ET-022-09
LIGO-G0900648-x0

Thermal noise in 3rd generation gravitational wave detectors

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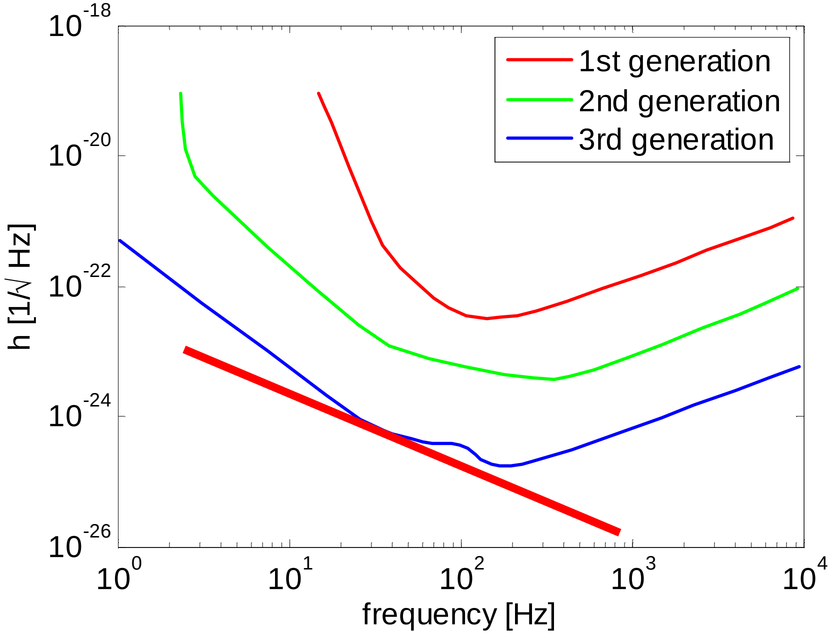
8th Edoardo Amaldi Conference in Gravitational Waves
Columbia University, New York

Introduction

- currently design study in Europe concerning a 3rd generation detector (Einstein Telescope – ET)
- improvement of roughly a factor of 10 between different generations of GWD
- 3rd generation gravitational wave detectors will be limited by several kinds of noise

- critical limitation:
  - seismic noise (gravity gradient)
  - thermal noise

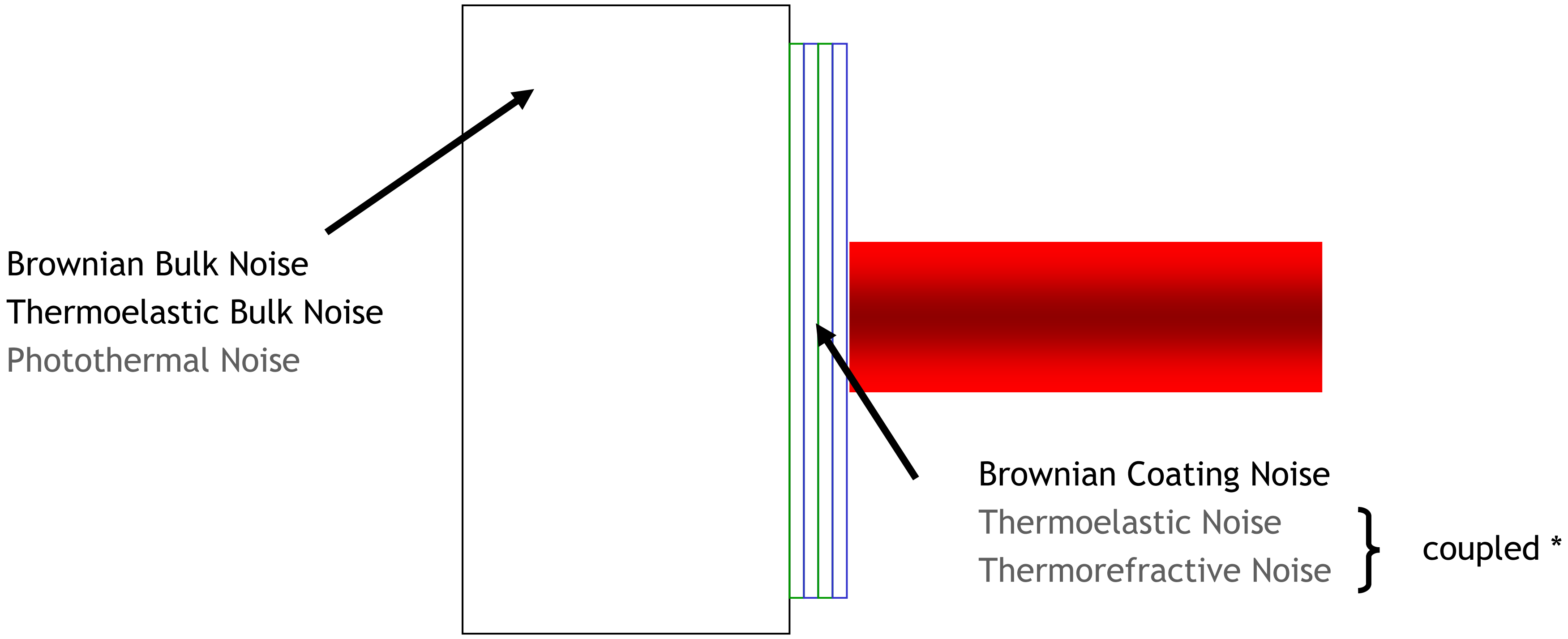


Thermal Noise

- thermal noise is dependent on
    - temperature ↔ thermal energy
    - mechanical loss ↔ spectral distribution
    - spatial distribution ↔ inhomogeneous losses
- minimum noise will be achieved for low mechanical loss at lowest possible temperatures
- lossy parts need to be far away from the interaction laser-surface

Thermal Noise

- main contribution arises from:



Brownian Bulk Noise
Thermoelastic Bulk Noise
Photothermal Noise

Brownian Coating Noise
Thermoelastic Noise
Thermorefractive Noise

} coupled *

* [Evans et al. 2008]

Bulk Thermal Noise

- Brownian thermal noise

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

[Liu, Thorne 2000]

- thermoelastic noise

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

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

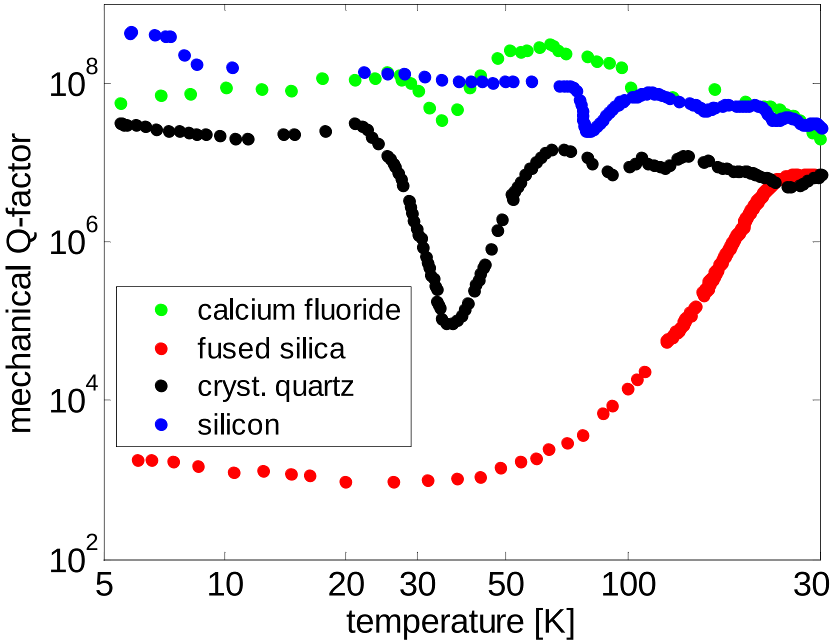
$$J(\Omega) = \sqrt{\frac{2}{\pi^3}} \int_0^{\infty} du \int_{-\infty}^{+\infty} dv \, \frac{u^3 e^{-u^2/2}}{(u^2+v^2)[(u^2+v^2)^2+\Omega^2]}$$

correction term
for non-adiabatic
case

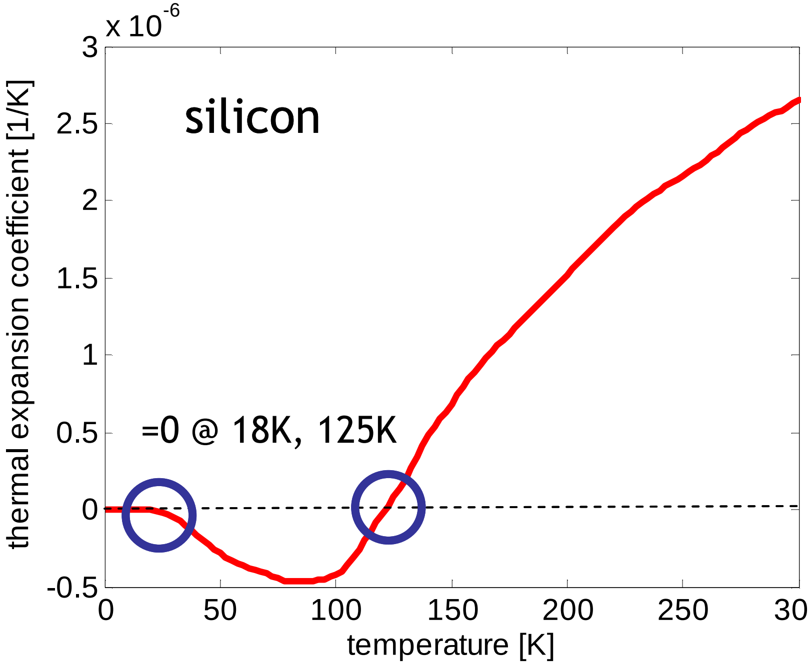
$$\Omega = \frac{\omega}{\omega_C} \qquad \omega_C = \frac{\kappa}{\rho C r_0^2}$$

Bulk Thermal Noise

- material selection is driven by thermal and mechanical properties



[Schwarz et al. 2009]



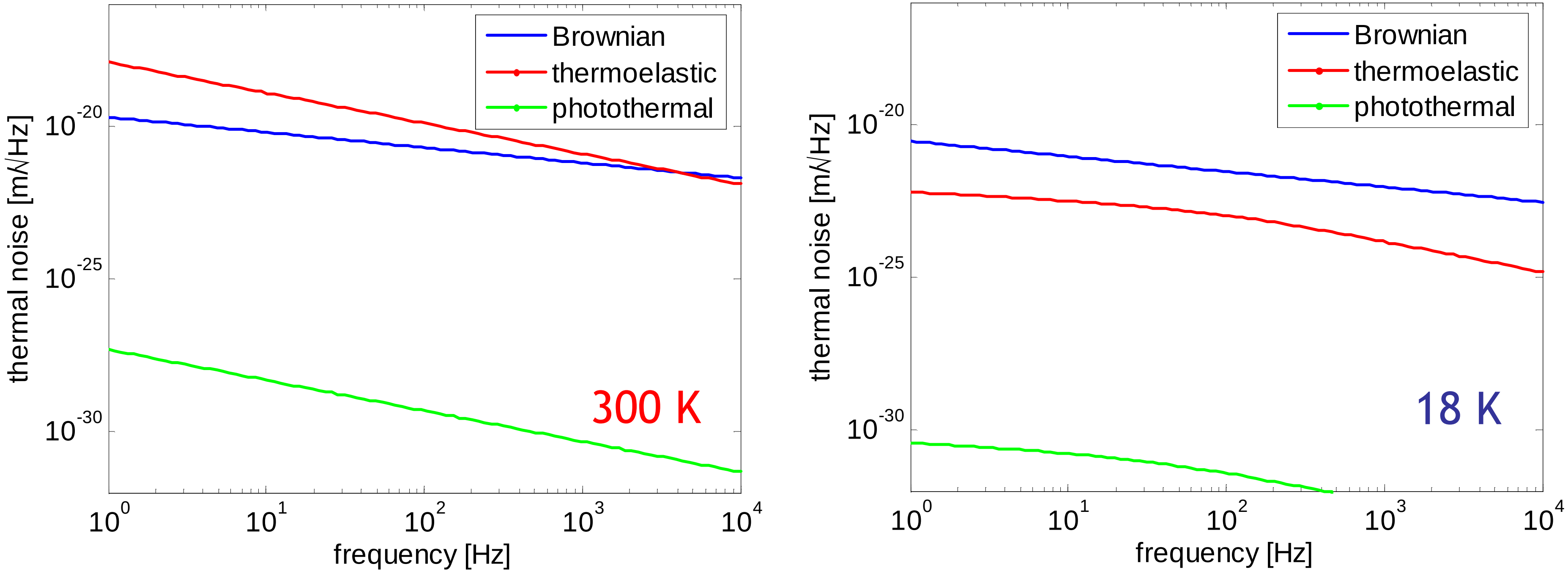
[Touloukian et al. 1970]

- silicon has excellent properties for low noise optics

[Winkler et al., Phys. Rev. A 44 (1991), Rowan et al., Proceedings of SPIE 292 (2003)]

Bulk Thermal Noise

- Si(111) substrate, w = 60 mm, Q = 3×10^8 (@ 300K), Q = 1×10^9 (@ 18K)



around 18 and 125 K Brownian thermal noise dominates → reduction of thermal noise by use of low loss materials

Coating Thermal Noise

- Brownian thermal noise

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

[Harry et al. 2002]

- thermo-optical noise ->thermoelastic/thermorefractive noise

$$S_{TO}(\omega,T) \approx \frac{2\sqrt{2}}{\pi}\frac{k_BT^2}{w^2\sqrt{\kappa C\omega}} \times \left(\underline{\alpha_C d - \frac{\partial n}{\partial T}\lambda - \alpha_S d\frac{C_C}{C_S}}\right)^2$$

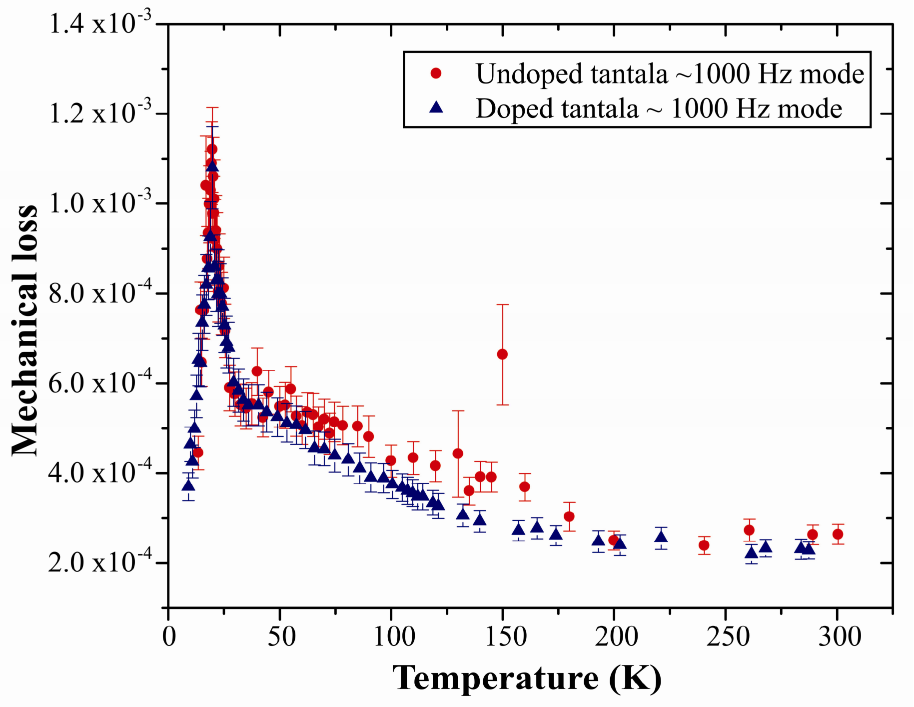
[Evans et al. 2008]

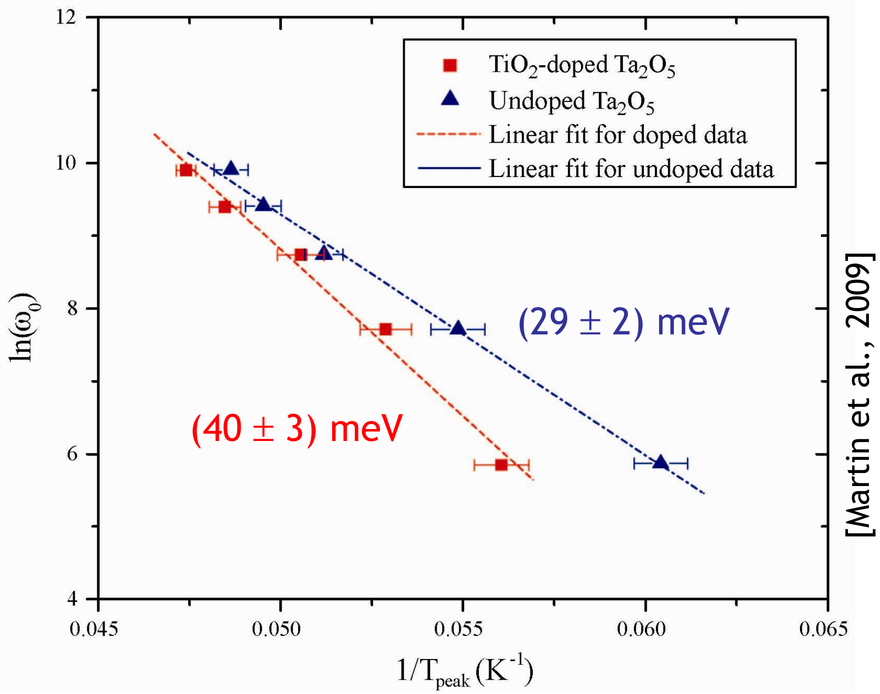
compensation of different contribution is possible

values of the temperature dependence of several properties up to now not available → but: compensation or reduction at cryogenic temperatures expected

Coating Thermal Noise

- influence of doping on the mechanical losses of coating materials



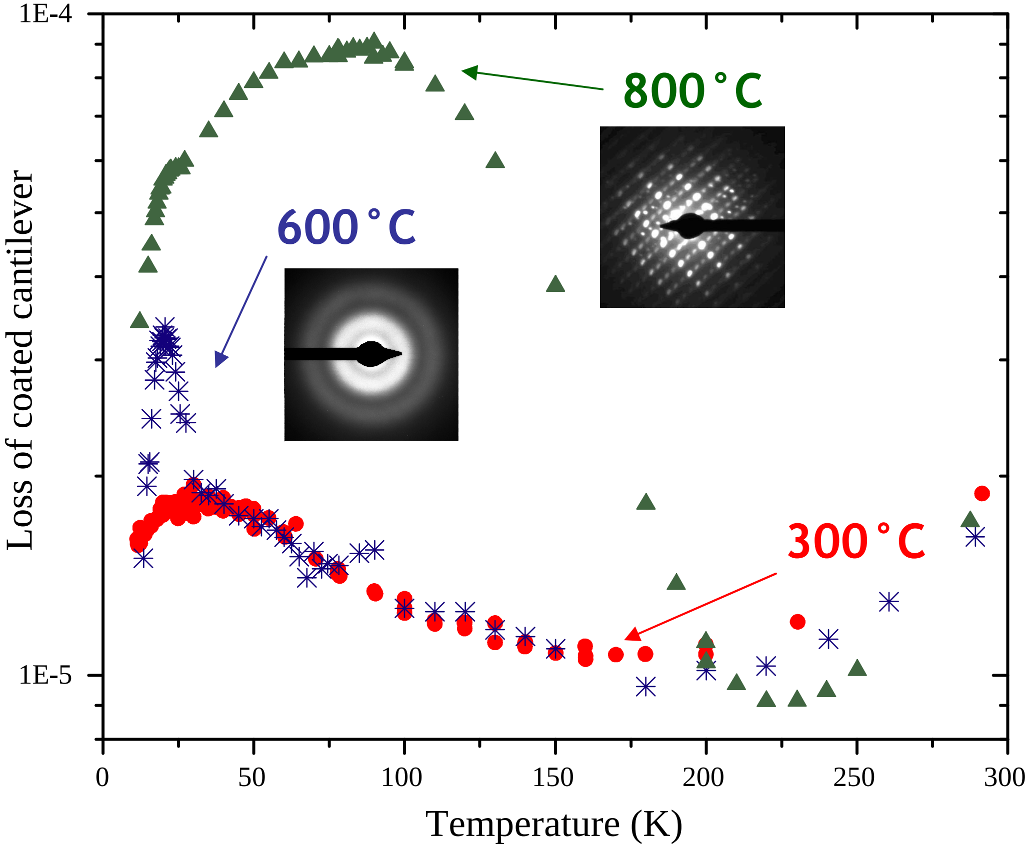


[Martin et al., 2009]

doping changes the microscopic structure → change in activation energy

Coating Thermal Noise

- influence of heat treatment on the mechanical losses of coating materials

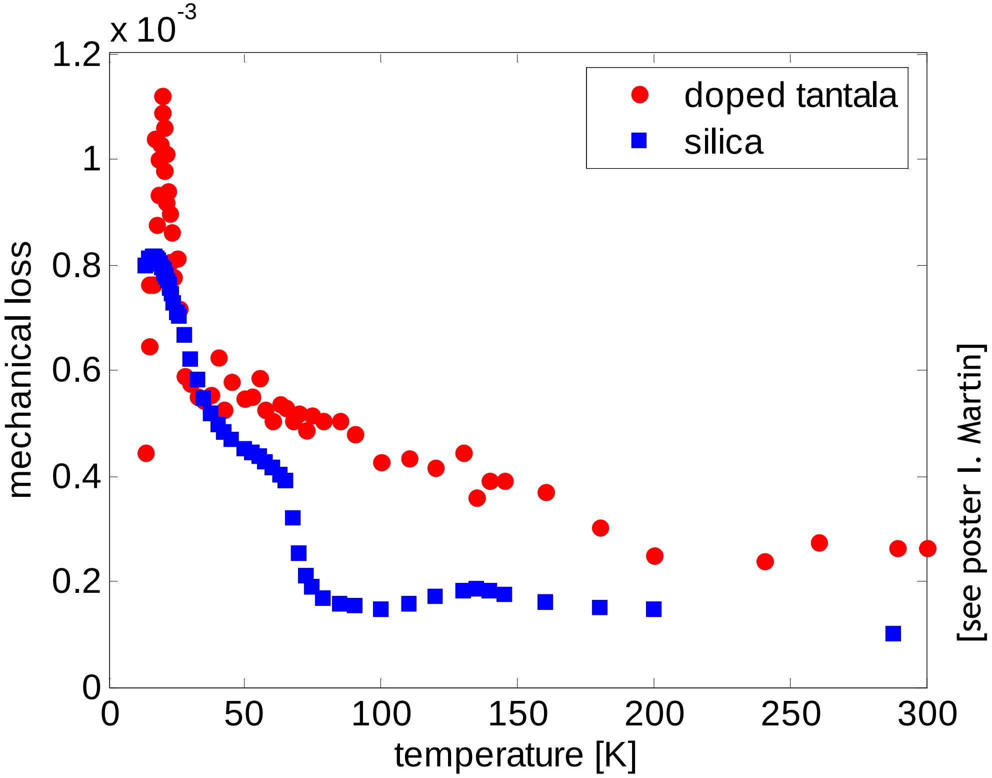


- annealing improves optical properties
- low temperature loss peaks appear during heat treatment (T_{peak} ~ 20 K)
- electron diffraction reveals crystallisation above 800°C

[see poster R. Bassiri]
[see poster S. Penn]

Coating Thermal Noise

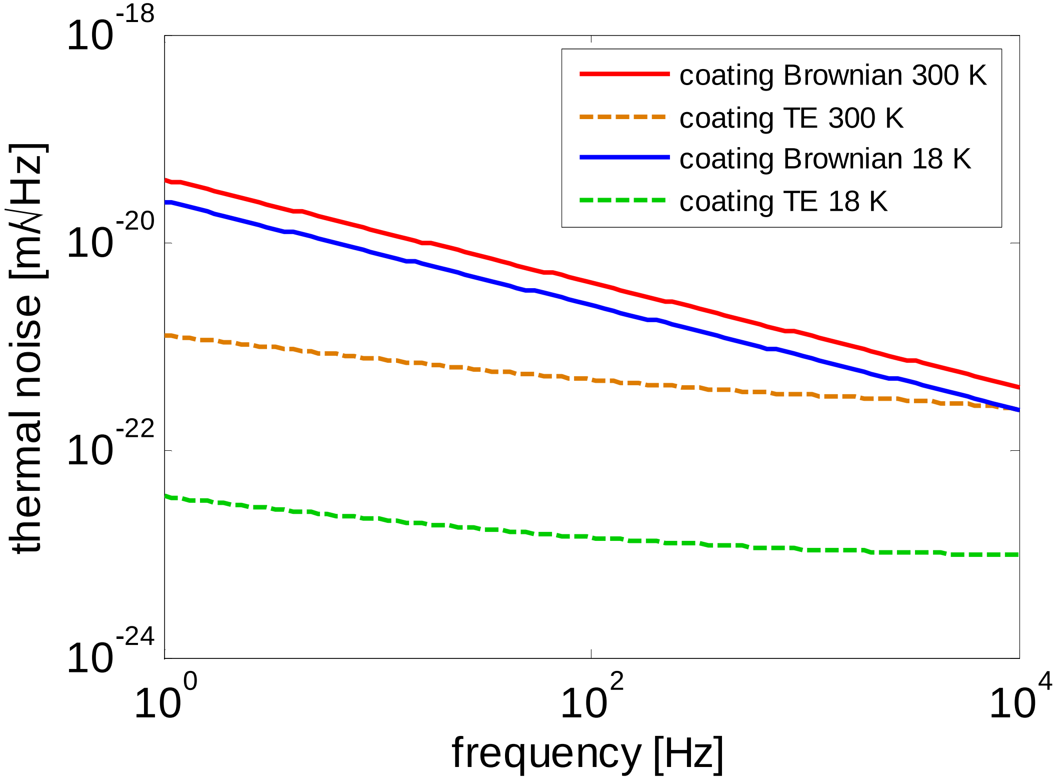
- currently available mechanical loss values



	300 K	18 K
silica	4×10^{-5}	7×10^{-4}
$Ti:Ta_2O_5$	2×10^{-4}	1×10^{-3}

increasing loss down to ~ 20 K for both materials

Coating Thermal Noise

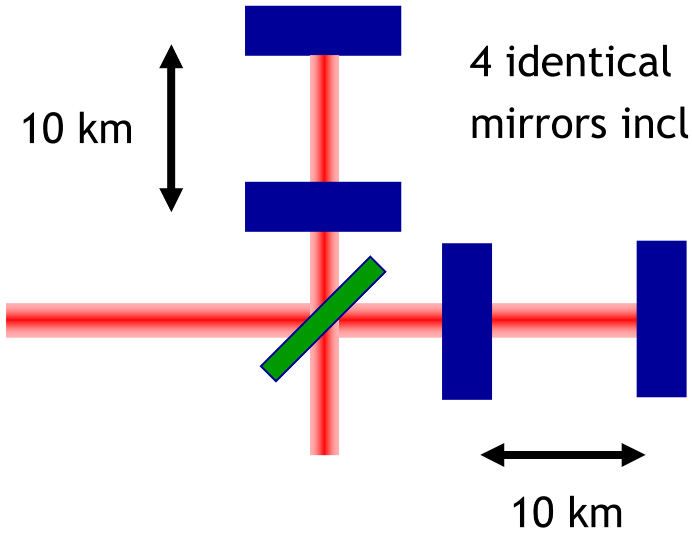


- Brownian thermal noise dominates
- thermoelastic noise is much smaller
- Evans et al. 2008: (partly) cancellation of thermoelastic and thermorefractive noise → Brownian noise remaining relevant noise component

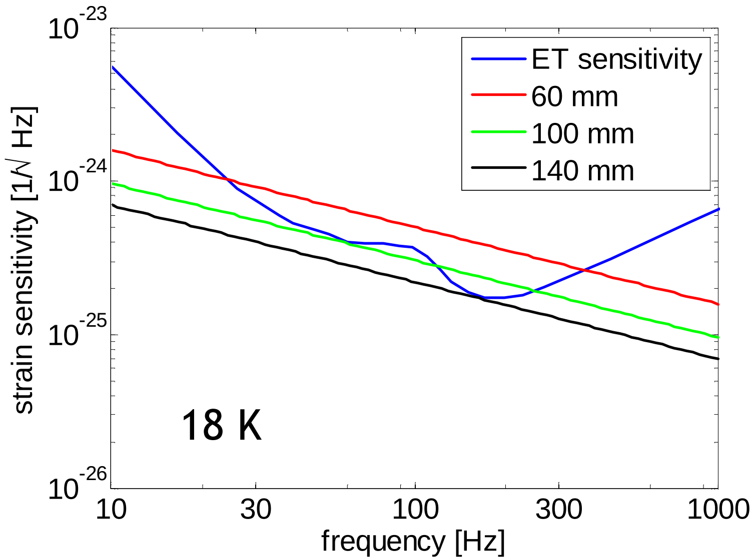
Coating thermal noise is determined by Brownian thermal noise. The loss peaks in the mechanical loss spectrum at around 18 K reduce the expected improvement of the GWD.

Design Sensitivity

- in order to achieve the desired sensitivity a larger beam radius is needed



4 identical mirrors included



masses up to 500 kg needed if an Adv. LIGO aspect ratio is assumed

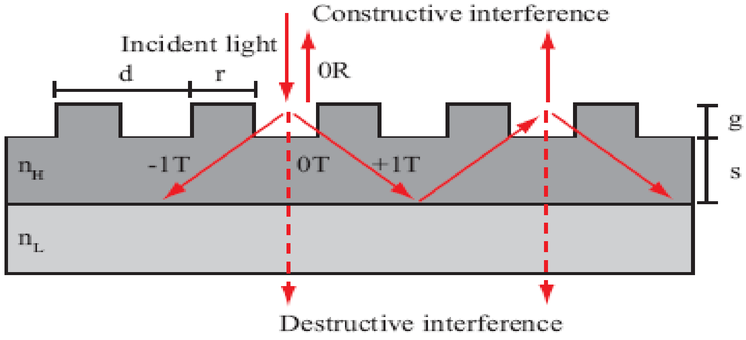
↔ technical limits (ROC needed for stable cavity not available)

Brownian thermal noise of the coating:

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

Novel Approaches

- resonant waveguide

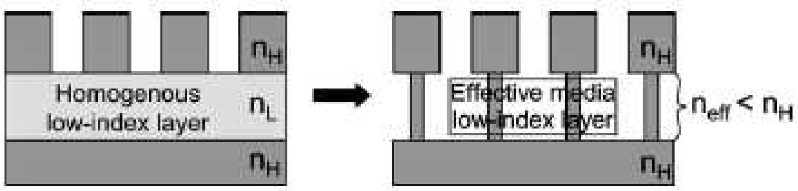


[Brückner et al., Optics Express 17 (2009) 163 – 169]

thickness of tantala by one order of magnitude smaller than in dielectric stacks

reduced thermal noise

- monolithic waveguide



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

no lossy dielectric materials needed, no interfaces, excellent thermal properties

reduced thermal noise

Resonant Waveguide Concept

- noise estimation

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

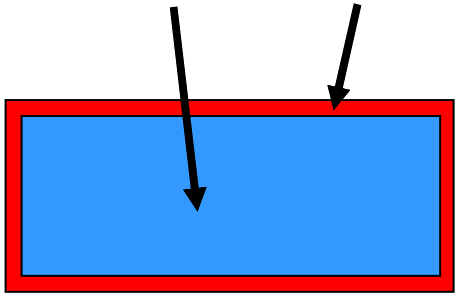
thickness of tantala smaller by one order of magnitude → thermal noise is reduced by √10 (other types of noise much smaller)

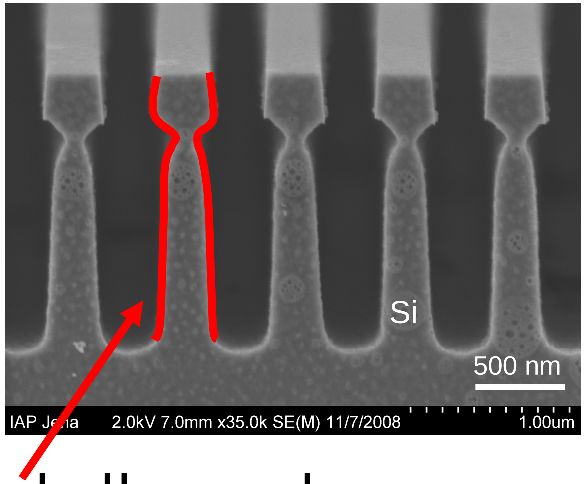
- still: optical absorption → heating in the waveguide

Monolithic Waveguide Concept

- mechanical loss will be influenced by the surface layer

$$\varphi = \varphi_{\mathrm{bulk}} + \varphi_{\mathrm{surface}}$$





- surface is increased compared to bulk samples
- modelling of surface losses similar to fused silica

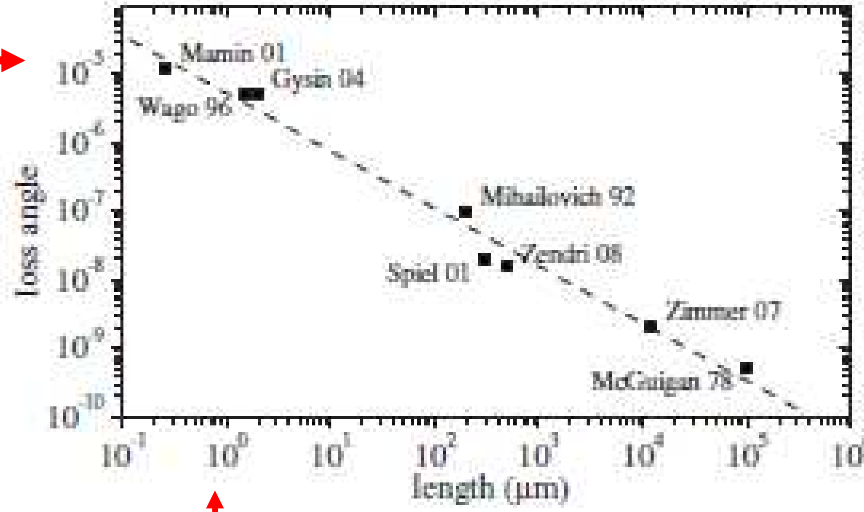
$$\varphi_{\mathrm{surface}} \sim \frac{S}{V}$$

S … surface area
V … volume

Monolithic Waveguide Concept

- until now no systematic investigation of silicon surface loss (reason: temperature as an additional parameter)
- compilation of several loss measurements vs. smallest dimension of the sample (~ V/S)
- temperature ~ 1-15 K

$\varphi \sim 10^{-5}$ →

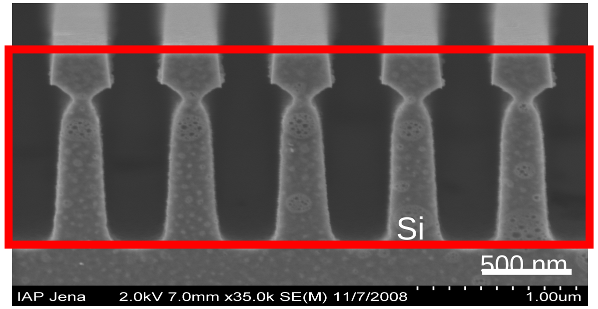


[Zendri et al. 2008]

↑
structure size of the T-structure

Monolithic Waveguide Concept

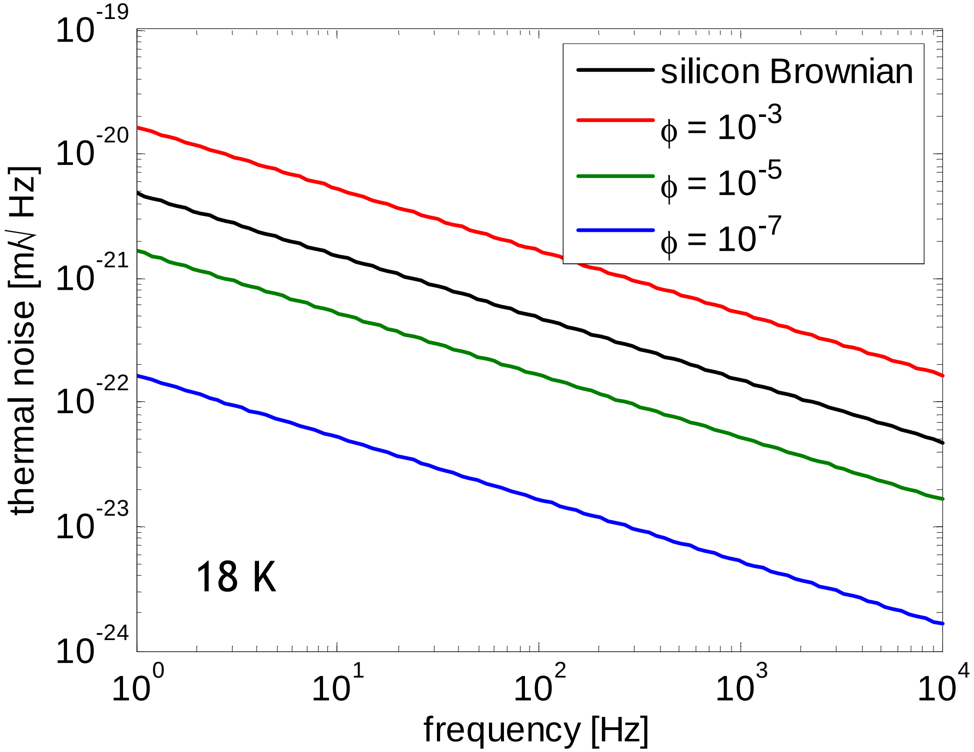
- estimation of the Brownian thermal noise at 18 K



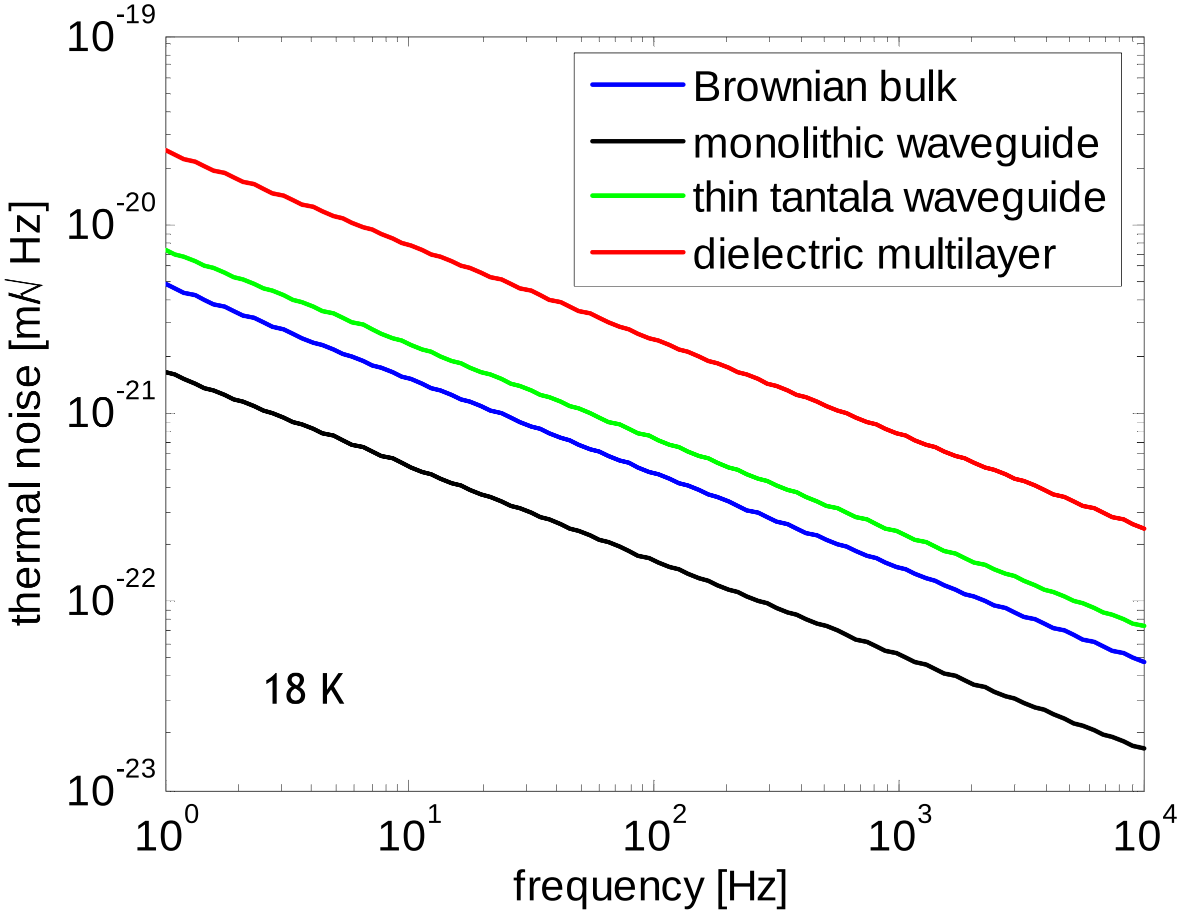
all structures are smaller than the wavelength of the laser light → structure is not resolved by laser → treatment as "effective media"

Y = 100 GPa (Si: 130 – 188 GPa)
t = 1.5 μm

volume averaged thermal properties



Comparison of the different concepts



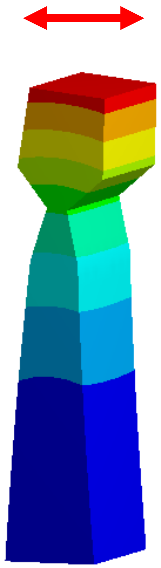
T-structure adds no significant noise to the bulk Brownian noise

↓

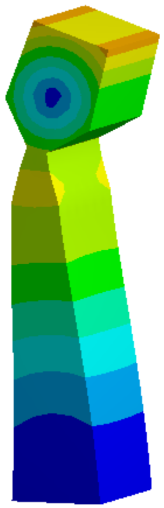
total noise is governed by bulk Brownian noise

Summary

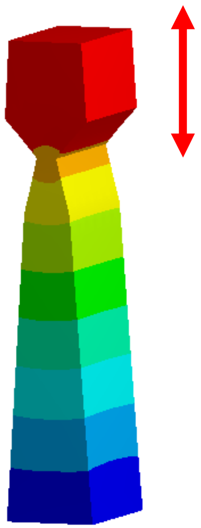
- silicon remains an attractive option for a 3rd generation detector substrate material
- dielectric multilayer stacks provide significant Brownian thermal noise of mirrors → large beam diameters needed
- investigation on reducing the mechanical loss by heat treatment is ongoing
- monolithic resonant waveguides provide a low thermal noise concept for mirrors and cavity couplers
- experimental verification of surface loss predictions currently underway
- novel low noise concept for a beamsplitter still needed



133 MHz



510 MHz



1.3 GHz

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