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Jessica Dück, Nico Lastzka, •Sebastian Steinlechner,
Roman Schnabel and Karsten Danzmann

Absorption Measurements on Silicon

Institute for Gravitational Physics, Leibniz Universität Hannover and
Max Planck Institute for Gravitational Physics (Albert Einstein Institute)
Callinstr. 38, 30167 Hannover, Germany

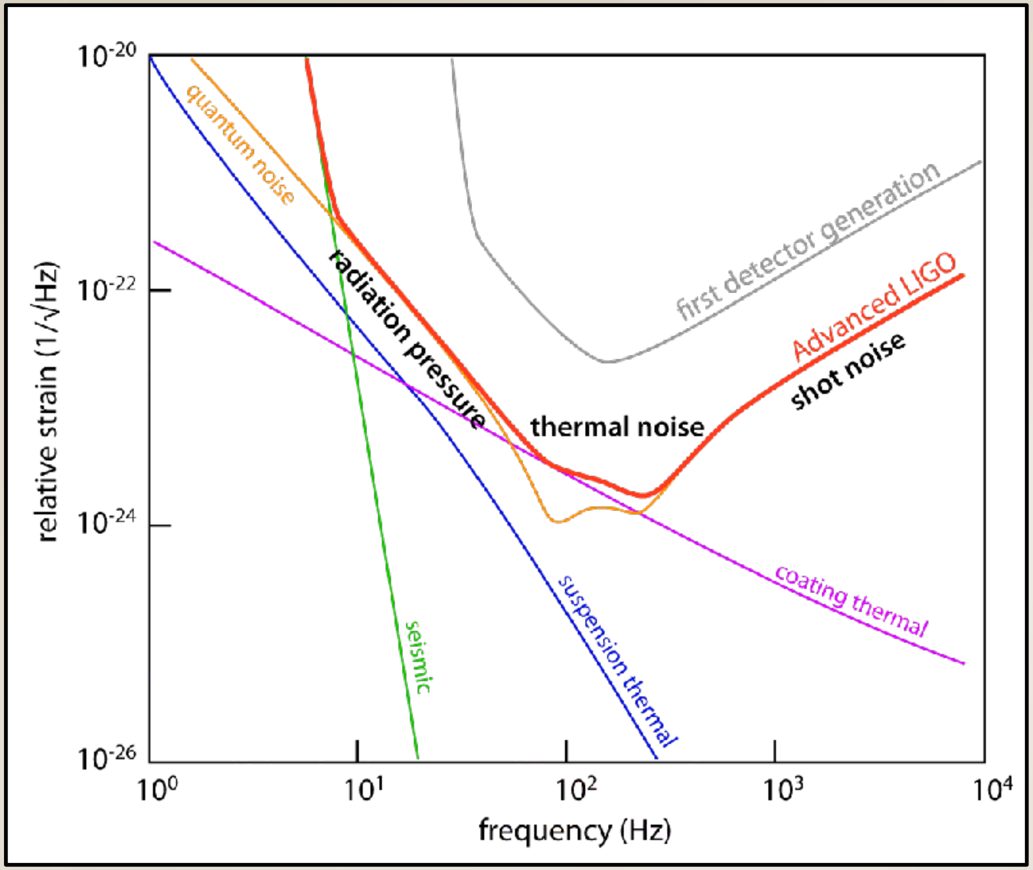
Max Planck Institut
for Gravitational Physics
AG Quantum Interferometry

Centre for Quantum Engineering
and Space Time Research

Leibniz Universität Hannover

Limits to gravitational-wave detection sensitivity

- Mid-frequency detection band limited by thermal noise
- Various noise sources are proportional to T or even T^2
- Cryogenic techniques could reduce noise level drastically



Thermorefractive noise:

$$S_{TR}(f) \propto \beta^2 k_B T^2$$

Thermoelastic noise:

$$S_{TE}(f) \propto \alpha^2 k_B T^2$$

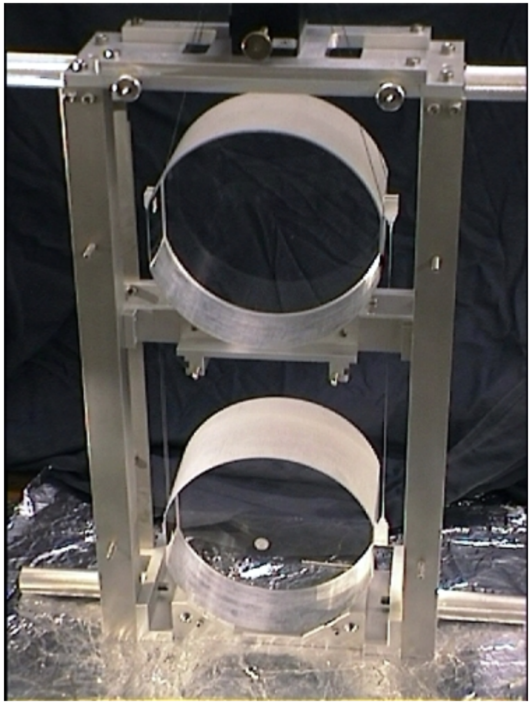
Substrate brownian noise:

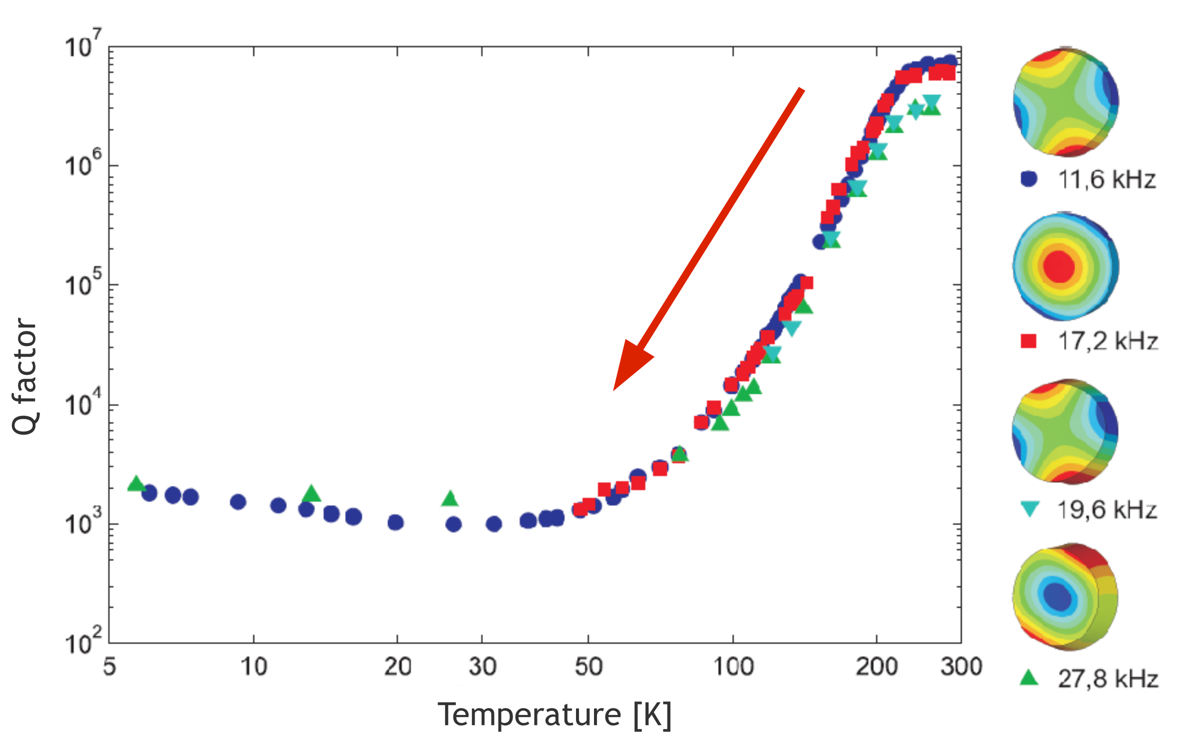
$$S_{bulk}(f) \propto k_B T$$

Current test-mass material: fused silica

Fused silica

- + well known material
- + excellent optical properties (Suprasil SV311: 0.25ppm/cm absorption @ 1064nm)
- – high damping at low temperatures (Debye peak) → not suitable for cryogenic detectors

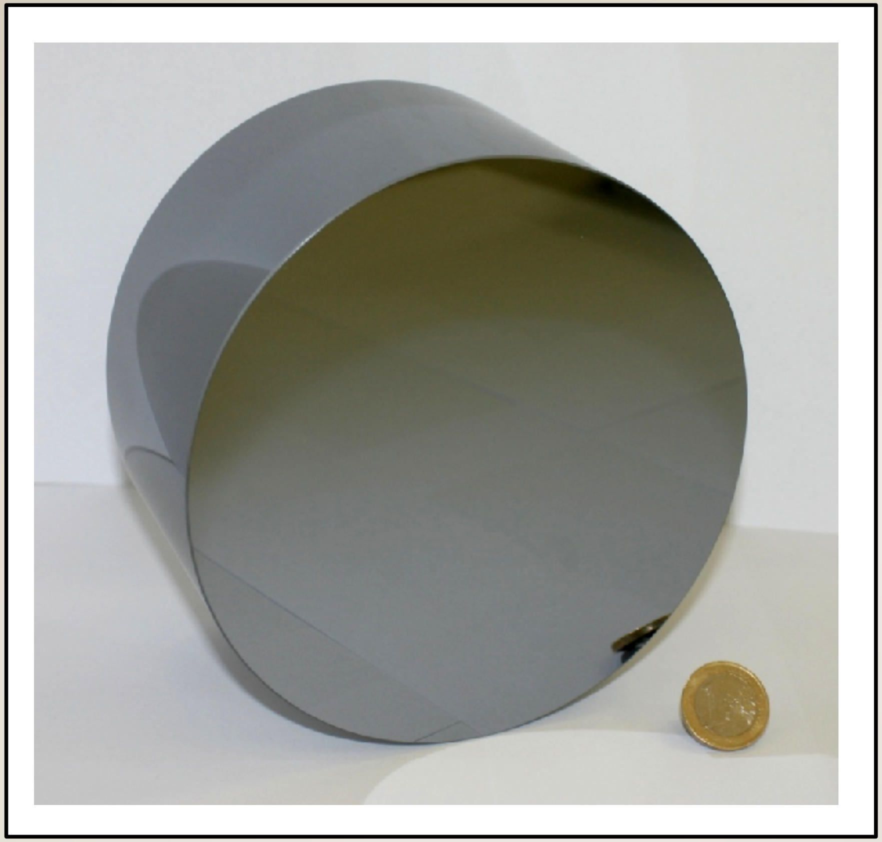




R. Nawrodt, PhD thesis

Silicon as a test-mass material

- Crystalline silicon available in large dimensions
  450mm wafers will be introduced in upcoming years
- “Industrial quality” is already extremely pure

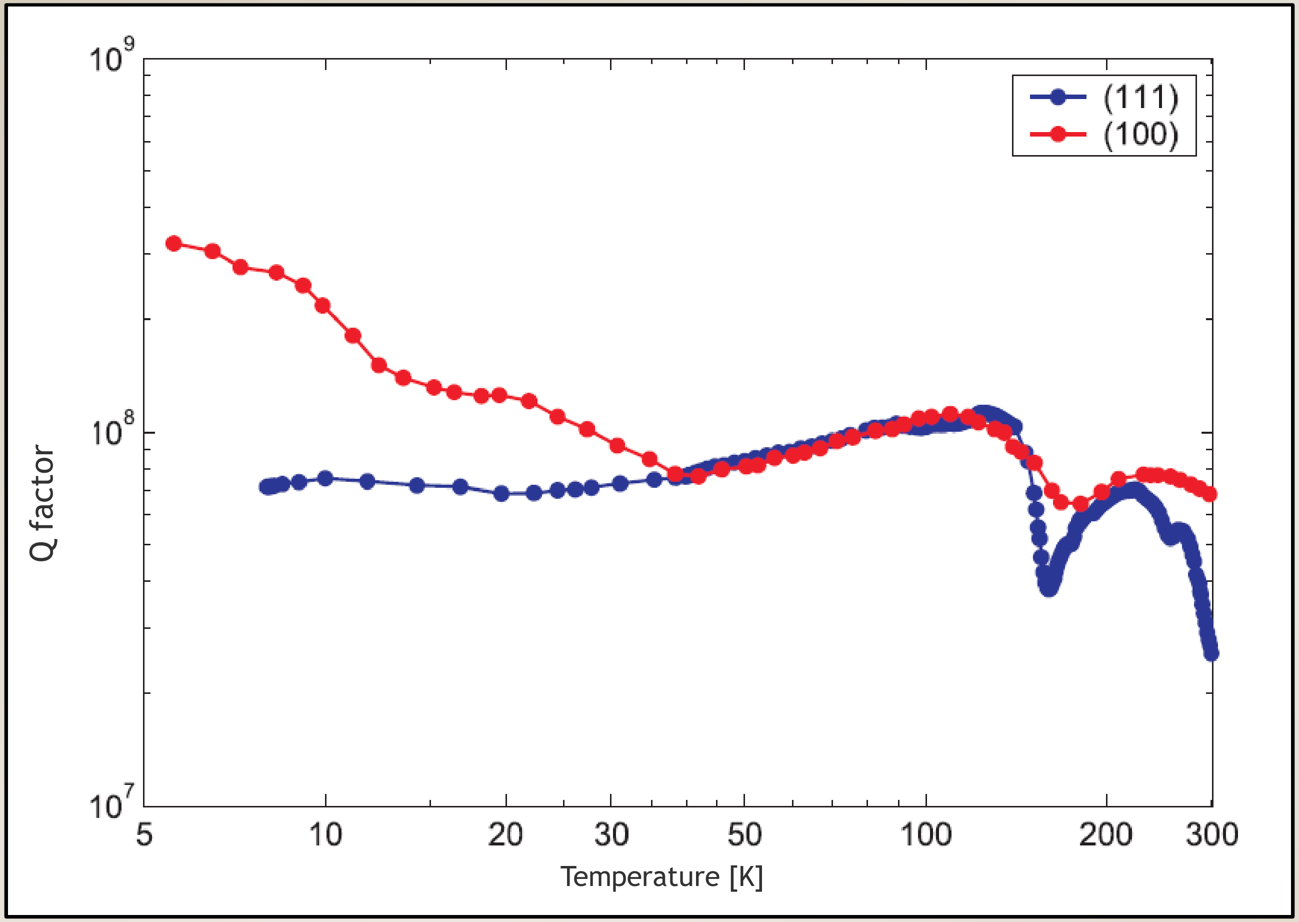


Uni Jena

wikipedia.de

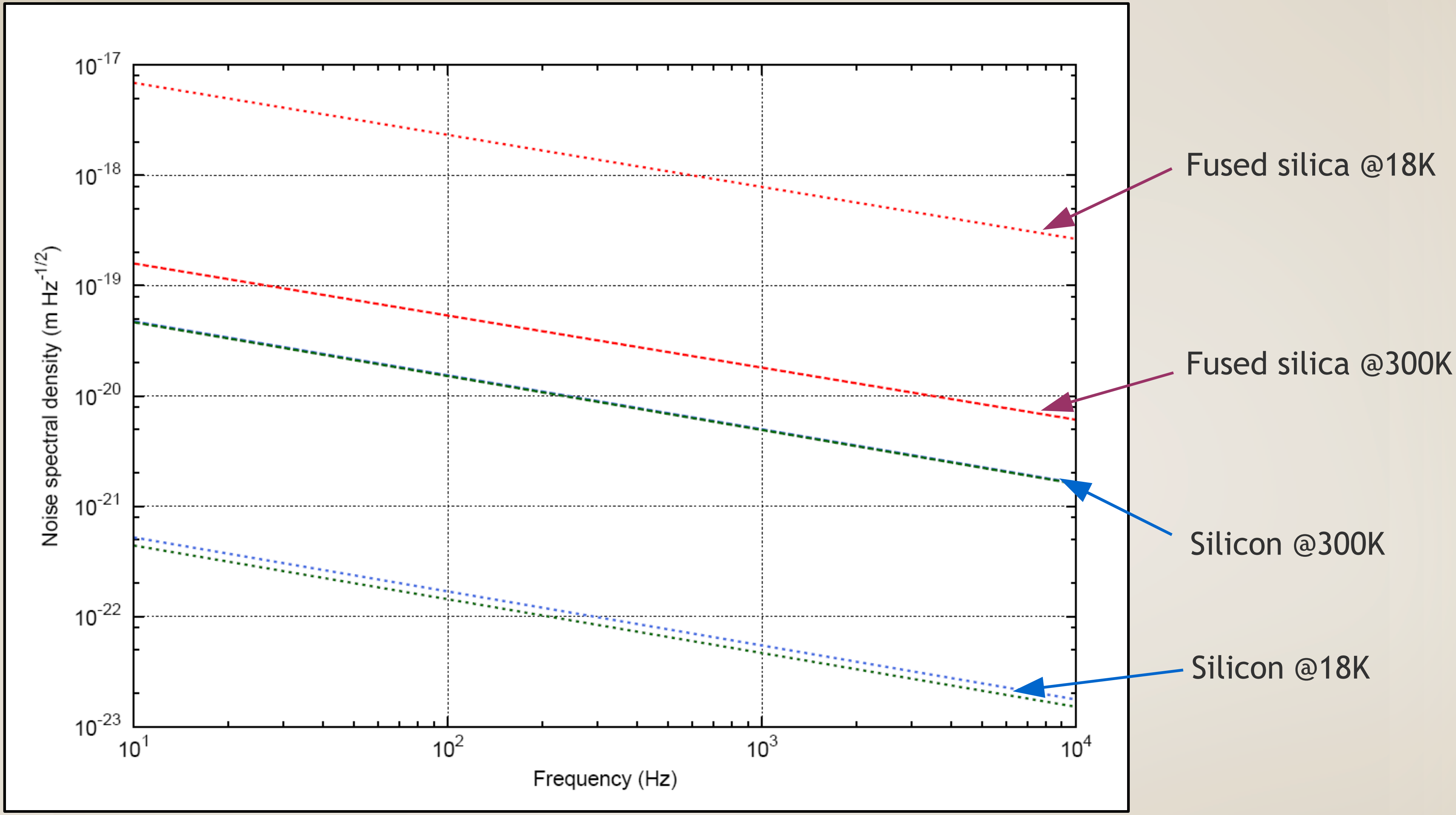
Properties of crystalline silicon: Q factor

- Q values exceeding 10^8 have been measured



R. Nawrodt, PhD thesis, Uni Jena

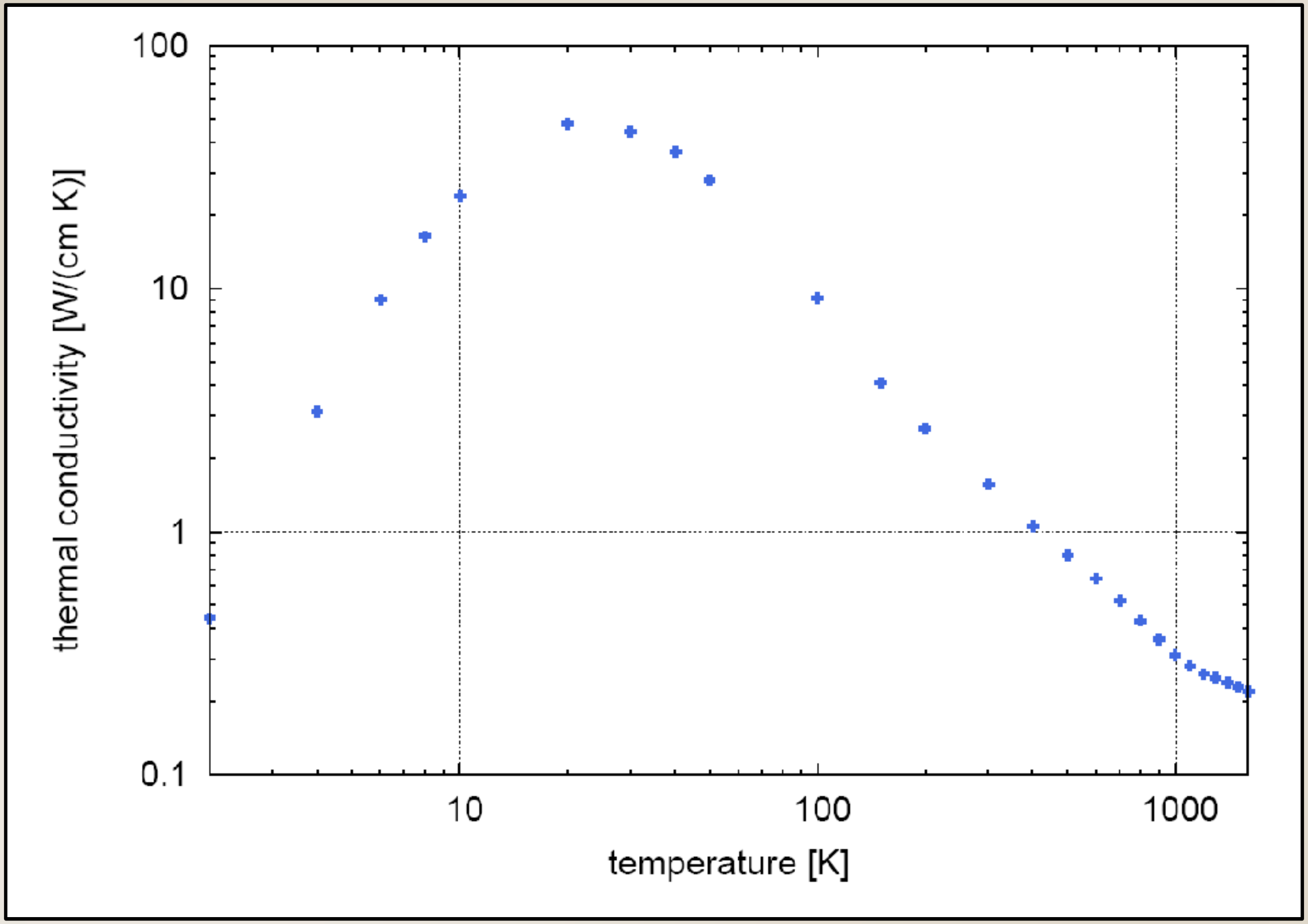
Brownian Noise projection for silicon test masses in GEO 600



A. Schröter, PhD thesis, Jena

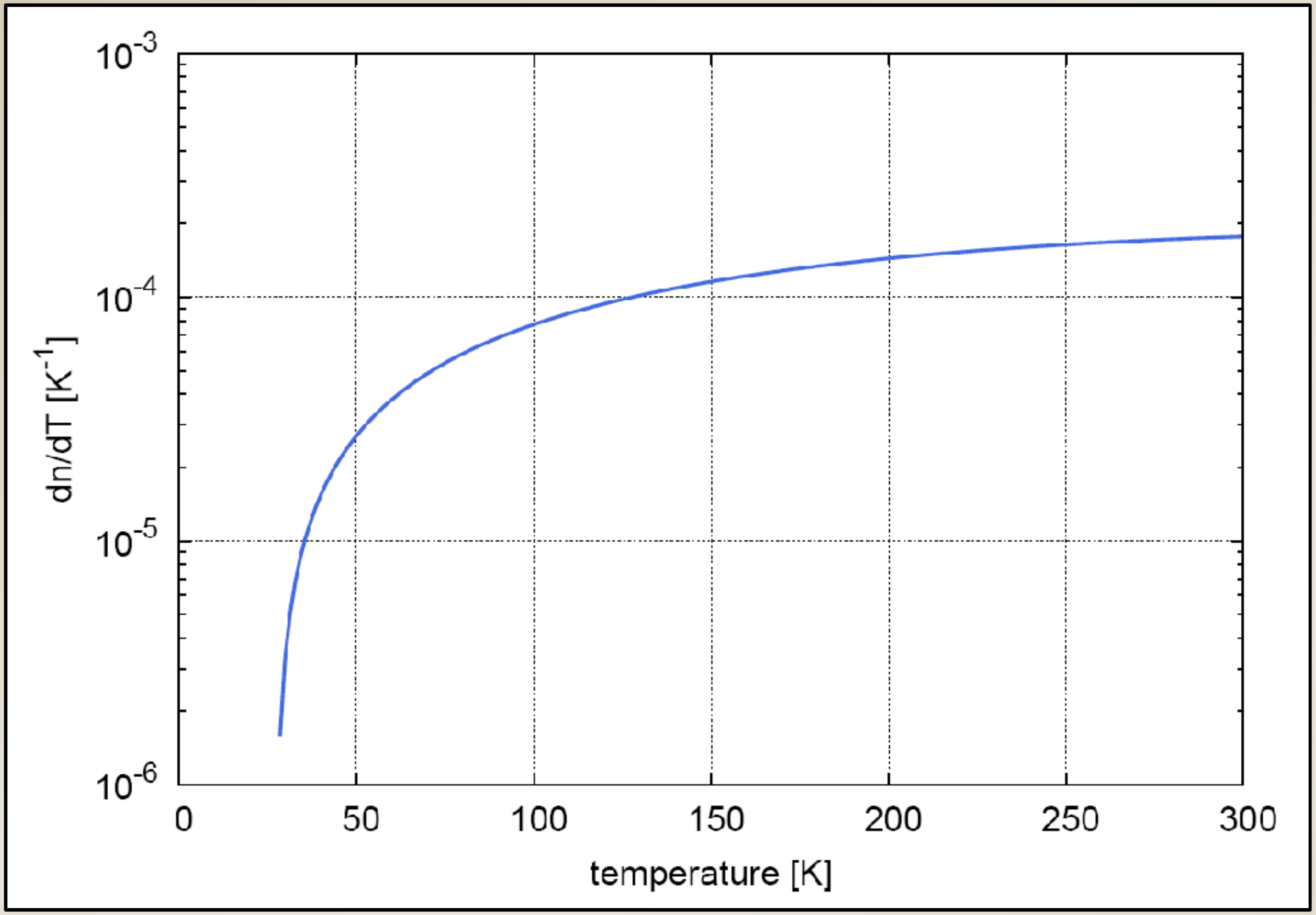
Properties of crystalline silicon: thermal conductivity

- Very high thermal conductivity:
  > 10 W/(cm K) between 10K and 100K
  (compare with 10^{-3}..10^{-2} W/(cm K) for glass, 3.9 W/(cm K) for copper @ 300K)



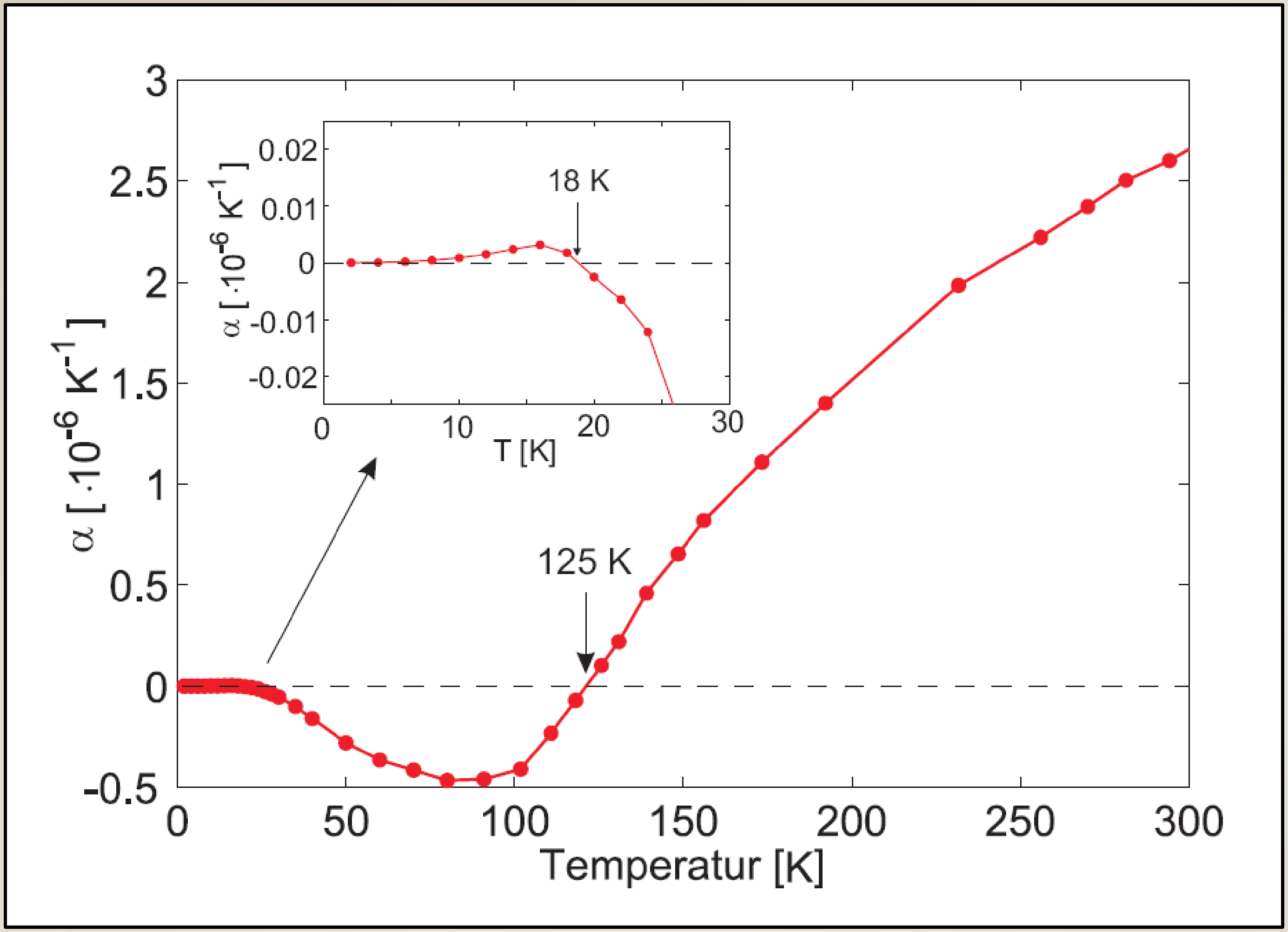
Properties of crystalline silicon: thermo-optic coefficient dn/dT

- Low thermo-optic coefficient dn/dT → low thermo-refractive noise



Properties of crystalline silicon: thermal expansion

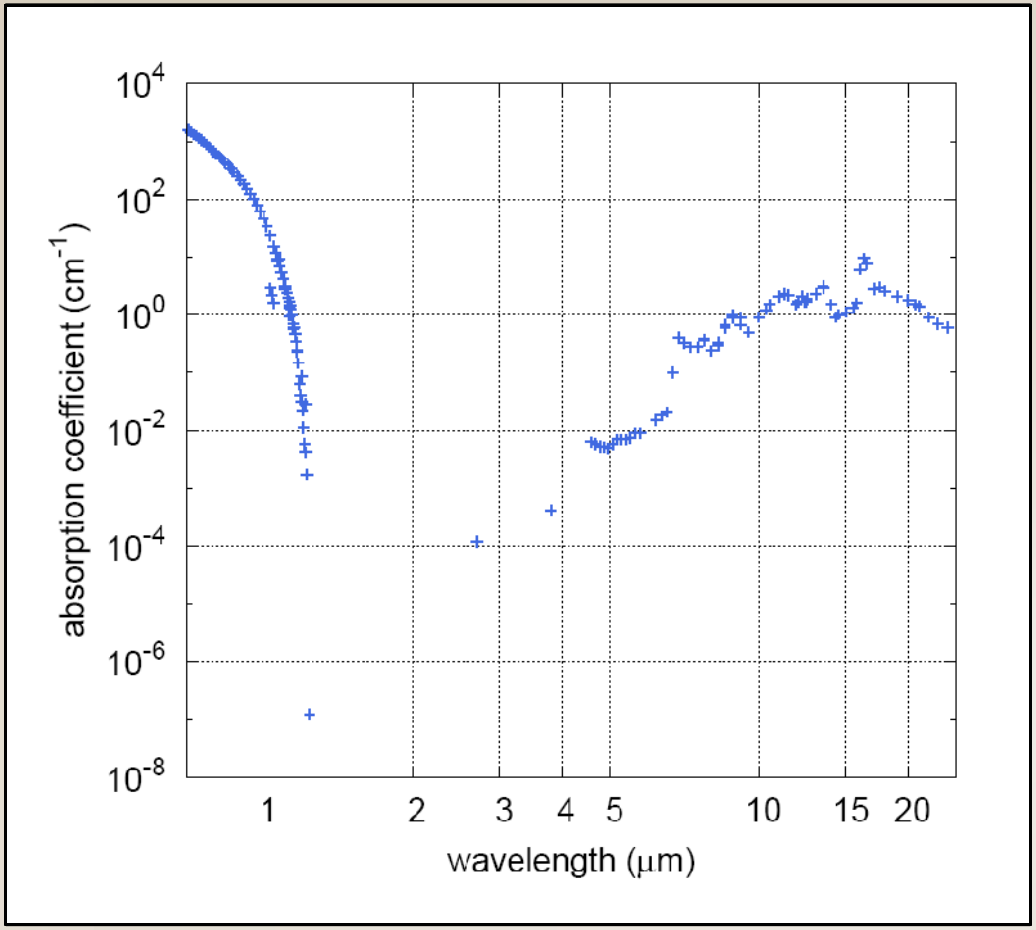
- Thermal expansion higher than in fused silica at room temperature
- two zero crossings (18K and 125K) → vanishing thermoelastic noise



Thermoelastic noise:

$$S_{TE}(f) \propto \alpha^2 k_B T^2$$

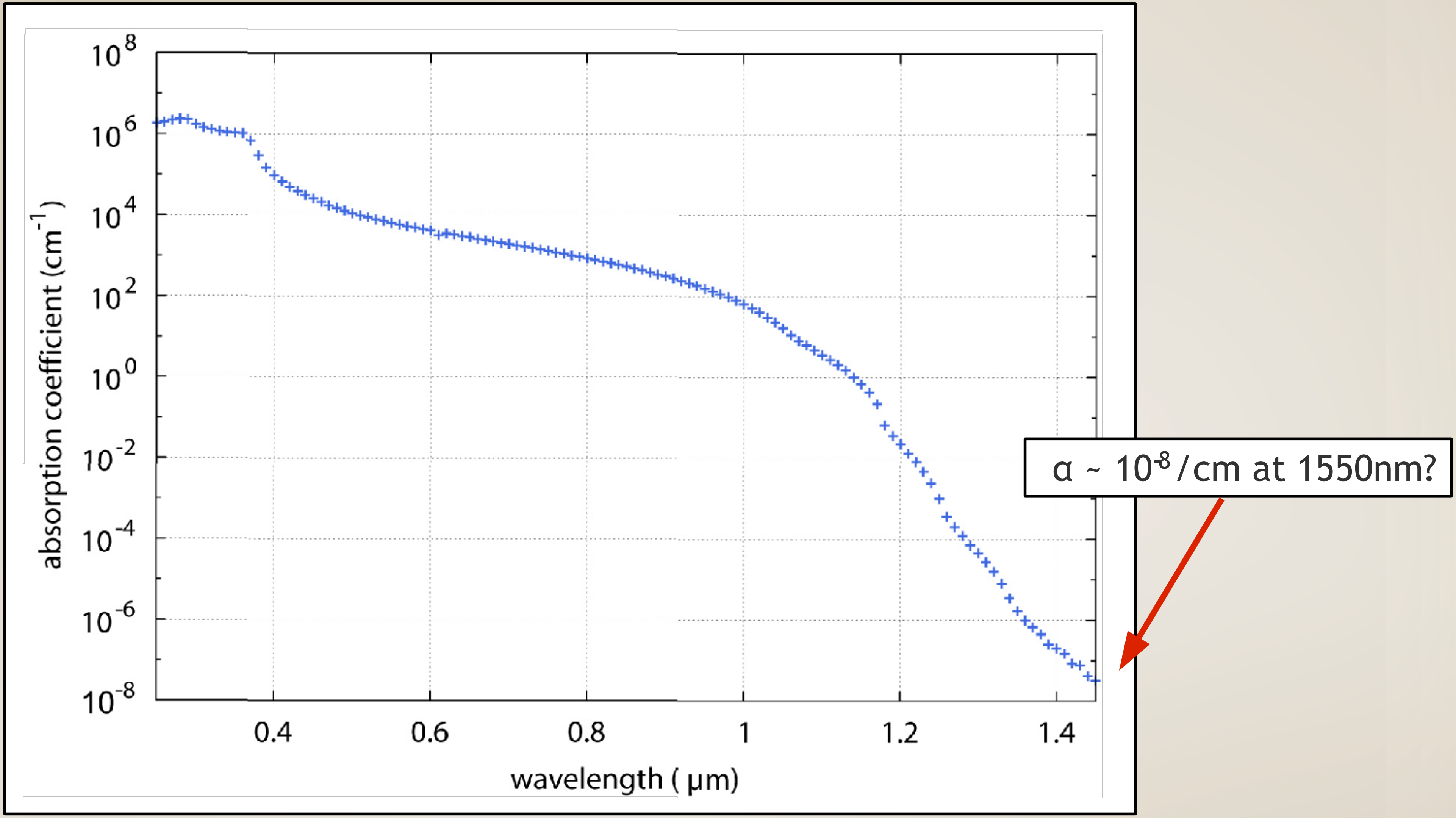
Properties of crystalline silicon: Absorption coefficient



Hull, Properties of Crystalline Silicon, 1998

- Absorption coefficient orders of magnitude too high at 1064nm
- Transparency window between 1.4µm and 2.5µm
- No measurement data available in this window
- Measurements up to now mainly motivated by solar cell research, low absorption regime not interesting

Properties of crystalline silicon: Absorption coefficient



Keevers/Green, 1995

Measurement of small absorption coefficients

Is the absorption coefficient α really as low as 10^{-8} /cm?

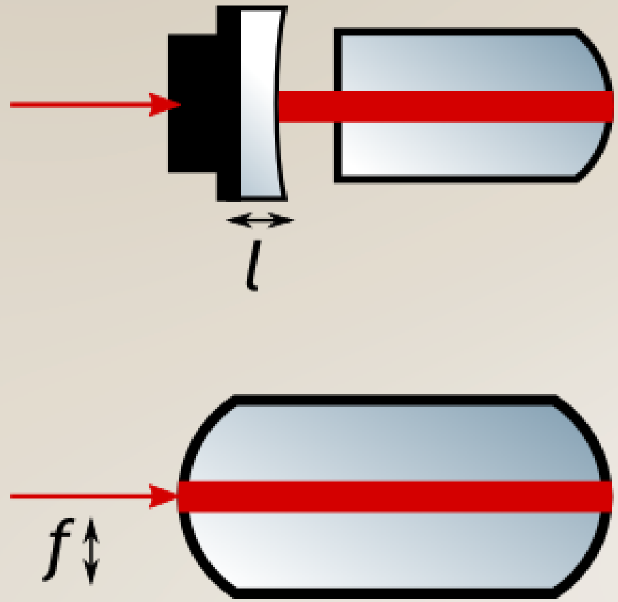
Directly measuring $I = I_0 \, e^{-\alpha x}$ is not sensitive enough

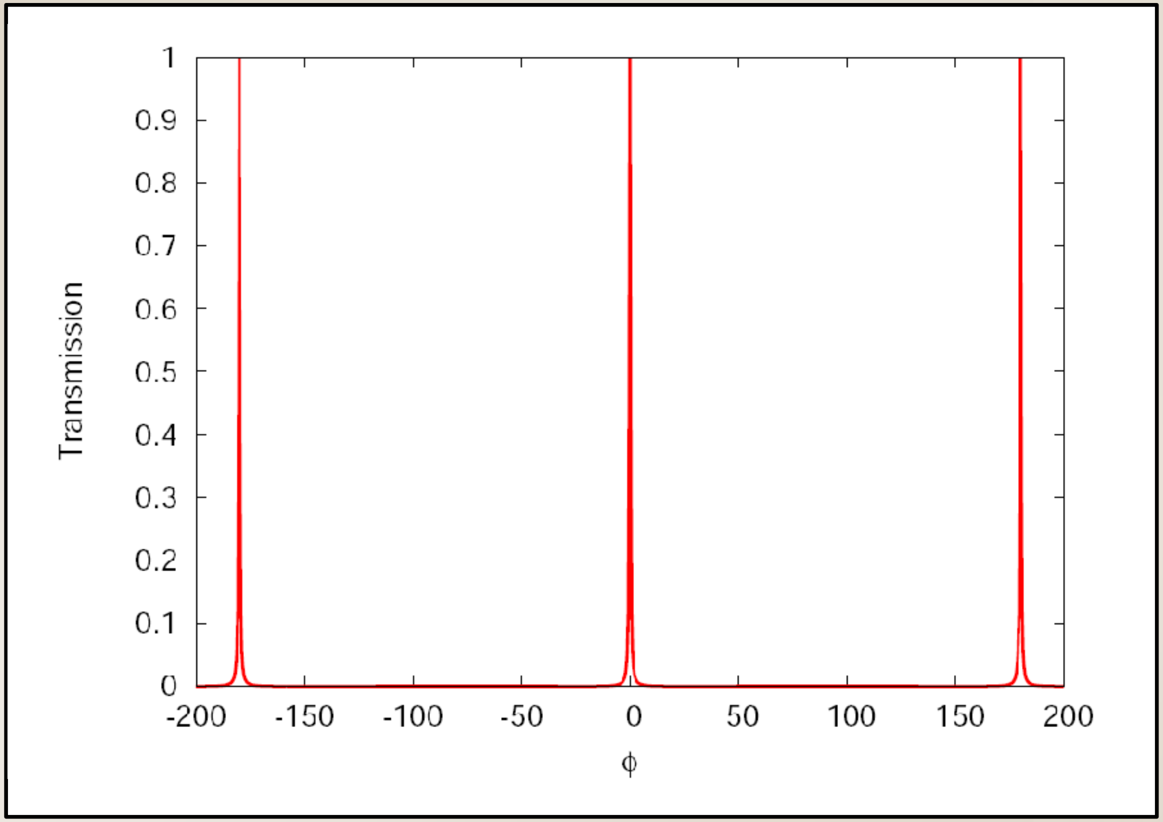
Measure effects of temperature change due to absorption: dn/dT

- Mirage method (thermal lensing)
- Our new method: "thermal kerr" effect
- Can only measure $\alpha \frac{dn}{dT}$, need to know various material constants
- High power needed for sufficient temperature increase
  → power built-up in high finesse cavity

Thermal Kerr effect

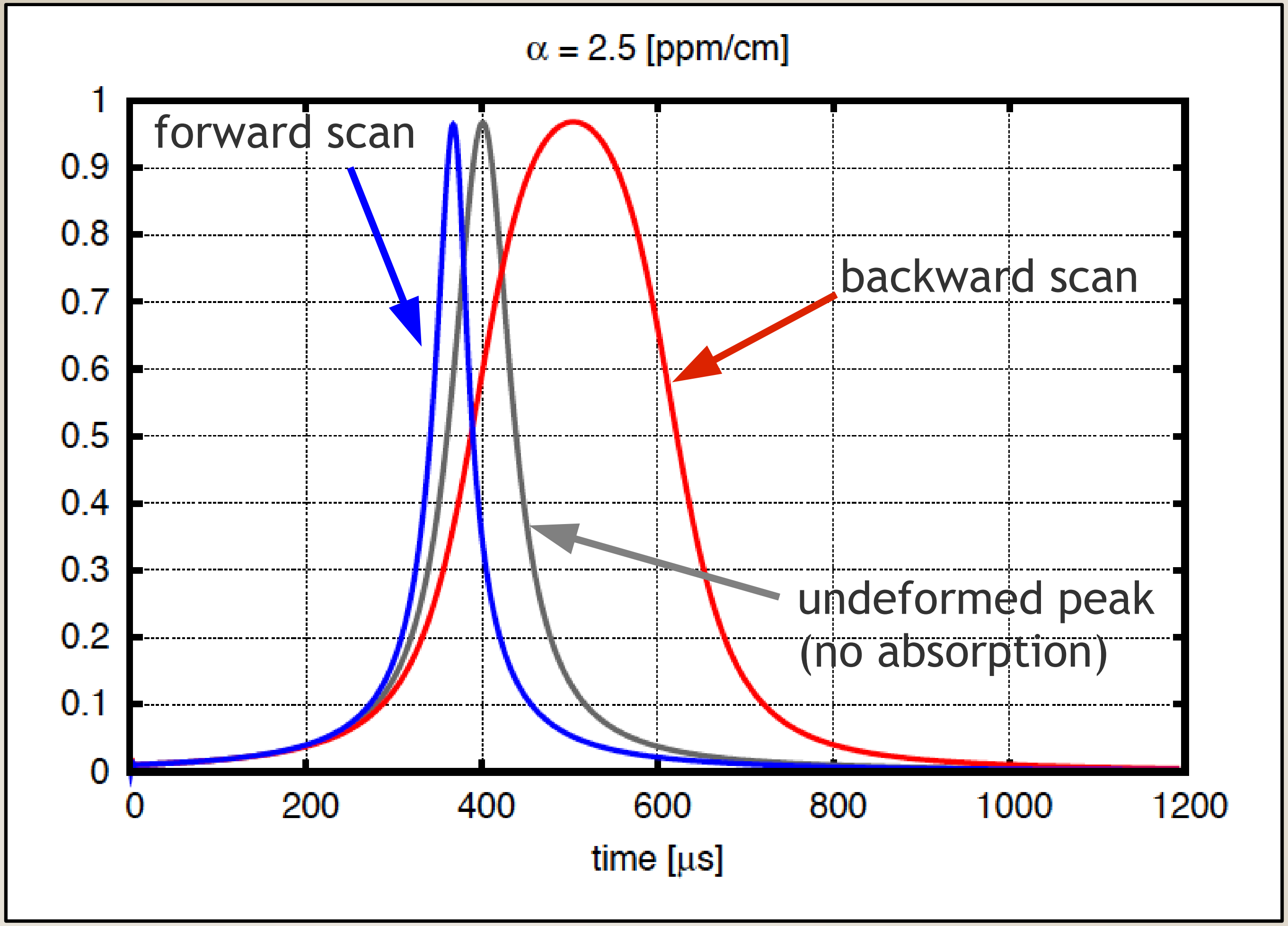
- High finesse cavity is scanned with varying speeds over one Airy peak (with PZT or by tuning the laser frequency)
- Both scan directions used





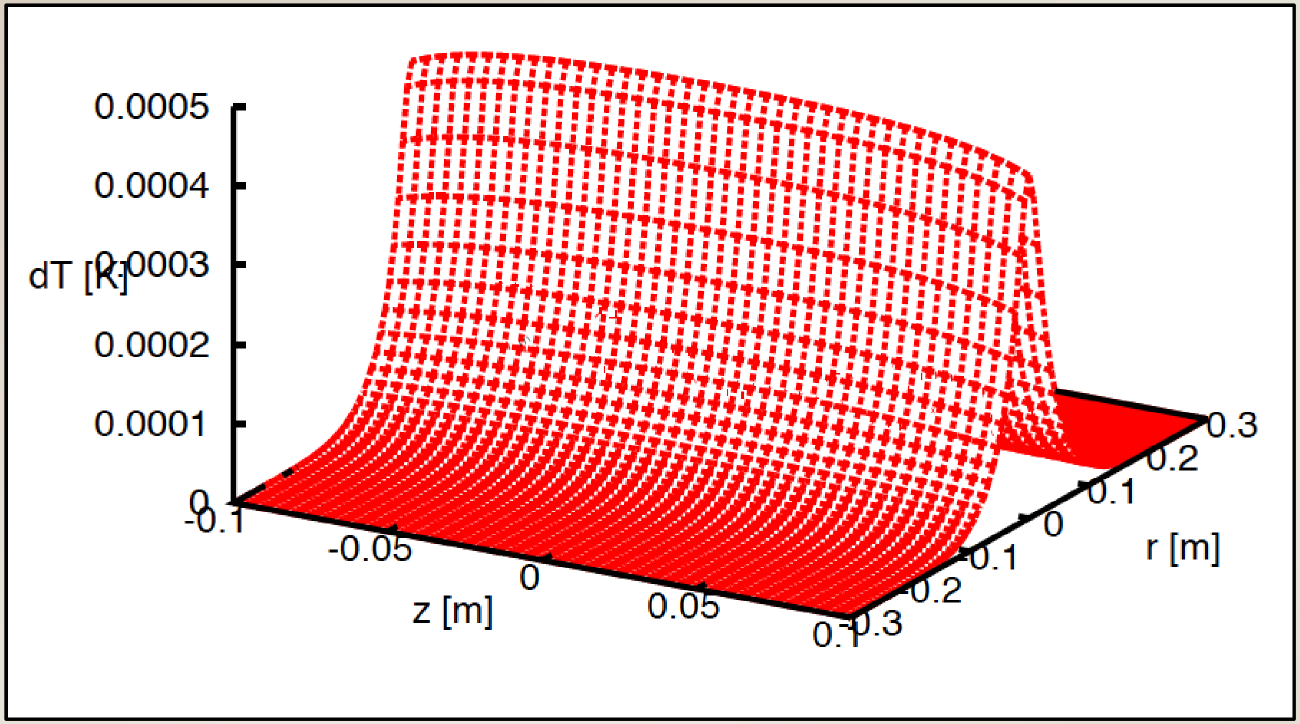
Measurement principle

- dn/dT introduces additional phase shift depending on scan direction, deforming cavity Airy peaks



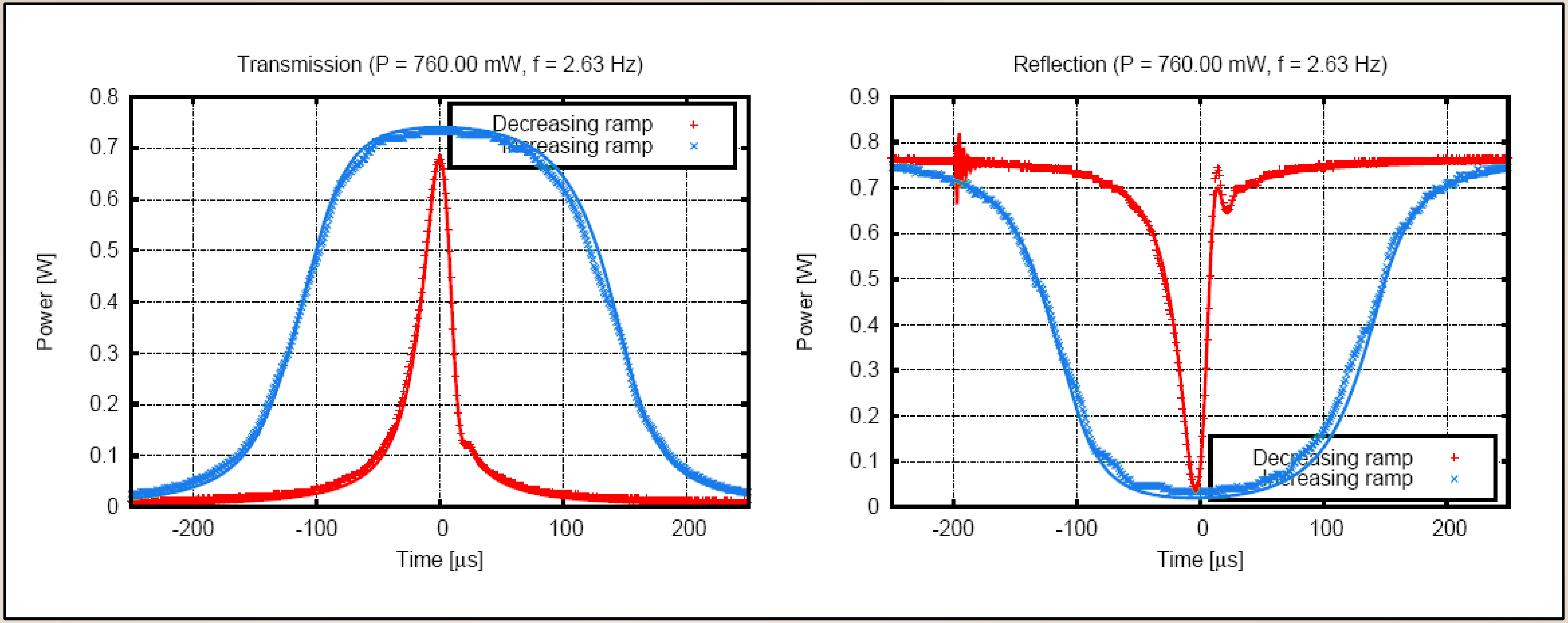
Measurement principle

- Simulation program calculates time-dependant temperature profile inside cavity
- (almost) analytical model as presented by Hello & Vinet



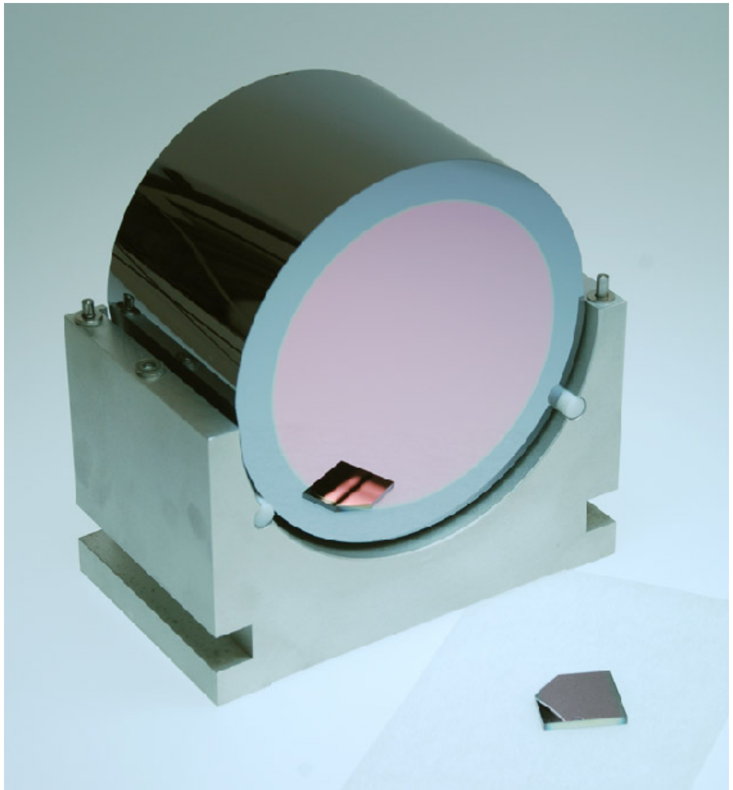
First measurement results

- Tested measurement with ring mode-cleaning cavity (F ~ 10000), absorption coming from mirror coatings
- Very good agreement between experimental and simulated data
- Simulation parameters yield absorption coefficient



Setup for absorption measurements on Silicon

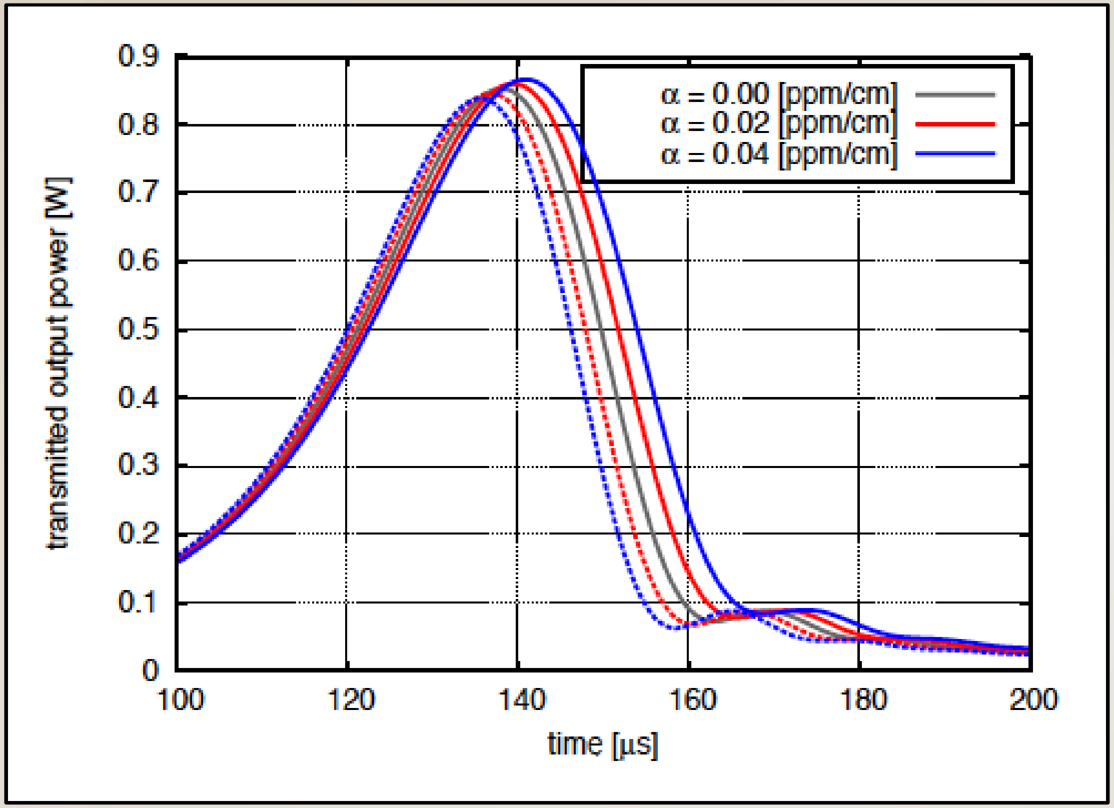
- Monolithic silicon cavity
  - 10cm diameter, 6.5cm length
  - Residual boron doping < 10^{12} /cm^{-3}
  - Mirror ROC 1m
  - estimated round-trip absorption 1ppm
- HR coated with SiO_2/Si
  - 170ppm transmission
  - Finesse F ~ 18500
- First measurements coming soon



What results do we expect?

- Residual doping will probably contribute most to the absorption:

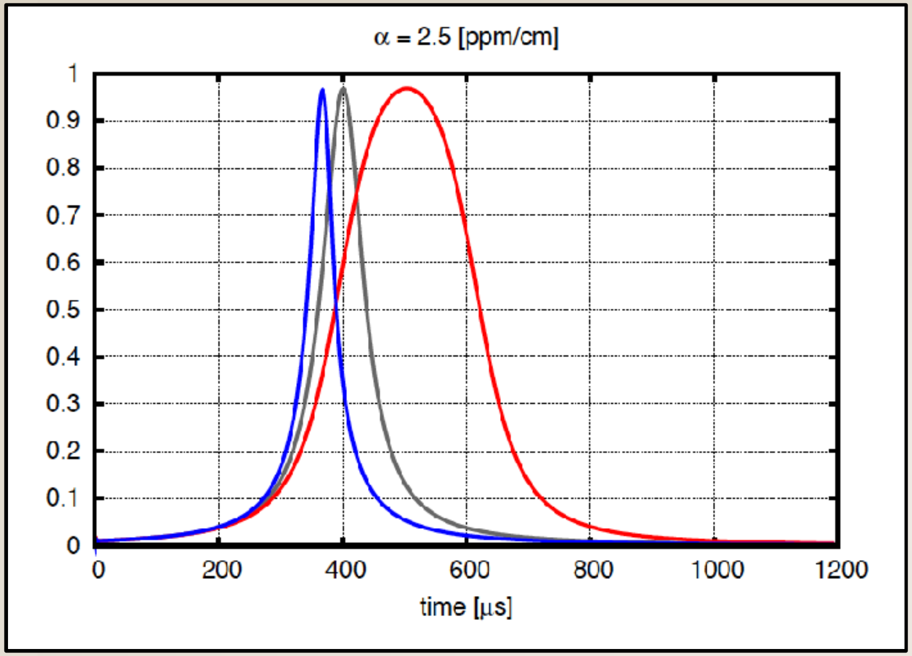
$$\Delta\alpha = \frac{q^3\lambda^2}{4\pi^2 c^3 n\epsilon}\cdot\left(\frac{N_e}{m_{cc}^2\mu_e}+\frac{N_h}{m_{ch}^2\mu_h}\right)\approx 3\cdot 10^{-7}/cm$$

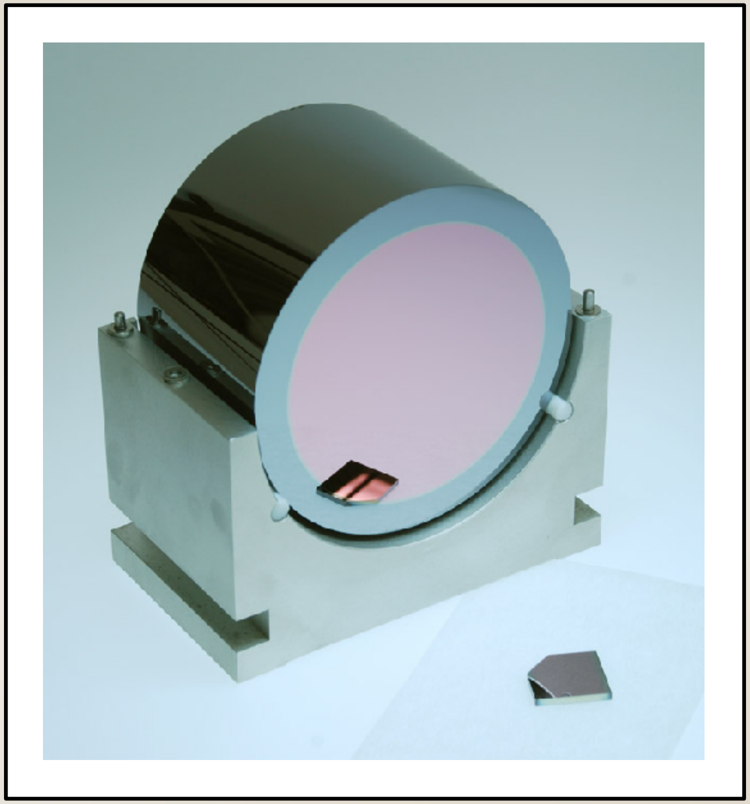


- With sensible assumptions for laser power and coating properties, absorptions in the 0.01ppm/cm regime (10^{-8}/cm) should be measurable

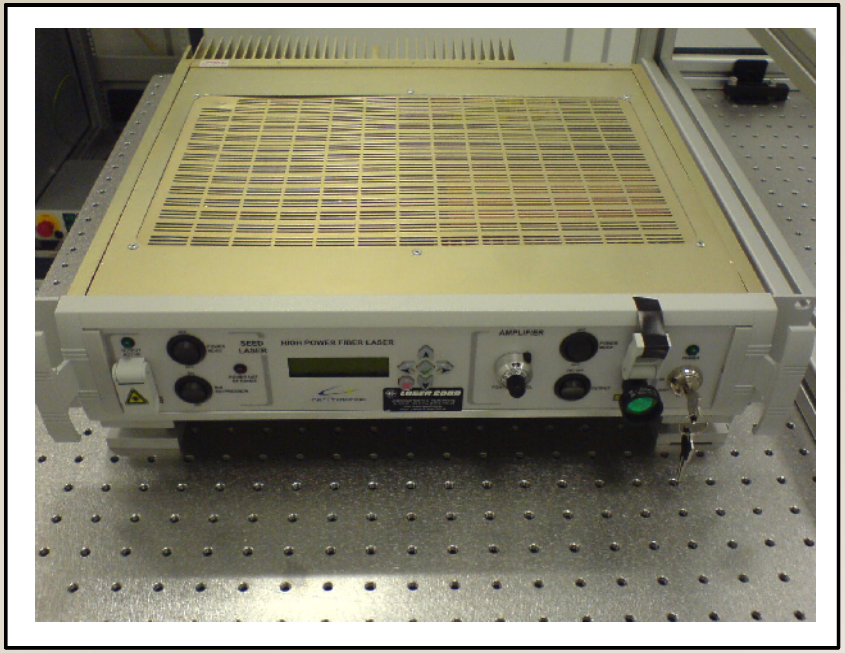
Current and upcoming work

- Currently validating measurement method
- First silicon measurements soon
- Confirm measurements with different method (Mirage?)

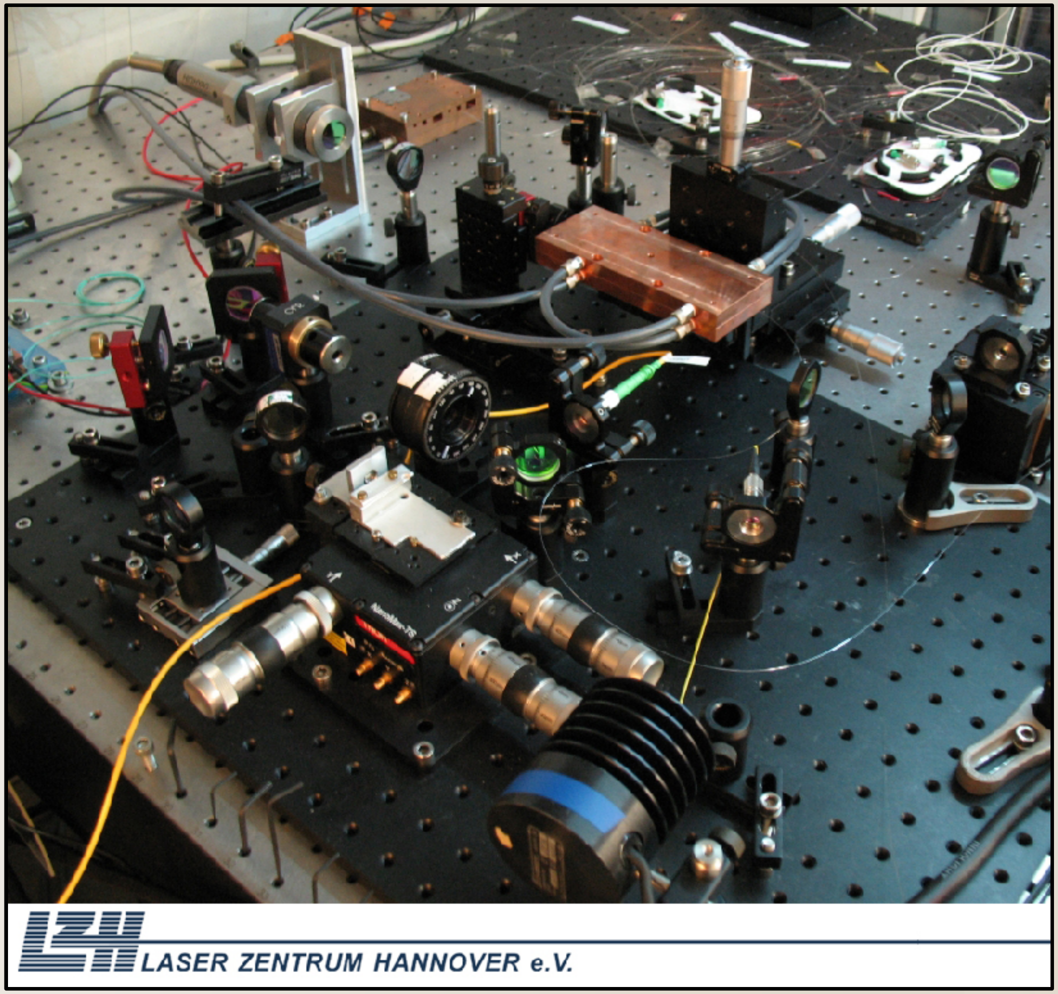




1550nm laser sources

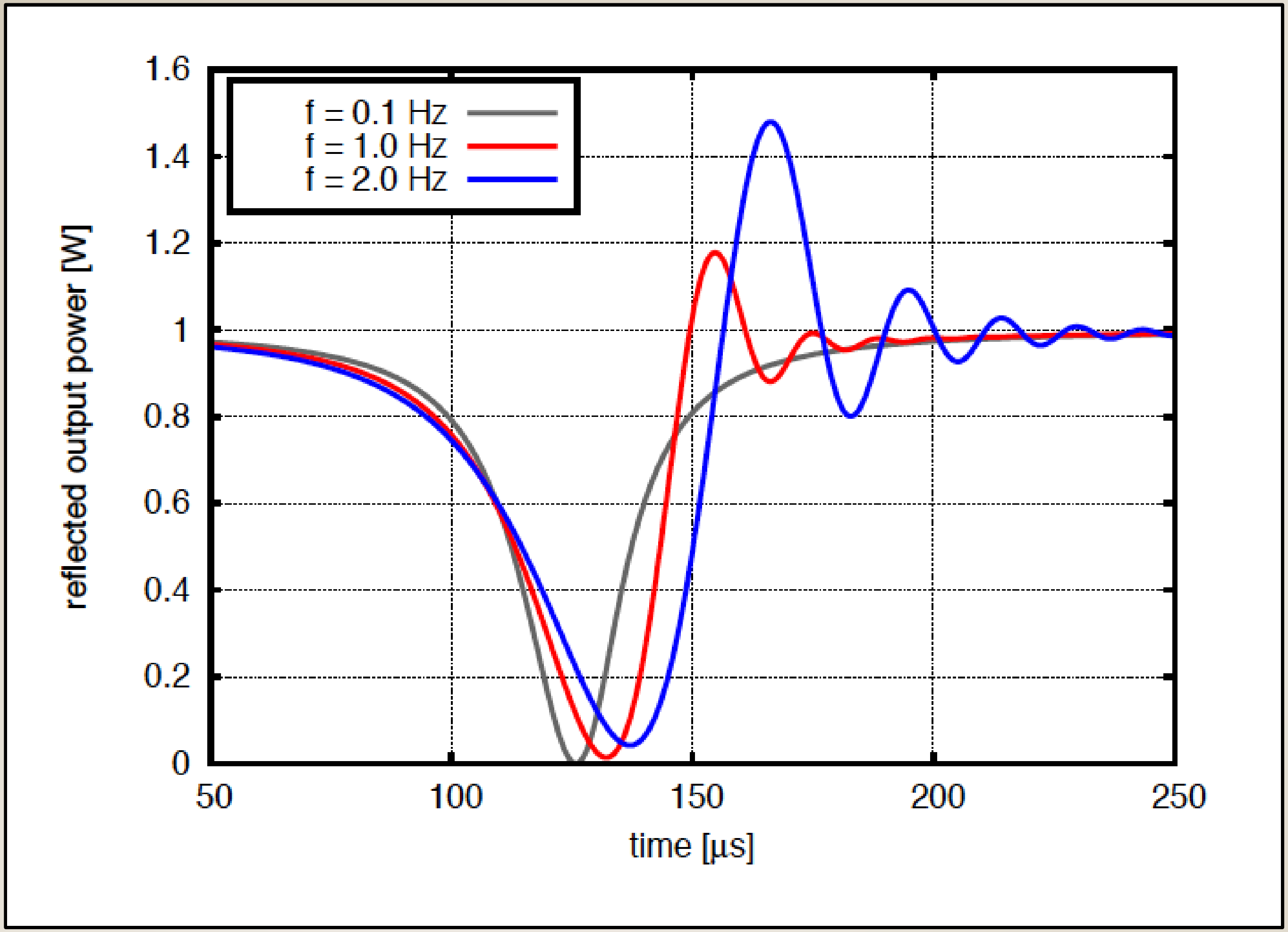


- Up to 2W cw, singlemode,
  PM output commercially available
- LZH builds fibre amplifier with
  10W output,
  100W expected in 2-3 years



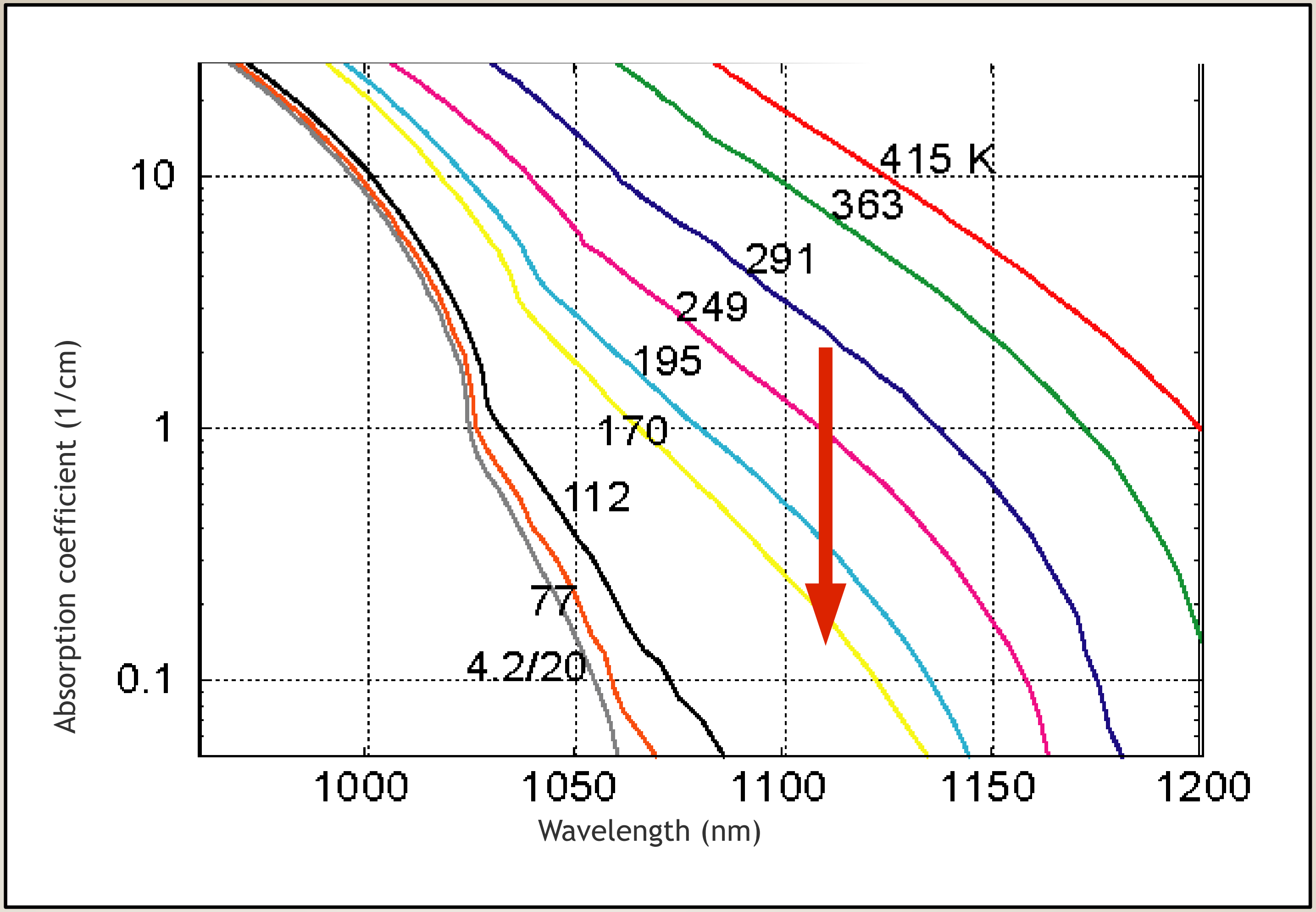
Measurement principle

- Fast scans are unaffected by absorption, ringing can be used to find correct cavity parameters (mirror reflectivities)



Temperature dependance of absorption coefficient

- Absorption coefficient drops with temperature



Monolithic mirrors

- T-structure gratings act as monolithic mirrors
- No coating thermal noise
- R > 99% demonstrated