Mirrors for the Einstein Telescope

- coating requirements for gravitational-wave detection

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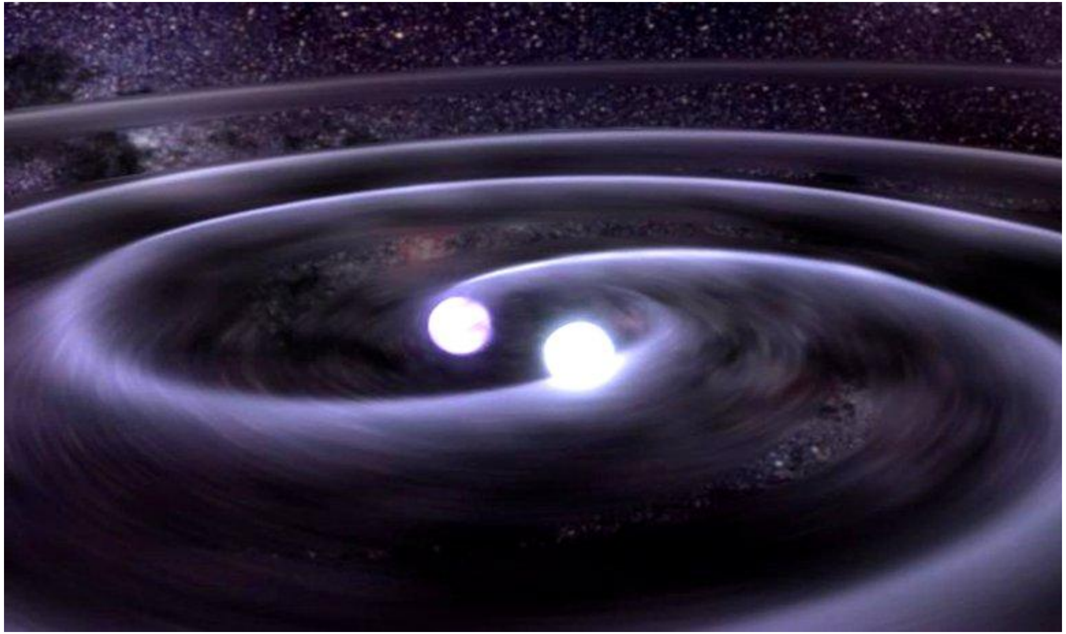
Gravitational Waves

- Predicted by Einstein
- Generated by massive, accelerated objects: colliding neutron stars, supernovae, black hole mergers, ...
- Travel with the speed of light
- Not disturbed by matter
- Can make ‘dark’ and hidden objects visible
- Provide more information about the world we live in

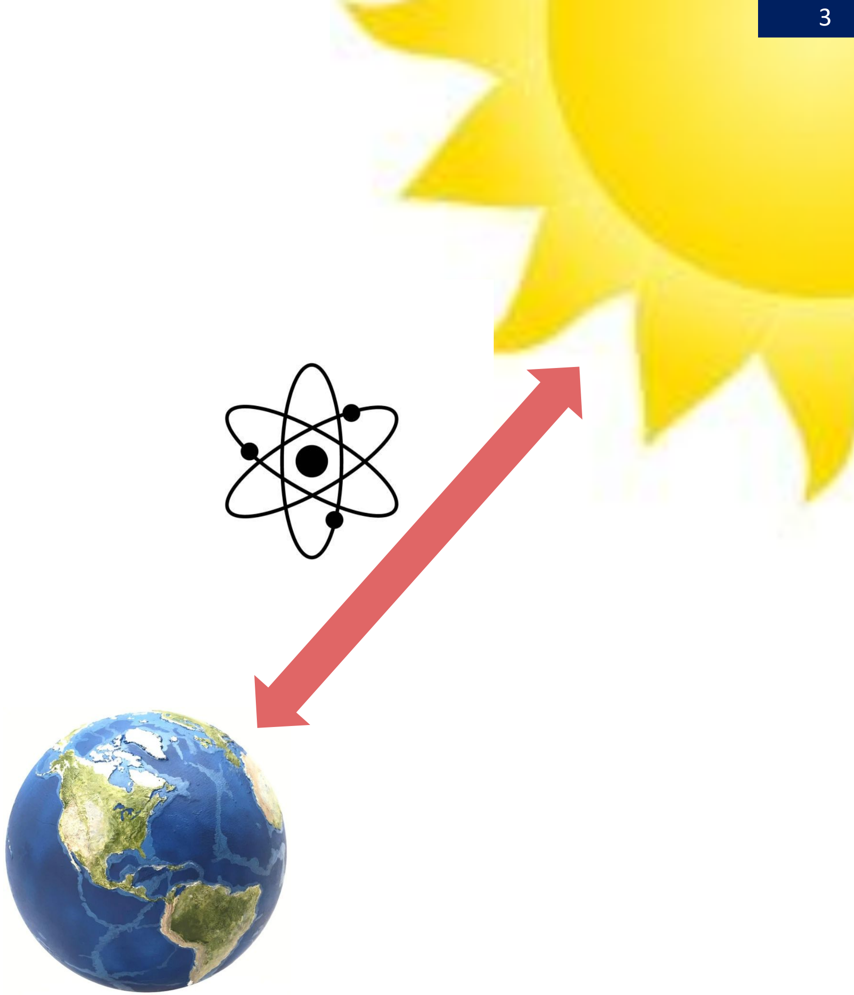


Gravitational Waves

- Cause tiny length changes

“Change the distance between Earth and Sun by less than the diameter of an atom”

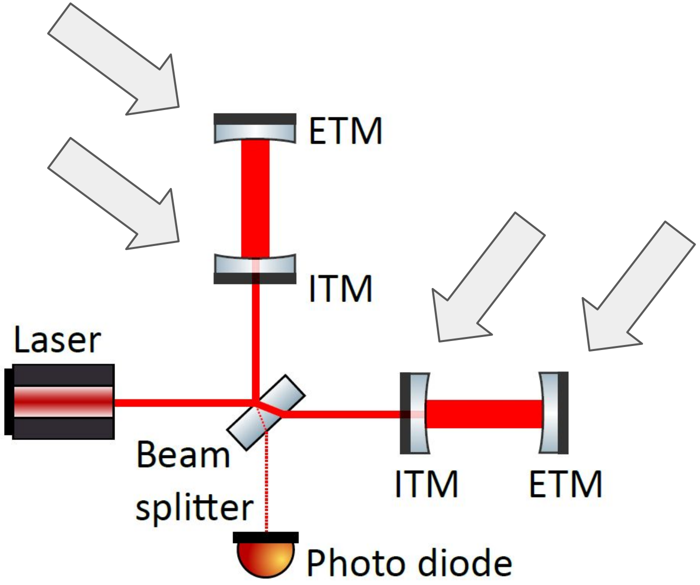
- Took almost 60 years from starting to construct the first detector to measuring the first gravitational wave in 2015



Gravitational Wave Detectors

- Michelson interferometer - using many ‘tricks’ to increase the sensitivity
  - Several kilometer long arms
  - Suspended mirrors
  - High laser power
  - Squeezed light
  - Arm cavities formed by input test masses (ITMs) and end test masses (ETMs)
  - …

- Currently: 5 active detectors:
  - LIGO in Livingston and Hanford, US
  - Virgo in Cascina (near Pisa), Italy
  - GEO600 in Ruthe (near Hannover), Germany
  - KAGRA in Kamioka mine, Japan

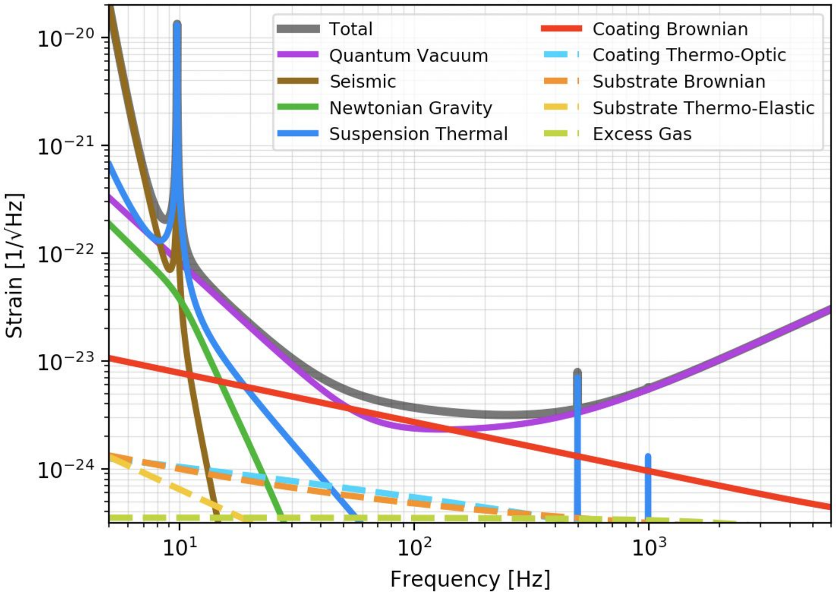


Gravitational Wave Detectors

Limitations of Current Gravitational Wave Detectors

- < 50Hz
  - Seismic / environmental noise, coupling either directly or via gravity gradient forces
  - Radiation pressure noise, photons pushing on suspended mirrors
- around 100Hz
  - Coating thermal noise, Brownian motion of mirror surface
- > 1 kHz
  - Shot noise, counting statistics of photons

Advanced LIGO design sensitivity
(example of a current generation detector)

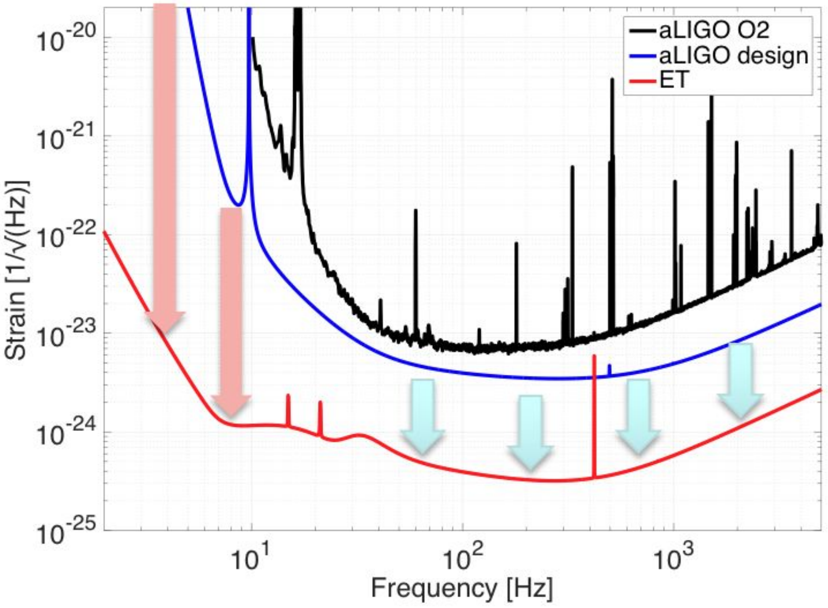


Plans and Challenges of Future Detectors

- Aim for ***a factor 10 improvement*** at mid and high frequencies
  "within reach of continuous improvements"
- Low frequencies: improvement more ***a factor of 100 to 1000***
  → only possible with new approaches *"disruptive technologies"* (e.g. cryogenics)

- Plan for the Einstein Telescope: Split detector into
  - Room temperature and high laser power at high frequencies
  - Low temperature (see next slide) and low laser power at low frequencies

Einstein Telescope design sensitivity
(example of a next generation detector)



Coating Thermal Noise (simplified model)

Coating thermal noise (CTN)

- Lower for larger beams
- Determined by material properties of coating and substrate
- Frequency dependent: more prominent at low frequencies
- Temperature dependent
  $\longrightarrow$ motivation for cryogenic mirrors (at low frequencies)
- Thin coating

mirror temperature

mirror temperature (depends on reflectivity and refractive indices)

$$\mathrm{CTN} = \sqrt{\frac{4k_\mathrm{B}T}{\pi^2 f w^2 Y_\mathrm{sub}}\, d\phi \left[\frac{Y_\mathrm{coat}}{Y_\mathrm{sub}} + \frac{Y_\mathrm{sub}}{Y_\mathrm{coat}}\right]}$$

beam radius (on mirror)

coating mechanical loss

$\longrightarrow$ materials with low mechanical loss needed

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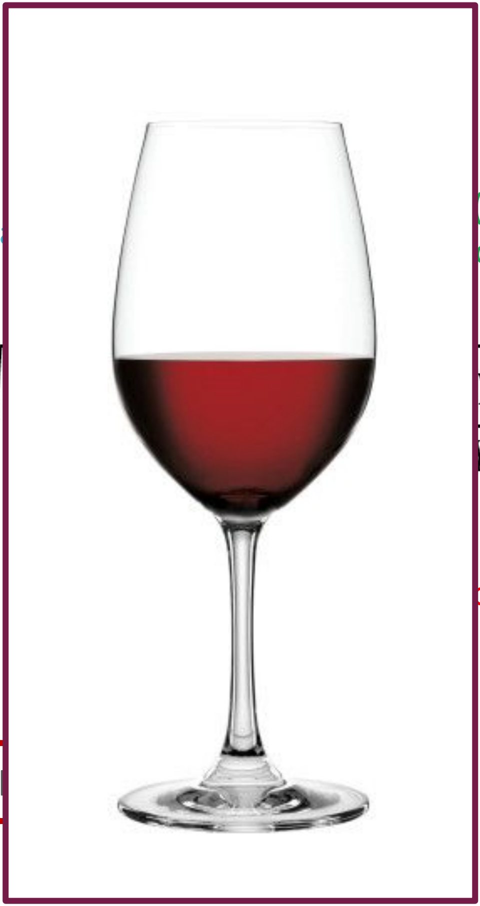
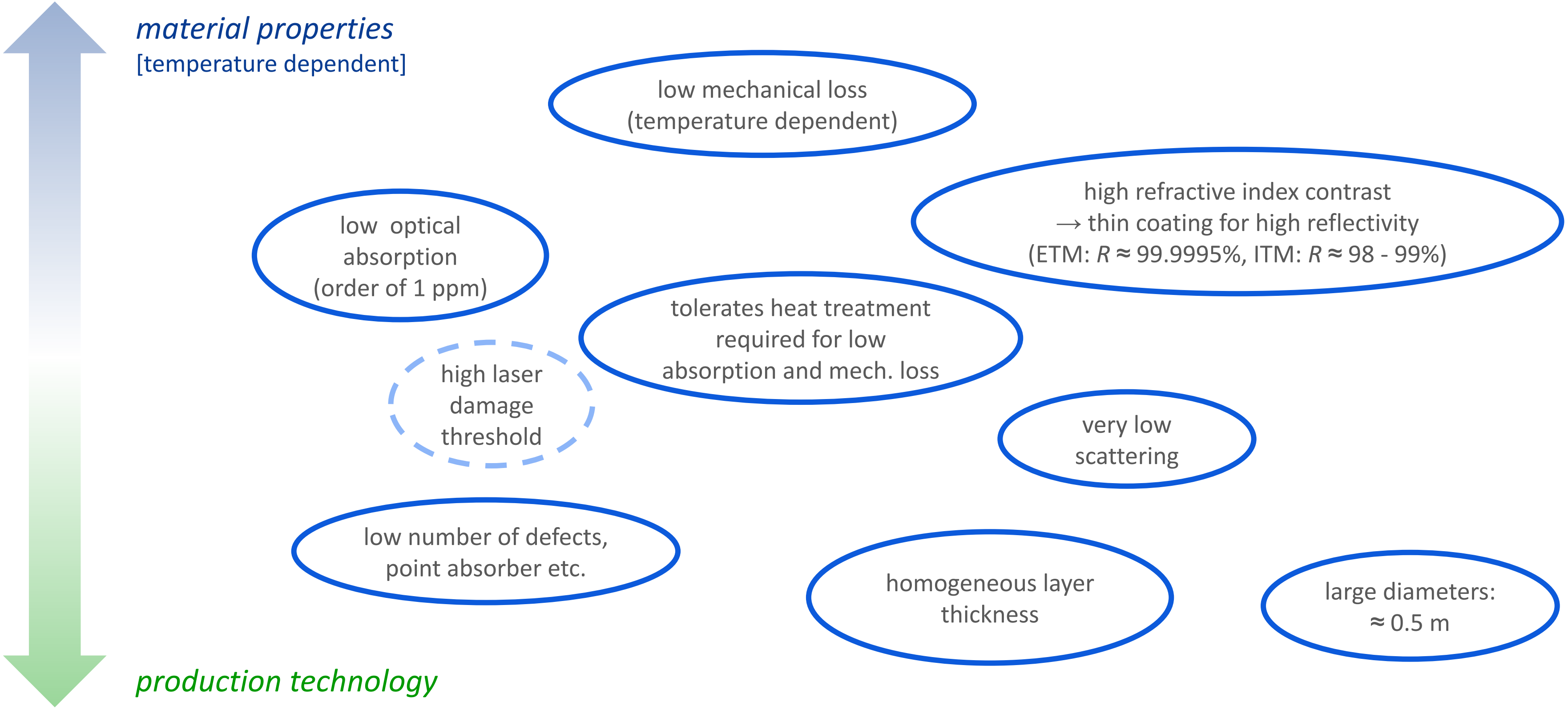
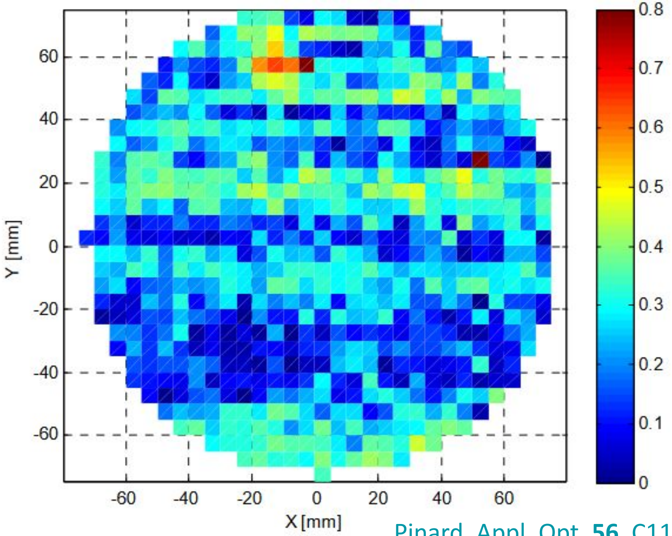


The Coating Requirements

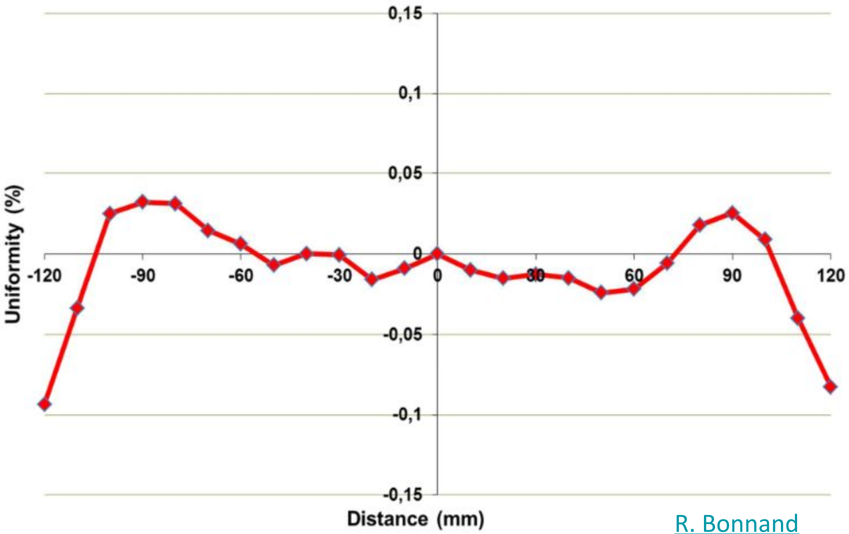


Absorption and Uniformity of Current Coatings

- Made of Ta_2O_5 doped with TiO_2 (high refractive index; n=2.09 @1064nm) and SiO_2 (low refractive index; n=1.45 @1064nm): TiO_2 :Ta_2O_5 dominates coating thermal noise
- Deposited by Laboratoire des Matériaux Avancés (LMA) via ion beam sputtering (currently GW standard)
- Low optical absorption (ITMs: 0.22ppm; ETMs: 0.27ppm) and low scattering
- Diameter:34cm



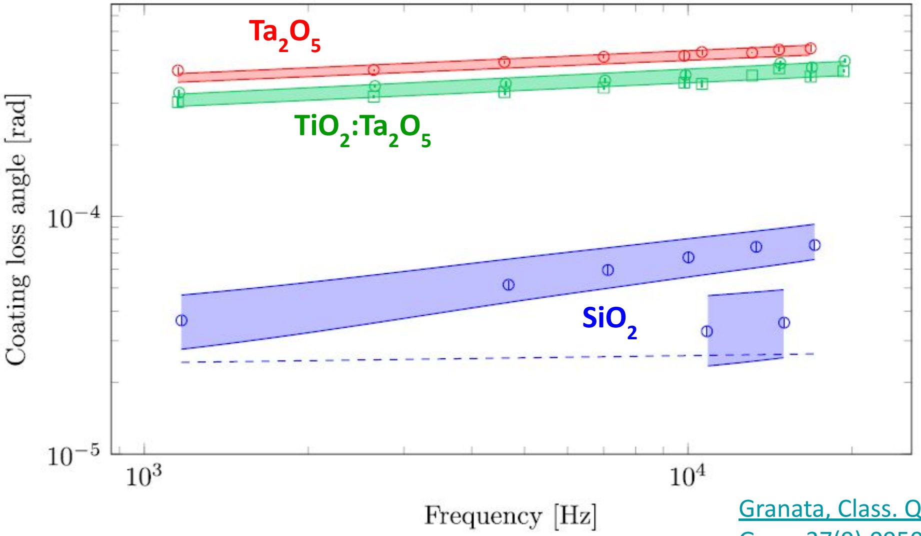
Pinard, Appl. Opt. **56**, C11-C15, 2017



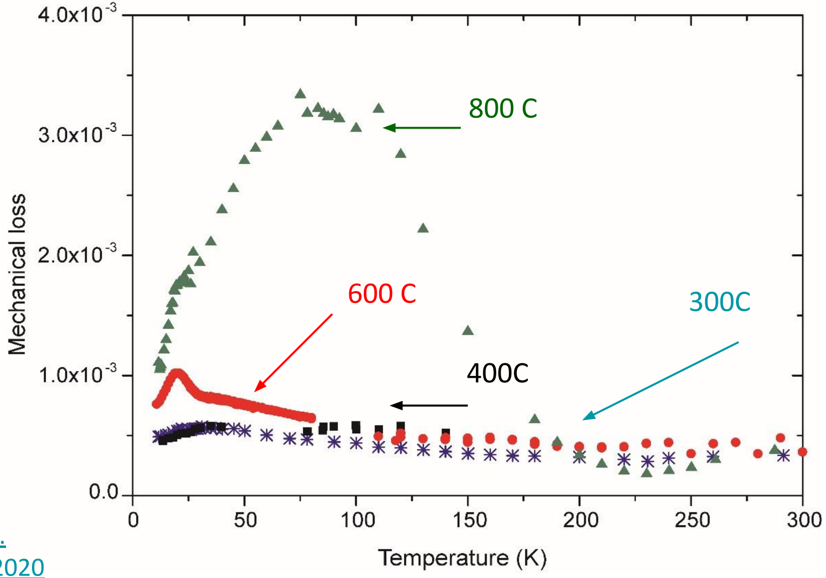
R. Bonnand

Mechanical Loss

- Left: Mechanical loss of current materials measured at room temperature
- Right: Mechanical loss of Ta_2O_5 as a function of temperature, and at various heat treatment temperatures



Granata, Class. Quant. Grav., 37(9):095004, 2020

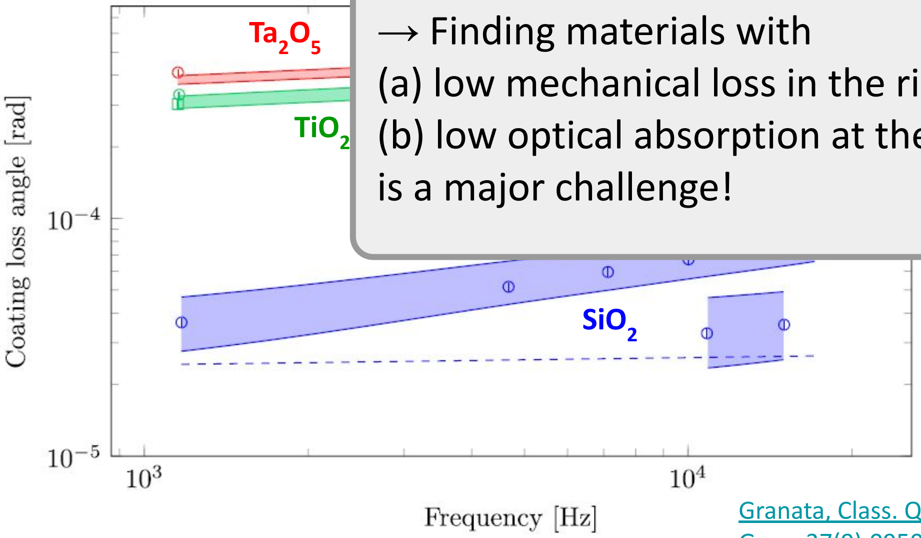


Martin, Class. Quant. Grav. 27 225020, 2010

Mechanical Loss

- Left: Mechanical loss of current materials measured at room temperature
- Right: Mechanical loss of Ta_2O_5 as a function of temperature, and at various heat treatment temperatures

→ Finding materials with
(a) low mechanical loss in the right temperature range and
(b) low optical absorption at the right wavelength
is a major challenge!



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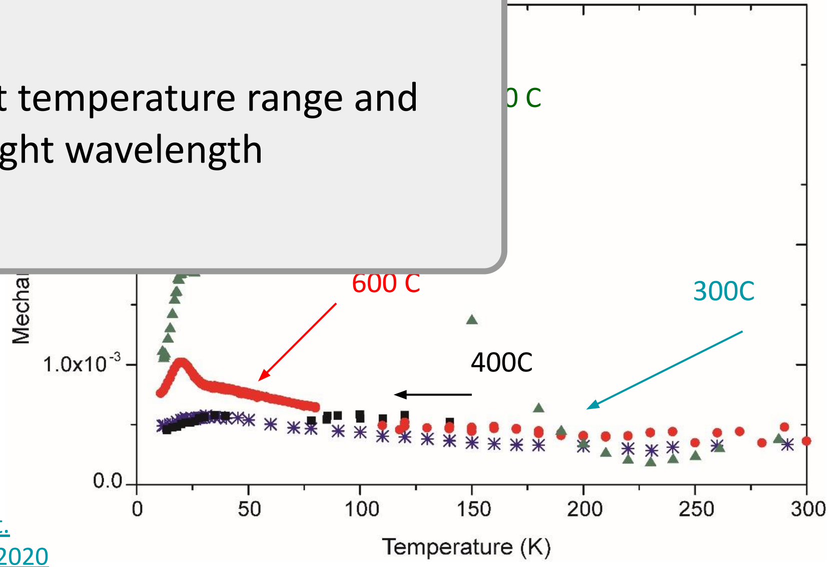


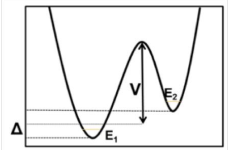
Martin, Class. Quant. Grav. 27 225020, 2010

Finding Materials…

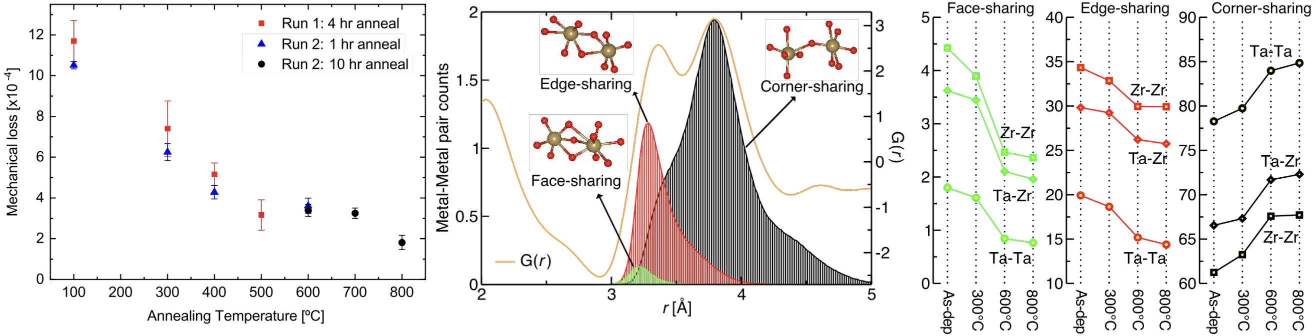
… is a mix of 'trial and error' and of understanding and modelling the structure

Example: Atomic structure characterization and modeling

Two Level System (TLS model)



- ➢ Evidence: Correlation of structural properties to mechanical loss via two-level-systems (TLS)
- ➢ X-ray, electron scattering used to probe local structure:



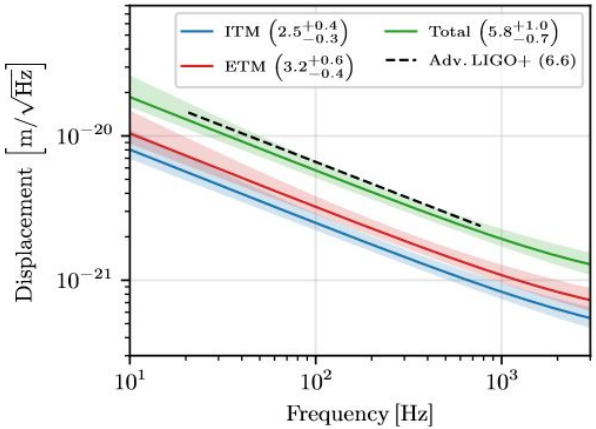
- ➢ Led to hypothesis that TLS contributing to room temperature loss involves edge- and face-shared polyhedra
- ➢ Materials with low ES and FS, and mostly CS structures should result in low RT loss, e.g. SiO_2, GeO_2

[Prasai et al., Phys. Rev. Lett., 123:045501, 2019]

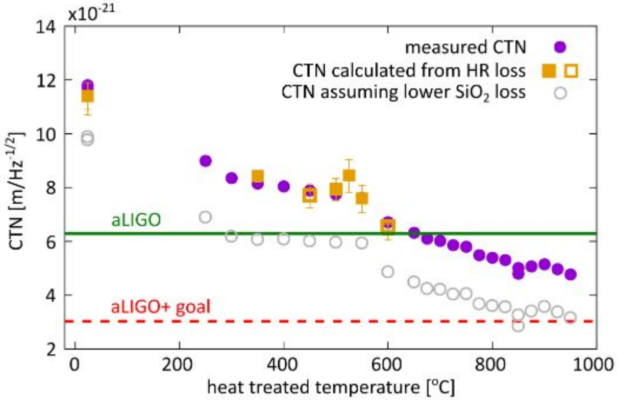
Coating Development

Candidate materials for next upgrades of current LIGO/Virgo detectors:

- ➢ Mixture of GeO_2 and TiO_2
  - ○ Low mechanical loss
  - ○ Theoretically estimated to have 2x reduced CTN compared to current coatings
- ➢ Mixture of SiO_2 and TiO_2
  - ○ Sightly higher mechanical loss than GeO_2 - TiO_2 mix, but similar/lower CTN
- ➢ Working on reduction of cracks/bubbles after heat treatment



Vajente, Phys. Rev. Lett., 127:071101, 2021



McGhee, Phys. Rev. Lett., **131:171401,** 2023

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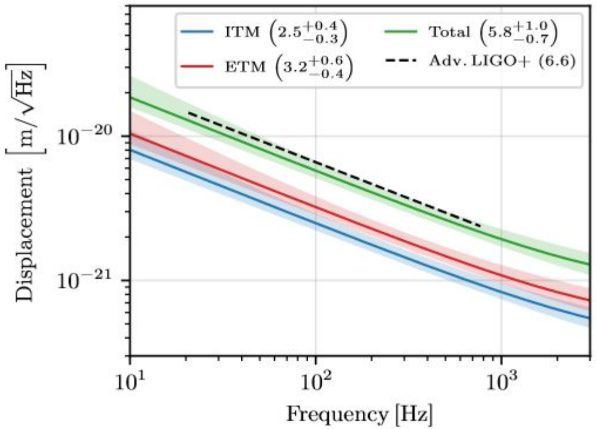
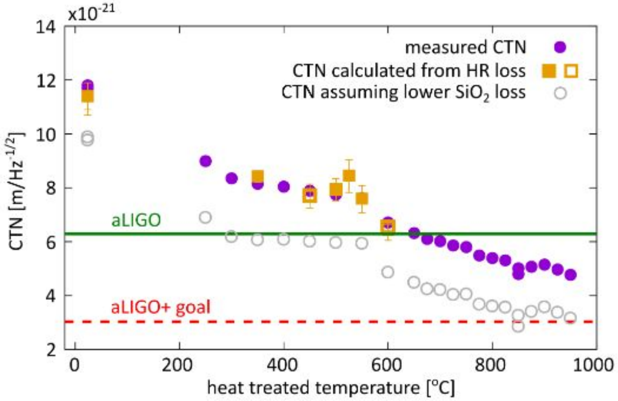
Coatings meeting meeting the requirements of LIGO/Virgo upgrades: Also suitable for ET-HF ('room temperature ET')



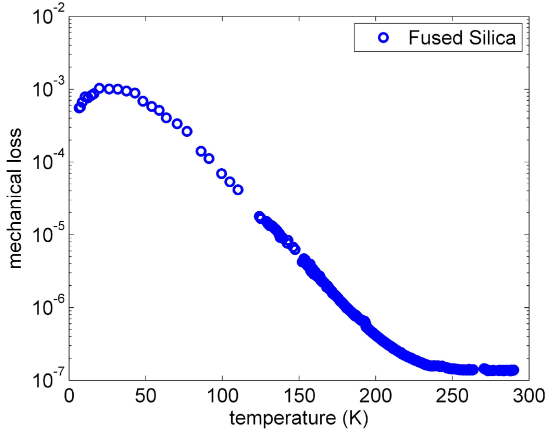
Vajente, Phys. Rev. Lett., 127:071101, 2021

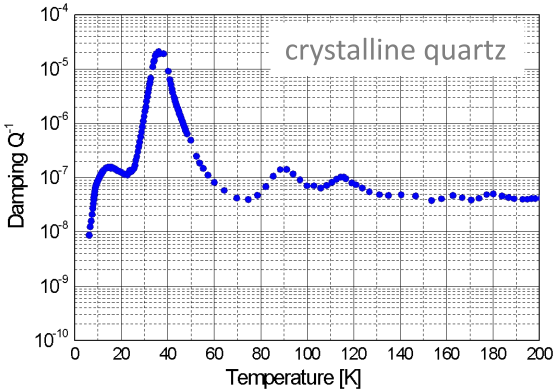


McGhee, Phys. Rev. Lett., **131:171401,** 2023

Cryogenics/other coating options

- Cryogenic detector operation, and the use of other detector wavelengths (e.g. 1550nm or 2um, instead of 1064nm) offers many other material options, e.g. a-Si, SiN_x, …
- Singlecrystalline multilayers (AlGaAs, GaP, etc.) show very low mechanical loss and optical absorption
  - For use of room-temperature SiO_2 mirrors: substrate transfer + bonding needed
  - For use of low-temperature crystalline mirrors (silicon, sapphire, …): can potentially be grown directly on the mirror substrate
- Multimaterial coatings: combining more than two materials
- 'Coating-free' mirrors: gratings
- Crystalline-amorphous hybrid coatings: crystalline toplayer
- Implanttion of layers into the crystalline substrate via ion implantation
- …





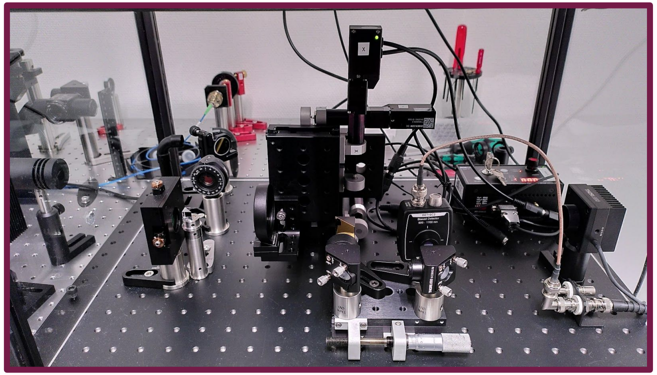
Schroeter, arXix:0709.4359, 2007

What we do

Measurements of:

- ➢ Optical absorption
  - ○ usually on fused silca substrates, 1” in diameter
- ➢ Mechanical loss
  - ○ Room temperature: usually on fused silica substrates, 2 or 3” in diameter, 1mm thick
  - ○ Cryogenics: silicon or sapphire samples, 2” in diameter, between 1 and 5mm thick
- ➢ Spectrophotometry: refractive index and thickness needed to analyse mechanical loss and absorption
- ➢ Various cycles of heat treatments

→ characterisation of samples can take weeks to months (depending on what we want to know/optimise)

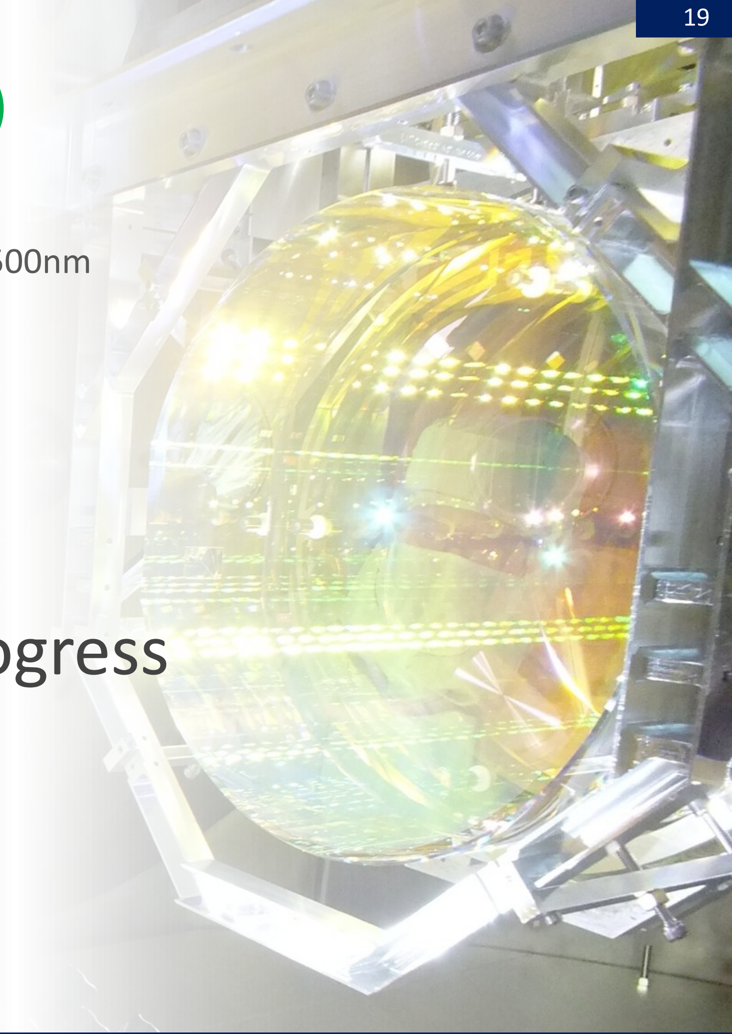


What we need for development

- Suggestions & capabilites for ‘new/interesting’ materials
- Small-scale samples for R&D: initially just single layers of order of 500nm
- Transparency and good knowledge of deposition procedure
- Quick turn-around (deposition, characterisation and optimisation)
- Capacity for optimisation
- Reproducibility
- Transferable procedures
- …

What we **do not** need for making progress

- The ‘final mirror’
  - capability to coat large/heavy mirrors
  - high thickness uniformity
  - high reflectivity
- Large numbers of samples



Summary

- ➢ For the Einstein Telescope, we need large-scale mirrors of ~0.5m diameter with
  - High reflectivity
  - Low thermal noise (→ low mechanical loss)
  - Low optical absorption
  - High uniformity (of thickness, but also of all other properties)
  - …
- ➢ Most likely different solutions are needed for
  - ET-HF (room temperature, 1064nm)
  - ET-LF (cryogenic temperatures, 1550nm or 2um)
- ➢ Currently: R&D phase
  - Looking for materials with suitable properties
  - Optimising & understanding materials
  - …

Coatings for GW detectors:
World-wide effort
> 40 institutions
> 200 researchers

Thank you for your attention!