Low-noise optical coatings for the next-generation gravitational wave interferometers

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Virgo Coating R&D Collaboration

INFN - Padova

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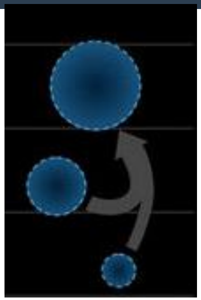
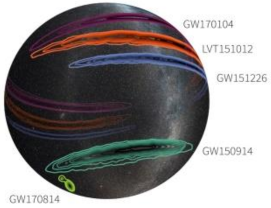
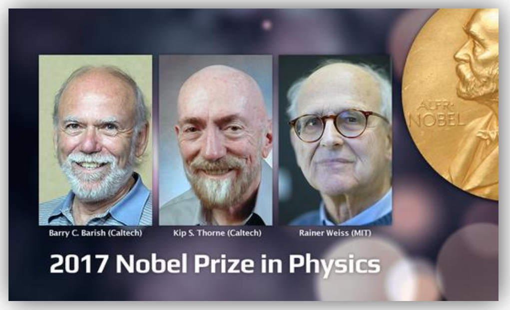
CERN-PCB workshop

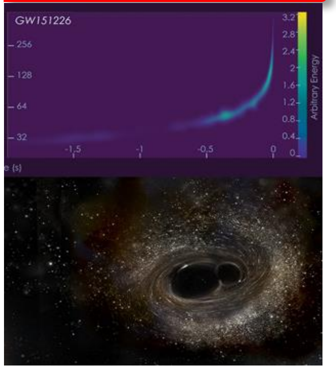
A storm of waves…

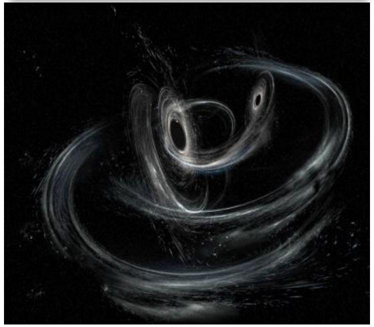


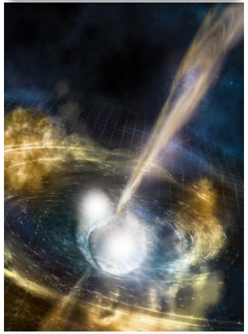


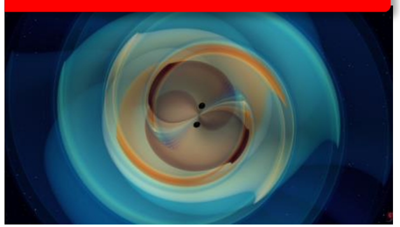


2015 2016 2017 2018 2019

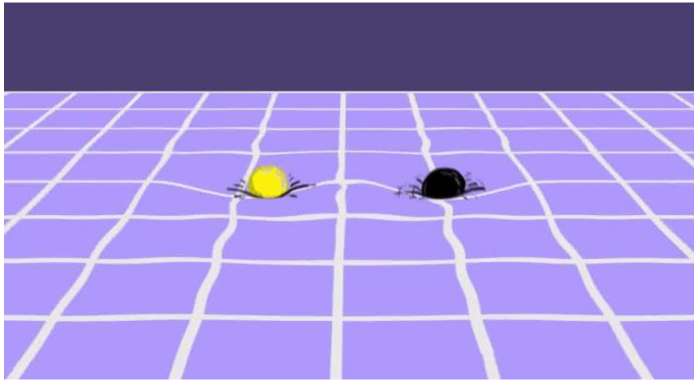




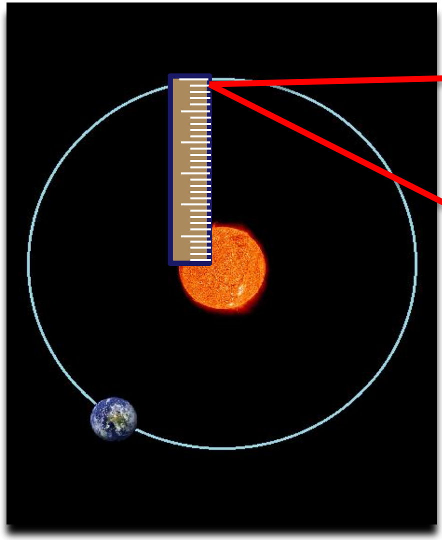


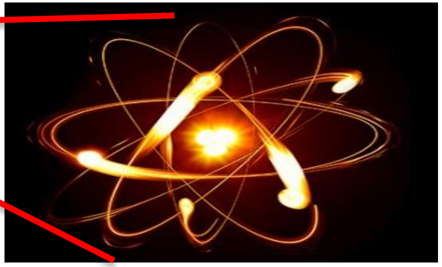


A small displacement… really small!



- GW are a modulation of the space-time metric propagating at the speed of light.
- They have two polarization states
- Generated by mass distributions with a time dependent quadrupole moment (e.g. spiralling massive bodies)
- Produce a differential length change along the directions perpendicular to the propagation direction.





$$\frac{Length\ variation}{Length} = 10^{-21}$$

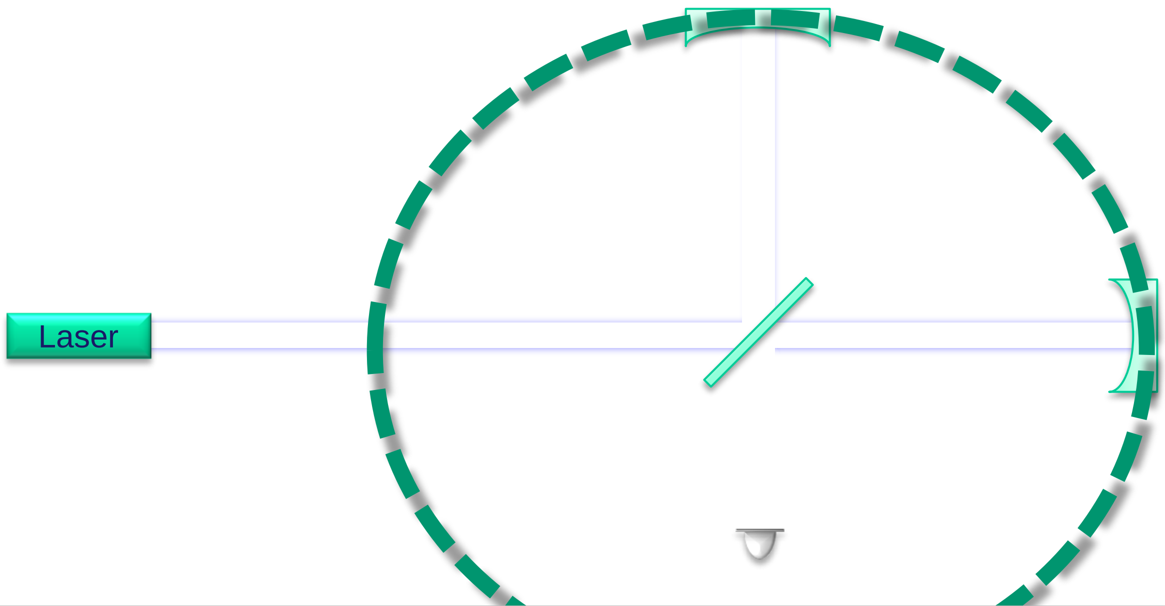
Equivalent to measure a displacement of the size of one atom compared to the Earth – Sun distance!

The right instrument: the interferometer

Inherently differential

“Easy” to scale up

Broadband



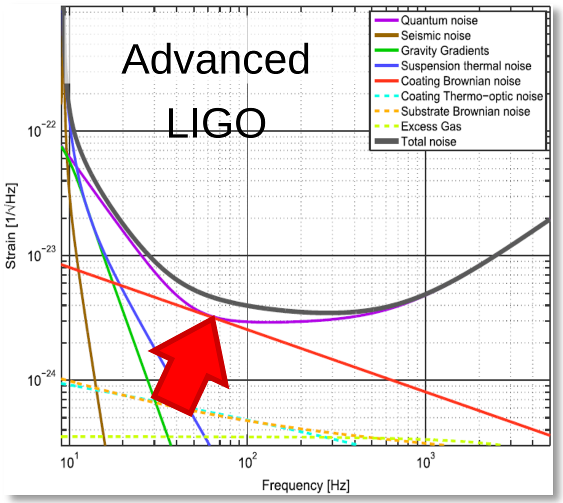
Need to be able to measure incredibly small mirror displacements: less than 1/1000 of the size of a proton!

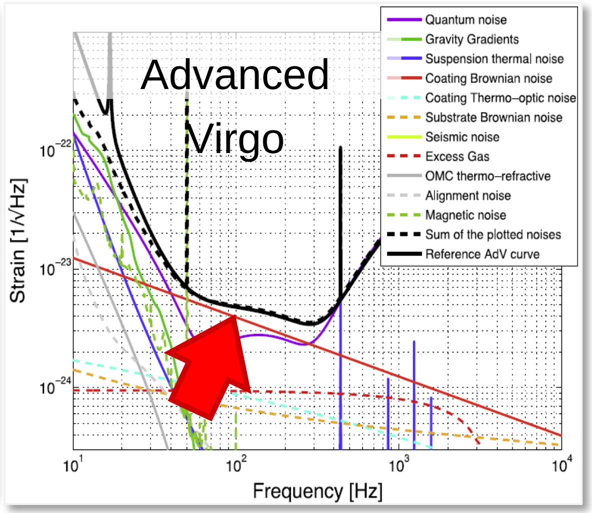
Need to be sure that nothing else is moving the mirrors by this tiny amount: ground vibrations, for example, are billions of times too big!

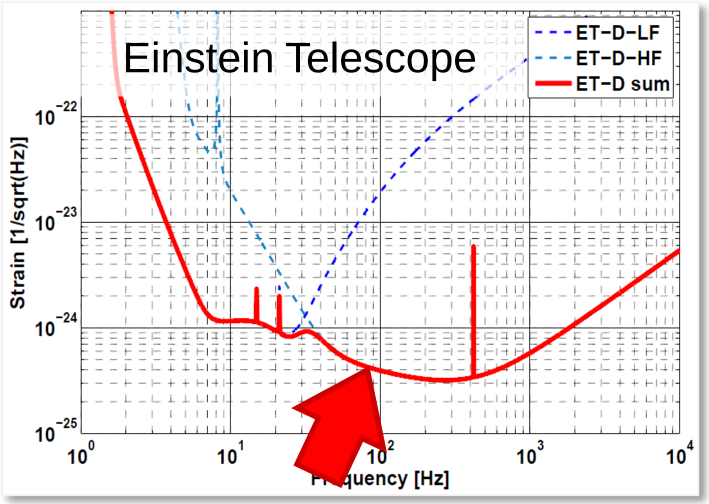
The winning team of the moment

The Coating Thermal Noise (CTN) Issue

Noise floor in present & future GW detectors

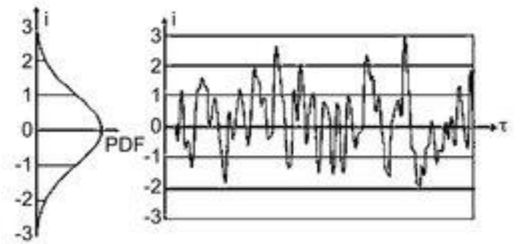


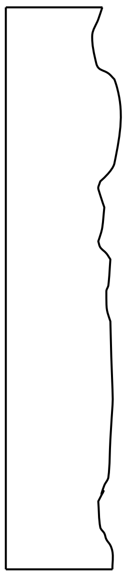




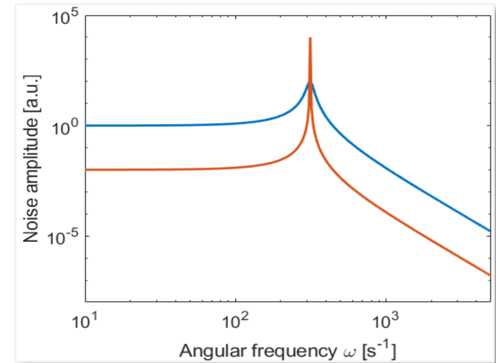
- Aasi et al, Class. Quantum Grav. 32 (2015)
- Acernese et al, Class. Quantum Grav. 32 (2015)
- Hild et al, Class. Quantum Grav. 28 (2011)
- Abernathy et al, ET note ET-0106C-10 (2011)

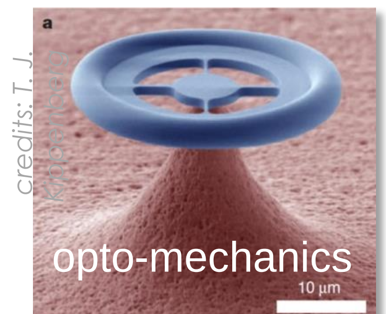
Thermal Noise





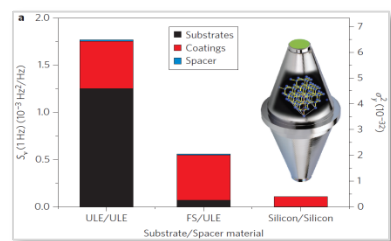
- Produced by the thermal motion of the mirror surfaces
- intensity proportional to system internal friction (F-D theorem) characterized by the **loss angle Φ = 1/Q**
- **Less dissipation → less noise**
- **Common problem in several high-precision experiments**



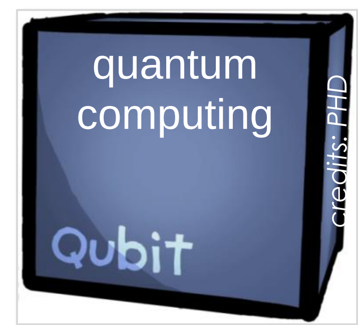


Aspelmeyer et al, Rev. Mod. Phys. 86 (2014)

frequency stabilization



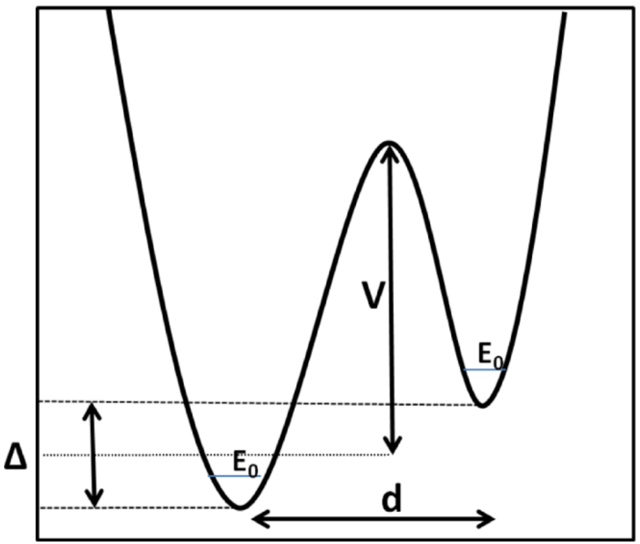
Kessler et al, Nat. Photon 6 (2012)

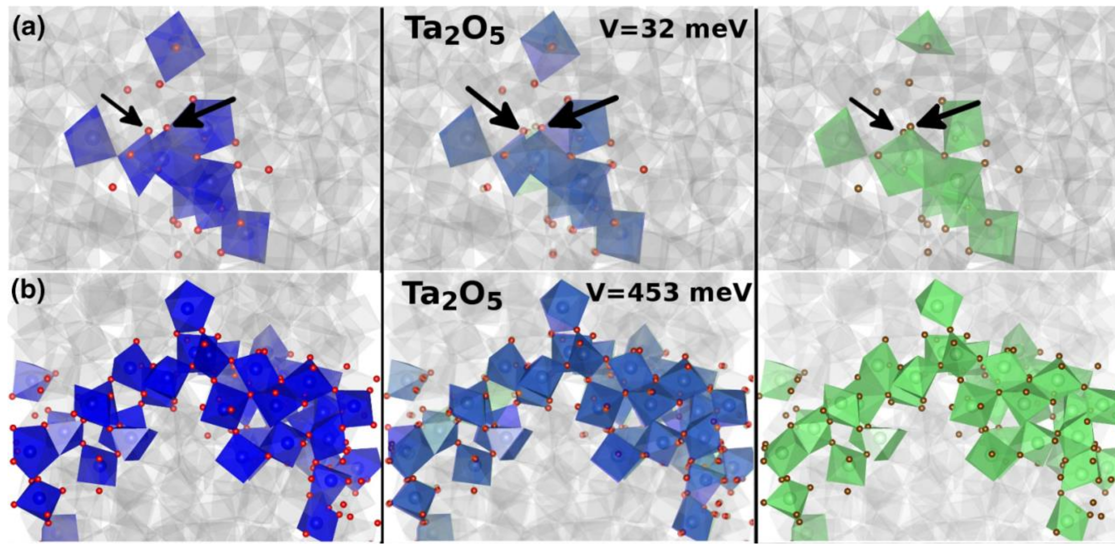


Martinis et al, Phys. Rev. Lett. 95 (2005)

Microscopic Picture: two-level system

In amorphous solids, the lack of long-range order allows for low-energy, thermally activated excitations involving small groups of atoms that serve as the fundamental source of this energy dissipation.





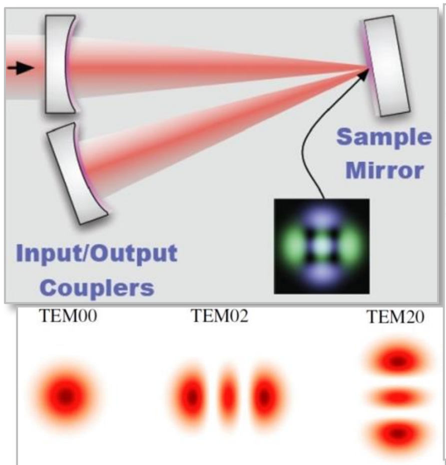
Anderson, P. W.,et al., *Phil. Mag.* 25.1 (1972): 1-9.
K. S. Gilroy and W. A. Phillips, Phil. Mag. B 43, 735 (1981)

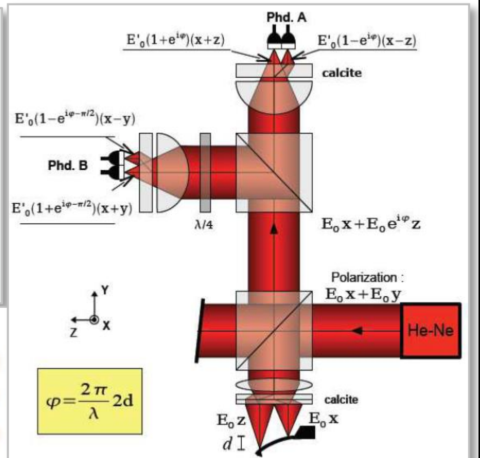
Trinastic et al. PRB **93**, 014105 (2016)

How can we measure it?

Direct approach:

- Folded Fabry- Perot cavities
- quadrature phase differential interferometry

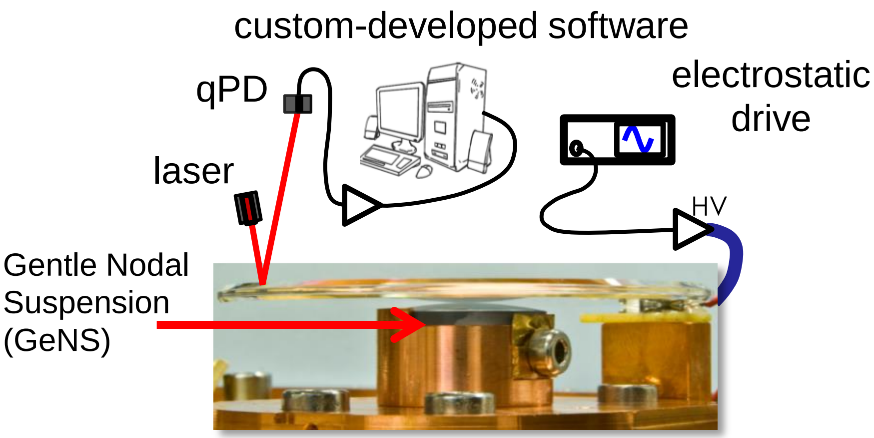




Gras and Evans, Phys. Rev. D 98, 122001
Li et al, Phys. Rev. D 89 (2014) K. Numata et al., Phys. Rev. Lett. 91, 260602 (2003)
E. D. Black et al., Phys. Lett. A 328, 1 (2004

Indirect approach:

- loss angle measurement



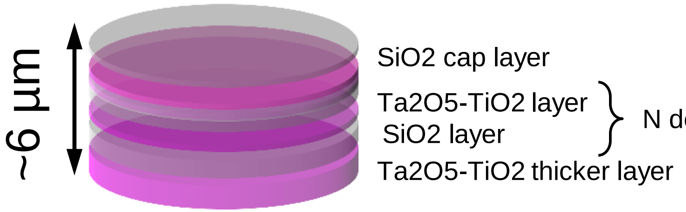
Ring-down time of selected vibrational modes

Granata et al, Phys. Rev. D 93 (2016)
Granata et al, Arch. Metall. Mat. 60 (2015)
Cesarini et al, Rev. Sci. Instrum. 80 (2009)

The two approaches give comparable results (even though not in full agreement)

CTN power spectrum

The most critical material is the high-index one



In a Fabry-Perot geometry:

$$S_{\mathrm{CTN}} \propto T \frac{d\phi}{w^2}$$

Temperature

Cryogenic detectors

Coating thickness

Increased constrast

$n_H - n_L$

Mechanical Loss angle

New materials

Beam Waist

extended uniformty

Harry et al, Class. Quantum Grav. 19 (2002)

State of the art

Amorphous coatings deposited by Ion Beam Sputtering (IBS) @LMA

- **Ta2O5**
- **TiO2 – Ta2O5**

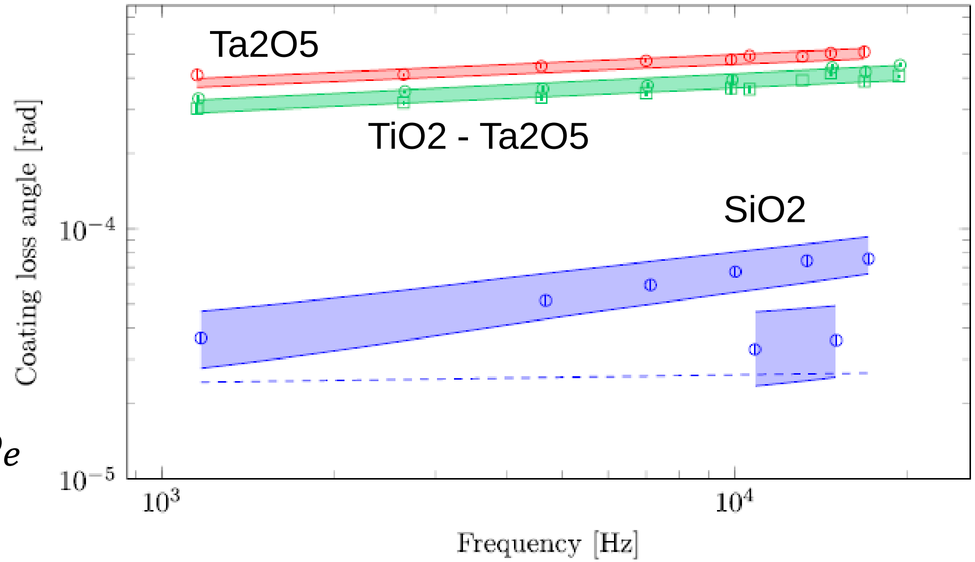
High Index
(n = 2,05 – 2.09)

- **SiO2**

Low index
(n = 1,45)

$$\phi_H(f) = a_H f^{b_H} \qquad \phi_L(f) = a_L f^{b_L} + \varepsilon d\phi_e$$

Optical absorption losses below 1 ppm per layer @ 1064nm!



Mechanical loss angle after deposition and thermal treatment

Granata et al, Class. Quantum Grav. 37 (2020)
Amato et al. Journal of Physics: Materials 2.3 (2019): 035004

How can we do better?

A recipe

- A material
- A deposition method
- A post-deposition treatment

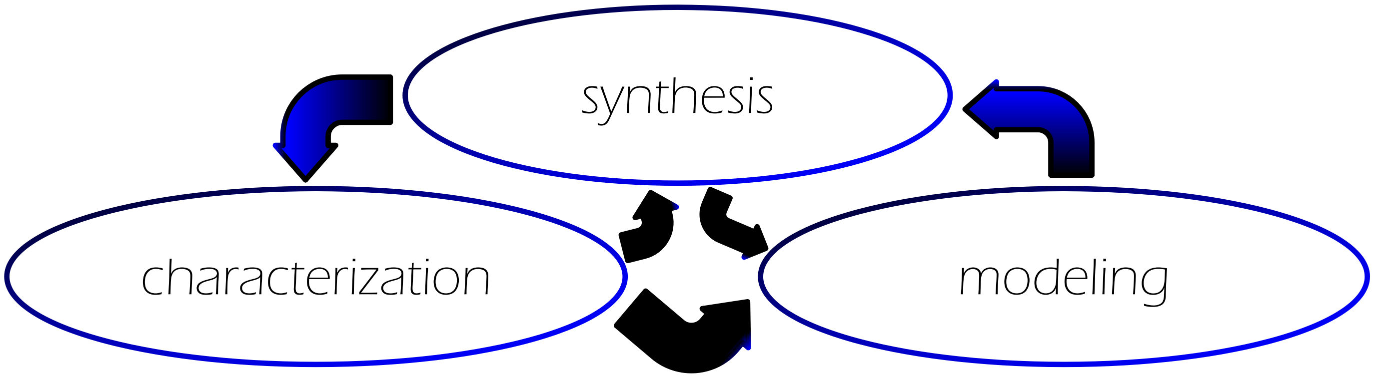
The constraints

•Low loss
(3 times lower than AdV)

•Same absorption and scattering

•To be deposited by Laboratoire Matériaux Avancés (LMA), the only lab presently producing GW ITF optics

The Virgo Coating R&D strategy



- OXIDE MIXING
- HIGH COORDINATION NUMBER GLASSES

- CRYSTALLIZATION
- ANNEALING
- DEPOSITION TECHNIQUES

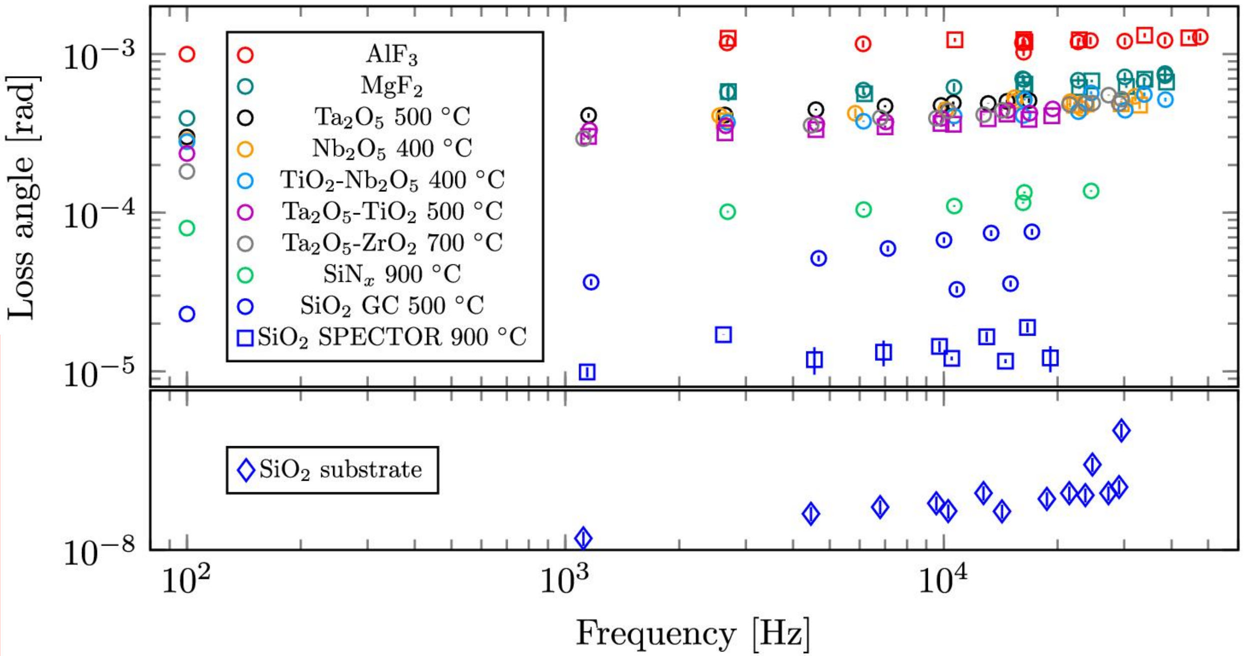
- METROLOGY
- THEORETICAL MODELLING

Perspectives

New materials

- Oxides
- Nitrides
- Amorphous semiconductors
- Crystalline coatings

The capability to characterize the physico-chemical properties of the deposited materials together with mechanical losses is essential!

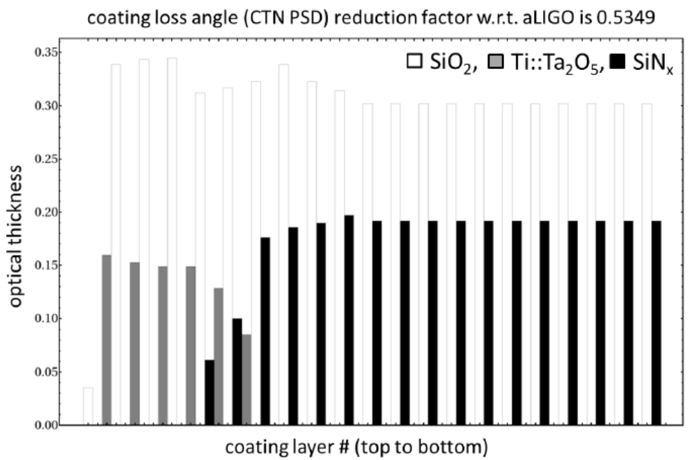


M. Granata, et al., "Progress in the measurement and reduction of thermal noise in optical coatings for gravitational-wave detectors," Appl. Opt. **59,** A229-A235 (2020);

Perspectives

Ternary Coatings

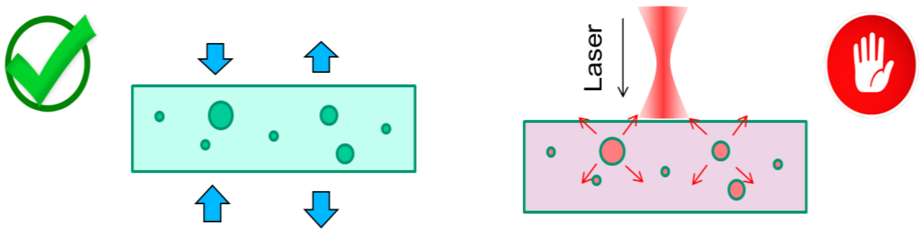
“Smart” design taking advantage of materials with high refractive index (fewer layers) and acceptable mechanical loss but high extinction. The latter problem is kept under control by placing the most absorbing materials at the bottom



VIR-1006A-21 document for details and references therein

Crystallization

Induce the formation of tiny nanocrystals to enchance the matrix stiffness without increasing the scattering losses



Reduce the density of TLSs by favoring the controlled formation of nanocrystals inside the amorphous matrix!

However: avoid scattering form the nanocrystals

Required:
- Precise control of the crystallization process
- Optical and mechanical characterization
- Theoretical modelling

VIR-0784A-21 document for details and references therein

Conclusions

- Take home message: GW science is a very interdisciplinary and fast growing field. Optics and materials science are essential tools.
- Ultra-low absorption coatings are available, but thermal noise is the next wall to climb.
- Several strategies are in place at the VIRGO Coating R&D collaboration.