High-precision mirrors for low-noise interferometry:

the hidden quest behind the detection of the Gravitational Waves

Gianpietro Cagnoli

Acknowledgments

- Coating development and characterization
  - ♦ The Virgo-LMA group

- Structural analysis and modeling of amorphous materials
  - ♦ The Soprano group at the ILM

Take home messages

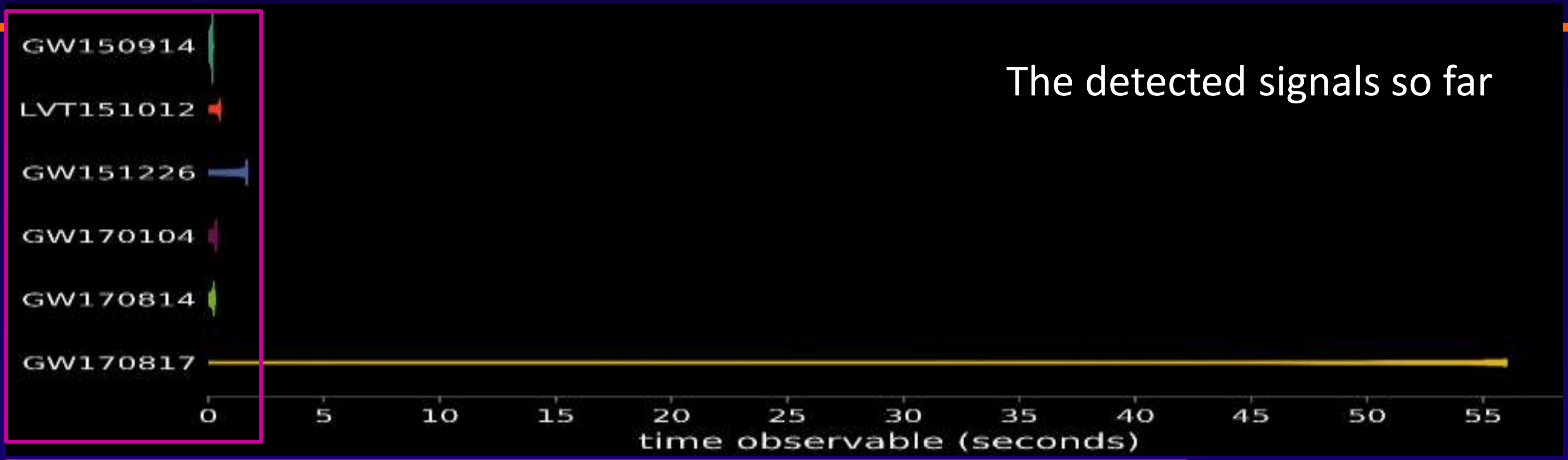
- The first detection was made because of better mirrors and suspensions with respect to the 1st generation of detectors

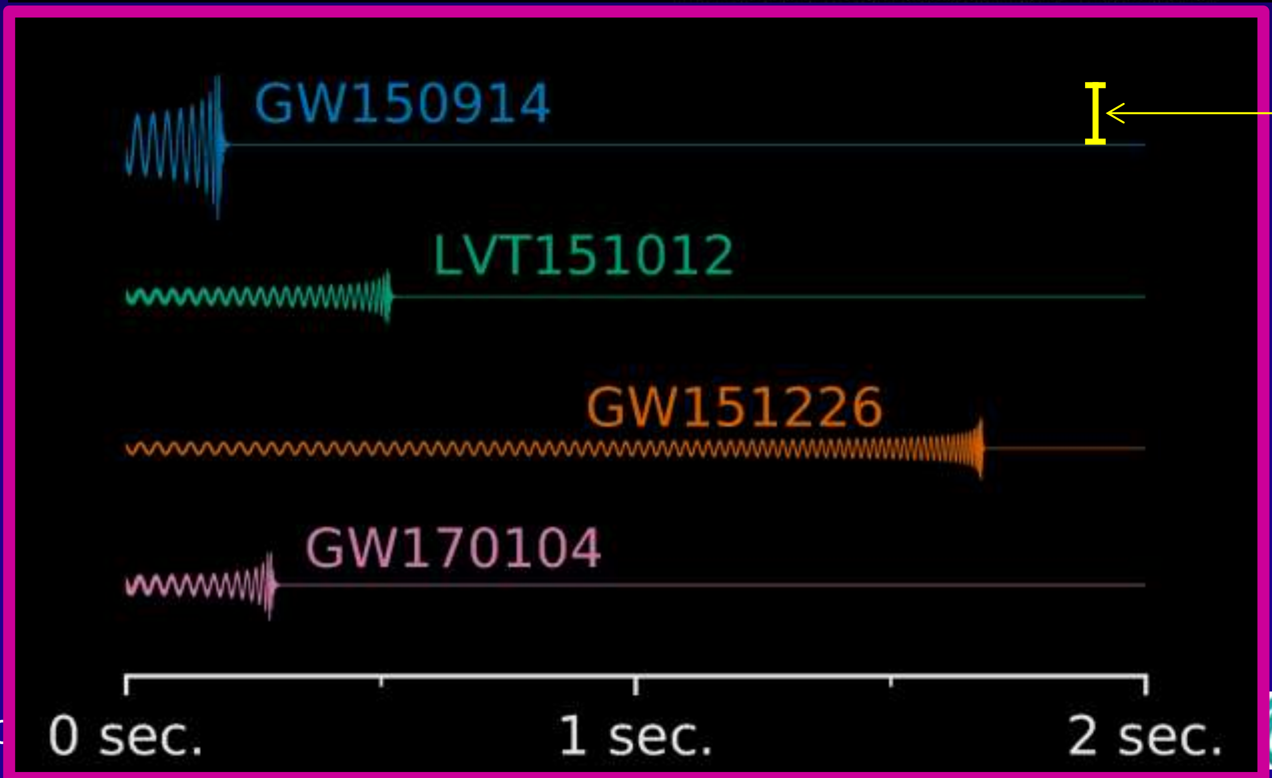
- Internal friction is the factor that keeps us away from listening the entire visible Universe

Content

- How precise the mirrors need to be
- The AdV mirrors
- Noise in mirrors?
- Internal friction in amorphous materials
- The future

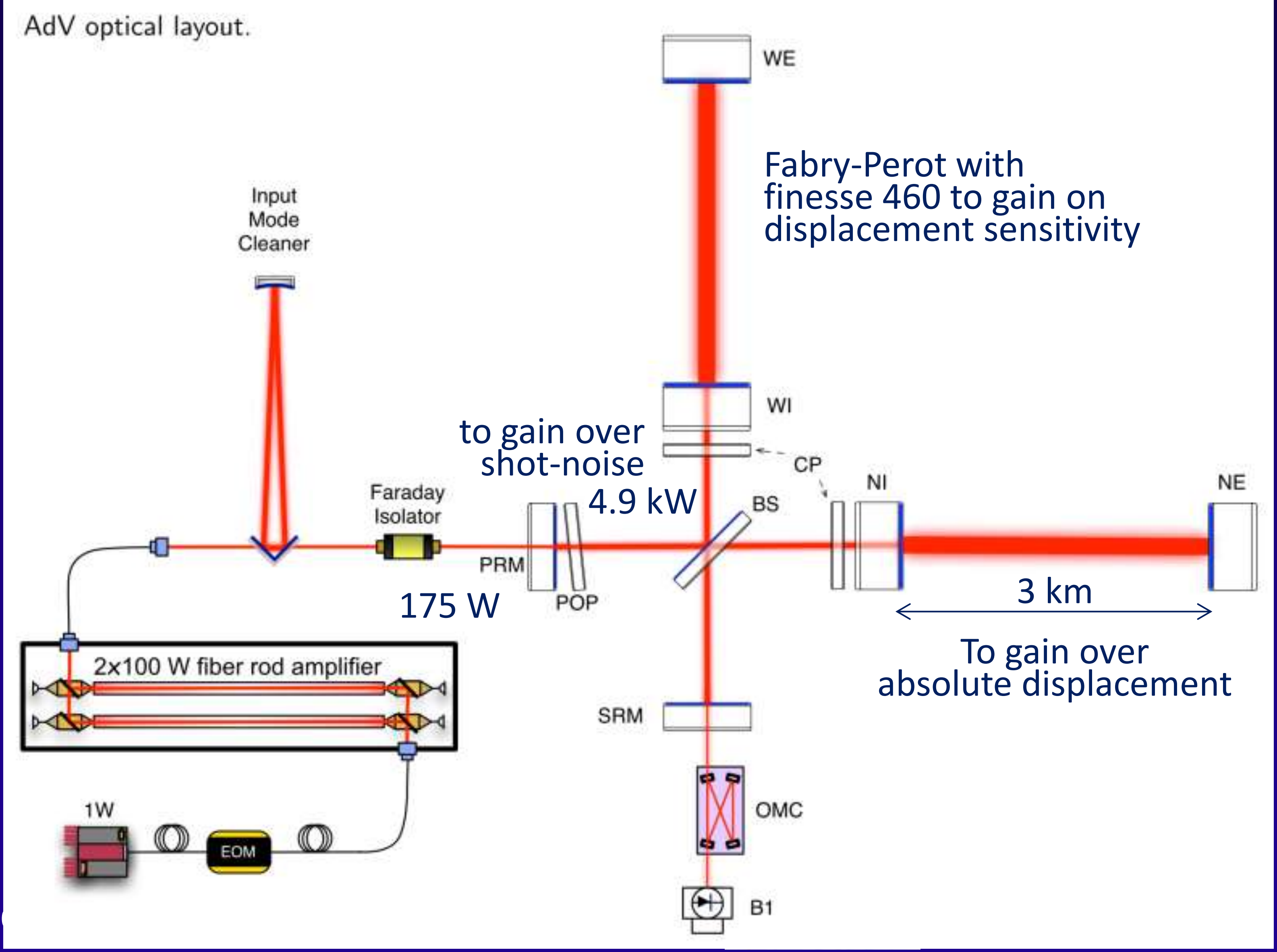
A problem of SNR



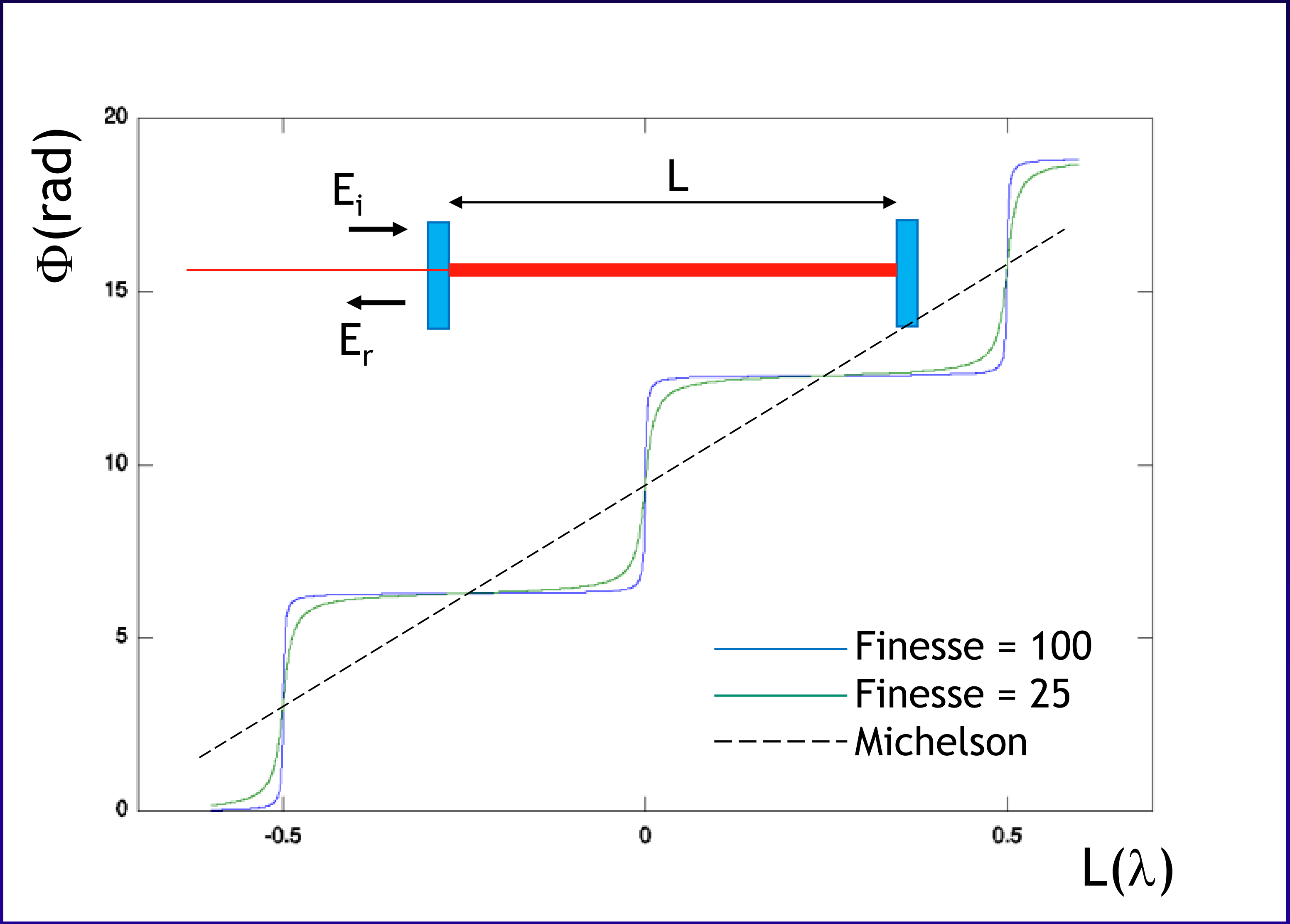


Strain of 10^{-21}

The interferometer Advanced Virgo



Displacement sensitivity of a Fabry-Perot cavity

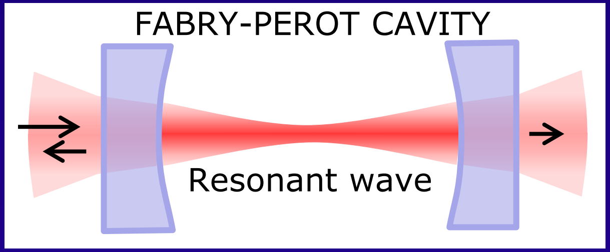


Cavity optical requirements for Advanced Virgo

Advanced Virgo main optical parameters			
Light Power			
Arm cavity power	650 kW	Power on the BS	4.9 kW
Arm cavity geometry			
Cavity length	2999.8 m		
IM RoC	1420 m	EM RoC	1683 m
Beam size on IM	48.7 mm	Beam size on EM	58.0 mm
Waist size	9.69 mm	Waist position from IM	1363 m
Arm cavity finesse			
Transmission IM	1.4%	Transmission EM	1 ppm
Finesse	443	Round-trip losses	75 ppm

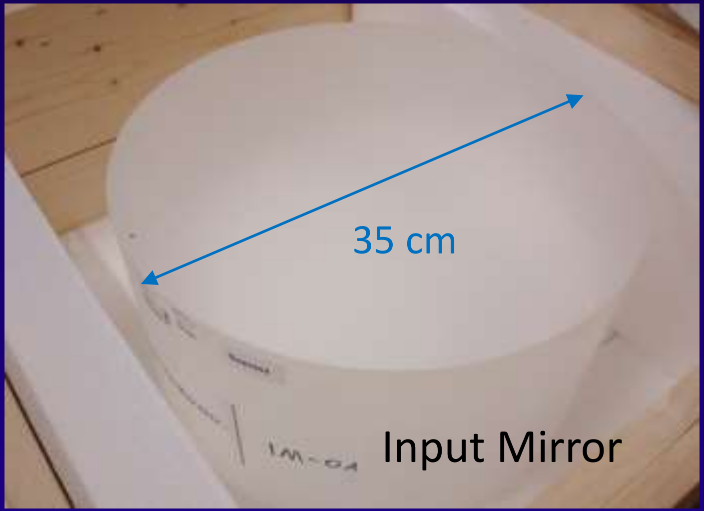
A photon makes about 130 round trips (260 reflections, 780 km) before going out the cavity:

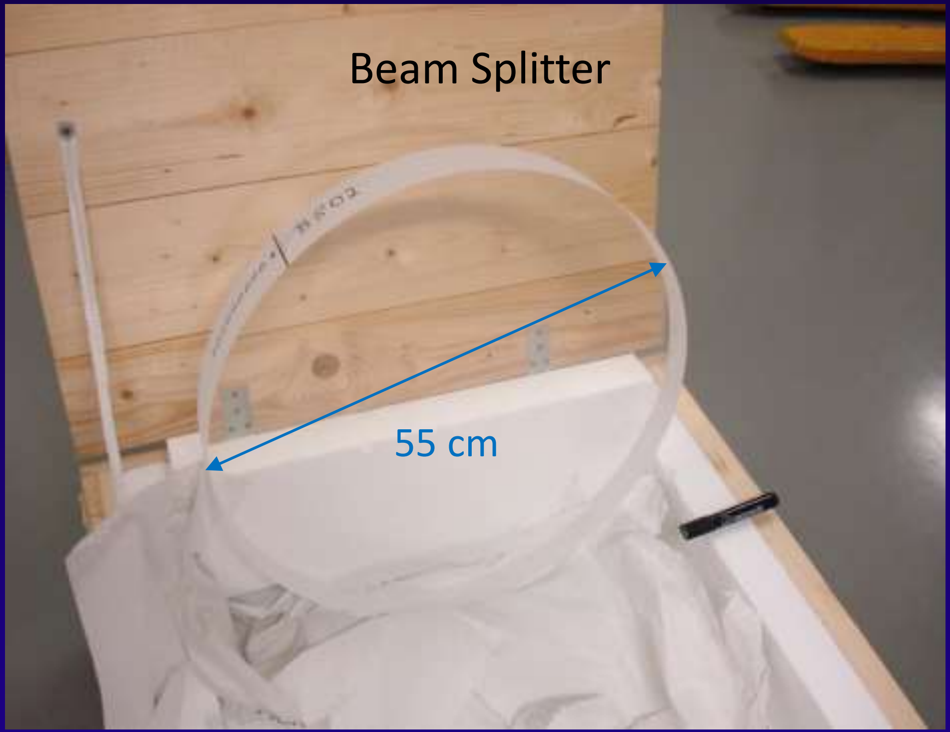
THE ROUND TRIP LOSSES HAVE TO BE MINIMAL



- Optical losses
  - 25 ppm { Absorption, Scattering }
  - 50 ppm Wavefront distortion

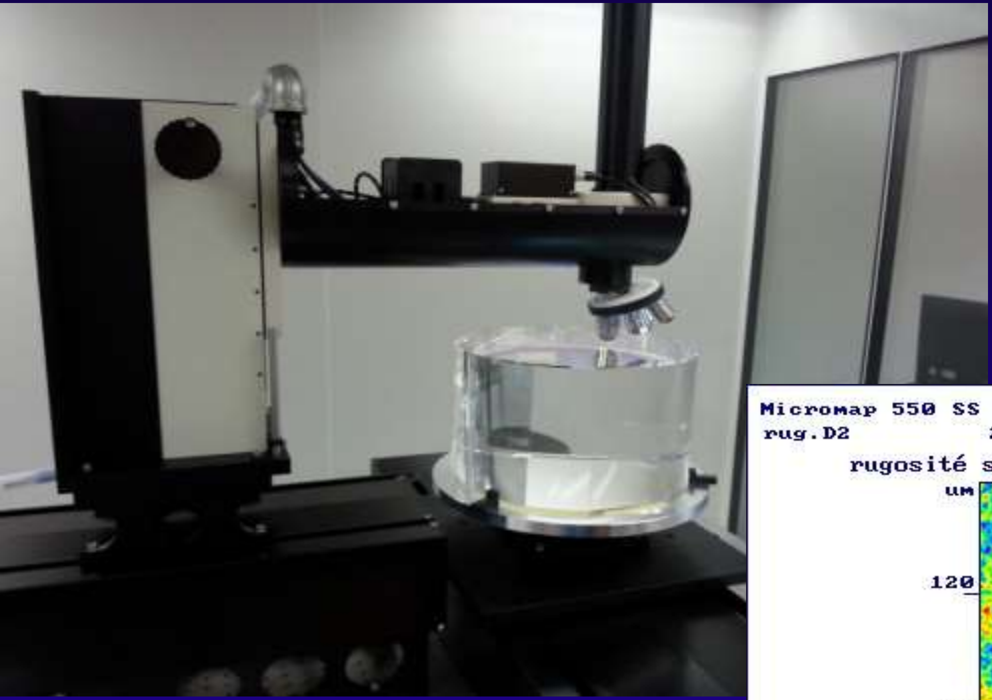
The substrates





- ✓ Low absorption fused silica (Suprasil 3002)
  0.25 ppm/cm @1064nm (LMA measurement)
- ✓ Diameter = 35 cm
- ✓ Thickness = 20 cm, Weight = 40 kg
- ✓ Blank cost 130 k€ (without polishing)

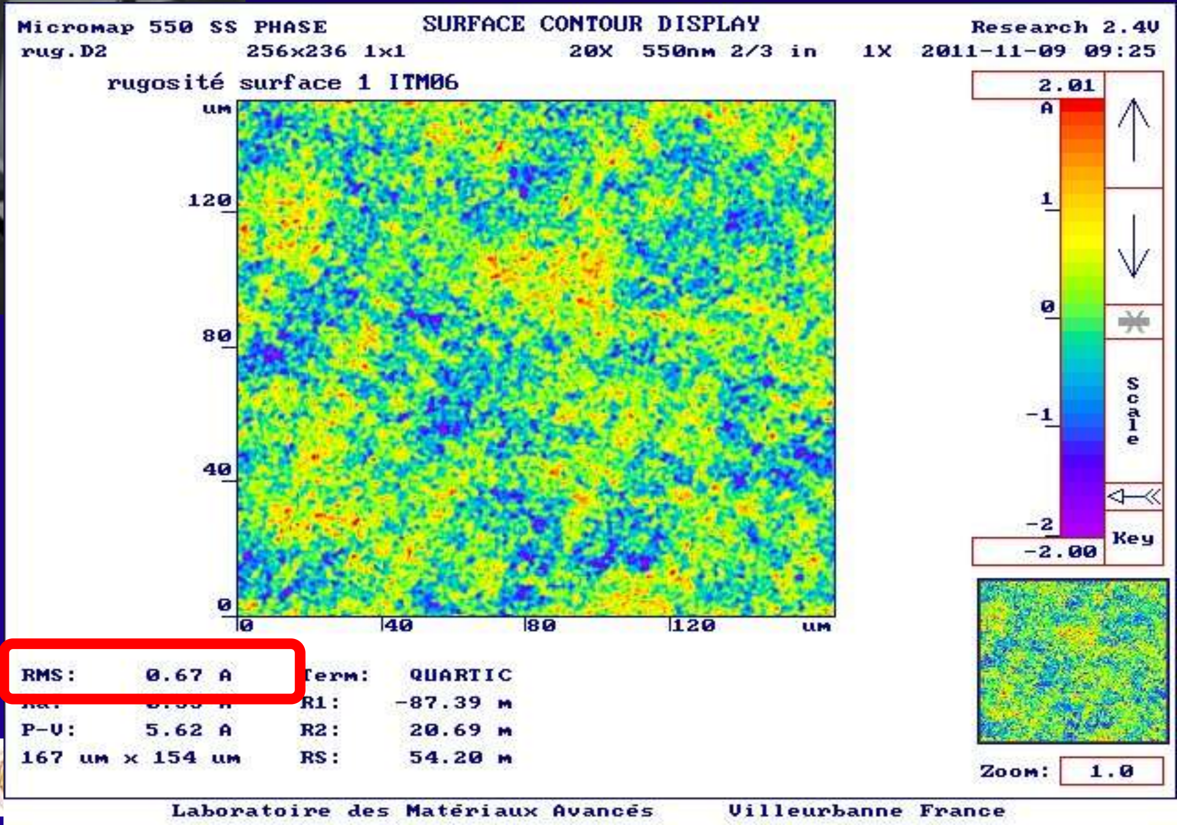
The substrate micro roughness



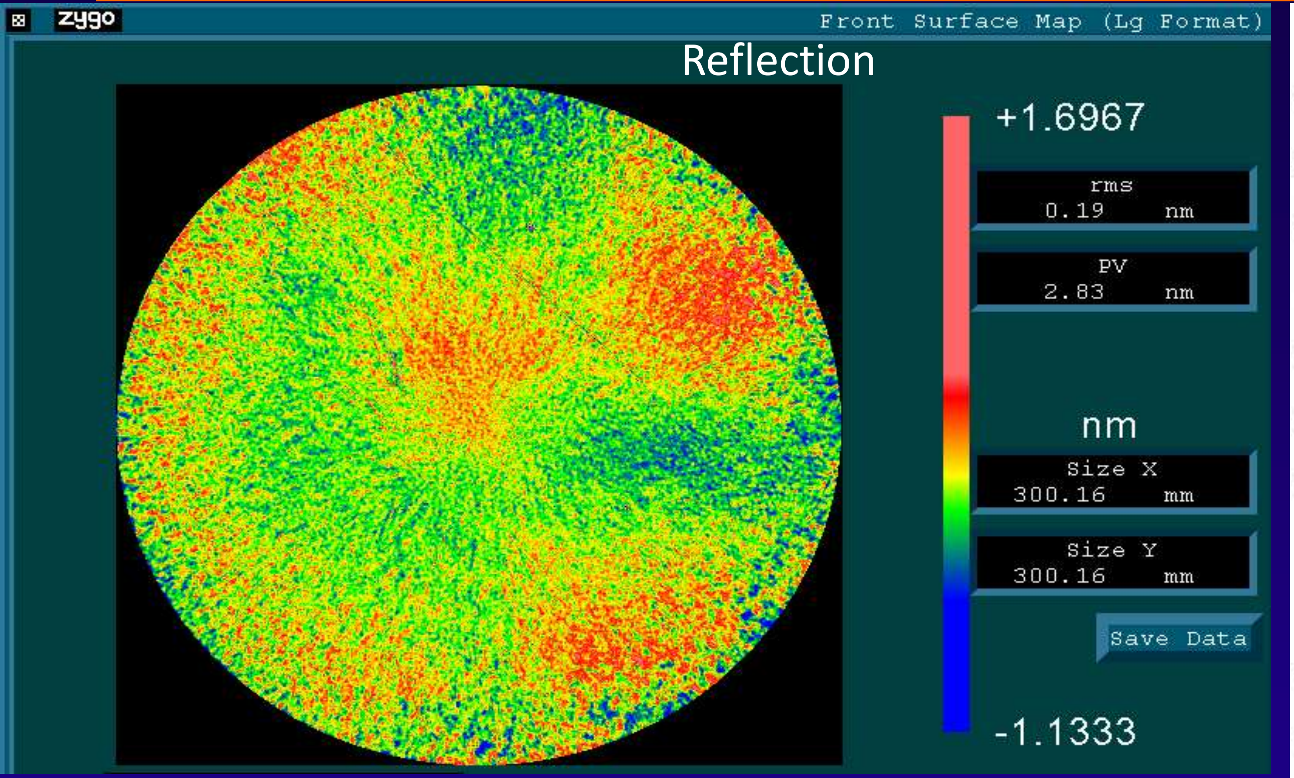
RMS Flatness needed : **< 0.5 nm RMS** on Ø15/16 cm (never obtained before)

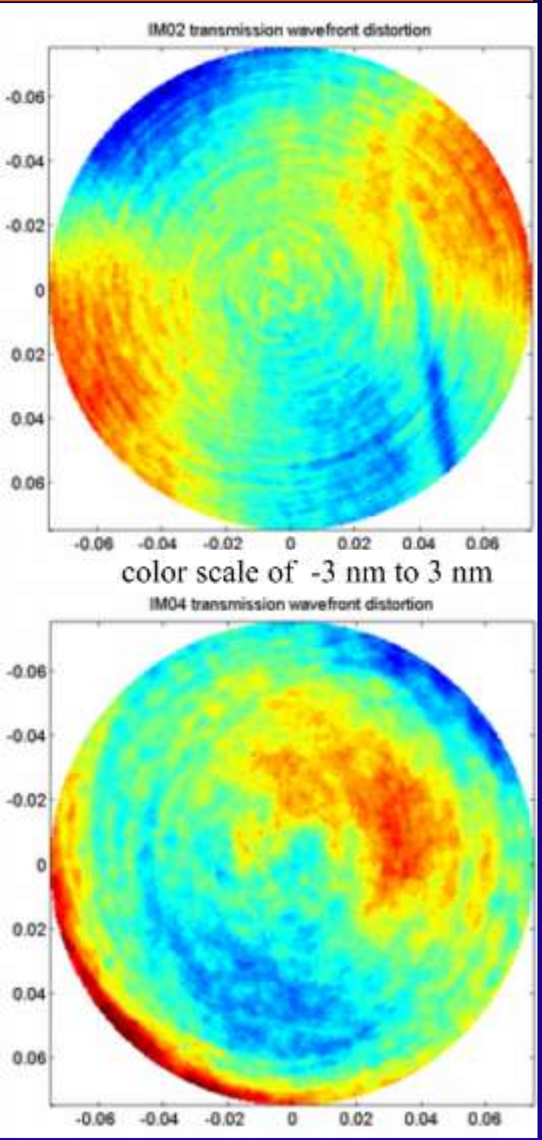
Ion Beam Figuring polishing (ZYGO corp.)

0.67 +/- 0.1 Angströms RMS



The substrate wave front distortion



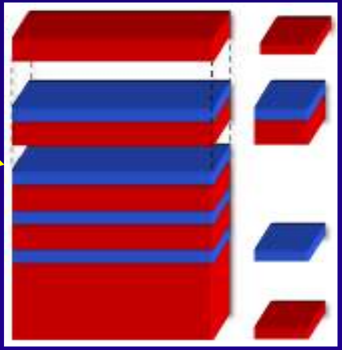


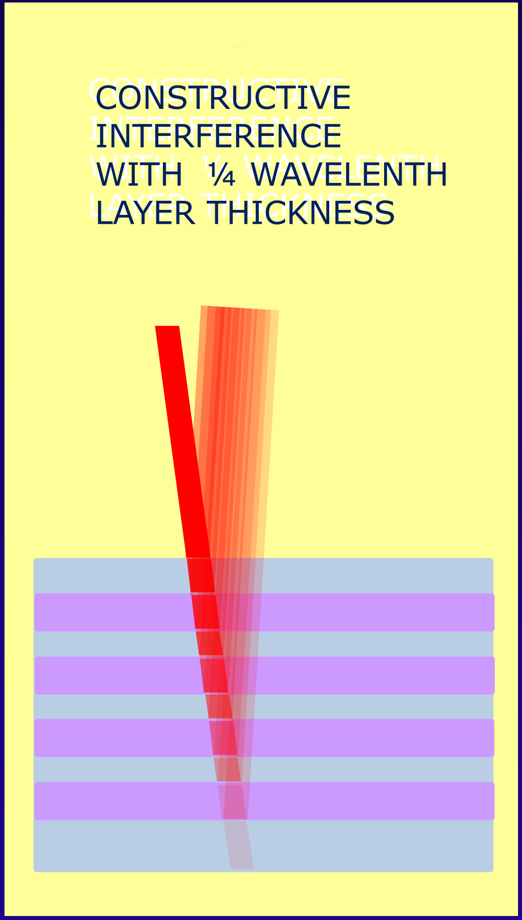
Advanced Virgo IM substrate:
0.19 nm RMS - 2.8 nm PV (30 cm diam.)

Transmission

The optical interference coatings

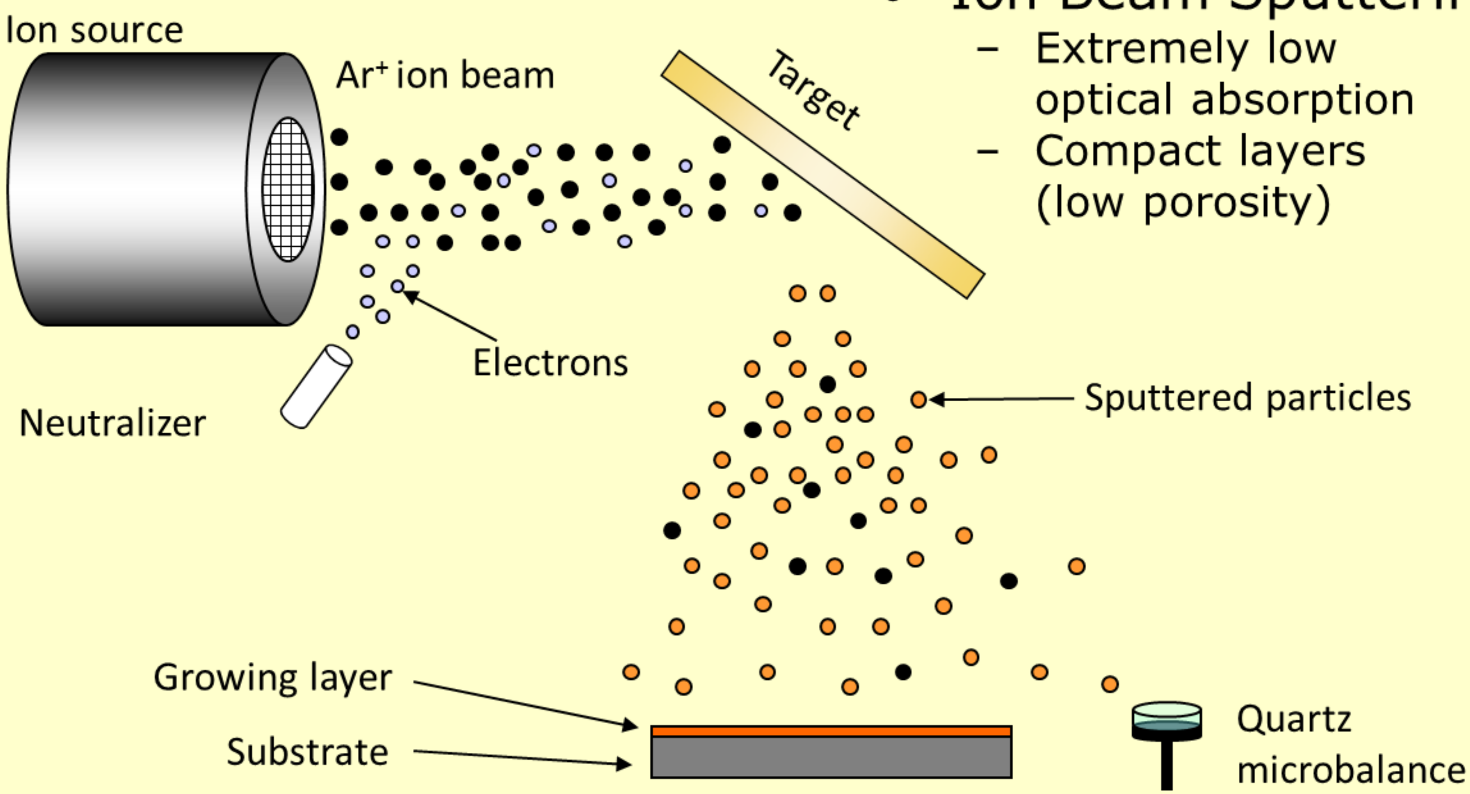
- They are used for optical filters and in all laser mirrors
- Combining the phase of reflected and transmitted beams
- Transparent materials with different refractive indexes:
  - Silica SiO_2: n ~ 1.4
  - Tantala Ta_2O_5: n ~ 2.1
  - 18 pairs for 99.999% reflection (~5.9μm total)





The Ion Beam Sputtering

- Ion Beam Sputtering
  - Extremely low optical absorption
  - Compact layers (low porosity)



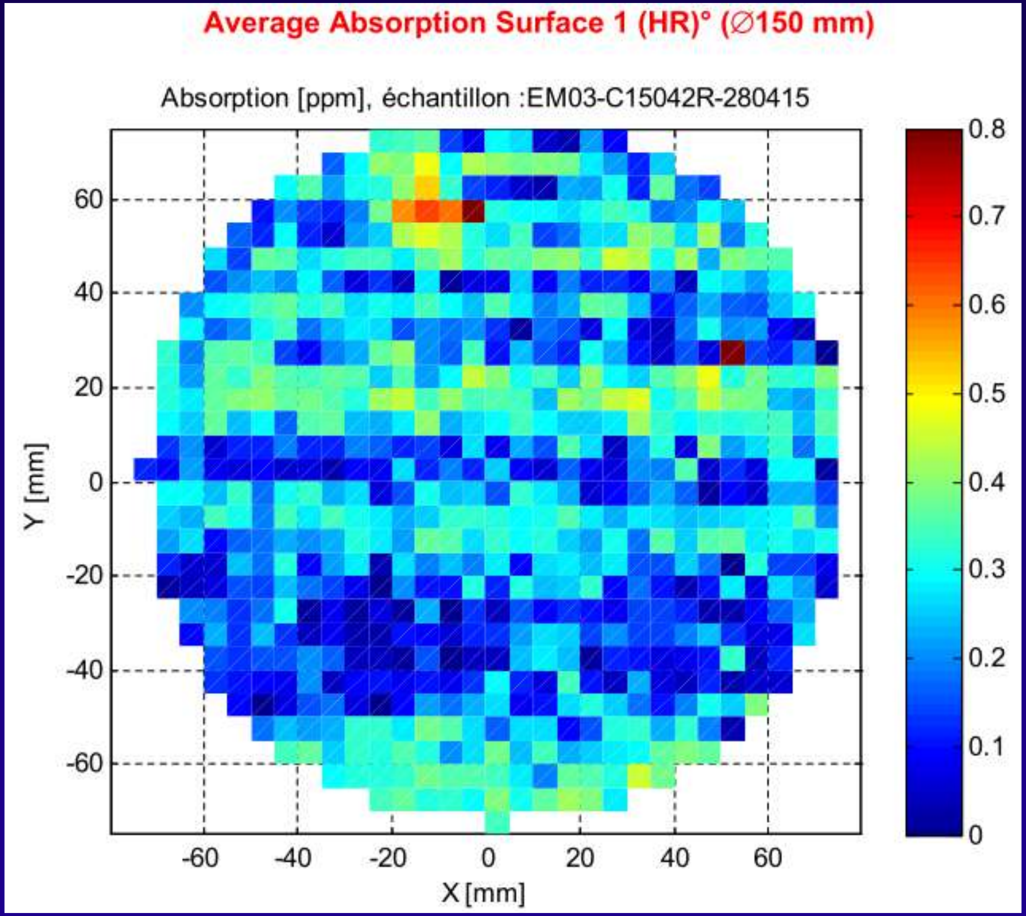
After deposition coatings are annealed to reduce the optical absorption below 1 ppm

The coater

The AdV mirrors

		IM	EM
Substrate material		Suprasil 3002	Suprasil 312
Material absorption	[ppm/cm]	<0.3	<3
Geometry			
Thickness	[mm]	200	200
Diameter	[mm]	350	350
Wedge	[µrad]	<3	1000
RoC of High Reflectivity (HR) face	[m]	1420	1683
RoC of AR face	[m]	1420	>100000
Coating			
Coating diameter	[mm]	340	340
Baffle clear aperture	[mm]	330	330
HR coating		R=0.986	T<1ppm
AR coating		TBD	R<100ppm
Absorption	[ppm]	<1	<1

AdV coating absorption



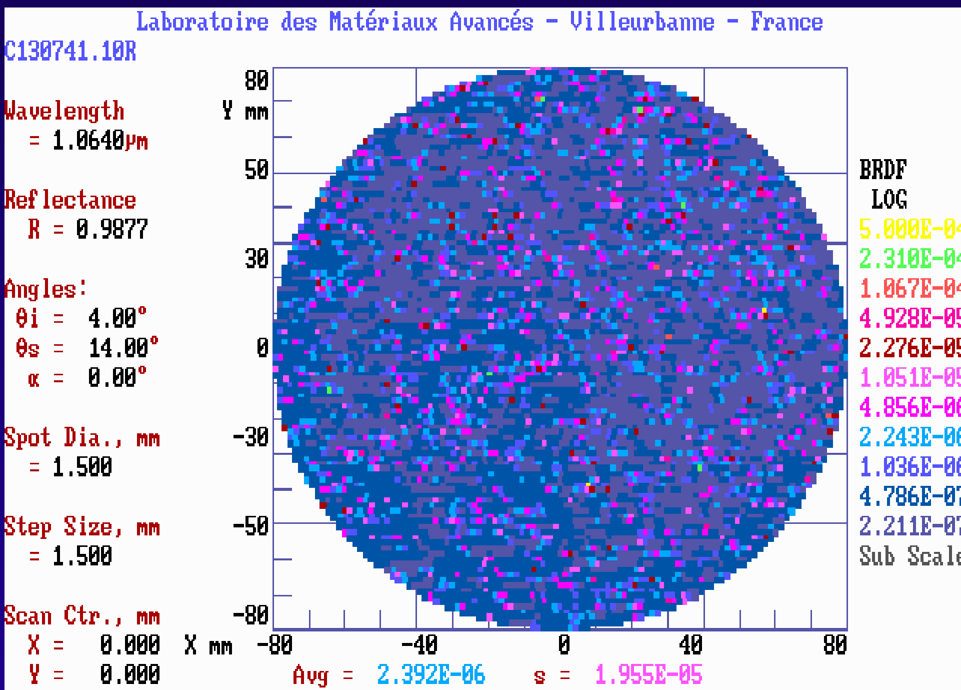
The absorption on the 20 mirrors for LIGO and on the 4 for Virgo is in the range $[0.14, 0.40]$ ppm

AdV coating scattering

The scattering comes from roughness and point defects

Average scattering level on Ø160 mm achieved :

- 10 ITMs : **3.7 +/- 1.2 ppm**
- 10 ETMs : **4.9 +/- 1.5 ppm**
- Best result : **2.3 ppm**

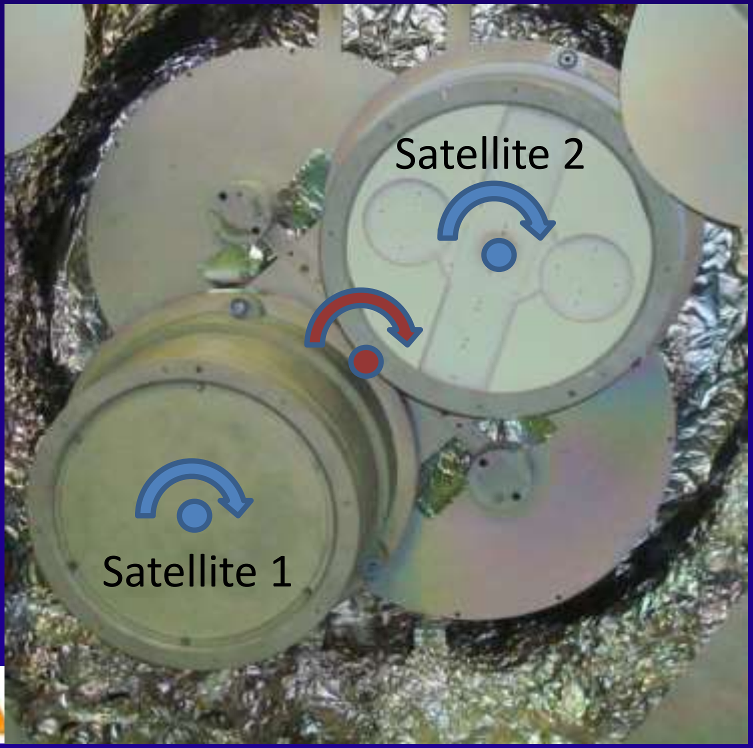


Ultrasonic bath

150 m² clean room class ISO3

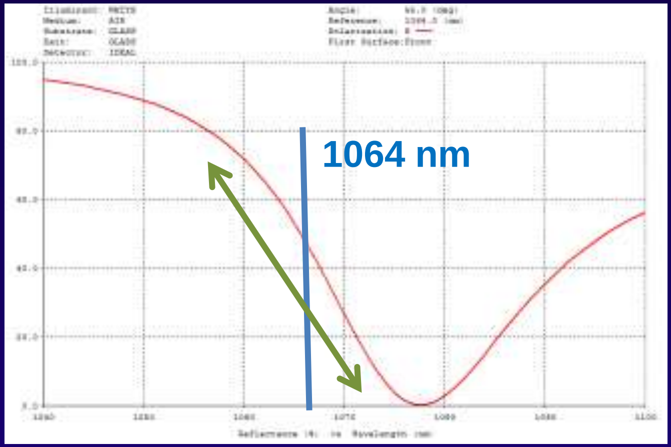
The big challenge: coating uniformity

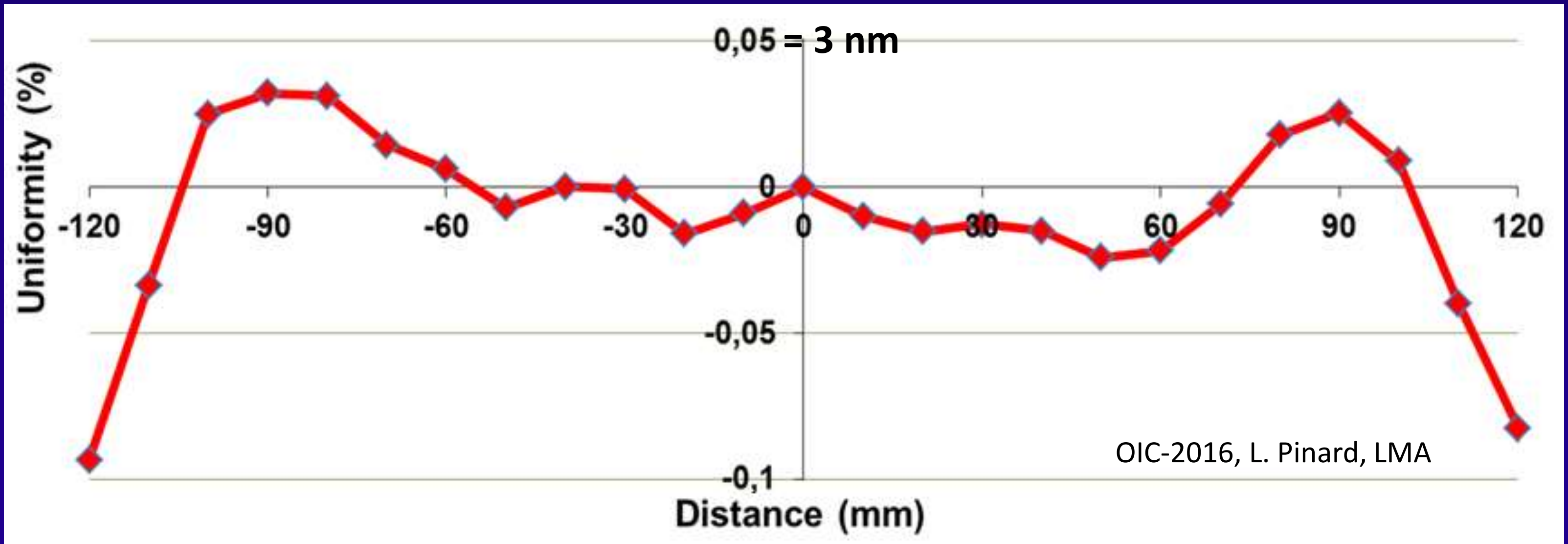
- Requirements
  - ♦ Coating uniformity : **< 0.5 nm RMS Ø15/16 cm** (All Zernike terms amplitude **< 0.5 nm**)
  - ♦ The total thickness of the 38 films is 5900 nm
- Solutions
  - ♦ Simple rotation was not good enough
  - ♦ Planetary motion



The big challenge: coating uniformity

- Measurements through the edge position of the transmission band
- 4 years of development to achieve a uniformity better than 0.05%

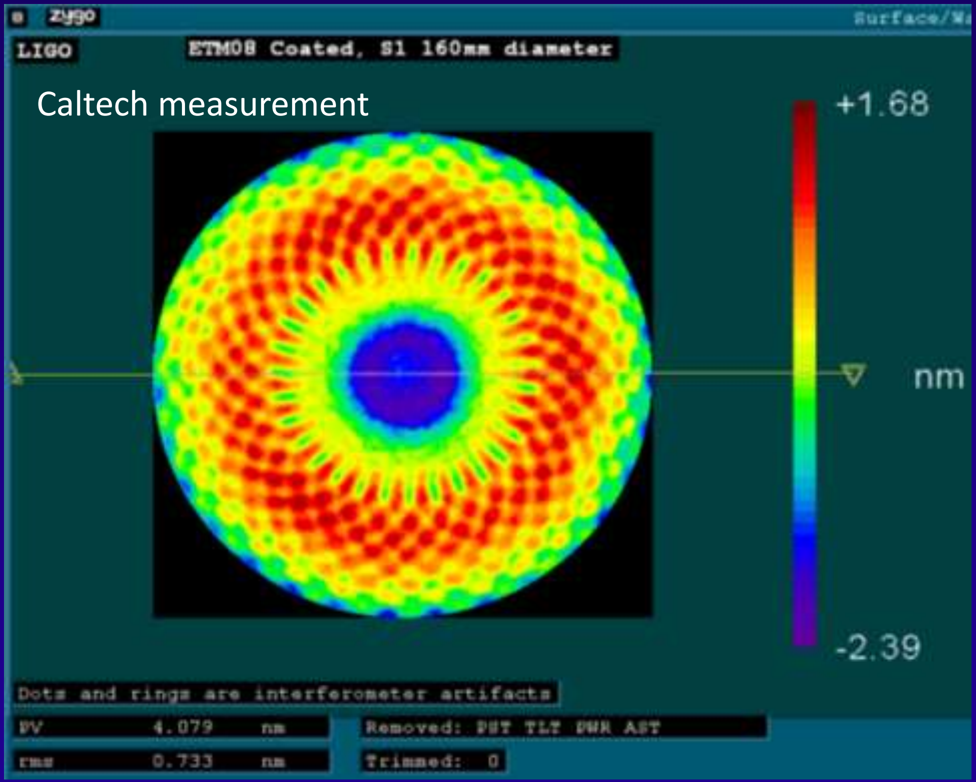




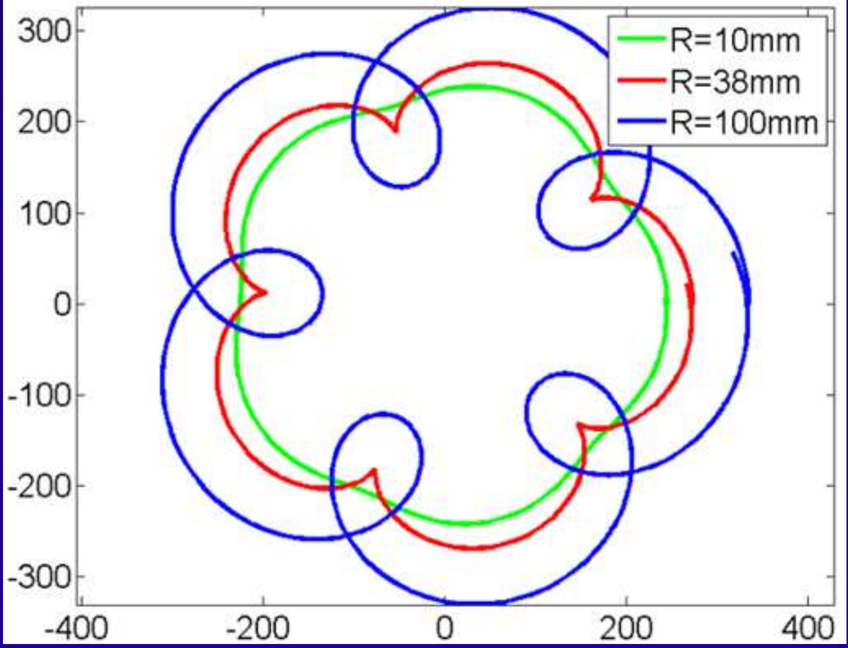
… but

The *Spirals* !!!

- Periodicity of motion + radial motion
- 1.9 nm maximum = 46 s of exposition difference over 40 h of deposition duration

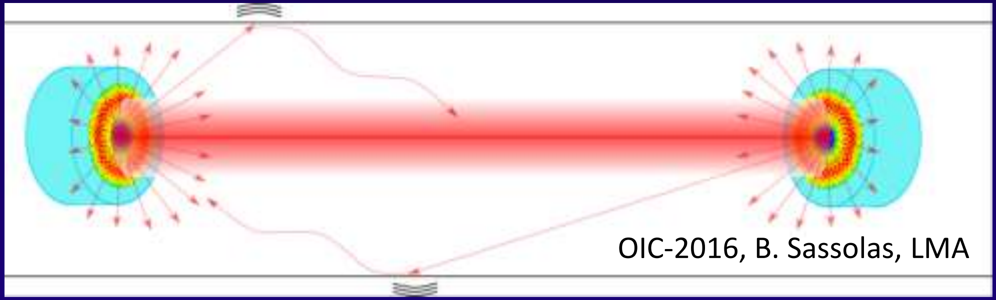


Motion of 3 points on a mirror placed at 3 different radii

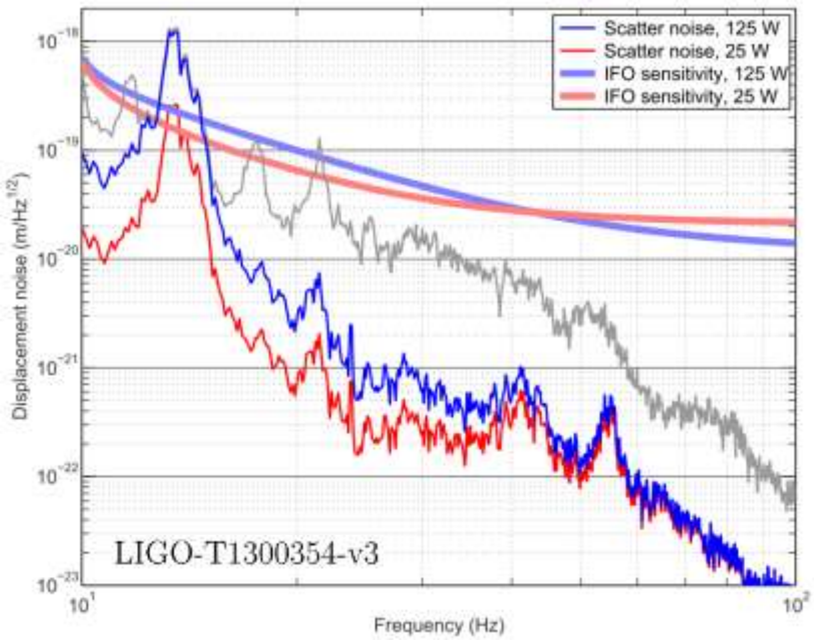


The problem with the *spirals*

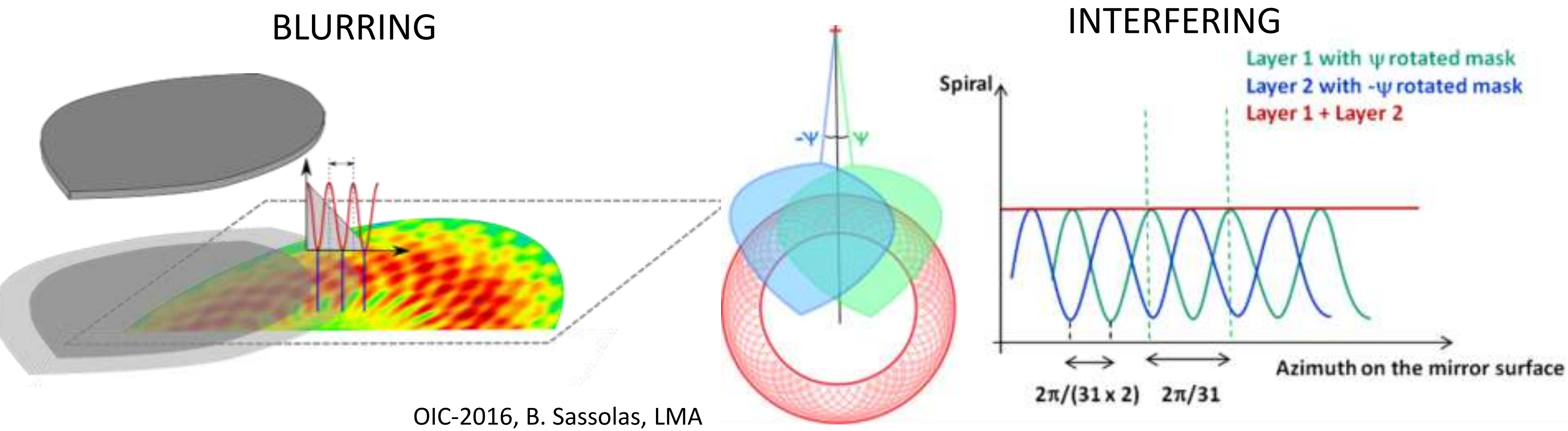
- Virgo did not have any problem
- LIGO picked up vibrations from the vacuum tube



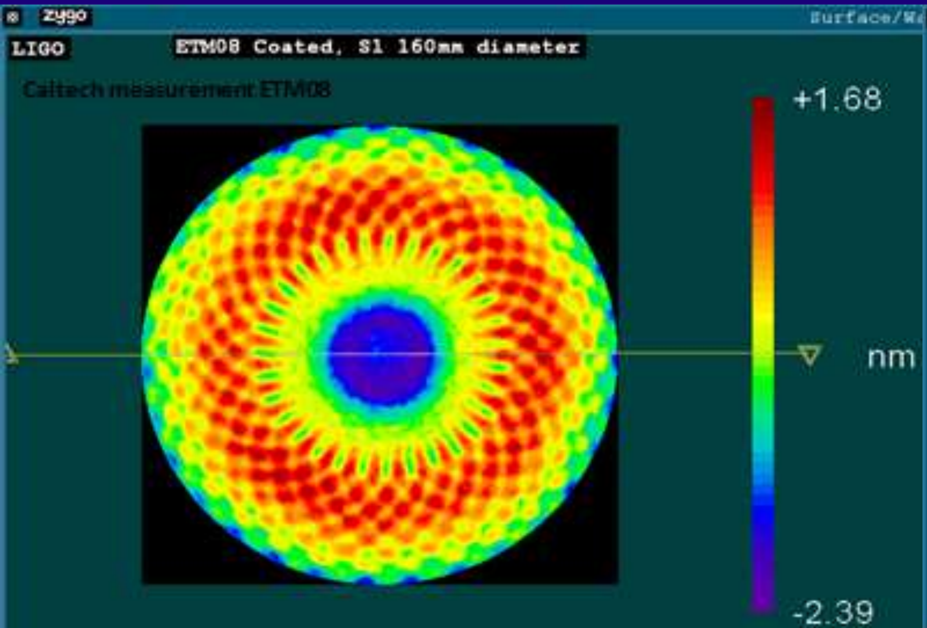
- A solution to the spirals had to be found

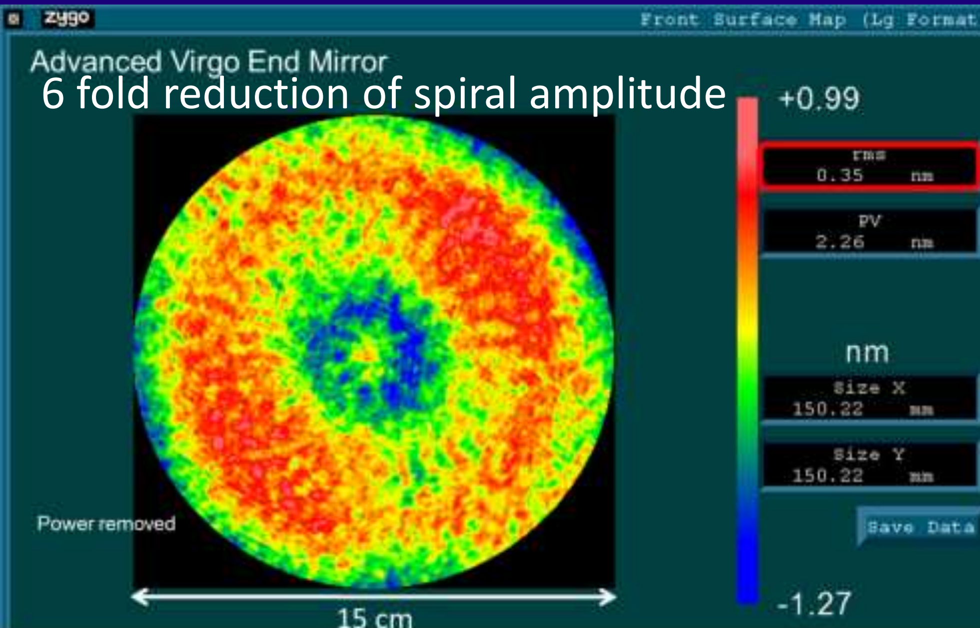


The interference solution



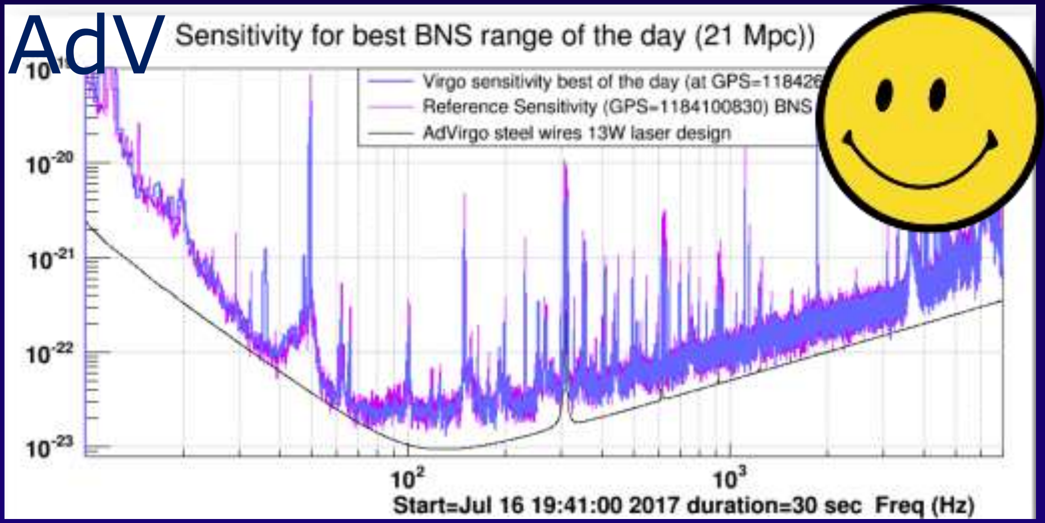
OIC-2016, B. Sassolas, LMA





The interferometer works !

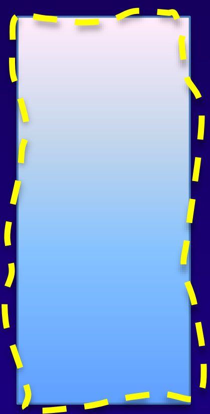
- Mesurements on AdV
  - ♦ Round trip losses 50 ± 10 ppm
  - ♦ Contrast defect ~ 10 ppm



- The goal:
  to measure atto-m displacements
  - ♦ It is crucial to limit noise internal to the detector
  - ♦ The reflecting surface position fluctuates

Thermal noise in solids

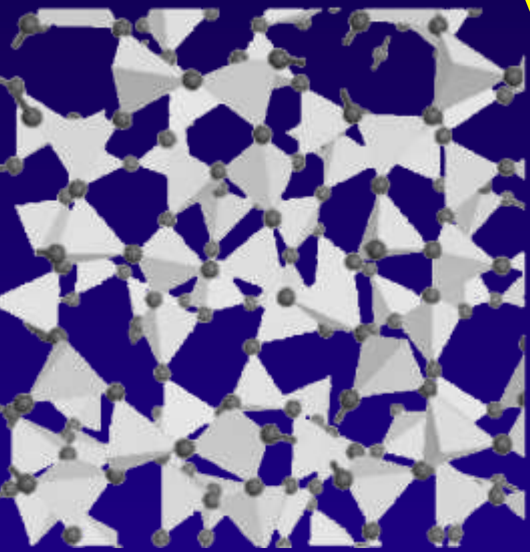
- Atoms occupy equilibrium positions
- Finite temperature

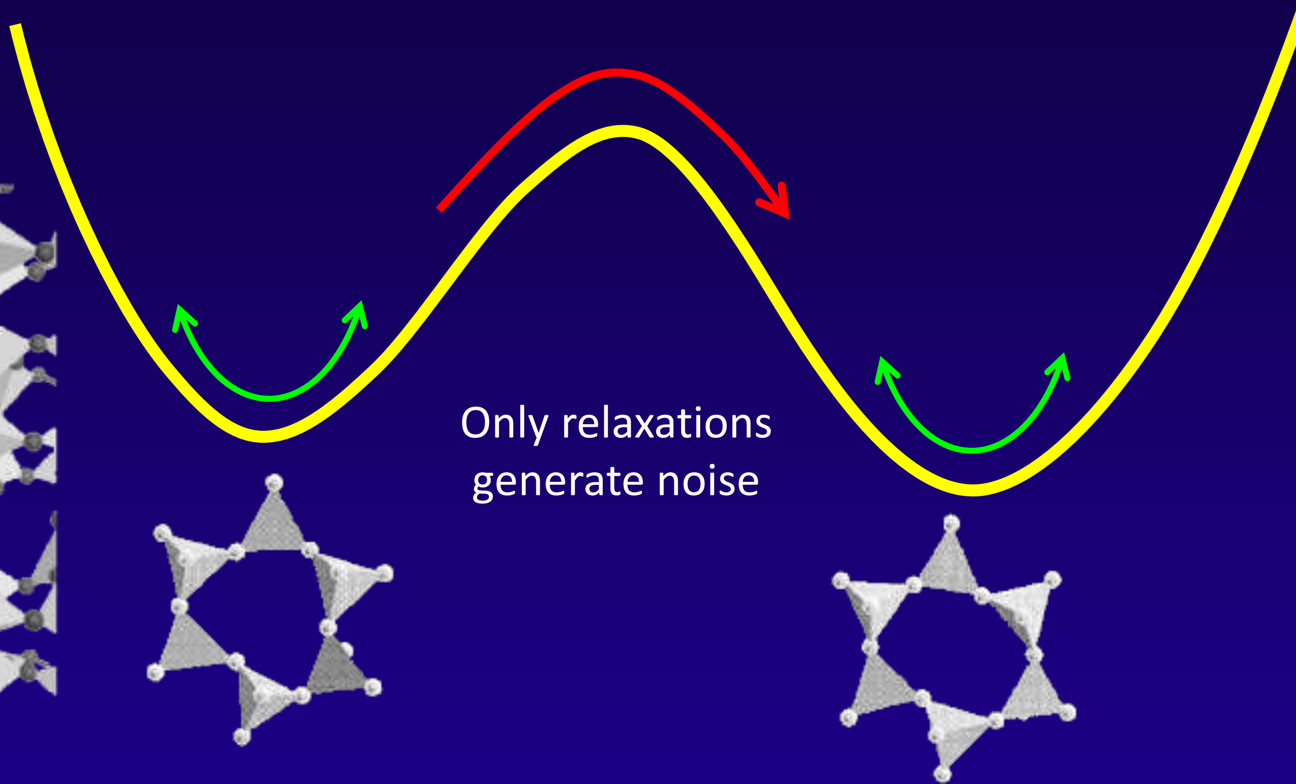


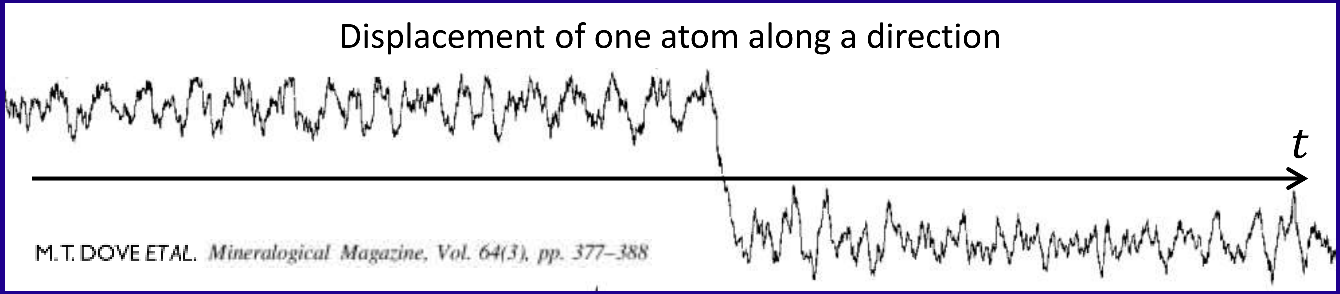
  - ♦ Atoms vibrate around their equilibrium positions
  - ♦ The shape of solids changes continuously but in a ”predicted” way, mostly…
- Thermal noise
  - ♦ Driven by thermal agitation atoms hop from one equilibrium position to another in a random (in time and space) way

Vibrations and relaxations

An example:
silica glass

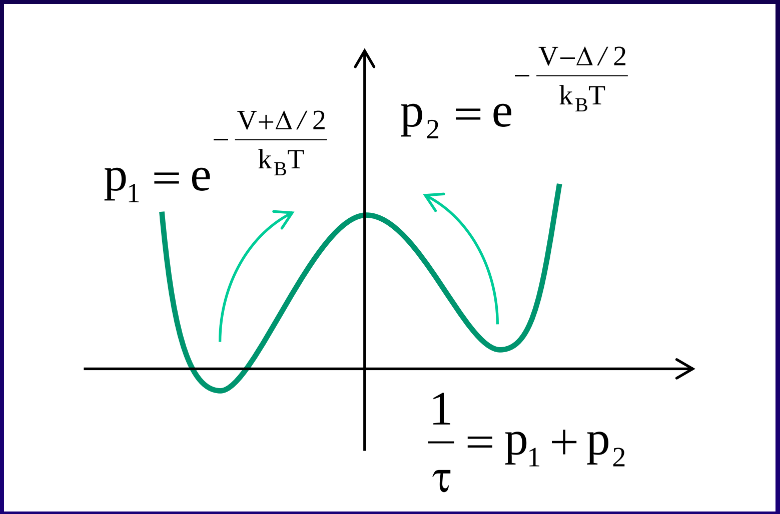






The ADWP model

K. S. Gilroy and W. A. Phillips Philosophical Magazine B, 1981, Vol. 43, No. 5, 735–746

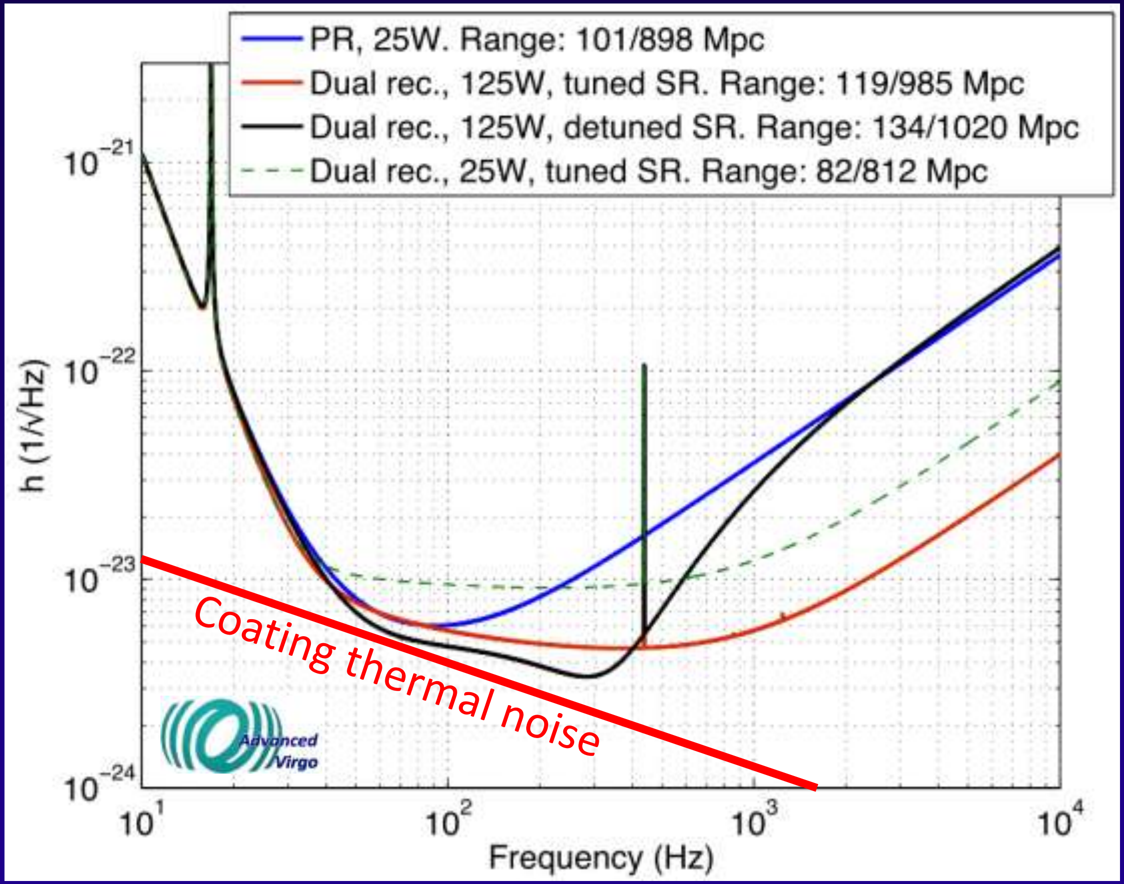


- Distribution of local minima in the configuration space, separated by energy barriers (energy landscape)

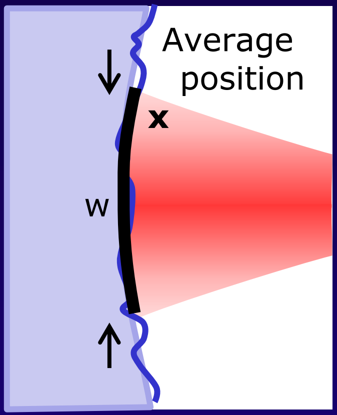
$$\tau = \tau_0 \operatorname{sech}\left(\frac{\Delta}{2k_B T}\right) \exp\left(\frac{V}{k_B T}\right),$$

- Relaxations too fast or too slow with respect to the typical observational time (from 10^{-1} s to 10^{-4} s) do not contribute to the noise
- The barrier height distribution f(V) and the asymmetry distribution g(Δ) shape the frequency and temperature dependence of noise

How important is the coating thermal noise?



From noise to losses



Fluctuation-Dissipation Theorem

$$S_{xx} = 4 k_B T \cdot \frac{\Re\{Y(\omega)\}}{\omega^2}$$

$$Y(\omega) = Speed(\omega) / Force(\omega)$$

Harry G M *et al* 2002 *Class. Quantum Grav.* **19** 897–917

$$S_{xx} \approx 2 k_B T \frac{1-\sigma}{\sqrt{\pi^3} w Y_{sub}} \frac{\varphi_{eff}}{f}$$

Mechanical loss angle

Thermal Energy

1/Rigidity

The stratified structure of coatings makes || different from ⊥

$$\varphi_{eff} \approx \varphi_{sub} + \frac{d}{\sqrt{\pi} w} \left(\frac{Y}{Y_\perp} \varphi_\perp + \frac{Y_{||}}{Y} \varphi_{||} \right)$$

Coating thickness

- Strategies to reduce thermal noise
  - Reducing the temperature
  - Increasing the beam size
  - Reducing the coating thickness
  - Reducing the internal friction

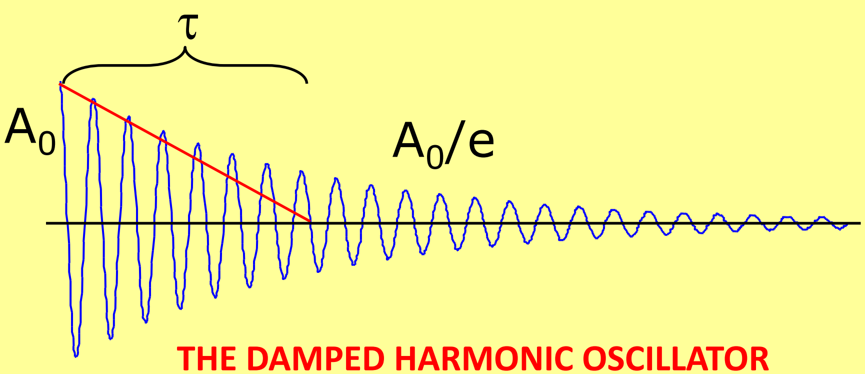
The loss angle

- Fourier's Transform of the modulus e(t)

$$\sigma(t) = \int_{-\infty}^{t} e(s-t)\cdot\varepsilon(s)\,ds$$

$$\sigma(\omega) = \left[\mathrm{E_R}(\omega) + i\,\mathrm{E_I}(\omega)\right]\cdot\varepsilon(\omega)$$

THE LOSS ANGLE → $\varphi(\omega) \sim \frac{\mathrm{E_I}(\omega)}{\mathrm{E_R}(\omega)}$



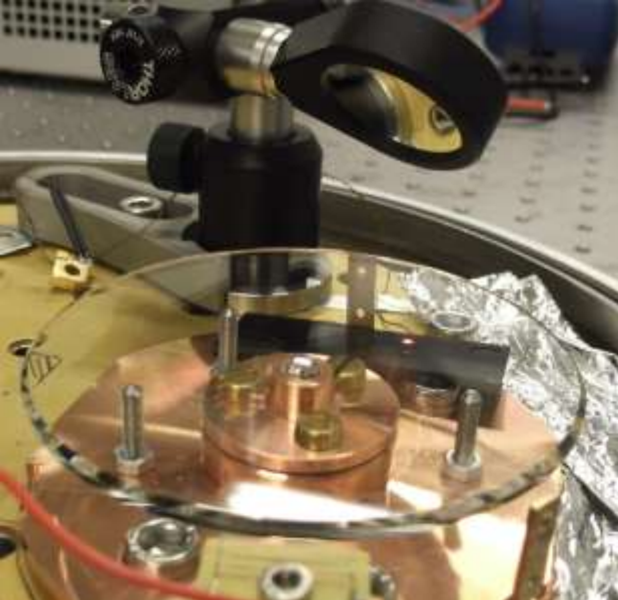
THE DAMPED HARMONIC OSCILLATOR

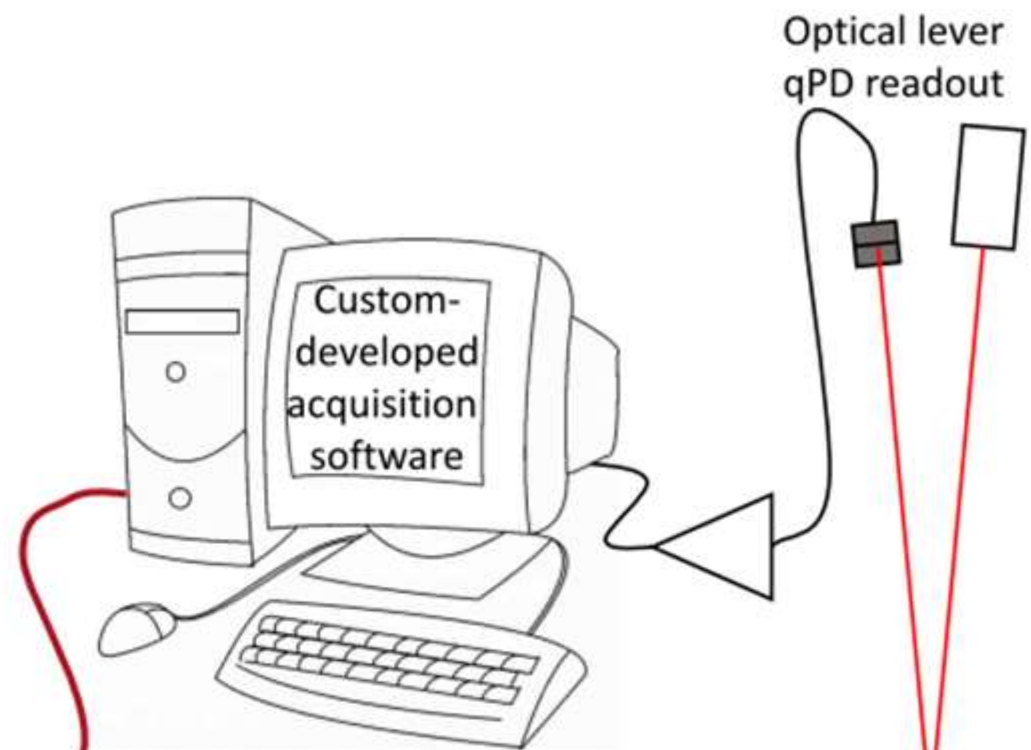
$$Q = \frac{2\pi\,E_{Stored}}{E_{dissipated}} = \pi\,f_0\,\tau$$

$$\varphi = \frac{1}{Q}$$

OPERATIVE DEFINITION OF φ

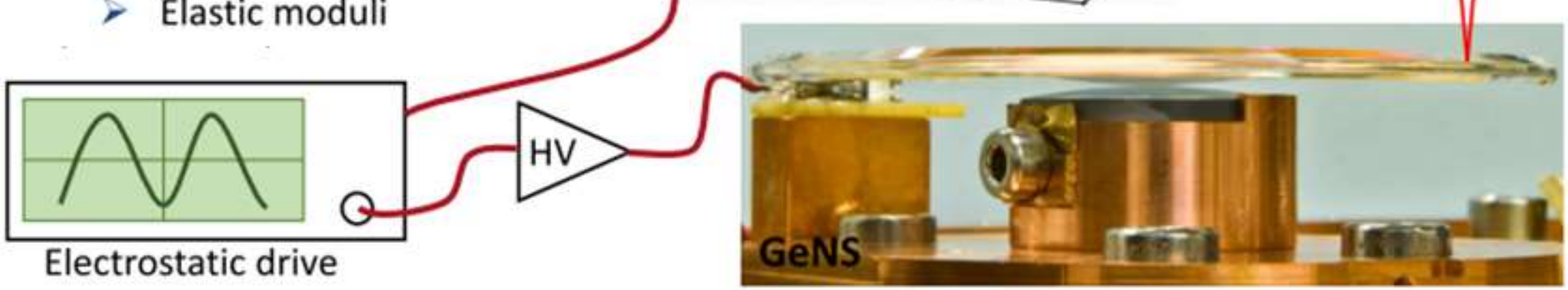
How to measure φ: GeNS





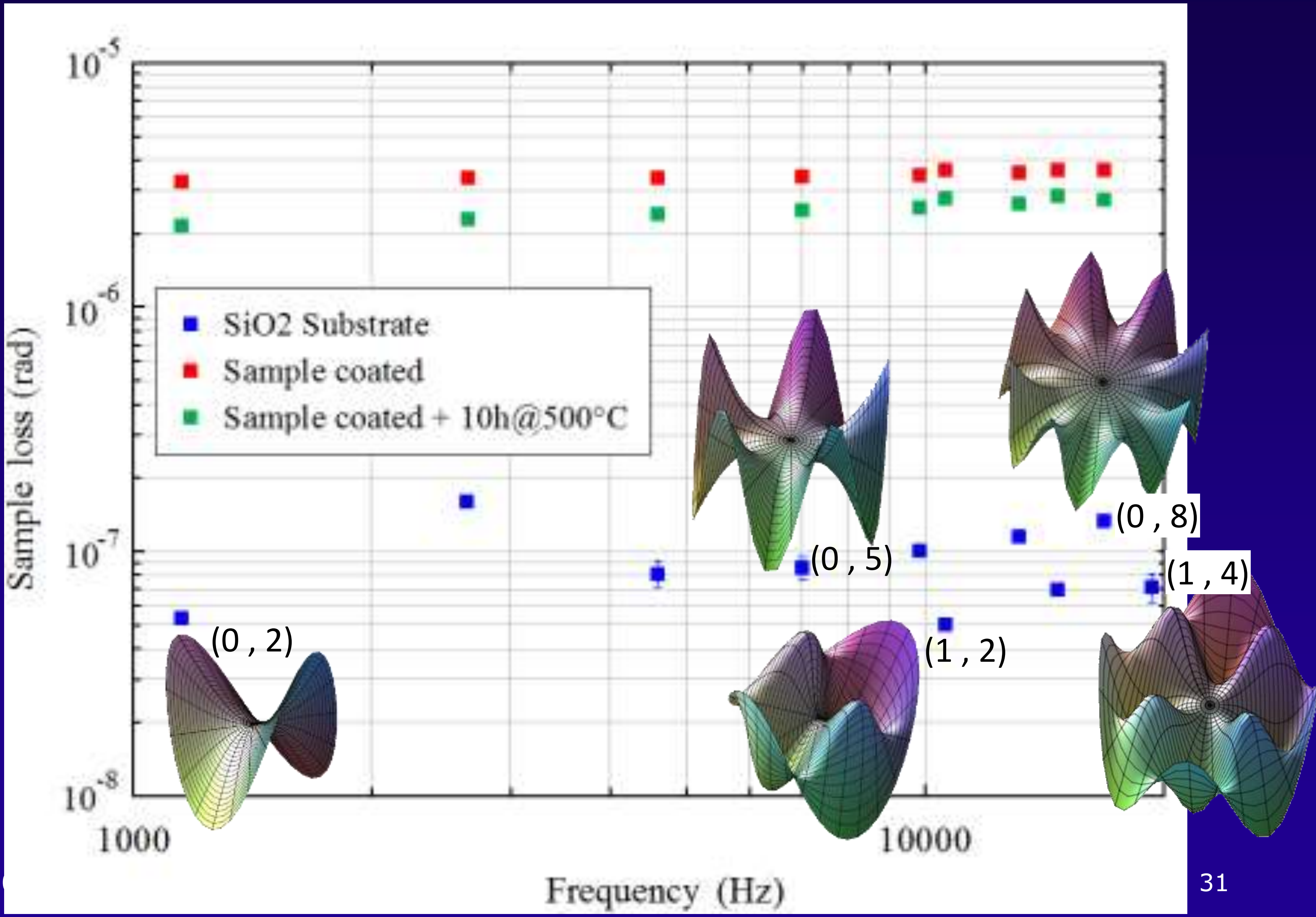
GeNS – Gentle Nodal Suspension

- Clamp free
- High repeatability
- Non-destructive measures of:
  - Dilution factor
  - Mechanical loss
  - Elastic moduli



Granata & al, *Archives of Metallurgy and Materials* 60,1 (2015)
Cesarini & al, *Class. Quantum Grav.* 27 (2010)
Cesarini & al, *Rev. Sci. Instrum.* 80 (2009)

Examples of internal friction measurements

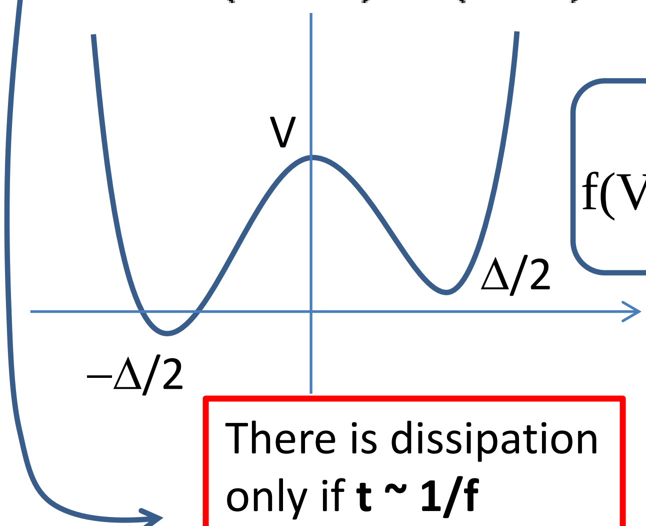


- Materials used in AdV coatings
  - ♦ Silica (SiO_2)
  - ♦ Mixing Tantala-Titania (Ta_2O_5-TiO_2)
- Next:
  - ♦ What we know about their internal friction

TLS model in fused silica

- Fused silica has a large density of TLS
- Esponentially distributed over the barrier energy V

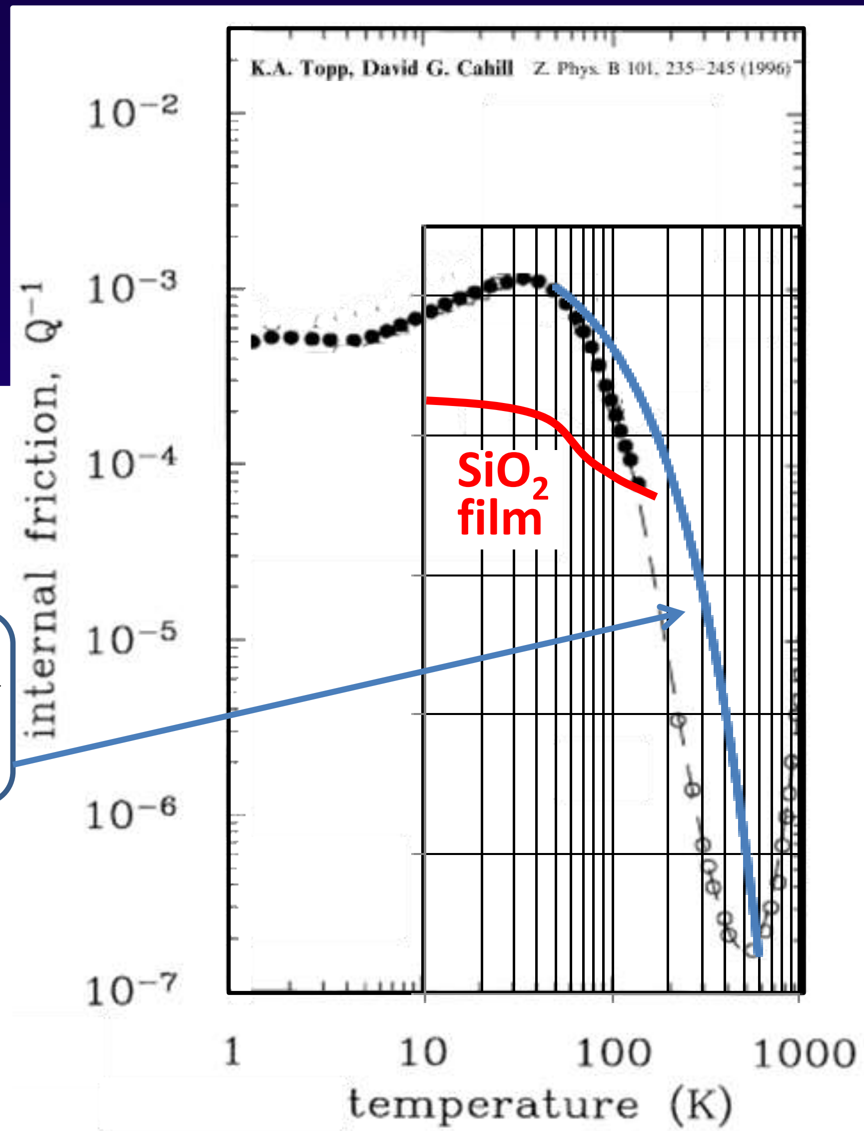
$$\tau = \tau_0 \operatorname{sech}\left(\frac{\Delta}{2k_B T}\right)\exp\left(\frac{V}{k_B T}\right),$$



$$f(V) = f_0 \cdot e^{-\frac{V}{25\text{meV}}}$$

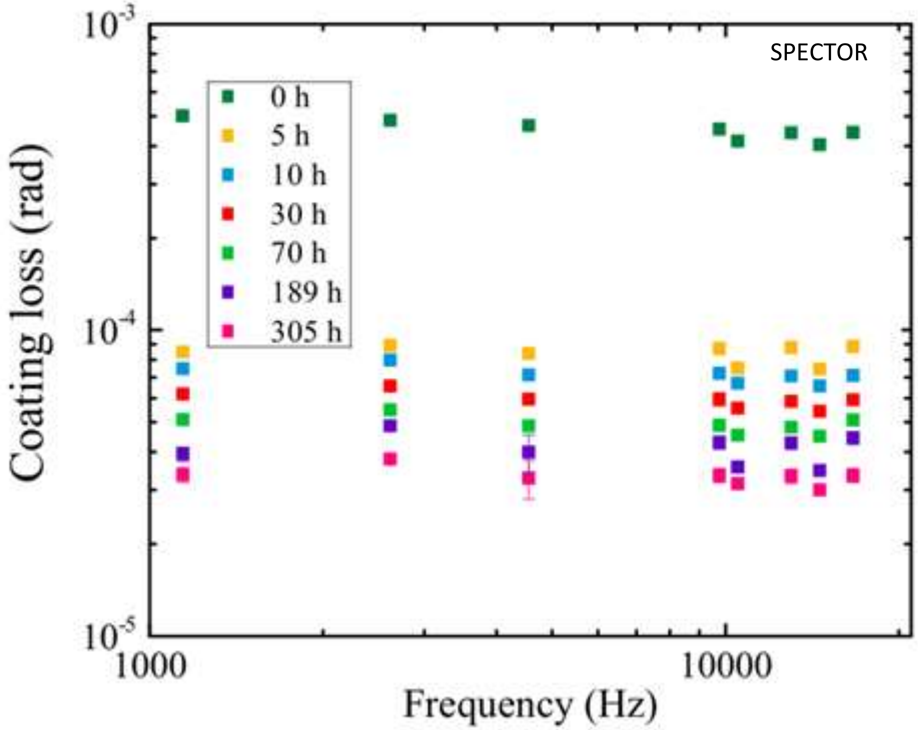
There is dissipation only if **t ~ 1/f**

F. Travasso et al. / Materials Science and Engineering A 521–522 (2009) 268–271

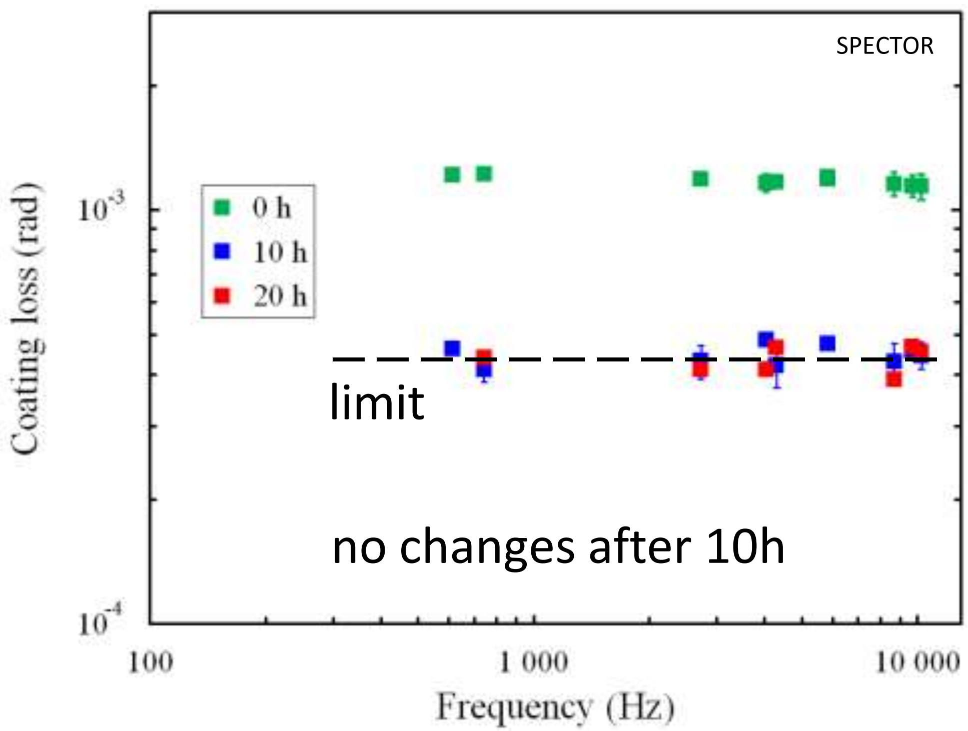


Silica vs Tantala film friction evolution during annealing

SiO2

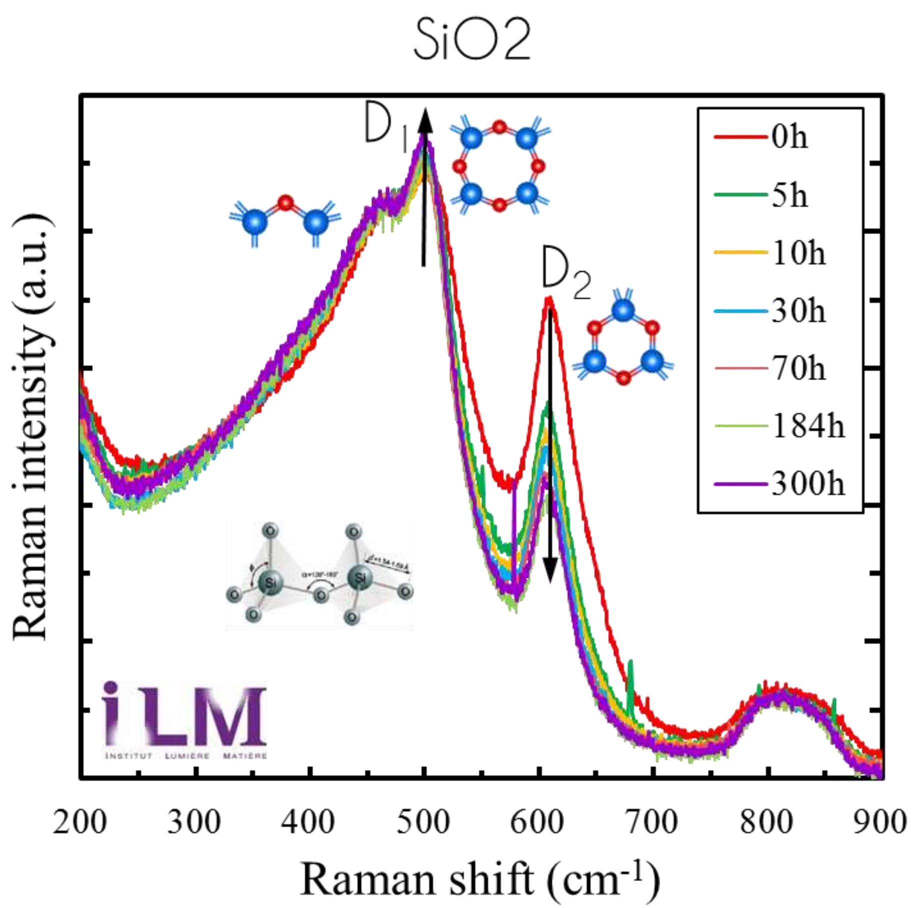


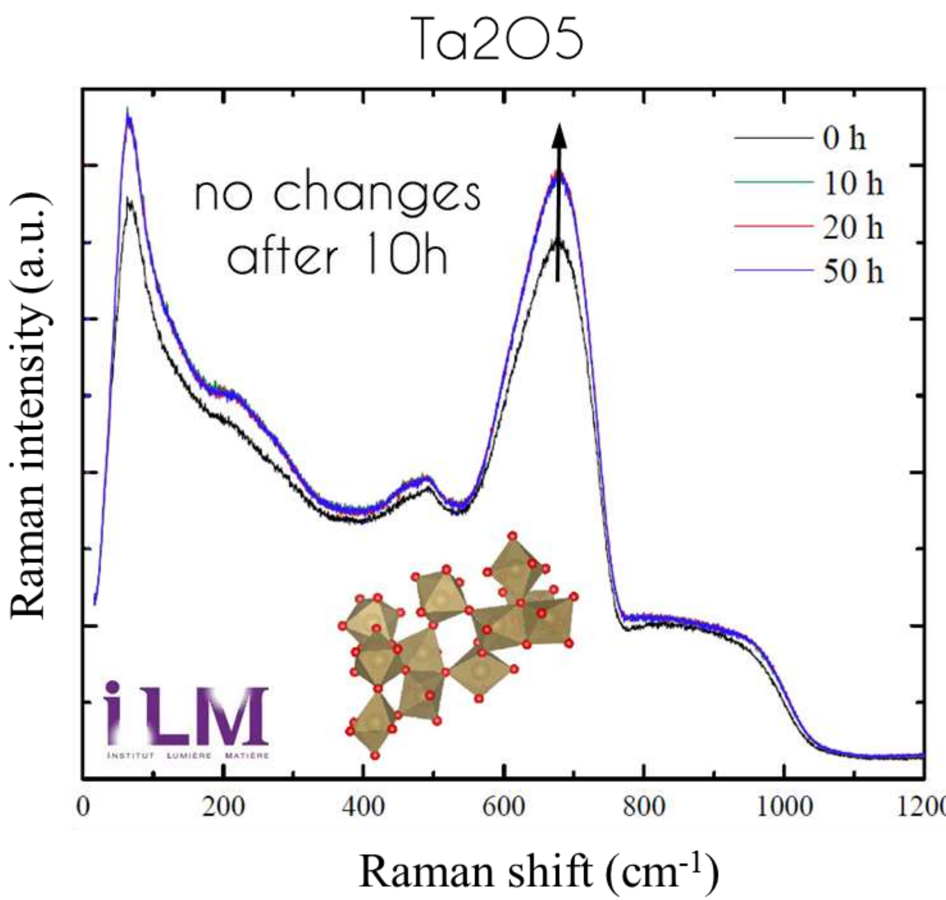
Ta2O5



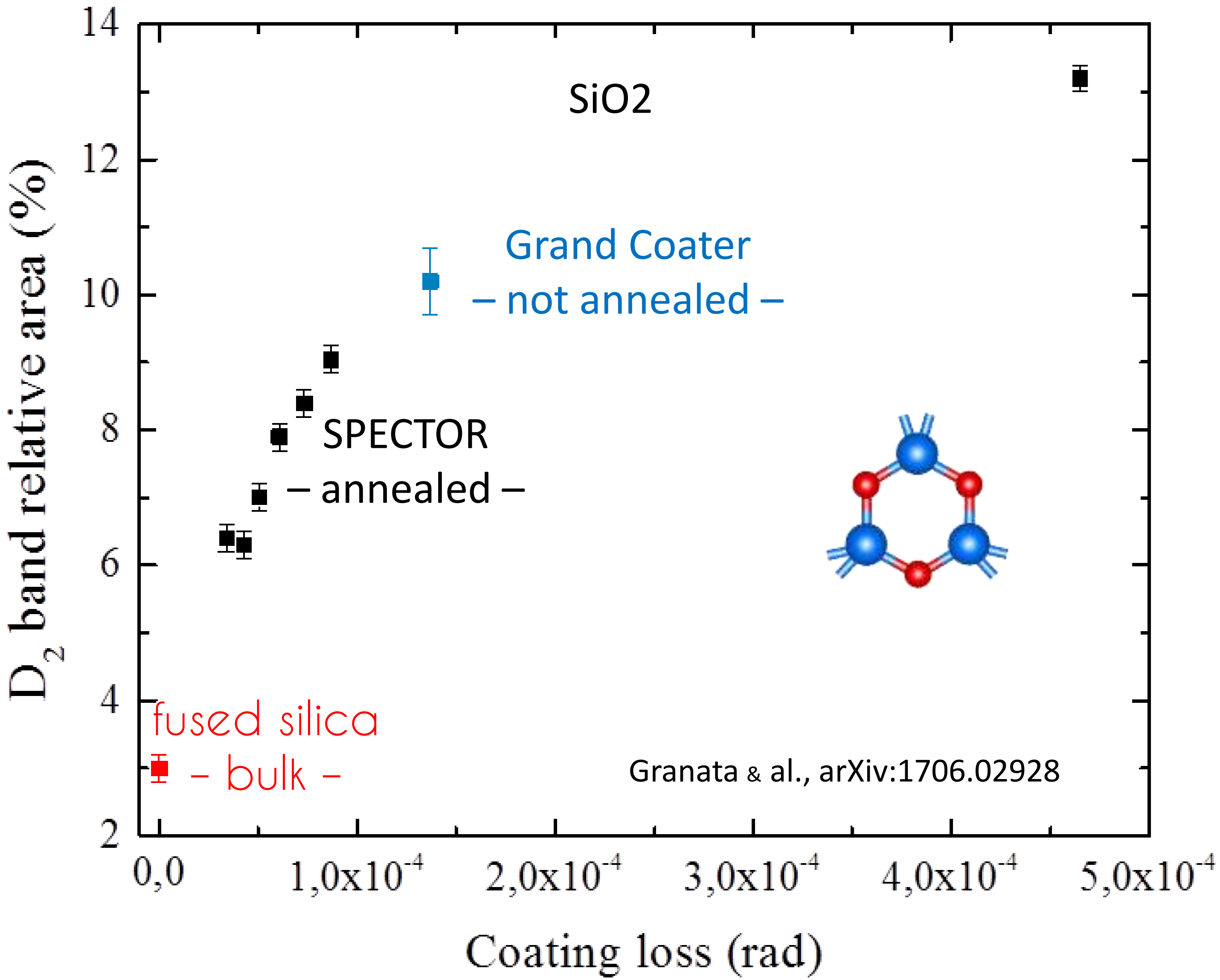
T_a = 500° C

Silica vs Tantala films structure evolution during annealing

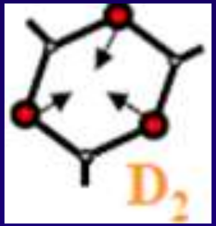


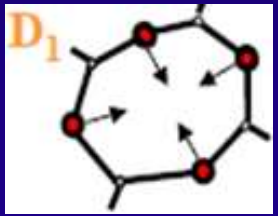


The correlation D_2-φ



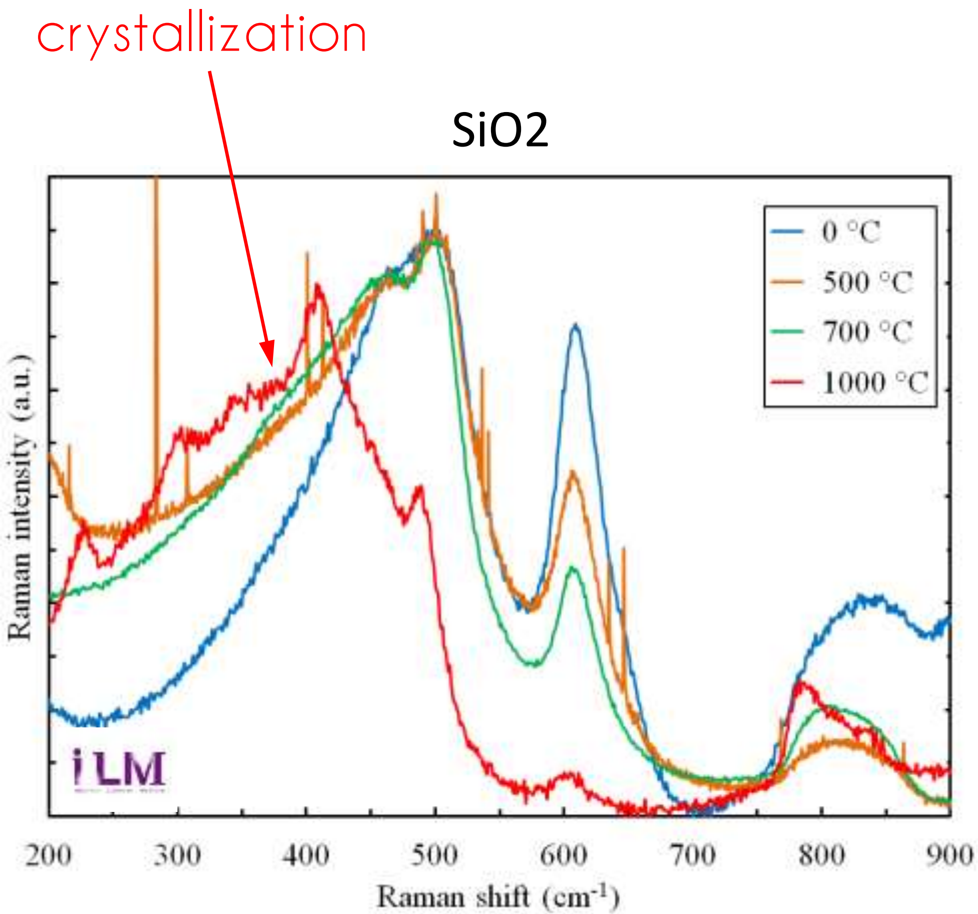
Why there is a correlation?

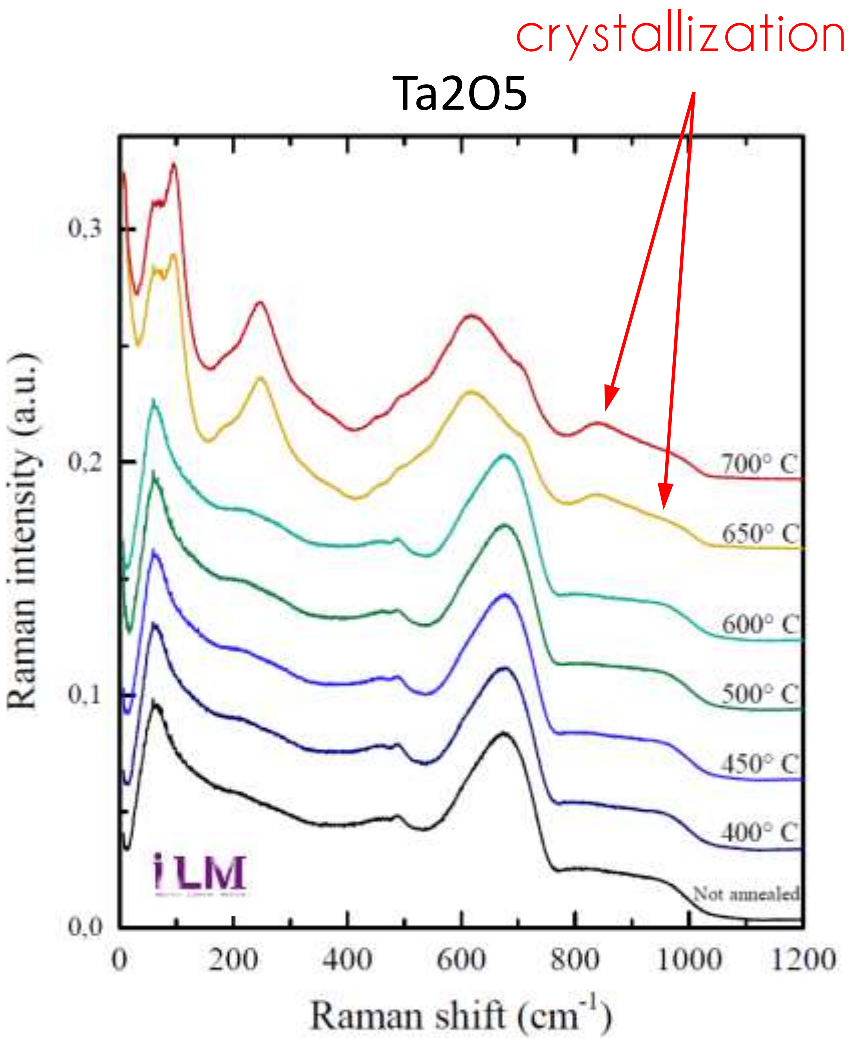
- At room temperature and at f~1 kHz losses come from TLS with V~0.5 eV
- Activation energy of 

is ~0.43 eV
- Activation energy of 

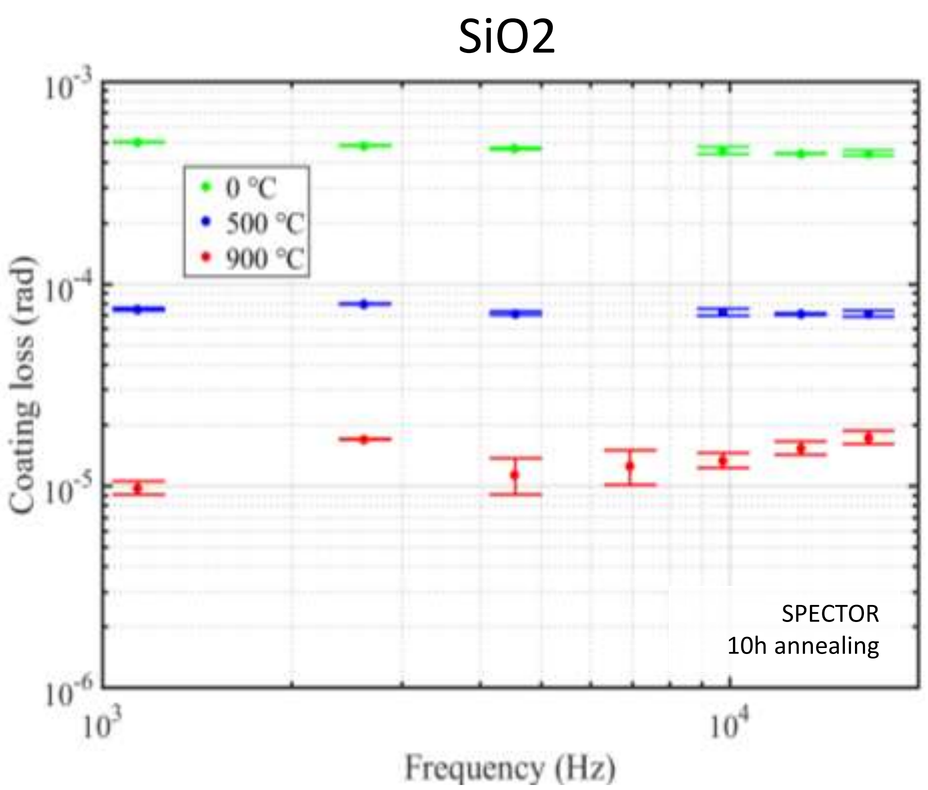
is ~0.14 eV
- Annealing might re-shape the barrier height distribution

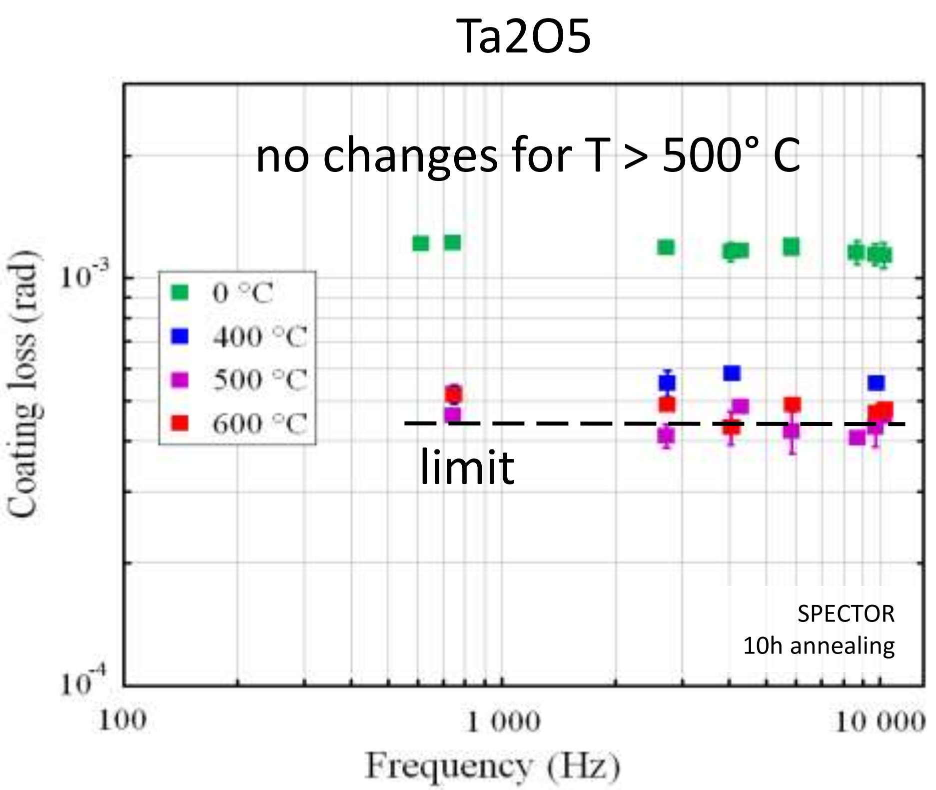
Silica vs Tantala films structure evolution at different T



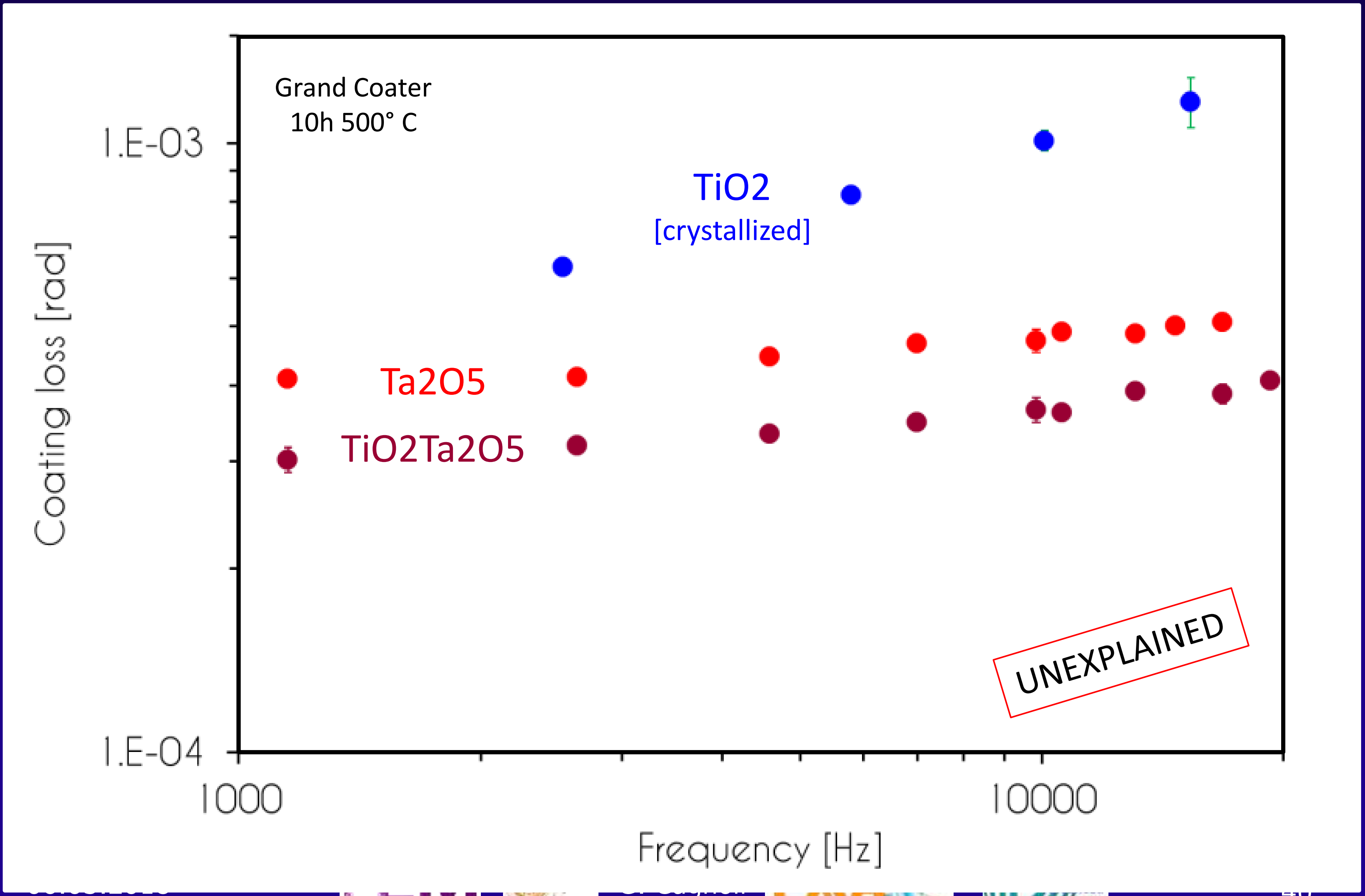


Silica vs Tantala frction evolution at different T



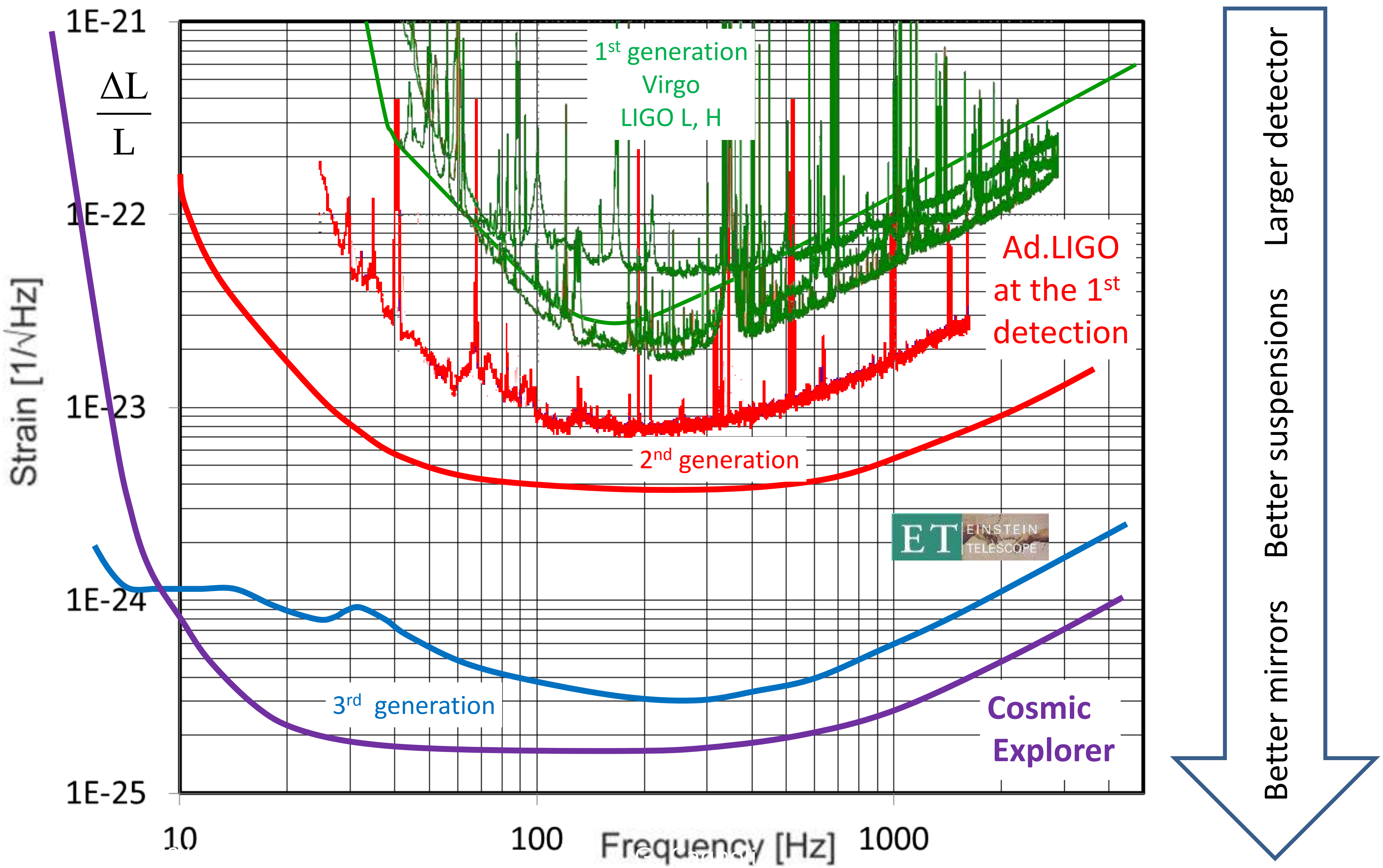


Mixing oxides sometimes works !

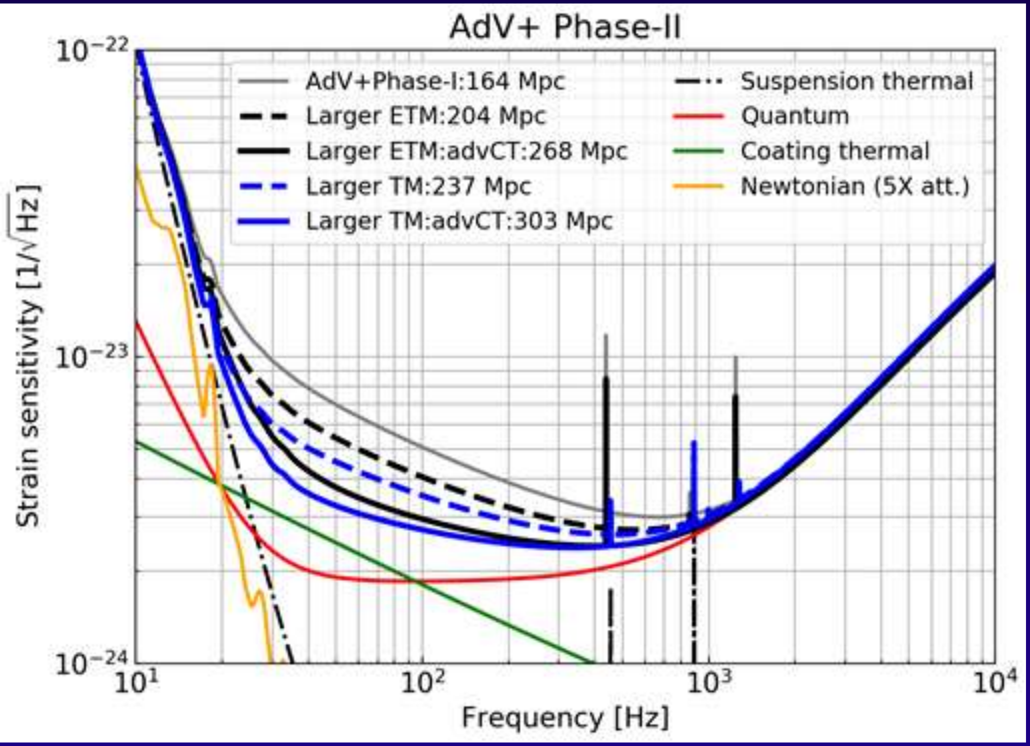


The future

Detector generations

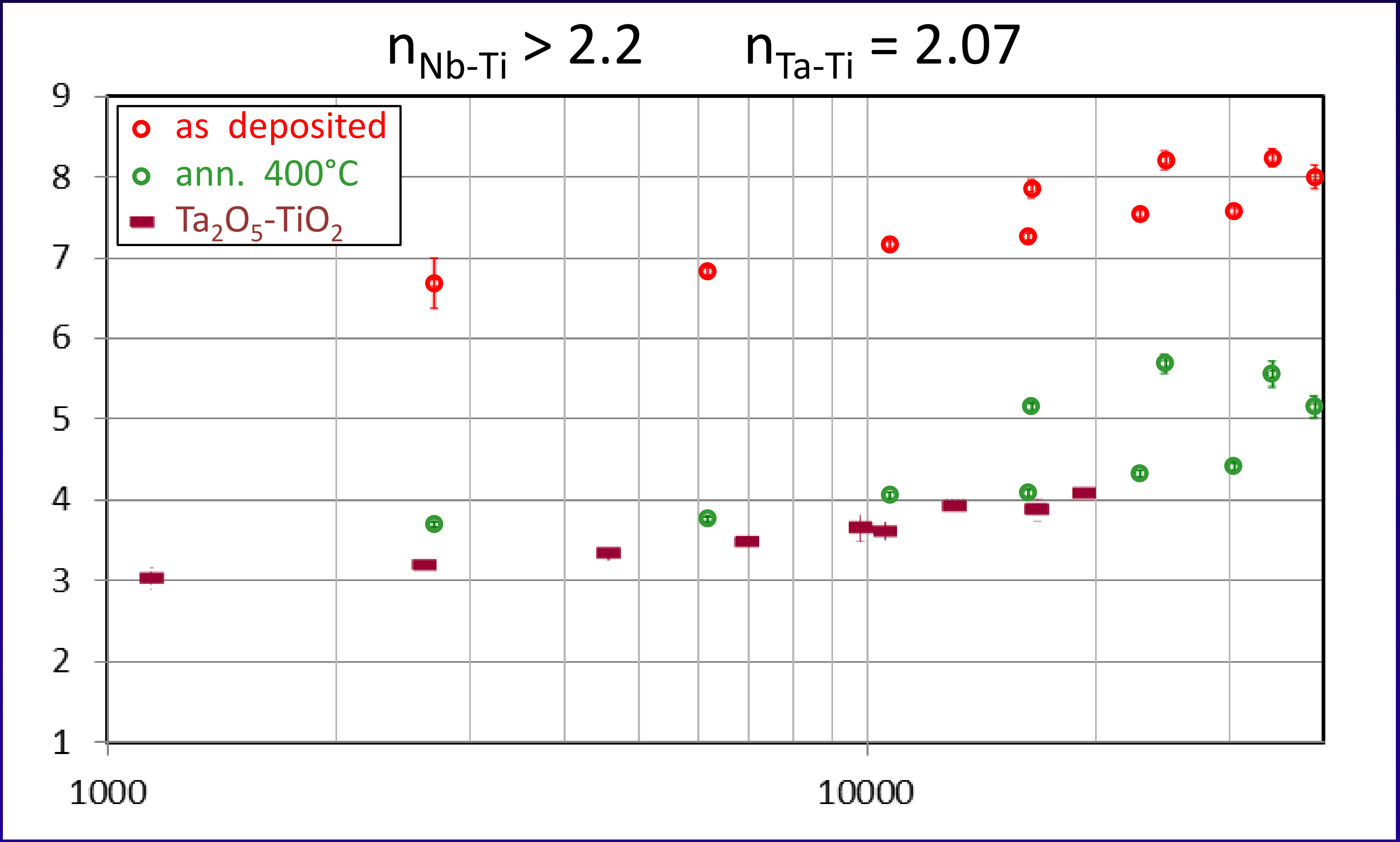


AdV+: a possible upgrade of Advanced Virgo



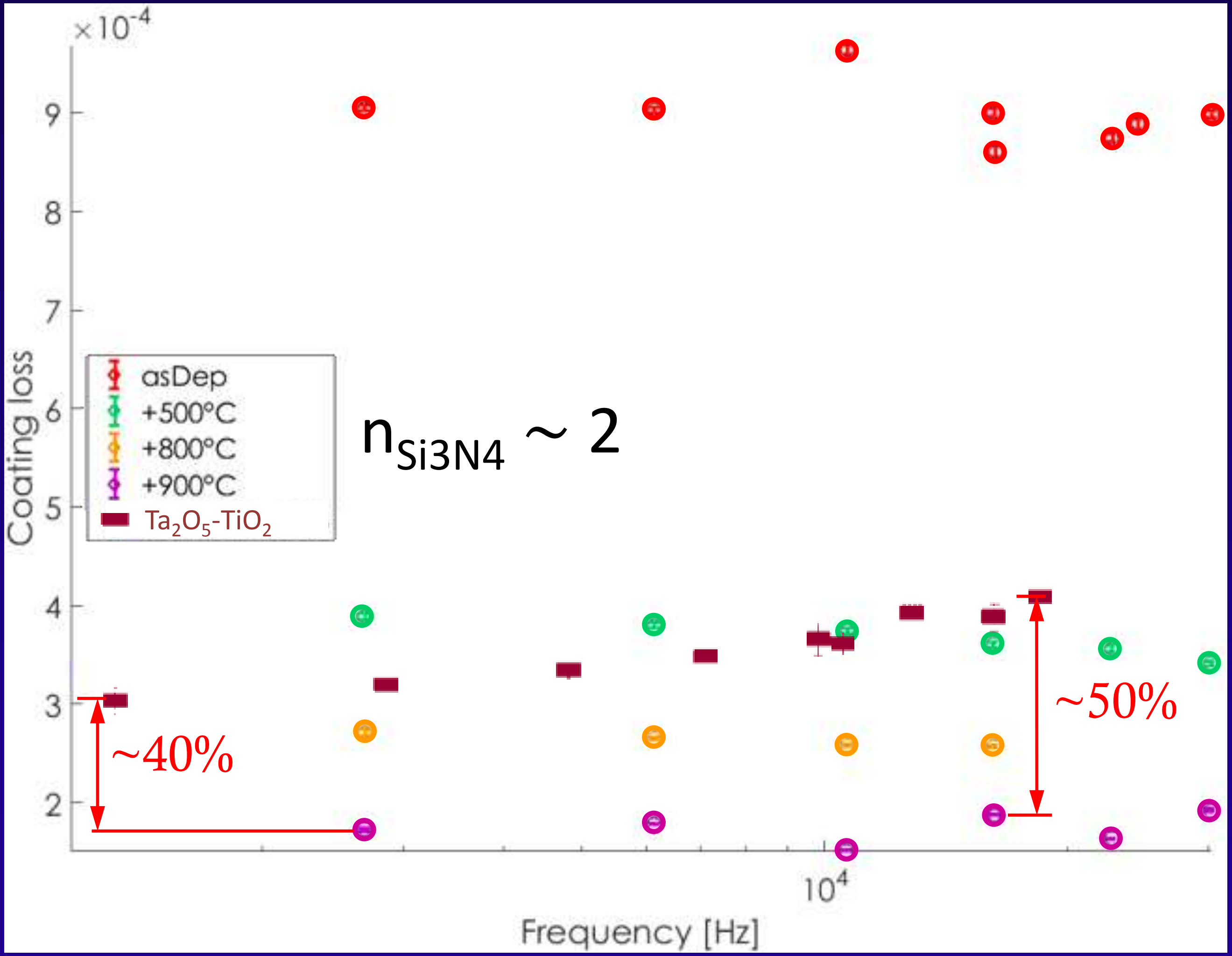
- Spot size and mirrors
  - ♦ × 1.57
- Internal friction
  - ♦ ÷ 3
- Newtonian noise cancellation
  - ♦ Factor 5

New materials: Nb_20_5-$Ti0_2$



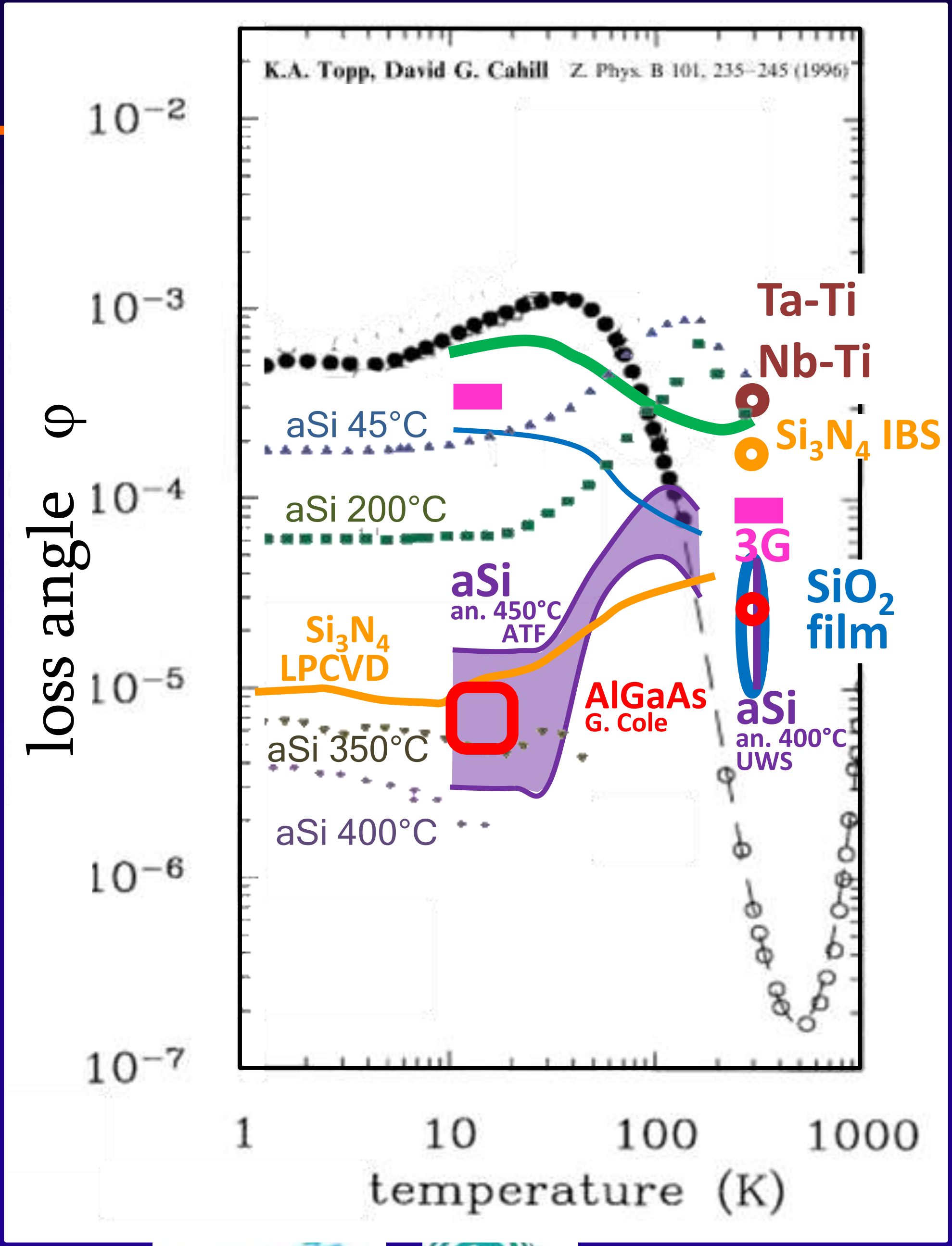
New materials: Si_3N_4 (IBS)

Inspired by the work of Xiao Liu   Liu X. et al., Mater. Res. Soc. Symp. Proc. 989 (2007)



Materials panorama

- Multilayer coating (HR)
  - Granata M. et al., OPT. LETT. 38 (24) 5298(2013)
  - Granata M et al., PRD 93, 012007 (2016)
- aSi from 45° to 400°
  - Liu X. et al. PRL 113, 025503 (2014)
- Si_3N_4 LPCVD
  - Liu X. et al. Mater. Res. Soc. Symp. Proc. Vol. 989 (2007)
- AlGaAs
  - Crystalline coatings G. D. Cole, SPIE Optics & Photonics, 8458–07 2012

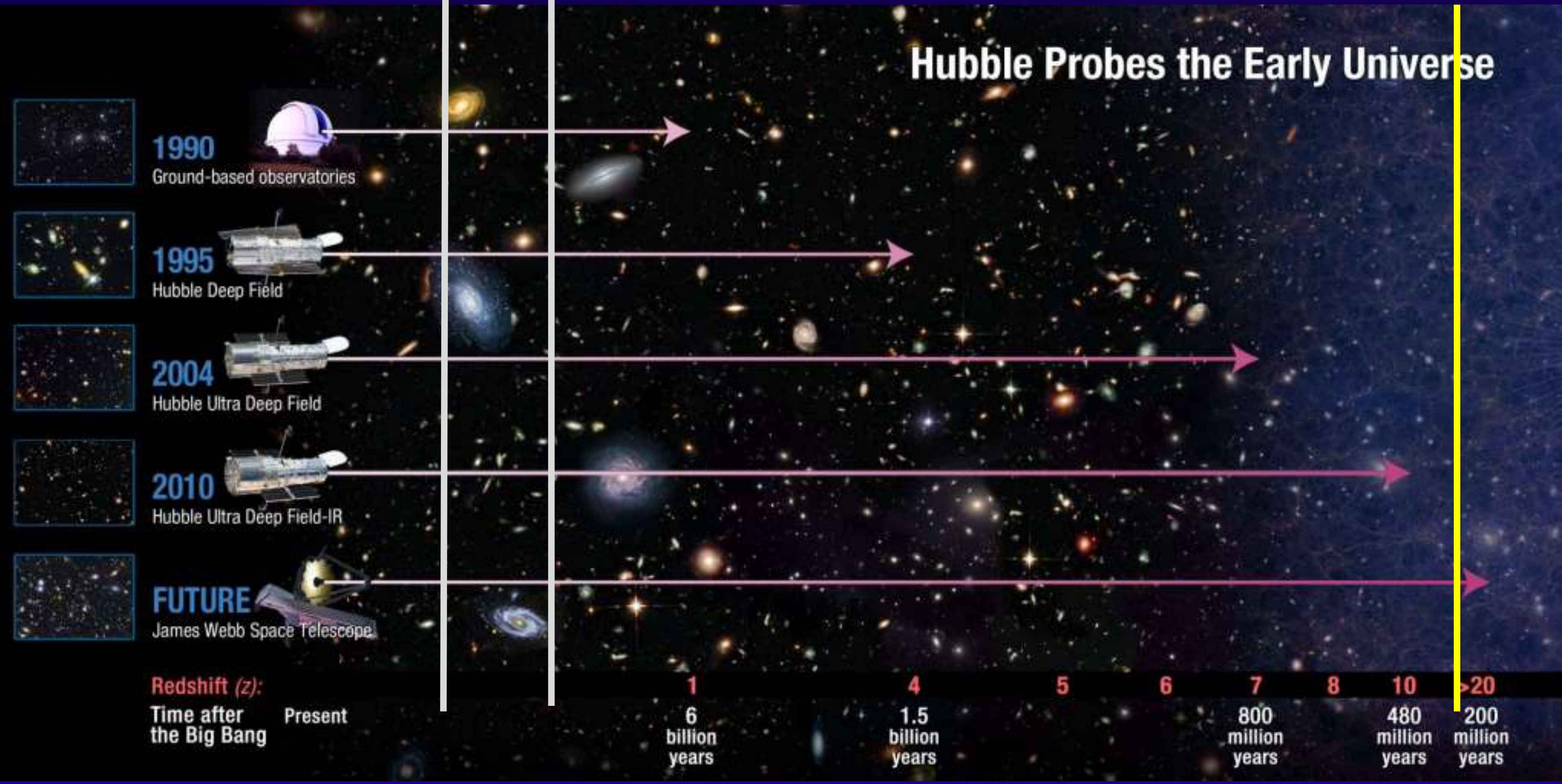


GW150914

See you at the other end of the Universe !!

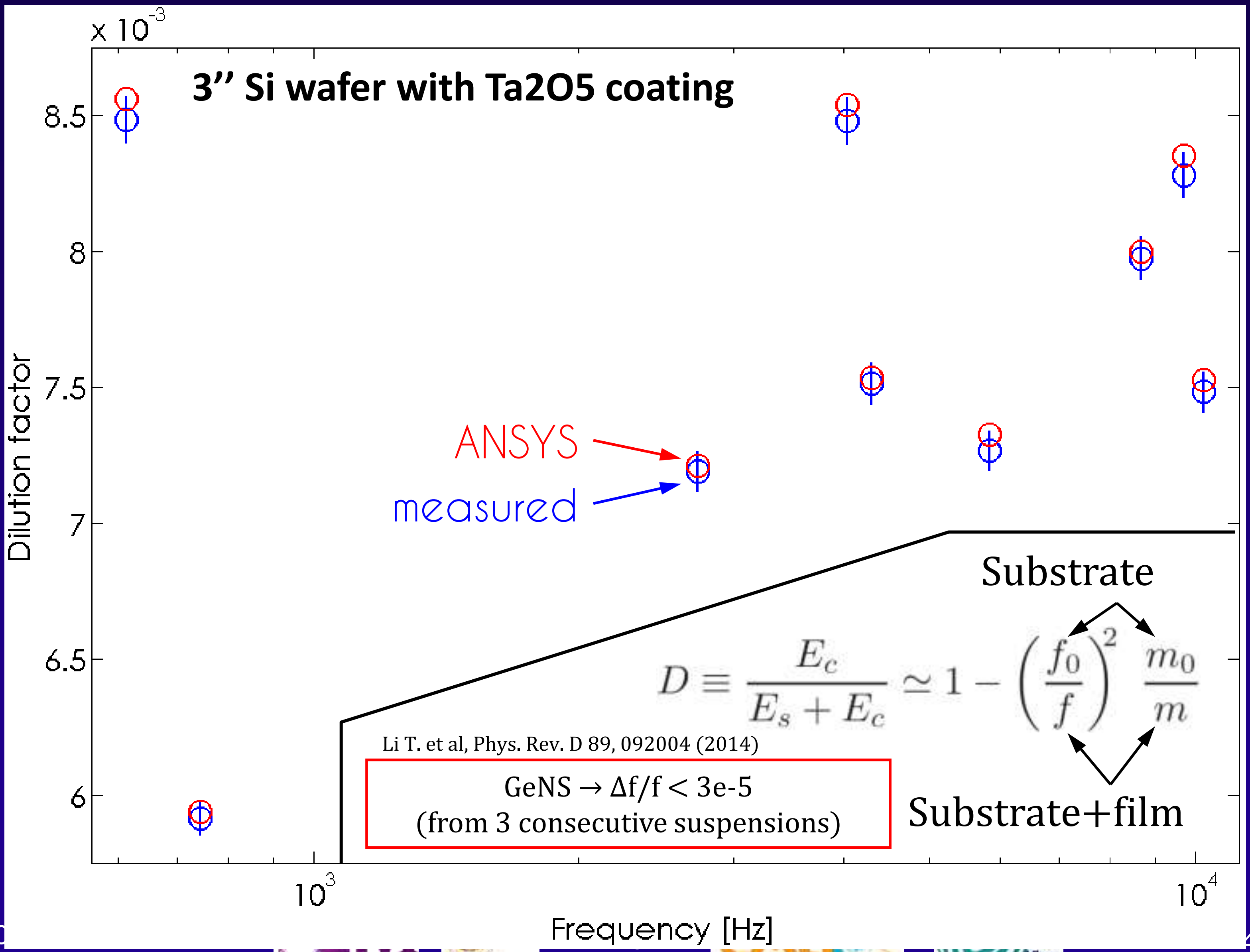
3rd Gen. maximum detection distance

GW170104

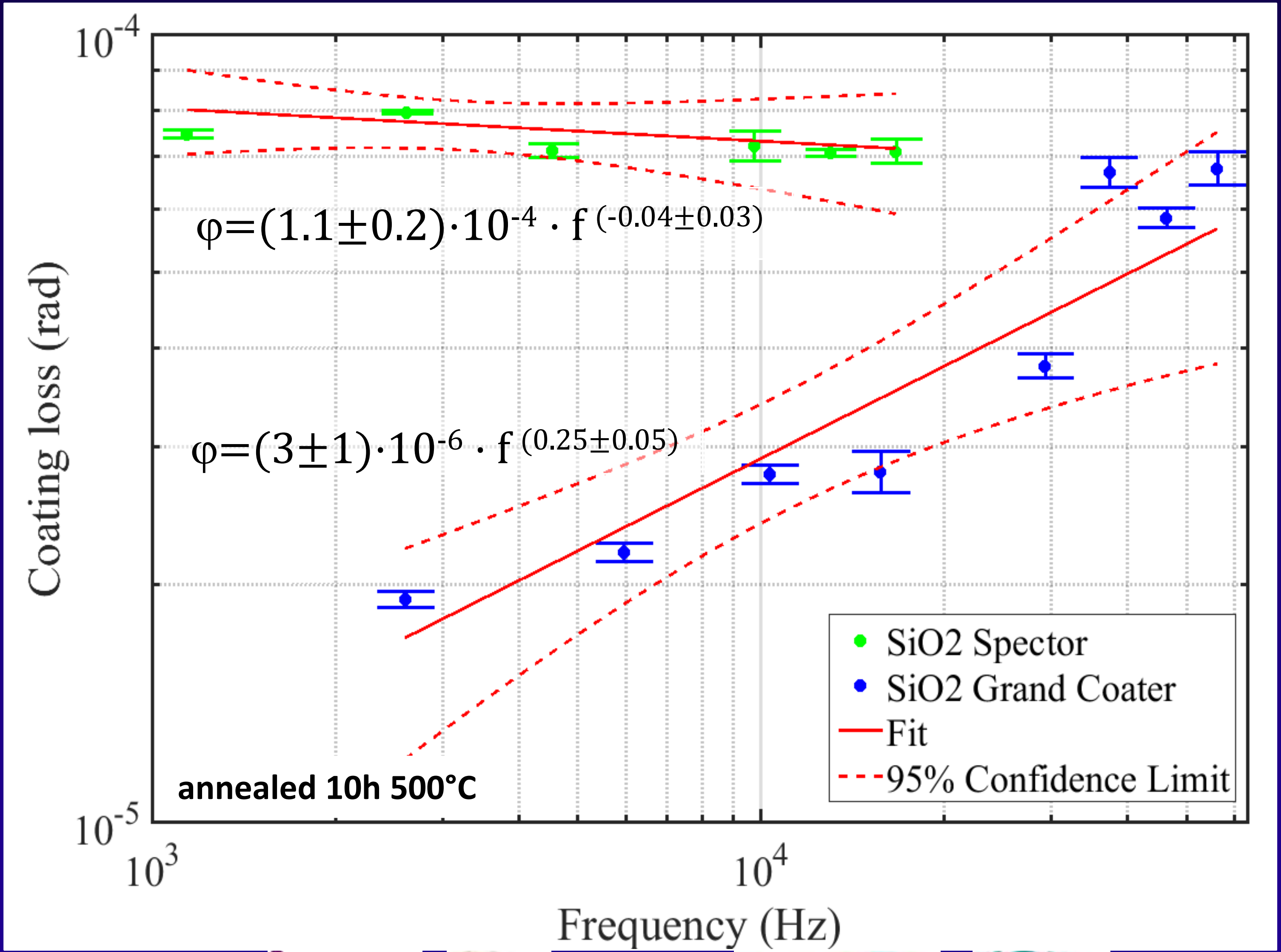


Thank you for your attention

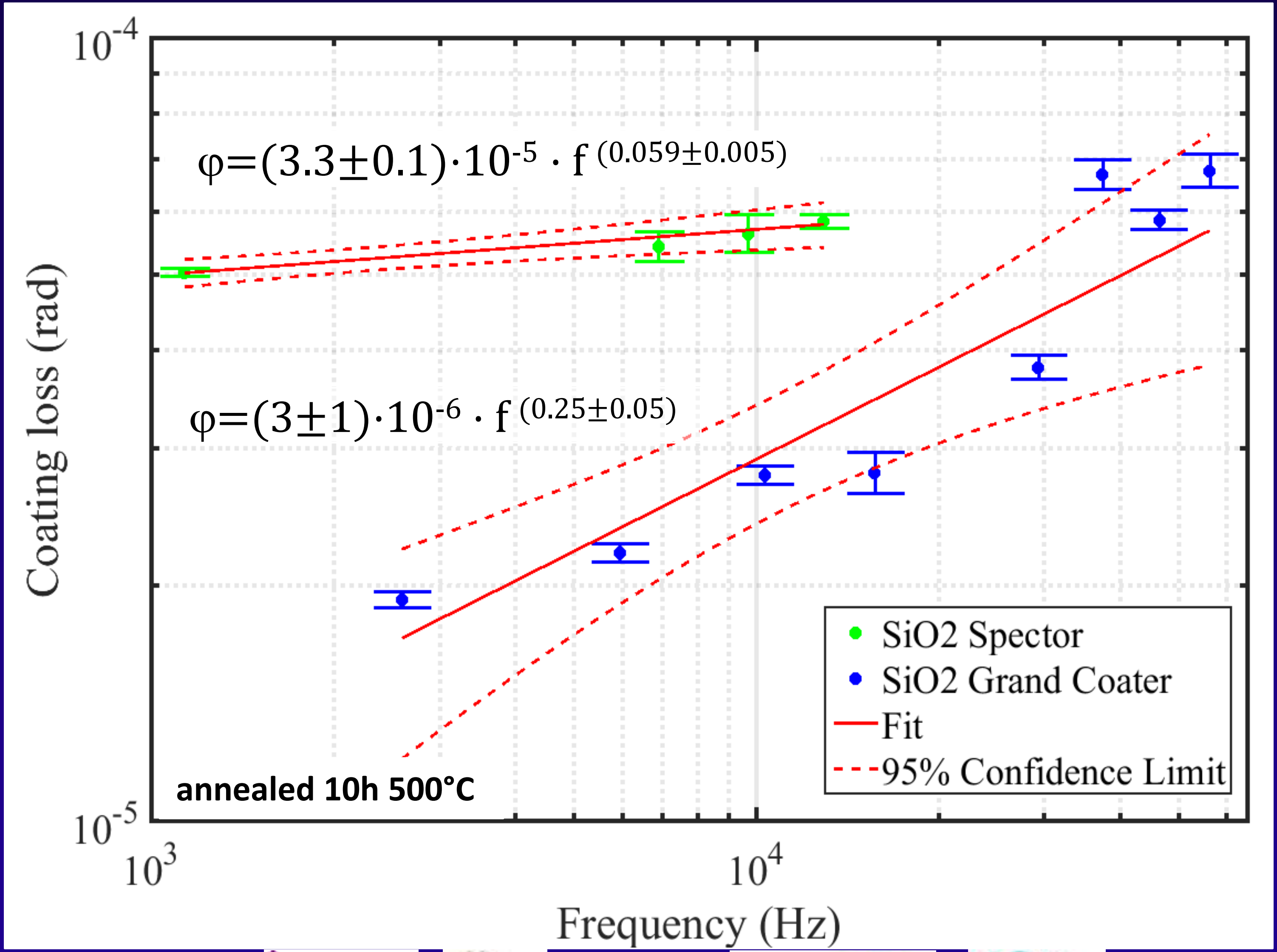
Measurement of the dilution factor



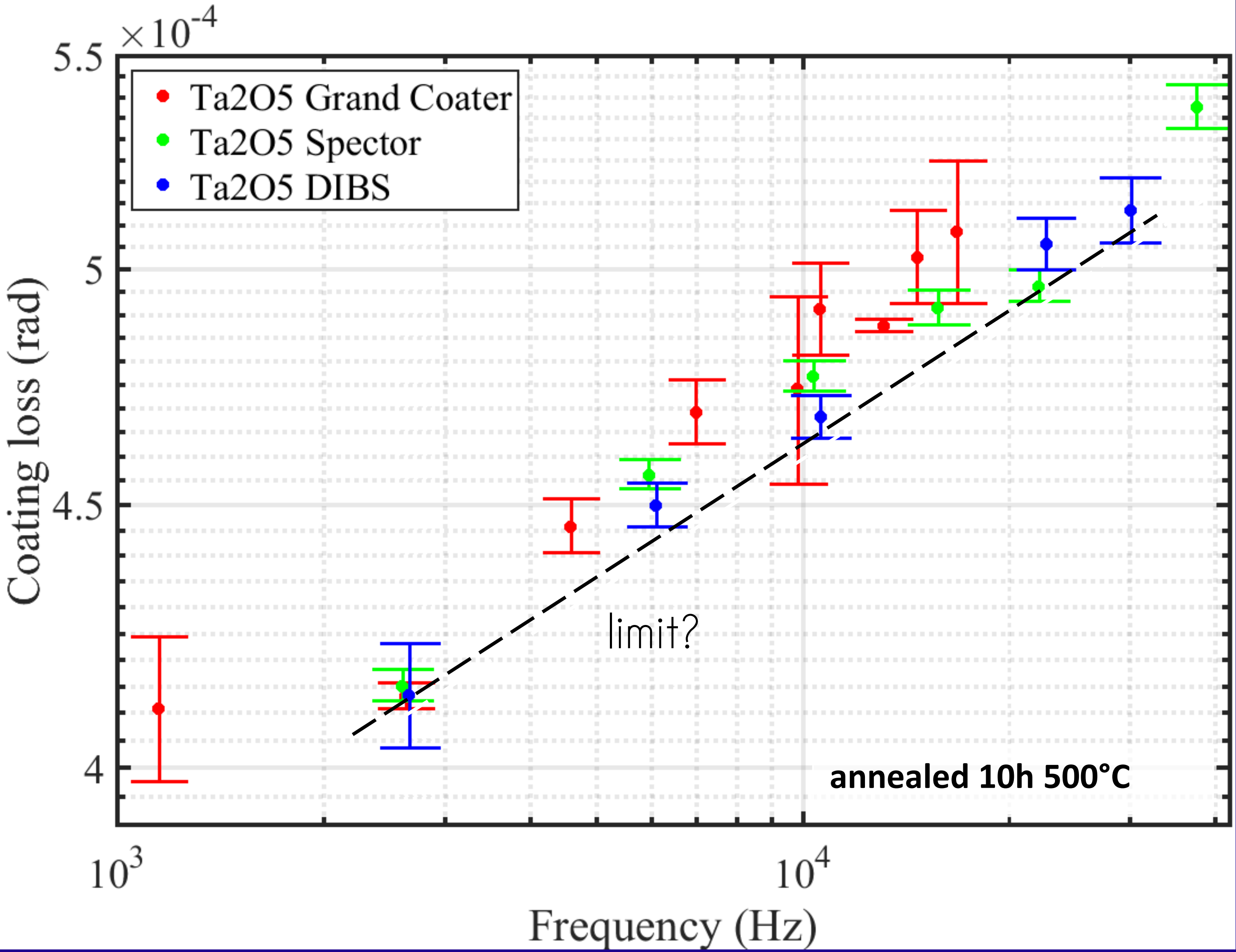
Silica
different coaters and parameters



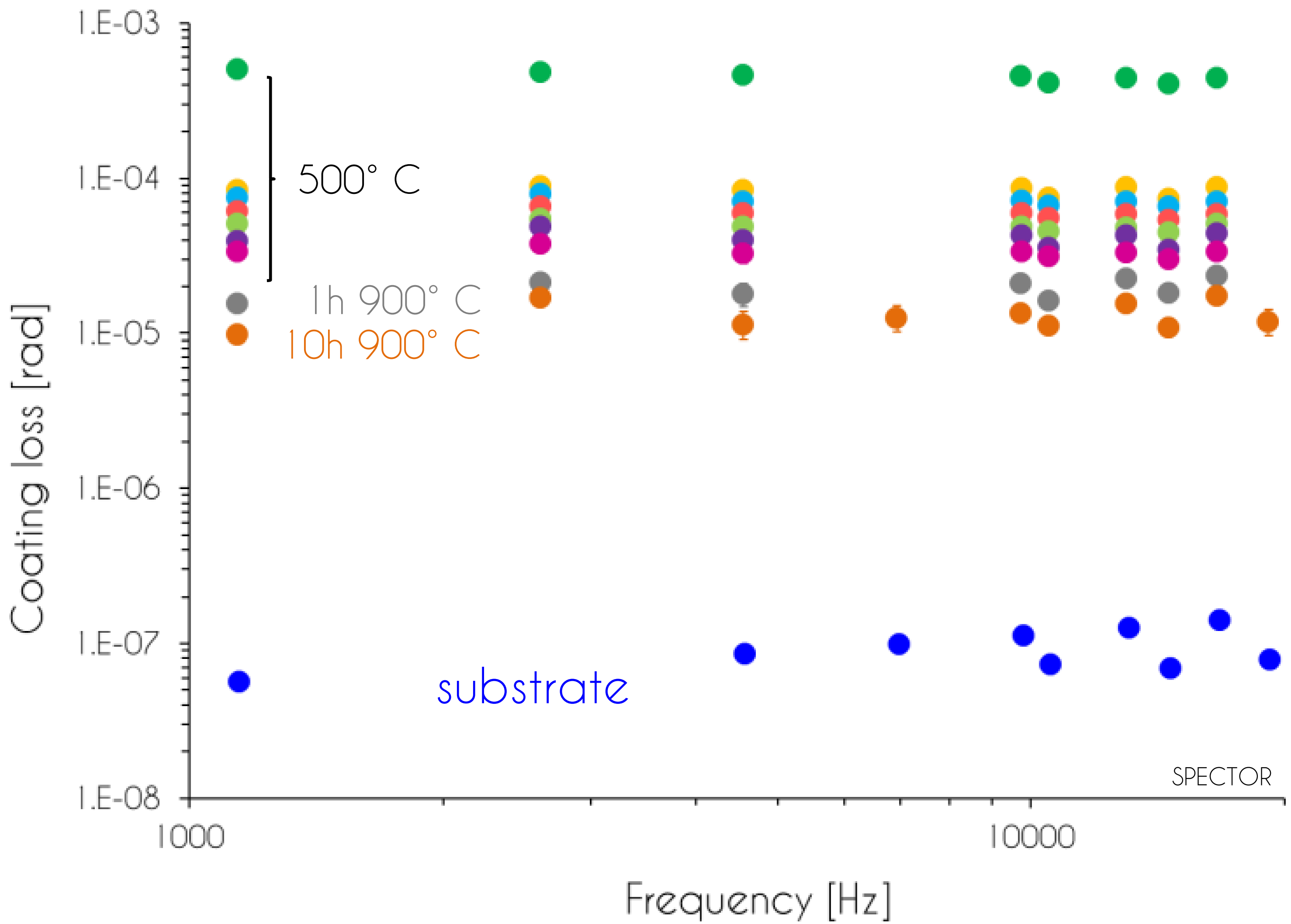
Silica
different coaters same parameters



Tantala
different coaters and parameters



SiO2 evolution



New materials: Nb_20_5-$Ti0_2$