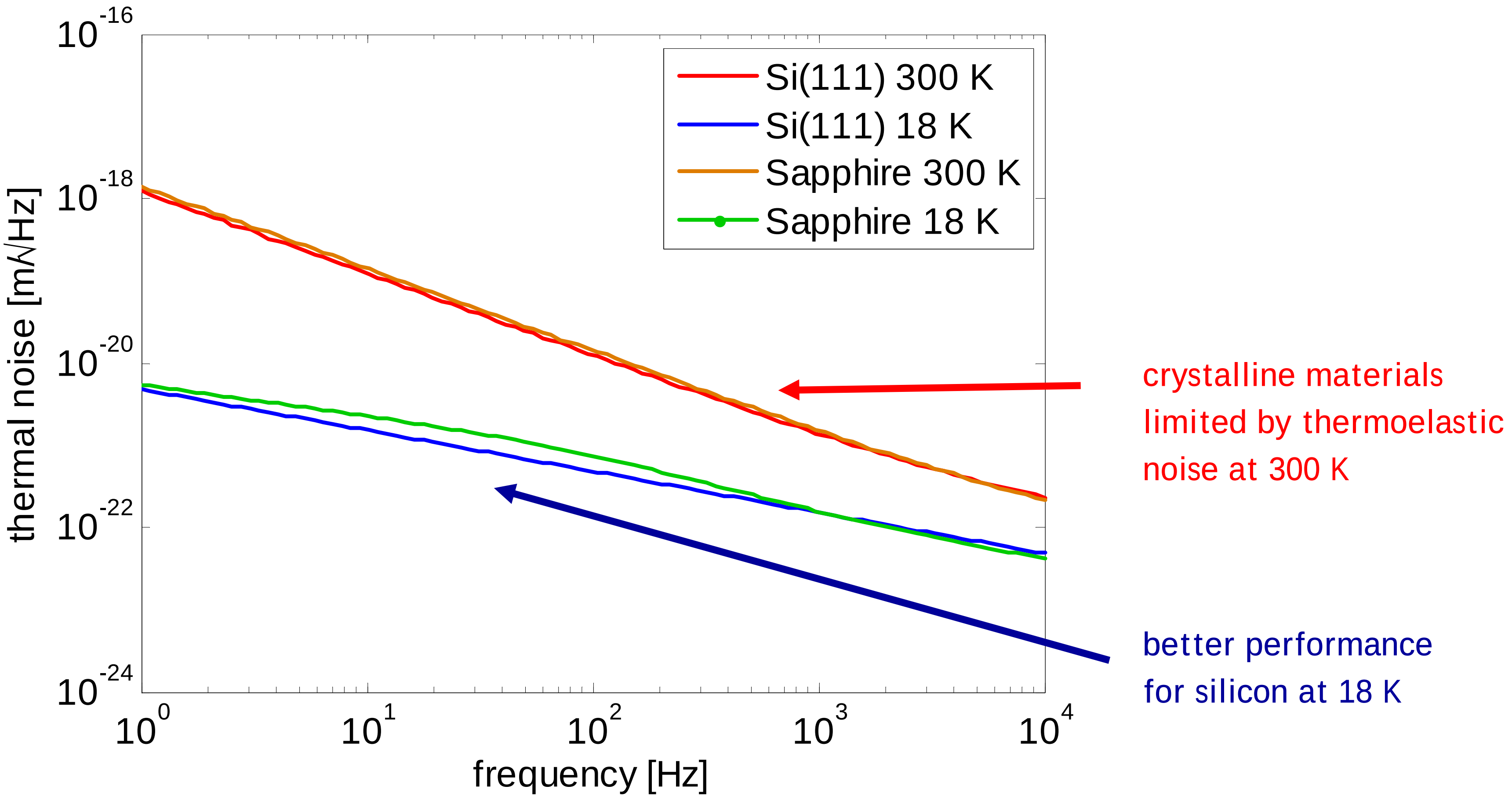
- thermoelastic (~18 K, full calculation)



- reduction of thermoelastic noise in the low frequency band
- higher thermoelastic noise for amorphous materials at 18 K

Bulk thermal noise

- total bulk thermal noise (Brownian + TE)



crystalline materials limited by thermoelastic noise at 300 K

better performance for silicon at 18 K

Coating thermal noise

- Brownian thermal noise

infinite test mass:

$$S_x(f,T) \approx \frac{2k_B T}{\pi^2 f}\frac{d}{w^2\,Y}\left(\frac{Y'}{Y}\phi_\parallel + \frac{Y}{Y'}\phi_\perp\right)$$

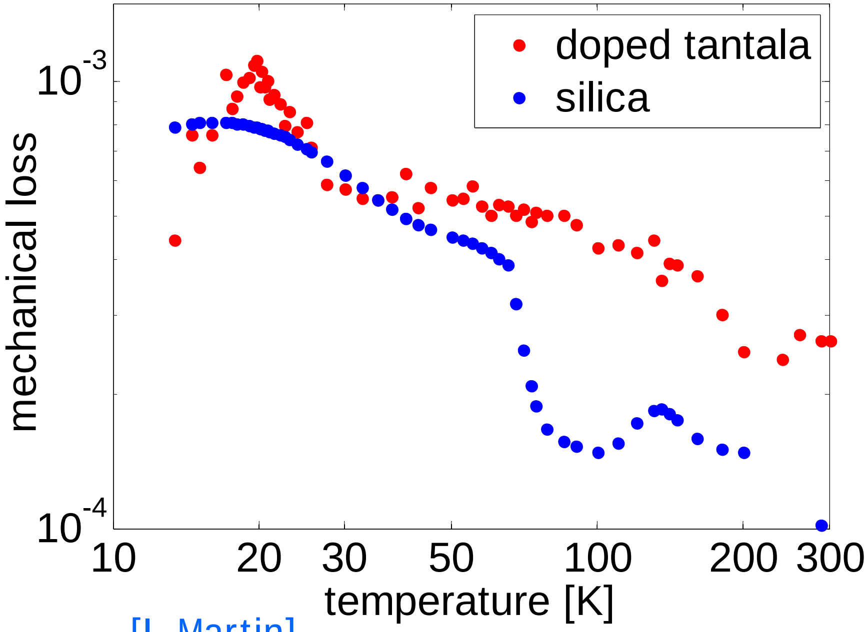
finite test mass: ANSYS + Levin’s direct approach [Levin 1998]

calculation by [K. Somiya et al., LIGO-P080121-00-Z]

- material selection:
  - Young’s modulus and ratio
  - mechanical loss

mechanical loss measurements

[see I. Martin’s talk]



[I. Martin]

Coating thermal noise

- thermoelastic noise

$$S_{TE}(f,T)=\frac{8k_B T^2}{\pi^2 f}\frac{L}{w^2}\frac{\alpha_S C_F}{C_S}(1+\sigma_s)^2\,\tilde{\Delta}^2\,g(\omega)$$

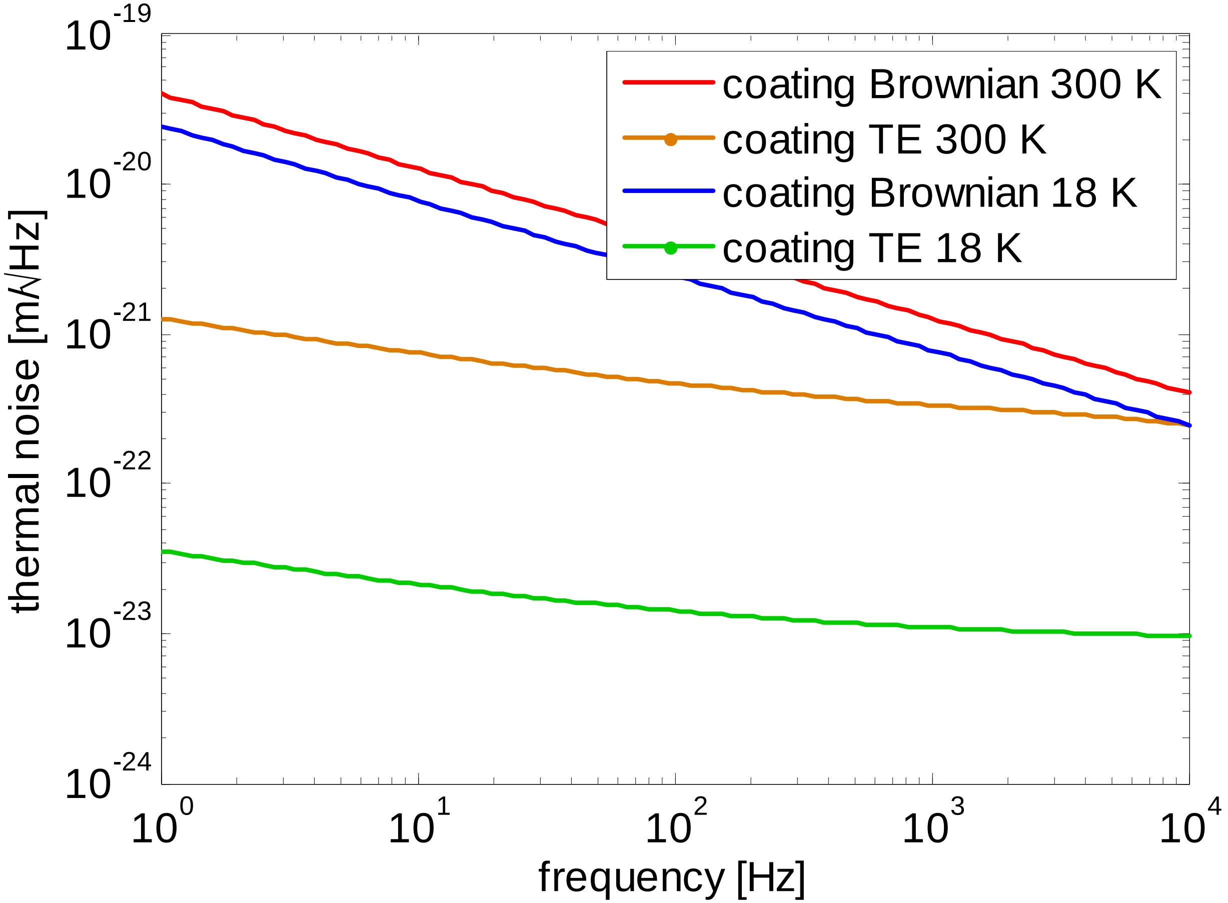
[Braginsky, Fejer et al. 2004]

$$\tilde{\Delta}^2=\left\{\frac{C_S}{2\alpha_S C_F}\left(\frac{\alpha}{1-\sigma}\left[\frac{1+\sigma}{1+\sigma_S}+(1-2\sigma_S)\frac{E}{E_S}\right]\right)_{AVG}-1\right\}^2$$

$$g(\omega)=\mathrm{Im}\left[-\frac{1}{\sqrt{i\omega\tau_F}}\frac{\sinh\sqrt{i\omega\tau_F}}{\cosh\sqrt{i\omega\tau_F}+R\sinh\sqrt{i\omega\tau_F}}\right]\qquad \tau_F=\frac{L^2}{\kappa}\ \text{ and }\ R=\sqrt{\frac{\kappa_F C_F^2}{\kappa_S C_S^2}}$$

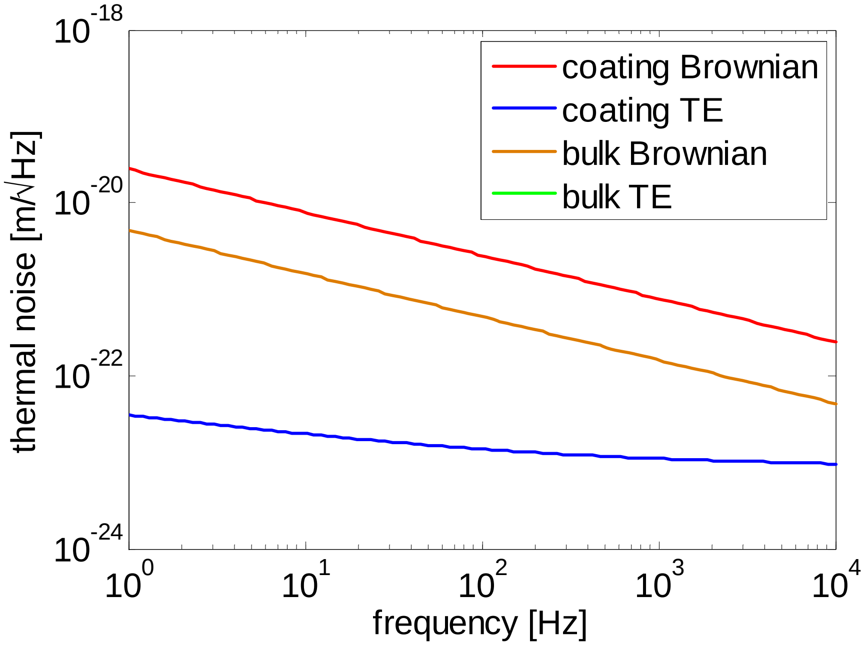
- thermoelastic noise is also dependent on material combination
- coating material = amorphous → no further reduction by "non-adiabatic" case

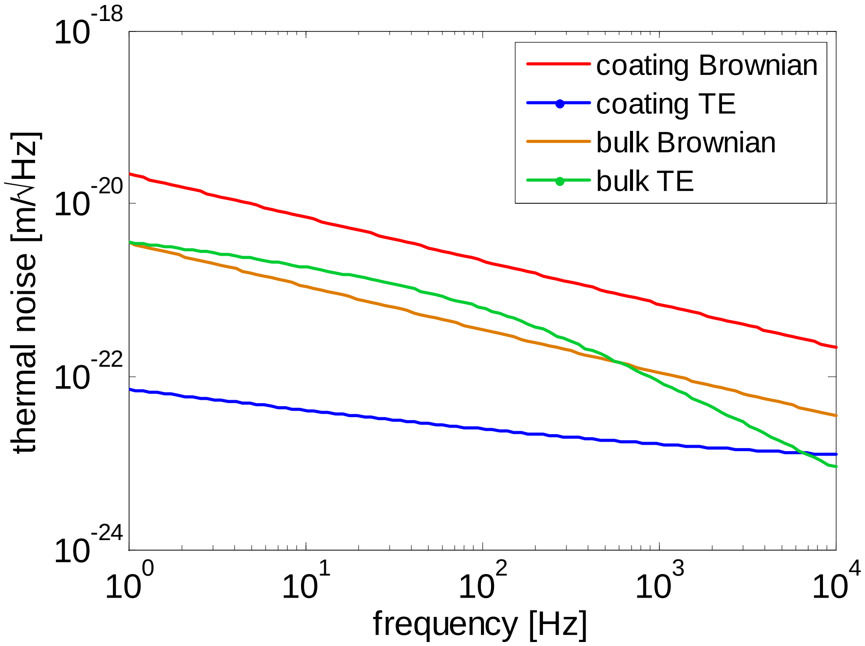
Coating thermal noise



Brownian noise dominates at room temperature and cryogenics

Mirror thermal noise


Si(111)

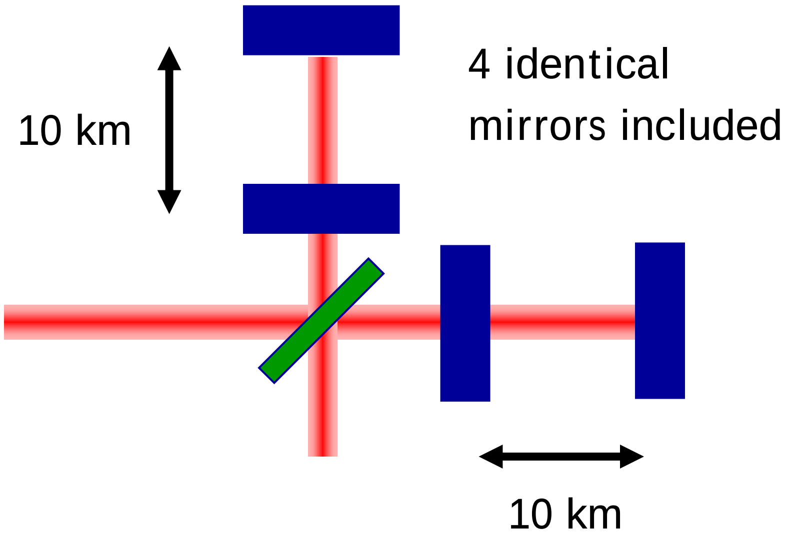

Sapphire

→ currently, the bulk material selection is not driven by bulk thermal noise

advantage of silicon: availability in large pieces (semiconductor industry!)

Mirror thermal noise

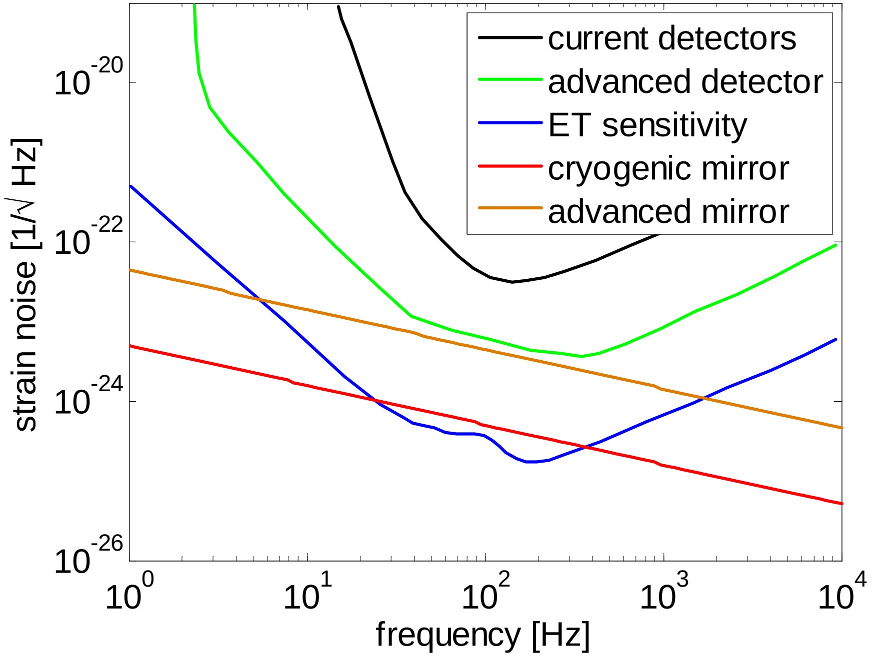
- strain sensitivity curve



10 km

4 identical mirrors included

10 km



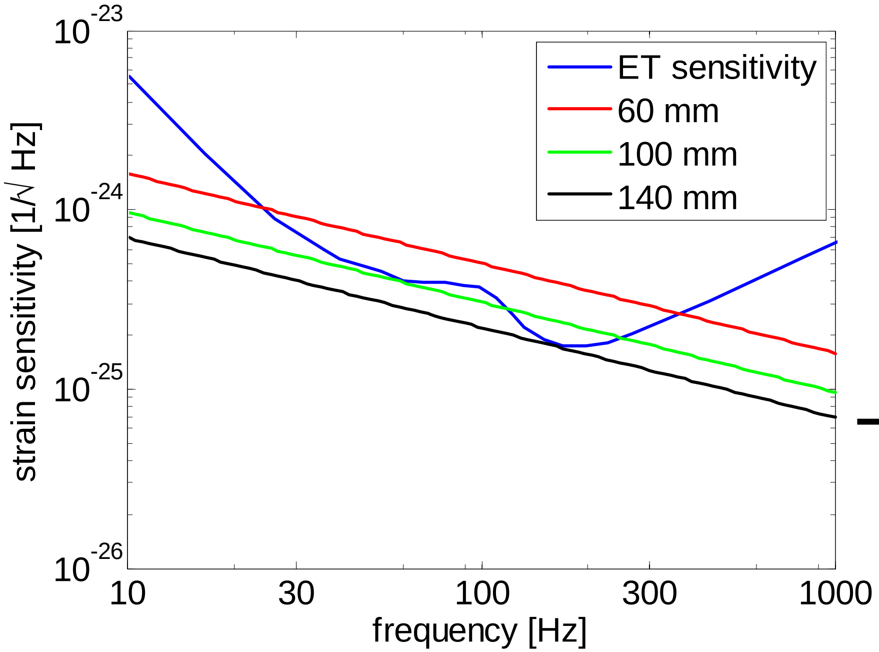
Just changing the material of an Advanced Ligo mirror brings us close to ET’s sensitivity curve – but there is still sensitivity missing.

Mirror thermal noise

- possible techniques to further reduce thermal noise
  - bigger beam diameter
  - better coatings
  - reduced coating thickness (optimized coatings, resonant waveguide mirrors)
  - monolithic resonant waveguides in silicon

Upscaling

- increasing the beam diameter with constant mirror aspect ratio



→ 532 kg needed

+

ROC currently not achievable

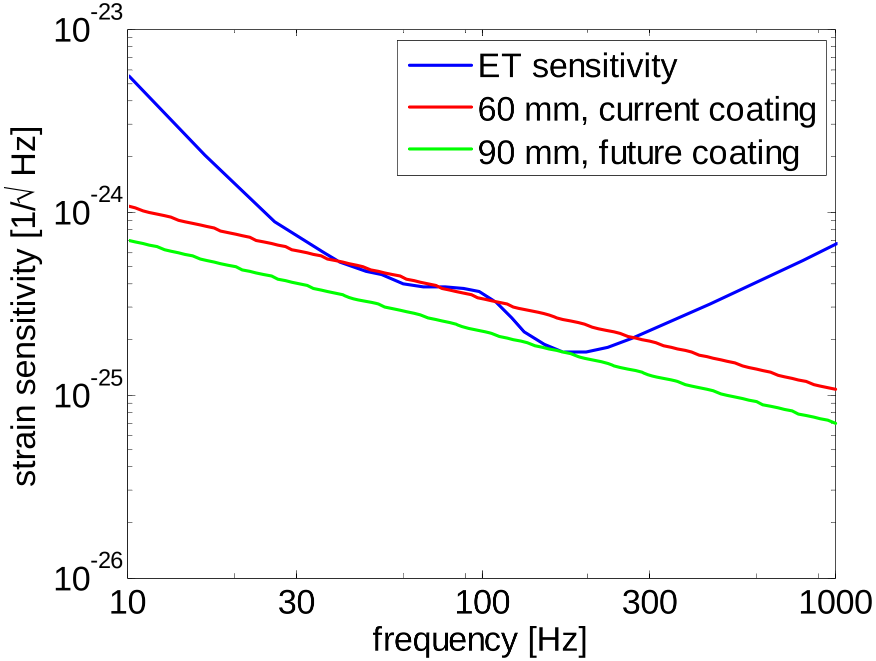
- what mass is needed (radiation pressure)

~ 120 kg [S. Hild et al., arXiv: 0810.0604v2]

(probably more: up to 200 kg – but to be added in thickness)

Towards a realistic geometry

- assuming 150 kg and Advanced Ligo aspect ratio



- needs coating improvement at 18 K to:

  2×10^{-4} (silica) and 4×10^{-4} (tantala)

[see I. Martin’s talk]

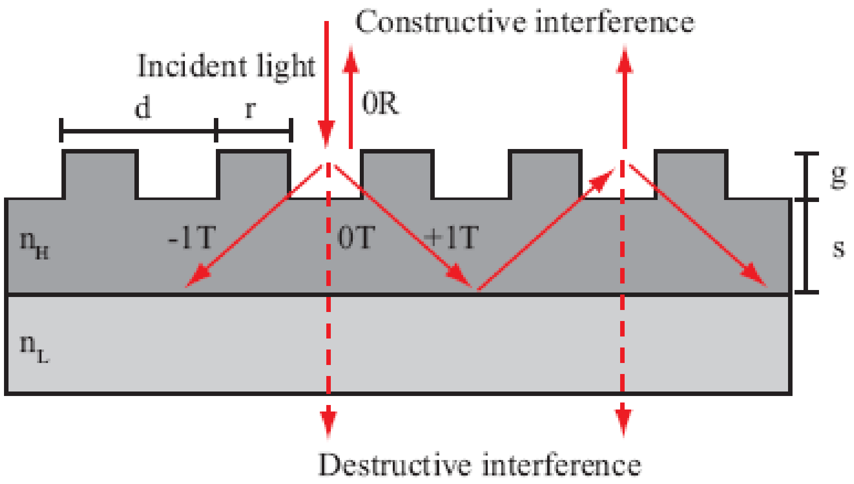
Challenges with dielectric coatings

- mechanical loss needs to be reduced at cryogenic temperatures
- local heating?

  multilayer stack forms thermal insulator between absorbing part and well conducting substrate → massive local heating?
- optical absorption (e.g. 1-3 MW, 1 ppm)

Resonant Waveguide Concept

- optical idea



[Brückner et al., Optics Express 17 (2009) 163 – 169]

no 1st orders in air and substrate

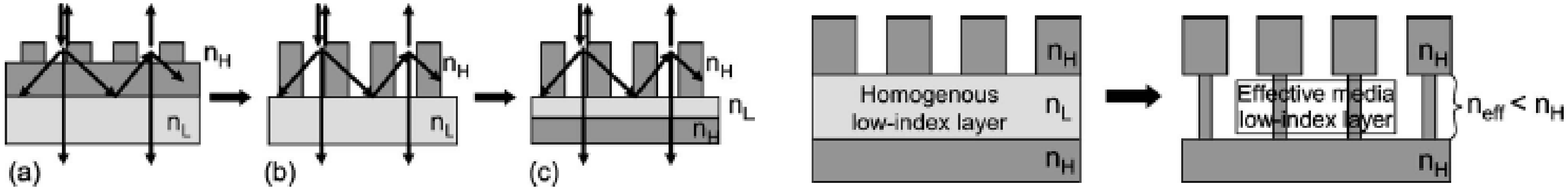
+/- 1st order in high index material

[H. Lück’s talk]

- advantages from the thermal noise point of view (thinner tantala layer!)
- cooling issues (lower absorption due to thinner layers)

Monolithic Resonant Waveguide Concept

- optical idea



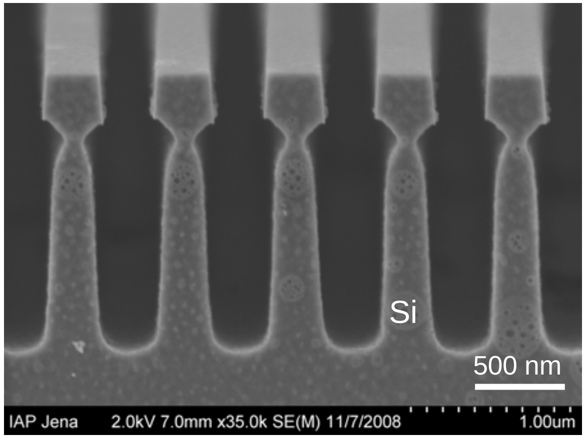
[Brückner et al., Optics Letters 33 (2008) 264 - 266]

- no tantala layer needed (expected low loss)
- monocrystalline structure → high thermal conductivity
- probably just small absorption at 1550 nm

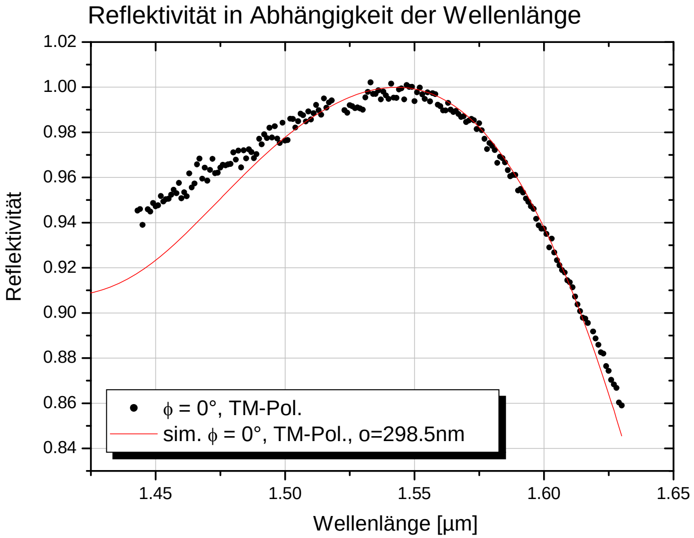
  (R. Schnabel’s talk @ Amaldi 2009)

Monolithic Resonant Waveguide Concept

How realistic are these fancy structures?



fist design

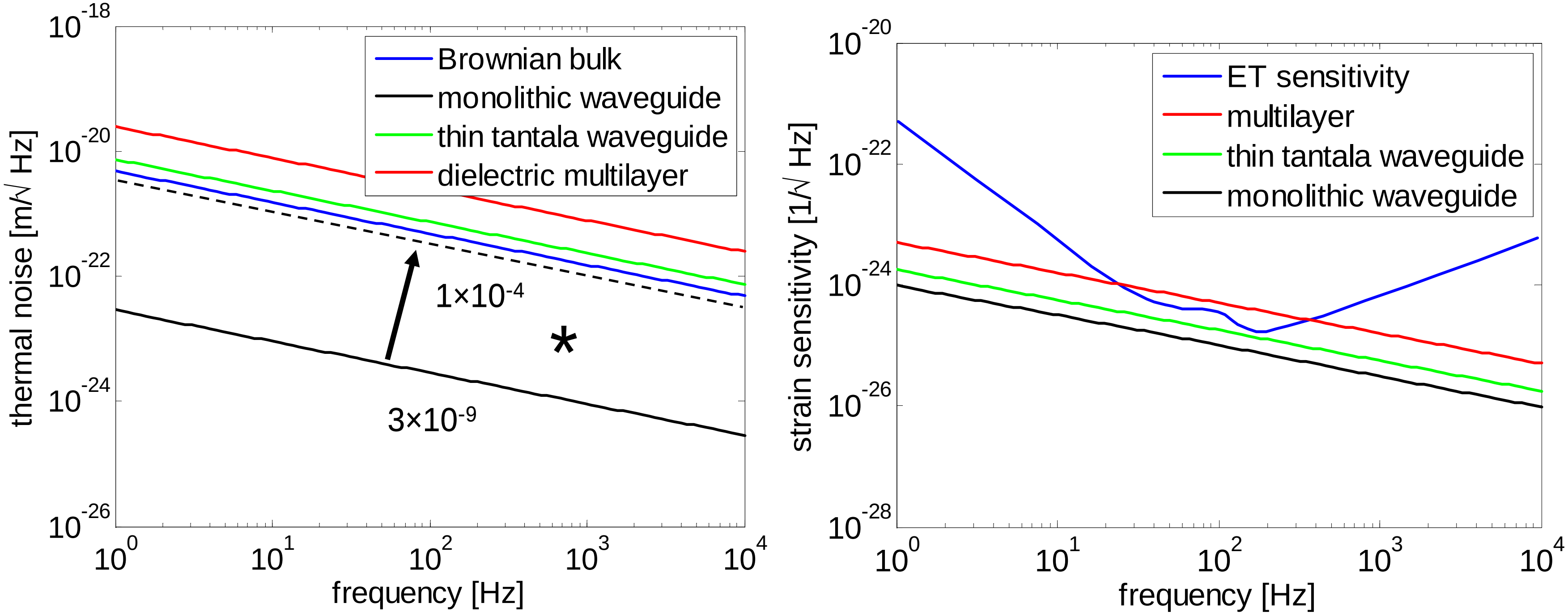


first initial test: ~ 99.8%

see details in talk of F. Brückner @ Amaldi

Initial thermal noise comparison

- What noise reduction can be expected with waveguide mirrors?



Advanced LIGO mirror geometry assumed.

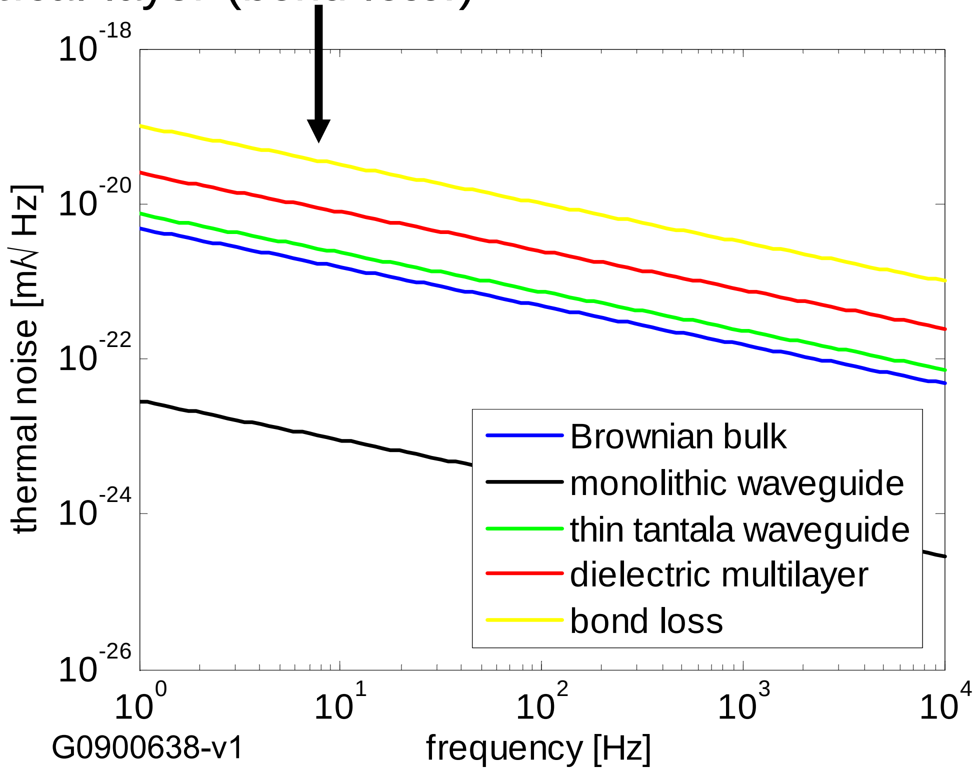
* systematic investigation of surface losses at low temperatures needed

Monolithic Resonant Waveguide Concept

- open questions:
  - optical absorption @ 1550 nm and 20 K?
  - increased surface of silicon → surface loss analysis needed (poster @ Amaldi)
  - How to attach the optical layer (bond loss!)

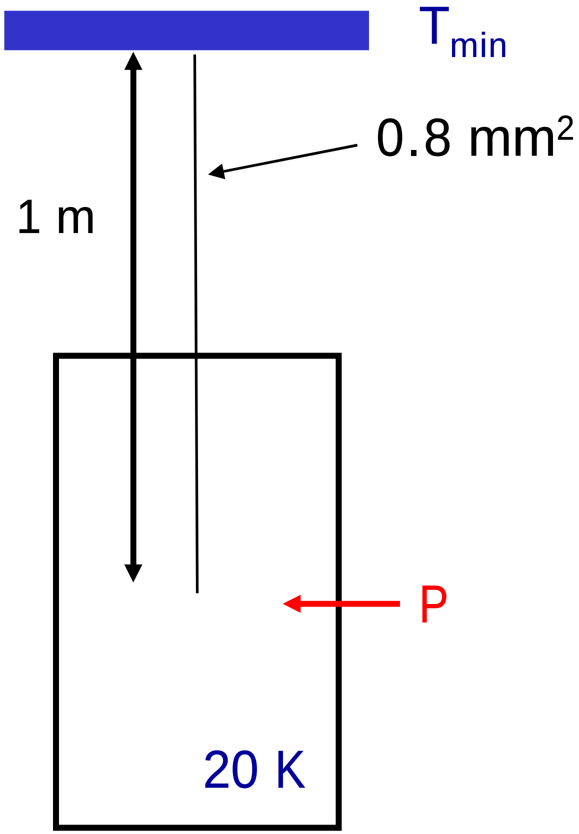
bond loss ~ 0.1

waveguide fabricated on 500 µm wafer



Thermal issues of the suspension

- heat extraction thru suspension



maximum extractable power
(assuming high thermal conductivity)

T_{min} [K]	Silicon
2	28 mW
5	27 mW
10	23 mW
15	11 mW

Summary

- summary of thermal noise calculation on selected materials and geometries
- 150 kg might be useful and available, additional mass can be added in thickness without changing beam diameter
- coatings need to be improved:
  - better materials
  - thinner layer thicknesses (especially tantala)
  - reduction of thermal noise and thermal load by use of waveguides
- investigation of bond losses (mechanical and thermal!) will be very important for compound optics (waveguides, suspensions)
- see upcoming talks/poster about silicon optics @ Amaldi