Properties of silicon and coatings for a low-temperature detector

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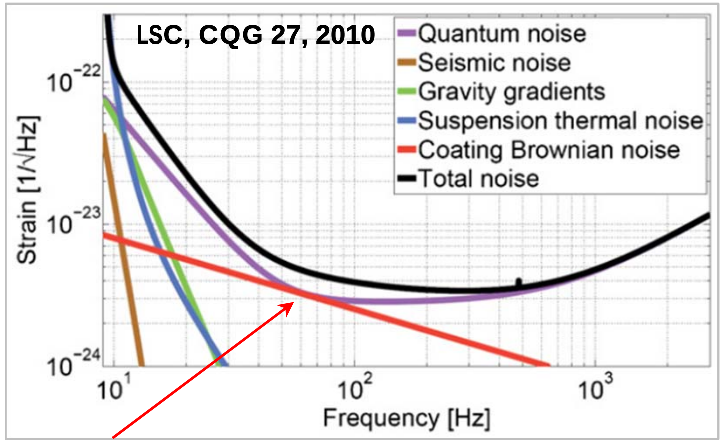
GWADW – Elba, May 24th 2013

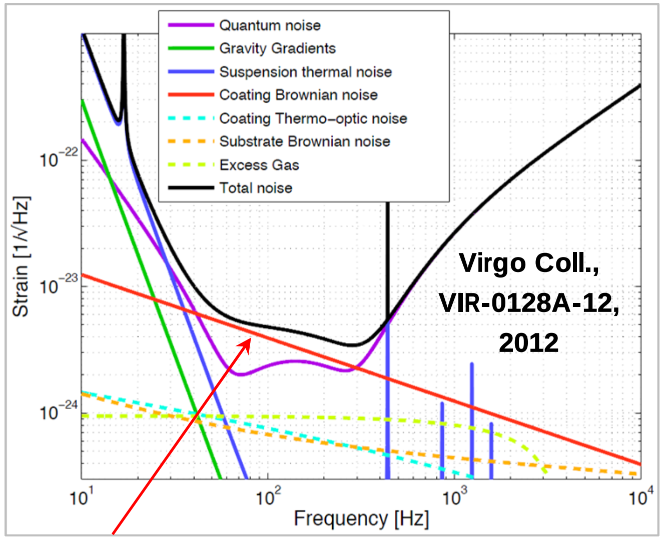
Outline

- Introduction
- Experimental setups
- Results
- Summary and conclusions

Motivation

future gravitational-wave (GW) interferometerswillbelimited by coating thermal noise

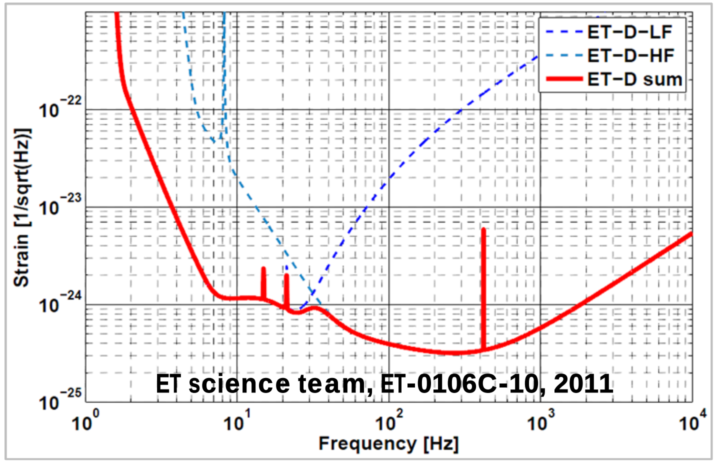




a solution: cryogenic GW detectors → R&D on substrates and coatings

→ low-temperaturecharacterization of
- substrate optical absorption α(T)
- coating mechanical lossΦ_c(T)

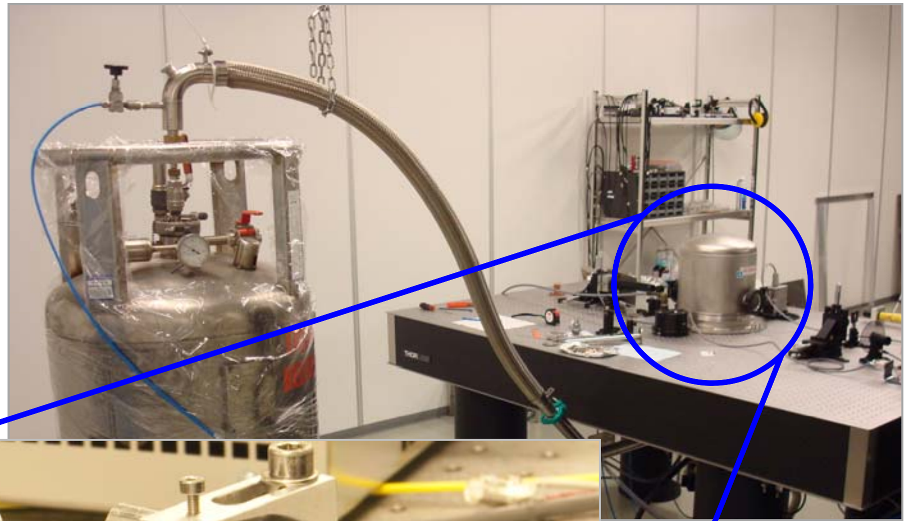
→ best cryogenic resonators

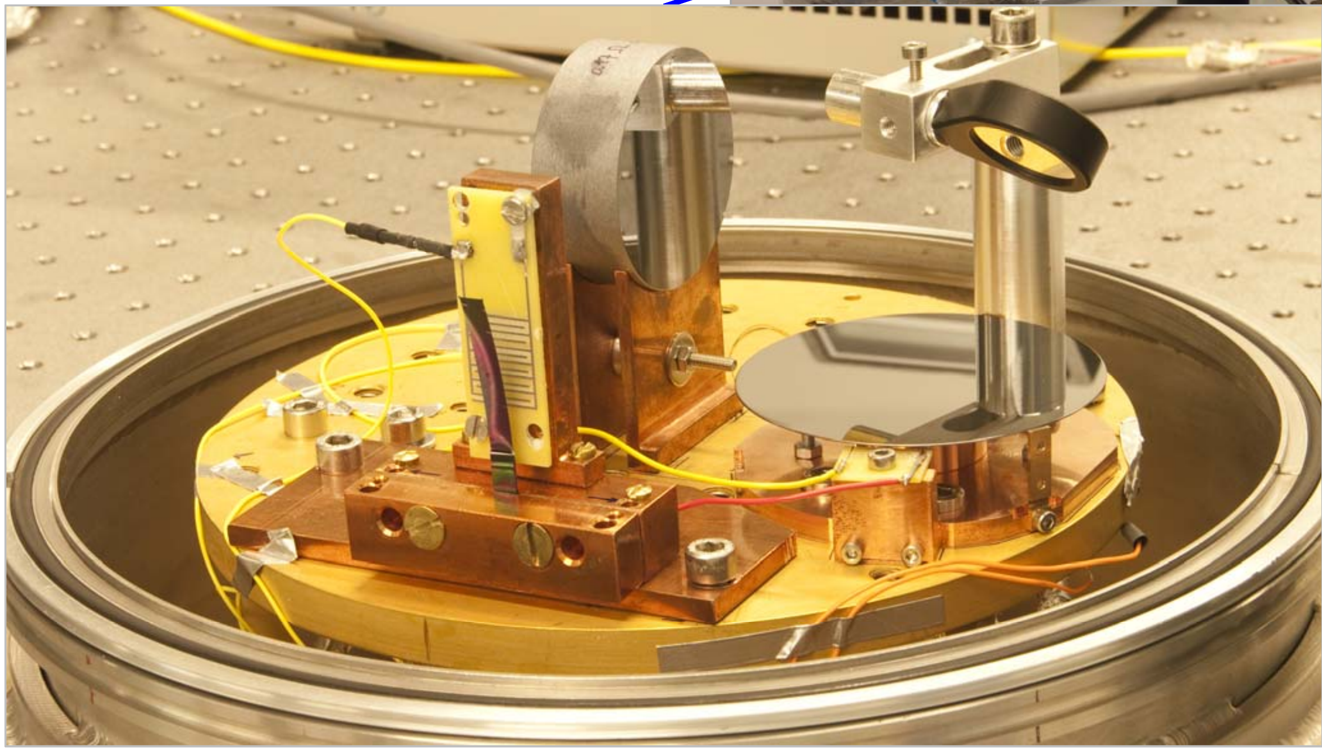


Experimental setup

continuous-flow cryostat:
- liquid He, T < 10 K

3 experiments:
- substrate absorption
- coating loss: disks [GeNS]
  cantilever blades





Substrate optical absorption

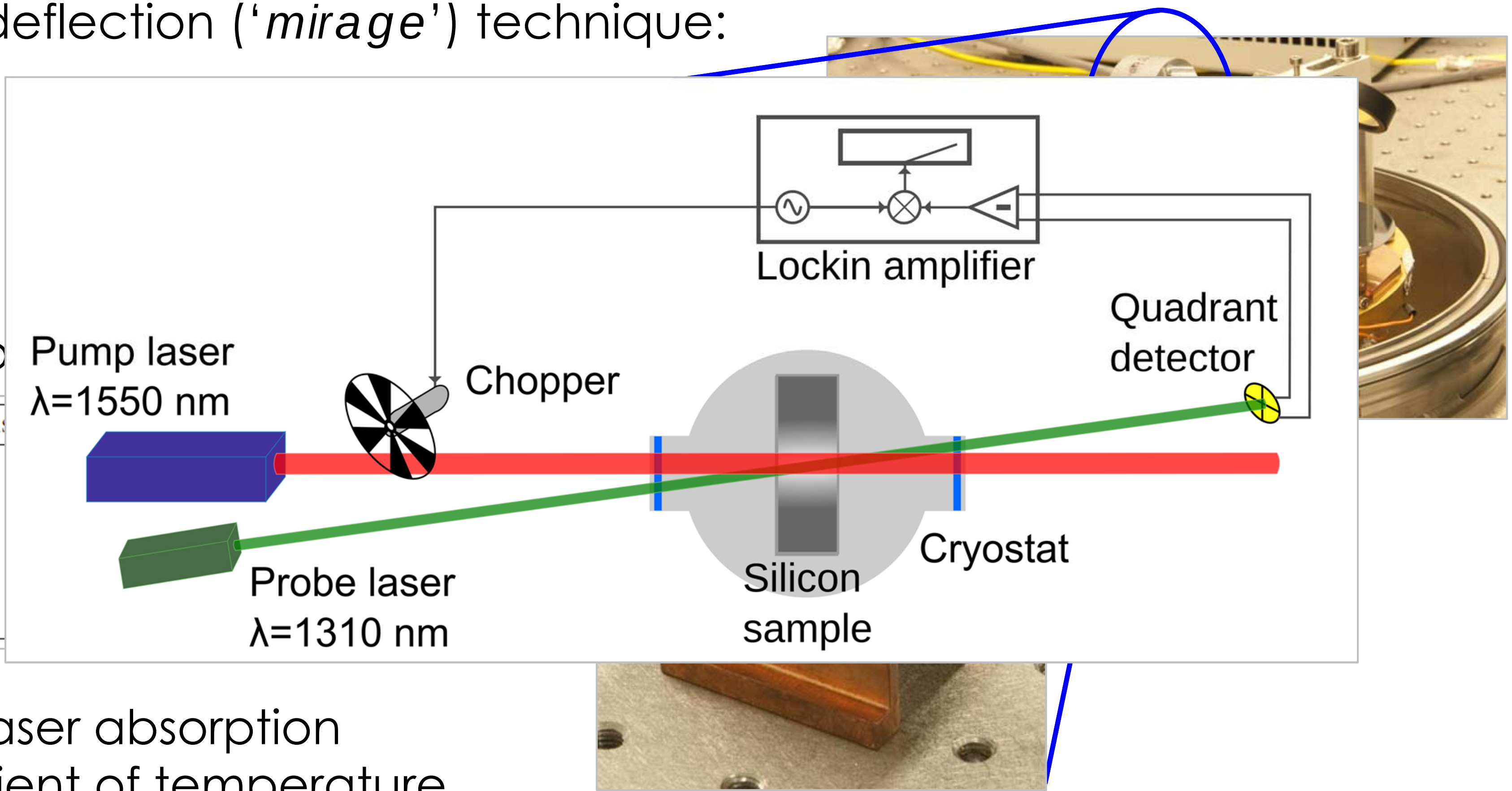
[see also previous talk by J. Komma]

Measurements

photo-deflection (‘*mirage*’) technique:

all n-do

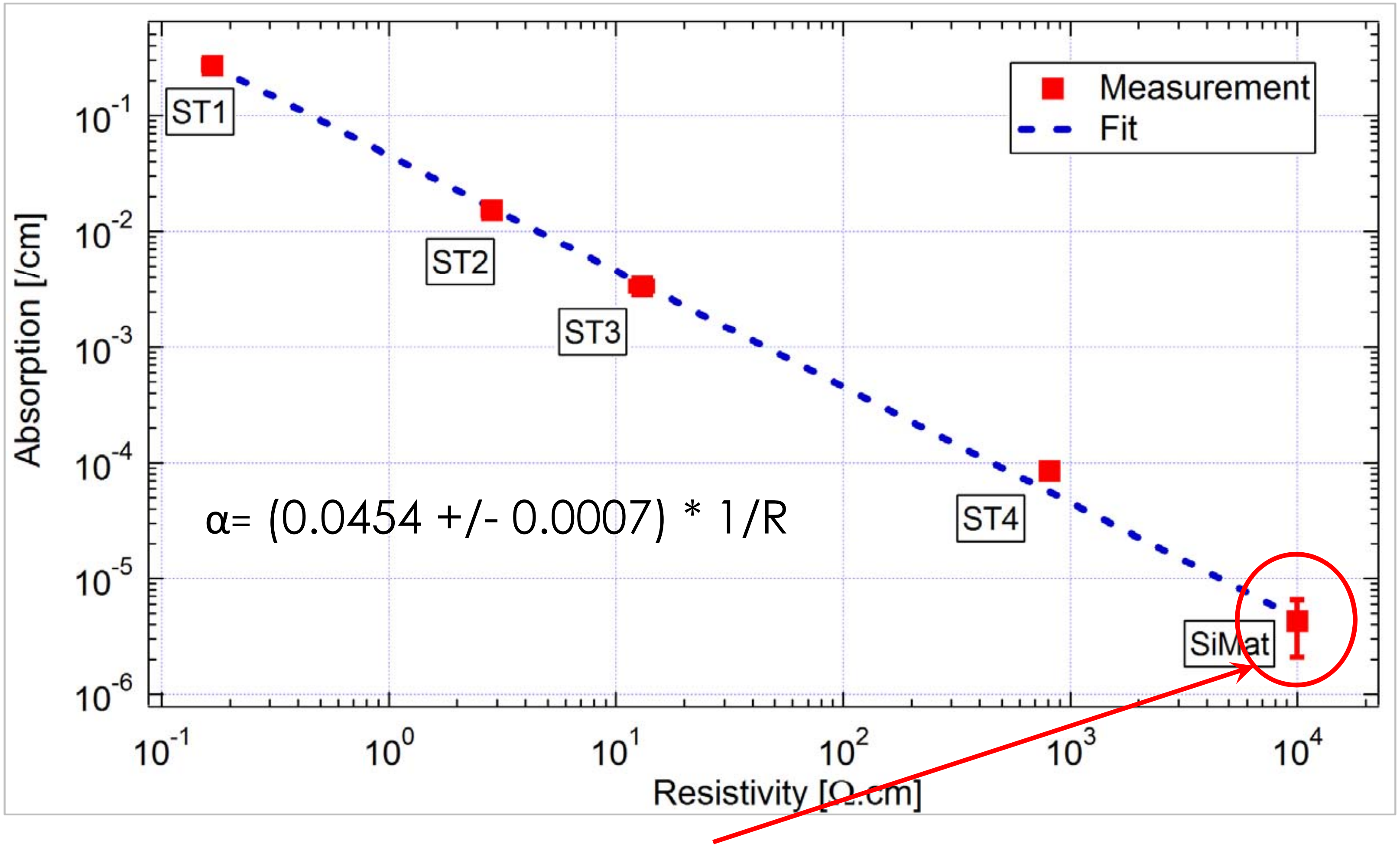
Name	Resi
ST1	
ST2	
ST3	
ST4	
SiMat	



pump laser absorption
→ gradient of temperature
→ gradient of refractive index n(T)
→ probe laser deflection

very accurate but indirect measurement → calibration → ppm/cm

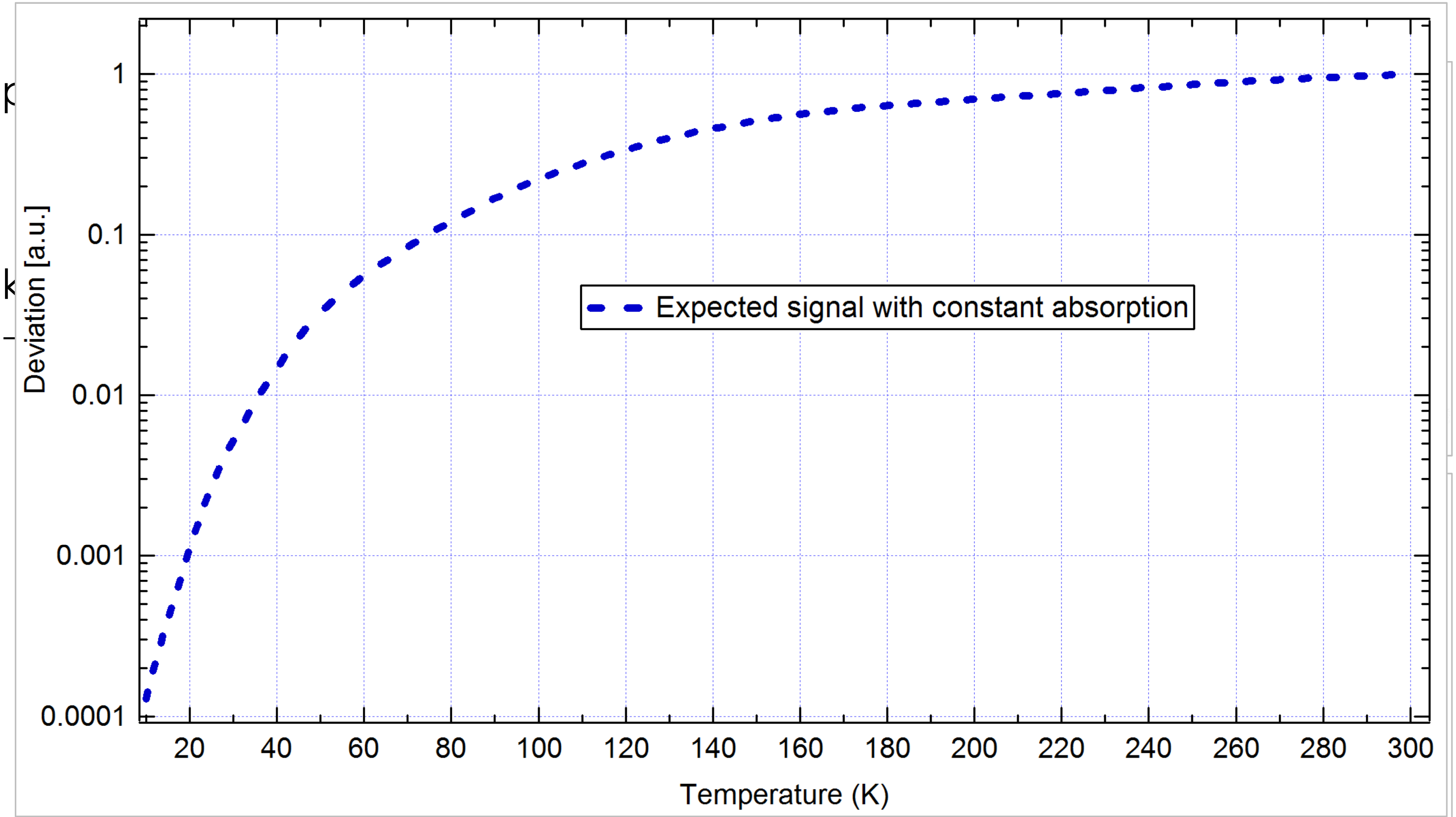
Room-temperature results



α= 4.3 ppm/cm: lowest Si absorption measured so far

more details: J. Degallaix & al., accepted for publication on Optics Letters

Low temperature - theory



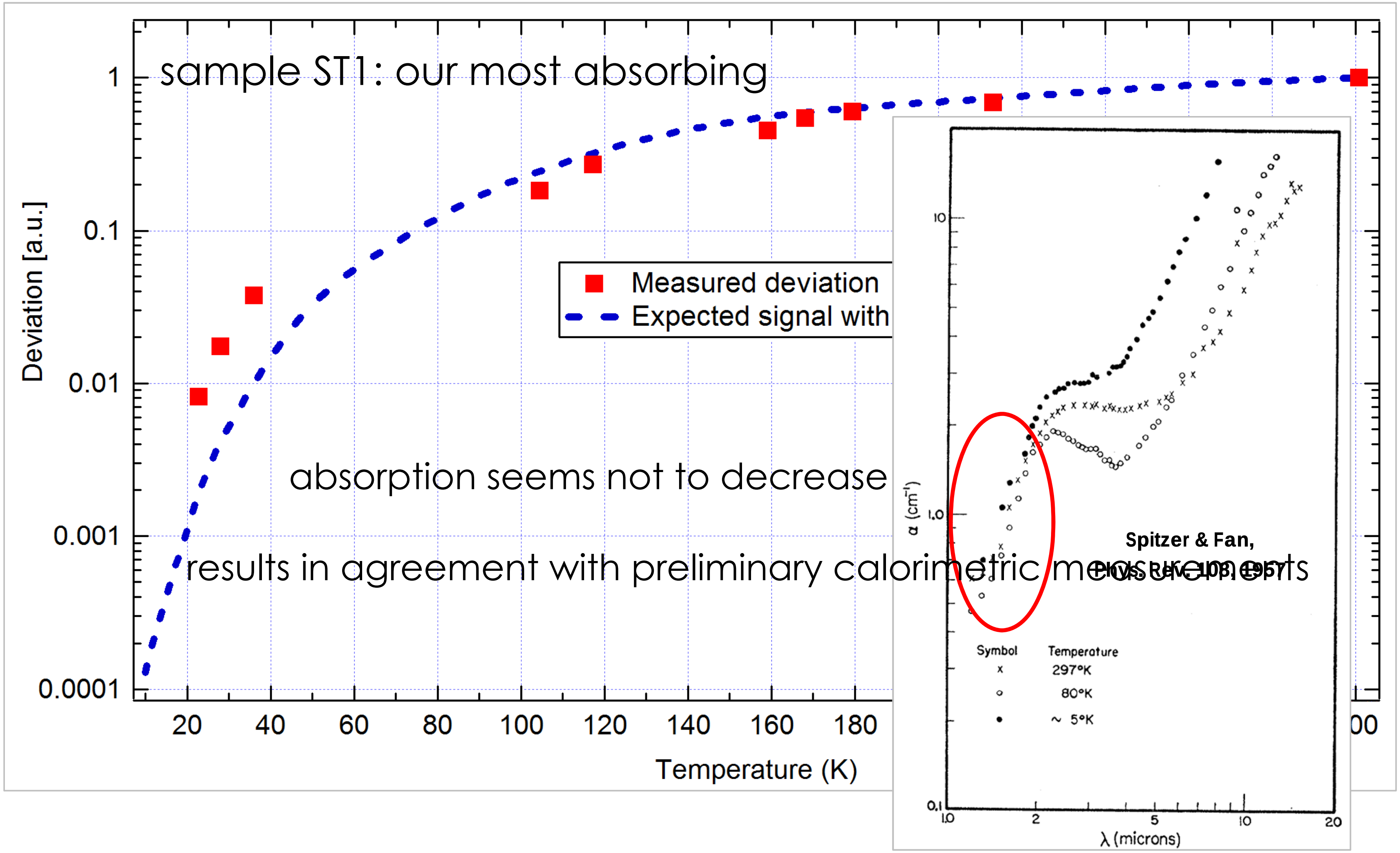
temperature (K)

Komma & al., Appl. Phys. Lett. 101, 2012

0 50 100 150 200 250 300

Temperature [K]

Low-temperature results



sample ST1: our most absorbing

absorption seems not to decrease

results in agreement with preliminary calorimetric measurements

Coating mechanical loss

– disks –

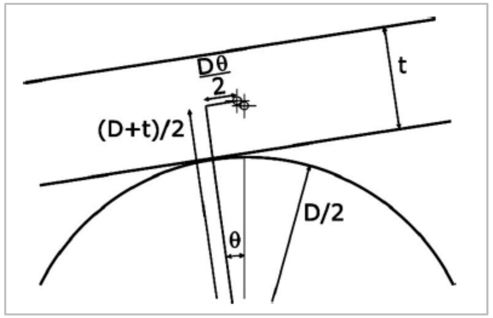
[see also R. Flaminio's talk of last wednesday]

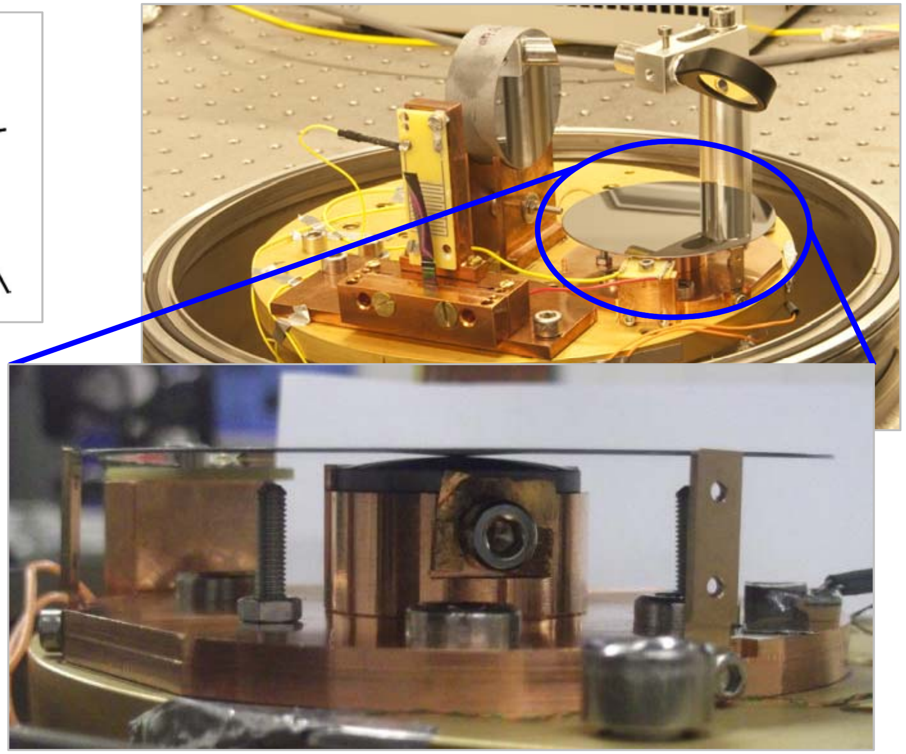
Gentle Nodal Suspension – GeNS

system developed in Florence for Q measurements on thin disks

Cesarini& al., Rev. Sci. Instrum. 80, 2009

Cesarini& al., Class. Quantum Grav. 27, 2010





1”-silicon lens, 63mm radius of curvature
3”-diameter, 460μm-thick silicon disk
contact point position accuracy < 10μm

PROs:
- easy procurement of samples
- higher mode density than 1D resonators
- high repeatability of measurements
  Q and frequency
- suspension point displaced easily

CONs:
- drum mode cannot be excited
- excess loss for modes rolling over the sphere

Measurements

ringdown technique [seealso P. Puppo's talk]:

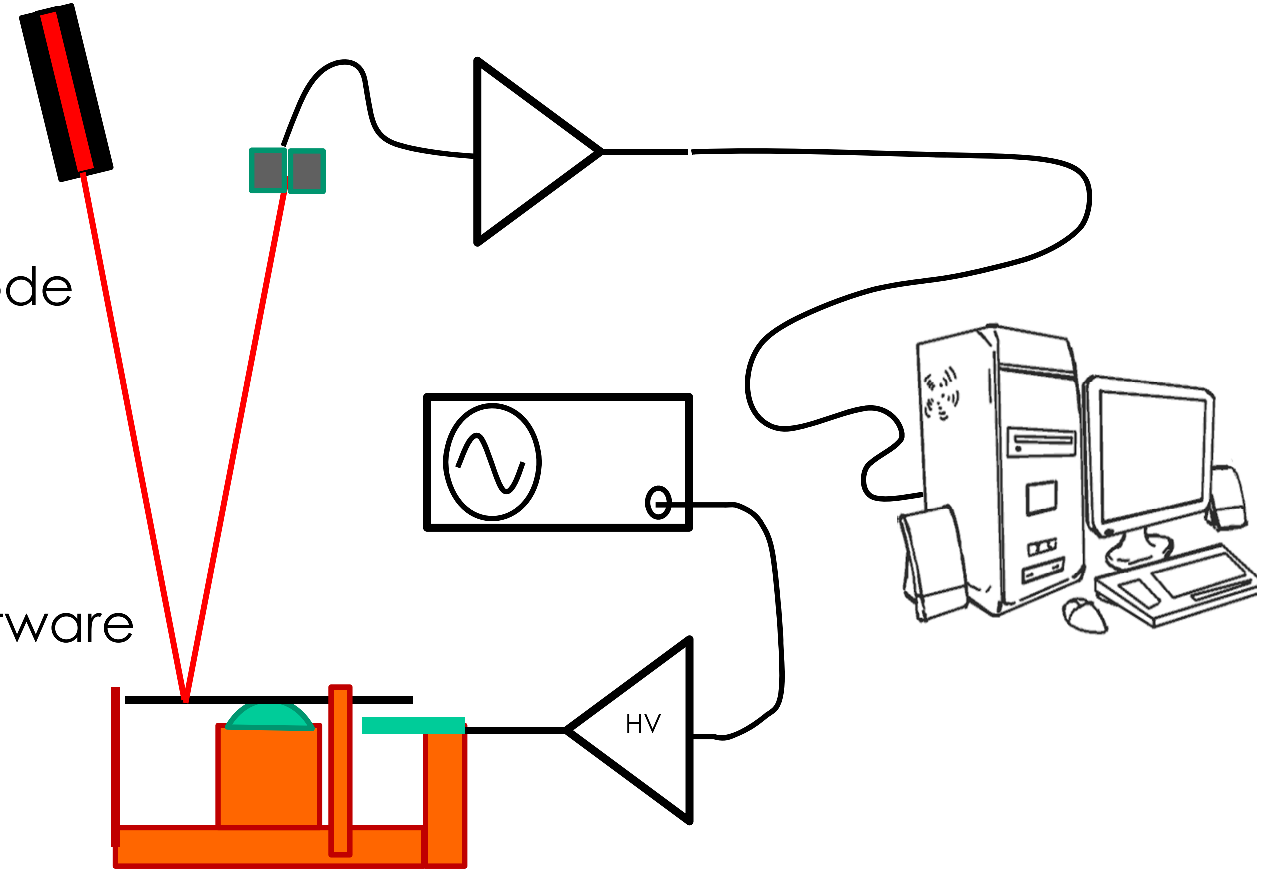
1.electrostatic excitation
2. free ringdown

vibration readout:

•optical lever
• quadrant photodiode

data acquisition:

•LabVIEW-based software



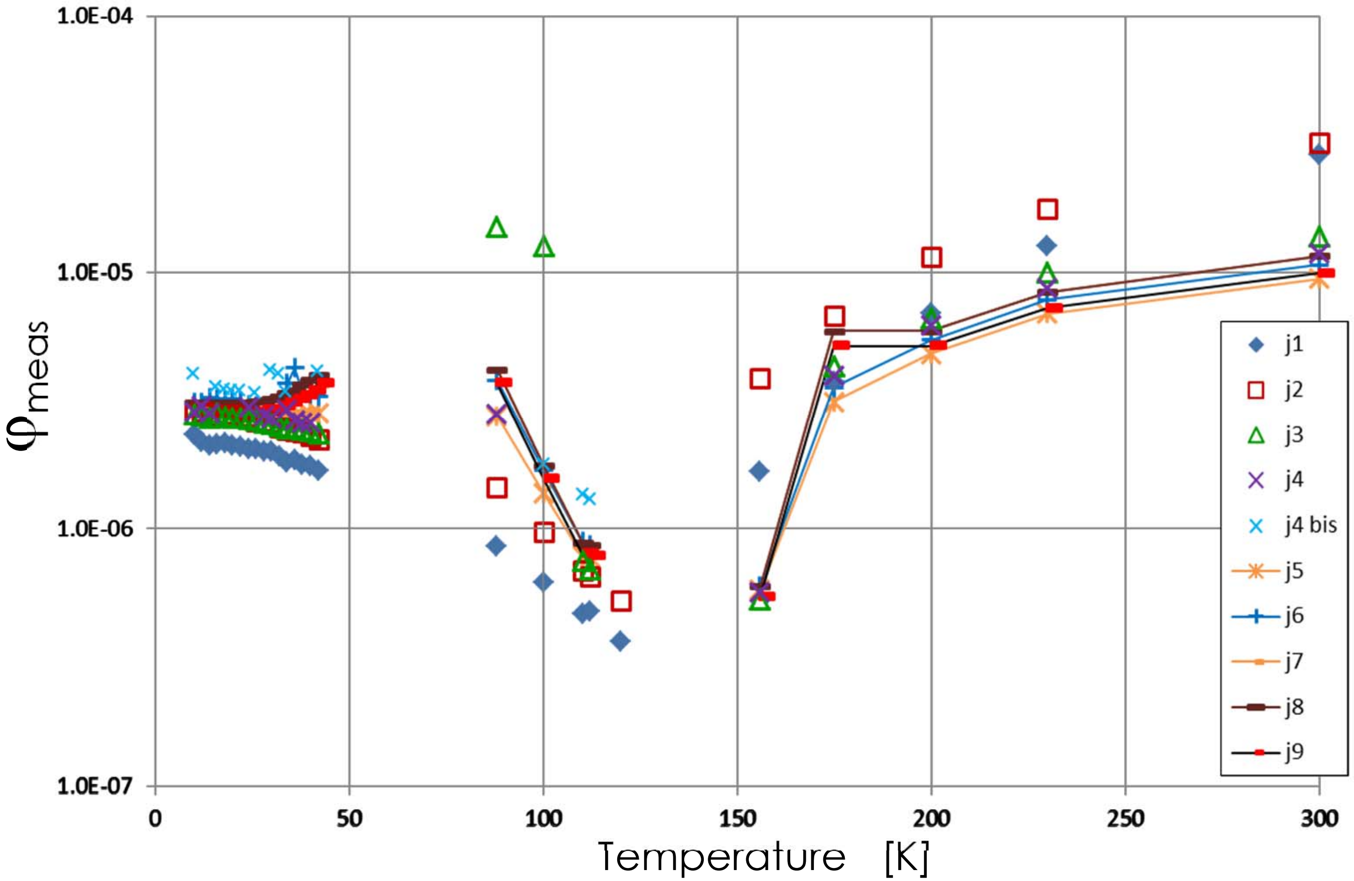
Results

raw data of sample W13006

• substrate: 460μm-thick, 3” diameter, <100>-silicon wafer

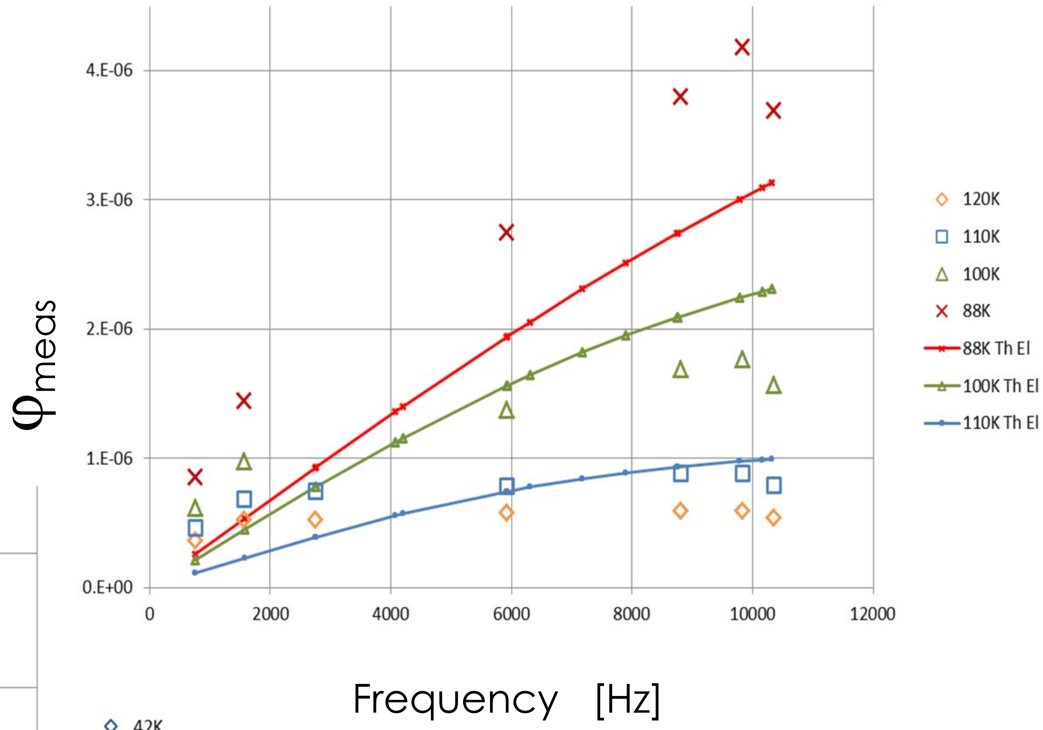
• coating: 2.5μm ion-beam sputtered silica annealed at 500° C

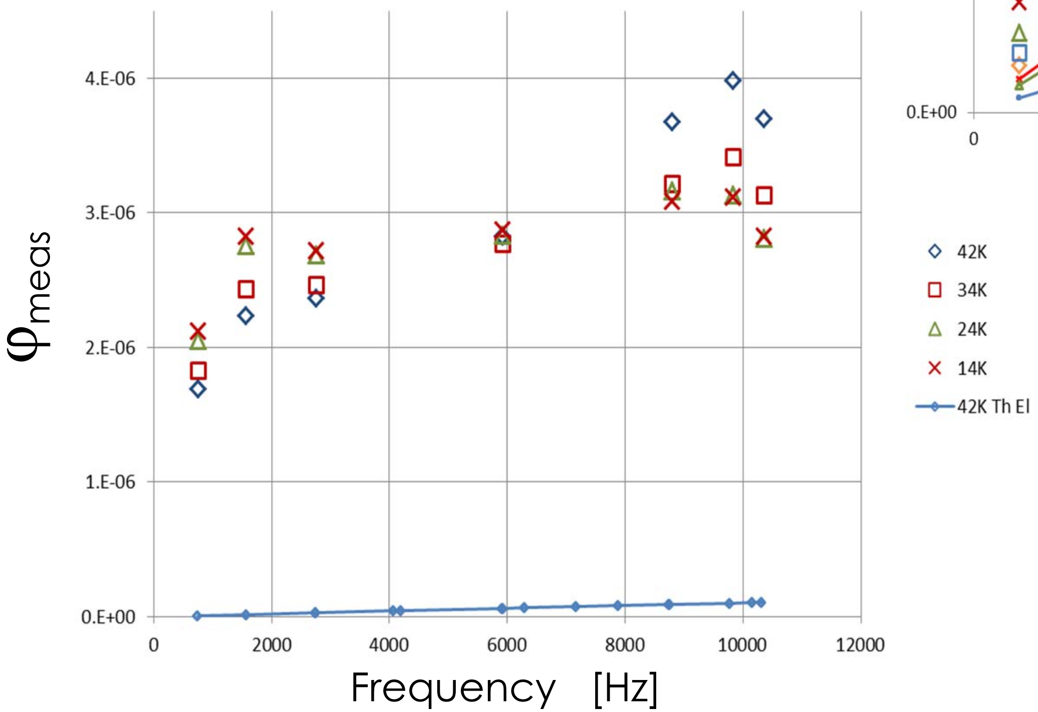
- several modes show beating
- temperature gaps due to the L-He ended prematurely
- measured temperature is the cold plate one



Frequency dependence

isotropic thermoelastic loss
partially explains
the measured loss





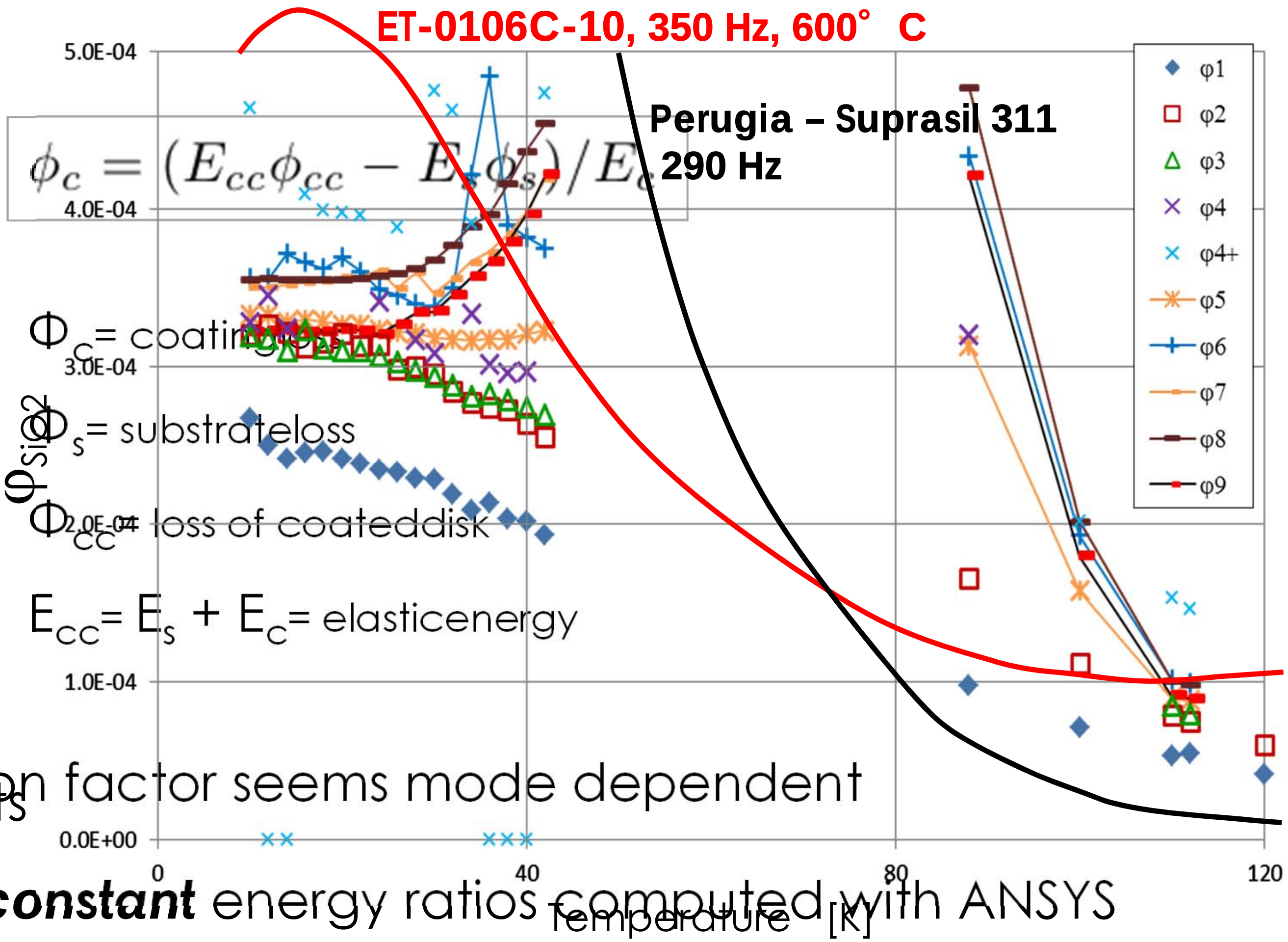
isotropic thermoelastic loss does not explain the measured loss

power-law behaviour below 42 K

to be confirmed by next measurements

Coating loss

	Mode #	f [Hz]
φ1	0,2	745
φ2	0,3	1560
φ3	0,4	2740
φ4	0,5	4180
φ5	0,6	5900
φ6	0,7	7890
φ7	1,4	8770
φ8	2,2	9800
φ9	0,8	10150



$$\phi_c = (E_{cc}\phi_{cc} - E_s\phi_s)/E_c$$

Φ_C = coating loss

Φ_S = substrate loss

Φ_{CC} = loss of coated disk

$E_{CC} = E_S + E_C$ = elastic energy

to be confirmed by further measurements

dilution factor seems mode dependent

usual analysis: ***constant*** energy ratios computed with ANSYS

Coating mechanical loss

– blades –

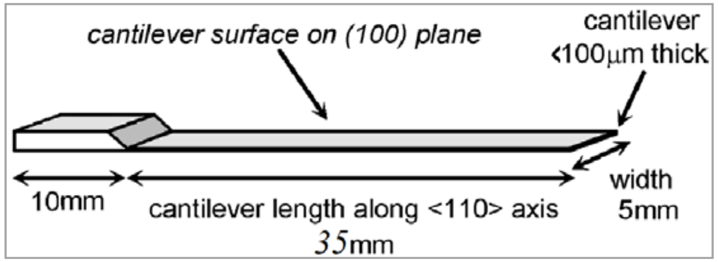
in collaboration with

K. Craig, L. Cunningham, M. Hart, J. Hennig, J. Hough,
I. MacLaren, I. W. Martin and S. Rowan
Institute for Gravitational Research (IGR), University of Glasgow

Samples

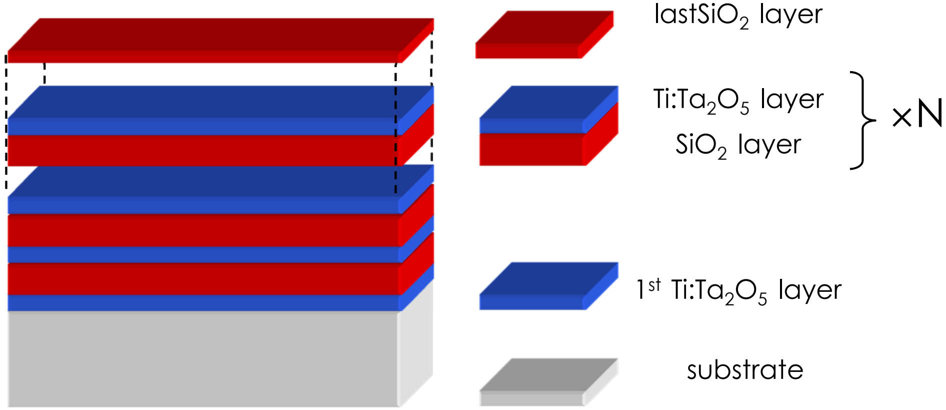
Silicon blades provided by IGR:

- low-loss at low temperature
- geometry→ enhance coating features



ion-beam sputtered optimized[*]coating designed & realized by LMA for aLIGO:

- thickness = 5.9 μm (cavity end mirrors)
- T < 5 ppm @ 1064 nm
- optical absorption < 0.5 ppm
- low loss at room temperature



4 nominally-identical Si samples:

- 1 uncoated control blade
- 3 coated blades

+ 1 SiO2 coated blade to cross-check room-temperature loss

[*] J. Agresti et al., SPIE Proc., 6286, 2006

Measurements

ringdown technique:

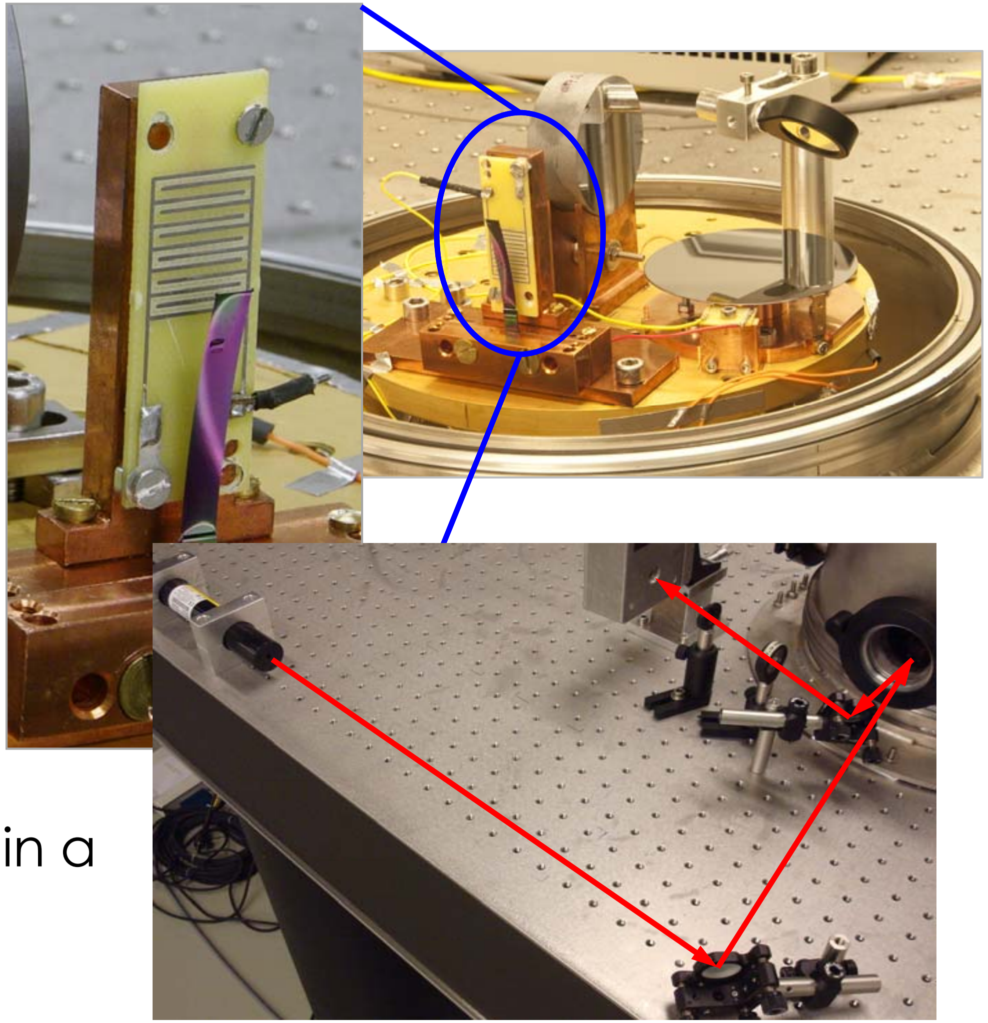
1. electrostatic excitation
2. free ringdown

vibration readout:

- optical lever
- position-sensitive photodiode

data acquisition:

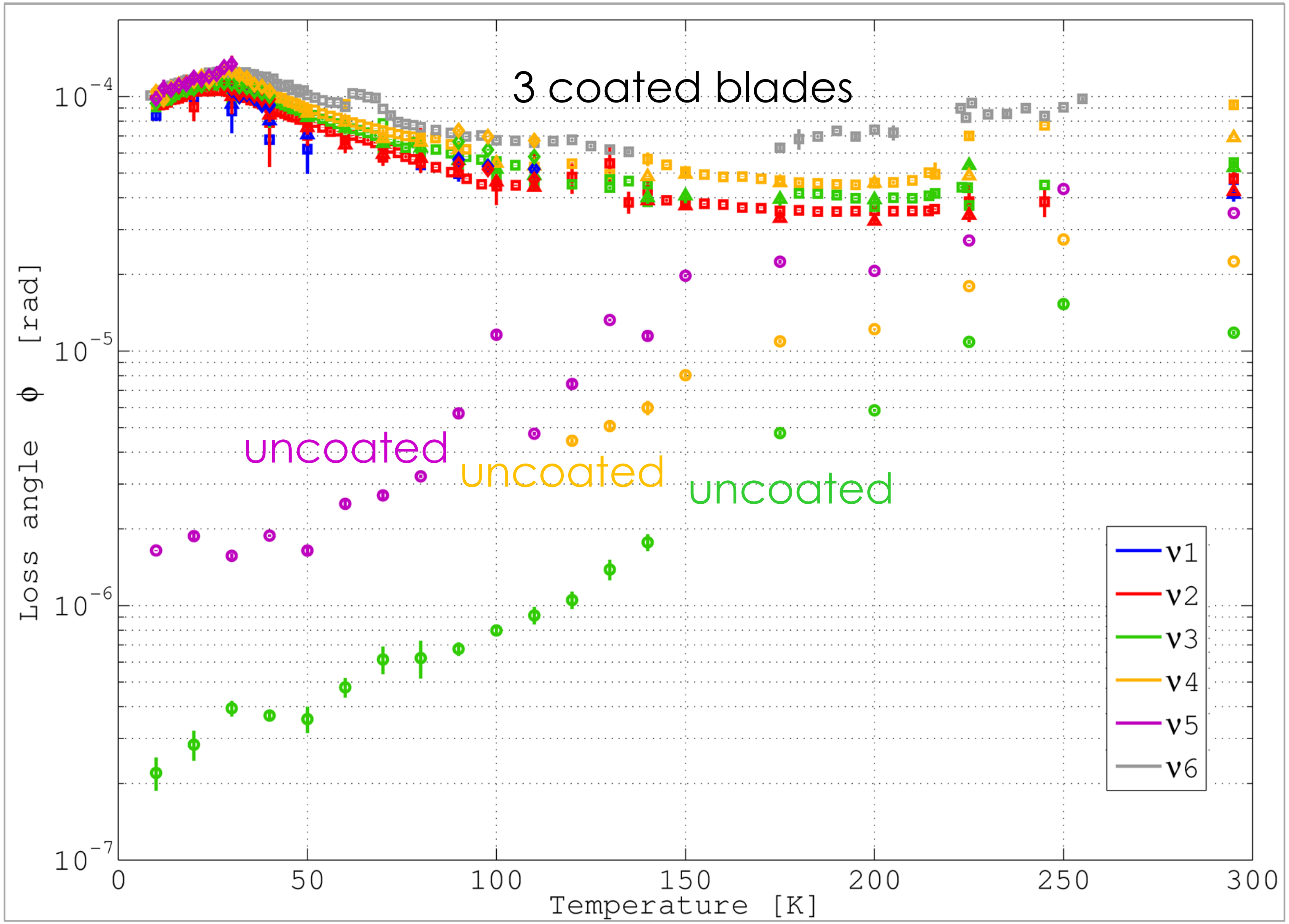
- LabVIEW-based software



same coated samples measured in a simlar setup at the IGR

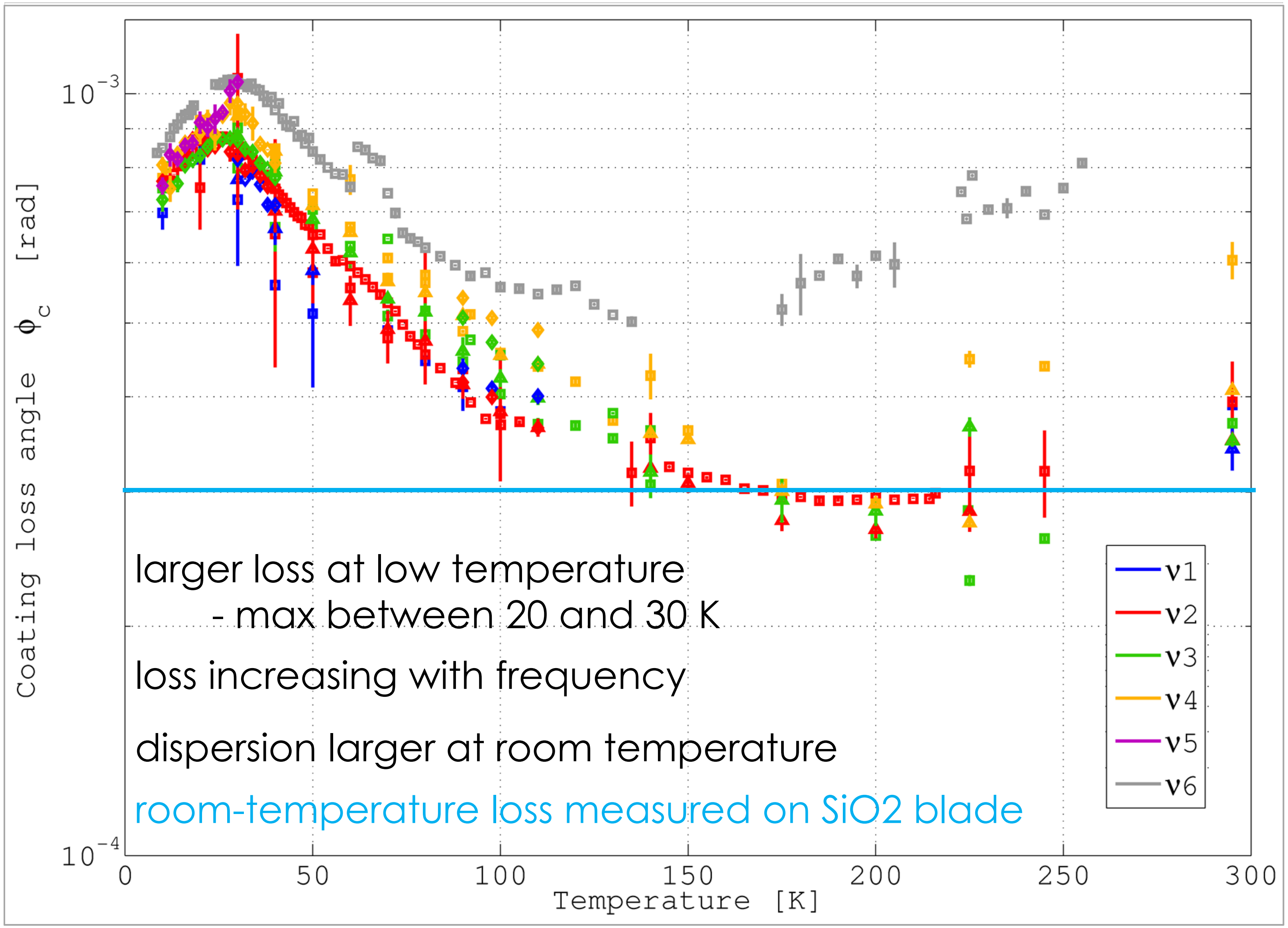
→ measurements do agree

Results

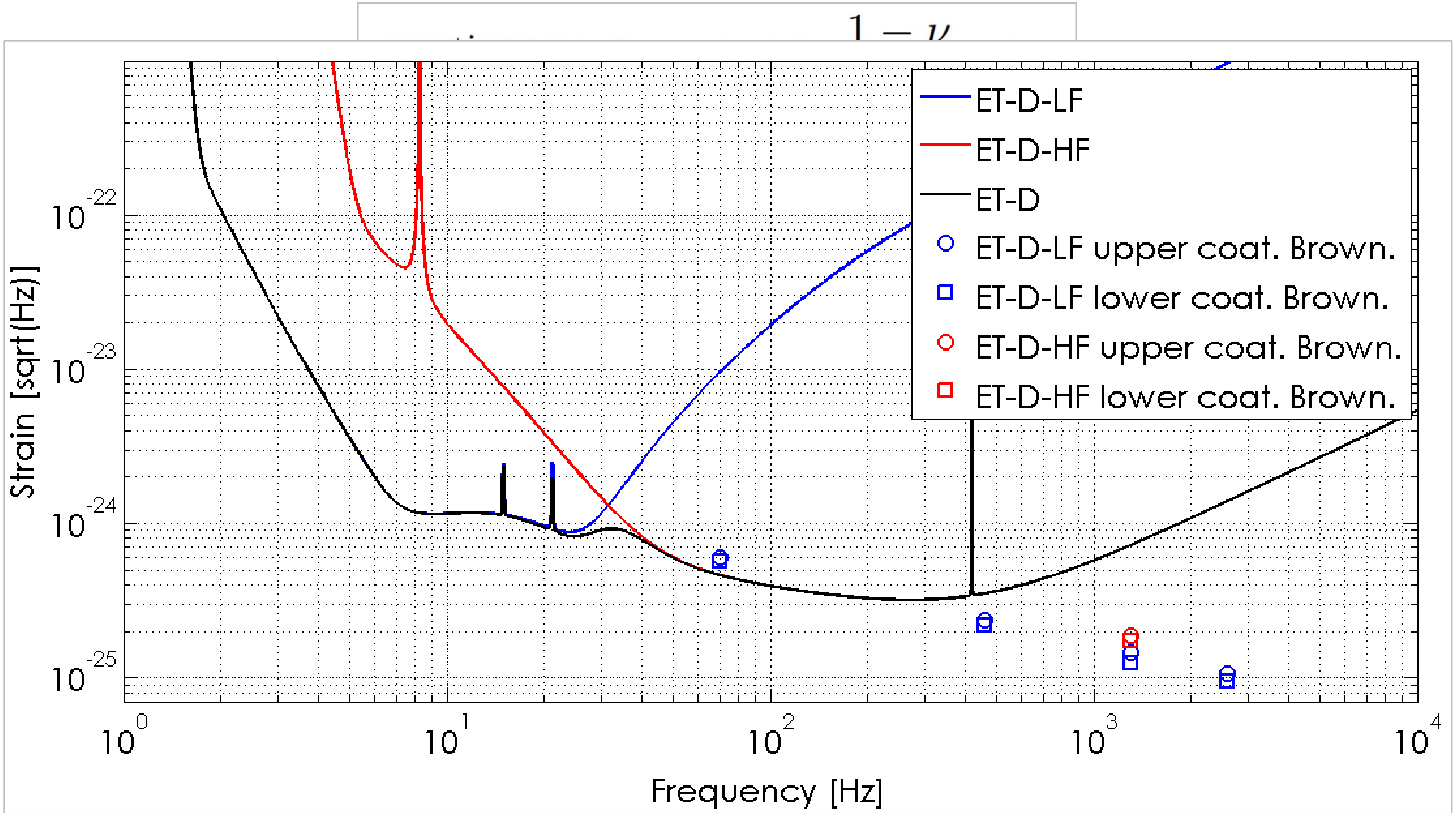


3 coated blades
uncoated
uncoated
uncoated
ν1
ν2
ν3
ν4
ν5
ν6
Loss angle φ [rad]
Temperature [K]

Coating loss



Estimation of coating thermal noise



M. Granata& al., Einstein Telescope 4th General Meeting, Hannover 2012, ET-0019A-12

Summary and conclusions

Summary and conclusions

LMA is carrying out cryogenic measurements
to characterize substrates and coatings at low temperature

- Si optical absorption:
  - seems not to decrease with temperature
  - to be confirmed with other samples

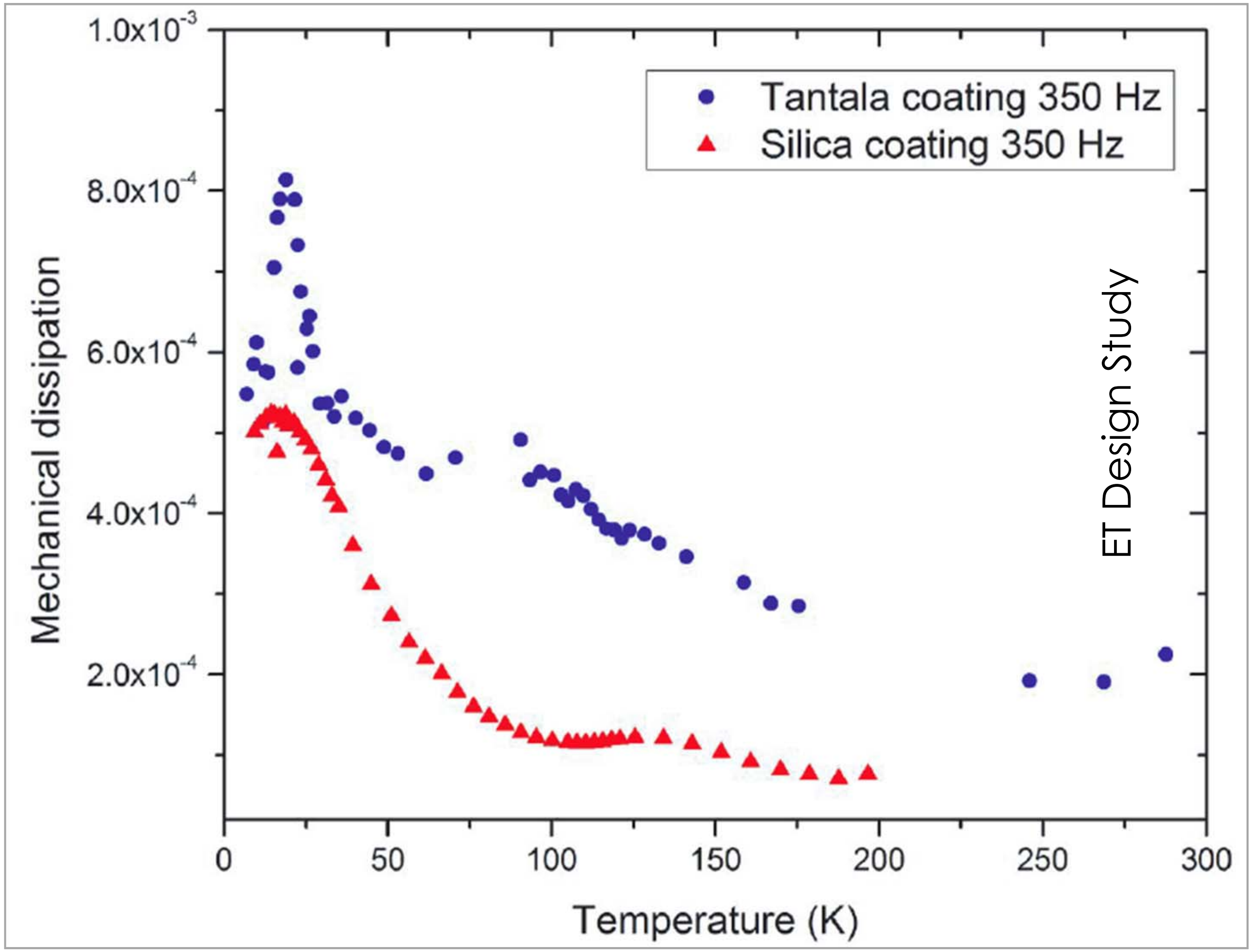
- coated disks: 1st cryogenic run with GeNS ever
  - anomalous behaviour of sputtered SiO_2 coating to be confirmed
  - check dilution factors and sample thermalization

- coated blades:
  - observed a low-temperature loss peak of coating stack
  - trend to be confirmed with other samples (ITM stack, …)
  - keep improving the coating for cryogenic mirrors

Thank you for your attention

Ion-beam-sputtered fused silica

•Φ(T, ν) for fused silica annealed @ $T_A^{AC} = 600°C$, ν = 350 Hz



ET Design Study

Coatingmechanicalloss

– blades –

in collaboration with

K. Craig, L. Cunningham, M. Hart, J. Hennig, J. Hough,
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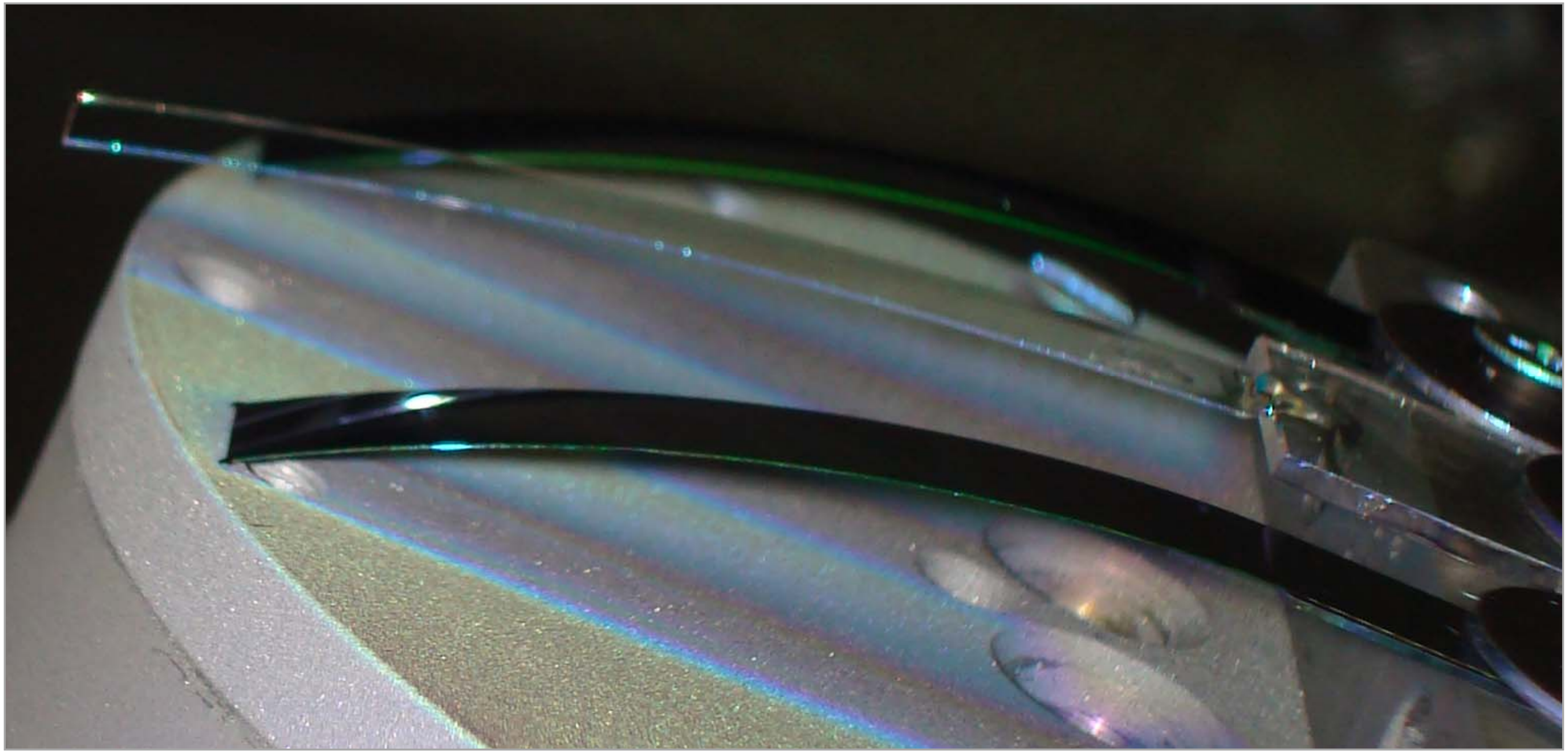
Annealing

in-air annealing:

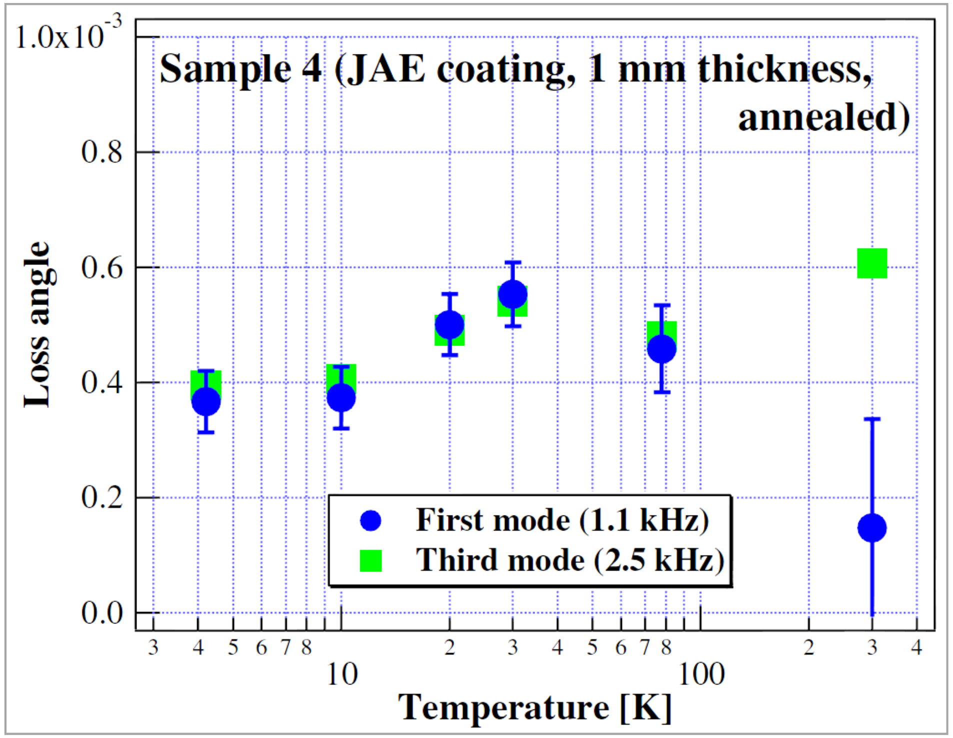
- before coating (improves bonding)
- after coating: 400°C < T_A^{AC} < 600°C (decreases stresses)



Previous measurements

*un*doped, thinner (4.8 um) Ta_2O_5/SiO_2stack on sapphire discs

Yamamoto & al., Phys. Rev. D 74, 2006



Parameters

anisotropic multilayer coating[*]:

1 = $Ti:Ta_2O_5$
2 = SiO_2

$d = d_1 + d_2 = 5.9\ \mu m$

$Y_1 = 7.32 \times 10^{10}$ Pa, $\sigma_1 = 0.17$
$Y_2 = 14.0 \times 10^{10}$ Pa, $\sigma_2 = 0.23$

for coatings @ 1064 nm, $\sigma_{\|} \sim 0.21$

?

measured in our setup

$$
\begin{cases}
Y_\perp = \dfrac{d_1 + d_2}{Y_1^{-1} d_1 + Y_2^{-1} d_2} \\[2ex]
Y_\| = \dfrac{Y_1 d_1 + Y_2 d_2}{d_1 + d_2} \\[2ex]
\phi_\perp = Y_\perp \left(\dfrac{Y_1^{-1} \phi_1 d_1 + Y_2^{-1} \phi_2 d_2}{d_1 + d_2} \right) \\[2ex]
\phi_\| = Y_\|^{-1} \left(\dfrac{Y_1 \phi_1 d_1 + Y_2 \phi_2 d_2}{d_1 + d_2} \right) \\[2ex]
\sigma_\perp = \dfrac{\sigma_1 Y_1 d_1 + \sigma_2 Y_2 d_2}{Y_1 d_1 + Y_2 d_2} \\[2ex]
\sigma_\| = F(Y_1, Y_2, \sigma_1, \sigma_2, d_1, d_2),
\end{cases}
$$

[*] Harry & al., CQG 19, 2002 / Harry, LIGO-T040029-00-R, 2004

Estimation of $\Phi_\perp$

$$\phi_\perp(\phi_1,\phi_2),\ \phi_{||}(\phi_1,\phi_2) \rightarrow \phi_\perp(\phi_{||},\phi_1)$$

previous equations + simple algebra:

$$\phi_\perp(T,\nu) = \frac{Y_\perp}{d}\left[\frac{\phi_{||}Y_{||}d}{Y_2^2} + \phi_1 d\left(\frac{1}{Y_1} - \frac{Y_1}{Y_2^2}\right)\right]$$

measured in our setup

measured by IGR group at Glasgow

data available so far[*]:

- $\Phi_1(T, \nu)$ for doped tantala annealed @ $T_A^{AC} = 600°C$
- $\Phi_1(T, \nu)$ for *un*doped tantala annealed @ $T_A^{AC} = 400°C$, $T_A^{AC} = 600°C$

for several modes

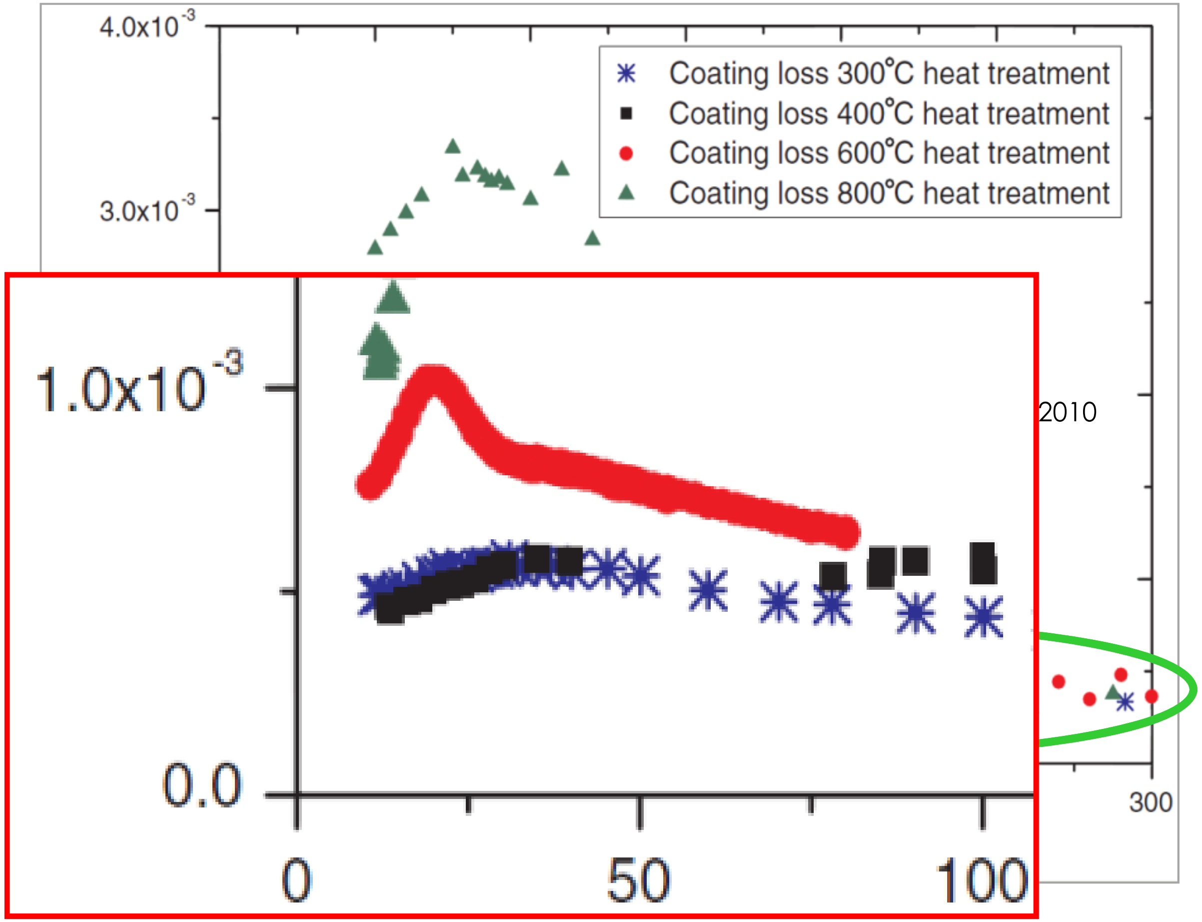
[*] I. W. Martin & al., CQG 26, 2009 / I. W. Martin & al., CQG 27, 2010

Issue

in our coating: Φ_1 annealed at 400°C $\leq T_A^{AC} <$ 600°C

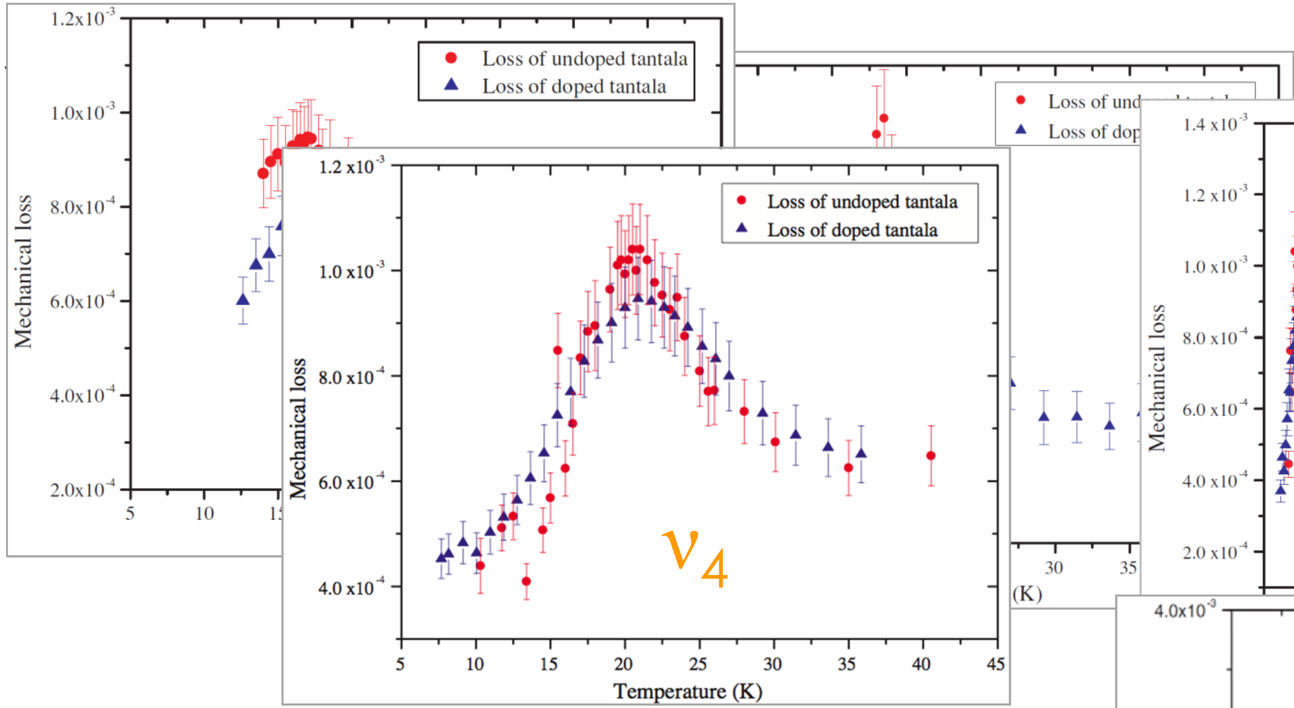
small difference at room T

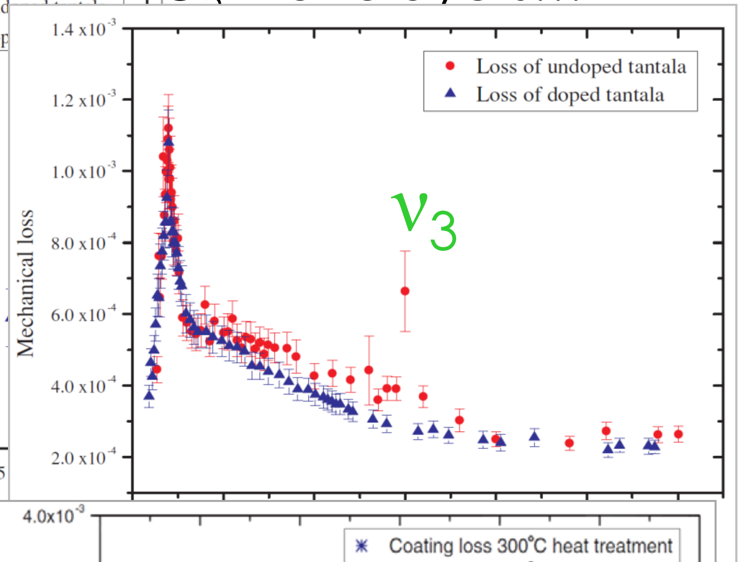
large difference at low T

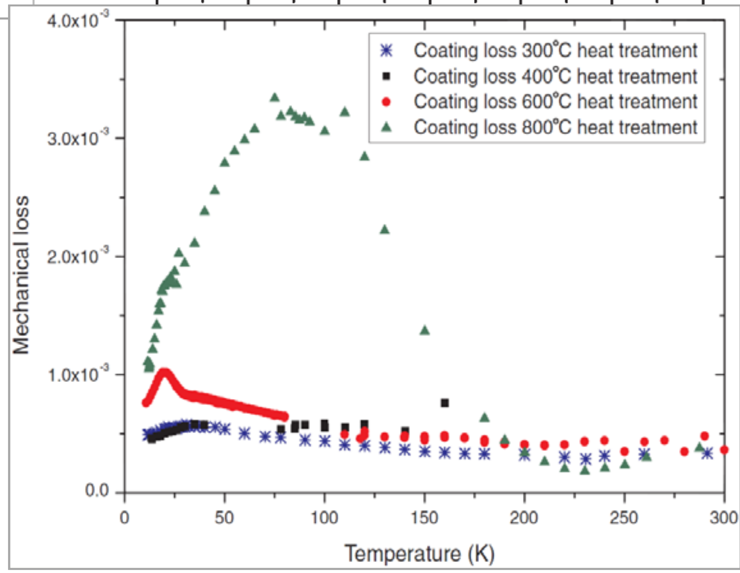


Solution

O_5 monolayers…







600°C-annealed Ti:Ta_2O_5 ➔ Φ_1 upper limit

400°C-annealed Ta_2O_5 ➔ Φ_1 lower limit

~ frequency independent

Graphs: I. W. Martin & al., CQG 26, 2009 / I. W. Martin & al., CQG 27, 2010

Estimation of coating thermal noise

anisotropic multilayer coating:

$\Phi_{\parallel}$ measured
$\Phi_{\perp}$ constrained

substrates[*]:

SiO$_2$ Y = 7.3 x 10^{10} Pa, σ= 0.17
sapphire Y = 40 x 10^{10} Pa, σ= 0.24
111-Si Y = 19 x 10^{10} Pa, σ= 0.22 (!)

$$\tilde{x}^2(T,\nu) = \frac{2k_BT}{(\pi w)^2\nu} A_{\mathrm{mirr}} = \frac{2k_BT}{(\pi w)^2\nu}\frac{(1-\sigma^2)}{Y}\frac{d}{Y_\perp} \times \left\{ \left[\frac{Y}{1-\sigma^2} - \frac{2\sigma_\perp^2 Y Y_\parallel}{Y_\perp(1-\sigma^2)(1-\sigma_\parallel)} \right] \phi_\perp + \frac{Y_\parallel \sigma_\perp (1-2\sigma)}{(1-\sigma_\parallel)(1-\sigma)}(\phi_\parallel - \phi_\perp) + \frac{Y_\parallel Y_\perp (1+\sigma)(1-2\sigma)^2}{Y(1-\sigma_\parallel^2)(1-\sigma)} \phi_\parallel \right\}.$$

(!) thickercoating for highreflectivity @ 1550 nm

[*] ET Design Study

Silicon substrate

shift of maximum reflectivity from λ = 1064 nm to λ = 1550 nm

→ thickness of coating increased by a = 1550 nm/1064 nm =1.46

$$d_{\lambda=1550\ nm} = a(d1_{\lambda=1064\ nm} + d2_{\lambda=1064\ nm}) = a d_{\lambda=1064\ nm}$$

… but stack parameters DO NOT change

$$\begin{cases} Y_\perp = \dfrac{d_1 + d_2}{Y_1^{-1} d_1 + Y_2^{-1} d_2} \\ Y_\parallel = \dfrac{Y_1 d_1 + Y_2 d_2}{d_1 + d_2} \\ \phi_\perp = Y_\perp \left(\dfrac{Y_1^{-1}\phi_1 d_1 + Y_2^{-1}\phi_2 d_2}{d_1 + d_2} \right) \\ \phi_\parallel = Y_\parallel^{-1} \left(\dfrac{Y_1 \phi_1 d_1 + Y_2 \phi_2 d_2}{d_1 + d_2} \right) \\ \sigma_\perp = \dfrac{\sigma_1 Y_1 d_1 + \sigma_2 Y_2 d_2}{Y_1 d_1 + Y_2 d_2} \\ \sigma_\parallel = F(Y_1, Y_2, \sigma_1, \sigma_2, d_1, d_2), \end{cases}$$