Bulk silicon mechanical loss for estimates of thermal noise

G. Hofmann[1], J. Komma[1], C. Schwarz[1], D. Heinert[1], K. Haughian[2], G. Hammond[2], P. Murray[2], K. Craig[2], P. Seidel[1], J. Hough[2], S. Rowan[2], and R. Nawrodt[1]

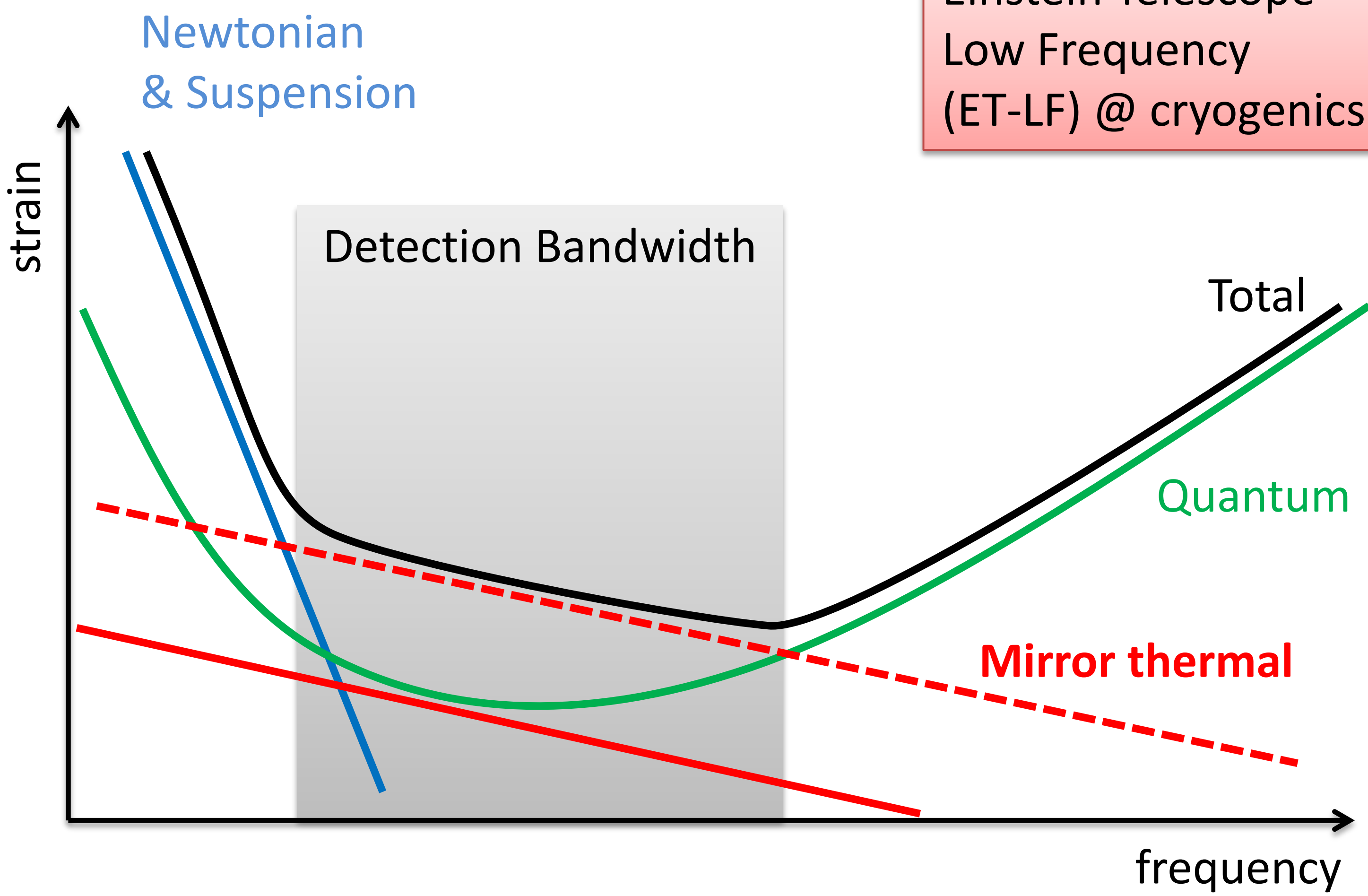
[1] Institut für Festkörperphysik, Friedrich-Schiller-Universität Jena, D-07743 Jena, Germany
[2] Institute for Gravitational Research, University of Glasgow, G12 8QQ Glasgow, UK

GWADW Elba 2013

May 23rd 2013

Noise estimate for future GW detector

Einstein Telescope
Low Frequency
(ET-LF) @ cryogenics



Outline

- Thermal noise in mirrors
  - Basic equations
- Temperature dependence of silicon material parameters
  - Bulk Brownian thermal and thermo-elastic noise estimates at low temperatures
- Mechanical loss in silicon
  - Mechanical loss at $120\ \mathrm{K}$
  - Crystal orientation of test masses
- Summary

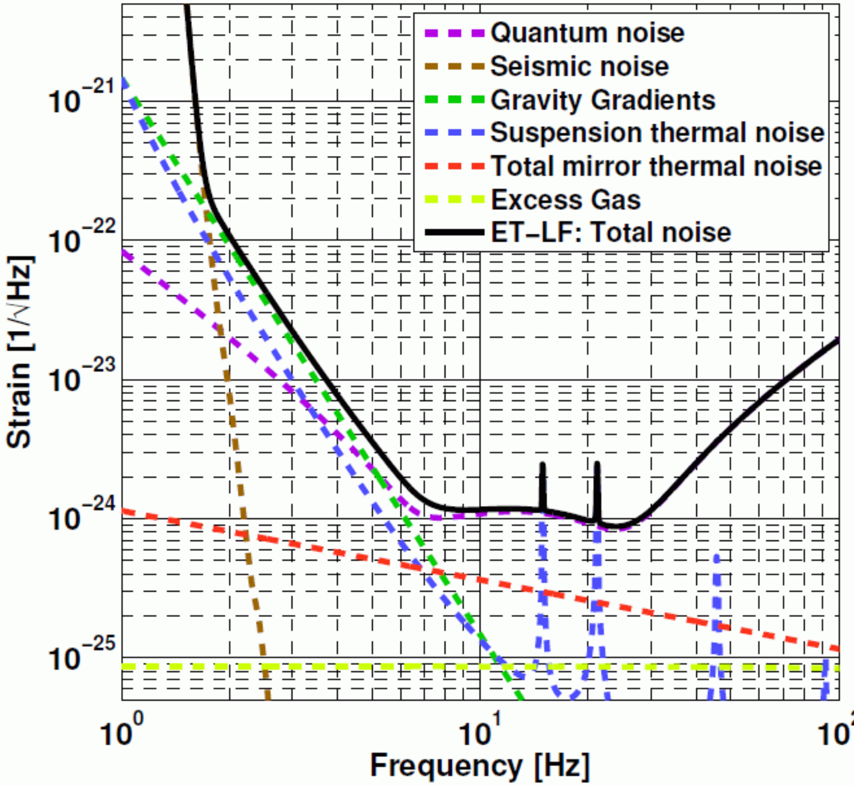
Thermal noise in mirrors

- Direct approach by Levin (1998):

$$S_z(f) = \frac{2\,k_B T}{\pi^2 f^2}\frac{W_{\text{diss}}}{F_0^2} \quad \text{where} \quad W_{diss} = 2\pi f U_{max}\phi$$

[ET Design Study (2011)]

- Mirror thermal noise:
  - Substrate
    - Substrate Brownian thermal noise
    - Substrate thermo-elastic noise
  - Coating
    - Coating Brownian thermal noise
    - Coating thermo-optical noise



Substrate thermal noise

- Brownian thermal noise:

$$S_{Brown}^{bulk} = 2k_B T \frac{1-\nu^2}{\sqrt{\pi^3} Y w f} \phi_{bulk}$$

[Braginsky et al. (1999), Liu & Thorne (2000)]

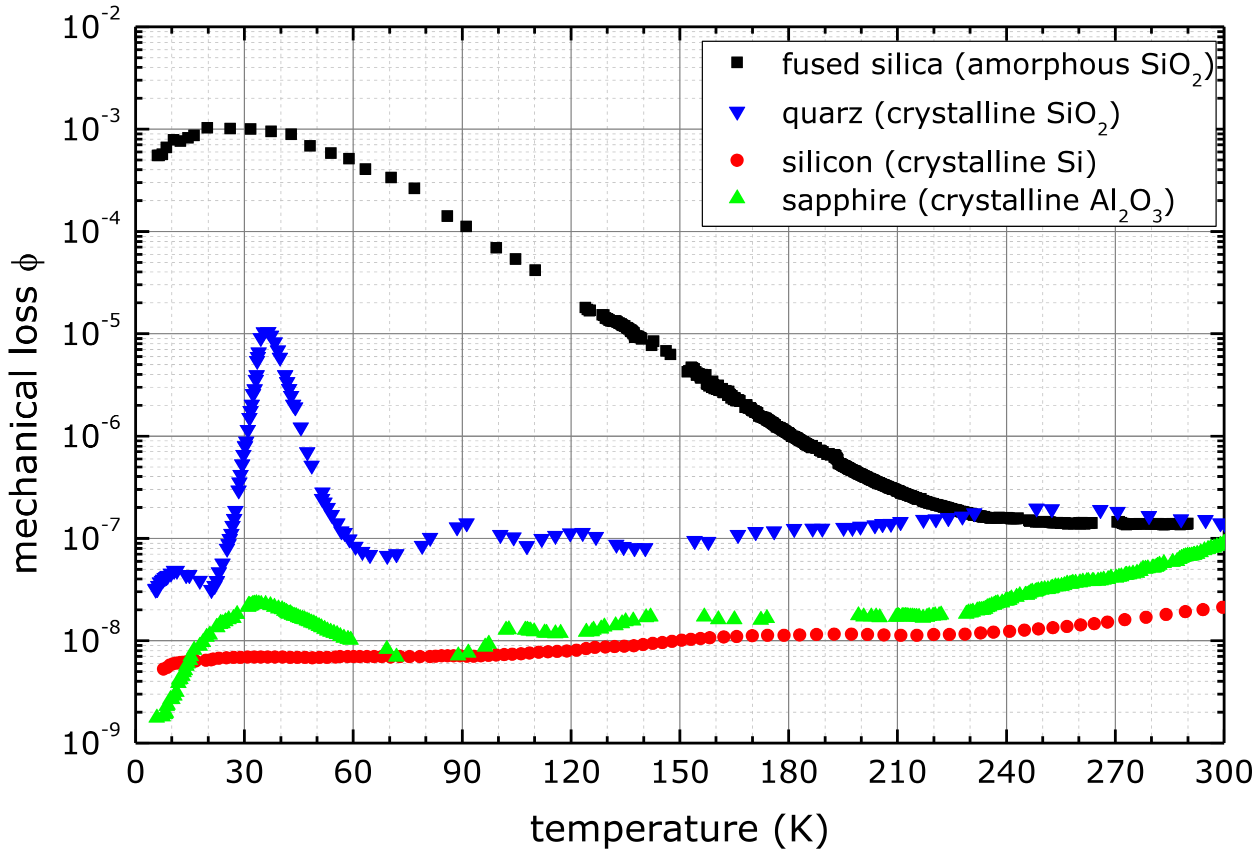
- Thermo-elastic noise

$$S_{TE}^{bulk} = 4\, k_B T^2 \frac{(1+\nu)^2 \alpha^2 w}{\sqrt{\pi}\kappa} J\left(\frac{2\pi f}{2\kappa / \rho C w^2}\right)$$

[Cerdonio et al. (2001)]

Depends on beam radius, temperature, and material parameters.

Mechanical loss ϕ at low temperatures



Fused silica:

high mechanical loss at low temperatures

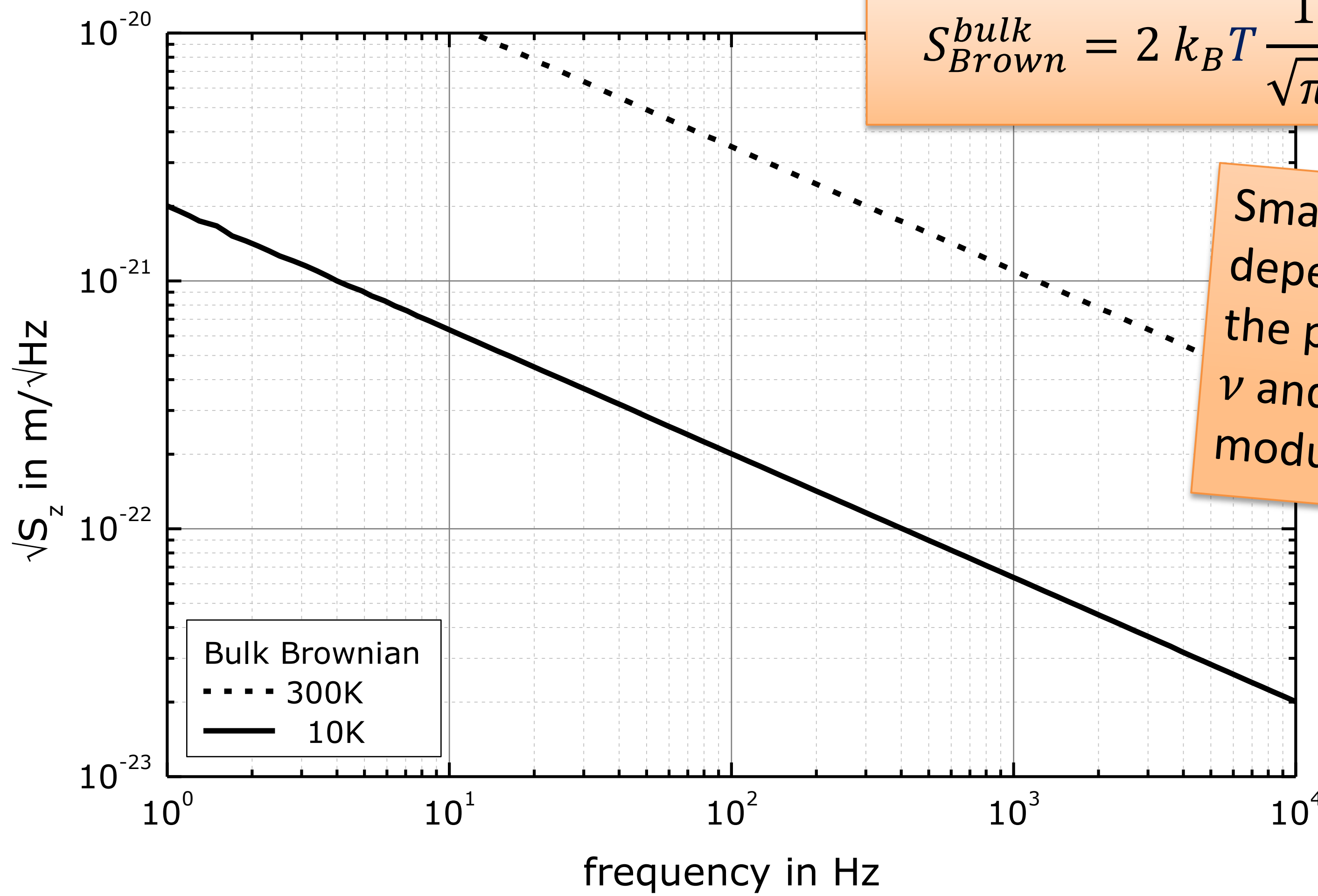
Crystalline materials: quartz, silicon or sapphire show very low losses at low temperatures

ET favours silicon

KAGRA will utilise sapphire

Bulk Brownian thermal noise at low temperatures

$$S_{Brown}^{bulk} = 2\,k_B T \frac{1-\nu^2}{\sqrt{\pi^3} Y w f}\,\phi_{bulk}$$

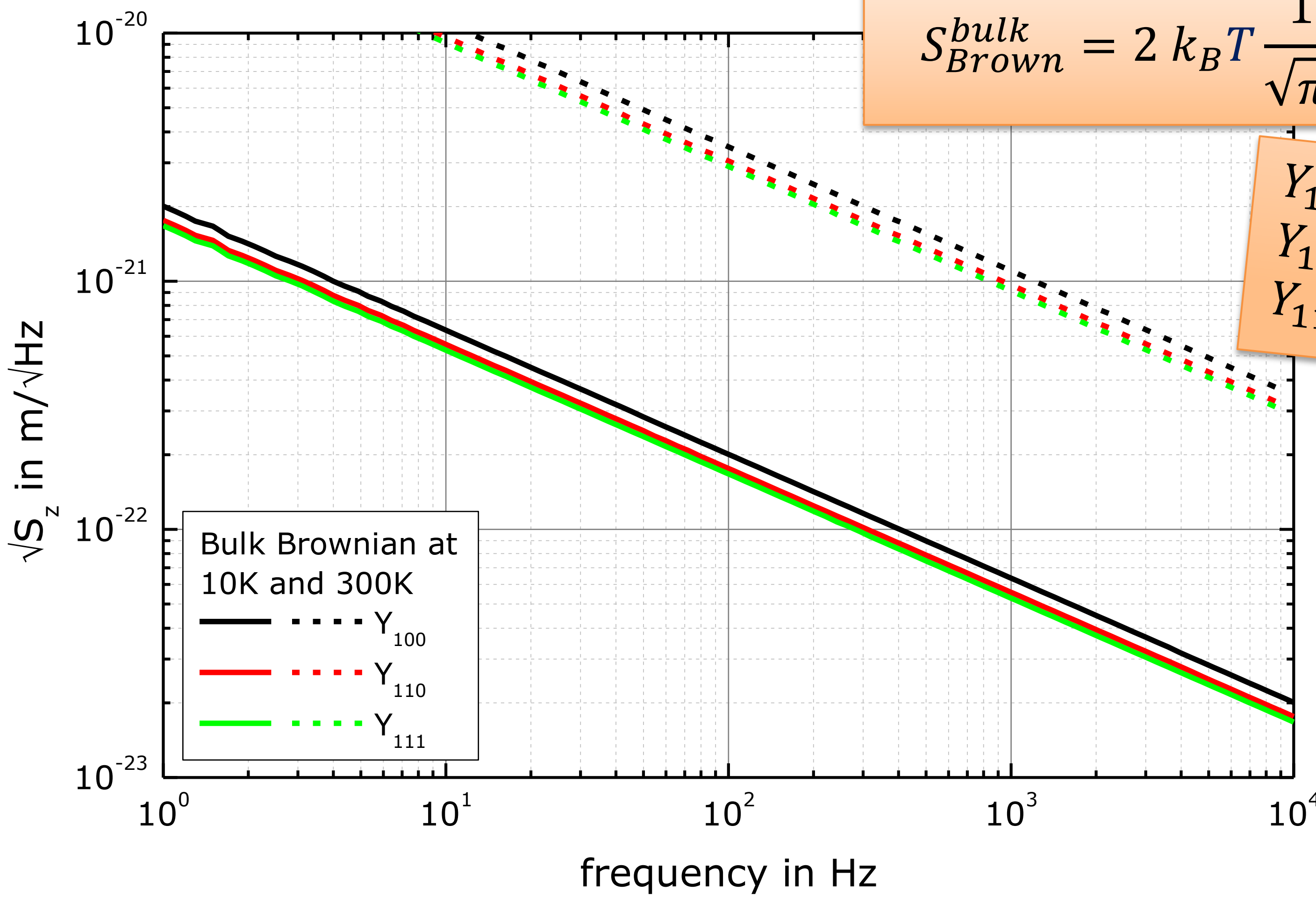


Small temperature dependence of the poissons ratio ν and the Young‘s modulus Y.

Influence of the crystal orientation

$$S_{Brown}^{bulk} = 2\, k_B T \frac{1 - \nu^2}{\sqrt{\pi^3} Y w f}\, \phi_{bulk}$$

$Y_{100} = 130$ GPa
$Y_{110} = 169$ GPa
$Y_{111} = 188$ GPa



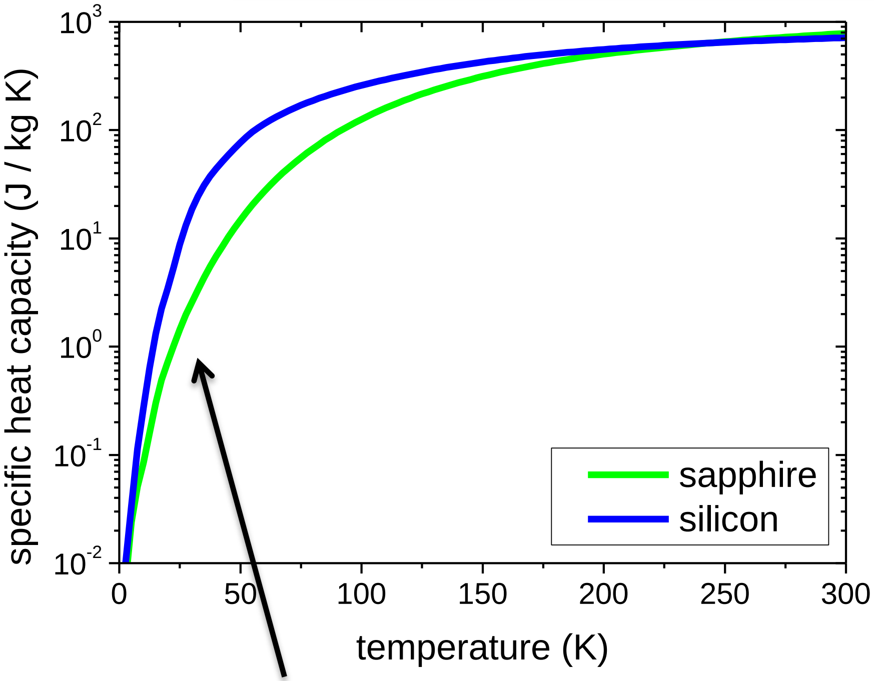
➔ Due to anisotropy the crystal orientation matters!

Temperature dependence of material parameters

- High temperatures

Dulong-Petit: C/$\rho \approx const.$

Experimental: $C \sim T$

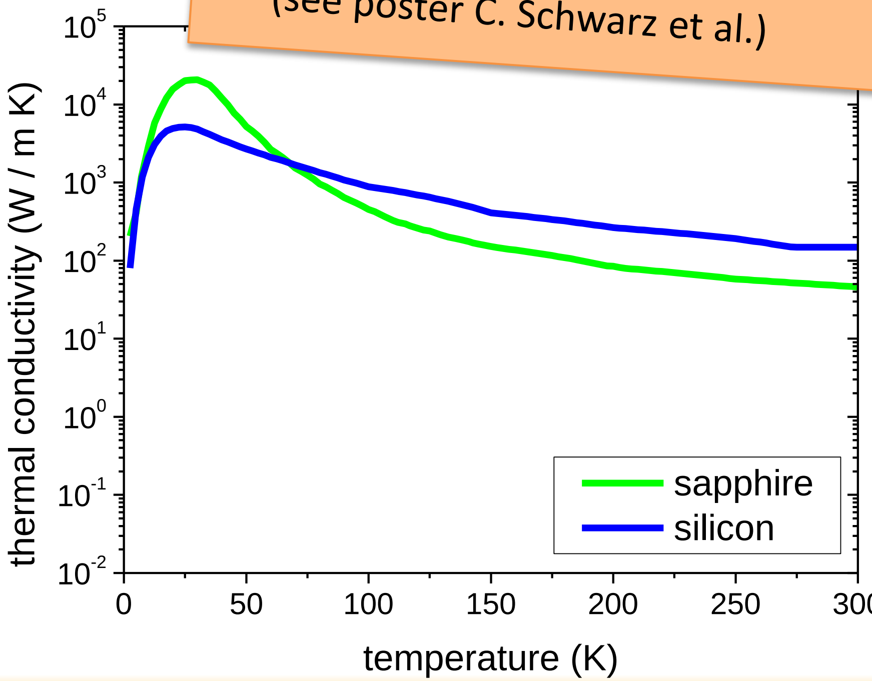


- Low temperatures

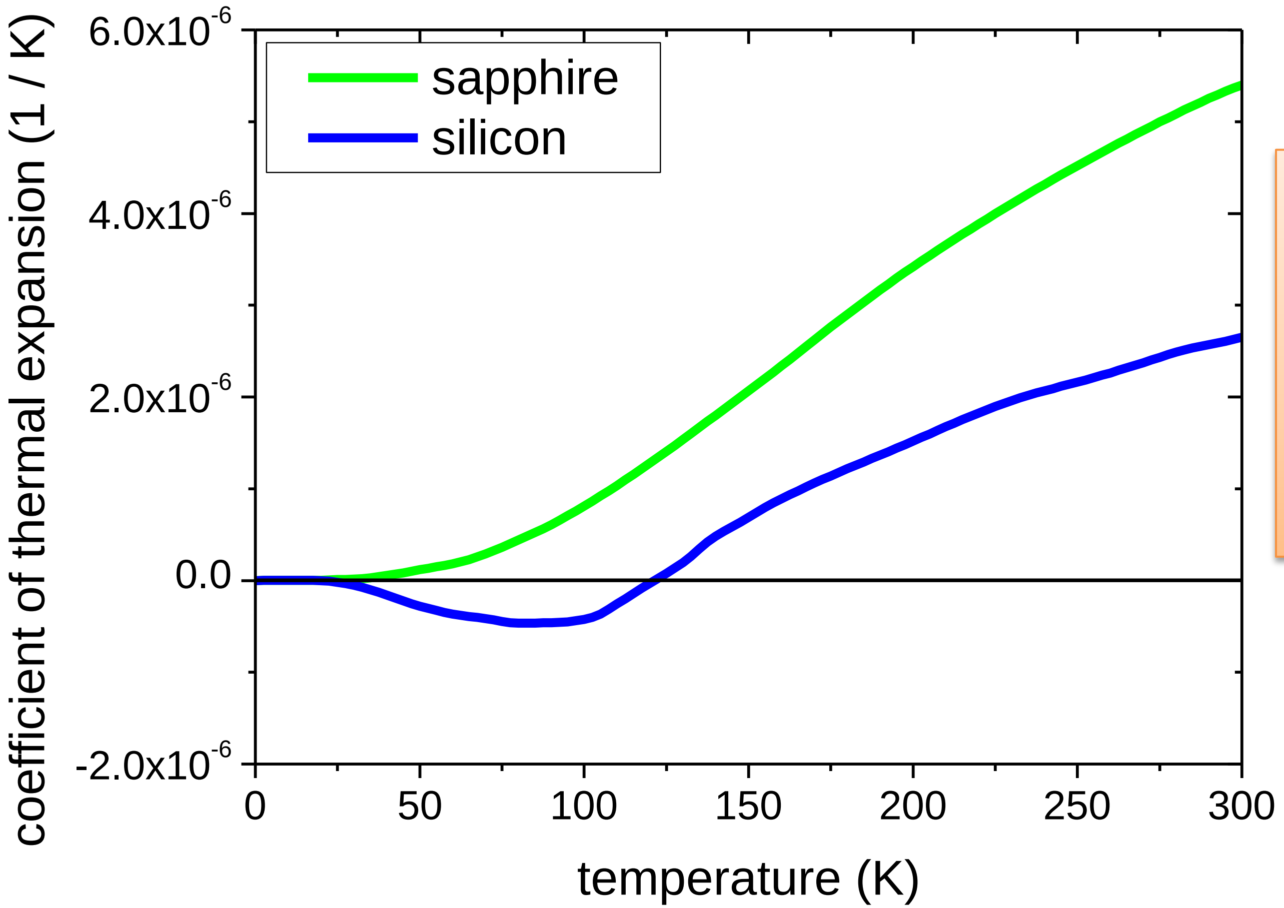
Debye: C ~ T^3 if $T < \Phi$

Thermal conductivity in crystalls:

- $\kappa = \frac{1}{3}\rho C v \lambda$ by phonons
- $\kappa \sim T^3$ due to C $(T \ll \Phi)$
- $\kappa \sim T^{-1}$ due to λ $(T \gg \Phi)$
- λ (and thus κ) might be limited by size and impurities (see poster C. Schwarz et al.)

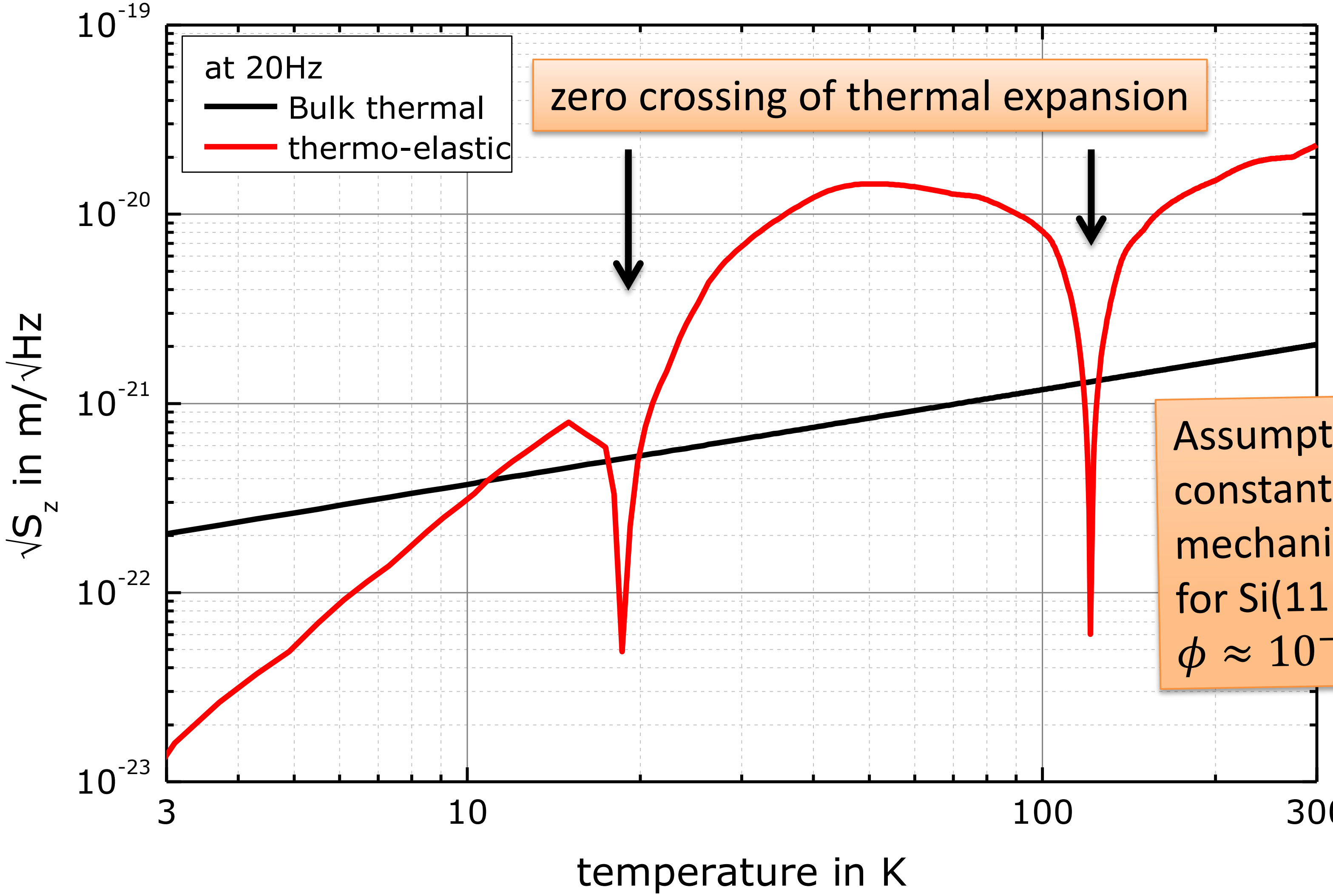


Temperature dependence of material parameters



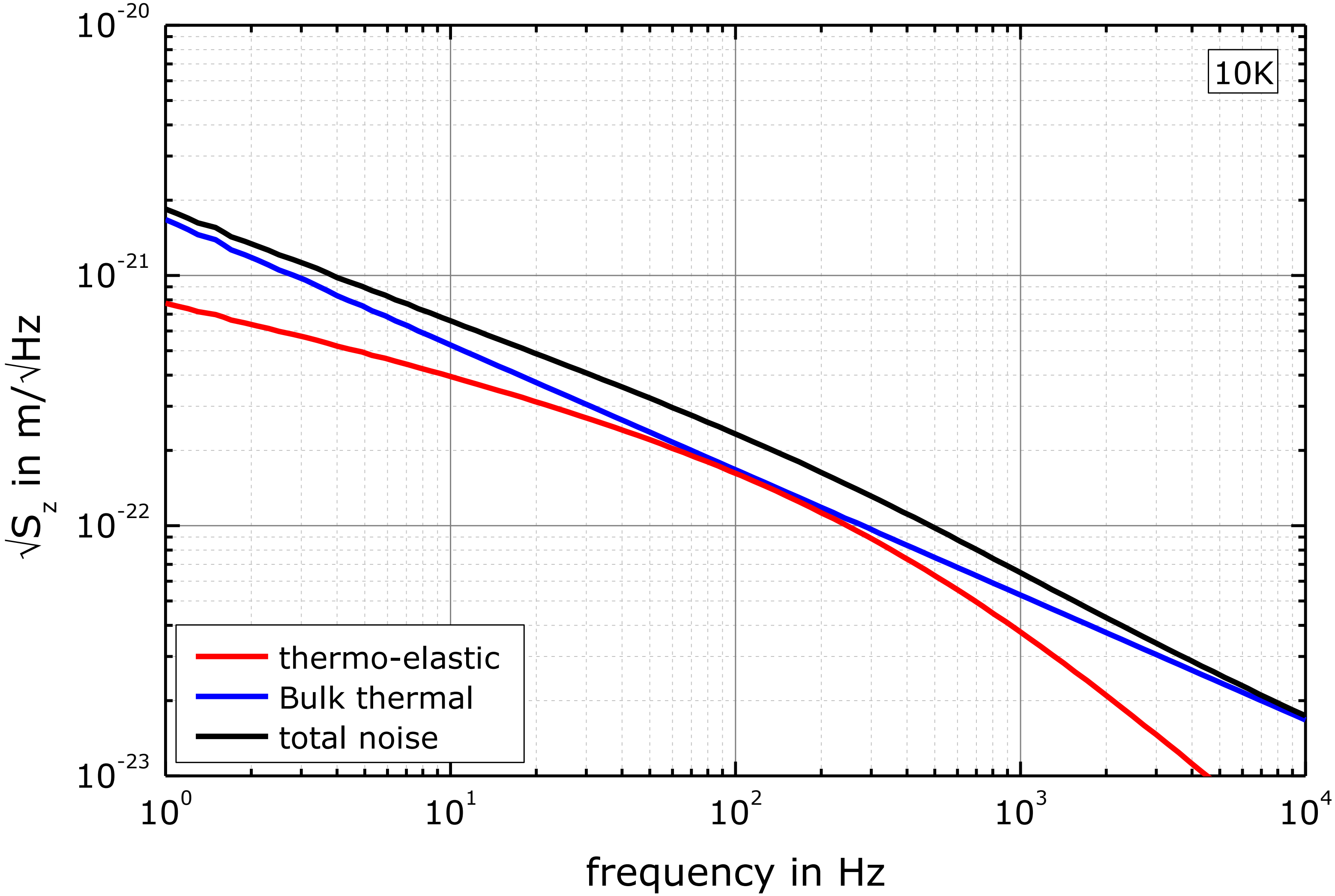
Zero crossing of the thermal expansion coefficient of silicon at 18 K and 120 K gives vanishing thermo-elastic noise ($\sim \alpha^2$)

Temperature dependence of thermal noise

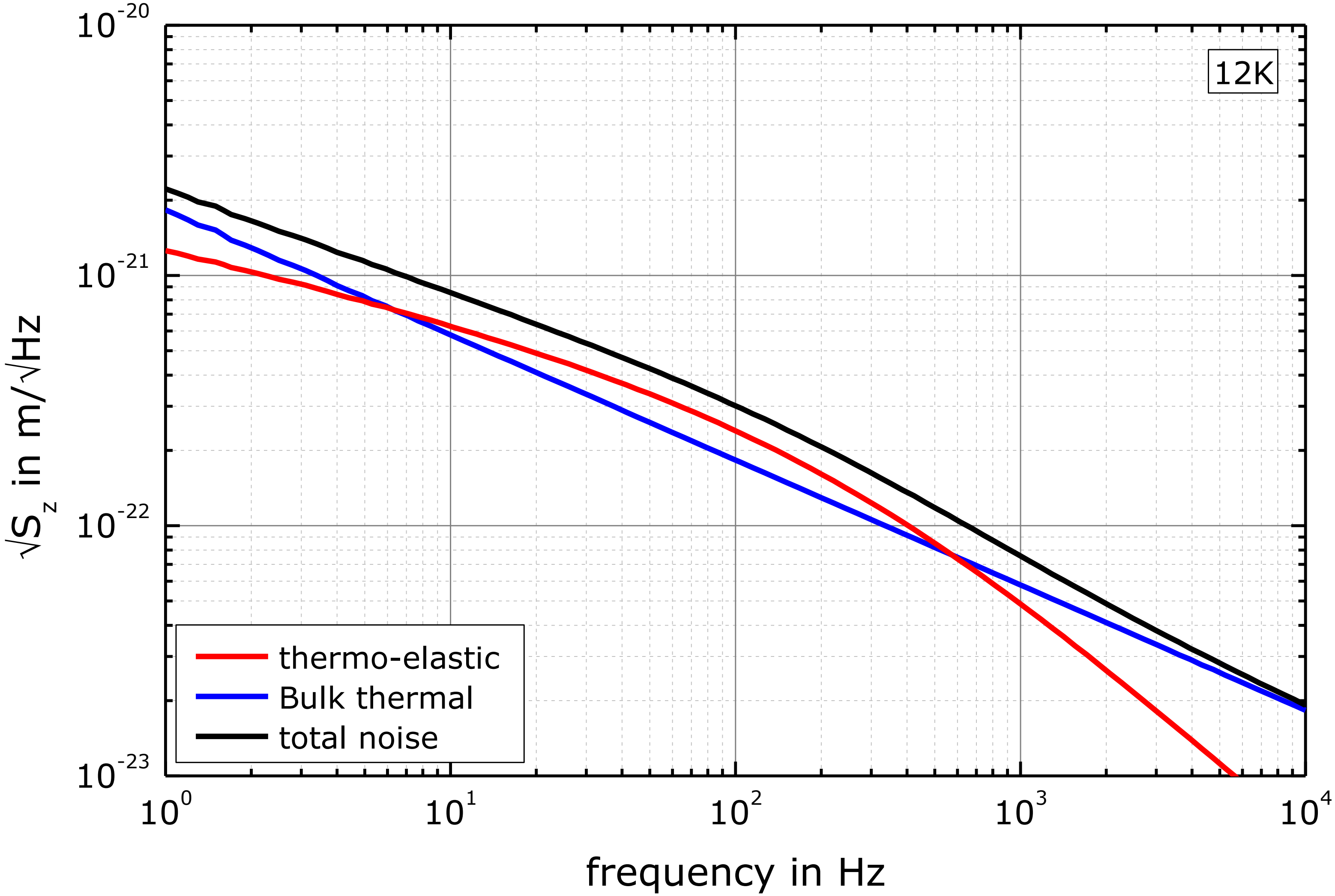


Assumption:
constant mechanical loss for Si(111)
$\phi \approx 10^{-9}$

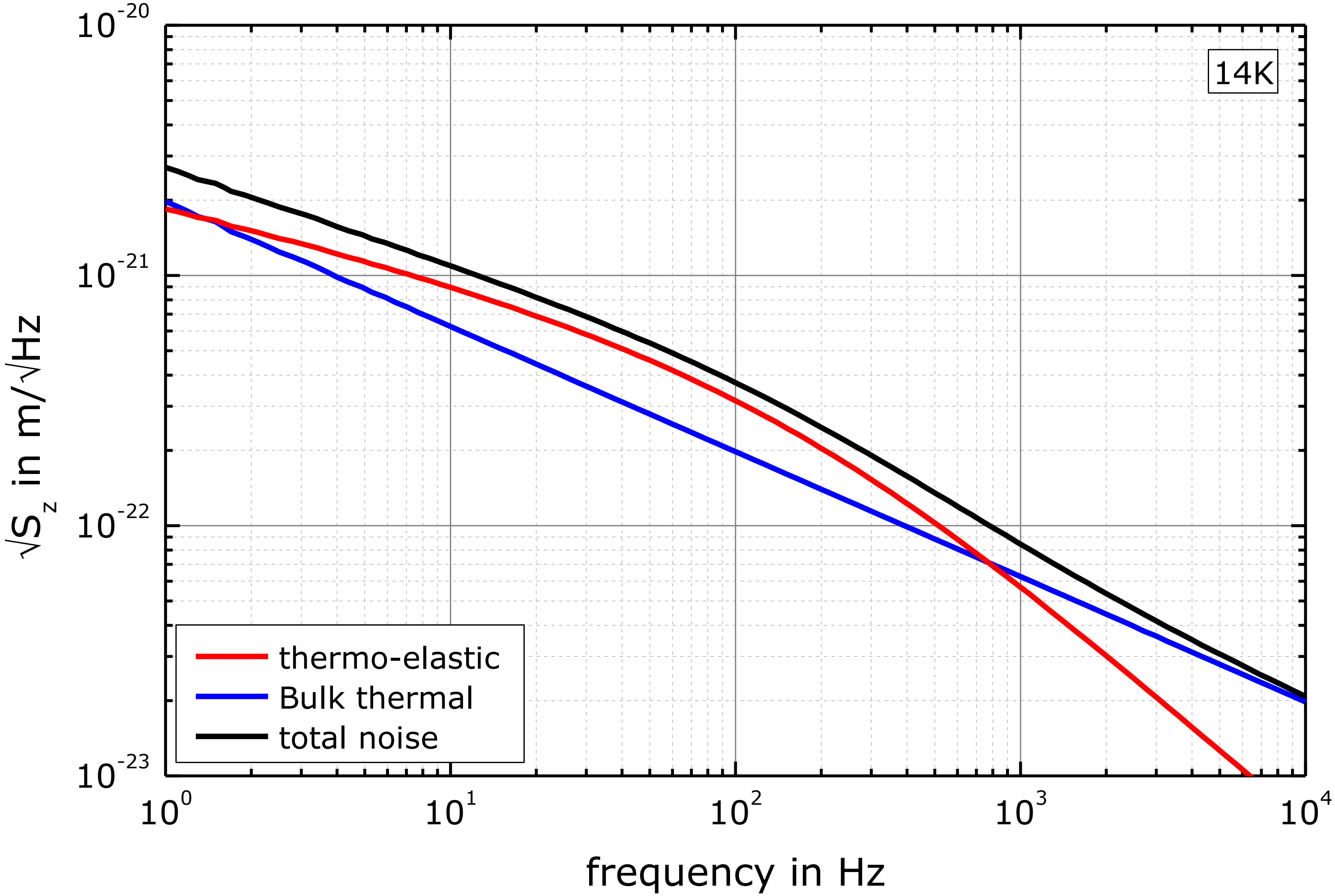
Temperature dependence of thermal noise



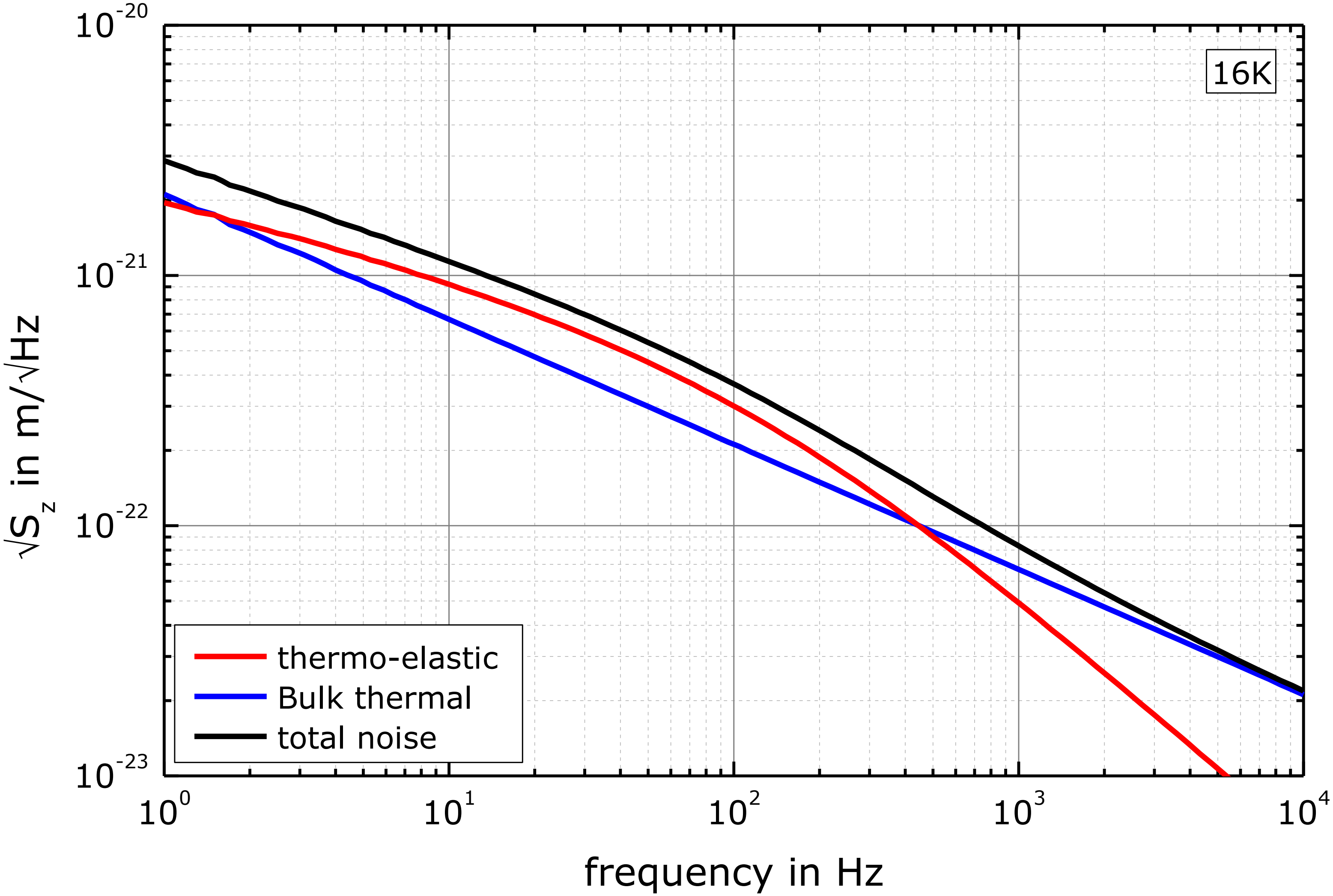
Temperature dependence of thermal noise



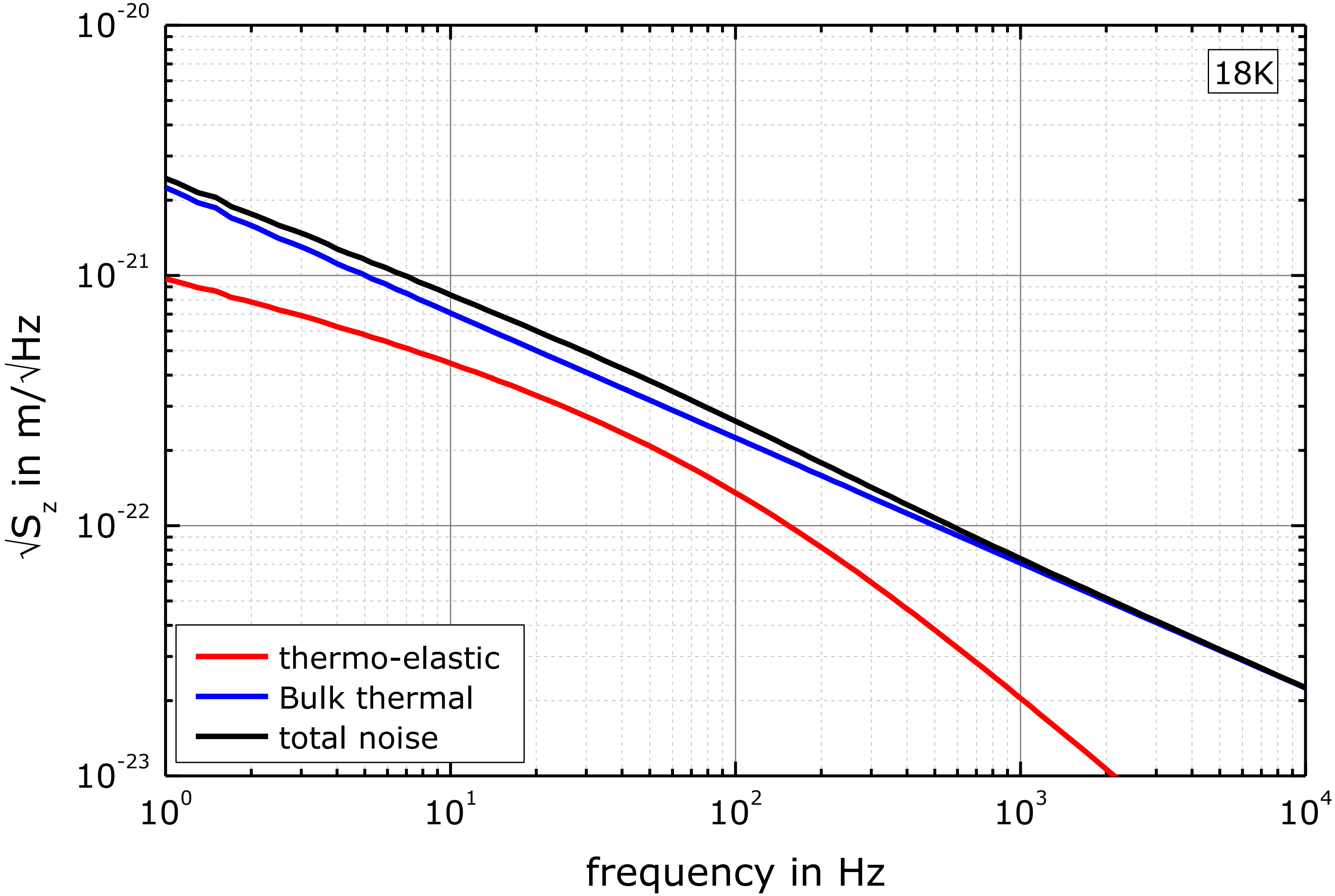
Temperature dependence of thermal noise



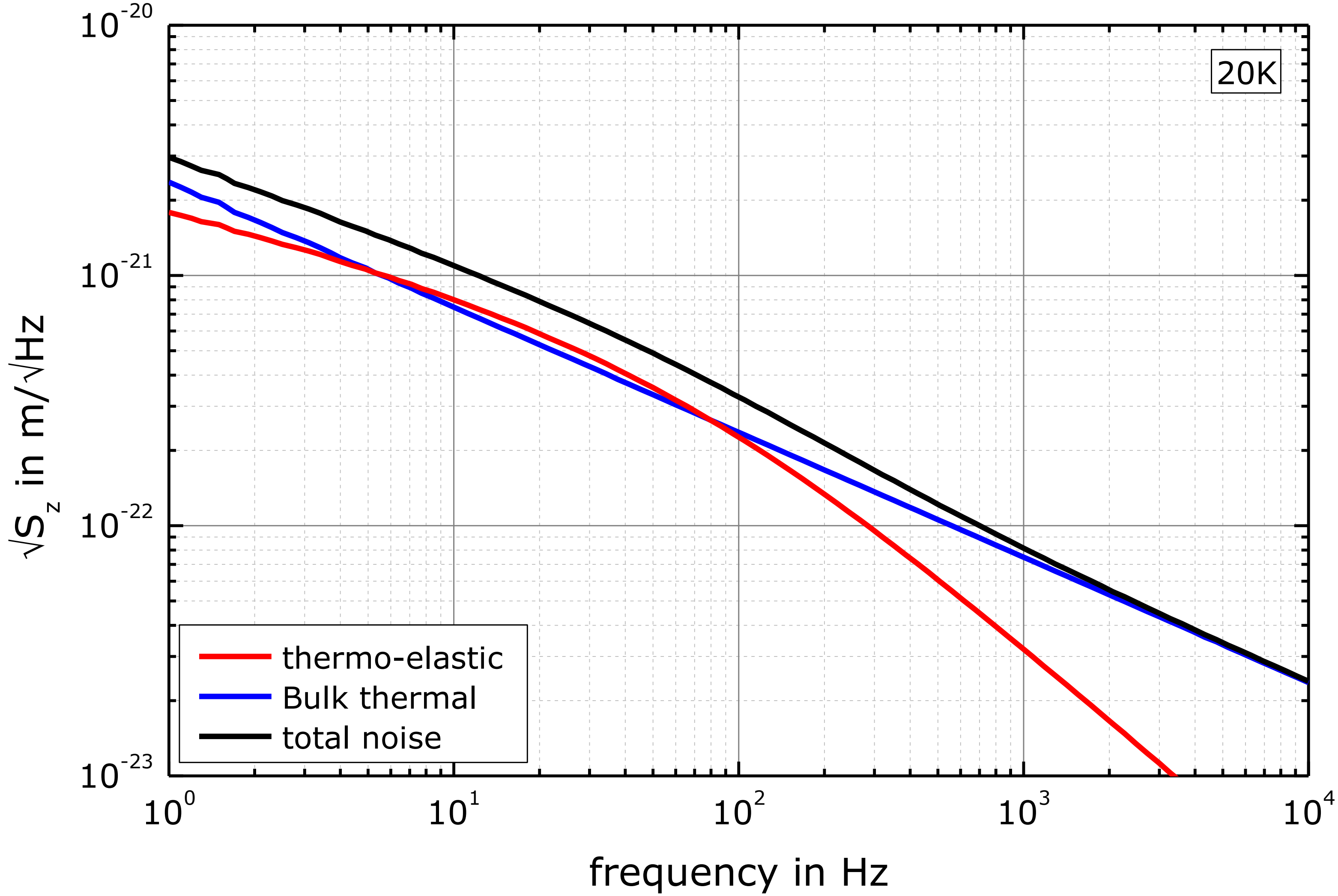
Temperature dependence of thermal noise



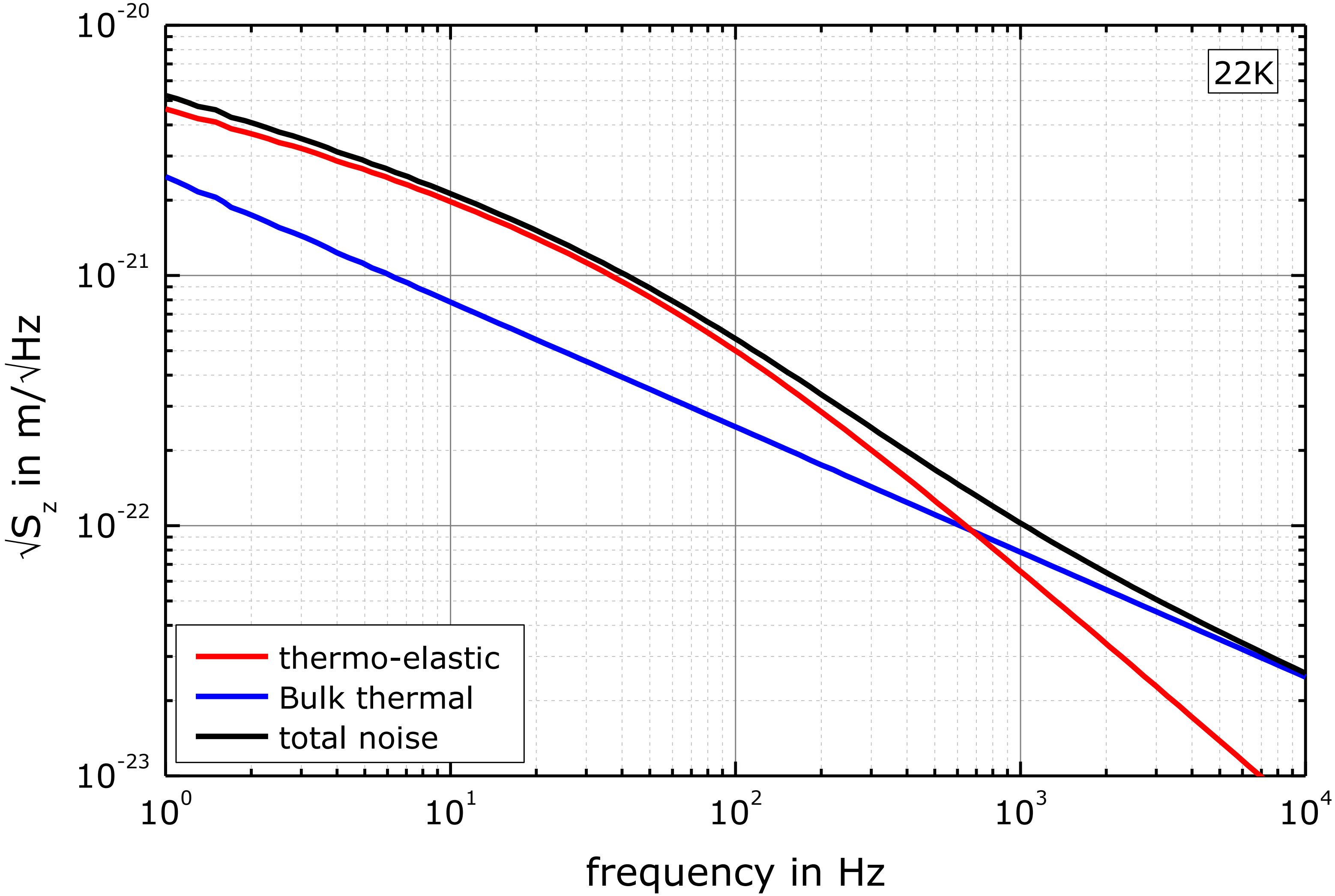
Temperature dependence of thermal noise



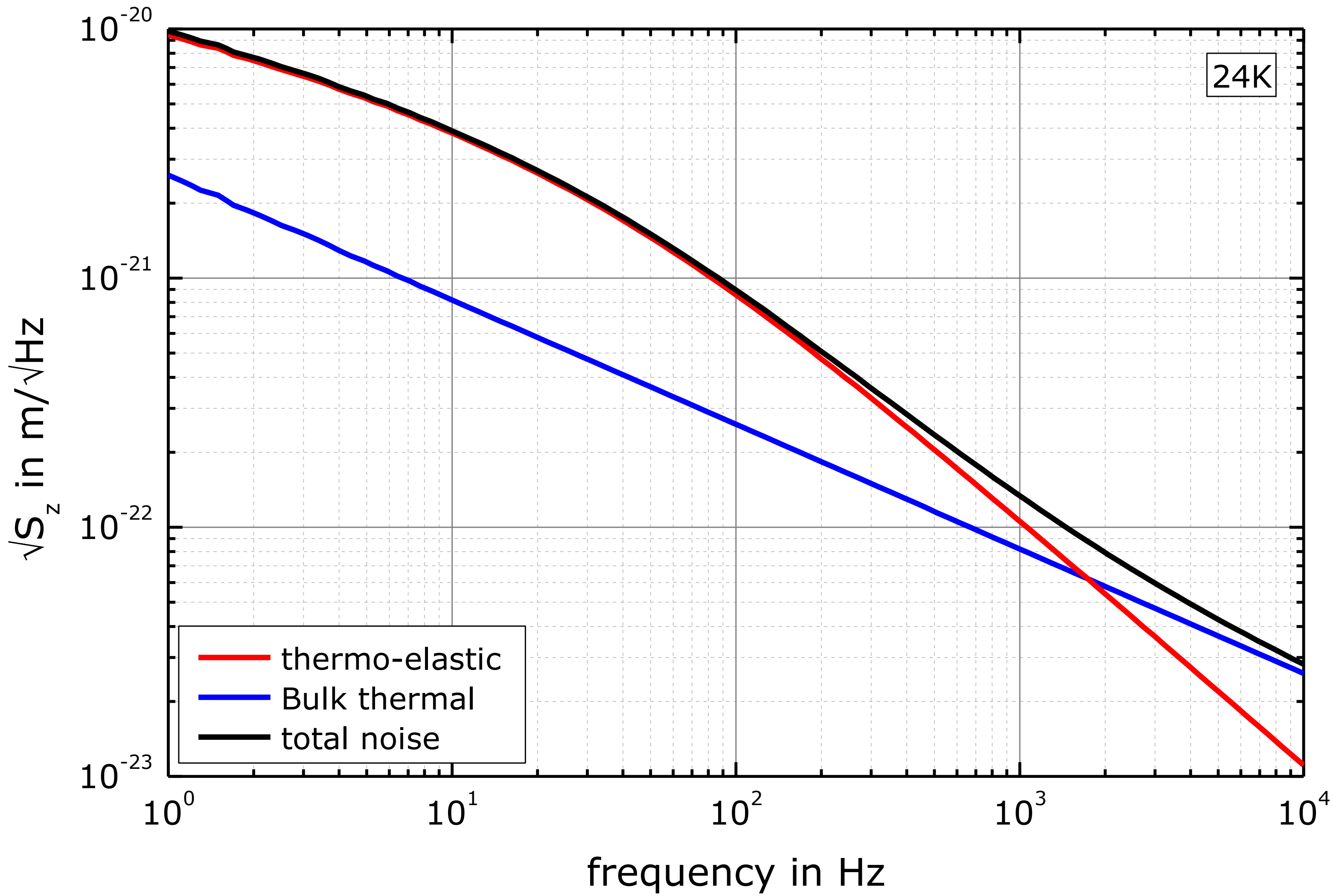
Temperature dependence of thermal noise



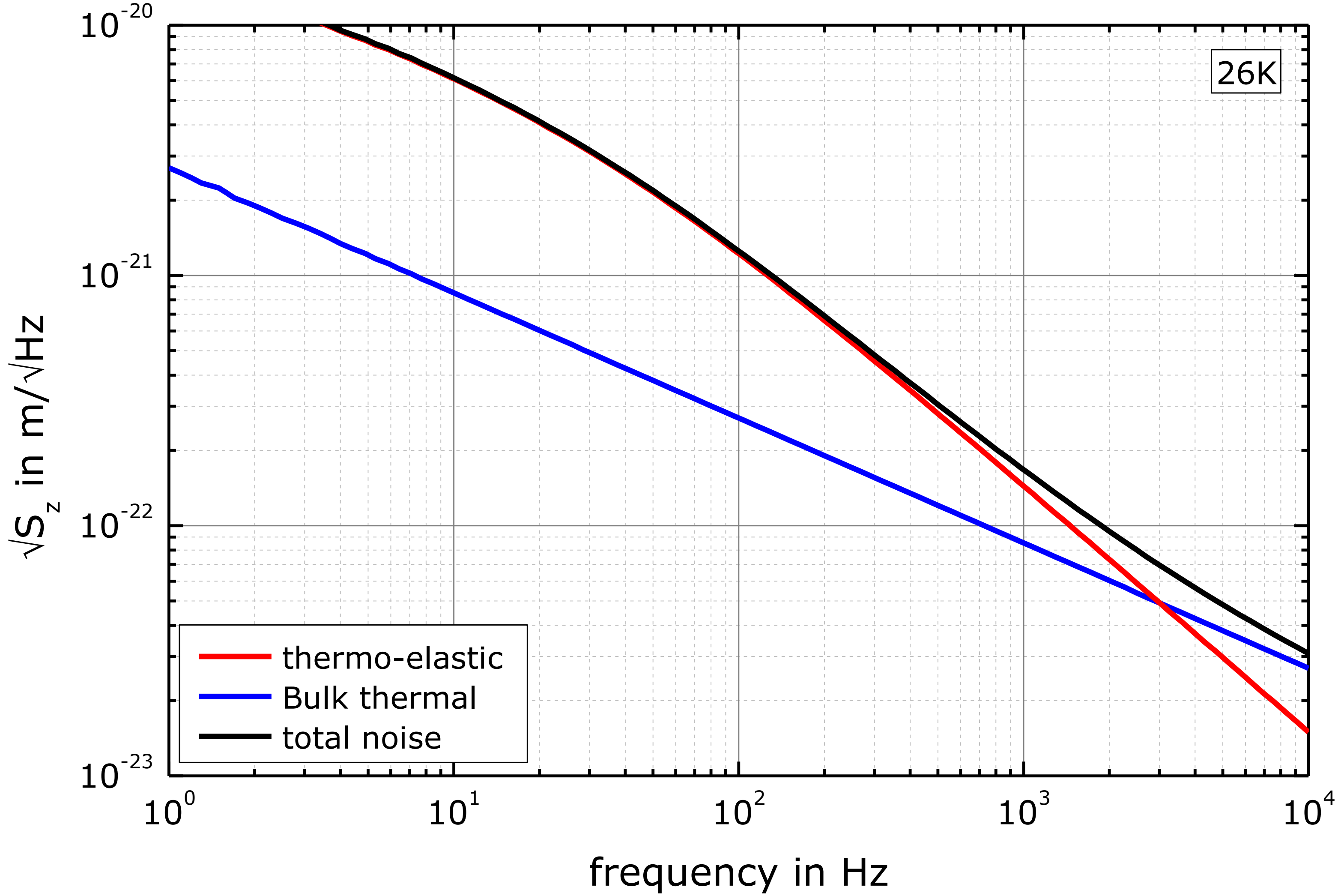
Temperature dependence of thermal noise



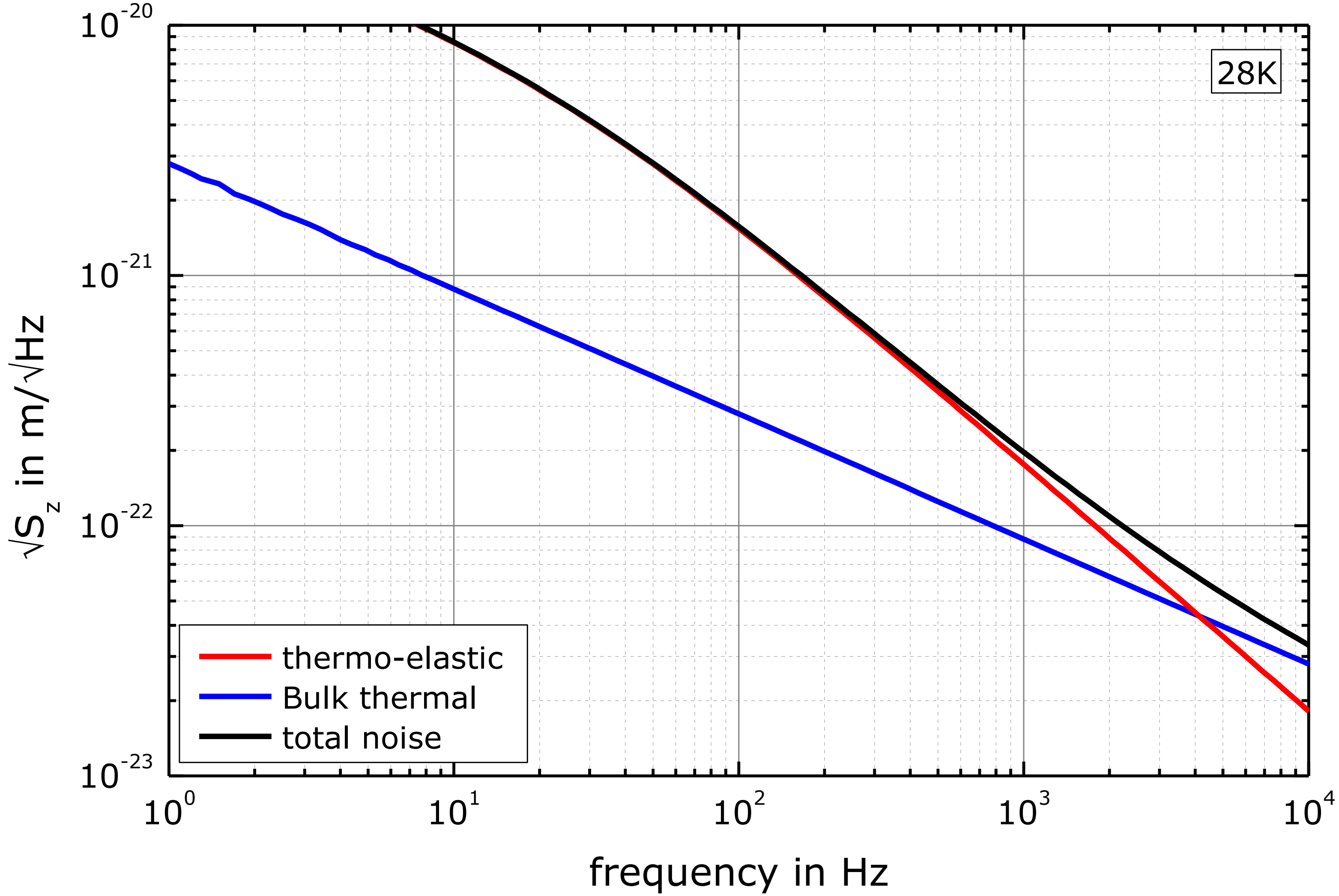
Temperature dependence of thermal noise



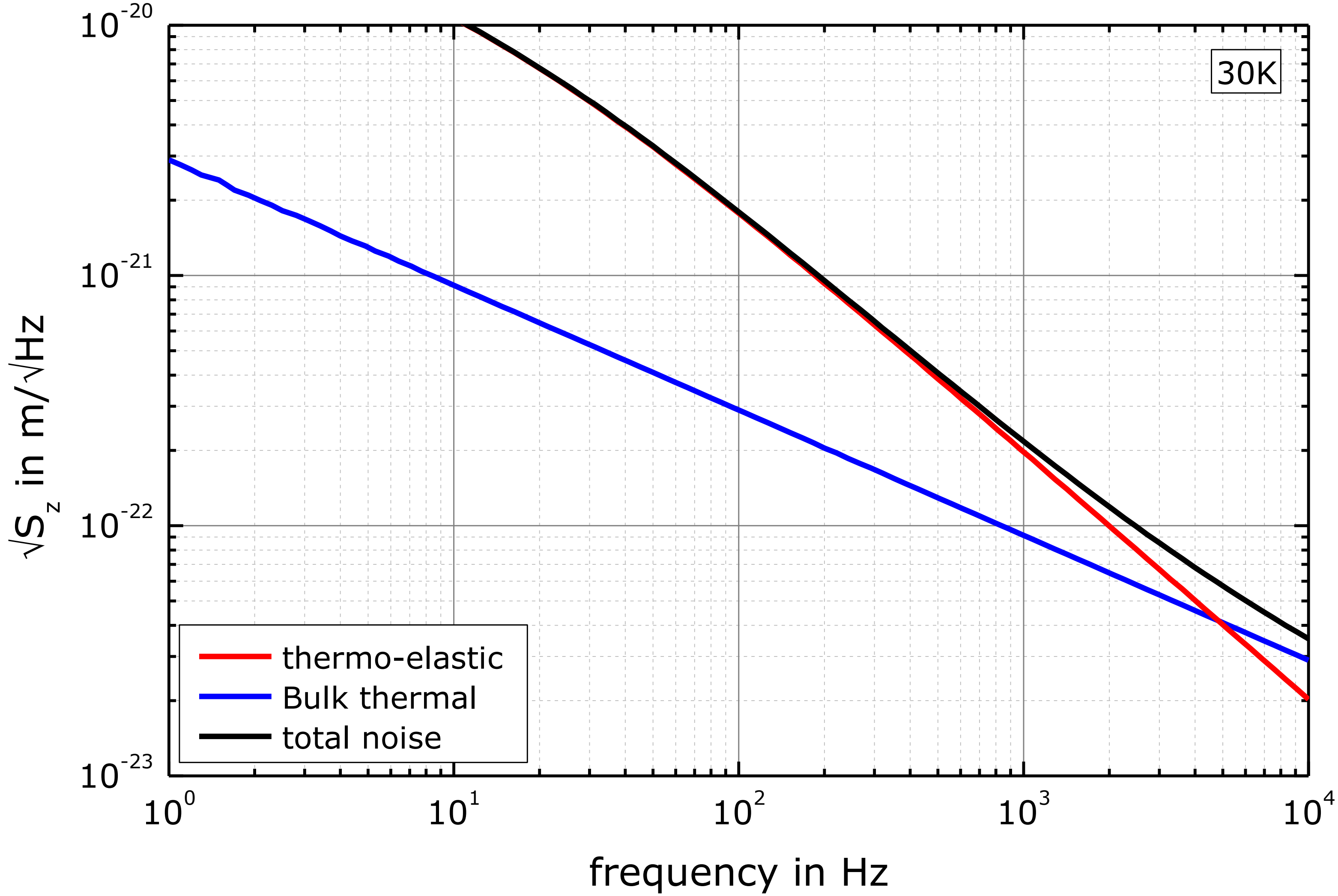
Temperature dependence of thermal noise



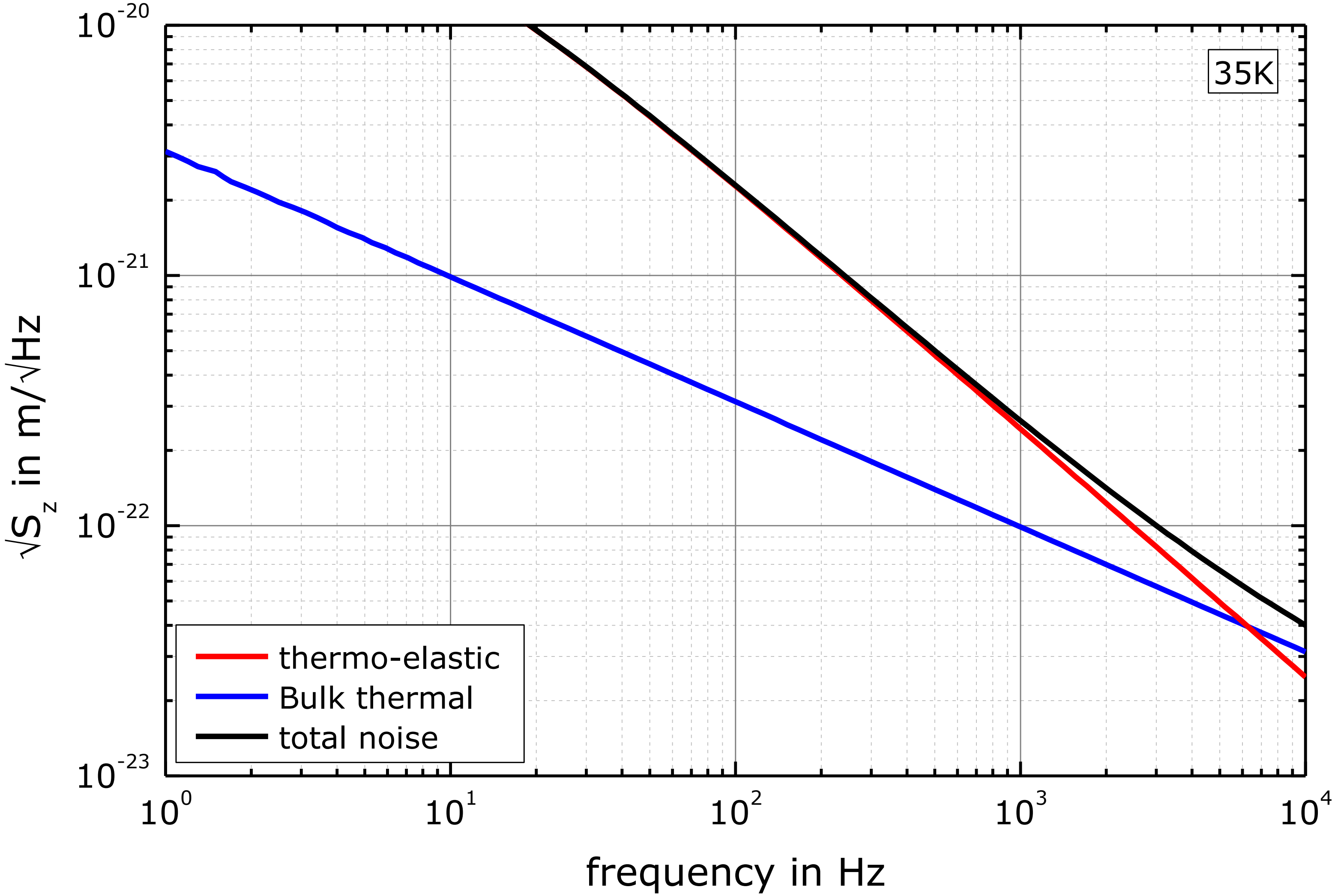
Temperature dependence of thermal noise



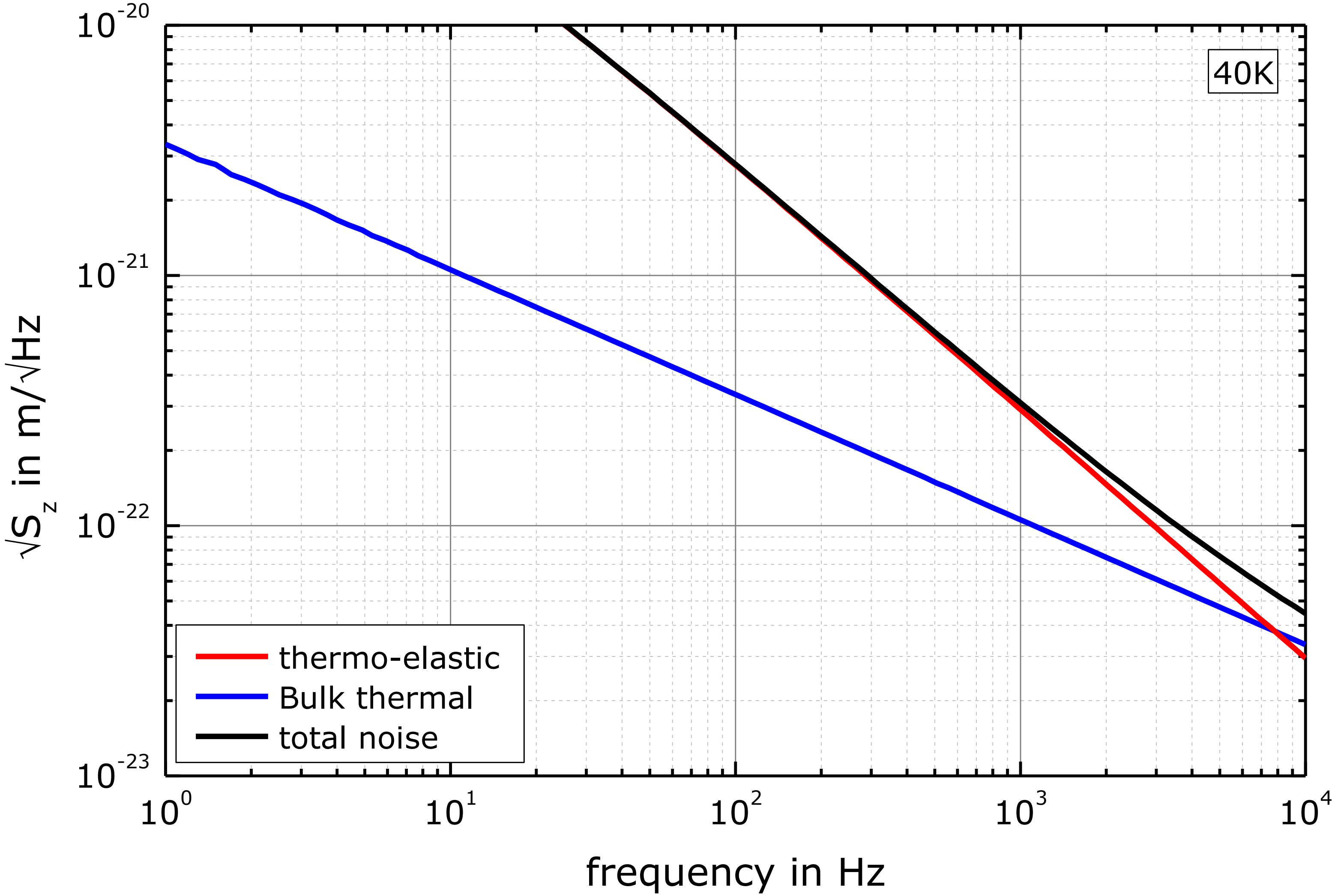
Temperature dependence of thermal noise



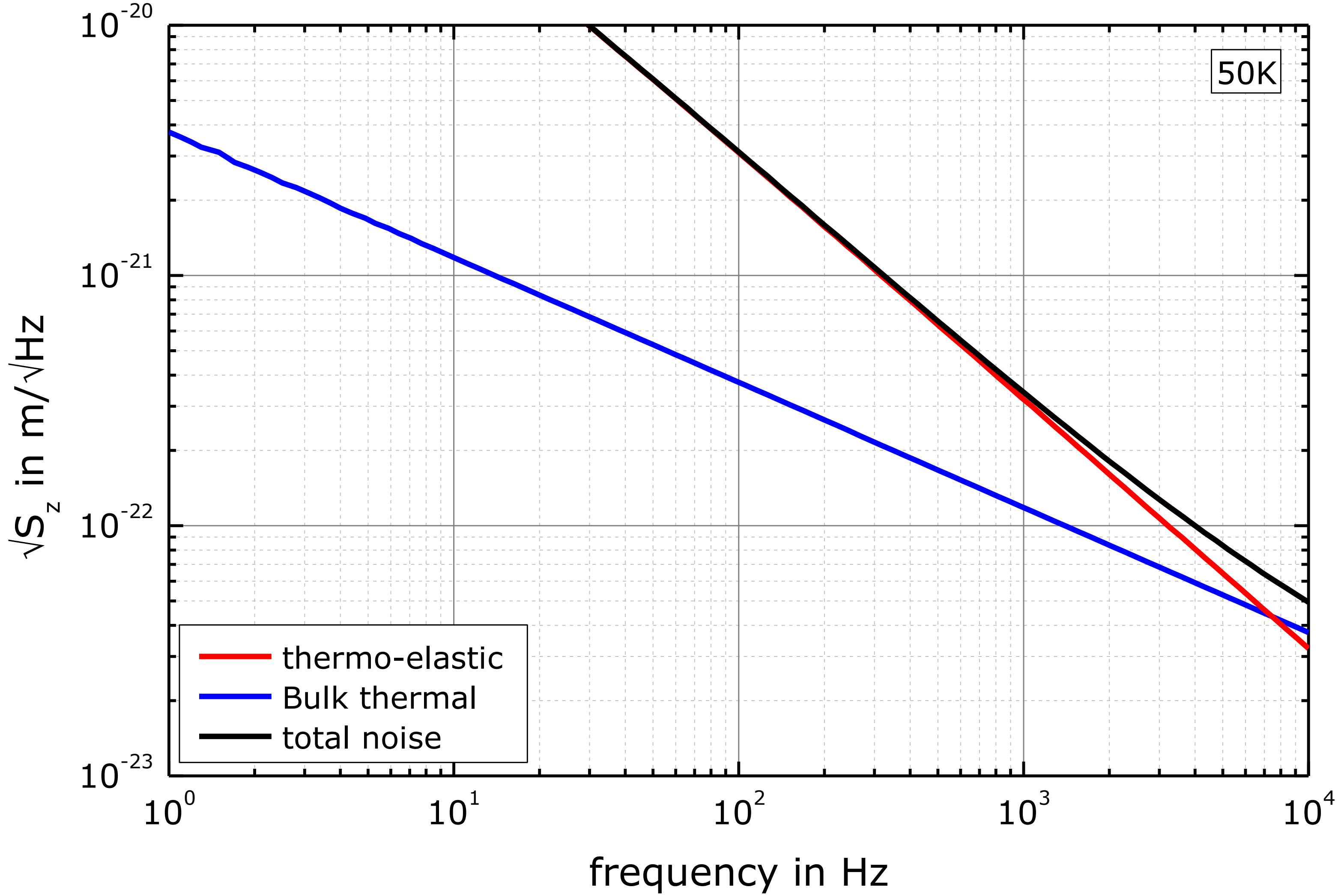
Temperature dependence of thermal noise



Temperature dependence of thermal noise

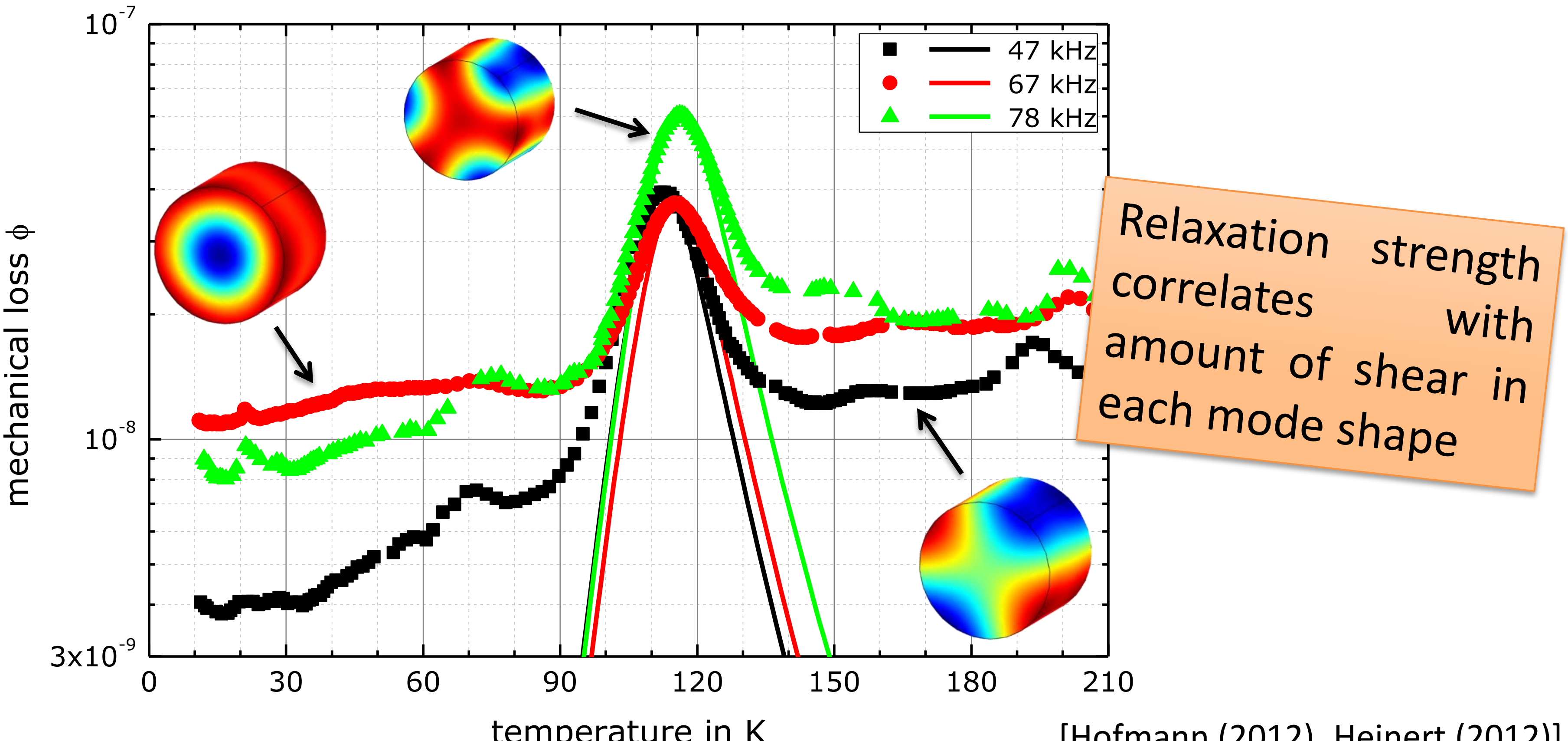


Temperature dependence of thermal noise



Silicon (111) dia. 65 mm x 50 mm

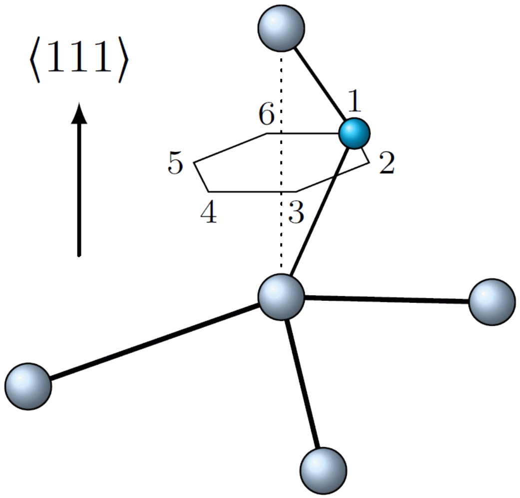
- Czochralski growth (CZ), loss peak at 120 K for every measured mode
- Activation energy: $E_A = 168$ meV (Arrhenius plot)



[Hofmann (2012), Heinert (2012)]

Silicon loss peak at 120K

- First assumption:
  Interstitial oxygen causes the peak
- Possible loss mechanisms:
  - Rotation due to six-fold symmetry
    ($E_A^{rot} \approx 4\,\text{meV} \ll E_A$)
    [Bosomworth et al. (1970)]



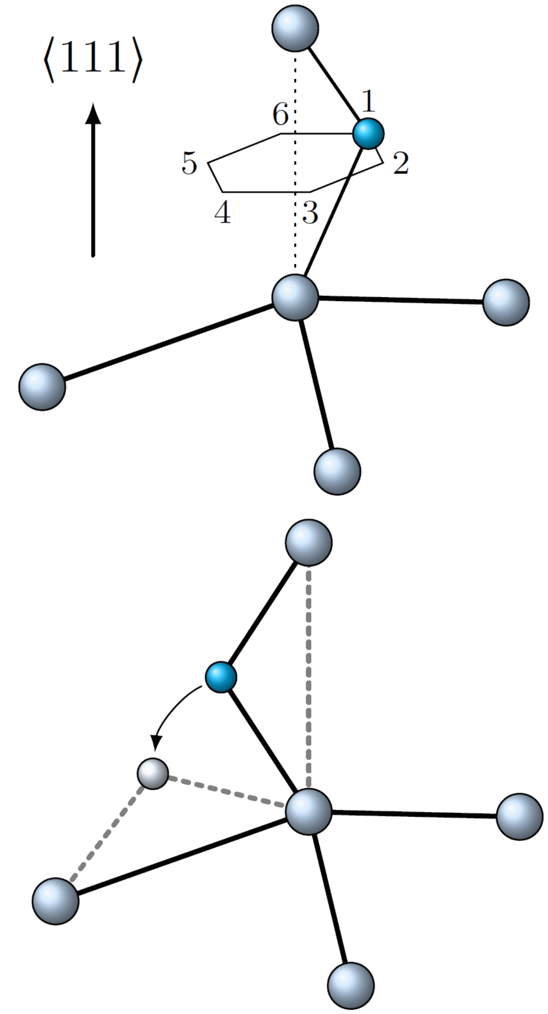
[Borghesi et al. (1995)]

Silicon loss peak at 120K

- First assumption:
  Interstitial oxygen causes the peak
- Possible loss mechanisms:
  - Rotation due to six-fold symmetry
    ($E_{\mathrm{A}}^{\mathrm{rot}} \approx 4\mathrm{meV} \ll E_{\mathrm{A}}$)
    [Bosomworth et al. (1970)]
  - Diffusion by hoping
    ($E_{\mathrm{A}}^{\mathrm{diff}} \approx 2.5\ \mathrm{eV} \gg E_{\mathrm{A}}$)
    [Haas et al. (1960), Corbett et al. (1964)]
- Kinks or dislocations in the crystal
  - Annealing did not change the loss peak

➔ on going research on this process

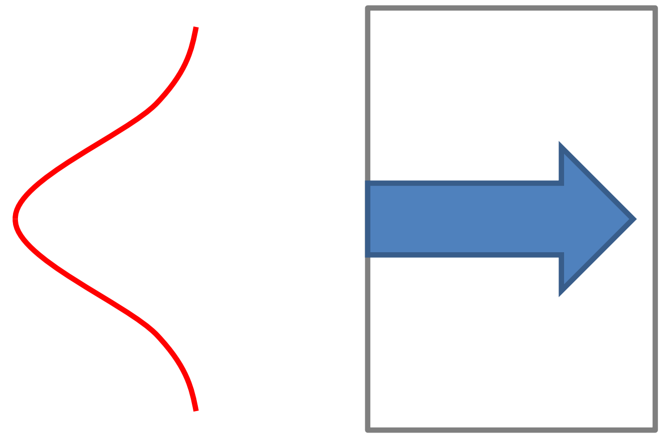
➔ thermal noise calculation including this observed loss peak



[Borghesi et al. (1995)]

Noise estimates from the observation

- How to deal with the observed loss peak?
  - Related to amount of shear
- Numerical analysis following Levin‘s approach
  - Apply gaussian pressure profile on the sample:
  - Calculate the elastic energy due to bending and shear:



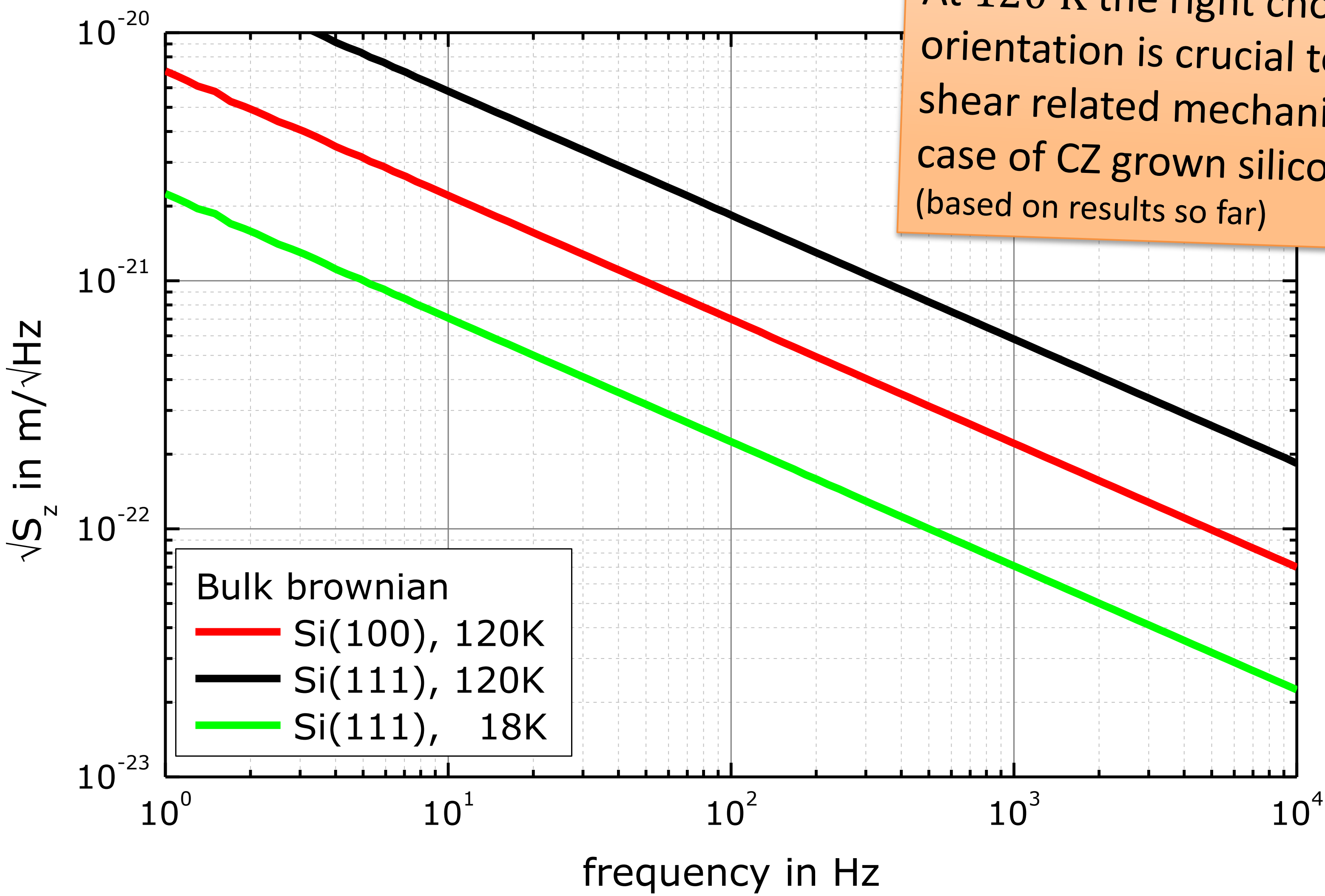
Orientation	$\langle 100 \rangle$	$\langle 110 \rangle$	$\langle 111 \rangle$
Bending energy	0,77	0,52	0,43
Shear energy	0,23	0,40	0,45

The amount of shear energy is smaller for a silicon test mass orientated in $\langle 100 \rangle$ than in $\langle 111 \rangle$. Thus also the contribution of mechanianical loss will be smaller.

DFG SFB TR7

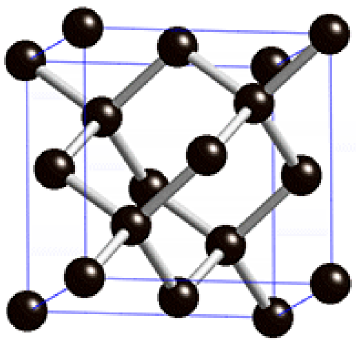
Comparison: thermal noise at 18 K and 120 K

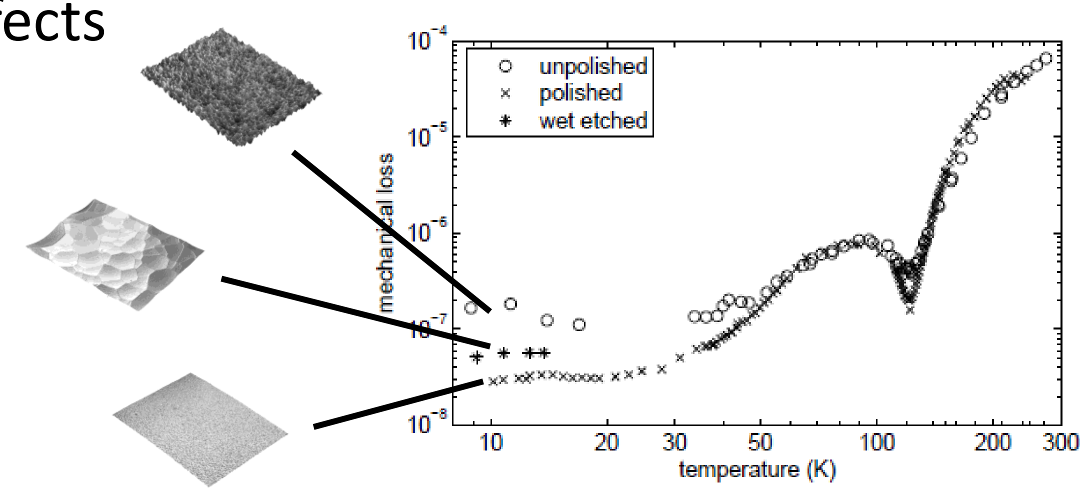
At 120 K the right choice of orientation is crucial to minimize shear related mechanical loss in case of CZ grown silicon.
(based on results so far)



Other things to care about

- Phonon-phonon interaction (Akhiezer damping)
- Phonon-electron interaction
  - Optical absorption due to free carriers (see J. Komma)
  - Codoping for adjustment
- Defects in the crystal lattice (kinks, dislocations …)
- Impurities, mainly carbon and oxygen (due to CZ growth)
- Size and surface effects





Summary

- Cryogenic silicon test mass → temperature should be $T \lesssim 24\ \mathrm{K}$ (above thermo-elastic exceeds)
- Recent results suggest orientations of silicon test masses of
  - $\langle 111 \rangle$ for temperatures $T \lesssim 24\ \mathrm{K}$ due to high Young's modulus
  - $\langle 100 \rangle$ at $120\ \mathrm{K}$ to minimize shear related mechanical loss
- Future work
  - Identification of loss mechanisms in CZ silicon
  - Comparison of isotropic and anisotropic TN calculation
  - Investigation of sapphire