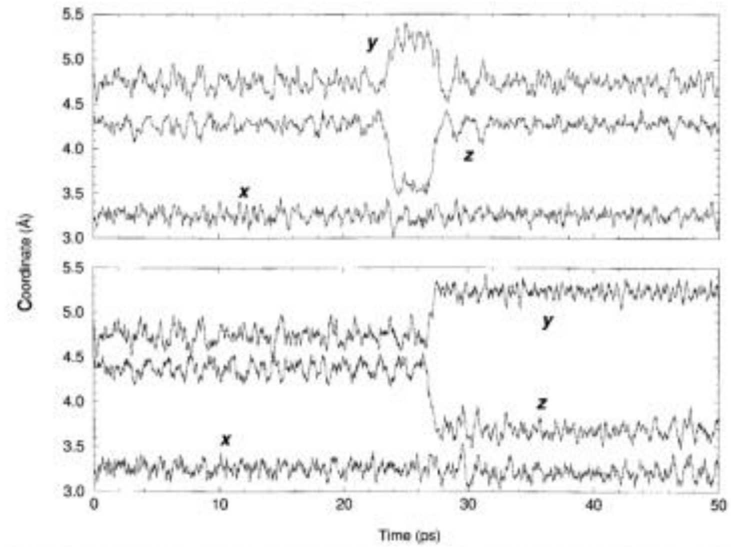
Coating thermal noise in AdV+

Matteo Lorenzini
on behalf of the Virgo collaboration

Thermal Noise

GENERAL FACTS:

- Thermal noise is a feature of **linear, dissipative systems** at thermal equilibrium
- Mechanical thermal noise is due to irreversible processes associated to typical **time constants** and **energy scales**
- These processes make possible a **leakage of energy** from quasi-normal modes to the off-resonance part of the spectrum
- The same mechanisms are responsible of the vibrational **energy dissipation** and of the **thermal fluctuations**

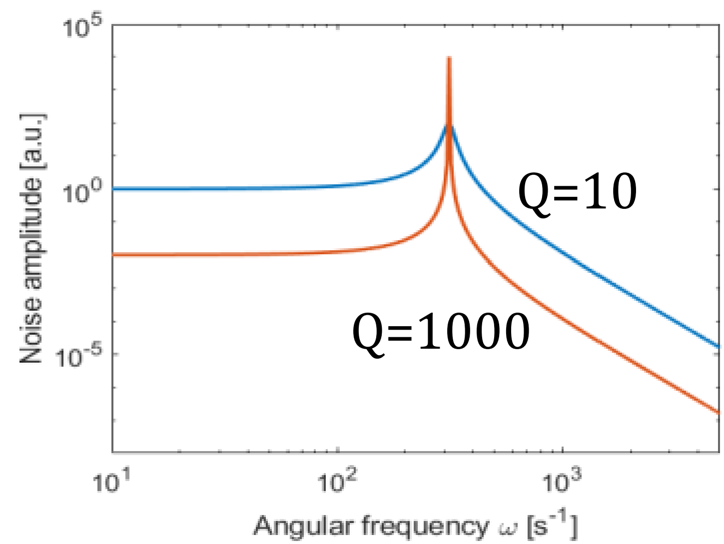


$$S_{xx}(\omega) = \frac{4k_B T}{\omega^2} Re(Y(\omega))$$

Fluctuation-dissipation theorem
H. B. Callen, T. A. Welton (1951)

The dissipative behaviour of the system is quantified by the **loss angle** $\phi(\omega)$.

$$\varphi = \frac{1}{Q} \quad \text{@QNM}$$



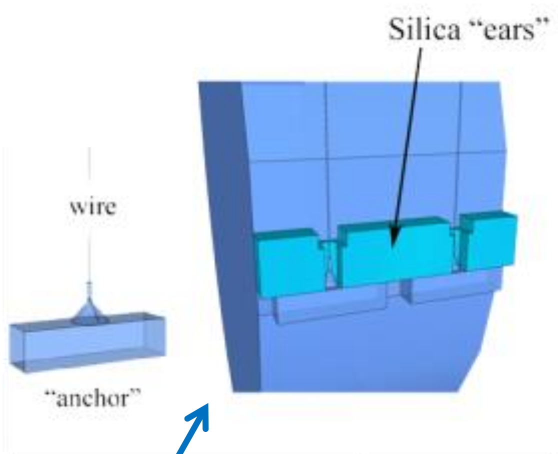
Thermal noise in GW detectors

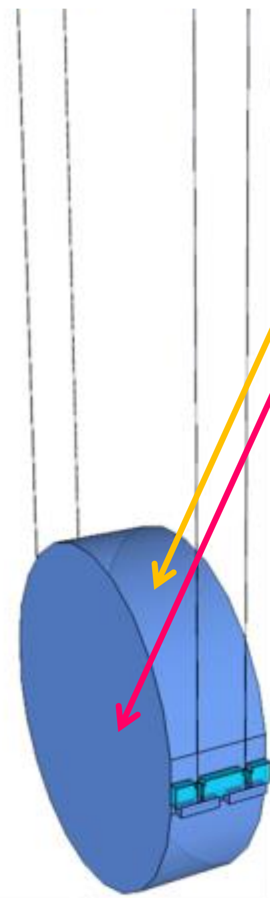
Thermal noise results in a source of **displacement noise** at the level of the test masses of GW detectors.

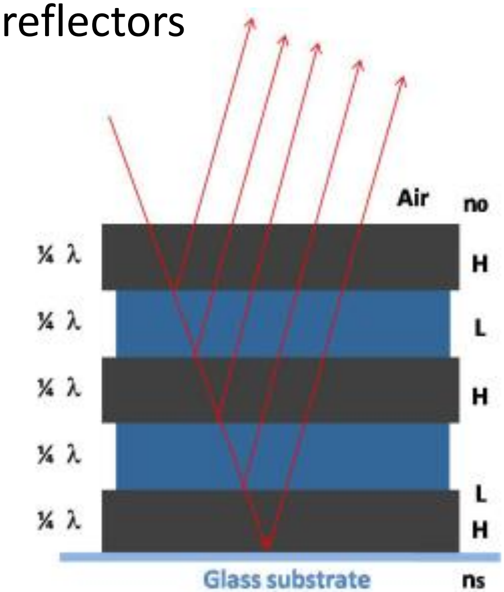
tens Hertz – hundreds Hertz

Mirror Thermal noise

- Fused Silica Bulk
- Multilayer thin film Bragg reflectors







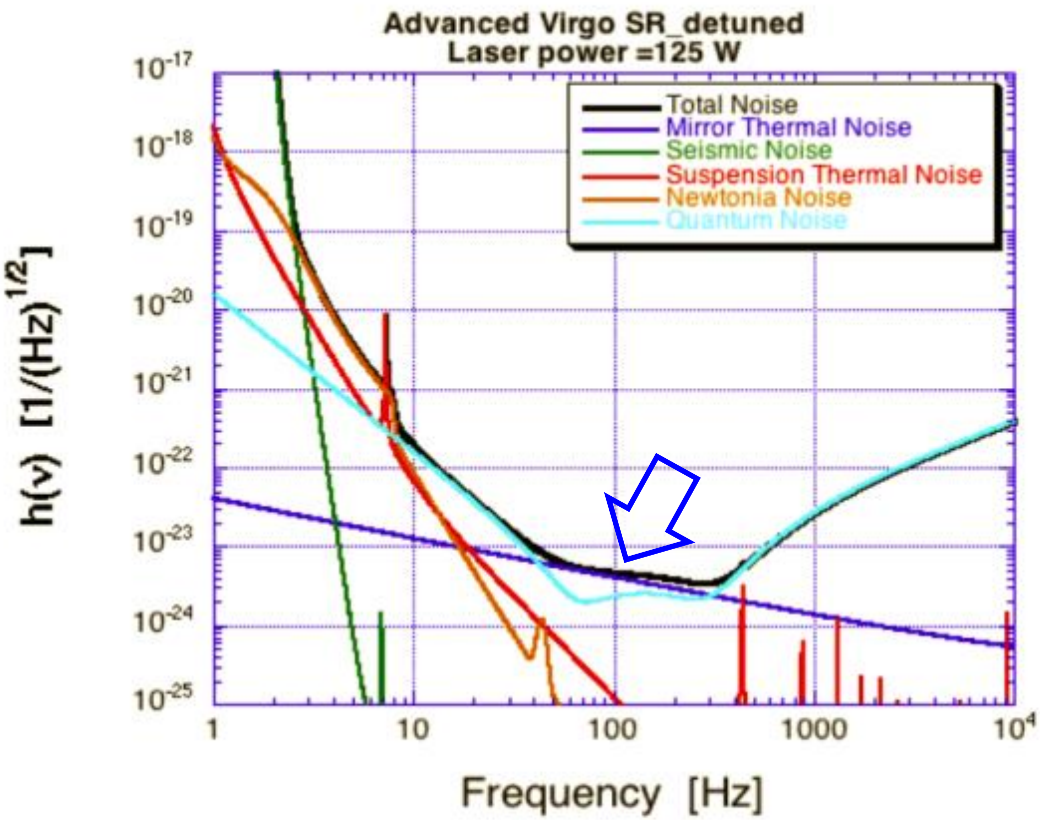
$$R = |r^2| = \left[\frac{(n_h/n_l)^{2N} - 1}{(n_H/n_L)^{2N} + 1} \right]^2$$

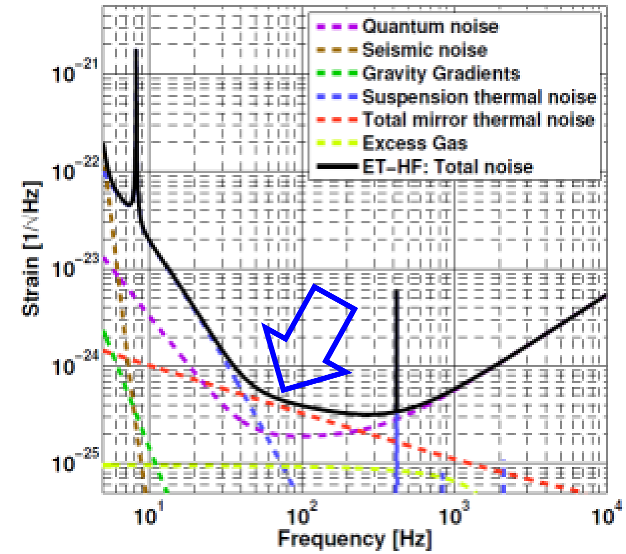
few Hertz – tens Hertz

Quasi-monolithic suspensions:

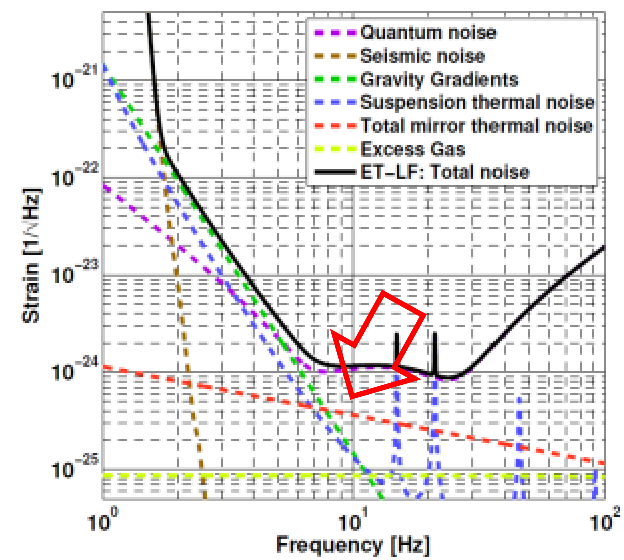
- Fused silica wires (pendulum, violin modes)
- Chemical bonding
- Upper stage clamps

A fundamental noise in GW detectors





ET-HF part



ET-LF part

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

AdV+ Phase I & II

AdV+ ***Phase I***: «hitting the thermal noise wall»

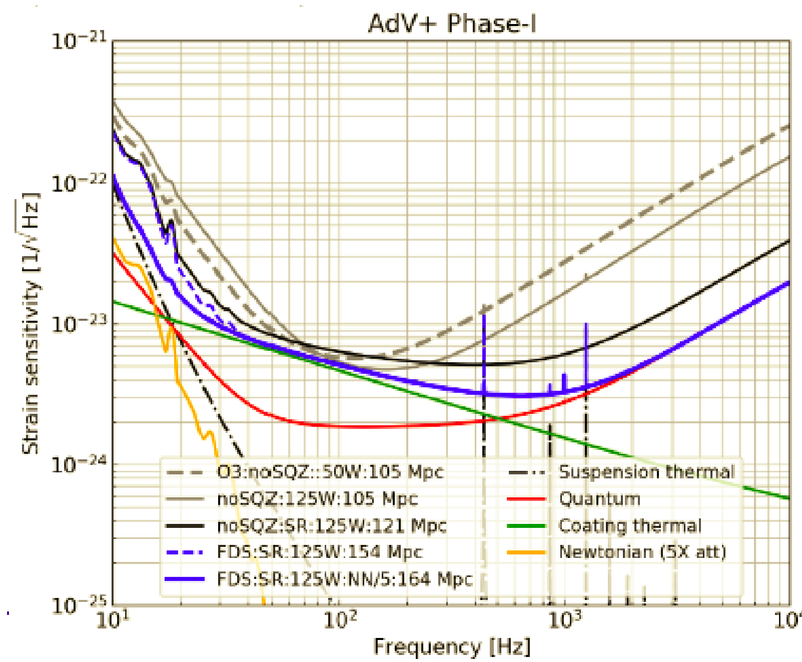
VIR-0284A-19

- Signal recycling
- Larger input power (40 W)
- Frequency dependent squeezing
- Newtonian noise cancellation

AdV+ ***Phase II***: «pushing the thermal noise wall»

- Further increase of laser power
- Large end masses (100 kg)
- **Larger beam size on ETM**
- **Better coatings**

Thermal noise reduction

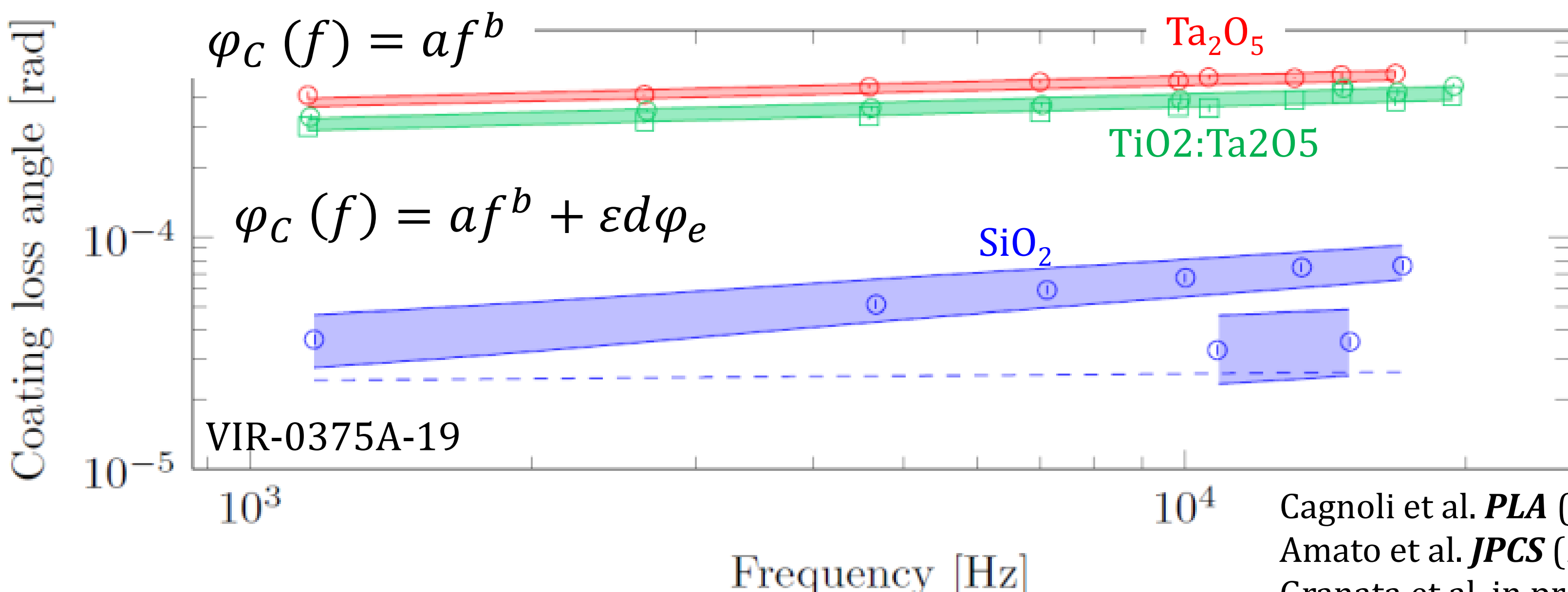


	2019	2020	2021	2022	2023	2024	2025
		Ph I		Ph II			
	O3		O4		O5		

Coatings: status of the art

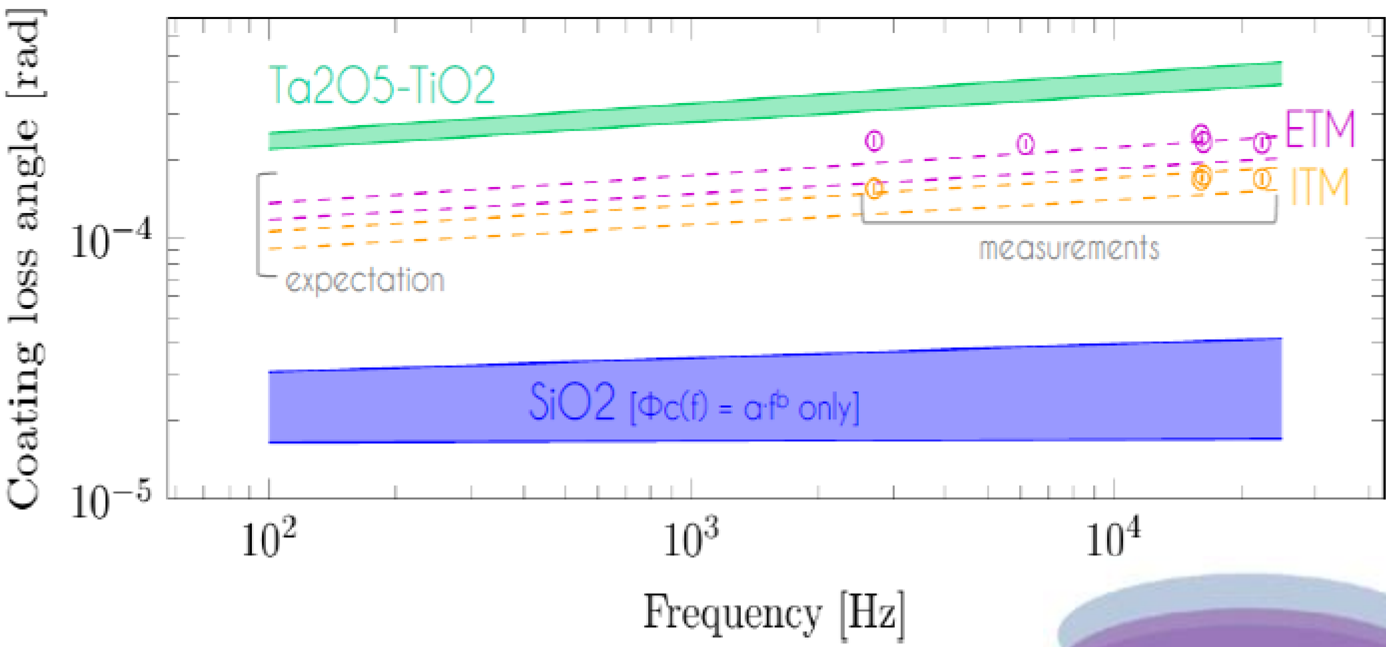
Single layer: $$\varphi_C = \frac{E_{TOT}}{E_C}\varphi_{MEASURED} + \left(1 - \frac{E_{TOT}}{E_C}\right)\varphi_{SUBSTRATE}$$

	a [10^{-4} rad Hz^{-b}]	b	n @1064 nm
Ta_2O_5	1.88 ± 0.06	0.101 ± 0.004	2.05 ± 0.01
Ta_2O_5-TiO_2	1.43 ± 0.07	0.109 ± 0.005	2.09 ± 0.01
SiO_2	0.2 ± 0.04	0.030 ± 0.024	1.45 ± 0.01



Cagnoli et al. ***PLA*** (2018), Amato et al. ***JPCS*** (2017), Granata et al. in prep.

Coating thermal noise: status of art



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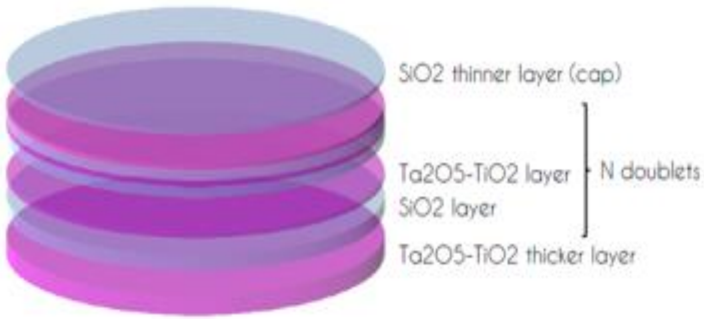
COATING STACKS

$$\boxed{\varphi_{STACK} = \frac{\sum_i t_i Y_i \varphi_i}{\sum_i t_i Y_i}}$$



- **Updated values** (see VIR-0375A-19)
- Better agreement between expectation and measurements with cantilever
- Expectation values close to measurements only f>2 kHz
- new loss measurements at low frequency would be helpful

Coating Thermal noise in AdV+

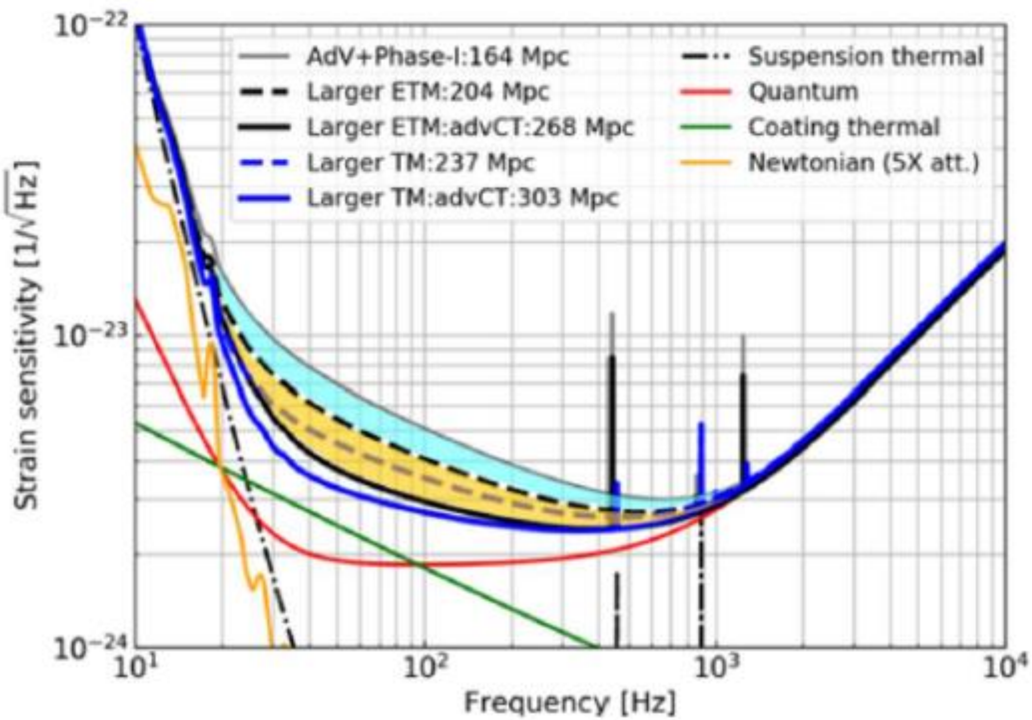
$$S_x(\omega) \propto \frac{T_K \cdot d}{w^2}\left(\frac{Y_c}{Y_s}+\frac{Y_s}{Y_c}\right)\cdot \phi_c$$

- The special combinatin of Young's moduli of coating Y_c and substrate Y_s indicates that the thermal noise minimum is achieved when the two are equal.
- The thickness dependence justify the search for the highest refractive index contrast (n_H-n_L) between the two materials of the coating stack

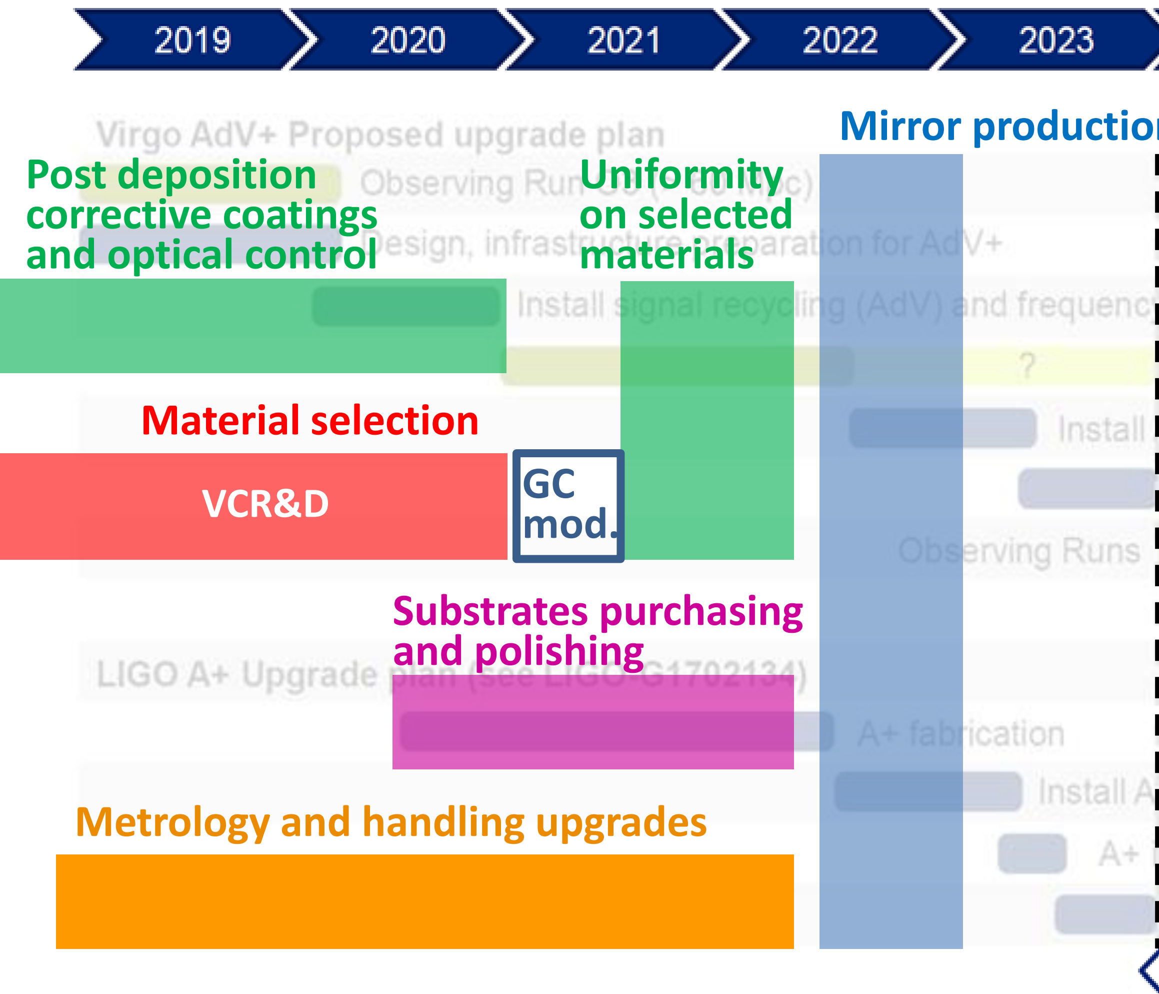
Phase II upgrades:
Factor 3 reduction of coating loss angle
Beam size increase on ETM

The approach to reducing coating thermal noise in AdV+ is based on:

1. Increase of the laser spot size on the end mirrors
2. Reduction of the loss angle of materials



Coating Research & Development in AdV+



The CRD SS aims to AdV+ optical coatings with:

- a total reduction of mechanical losses of a **factor 3**
- an optical absorption of **1 ppm**
- the material must be deposited with the existing facilities in LMA/IPNL (at most some modification of the Grand Coater with maximum delay of one year)

The research plan is focused on finding a solution for O5

CRD – Losses reduction strategies

Materials

Oxides

- Oxides Mixing
- High Index Silica Glasses

New materials

- Si_3N_4
- GaN
- SiC

Deposition

- Nano-layering
  - High index
  - Low index
  - HR stack

Post-deposition Treatments

- Annealing
- Outgassing
- Controlled crystallization

Absorption and Metrology

- Origin of absorption
- Loss measurement protocol with GeNS
- Thermoelastic effect calculation

Activities

Synthesis
- Coating deposition
- Heat treatments

Modeling
- Structure
- TLS relaxations

Macroscopic characterization
- Loss angle measurements
- Optical characterization
- Dielectric response
- Elastic constants
- Density

Microscopic characterization
- TEM, SEM
- Raman, Brillouin
- XRD, XPS, XAS
- AFM

Virgo Coating R&D collaboration

- **LYON**
  - ♦ IBS HighT, IAD
  - ♦ GeNS [300-10] K
  - ♦ FEA
  - ♦ Optical metrology
  - ♦ Pulsed Laser D
  - ♦ Rapid Th. Annealing
  - ♦ Raman, Brillouin
  - ♦ Physics of Glasses
  - ♦ Molecular Dynamics

- **GENOVA**
  - ♦ Ellipsometry
  - ♦ Optical properties
  - ♦ AFM, XPS
  - ♦ Raman

- **PADOVA**
  - ♦ MAG. SPUTTERING
  - ♦ XRD High T

- **URBINO**
  - ♦ GeNS Cryo
  - ♦ FEA

- **PERUGIA-CAMERINO**
  - ♦ Cantilevers & GeNS Cryo
  - ♦ Physics of Glasses
  - ♦ Brillouin, Raman
  - ♦ SEM, XRD, XAS

- **PISA**
  - ♦ Study of the crystallization processes
  - ♦ Physics of deposition and ultrastable glasses
  - ♦ Molecular Dynamics andModelling
  - ♦ Calorimetry and Dielectric response

- **ROMA 2**
  - ♦ Laser Polishing
  - ♦ GeNS 300K 1”
  - ♦ FEA and AFM
  - ♦ XPS
  - ♦ Ellipsometry

- **ROMA 1**
  - ♦ Structural characterization
  - ♦ Thermobalance

- **SALERNO/SANNIO**
  - ♦ IAD
  - ♦ SEM,TEM,AFM and XRD
  - ♦ nanolayered composites and Mie-metamaterials

♦ Sample production

♦ Characterization

Policies

- Basic ideas:
  - Avoid to duplicate efforts: clearly identified **research lines** (RL)
  - Groups opt in to the RL according to their interest+experience+resources
  - Interactions and information exchange between the RL guaranteed by collaboration meetings and top level coordination

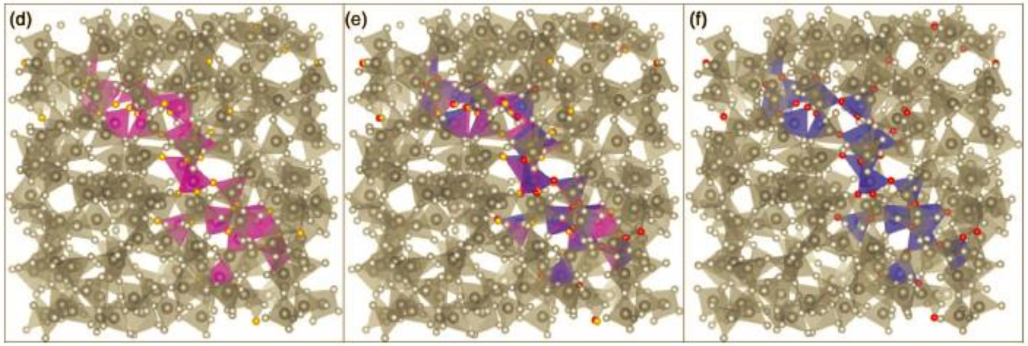
- RL-based approach requires a clear agreement on **publication policy**:

1) Each research line will produce papers that are signed only by the people that have worked on that line, describing very minimally the impact on GW detection.
2) Every year (or when the collaboration decides) VCR&D produces a review article signed by the all collaboration members.
3) Whenever the VCR&D collaboration thinks it is appropriate, of each article with promising results for GW the collaboration produces an article showing the impact on GW detectors. In this article prediction of sensitivity curves and detection range for one of more type of detectors will be calculated. These articles will have the signature of all collaboration members.

	when	**who signs**	**Impact on GW detection**
RL papers	At any time	RL members	NO
Review papers	~ yearly	All members	Possibly
GW papers	Upon decision	All members	YES

Guidance from TLS

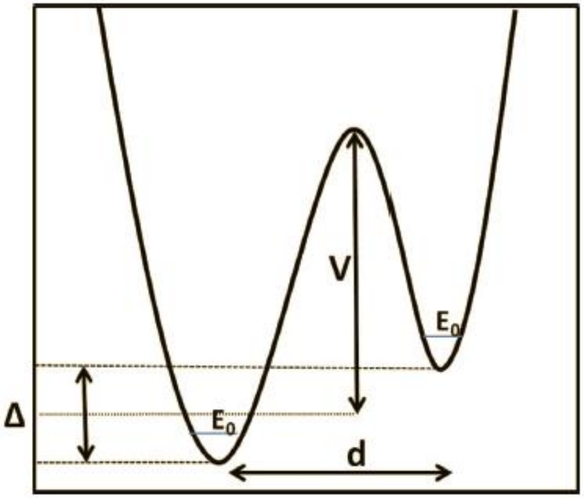
The anelastic behavior of amorphous materials is explained by the presence of a number of **metastable states**. Any two of these states that are **separated by an energy barrier** is called a **Two Level System (TLS)**.



R Hamdan, J P Trinastic, H P Cheng ***J Chem Phys*** 141 (2014)

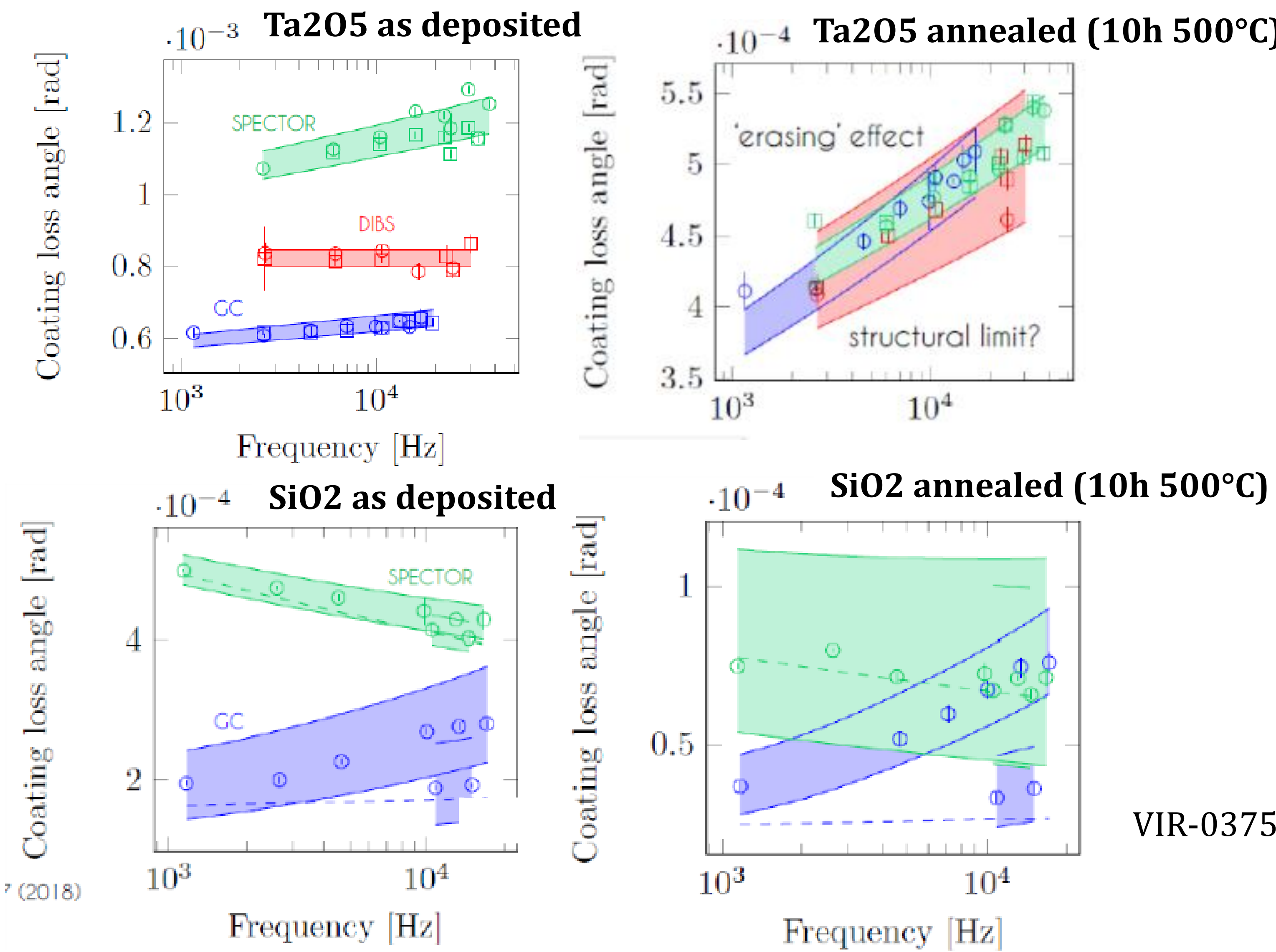
J. P. Trinastic et al., ***Phys. Rev. B*** 93, (2016)

- Not all the TLS contribute to the mechanical losses. The ones that are active are only **those that have a relaxation time comparable to the period T** of the strain wave propagating in the material. In our case the TLS that contribute to the mechanical losses at room temperature are those that have a barrier height of **about 0.5 eV**.
- In order to reduce the loss angle of amorphous materials two basic ideas can be pursued:
  - a reduction of the total number density of TLS;
  - an optimal distribution of TLS.



K. S. Gilroy &W. A. Phillips ***Philosophical Magazine B*** 43,5 (1981)

Deposition parameters and post deposition treatments



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New Materials

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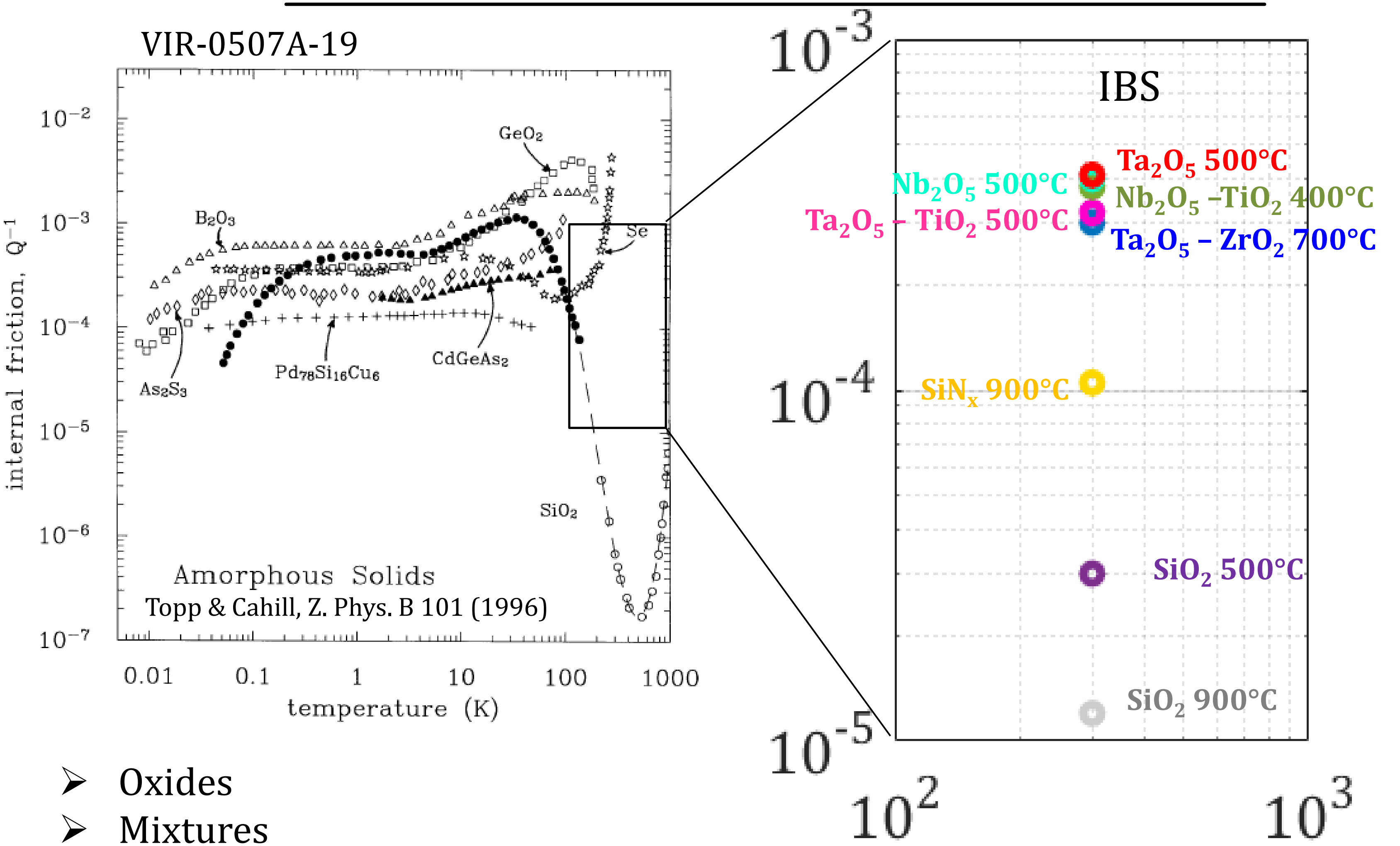
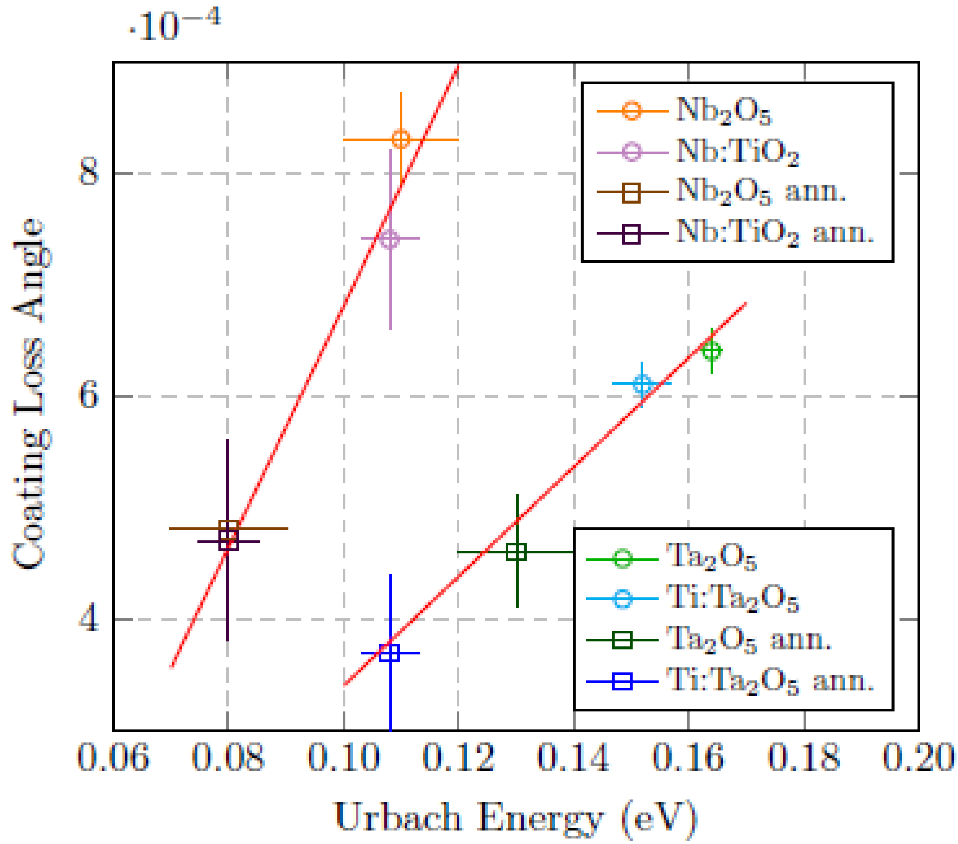


- Oxides
- Mixtures
- High coordination number glasses (see if HCNG show the tendency to reduce the TLS number thanks to the reduced freedom of each atom or molecule)

Absorption

The **Urbach energy** is a parameter which quantifies the homogeneity of the structure by absorption investigation, probing a multi-range structural organization. **Annealing and doping** modify the structure leading to a more organized/ homogeneous atomic dispositions, reducing the mechanical loss angle.



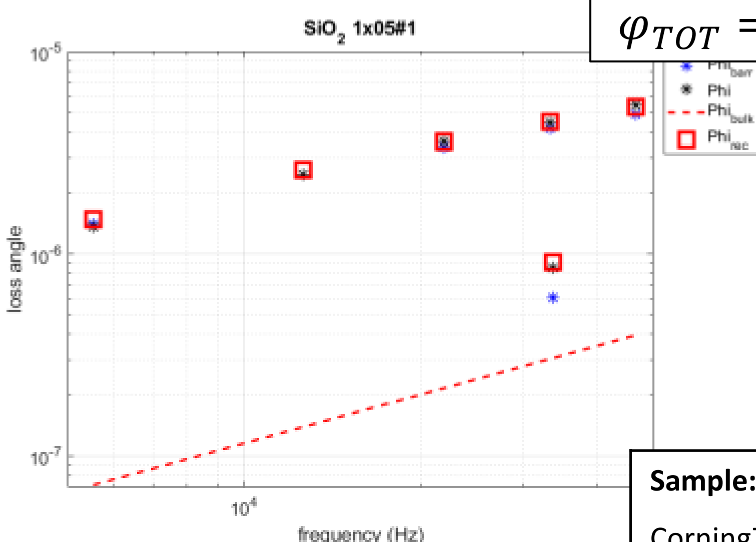
Amato et al 2019
arXiv:1903.06094

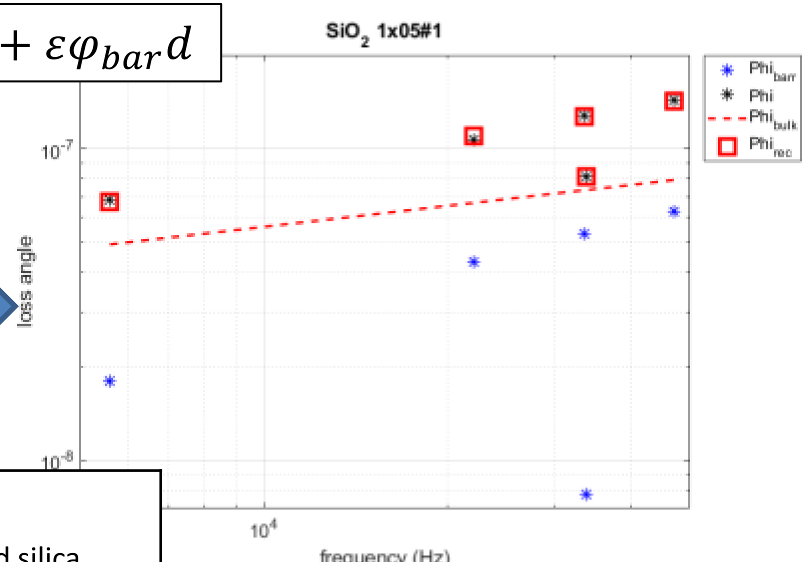
Metrology

Coating loss angle is obtained by difference: stability of substrates is mandatory

- ✓ remove experimentally the thermoelastic peak shift on the substrate caused by the presence of coating (*see poster by E. Cesarini et al.*)
- ✓ silicon or sapphire substrate needed for loss angle measurement at low temperature (*see talk by L. Mereni*)
- ✓ Set one reference silica disc to circulate within the GeNS laboratories
- ✓ **Establish a coating φ measurement protocol**
- ✓ Explain why cantilevers and discs give a significantly different value of coating loss (*interesting results presented by Simon Tait*)

$$\varphi_{TOT} = Af^{B} + \varepsilon\varphi_{bar}d$$





Sample:

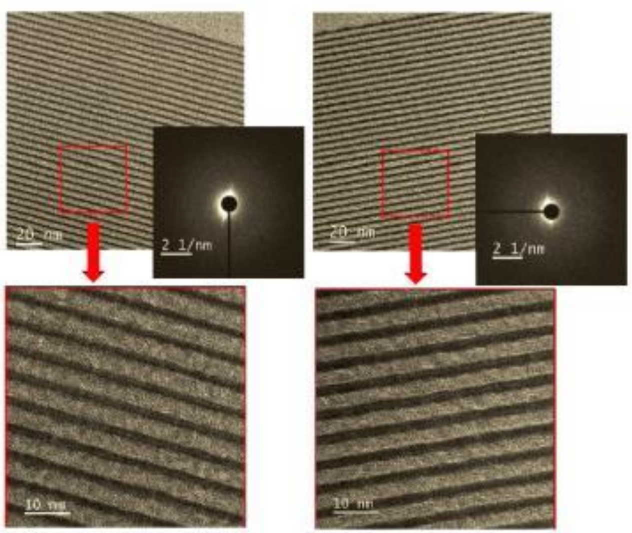
Corning7980 fused silica

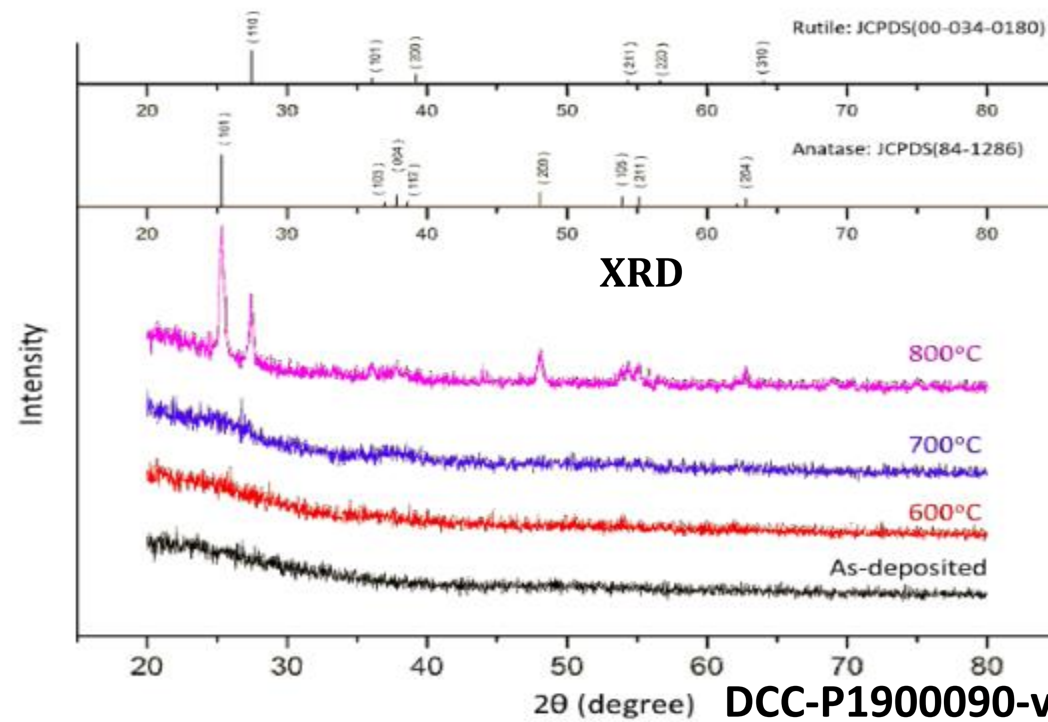
1 inch diam. – 0,5 mm thick.

Deposition Technolgy: Nano-layered coatings

Increase the annealing temperature by geometrical frustration of crystallization

- nm-layers of SiO2 interleaved with nm-layers of a high-index material: TiO2 (successful evidence already available), HfO2, ZrO2;
- possibility to achieve refractive index higher than that of TiO2:: Ta2O5
- The thickness of the nano-layers below 4 nm to reach interesting annealing temperature


(a) as deposited (b) annealed at 600°C



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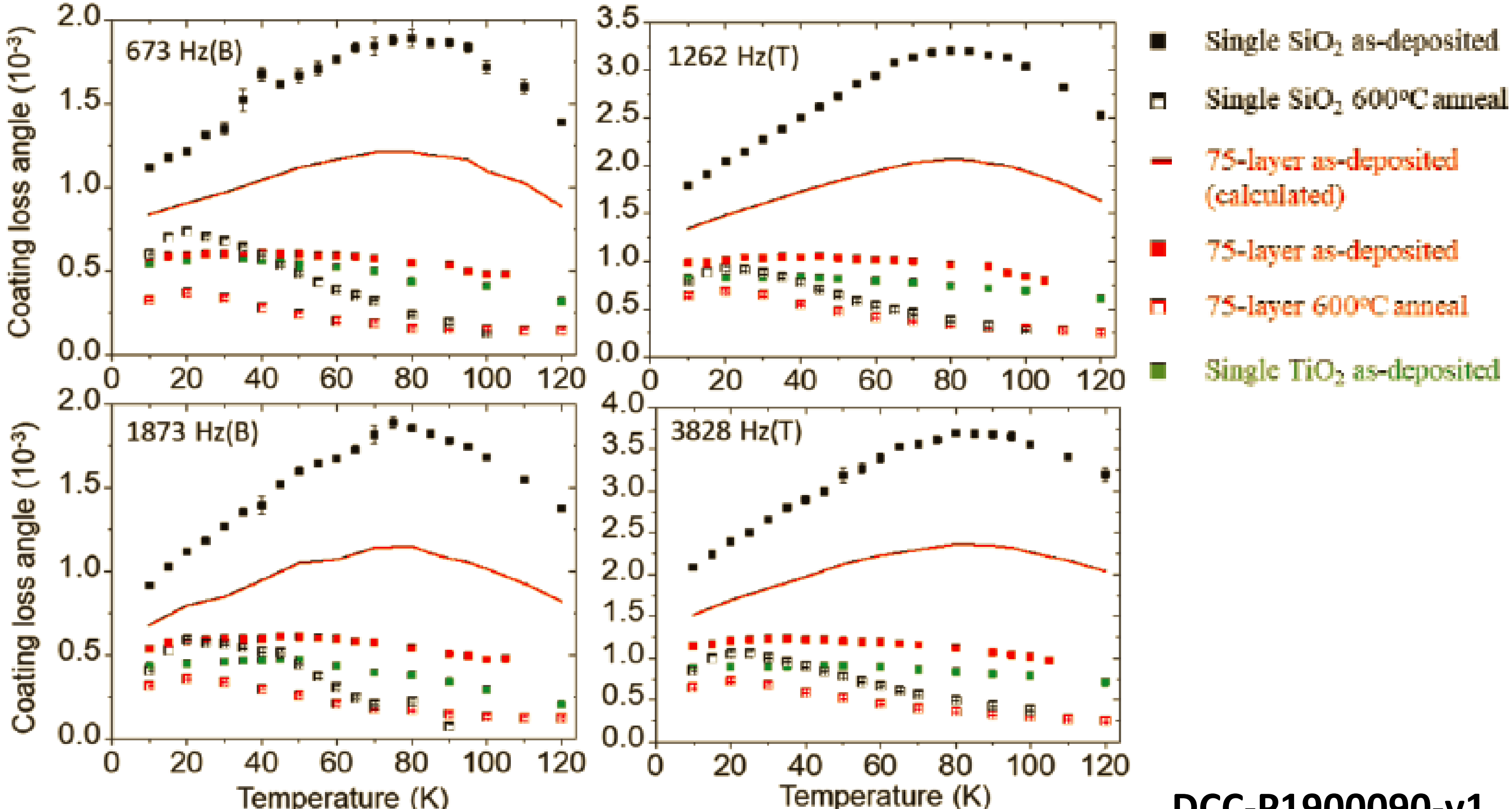
- TiO_2/SiO_2
- 1.8±0-1 nm / 3.6± 0.1 nm

Deposition Technolgy: Nano-layered coatings

It has been shown that nano-layers are able to significantly reduce both room and cryogenic mechanical losses for TiO_2/SiO_2 composites



DCC-P1900090-v1

New Deposition Technolgy (Nano-layered coatings)

Sannio Coater
(thanks to M.Principe)

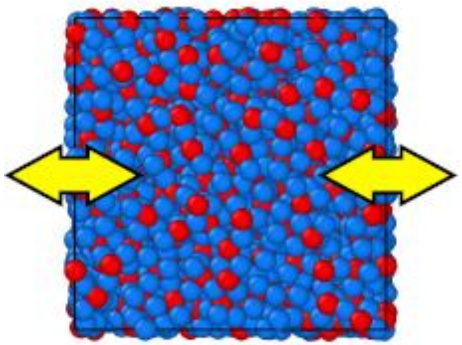
- High vacuum chamber
  (cryo + rot pumps)
- EB-gun with 6 pockets
  (2nd source will be installed)
- Plasma source
- Argon & Oxigen feeds
- Fully programmable with GUI
  (sub-nm accuracy/repeatability)
- Rotating substrate
  (to ehnance uniformity)
- Ceramic lamp substrate heaters

Common research activity for A+ and AdV+
Many doublets to investigate:

- ➢ High index refraction SiO_2 pair to one high index oxide (TiO_2, ZrO_2, HfO_2, Ta_2O_5 Nb_2O_5)
- ➢ Low index refraction SiO_2 pair (e.g Silica/alumina)
- ➢ HR multistack

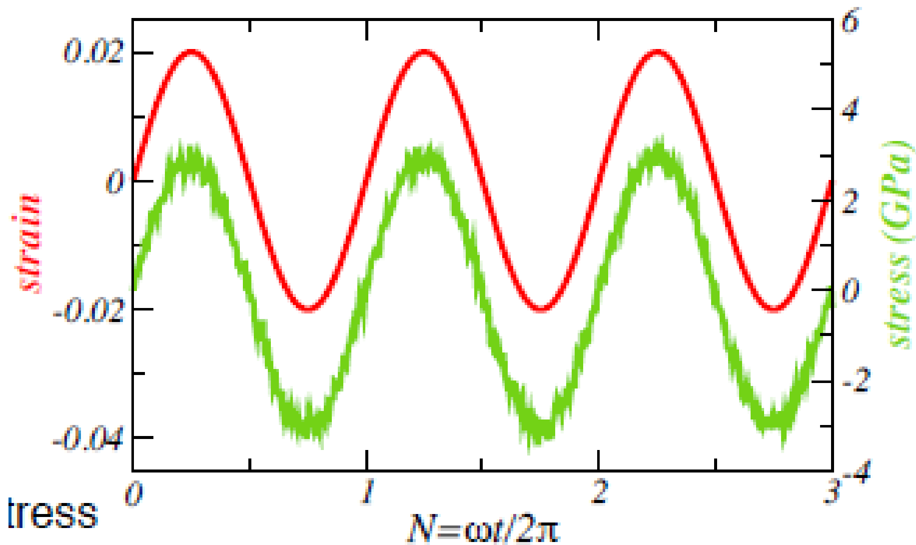
Modeling

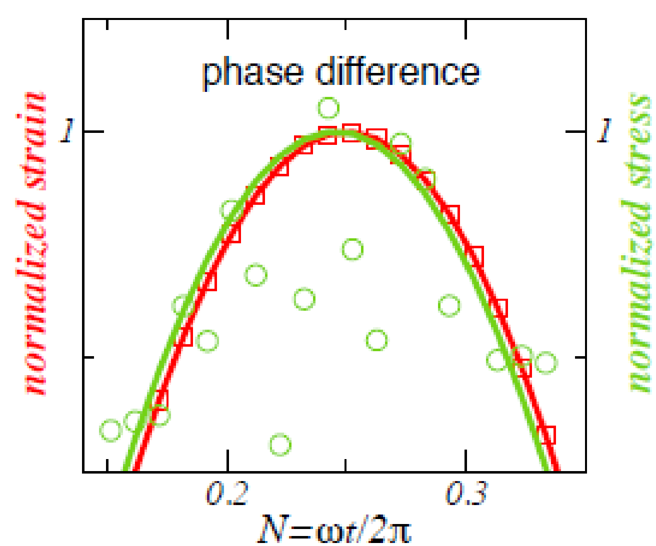
MD simulations of Dynamical Mechanical Spectroscopy (MD-DMS)
(see talk by F. Puosi on wednesday)



A theory-independent method, where the only ingredient is the force field of the specific glassy system (Ta_2O_5 in progress, SiC forseen)

Apply a sinusoidal strain with selected frequency along one direction and follow the time evolution of the corresponding component of stress ➡ **Direct measurement of dissipation**





VCRED – Losses reduction strategies

Oxides

- Oxides
- Mixing
- High Index Silica Glasses

New materials

- Nitrides
- Fluorides *(see poster M. Bischi et al.)*
- High Coordination Number Glasses

Materials

Deposition

- High Temperature
- Nano-layering
  - High index
  - Low index
  - HR stack

Absorption and Metrology

- Origin of absorption
- Loss measurement protocol with GeNS
- Thermoelastic effect calculation

Treatments

- Annealing
- Outgassing
- Controlled crystallization

CONCLUSIONS

- Phase II of AdV+ focuses on pushing down the thermal noise
- Preparatory works for Phase II include the upgrade to larger (end) mirrors and the search for **better coatings with a factor 3 reduction** of mechanical loss
- CRD deploys a set of **research lines** pursued in parallel to optimize the likelihood of getting to a breakthrough
- RLs share a publication policy to properly represent and safeguard the contributions of single groups
- Activities are ongoing:
  - Oxides, mixtures, nano-layered coatings
  - Structural modeling
  - Deposition parameters and annealing
  - Metrology: thermoelastic effect and edge effect in coatings
- VCR&D even larger effort on a longer timescale