

Mirrors for the Einstein Telescope

Jessica Steinlechner
30.04.2025

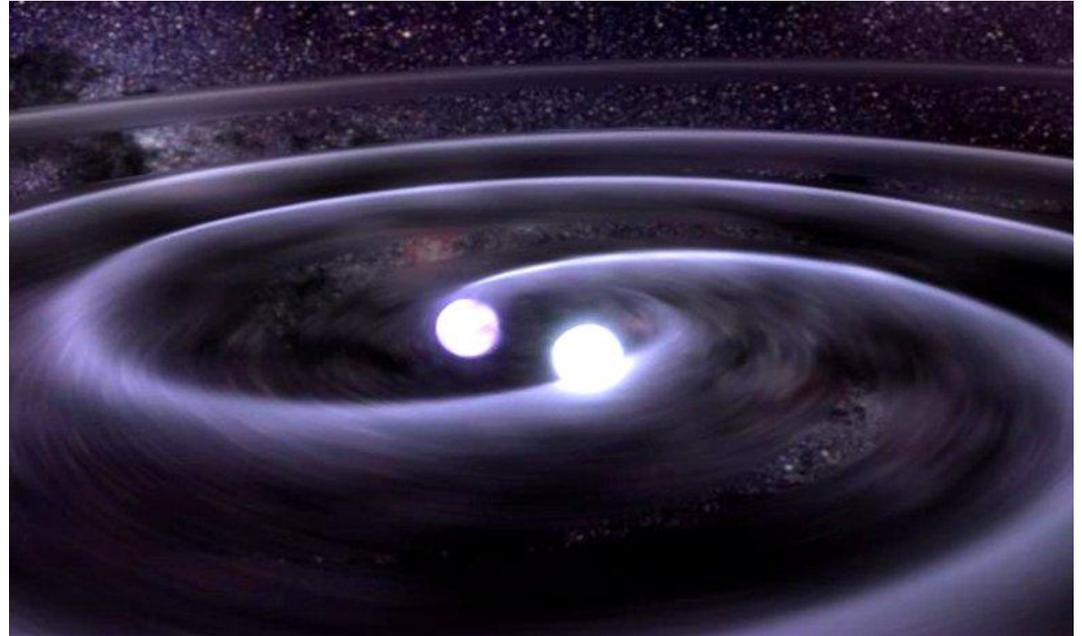
Overview

1. Gravitational wave detection: Background
2. Optical coatings and how they work
3. The challenge: Coating thermal noise
4. Material - options and how to find them
5. Coatings work in Maastricht

1. Gravitational wave detection: Background

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

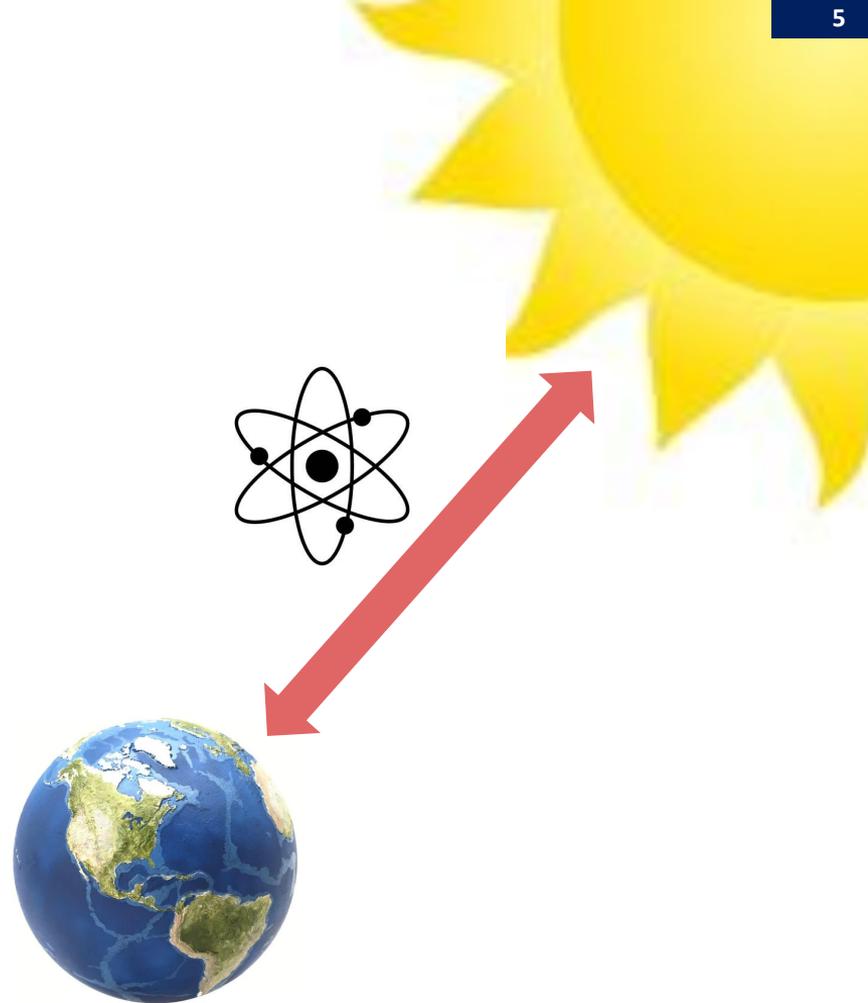


Gravitational Waves

- Cause tiny length changes

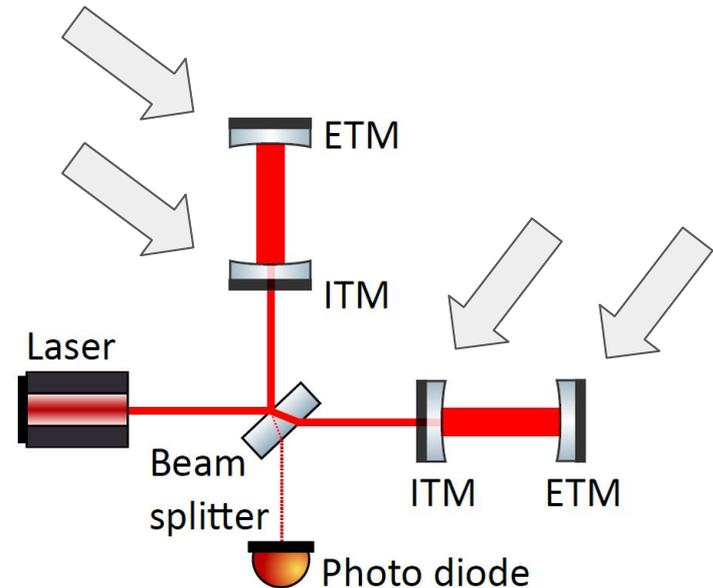
“Change the distance between Earth and Sun by less than the diameter of an atom”

- 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

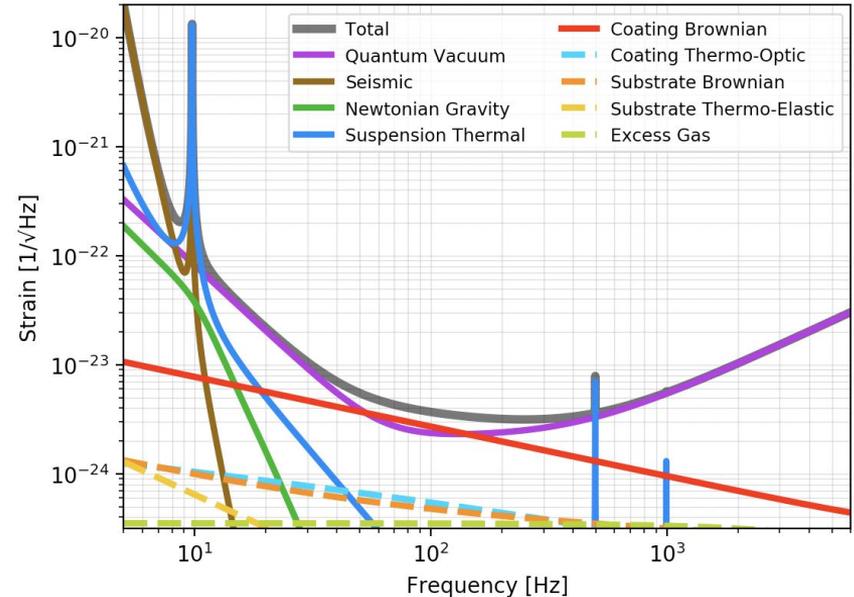


Virgo detector, Italy

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 surfaces
- > 1 kHz
 - Shot noise, counting statistics of photons

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



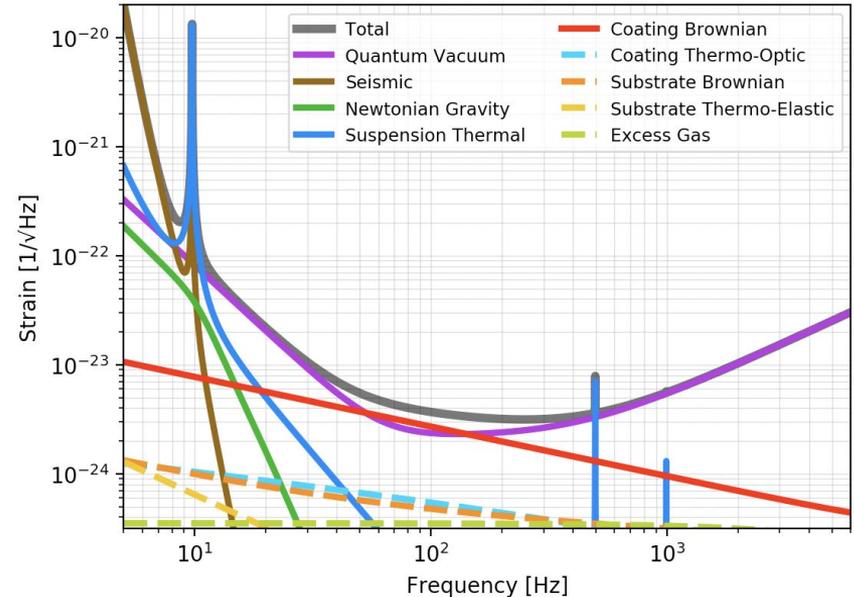
from <https://git.ligo.org/gwinc/pygwinc/tree/master>

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→ We need better coatings to make our detectors more sensitive.

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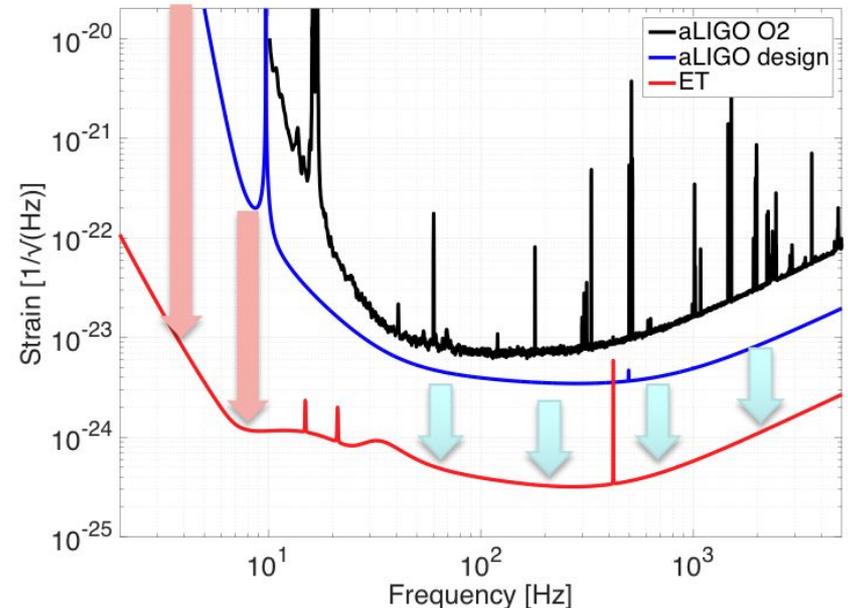


from <https://git.ligo.org/gwinc/pygwinc/tree/master>

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 and low laser power at low frequencies

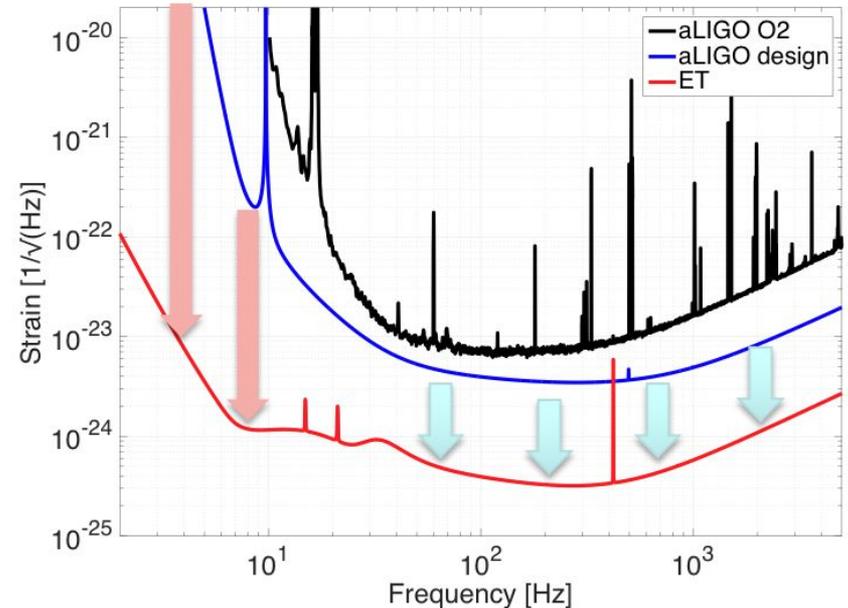
Einstein Telescope design sensitivity
 (example of a next generation detector)



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



→ Possibility of different coatings for room temperature and for cryogenics.

Summary

- Coated mirrors are central components for ET
- To achieve the ET design sensitivity, we need improved coatings
- The requirements are different for the high and low frequency detectors within ET (ET-HF and ET-LF)
→ possibly different coating solutions

2. Optical coatings and how they work

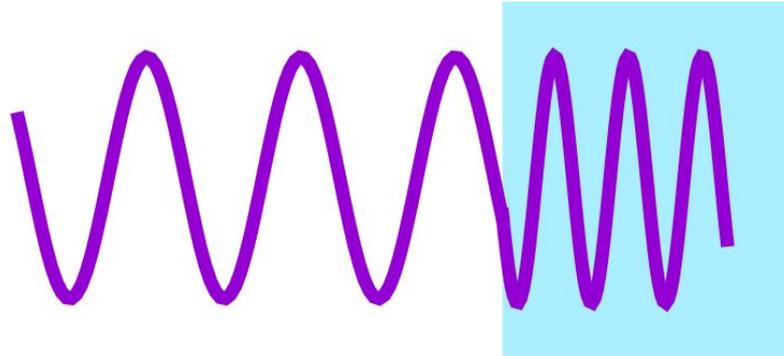
Reflection

- Reflection occurs whenever light travels between media of different **refractive index**
- E.g. reflection of glass: $\sim 4\%$



Refractive index

- 'optical density' → ratio of wavelength within and outside of a medium
- example: air, refractive index $n_1 \approx 1$ & medium with $n_2 = 2$



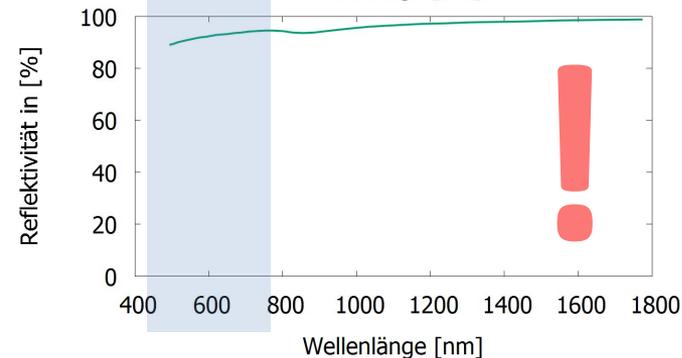
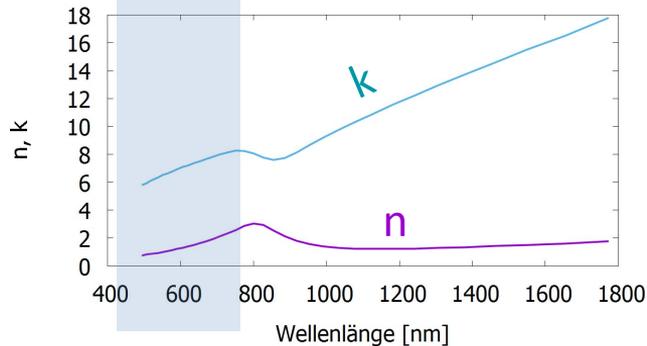
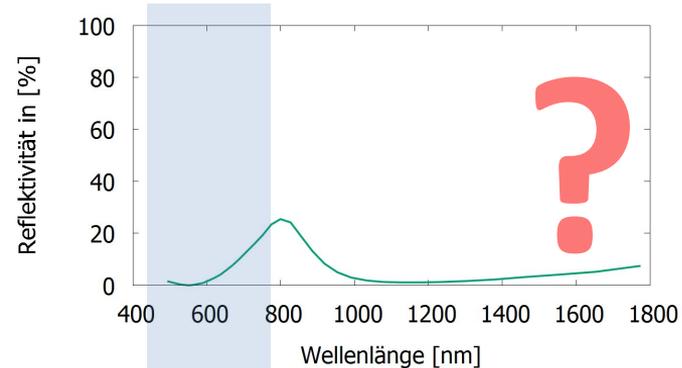
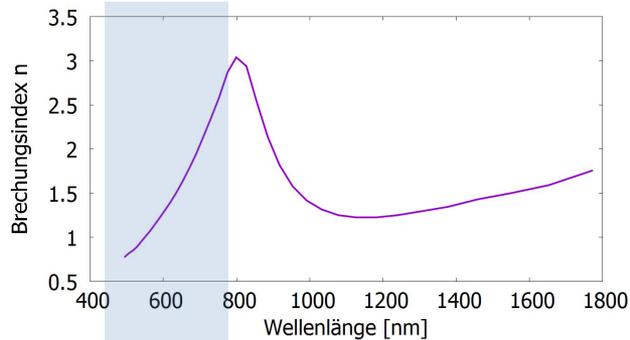
- reflectivity R of glass with $n_2 \approx 1.5$:

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2} \right)^2 \quad \rightarrow R \approx 4\%$$

R is wavelength & absorption dependence - aluminium

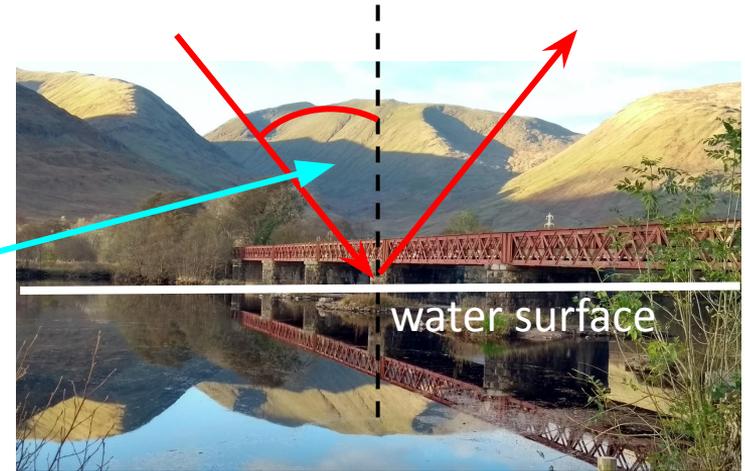
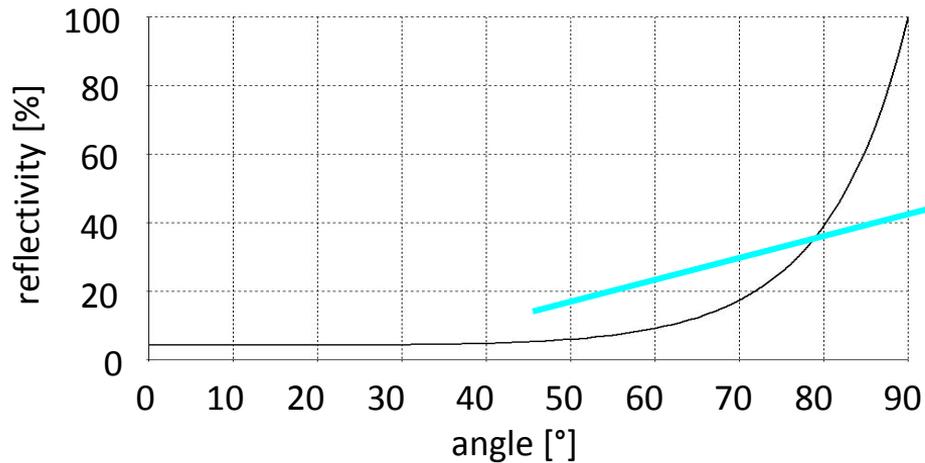
- Refractive index is wavelength dependent
- Refractive index is complex: $n \rightarrow n + ik$

$$R = \left(\frac{n - 1}{n + 1} \right)^2 \rightarrow R = \left(\frac{n + ik - 1}{n + ik + 1} \right)^2 = \frac{(n - 1)^2 + k^2}{(n + 1)^2 + k^2}$$



Angle dependence - example: water

- Refractive index is angle dependent: $R = \left(\frac{n - 1}{n + 1}\right)^2$ only valid for normal incidence
- $n_{\text{water}} = 1.33$



Reflectivity of a typical mirror

- Usually a thin layer of silver or aluminium on glass
- Reflects ~90%

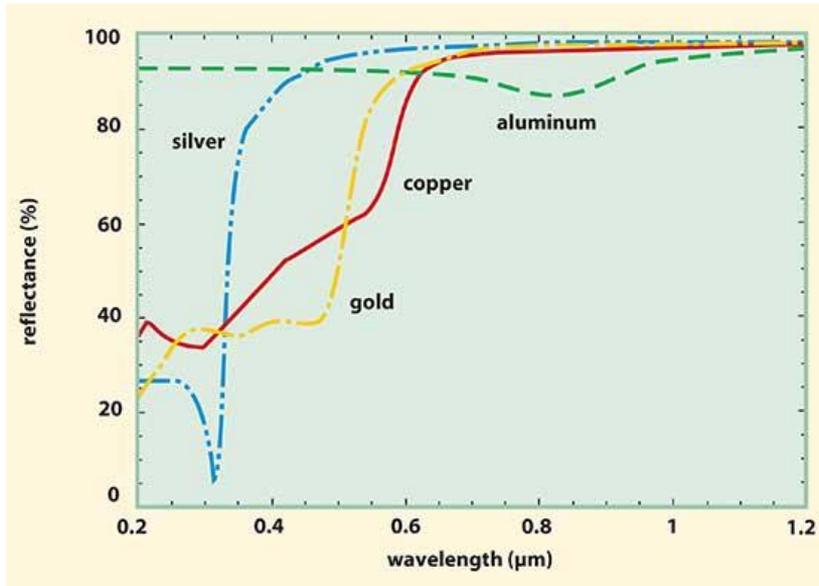


Figure taken from:

https://www.photonics.com/Articles/Mirrors_Coating_Choice_Makes_a_Difference/a25501

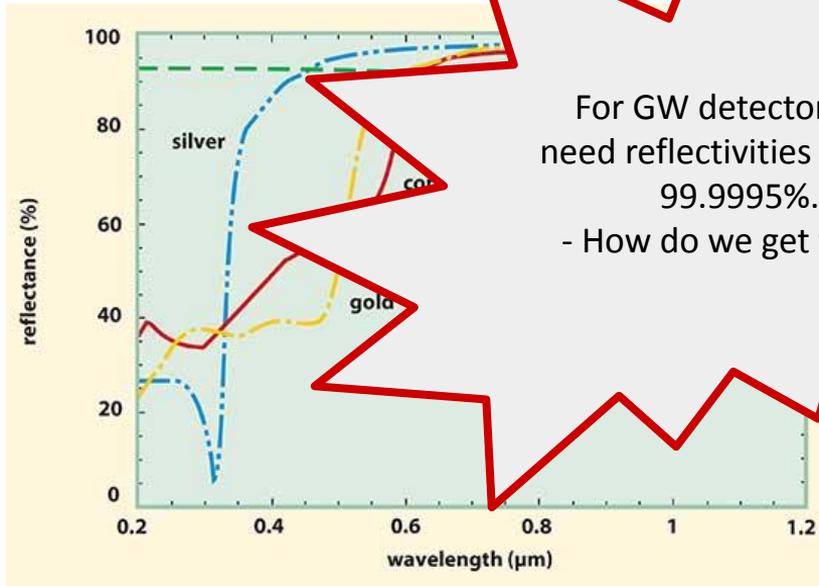


figure taken from:

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For GW detectors, we need reflectivities of up to 99.9995%.
- How do we get there?



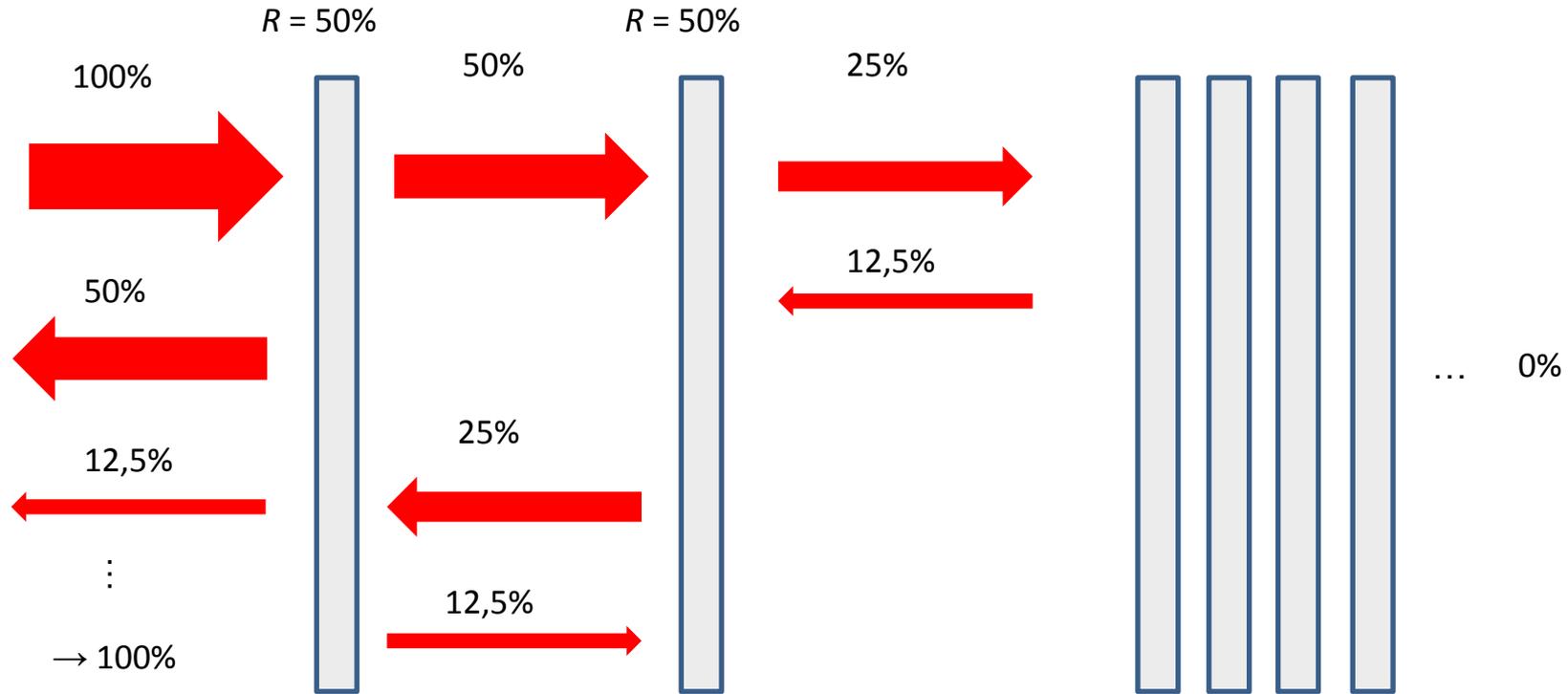
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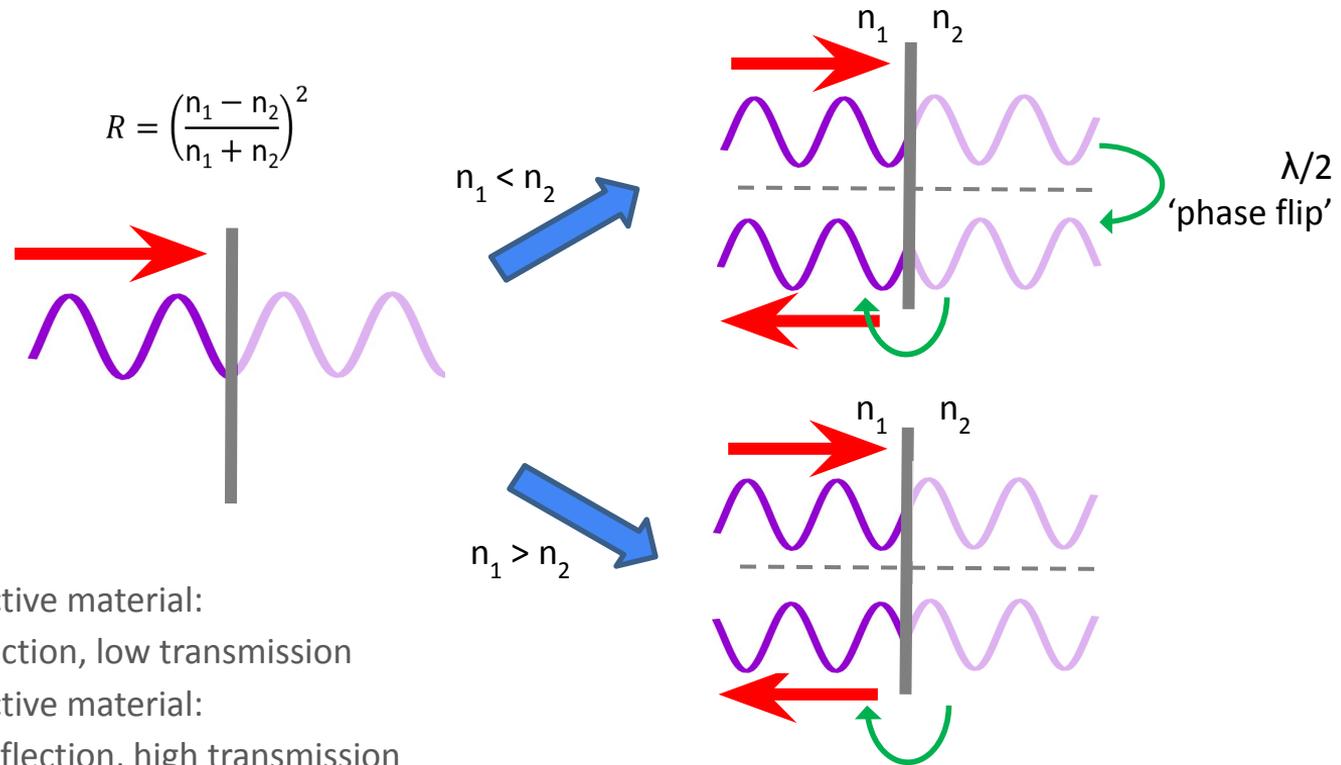
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Lets create a 'pile of mirrors'



Lets zoom in - part I

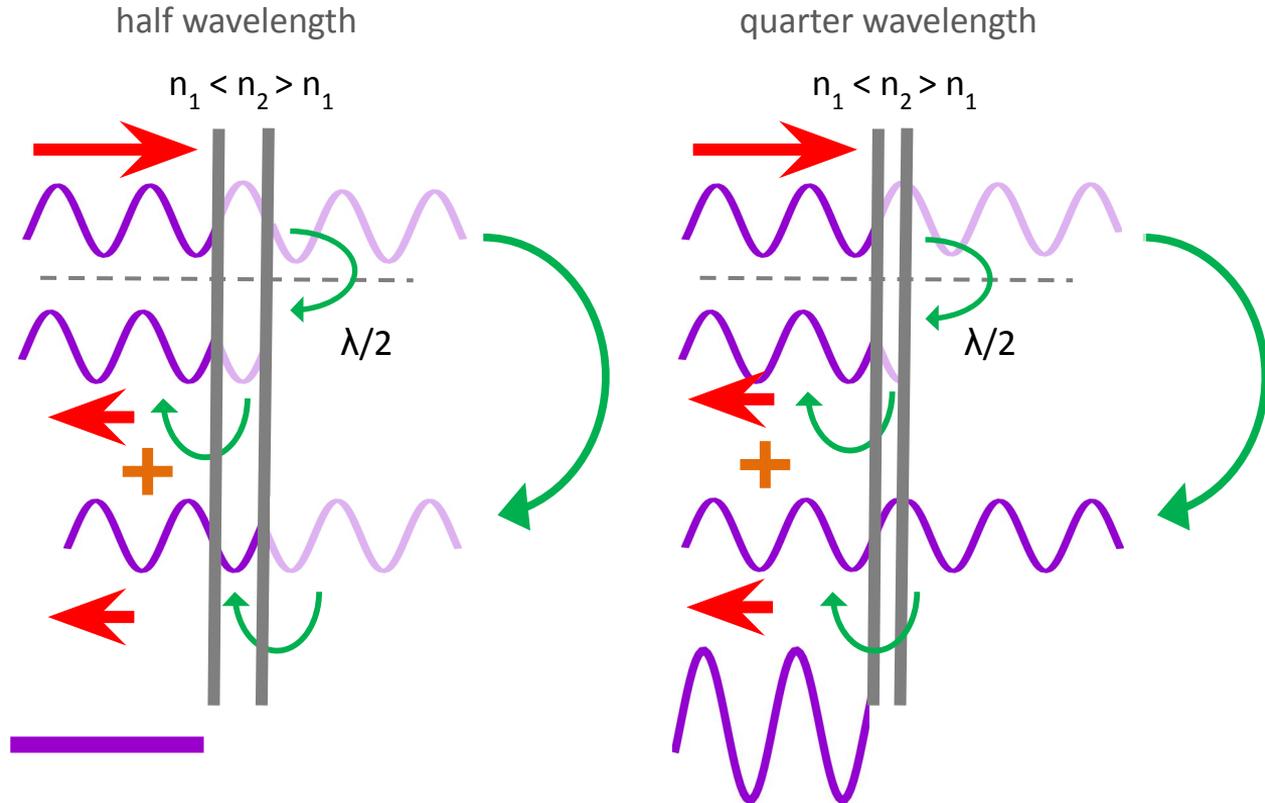


- From low to high refractive material:
phase flip → high reflection, low transmission
- From high to low refractive material:
no phase flip → low reflection, high transmission

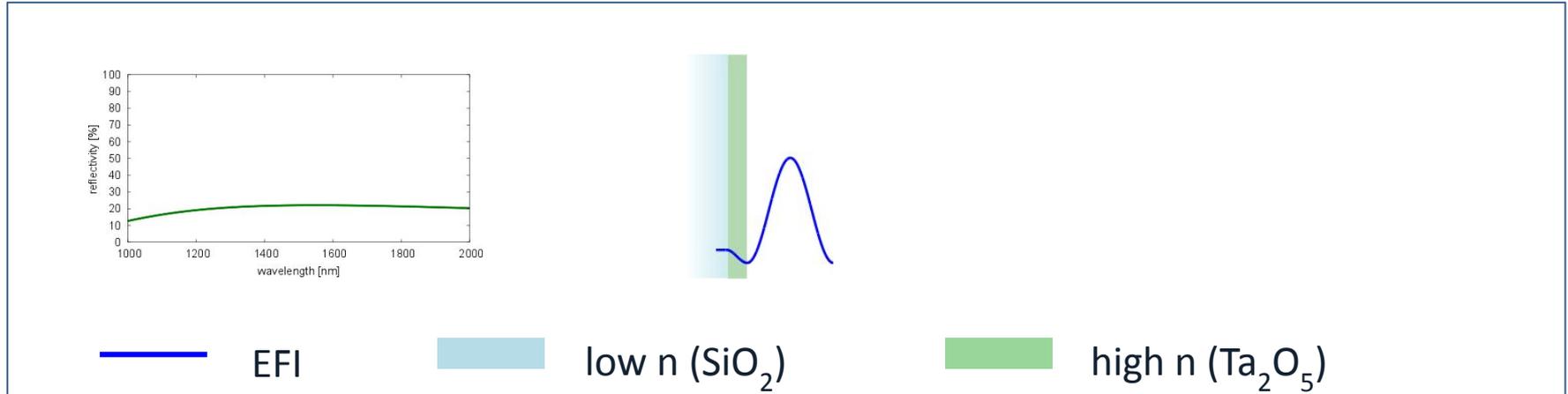
Lets zoom in - part II

Layer thickness:

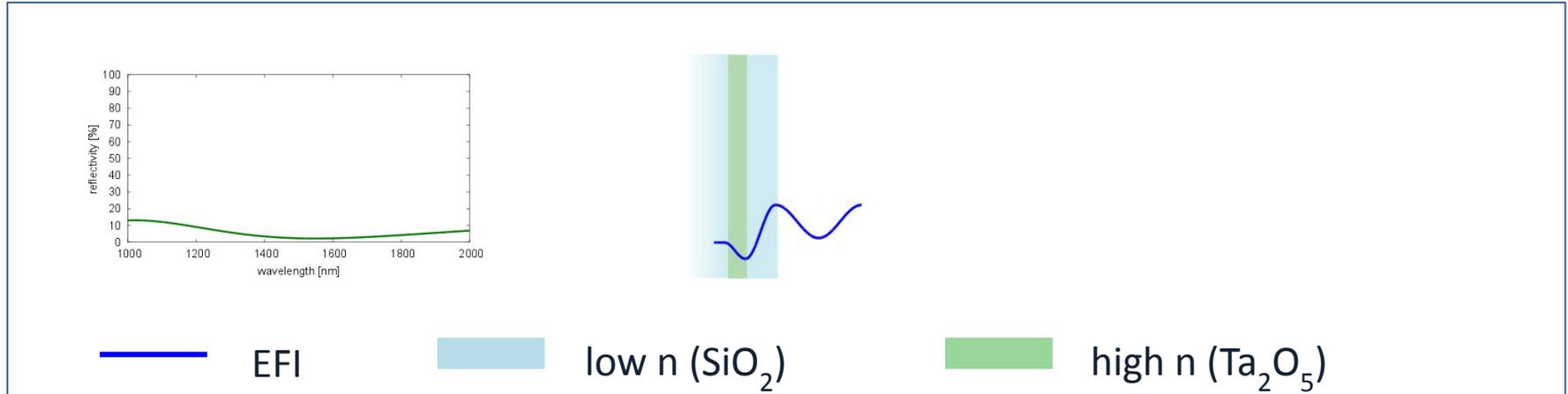
- Half wavelength optical*
layer thickness →
low reflection,
high transmission
- Quarter wavelength optical*
layer thickness →
high reflection,
low transmission



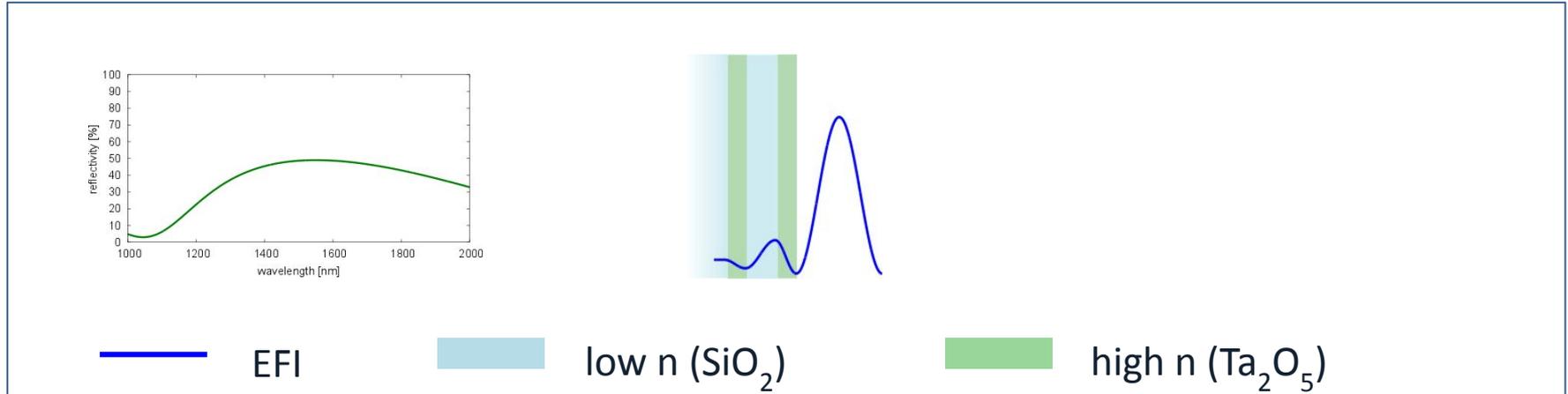
Creating a highly-reflective coating



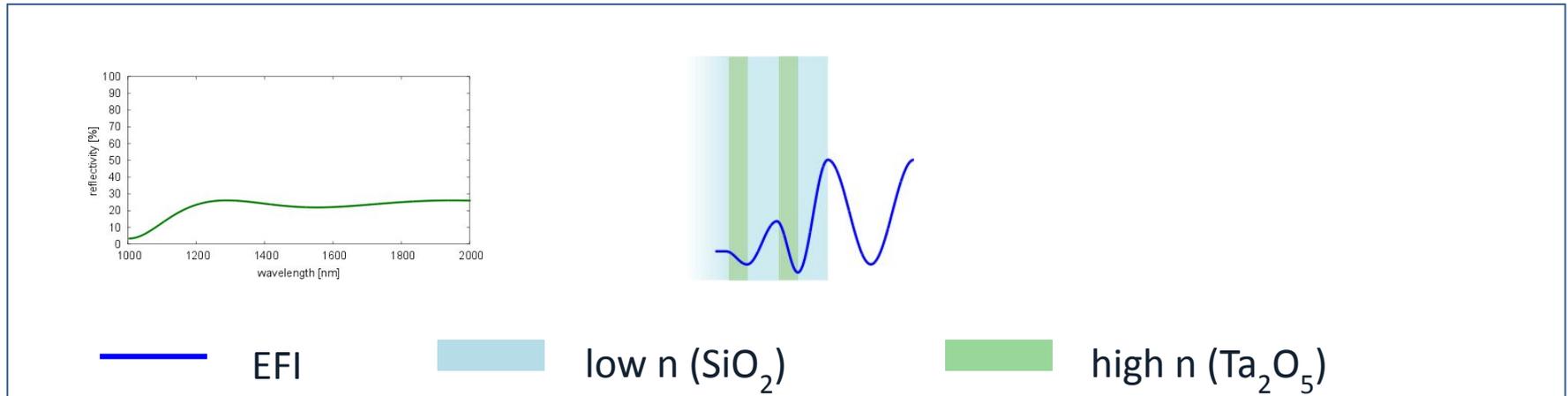
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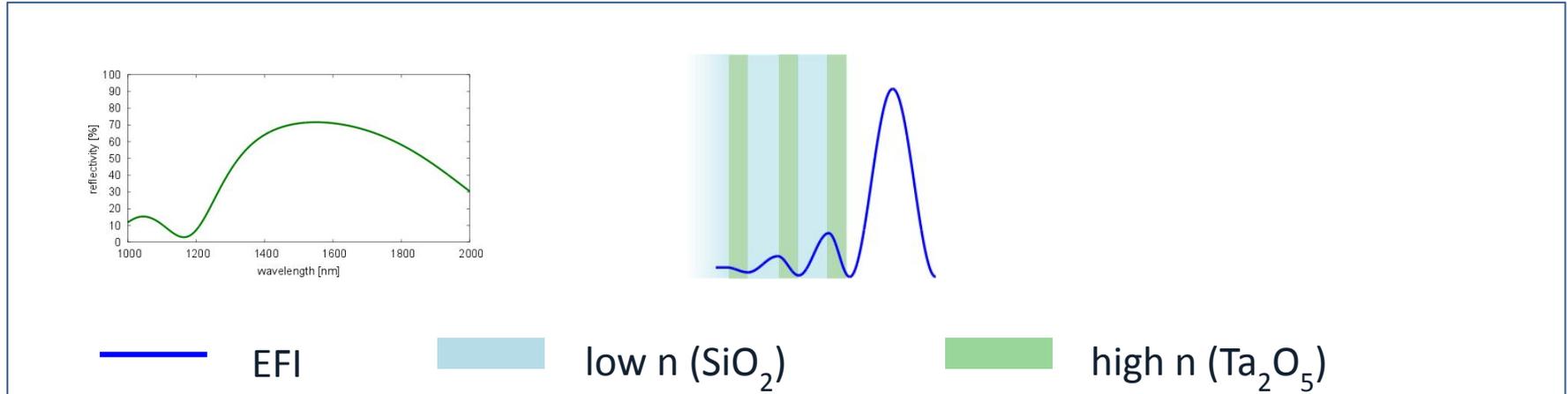
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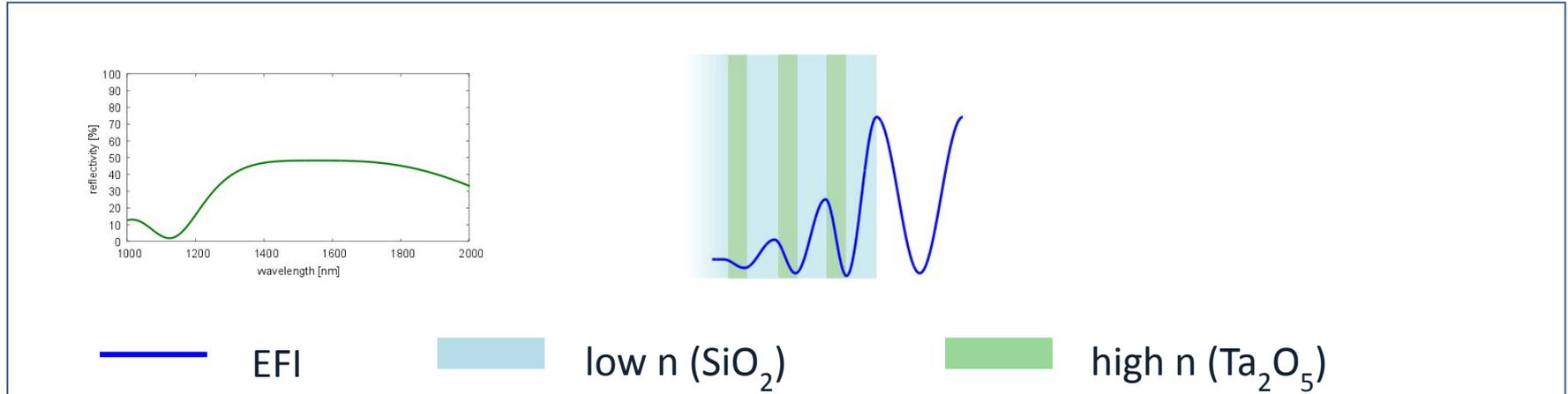
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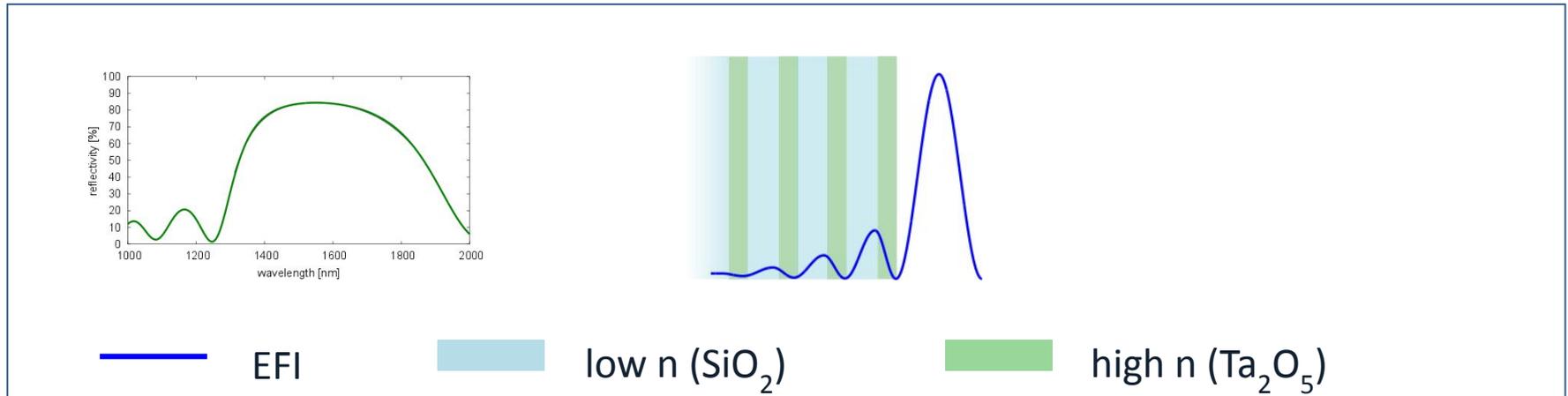
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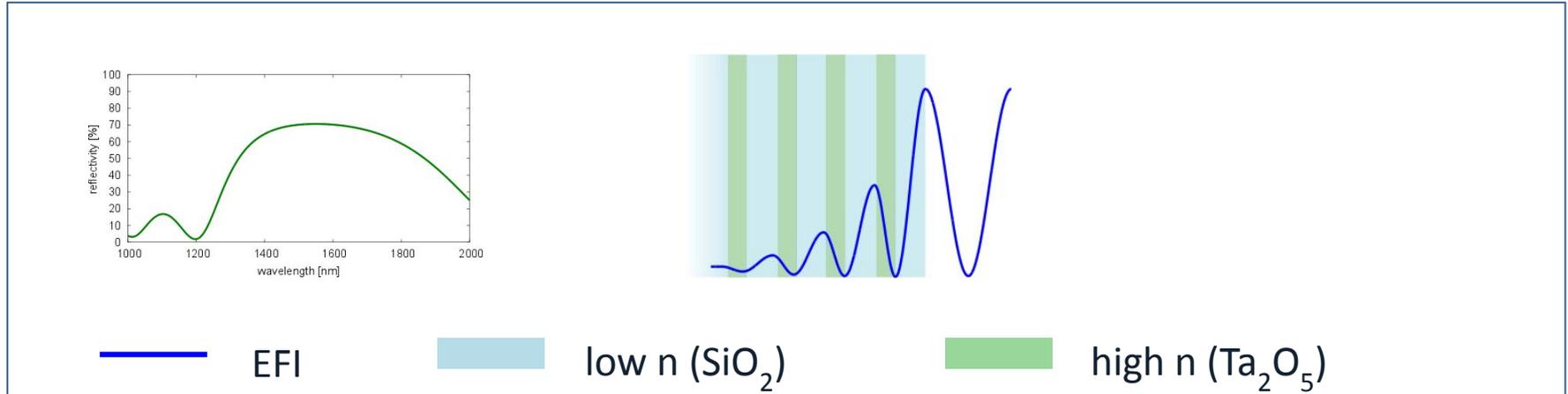
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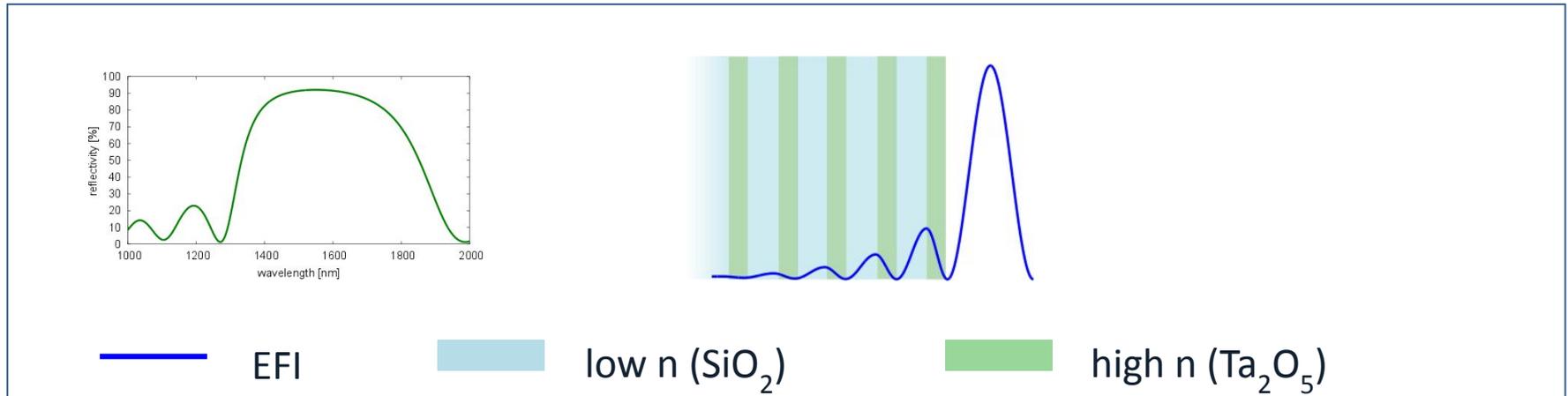
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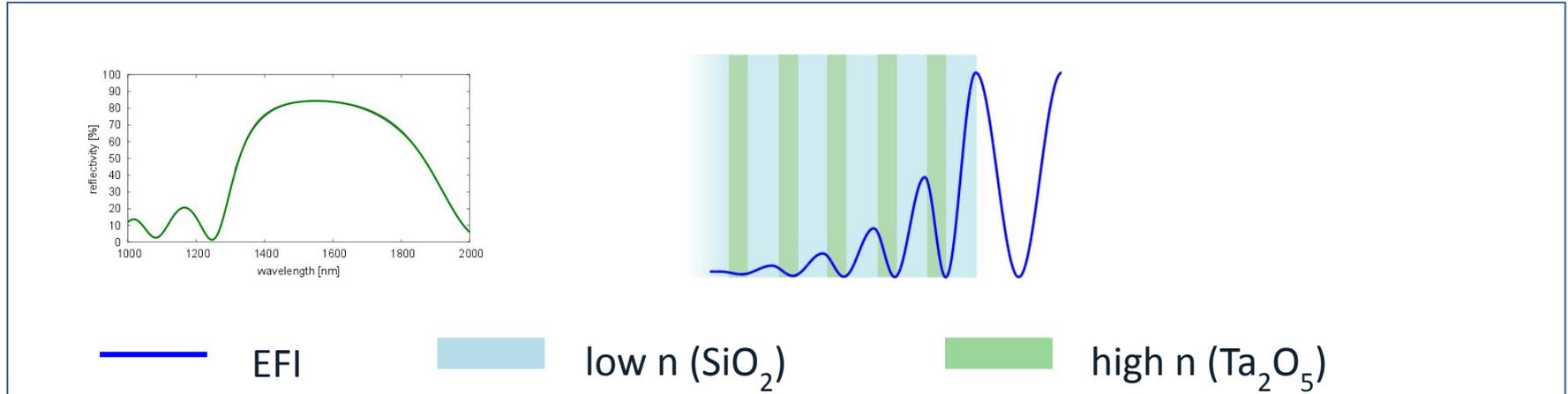
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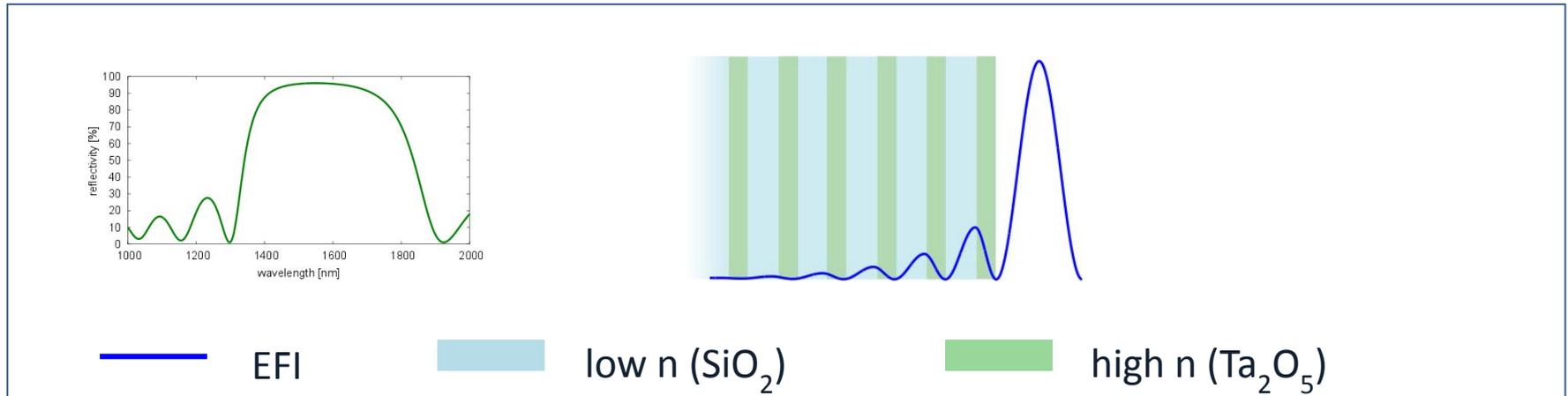
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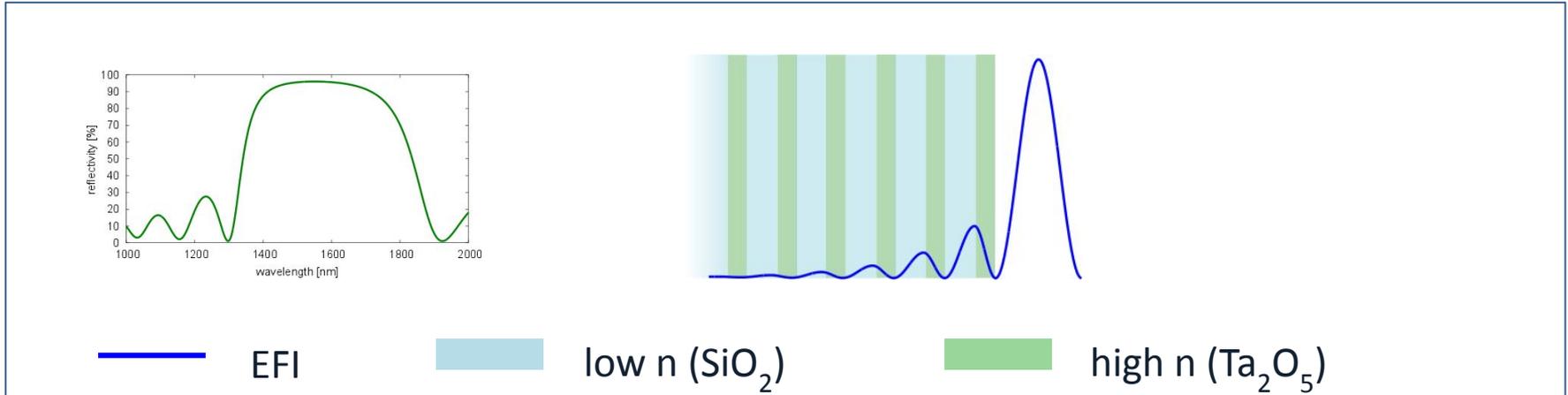


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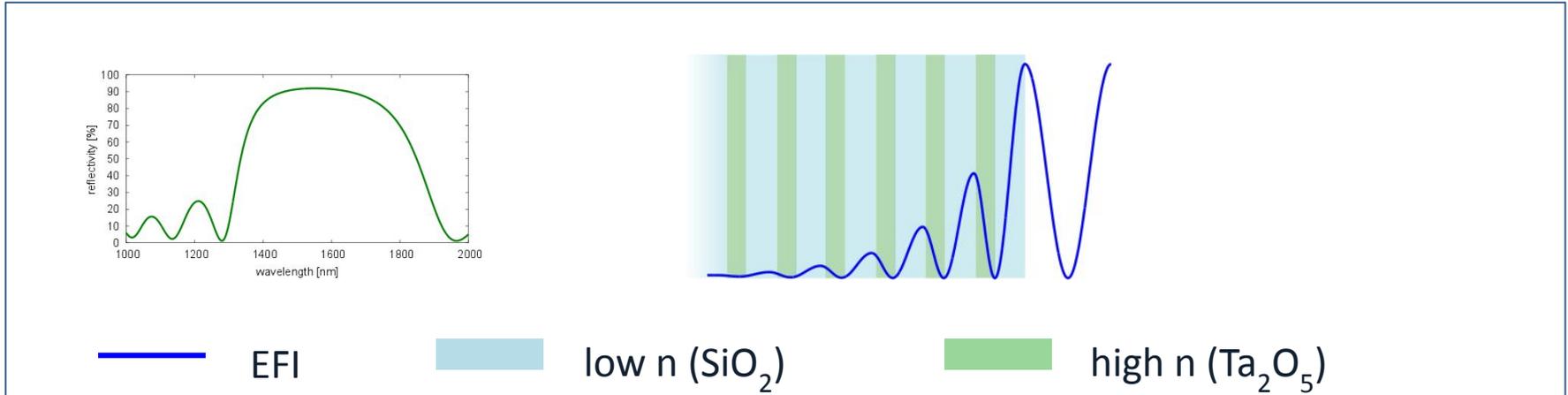
Creating a highly-reflective coating

- Has to be optimized for a specific angle and wavelength
- Number of layers required for a certain reflectivity depends on refractive index contrast of the two materials
- Can in principle reach 100% - limited by optical absorption and scattering



Creating a highly-reflective coating

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- Optical absorption is extremely wavelength, material and deposition dependent: Low absorption is important to avoid laser light loss, heating of the cryogenic mirrors and/or thermal deformations

Summary

- For ET mirrors, we need very high reflectivity of up to 99.9995%
- High reflectivity can be achieved by creating stacks of two alternating materials with different refractive index
 - we need two (or more) materials for a coating
- Reflectivity limitation: absorption and scattering
 - reflectivity of $\sim 99.999\%$ commonly achievable
 - current GW coatings: $\sim 0.25\text{ppm}$ absorption
 - scattering: $\sim 10\text{ppm}$

→ the optical quality is not the main issue!

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... the issue is to achieve low thermal noise in addition.

3. The challenge: Coating thermal noise

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
→ motivation for cryogenic mirrors (at low frequencies)
- Thin coating

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

↖ mirror temperature
↘ mirror temperature (depends on reflectivity and refractive indices)
↗ beam radius (on mirror)
↖ coating mechanical loss

→ materials with low mechanical loss needed

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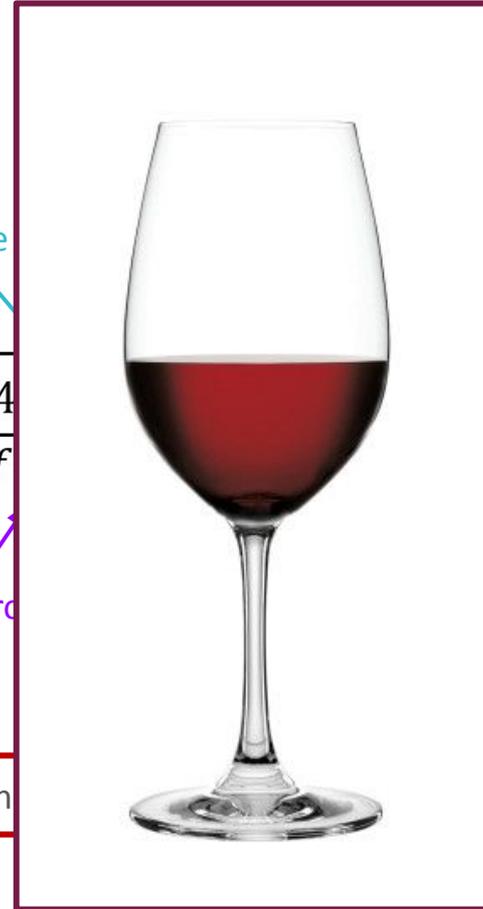
mirror temperature

$$\text{CTN} = \sqrt{\frac{4}{\pi^2 f}}$$

beam radius (on mirror)

ends on
indices)

cal loss



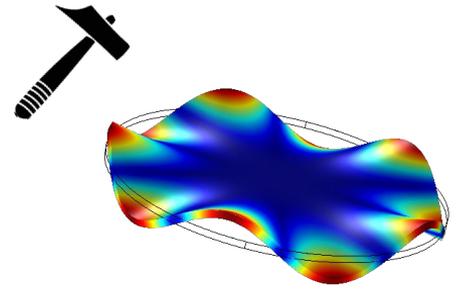
→ materials with low mechanical loss n

Mechanical loss: Measurement procedure

- disk dimensions: 2" or 3", order of 1 mm thick
- loss measurement of uncoated disk
 - several resonance modes
 - 5 - 10 ring downs per mode
 - 'resuspend' disks and repeat, until we have two consistent suspensions
- deposit coating
 - few hundred nm thick
 - repeat measurement procedure
 - calculate coating loss:

$$\begin{array}{c}
 \text{Compute this} \uparrow \\
 \boxed{\phi_{\text{coating}}} = \frac{E_{\text{substrate}}}{E_{\text{coating}}} \left(\boxed{\phi_{\text{coated}}} - \boxed{\phi_{\text{substrate}}} \right) \\
 \begin{array}{l}
 \text{from COMSOL} \rightarrow \\
 \downarrow \text{Measure the COATED substrate} \\
 \downarrow \text{Measure the UNCOATED substrate}
 \end{array}
 \end{array}$$

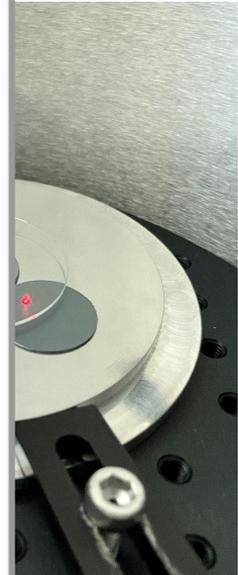
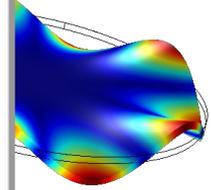
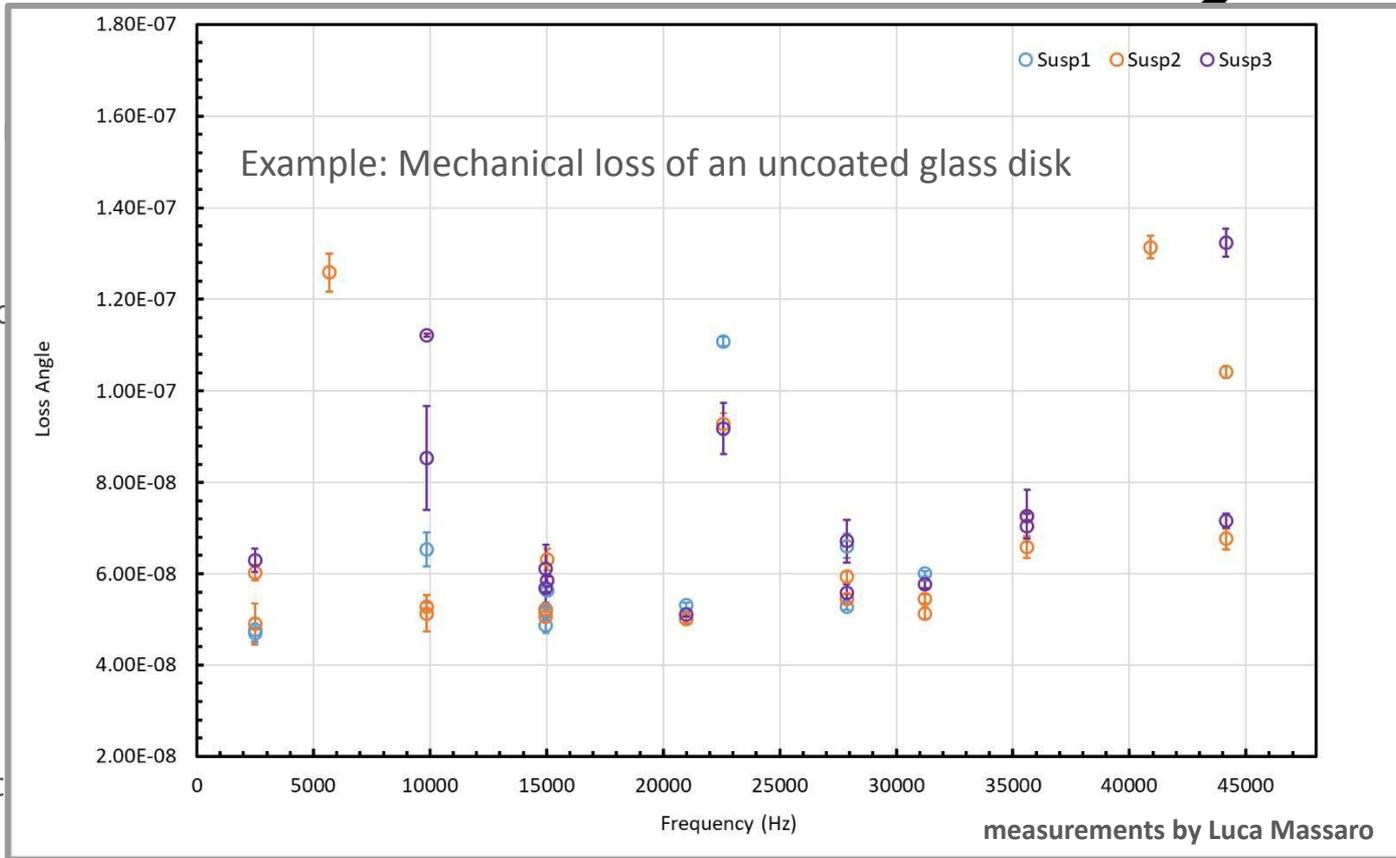
- heat treat coated disk, repeat procedure until the lowest loss is reached



Mechanical loss: Measurement procedure

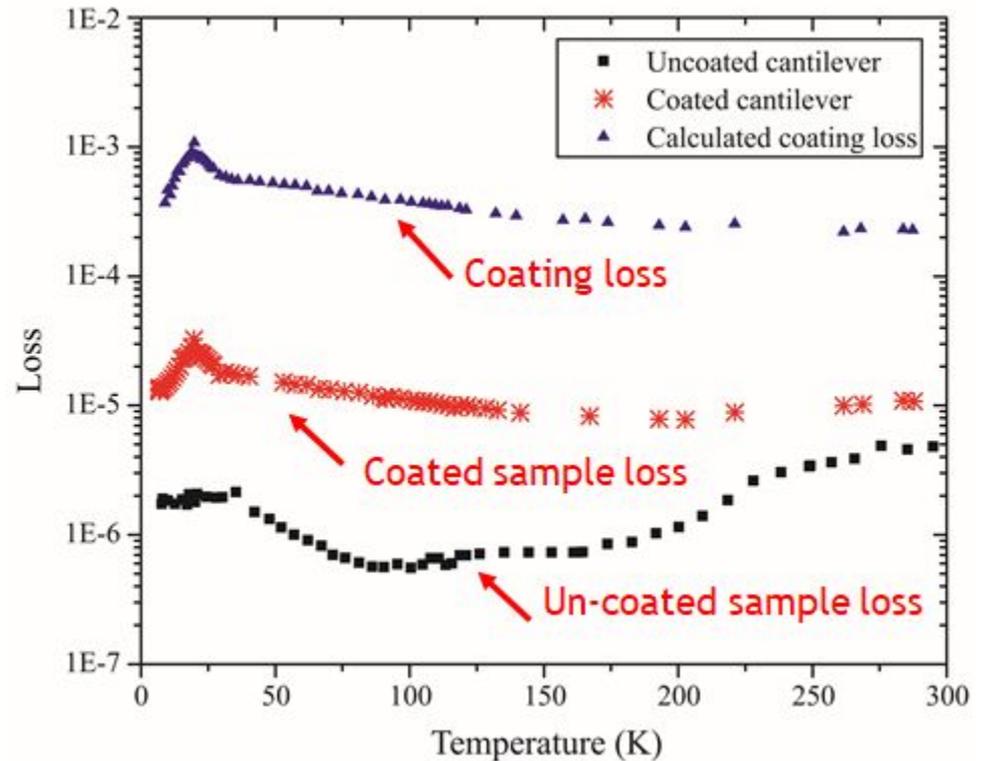


- disk
- loss
-
-
-
- dep
-
-
-
- heat



Temperature dependent mechanical loss

- mechanical loss: strongly temperature dependent material property
- temperature dependent measurement required for each material before and after coating deposition
- each point in this graph represents one full set of measurements as shown in the previous graph
- (cantilever: different substrate geometry)



Summary

- Materials with low mechanical loss are required to reduce CTN
- Mechanical loss is temperature dependent
 - loss measurements in general, and cryogenic measurements in particular, are very time consuming
- The higher the refractive index contrast between the two materials, the fewer layers we need
→ affects d in the CTN equation
- The big challenge is to find materials which have low CTN and also low optical absorption

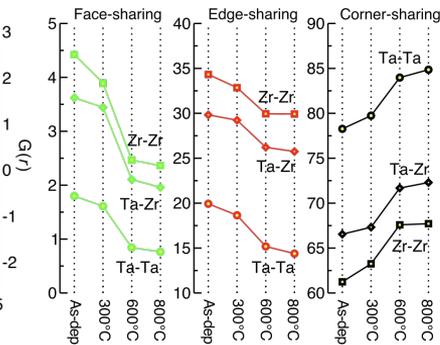
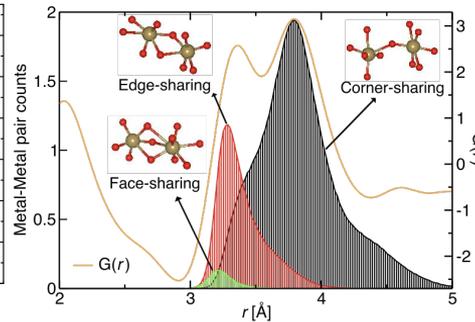
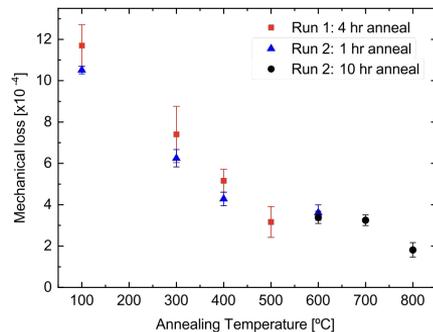
4. Material - options and how to find them

Finding Materials...

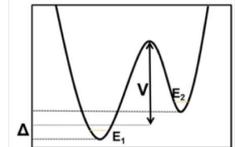
... is a mix of 'trial and error' and of understanding and modelling the structure

Example: Atomic structure characterization and modeling

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



Two Level System (TLS model)



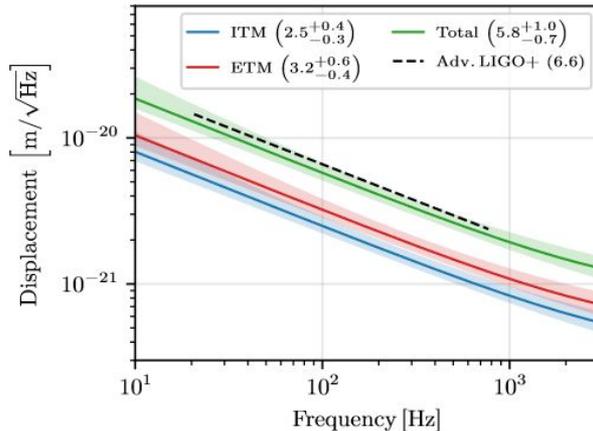
- Led to hypothesis that TLS contributing to room temperature loss involves edge- and face-shared polyhedra
- Materials with low ES and FS, and mostly CS structures should result in low RT loss, e.g. SiO_2 , GeO_2

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

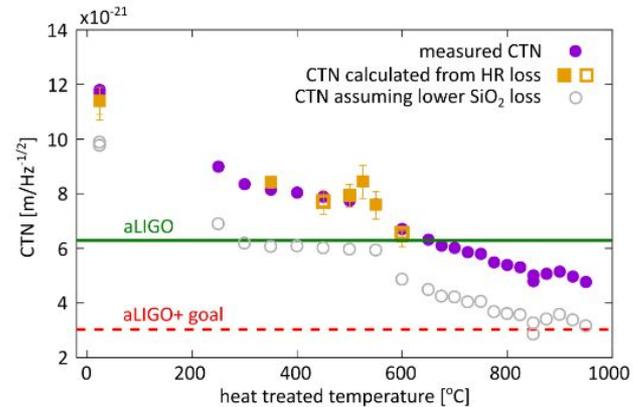
Coating Development

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
 - Slightly 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](#)



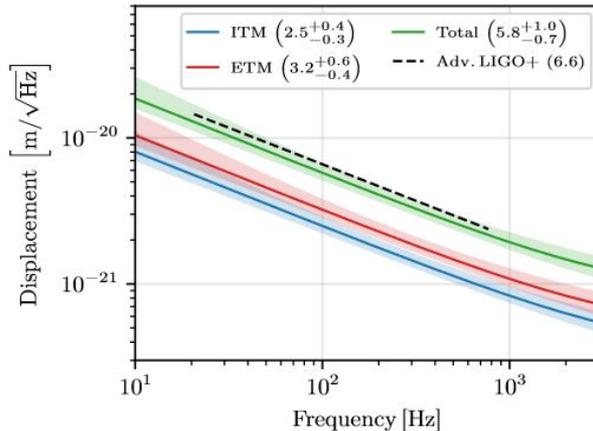
[McGhee, Phys. Rev. Lett., 131:171401, 2023](#)

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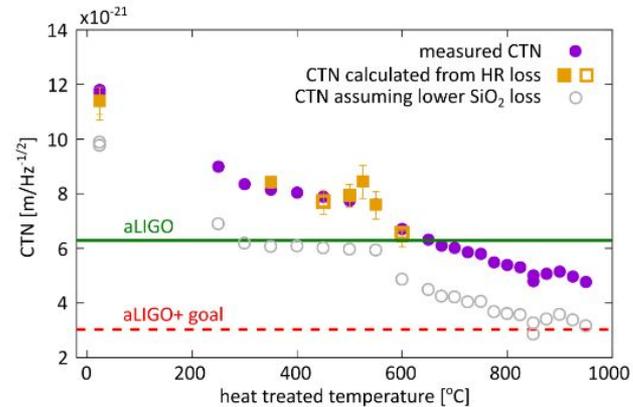
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Coatings meeting the requirements of LIGO/Virgo upgrades:
Also suitable for ET-HF ('room temperature ET')



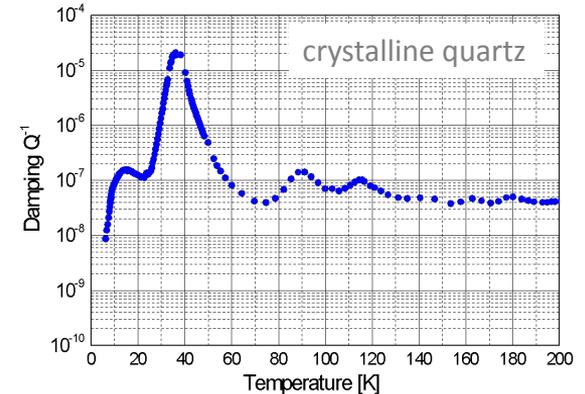
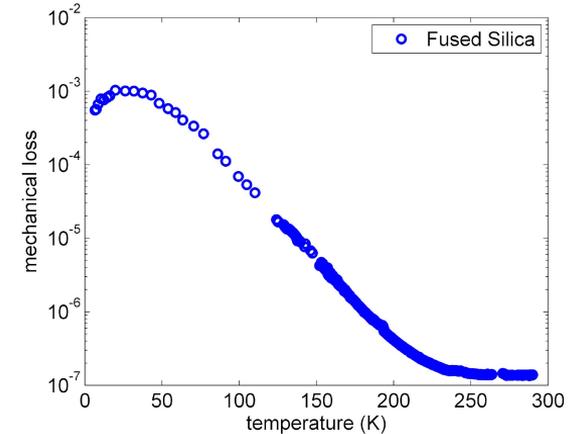
[Vajente, Phys. Rev. Lett., 127:071101, 2021](#)



[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 SiO₂ 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](#)
- Implantation of layers into the crystalline substrate via ion implantation
- ...

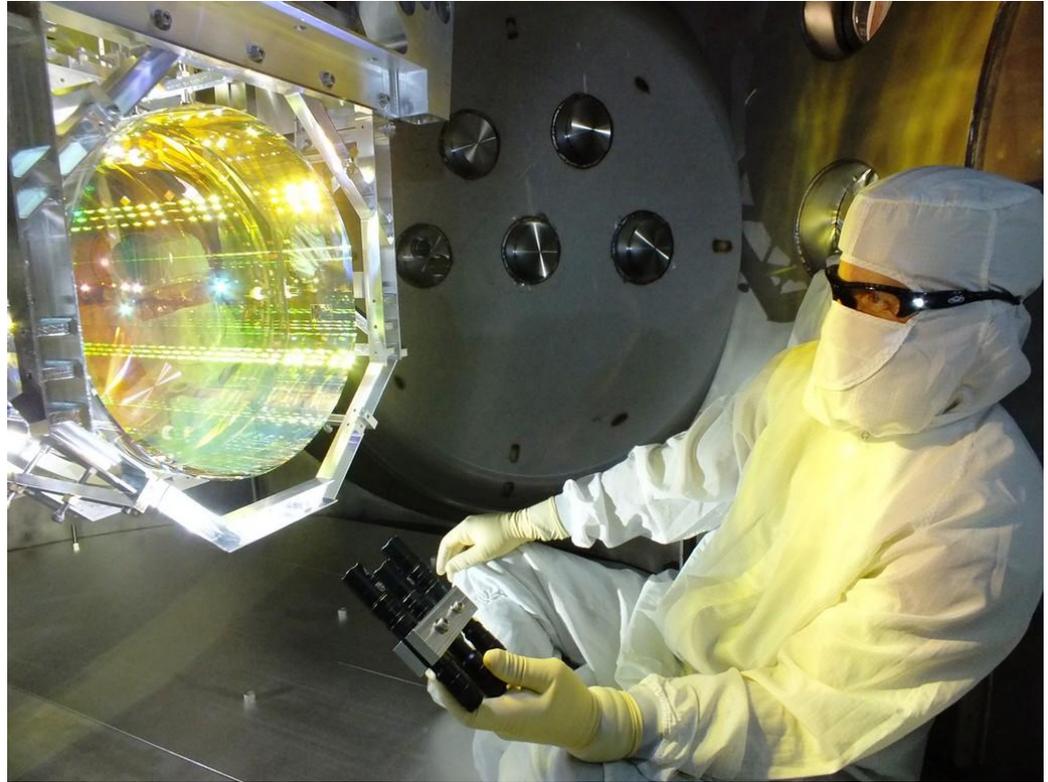


[Schroeter, arXiv:0709.4359, 2007](#)

Current Coatings

- Mirrors for current detectors:
 - made of amorphous materials
 - coated by [LMA, Lyon](#) via ion beam sputtering
 - lowest absorption & thermal noise coatings world wide

- Future mirrors:
 - LMA very strong candidate for coating of ET mirrors
 - Other facilities being created for large mirror coatings, e.g. EPOC in Scotland
 - Possibility of crystalline coatings
→ require different ways of coating production and bonding



Advanced LIGO ITM, image credits: [LMA, Lyon](#)

Summary

- Finding materials: Mix of 'trial and error' and of structural research and modelling
 - many material options

- Current coatings are made of two alternating amorphous materials
 - In the future, this could be more than two materials, crystalline coatings, hybrid coatings, or other structures in the mirrors

- Not only the material and its structure is relevant, but also the deposition parameters and facility
 - coating deposition is an 'art'
 - not any coating chamber can produce good coatings and measurements are time consuming: we have to choose carefully what is worth getting investigated

5. Coatings work in Maastricht

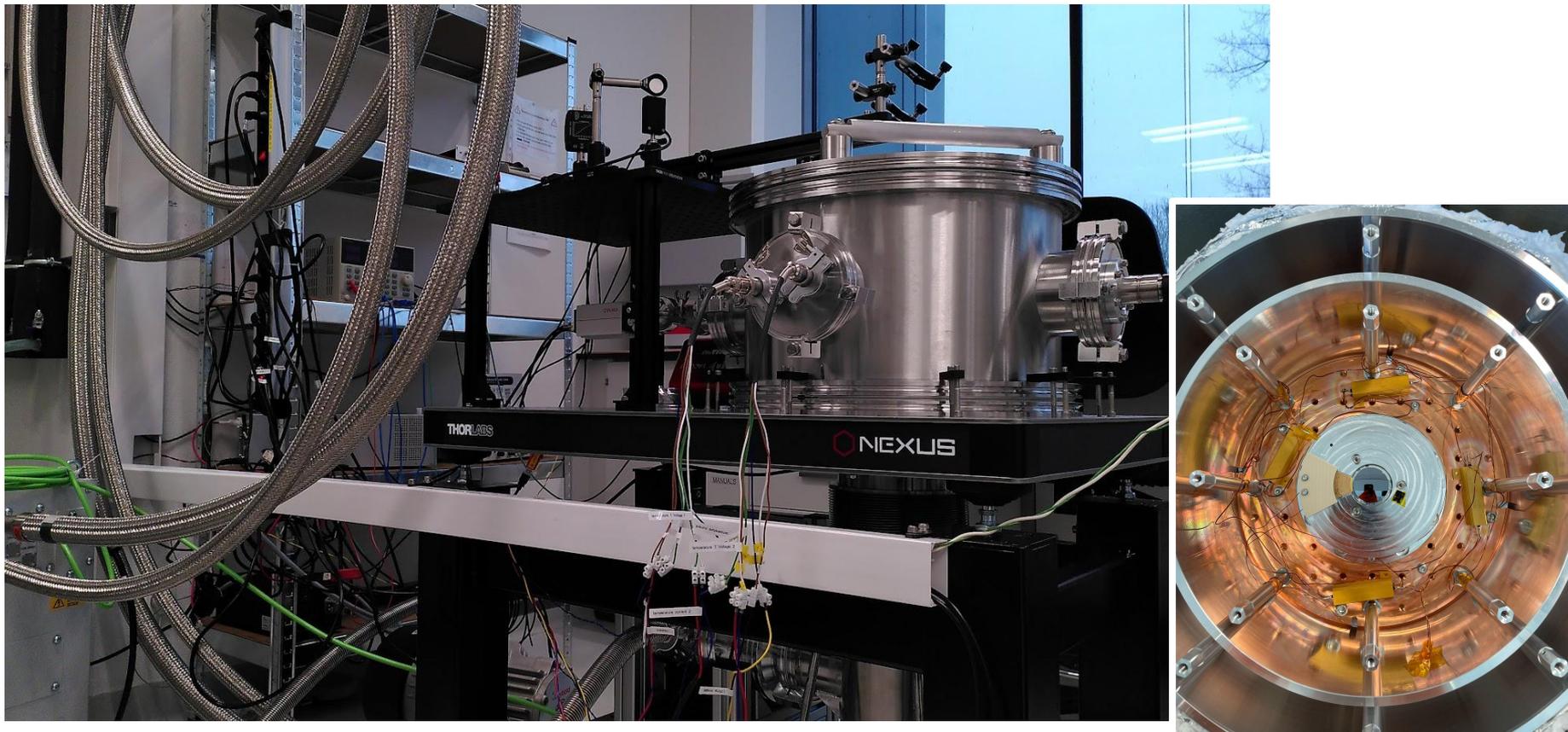


Coatings work in Maastricht

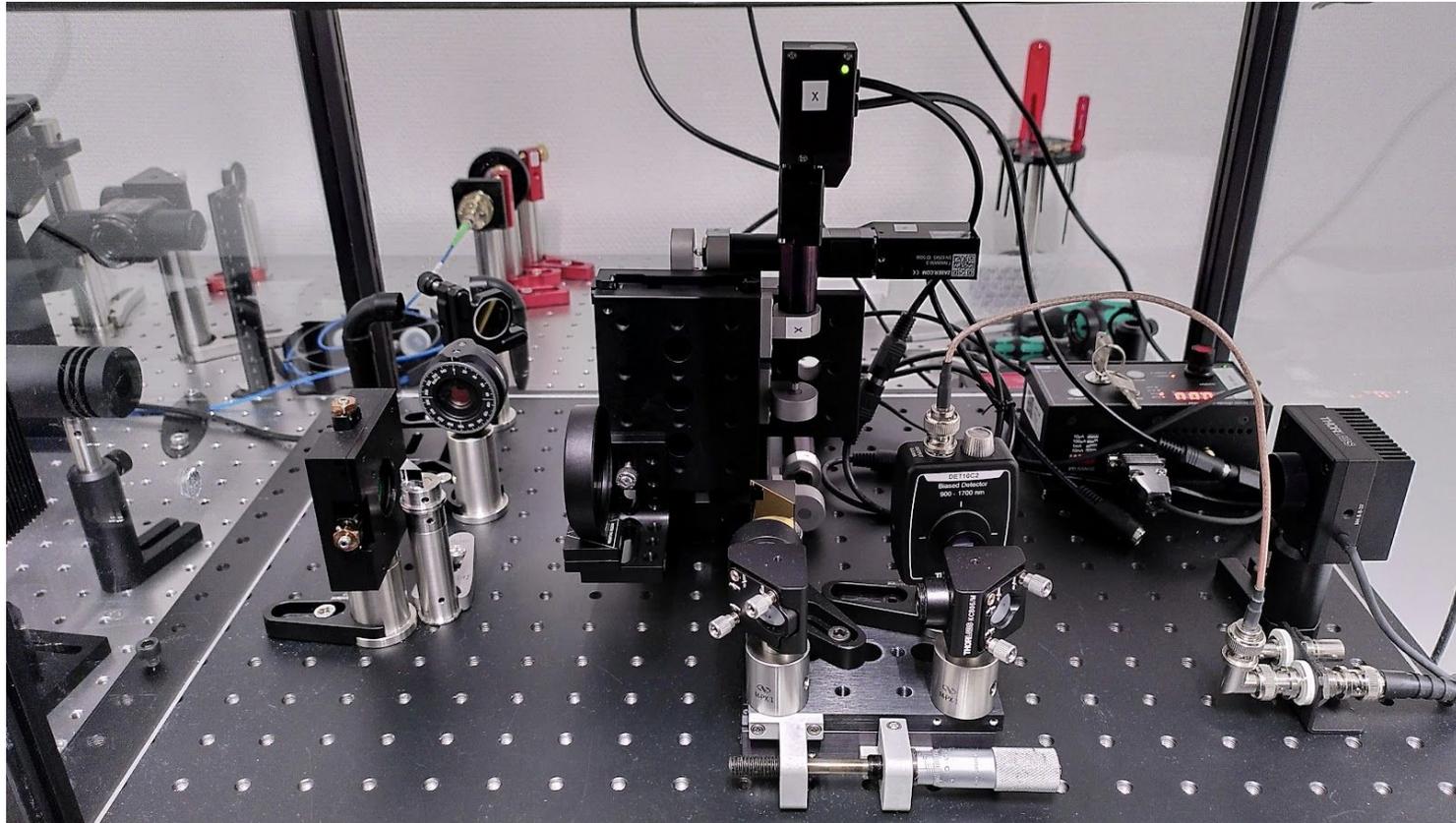
- Characterization of new materials for LIGO, Virgo and ET (no production)
 - amorphous and crystalline materials
 - mechanical loss: room temperature & cryogenics
 - optical absorption
 - refractive index and layer thickness
 - density
- development of new coatings designs
 - multimaterial coatings
 - crystalline toplayer
- investigation of ion implantation
 - implantation of O or N ions into silicon to create highly-reflective structures, replacing coatings
- investigation of ice growth on cryogenic mirrors

World wide collaboration: >50 groups, including several hundred scientists, working on coatings for GW detectors!

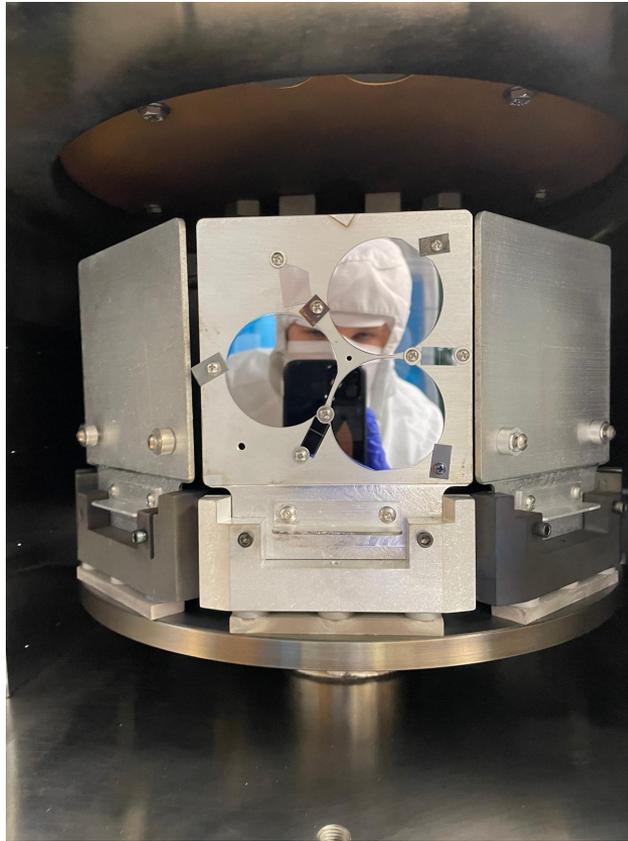
Our Cryostat



Our Optical Absorption Setup

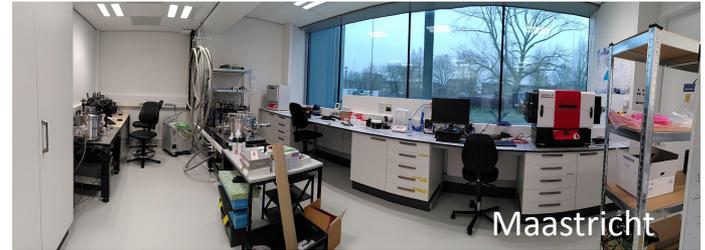


Our Ion Implanter...



... the 'California Lab'

Ion Implanter



Thank you!