Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

Ultrastable Lasers
New Developments and Challenges

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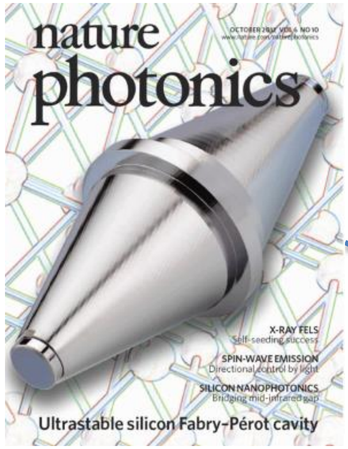
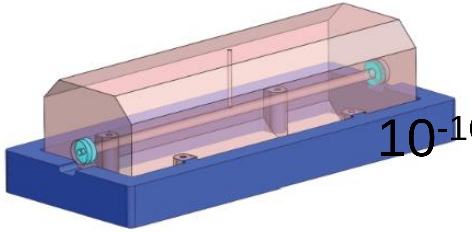
JILA, NIST and University of Colorado, Boulder, CO, USA

The 9th Symposium on Frequency Standards and Metrology
Kingscliff, Australia , 16-20 October 2023

Progress of cavity-stabilized lasers

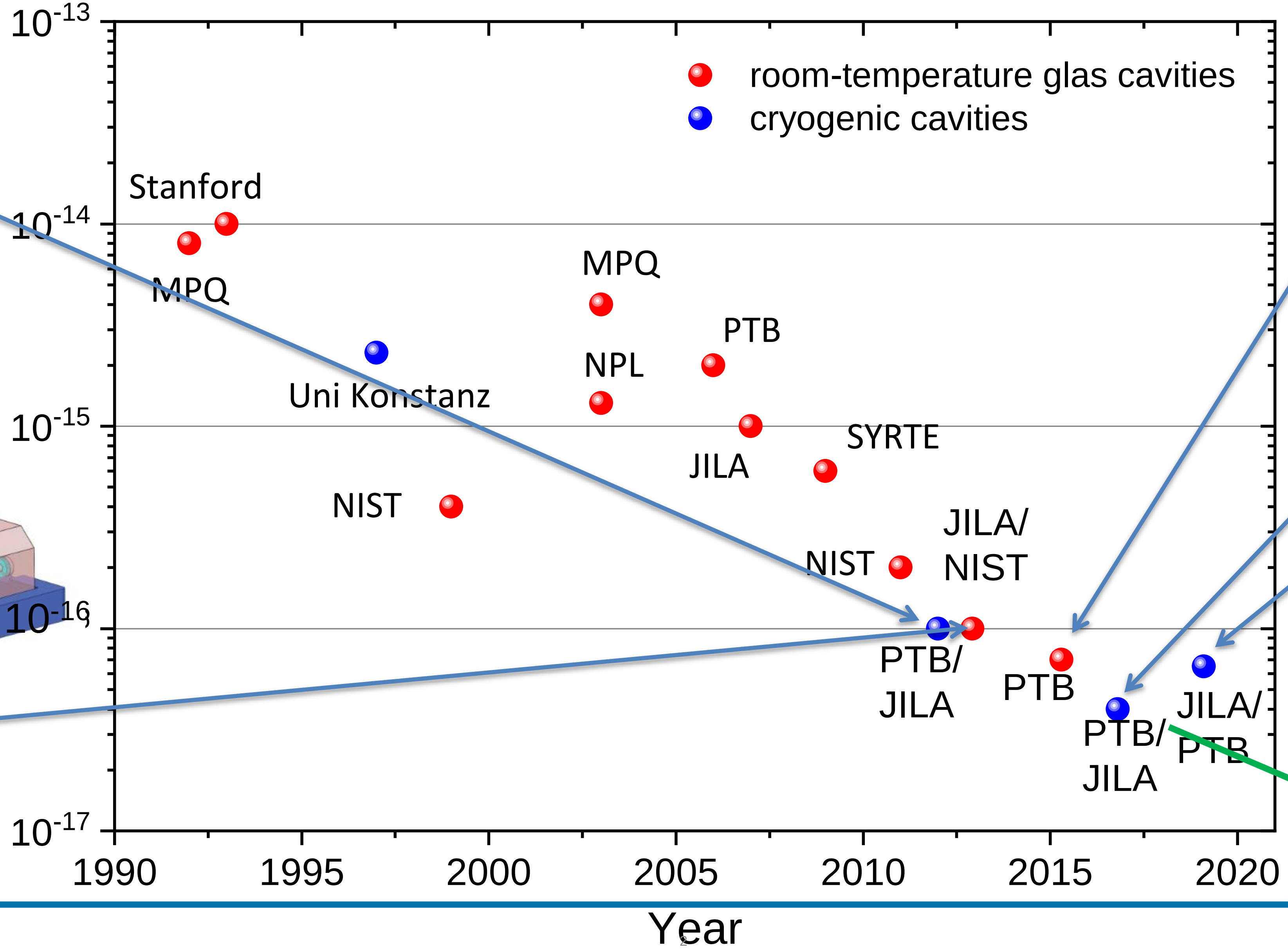


21 cm silicon
@ 124 K



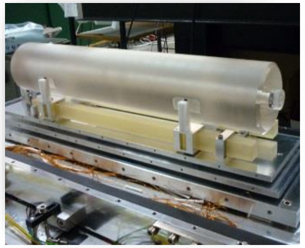
40 cm ULE

S. Häfner,
PhD thesis (2015)



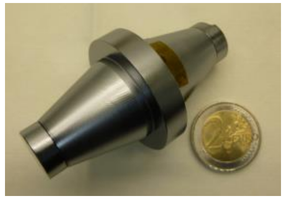
1×10^{-17} ?

48 cm
ULE

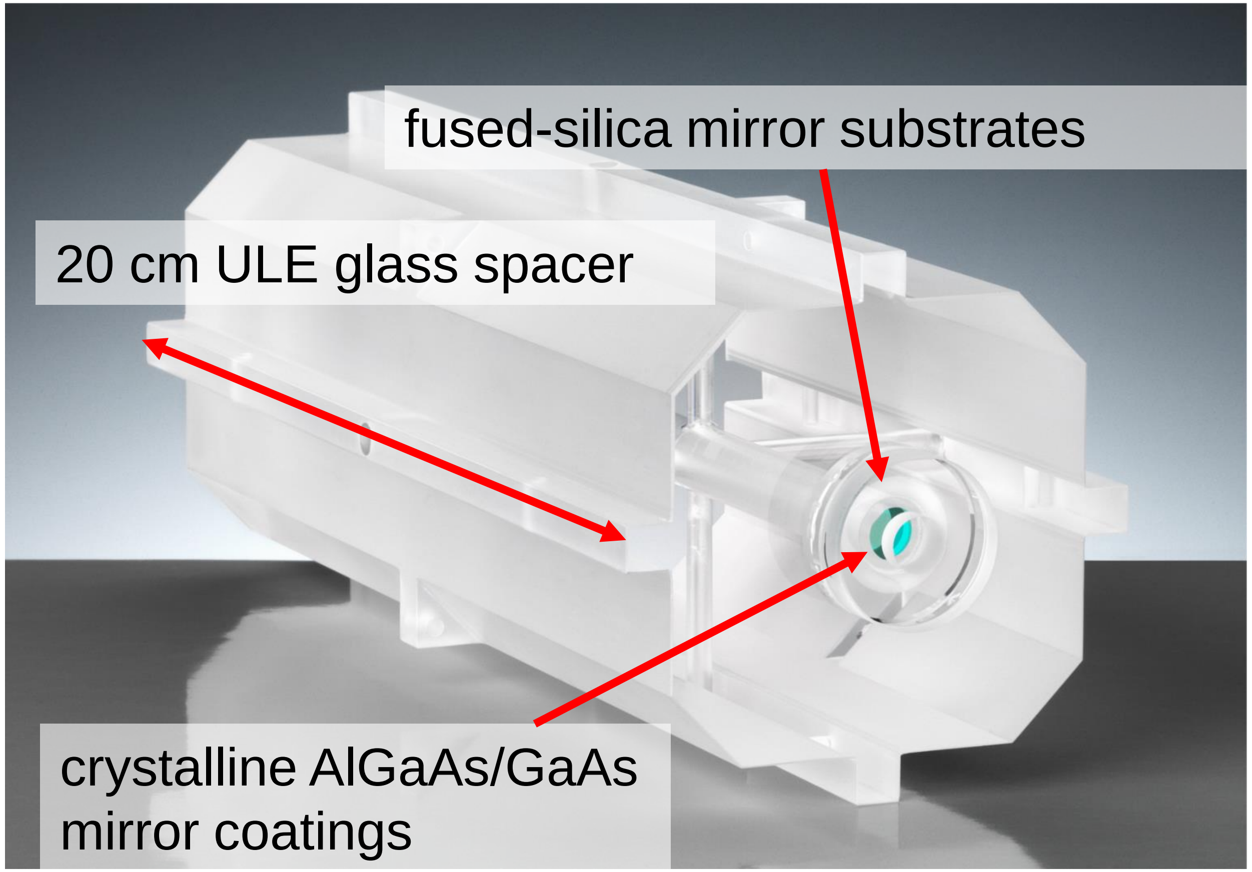


21 cm
silicon
@ 124 K

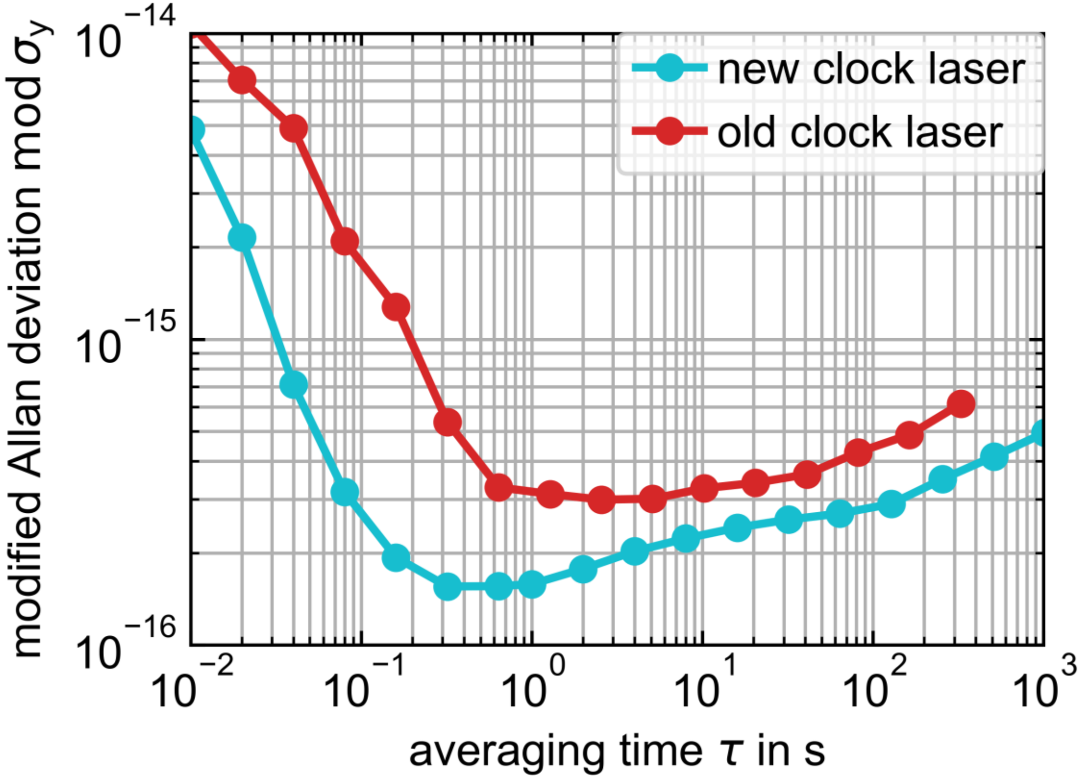
6 cm
silicon
@ 4 K



Transportable 1400 nm Sr clock laser

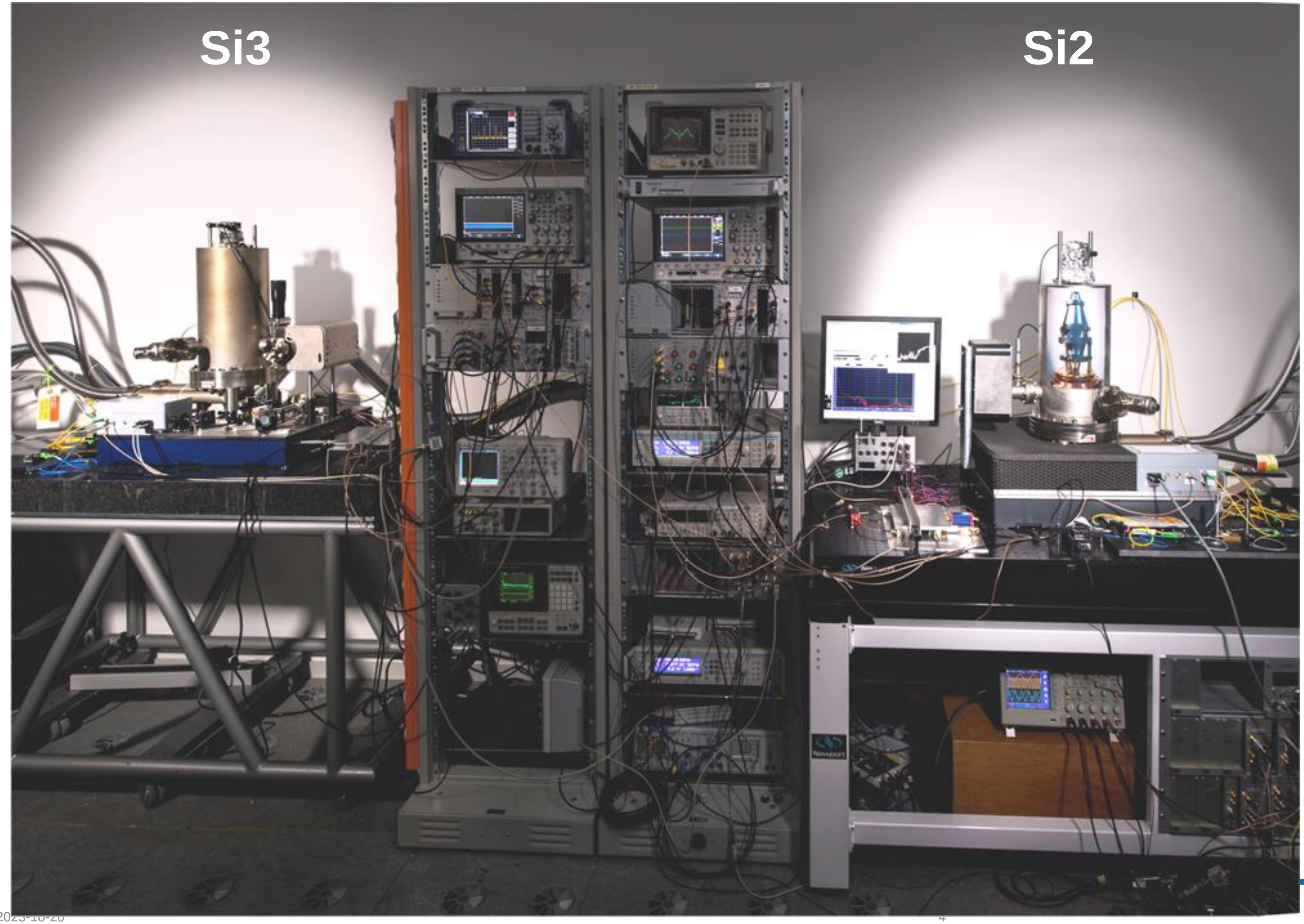


acceleration sensitivity:
3(3)×10^{-11}/g



S. Herbers, S. Häfner, S. Dörscher, T. Lücke, U. Sterr and C. Lisdat
Opt. Lett. **47**, 5441-5444 (2022)

Cryogenic silicon optical resonator

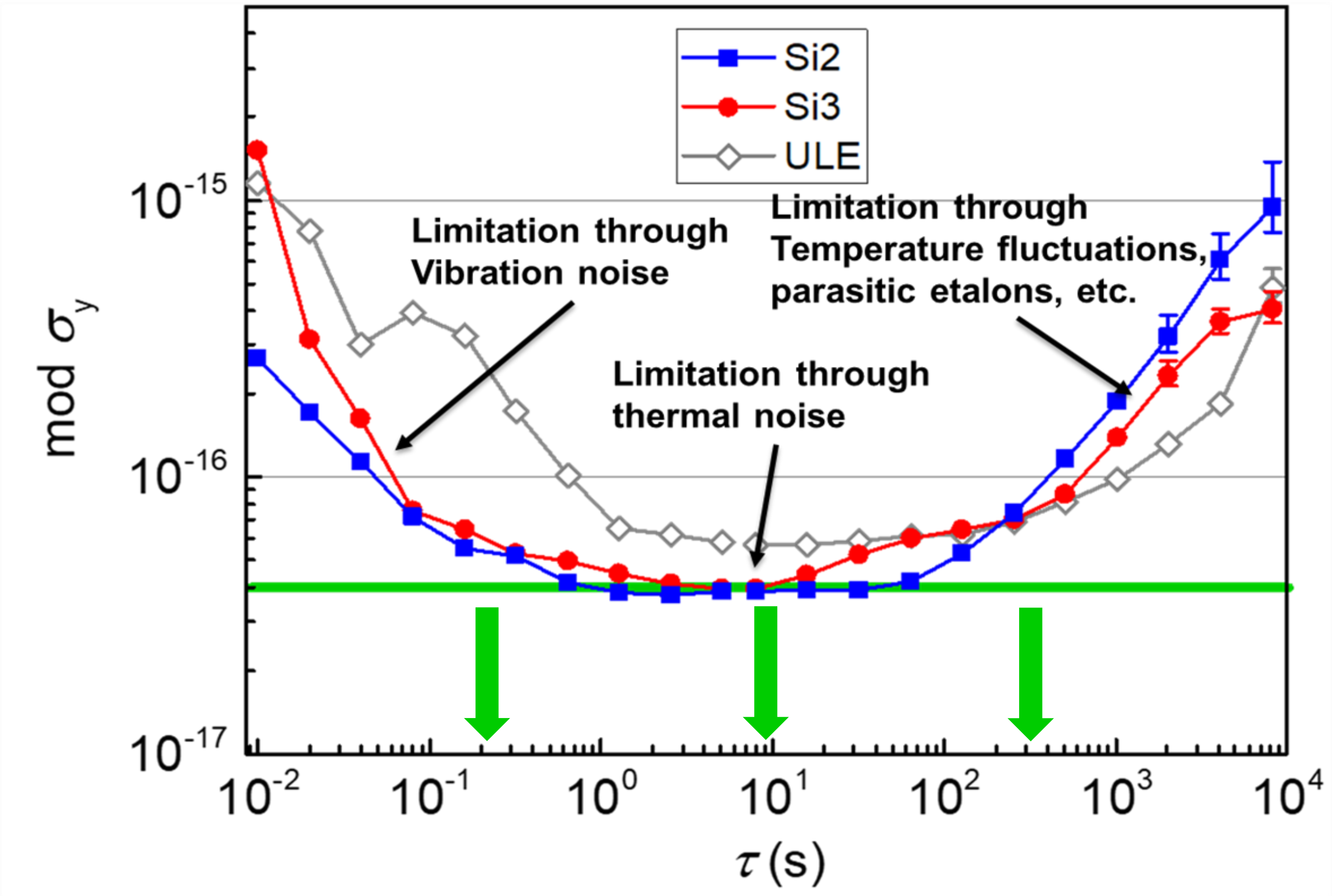


Silicon spacer

dielectric mirror coatings

- L = 212 mm
- T = 124 K
  zero thermal expansion

Cryogenic silicon optical resonator



Two systems with dielectric coatings

- L = 212 mm
- T = 124 K
- Stability limited by thermal noise to 4×10^{-17}
- Si3 moved to JILA in 2017

next steps - reduce thermal noise

D. Matei et al., Phys. Rev. Lett. **118**, 263202 (2017)

Flywheel for an optical timescale

PHYSICAL REVIEW LETTERS **123,** 173201 (2019)

ggestion | Featured in Physics

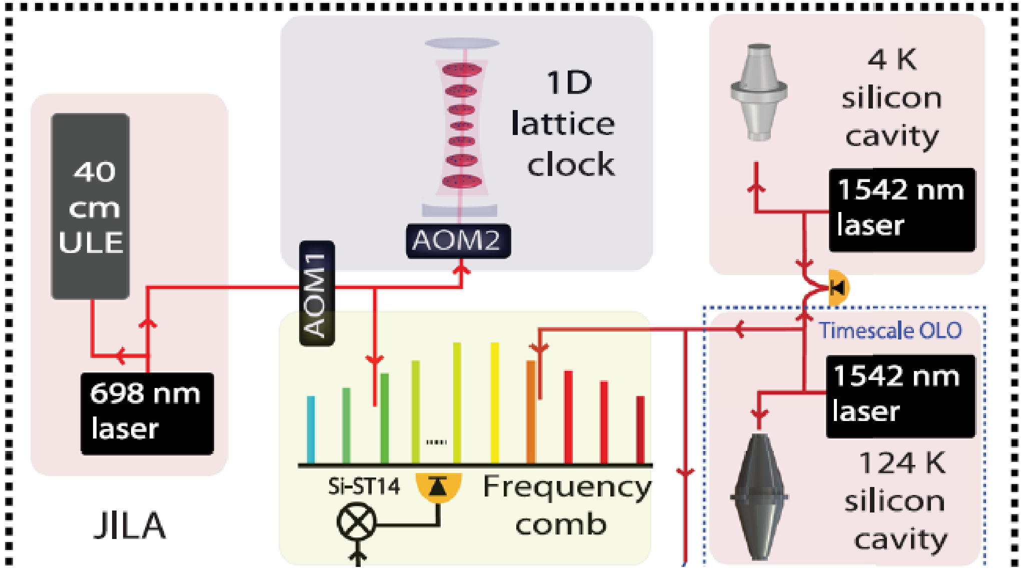
Demonstration of a Timescale Based on a Stable Optical Carrier

William R. Milner,[1,*] John M. Robinson,[1] Colin J. Kennedy,[1] Tobias Bothwell,[1] Dhruv Kedar,[1] Dan G. Matei,[2] Thomas Legero,[2] Uwe Sterr,[2] Fritz Riehle,[2] Holly Leopardi,[3] Tara M. Fortier,[3] Jeffrey A. Sherman,[3] Judah Levine,[3] Jian Yao,[3,†] Jun Ye,[1,‡] and Eric Oelker[1,§]

[1]*JILA, NIST and University of Colorado, 440 UCB, Boulder, Colorado 80309, USA*

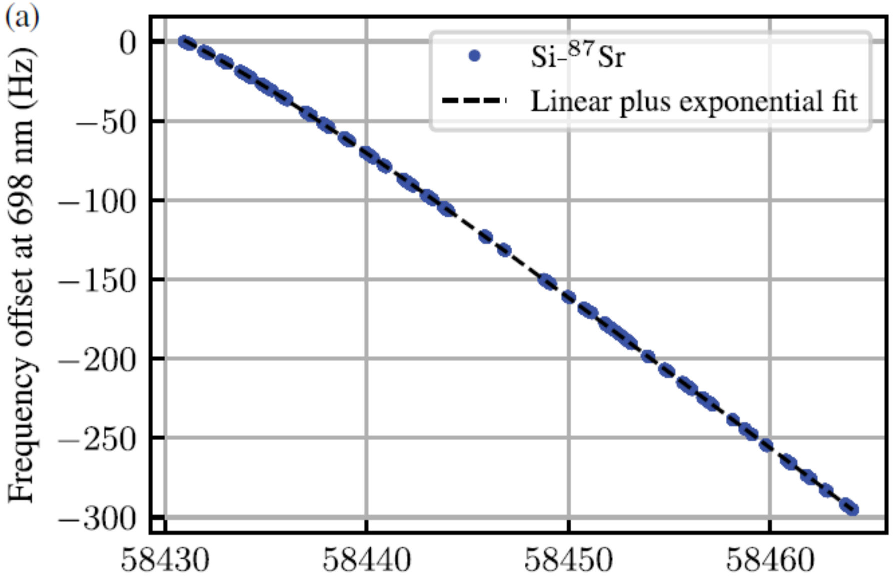
[2]*Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany*

[3]*National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305, USA*



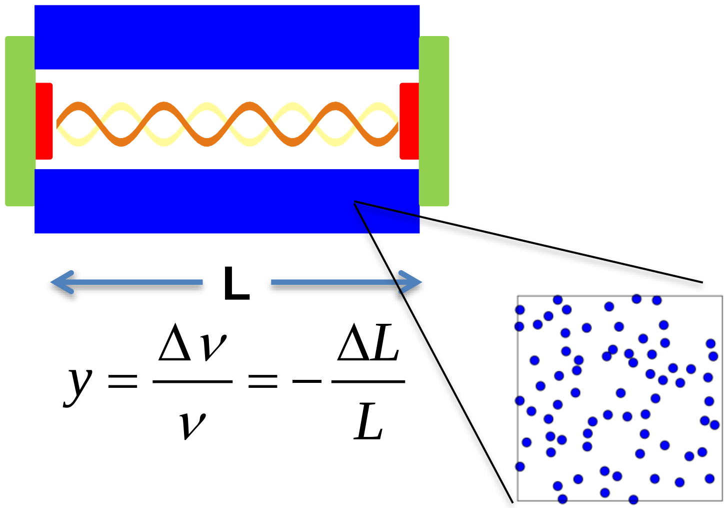
- daily measurements to Sr-lattice clock with 25 % uptime
- estimated error < 150 ps over one month

cavity drift in June 2023:
-48 µHz/s
-4.1 Hz/day
at 1542 nm
(about 1000 times less than ULE)



Brownian Noise in Fabry-Perot Cavities

High-finesse optical cavity



$$y = \frac{\Delta\nu}{\nu} = -\frac{\Delta L}{L}$$

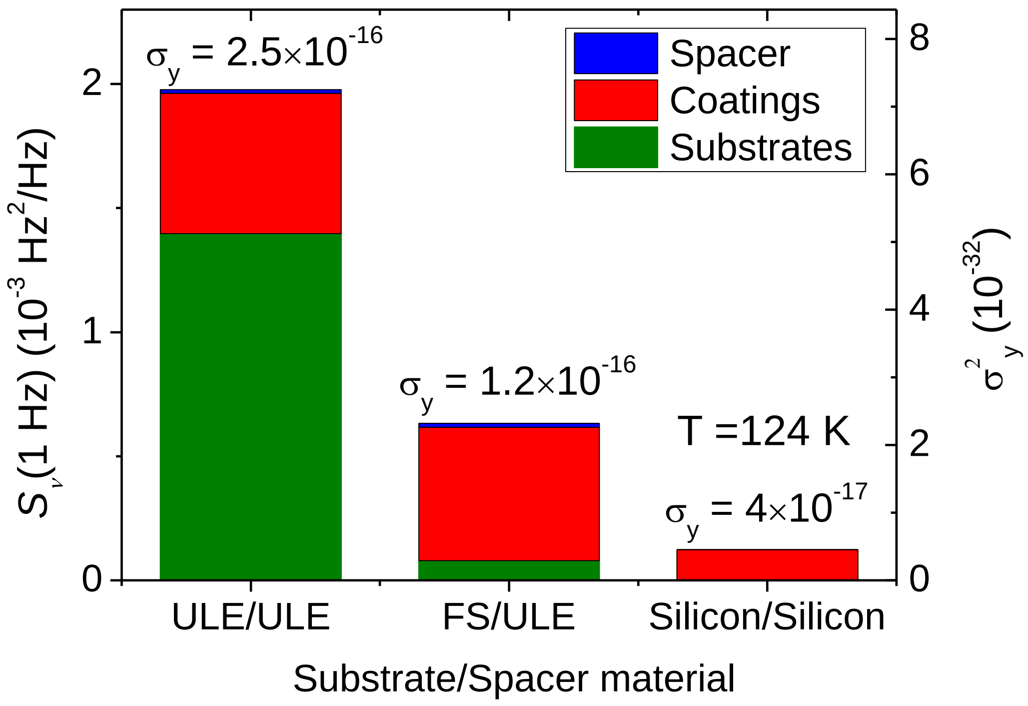
thermal noise reduction:

- go to low temperatures *T*
- enlarge cavity length *L*
- enlarge mode diameter
- choose low loss material φ_x

Fluctuation-dissipation theorem relates length fluctuations to mechanical loss φ_x

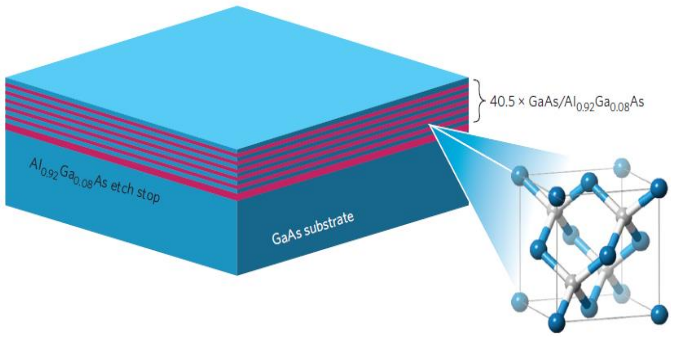
$$S_x \propto \frac{T \cdot \varphi_x}{f} \qquad \sigma_y^2 = 2\ln(2) \cdot \frac{S_x(1\,\mathrm{Hz})}{L^2}$$

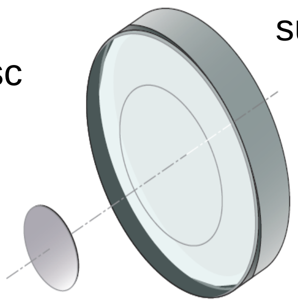
thermal noise for a 20 cm long cavity:



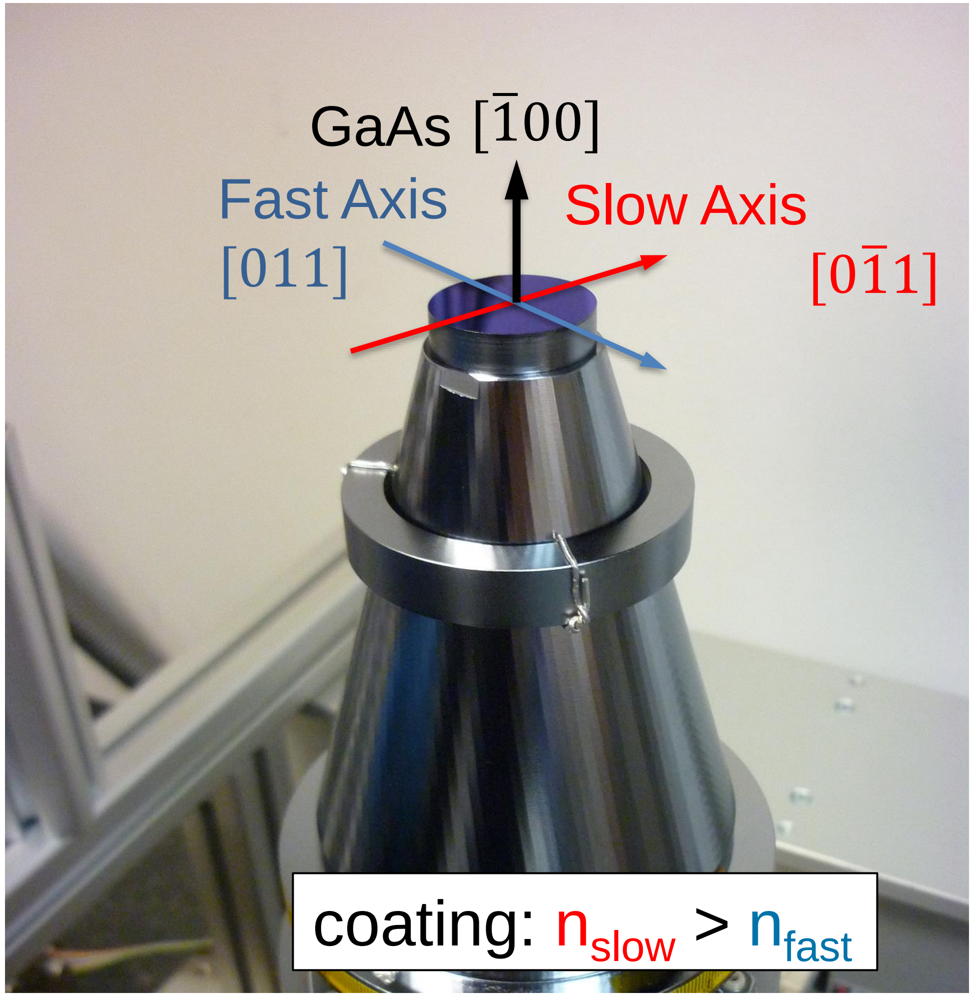
K. Numata, A. Kemery, J. Camp, Phys. Rev. Lett. **93**, 250602 (2004)

AlGaAs crystalline mirror coatings





Cole *et al.*, Nat. Phot. **7** (2013) 644

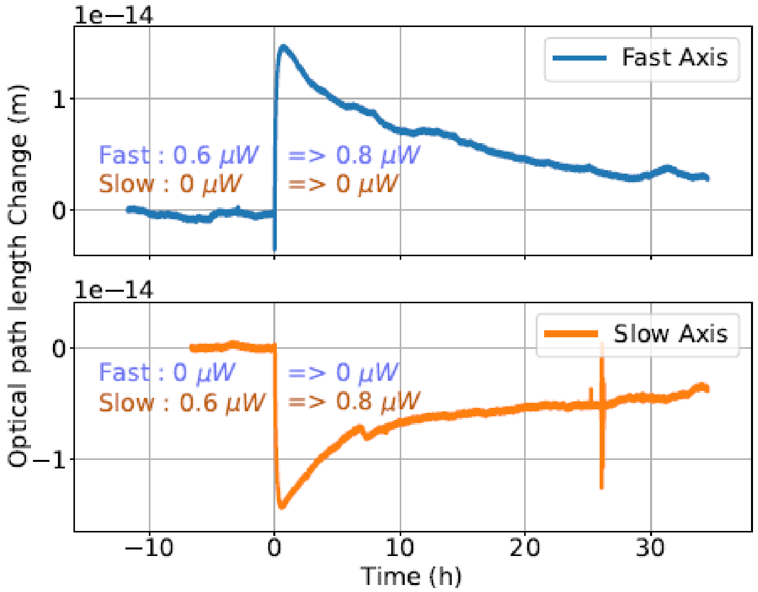


Cavity length	L = 212 mm
Mirrors	2x plano-concave (2 m ROC)
Finesse	380 000 at 124 K
Free Spectral Range	707 MHz
Birefringent mode splitting	200 kHz
Thermal noise	mod $\sigma_y(\tau) = 1\times10^{-17}$

Novel noise contributions at low temperatures

light-modified birefringence

- non-thermal, light-induced change of cavity resonance
- different sign for fast and slow axis
- time constant of many hours !

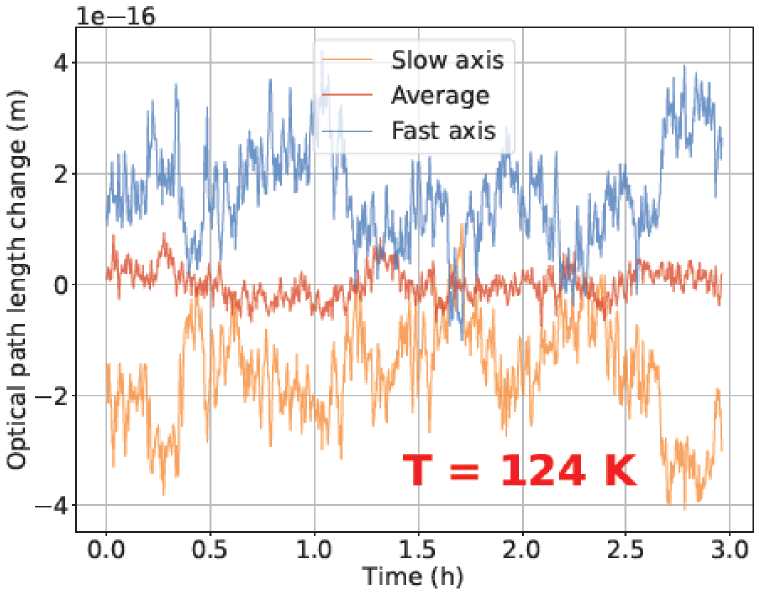


$\Delta n_{stat} \approx 10^{-4}$

$\Delta n_{photo} \approx 10^{-8}$

birefringent noise

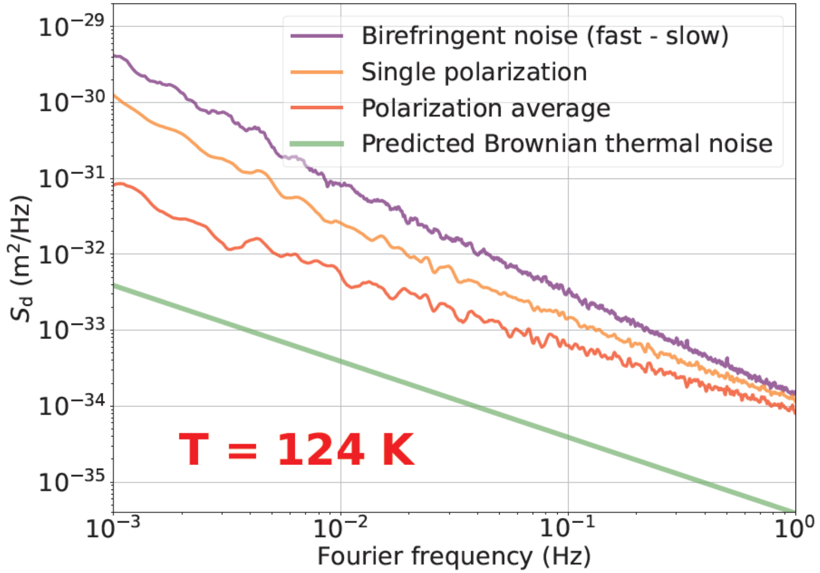
- even with stabilized laser power
- anticorrelated in fast and slow axis
- correlation length < mode diameter
- so far only observed at 4K, 16K, 124K



$\Delta n_{noise} \approx 10^{-10}$

global excess noise

- remaining noise when averaging birefringent noise
- exceeds Brownian thermal noise
- correlation length > mode diameter



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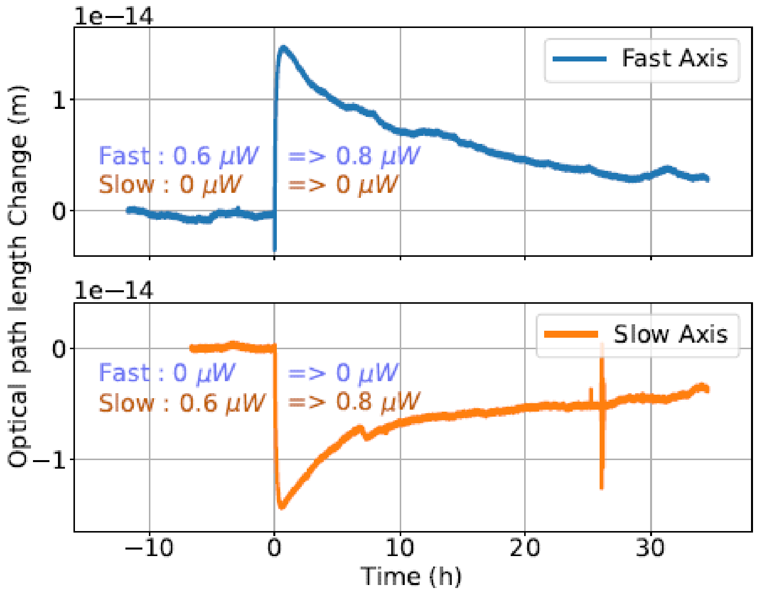


$\Delta n_{stat} \approx 10^{-4}$

$\Delta n_{photo} \approx 10^{-8}$

Possible explanation:
Light is exciting carriers in the AlGaAs / GaAs semiconductor building up electric field along the coating ?

linear electro-optic effect ?

$\Delta n \approx r_{41}\, n_0^3\, E$

- electro-optic tensor component r_{41} = 1.5 pm/V
- refractive index GaAs $n_0 \approx 3.48$

$\Rightarrow$ $E \approx 3$ kV/m

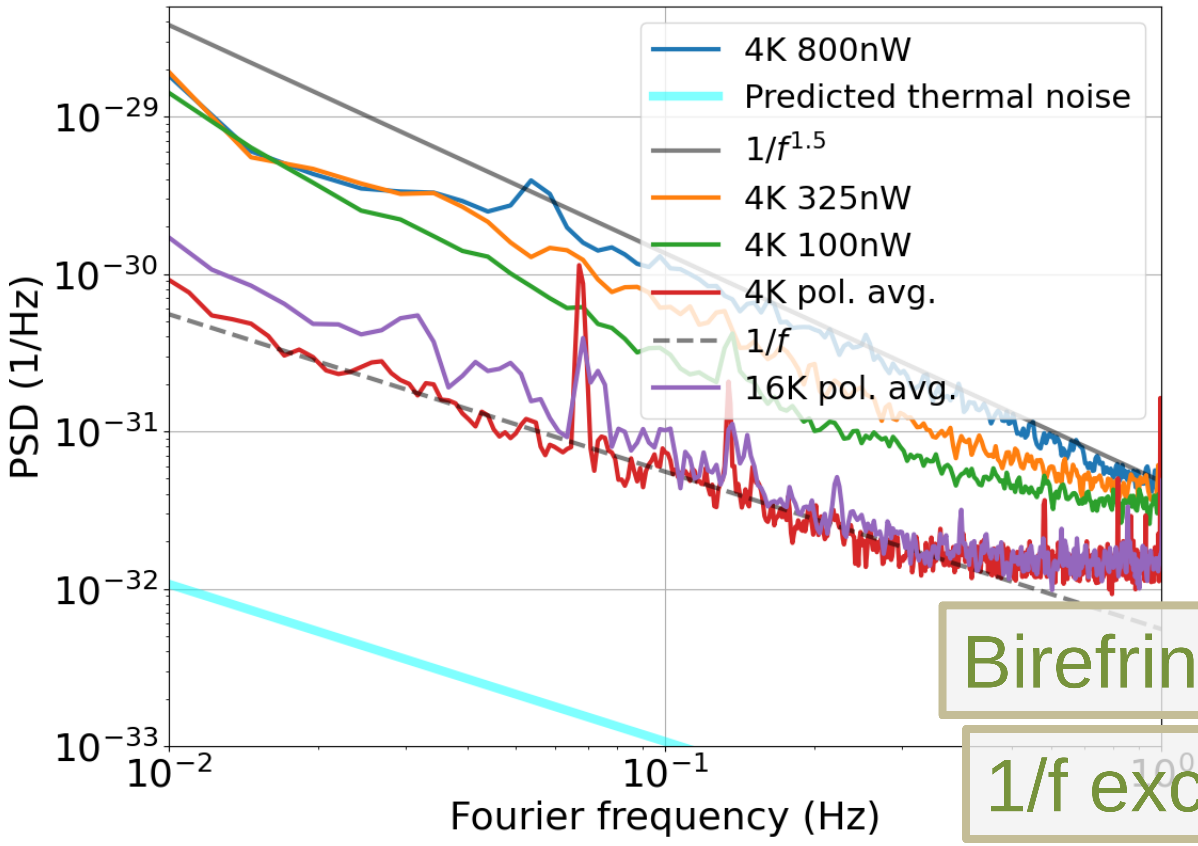
small compared to electric field strengths in heterojunctions

S. Namba, *J. Opt. Soc. Am.* ***51***, (1961) 76

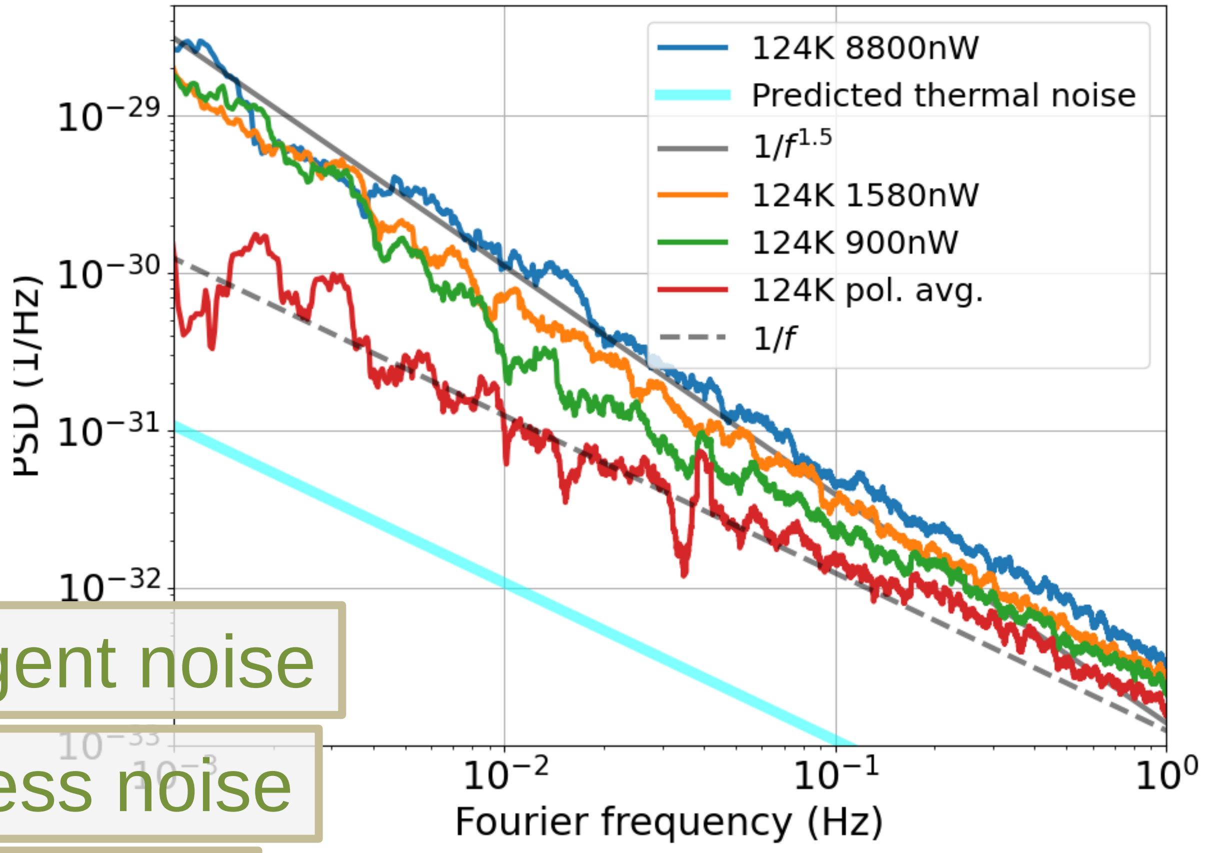
L. Ho, C. Buhrer, *Appl. Opt.* ***2**, 647 (1963)*

Measurements at 124 K and 4 K

JILA 6 cm Si cavity at 4 K



PTB 21 cm Si cavity at 124 K

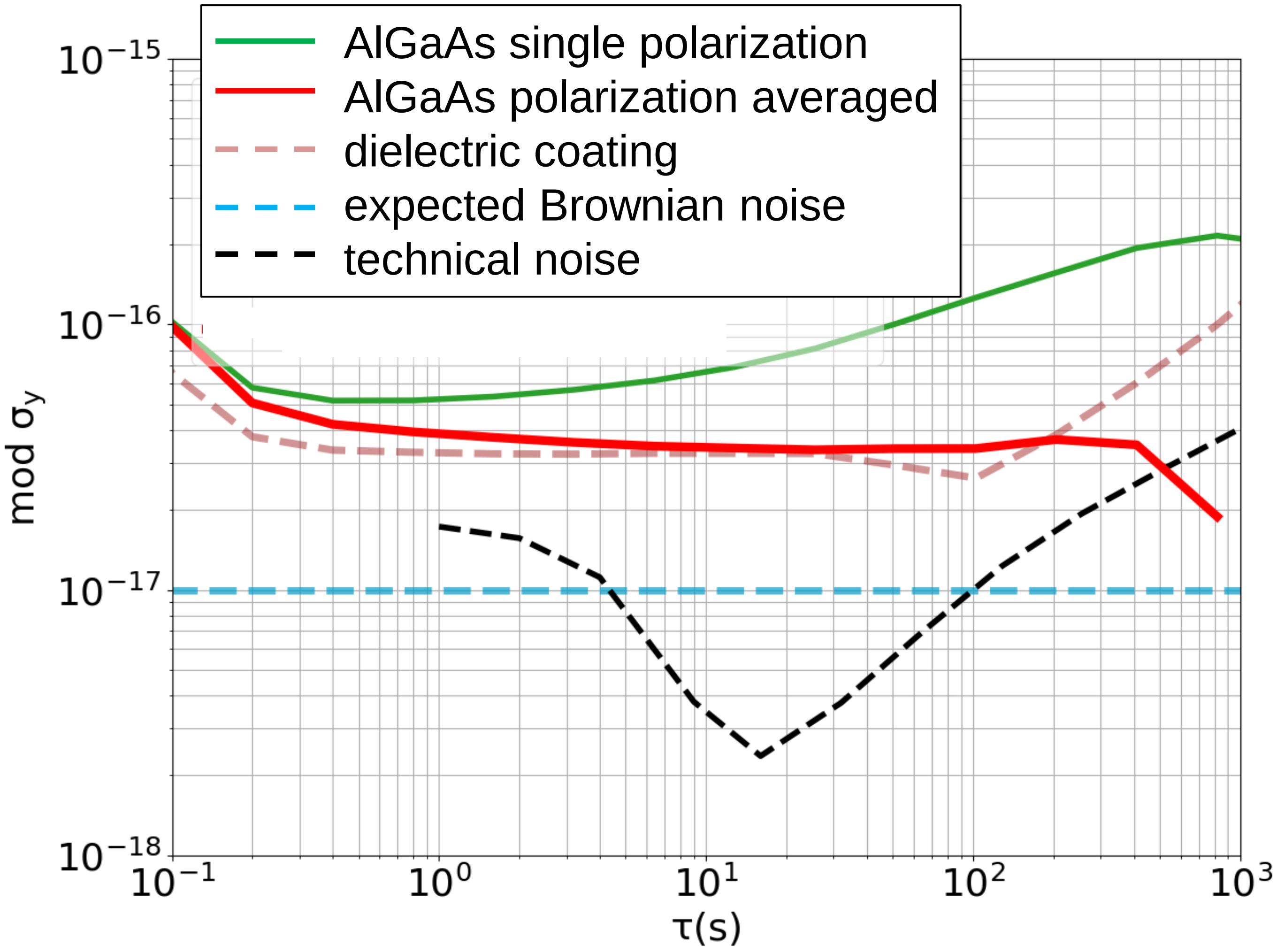


Birefringent noise

1/f excess noise

Non-thermal

Stability at 124 K

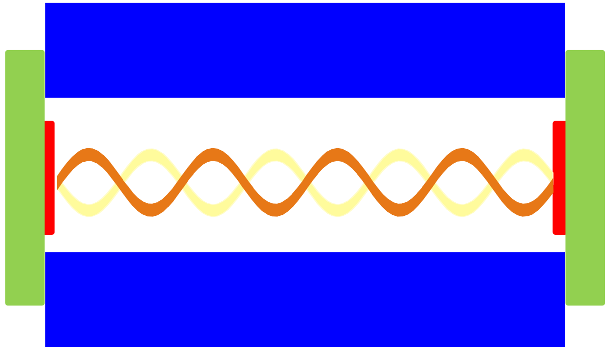


- Birefringent noise can be removed with polarization averaging
- The remaining frequency stability
  $\sigma_y \approx 4\times10^{-17}$
  is still higher than predicted thermal noise

Origin of remaining noise:

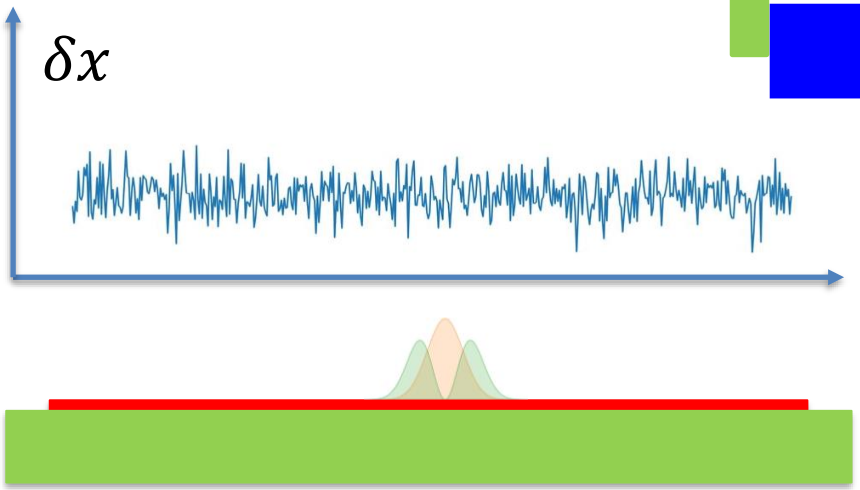
- Brownian thermal noise?
- $\varphi(124\text{ K}) \gg \varphi(300\text{ K})$?
- Other unidentified noise?

Spatial noise correlation on mirror



Local noise

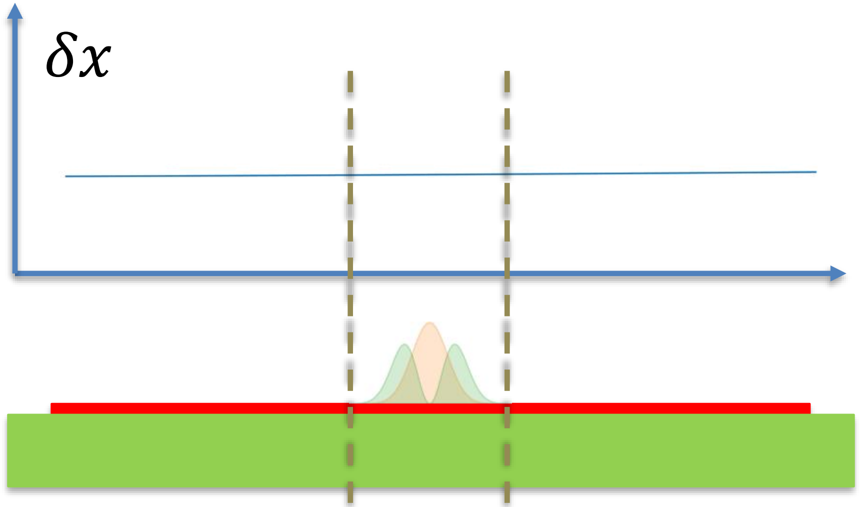
$l_{corr} \ll w$



- Coating Brownian thermal noise
- Birefringent noise

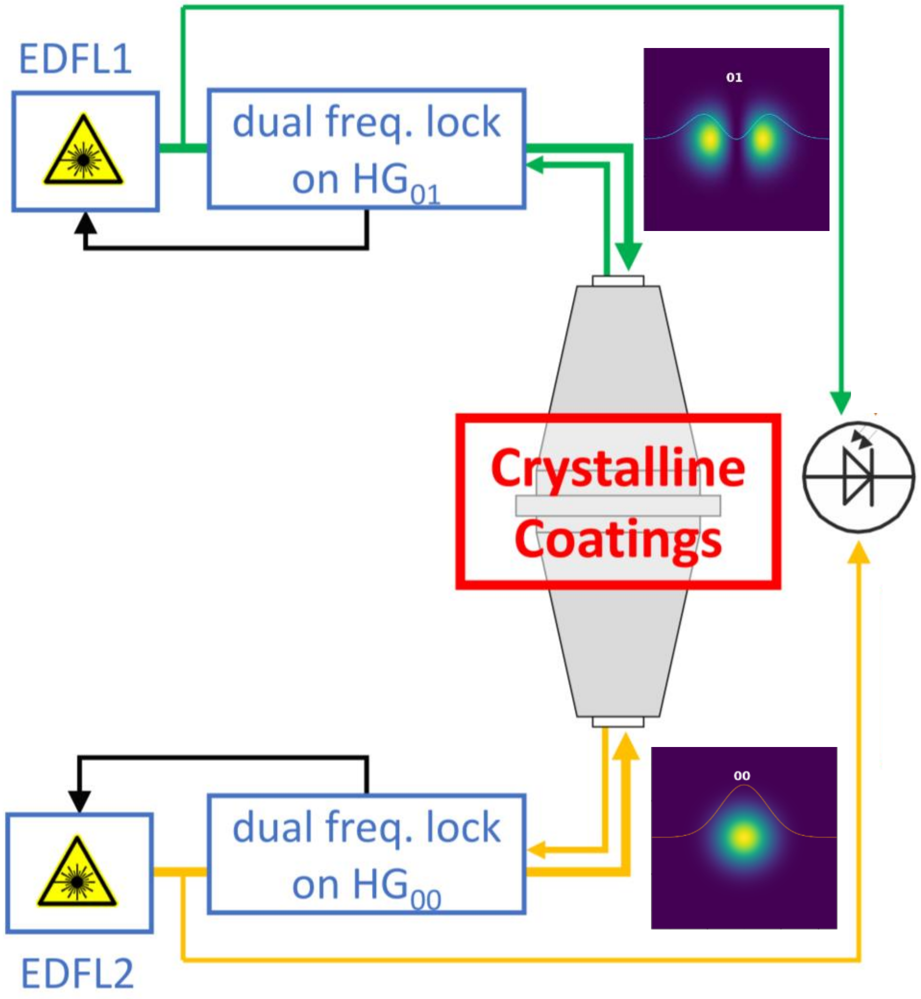
Global noise

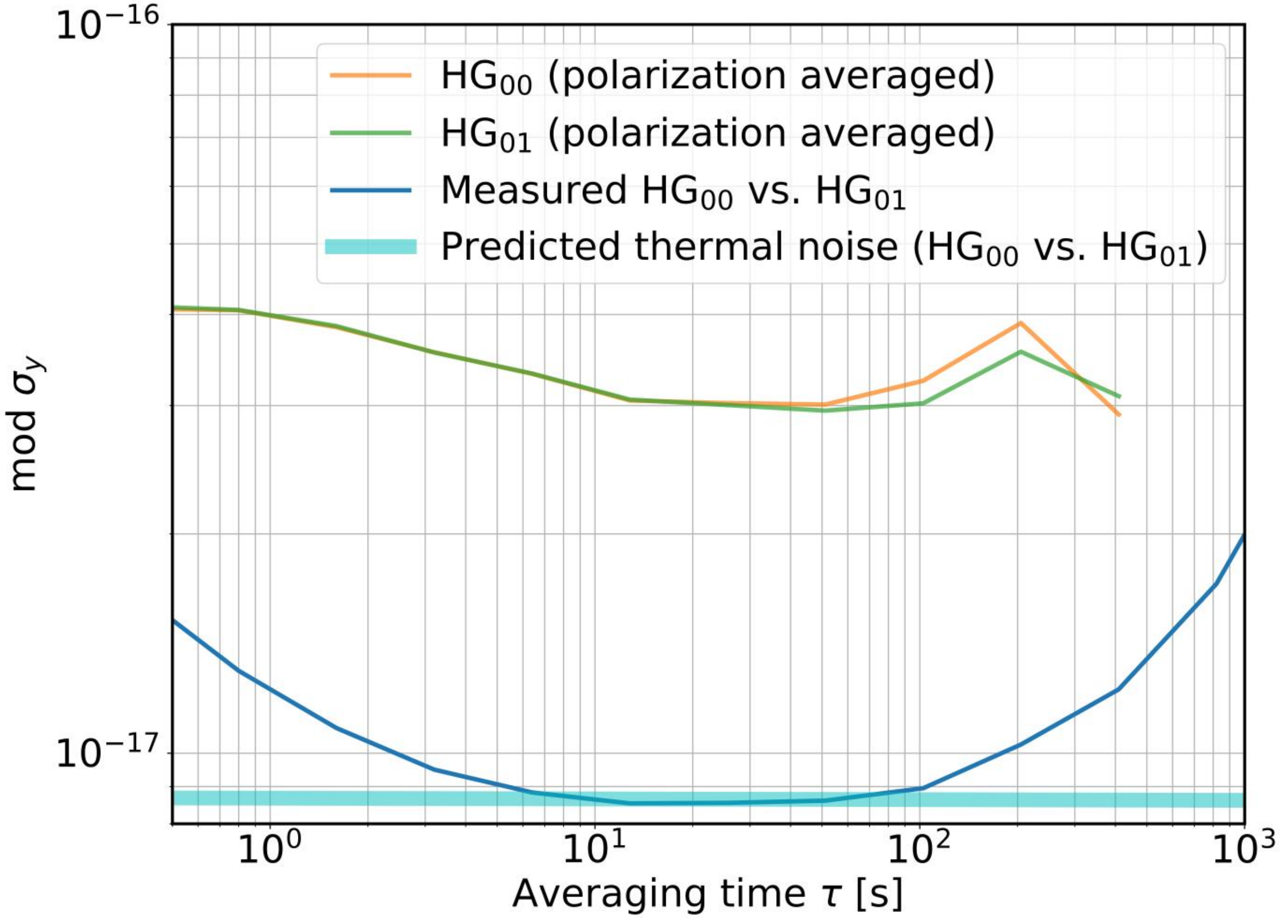
$l_{corr} \gg w$



- Cavity temperature fluctuation
- Vibrations
- Thermo-optic noise (τ > 1 s)
- etc.

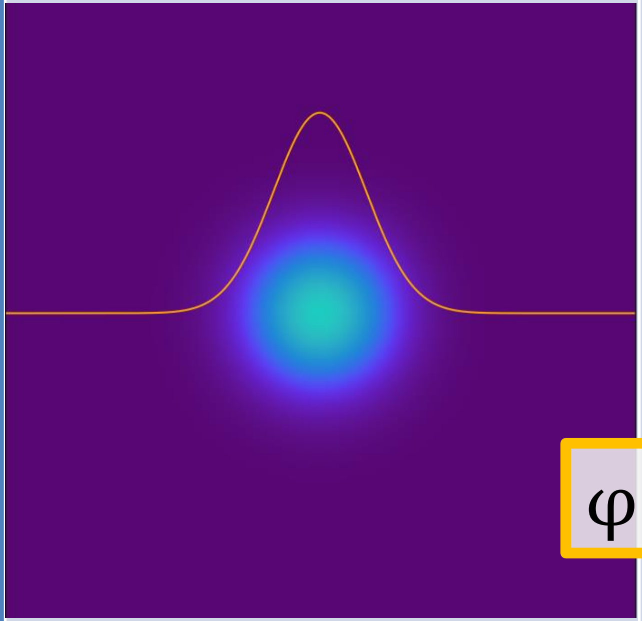
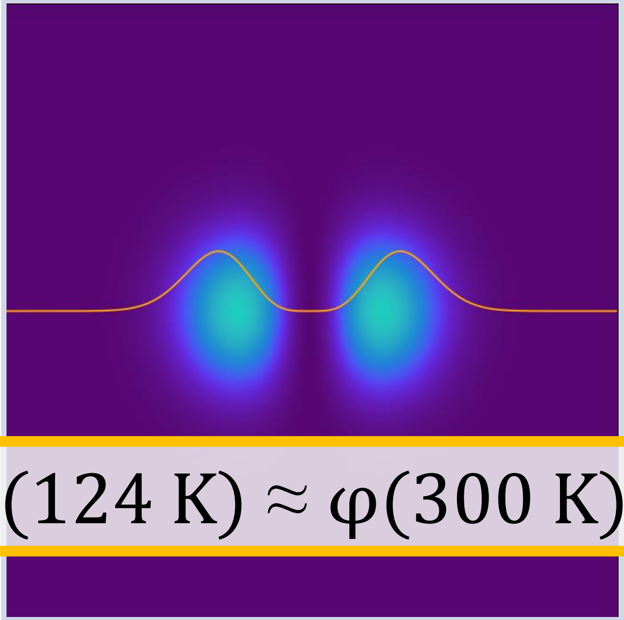
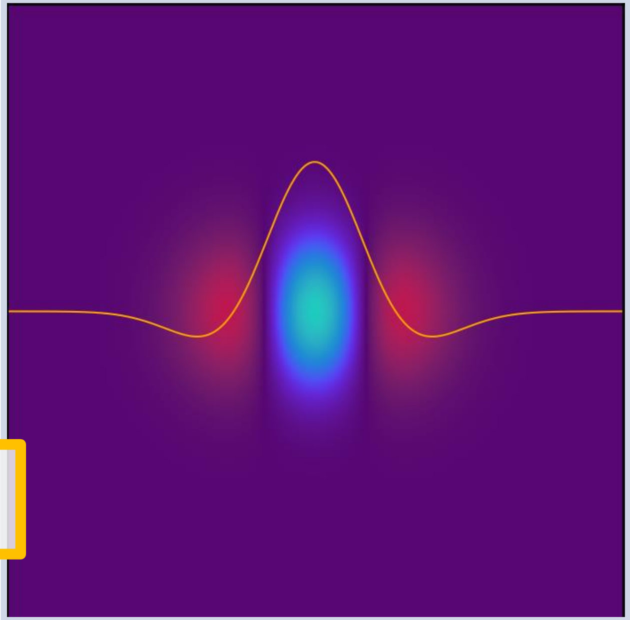
Measurement of Brownian thermal noise





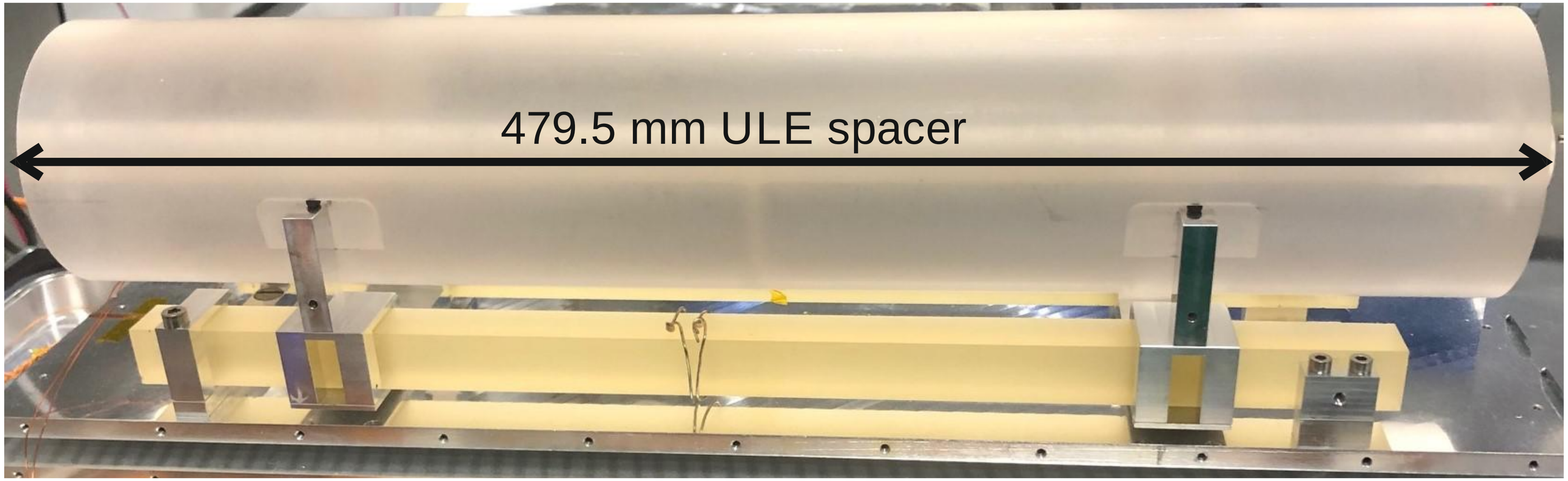
Brownian thermal noise

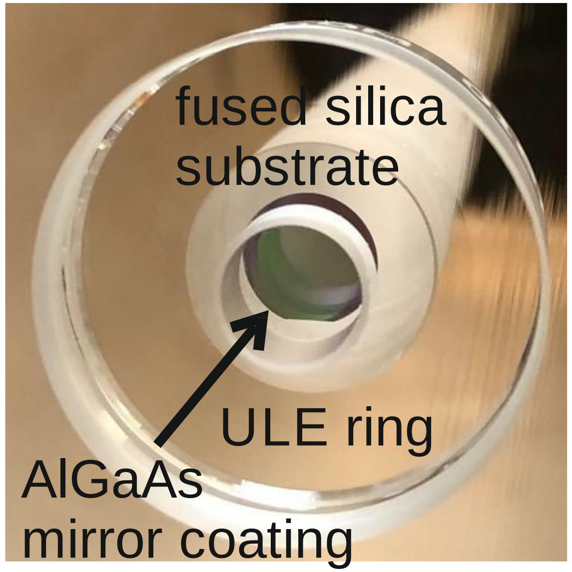
Determine upper limit of coating Brownian thermal noise

Mode	HG_{00}	HG_{01}	HG_{00}-HG_{01}
Integration profile			
Scaling of mod σ_y	1	$\sqrt{0.75}$	$\sqrt{0.75}$
Predicted noise level	mod $\sigma_{y_{00}} = 1.0 \times 10^{-17}$	mod $\sigma_{y_{01}} = 0.86 \times 10^{-17}$	mod $\sigma_{y_{\Delta}} = 0.86 \times 10^{-17}$
Measured/calculated	mod $\sigma_{y_{00}} = 0.97 \times 10^{-17}$	mod $\sigma_{y_{01}} = 0.84 \times 10^{-17}$	mod $\sigma_{y_{\Delta}} = 0.84 \times 10^{-17}$

$$\varphi(124\ \mathrm{K}) \approx \varphi(300\ \mathrm{K})$$

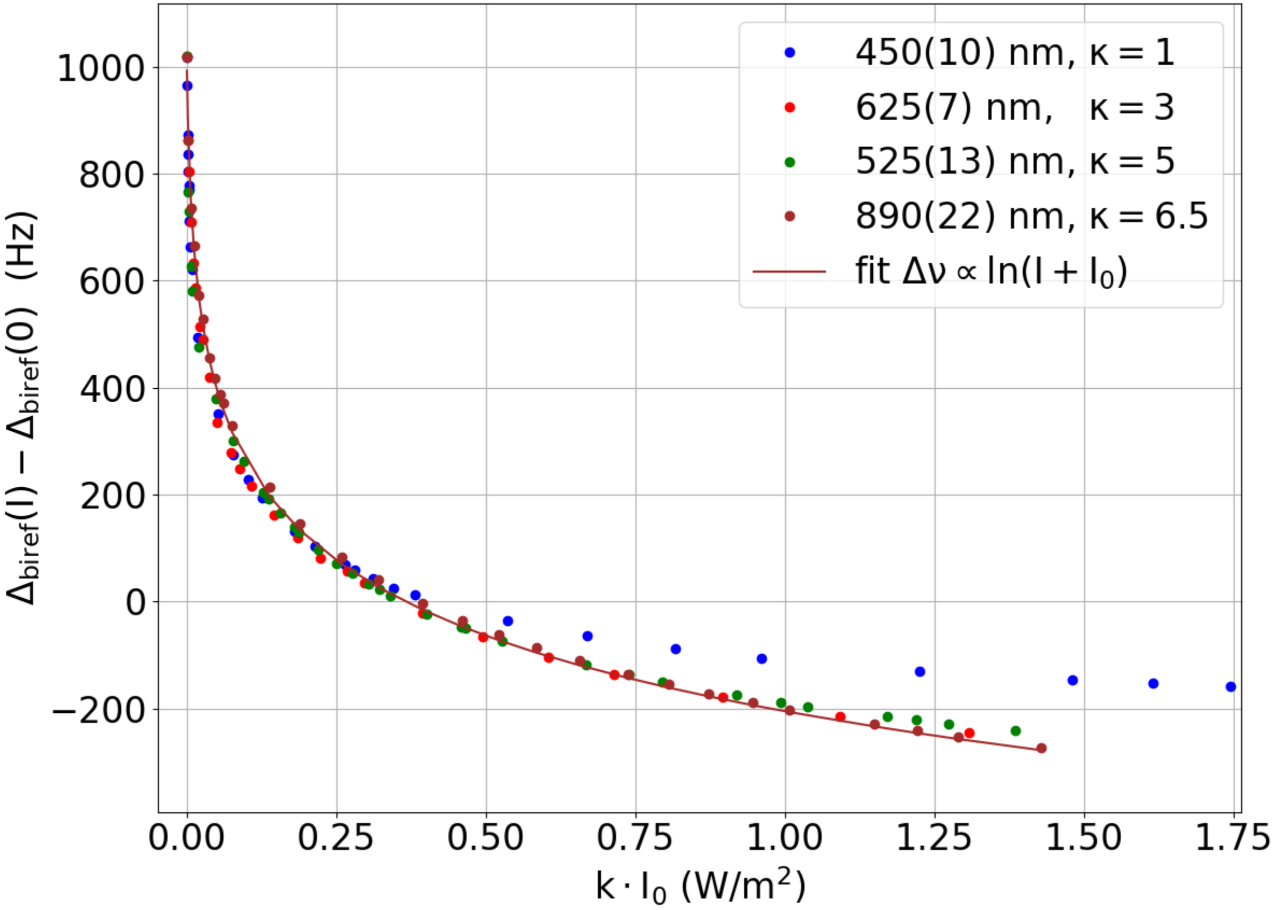
Further investigations at room temperature

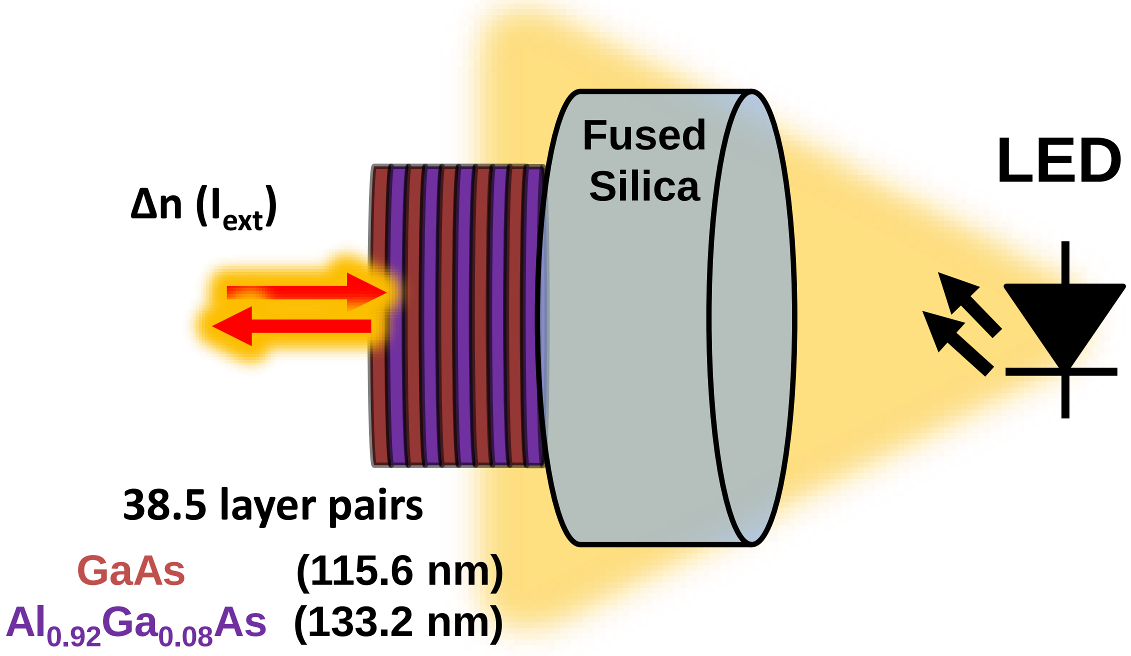




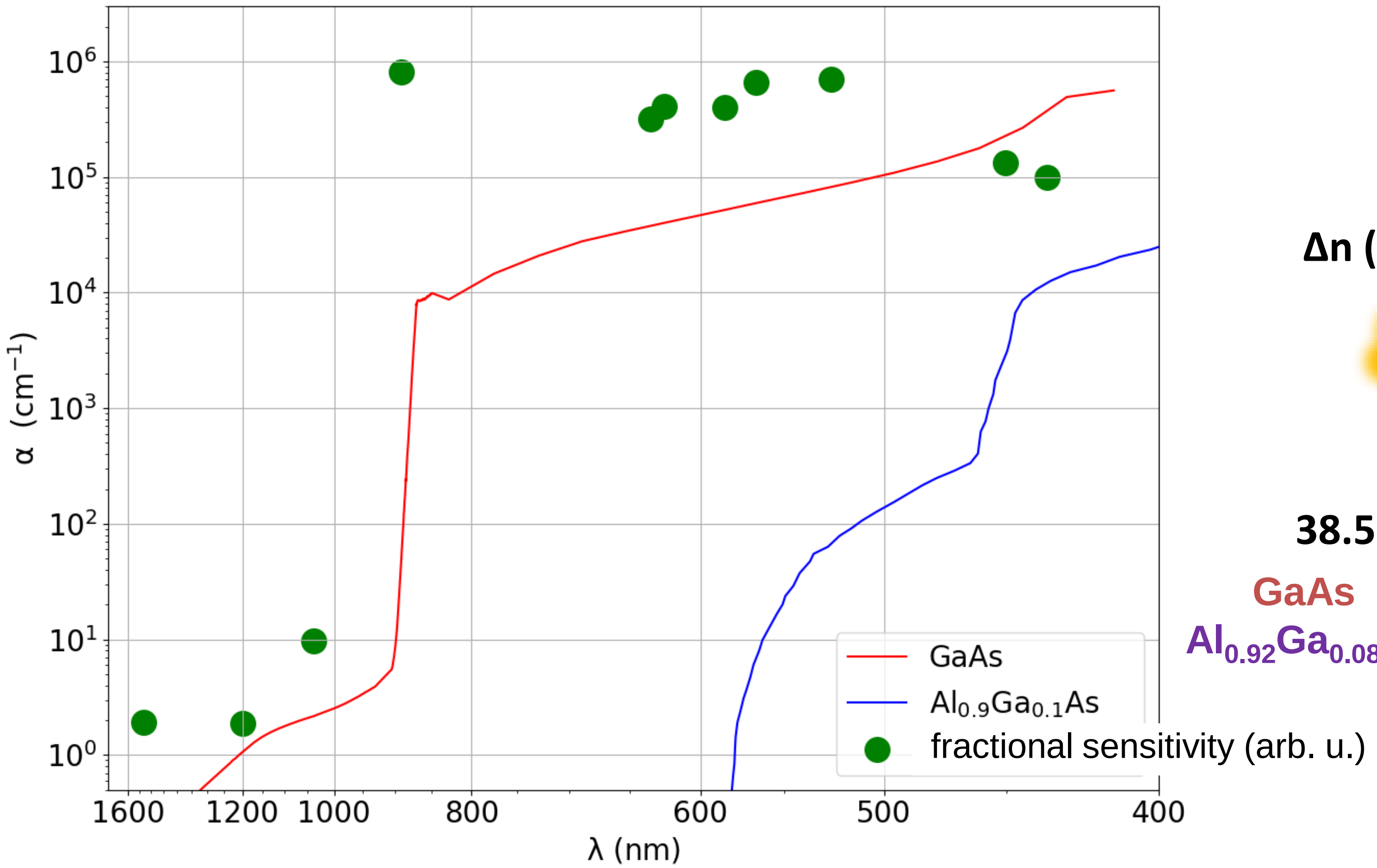
48 cm ULE cavity with AlGaAs mirror coatings at room temperature.

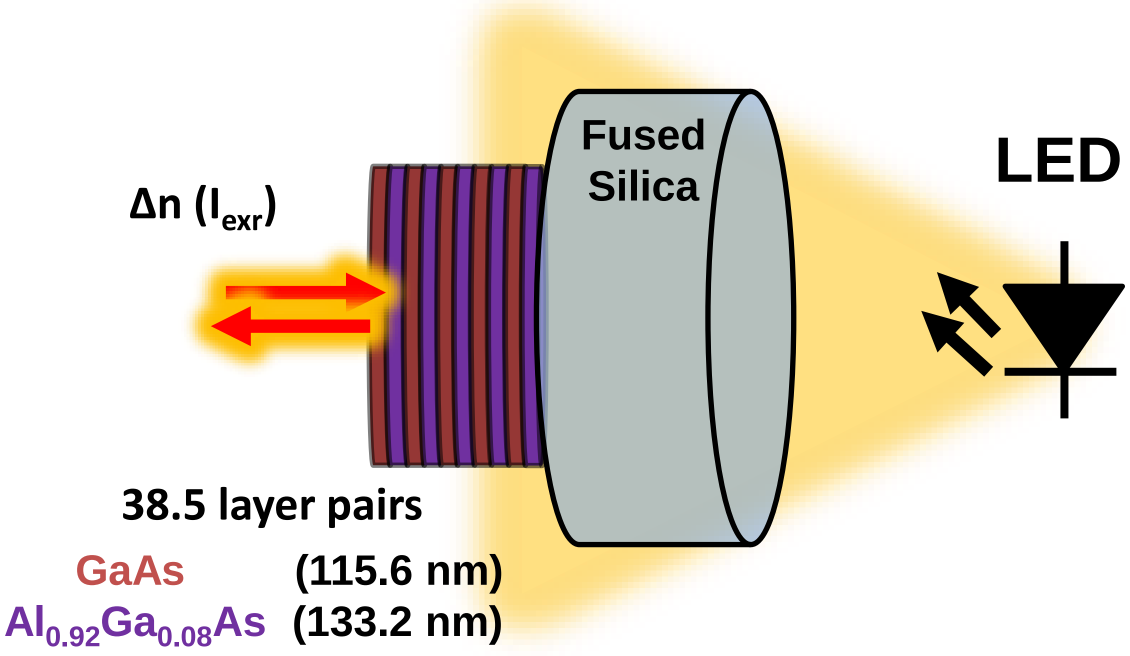
Sensitivity to external light





Wavelength-dependent sensitivity





Outlook

EMPIR – European Metrology Programme

NEXTLASERS

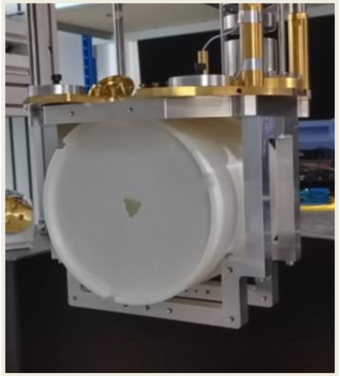
cryogenic cavities,

e.g.

10 mK closed-cycle dilution cryostat

12 kg silicon spacer

@ FEMTO-ST

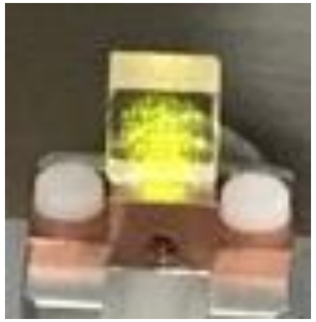


spectral holes

vibration isolation

nanostructured mirrors

large modes



PTB Physikalisch-Technische Bundesanstalt Braunschweig und Berlin

VTT

LINKS ISMB STI

Technische Universität Braunschweig

Lund University

hhu Heinrich Heine Universität Düsseldorf

Nicolaus Copernicus University in Toruń

LNE Laboratoire National de Métrologie et d'Essais

SYRTE Observatoire de Paris | PSL

Systèmes de Référence Temps-Espace

cnrs

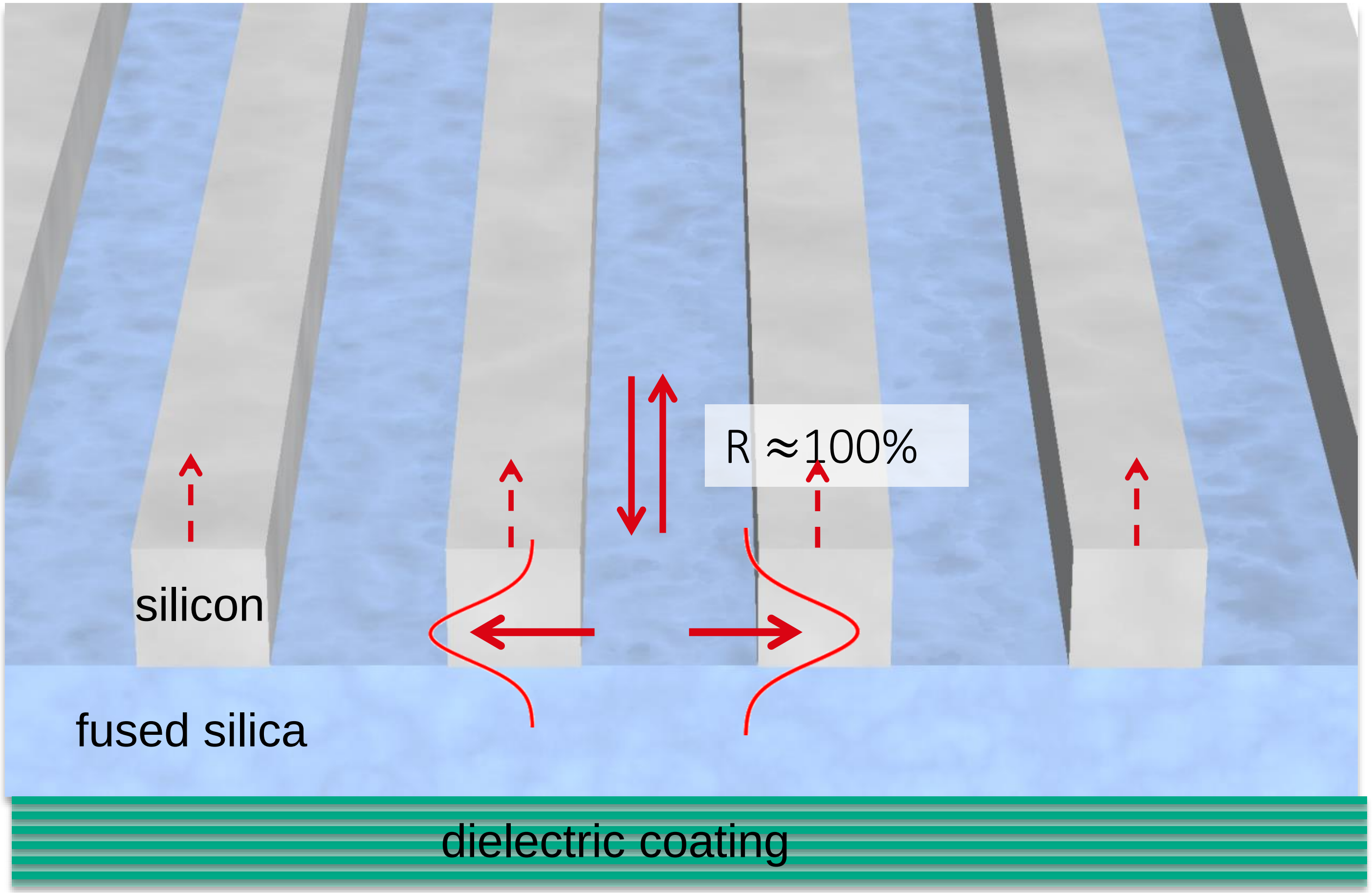
RI. SE

Institut de Recherche femto-st Sciences & Technologies

ensmm École Nationale Supérieure de Mécanique et des Microtechniques

INRiM Istituto Nazionale di Ricerca Metrologica

Nanostructured mirrors



Meta-Etalon mirror

- combine grating $R_1 \approx 99.9\ \%$ with rear dielectric mirror $R_2 \approx 99.9\ \%$
- thermal noise is mostly determined by silicon grating
- $\sigma_y = 4\times10^{-18}$ @ 124 K possible

First results of cavity with one meta-etalon:

- Finesse 12 000
- $R \approx 99.95\%$

S. Dickmann et al.
Commun. Phys. **6**, 16 (2023)

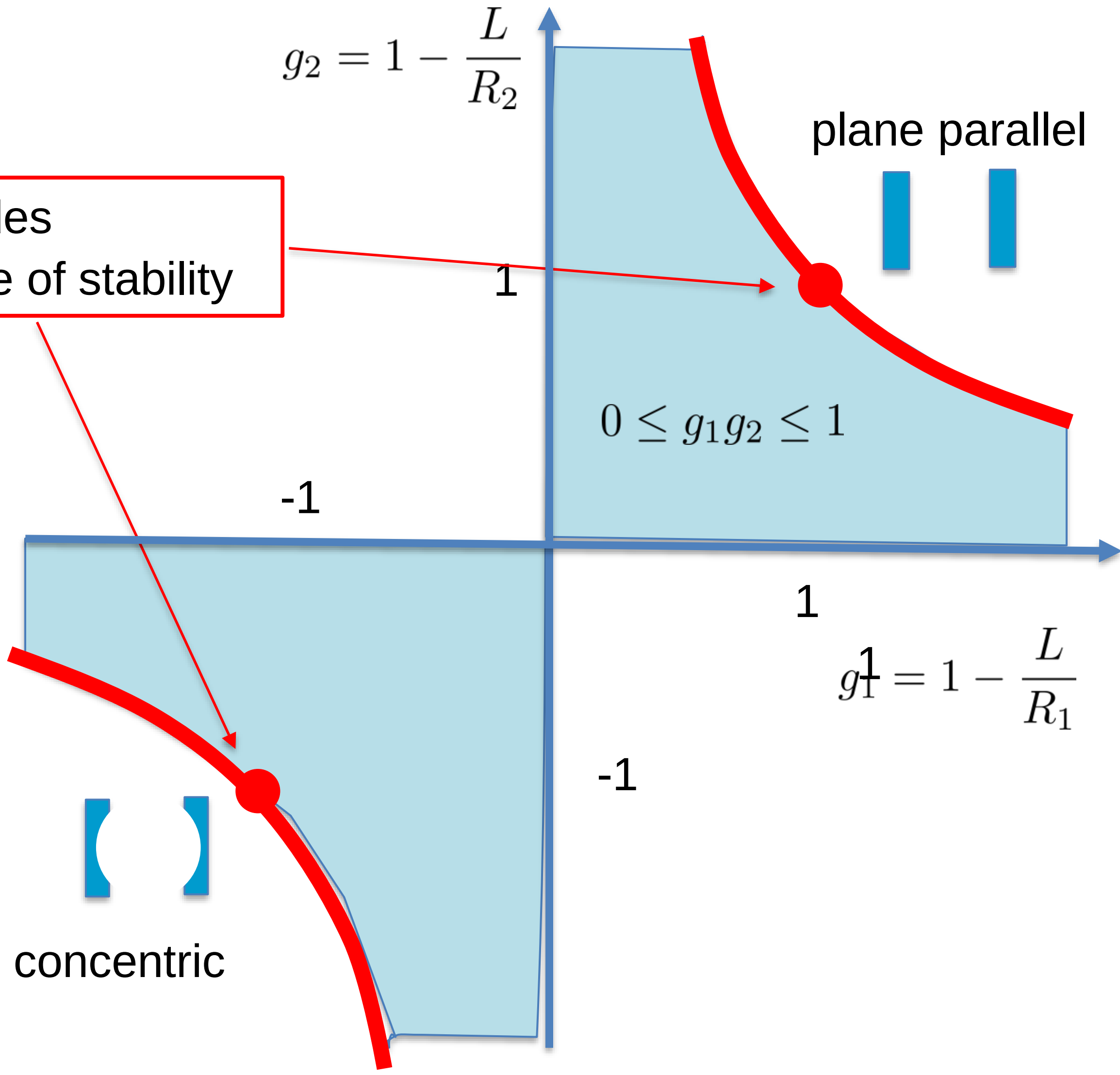
Large mode area cavities

Larger mode size:
smaller averaged thermal coating noise

R_1	R_2	rel. σ_y
1 m	plane	1.00
2 m	plane	0.84
5 m	plane	0.67
10 m	plane	0.56
20 m	plane	0.47
50 m	plane	0.37

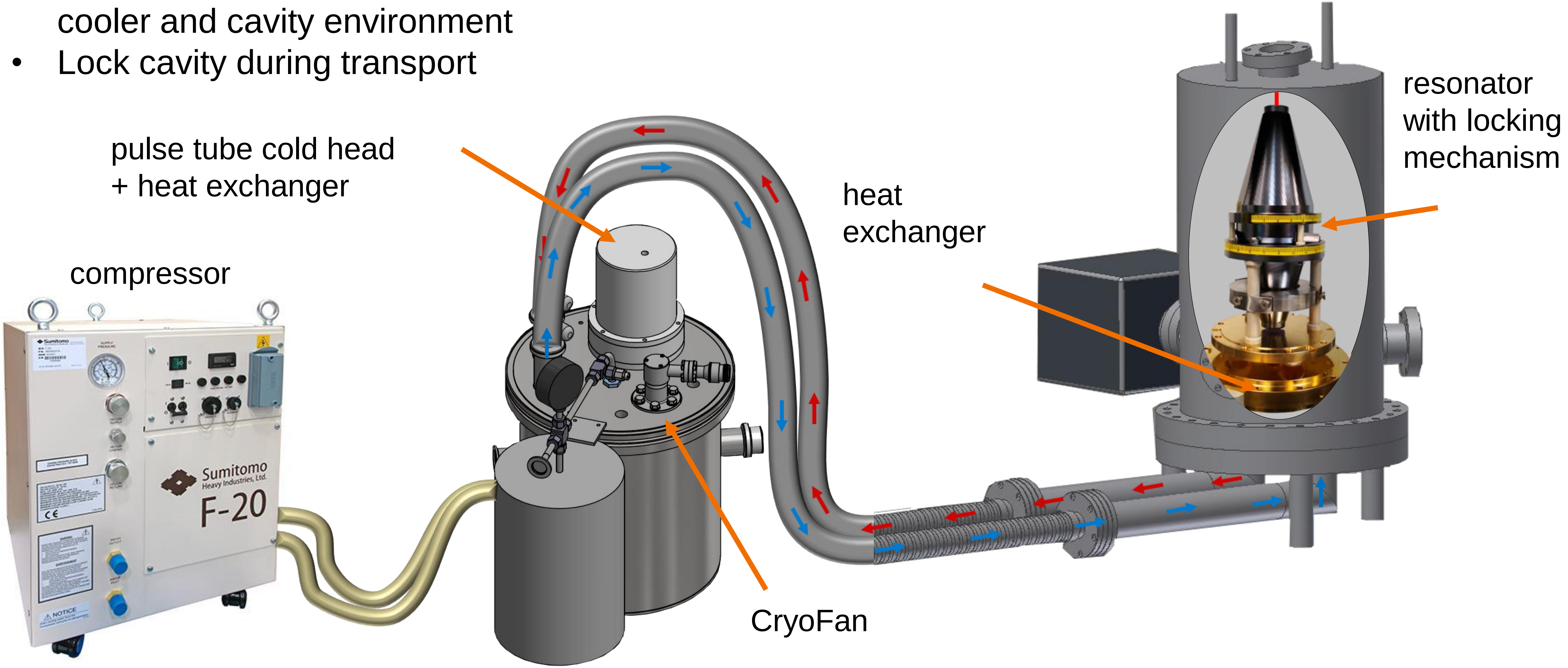
Problems:
mirror manufacturing

cavity assembly, tolerances:
mode shifts 1 mm for 10 arcsec deviation



Transportable 124 K Si system

- Cool cavity to 124 K by circulating cold gas between pulse tube cooler and cavity environment
- Lock cavity during transport



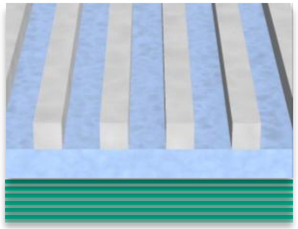
Summary

Summary

- silicon cavities at 124 K with dielectric coating reach thermal noise limit instability of 4×10^{-17}
- crystalline coatings so far do not provide lower instability

Outlook

- low-noise nanostructured meta-etalons F ≈ 12 000
- operation at 4 K
- transportable systems



Funding

DFG

SFB 1227

EXC2123 QuantumFrontier

NEXTLASERS

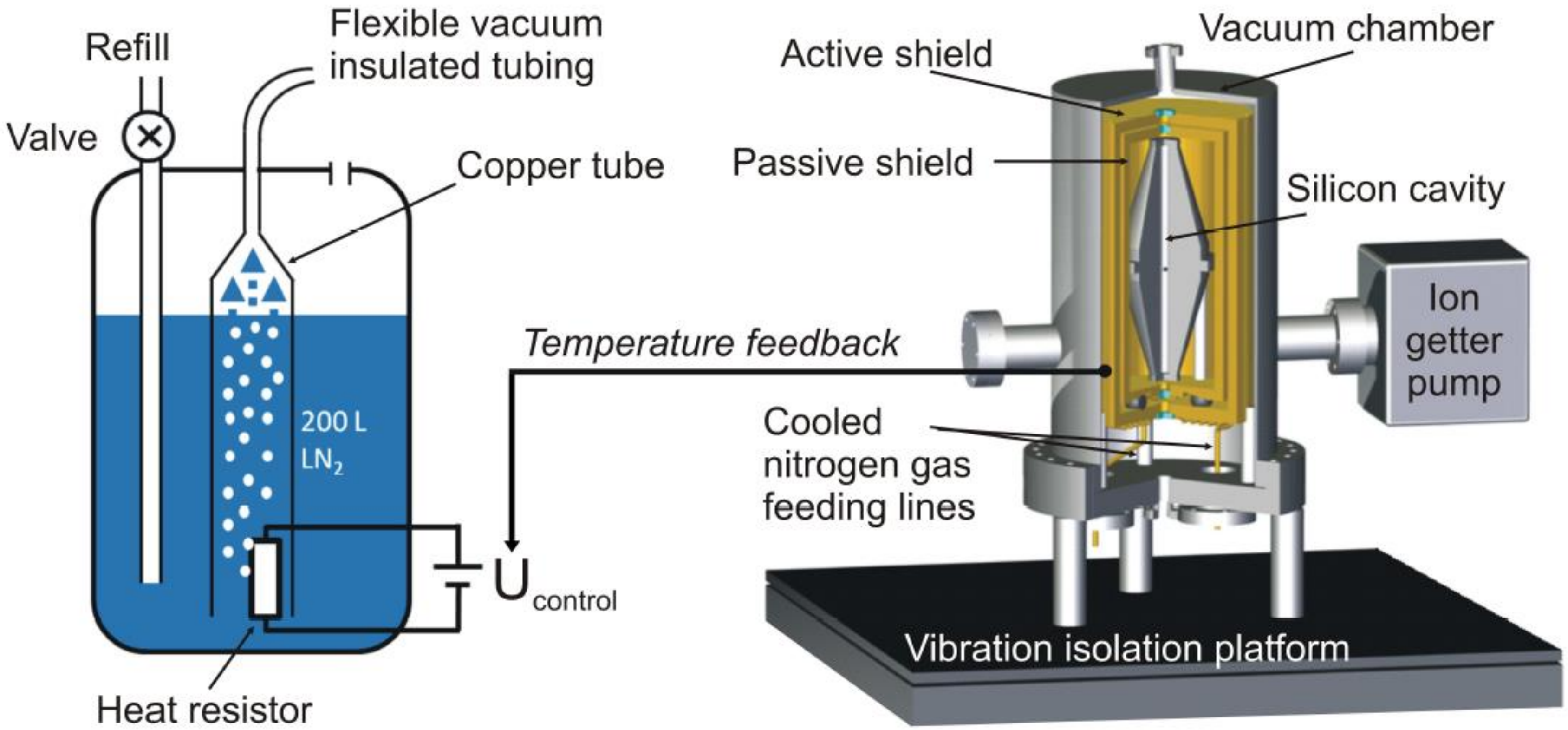
EMPIR EURAMET

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Max Planck-RIKEN-PTB Center for Time, Constants and Fundamental Symmetries

LN2-based 124K cooling system

about 10 W cooling power needed

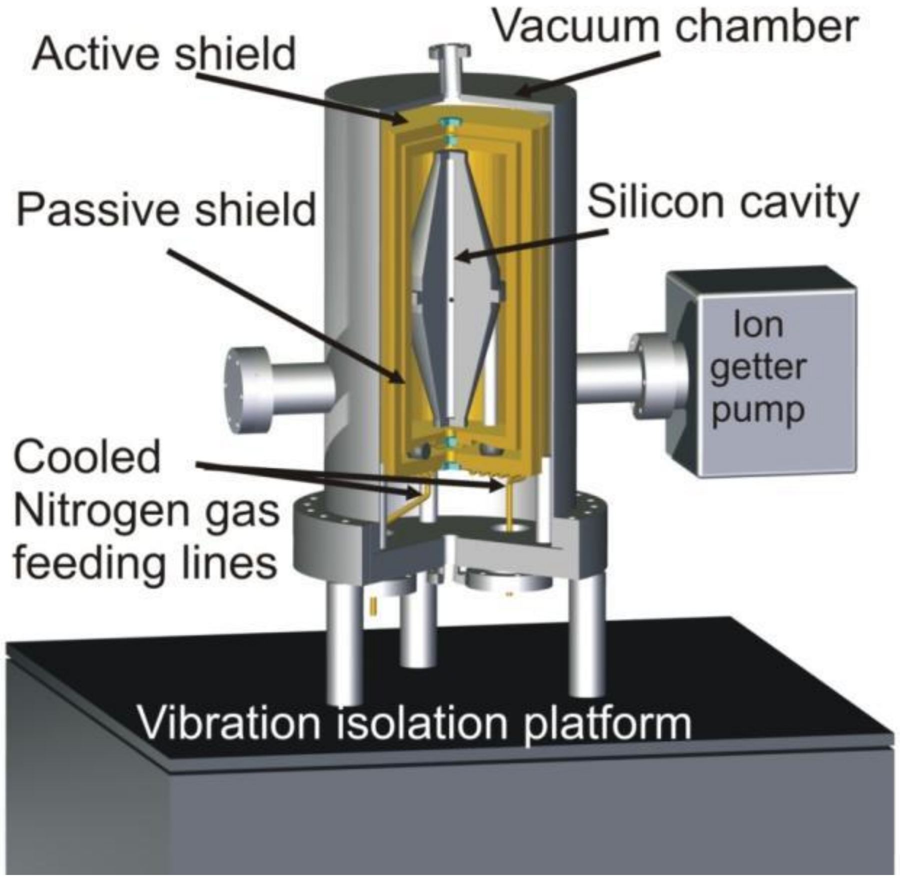


<u>drawbacks:</u>

- LN2 infrastructure needed
- about 400 liters LN2/ week needed
- two refills per week (holidays, X-mas …)

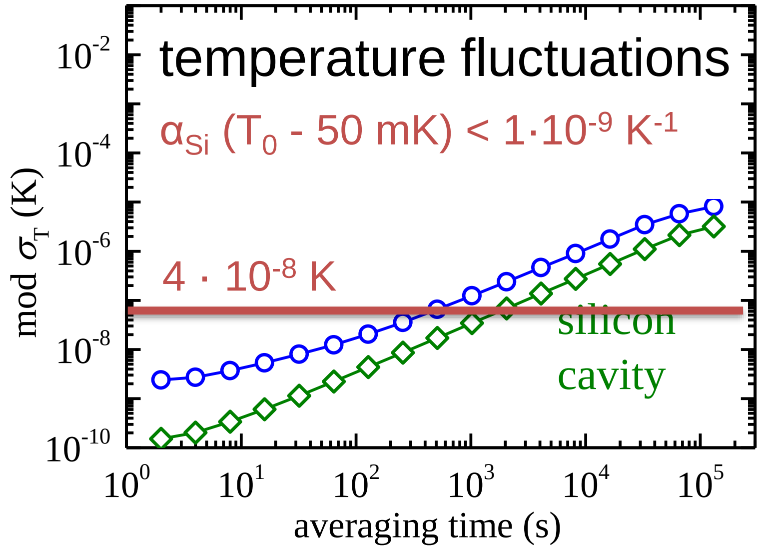
Replace the open loop LN2 system by a He-gas cooled, closed-cycle cooling to get a stand-alone and low-maintenance system.

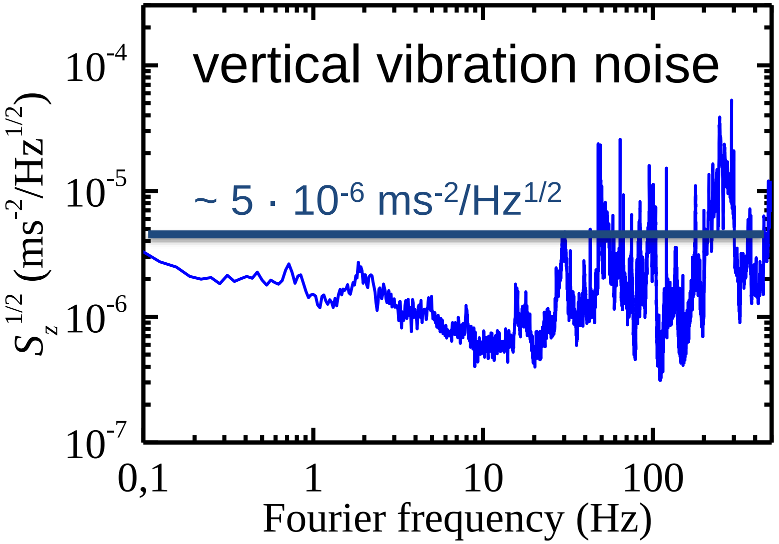
124 K Cryostat



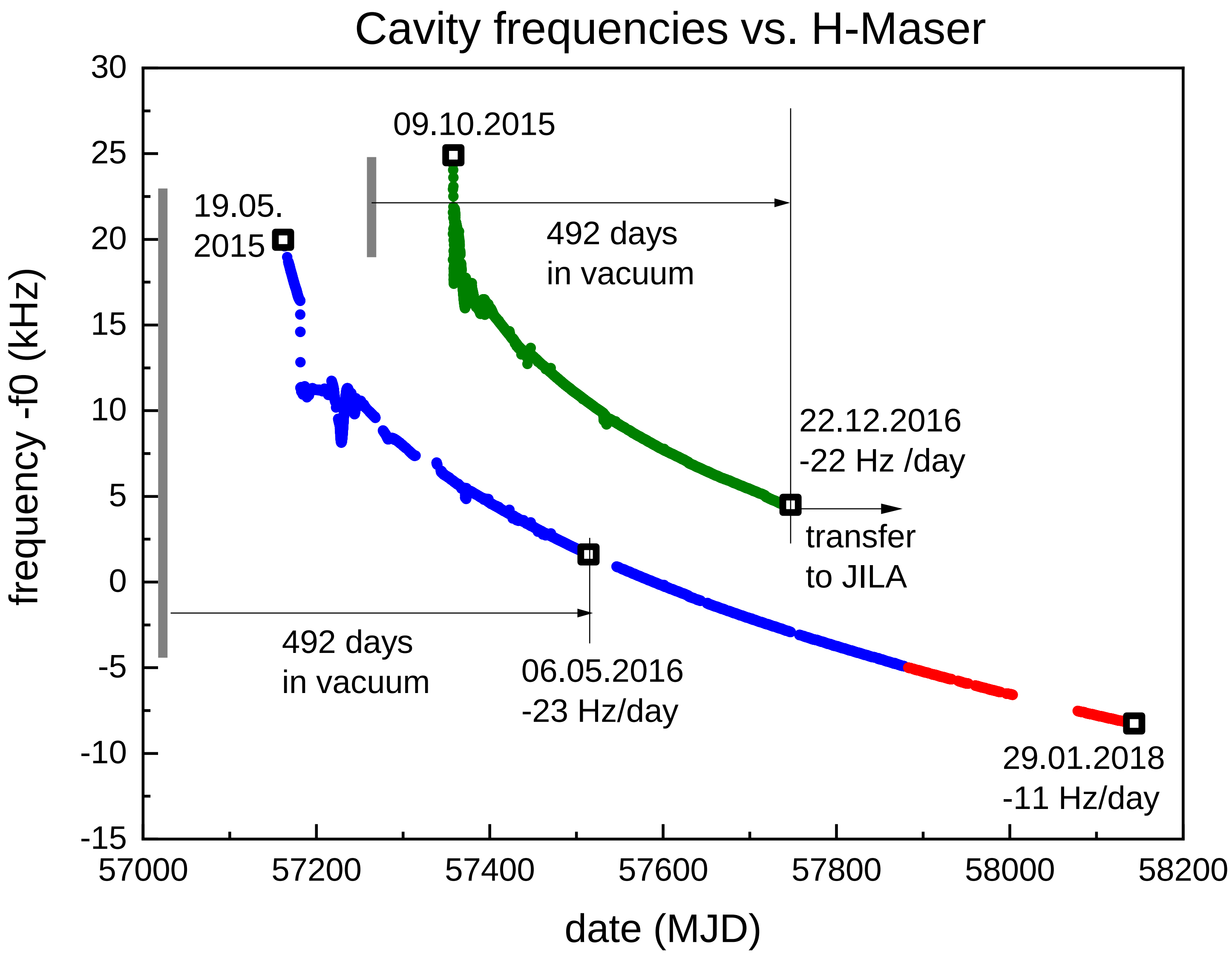
required vibration sensitivity
$\Delta L/L < 10^{-10}$ / ms^{-2}

T. Kessler et al., Nature Phot. **6**, 687-692 (2012)





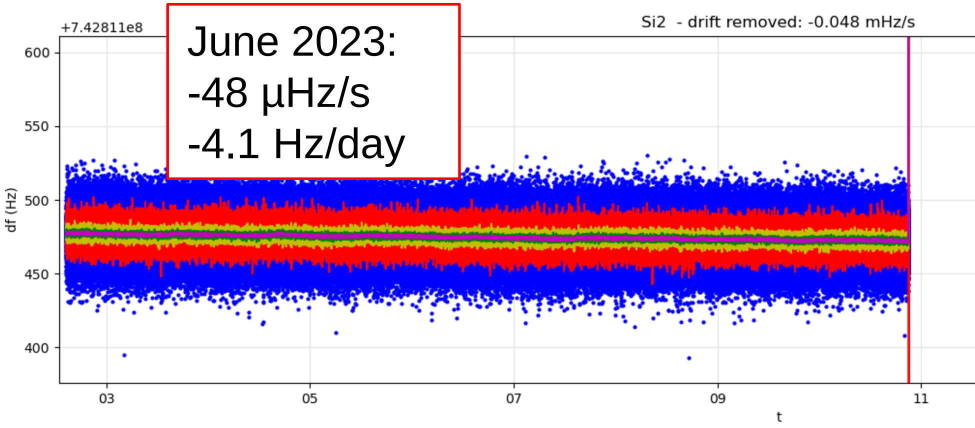
Long-term drift



Long-term frequency drift
~ 4 Hz/day - 2.4×10^{-19}/s

about 10^3 times smaller than ultralow expansion materials at room temperature

less than Hubble constant
$H_0 = 2.27 \times 10^{-18}$/s



Parasitic Etalons

light is fed back to cavity mode with parasitic reflectivity $R_\mathrm{p} = r_\mathrm{p}^2$

field changes mirror reflectivity (as seen from inside the cavity):

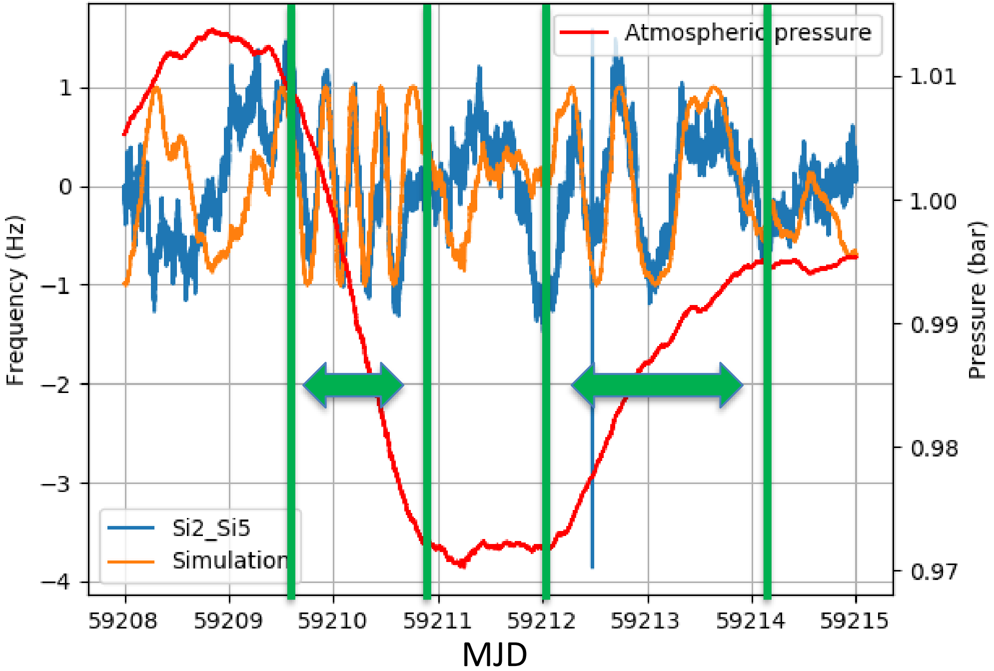
$$E_\mathrm{r} = rE_\mathrm{in}$$

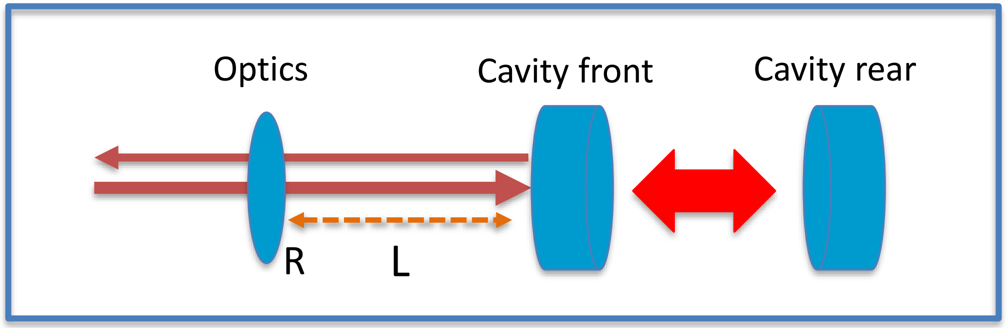
to

$$E_\mathrm{r} = (r + tr_\mathrm{p}te^{i\phi})E_\mathrm{in}$$

$$\delta\phi = t^2 r_\mathrm{p}\,\sin(\phi)$$

$$\delta\nu \approx \frac{1}{2} r_\mathrm{p}\,\sin(\phi)\Delta\nu_\mathrm{FWHM}$$





Periodic frequency fluctuation related to air pressure

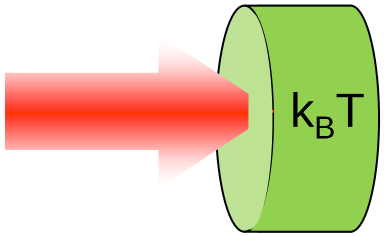
Parastic etalons

Model: $\Delta p \rightarrow \Delta n \rightarrow \Delta\phi \rightarrow \delta\nu$

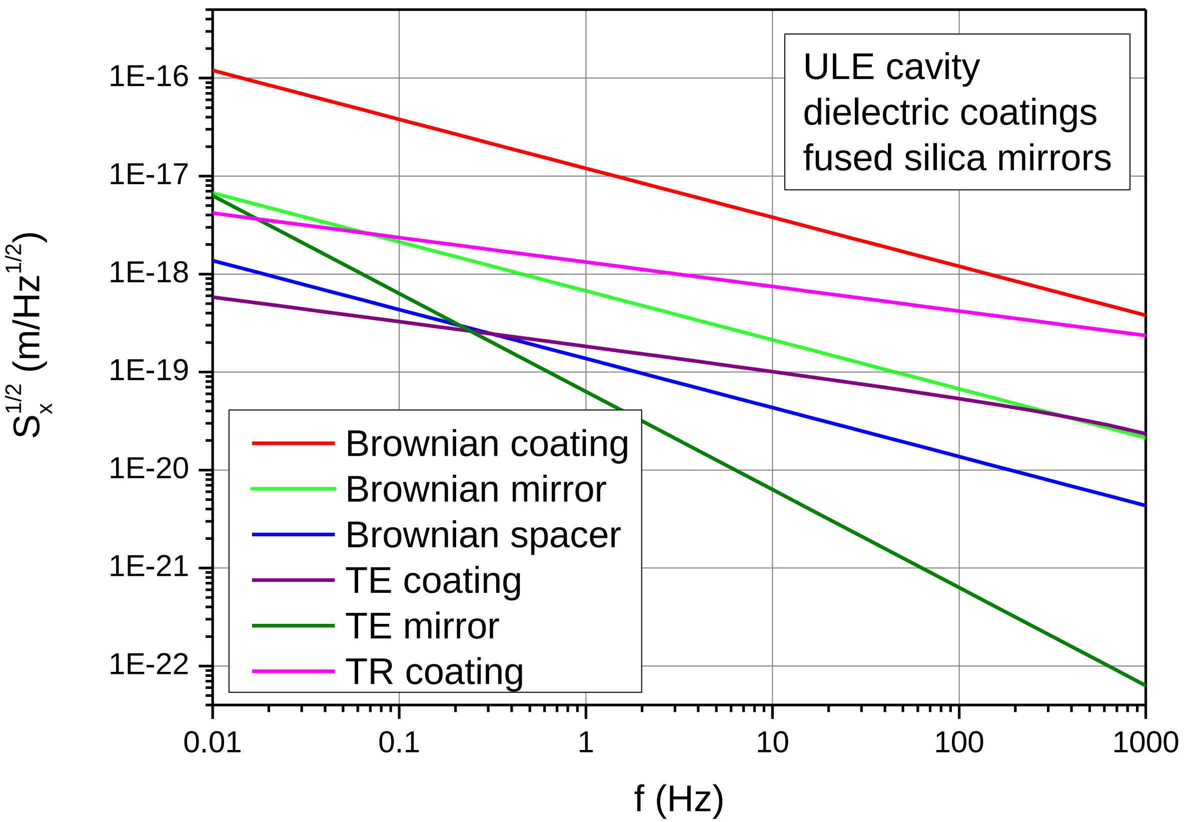
$R_p = 1.2 \times 10^{-6}$, L = 0.41 m

optimized: $R_p < 5 \times 10^{-8}$

Thermal-noise Zoo



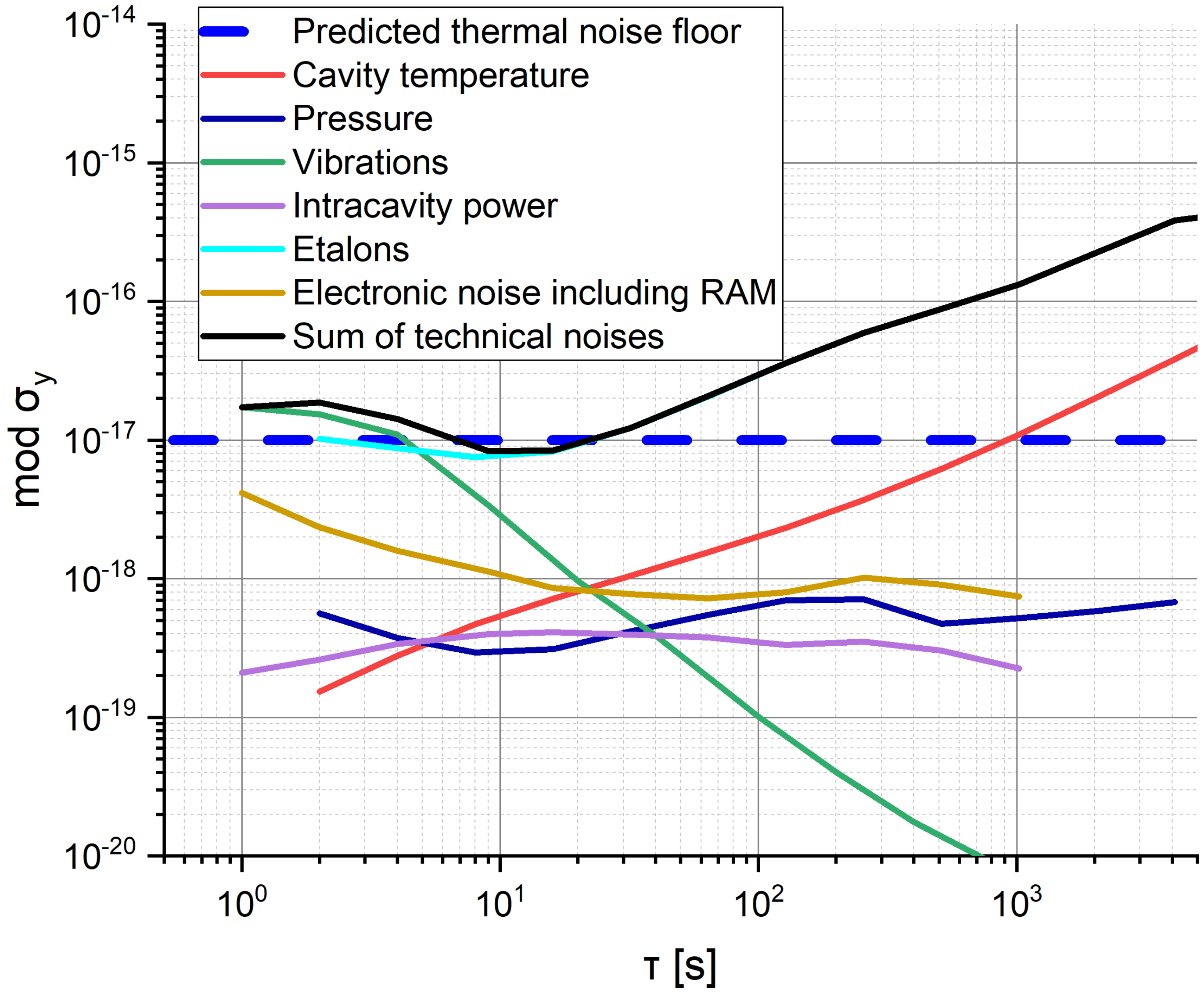
- **Brownian (thermal) noise:** internal friction in coating, mirror, spacer
- **Thermo-elastic:** thermal expansion from temperature fluctuations
- **Thermo-refractive:** refractive index change from temperature fluctuations
- many more ...



Thermal noise $S_x(f)$ for fused silica mirror with SiO_2 / Ta_2O_5 coating at 300 K
λ = 1542 nm, w = 400 µm

M. L. Gorodetsky
Thermal noises and noise compensation in high-reflection multilayer coating,
Phys. Lett. A **372**, 6813-6822 (2008)

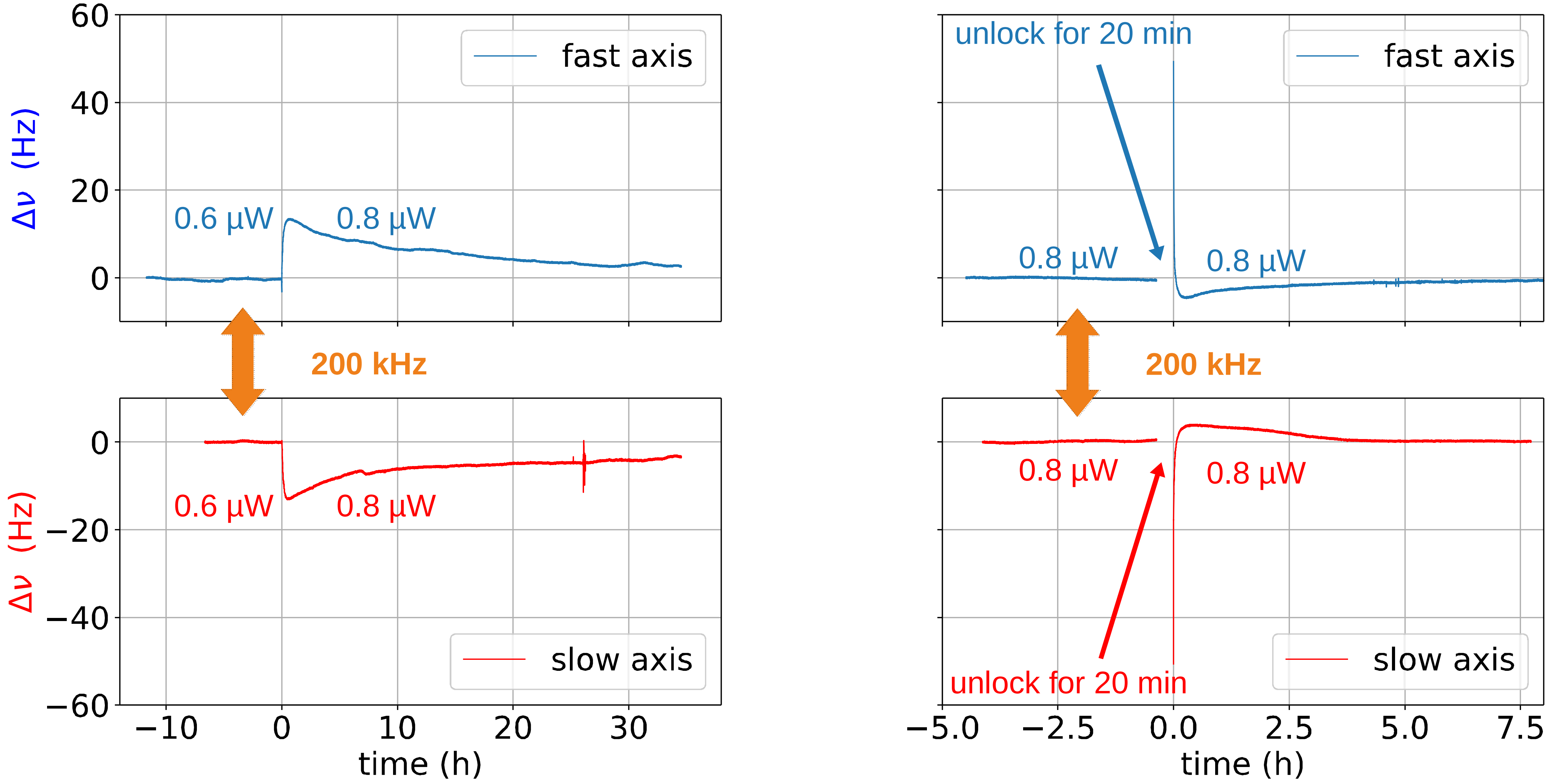
Evaluation of technical noise



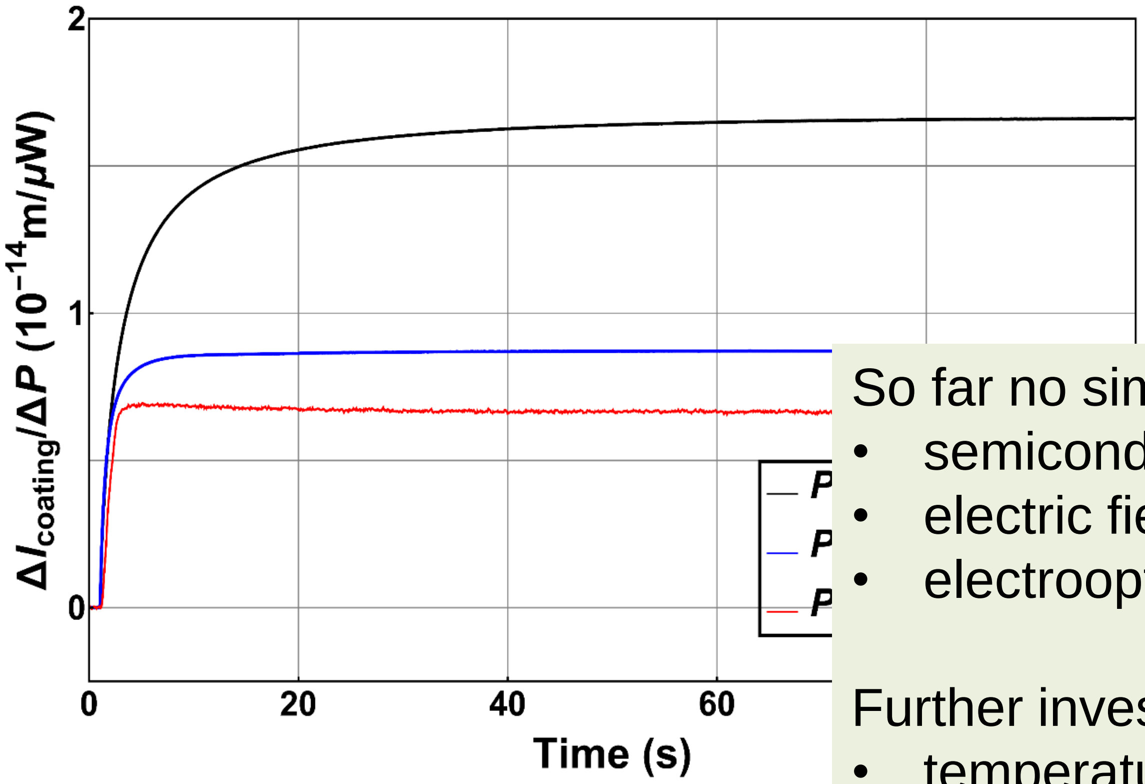
All technical noise sources are suppressed to below 10^{-17}

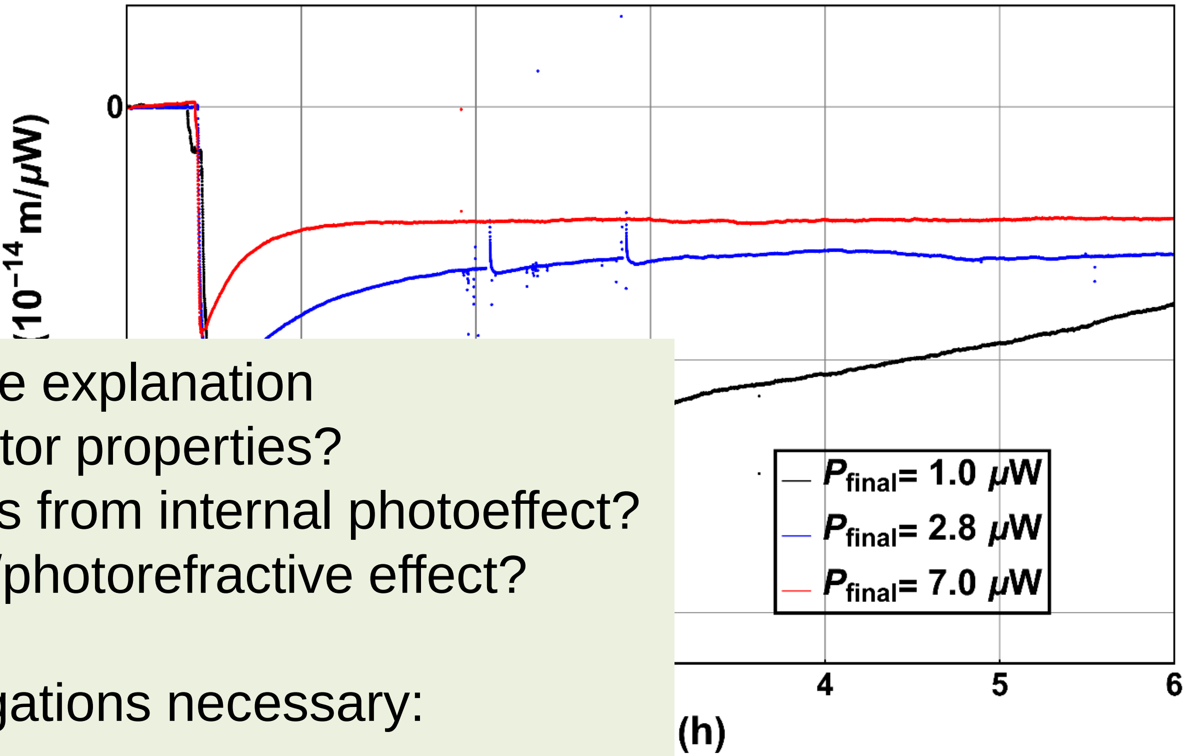
- residual amplitude modulation (RAM)
- vibrations with additional low frequency servo loop
- ….

AlGaAs coating - transient response



Transient response – power dependence





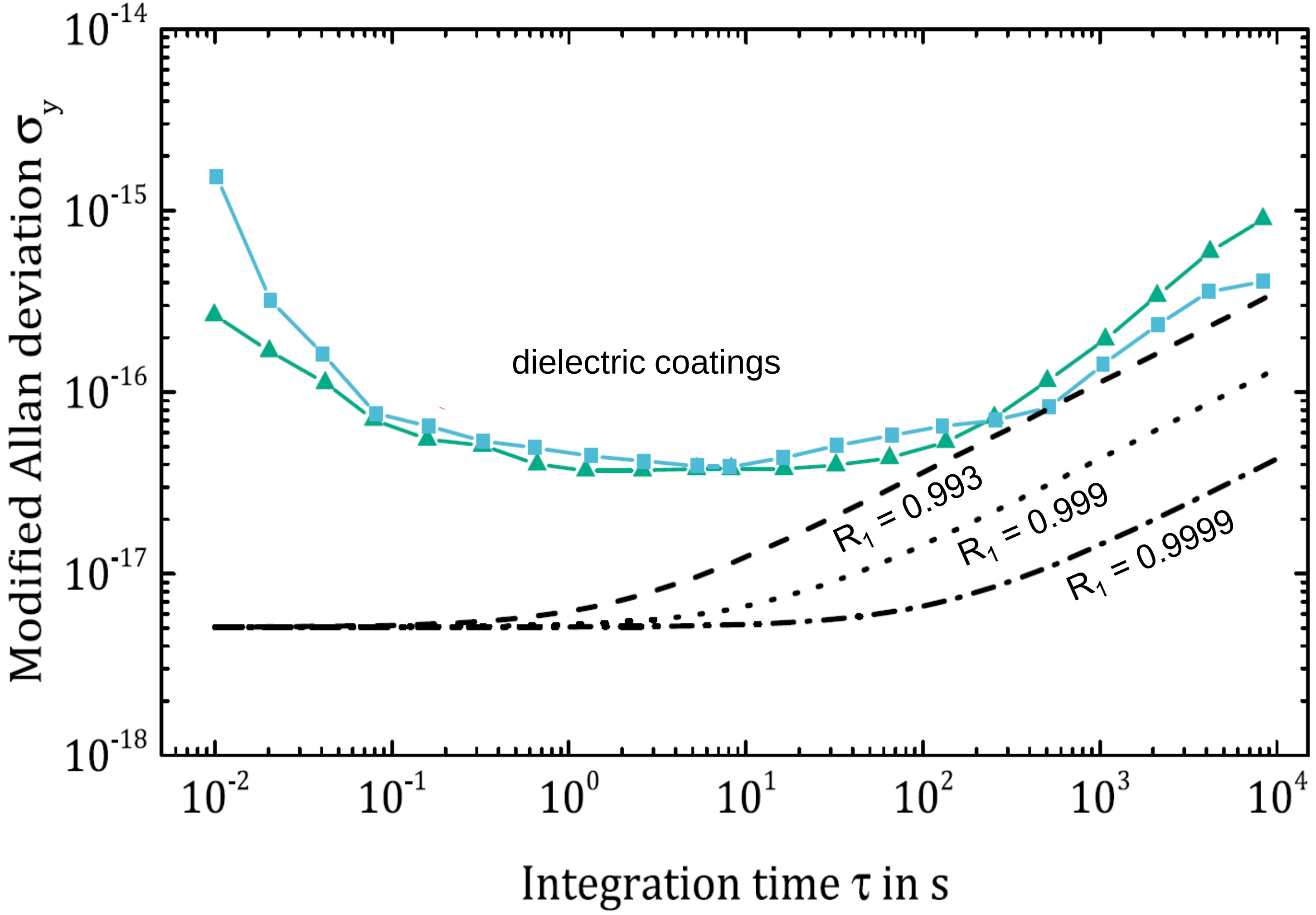
298 K

So far no simple explanation
- semiconductor properties?
- electric fields from internal photoeffect?
- electrooptic/photorefractive effect?

Further investigations necessary:
- temperature
- spatial correlations
- relation to noise

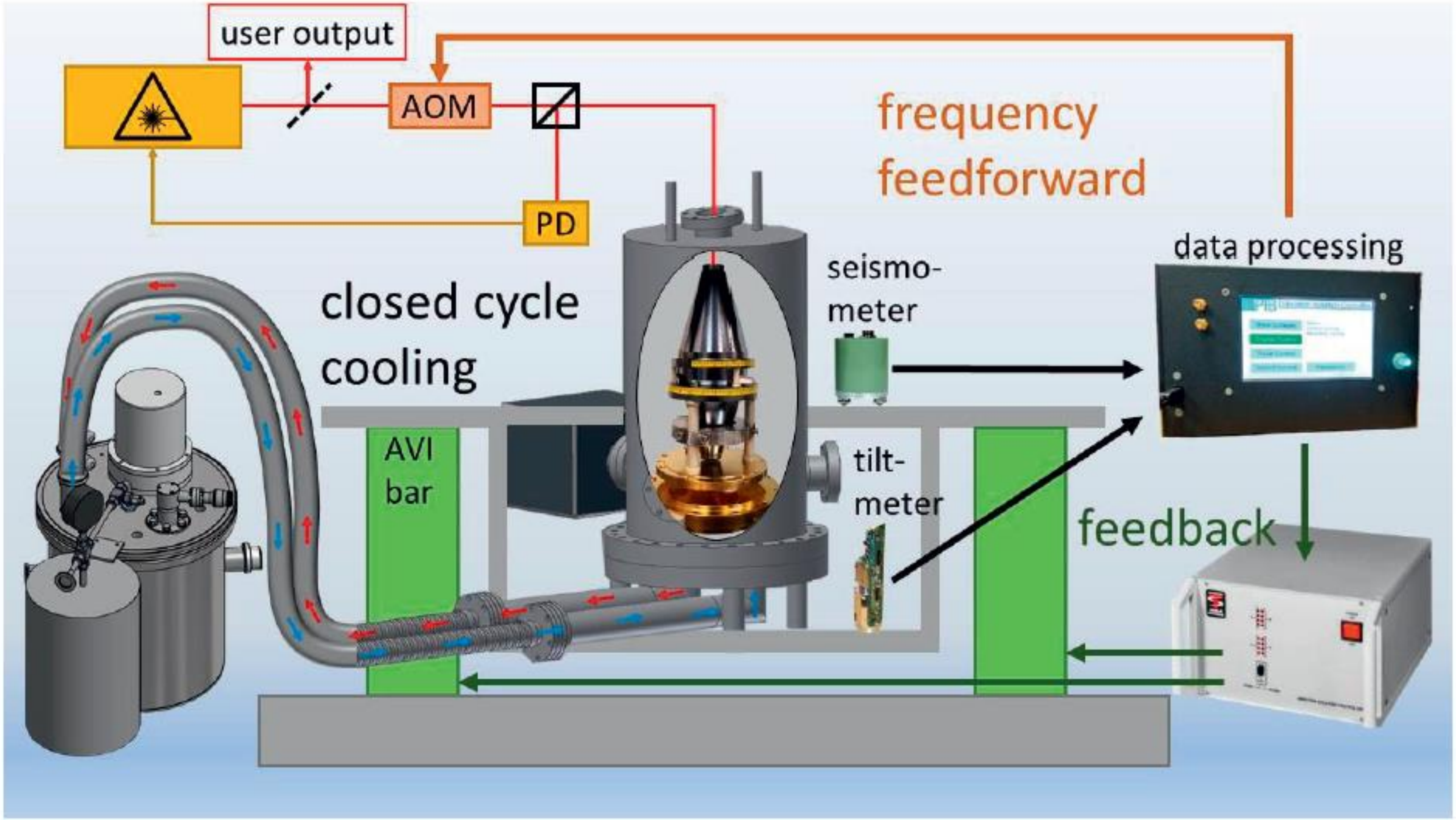
Compound Mirror Performance

- Ultrahigh reflectivity: combine grating $R_1 \approx$ 99.9 % + rear dielectric mirror $R_2 \approx 99.9$ %
- Thermal noise mostly determined by silicon grating - $\sigma_y = 4\times10^{-18}$ @ 124 K possible



J. Dickmann and S. Kroker,
Phys. Rev. D **98**, 082003 (2018)

Improvements on Silicon Systems



Goals:

Stand-alone system (towards field use)

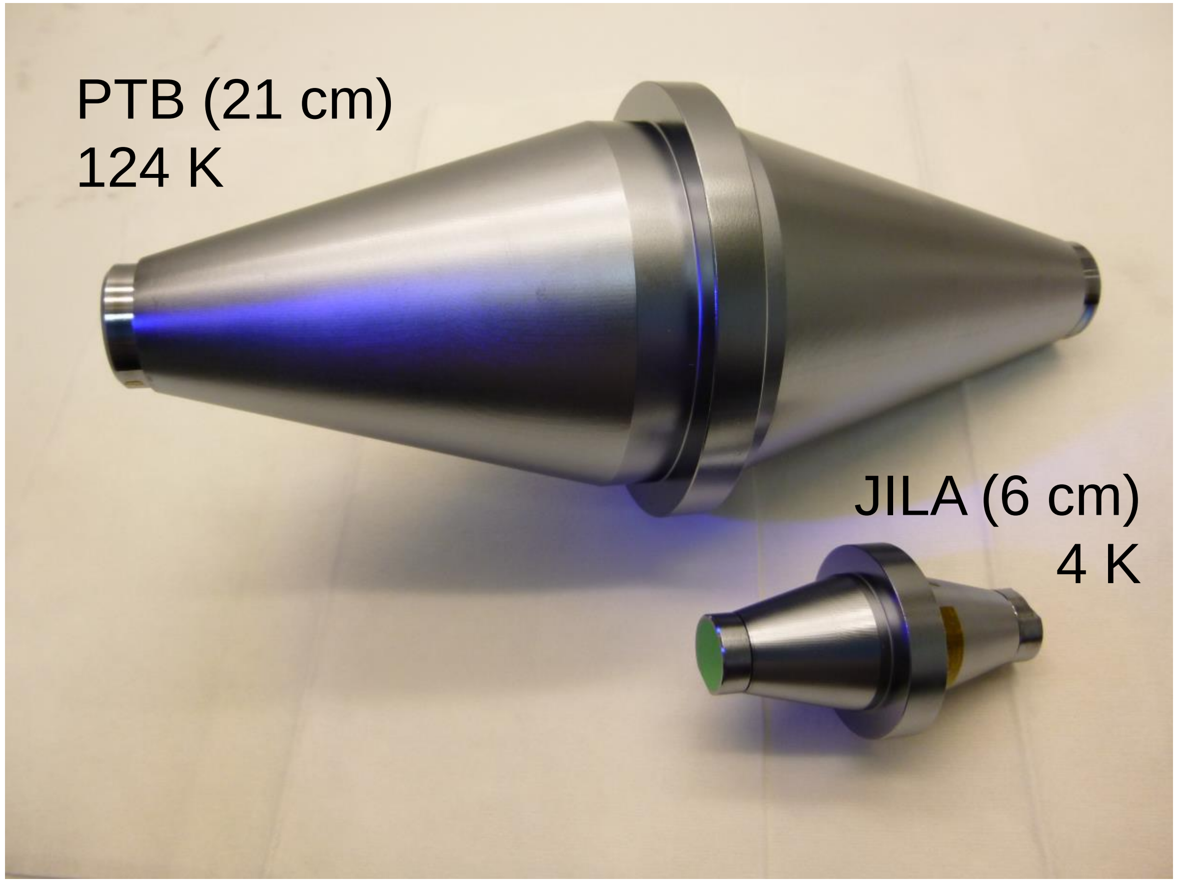
Reduce impact of by vibrations by additional feedback on AVI and feedforward technique (WP2)

He-based closed cycle cryostat

- Cryo system from TransMIT arrived at PTB
- Check cooling performance and vibration level on test system.
- Replace LN2-based cooling system of Si5 (124 K, 21 cm silicon, AlGaAs coatings)

TransMIT

Crystaline AlGaAs / GaAs multilayer

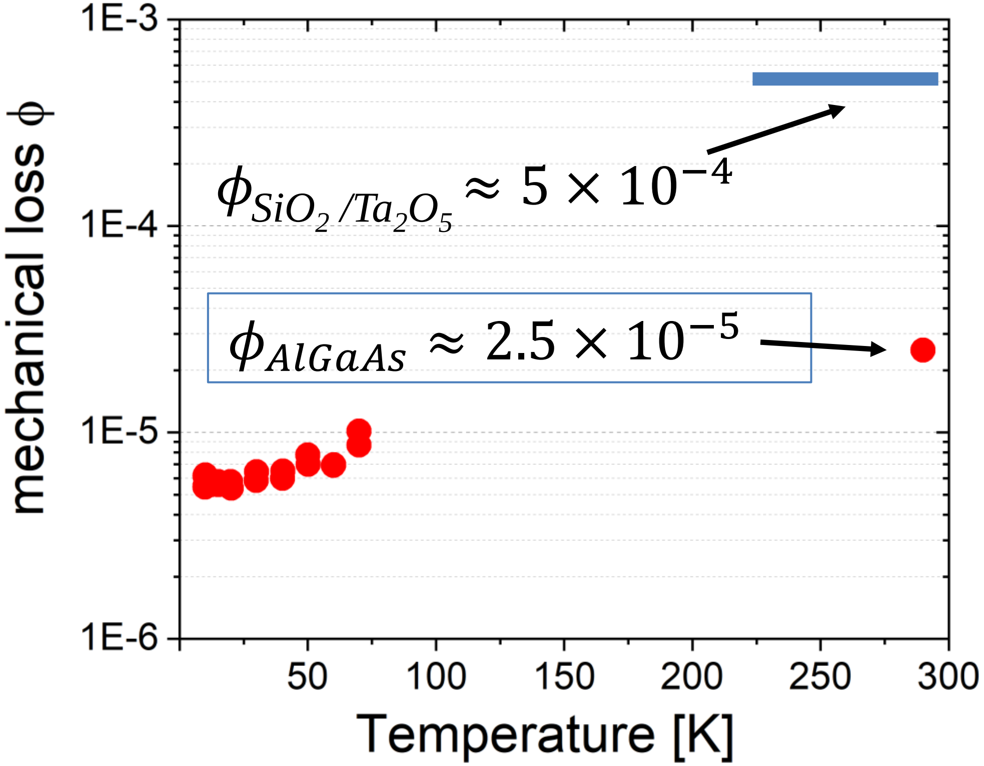


F = 400 000
$\delta\nu$ = 1.8 kHz

F = 290 000
$\delta\nu$ = 8.6 kHz

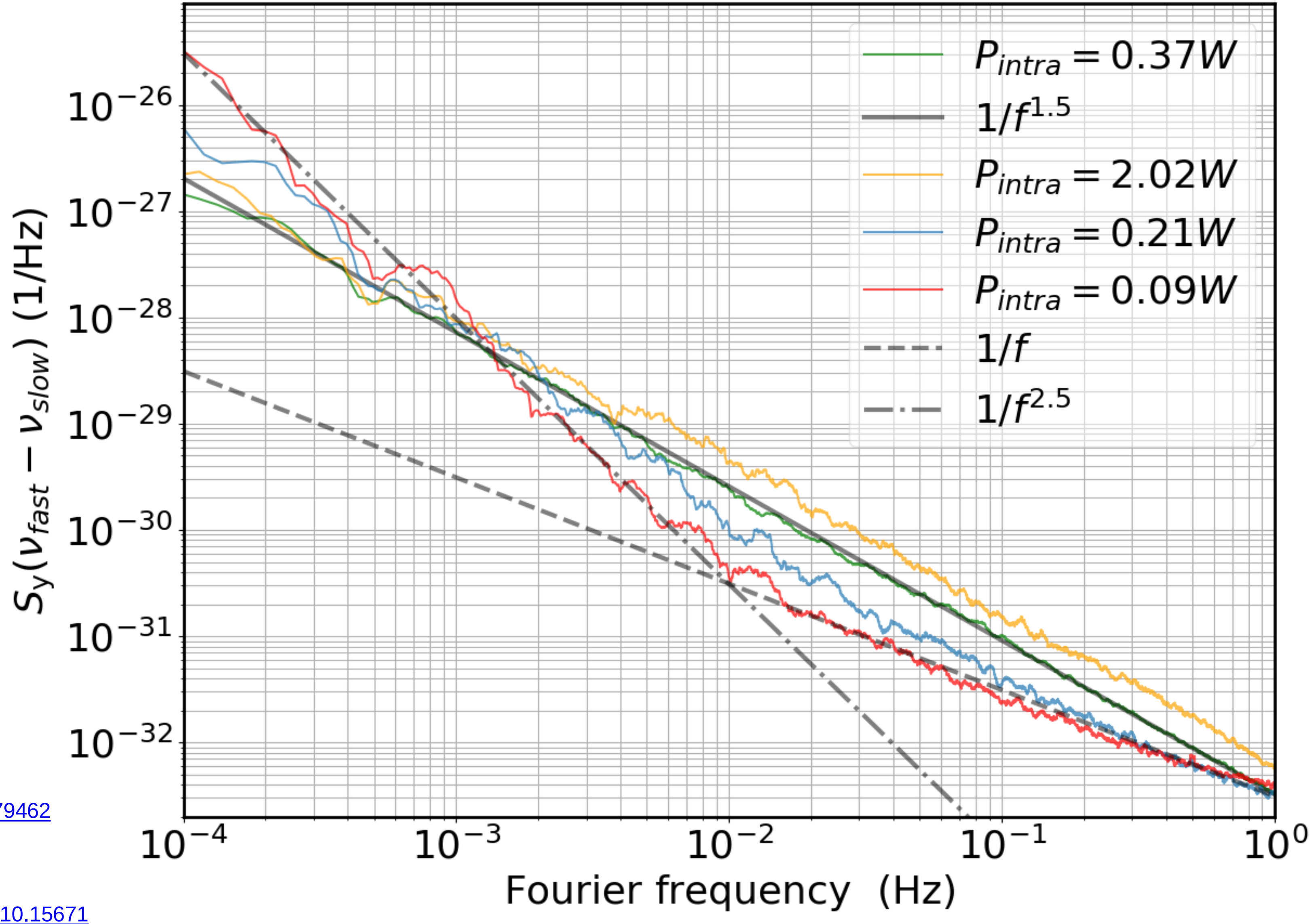
- Low optical absorption and scatter (A+S < 16 ppm)
- lower mechanical loss than dielectric coatings

→ reduced Brownian Thermal Noise



G. Cole *et al.*, Nat. Phot. **7** (2013) 644, Winkler *et al.*, Optica, **8** (2021) 686, G. Cole, *Proc. SPIE, (2012) 8458*, 845807

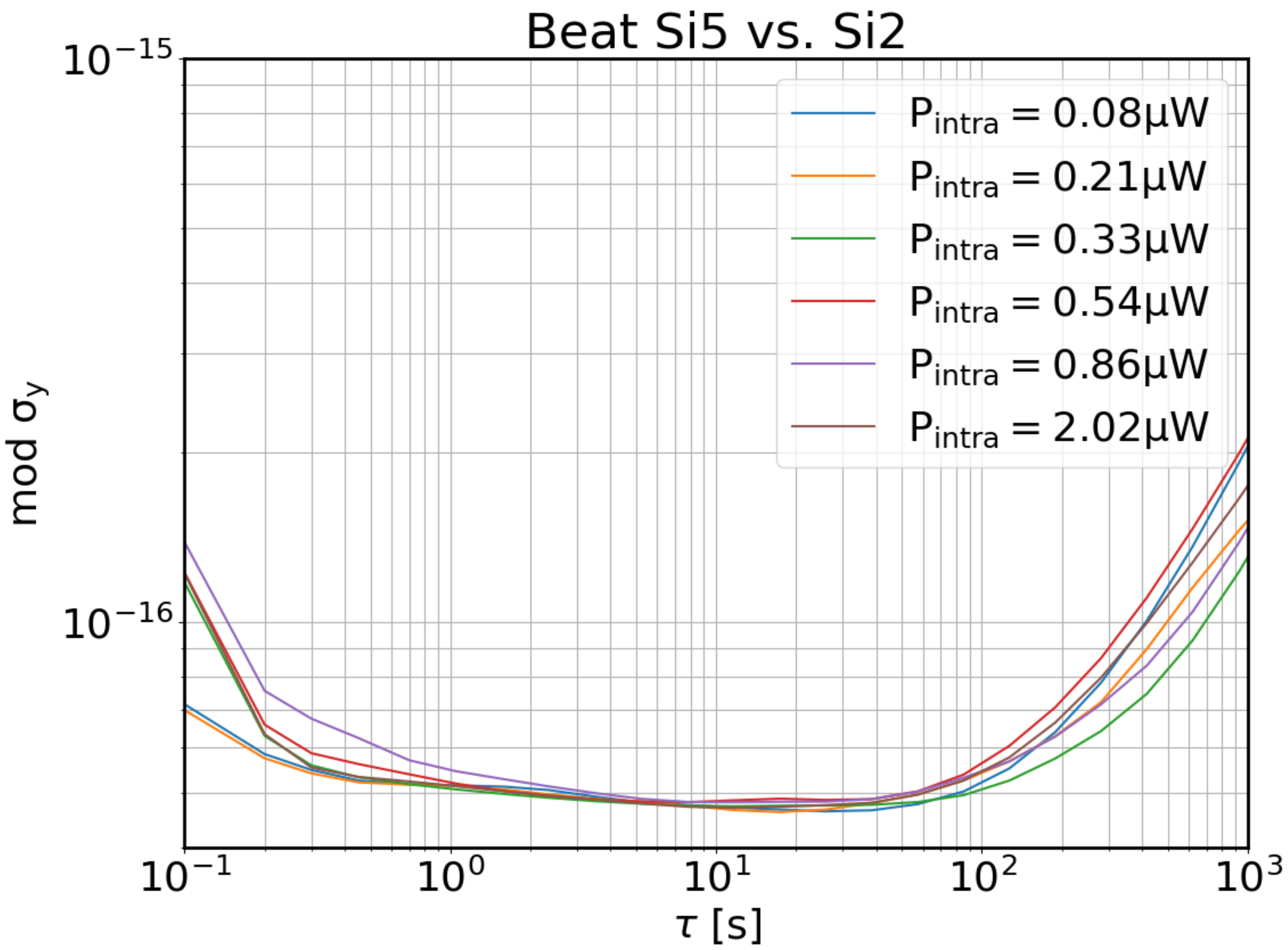
Birefringent noise – power dependence



D. Kedar et al.
Optica **10**, 464 (2023)
https://doi.org/10.1364/OPTICA.479462

J. Yu, et. al,,
arXiv:2210.15671 [physics.optics]
https://doi.org/10.48550/ARXIV.2210.15671

Excess noise



The excess noise:

- Long correlation length
- 1/f slope in PSD
- Independent of optical power

Change of splitting by intracavity power