Newton-Bhabha Fund

Coating Thermal Noise

Build-a-Detector WORKSHOP

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31/05/2021

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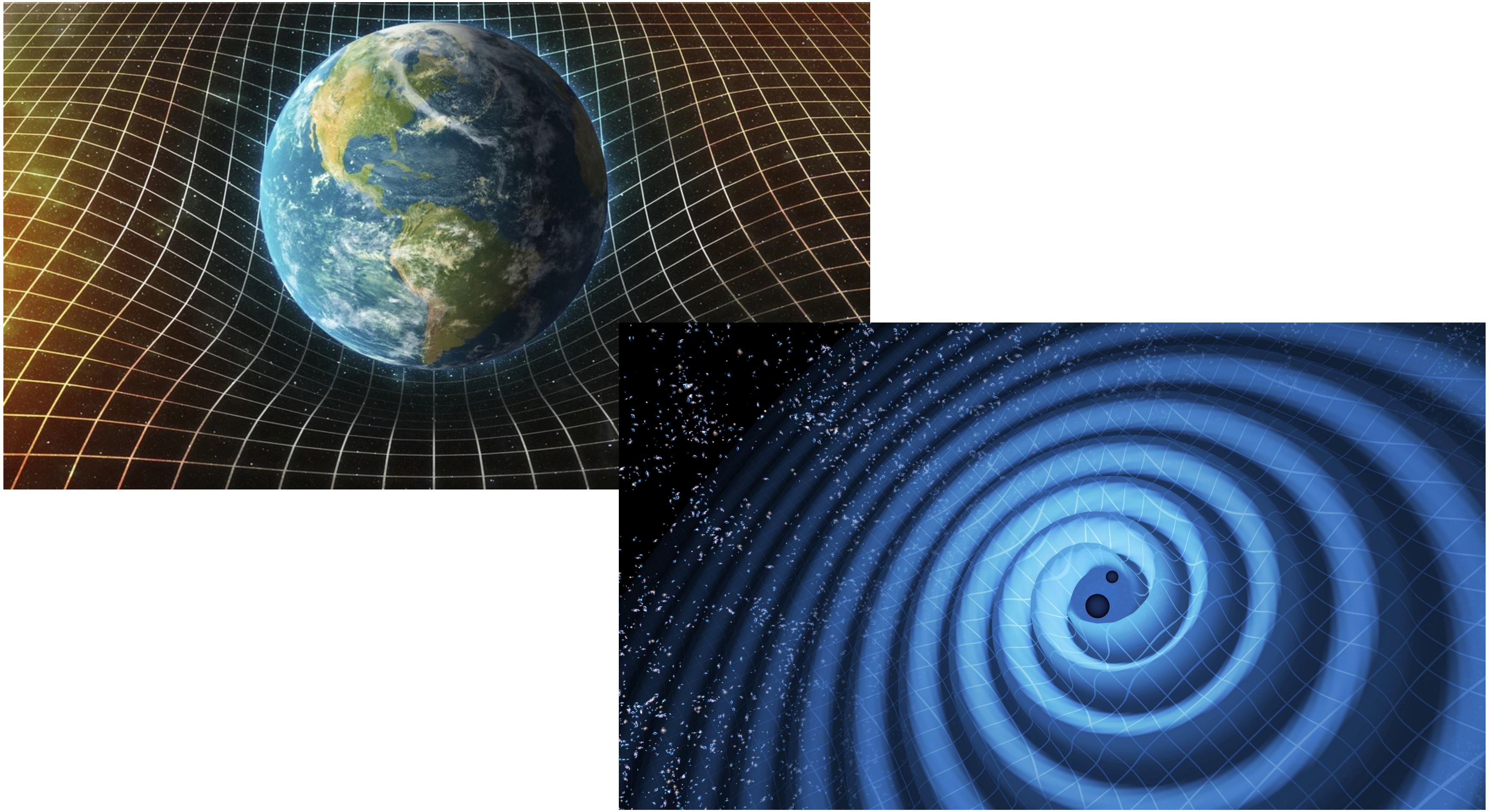
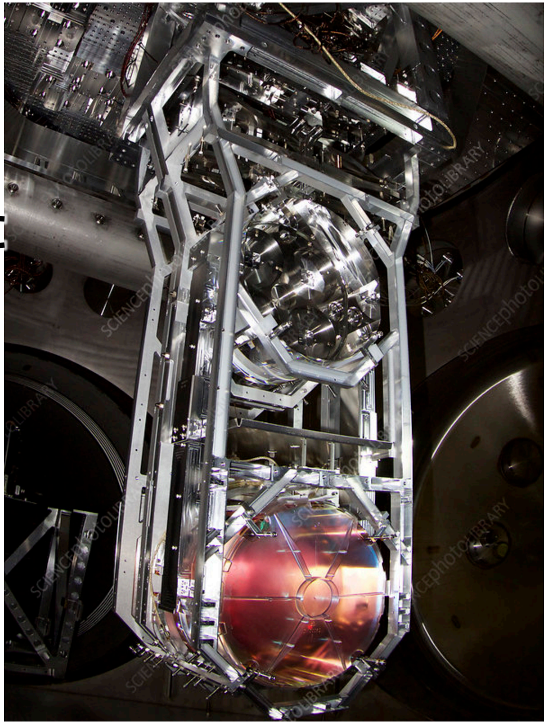
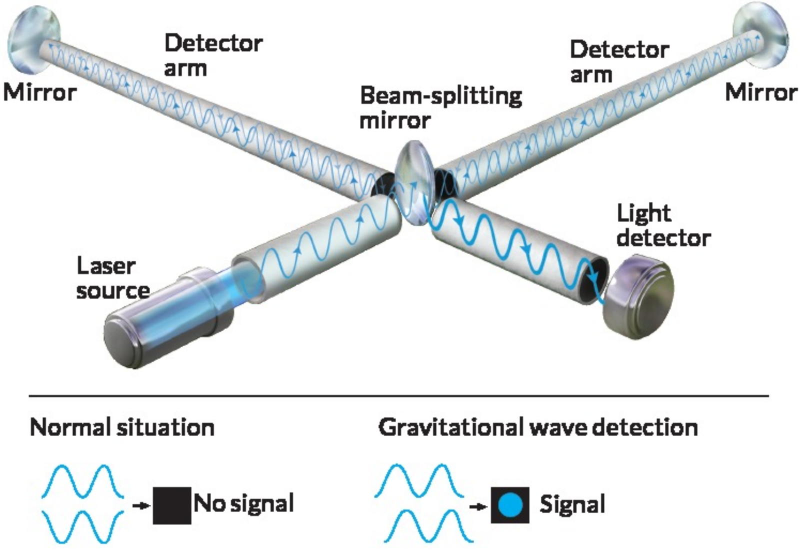
Overview



Overview

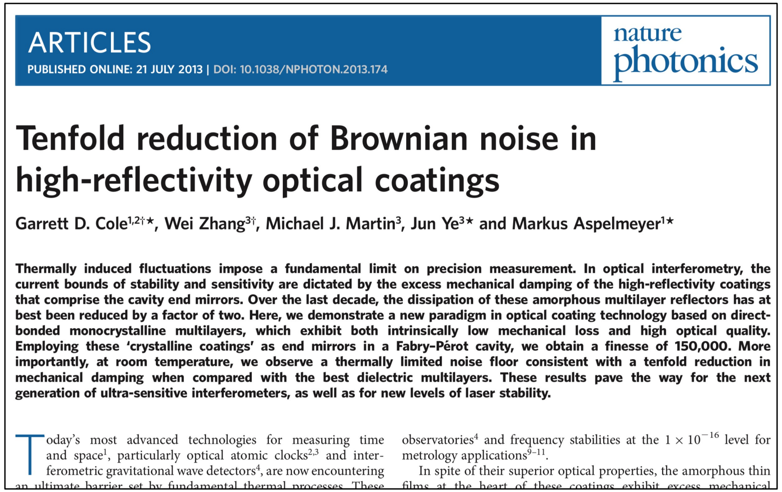



Mirror
Detector arm
Beam-splitting mirror
Detector arm
Mirror
Light detector
Laser source
Normal situation
No signal
Gravitational wave detection
Signal

Overview

- thermal noise in GW detectors (revision)
- important material properties
- mechanical loss measurements
  - bulk
  - coatings
- (optics…)
- summary

Thermal noise in ultra-stable optical cavities… e.g.:



ARTICLES

nature photonics

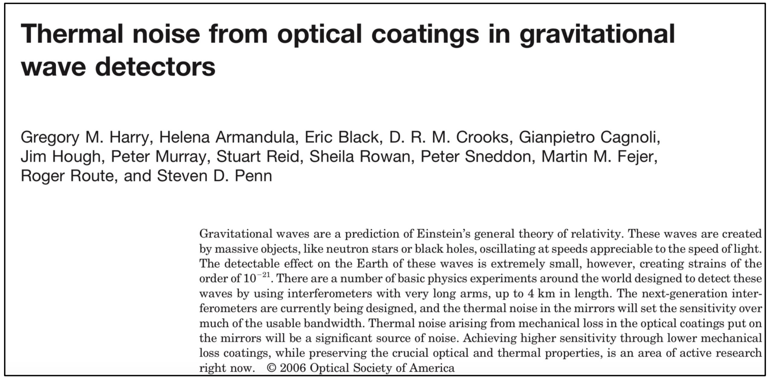
Tenfold reduction of Brownian noise in high-reflectivity optical coatings

Garrett D. Cole[1,2†]*, Wei Zhang[3†], Michael J. Martin[3], Jun Ye[3]* and Markus Aspelmeyer[1]*

Thermally induced fluctuations impose a fundamental limit on precision measurement. In optical interferometry, the current bounds of stability and sensitivity are dictated by the excess mechanical damping of the high-reflectivity coatings that comprise the cavity end mirrors. Over the last decade, the dissipation of these amorphous multilayer reflectors has at best been reduced by a factor of two. Here, we demonstrate a new paradigm in optical coating technology based on direct-bonded monocrystalline multilayers, which exhibit both intrinsically low mechanical loss and high optical quality. Employing these 'crystalline coatings' as end mirrors in a Fabry-Pérot cavity, we obtain a finesse of 150,000. More importantly, at room temperature, we observe a thermally limited noise floor consistent with a tenfold reduction in mechanical damping when compared with the best dielectric multilayers. These results pave the way for the next generation of ultra-sensitive interferometers, as well as for new levels of laser stability.

Today's most advanced technologies for measuring time and space[1], particularly optical atomic clocks[2,3] and interferometric gravitational wave detectors[4], are now encountering an ultimate barrier set by fundamental thermal processes. These observatories[4] and frequency stabilities at the 1×10^{-16} level for metrology applications[9–11].

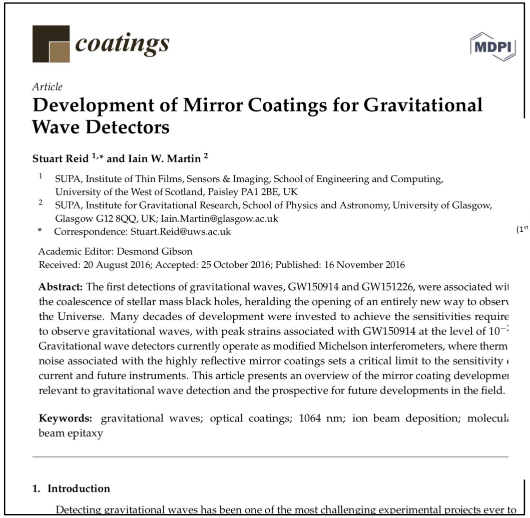
In spite of their superior optical properties, the amorphous thin films at the heart of these coatings exhibit excess mechanical



Thermal noise from optical coatings in gravitational wave detectors

Gregory M. Harry, Helena Armandula, Eric Black, D. R. M. Crooks, Gianpietro Cagnoli,
Jim Hough, Peter Murray, Stuart Reid, Sheila Rowan, Peter Sneddon, Martin M. Fejer,
Roger Route, and Steven D. Penn

Gravitational waves are a prediction of Einstein's general theory of relativity. These waves are created by massive objects, like neutron stars or black holes, oscillating at speeds appreciable to the speed of light. The detectable effect on the Earth of these waves is extremely small, however, creating strains of the order of 10^{-21}. There are a number of basic physics experiments around the world designed to detect these waves by using interferometers with very long arms, up to 4 km in length. The next-generation interferometers are currently being designed, and the thermal noise in the mirrors will set the sensitivity over much of the usable bandwidth. Thermal noise arising from mechanical loss in the optical coatings put on the mirrors will be a significant source of noise. Achieving higher sensitivity through lower mechanical loss coatings, while preserving the crucial optical and thermal properties, is an area of active research right now.



coatings

MDPI

Article

Development of Mirror Coatings for Gravitational Wave Detectors

Stuart Reid [1,*] and Iain W. Martin [2]

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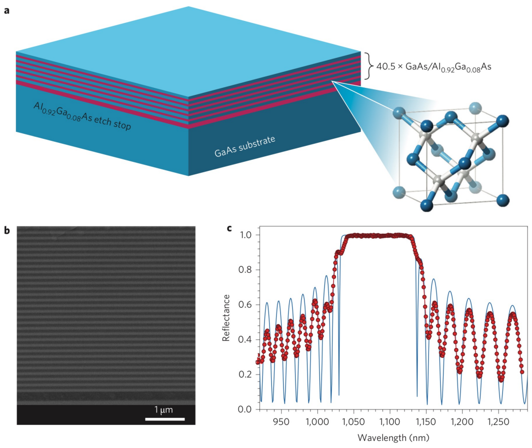
Received: 20 August 2016; Accepted: 25 October 2016; Published: 16 November 2016

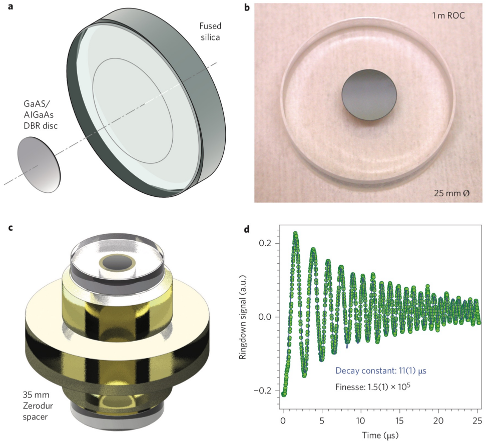
Abstract: The first detections of gravitational waves, GW150914 and GW151226, were associated wi the coalescence of stellar mass black holes, heralding the opening of an entirely new way to observ the Universe. Many decades of development were invested to achieve the sensitivities require to observe gravitational waves, with peak strains associated with GW150914 at the level of 10^{-} Gravitational wave detectors currently operate as modified Michelson interferometers, where therm noise associated with the highly reflective mirror coatings sets a critical limit to the sensitivity current and future instruments. This article presents an overview of the mirror coating developme relevant to gravitational wave detection and the prospective for future developments in the field.

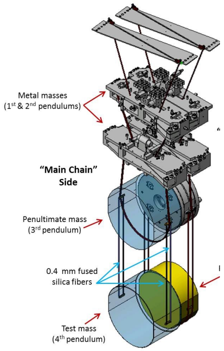
Keywords: gravitational waves; optical coatings; 1064 nm; ion beam deposition; molecul beam epitaxy

1. Introduction

Detecting gravitational waves has been one of the most challenging experimental projects ever to





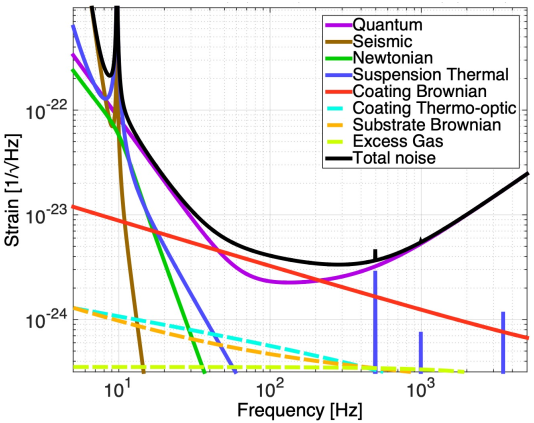


Thermal noise in GW detectors

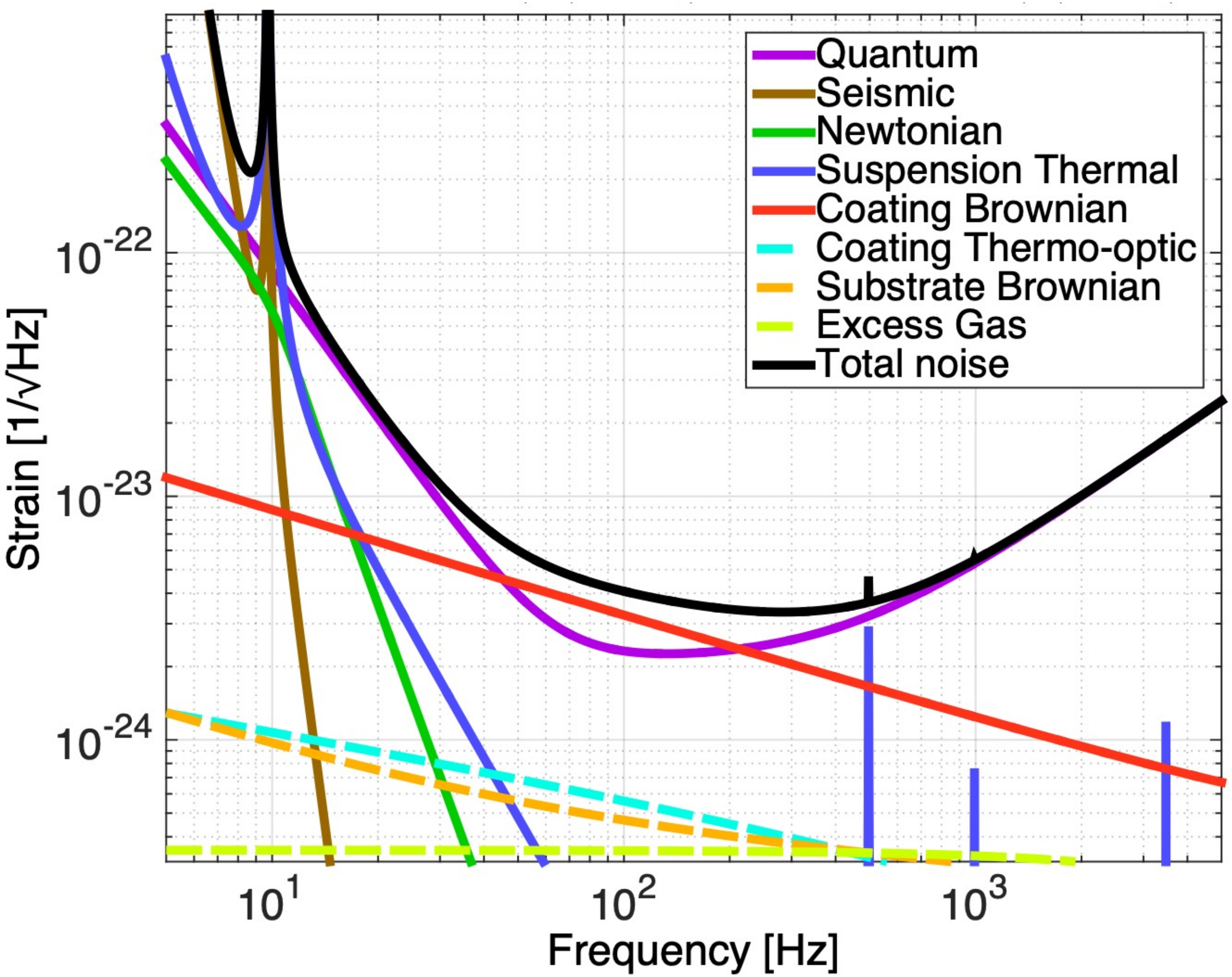
- GW detectors are amongst the most sensitive tools today.

- operation at the technical and scientific limitations (noise, cross coupling, *etc*.)

- improving the instruments means fighting with physics
  - novel techniques (setups, cryogenics, etc.)
  - novel materials (change of material for optical components)
  - …



Thermal noise in GW detectors



Thermal noise in GW detectors

$$S_x(f) = \frac{4k_BT}{\pi^2 f}\frac{1-\nu^2}{Y}\left(\frac{1-2\nu}{1-\nu}\right)\frac{d}{w^2}\phi$$

w = beam spot size
d = coating thickness
Y = Young's modulus
ν = Poisson's ratio

How to reduce coating Brownian noise:

- Larger beam
- Coating thinner
- Low T
- Reduce ϕ, loss angle

N. Nakagawa et al. Phys. Rev D 65 (2002) 102001
Y. T. Liu et al. Phys. Rev. D 62 (2000) 122002
T. Hong et al. Phys. Rev. D 87 (2013) 082001
G. H. Harry et al. Class. Quantum Grav. 19 (2002) 897

Thermal noise in GW detectors

- The first generation of interferometric GW detectors (LIGO, Virgo, GEO600, TAMA300) reached their design sensitivities in a wide range of frequencies.

- Current 2nd gen detectors (Adv. LIGO, Adv. VIRGO) based on:
  - fused silica optics (best optical material currently available)
  - fused silica suspensions *(i.e. lower stage mirror suspension is monolithic)*

- friction between the suspension and the optics can be avoided by using the low mechanical loss jointing technique of hydroxide catalysis bonding

- Upgrades 2nd gen detectors are in progress A+ and AdV+

- KAGRA in Japan is exploiting the use of sapphire mirrors and suspensions at cryogenic temperature, to further reduce Brownian thermal noise.

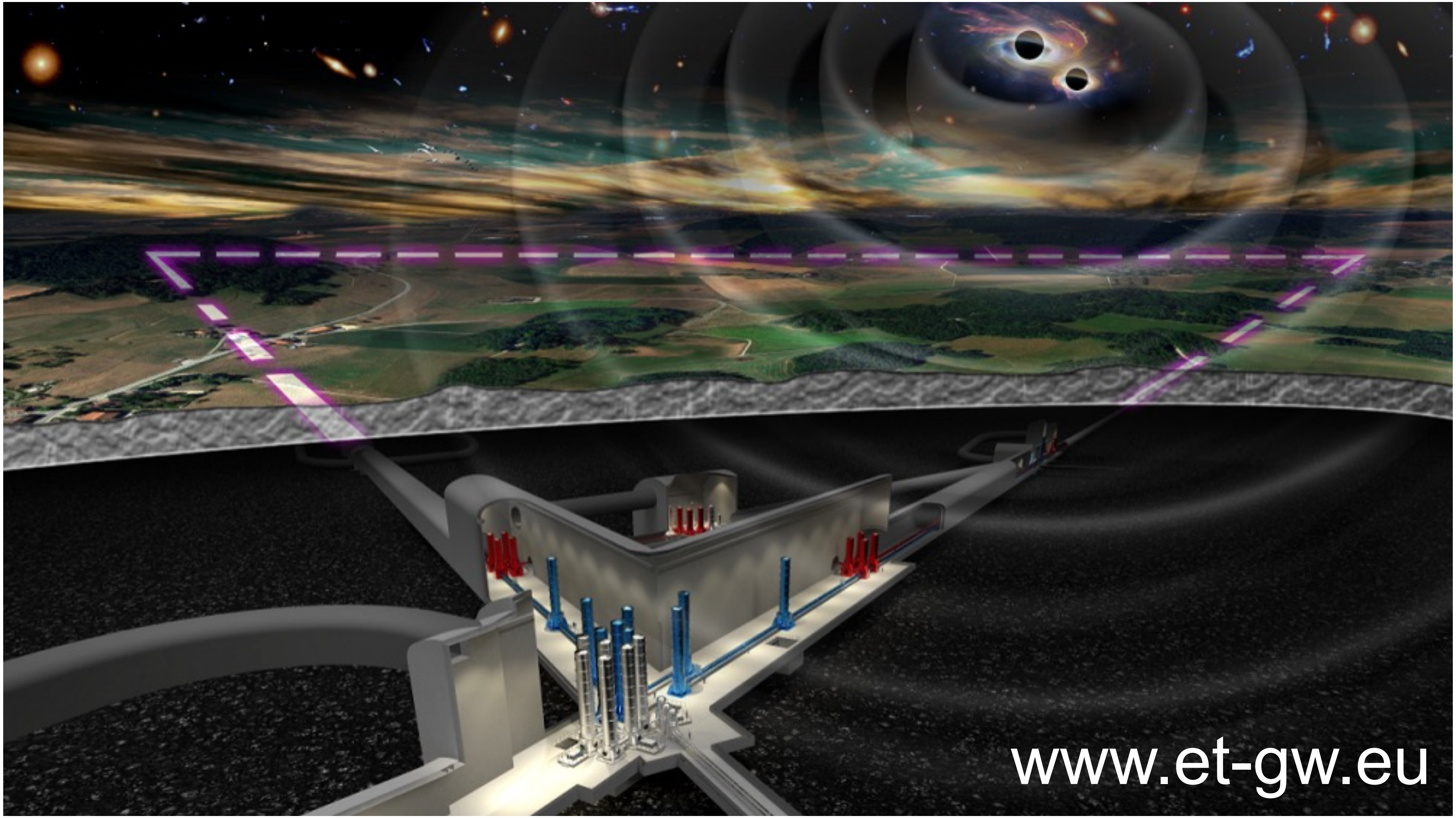
Thermal noise in GW detectors

- Both US and Europe have conceptual designs for 3rd generation detectors – Cosmic Explorer and the Einstein Telescope.

- aims:
  - What technologies are needed to increase sensitivity by a factor of 10 compared to 2nd generation?
  - How might such a design look like?
  - Which materials should be used? Which design?
  - (How much does it cost?)

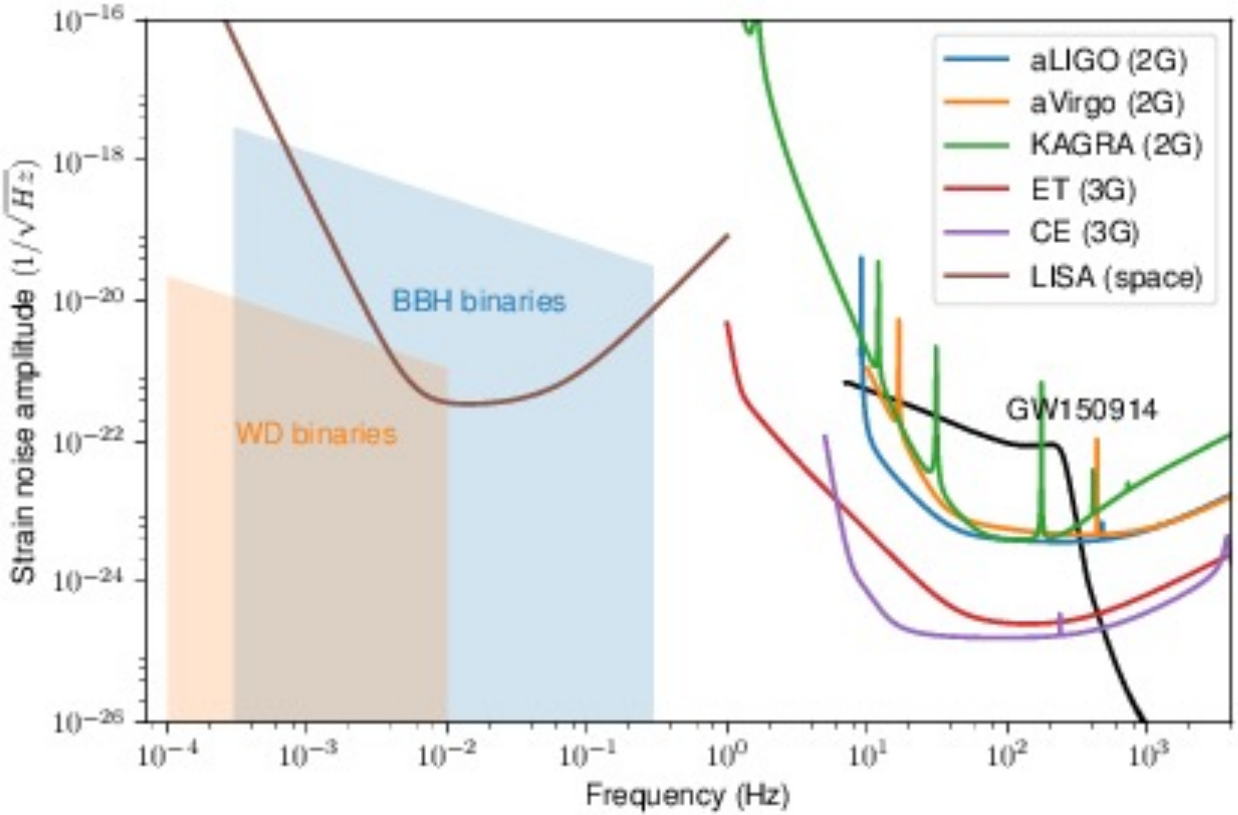
- homepage: www.et-gw.eu

Thermal noise in GW detectors



Thermal Noise in GW detectors

improvement of the sensitivity between different generations of GW detectors:



Qn: does the strain-sensitivity plot give the whole picture?
(hint: these are strain sensitivities for optimum incidence of GW)

Thermal noise in GW detectors

- Parts of the Einstein Telescope have to be operated at cryogenic temperatures to reduce thermal noise.

- natural links between ET and KAGRA:
  - cryogenics
  - pulse tube vs. LHe cooling
  - contamination of the mirrors due to cryotrapping
  - general: pioneering technology in cryogenics

  - Researcher exchanges between Japanese and Einstein Telescope researchers was funded through European initiative in (2012-17).

Thermal noise in GW detectors

- a reminder of thermal noise:
  - two different types

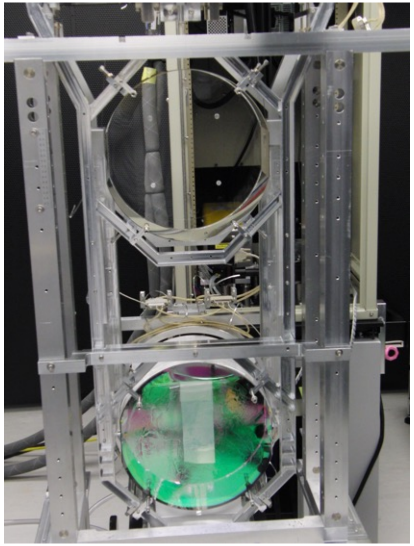
(1) fluctuating thermal energy → Brownian thermal noise
(2) fluctuating temperature → thermo-elastic, thermo-refractive, thermo-optic

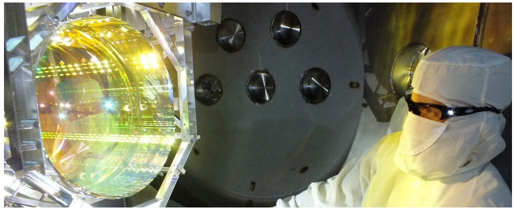
temperature dependent parameter (e.g. CTE, dn/dT) links temperature fluctuation and phase fluctuation of the detector

Thermal noise and importance of coatings

- Introduction -

Reminder of relevance of coatings





Original requirements for aLIGO (at 1064nm):

Absorption < 0.5 ppm required (goal < 0.3 ppm)
Scatter < 2 ppm required (goal < 1 ppm)
ITM transmission: (5 ± 0.25) × 10^{-3}.
ETM transmission: < 10 ppm (goal < 5 ppm)

IBS

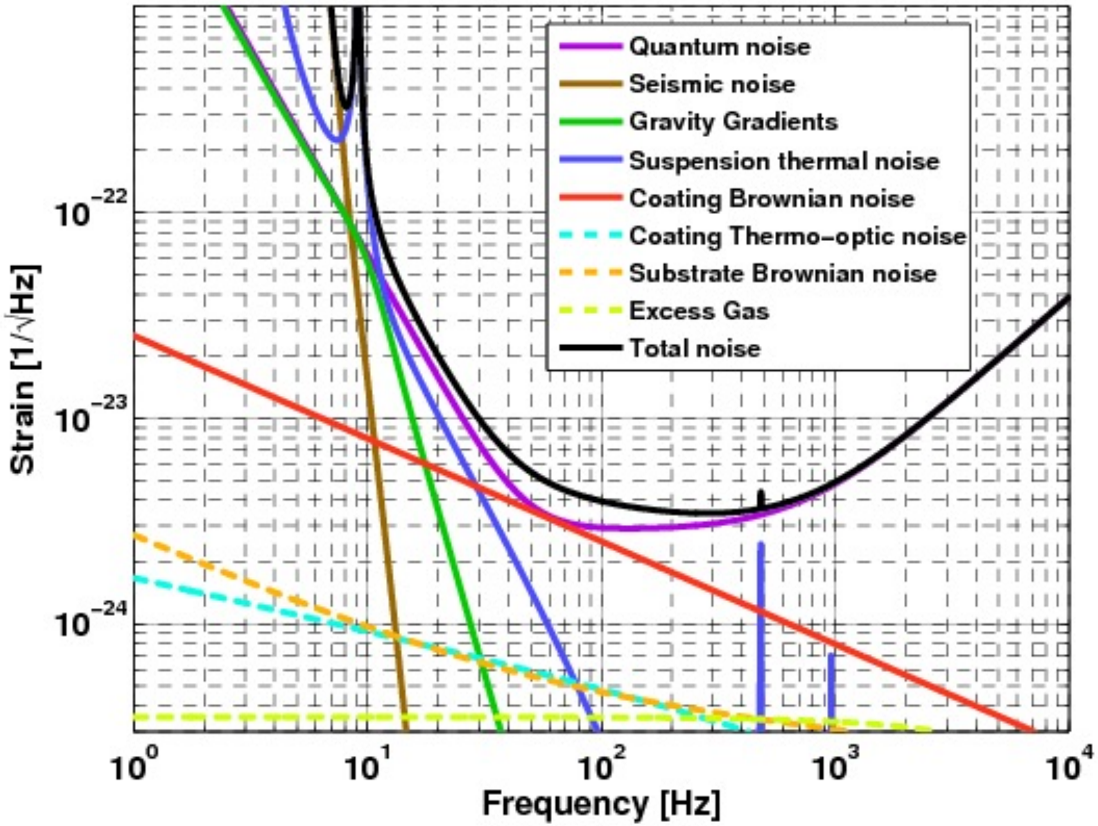
Test Mass HR matching = 2 (T1-T2)/(T1+T2)
< 1 × 10^{-2} required (goal 5 × 10^{-3})
AR reflectivity: 200 ± 20 ppm

Mechanical loss: 3 × 10^{-5} (goal 1 × 10^{-4})

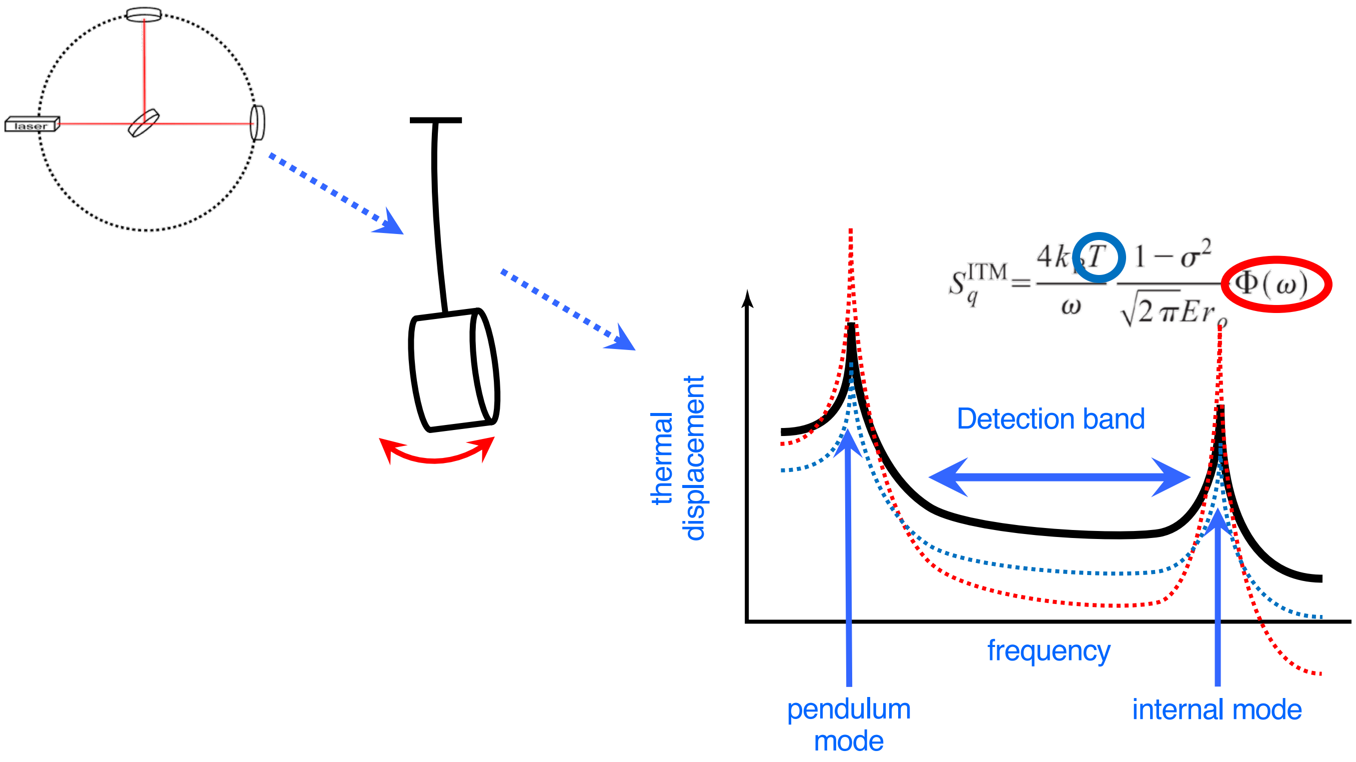
???

Likely requirements for aLIGO+ and beyond?
(Note A+ upgrades, approved in 2018, state a mechanical loss of 9 × 10^{-5}.

Sensitivity curve for aLIGO



Reducing thermal noise in the detection band



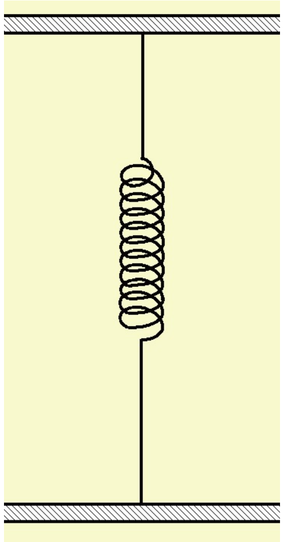
$$S_q^{\mathrm{ITM}} = \frac{4k_BT}{\omega}\frac{1-\sigma^2}{\sqrt{2\pi}Er_o}\Phi(\omega)$$

Mechanical loss

- Introduction -

Basics of mechanical loss

- elastic behaviour of a solid



Hook's Law

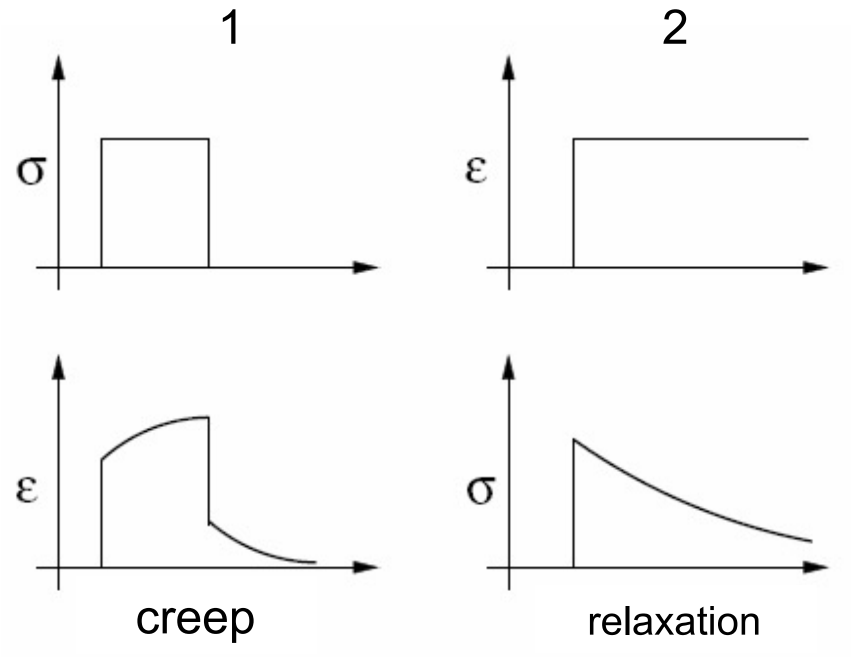
$$\sigma = E \cdot \varepsilon$$

σ … stress
ε … strain
E … Young's modulus

instantaneous reaction, full recovery

Basics of mechanical loss

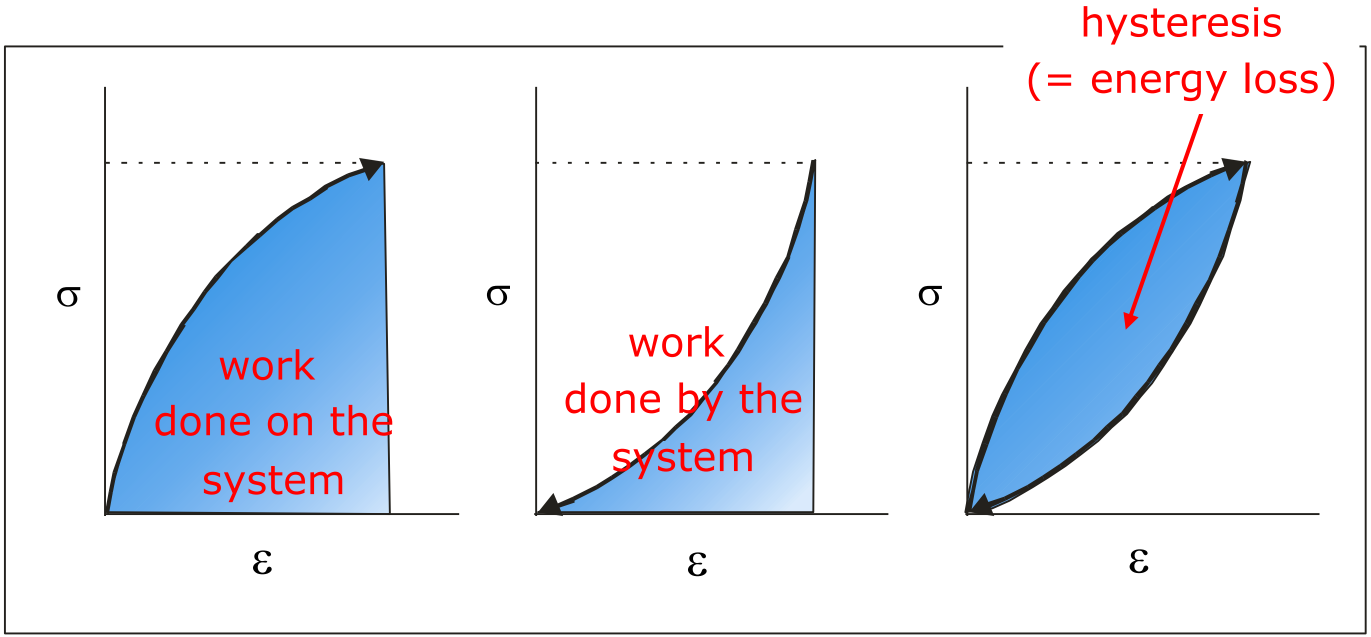
- anelastic behaviour of a solid



only partial instantaneous reaction, full recovery after t = ∞

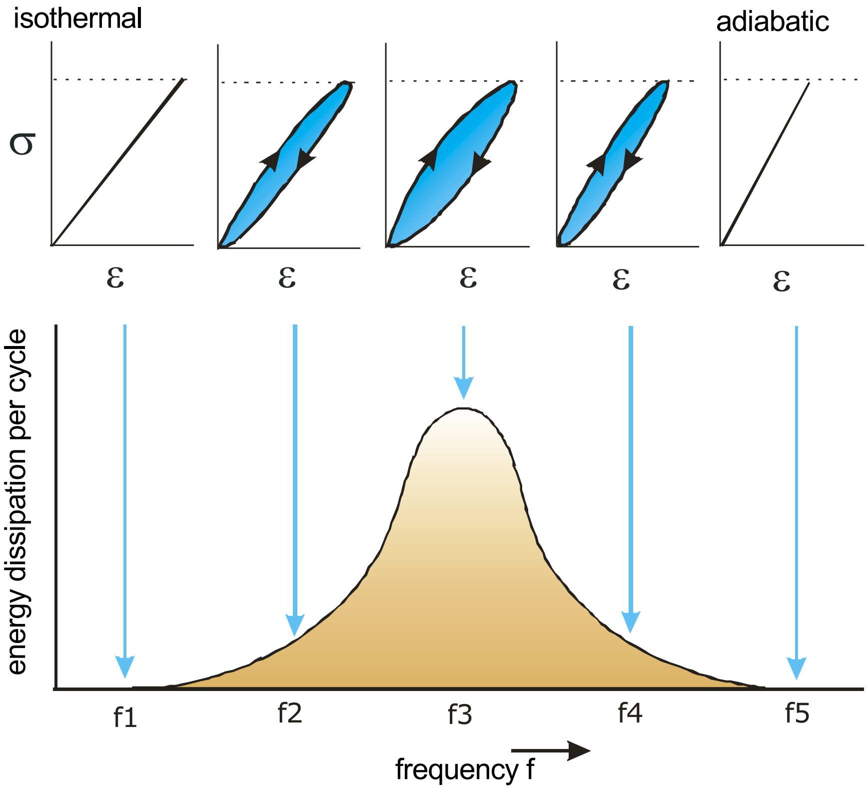
Basics of mechanical loss

- periodic process – anelasticity and mechanical loss



energy loss related to mechanical loss by means of: $\varphi = \frac{1}{2\pi} \frac{\Delta E}{E}$

Basics of mechanical loss



Basics of mechanical loss

- definition of the mechanical loss = phase lag between stress and strain
- measurement via the mechanical Q-factor at a resonance
- keep in mind:

  The mechanical loss is a continuous function but we
  just probe it at certain frequencies (resonant frequencies)
  of a system → no full knowledge available.

Loss mechanisms

- There are many different origins of loss in solids.
- Focus on 3 dominant ones often cited in literature:
    - phonon-phonon interaction
    - thermo-elastic loss
    - impurity driven losses

Loss mechanisms

- Phonon-phonon-damping (Akhiezer-/Landau-Rumer-Damping)

Phonons are forming a certain distribution when in equilibrium. At low frequency excitations the acoustic vibration (= phonon) modulates the lattice → new local equilibrium → redistribution consumes energy → loss.

(Akhiezer loss)

If the phonon energy is high (high frequency vibration) the acoustic phonon directly interacts with the phonons of the given distribution → direct phonon scattering → redistribution consumes energy → loss.

(Landau-Rumer-Loss)

Basics of mechanical loss

- thermo-elastic damping

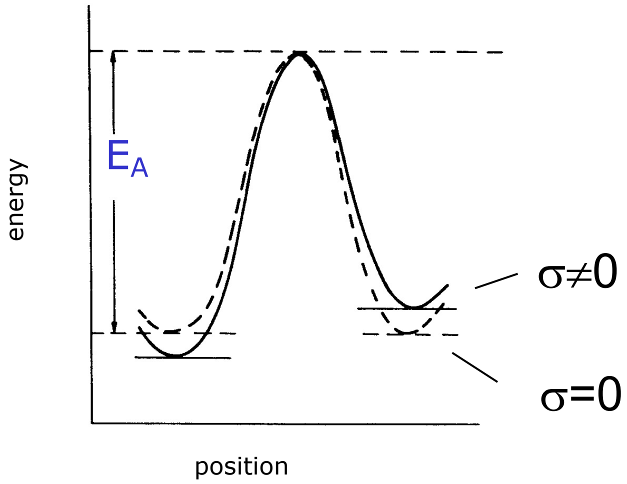
  If a sample is deformed certain parts will be compressed or expanded → local heating or cooling (depending on CTE). Sample is now in thermal non-equilibrium → heat flux → entropy is increased → loss.

- impurity driven damping

  Impurities can occupy different positions in a lattice depending on the applied stress. If an external vibration is applied it might be energetic better to change positions → loss.

Basics of mechanical loss

- The transition between 2 (quasi-)stable positions can be modelled with a double-well potential:



$$\phi(\omega) = \Delta \frac{\omega\tau}{1+(\omega\tau)^2}$$

„Debye peak“

Δ … relaxation strength

τ … relaxation time

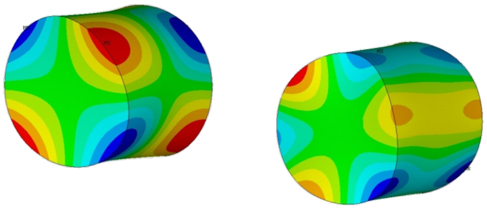
thermally activated process:

$$\tau = \tau_0 e^{\frac{E_A}{k_B T}}$$

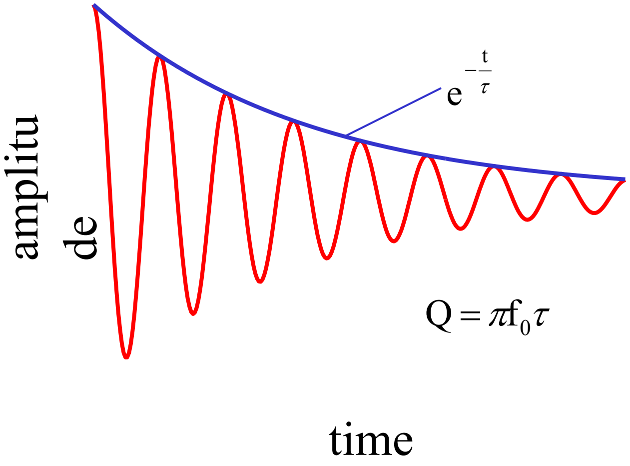
E_A … activation energy

τ_0 … relaxation constant

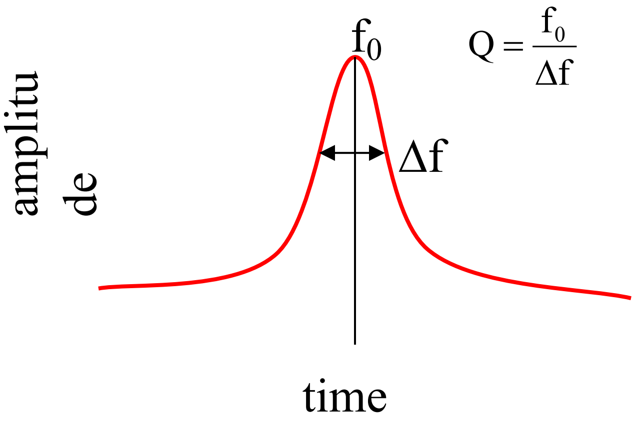
Basics of mechanical loss



- ring-down measurements

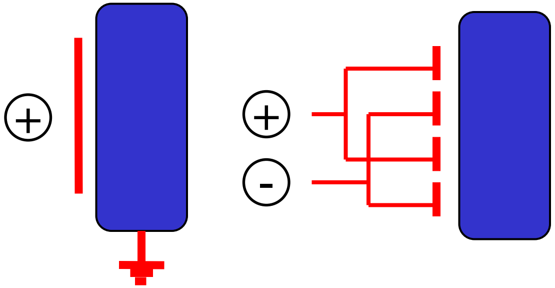


- bandwidth measurements

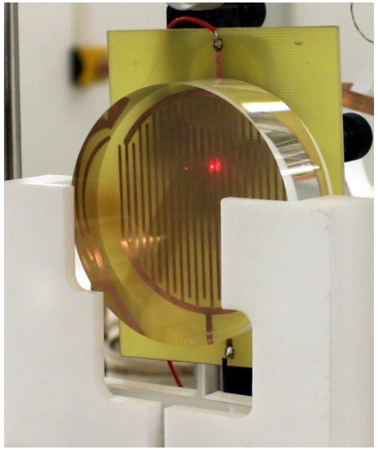


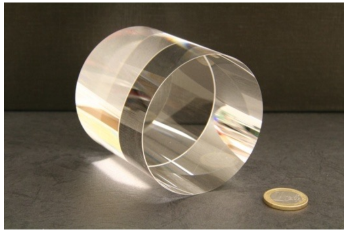
Basics of mechanical loss

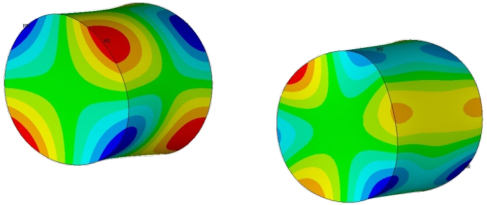
- excitation of modes
  - mechanical (e.g. piezo)
  - electro-static



- vibration read-out
  - electrical read-out (capacitor)
  - optical read-out (e.g. optical lever, interferometric techniques)

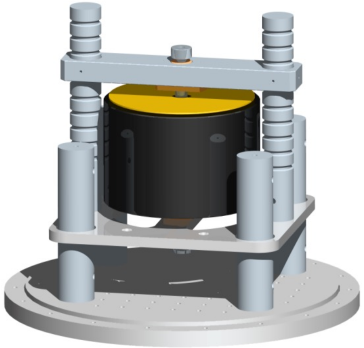


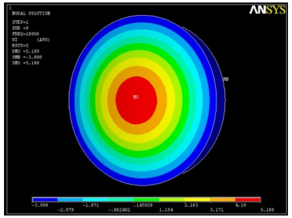


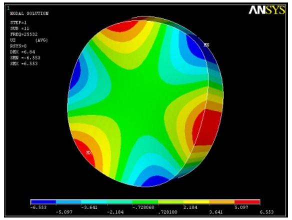


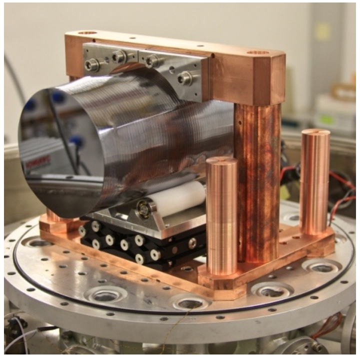
Mechanical loss

- Bulk Materials -



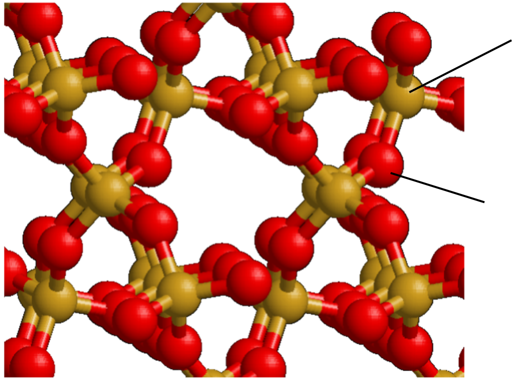






Selected examples - Quartz

- crystalline quartz is well known → toy material to investigate setups and data processing tools



cryst. quartz shows channels along its c-axis

hydrothermal growth of crystal

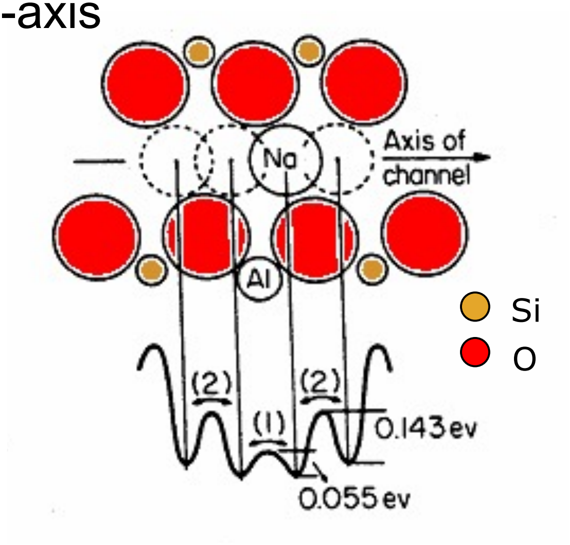
↓

grown from solution under pressure (~ 500 bar) at elevated temperatures containing:

- water
- silicon dioxide
- sodium carbonate / hydroxide

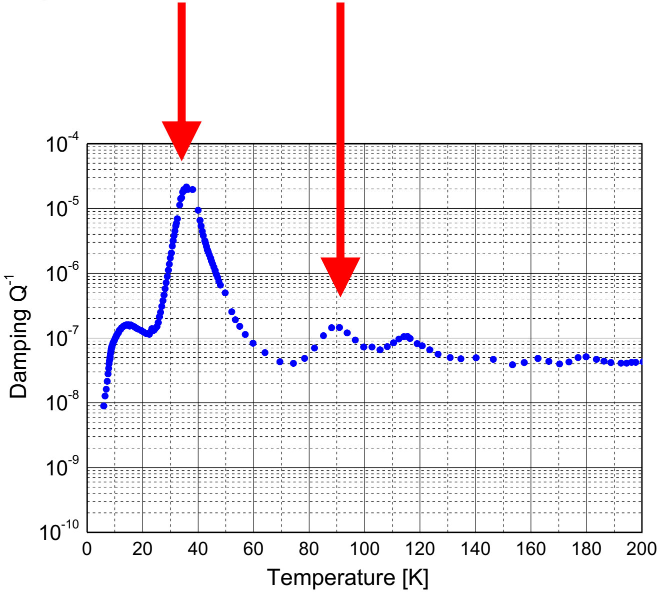
Selected examples - Quartz

impurities trapped in multiple well potential along the c-axis



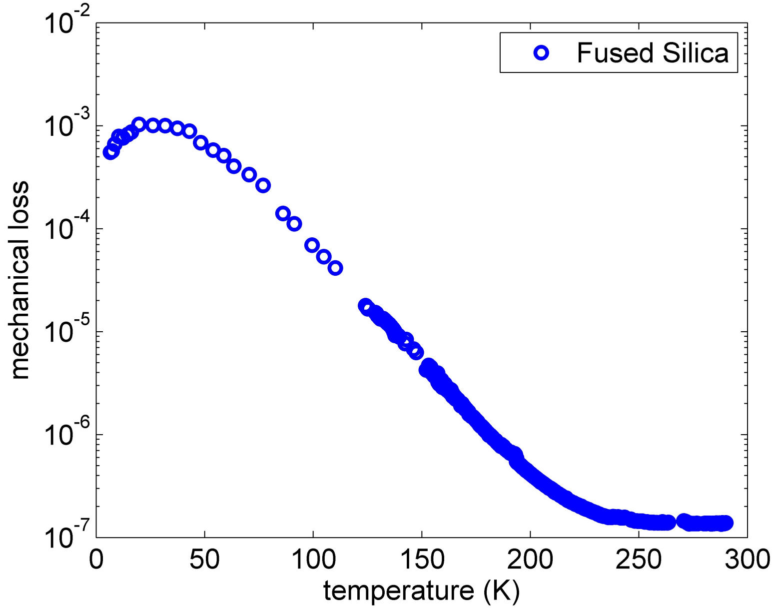
loss process is orientation dependent
→detailed study needs different cryst. cuts from the same material

loss peaks associated with sodium



activation energy from experiment:
~ 55 meV

Selected examples – Fused Silica



fused silica:

- very low loss at room temperature reaching 4×10^{-10}
- large loss peak around 30K

↓

not suited for cryogenic use in GW detectors

origin of the peak:

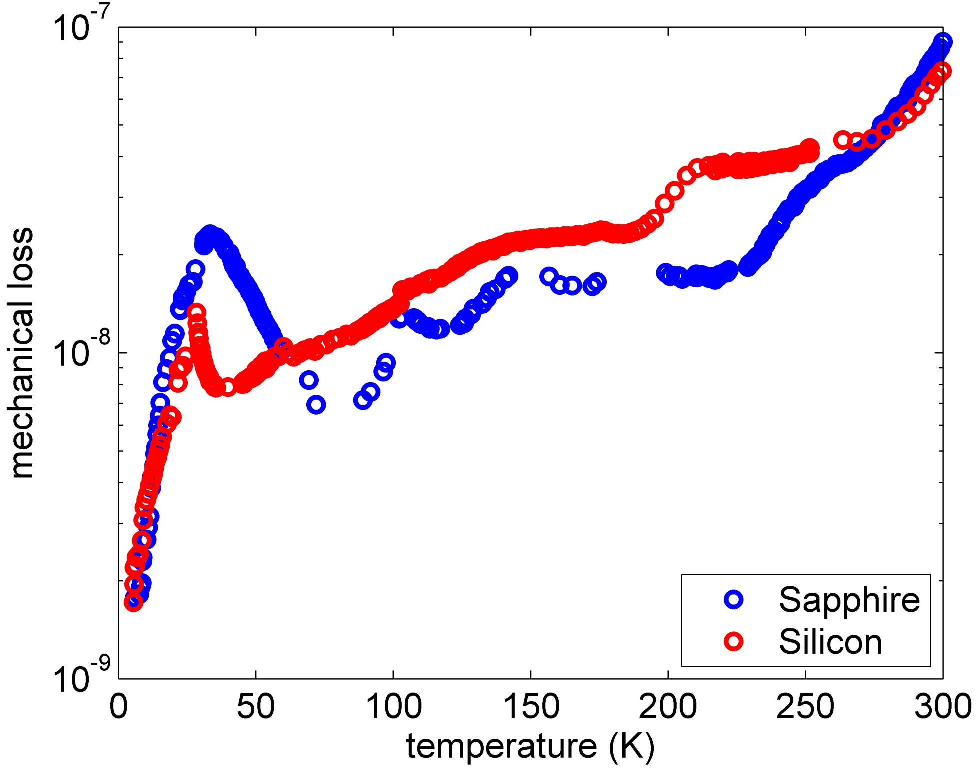
Amorphous silica has a near but no far order. Thus, loss processes get a distribution of loss parameters. The peak is the superposition of all of them.

Selected examples – Sapphire/Silicon

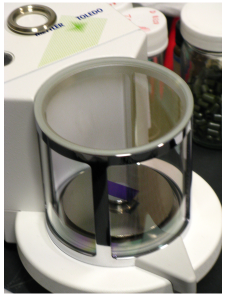
- crystalline materials needed for cryogenic operation
- different candidate materials have been discussed in the past
- possible candidate materials are sapphire (KAGRA) and Si (ET)
- reasons:
  - both are optical materials (remember, FS is currently the best optical material)
  - both are available in rather large pieces
  - high thermal conductivity
  - coating techniques available
- while sapphire can be operated at 1064nm, silicon demands a change of the laser wavelength due to its optical absorption

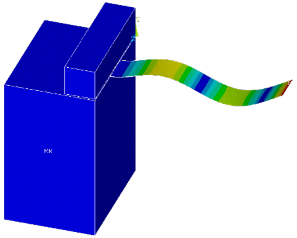
Selected examples – Sapphire/Silicon

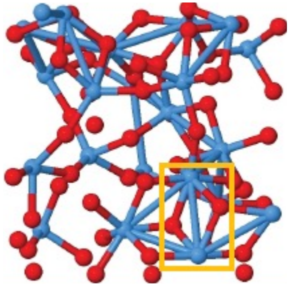
- mechanical loss of silicon and sapphire is comparable at cryogenic temperatures (Q‘s up to several 10^9 achieved)



test measurement of silicon and sapphire samples [U Jena]

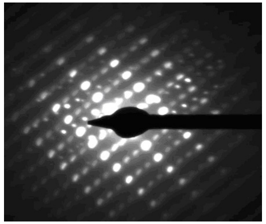


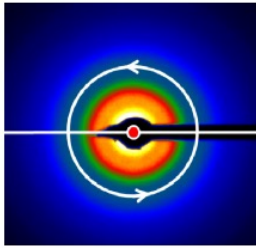


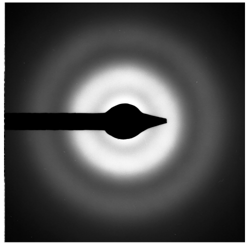


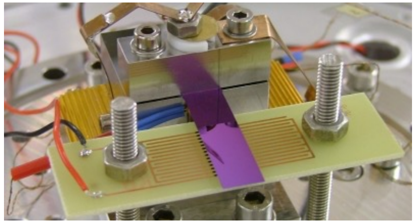
Mechanical loss

- Coating Materials -







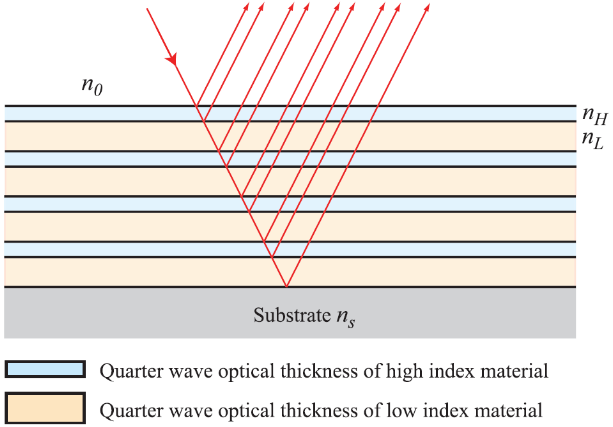


Optical coatings

- Requirements – high reflectivity, low optical absorption (< 1ppm)
- Multilayer coatings of dielectric materials, λ/4 thick
- Reflectivity from difference in refractive index, and number of layers, 2*N*.

$$R_{2N} = \left(\frac{n_s f - n_0}{n_s f + n_0}\right)^2$$

$$f = (n_H/n_L)^{2N}$$



- Current detectors use silica (*n*=1.45) / tantala (*n*=2.03) coatings, ~ 15 bi-layers

Coating thermal noise

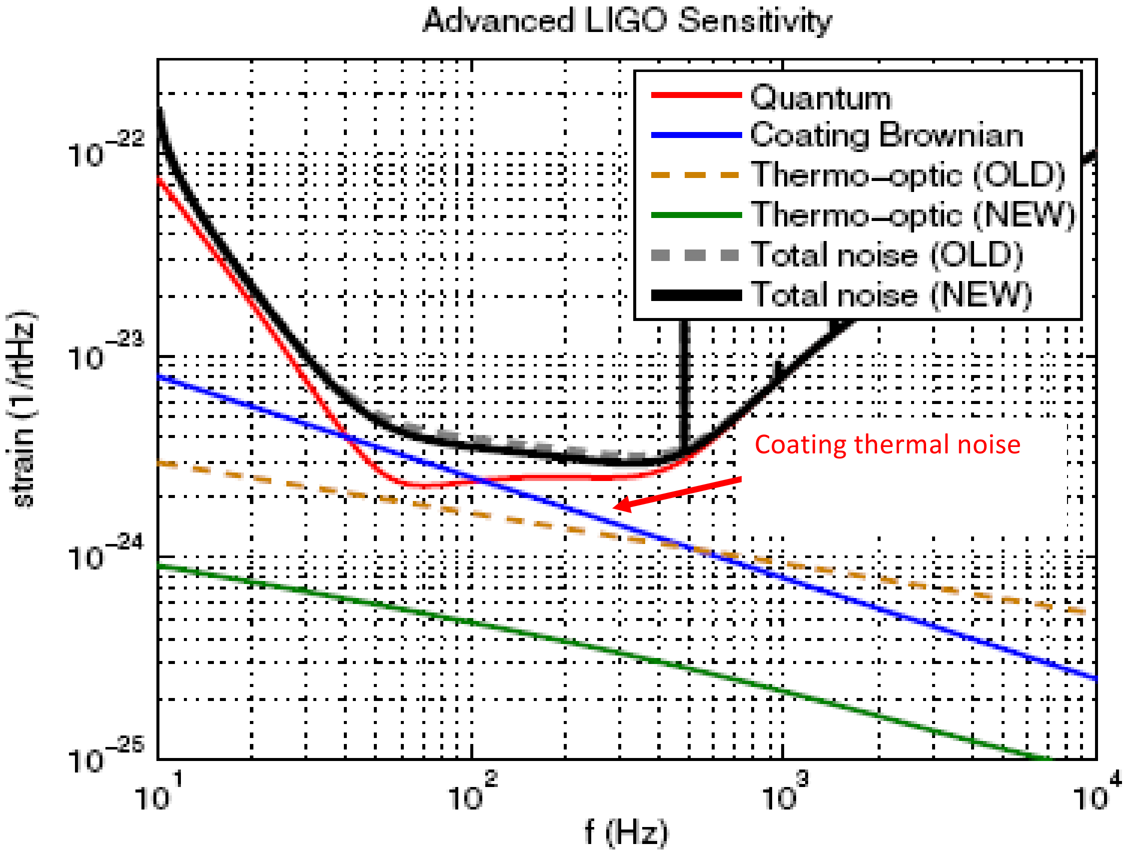
- Levin – interferometer most sensitive to mechanical loss close to the reflected laser beam
  - Thus mechanical loss of coatings is particularly important

- Coating loss dominated by the loss of the tantala layers
  - $\phi_{tantala} \sim 4\times10^{-4}$
  - $\phi_{silica} \sim 5\times10^{-5}$

- Measurements suggested no observable loss from coating layer interfaces (however recent results from LMA, Lyon, suggest some interface loss may be observable)

- Doping Ta_2O_5 with TiO_2 can reduce the loss by ~40% (used in aLIGO / Adv. Virgo)

Coating thermal noise

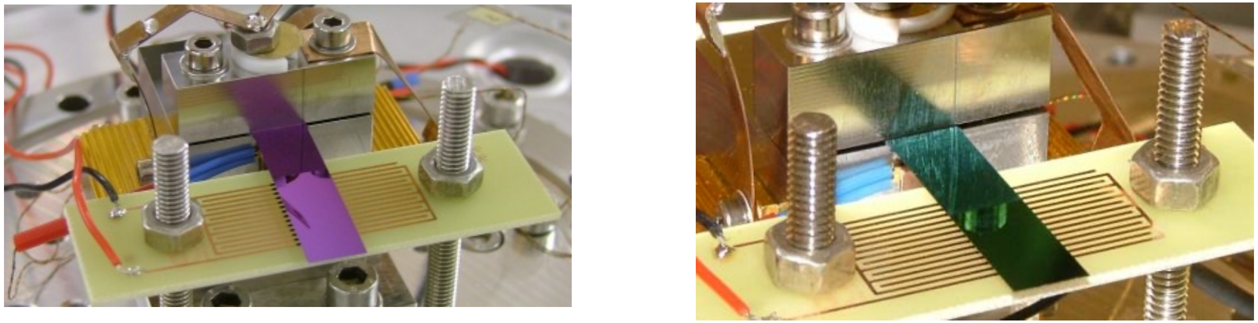


- Coating thermal noise expected to limit achievable sensitivity of future GW detectors at their most sensitive frequencies

Coating loss measurements

- First cryogenic measurement of silica/tantala coating by Yamamoto et al, showed possible slight increase in loss at low temperature

- Cryogenic loss studies of mono-layers of individual coating materials carried out in collaboration between Glasgow, Jena, LMA
  - Study individual materials in isolation
  - Identify microscopic dissipation mechanisms
  - Test coating performance at cryogenic temperatures

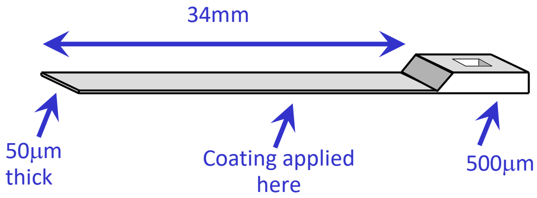


Single layer coatings of silica (left) and tantala (right), clamped for loss measurements

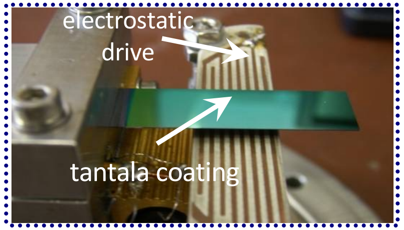
Measuring coating loss - 1

$$\phi(f_0) = \frac{\Delta f}{f_0} = \frac{E_{\text{lost per cycle}}}{2\pi E_{\text{stored}}}$$

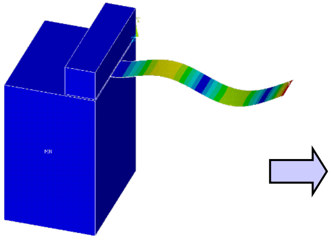
- Single layers of a coating material applied to silicon cantilever substrates



- Loss measured from exponential ring-down of bending modes

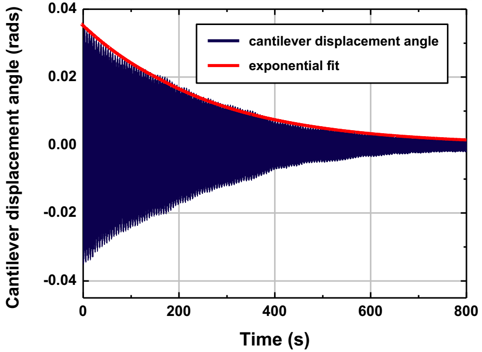


coated cantilever in clamp within cryostat



bending modes excited via eletrostatic drive

$$A(t) = A_0 e^{-\phi(\omega_0)\frac{\omega_0 t}{2}}$$

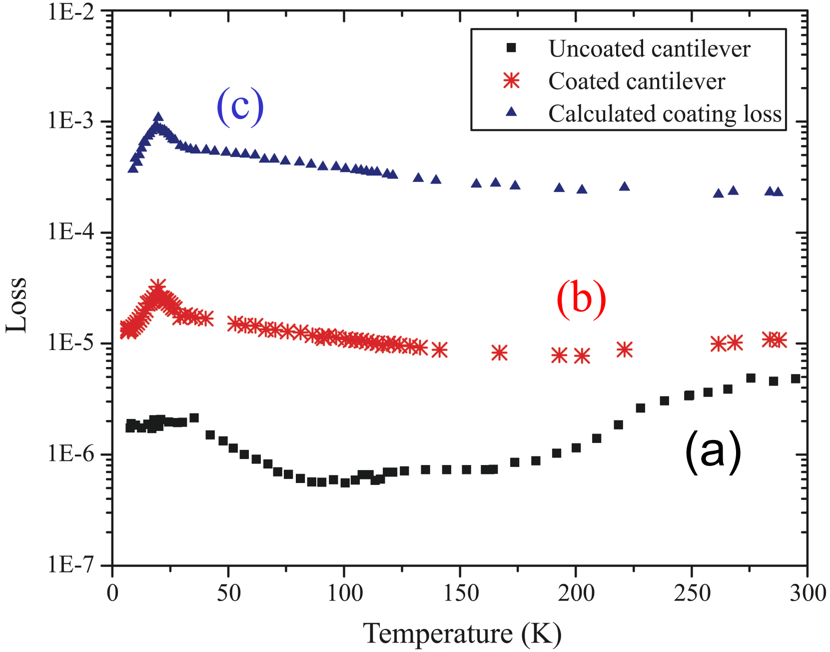


loss from free decay of amplitude

Measuring coating loss - 2

- Loss of coating layer calculated from difference in loss of a coated and un-coated cantilever

- Scaling factor accounts for fraction of total elastic energy stored in the coating



Loss of (a) uncoated silicon cantilever with thermal oxide layer, (b) cantilever coated with 500 nm of TiO_2-doped Ta_2O_5 (14.5% Ti) and (c) the calculated loss of the coating layer

$$\phi_{\text{coating}} = \frac{Y_{cantilever}}{3Y_{coating}} \frac{t_{cantilever}}{t_{coating}} (\phi_{coated} - \phi_{un-coated})$$

Loss peak analysis - tantala

- Debye-like mechanical loss peaks

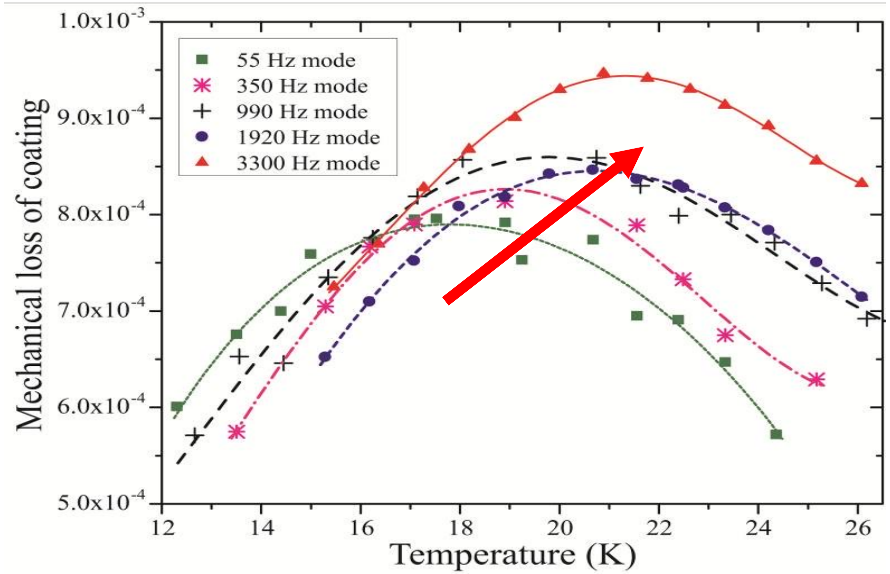
$$\phi(\omega) = \Delta \frac{\omega\tau}{1+(\omega\tau)^2}$$

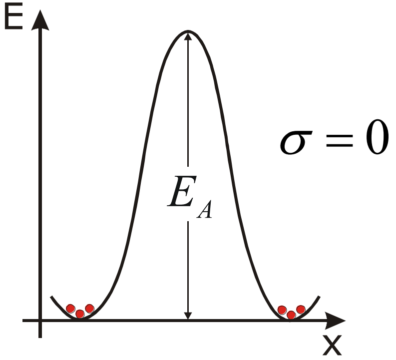
Δ … relaxation strength
τ … relaxation time

- thermally activated process

$$\tau = \tau_0 e^{\frac{E_A}{k_B T}}$$

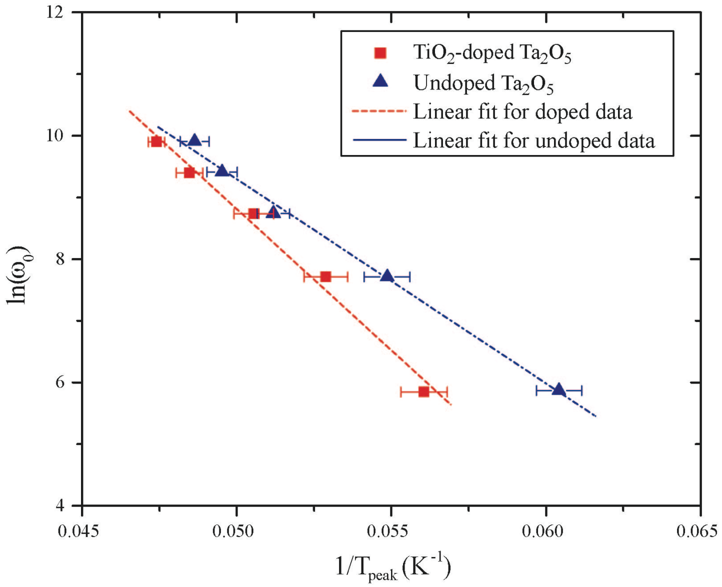
E_A … activation energy
τ_0 … relaxation constant





double well potential
without external stresses

Loss mechanism parameters – Arrhenius plot

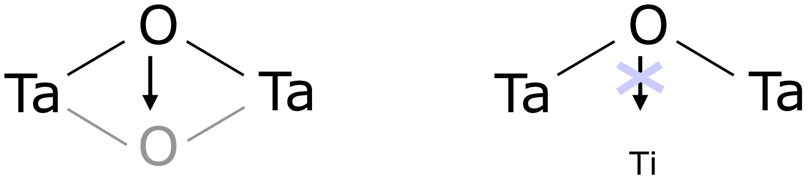


- Activation energy
  - (40 ± 3) meV for TiO_2 doped Ta_2O_5
  - (29 ± 2) meV for undoped Ta_2O_5

- Doping with TiO_2 increases the activation energy.
- Transition between two stable states appears to be hindered

Possible microscopic processes

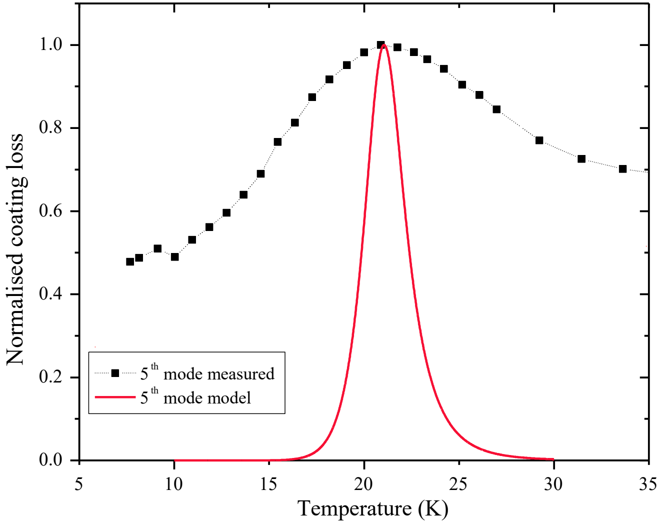
- no long-distance order in coating materials (amorphous)
- possible transitions of atoms / atom groups



- doping might block possible positions → increase of activation energy

Distribution of model parameters

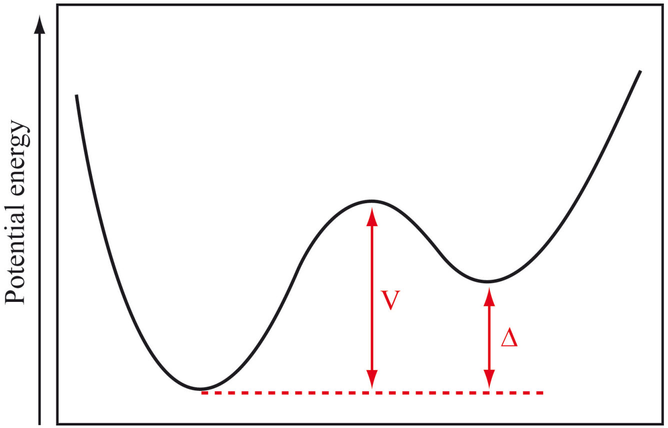
- Debye loss peak plotted using calculated activation energy and relaxation constant



- Much narrower than experimental peak
- Amorphous structure results in a distribution of activation energies.

Distribution of parameters

- refined model: asymmetric double-well potential
- barrier height distribution g(V)
- asymmetry distribution f(Δ)



$$\phi = \frac{\gamma^2}{k_B T C_{ii}} \int_0^\infty \int_0^\infty \frac{\omega\tau}{1+(\omega\tau)^2} \operatorname{sech}^2\left(\frac{\Delta}{2k_B T}\right) f(\Delta) g(V) d\Delta dV$$

[Gilroy, Phillips 1981]

- γ represents the coupling between strain and the dissipation mechanism
- C_{ii} is the elastic constant of the material

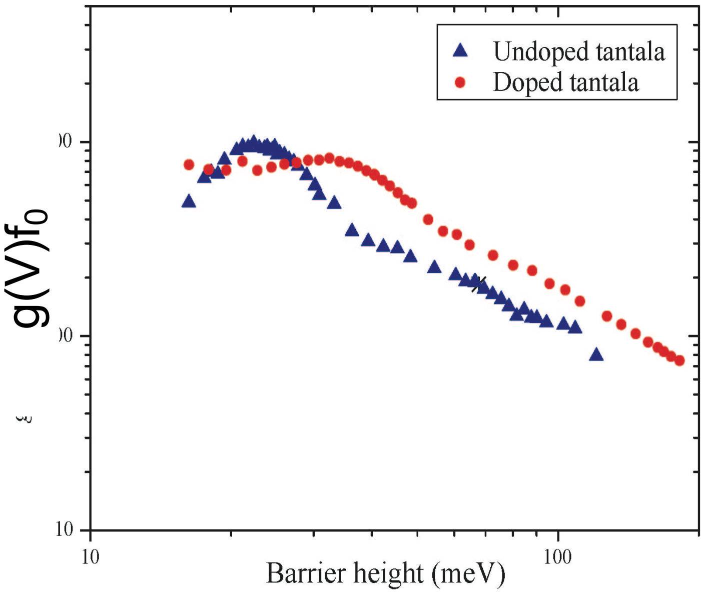
Distribution of barrier heights

- asymmetric double well potential:

$$\phi = \frac{\pi\gamma^2 f_0}{C_{ii}} k_B T g(V)$$

[Gilroy, Phillips 1981]

g(V) … barrier height distribution

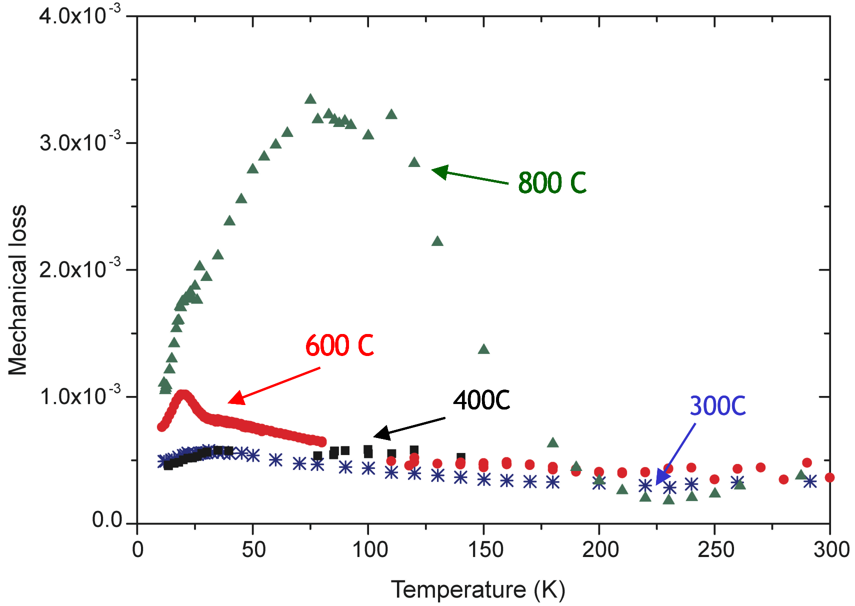


- barrier height distribution contains information about the microscopic structure

- doping changes height and distribution of barrier heights

[Martin et al. 2009]

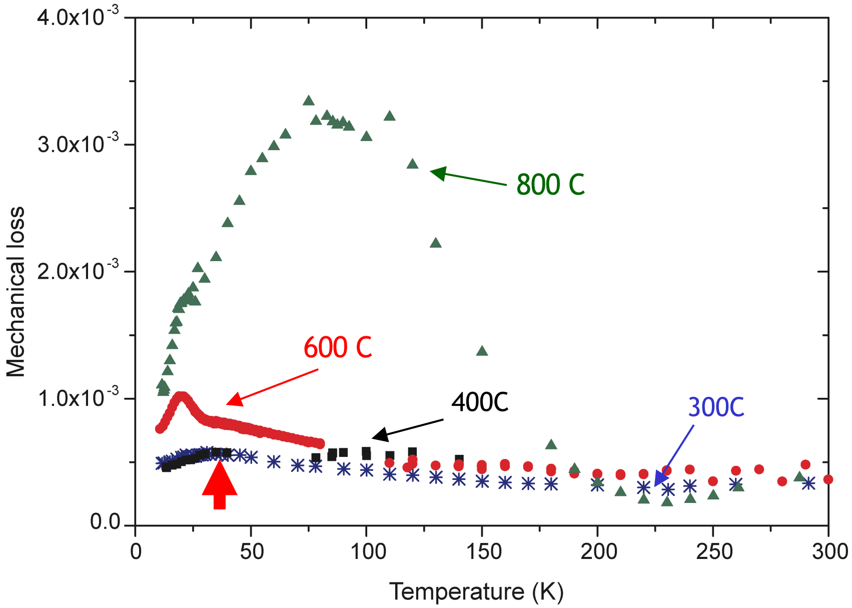
Effect of heat treatment temperature on Ta_2O_5 loss

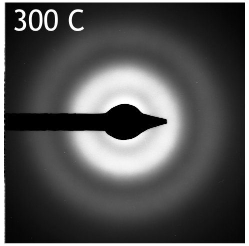


Loss at 1.9 kHz of 0.5 μm thick un-doped Ta_2O_5 coatings heat treated at 300, 400, 600 and 800 C. (Coatings from CSIRO)

- Three loss peaks, triggered at different post-deposition heat-treatment temperatures

Effect of heat treatment temperature on Ta_2O_5 loss



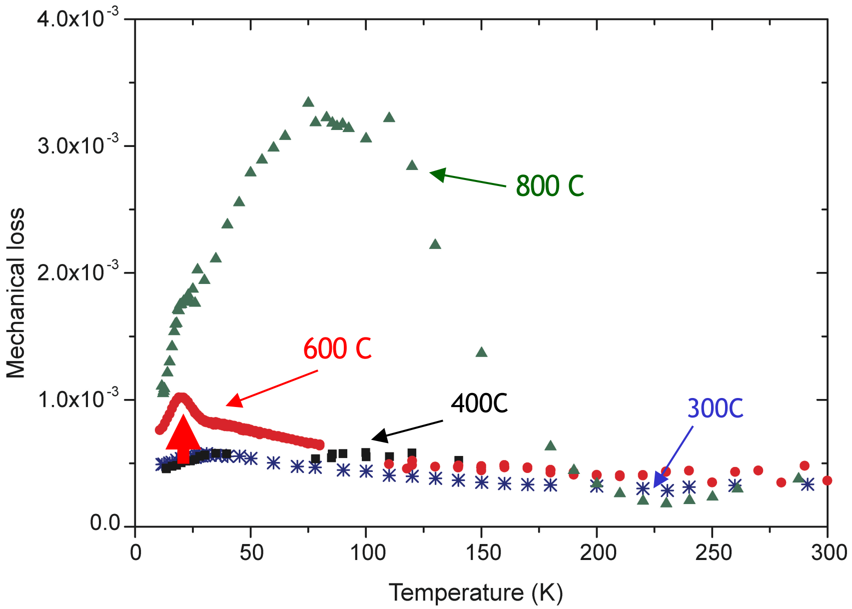


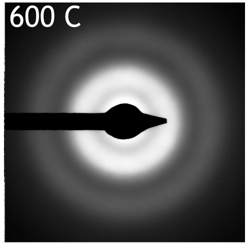
Above: Electron diffraction pattern of Ta_2O_5 heat treated at 600 C

Left: Loss at 1.9 kHz of 0.5 µm Ta_2O_5 coatings annealed at 300, 400, 600 and 800 C.

- 35 K peak
  - Observed in Ta_2O_5 heat treated at 300, 400 C, and likely in Ta_2O_5 heat treated at 600 C
  - Activation energy 54 meV
  - Analogous to dissipation peak in fused silica, involving thermally activated transitions of oxygen atoms?

Effect of heat treatment temperature on Ta_2O_5 loss



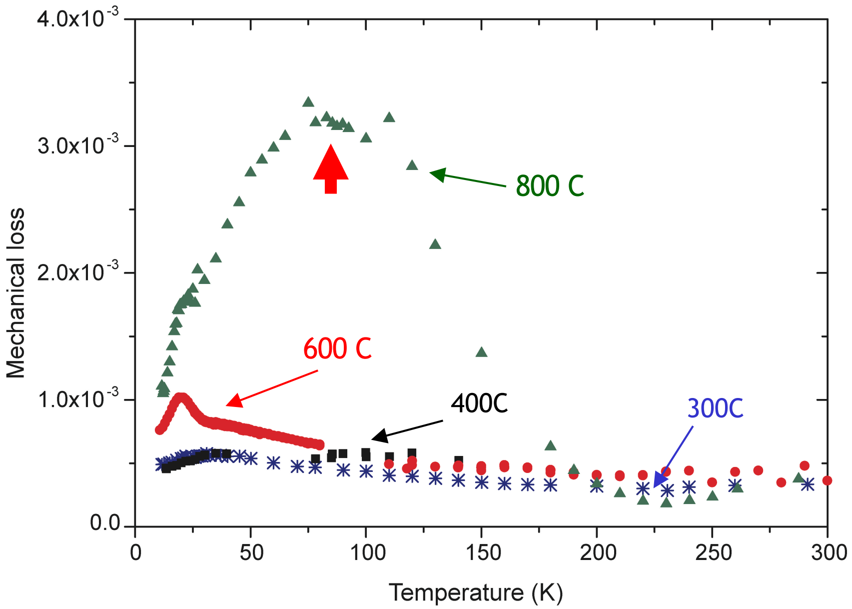


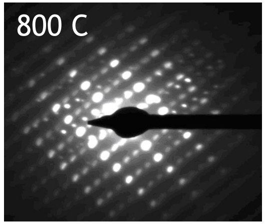
Above: Electron diffraction pattern of Ta_2O_5 heat treated at 600 C

Left: Loss at 1.9 kHz of 0.5 μm Ta_2O_5 coatings annealed at 300, 400, 600 and 800 C.

- 18 K peak
  - Observed in Ta_2O_5 heat treated at 600 C and 800 C
  - Related to structural changes brought on by heat treatment close to crystallisation temperature?

Effect of heat treatment temperature on Ta_2O_5 loss



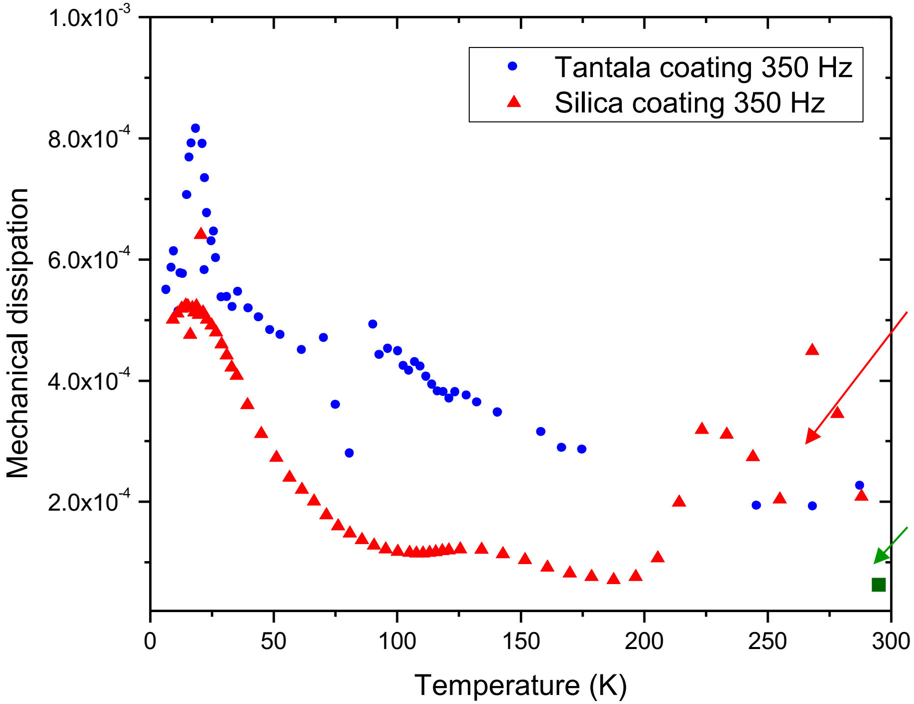


Above: Electron diffraction pattern of Ta_2O_5 heat treated at 800 C

Left: Loss at 1.9 kHz of 0.5 μm Ta_2O_5 coatings annealed at 300, 400, 600 and 800 C.

- 90 K peak
  - Observed in coating heat treated at 800 C
  - Large, broad loss peak likely to be related to (expected) onset of polycrystalline structure due to high temperature heat treatment. Loss mechanism could be e.g. phonon scattering at grain boundaries

Loss of silica coatings

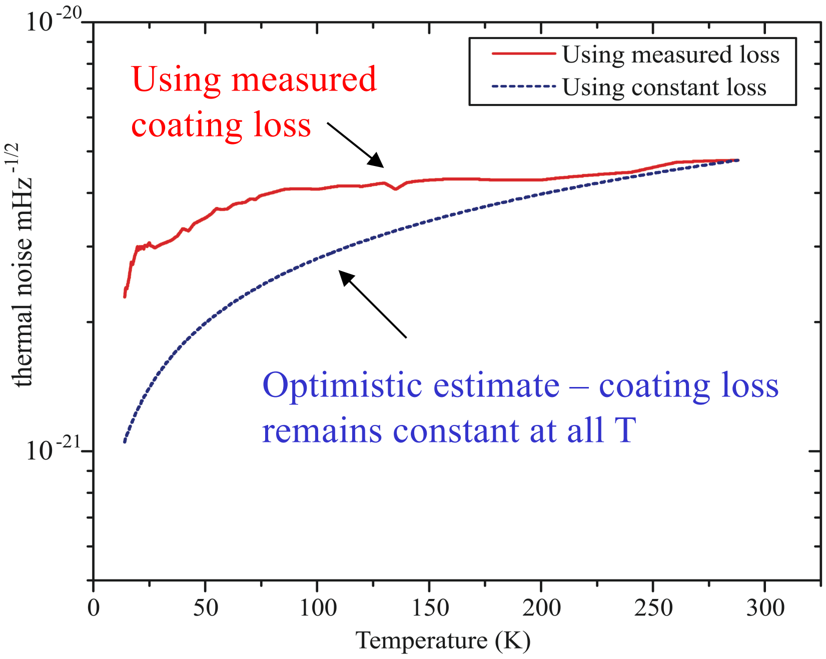


Scatter at higher temperatures, possibly due to loss into clamp.

Repeated room temperature measurement of silica coating loss.

- Loss of SiO_2 will have a significant contribution to coating thermal noise below 100 K

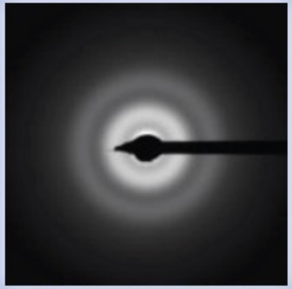
Coating thermal noise at 100 Hz



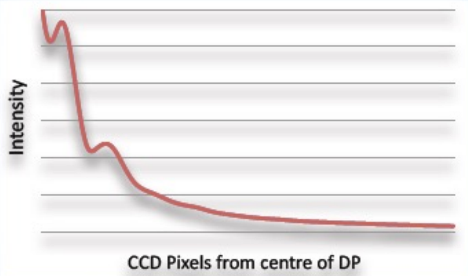
- If coating loss was constant with temperature, could gain factor of ~ 4 in TN at 18 K
- Measured coating losses imply we can only gain a factor of ~ 1.7 in coating TN by cooling to 18 K

Probing links between atomic structure and loss

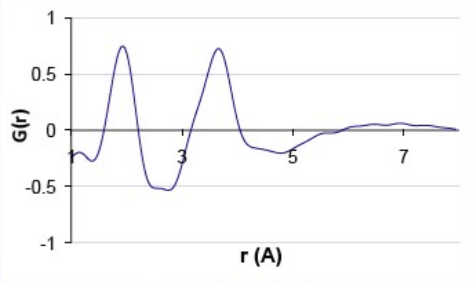
- Short range structure of amorphous materials probed by Reduced Density Function analysis of TEM electron diffraction data
  - RDF is a Fourier transform of the information gained from the intensity profile of a diffraction pattern
  - RDF gives statistical representation of where atoms are located with respect to a central atom



Diffraction pattern of tantala



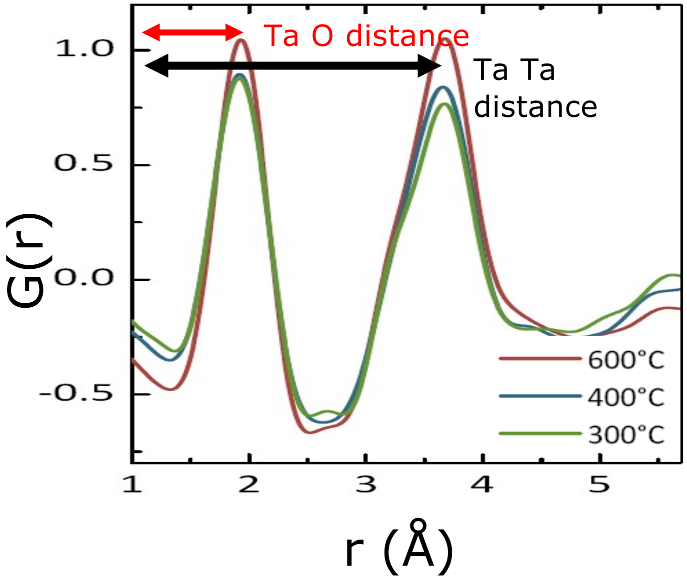
Resulting intensity profile (arbitrary units)



Reduced density function

$$G(r) = 4\int_0^\infty \varphi(q)\sin(qr)dq$$

The Reduced Density Function (RDF)

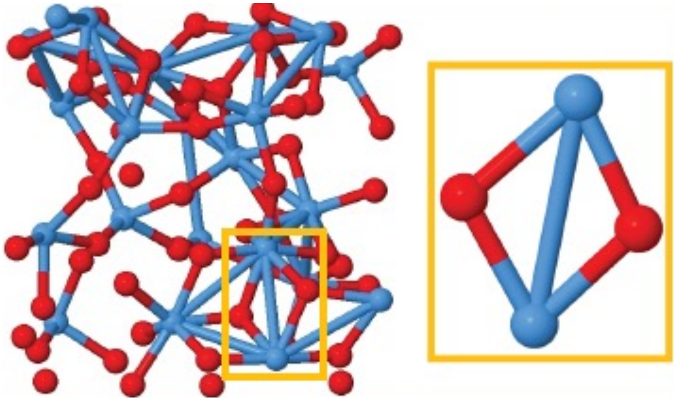


RDFs of heat-treated tantala coatings[1]

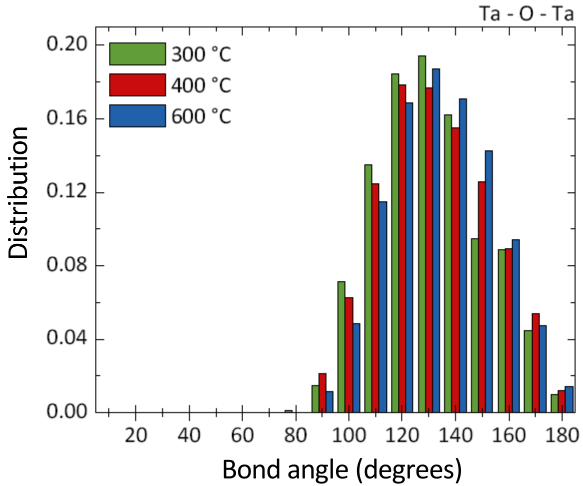
- Interpreting RDFs
  - Peak position - nearest neighbour distances
  - Peak height – nearest neighbour abundances
  - Peak width – indicates level of order in structure

Structural modelling

- RDF can be used as basis for Reverse Monte Carlo models of the microstructure, allowing e.g. bond angle distributions to be extracted
  - Molecular dynamics simulations used to ensure models are energetically stable



Ta – blue O - red

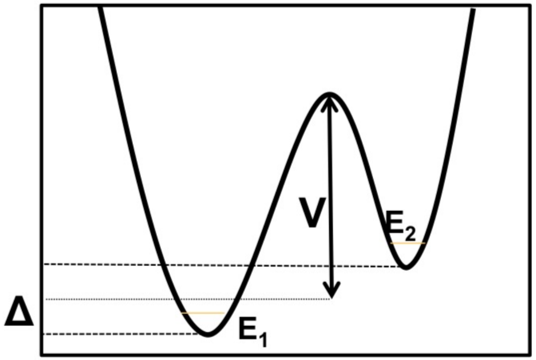


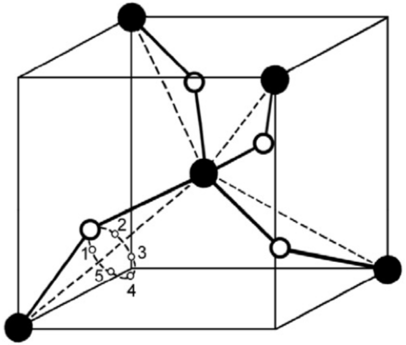
Current / future coatings research

- Alternative high-index coating materials e.g. amorphous Si, hafnia
- Alternative low-index materials e.g. Al_2O_3
- Exploring links between short-range atomic structure and loss
- Reduced coating / coating-free optics – diffractive optics and resonant waveguide mirrors

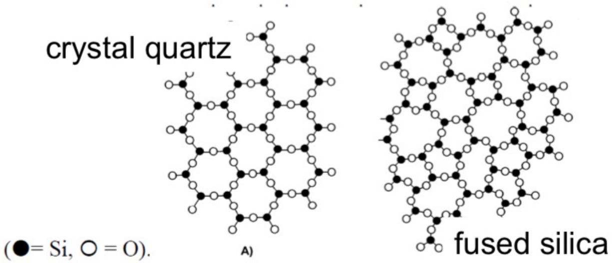
“Ideal glass” theory

- Conventionally associated with low energy excitations (LEEs)
  - conceptualized as two-level systems (TLS)





Oversimple picture: bond flopping



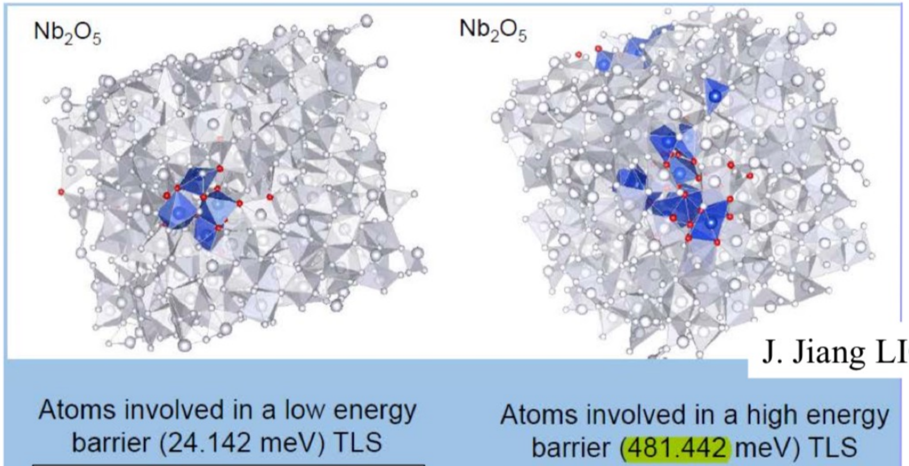
Distribution of TLS in silica
due to disordered structure

figures from B.S. Lunin monograph

Guidance – molecular dynamics simulations

- Molecular dynamics calculations for amorphous materials
  - provide insight into dissipation mechanisms

- Some observations: simple bond-flopping inadequate picture fails
  - TLS involves dozens of atoms in nm-scale configurations
    “medium-range” order important



J. Jiang LIGO G1800533

Atoms involved in a low energy barrier (24.142 meV) TLS

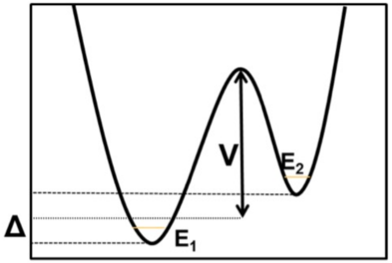
Atoms involved in a high energy barrier (481.442 meV) TLS

cause cryogenic losses

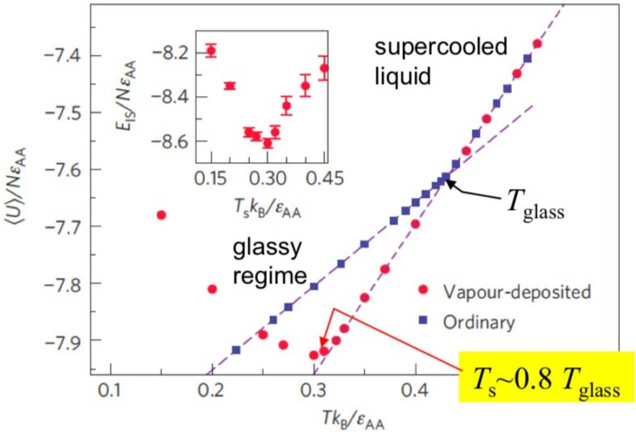
cause 300 K losses

J. Trinastic, R. Hamdan, C. Billman, H. Cheng, *Phys. Rev.* **B93** , 014105 (2016)

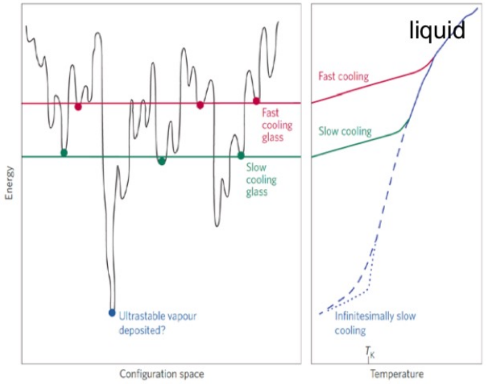
“Ideal glass” theory

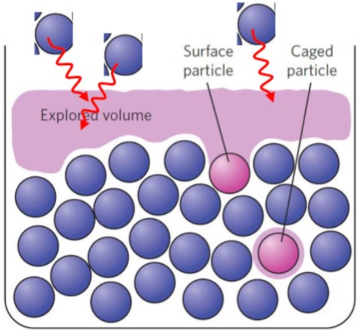


liquid vs vapor deposition)



reach more stable glass from vapor than liquid





S. Singh, *Nature Mater.* **12,** 139 (2013)

“Ideal glass” theory

- a-Si experiment: steep improvement for deposition at $T_s \sim$ 400 C: $\phi \sim 10^{-6}$ (!)
  - much lower loss than deposit at 300 C and anneal at 400 C

    critical $T_s / T_{\text{glass}} \sim 0.75$ vs predicted $T_s \sim 0.8\ T_{glass}$

- First example of inorganic ultra-stable glass
  - potential for Voyager mirror coating

    but has too high optical absorption

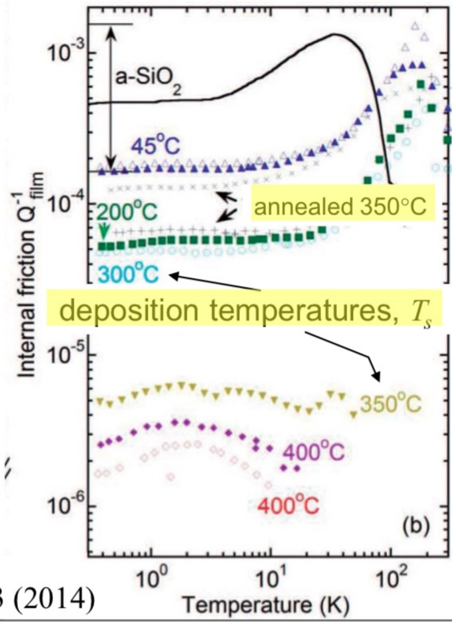
Formation of ultrastable glass favored by:

Deposition at elevated temperature: $T_s \sim 0.8\ T_{\text{glass}}$

Low deposition rates

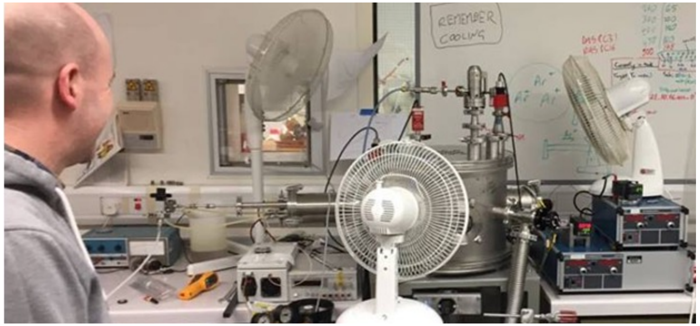
Ion-beam assisted deposition (?)

Applicable to amorphous oxides?

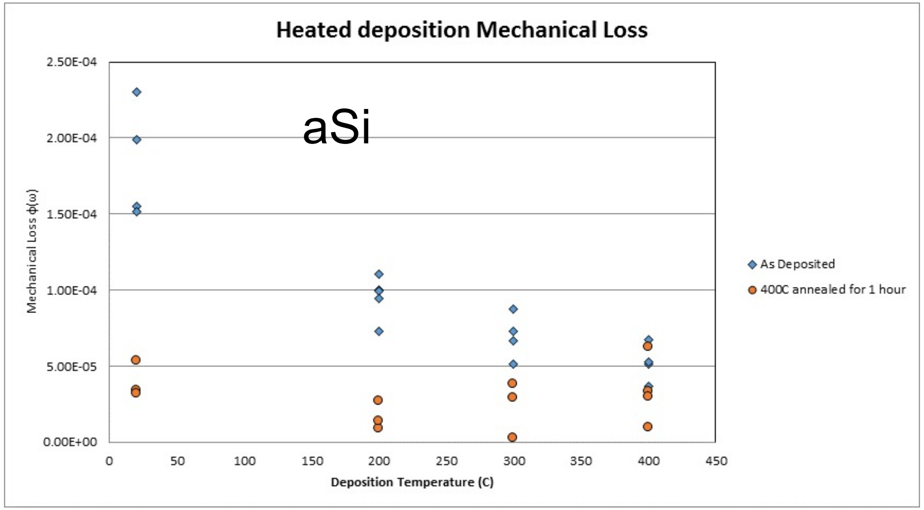


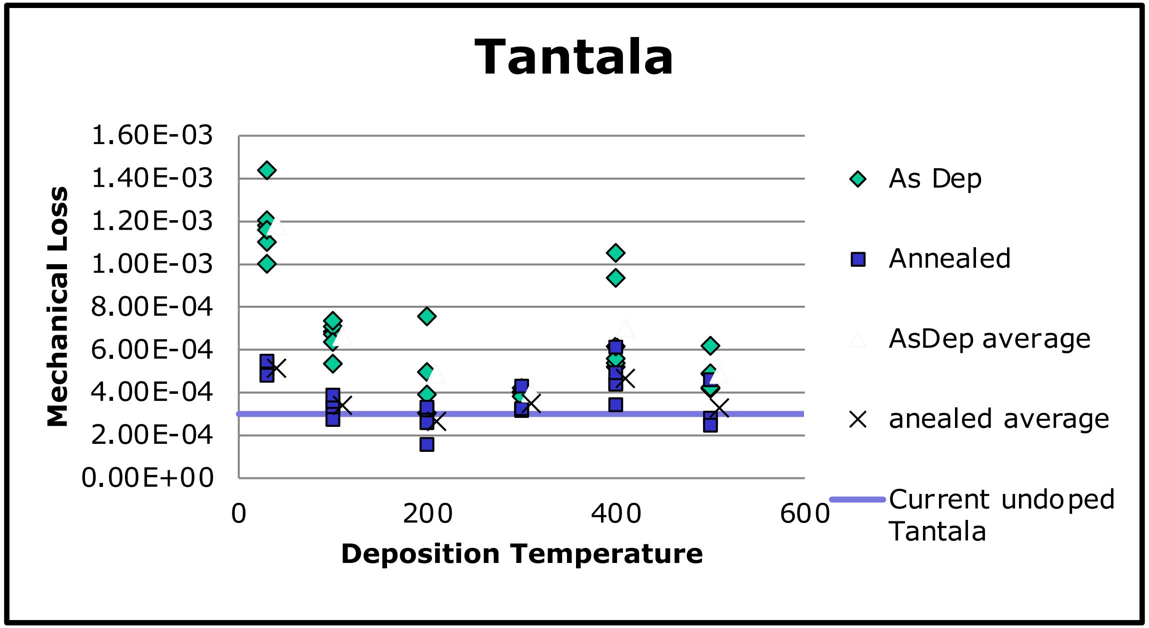
X. Liu, F. Hellman, et al, *PRL* **113**, 025503 (2014)

“Ideal glass” theory



UWS/Strath/Glasgow attempt



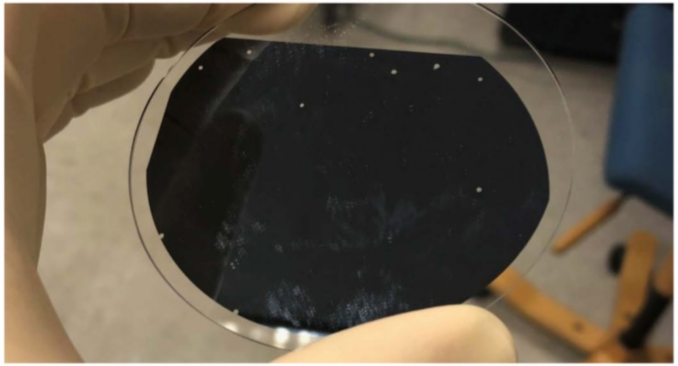


“Ideal glass” theory

Why not just make crystal coatings!??!!?!?!

MBE crystalline coatings

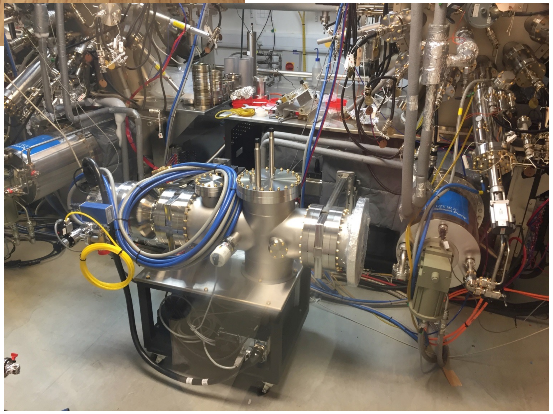
- Absorption and mechanical loss OK for all applications
  - scatter statistics need further characterization
  - uniformity over larger areas? under study



- Note also environmental and thermodynamic tolerances
  - via electro-optic and piezoelectric effects
  - needs further study

- Scaling to suitable dimensions
  - G. Cole: ~$40M (GaAs substrate + MBE + bonding tool)

MBE crystalline coatings

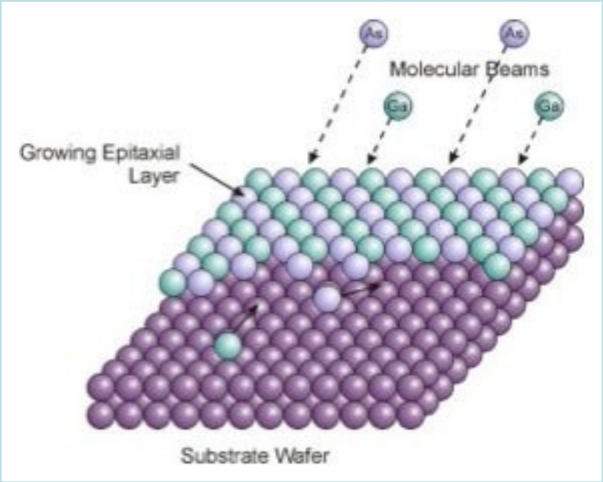


GSS
Gas Sensing Solutions

STANFORD
UNIVERSITY

UWS UNIVERSITY OF THE
WEST of SCOTLAND

University
of Glasgow



Most recent guidance from modelling (for amorphous coatings)

High precision detection of change in intermediate range order of amorphous zirconia-doped tantala thin films due to annealing

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Understanding the local atomic order in amorphous thin film coatings and how it relates to macroscopic performance factors, such as mechanical loss, provides an important path towards enabling the accelerated discovery and development of improved coatings. High precision X-ray scattering measurements of thin films of amorphous zirconia-doped-tantala (ZrO_2-Ta_2O_5) show systematic changes in intermediate range order (IRO) as a function of post-deposition heat-treatment (annealing). Atomic modeling captures and explains these changes, and shows that the material has building blocks of metal-centered polyhedra and the effect of annealing is to alter the connections between the polyhedra. The observed changes in IRO are associated with a shift in the ratio of corner-sharing to edge-sharing polyhedra. These changes correlate with changes in mechanical loss upon annealing, and suggest that the mechanical loss can be reduced by developing a material with a designed ratio of corner-sharing to edge-sharing polyhedra.

Amorphous thin film coatings are technologically impor-
ant materials that often limit the performance of a va-

lization, allowing thin-films to remain amorphous after annealing up to 800°C [9]. For the zirconia-doped tantala

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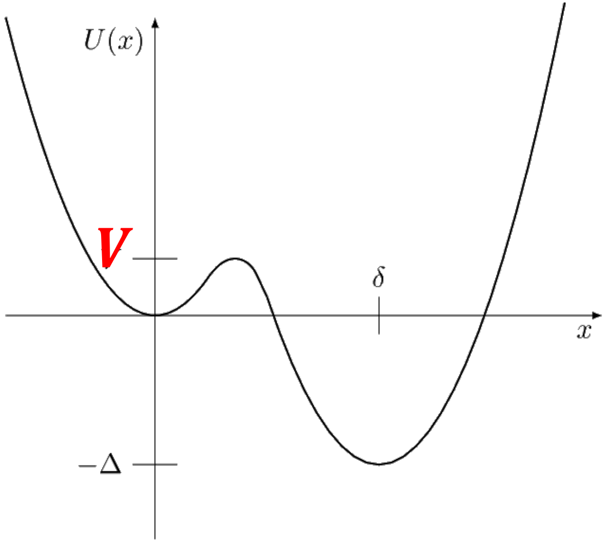
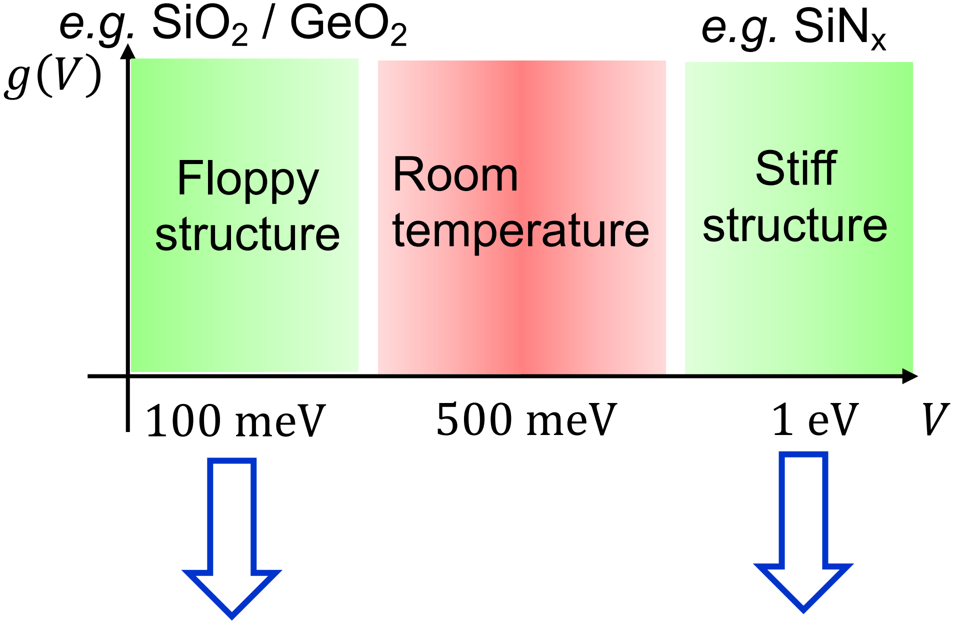
Most recent guidance from modelling (for amorphous coatings)

Origin of mechanical losses

TLS with the dynamics driven by Asymmetric Double Well Potential



$$\tau = \tau_0(\Delta) \cdot e^{V/k_B T}$$



e.g. SiO_2 / GeO_2

e.g. SiN_x

Floppy structure

Room temperature

Stiff structure

Most of oxides

High coordination number amorphs

Often bad optical properties (*k*)

What have we learned?

- material properties strongly determine the thermal noise performance of a detector
- simple temperature scaling is dangerous and leads to wrong results
- (A distribution of) TLSs describe mechanical losses in amorphous coatings
- material science (understanding temperature behaviour of parameters) is needed to optimise future detectors
- a wide and open field…

Homework/Icebreaker: don’t forget ☺

Coating Brownian thermal noise:

$$S_x(f) = \frac{4k_BT}{\pi^2 f}\frac{1-\nu^2}{Y}\left(\frac{1-2\nu}{1-\nu}\right)\frac{d}{w^2}\phi$$

w = beam spot size
d = coating thickness
Y = Young’s modulus
ν = Poisson’s ratio

How to reduce coating Brownian noise:

- Larger beam
- Coating thinner
- Low T
- Reduce ϕ, loss angle

N. Nakagawa et al. Phys. Rev D 65 (2002) 102001
Y. T. Liu et al. Phys. Rev. D 62 (2000) 122002
T. Hong et al. Phys. Rev. D 87 (2013) 082001
G. H. Harry et al. Class. Quantum Grav. 19 (2002) 897

Homework/icebreaker:

PHYSICAL REVIEW D **91,** 042001 (2015)

Thermal noise reduction and absorption optimization via multimaterial coatings

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Future gravitational wave detectors (GWDs) such as Advanced LIGO upgrades and the Einstein Telescope are planned to operate at cryogenic temperatures using crystalline silicon (cSi) test-mass mirrors at an operation wavelength of 1550 nm. The reduction in temperature in principle provides a direct reduction in coating thermal noise, but the presently used coating stacks which are composed of silica (SiO_2) and tantala (Ta_2O_5) show cryogenic loss peaks which results in less thermal noise improvement than might be expected. Due to low mechanical loss at low temperature amorphous silicon (aSi) is a very promising candidate material for dielectric mirror coatings and could replace Ta_2O_5. Unfortunately, such an aSi/SiO_2 coating is not suitable for use in GWDs due to high optical absorption in aSi coatings. We explore the use of a three material based coating stack. In this multimaterial design the low absorbing Ta_2O_5 in the outermost coating layers significantly reduces the incident light power, while aSi is used only in the lower bilayers to maintain low optical absorption. Such a coating design would enable a reduction of Brownian thermal noise by 25%. We show experimentally that an optical absorption of only (5.3 ± 0.4) ppm at 1550 nm should be achievable.

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I. INTRODUCTION

Future gravitational wave detectors (GWDs) such as
dvanced LIGO upgrades and the low frequency (LF)
etector within the Einstein Telescope (ET) [1,2] are
lanned to operate at cryogenic temperature to reduce
ermal noise. Operation at low temperatures requires a
placement substrate material for the presently used fused
lica test-mass mirrors. Showing low mechanical loss at
w temperatures [3], crystalline silicon (cSi) is planned to
at cryogenic temperature. Therefore, low mechanical los
at low temperature makes amorphous silicon (aSi)
very promising candidate material for dielectric mirro
coatings and could replace Ta_2O_5 in the presently use
coatings as a first step in improving the overall coatin
loss.

A standard highly reflective (HR) quarter-wavelengt
coating is composed of a stack of alternating materials o
differing refractive indices, where each layer has an optica

PHYSICAL REVIEW LETTERS **125,** 011102 (2020)

Demonstration of the Multimaterial Coating Concept to Reduce Thermal Noise in Gravitational-Wave Detectors

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Thermal noise associated with the mechanical loss of current highly reflective mirror coatings is a critical limit to the sensitivity of gravitational-wave detectors. Several alternative coating materials show potential for reducing thermal noise, but cannot be used due to their high optical absorption. Multimaterial coatings have been proposed to enable the use of such materials to reduce thermal noise while minimizing their impact on the total absorption of the mirror coating. Here we present experimental verification of the multimaterial concept, by integrating aSi into a highly reflective SiO_2 and Ta_2O_5 multilayer coating. We show a significant thermal noise improvement and demonstrate consistent optical and mechanical performance. The multimaterial coating survives the heat treatment required to minimize the absorption of the aSi layers, with no adverse effects from the different thermomechanical properties of the three materials.

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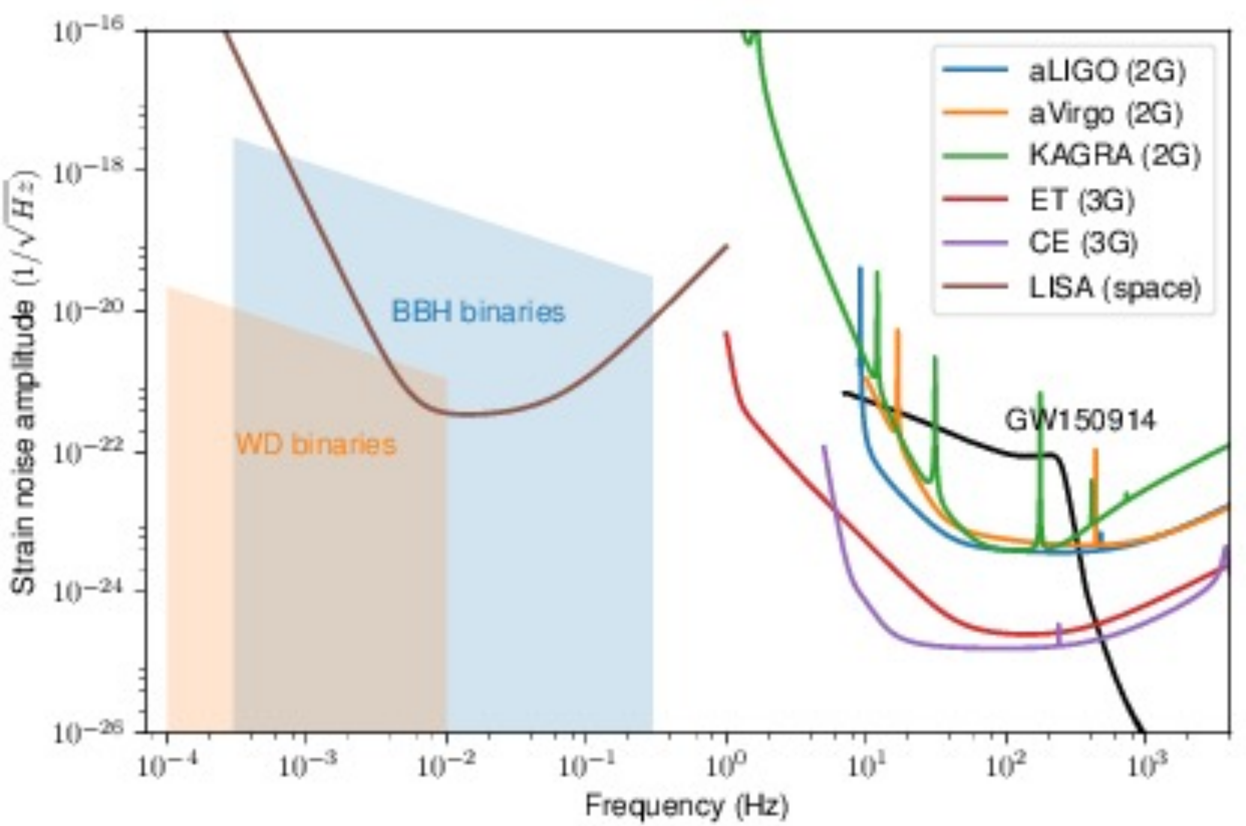
Introduction.—A number of gravitational-wave signals
rom binary black-hole mergers [1–5] and from a neutron-
tar merger [6] have been detected during the first two
bserving runs of the Advanced LIGO [7] and Advanced
irgo [8] gravitational-wave detectors. At their most
ensitive frequencies, these detectors are limited by thermal

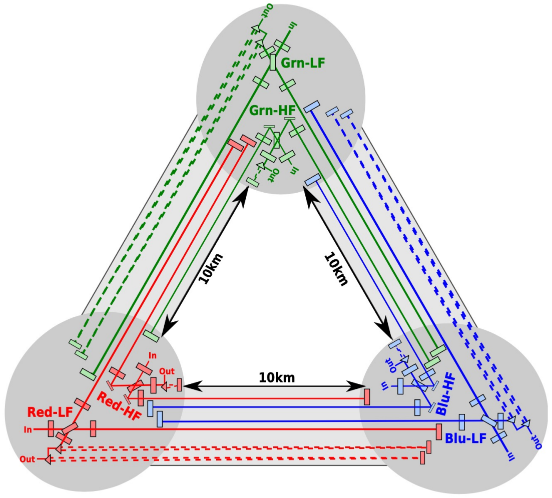
Amorphous silicon (aSi) is one of the most promising options to replace Ta_2O_5 in HR coatings. It can have very low mechanical loss [28] and the high refractive index enables significantly thinner coatings to be made, which further reduces the thermal noise. However, aSi shows too high optical absorption. Recent work has shown that the

Explain the principal of multimaterial coatings for optimizing the thermal noise and optical absorption in GW mirror coatings

Homework/icebreaker #2

improvement of the sensitivity between different generations of GW detectors:





ET

Qn: does the strain-sensitivity plot give the whole picture?
(hint: these are strain sensitivities for optimum incidence of GW)